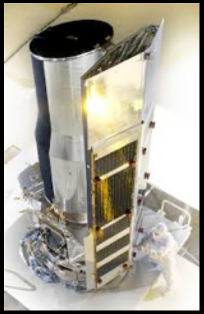
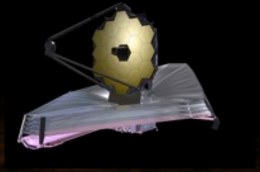
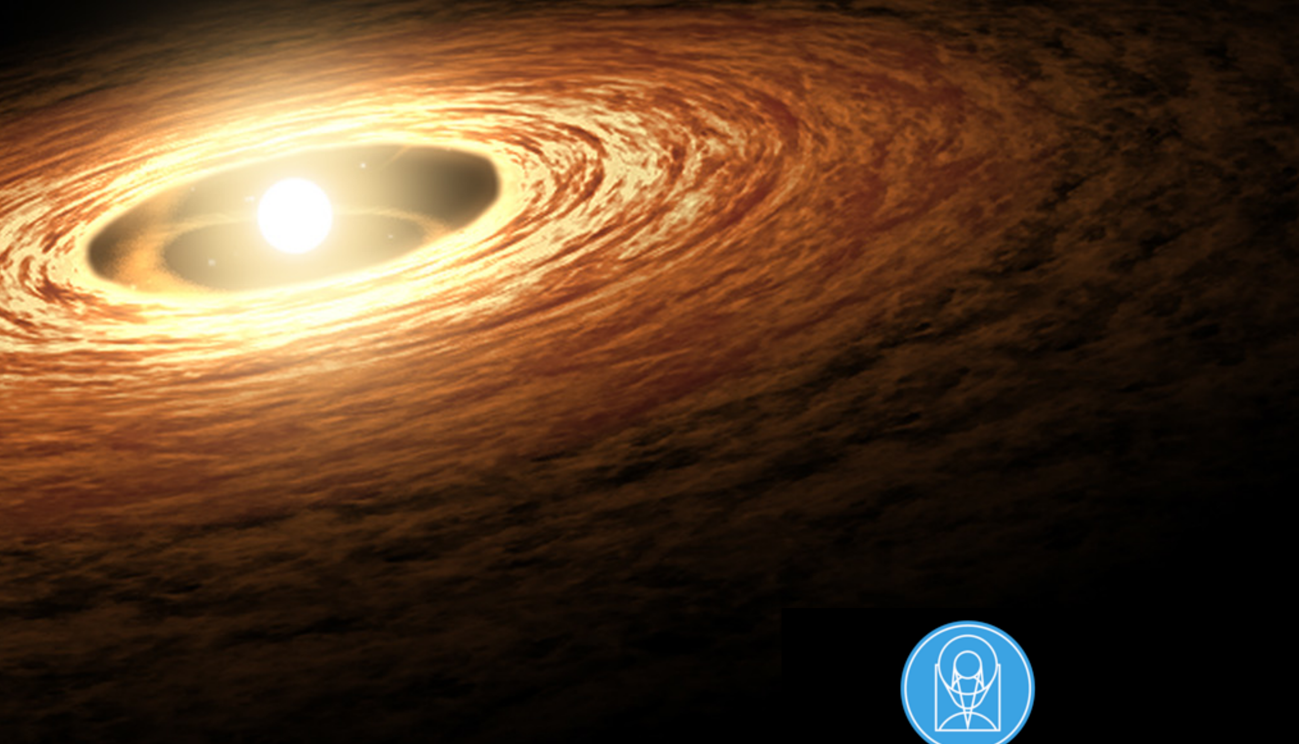
Altering the Seeds of Planet Formation







Joel D. Green

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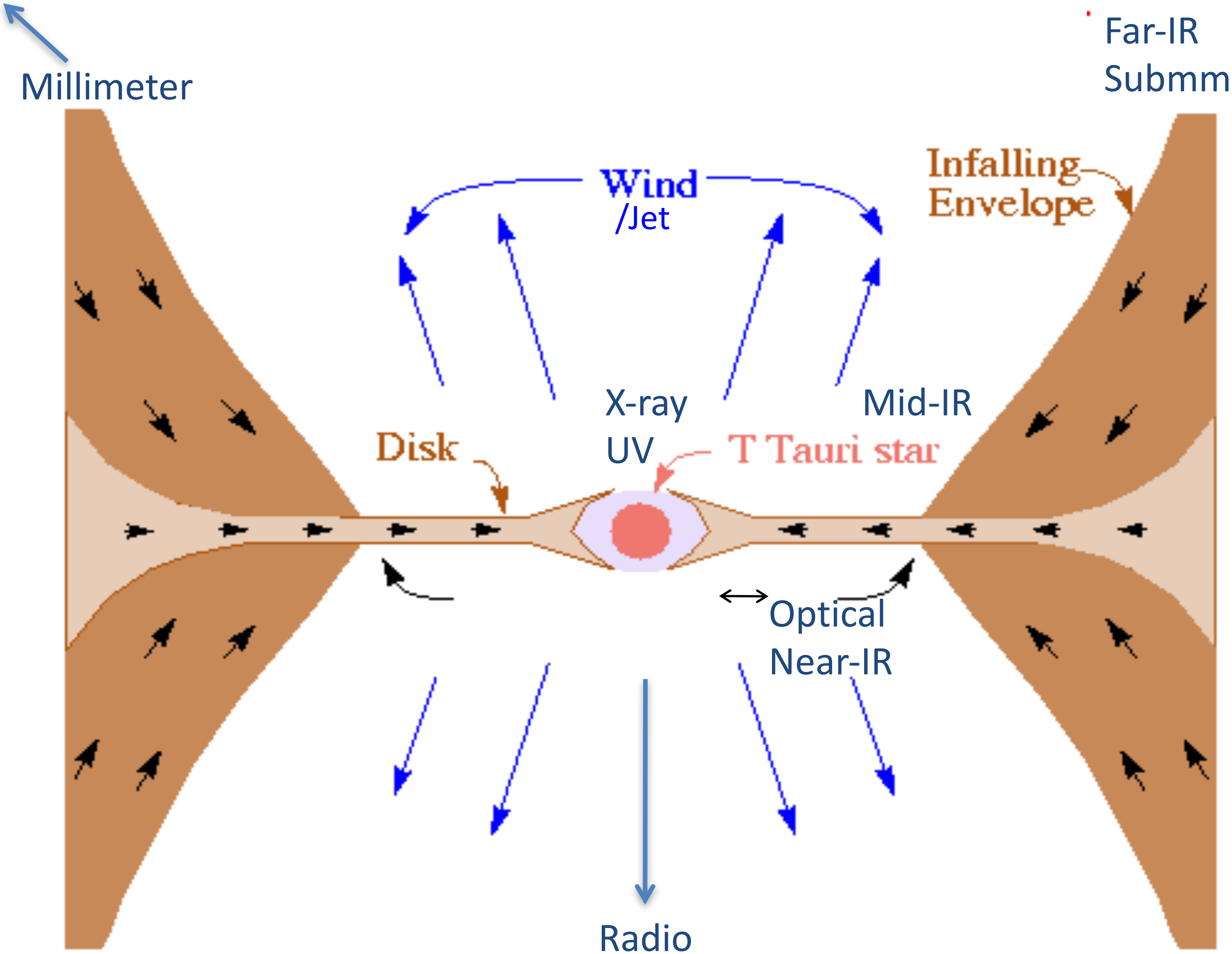
Project Scientist, Office of Public Outreach

Space Telescope Science Institute

Dissecting the Spectrum of a Low Mass Star



Millimeter

Far-IR
Submm

/Jet

X-ray
UV

Mid-IR

Optical
Near-IR

Radio

Modified from Hartmann & Kenyon, 1996, ARAA, 34, 207

Mass ~ < 2 $M_\odot$

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

Standard evolutionary scenario

single isolated low-mass star

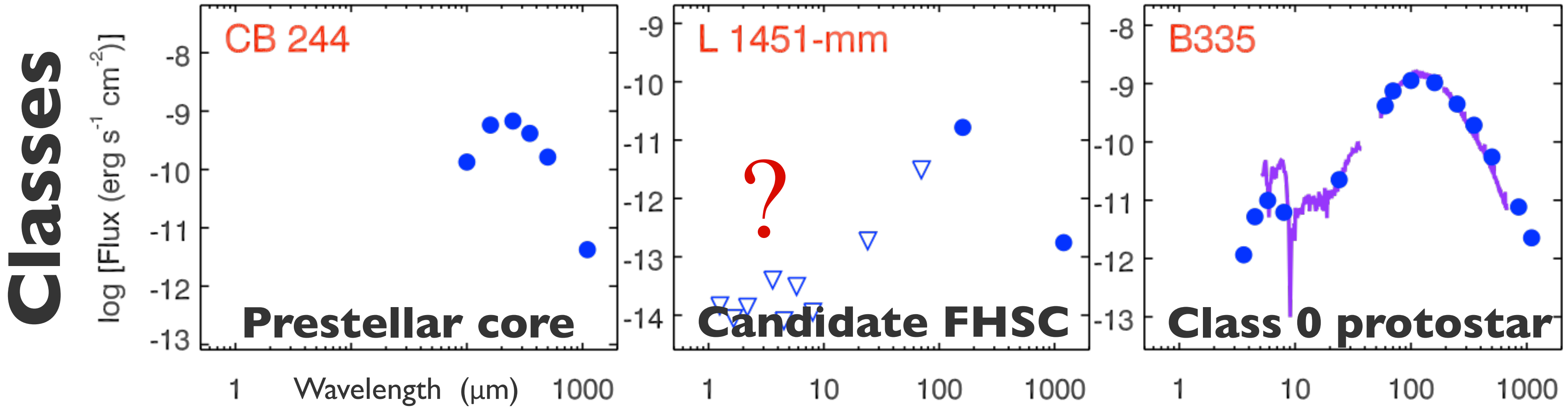
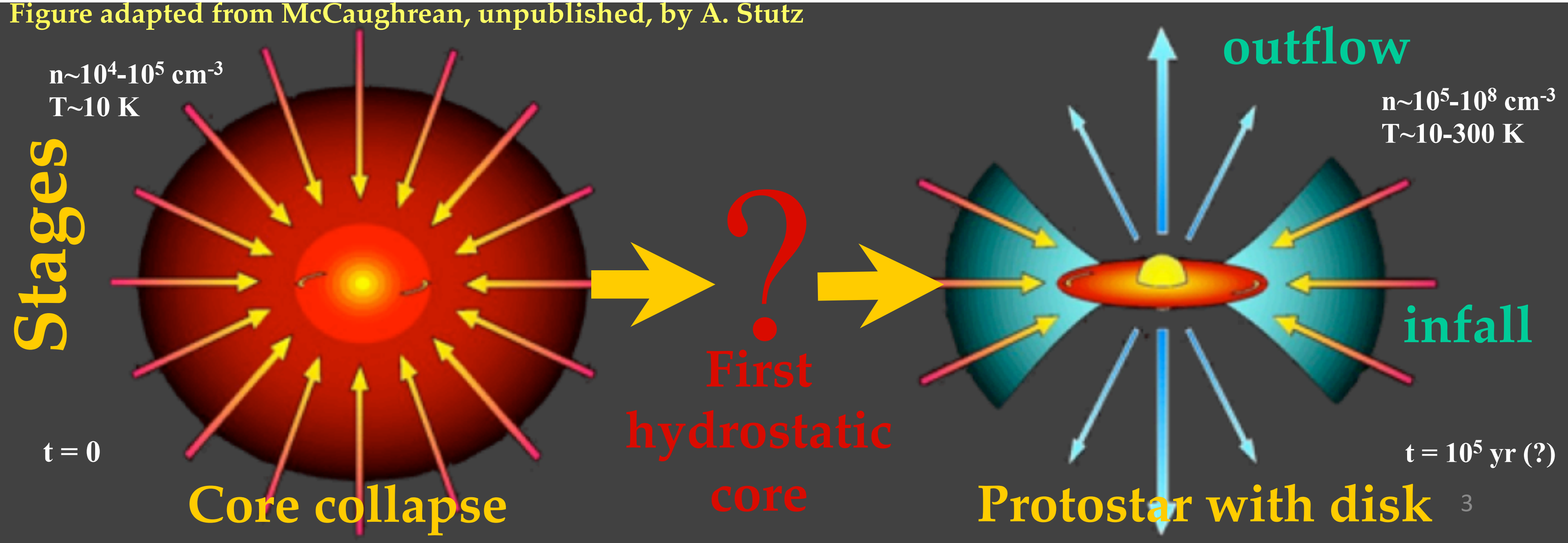


Figure adapted from McCaughrean, unpublished, by A. Stutz

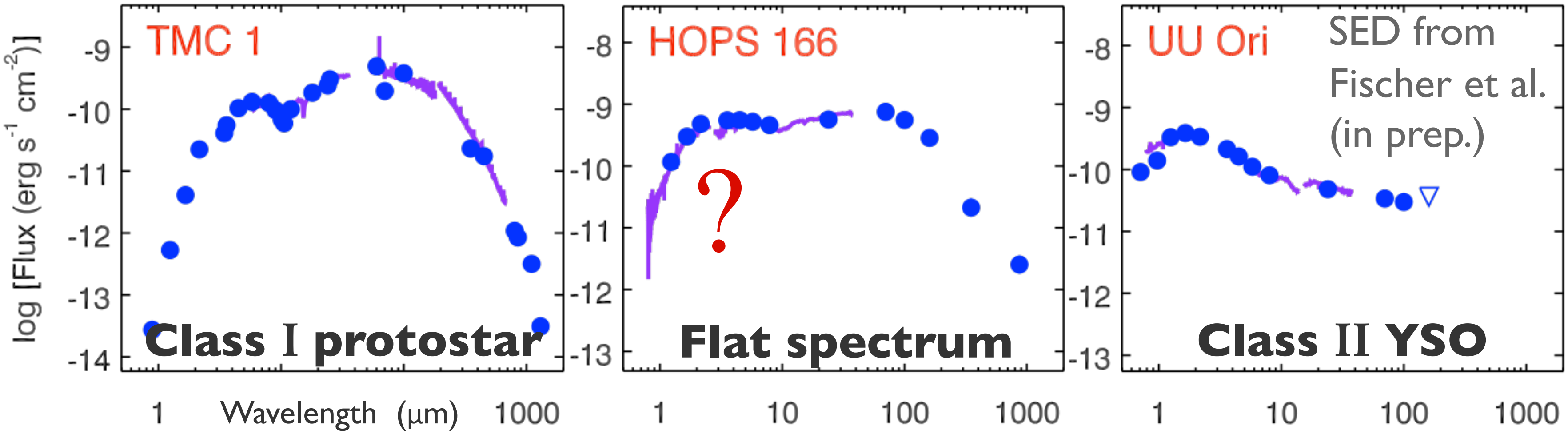


SEDs from Dunham et al. (2013), PPVI review chapter

Standard evolutionary scenario

single isolated low-mass star

Classes



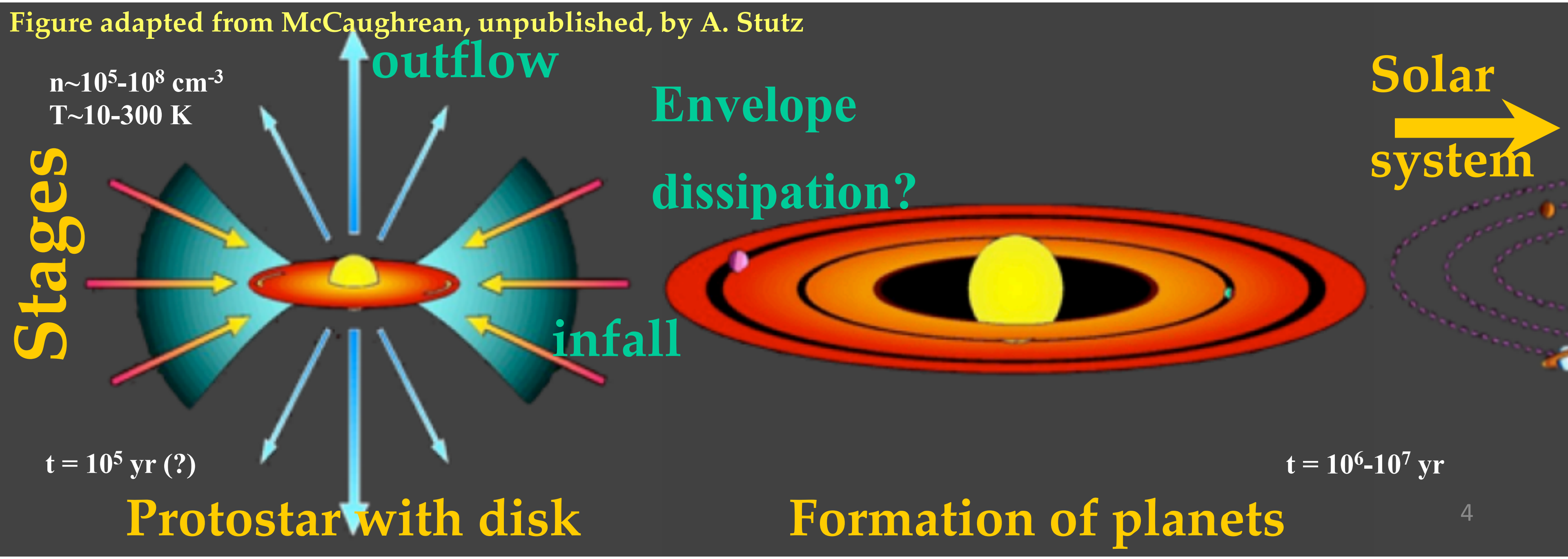


Figure adapted from McCaughrean, unpublished, by A. Stutz

Stages

n~10^5-10^8 cm^{-3}
T~10-300 K

outflow

Envelope dissipation?

infall

Solar system

t = 10^5 yr (?)

t = 10^6-10^7 yr

Protostar with disk

Formation of planets

What sets the conditions in the protoplanetary disk?

- In the usual paradigm, the Class I protostar lifetime is ~ 0.5 Myr (Evans+09), during which the envelope thins and eventually vanishes

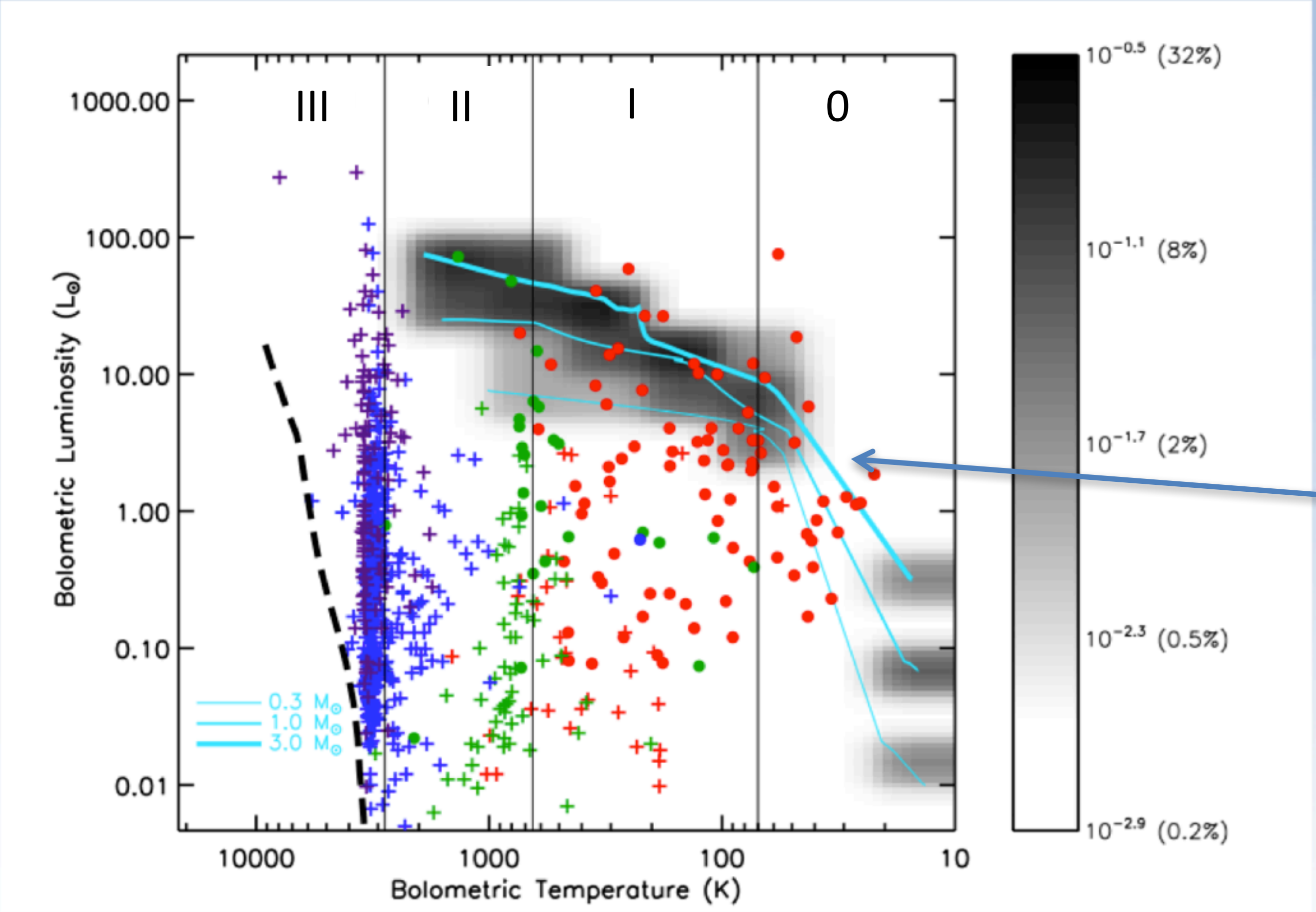
- The accretion rate from disk to star diminishes and planets form

- But does accretion decrease *steadily* from 10^{-5} $M_\odot/yr$ in Class I to 10^{-8} in T Tauri stars, to 10^{-10} or less in Class III sources?

Unraveling the Picture

L(acc) ~ dM/dt ~ c_s^3/G (Shu 1977; Singular Isothermal Sphere collapse model)

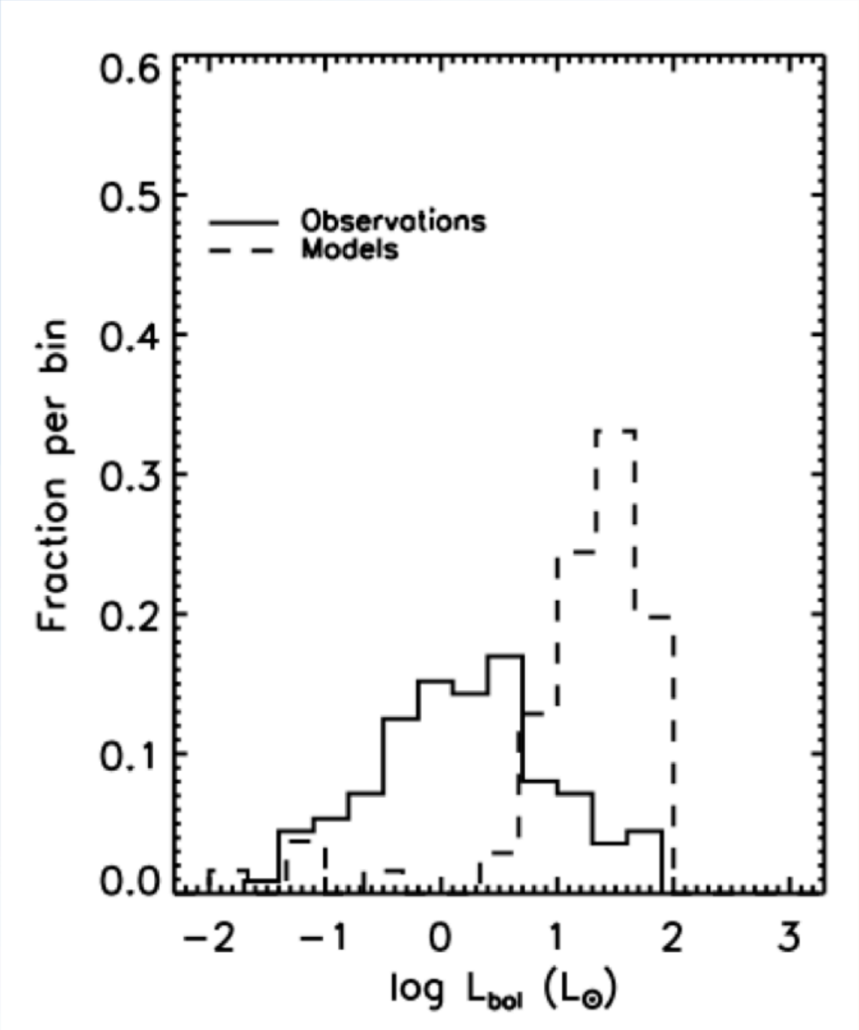
Bolometric (total) luminosity = Luminosity (internal) +
Luminosity (accretion)



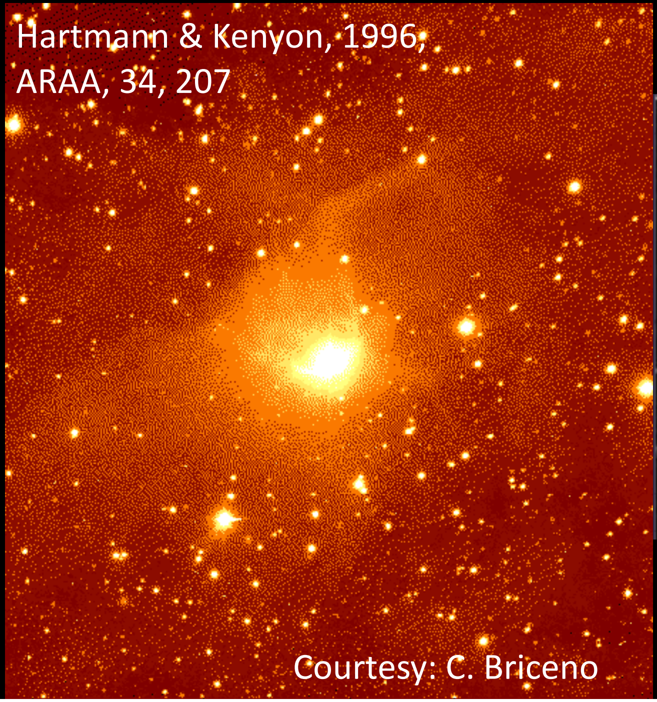
Model luminosities for 0.3-3 $M_\odot$ young stars

Dunham et al. 2010, ApJ, 710, 470

There is a huge population of "underluminous" protostars!

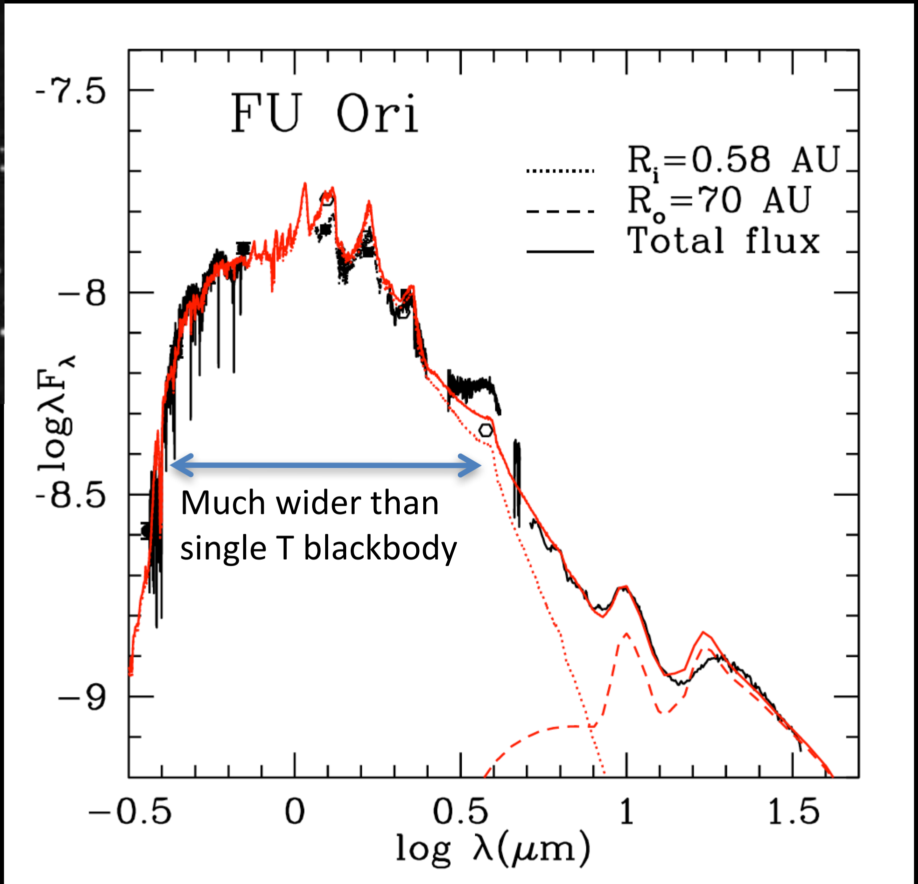


The FU Orionis Eruption: 1936



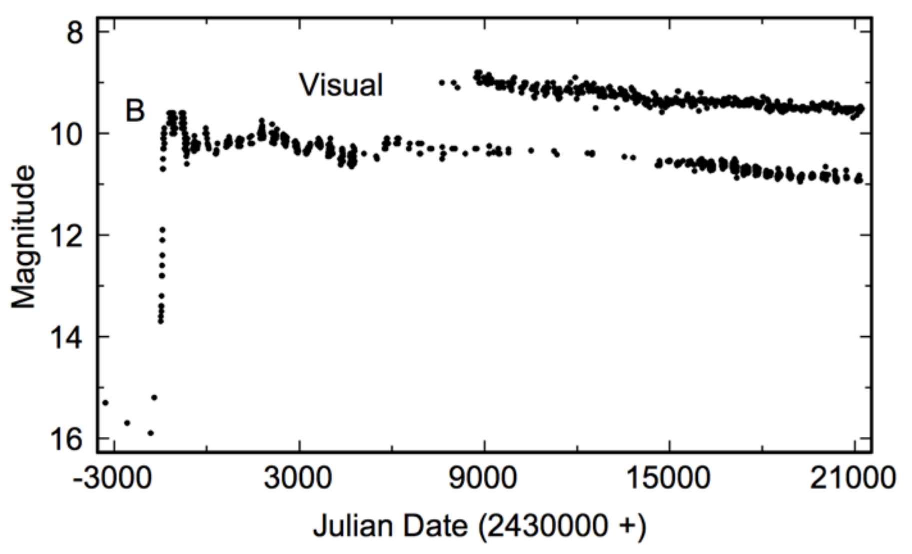
Hartmann & Kenyon, 1996, ARAA, 34, 207

Courtesy: C. Briceno



Much wider than single T blackbody

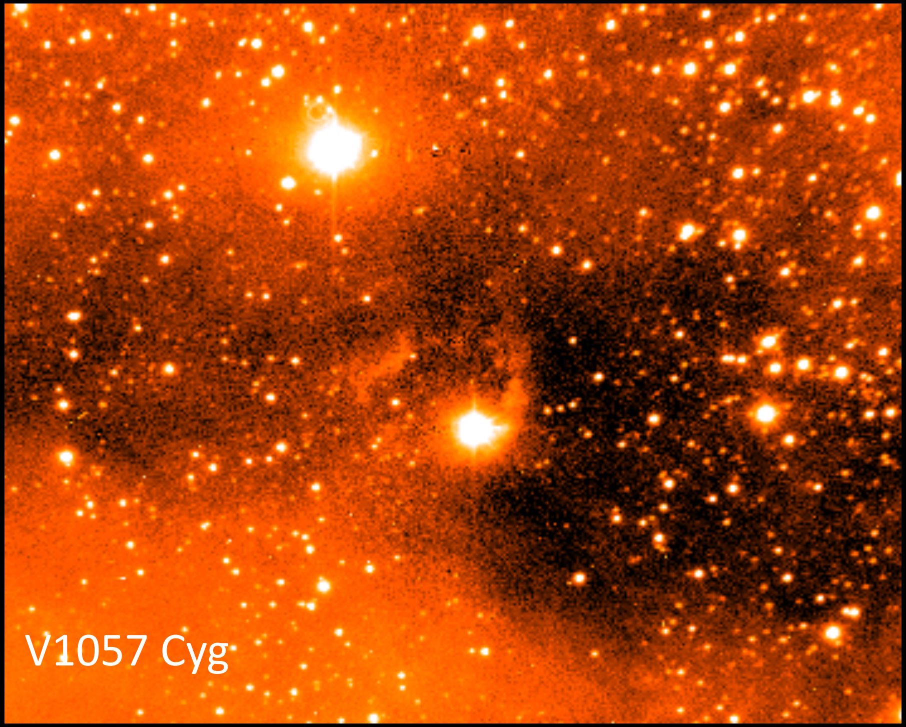
Zhu et al. 2008, ApJ, 684, 1281

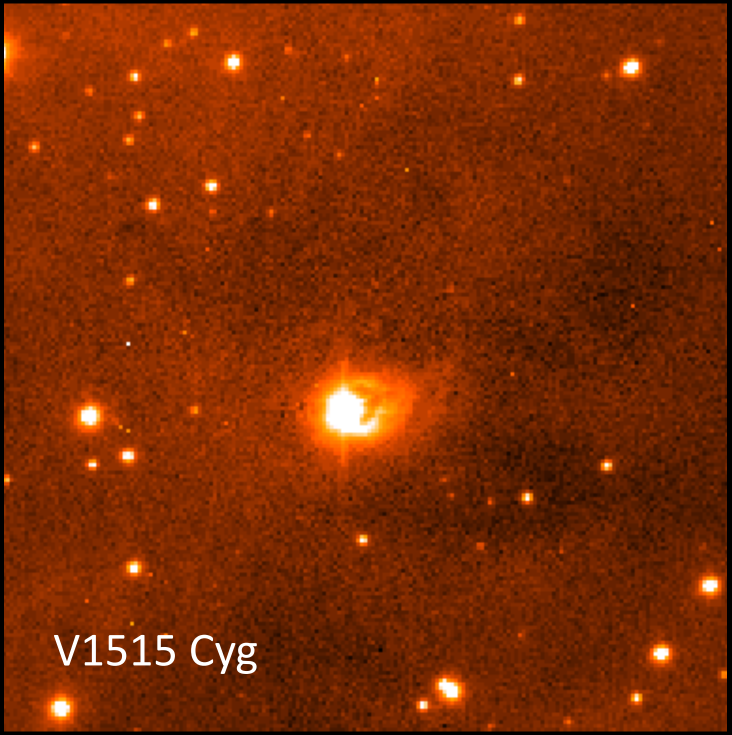


Kenyon et al. (2000, ApJ, 531, 1028)

Additional FUors 1950-1978

Hartmann & Kenyon, 1996, ARAA, 34, 207

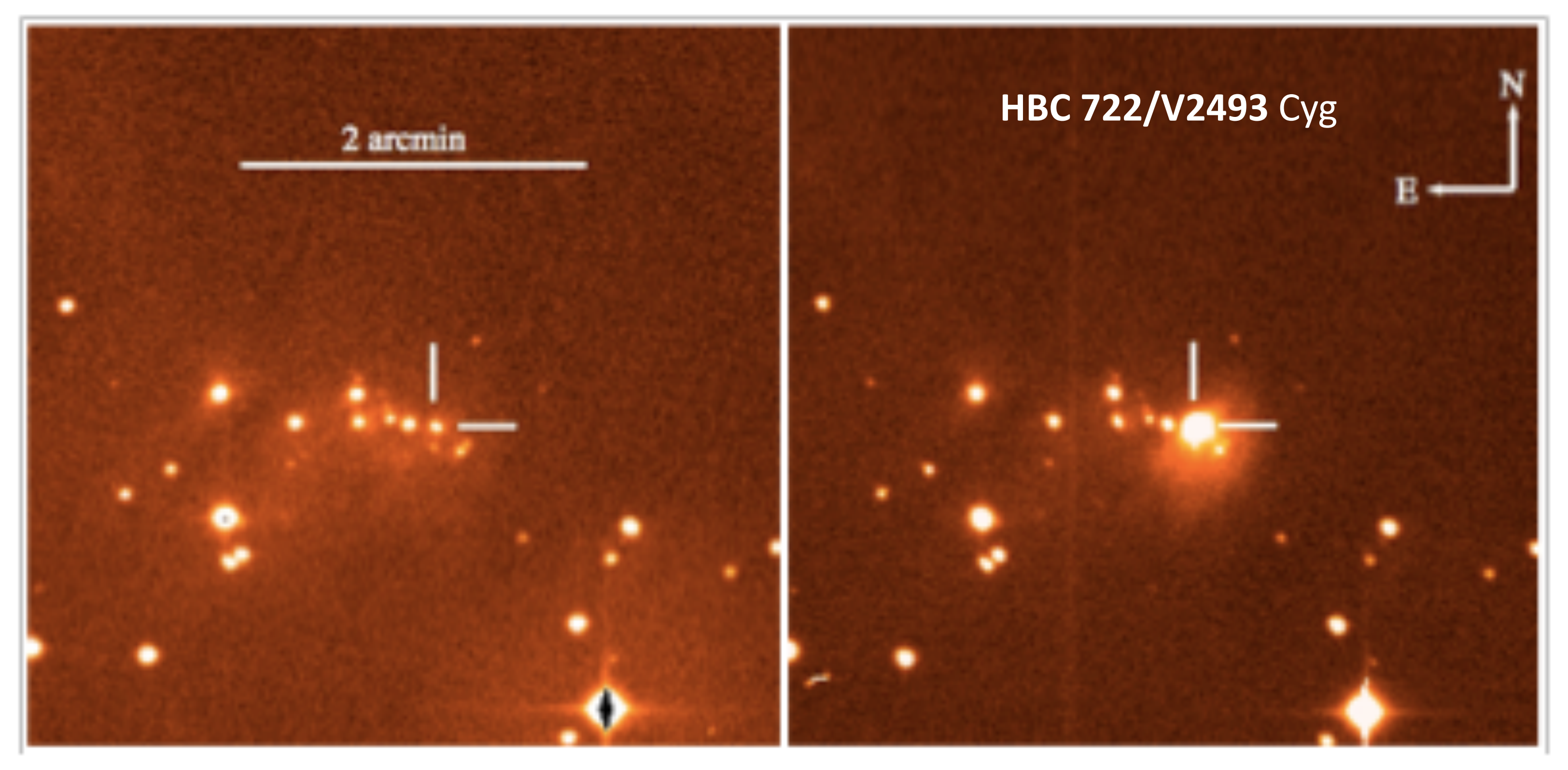




A few other stars with similar properties to FU Orionis were discovered, forming the “classical” FUor group (Herbig, 1977, ApJ, 217, 693; Elias, 1978, ApJ, 223, 859)

Meanwhile, in Cygnus…

August 17, 2010: Semkov & Peneva (2010), ATel , 2801, announces outburst



Region in between the North America & Pelican Nebulae, distance 520 pc

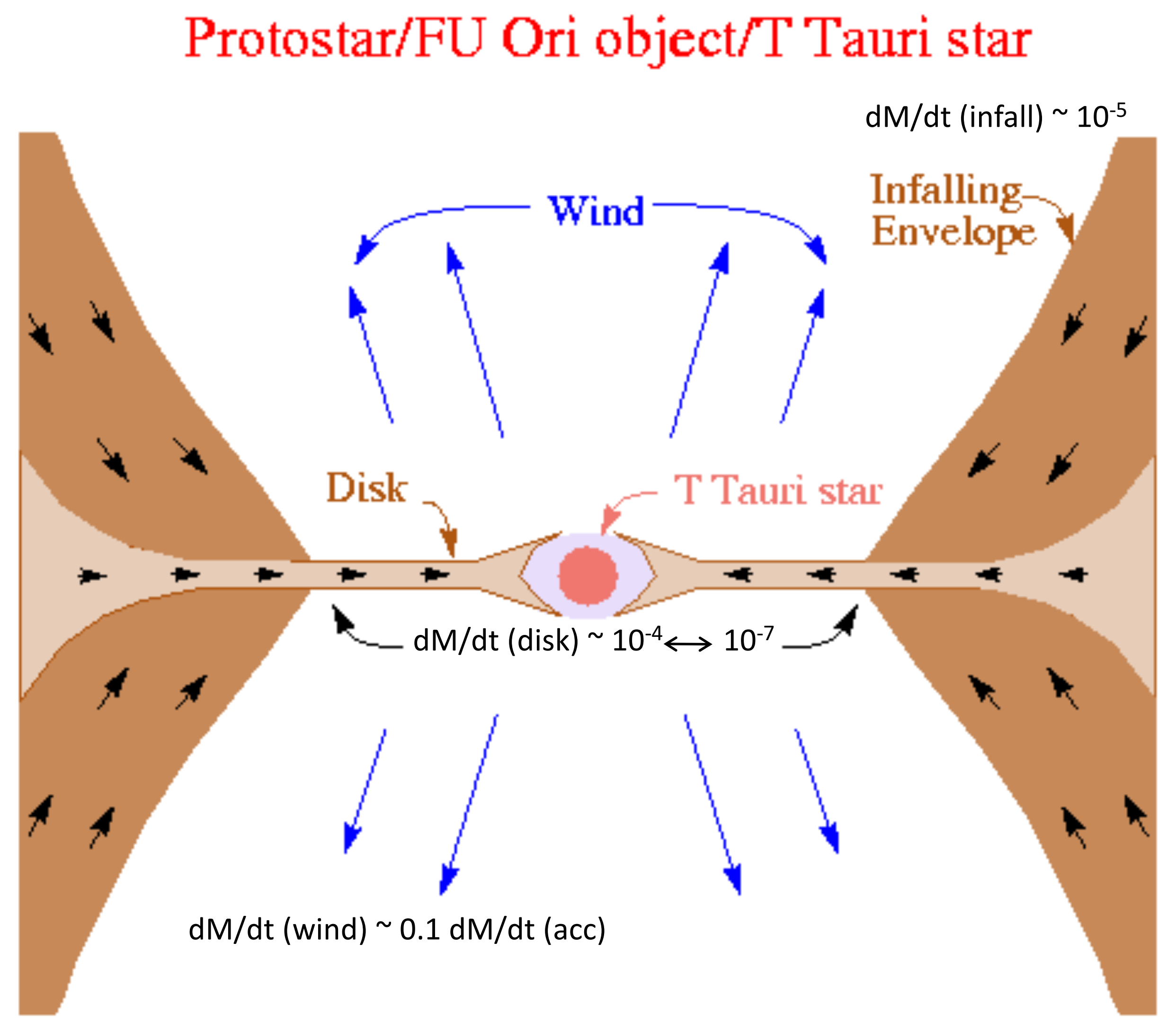
Green+11, +13
Semkov et al., 2012, A&A, 542, 43

The Classical FUor Group

- About 10 objects have observed eruptions greater than 4.5 mag, with a slow (~ 100 yr) relaxation timescale, identified as young stars (Audard+14, PPVI)

- About 10 additional candidates with similar spectral characteristics to FUors, but no observed large eruption

Protostar to Protoplanetary Disk: the Nature of Accretion



Modified from Hartmann & Kenyon, 1996, ARAA, 34, 207

Why study these sources?

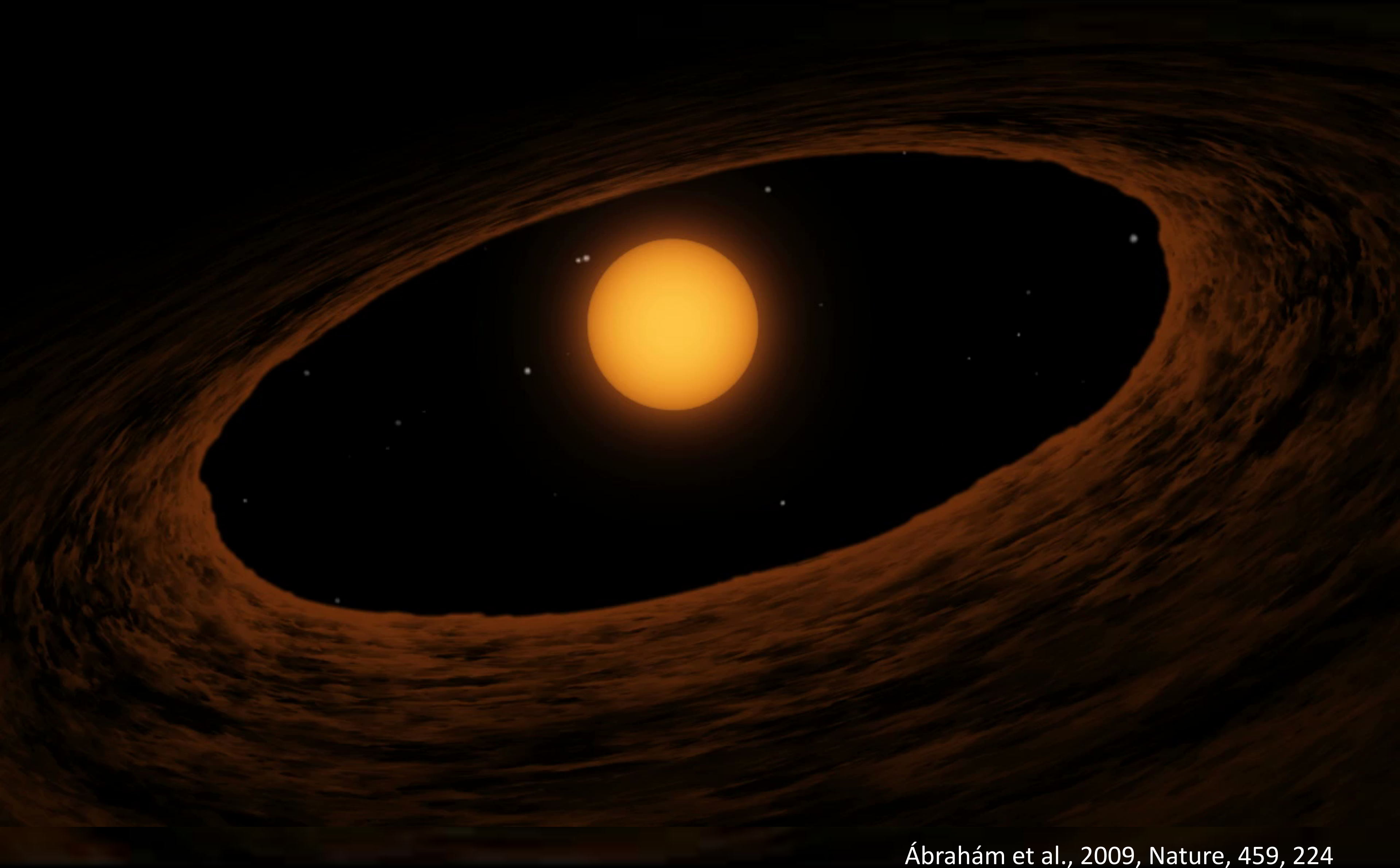
- Represent stages wherein most of the YSO mass *may* be accumulated

- Accretion mechanism may differ from the classical magnetospheric TTS accretion model: "new" accretion physics

- Diagnostic for outburst triggering mechanisms, an important problem

- Offer "unveiled" examples of YSOs with accretion rates comparable to embedded sources

EXors and FUors are a Natural Laboratory for Accretion Physics



Ábrahám et al., 2009, Nature, 459, 224

Courtesy: R. Hurt, SSC

Key Questions

- What is the triggering mechanism of these bursts?
- What effect does a burst have on the protoplanetary system?
- Are (multiple) bursts common to most protostars?
- Do FUors/EXors solve the Luminosity Problem?

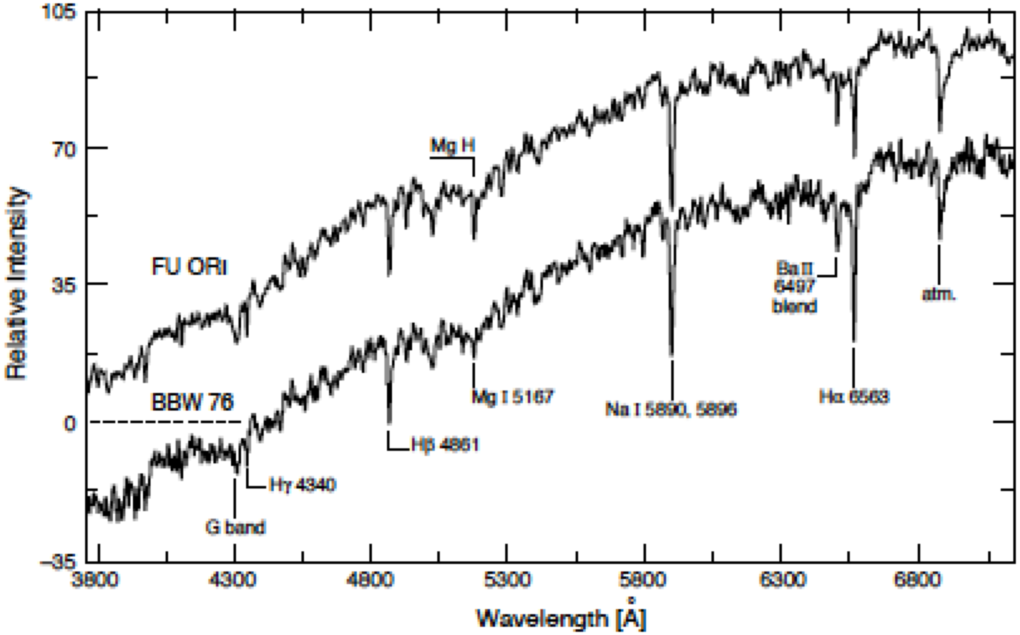
How are FUors different than other young stars?

“Unfortunately, you never know when or where it's ever gonna strike.”

Optical Spectroscopy

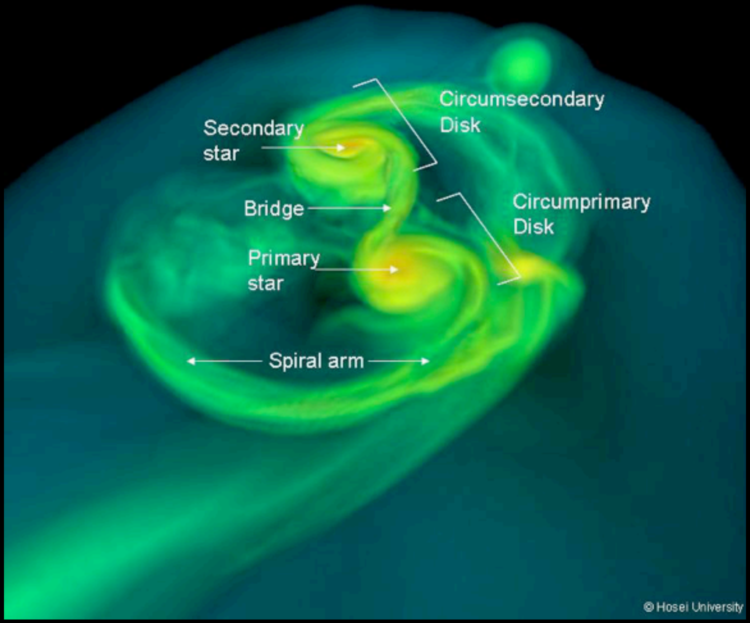
- Broad blueshifted absorption in Na and Balmer lines (although sometimes P Cygni or weak emission in Hα)
  - Drive powerful winds
- Magnetospheric accretion lines usually disappear during burst, or are not observed
- Optical F-G supergiant in many cases; in weaker bursts, stellar continuum may still dominate

We lack pre-outburst IR data (dust, gas, disk, envelope properties)



Potential Triggers of Burst Behavior

- Intrinsic luminosity changes due to disk-related instabilities
- Binarity: e.g, FU Ori (Reipurth & Aspin, 2004, ApJ, 608, 65)
  - Mass transfer? Instability triggered by perturbing the disk externally?
- Variable extinction (flared disks, periodic obscuration); Morales-Calderón et al. 2012, ApJ, 733, 50

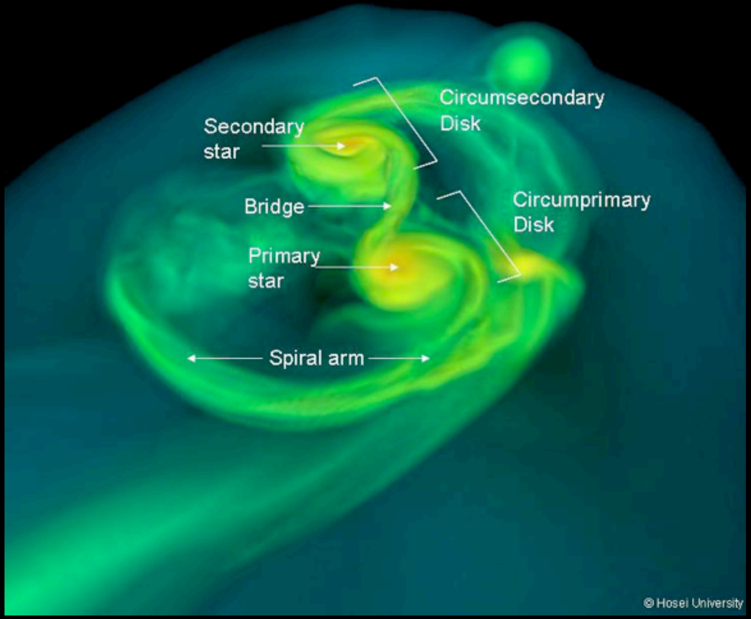


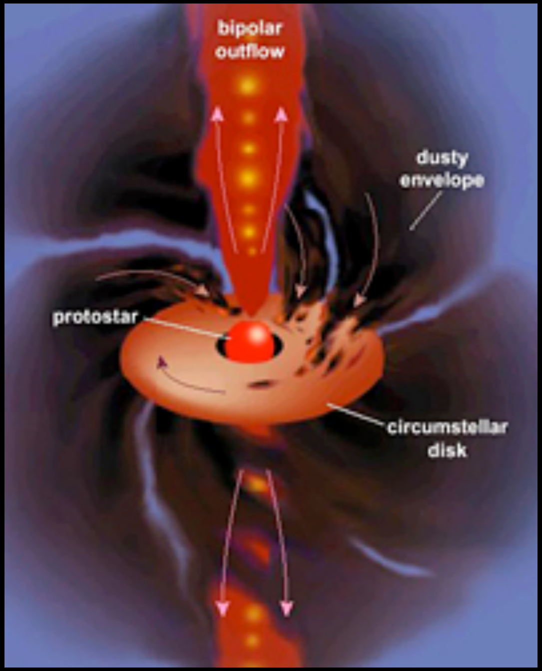
What is the triggering mechanism of these bursts – external to disk?

(1) **Binary interactions** – any stage
(but requires binary companion at certain distance)

(2) **Spasmodic accretion/infall variation** – Stage 0/I, requires massive envelope and/or large disk fragmentation

Vorobyov & Basu 2005-2008; Tassis 2005





Experiment #1: Are FUors Binaries?

Are FUors just binary interactions?

- If we can rule out binary stellar mass companions for most of the classical FUors, the binarity-driven accretion mechanism is disfavored
  - FU Ori is a binary, RNO 1B/1C are binary FUor system

- Non-redundant aperture masking data suggests a companion around V1057 Cyg!
  - BUT: V1515 Cyg and HBC 722 lack companion (within constraints of observations -> deeper needed)
  - 30 AU separation -> implies roughly equal mass binary, with 10 AU disk.
  - Material accreted during the burst ~ 0.0045 Msun
  - Material available in MMSN disk < 10 AU ~ 0.005 Msun
  - If binarity triggers outburst behavior, it cannot occur during every periastron: refilling time too long

Experiment #2: How does line emission evolve during the burst, and what is it tracing?

Disk-only Instability Scenarios

- Thermal disk instability / planet-driven instability (Bell & Lin 1994; Lodato & Clarke 2004) – Stage II

- GI/MRI instability (Zhu et al. 2007-2010) – early Stage II, requires moderate mass disk, and varying viscosity in the disk zones

- Gravo-magneto instability (Martin, Lubow, Livio & Pringle 2012) requires high magnetic Reynolds number, or varying viscosity in the disk zones

A Close Relationship Between Accretion and Outflow?

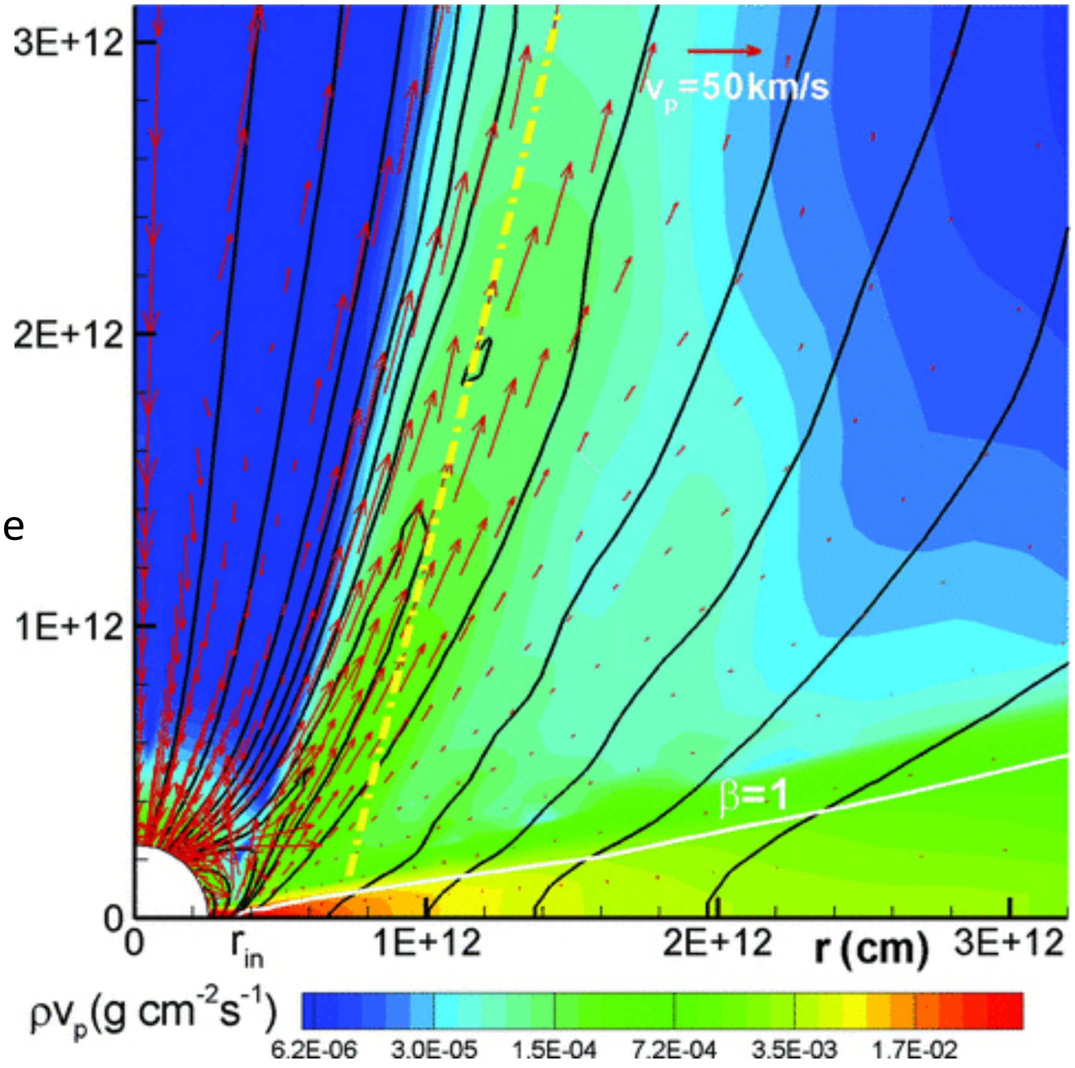
-Accreting matter compresses the magnetosphere of the star

-Field lines enhanced via differential rotation between disk and star

-Conical winds & outflows twist from the inner disk

Romanova et al., 2009, MNRAS, 399, 1802
Kurosawa and Romanova, 2012, MNRAS, 426, 2901

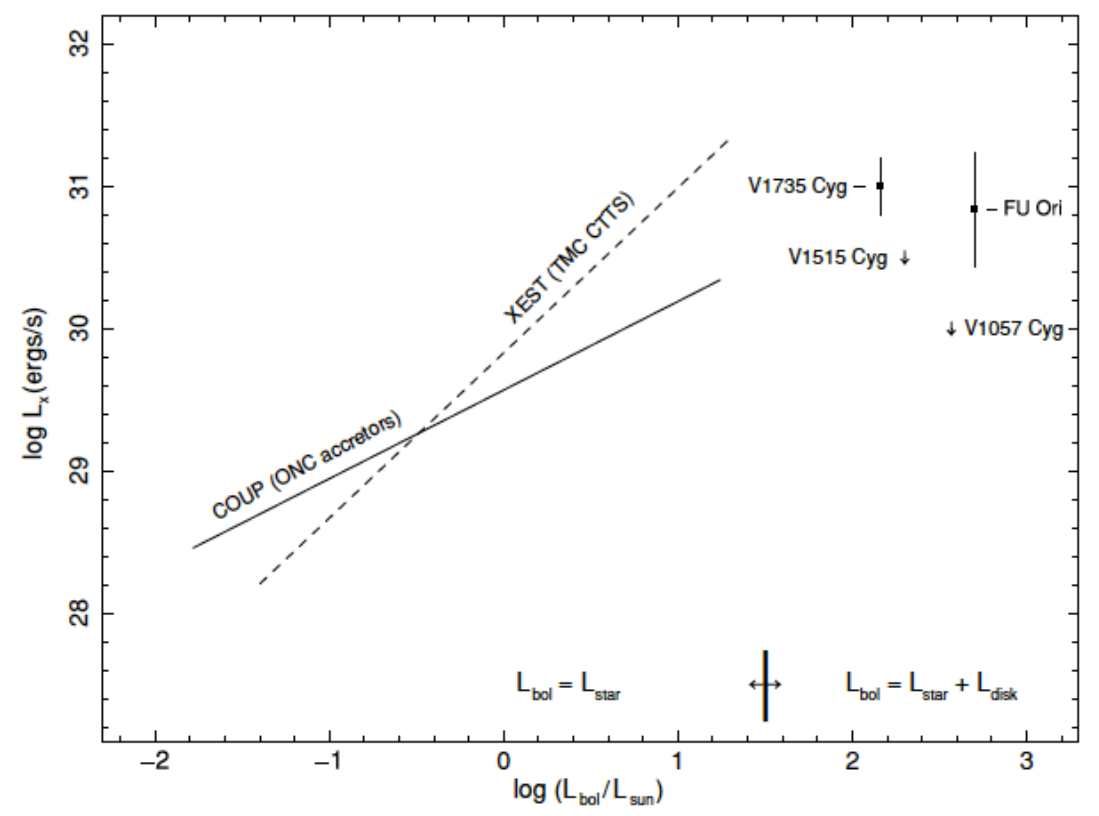
Figure from Königl A et al. MNRAS 2011;416:757-766



Disk–star interaction and the formation of a conical wind. The wind/outflow base originates very close to the stellar photosphere.

FUors and X-rays

- FUors are X-ray bright, compared to X-ray active T Tauri stars, but not relative to the total system output
- Multiple (hard and soft) X-ray components sometimes seen but can be attributed to binaries?
- Chandra/XMM studies ongoing to track emission during burst – accretion column obscuration (in prep.)?

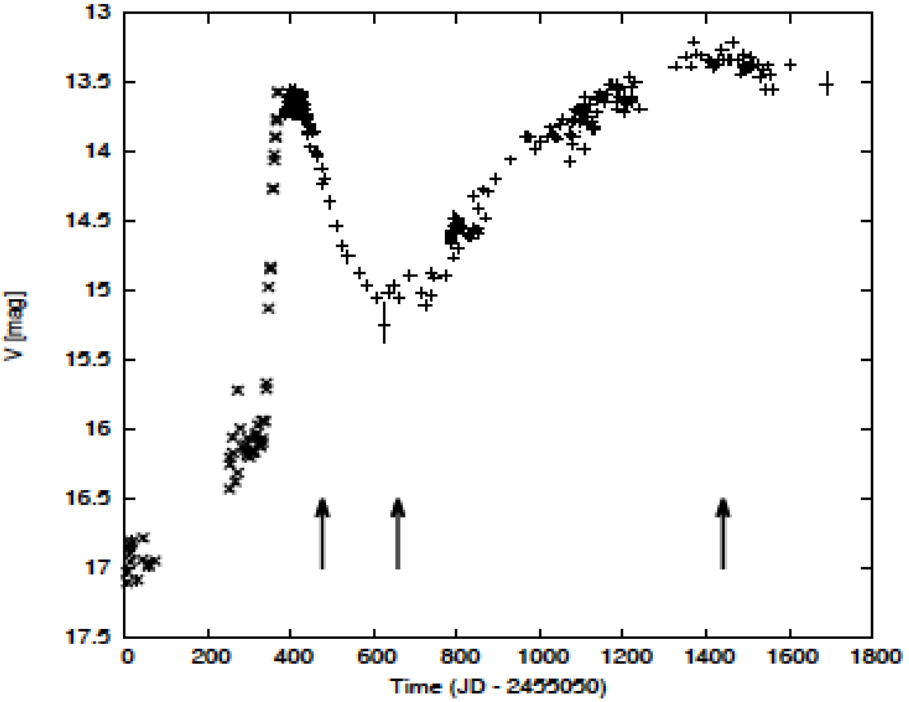


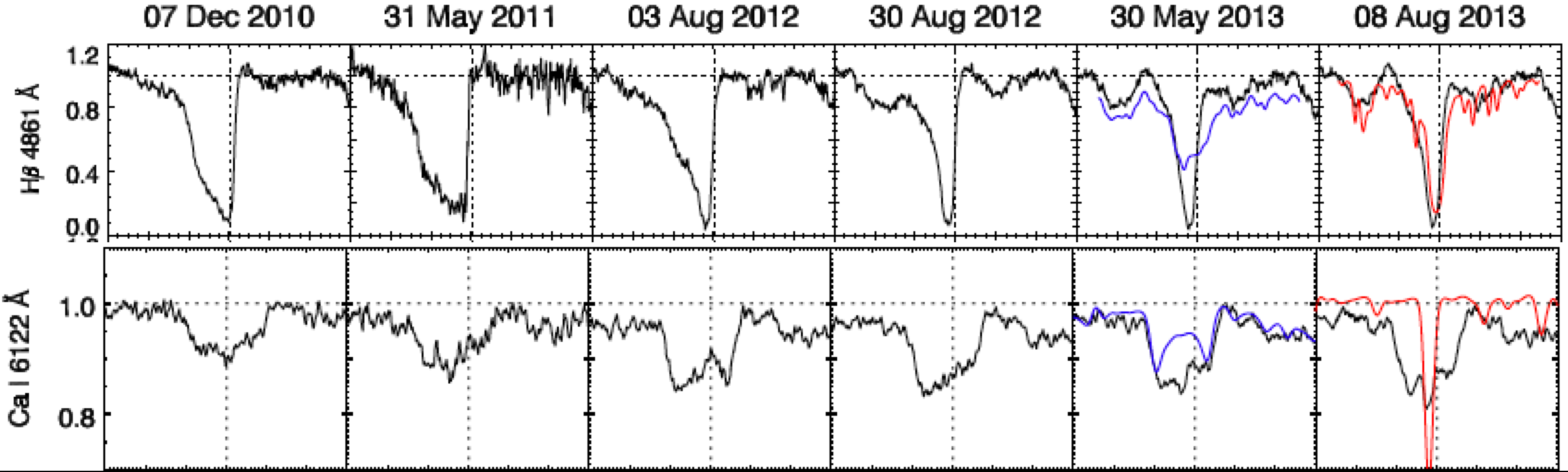
Hard X-rays = magnetically-driven
Soft X-rays = accretion processes

e.g. Grosso et al. 2010, A&A 522, A56

Skinner et al., AJ, 2006, 643, 995; Skinner et al. 2009, ApJ, 696, 766

Longitudinal Studies: The Burst of HBC 722





Lee+15

Diary of a Burst

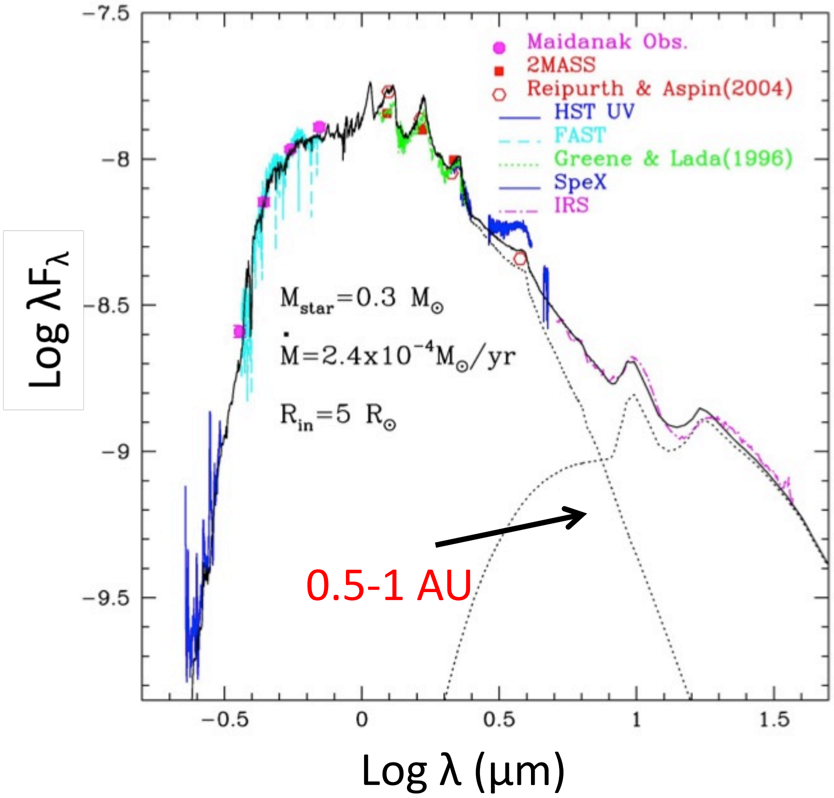
- 2010: 400 km/s outflow/wind
- 2011-2012: luminosity & accretion rate decreases, but wind remains strong. Hot inner disk dominated rotation profiles as central star fades.
  - X-rays indicate accretion onto central star activated
- 2013-14: Disk heat moves outward (viscous dissipation?) as profiles narrow (IGRINS).
  - X-rays indicate large column of dust-depleted absorbing material

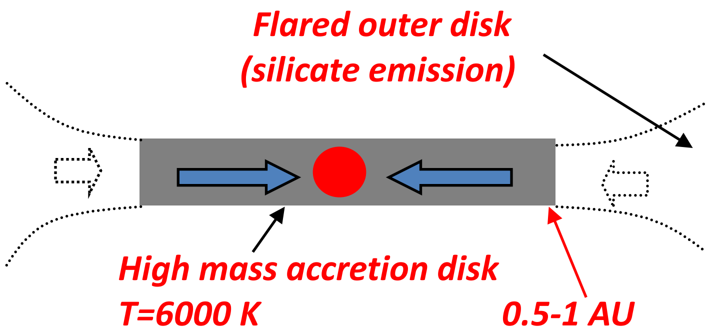
- Outer disks affected on longer timescales (years)

- Envelope chemistry, ice composition are affected (years to decades…) if envelopes are still present

Experiment #3: How does the disk change during a burst?

Rapidly Accreting Disk Model of FU Ori





Flared outer disk (silicate emission)

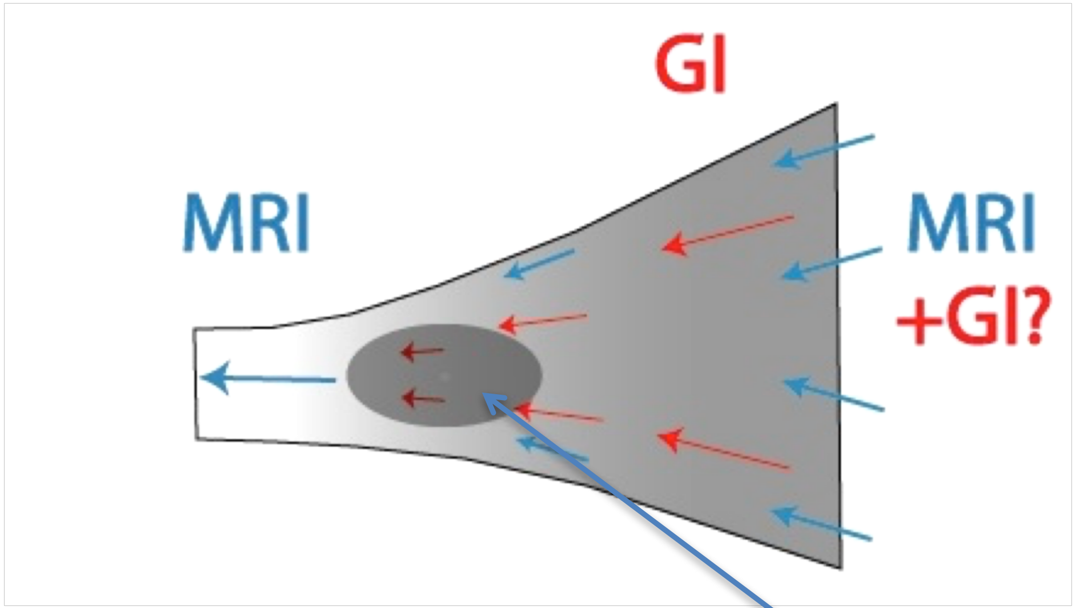
High mass accretion disk T=6000 K

0.5-1 AU

Zhu et al 2007, ApJ, 669, 483
Zhu et al. 2008, ApJ, 684, 1281

- Optical peak is much wider than blackbody
- Hot inner disk
- **Accretion rate inferred from model is 2.4 x 10^{-4} $M_\odot$/yr !**
- Typical Class II accretion rate ~ 10^{-8} $M_\odot$/yr – how do we drive this increase?

Magnetorotational + Gravitational Instability Model (MRI+GI)



Armitage et al. 2001, MNRAS, 324, 705
Zhu et al. 2009, ApJ, 694, 1045
Zhu et al. 2010, ApJ, 714, 1143
Martin & Lubow 2011, AJ, 740, 6
Martin et al. 2012, MNRAS, 423, 2718
Bae et al. 2013, ApJ, 764, 141

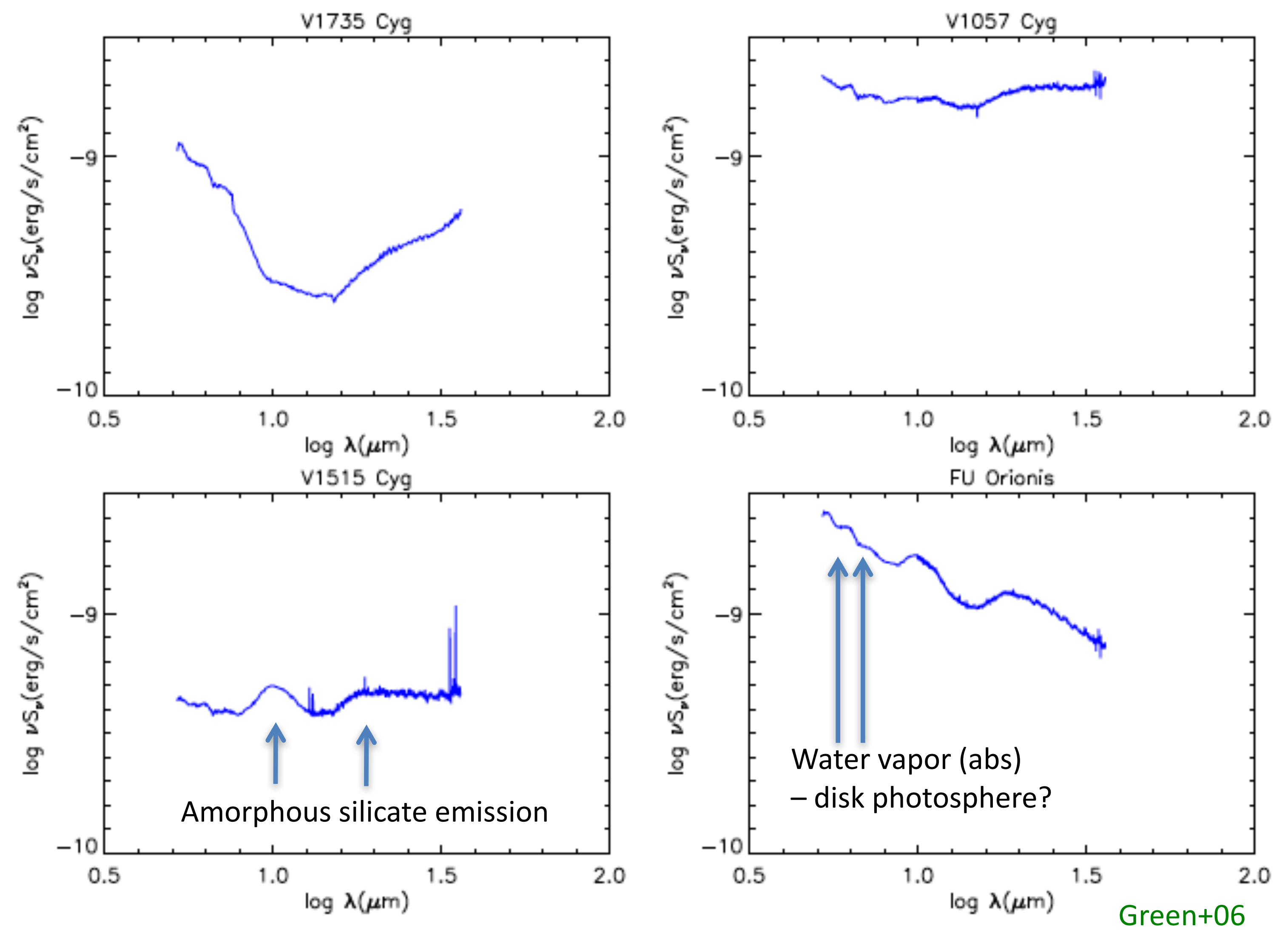
GI: Outer Disk: $Q = c_s\Omega / \pi G\Sigma \sim 1$
MRI: Inner Disk (hot/highly ionized)

Transition region: (1-10 AU) GI-MRI junction not smooth => episodic accretion

Predicts correct outburst strength and timescale
But the details of MRI triggering are uncertain

Key zone is 1-10 AU
Single burst

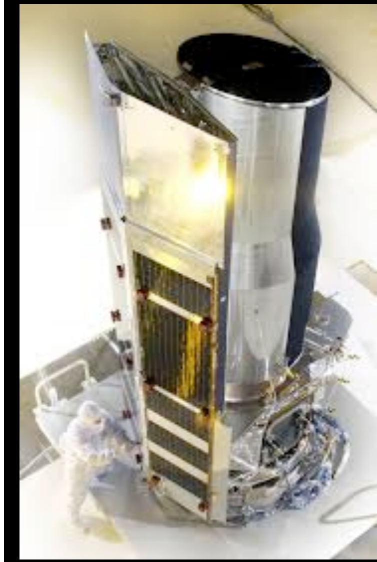
FUor silicate dust is amorphous
50-90% of T Tauri stars show crystalline features



Amorphous silicate emission

Water vapor (abs)
– disk photosphere?

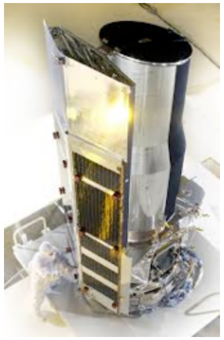
Green+06



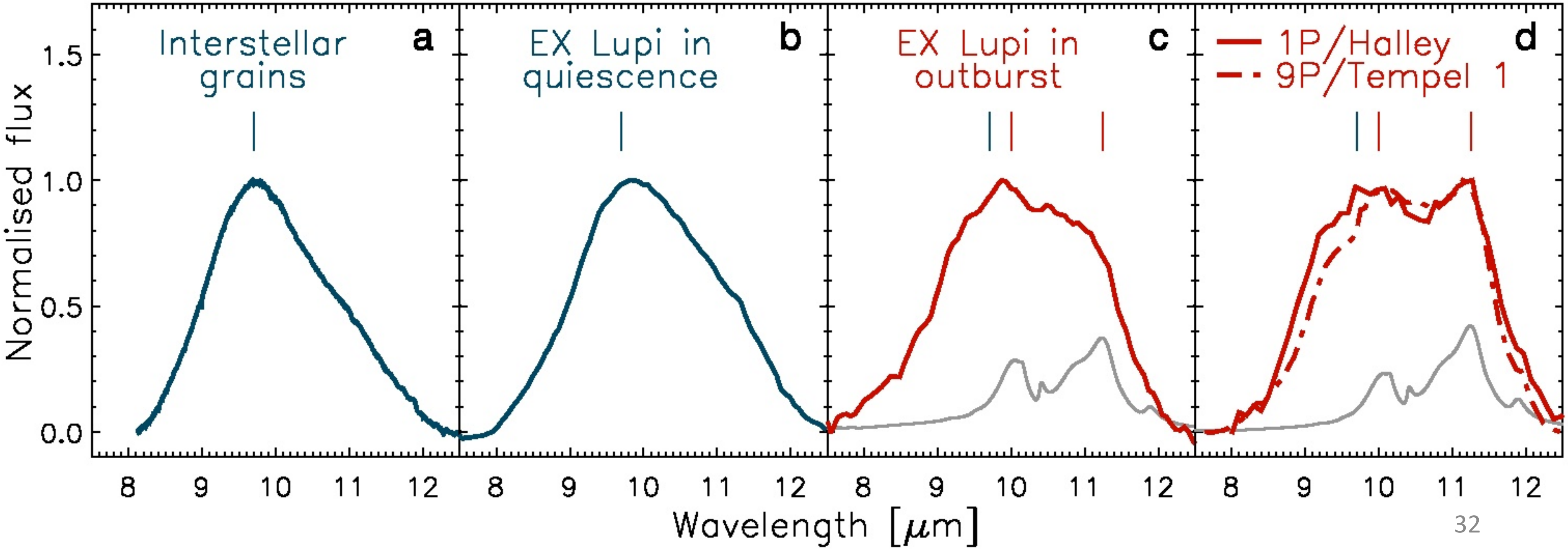
Spitzer

Real Time Changes in Dust Properties?

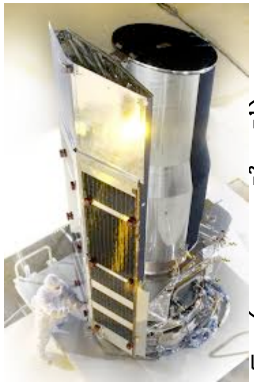
Does dust processing from flash heating (or vertical transport and stirring of dust grains) occur on few month timescales?



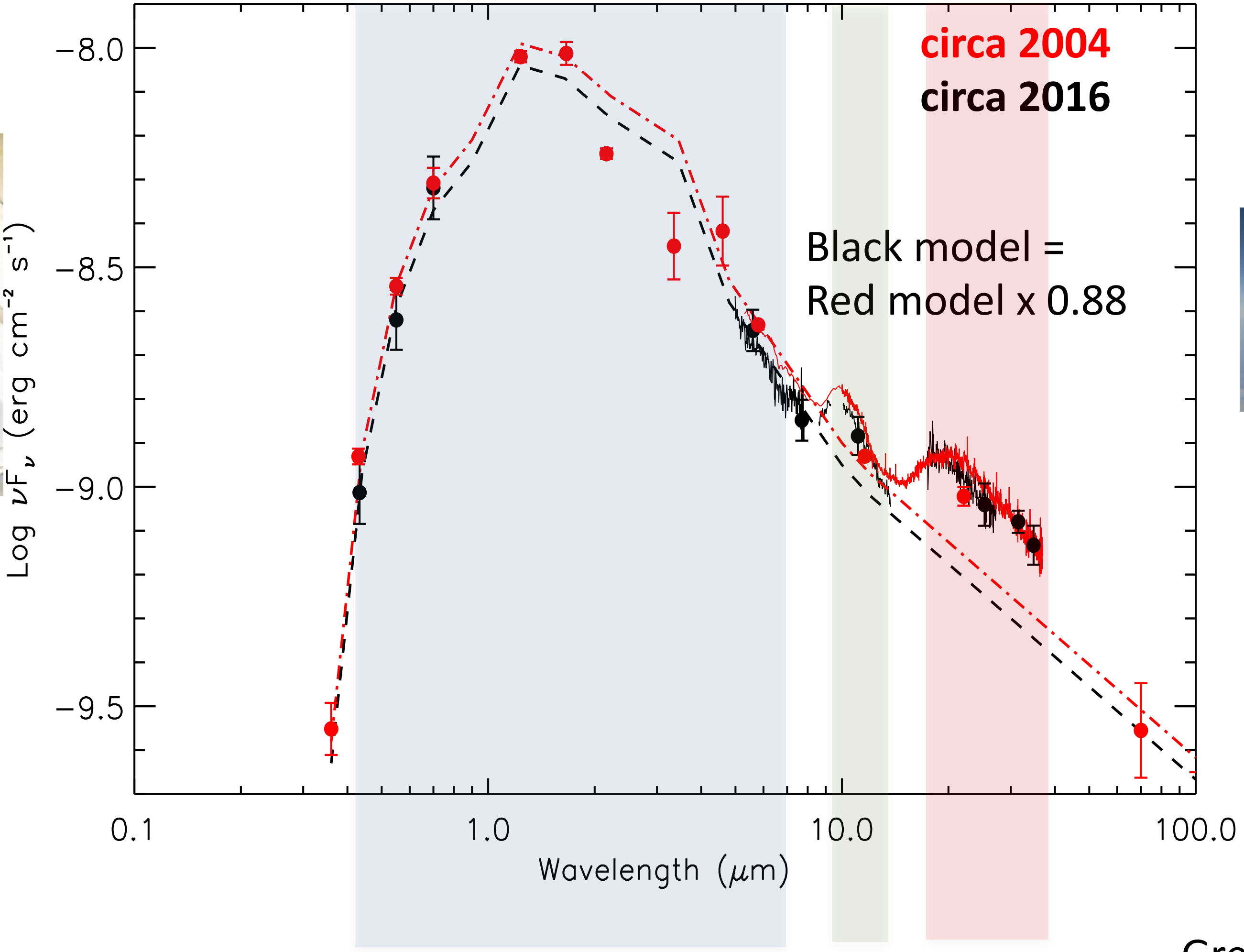
Ábraham et al., 2009, Nature, 459, 224



FU Orionis in Outburst



Spitzer-IRS 2004



SOFIA-FORCAST 2016

Green+16c

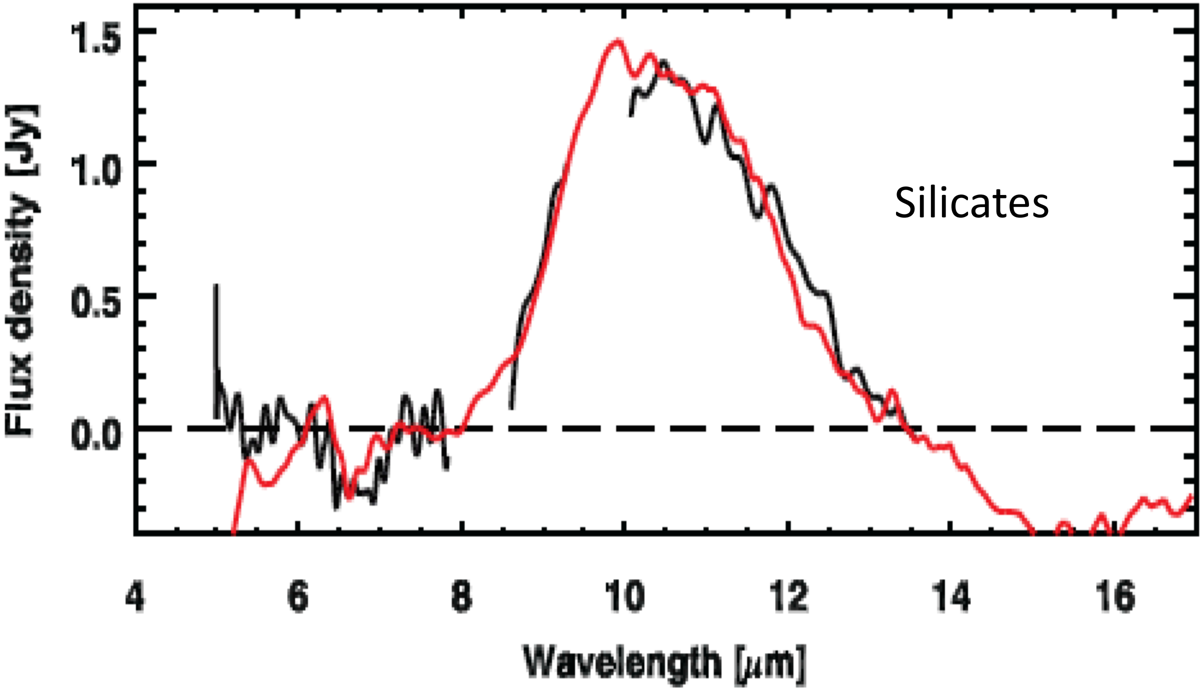
Green+06

% Change 2004-16: -12% -7% <=7%

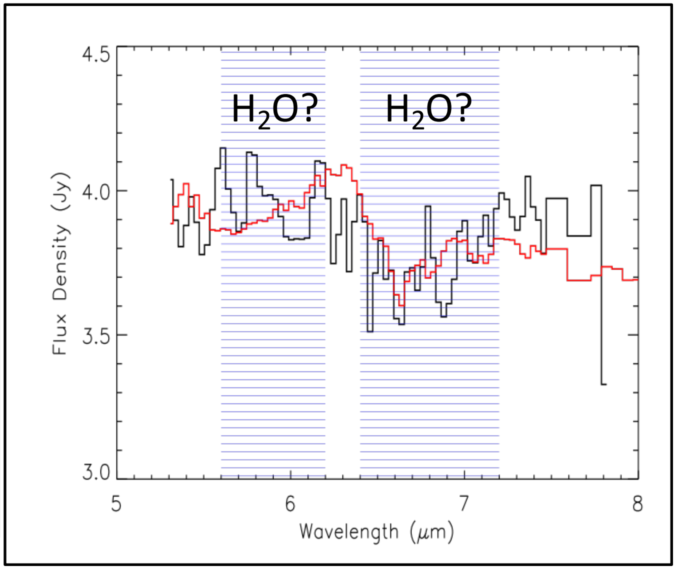
Overall uncertainty ~ 4.2%

No change in solid state features

Dust



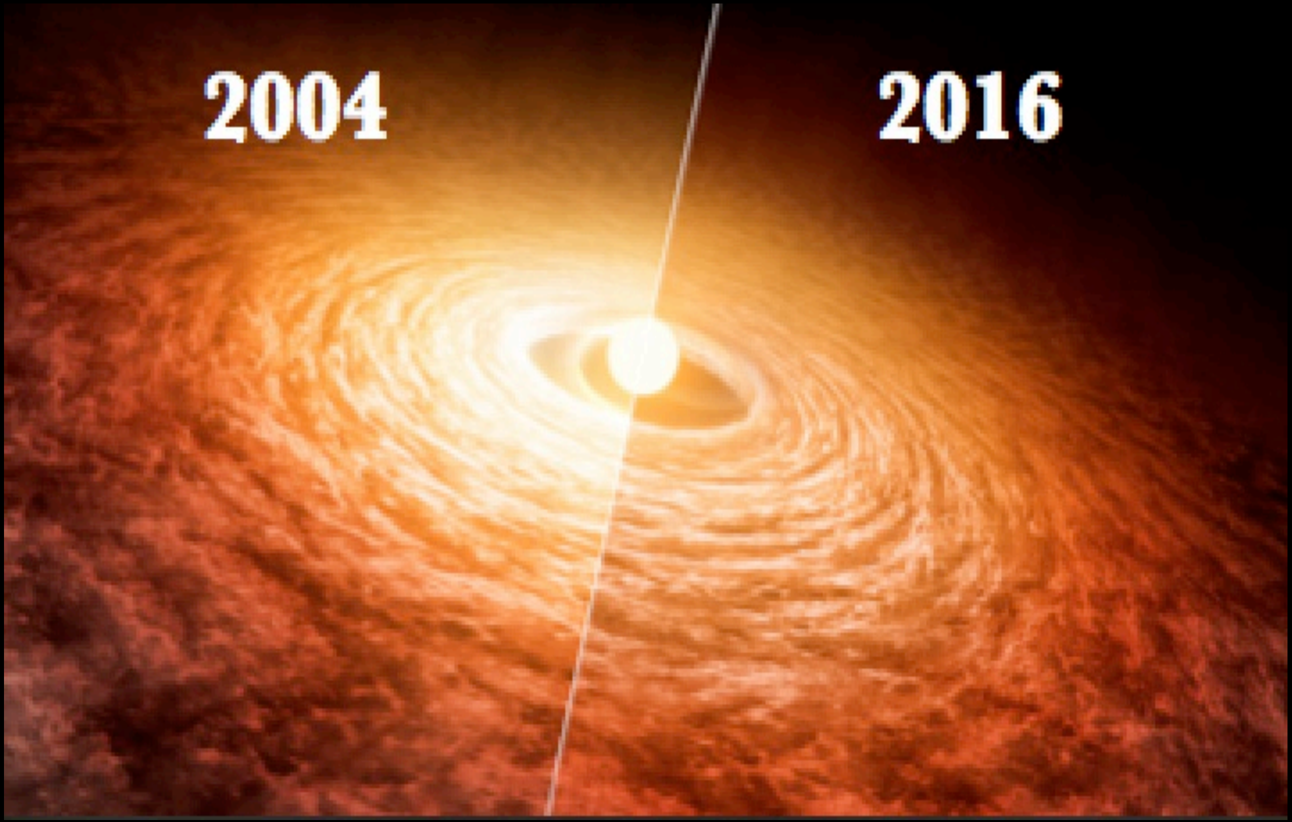
Hot gas



Green+16c

Green+06

Depletion of the innermost disk regions?
Cooling?



Do FUors Solve the Luminosity Problem?

(Updated from Hartmann & Kenyon, 1996, ARAA, 34, 207)

FUors are rarely **seen**…

but they are common events!

Within 1 kpc of the Sun:

$10^4 - 10^5$ T Tauri stars x avg. accretion rate $10^{-8}\ M_\odot\,yr^{-1} = 10^{-3}\ M_\odot\,yr^{-1}$

10 FUors, combined accretion rate ~ few x $10^{-4}\ M_\odot\,yr^{-1}$

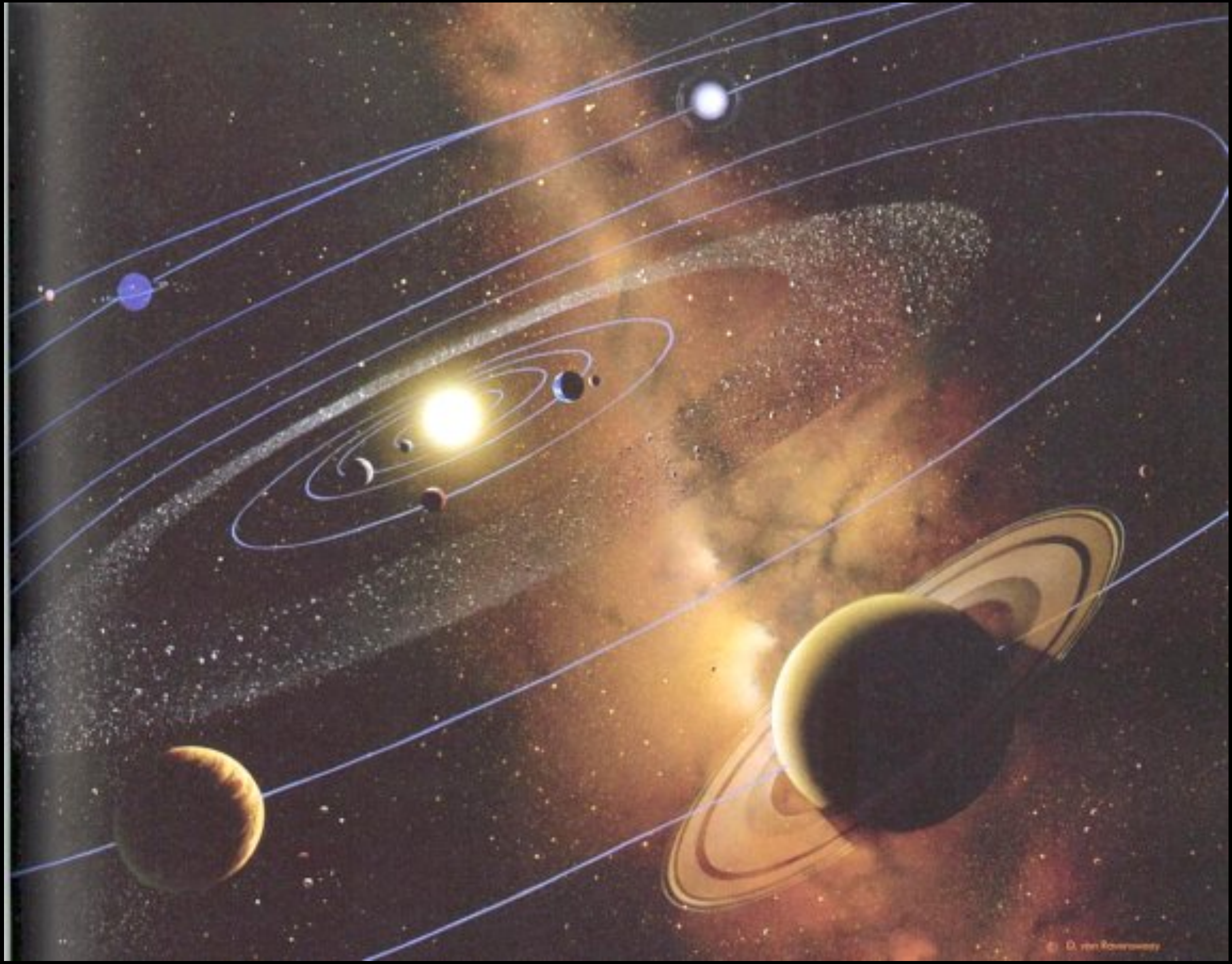
FUors are responsible for ~ 10-50% of the current nearby accretion

About 10 FUors since 1936; average star formation rate 1 / 50 yr

FUors occur at several times the rate of star formation; averaging multiple bursts per star

(FUor list updated from Reipurth & Aspin 2010, Evolution of Cosmic Objects through their Physical Activity, 19; SFR from Miller & Scalo 1979, ApJS, 41, 513; see also Offner & McKee 2011, ApJ, 736, 53)

Did it happen here?

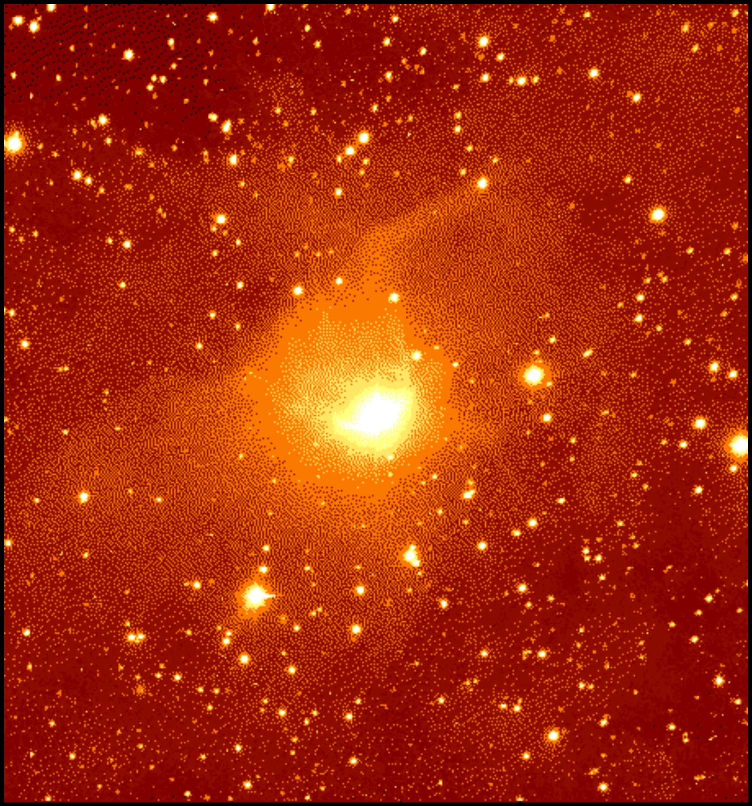


Stardust mission reveals crystalline dust in comets (Brownlee et al. 2012)

Depletion of certain volatiles in the inner solar system evidence of transient heating?
(Hubbard & Ebel 2014)

Outward transport of CAIs?
Wurm & Haack (2009)

FUors (may) anchor the fossil record of our Solar System to the protostellar development timescale

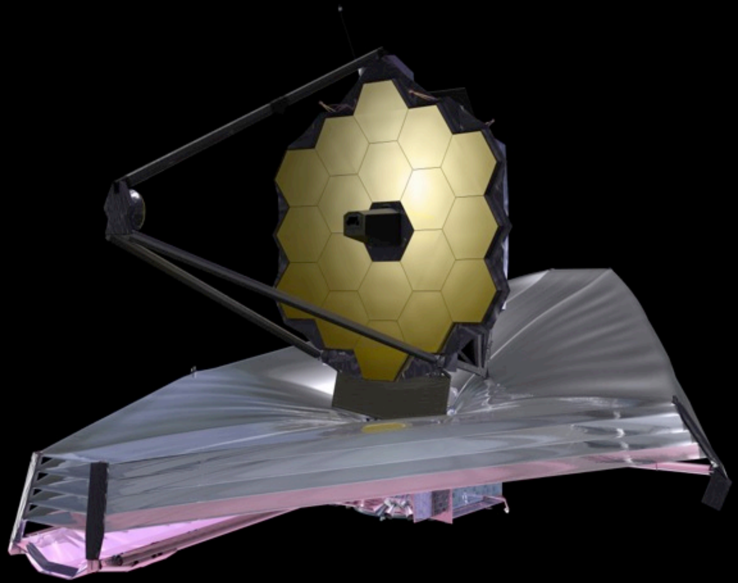


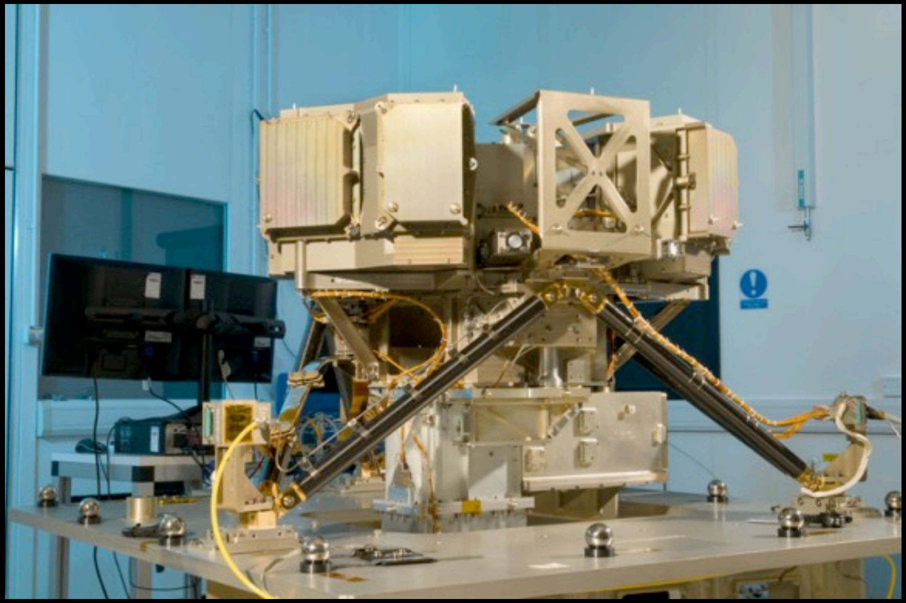
What are the contributions of the FUor/EXor observational group to our understanding of young stars?

Answer Sheet? (Intriguing, but not complete)

- What is the triggering mechanism of these bursts? Disk instability or planetessimal trigger favored
  - Are (multiple) bursts common to most protostars? Likely but need better stats
- What effect does a burst have on the protoplanetary system? Enhanced heating out to a few AU; changes inner disk composition, depletes disk mass
- Do FUors/EXors solve the Luminosity Problem? Potentially, but statistics are poor

JWST-MIRI and NIRSpec can track FUors during burst





Solids Around Young Stars

- How is dust changed by surviving the “baking” environment of an FU Orionis outburst? How do the crystalline silicates in th disk, and the pure CO_2 ices in the envelope, change as a result of the burst?

- Unprecedented spectral resolution of MIRI will reveal composition of disks

Upheaval in the Disk – Gas Tracers

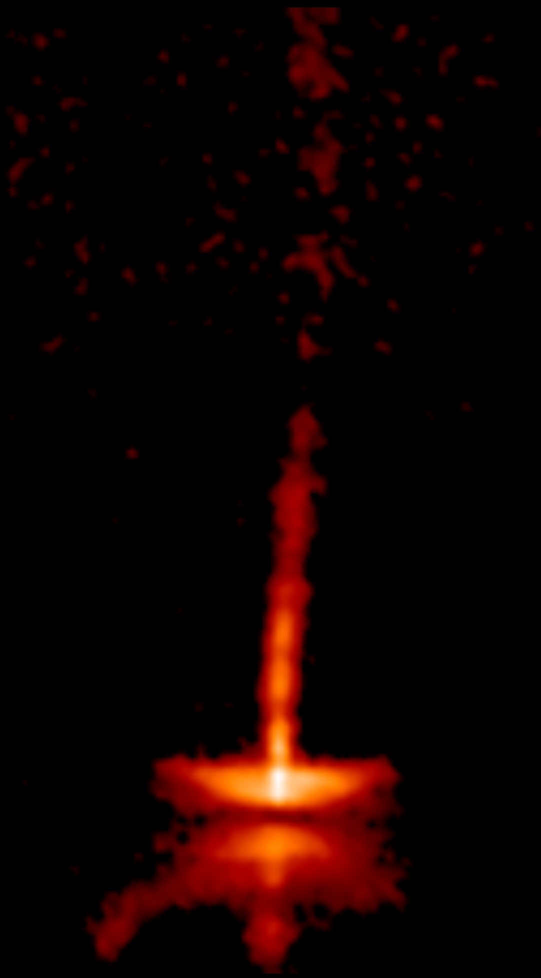
- Hot disk photosphere – thermal inversion could constrain vertical structure models
- What is the triggering event for FUors?
  - Gas in the upper layers of the disk photosphere tells a story
  - Is collapse inside-out (inner disk instability), outside-in (fragmentation), or multi-layered?

JWST-MIRI

Summary

- 5-50% of total low mass YSO accretion occurs in FUor bursts
- FUors may “balance” the distribution of low luminosity sources
- In evolutionary stage, FUors appear to straddle the Stage I/II boundary – a selection effect of optical burst detection
- Outbursts affect disk and envelope chemistry and mass prior to the main epoch of planet formation
  - **Inside-out collapse likely explanation**
  - **Binarity may play a role but not required**
- Possible explanation for depletion of volatiles in inner solar system; offer a partial solution to the transport of newly crystallized small dust grains in disks
- Dust and gas properties are relatively stable during large bursts after initial settling period ~ 2-3 yr

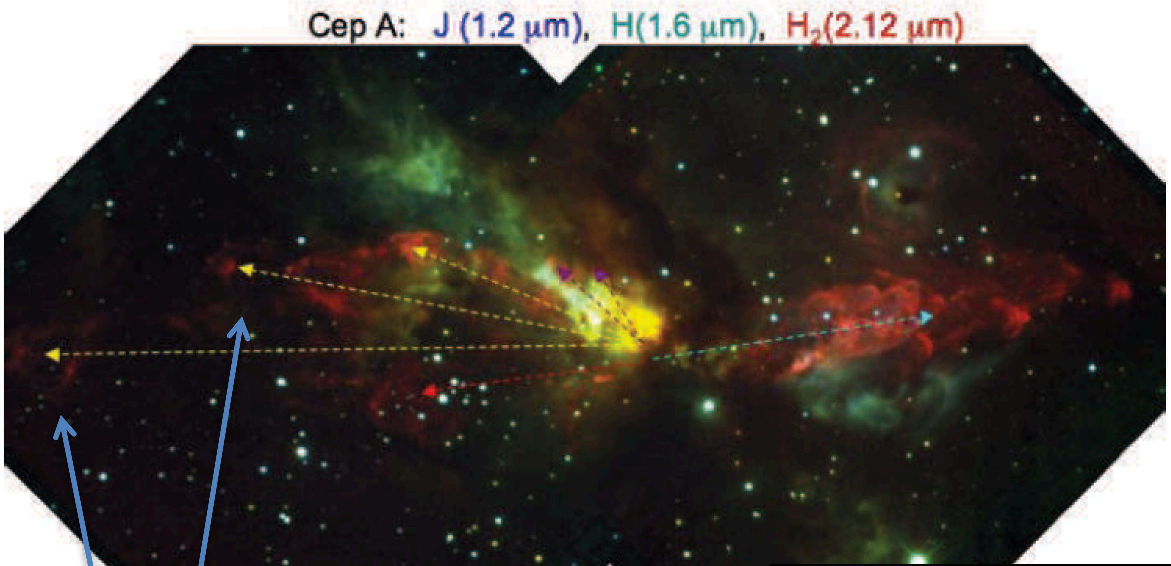
EXTRA SLIDES



HH30 jet

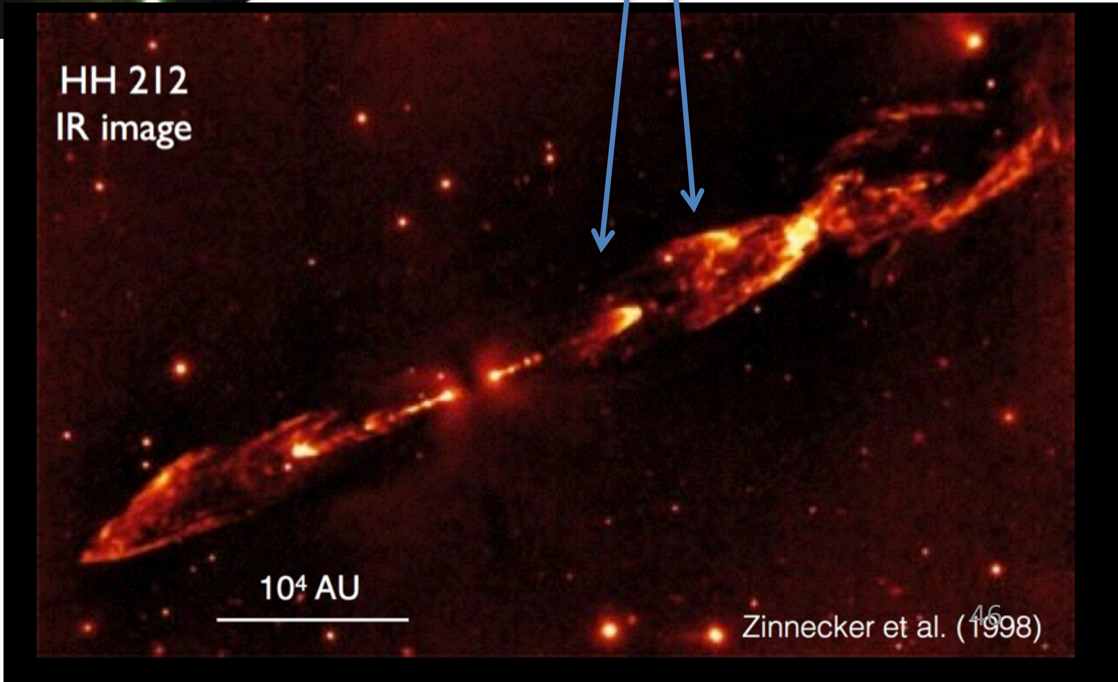
HST/WFPC2; 1995-2000 (A. Watson)

Episodic Accretion & Outflow?



10^3 yr timescale

10 yr timescale



Zinnecker et al. (1998)