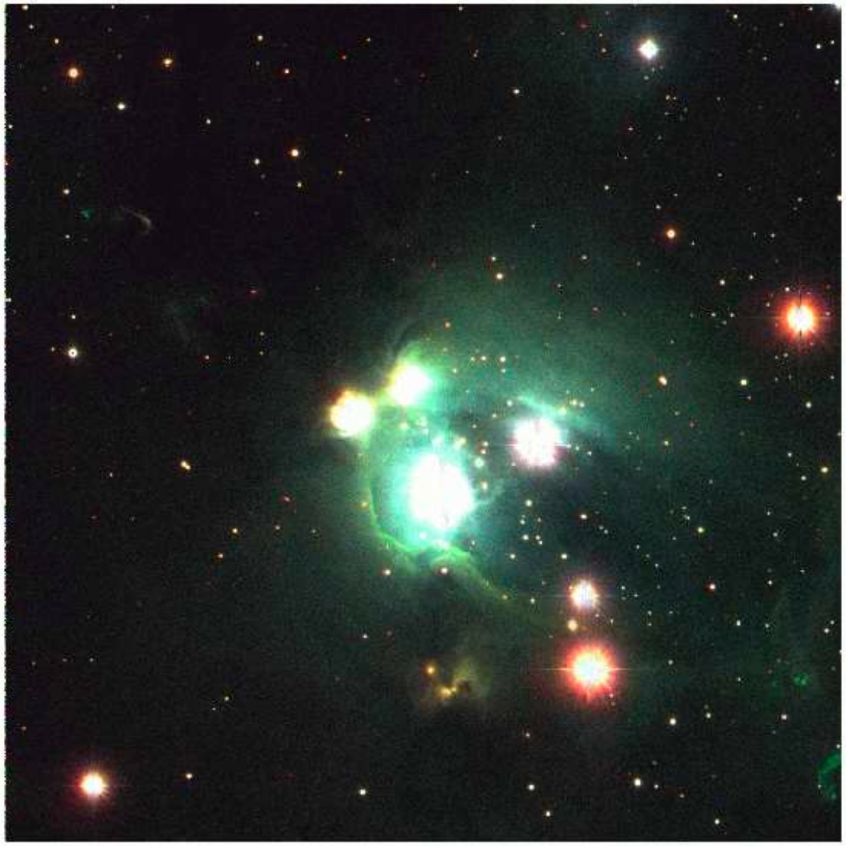
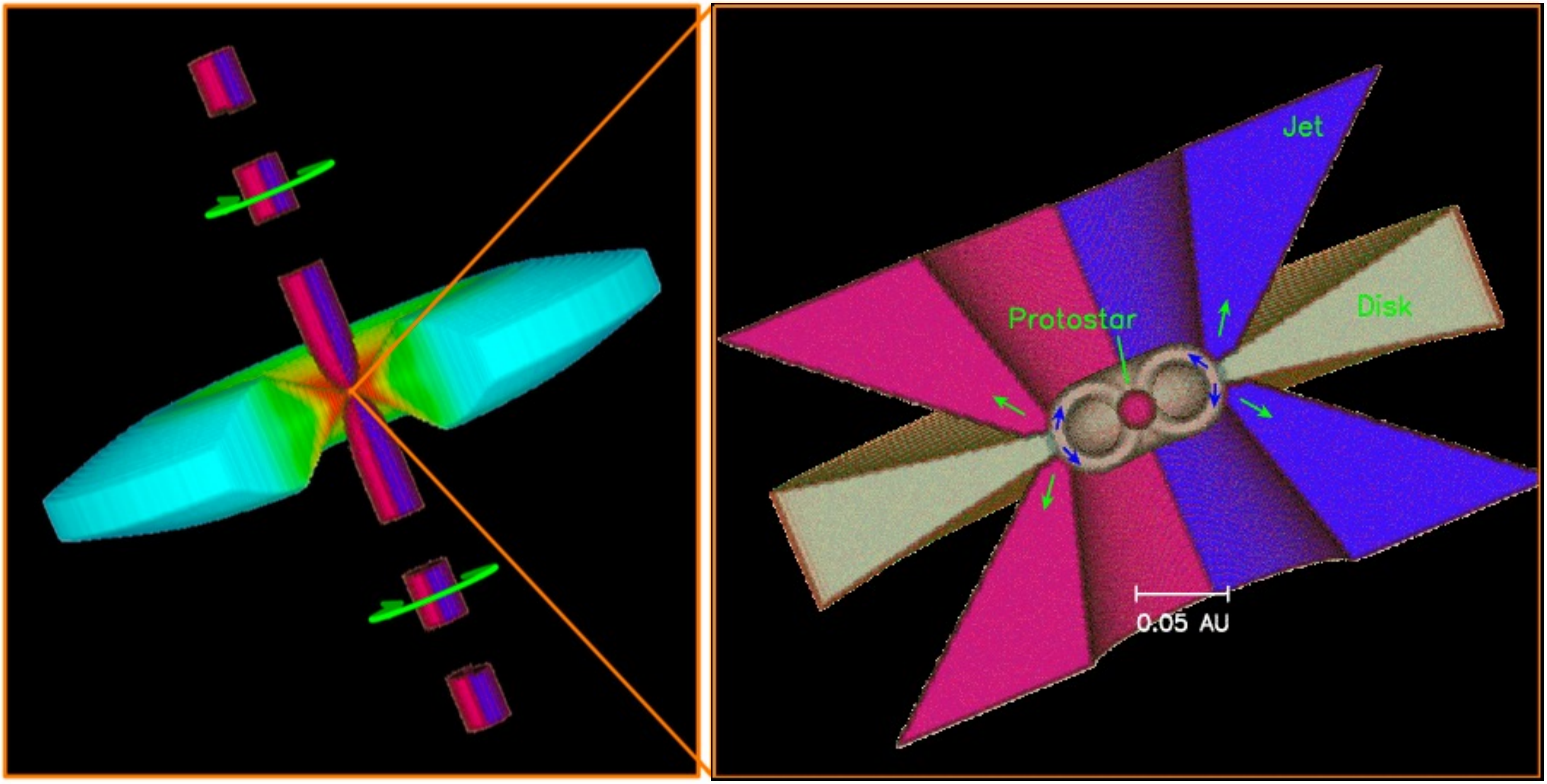


DETERMINATION OF STELLAR PROPERTIES OF YOUNG STARS (OBSERVATIONS)

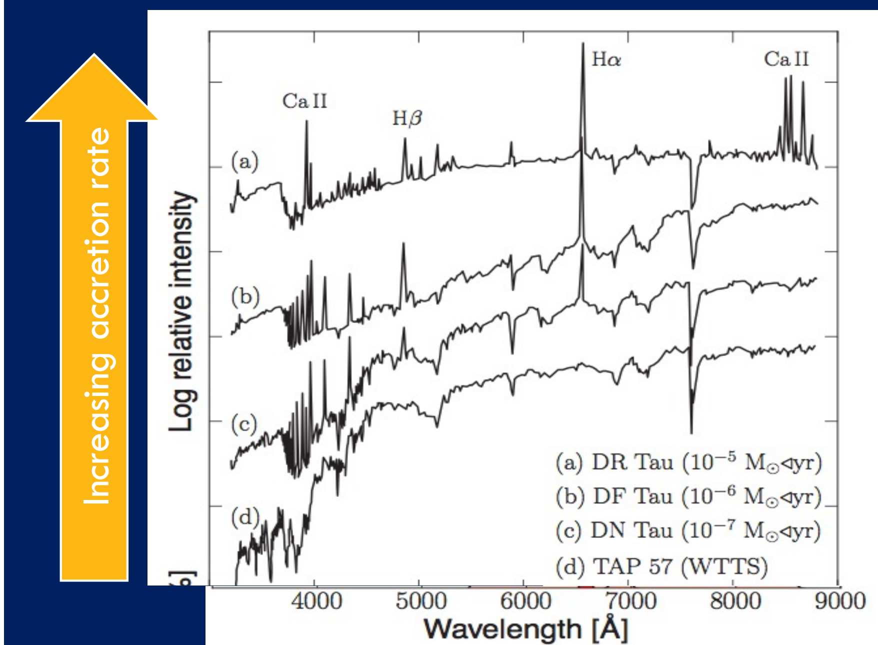
lynne a. hillenbrand (caltech)

CARTOON OF AN INDIVIDUAL YOUNG STAR ACCRETION/OUTFLOW SYSTEM

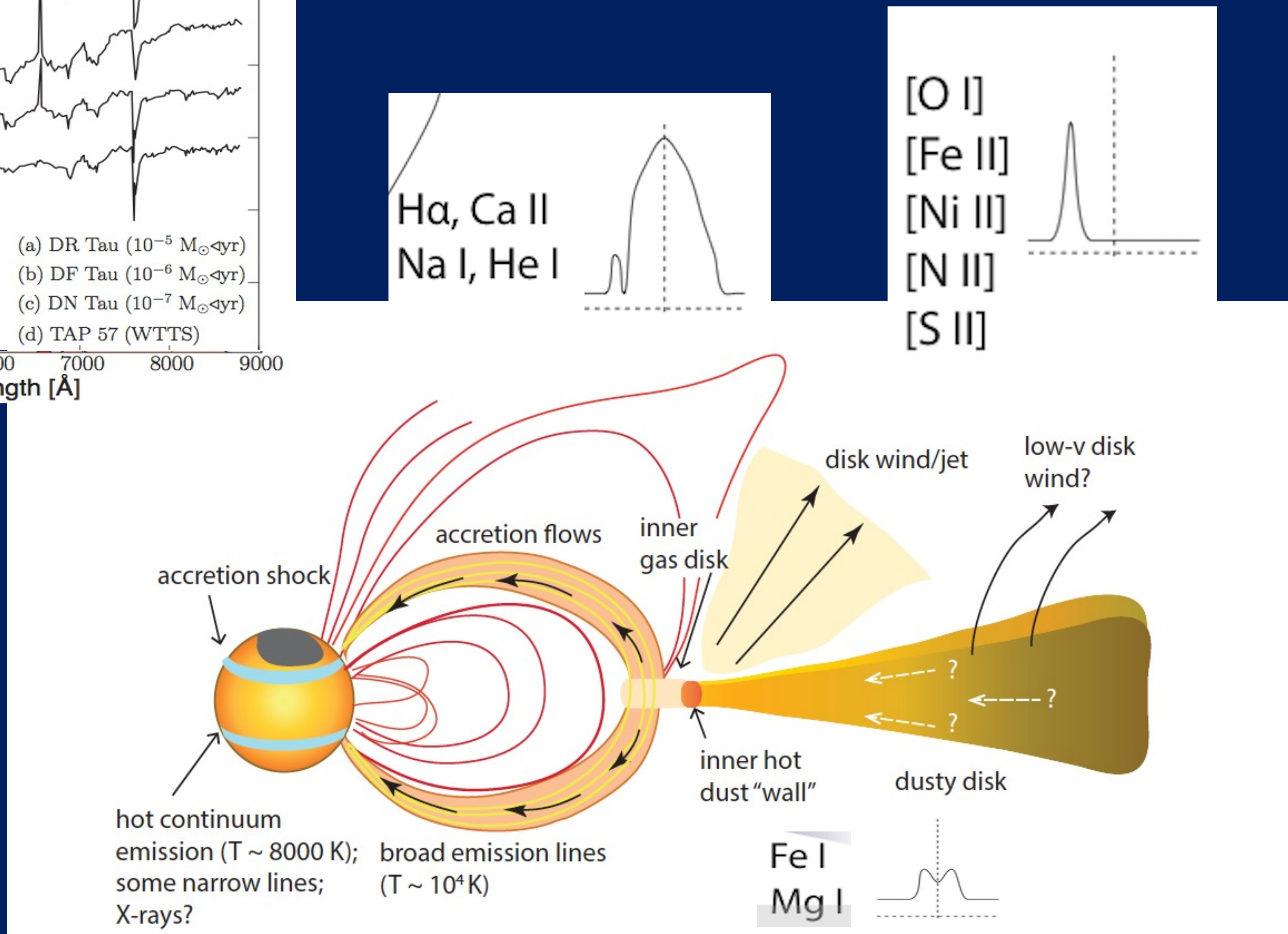


[ALMA press release team]

HOW CAN WE STUDY THE UNDERLYING STAR WITH ALL THIS EXTRA MUCK?



[Barensten et al. 2013]



[Hartmann, Herczeg, Calvet 2016]

- line emission and continuum "veiling" complicates spectral typing.
- continuum excess also distorts broadband colors.

WHAT ARE WE TRYING TO INFER -- ABOUT THE STAR ITSELF?

TEMPERATURE as a basic radiative stellar characteristic

LUMINOSITY or integrated brightness e.g. to interpret an L_{IR}/L_* measurement

MASS e.g. for assessing M_2/M_1 from RV measurements

RADIUS e.g. for assessing R_2/R_1 from transit/eclipse measurements

AGE for timescale and evolution questions

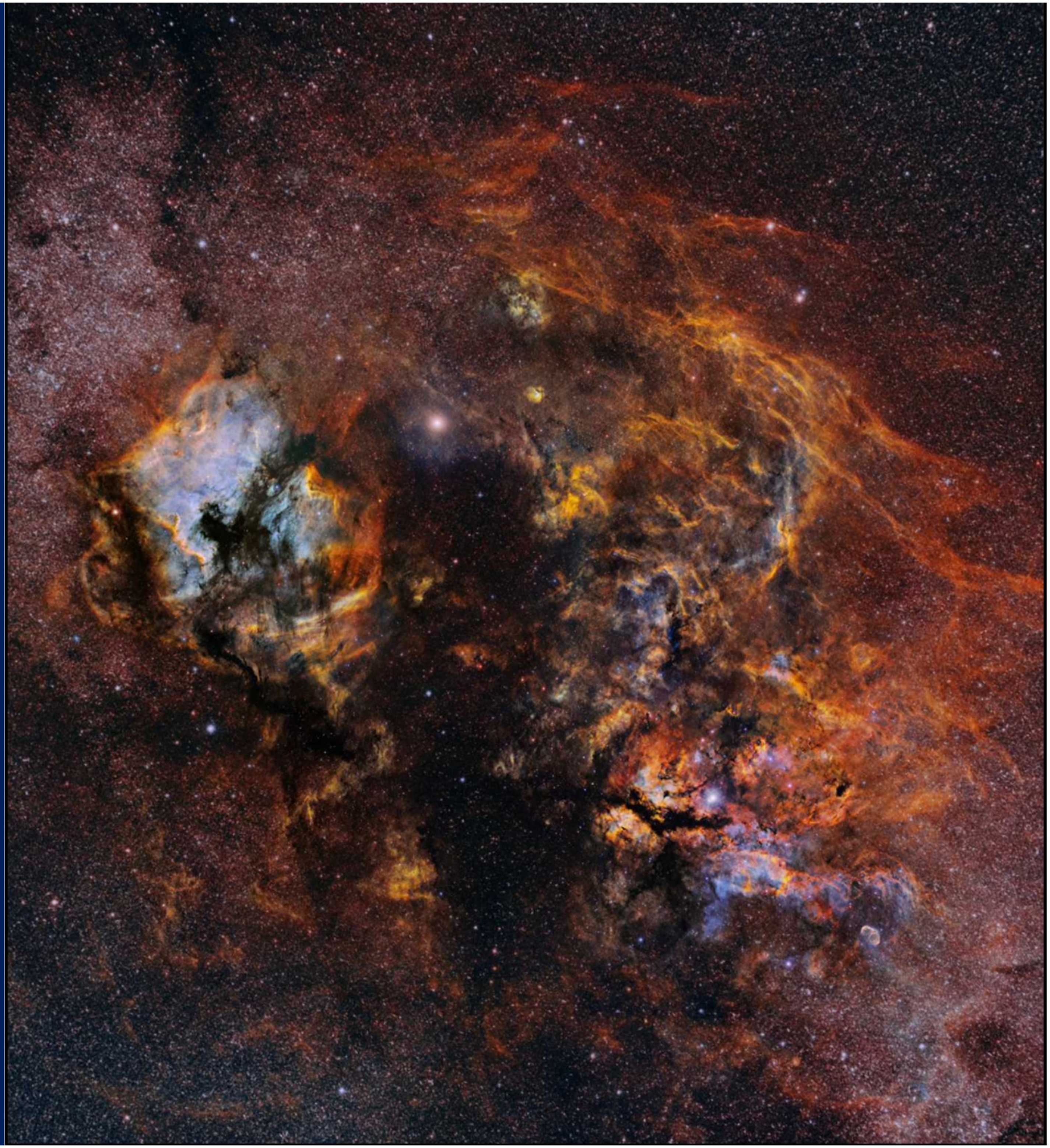
I predict there will be many many plots at this Sagan conference showing some star/disk/planet parameter as a function of age.

Bear in mind that ages remain uncertain at the 20-200+% level. Yes, all ages.

JUST ONE EXAMPLE AMONG THOUSANDS OF STAR FORMING COMPLEXES IN THE GALAXY

(cygnus region)

d ~0.8kpc

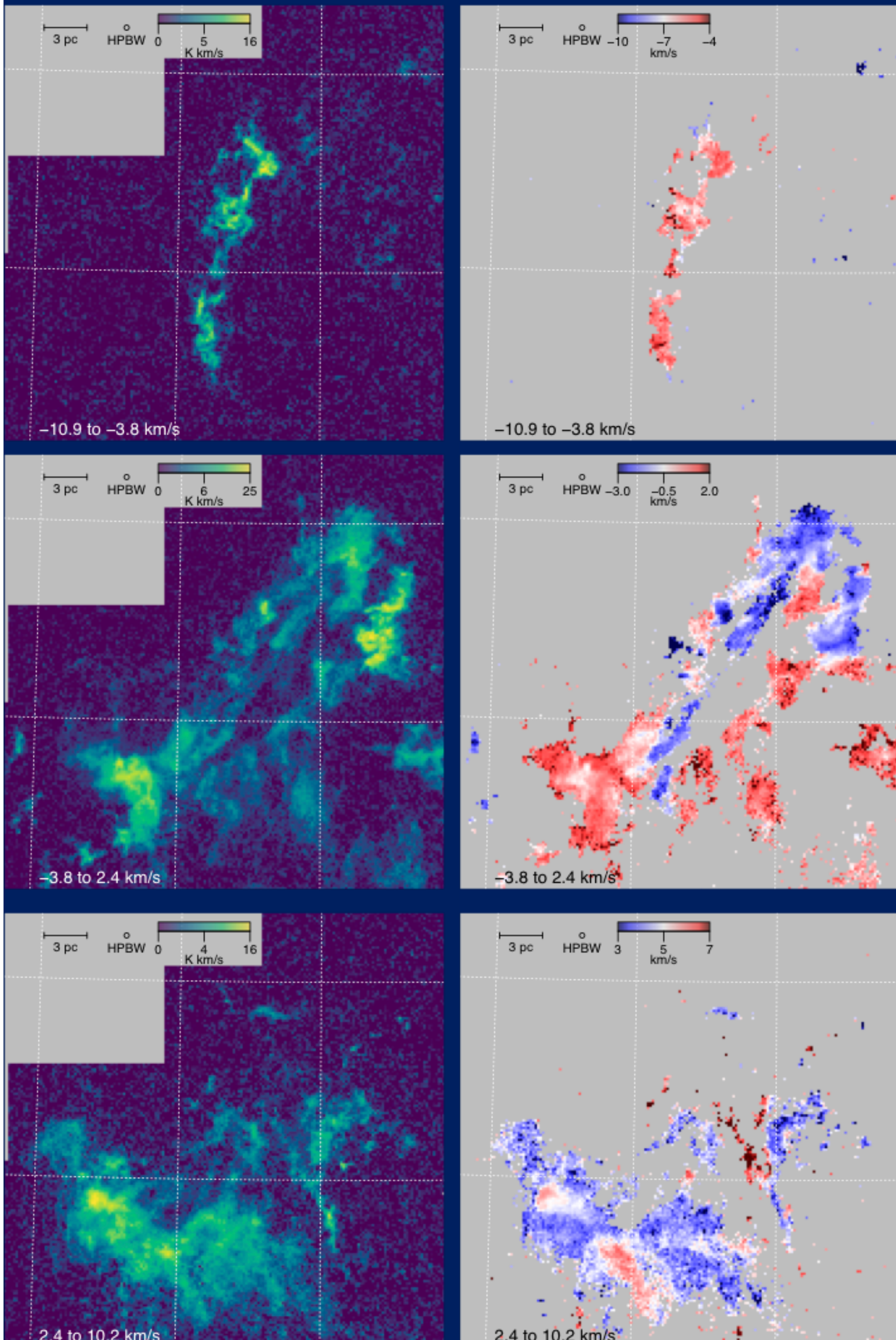


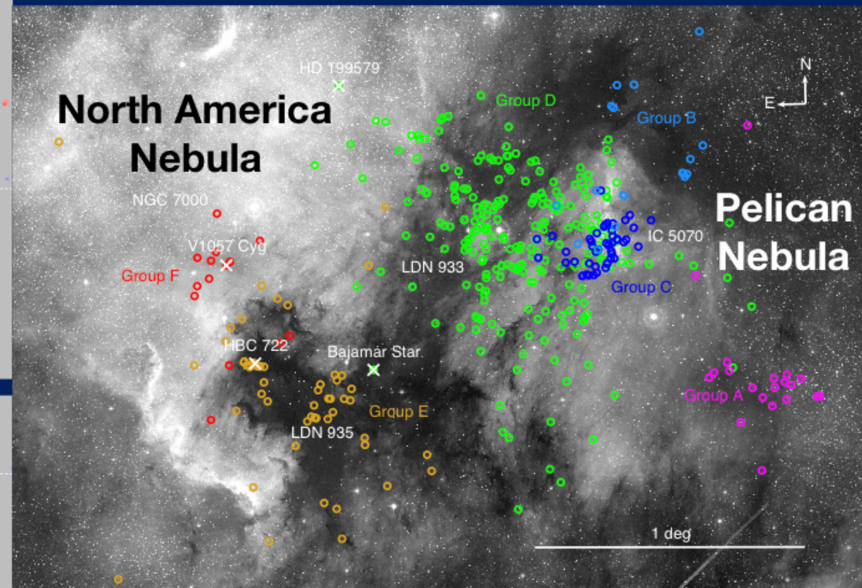
WHAT CAN WE MEASURE AND DERIVE?

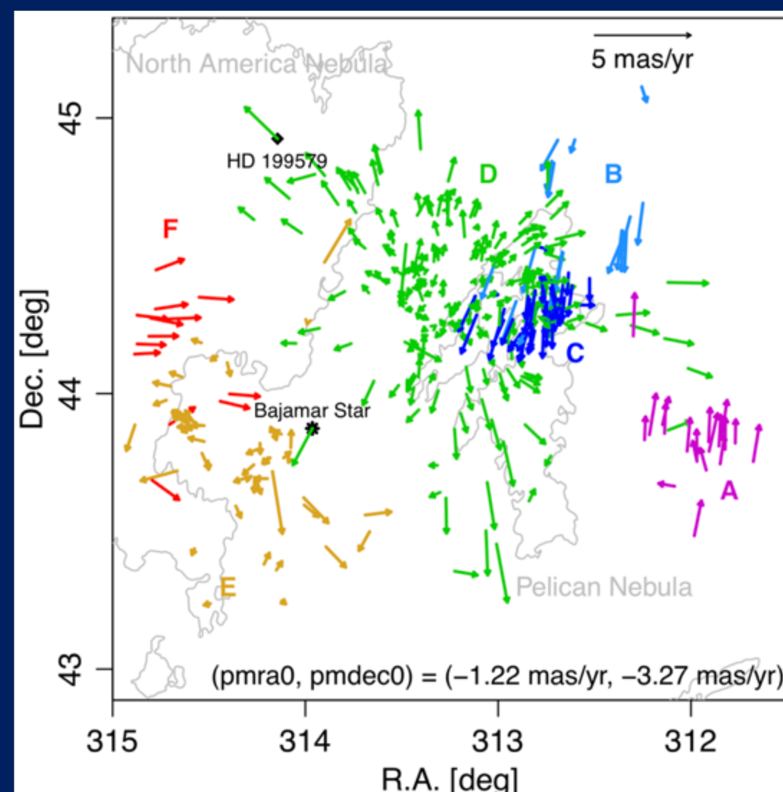
Parallax → distance (amazing!)

Positions and Proper Motions → clustering and 2D kinematics

CLUSTER KINEMATICS!







expansion time scales of 1.5-3 Myr

[Kuhn et al 2020]

WHAT CAN WE MEASURE AND DERIVE?

Parallax → distance (amazing!)

Positions and Proper Motions → clustering and 2D kinematics

Photometry → spectral energy distribution

excess relative to a(n extincted) stellar model → disk properties

variability → radiative and dynamical processes

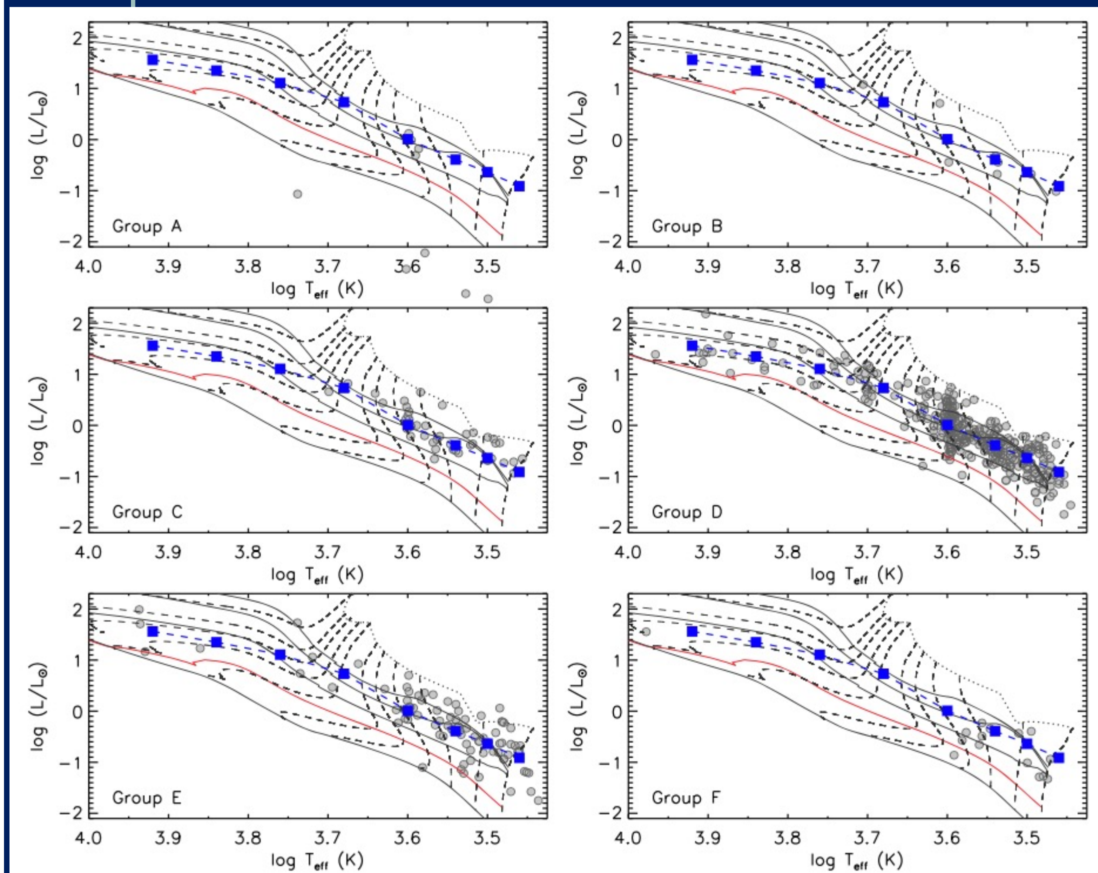
Spectroscopy → temperature and perhaps gravity

radial velocity (variability implies multiplicity)

rotational velocity

composition (if you work hard)

STELLAR AGES VIA HRD ARE COMPARABLE TO (SUB-)CLUSTER EXPANSION TIMES



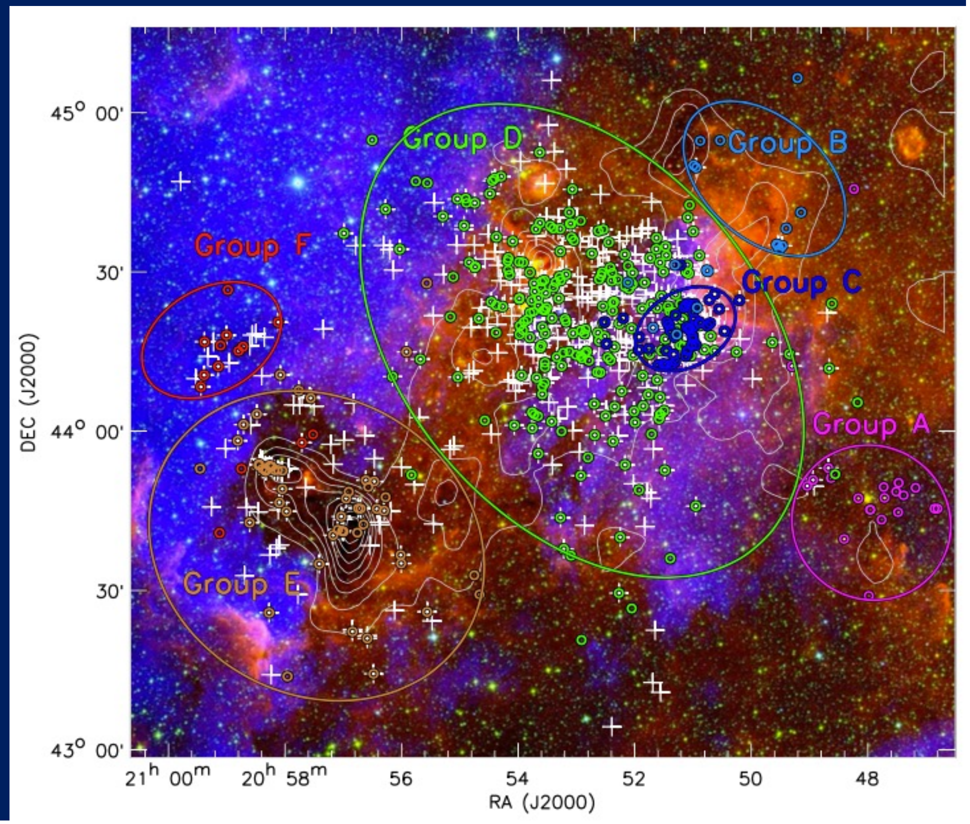
Median L(T) ➔ ~1 Myr age at low masses but higher masses "older".

Relative to median age:

- group F is <u>oldest</u>
- group D next oldest
- groups A and B sparse but ~median
- groups C and E <u>younger.</u>

Also Δ(log L)= 0.3-0.4 !!

Why **<u>still</u>** so large given rigorous membership vetting?

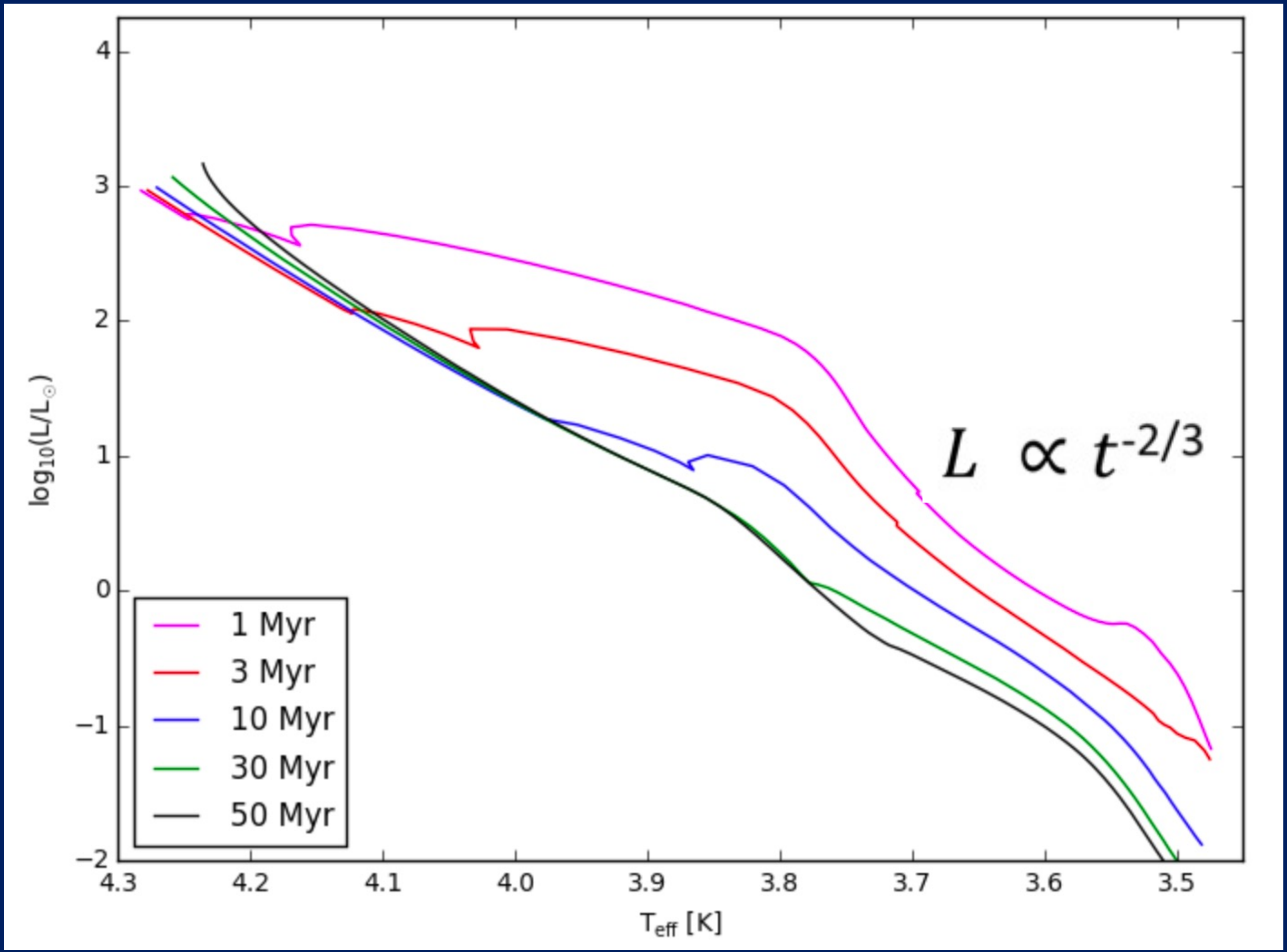


[Fang et al 2020]

STELLAR CONTRACTION THEORY - HRD

- interior physics
- atmosphere

- “birthline” effects



Despite improvements, pre-main sequence evolutionary tracks are not yet able to reproduce young cluster luminosity vs effective temperature sequences.

They remain our most useful tool however.

FLOWCHART FOR YOUNG STAR HRD

SED or (mags + colors)
Info on disk/accretion
Spectral type (or temperature)

Can influence colors/spectrum.
Also causes variability.

observational errors

$\log T_{eff}$

+

SpT → stellar temperature = f (spectral class, luminosity class)
Intrinsic colors = f (temperature, gravity)
Reddening law / Extinction = f (wavelength, grain properties)

from lookup tables

systematic differences among various calibration scales

A_V +

SED or (mag + BC)
Distance

$\log L/L_{sun}$

accumulated error in observations, variability, accretion effects, calibration systematics, and uncertain distance

$\log L/L_{sun}$ + log Teff

from above

R/R_{sun}

+

pre-main sequence evolutionary tracks and isochrones

from theory

Can be straight interpolation or bayesian probability distribution

M/M_{sun} and age/Myr

differences in track physics leads to systematic difference in mass/age results

YOUNGER STARS HAVE SOME COMPLICATIONS

Young stars are active, with blue-ing at short wavelengths.

- underlying spottedness
- superposed accretion effects.

Young stars have surrounding dust/gas, causing red excess at longer wavelengths.

Debate regarding wavelengths at which we can measure mostly the stellar photosphere (vs disk/accretion effects) and hence how to best determine

- extinction correction to account for reddening
- bolometric correction from measured flux to luminosity.

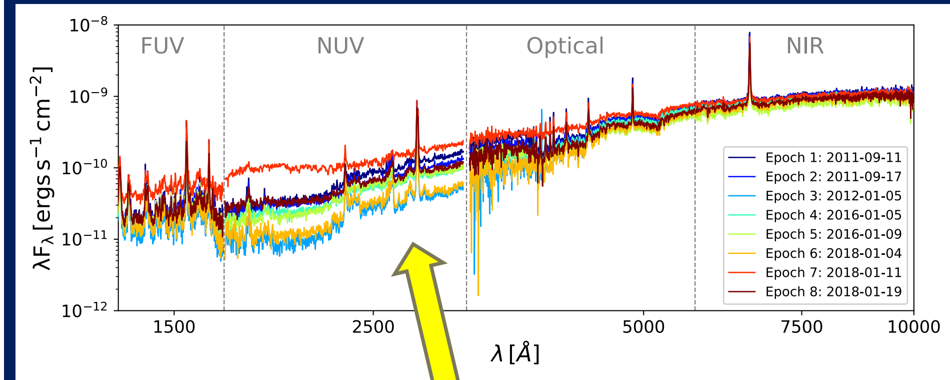
Complication of variability:

- use median magnitude?
- use bright state for dippers/faders?
- use faint state for bursters?

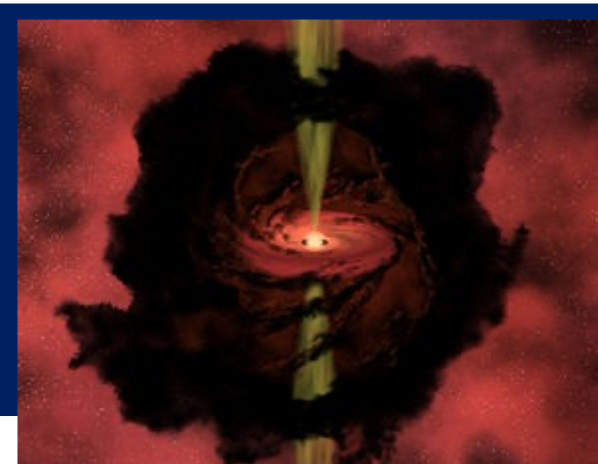
Median RMS values in the ONC:

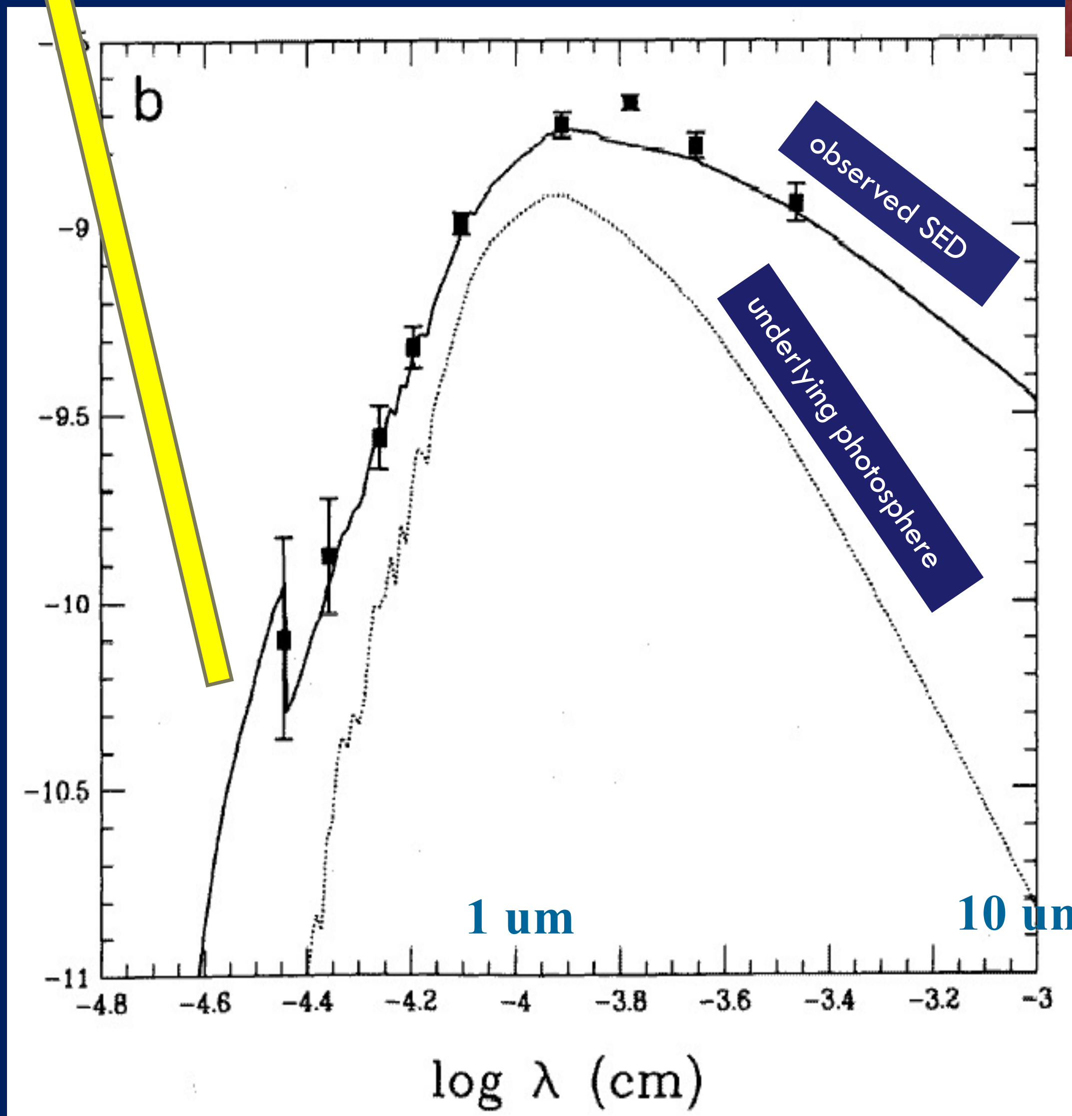
<0.19> mag at 0.8 um
<0.14> mag at 1.2, 1.6, 2.2 um
<0.07> mag at 3.6, 4.5 um

High variability tail extends to >2 mag!



[Robinson et al. 2019]





SPECTRAL TYPES PLUS VEILING

accretion causes "veiling" of spectral lines, filling them in

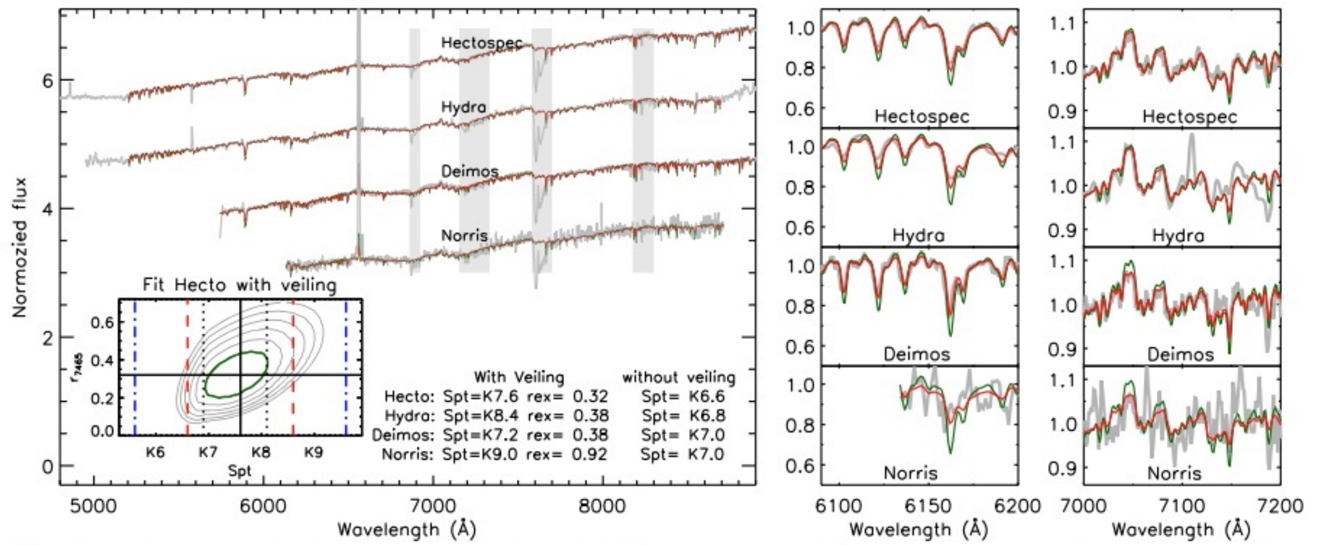


Figure 2. Illustration of our spectral template fitting method for Source ID 103, which was observed with all the four spectrographs used in this study. Left: best-fit X-shooter empirical spectral templates (red including veiling in the template model and green without veiling) overplotted on the observed spectra (gray). Vertically oriented gray bars indicate regions masked due to potential contamination from emission lines or telluric features. The inset contours show the distribution of the reduced χ^2 derived from fitting the Hectospec spectrum with X-shooter templates with different combinations of SpT and r_{7465}. The green contour is for the minimum reduced χ^2+0.05. The solid lines show the SpT$^{\text{best}}$ (vertical solid line) and r_{7465}^{best} (horizontal solid line) with the minimum reduced χ^2. The two vertical dotted lines show the spectral type range with χ_r^2 within $\chi_{r,\min}^2$+0.05. Vertical red dashed and blue dashed–dotted lines are used to qualify our spectral classification (see Section 5.1). Right: zoomed-in comparison of the target spectra and the best-fit template with (red) and without (green) veiling within 6090–6200 Å and 7000–7200 Å. The veiled model (red) is a better fit to the observed spectrum (gray).

no veiling to worry about

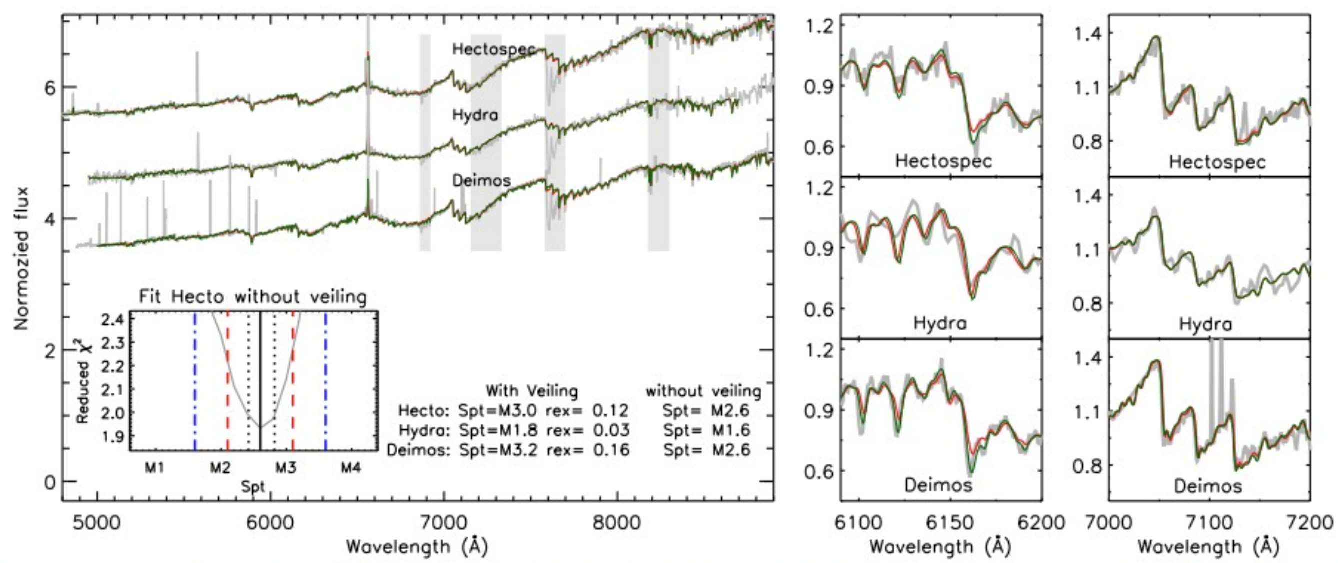


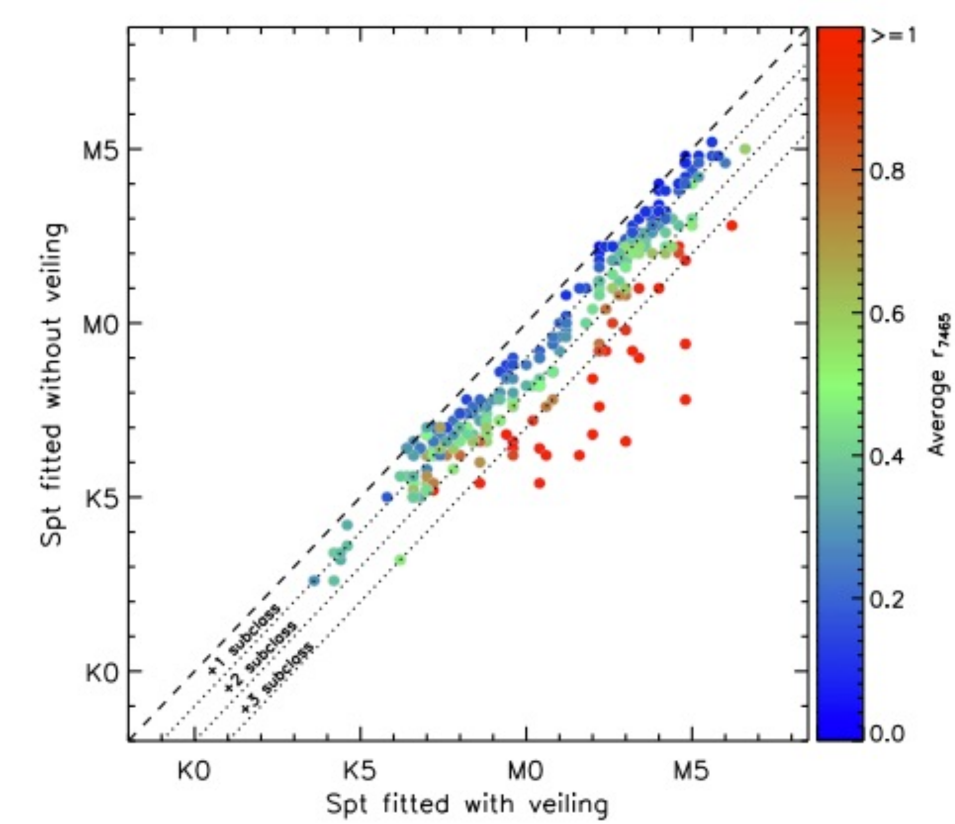
Figure 3. Same as Figure 2, but for Source ID 232. In this case the nonveiled model (green) is the preferred fit to the observed spectrum (gray). In the left panel, the inset shows the distribution of reduced χ^2 derived from fitting the Hectospec spectrum with X-shooter templates having different SpT. Vertical lines represent the same quantities as in Figure 2.

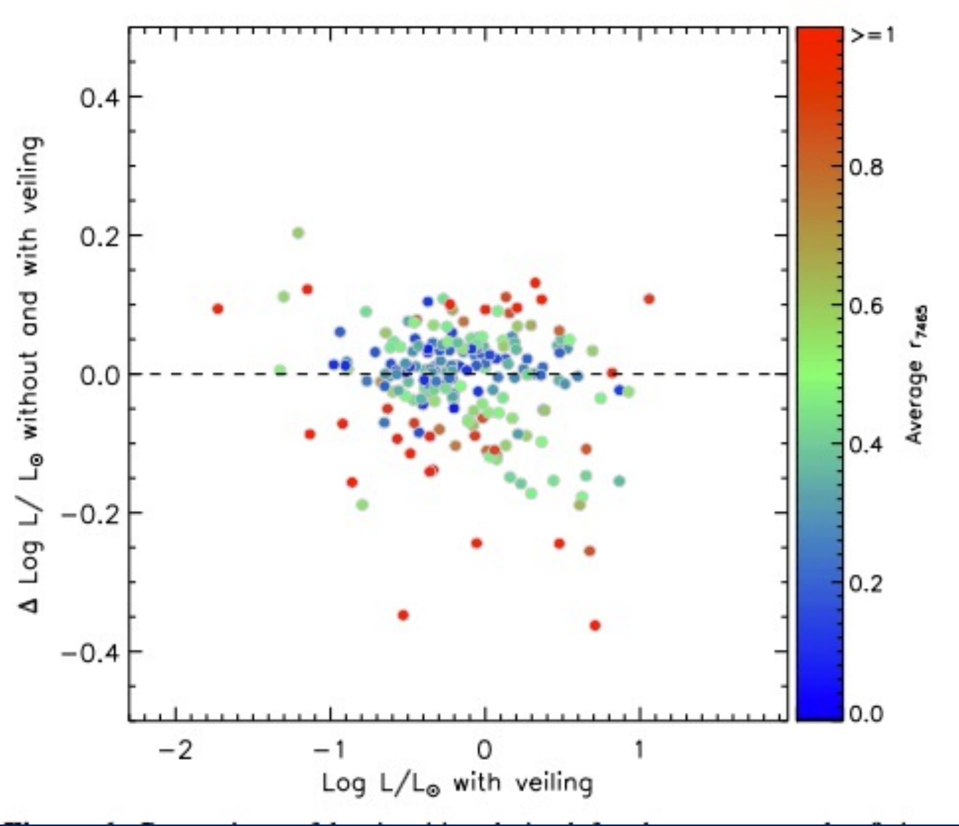
[Fang et al. 2020]

HOW ACCURATE ARE THE HR DIAGRAMS? (VEILING)

Accretion systematically affects spectral types, biasing them earlier, implying hotter temperatures.

Accretion causes scatter in luminosities with typical Δ(log L) < 0.15.

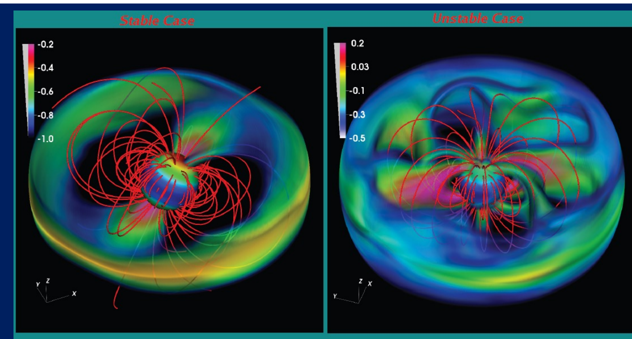


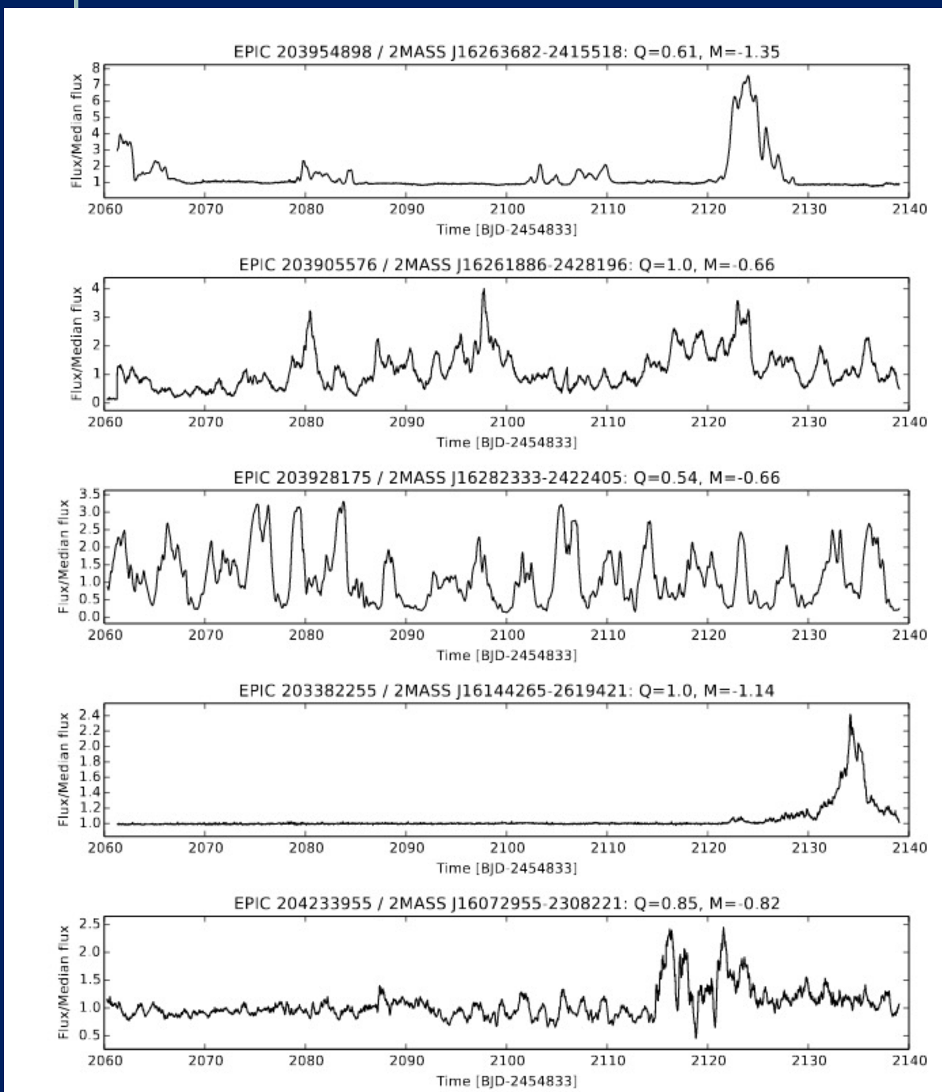


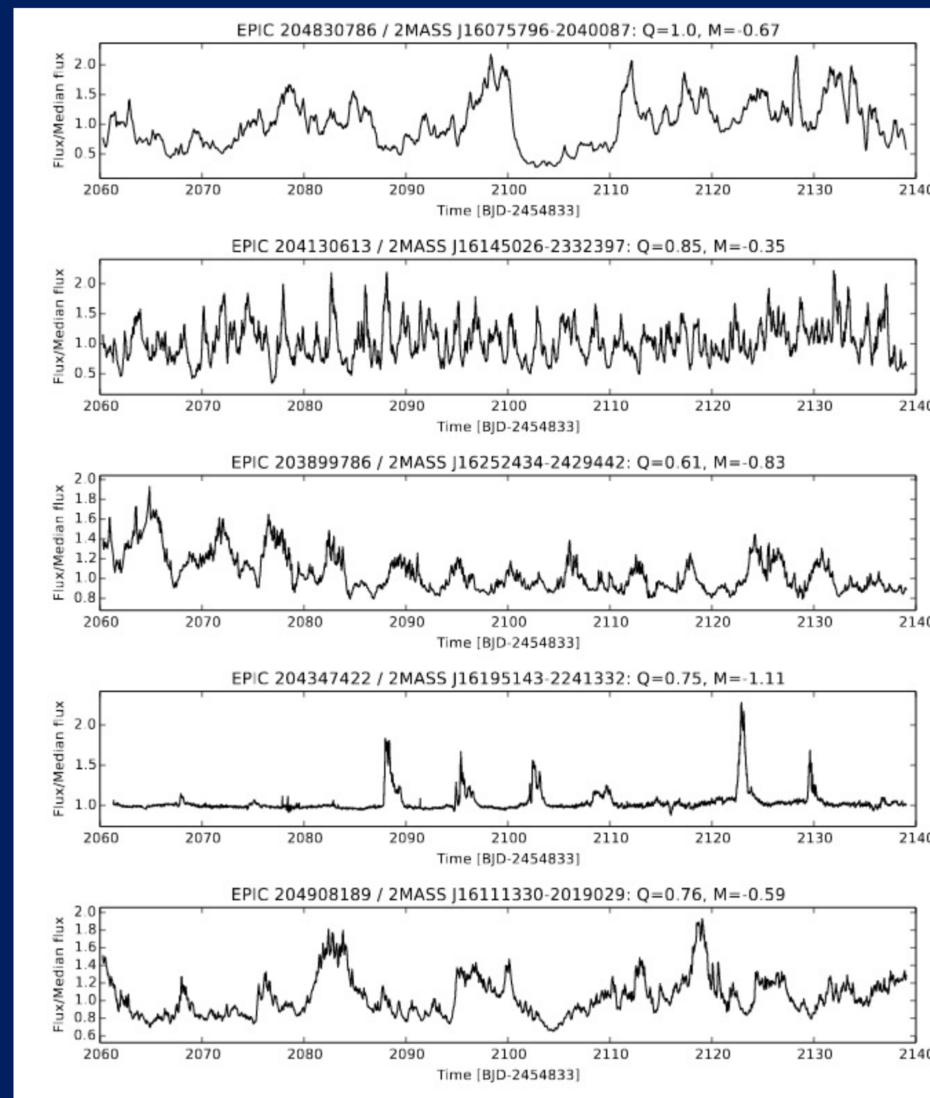
[Fang et al. 2020]

A CONTINUUM OF ACCRETION BURST BEHAVIOR

~15% of objects with disks are "bursty" with both aperiodic and quasi-periodic behavior.

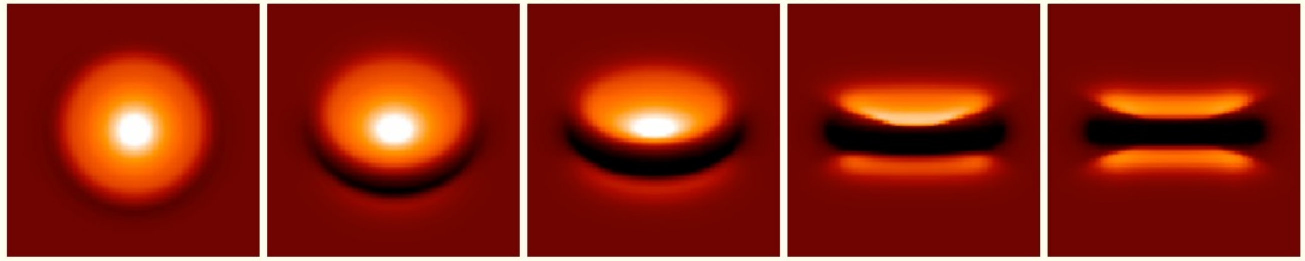




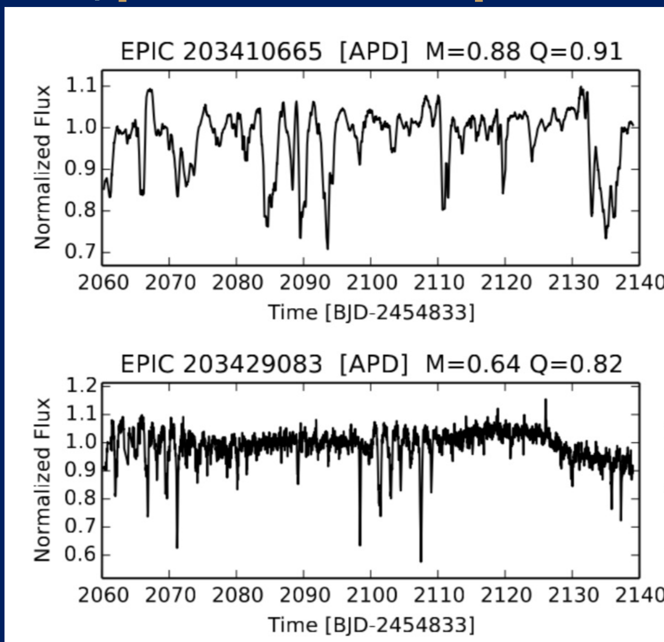


[Cody et al. 2017]

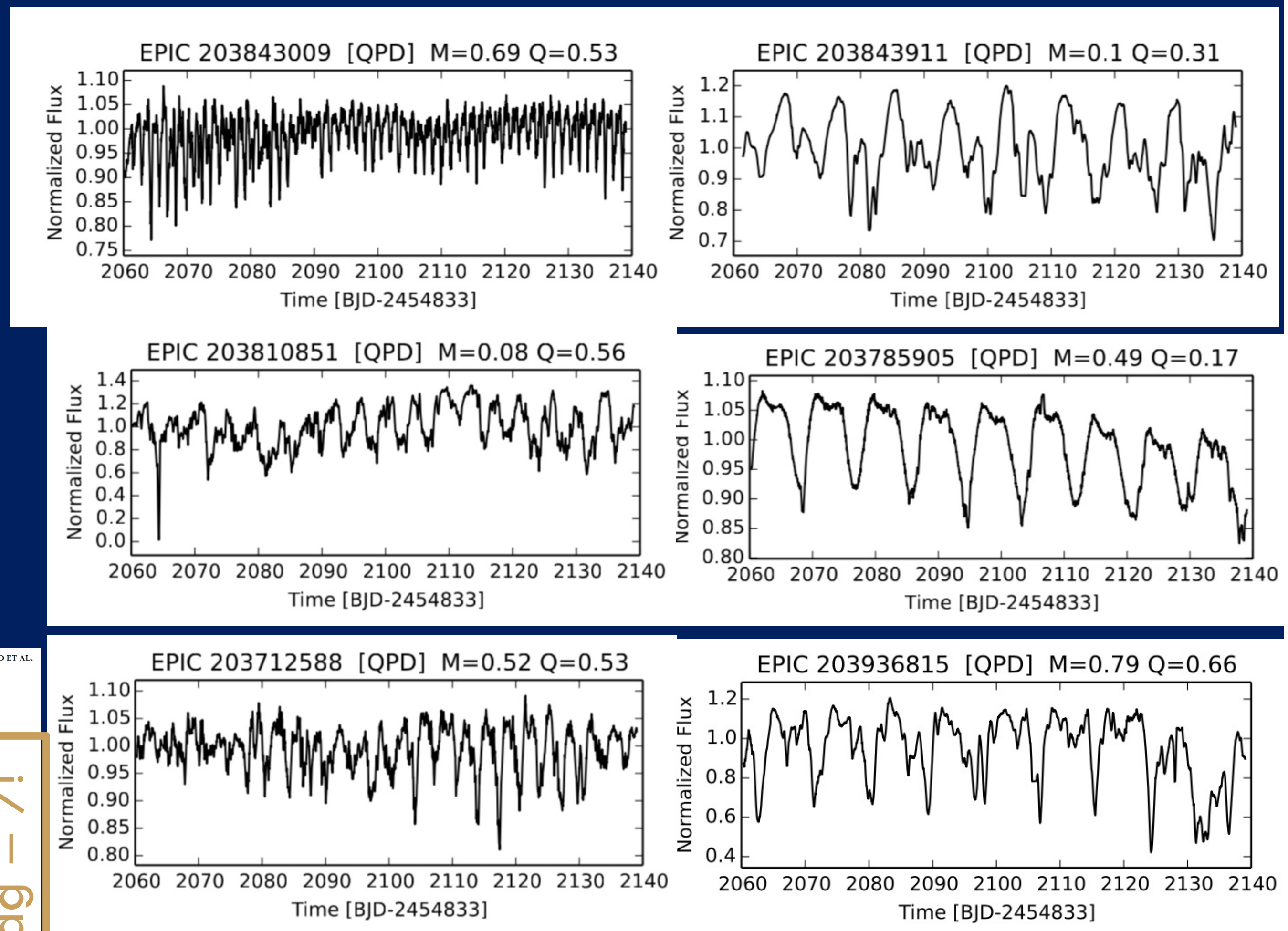
ALSO A CONTINUUM OF DIPPING/FADING BEHAVIOR



Aperiodic Examples



Quasi-periodic Examples



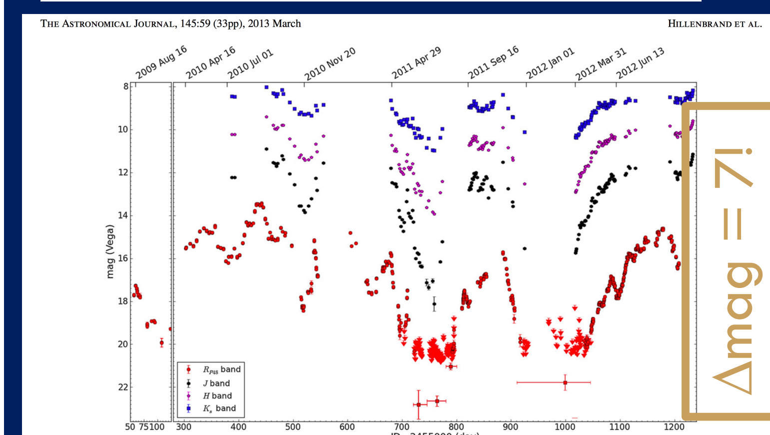


Figure 1. Multi-wavelength light curve of PTF 10nvg with UT dates indicated above the figure. From bottom to top the data streams represent variability in the R band (red; data from PTF) and in the J, H, and K bands (black, purple, and blue respectively; data from PAIRITEL). Error bars are shown, but the uncertainty in magnitude is typically smaller than the size of the symbols. During faint states when the source was not detected in individual frames, photometry was measured from sta[cked] PTF images (red squares, in the 21–23 mag range); horizontal error bars indicate the time range of measurements included in each stack.

[Cody and Hillenbrand 2018]

see also Ansdell 2016 and Hedges 2018

A FEW MAIN MESSAGES

HR diagrams remain a valuable tool for deriving R/Rsun, M/Msun, and AGE.

- care needed when placing young stars

Origin of luminosity spreads still not entirely clear.

- not readily explained by observational errors or photometric variability or distance spreads

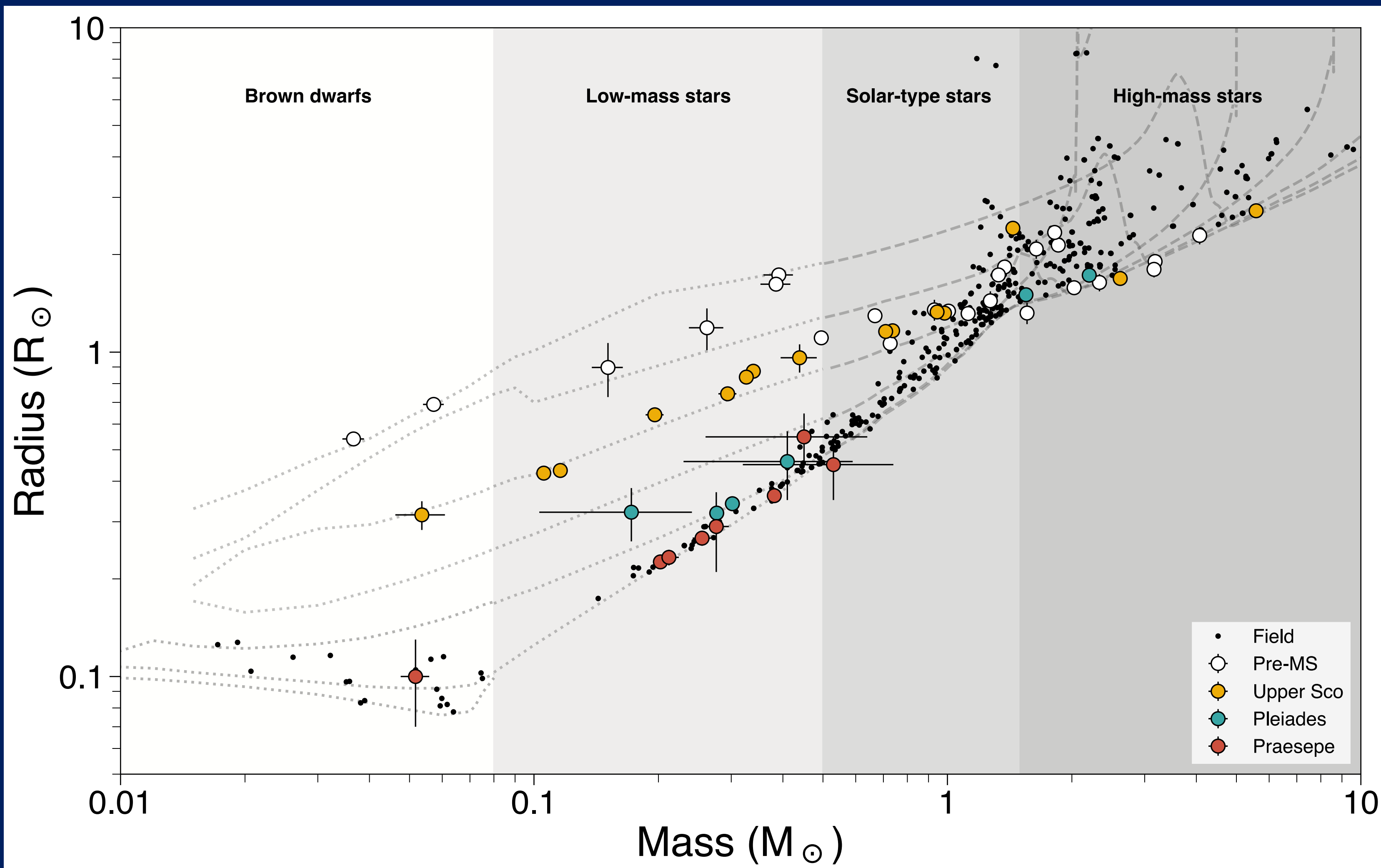
Empirical isochrones, from run of median L(T) with T, cross theoretical isochrones.

- still missing ingredients in evolutionary theory – currently thought to be accretion history

There is an important check on the models, which is to measure M,R directly.

FUNDAMENTALLY DERIVED MASS AND RADIUS

- Cluster member DLEBs (double-line eclipsing binaries) are extremely valuable as tests of theory.
- Match to isochrones in R vs M is *pretty good*
- However, discrepancies in L vs T, which are radiative properties rather than fundamental.
- Typically need to shift model temperatures cooler by ~150-200 K to match data.
    - spots / magnetism?



[David et al 2019]

OTHER OBSERVED PROPERTIES OF YOUNG STARS

Rotation

Activity

Magnetic field

Lithium

Can be used as age proxies, with caution.

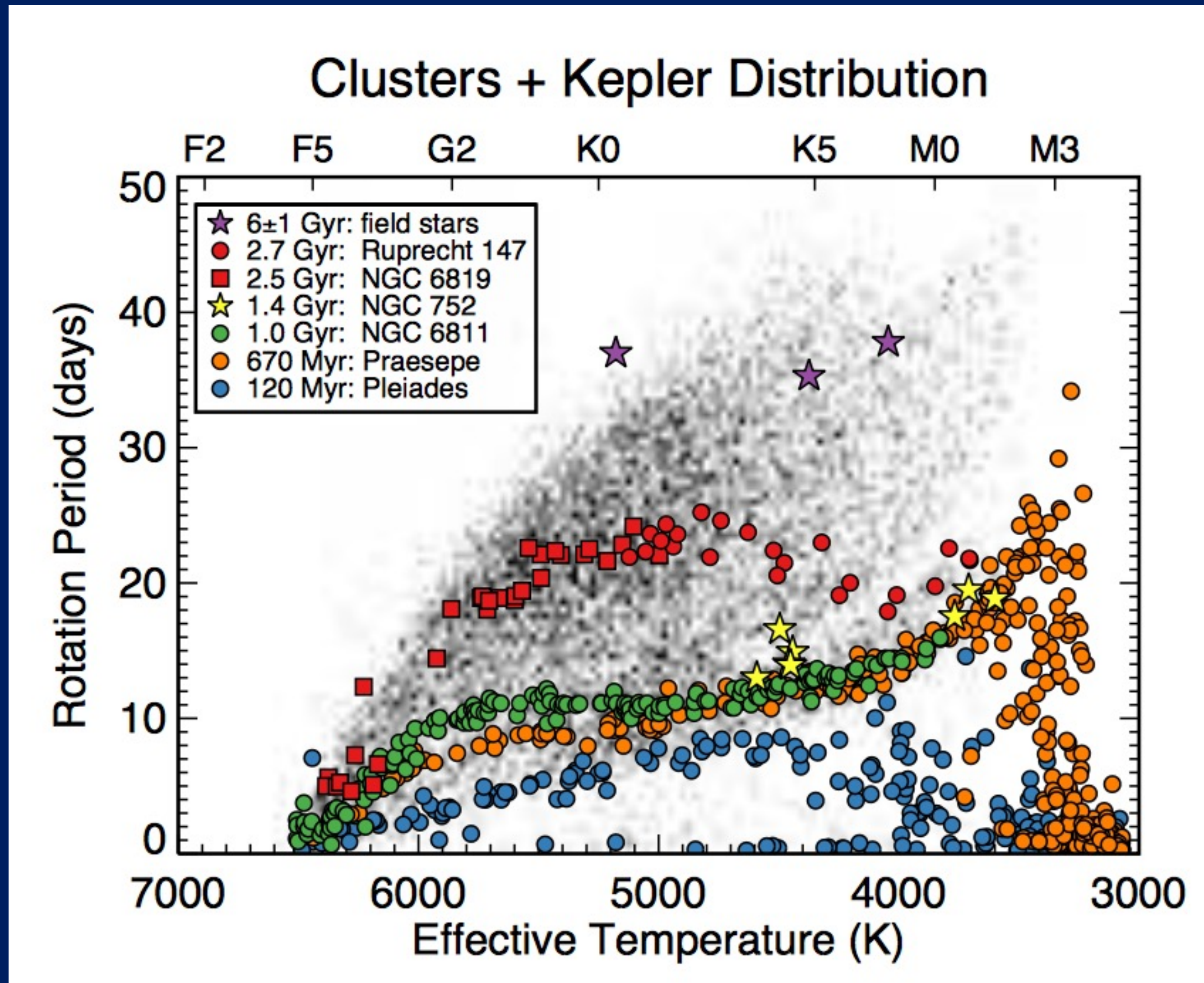
Main advantage is diagnostic power where HR diagram is powerless (on MS).

AGES FROM PROBES OF ANGULAR MOMENTUM

measurements:

- time series photometry
  ➔ period

- high dispersion spectrum
  ➔ rotational velocity



[Curtis et al 2020]

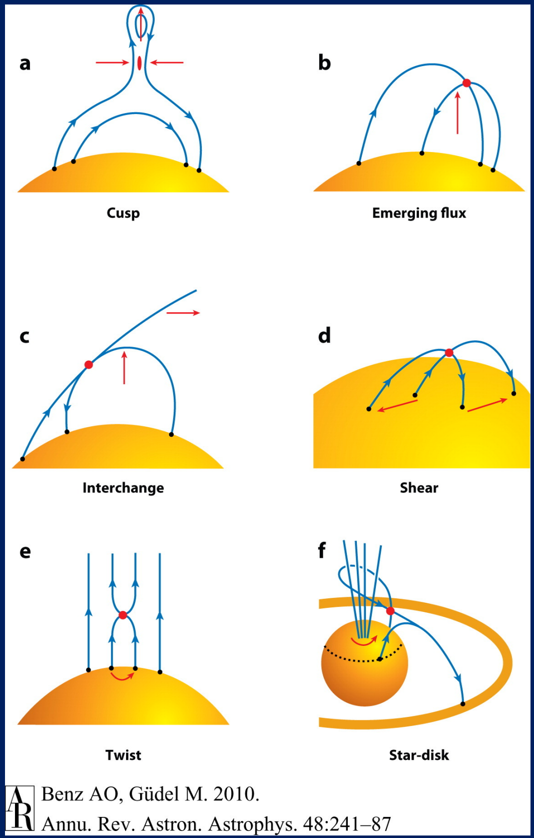
AGES FROM PROBES OF "ACTIVITY"

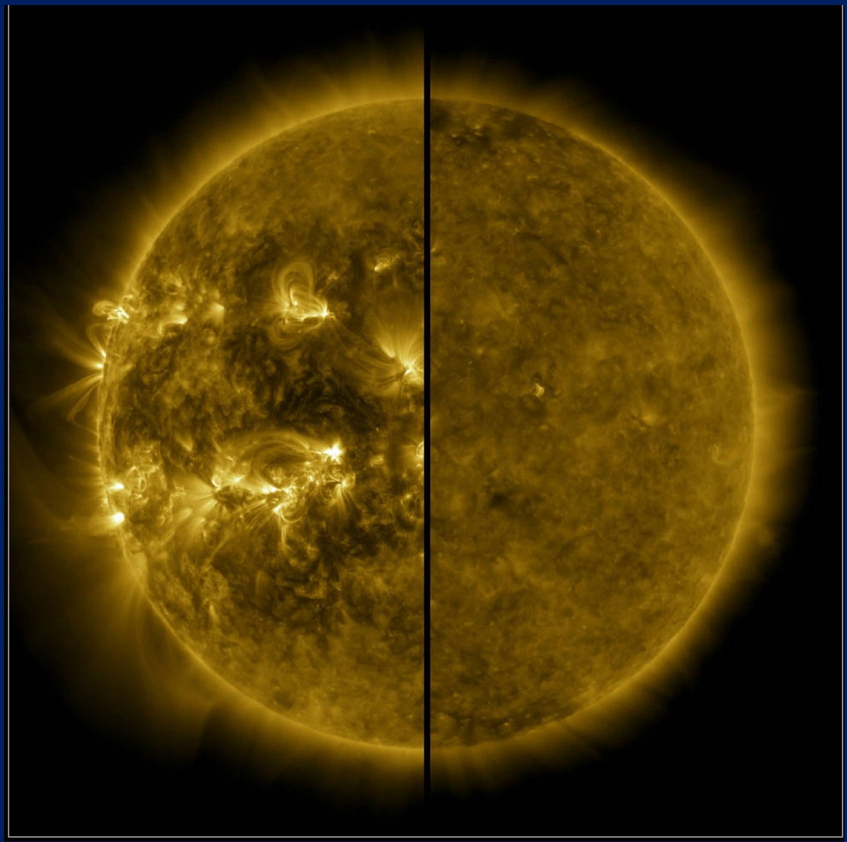
Xray luminosity

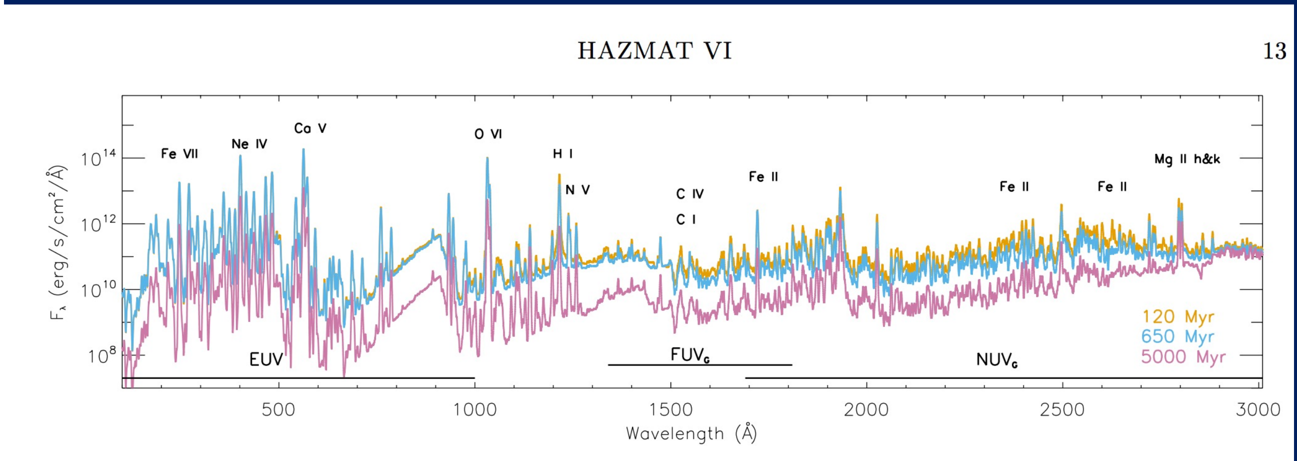
UV continuum excess

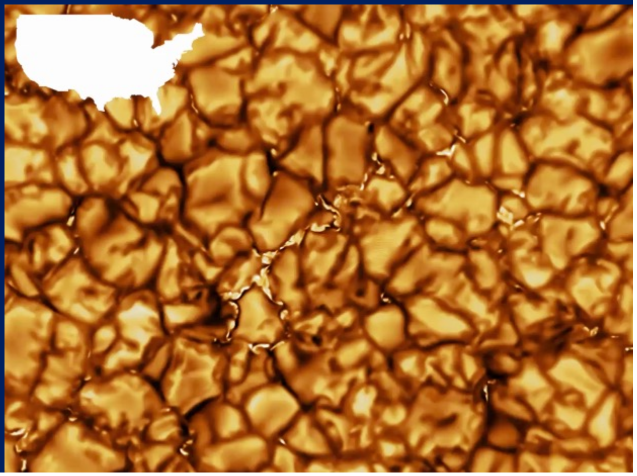
Chromospheric lines

Flaring









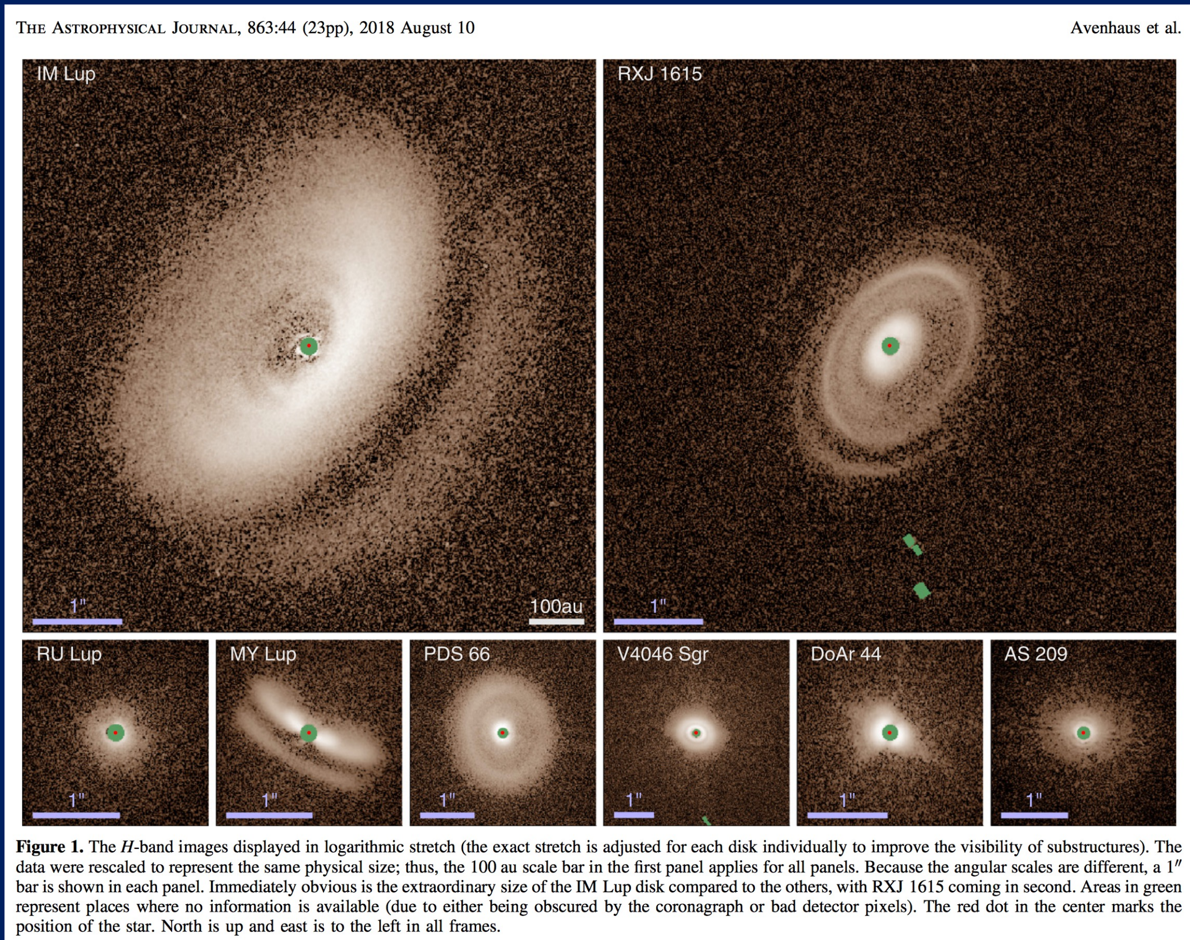
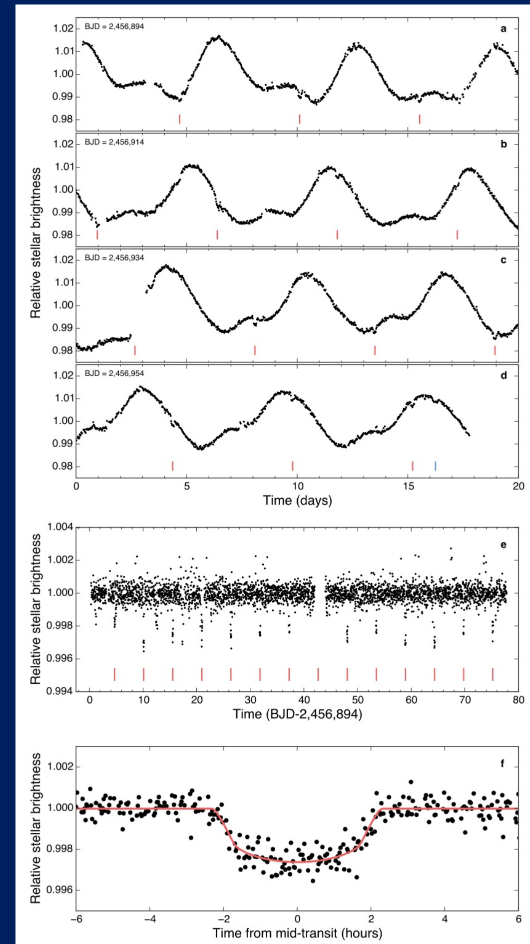

THE ASTROPHYSICAL JOURNAL, 863:44 (23pp), 2018 August 10 Avenhaus et al.

Figure 1. The *H*-band images displayed in logarithmic stretch (the exact stretch is adjusted for each disk individually to improve the visibility of substructures). The data were rescaled to represent the same physical size; thus, the 100 au scale bar in the first panel applies for all panels. Because the angular scales are different, a 1″ bar is shown in each panel. Immediately obvious is the extraordinary size of the IM Lup disk compared to the others, with RXJ 1615 coming in second. Areas in green represent places where no information is available (due to either being obscured by the coronagraph or bad detector pixels). The red dot in the center marks the position of the star. North is up and east is to the left in all frames.

K2-33; David et al (2016)



CLOSING REMARKS