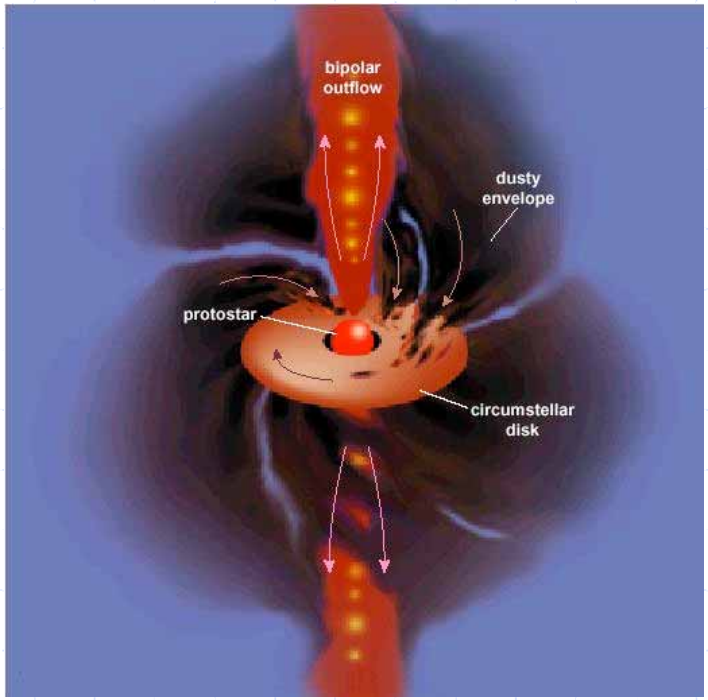
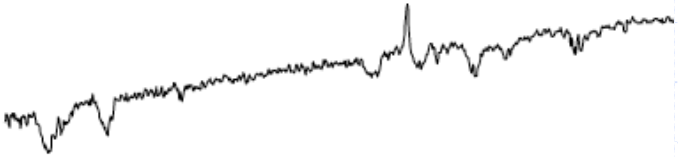
A Recent IR Spectroscopic Survey of Accreting Protostars - AND - *Looking forward to SOFIA*



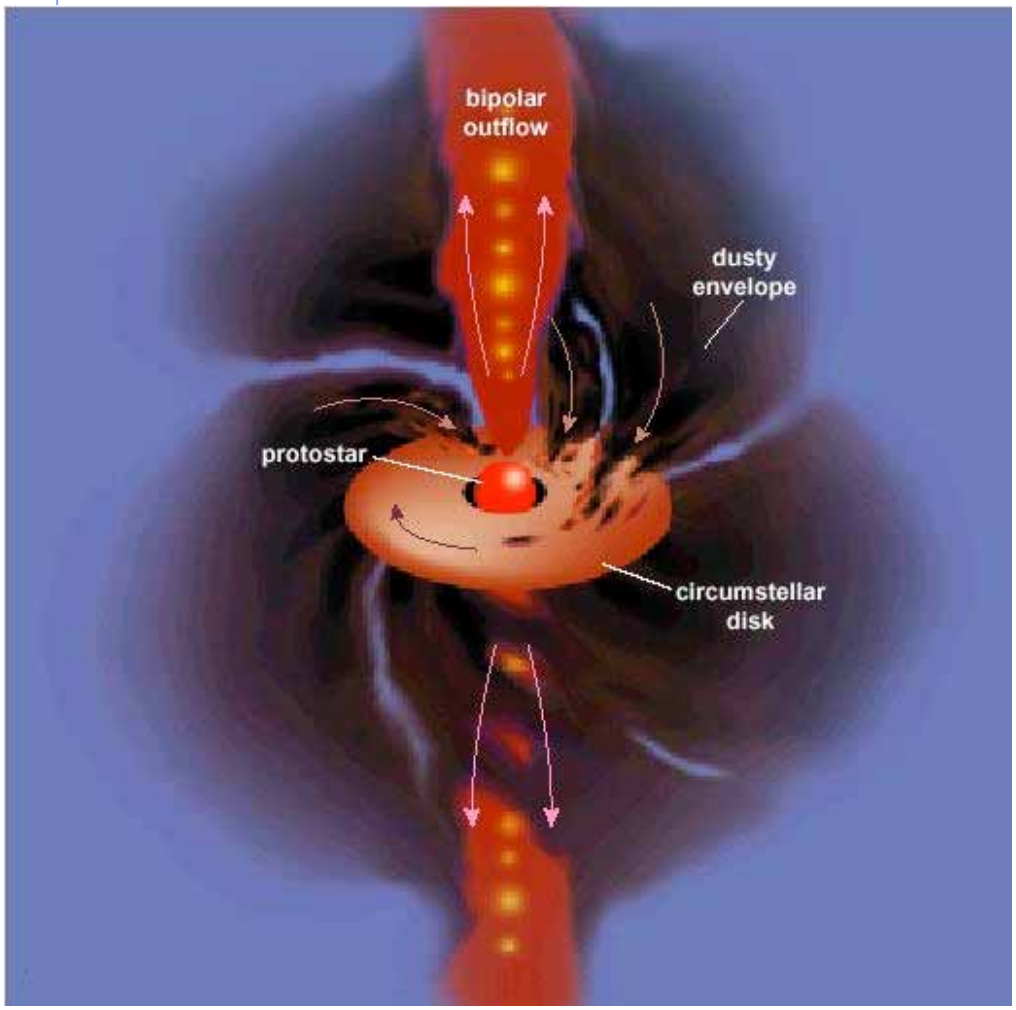


Tom Greene (NASA Ames)

What is this all about?

- Youngest embedded low-mass stars are now characterized by IR and sub-mm photometry but nearly impossible to study with visible spectroscopy (Av ~ 10 – 50+ mag)
- Very little is known about the stellar astrophysics of accreting protostars: they are too obscured
- IR spectroscopy is changing this: can measure stellar properties, accretion properties, angular momenta, rad vel
- I'll also say a bit about SOFIA and laboratory astrophysics needs

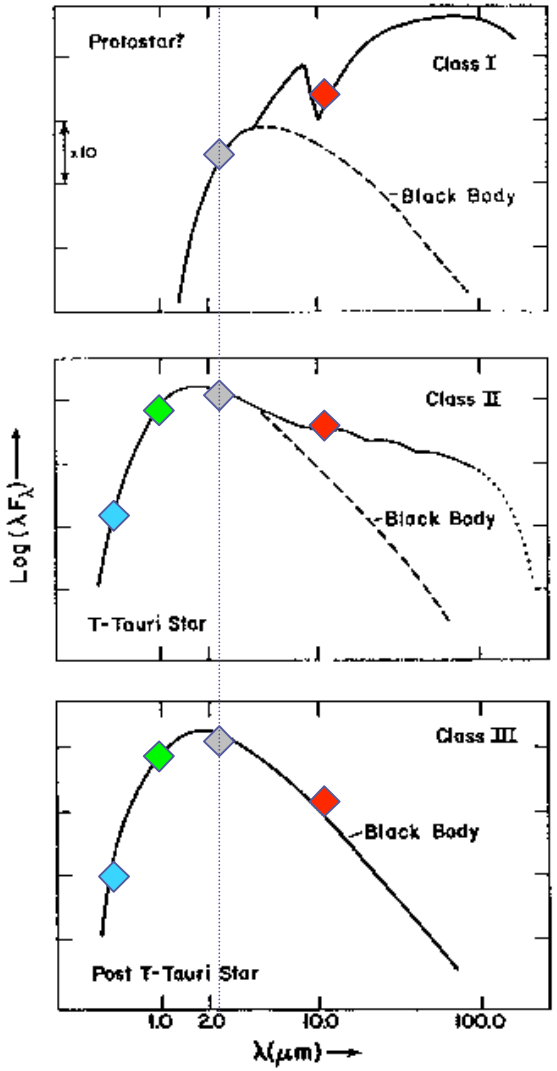
Study Goals / Low Mass Protostellar Anatomy



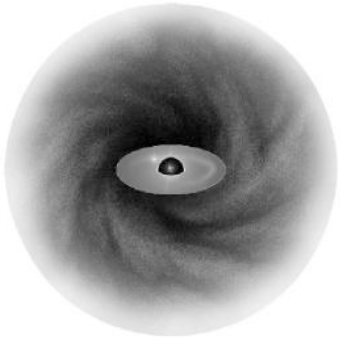
- Protostars:
  - Envelope ~1000 AU
  - Accretion disk ~ 100 AU
  - Embryonic core ~ ???
- Central embryonic stellar cores are essentially unobserved (but recent progress by White & Hillenbrand 2004)
- Goal of this study is to establish initial stellar astrophysics of protostars (T_{eff}, v_{rot}, log g, etc.), gauge their circumstellar environments (veiling, accretion diagnostics), radial velocities / motions.

Where Does the Energy Come Out?

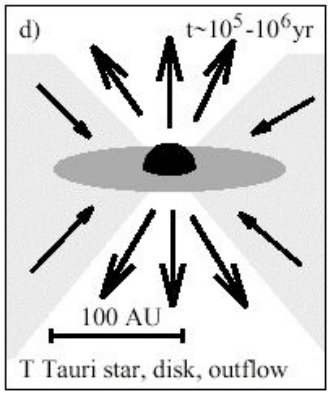
C. Lada 1987



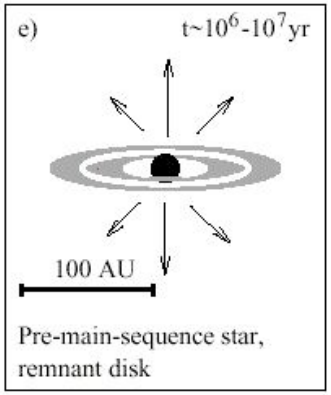
Protostar



T Tauri Star



Young System



EVOLUTION

Observational Approach

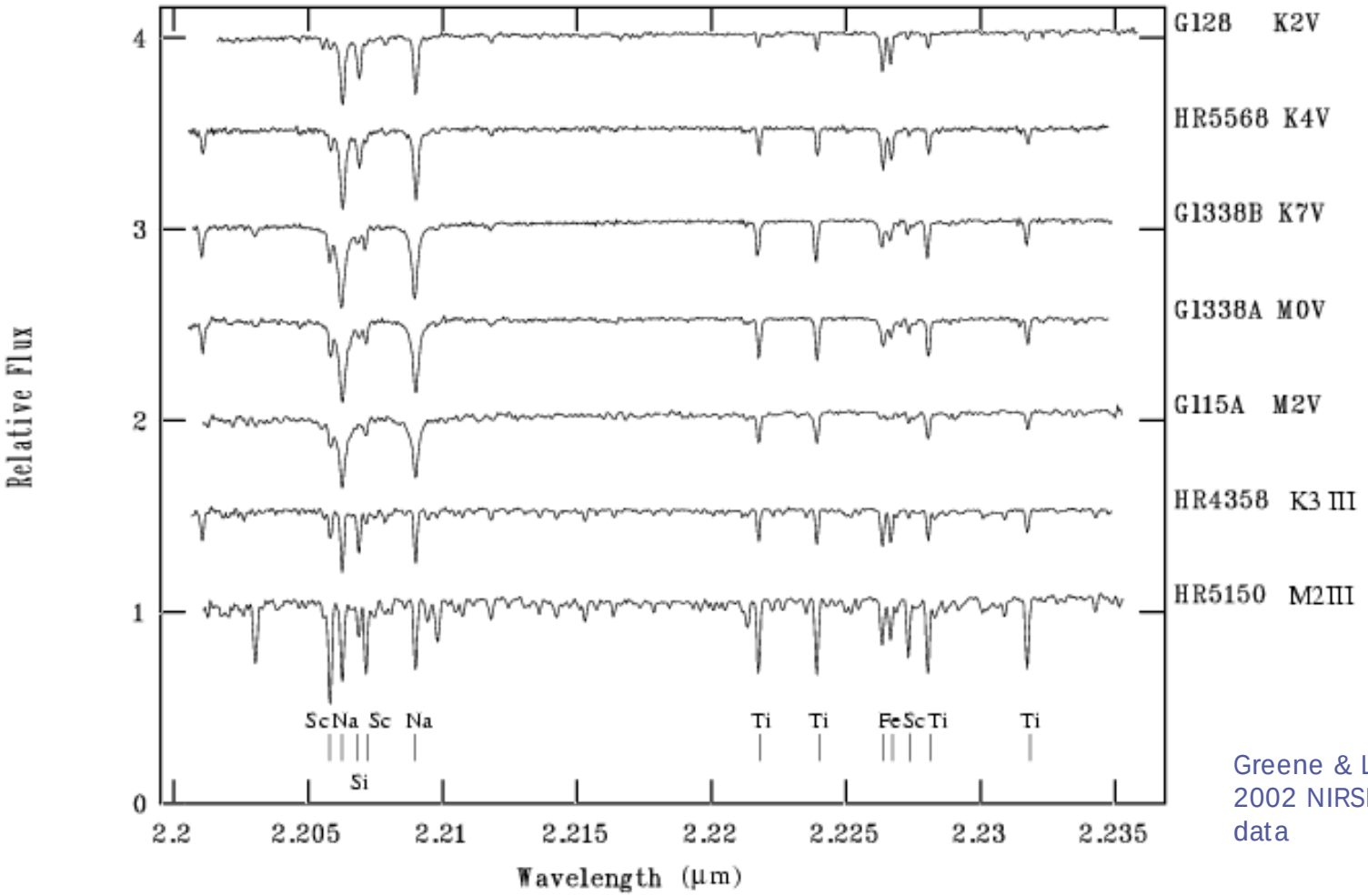
- Observe IR-selected Flat-spectrum & Class I accreting protostars.
  - Relatively faint in near-IR and highly veiled: most near-IR emission is IR excess, not directly photospheric
- High-resolution (R ~ 18,000) spectra yield spectral types, surface gravities continuum veiling, radial velocities, & $v \sin i$ rotation velocities.
  - Need resolution this high to eliminate veiling / spectral type degeneracies and resolve velocities
  - Determine properties by RMS fitting to spectra synthesized from NEXTGEN (Hauschildt et al. 1999) pre-main-sequence models
- Compare results to T Tauri stars to diagnose differences in stellar properties, accretion properties (veiling), angular momenta, space velocities

NIRSPEC Survey of Class I and Flat Spectrum YSOs

- Keck NIRSPEC Observations
  - R=18000 over 2.08 – 2.45 μm in 7 non-contiguous orders
  - 4 runs May 2000 to June 2003 (NASA time)
  - 52 IR-selected Class I and Flat-spectrum protostars in Oph (20), Ser (13), Tau-Aur (13), and other (6) regions
- Collaborators K. Covey (U. Washington) , G. Doppmann (GEMINI), and C. Lada (CfA)
- Previous publication of initial results of 2 objects (AJ Oct 2002): found high veiling, high accretion, and fast rotation
- 2 papers on entire sample now in press by **G. Doppmann** & **K. Covey** (with another one on the way).

Power of High-Resolution IR Spectroscopy

- High-resolution 2 μm spectroscopy is very diagnostic of stellar characteristics (shown by Kleinmann & Hall, Wallace & Hinkle, Meyer)

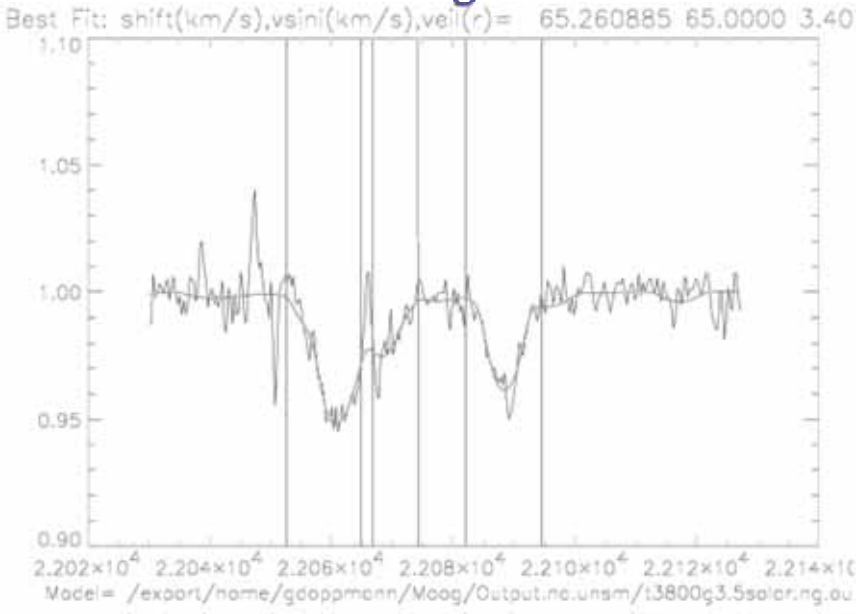


Greene & Lada 2002 NIRSPEC data

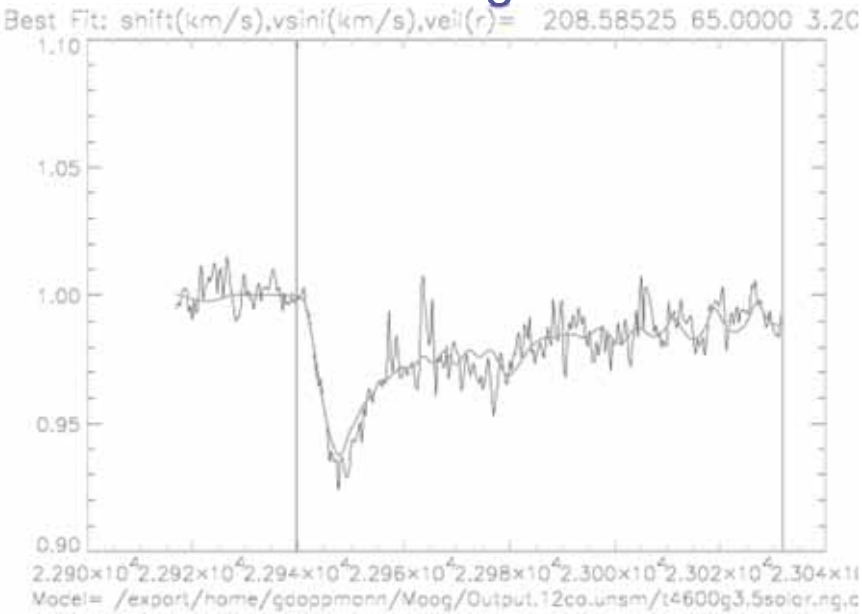
Doppmann Model Fits to NIRSPEC spectra

- Initial fits of NIRSPEC data to PMS models: solve for Te, Log g, v sin i, v_{rad}, & veiling by minimizing RMS differences
- Class I YSO Oph IRS 67 below has v sin i = 65 km/s, T_{eff} ~ 4000 K, r_k = 3.3

Na Region



CO Region

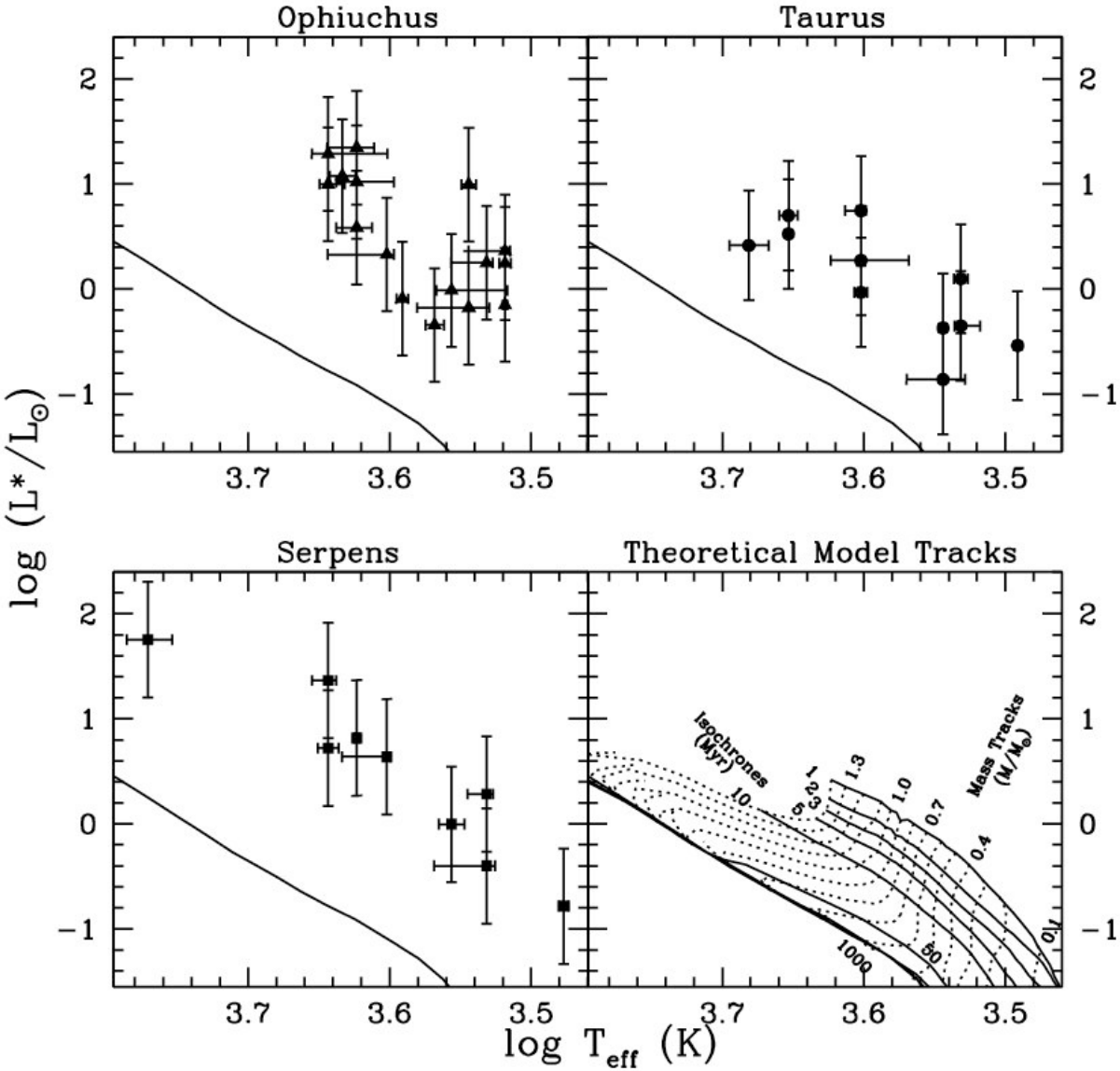


Spectral Types, Surface Gravities, Stellar Luminosities

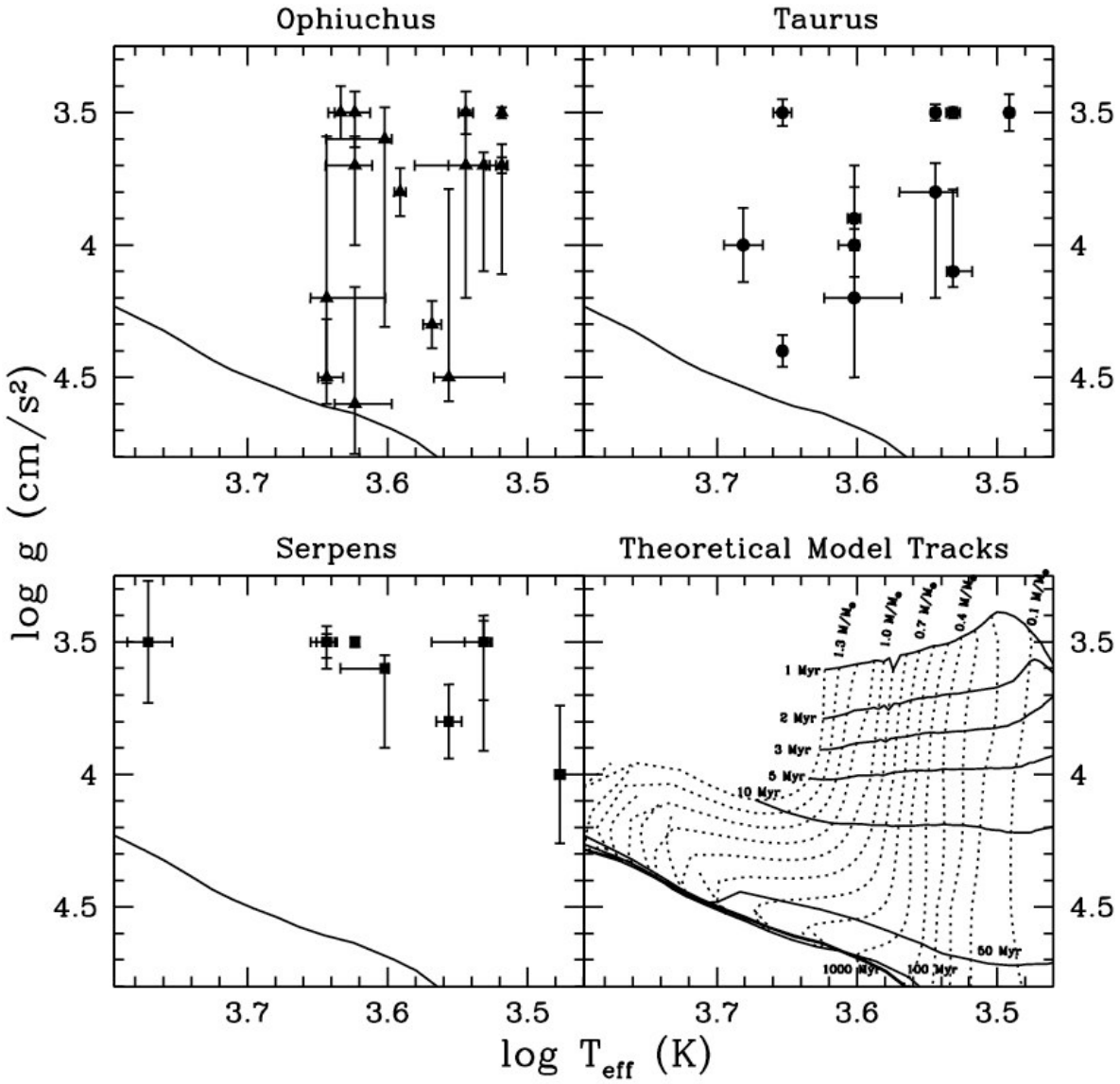
- Class I / flat spectrum protostars have late spectral types, surface gravities, and *stellar* luminosities (accretion removed) similar to those of PMS Class II stars.

- Put them in H-R diagrams...

Doppmann et al. H-R Diagrams: L_* vs. Teff



Doppmann et al. H-R Diagrams: Log g vs. Teff



Caveats to H-R Diagram Interpretation

- PMS structure models may not have totally accurate physics for protostars due to accretion effects (but are the best we have).
- Stellar luminosities are very uncertain due to effects of scattering on colors (extinction), distances, etc.
- Non-accreting PMS models are not appropriate for determining ages from H-R diagrams (masses probably OK)

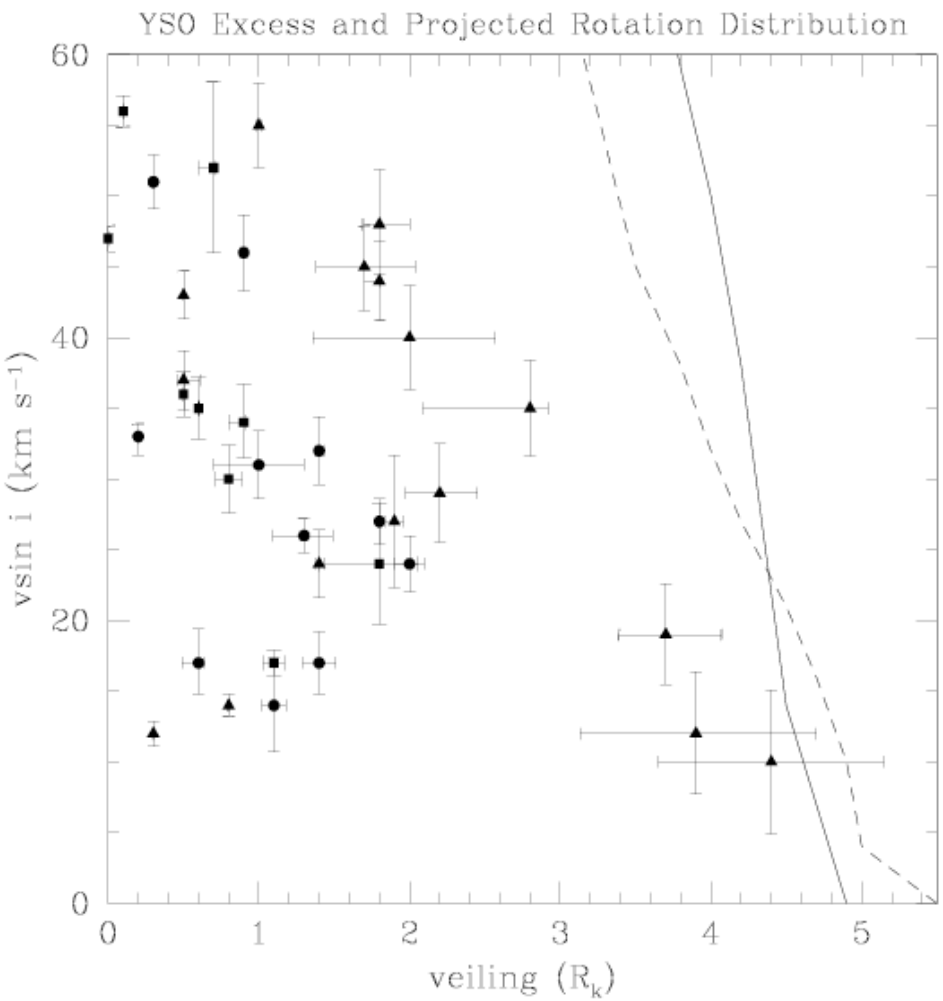
Veiling: Higher than Class II / CTTS

- For finite S/N, sensitivity to veiling and rotation are related. Lines show 2 σ detection limits for 3500K and 4600K stars given S/N=180.
- 11/52 objects are too veiled to have measurable abs. lines
- In the same region, the mean veiling of Class I / flat objects is significantly higher than for Class II / CTTS:

  $\langle r_k \rangle_{I/flat} = 2.21$ (Oph)

  $\langle r_k \rangle_{II} = 0.94$ (Oph)

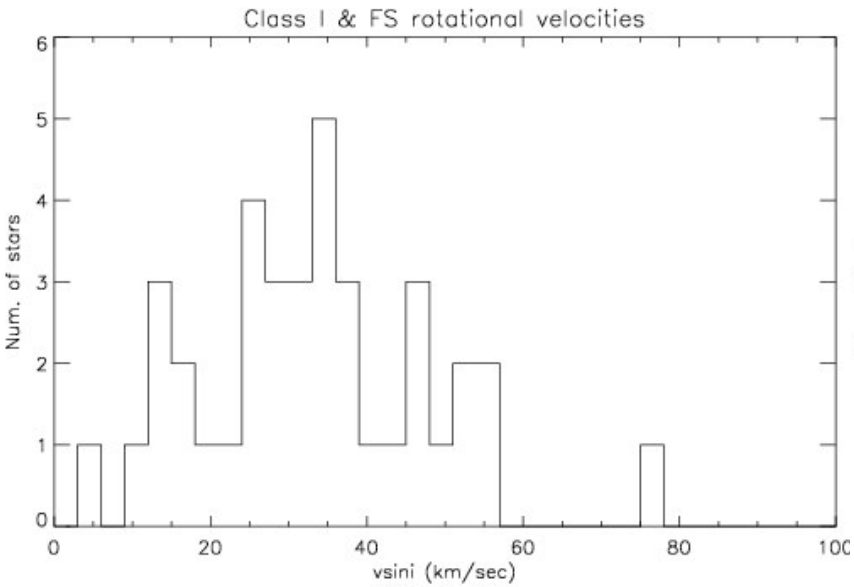
  K-S test indicates < 1% chance of same parent population (used lower limits for veiled objects)

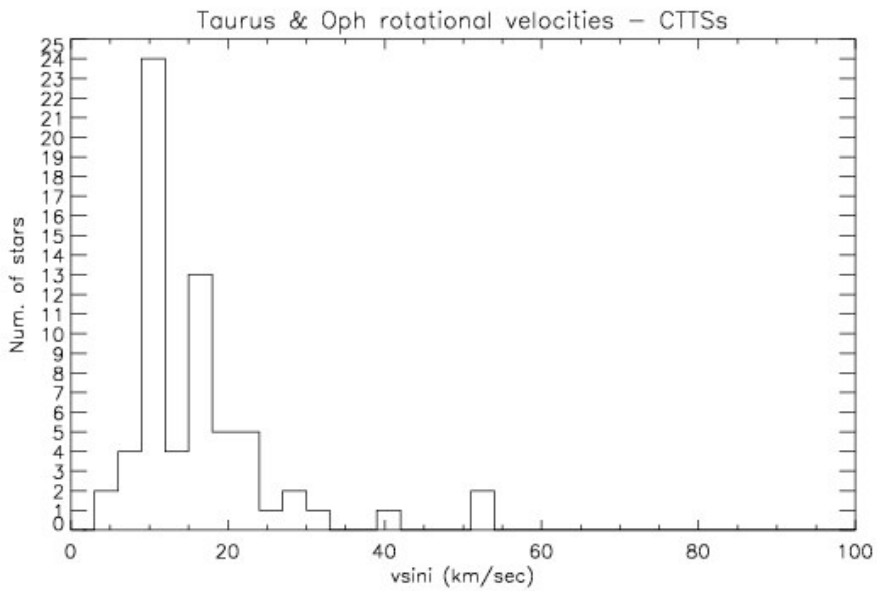


Covey et al. Angular Momentum study

- Used the Doppmann et al. projected rotation velocities to derive the most likely angular momentum distribution for the objects (statistical inversion technique).
- Also did this for existing observations of T Tauri stars in the same regions (rho Oph & Tau-Aur); same range of spectral types.
- Found that the protostars and T Tauri stars had significantly different angular momenta; angular momentum must evolve from Class I --> PMS phases.
- Angular momentum evolution is consistent with magnetospheric disk locking given likely object accretion rates and ages.

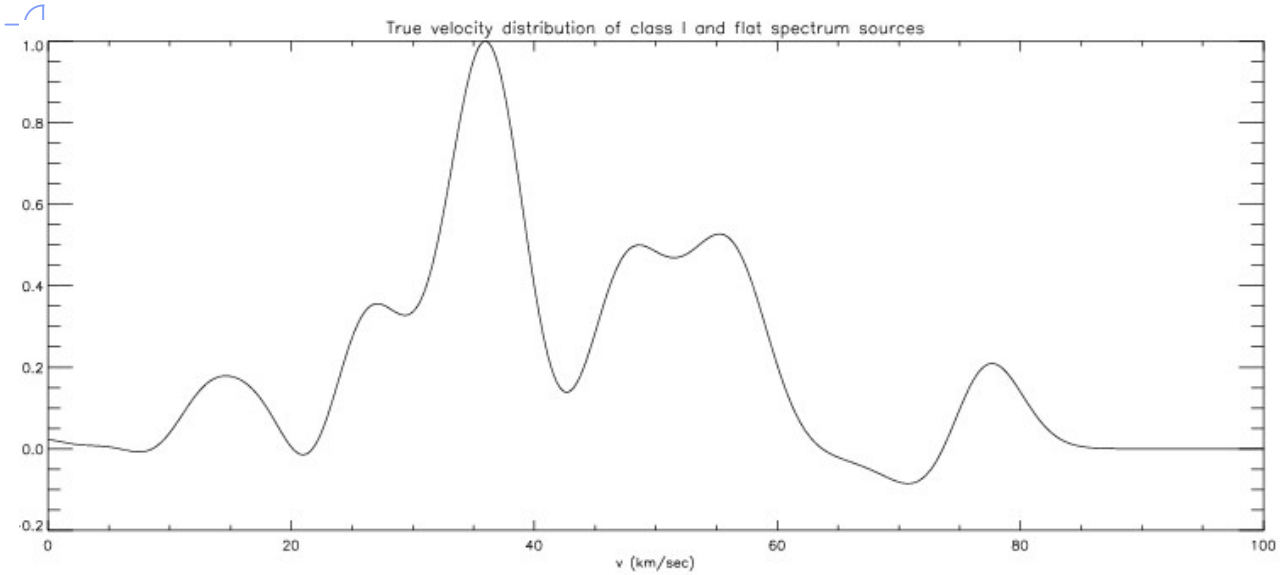
Covey et al: Projected Rotation Velocities

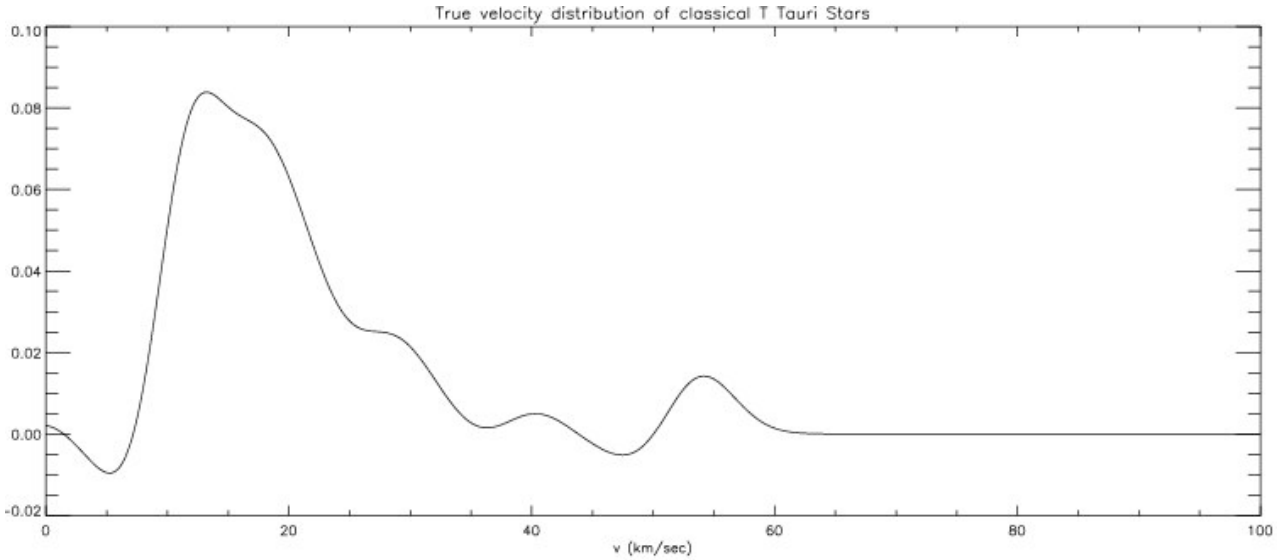




- Class I/FS and CTTS projected rotation velocities have very different distributions
- Implies protostars lose 1/2 their angular momenta by CTTS phase

Covey et al: Equatorial Rotation Velocities



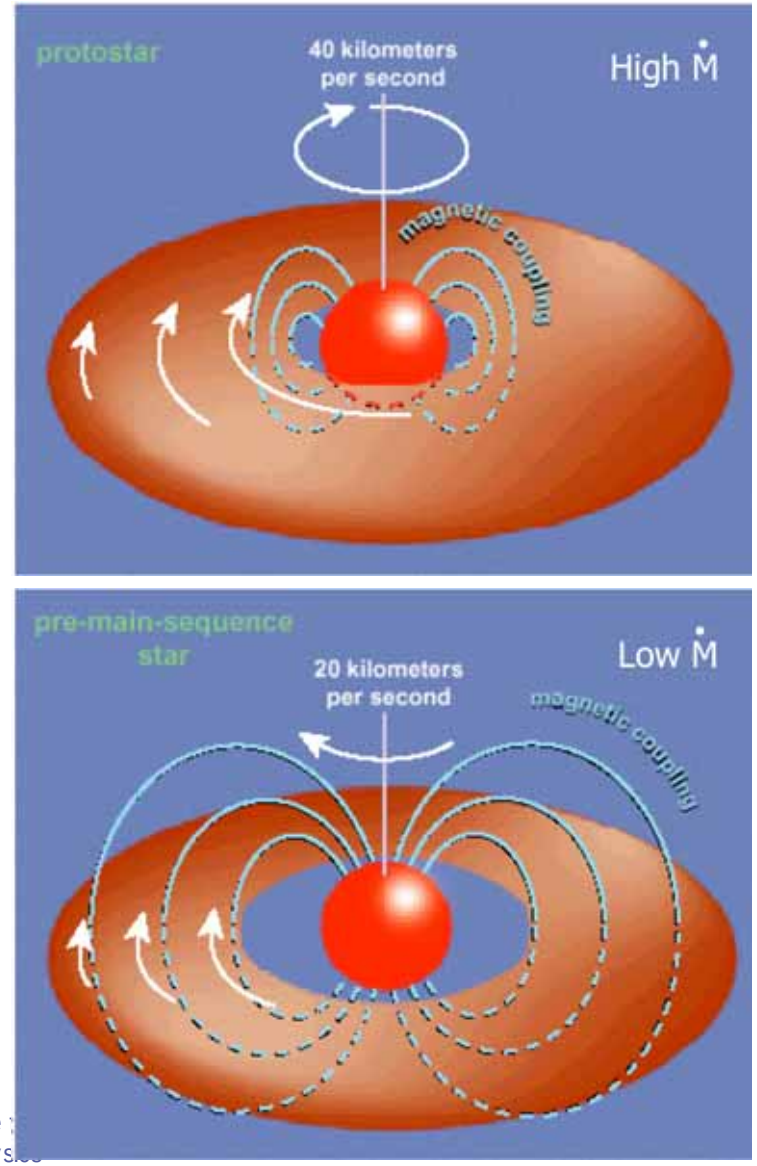


- Stars have lost nearly all AM by the class I phase, and Class I/FS velocities are not close to breakup.
- Class I/FS sample (top; v_{eq} ~ 38 km/s) and T Tauri sample (bottom; veq ~ 18 km/s) have <0.1% chance of being identical.

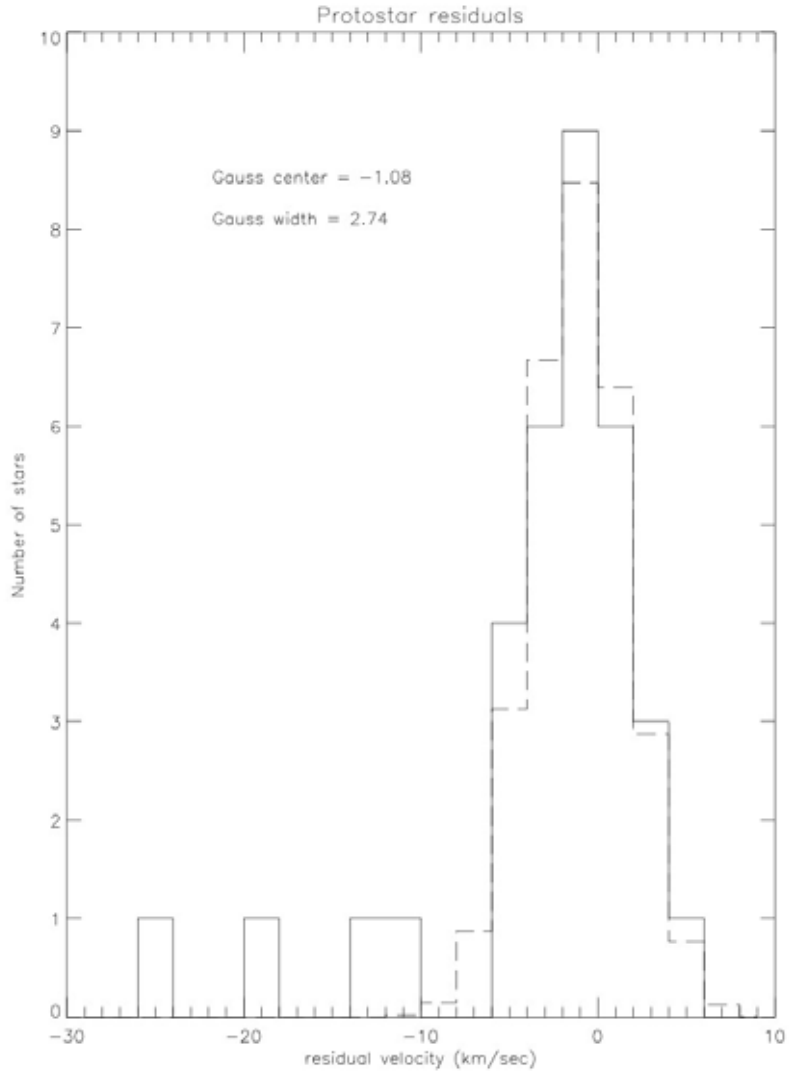
Covey et al: Angular Momentum Evolution

- The characteristic v_{eq} ~ 38 km/s rotation velocities of Class I/FS are consistent with disk locking at co-rotation radii (~ $2R_*$) for typical mass accretion rates.

- The factor of 2 drop in rotation rates between Class I/FS and Class II implies a factor of 5 or greater drop in the mass accretion rates (assuming disk-locking and magnetospheric accretion).



Covey et al: Radial Velocity Dispersion



- Distribution of Class I/FS radial velocity residuals are consistent with 0 velocity difference EXCEPT for 4 outliers (each 3σ or more). Similar to CTTS distribution (Hartmann 1986)
- Not quite sensitive enough to probe degree of stellar dynamical interactions of the proto-clusters.
- Outliers have velocities higher than predicted for most ejection events.
- Outliers may be very close binaries, but imply a binary fraction greater than CTTSs... perhaps an interesting result.

For further work...

- Need better atomic constants to model some near-IR lines (e.g., 2.1061 μm Mg I)
- Need better far-IR bolometric luminosities to determine accretion properties... need SOFIA!!

SOFIA Program Overview

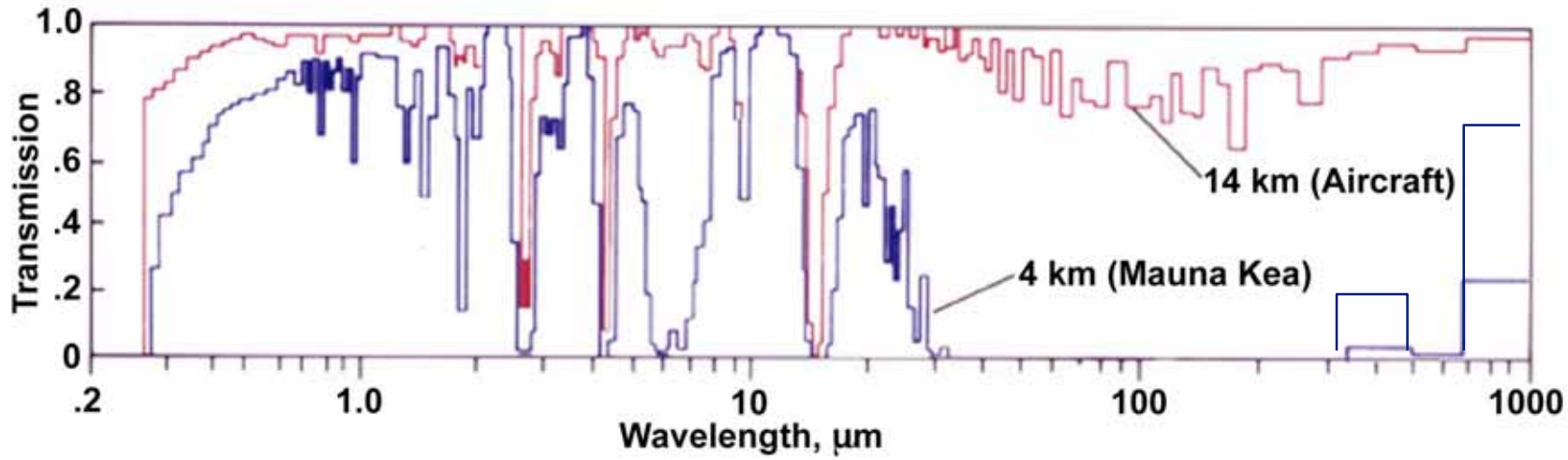
Description

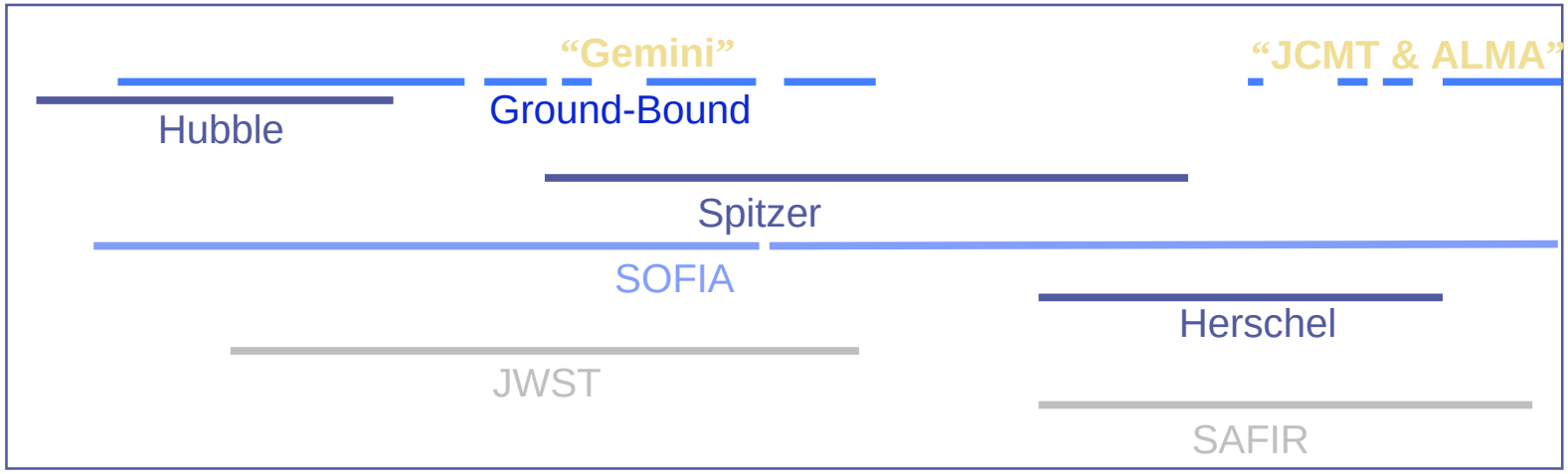
- 2.5 meter infrared telescope in 747SP aircraft
- Designed for 20 years of operation
- 2006 Operational Readiness Review
- Nearly all observing time is for GOs - annual cycle
- Optimized for far-infrared and submillimeter observations
  - 9 first generation science instruments:
  - Visible to submillimeter cameras, infrared and submillimeter spectrographs, with unique time, spatial, and spectral resolution capabilities
  - Instruments will be changed and upgraded over lifetime
- Hands-on training for future scientists and an icon for education and public outreach

Organization

- Program Lead: Ames Research Center
- International collaboration with DLR
- Prime Contractor: Universities Space Research Association (USRA)

Atmospheric Transmission/Observatories

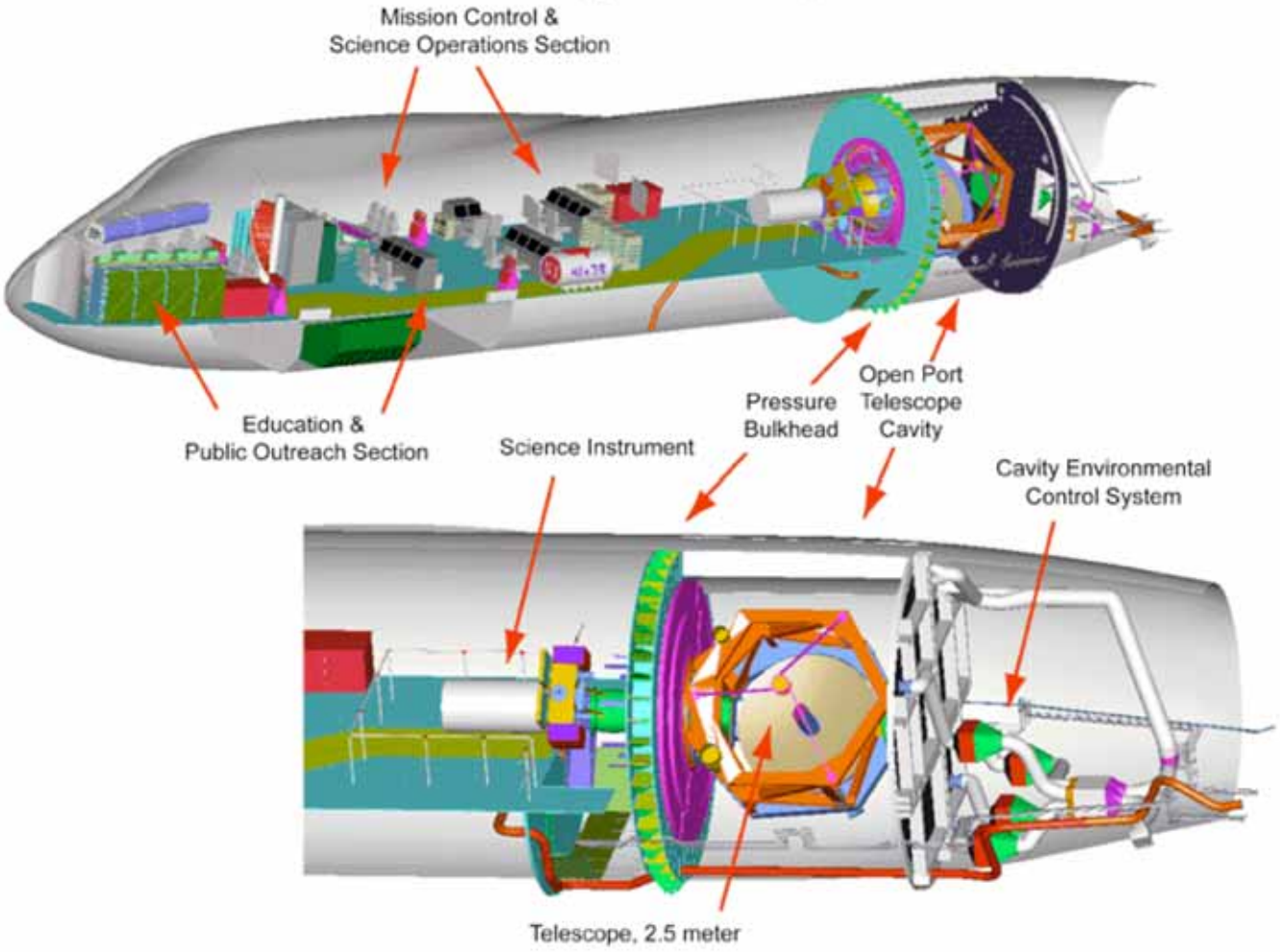




Infrared/Sub-MM Observatories

Layout of Personnel and Accomodations

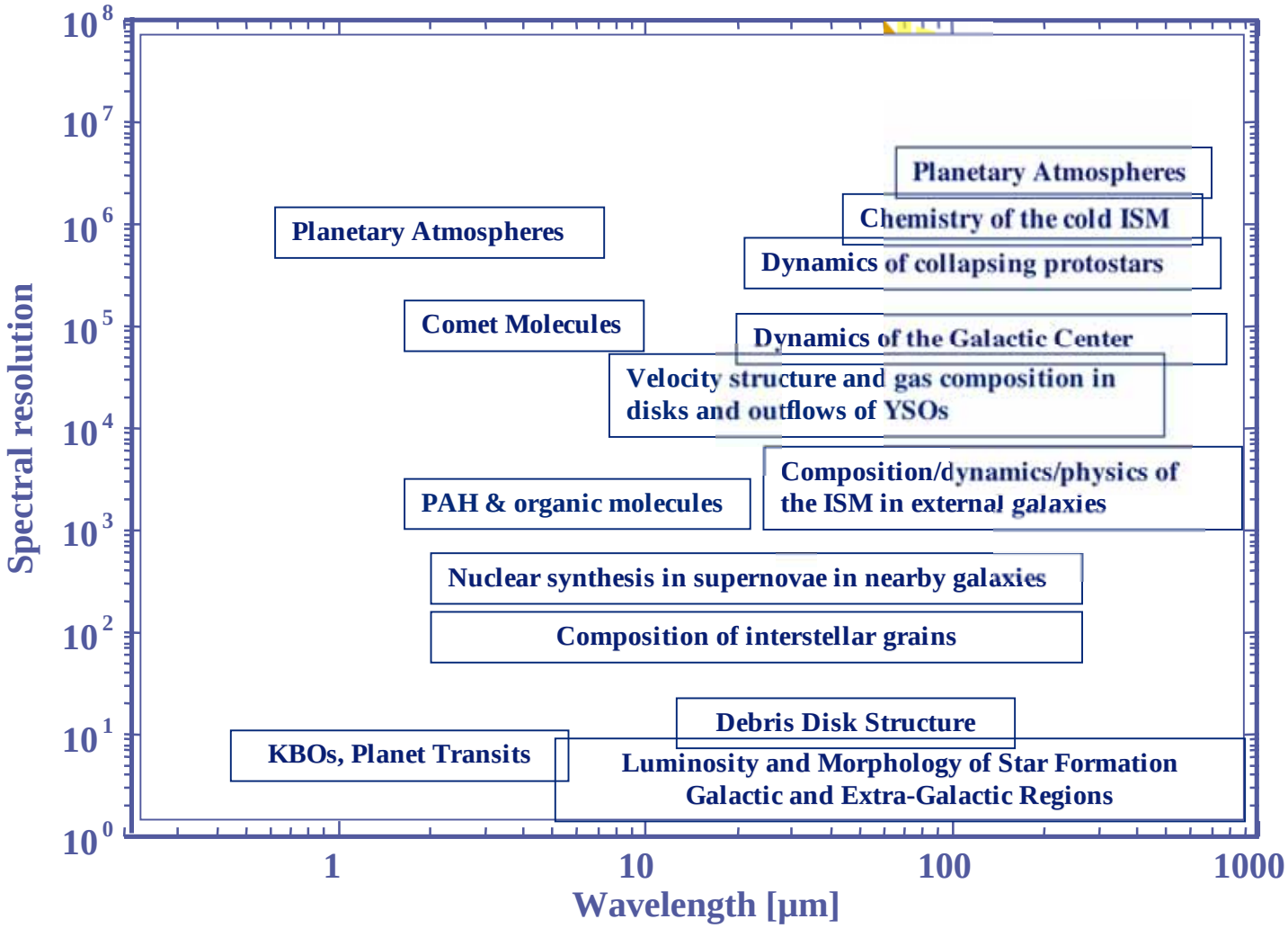
(upper deck not shown)



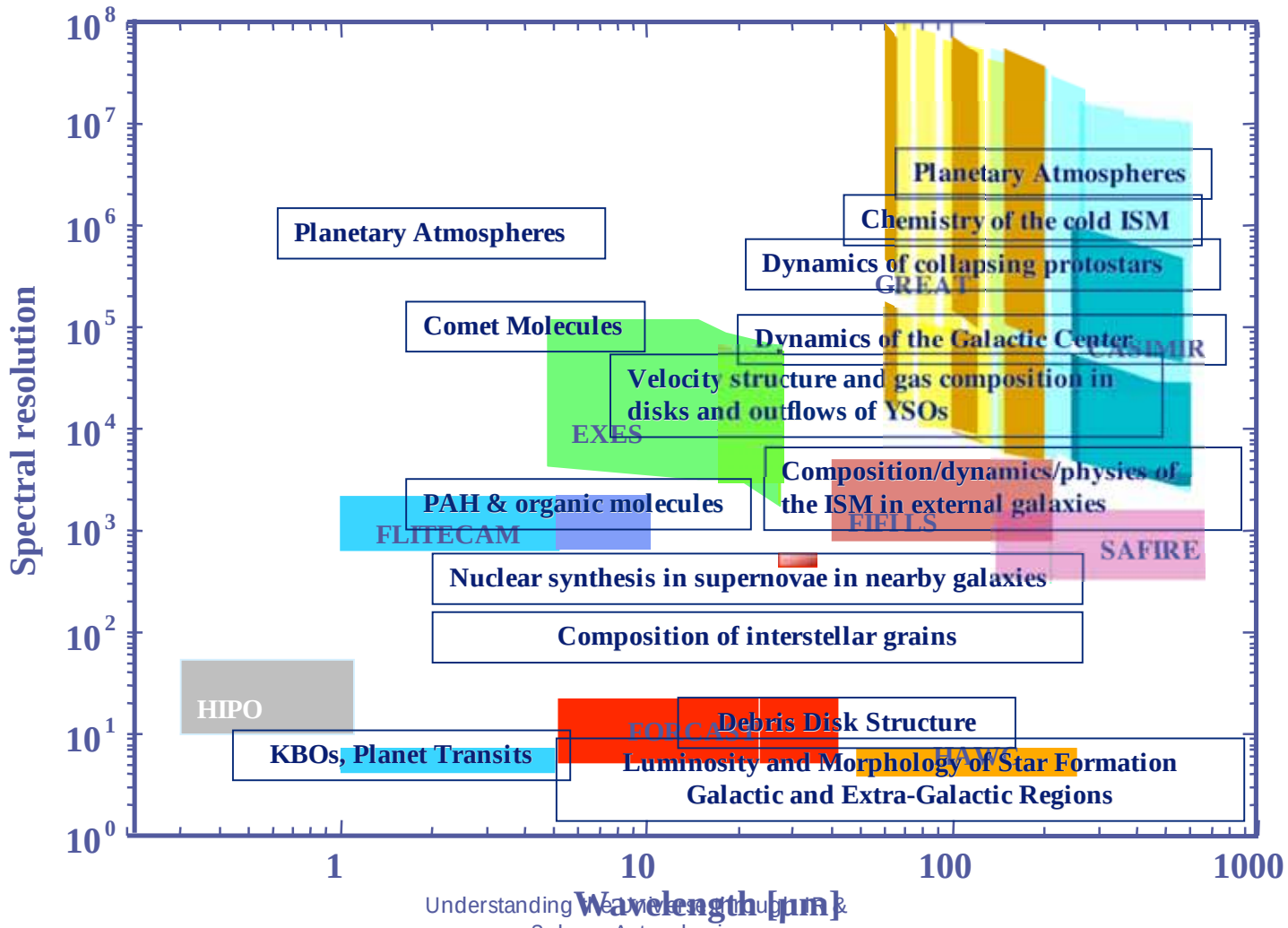
Sample SOFIA Science Cases

Infrared studies of cometary dust using SOFIA
Exploring Kuiper Belt Objects with Stellar Occultations
Water in Space: Comets and the Interstellar Medium
Prebiotic chemistry and protoplanetary disks
Debris disks
Precise Photometry of Extrasolar Planet Transits
Magnetic Fields, Turbulence, and Star Formation
IR dark clouds: The sites for the earliest stages of star formation
Photochemistry and Shocks in Circumstellar Envelopes
Supernova Remnants: Enrichment and Processing of Heavy Elements
New Insights into the Physics of Infrared Cirrus
Star Formation in the Central Molecular Zone of the Galaxy
The Circumnuclear Disk: Chemistry of Warm Galactic Center Clouds
High Mass Star Formation in Milky Way & Local Galaxies / SOLONG
Deep surveys for far-IR luminous galaxies

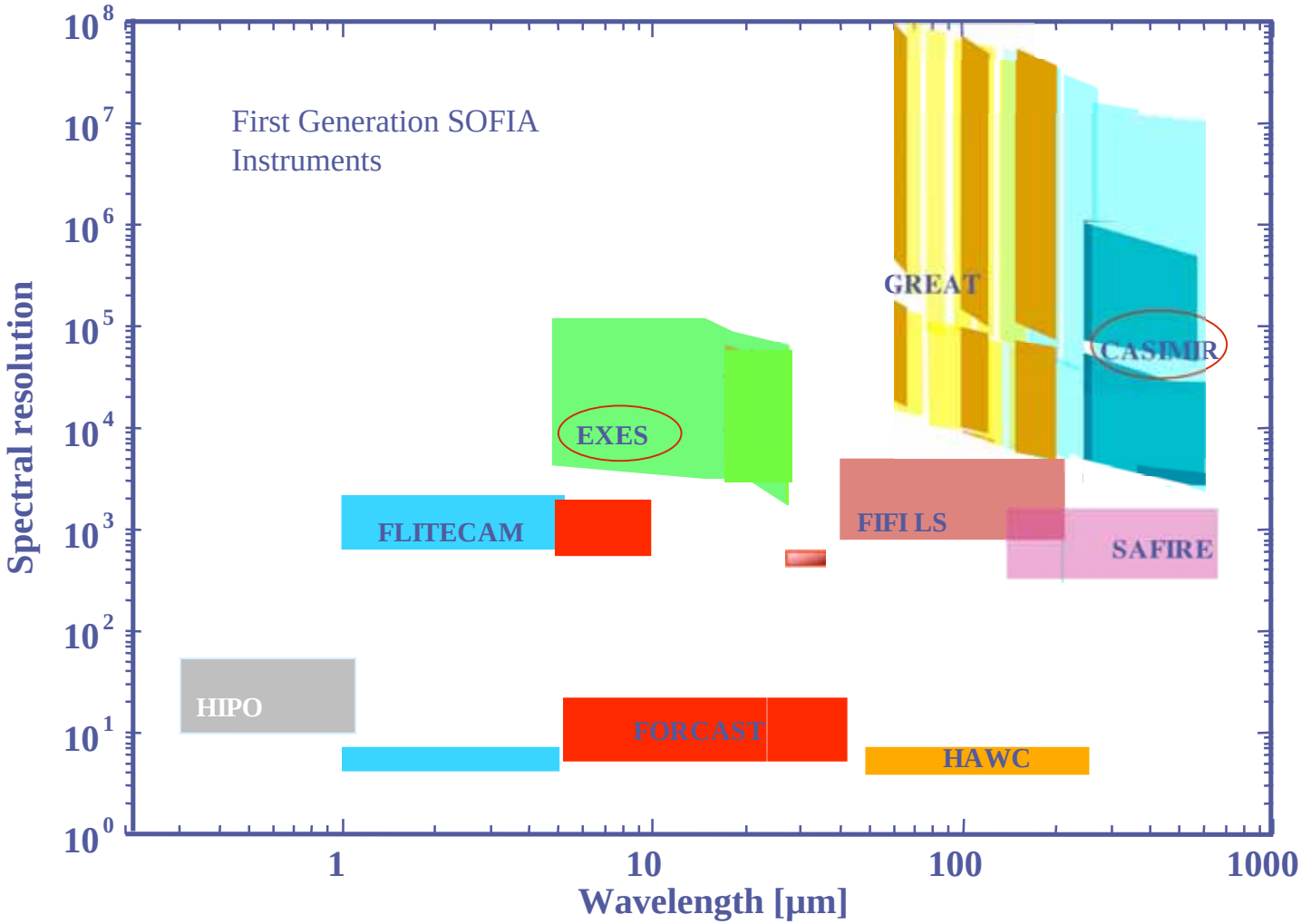
Spectral coverage enables SOFIA to study many phenomena at optimum wavelengths and resolution ....



Spectral coverage enables SOFIA to study at the optimum wavelengths and resolution many phenomena....



SOFIA's first generation of Science Instruments....

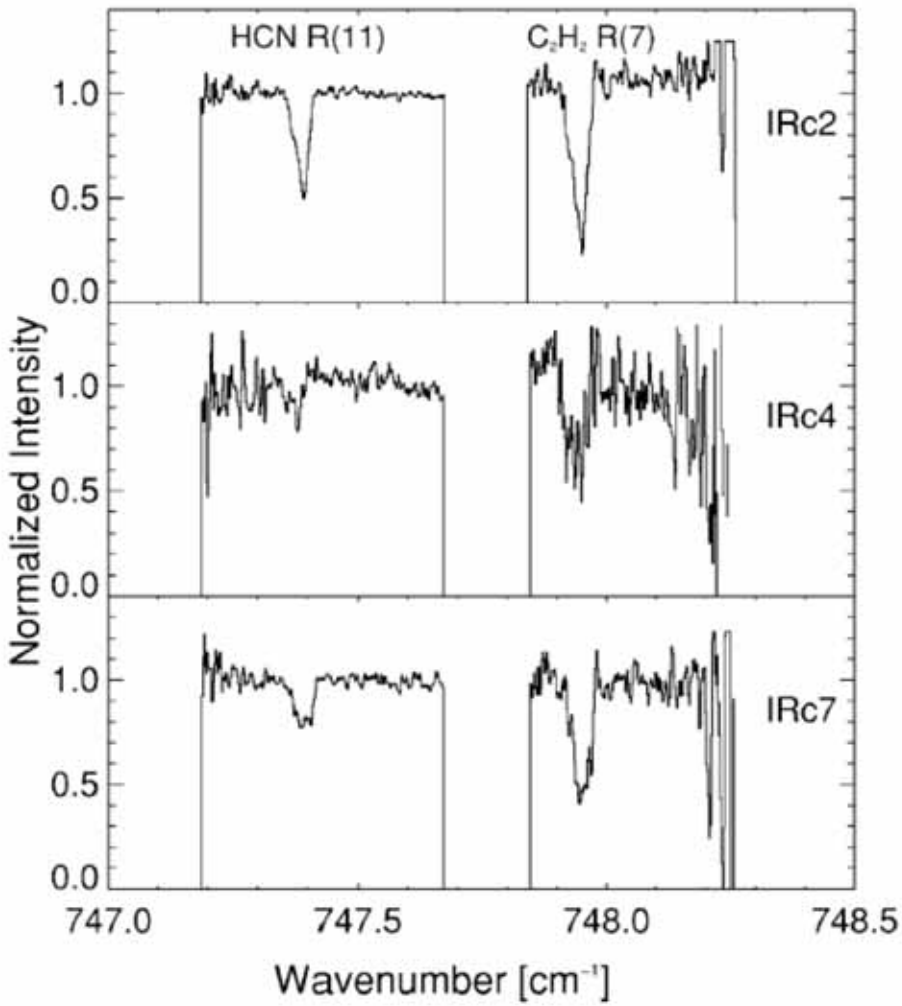


Focus on two (of 9) SOFIA Instruments

- EXES spectrograph
  - 5-28 μm R~10^5 grating (echelon) spectrograph
  - H_2, H_2O, CH_4, C_2H_2, (ro-vib lines in molecules w/o perm. dipole moments), H_2SO_4, fine structure lines, forbidden lines (Ni, Co, Fe, Ar, Ne, O in SNe)
  - Velocity-resolved molecular spectra of star-forming gas, circumstellar disks, molecular clouds, comets, planetary atmospheres, winds, etc.

- CASIMIR spectrograph
  - 500 GHz – 2.1 THz bands (150 – 600 μm)
  - "High" J CO lines, H_2O and isotopes, OH, CH, CH^+, HD, HF, CH, SiH, NH_3, Si, etc.
  - Velocity-resolved studies of AGN, glactic center, molecular cloud chemistry, shocks, protostars, post-AGB stars, PN, SNRs.

EXES Science Teaser (TEXES data)



Actual HCN and C2H2 absorptions seen with TEXES towards IR source embedded in Orion. Noise near the spectra ends are caused by atmosphere (not a problem for EXES on SOFIA), but line structures are real.

There are multiple velocity components where there had been assumed to be a single component of a different width.

Lab Astrophysics Data Needs

- More accurate *transition frequencies* (0.01 cm^{-1} for EXES) and *energy levels*, particularly for high rotational and ro-vibrational states (H_2O, SO_2, CH_3, etc.)
- Band-strength (or dipole matrix element) data if frequencies are to be derived from observations
- Better collision coefficients needed
- Knowledge of probabilities of other excitation methods (gain ab/desorptions, molecular formation, chemistry) needed to interpret gas in star formation regions (e.g., abundances of deuterated molecules)
- Interpret evolution of Ortho / Para ratios in star formation regions
- Compilations of data and formulae needed to address these types of problems
- **PLEASE SEND ME OTHER IDEAS; I'll FORWARD TO NASA HQ!**

SOFIA wants to fly!