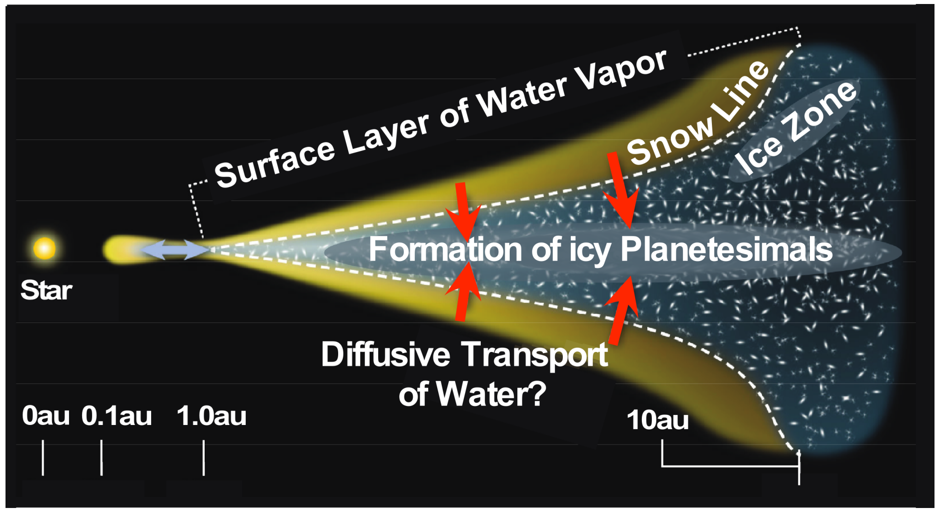
Key Open Questions in the Far-Infrared/Submillimeter Achievable with SOFIA

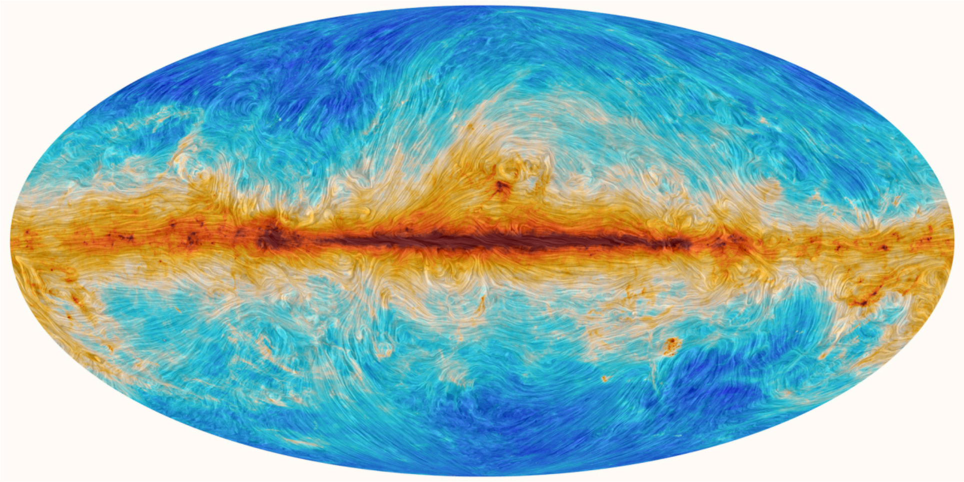
Within the Next Few Years

Gary Melnick
Harvard-Smithsonian Center for Astrophysics
November 14, 2017

To eliminate all suspense…

- Properties of protoplanetary disks
- The role of magnetic fields in star formation
- Abundance gradients across the Galaxy





Protoplanetary Disks

Key questions…

- What is the total gas mass in disks?
- How much water is there in disks – in both gas and ice – and available to forming planets?

Why do we want to know the total gas mass in disks?

1) The most fundamental quantity that determines whether planets can form is the protoplanetary disk mass; forming planetary systems like our own require a minimum disk mass of ~0.01 $M_\odot$.

2) We want to know the timescale for planet formation, which we believe is tied to the gas dissipation timescale.

3) We want to know the ‘true’ abundance of gas-phase species.

Problem #1:

H_2 is the dominant gas-phase species in disks, but its high 1st excited state, E_{ul}/k (H_2, J=2–0), is 510 K above the ground state, makes H_2 a very poor emitter within $T_{gas} < 100$ K.

Why do we want to know the total gas mass in disks?

Problem #2:

Usually, we observe CO as a proxy for H_2 (and multiple x 10^4), but CO emission is dominated by the warm surface layers and there's evidence that CO is frozen out in the disk mid-plane.

Problem #3:

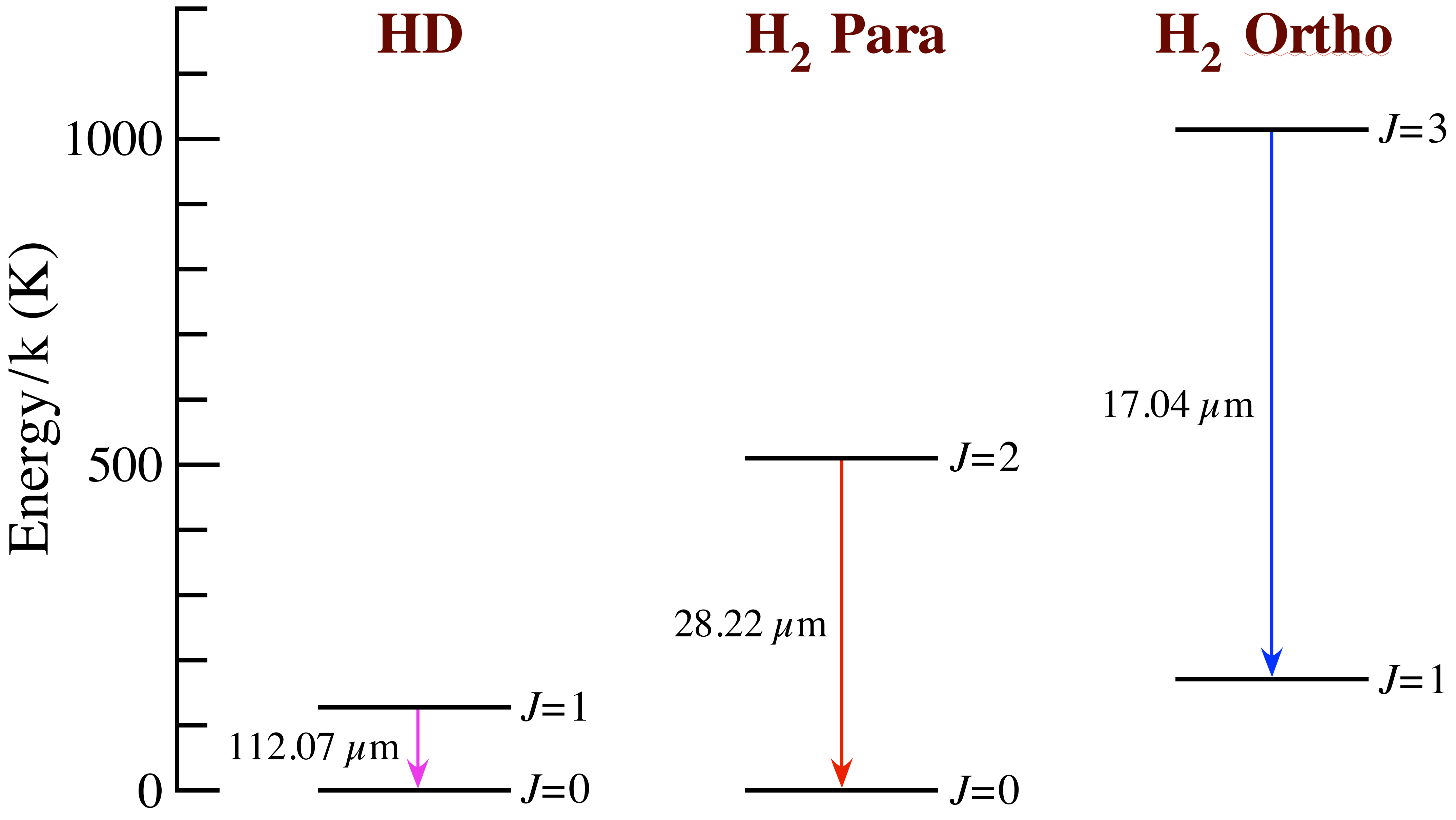
At sub-mm/mm wavelengths the dust emission is optically thin, probing the disk dust mass.

With an assumed dust opacity coefficient and the ratio of the dust-to-gas mass, derive the disk gas mass from the dust mass.

A variety of sensitive observations have demonstrated that grains have likely undergone growth to sizes 1 mm to 1 cm (at least) in many systems.

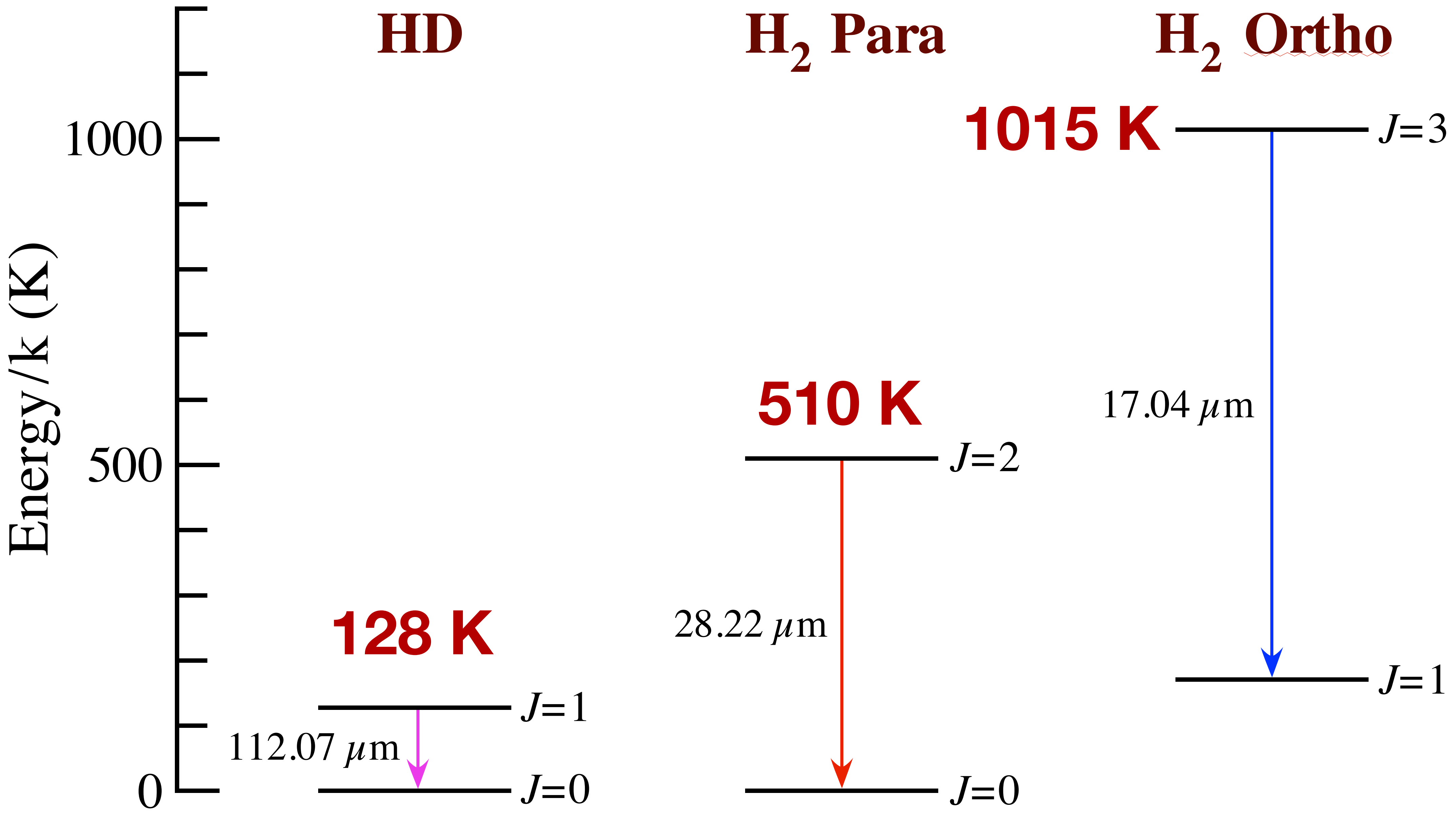
Thus, the dust opacity is uncertain and the gas-to-dust ratio is likely variable.

The solution lies in observing HD in the far-infrared

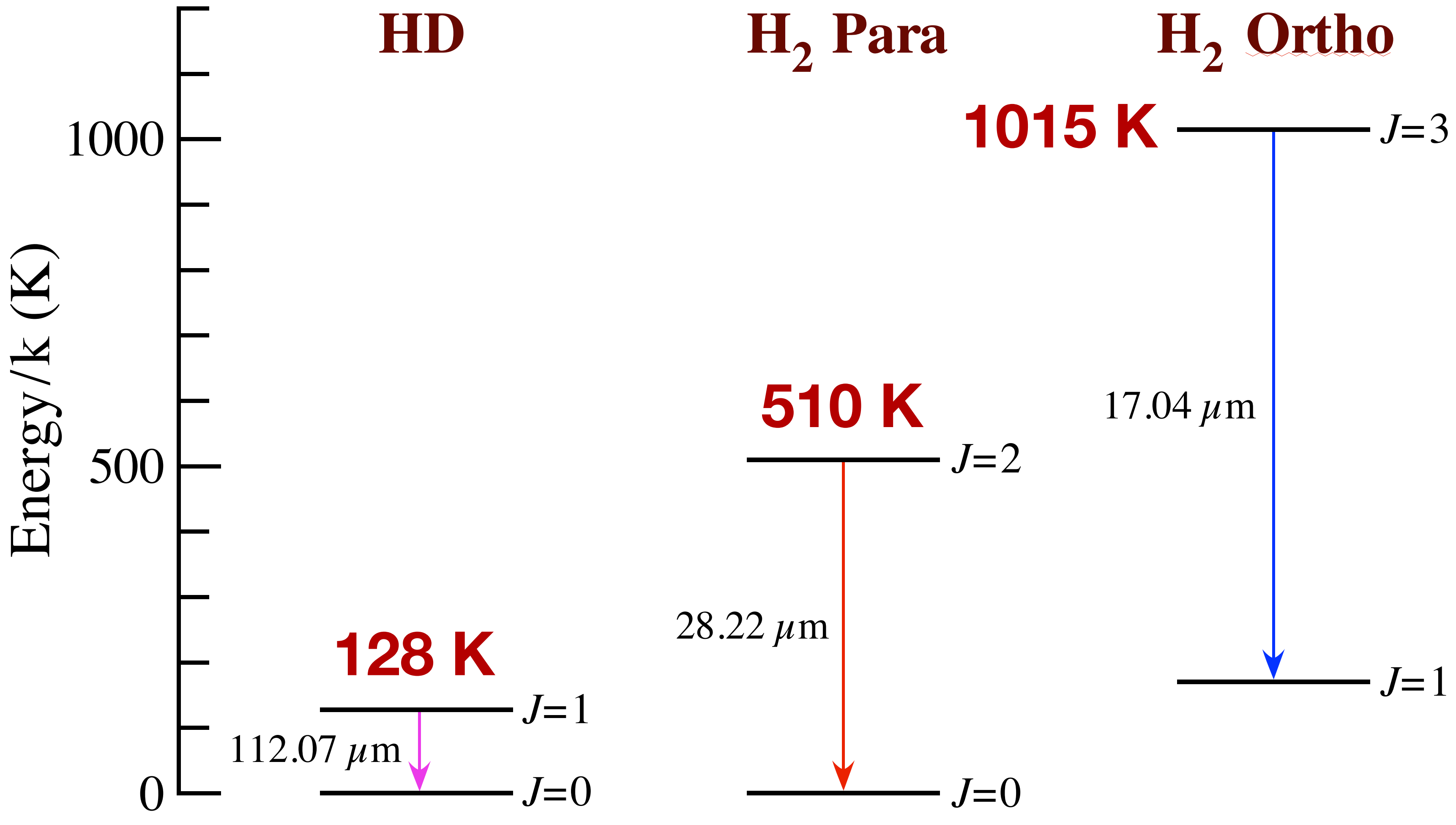


Unlike CO, HD and H_2 are only weakly bound on the cold (T~10 – 20 K) dust grains that reside in the mass carrying disk midplane.

The solution lies in observing HD in the far-infrared



HD's lower energy above the ground state, E_u/k, makes it more readily excited in cold gas than H_2.



For optically thin emission: $I = A_{ul}\, h\nu\, N_u / 4\pi$

A_{ul} 5.4 x 10^{-8} s^{-1} 2.9 x 10^{-11} s^{-1} 4.8 x 10^{-10} s^{-1}

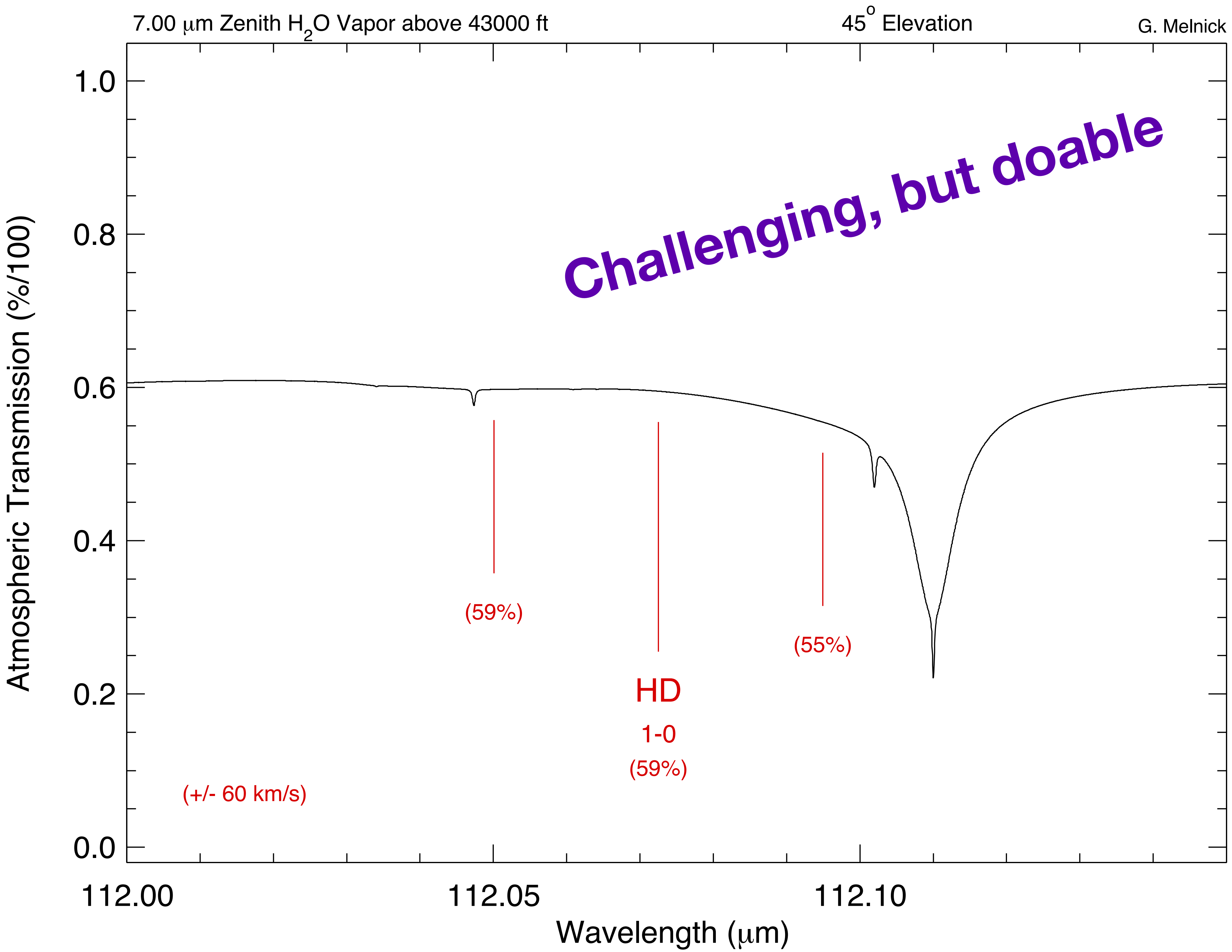
$N_u = f_u N_{total}$

$f_u(\mathrm{HD}\ J=1) \sim 3 \exp(-128.5/T_{gas})$ $f_u(\mathrm{H_2}\ J=2) \sim \exp(-510/T_{gas})$

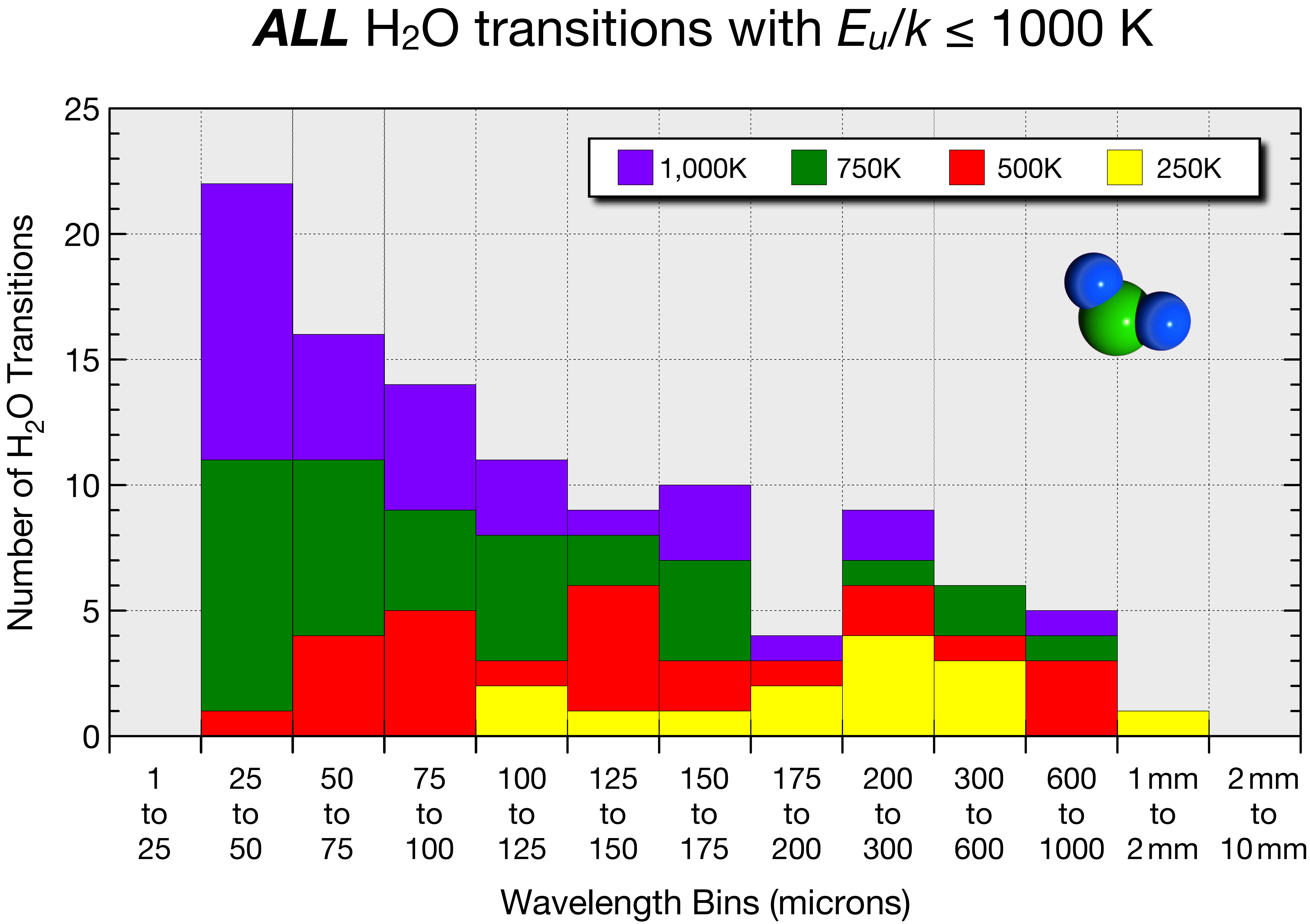
At 25 K, $f_u(\mathrm{HD}\ J=1) > 10^7\ x\ f_u(\mathrm{H_2}\ J=2)$; $A_{ul}\,(HD) > 1800\ x\ A_{ul}\,(H_2)$

Even with [HD/H_2] ~ 3 x 10^{-5}, *I*(HD) > 700,000 x *I*(H_2) at 25 K

Atmospheric transmission around the HD *J*=1-0 line

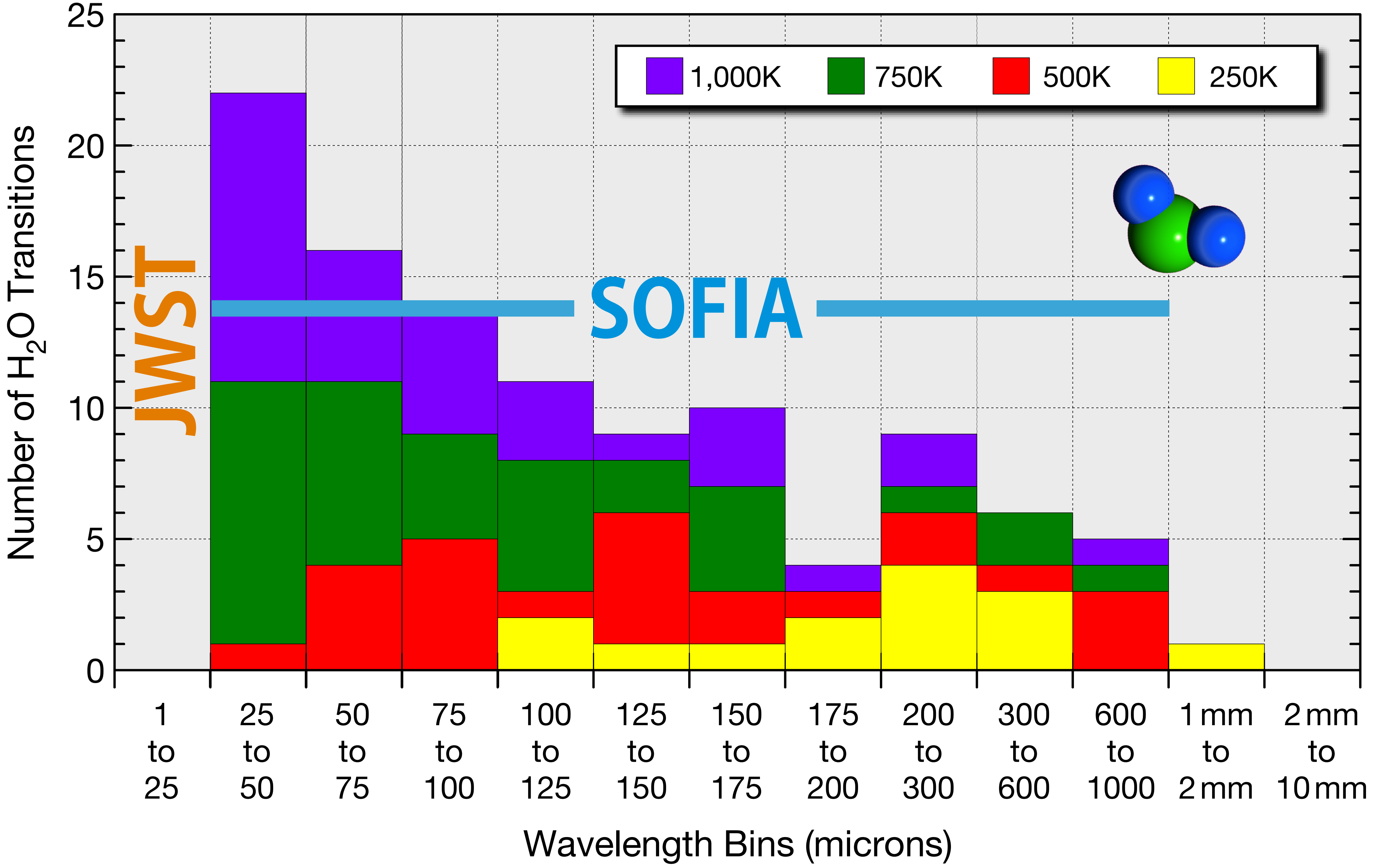


Water content of disks…

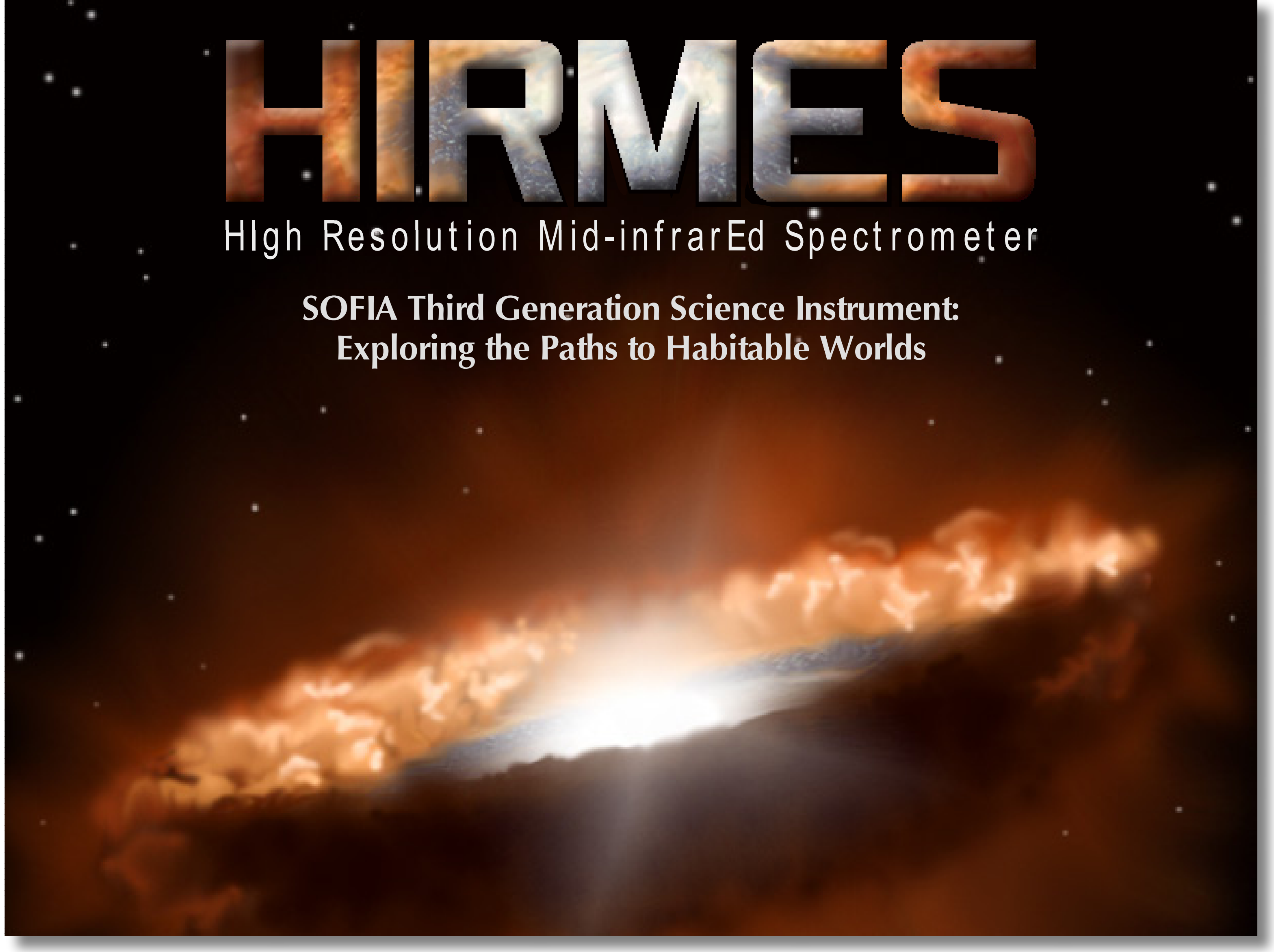


Water content of disks…

106 of 107 H_2O transitions with $E_u/k \leq 1000$ K
lie between 25 µm and 1mm



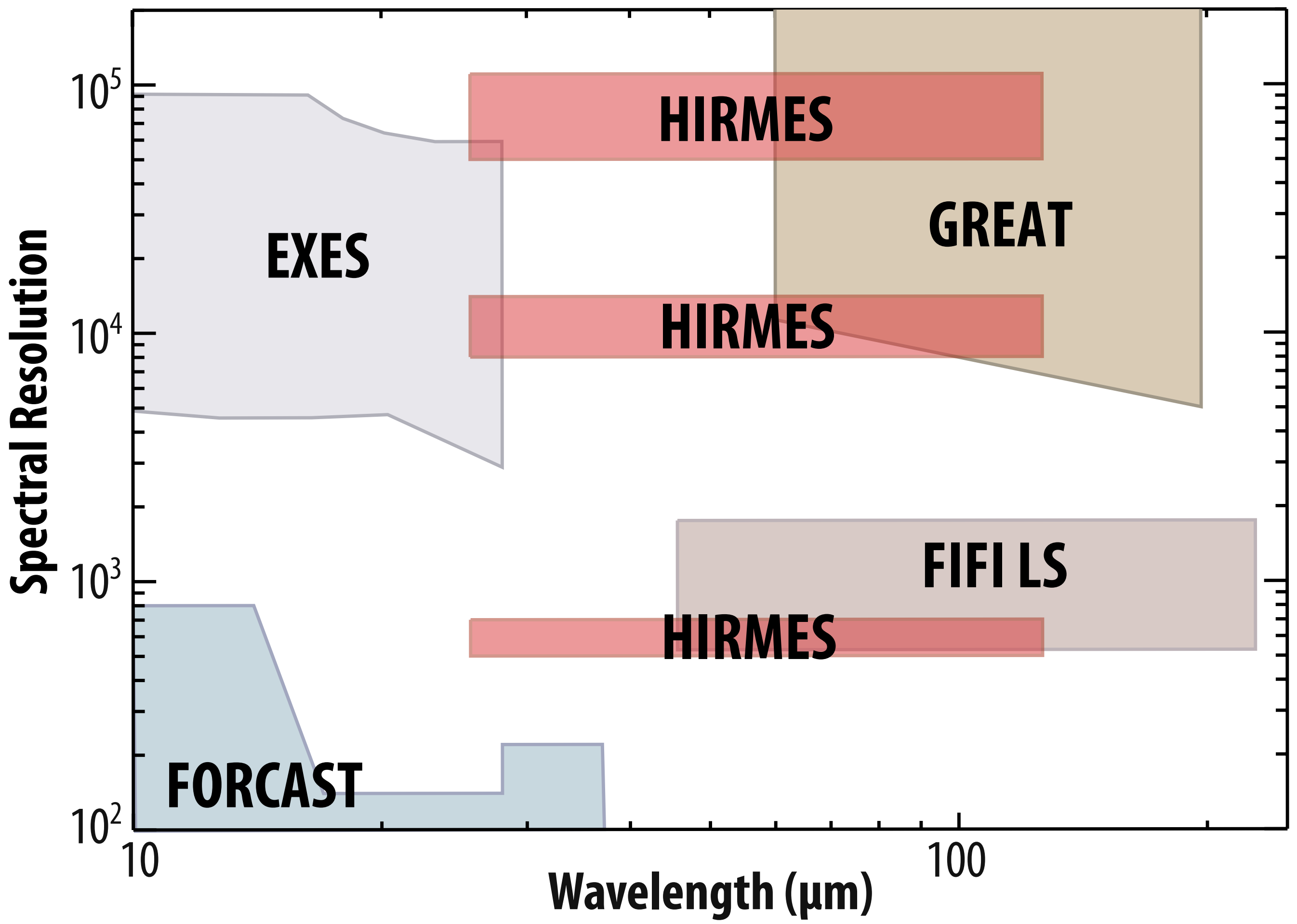
Unfortunately, not all of these transitions are observable by SOFIA



Selected by NASA, September 7, 2016

Harvey Moseley	GSFC	PI
Alexander Kutyrev	GSFC	Deputy PI
Ted Bergin	UMichigan	
Gordon Bjoraker	GSFC	
Gary Melnick	CfA	
Stafanie Milam	GSFC	
David Neufeld	JHU	
Klaus Pontoppidan	STScI	
Aki Roberge	GSFC	
Gordon Stacey	Cornell	
Dan Watson	Rochester	
Ed Wollack	GSFC	

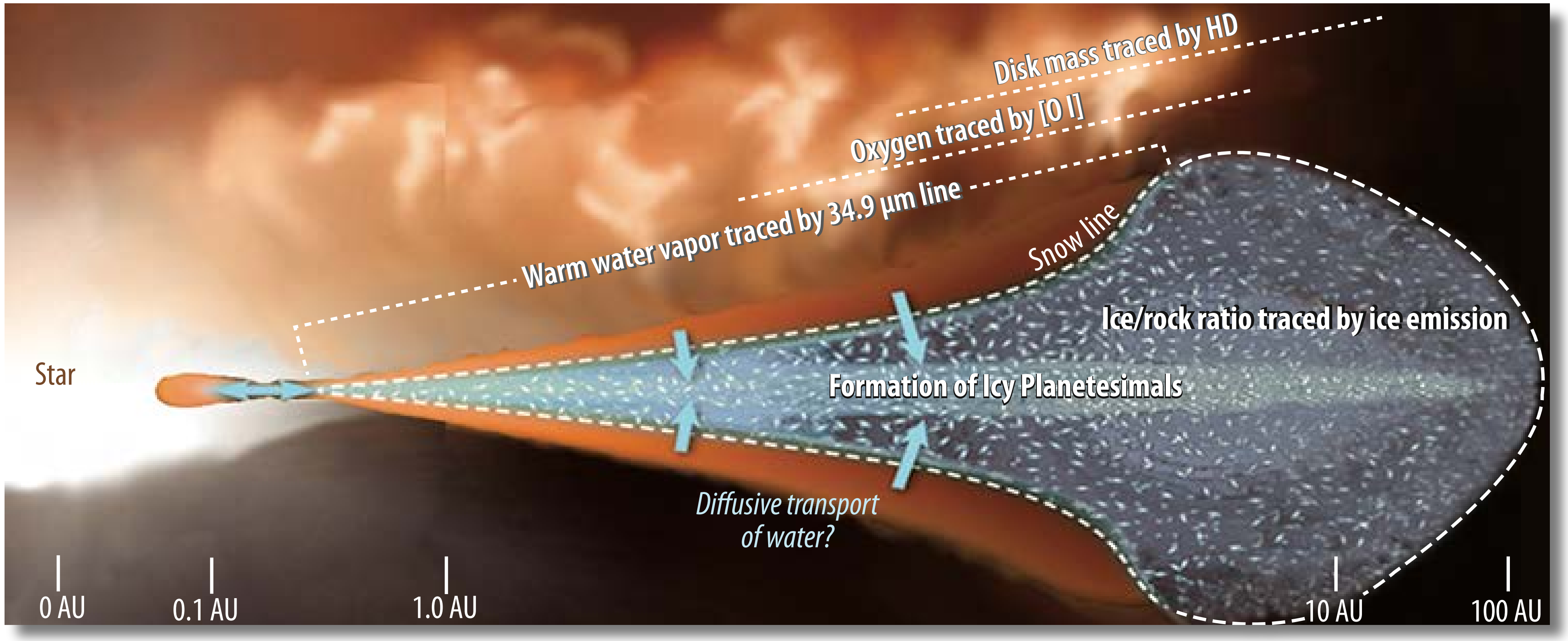
- HIRMES will provide low (R~600) to very high (R~100,000) spectral resolving power over the spectral range 25-122 µm.



- HIRMES combines grating dispersive spectroscopy and Fabry-Pérot tunable narrow-band filters with high-efficiency background-limited bolometer detectors.

- 64 x 16 array of TES detectors for Low- and Medium-Res module
  16 x 8 array of TES detectors for the High-Res FPI

Main disk science goals:



- Measure the HD line at 112 μm; Disk mass + kinematics

TW Hya

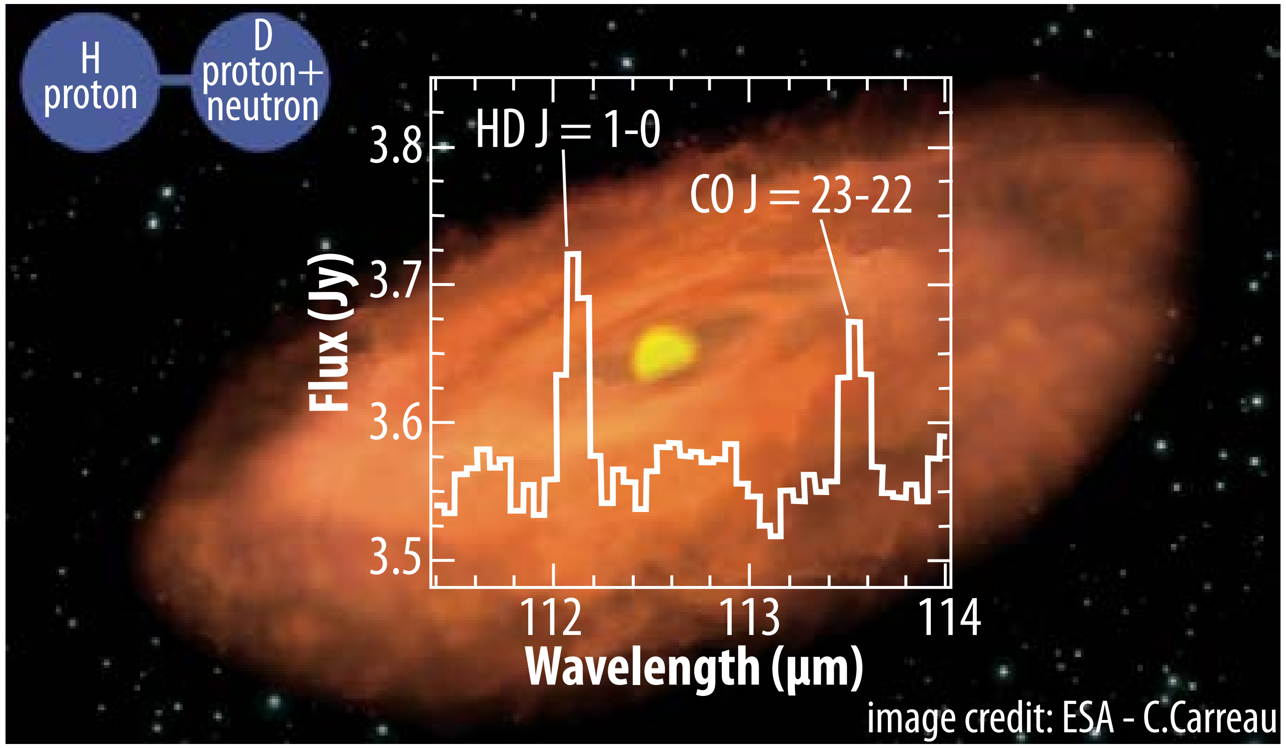
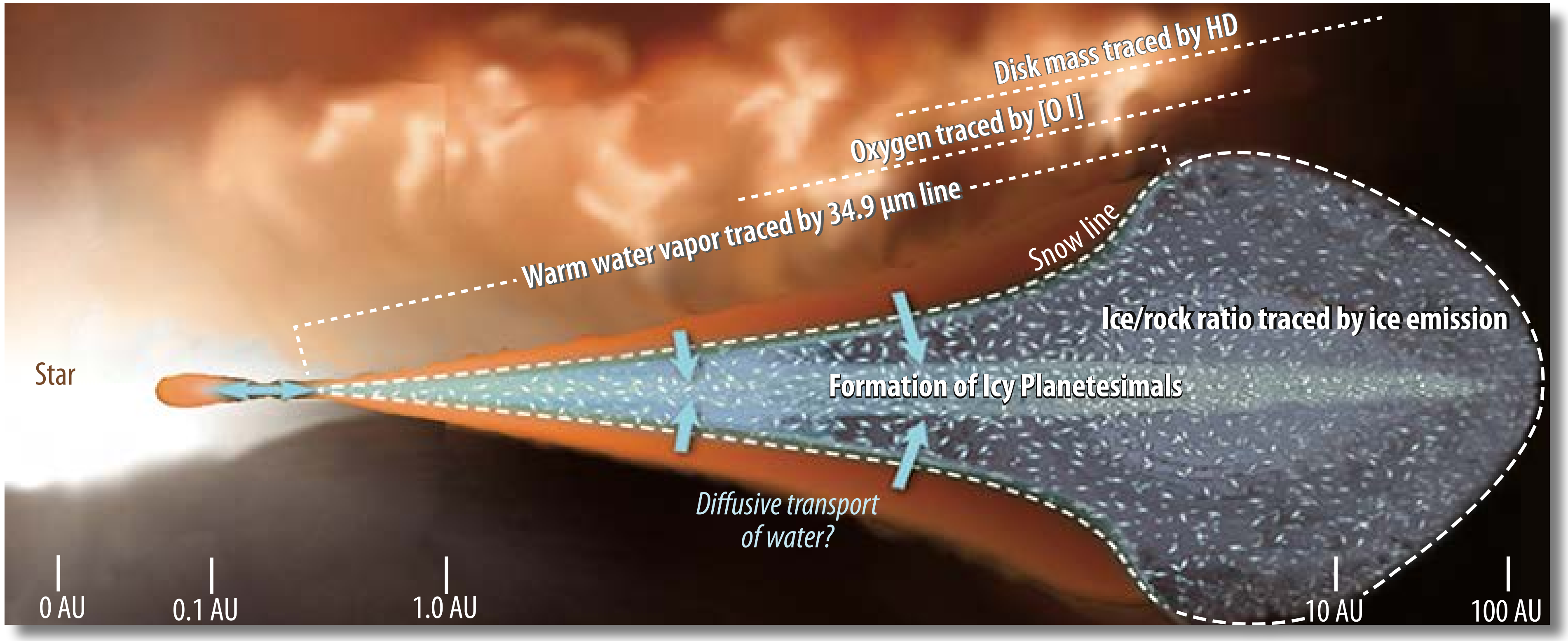


image credit: ESA - C.Carreau

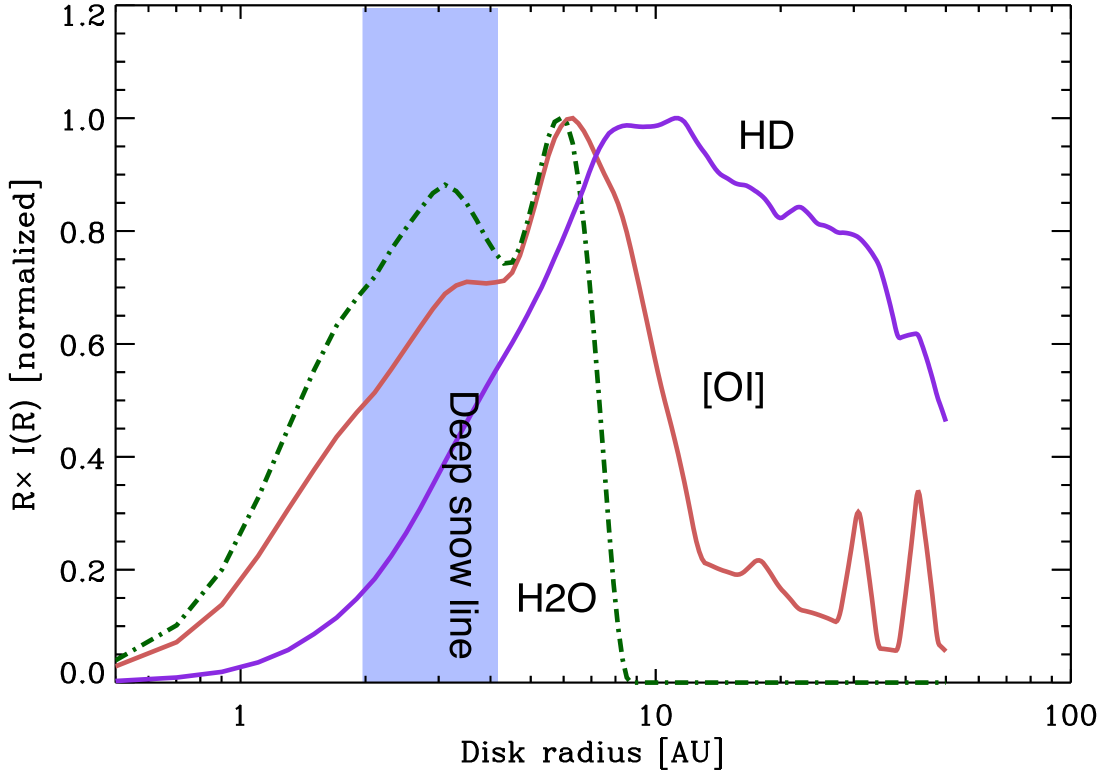
HI2040

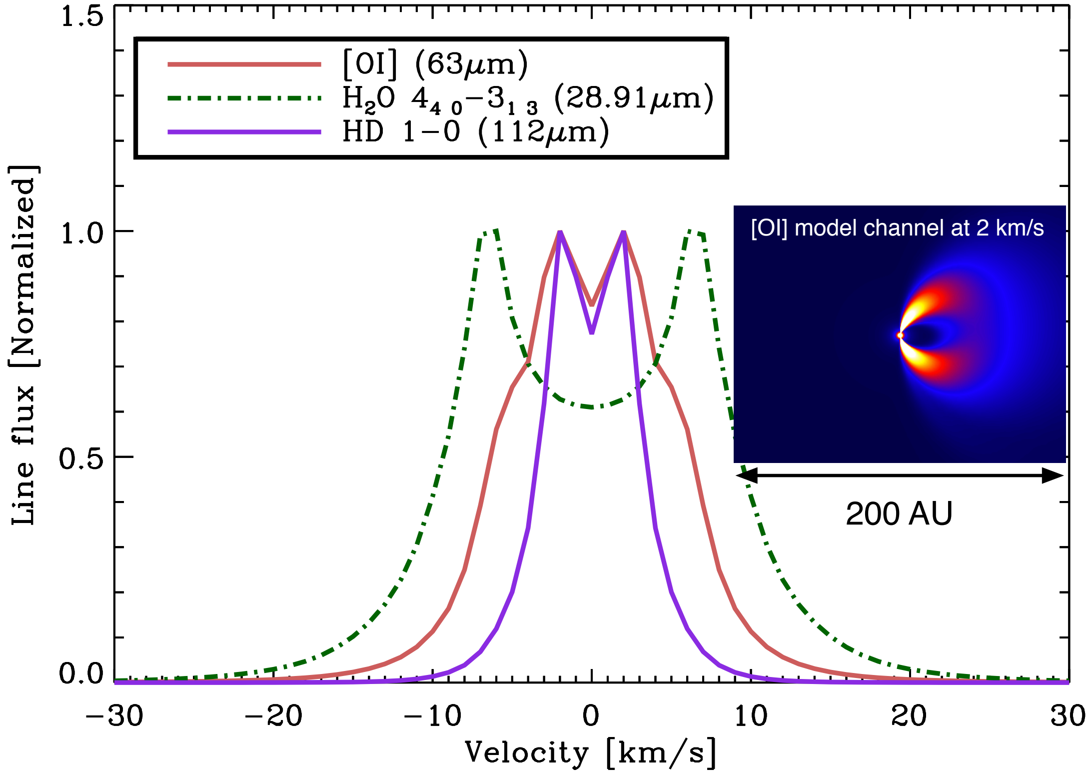
Main disk science goals:



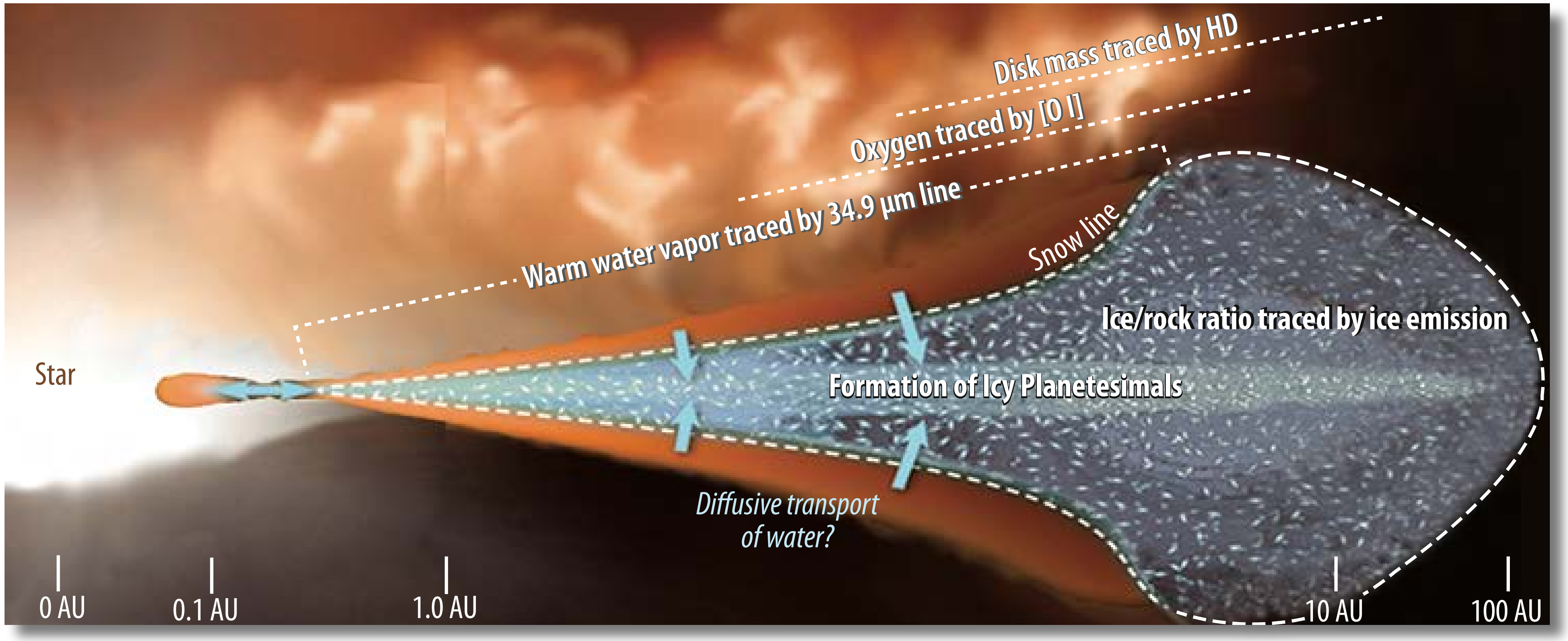
- Measure the HD line at 112 µm; Disk mass + kinematics

Need high spectral resolving power



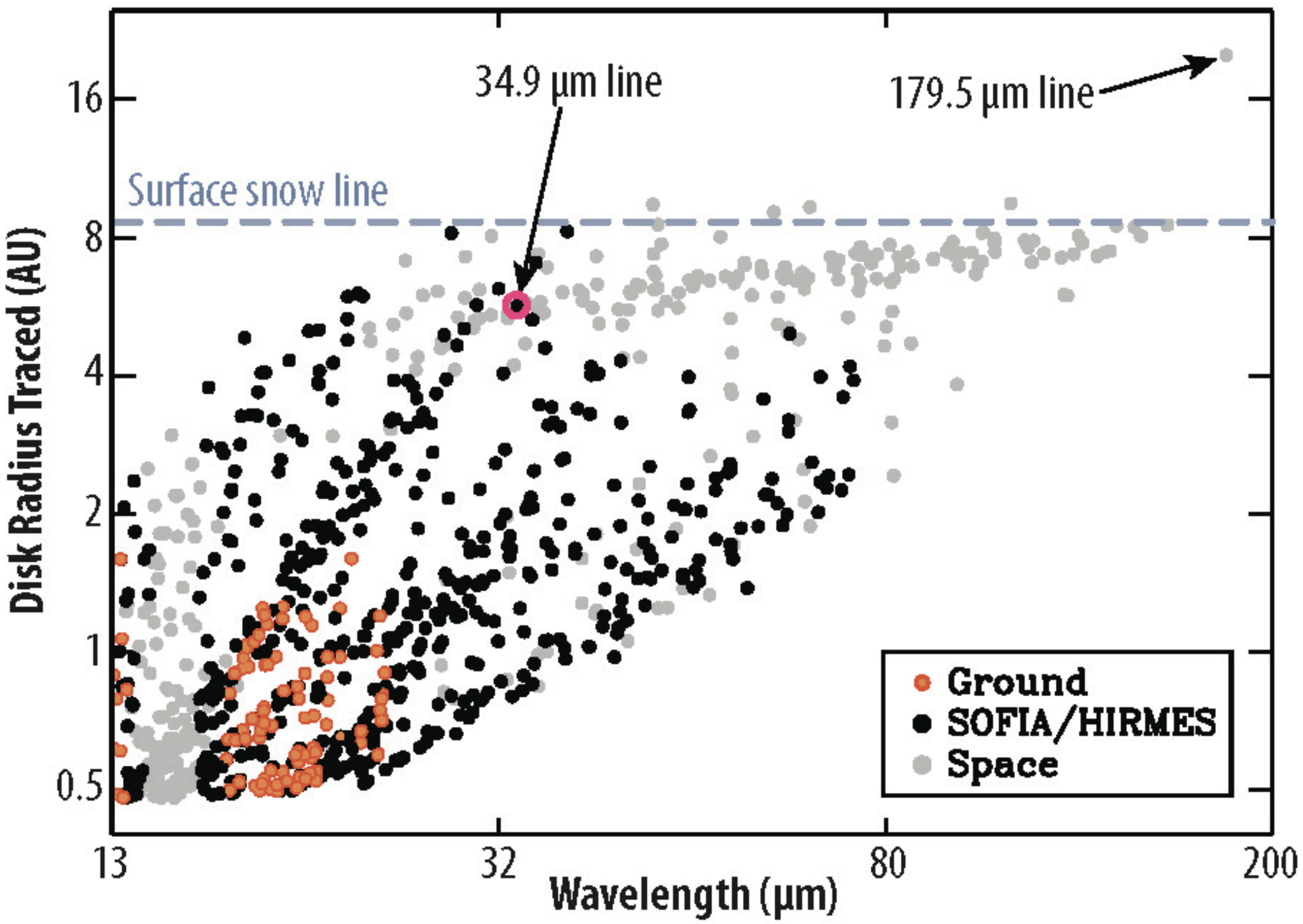


Main disk science goals:

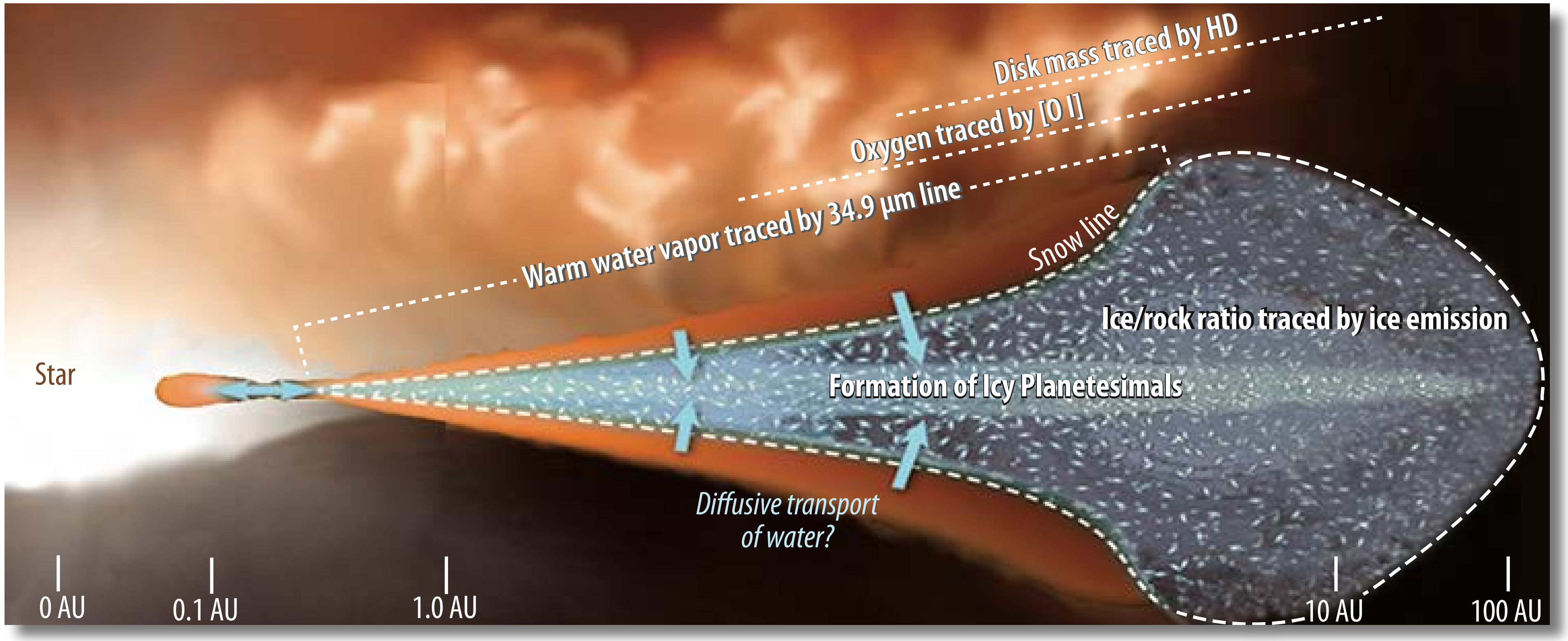


- Measure the HD line at 112 µm; Disk mass + kinematics
- Measure [OI] 63 µm and warm H_2O 28 - 38 µm; Amount of O and H_2O inside the snowlike

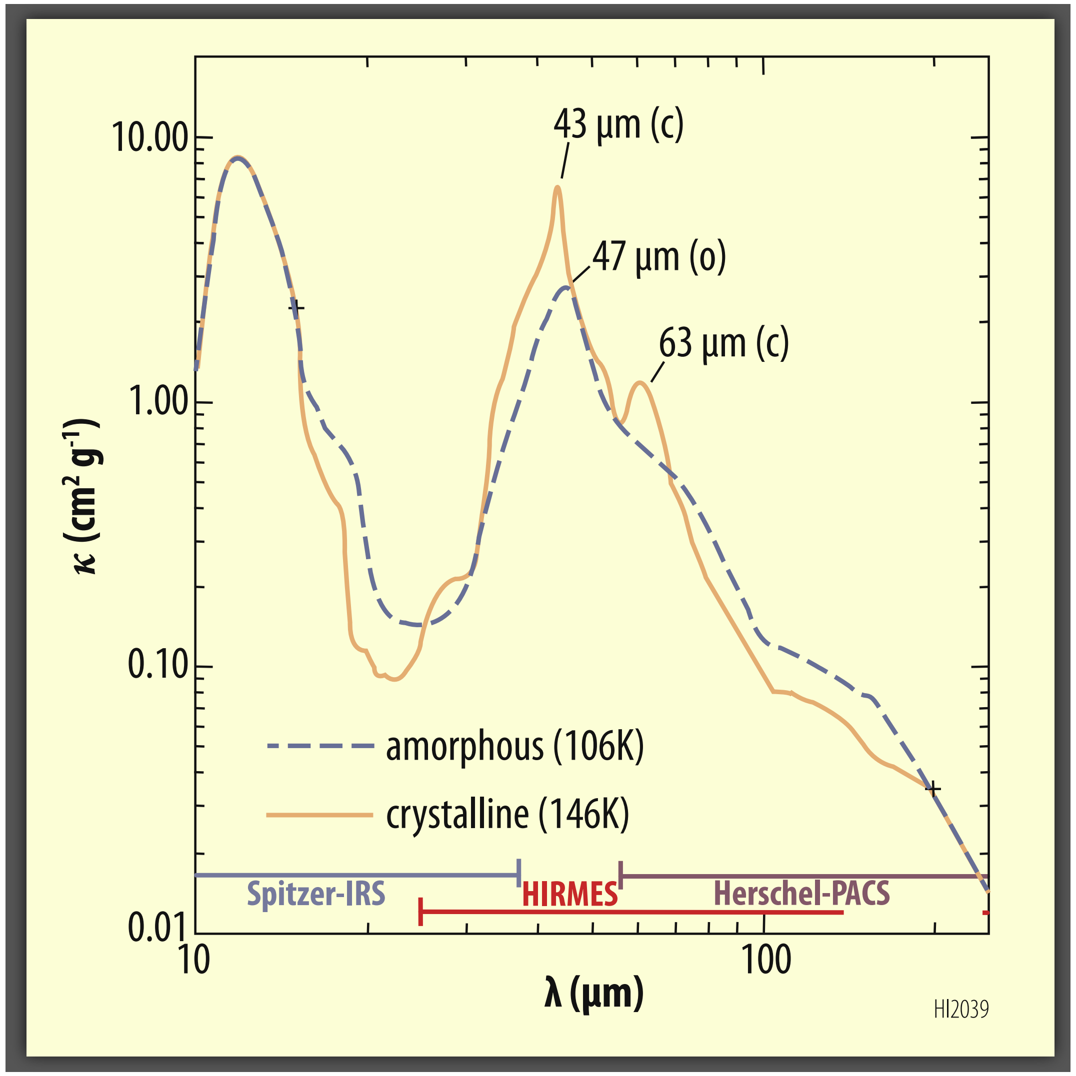
H_2O Lines Detectable by HIRMES



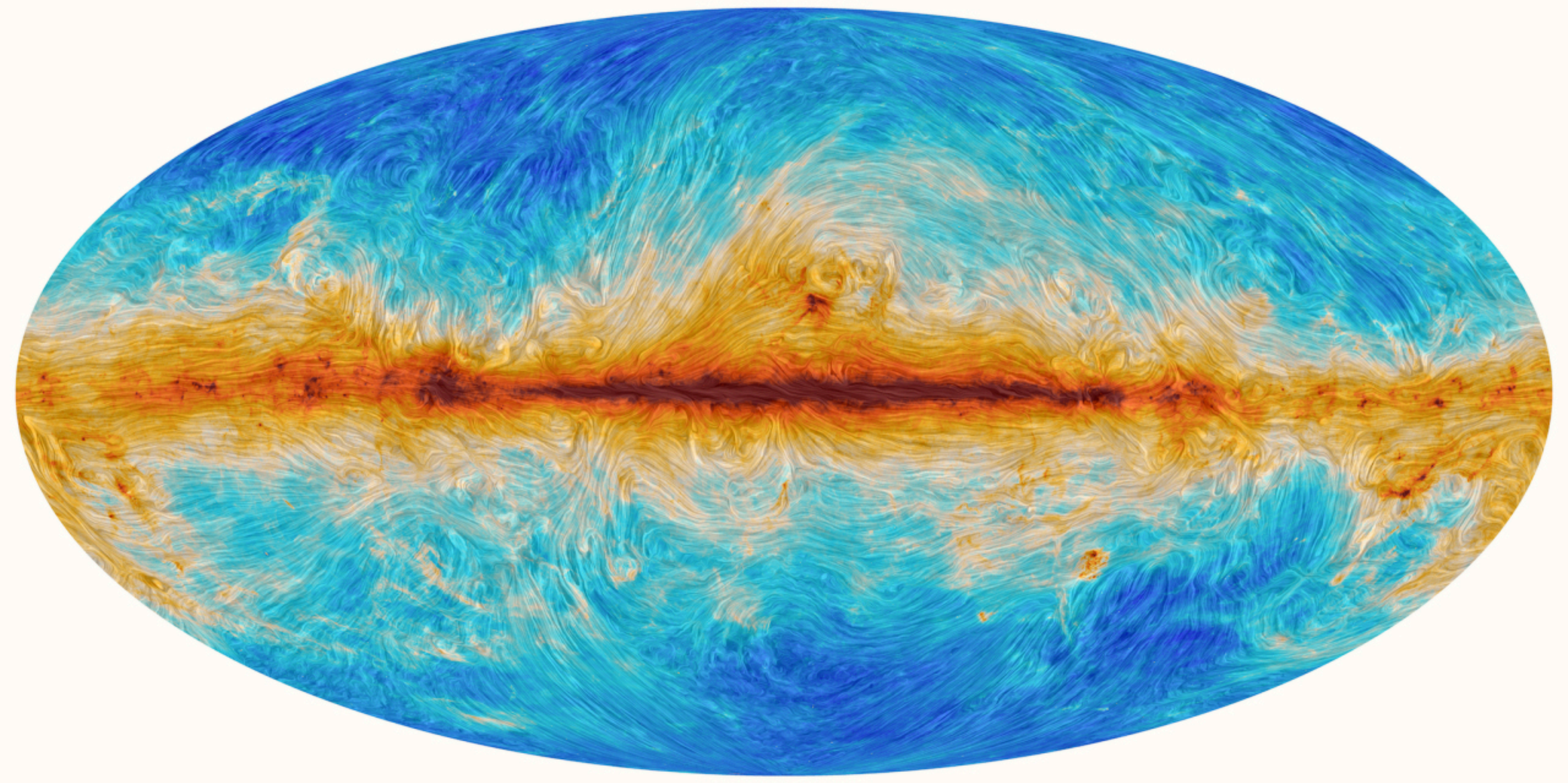
Main disk science goals:



- Measure the HD line at 112 µm; Disk mass + kinematics
- Measure [OI] 63 µm and warm H_2O 28 - 38 µm; Amount of O and H_2O inside the snowlike
- Determine the amount of H_2O-ice beyond the snowline; Measure crystalline (43 µm and 63 µm) and amorphous (47 µm) features

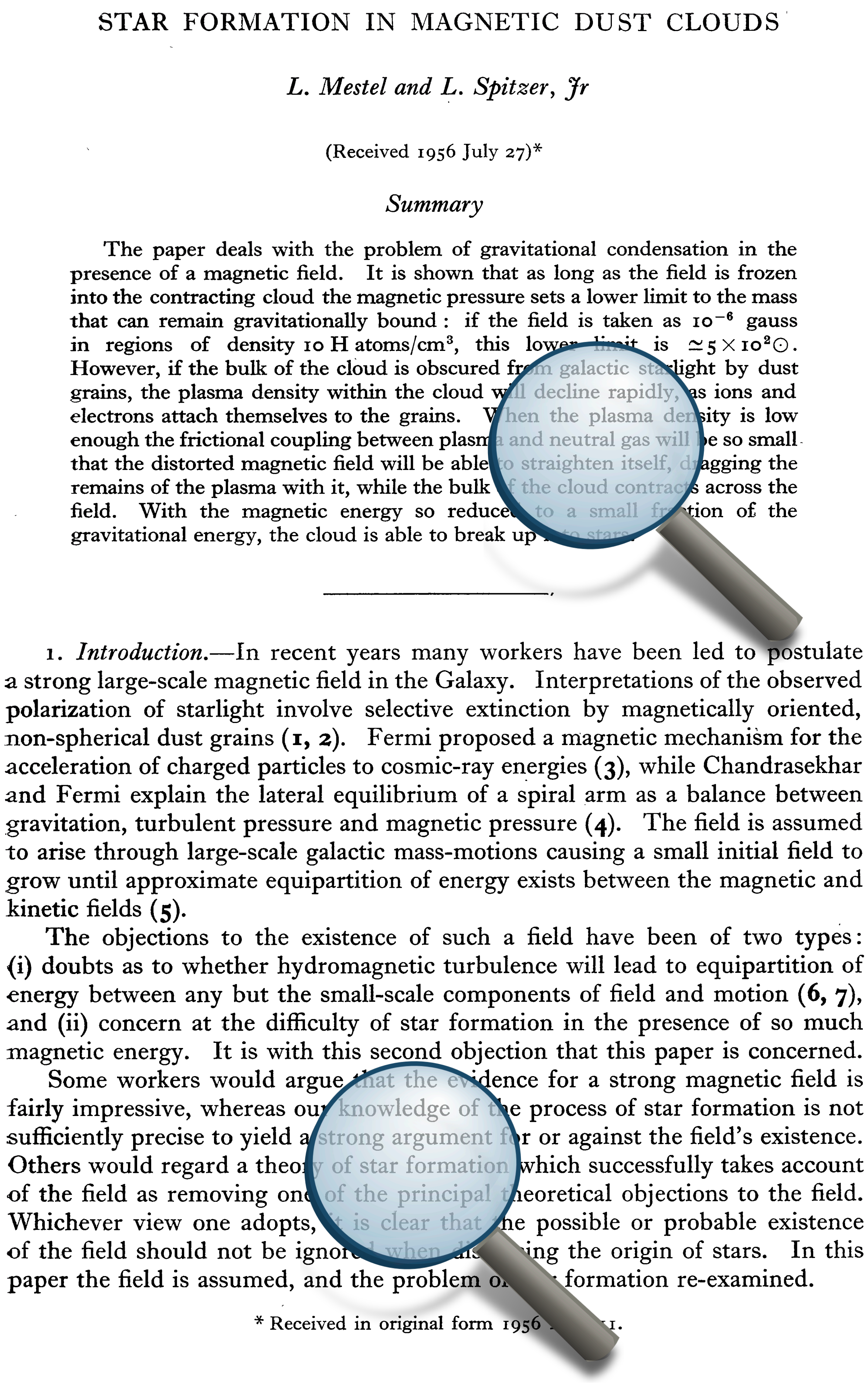


Polarization Studies of Star Formation



Planck polarization map of the sky

1956 MNRAS, 116, 503



STAR FORMATION IN MAGNETIC DUST CLOUDS

L. Mestel and L. Spitzer, Jr

(Received 1956 July 27)*

Summary

The paper deals with the problem of gravitational condensation in the presence of a magnetic field. It is shown that as long as the field is frozen into the contracting cloud the magnetic pressure sets a lower limit to the mass that can remain gravitationally bound: if the field is taken as 10^{-6} gauss in regions of density 10 H atoms/cm^3, this lower limit is $\simeq 5 \times 10^2 \odot$. However, if the bulk of the cloud is obscured from galactic starlight by dust grains, the plasma density within the cloud will decline rapidly, as ions and electrons attach themselves to the grains. When the plasma density is low enough the frictional coupling between plasma and neutral gas will be so small that the distorted magnetic field will be able to straighten itself, dragging the remains of the plasma with it, while the bulk of the cloud contracts across the field. With the magnetic energy so reduced to a small fraction of the gravitational energy, the cloud is able to break up into stars.

1. *Introduction.*—In recent years many workers have been led to postulate a strong large-scale magnetic field in the Galaxy. Interpretations of the observed polarization of starlight involve selective extinction by magnetically oriented, non-spherical dust grains (**1, 2**). Fermi proposed a magnetic mechanism for the acceleration of charged particles to cosmic-ray energies (**3**), while Chandrasekhar and Fermi explain the lateral equilibrium of a spiral arm as a balance between gravitation, turbulent pressure and magnetic pressure (**4**). The field is assumed to arise through large-scale galactic mass-motions causing a small initial field to grow until approximate equipartition of energy exists between the magnetic and kinetic fields (**5**).

The objections to the existence of such a field have been of two types: (i) doubts as to whether hydromagnetic turbulence will lead to equipartition of energy between any but the small-scale components of field and motion (**6, 7**), and (ii) concern at the difficulty of star formation in the presence of so much magnetic energy. It is with this second objection that this paper is concerned.

Some workers would argue that the evidence for a strong magnetic field is fairly impressive, whereas our knowledge of the process of star formation is not sufficiently precise to yield a strong argument for or against the field's existence. Others would regard a theory of star formation which successfully takes account of the field as removing one of the principal theoretical objections to the field. Whichever view one adopts, it is clear that the possible or probable existence of the field should not be ignored when discussing the origin of stars. In this paper the field is assumed, and the problem of star formation re-examined.

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* Received in original form 1956

When the plasma density is low enough the frictional coupling between plasma and neutral gas will be so small that the distorted magnetic field will be able to straighten itself, dragging the remains of the plasma with it, while the bulk of the cloud contracts across the field. With the magnetic energy so reduced to a small fraction of the gravitational energy, the cloud is able to break up into stars.

Unless the effects of B-fields are reduced (by reduced fractional ionization), B-fields inhibit star formation

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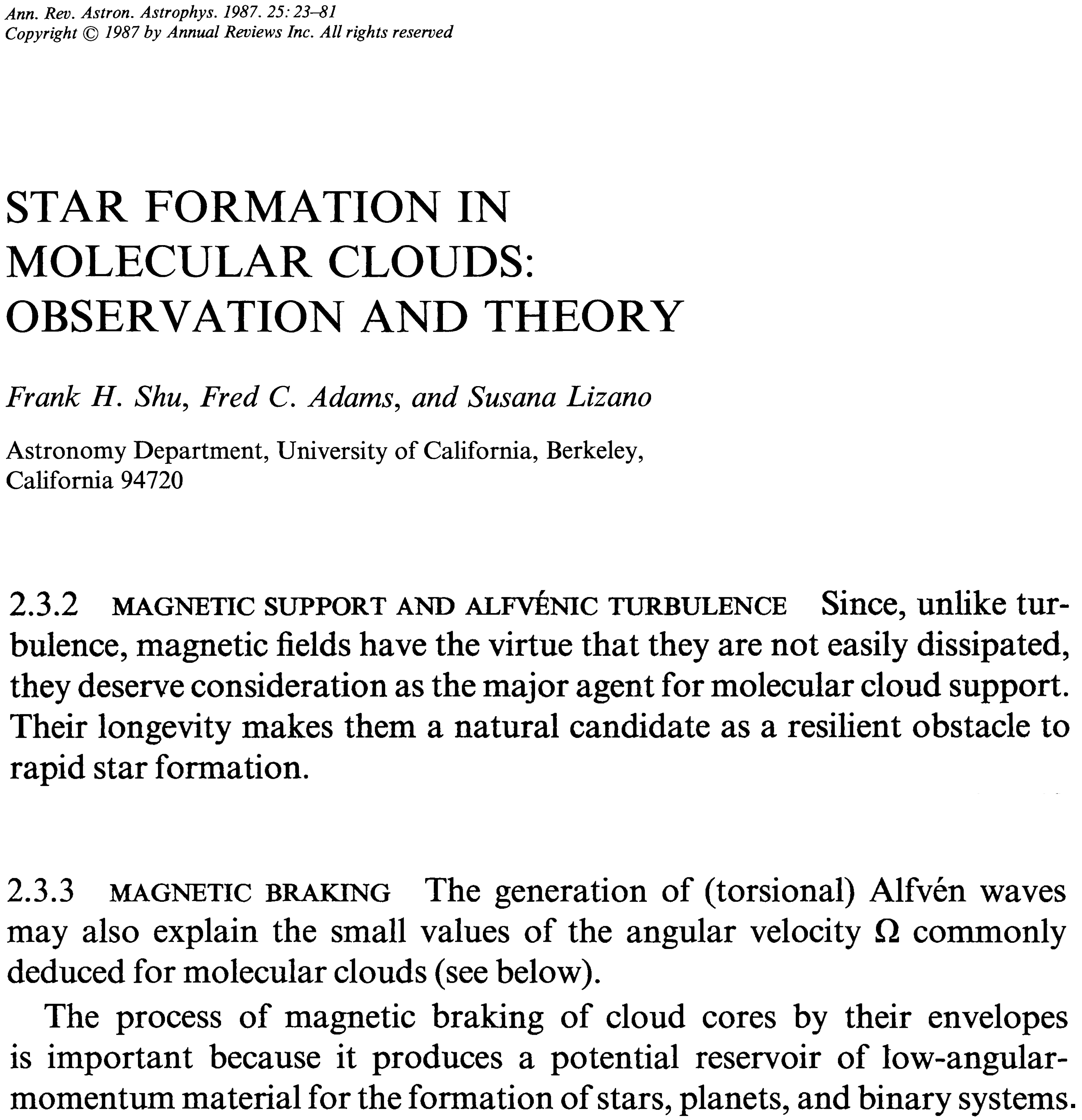
…30 years later



Ann. Rev. Astron. Astrophys. 1987. 25: 23–81
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STAR FORMATION IN
MOLECULAR CLOUDS:
OBSERVATION AND THEORY

Frank H. Shu, Fred C. Adams, and Susana Lizano

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2.3.2 MAGNETIC SUPPORT AND ALFVÉNIC TURBULENCE Since, unlike turbulence, magnetic fields have the virtue that they are not easily dissipated, they deserve consideration as the major agent for molecular cloud support. Their longevity makes them a natural candidate as a resilient obstacle to rapid star formation.

B-fields *inhibit* star formation

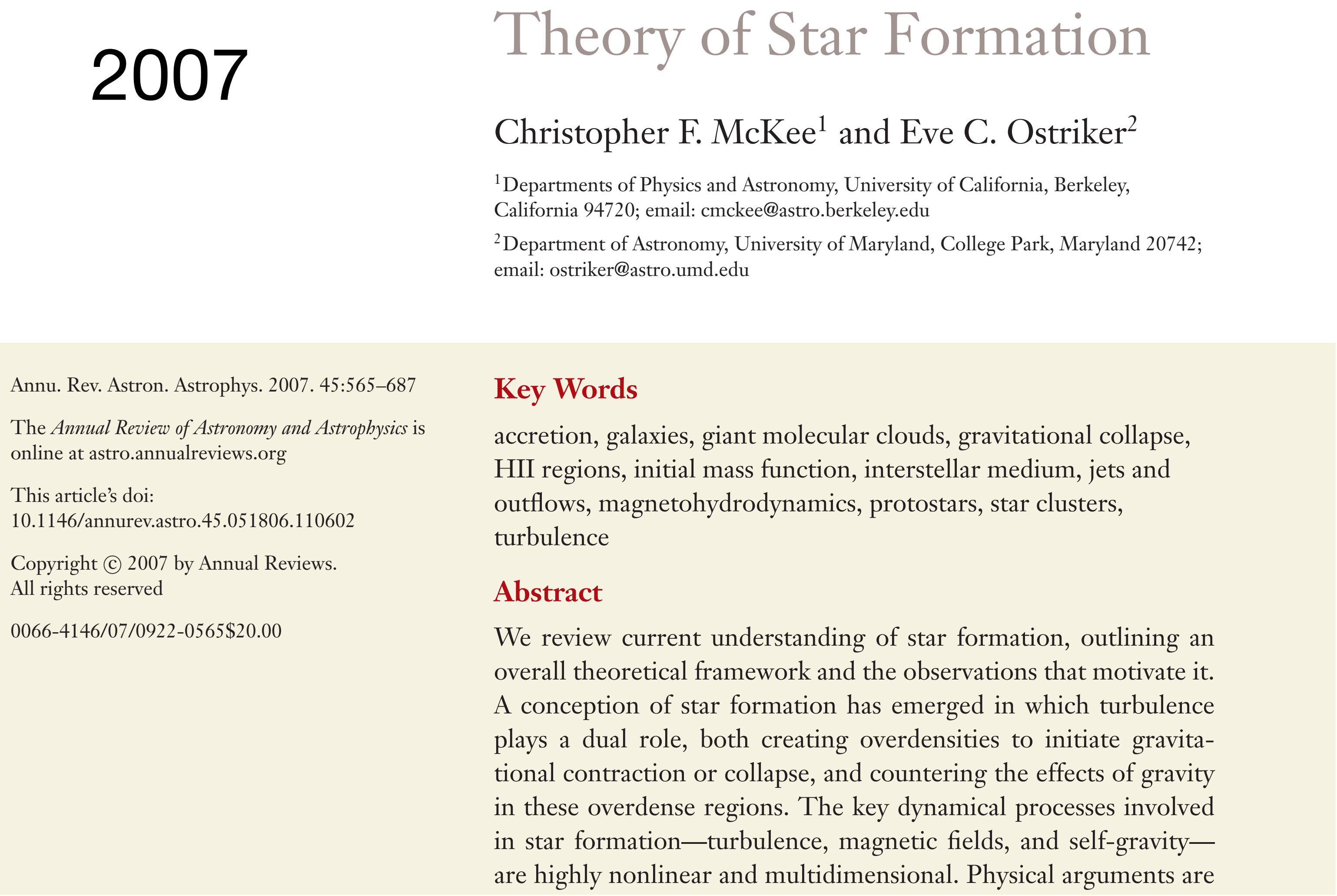
2.3.3 MAGNETIC BRAKING The generation of (torsional) Alfvén waves may also explain the small values of the angular velocity Ω commonly deduced for molecular clouds (see below).

The process of magnetic braking of cloud cores by their envelopes is important because it produces a potential reservoir of low-angular-momentum material for the formation of stars, planets, and binary systems.

B-fields *foster* star formation

2007

...20 years later



Theory of Star Formation

Christopher F. McKee[1] and Eve C. Ostriker[2]

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Annu. Rev. Astron. Astrophys. 2007. 45:565–687

The *Annual Review of Astronomy and Astrophysics* is online at astro.annualreviews.org

This article's doi:
10.1146/annurev.astro.45.051806.110602

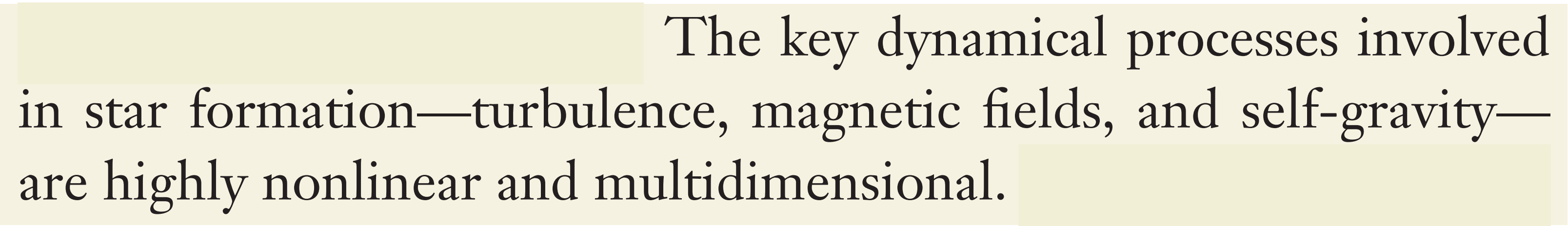
0066-4146/07/0922-0565$20.00

Key Words

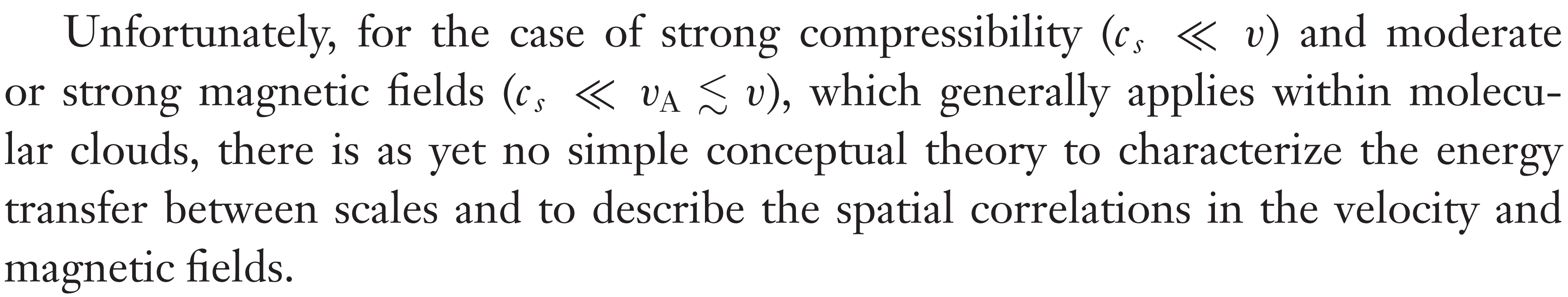
accretion, galaxies, giant molecular clouds, gravitational collapse, HII regions, initial mass function, interstellar medium, jets and outflows, magnetohydrodynamics, protostars, star clusters, turbulence

Abstract

We review current understanding of star formation, outlining an overall theoretical framework and the observations that motivate it. A conception of star formation has emerged in which turbulence plays a dual role, both creating overdensities to initiate gravitational contraction or collapse, and countering the effects of gravity in these overdense regions. The key dynamical processes involved in star formation—turbulence, magnetic fields, and self-gravity—are highly nonlinear and multidimensional. Physical arguments are



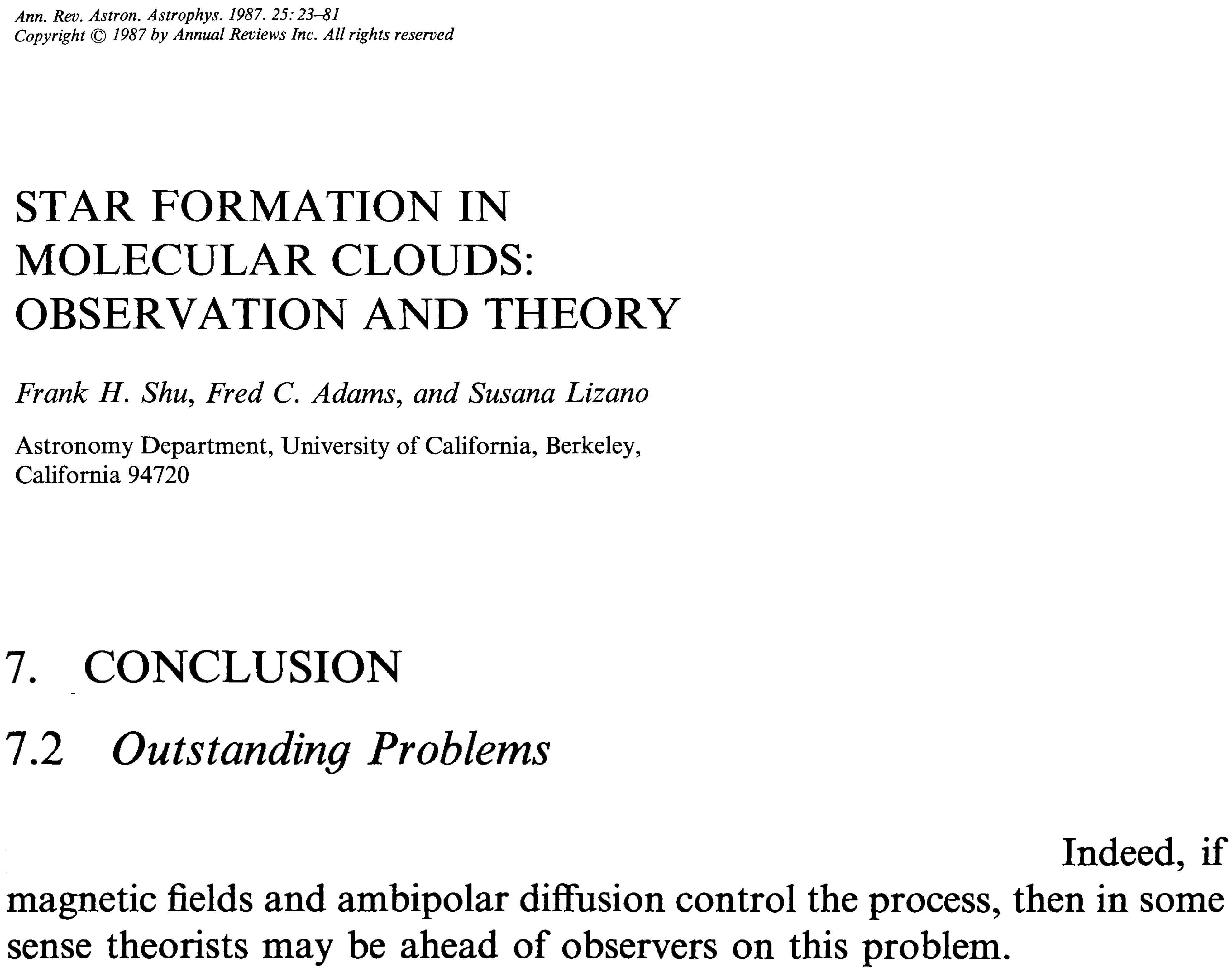
The key dynamical processes involved in star formation—turbulence, magnetic fields, and self-gravity—are highly nonlinear and multidimensional.



Unfortunately, for the case of strong compressibility ($c_s \ll v$) and moderate or strong magnetic fields ($c_s \ll v_A \lesssim v$), which generally applies within molecular clouds, there is as yet no simple conceptual theory to characterize the energy transfer between scales and to describe the spatial correlations in the velocity and magnetic fields.

This problem is *really* hard. B-fields may help, they may hurt.

1987



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STAR FORMATION IN MOLECULAR CLOUDS: OBSERVATION AND THEORY

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California 94720

7. CONCLUSION

7.2 *Outstanding Problems*

Indeed, if magnetic fields and ambipolar diffusion control the process, then in some sense theorists may be ahead of observers on this problem.

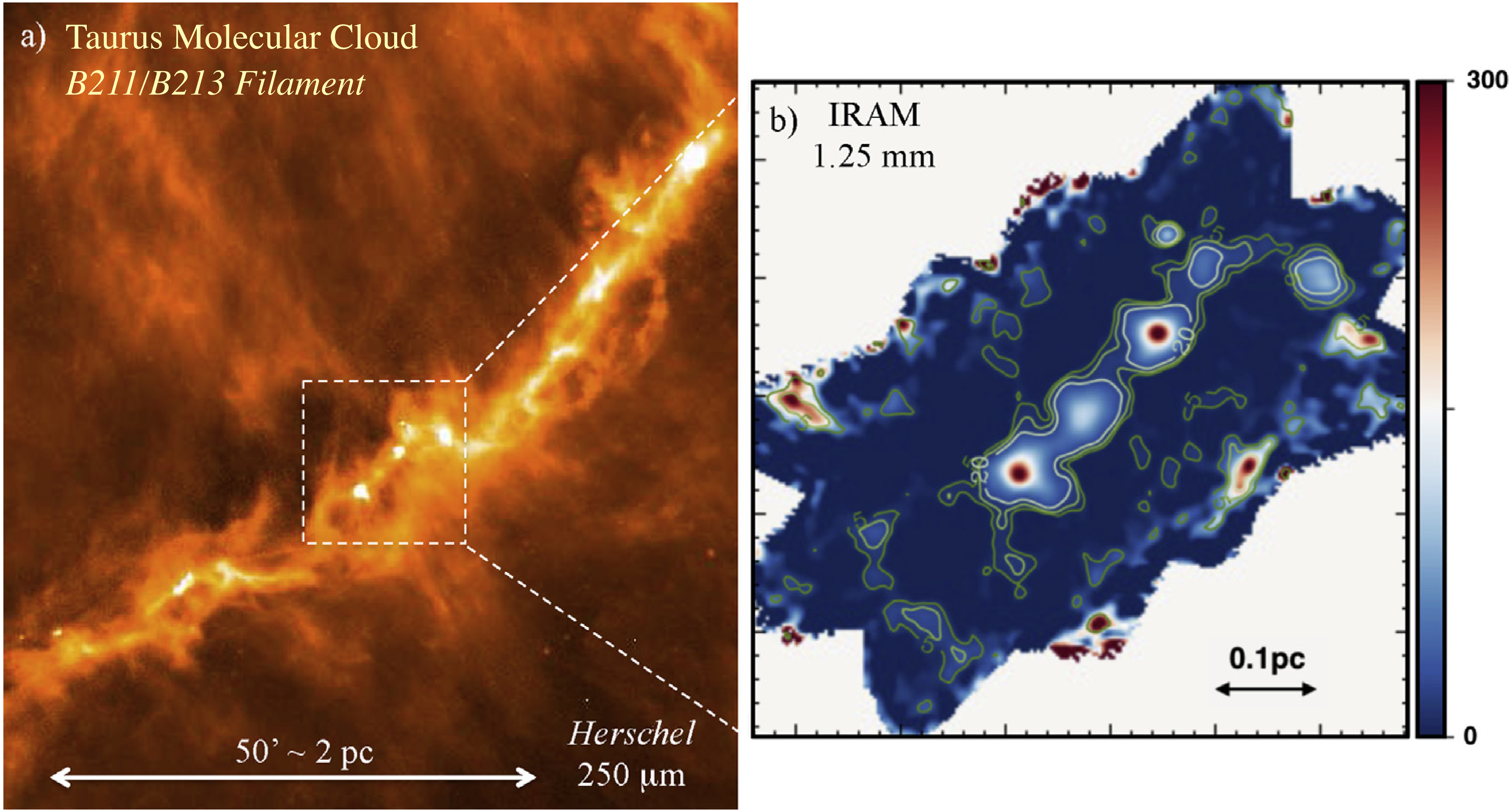
… thus laying down the gauntlet for observers.

Herschel/SPIRE 250 μm dust continuum image of a portion of the Polaris flare translucent cloud (*d* ~ 140 pc).

Take note of the filaments

After Andre et al. 2010; Miville-Deschenes et al. 2010.

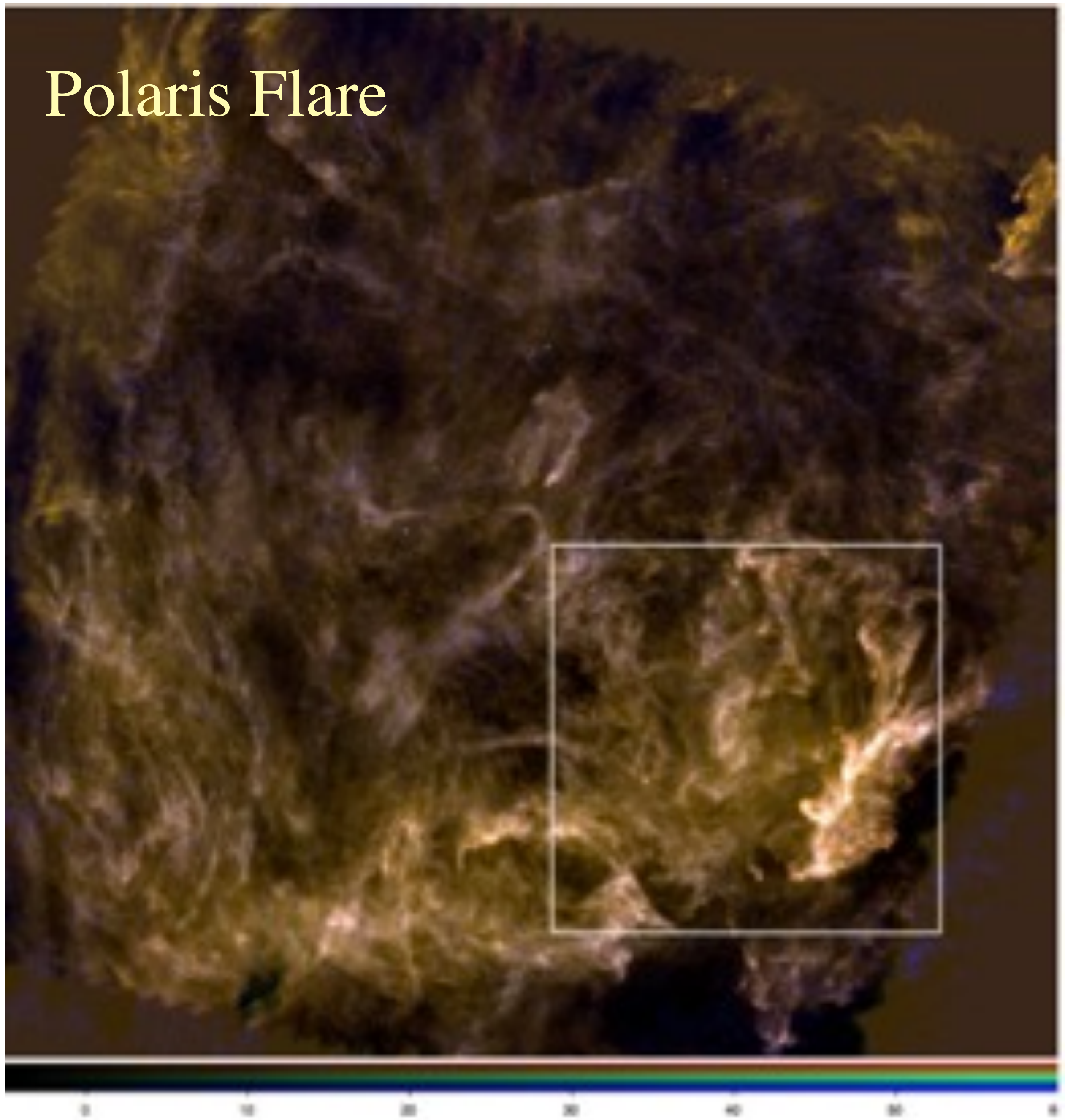
Filaments appear to be preferred sites of star formation

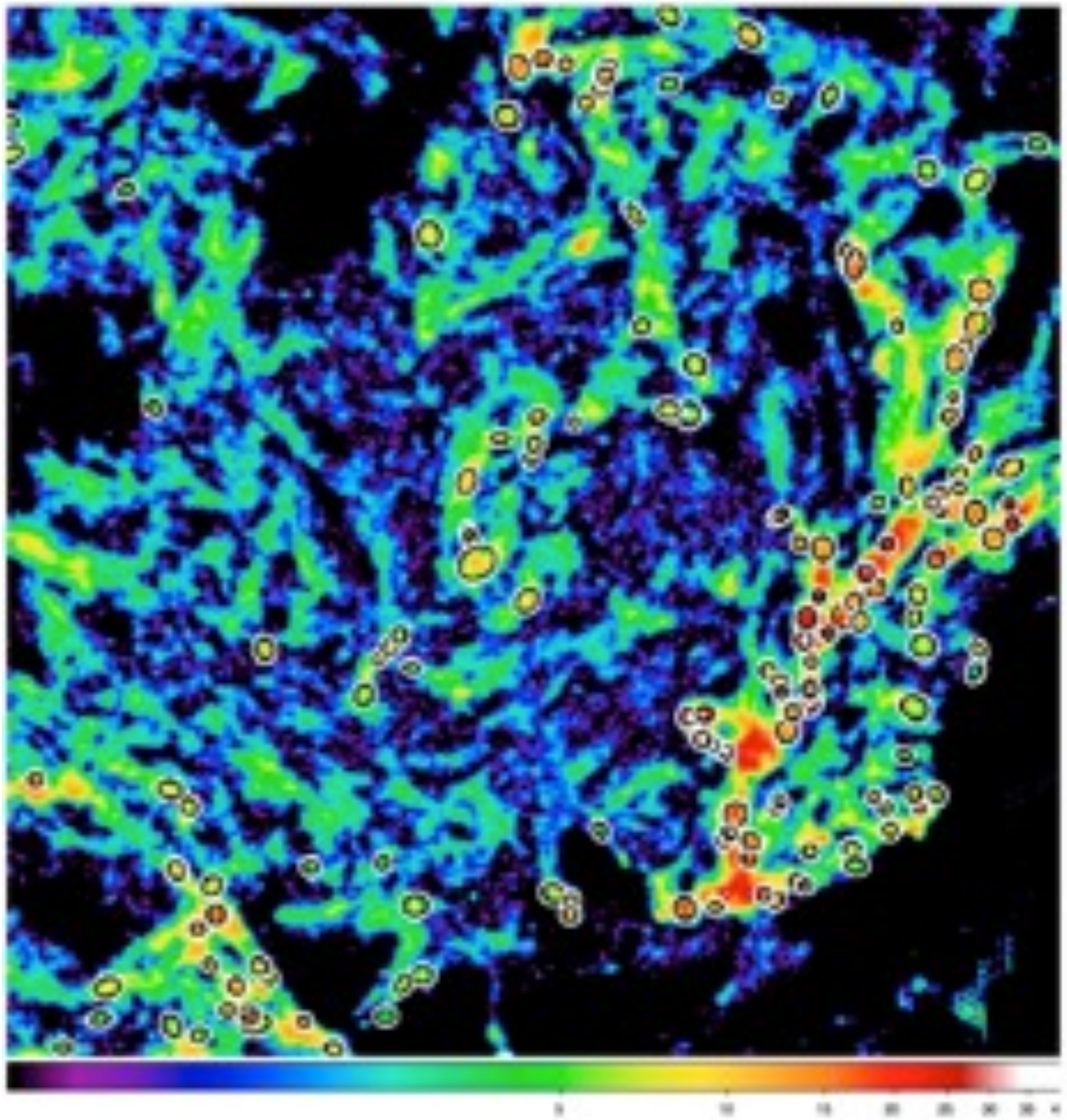


Palmeirim et al. 2013
Marsh et al. 2016

Bracco et al. 2017

Filaments appear to be preferred sites of star formation

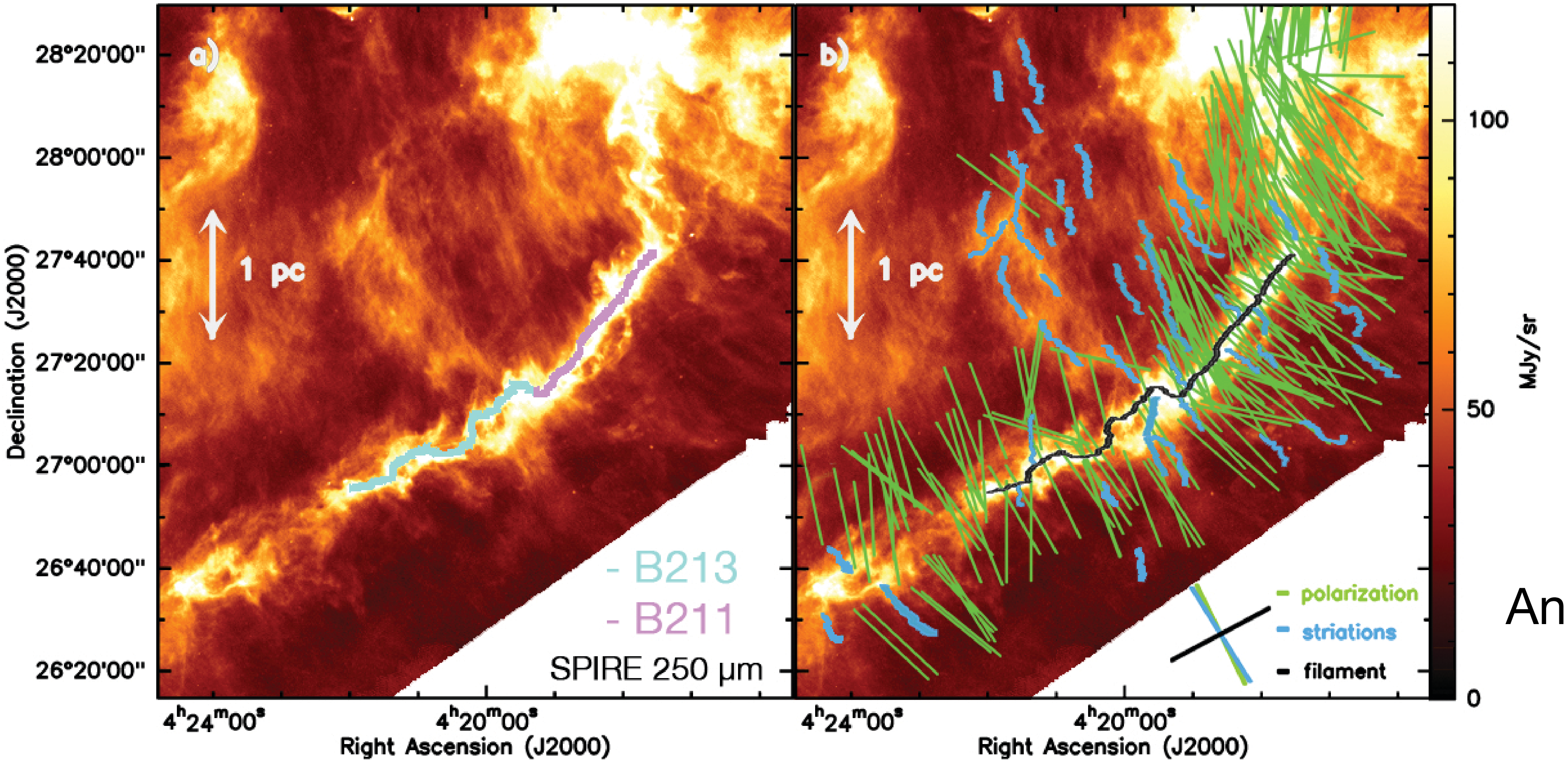




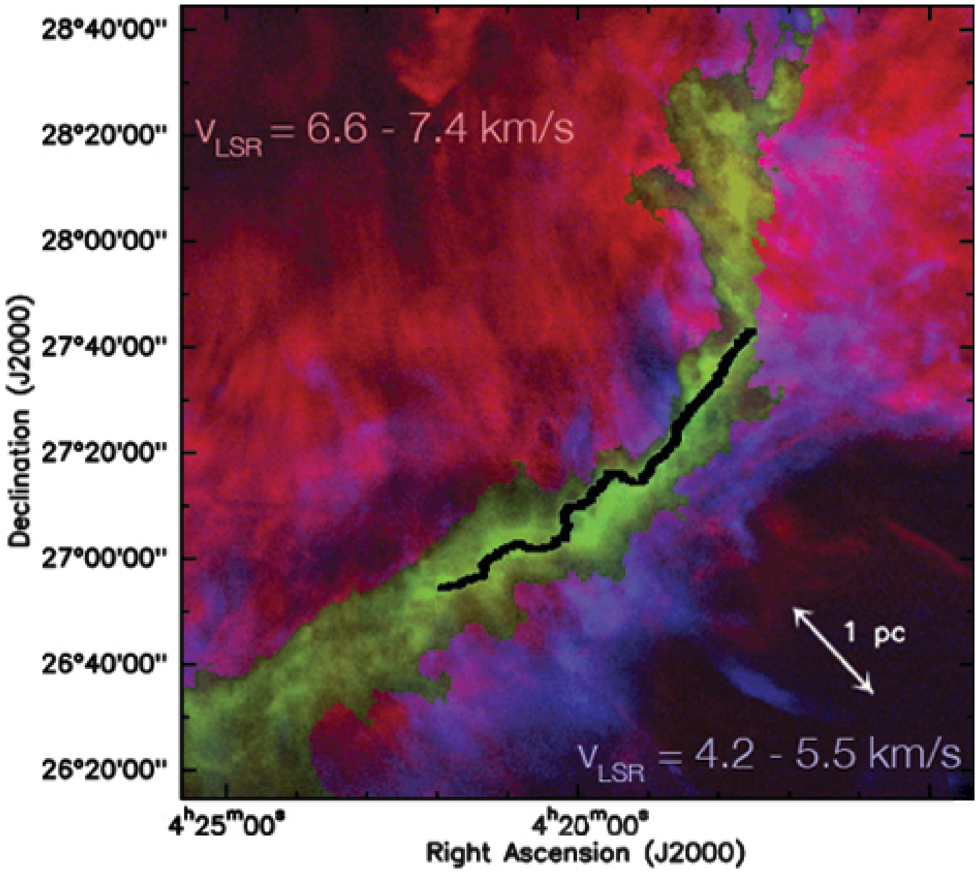
Men’shchivov et al. (2010)

More than 300 starless cores are found, most lie in filaments

Taurus B211/213



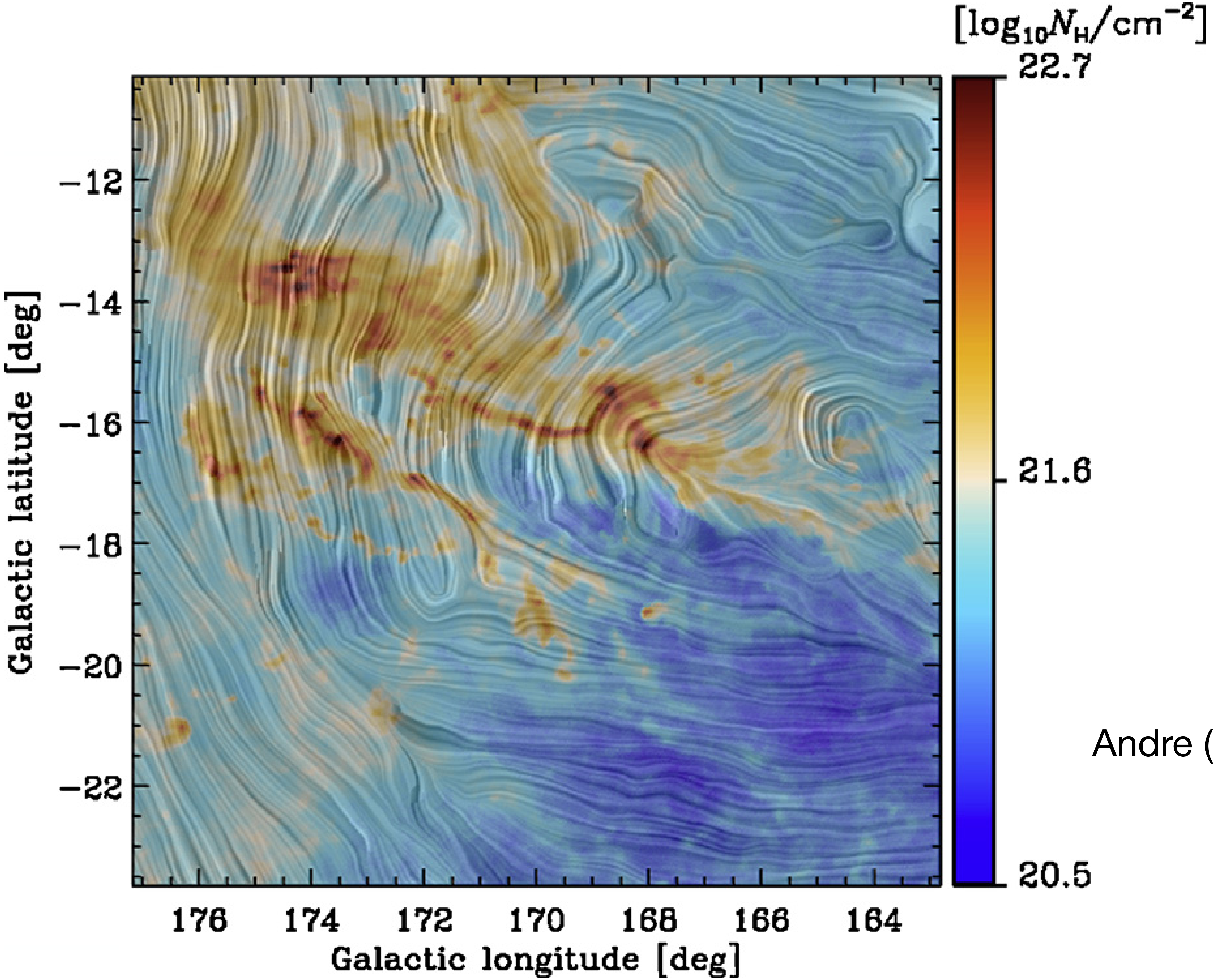
Andre (2017)



CO data (left; Goldsmith et al. 2008) show gas motions toward the filaments.

H-band polarization vectors (top) show that the B-fields are aligned with the striations (marked in blue), suggesting the B-fields channel the gas into the filaments.

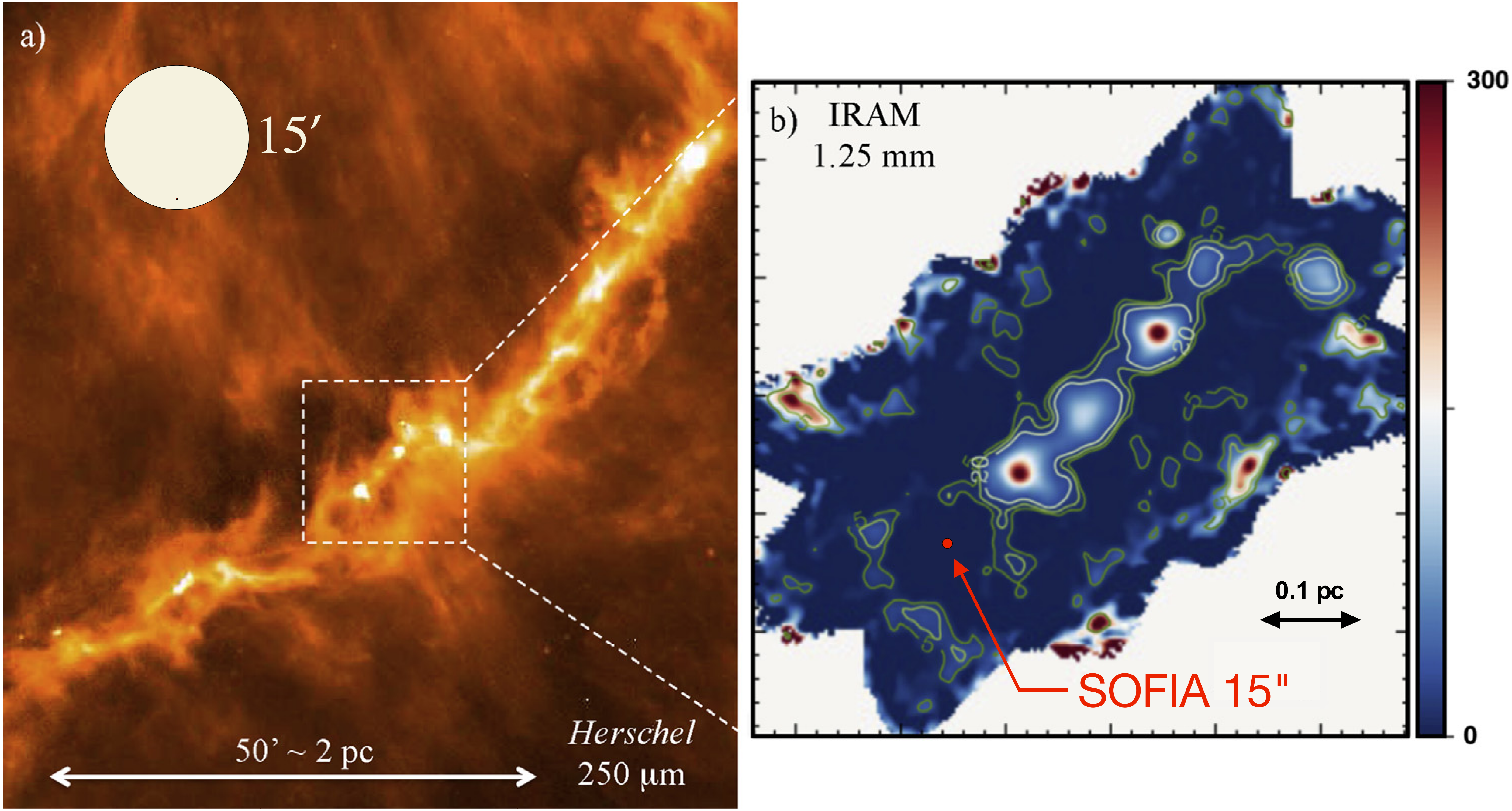
This is also seen in the Planck data



Andre (2017)

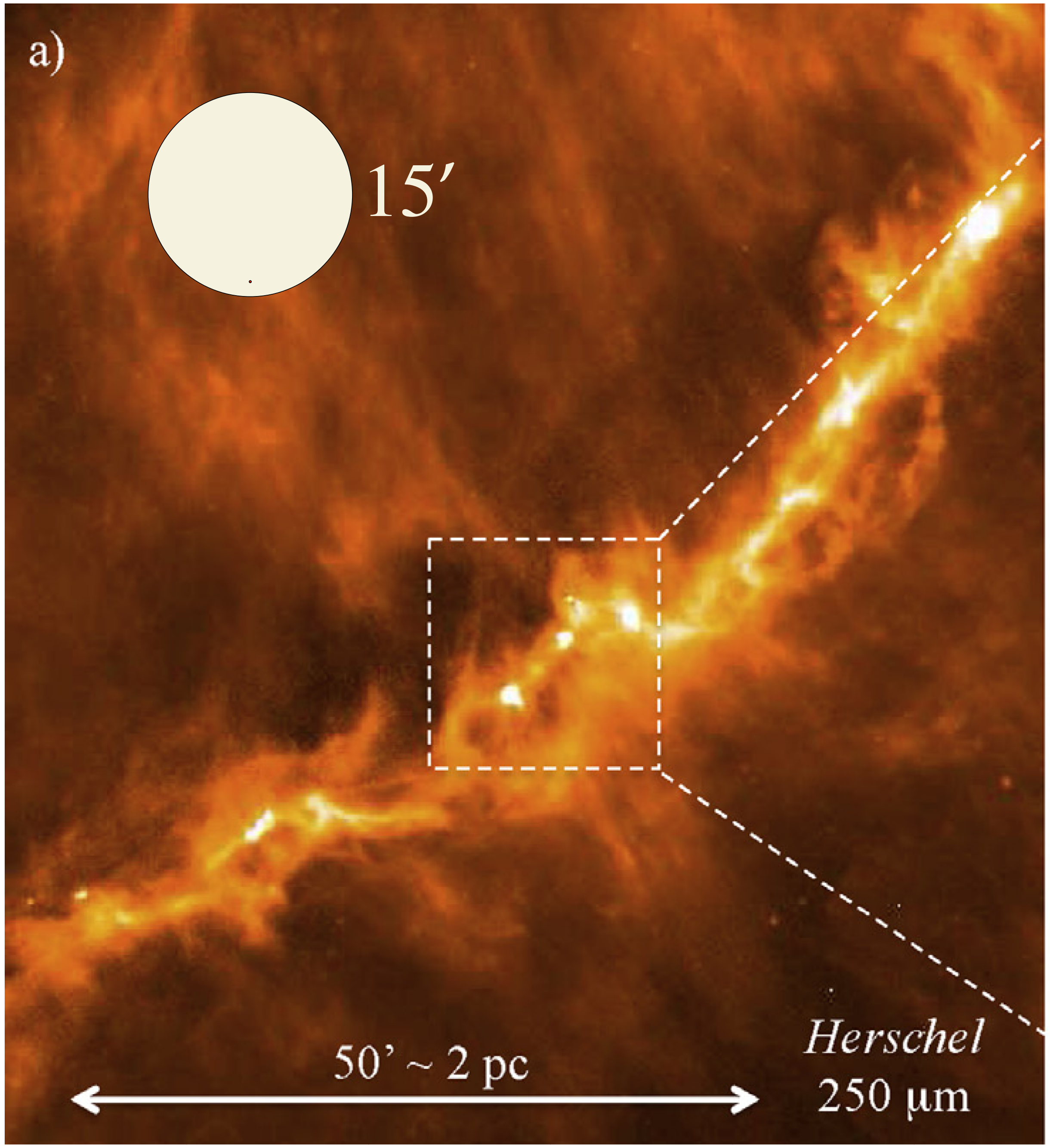
Magnetic field and column density map of Taurus

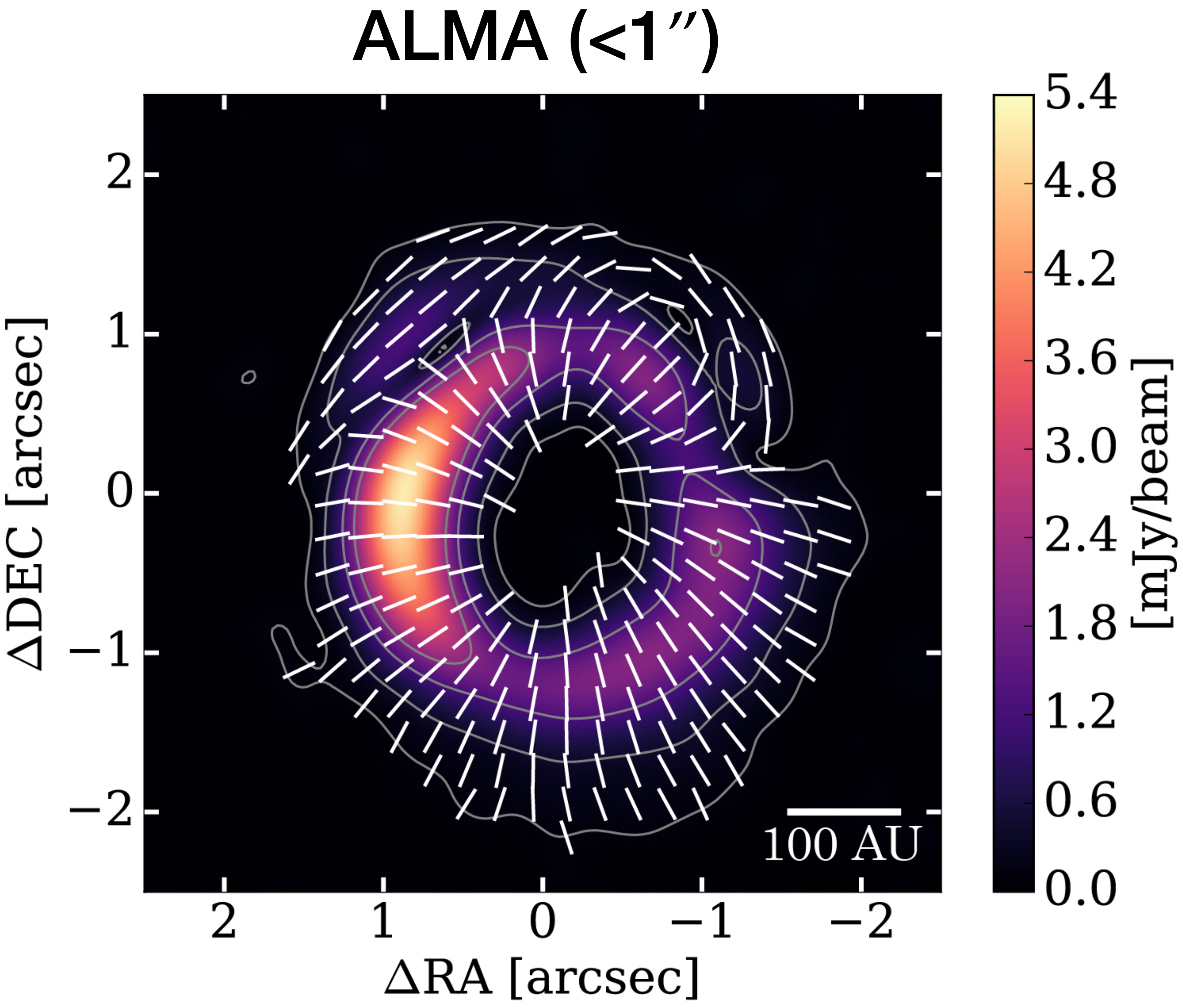
SOFIA/HAWC+ is the next step…



SOFIA/HAWC+ is the next step…

It bridges the gap in spatial scale between Planck and ALMA

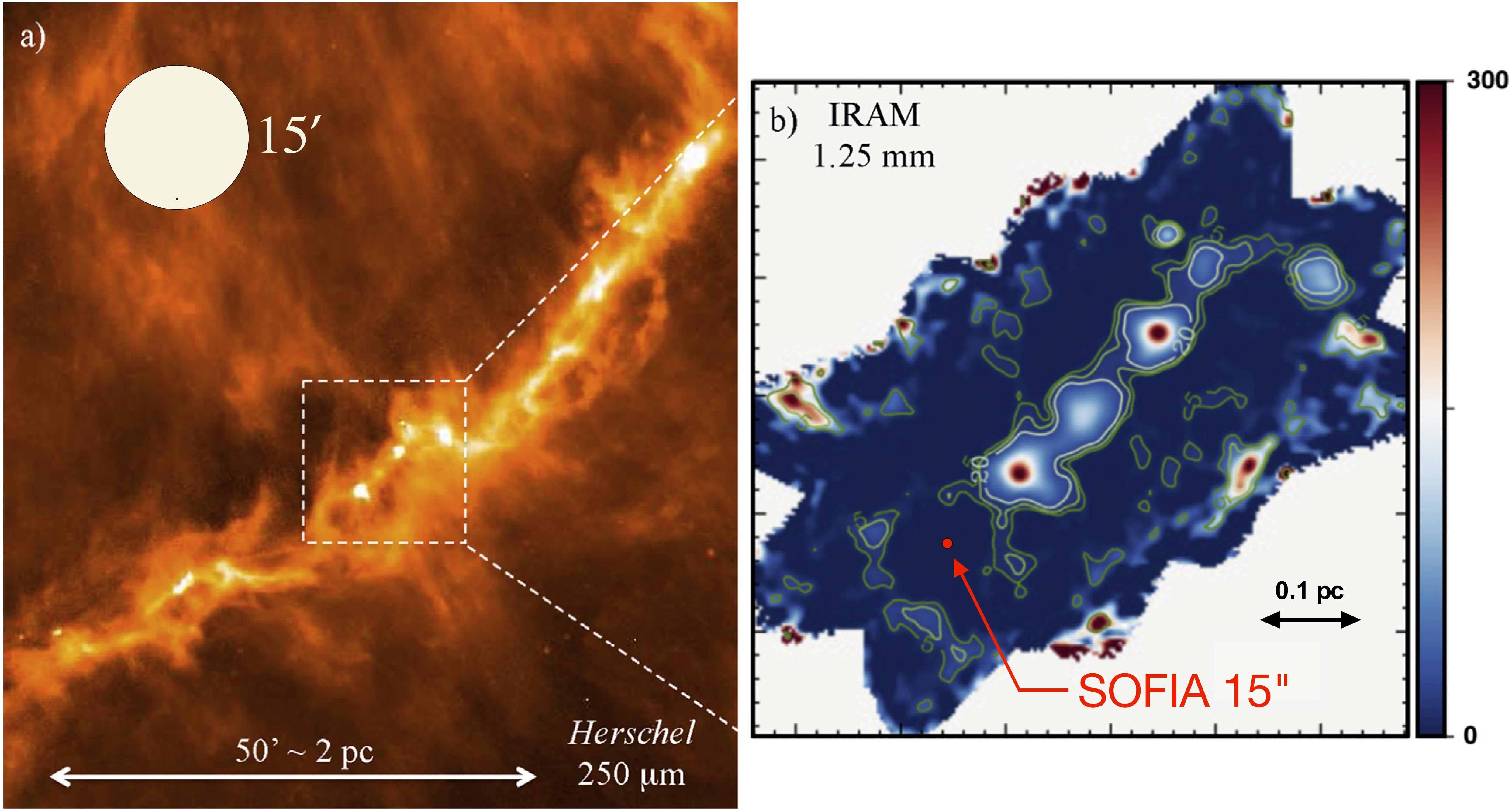




SOFIA/HAWC+ is the next step…

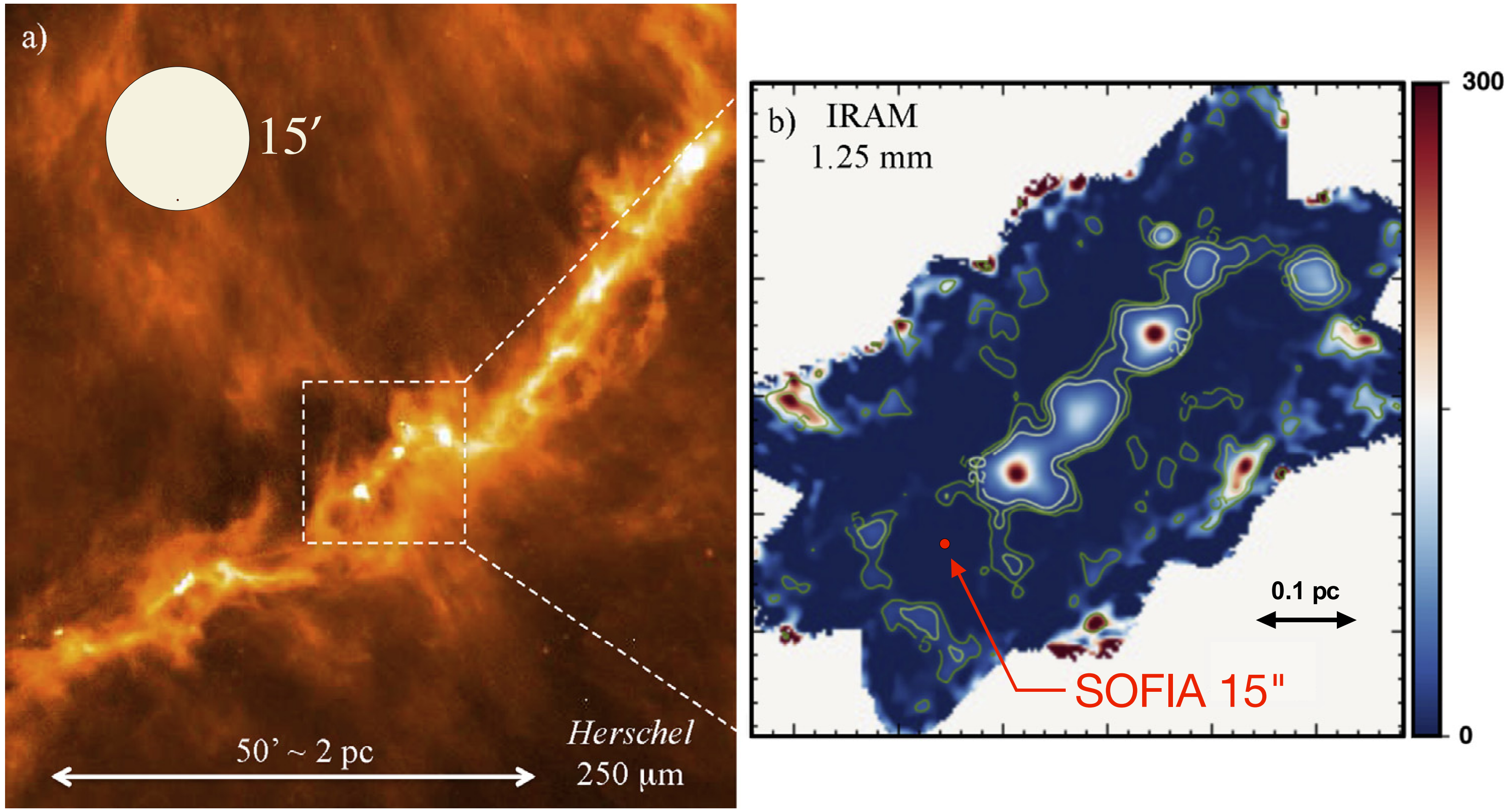
It bridges the gap in spatial scale between Planck and ALMA

HAWC+ can do large-area polarization mapping, ALMA cannot



The influence of B-fields on star formation is likely so complex and varied that a focus on a few filaments, or even one molecular cloud, might not suffice to tease out the subtleties of its role.

A large-area polarization survey of the Galactic plane by SOFIA would leave a lasting legacy (and might finally settle more than 60 years of conjecture about the role of B-fields).

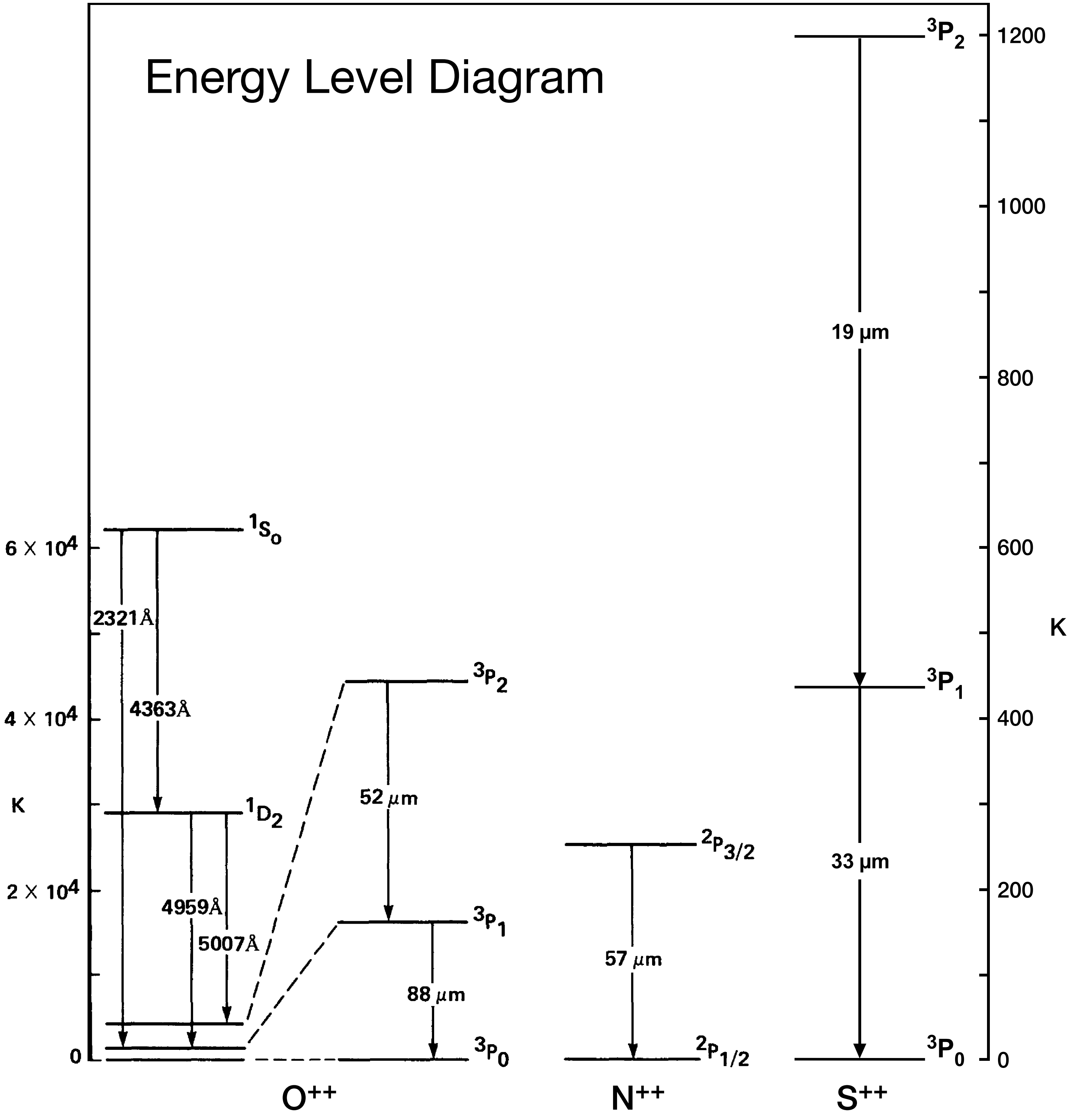


Abundance Gradients Across the Galaxy

Motivation…

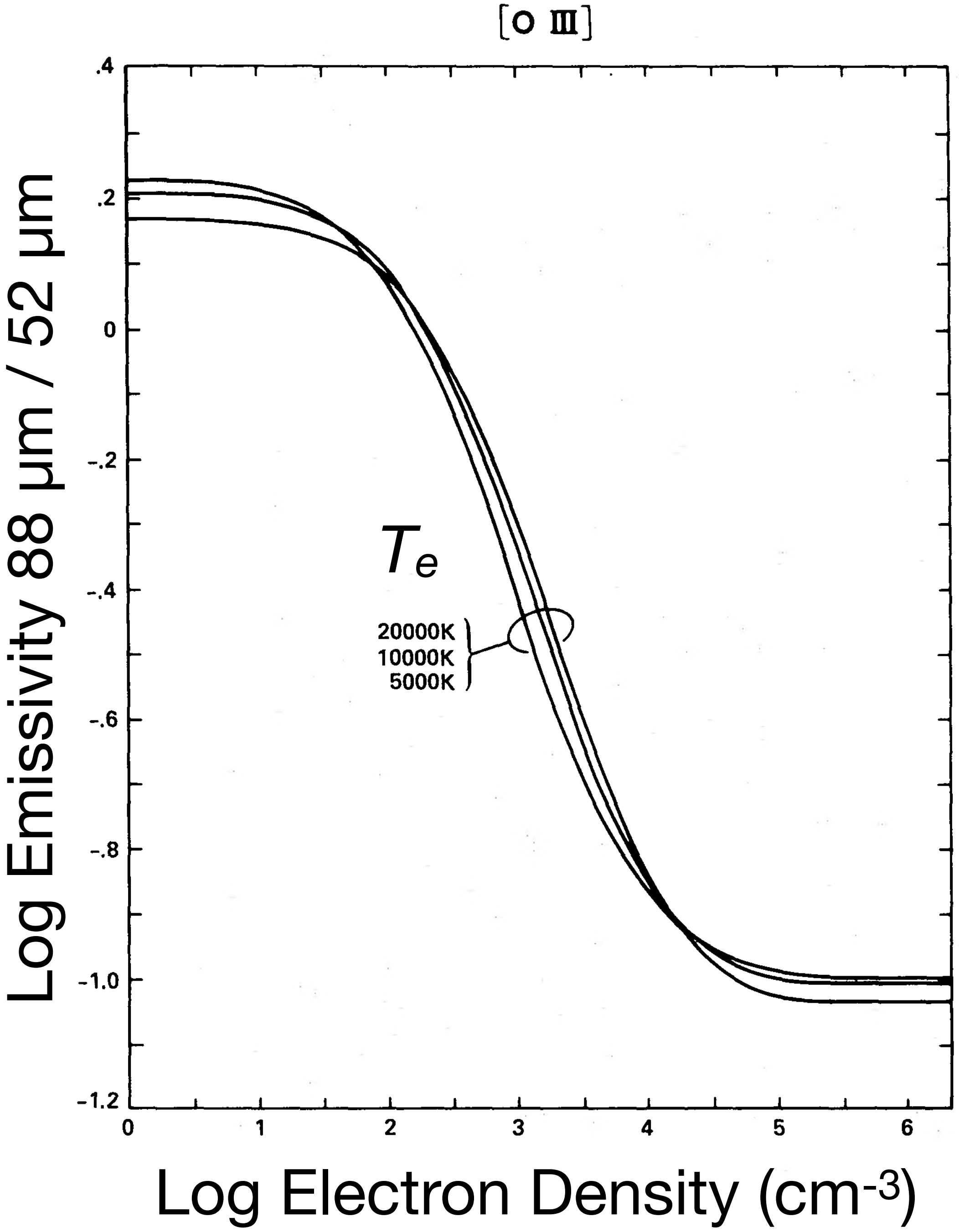
- The present distribution of chemical abundances in the Galactic plane is a function of many variables:
  - The historical star formation rate
  - The initial mass function and the relative yield of elements
  - The infall of material from the Galactic halo
  - Radial inflows or outflows of gas
- By comparing the distribution of Galactic abundances to those in other galaxies, we can infer the morphology and other properties of our Galaxy.
- Improved models of the time evolution of the abundances in our Galaxy allows us to better understand high-redshift galaxies early in their evolution.

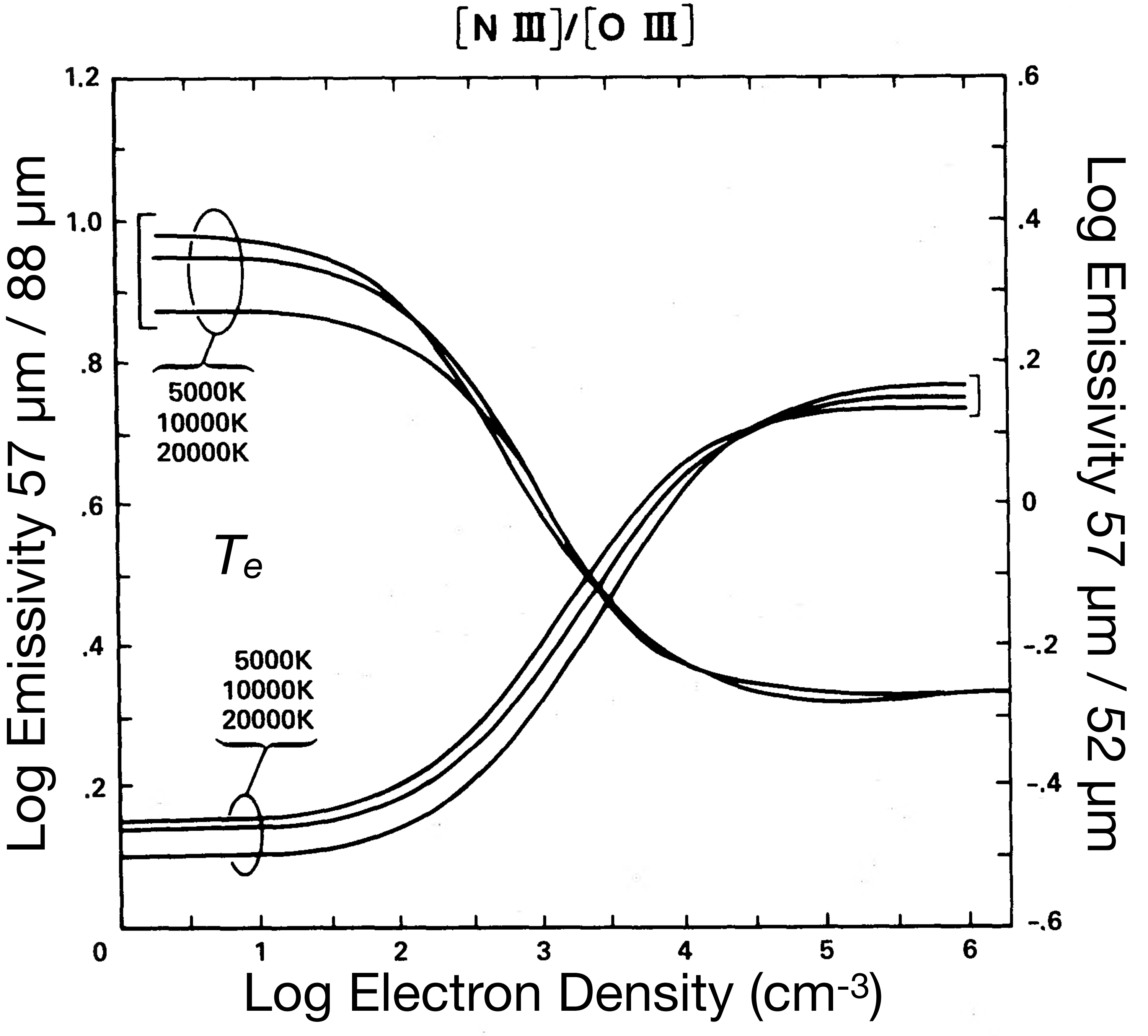
The infrared is home to several diagnostic fine-structure lines



The advantages of infrared fine-structure diagnostics

- IR fine-structure less are less sensitive to T_e than optical and UV lines





After Lester et al. 1983

The advantages of infrared fine-structure diagnostics

- IR fine-structure less are less sensitive to T_e than optical and UV lines

- Extinction is low or nonexistent in the IR

  The Galactic plane can be sampled inward of 5 kpc (where optical lines are heavily extinct)

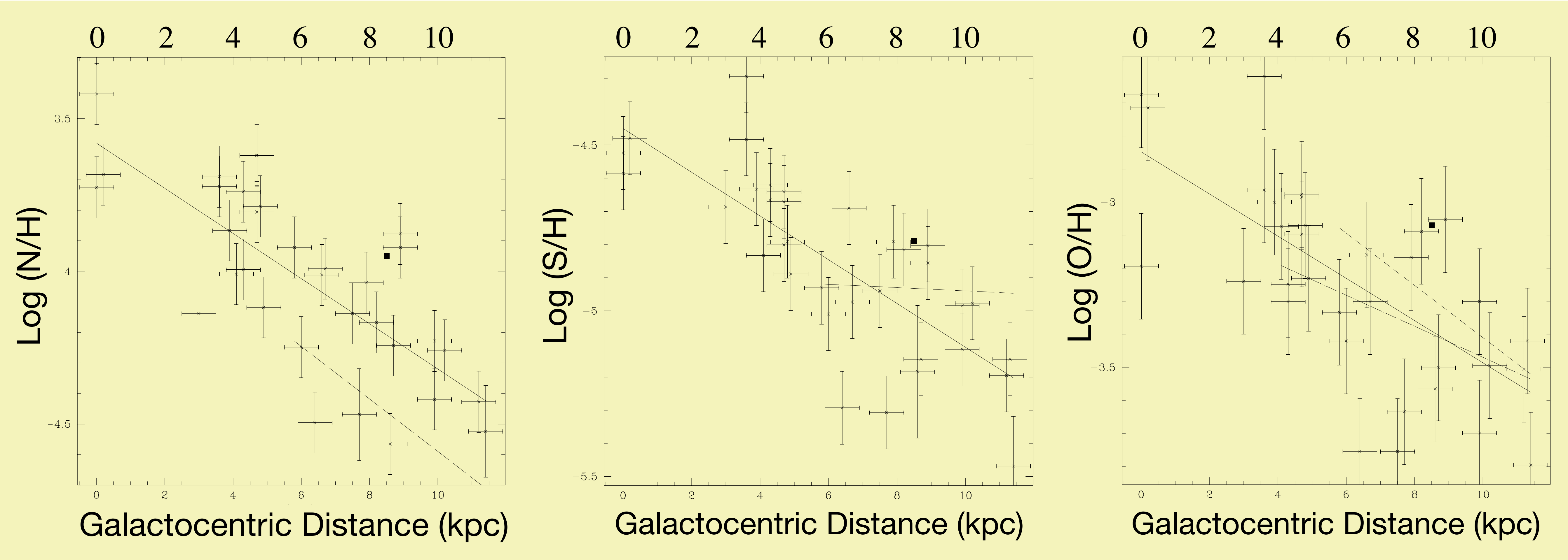
- S/H and N/H abundances are only weakly dependent on stellar T_{eff}
- Compact and UC HII regions are a very young component of the ISM, uncontaminated by products of stellar dredge-up.

(Radio continuum observations are used to determine the hydrogen column density.)

A lot of the pioneering work in this field was carried out by

Dan Lester
Harriet Dinerstein
Mike Werner

In the study below, 34 compact and UC HII regions were observed in [S III] 19 μm, [O III] 52 and 88 μm, and [N III] 57 μm



After Afflerbach, Churchwell, & Werner 1997, ApJ, 478, 190

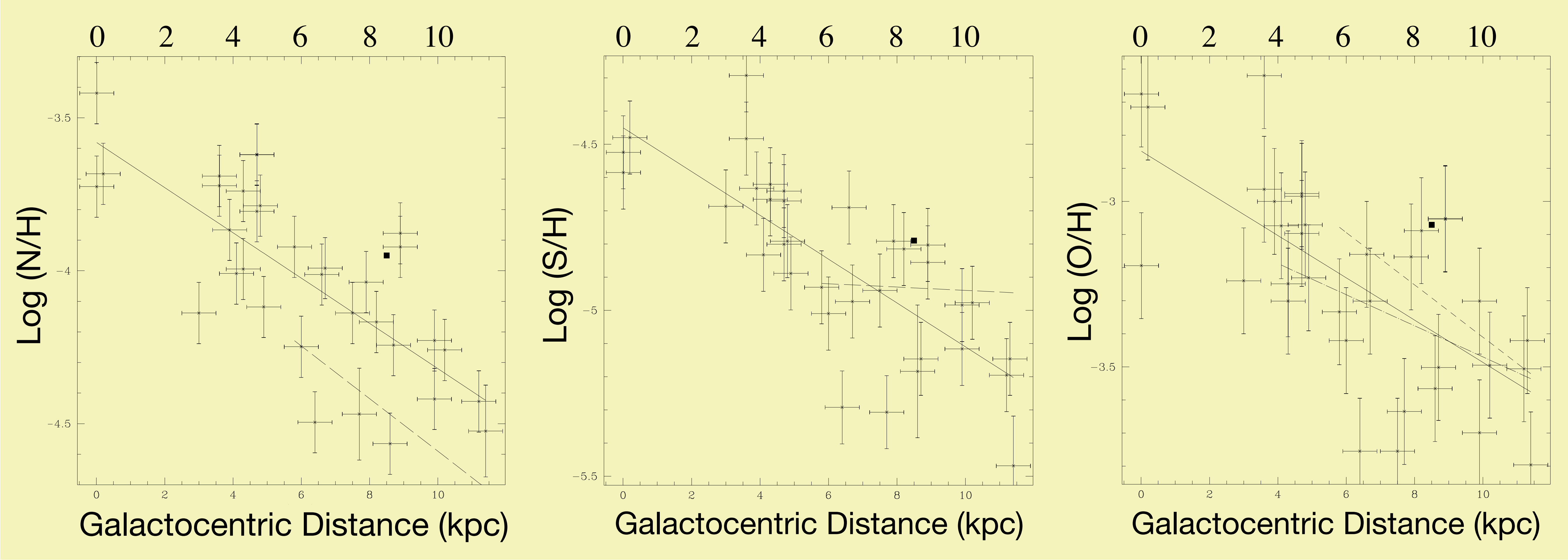
Data obtained with KAO Cryogenic Grating Spectrometer, R ≤ 6000

A modest SOFIA Key Program can improve on these results by virtue of its…

- 8x greater collecting area
- Higher spectral resolving power instruments (much greater line-to-continuum ratio)
- Much more sensitive detectors

Which enable the detection of weaker lines and less luminous sources

Data obtained with KAO Cryogenic Grating Spectrometer, R ≤ 6000



After Afflerbach et al. 1997

In Conclusion…

Just as HST enhanced its science stature with such projects as the Hubble Deep Field and the Hubble Constant Key Project, SOFIA should allocate the time and resources to enable a few programs that will have a lasting impact and will be of interest beyond the infrared community.

The examples I've presented are by no means exhaustive – they may not even appear on your list of things to do – *but they can all be accomplished with existing or selected instruments, and they can be started within the next few years.*