Probing the assembly of the youngest protostars with NIRSpec

Tom Greene (NASA Ames),
E. van Dishoeck, M. Ressler,
M Barsony, Gully

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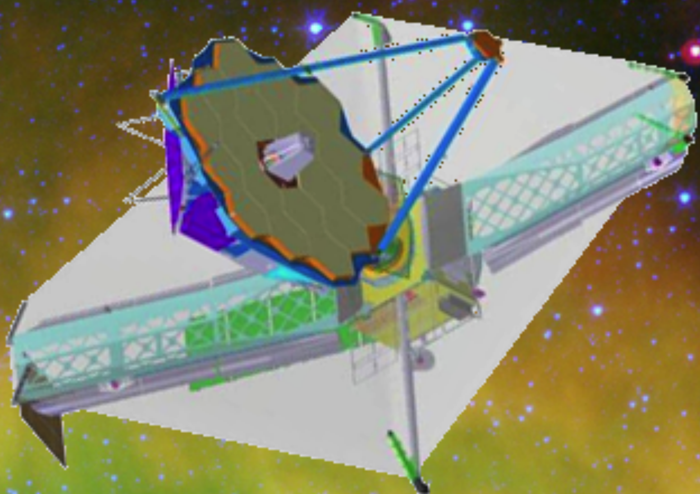
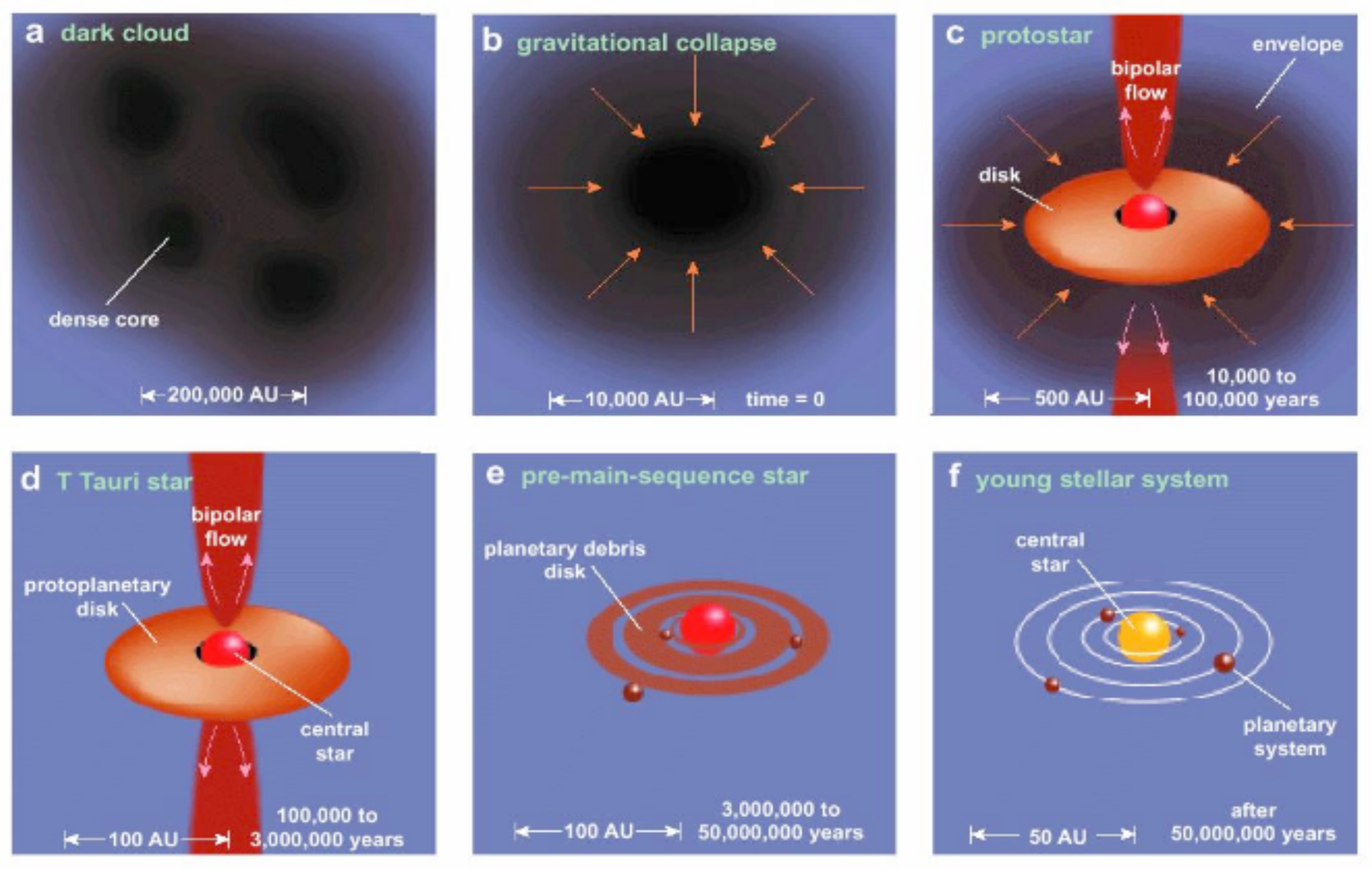


Spitzer Serpens A image courtesy of NASA/JPL-Caltech/L. Cieza (UT)

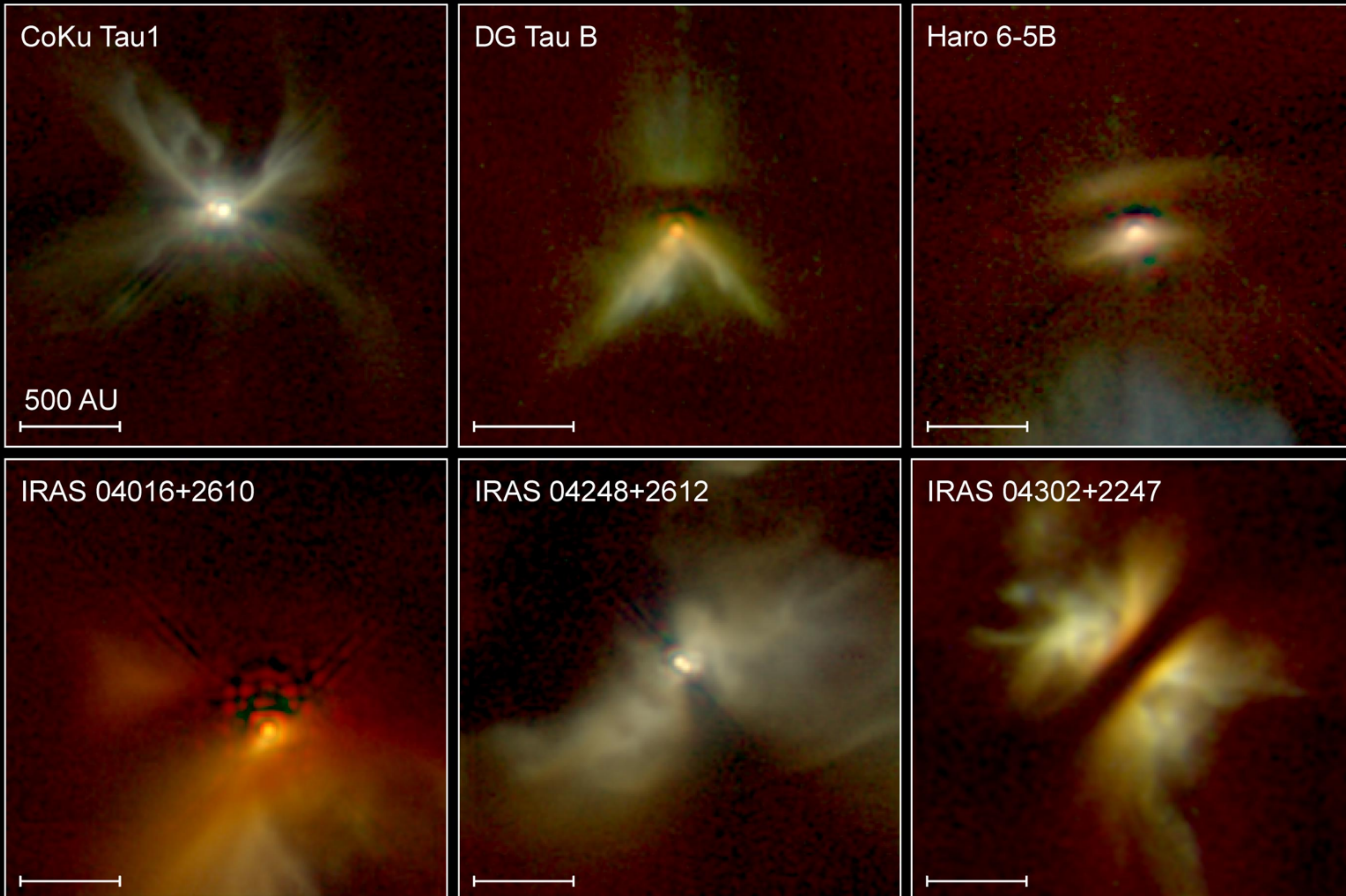
Topics

- Low-mass star formation paradigm
- Questions about central protostars
- Progress on understanding Class I protostars
- Going younger: Class 0 protostars & observational considerations
- JWST Class 0 program
- Keck reconnaissance: Serpens S68N: First Class 0 photosphere
- Related JWST programs

Where do stars and planets come form?



Greene 2001 Am. Sci.; adapted from Hogerheijde 1998 andShu et al. 1993

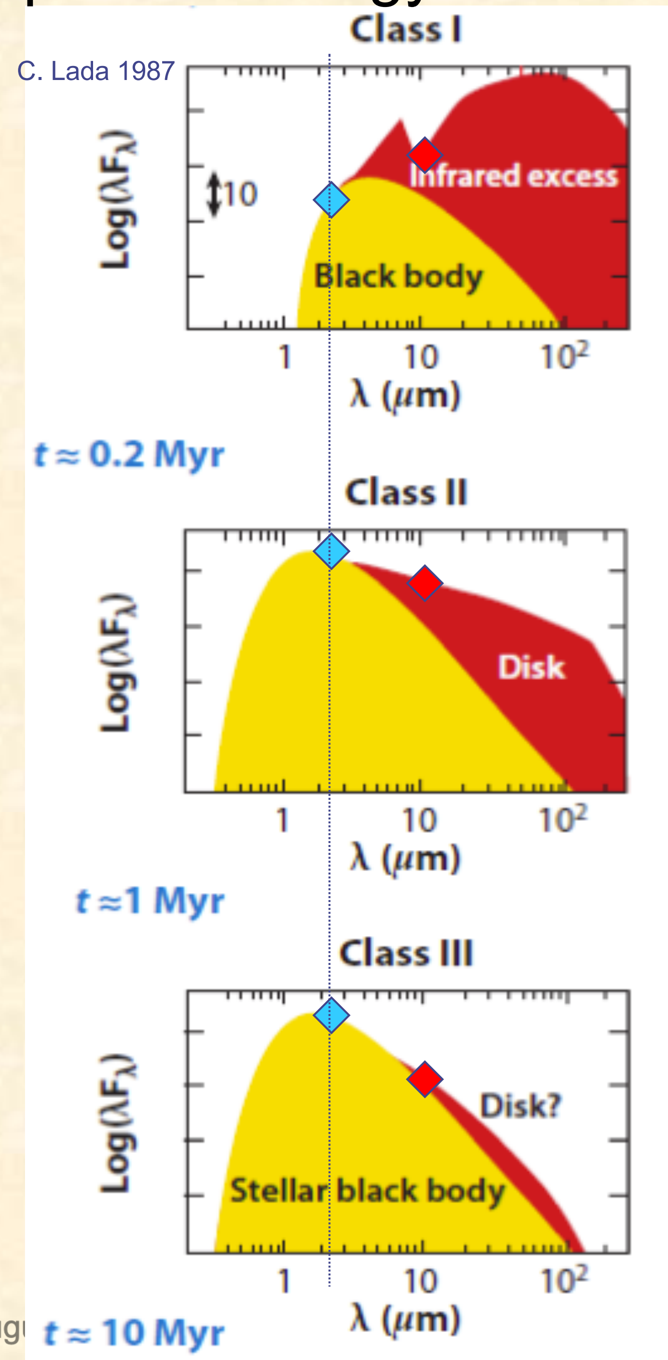


Young Stellar Disks in Infrared

Hubble Space Telescope • NICMOS

SEDs and Young Stellar Objects (20th Century)

Spectral Energy Distributions

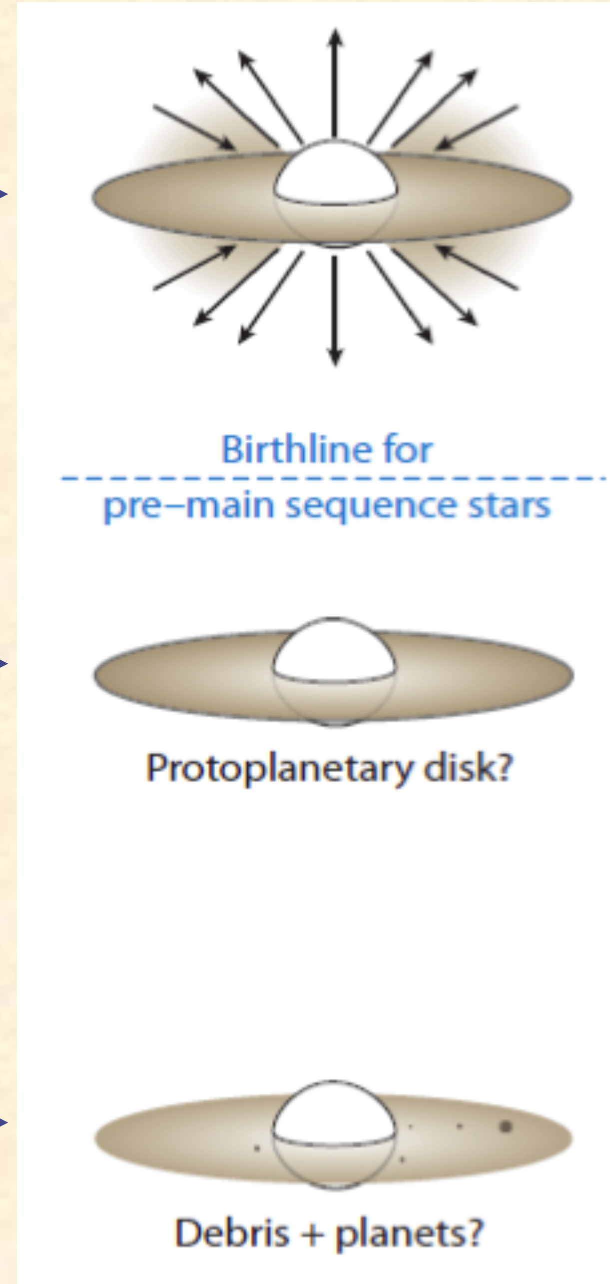


Final stage Protostar

T Tauri Star

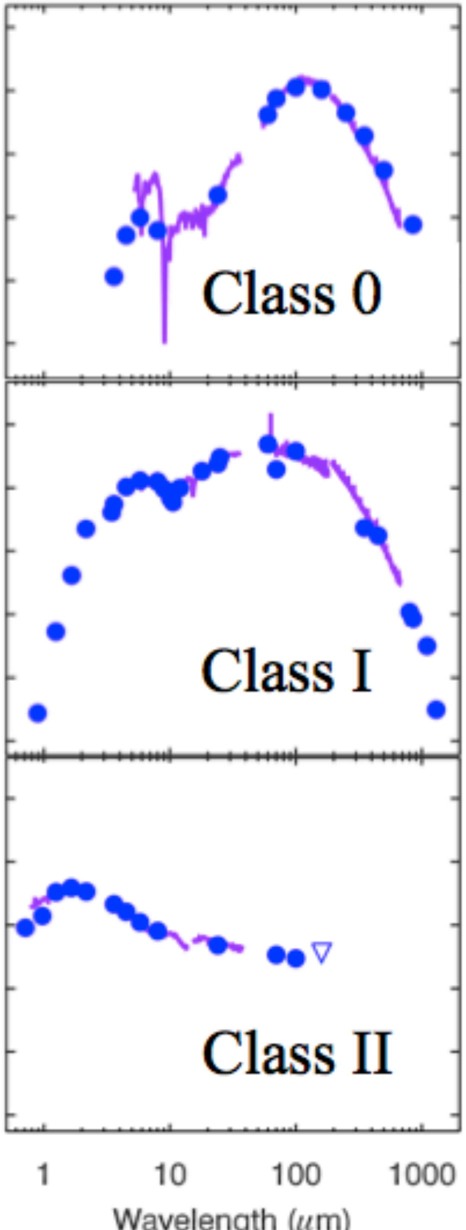
Young System

Evolutionary Stages



EVOLUTION

Observational classes / evolutionary stages



$$\alpha = \frac{d\log(\lambda S)}{d\log\lambda}$$

Class 0
L_{SMM}/L_{BOL} > 0.5%
$T_{BOL} \leq 70$ K

Class I
$\alpha \geq 0.3$
70 K < $T_{BOL} \leq 670$ K

Flat
$-0.3 \leq \alpha < 0.3$

Class II
$-1.6 \leq \alpha < -0.3$
670 K < $T_{BOL} \leq 2800$K

Class III
$\alpha < -1.6$
$T_{BOL} > 2800$ K

★SED slope (α method): original criteria for Classes (Lada 1987; Greene et al., 1994)

★L_{SMM}/L_{BOL}: added later to identify Class 0 (Andre et al., 1993, also Maury et al., 2011)

★ Bolometric temperature (Myers & Ladd, 1993): the temperature of a black body with the same flux weighted mean frequency as the observed SED (see also Greene et al., 1994).

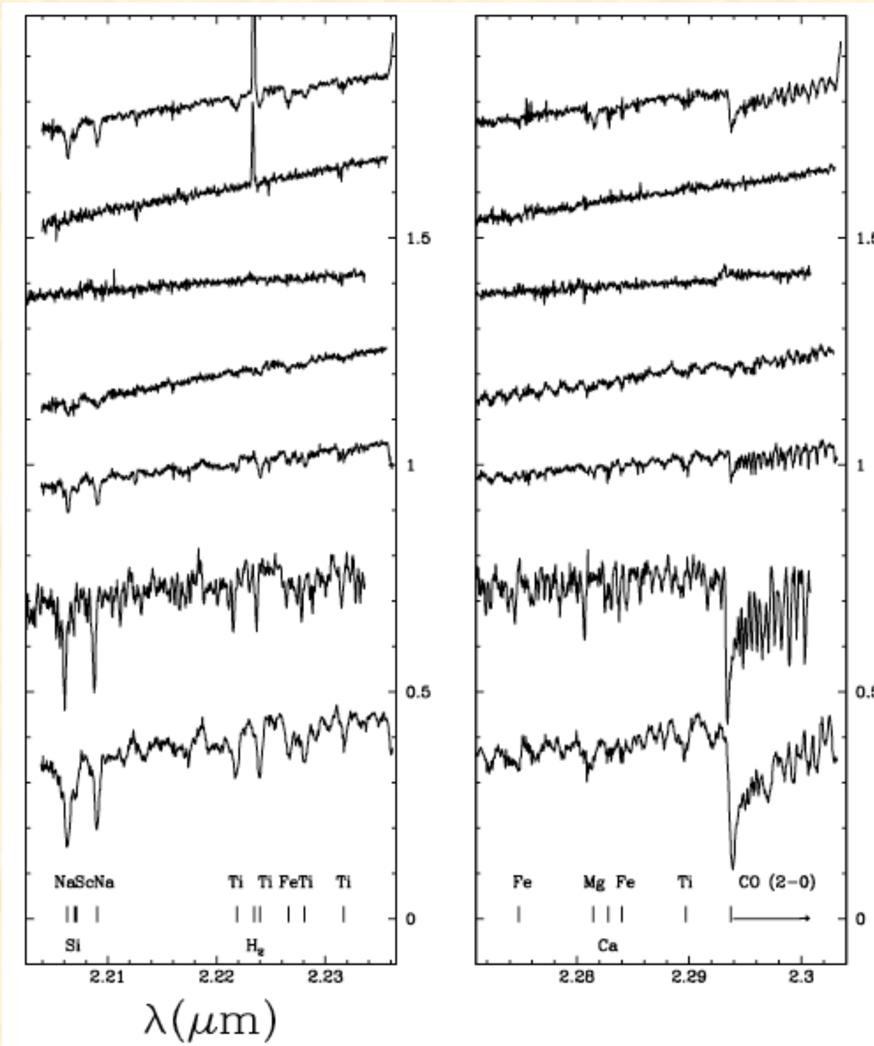
Slide from N. Evans

All SEDs from Dunham et al. (2013), PPVI review chapter

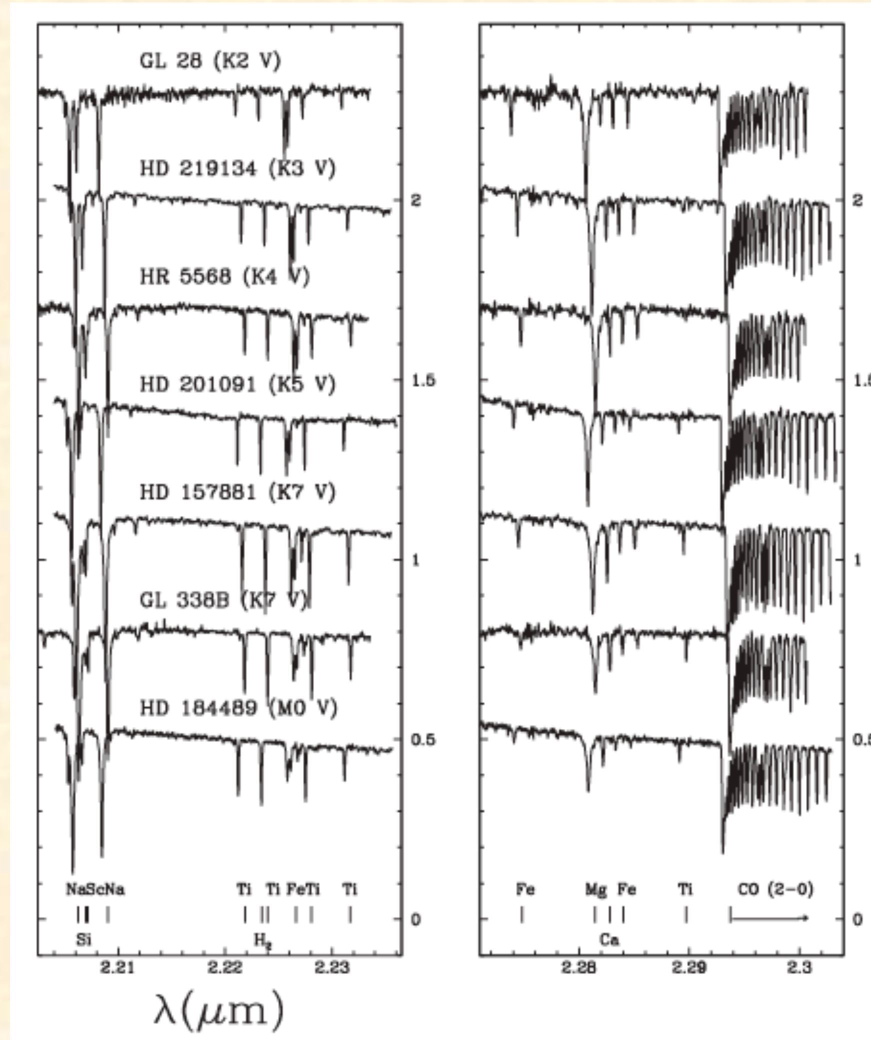
Questions about central protostars (Class 0/I)

- What are the T_{eff}, L_*, and log g of these objects?
  - Do their absorption features form in disks or stars?
- What fractions of protostar luminosities powered by mass accretion and by contraction of stellar photospheres?
  - At what rate do protostars accumulate mass? Continuous or episodic accretion?
- How can observations of their spectra inform models of masses, ages, lifetimes, internal structure, and circumstellar environments?
- What are the properties (masses, spatial extents) of their circumstellar disks?
- What are the angular momenta of these objects?
  - Evidence of regulation by a circumstellar disk?
  - How much AM evolution between freefall, Class 0, I, and T Tauri stages?

Class I Protostar near-IR Spectra



Class I protostars (ρ Oph)



Dwarf standards

- Generally have T-Tauri T_{eff} & log g but rotate rapidly and have high near-IR continuum veiling

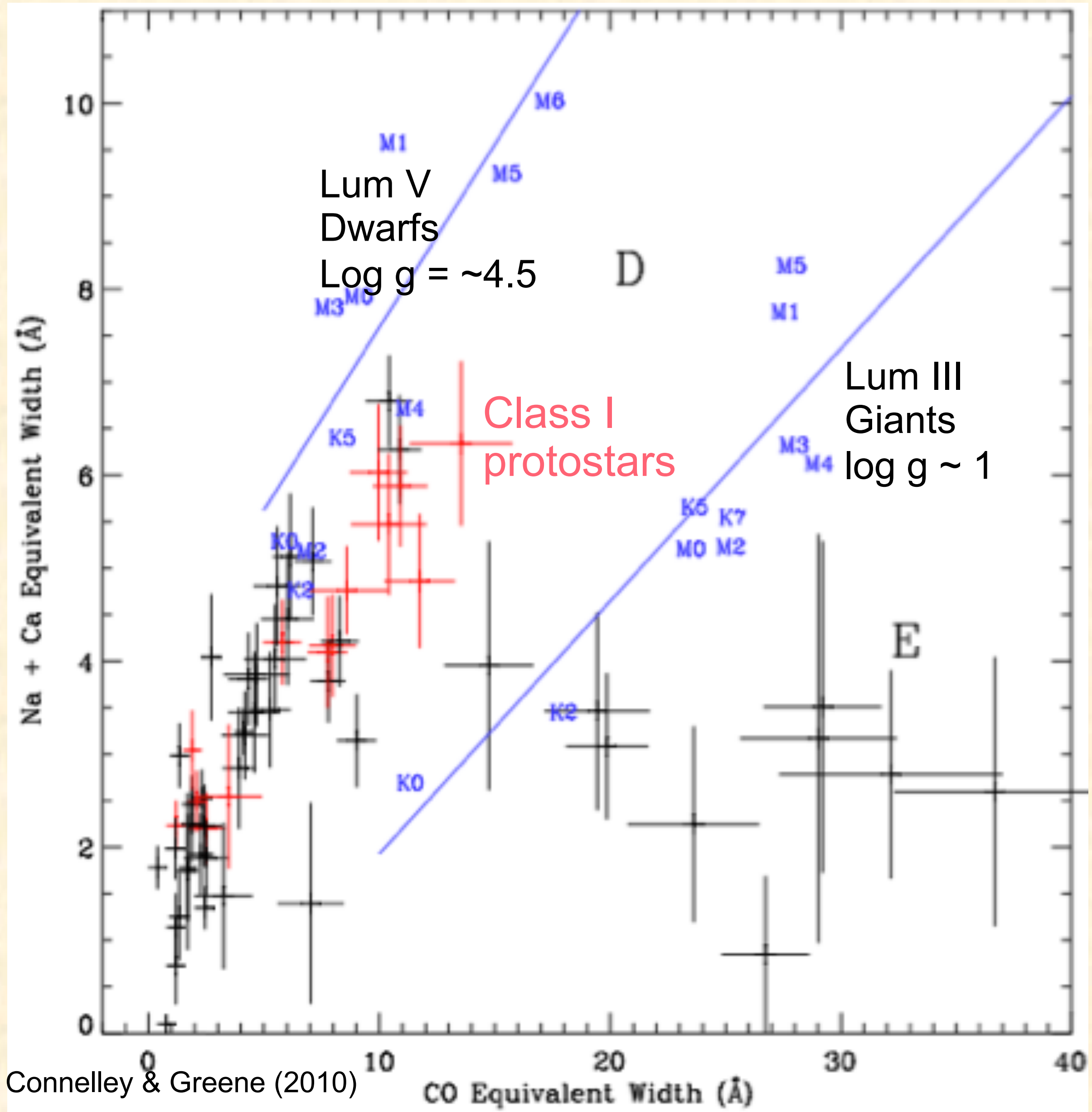
Keck NIRSPEC spectra from G. Doppmann+ (2005)

Protostar Surface Gravities

•Strengths and ratios of K-band atomic lines & CO tell:

- Temperature
  - Relates to mass
- Gravity:
  - Relates to age
  - dwarf, giant, or disk?

IR light from Class I protostars originates in stars (red)

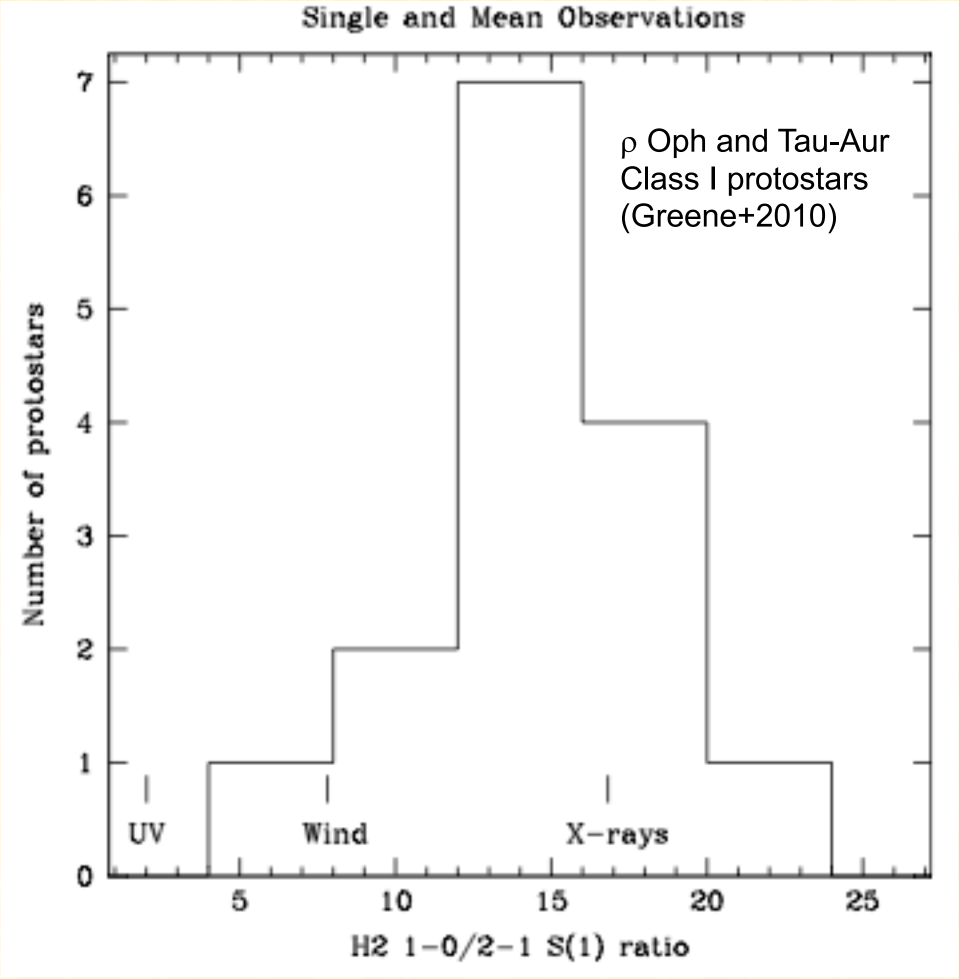


Connelley & Greene (2010)

What is nature of H_2 emission in protostars?

- Near-IR H_2 line ratios very sensitive to excitation source:
  - S(1) 1-0 / S(1) 2-1 = 1.9 **UV**; 7.7 **shock**; 17 **X-ray**
  - S(1) 1-0 / S(1) 3-2 = 3.5 UV; 130 X-ray
  - S(1) 1-0 is 2.1218 μm, S(1) 2-1 is 2.2477 μm, S(1) 3-2 is 2.3864 μm
- Weintraub et al. (2000) found H_2 emission from TW Hya to be excited by X-rays
- Protostars are strong X-ray emitters and drive jets that shock gas
- Protostars are also predicted to have considerable UV emission from accretion shocks (but can't escape due to extinction)
- H_2 emission may be the best way to diagnose the innermost radiation environments of protostars!

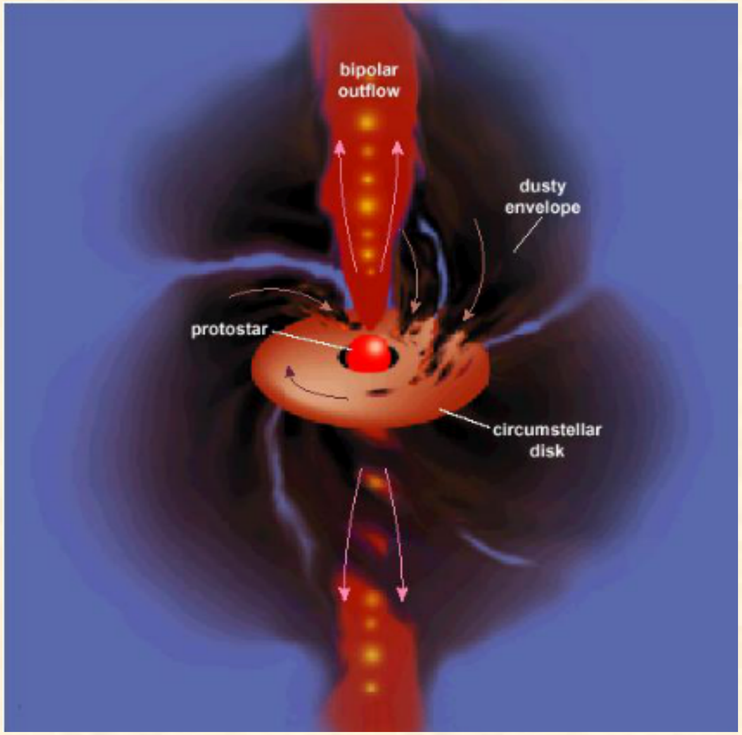
Class I 2 μm H2 emission and winds



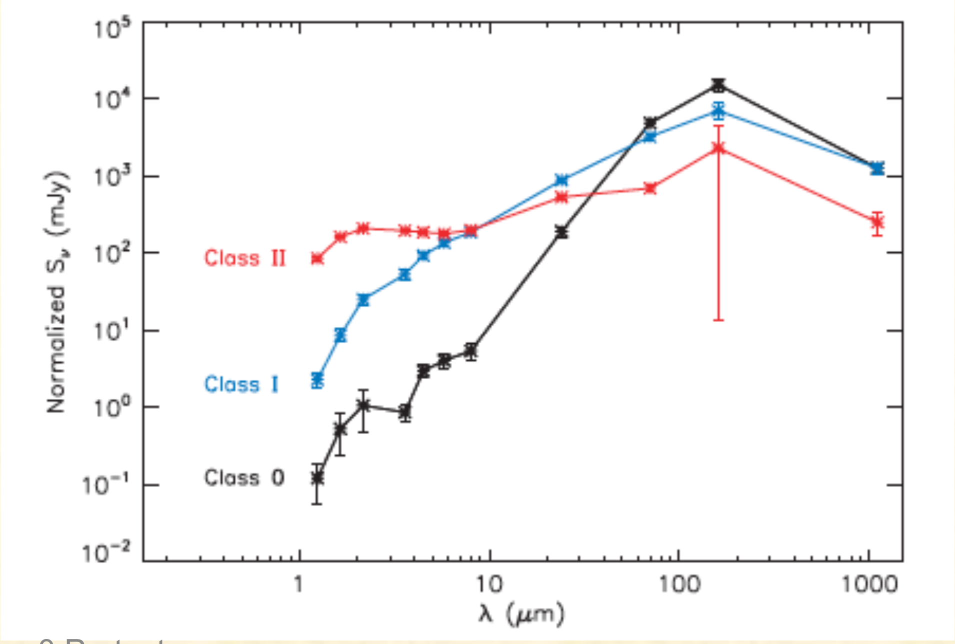
- Near-IR H2 emission in Class I protostars is consistent with shock excitation in protostellar winds or x-ray interactions
- Ambiguous determination may be due to multiple excitation mechanisms

Class 0 protostars: Yet to accrete majority of mass

- Age ~ 10,000 – 100,000 yr
- Strong outflow
- Massive or tiny disks?
- Massive Envelopes
- T ~ 30 K
- No visible / little IR light
- Unknown central stars:
  - *How are they assembled?*



Enoch+ (2009) mean Per * Ser YSO fluxes / SEDs

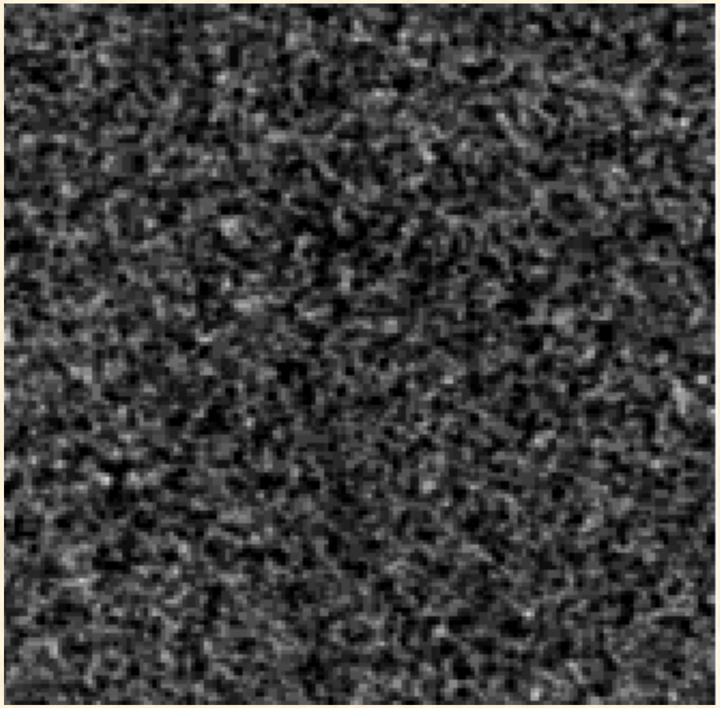


Observe Class 0 protostellar photospheres?

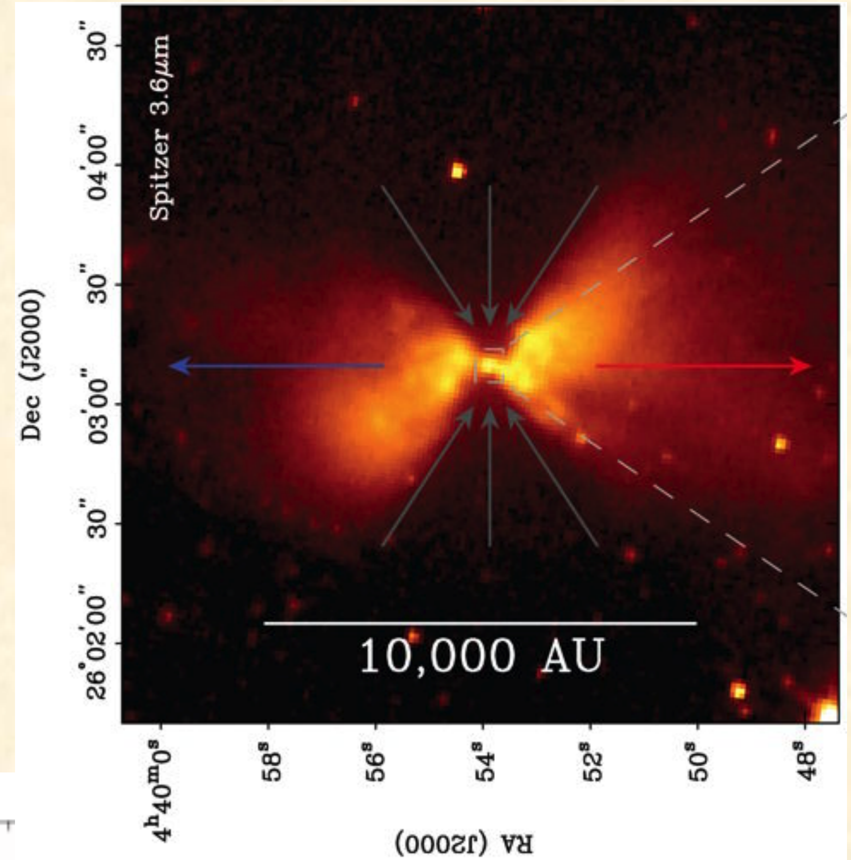
- Spitzer data show Class 0 are brighter than expected at $\lambda < 5\ \mu m$
- K-band spectra are best compromise for diagnosing photospheres
  - Not severely impacted by extinction ($A_k \sim 0.1\ A_v$)
  - Adequately strong lines diagnostic of Teff and log g (Doppmann+ 2005)
- Object selection is very tricky:
  - Spitzer + Herschel SEDs have Class 0 shape / $T_{bol} < 70$ K
  - mm emission confirms extended envelope (resolved interferometric images best)
  - Need K < ~17 mag nearly point sources for ~10-m telescopes
    - Near-IR source needs to be same as far-IR one
  - Lose >1/2 of Class 0s to above criteria. Remaining ones can still have veiled, featureless spectra

L1527 Class 0: Visible and Infrared Images

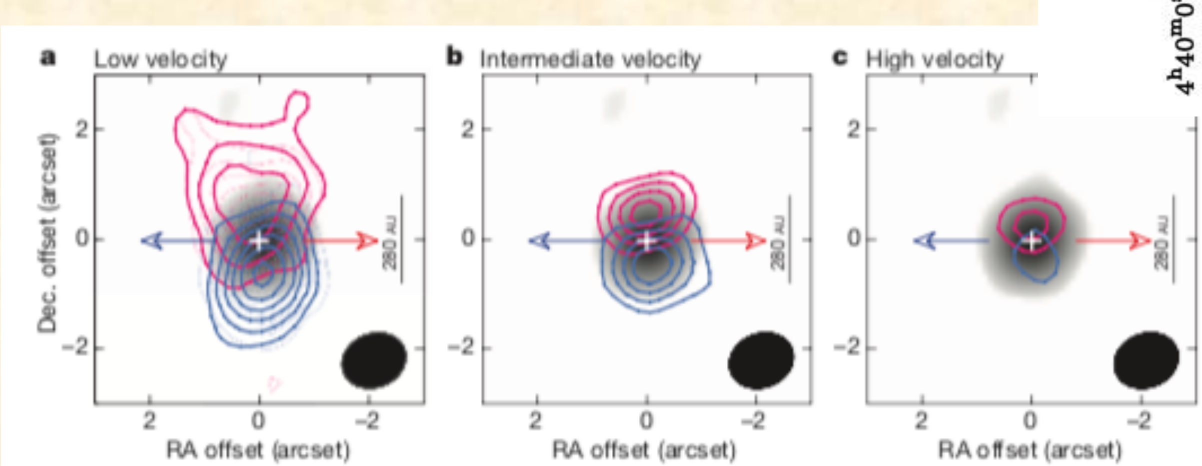
DSS Red Image



Spitzer IRAC 3.6μm IR

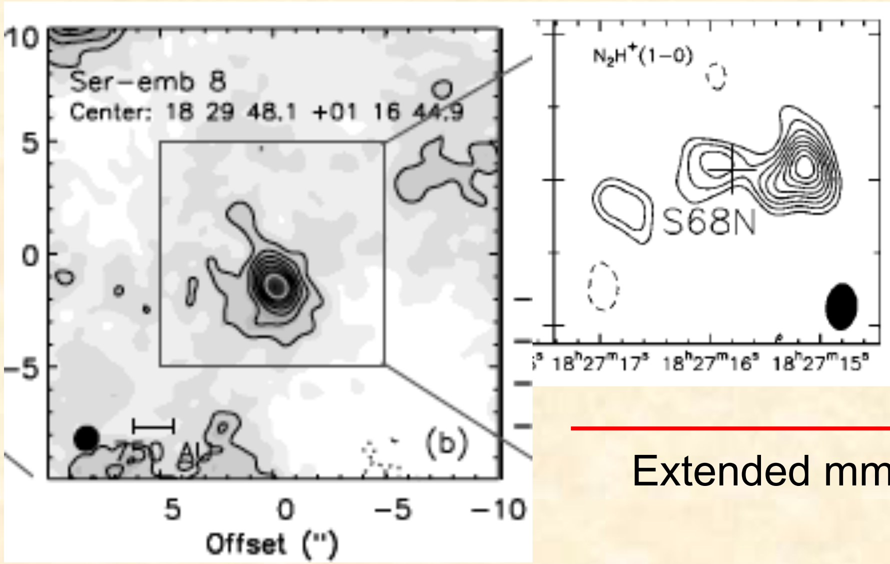


Tobin et al. 2010

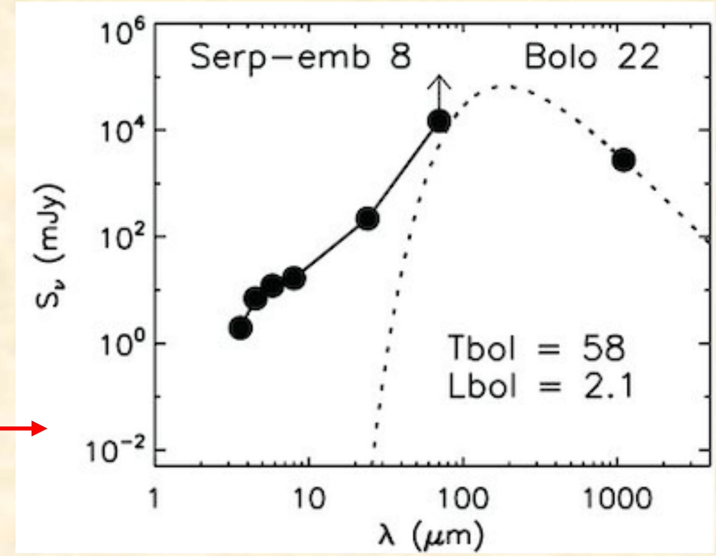


Central protostar mass ~0.2M from Keplerian rotation of ^{13}CO in disk (Tobin+ 2012 CARMA)

Class 0 selection for near-IR observations



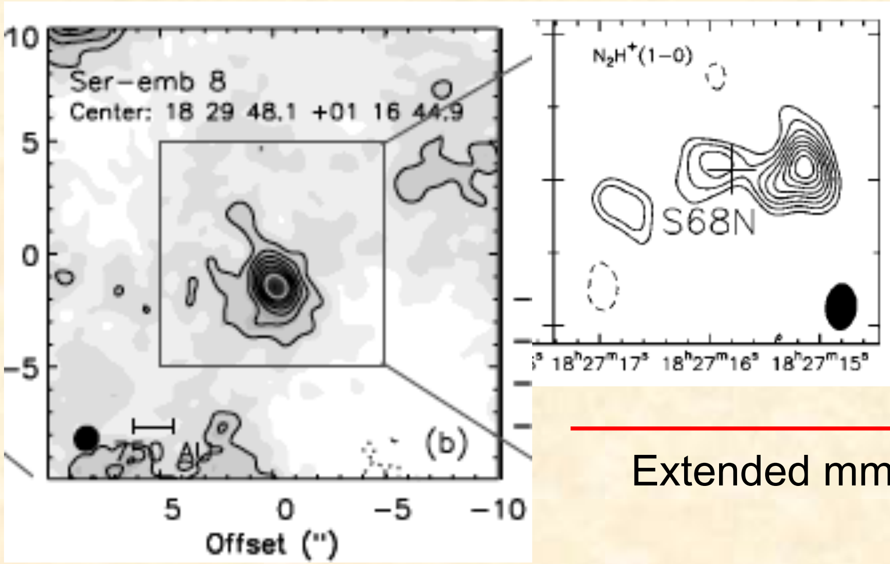
Extended mm envelope?



Ser S68N: L: CARMA 1.3 mm continuum
R: OVRO N2H+ (Enoch+ 2011; Testi+ 2000)

Ser S68N: Enoch+ (2009) Spitzer flux / SED

Class 0 selection for near-IR observations



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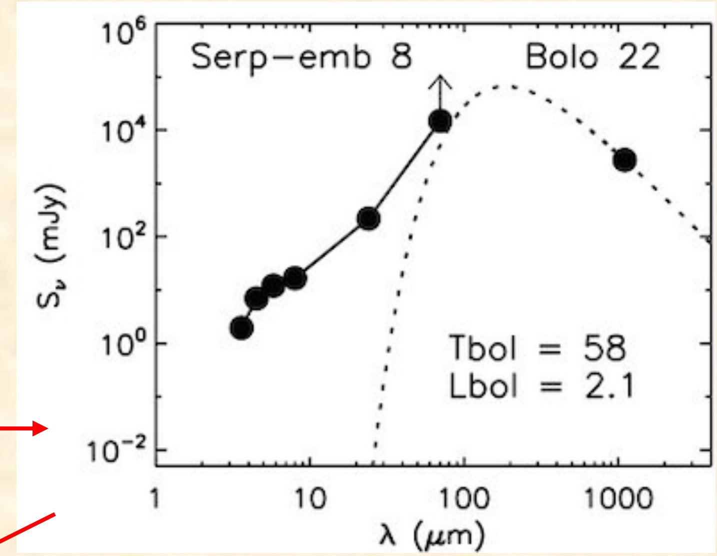
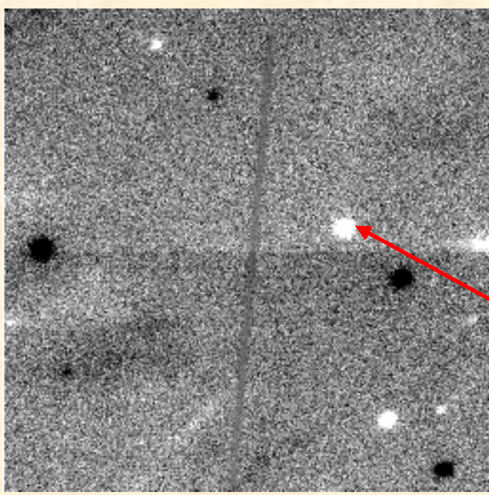


Ser S68N: Enoch+ (2009) Spitzer flux / SED

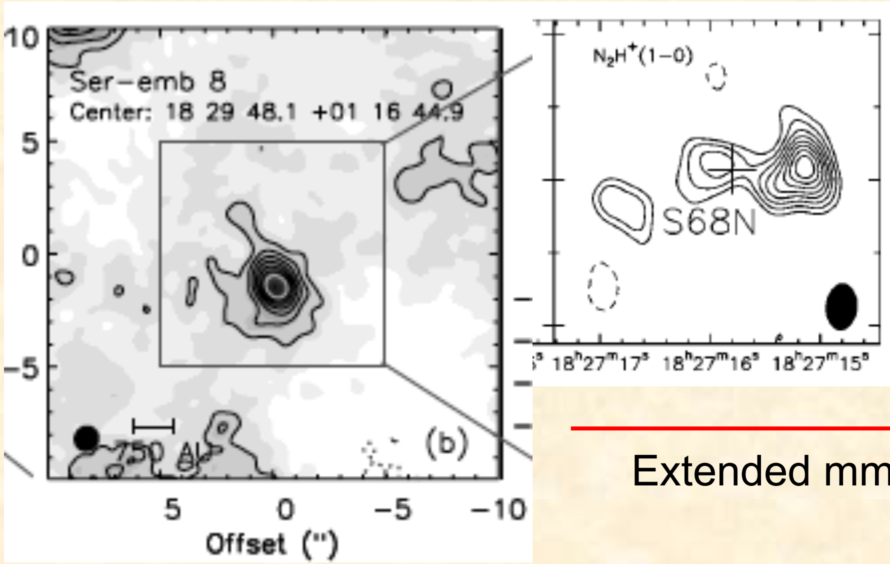
Bright enough in near-IR?



Point-like; not veiled?

Ser S68N: K-band
NIRSPEC
SCAM image
(invisible in 2MASS;
not in UKIDSS)

Class 0 selection for near-IR observations



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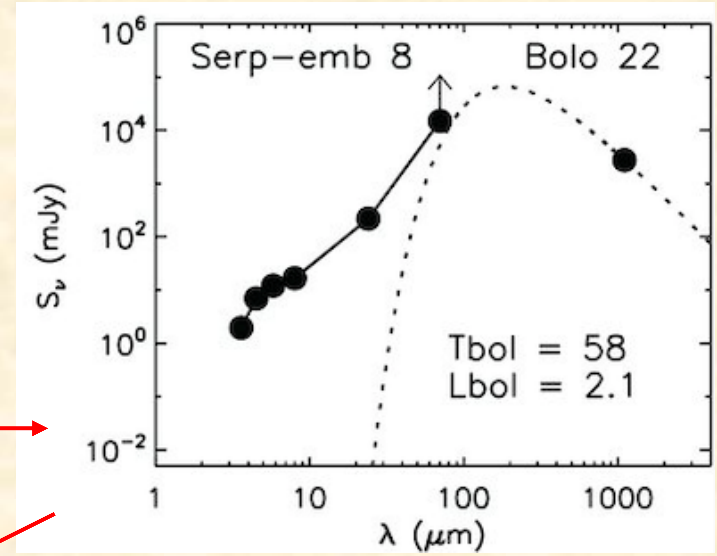

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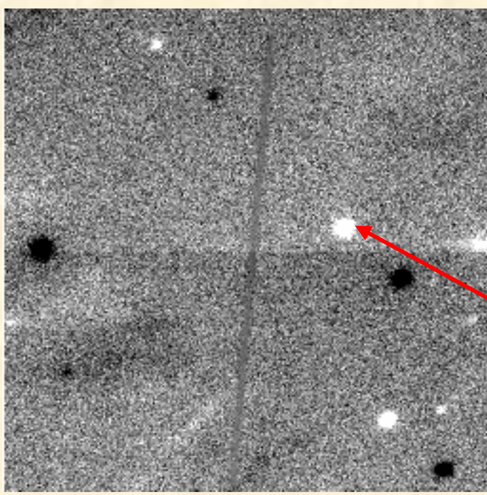
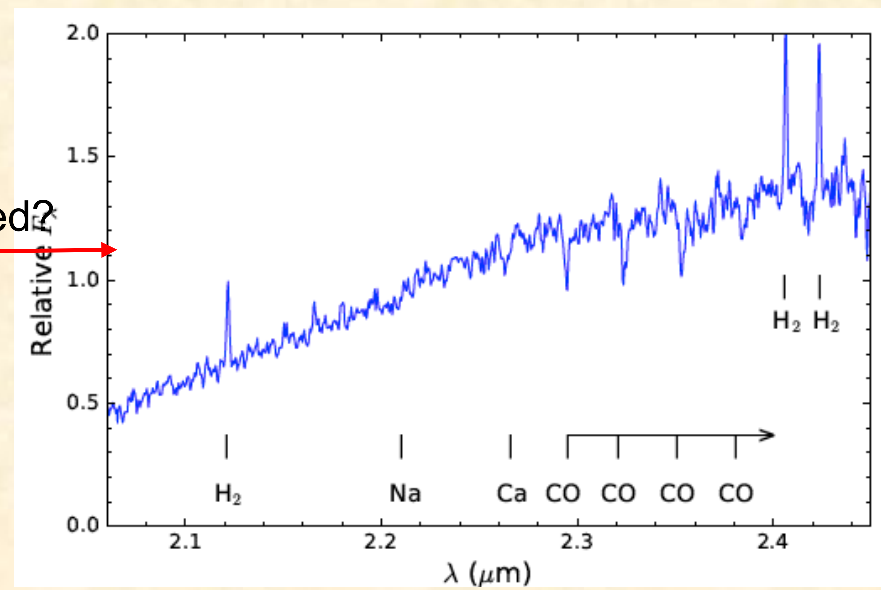


Ser S68N: K-band NIRSPEC SCAM image (invisible in 2MASS; not in UKIDSS)

Point-like; not veiled?



Ser S68N: NIRSPEC low-res spectrum (Greene+ 2018)

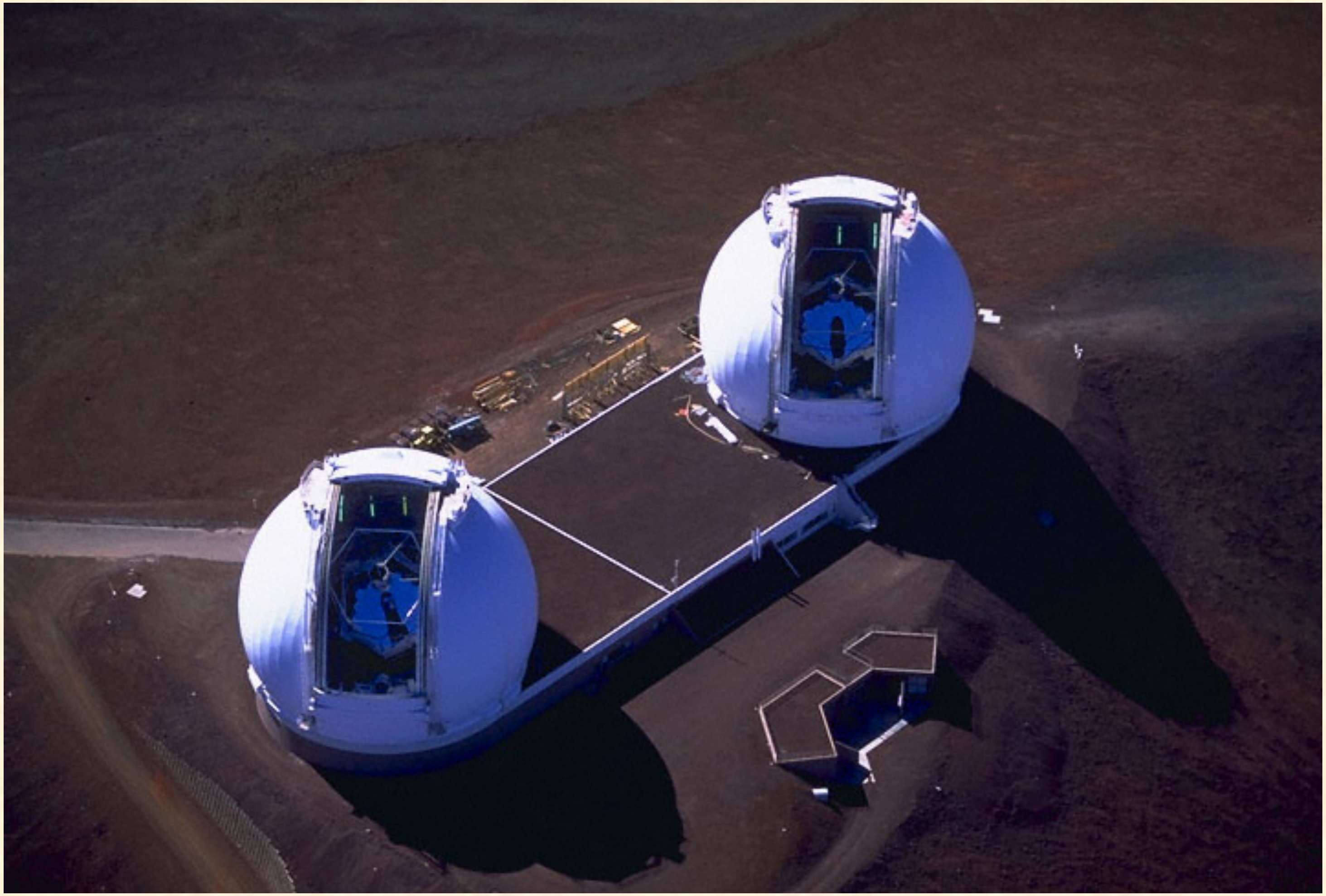
JWST Guaranteed Time Program

- Scheduled to observe 5 Class 0 protostars (2 Serpens, 3 Perseus) with in a ~17 hr guaranteed time program (program 1186):
  - NIRSpec IFU with G235M 1.7 – 3 μm + G395M 2.9 – 5 μm, R ~ 1000 (may switch to R ~ 2700 for some)
    - Combine with longer wavelengths to probe ices
  - SNR ~150
  - ~0.2" spatial resolution over 3" x 3" IFU:
    - Measure near-IR object size, resolve H2 emission

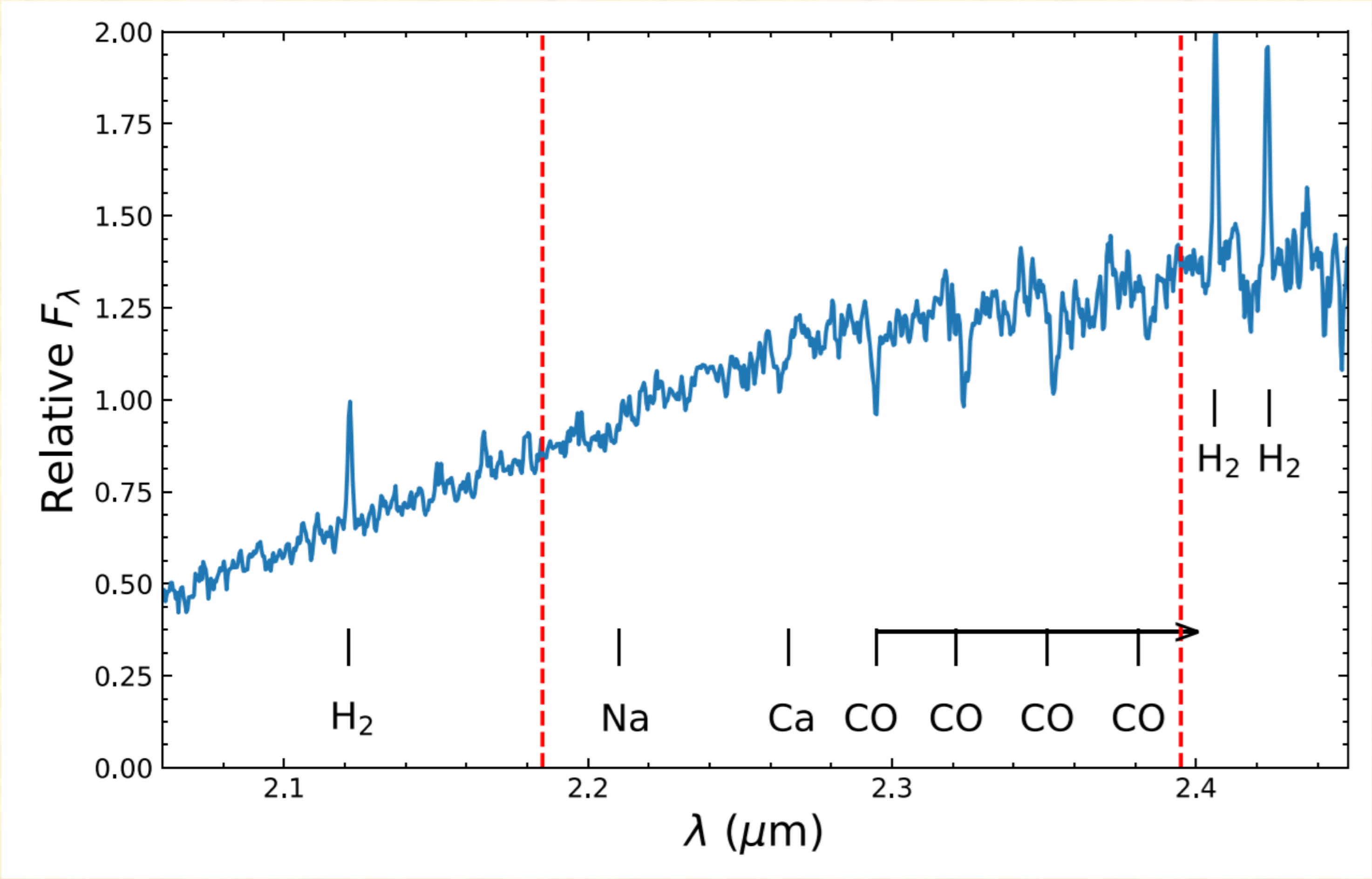
Table 1: Preliminary Class 0 Protostar List

Source Name	nIR RA and Decl. (J2000)	dist(pc)[a]	T_{bol}	M_{env}[b]	K(mag)[c]	$F_{3.6\mu m}$[d]	Comment[e]
L1448-C	03 25 38.84 +30 44 07.0	230	49–69	1–2	~16	3.0	1.6″, faint
Per-emb 25	03 26 37.46 +30 15 28.1	230	61	0.5	15.0	3.6	1.5″, OK
Per-emb 21	03 29 10.80 +31 18 22.2	230	45	2.5	17.0	1.8	1.0″, faint
Per-emb 28	03 43 51.02 +32 03 07.9	230	45–70	0.6	~15	6.8	1.4″, OK
Per-emb 8	03 44 43.95 +32 01 36.7	230	43	0.6	15.1	2.7	2.0″, OK
IRAS 04166	04 19 42.62 +27 13 38.9	140	~60	0.2	~16.5	~5	2.5″, faint
L1527 IRS	04 39 54.75 +26 03 07.8	140	36–67	2.0	18+	6.9	~ 10″, faint
Ser S68N	18 29 48.12 +01 16 44.6	436	57	9.4	~16.5	2.0	0.8″ OK A+E
Ser SMM 1	18 29 49.60 +01 15 21.9	436	~ 58	20	< 17	0.9	too faint
Ser SMM 3	18 29 59.31 +01 14 01.9	436	59	5.7	15.4	2.7	1.4″,OK, α=1

Initial reconnaissance with Keck NIRSpec



S68N: A little bit of near-IR light does get out…



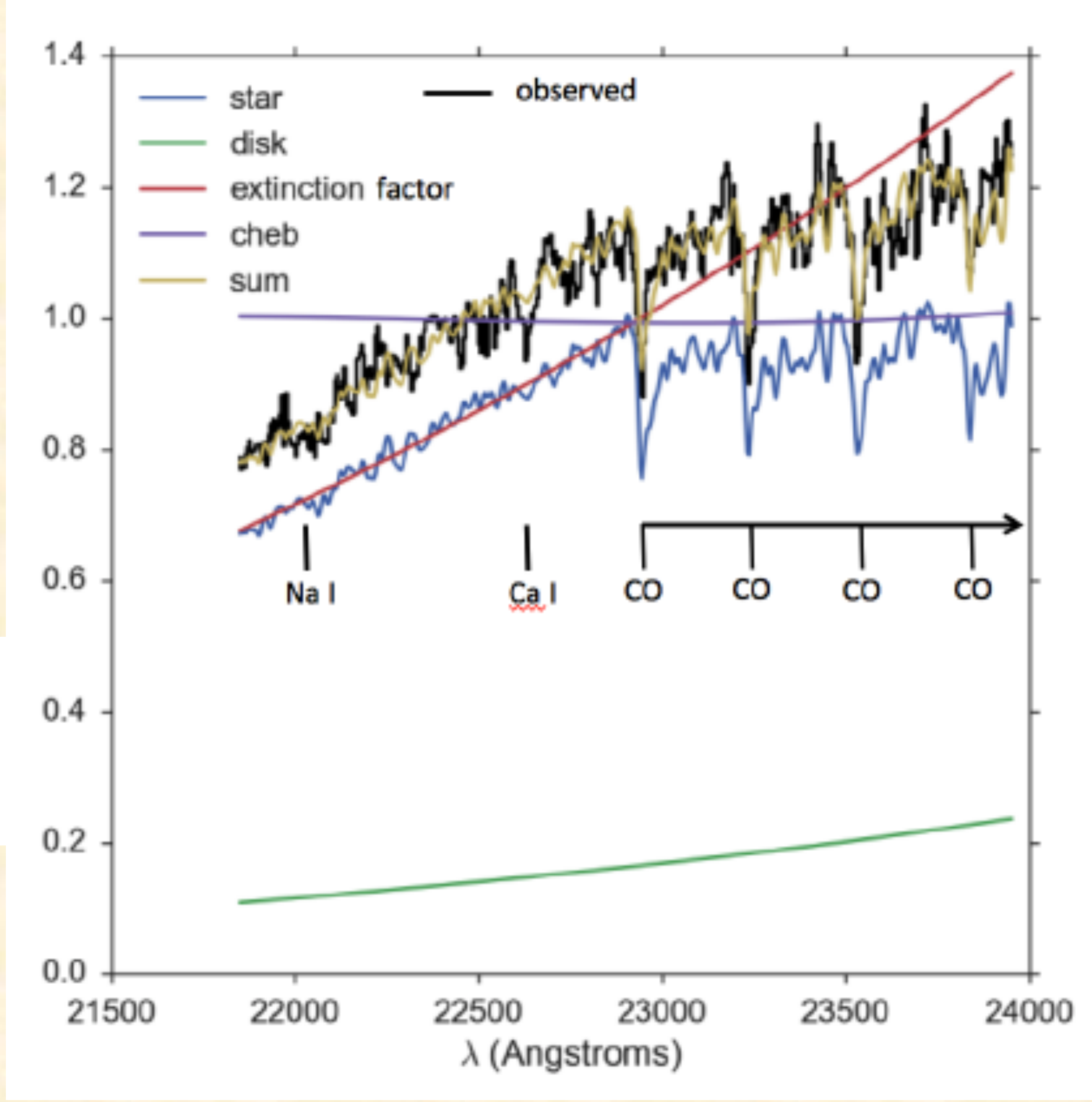
- Keck NIRSPEC low-res spectrum of Serpens S68N Class 0 protostar, S/N ~ 30 – 40 (Greene+ 2018)
- More Keck vetting of other Class 0 protostars is underway

S68N Spectral model

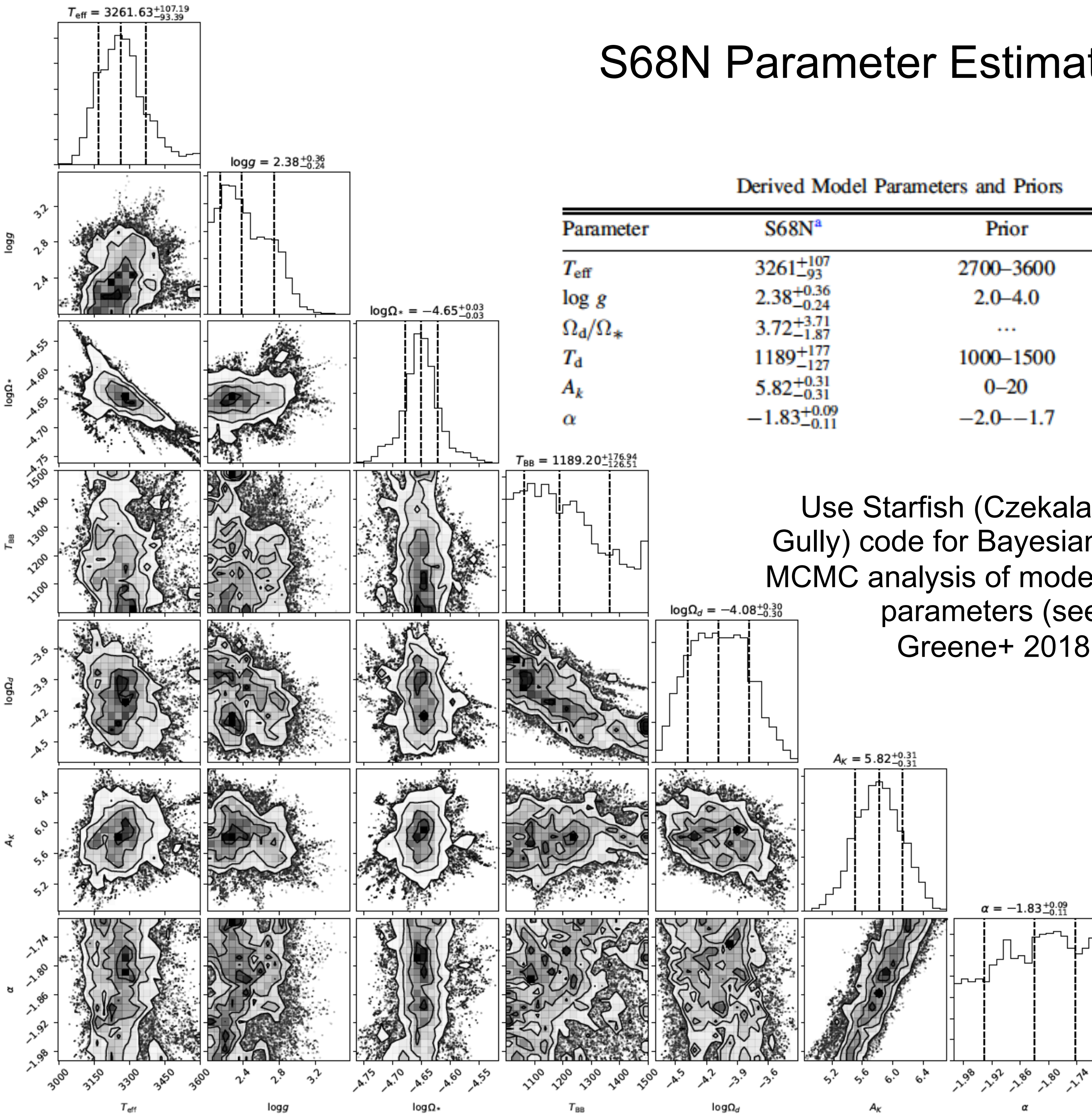
Model observed spectrum as sum of Phoenix model photosphere + circumstellar continuum veiling + extinction / reddening:

$$F_{p*,\lambda} = [F_{*,\lambda}(T_{\rm eff}, \log g, [{\rm Fe/H}])\Omega_* + B_\lambda(T_{\rm d})\Omega_{\rm d}]\ 10^{-0.4A_K\left(\frac{\lambda}{\lambda_K}\right)^\alpha},$$

$$r_k \simeq \frac{B_\lambda(T_{\rm d})\Omega_{\rm d}}{B_\lambda(T_{\rm eff})\Omega_*}.$$



S68N Parameter Estimation



Derived Model Parameters and Priors

Parameter	S68N[a]	Prior	Units
T_{eff}	3261^{+107}_{-93}	2700–3600	K
$\log g$	$2.38^{+0.36}_{-0.24}$	2.0–4.0	cm s^{-2}
Ω_d/Ω_*	$3.72^{+3.71}_{-1.87}$	...	
T_d	1189^{+177}_{-127}	1000–1500	K
A_k	$5.82^{+0.31}_{-0.31}$	0–20	mag
α	$-1.83^{+0.09}_{-0.11}$	−2.0–−1.7	

Use Starfish (Czekala, Gully) code for Bayesian MCMC analysis of model parameters (see Greene+ 2018)

S68N photosphere parameters

star

disk

extinction

Derived Model Parameters and Priors

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A_k	$5.82^{+0.31}_{-0.31}$	0–20	mag
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- Teff is similar to Class I and PMS stars, but log g is ~ 1 dex lower
  - Implies M3 – 3.5 Spectral Type, but radius ~3x larger than Class I or PMS star
  - Consistent with 0.2 $M_\odot$ star with R = 4.7 $R_\odot$: Inflated radius could be due to strong recent accretion (Baraffe+ 2017)
  - Note that we do not know the mass – would need velocity info from gas in a disk

Continuum veiling and extinction

- **Continuum MCMC model fit gives Av ~ 10 Ak = 58 mag to photosphere**
  - Consistent with the object's K-band flux
- **2.4237μm 1–0 Q(3) and 2.1218μm 1–0 S(1) H_2 emission lines have same upper level; their ratio implies Av~10 Ak = 48 mag**
  - Consistent with H_2 emission arising close to star
  - Results uncertain/underestimated due to a 2.42412 μm telluric line (Connelley & Greene 2010)
- ***H_2 line ratios consistent with excitation by shocks or x-rays but not UV***
- **Modest continuum veiling r_k ~ 0.1 implies no more circumstellar disk emission that Class I protostars with r_k ~ 1**
  - Could have same disk emission but $r_k = F_{disk}/F_*$ may be lower due to 3x larger radius
  - No indication of more warm circumstellar material than Class I

Related JWST GTO Programs

Progra m	PI	Title	Objects	Observations	Time
1290	E Van Dishoeck (Leiden)	MIRI EC Protostars Survey	Class 0 & 1 protostars	MIRI MRS IFU spectra of circumstellar gas & ices	39 h
1236	M. Ressler (JPL)	Protostellar Binaries in Perseus	Binary protostars in Perseus	MIRI MRS IFU spectra of circumstellar gas & ices	16 h