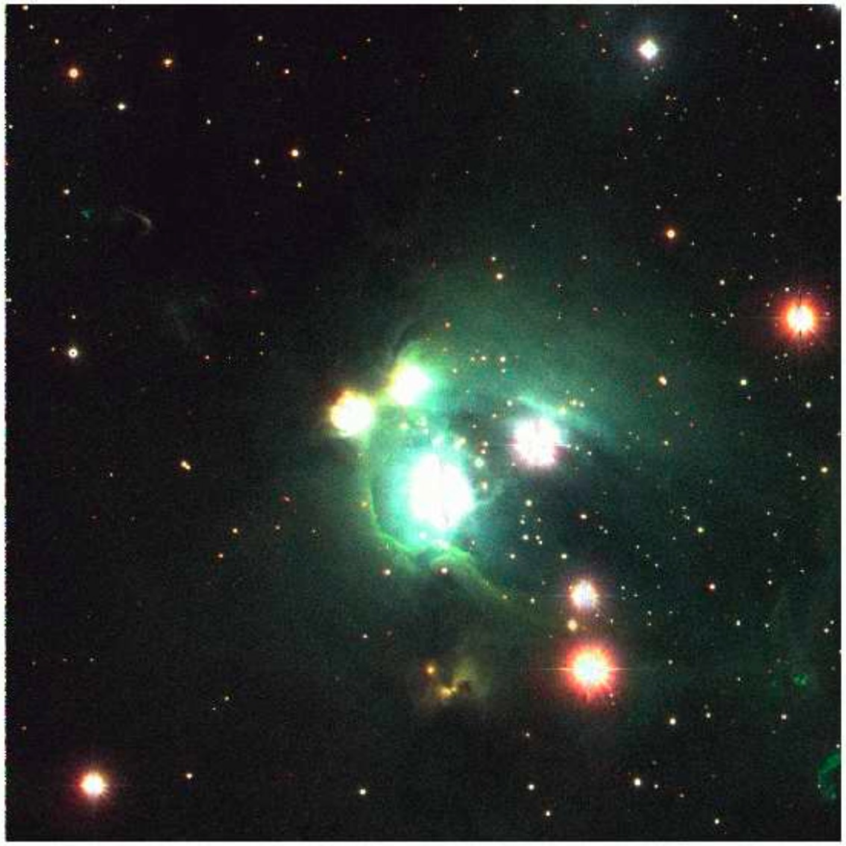


NOTE:

This talk complements videos presented by

- baraffe (stellar formation/evolution theory),
- megeath (protostars and star forming regions),
- gagne (young moving groups and field stars).

Live session panel w/baraffe, feiden, johns-krull

DETERMINATION OF STELLAR PROPERTIES OF YOUNG STARS (OBSERVATIONS)

lynne a. hillenbrand | (caltech)

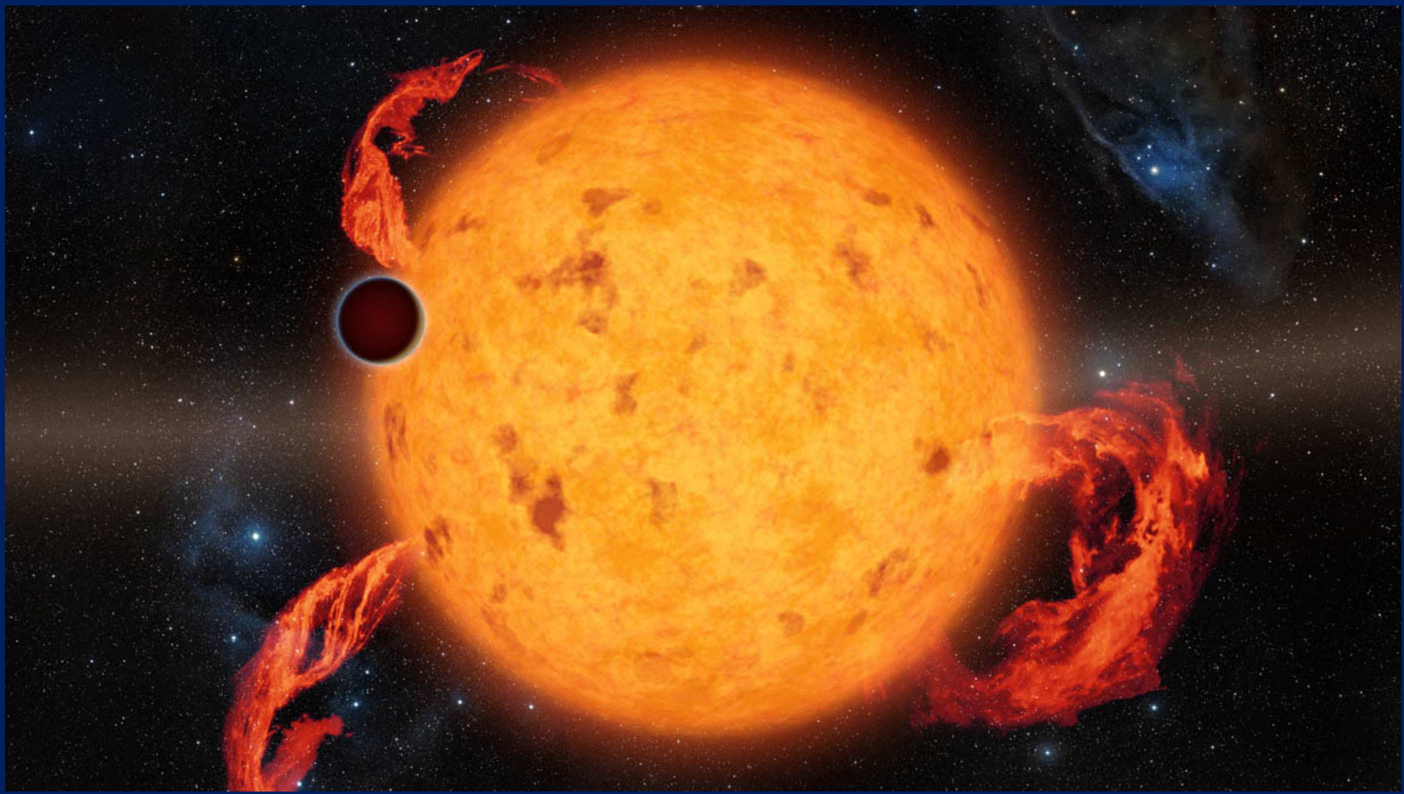
TOPICS TO BE COVERED

What we want to know about young stars (in the context of disks/planets).

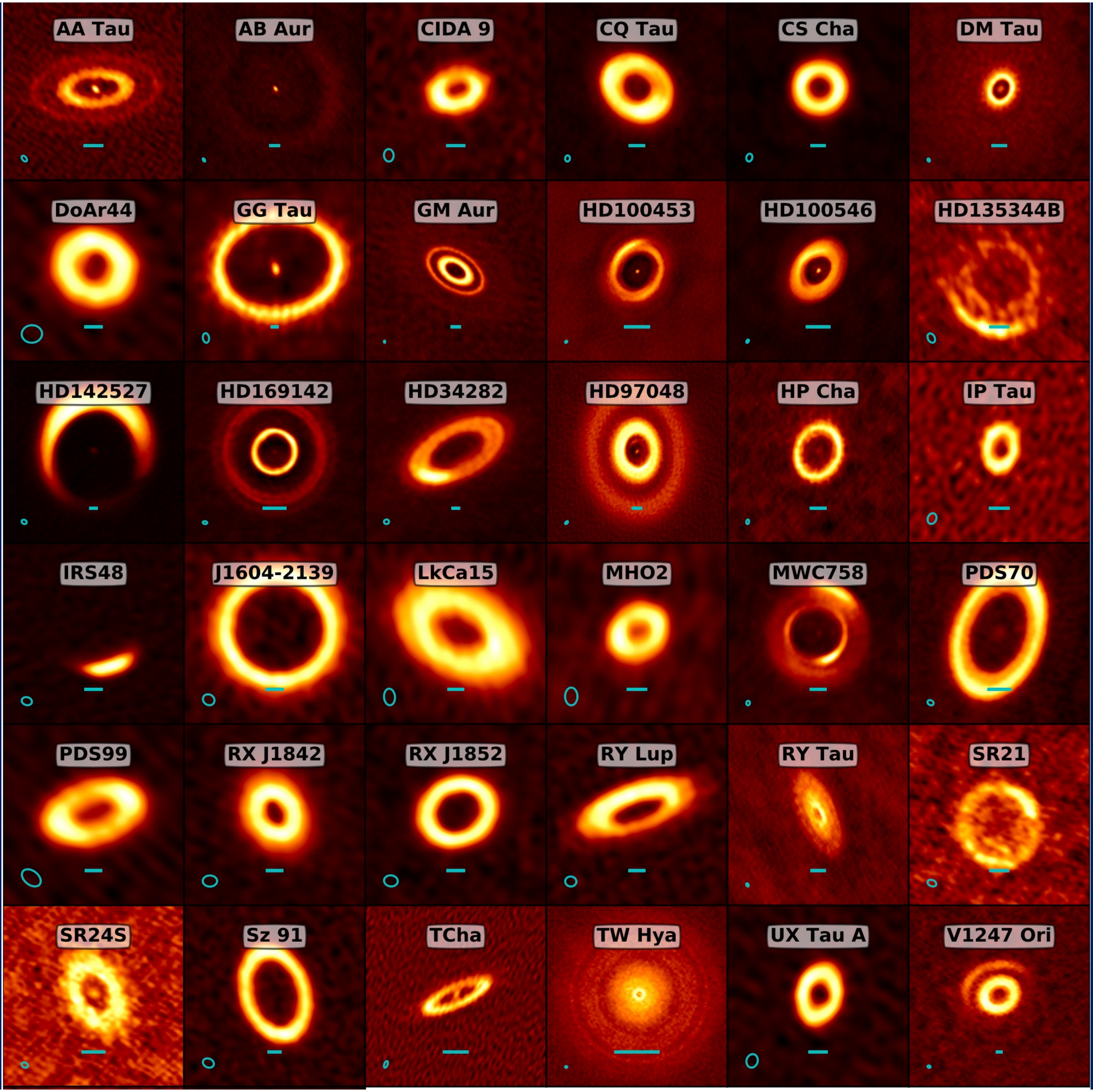
What we can observe.

What we can infer from the observed quantities.

Reliability of those inferences.



graphic by R. Hurt

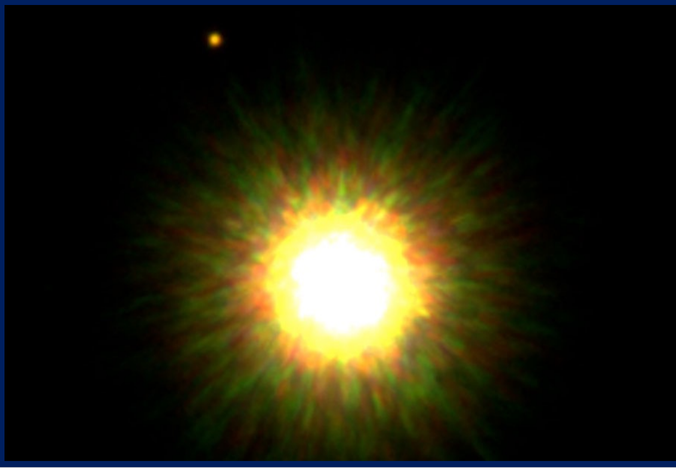


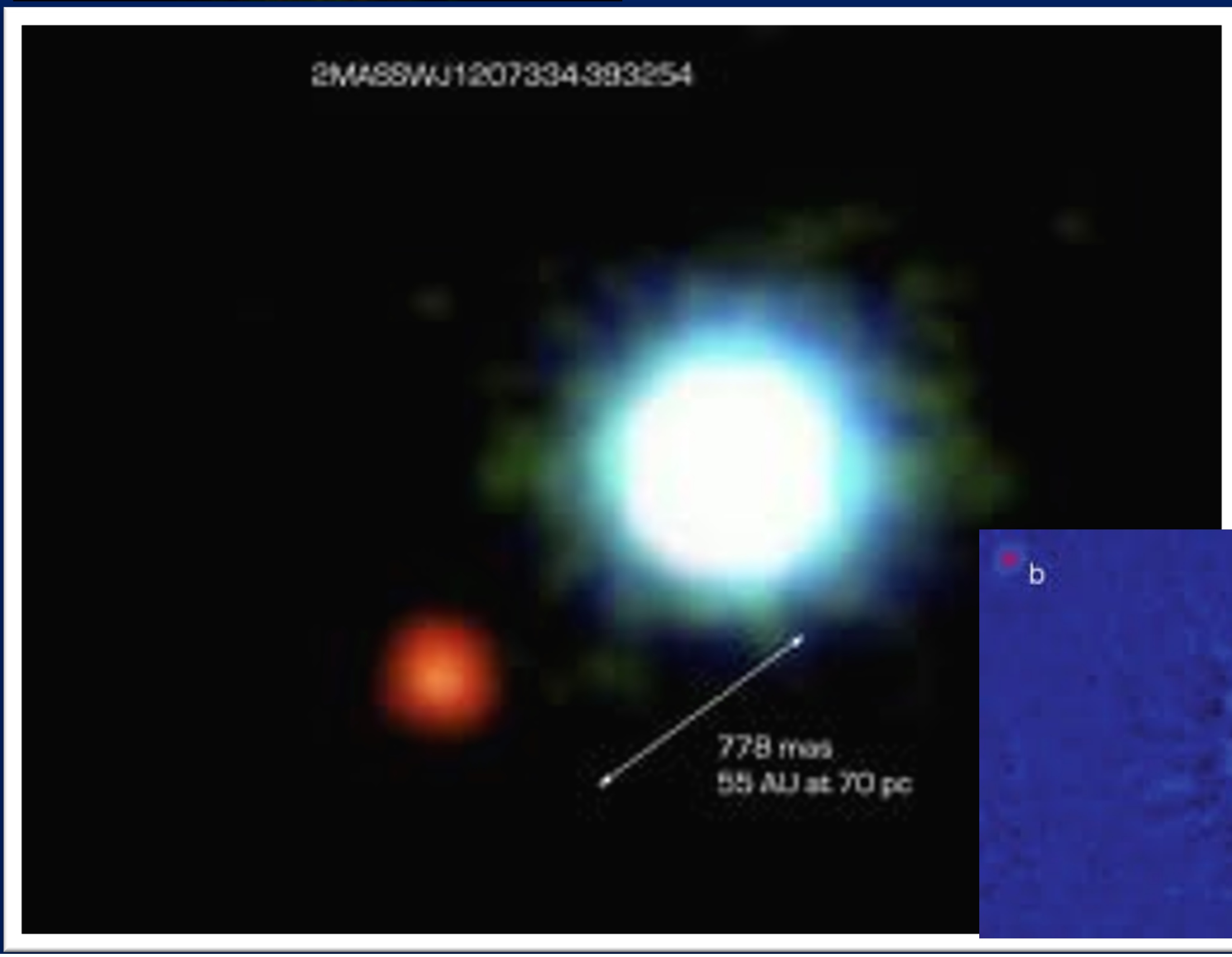
HOW DO DISK PROPERTIES DEPEND ON STELLAR MASS?

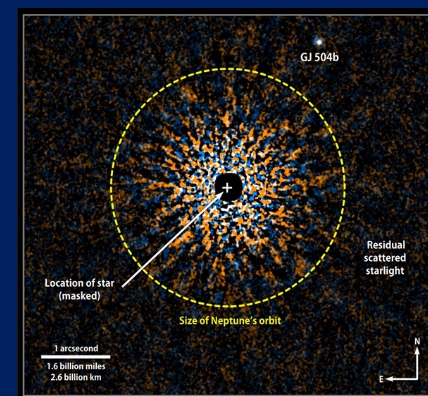
[Francis et al. 2020]

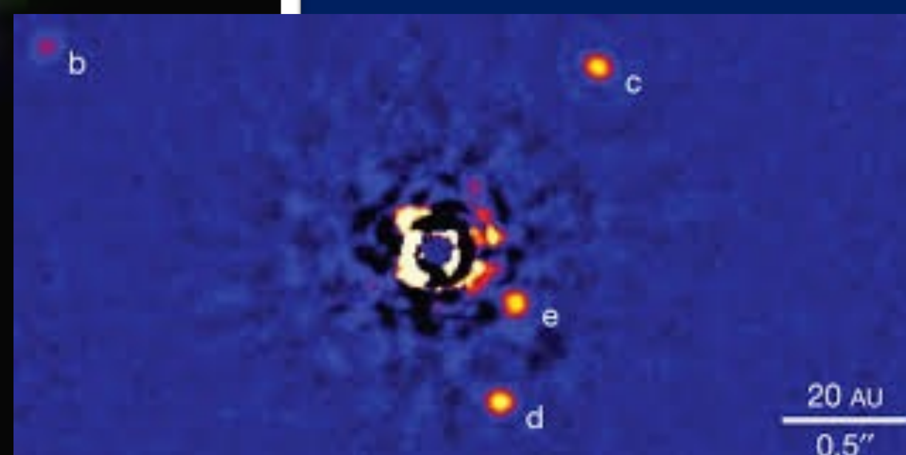
(slide from my 2014 sagan talk)

ARE THOSE FAINT OBJECTS PLANETS OR BROWN DWARFS?

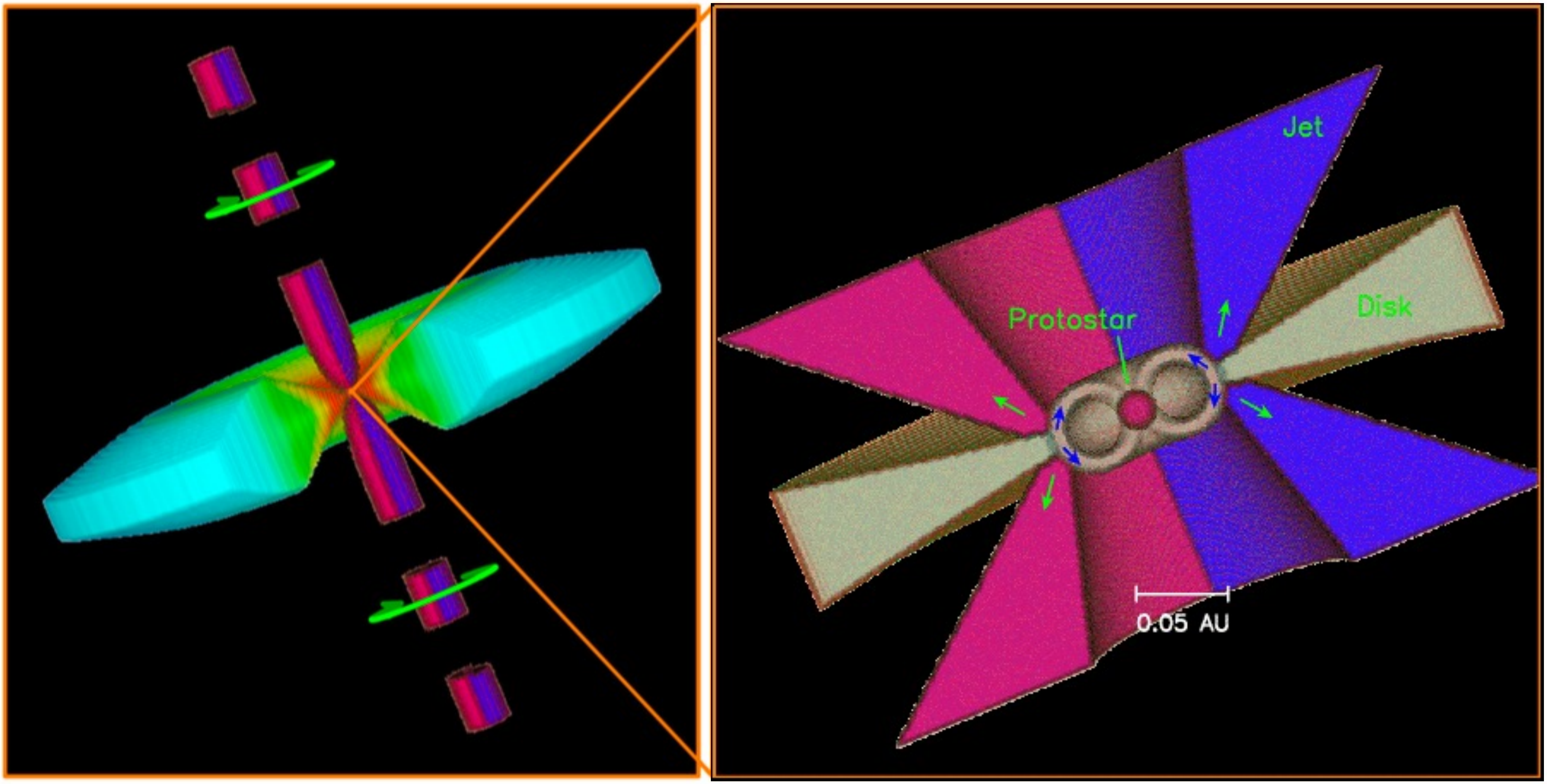








CARTOON OF AN INDIVIDUAL YOUNG STAR ACCRETION/OUTFLOW SYSTEM



[ALMA press release team]

YSO SEDS CONSIST OF UNDERLYING STELLAR PHOTOSPHERE + CIRCUMSTELLAR DUST/GAS

for a given geometry, there are many different possible SEDs.

[Robitaille 2017]

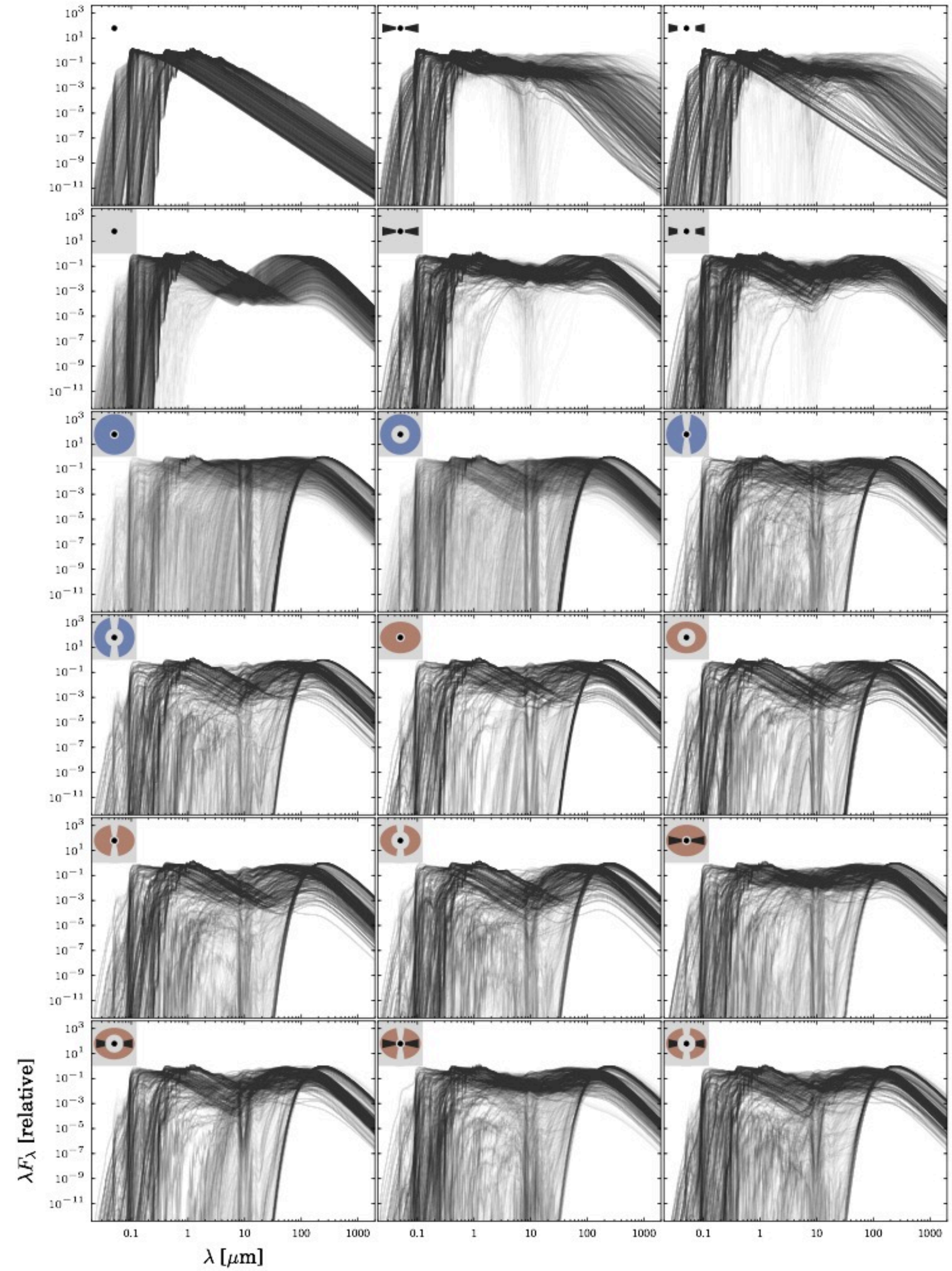


Fig. 2. A subset of 2000 SEDs for each model set, normalized to the total luminosity of each SED.

YSO SEDs consist of underlying stellar photosphere + circumstellar dust/gas

for a given SED, there are many different possible geometries.

[Robitaille 2017]

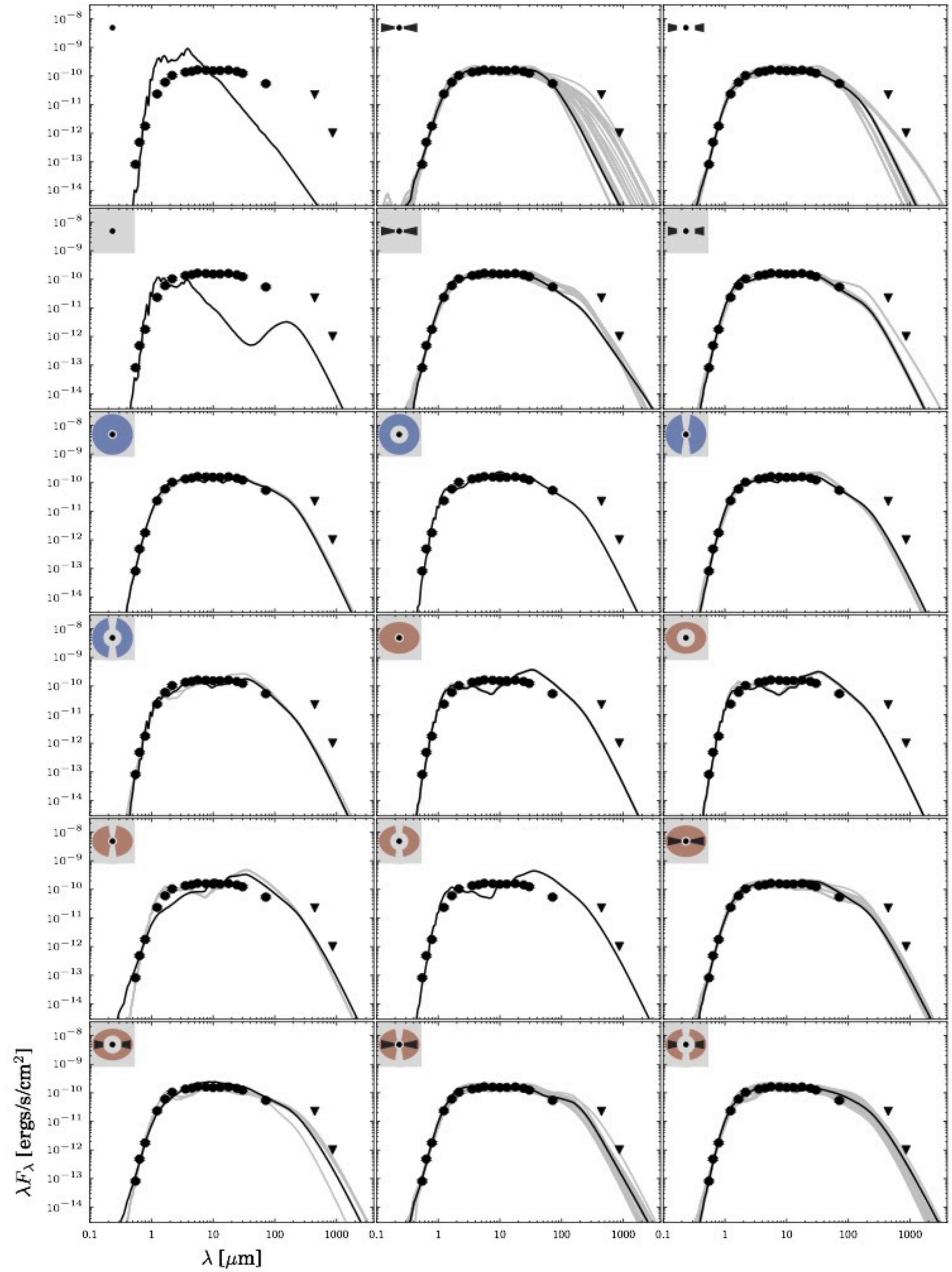
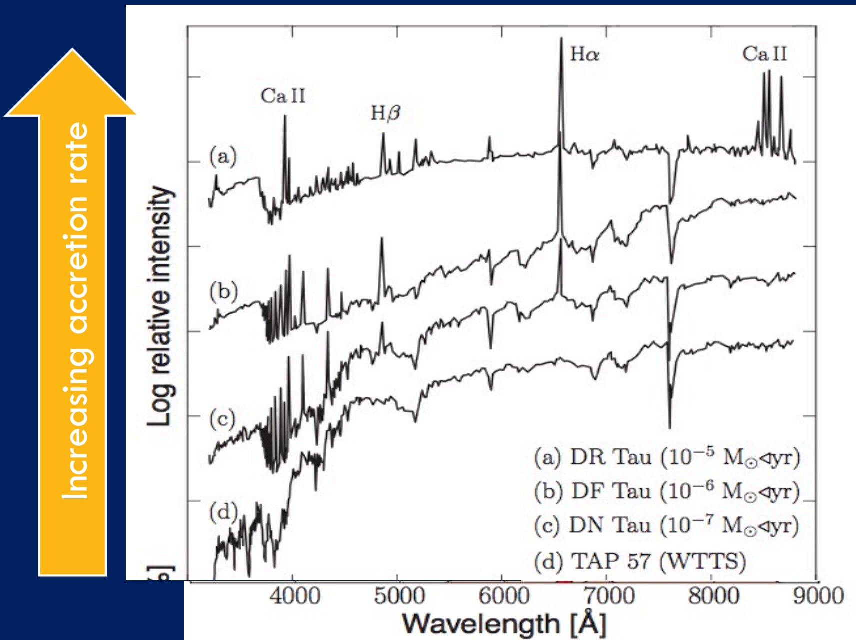
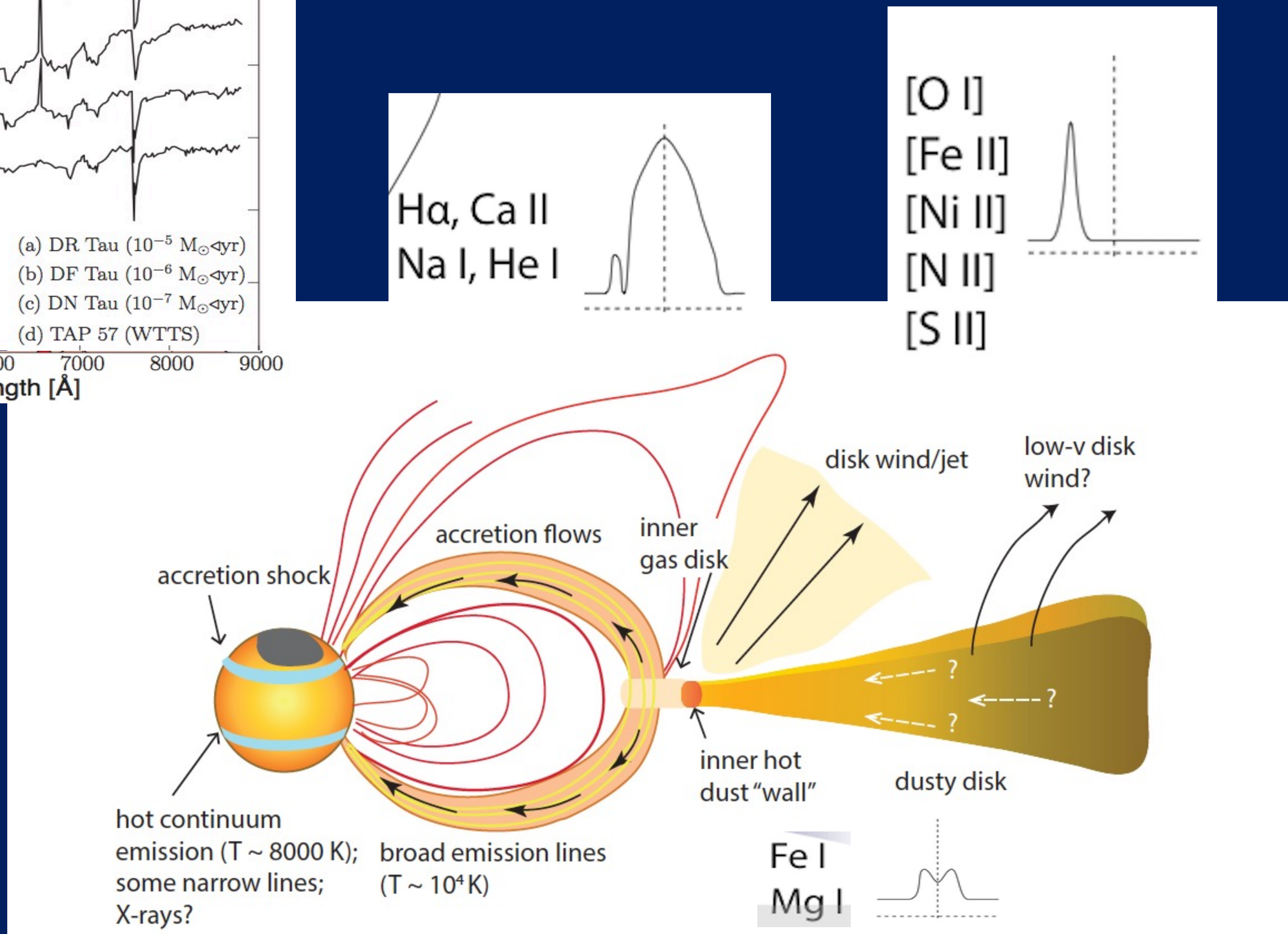


Fig. 3. Model fits to observations of source 20 in NGC2264 (using the source nomenclature from Forbrich et al. 2010), where each panel shows all the fits for $\chi^2 - \chi^2_{\rm best} < 3\,n_{\rm data}$ for a specific model set (and where $\chi^2_{\rm best}$ is determined for each model set individually).

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



[Barensten et al. 2013]



[Hartmann, Herczeg, Calvet 2016]

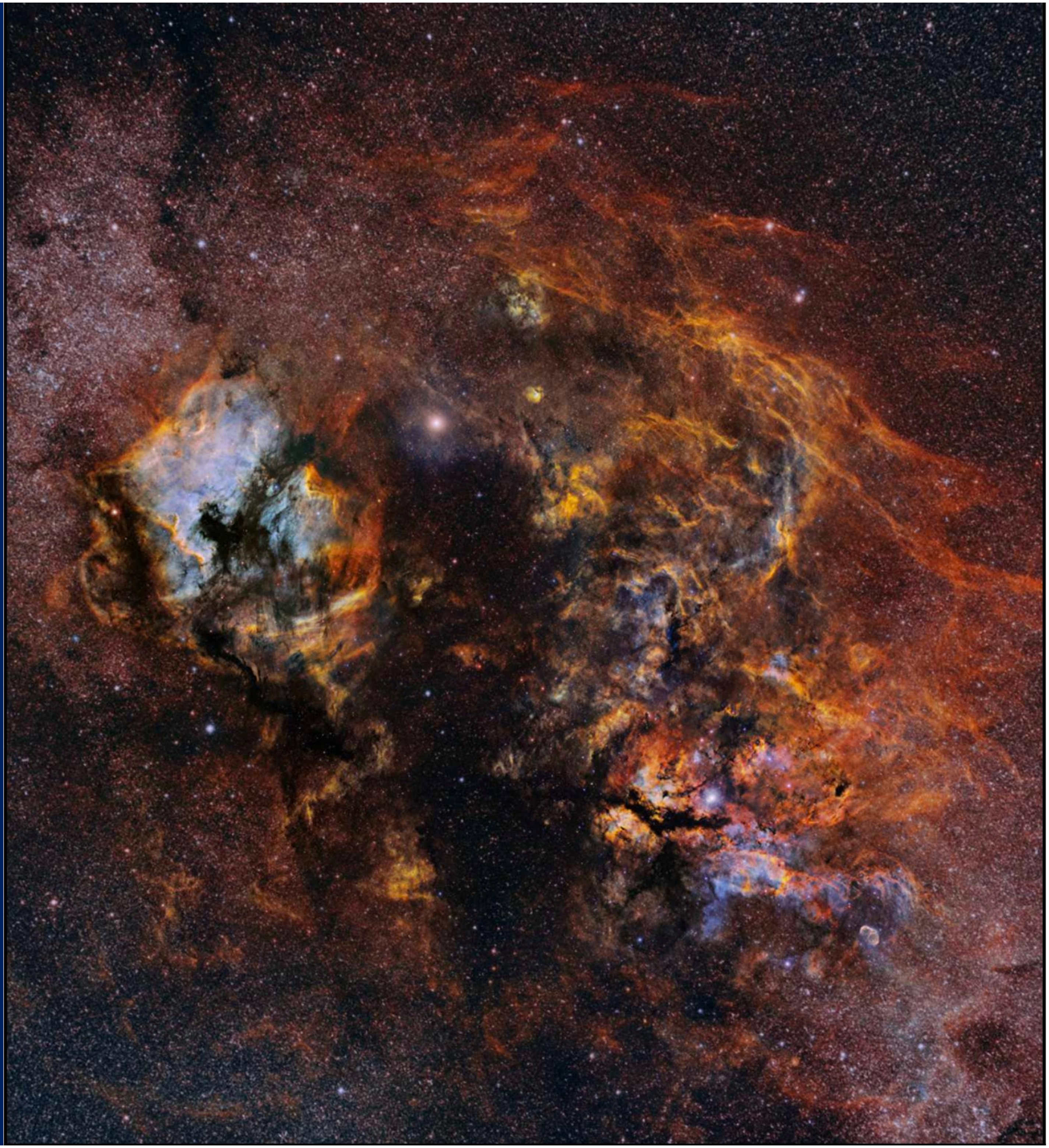
- line emission and continuum "veiling" complicates spectral typing.
- continuum excess also distorts broadband colors.


THE INFRARED MILKY WAY: GLIMPSE/MIPSGAL (3.6–24 microns)
SPITZER SPACE TELESCOPE
Galactic Latitude (degrees)
Galactic Latitude (degrees)
GLIMPSE team: Ed Churchwell (PI), Marilyn Meade, Brian Babler, Remy Indebetouw, Barbara Whitney, Christer Watson, Bob Benjamin, Steve Bracker, Thomas Robitaille, Stephan Jansen, Doug Watson, Mark Wolfire, Mike Wolff, Matt Povich, Tom Bania, Dan Clemens, Martin Cohen, Claudia Cyganowski, Kate Devine, Fabian Heitsch, Jim Jackson, Katharine Johnston, Chip Kobulnicky, John Mathis, Emily Mercer, Jeonghee Rho, Marta Sewilo, Susan Stolovy, Brian Uzpen
MIPSGAL team: Sean Carey (PI), Alberto Noriega-Crespo, Don Mizuno, Sachin Shenoy, Roberta Paladini, Kathleen Kraemer, Stephan D. Price, Nicolas Flagey, Erin Ryan, Daniela Goncalves, Remy Indebetouw, Thomas Kuchar, Eli Bressert, Francine Marleau, Jim Ingalls, Deborah Padgett, Luisa Rebull, Bruce Berriman, Babar Ali, Francois Boulanger, Roc Cutri, Bill Latter, Peter Martin, Marc-Antoine Miville-Deschenes, Sergio Molinari, Russell Shipman, Leonardo Testi
Poster designed by Thomas Robitaille and Robert Hurt

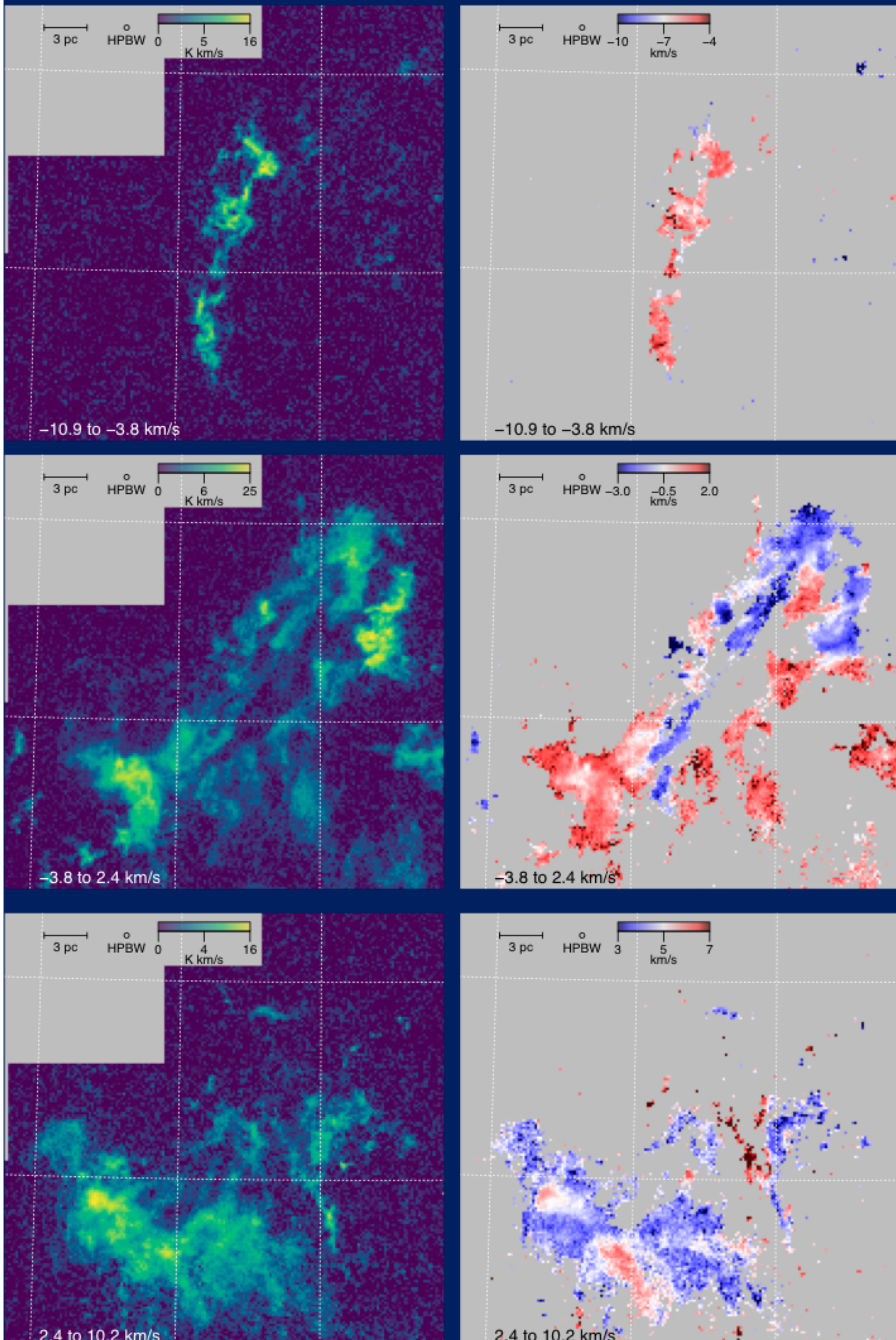
JUST ONE EXAMPLE AMONG THOUSANDS OF STAR FORMING COMPLEXES IN THE GALAXY

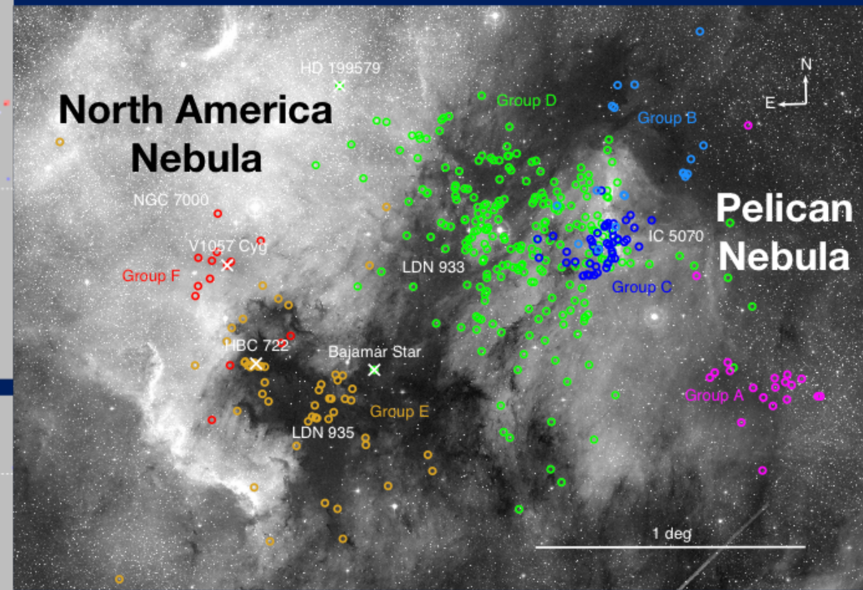
(cygnus region)

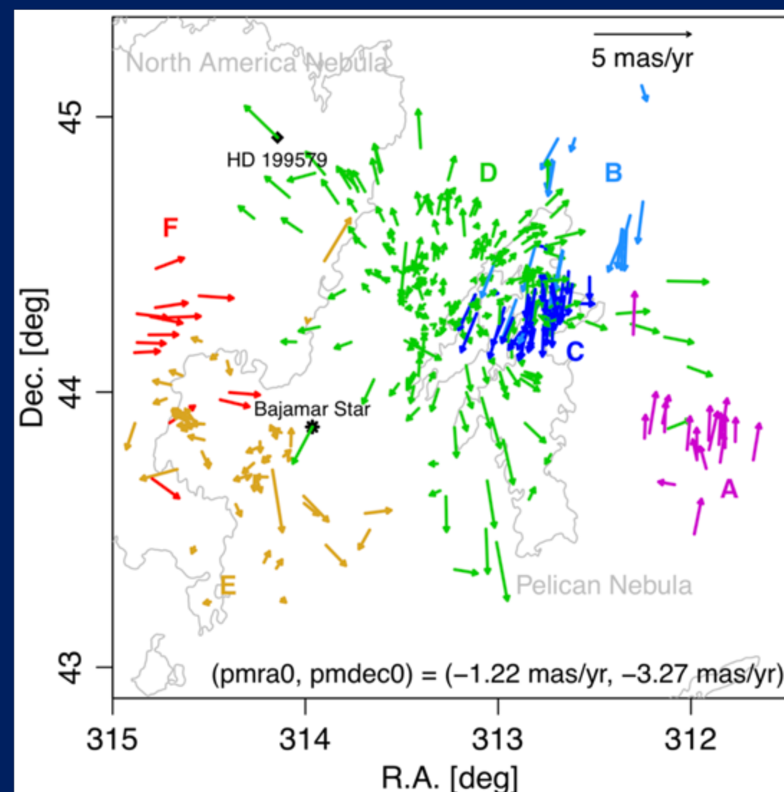
d ~0.8kpc



CLUSTER KINEMATICS!



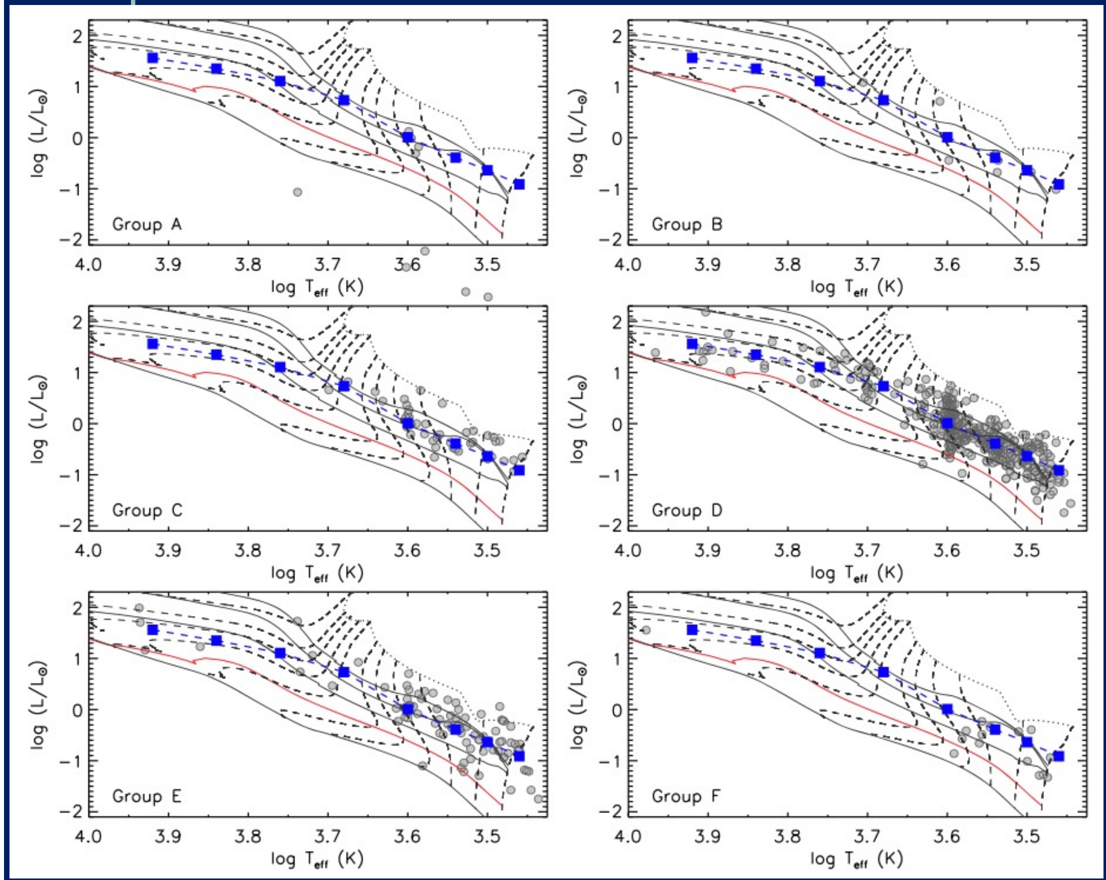




expansion time scales of 1.5-3 Myr

[Kuhn et al 2020]

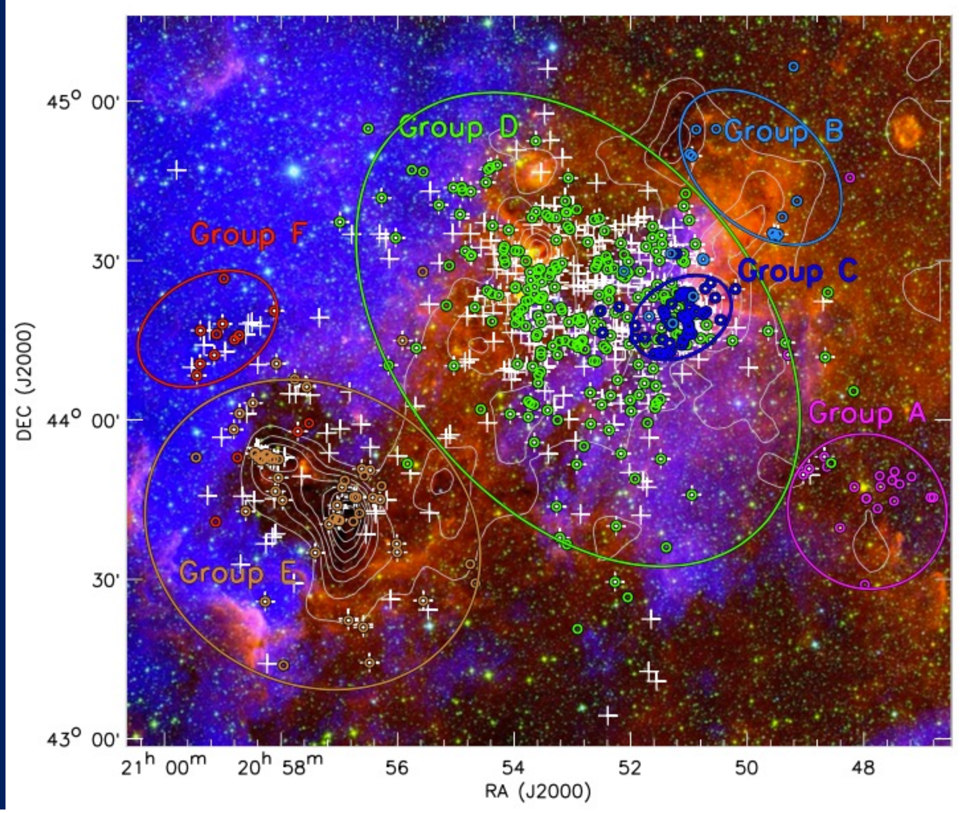
STELLAR AGES VIA HRD ARE COMPARABLE TO (SUB-)CLUSTER EXPANSION TIMES



Median L(T) ➔ ~1 Myr age

Relative to median age:

- group F is oldest
- group D next oldest
- groups A and B sparse but ~median
- groups C and E younger



But Δ(log L)= 0.3-0.4 !!

Why **still** so large given rigorous membership vetting?

[Fang et al 2020]

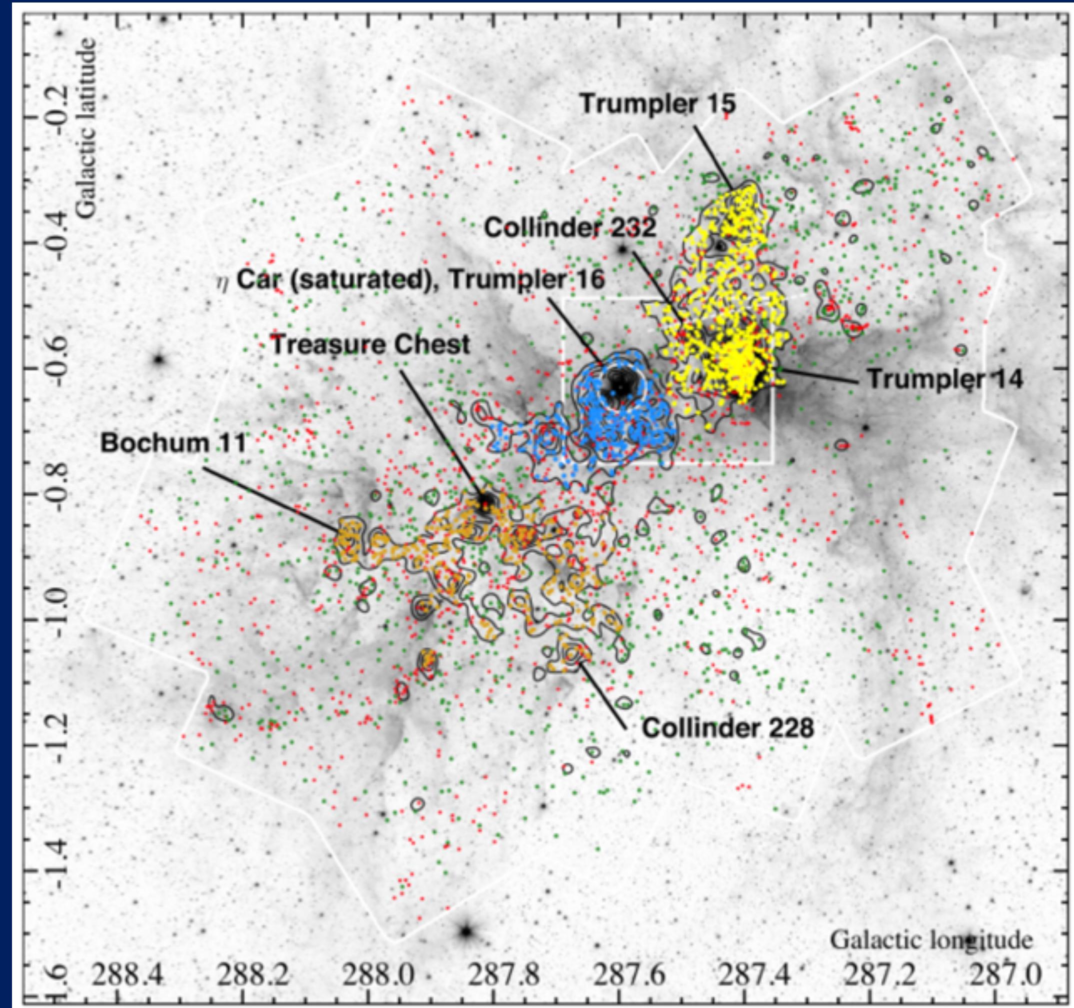
OPEN QUESTIONS REGARDING:

Cluster formation/dispersal timescales.

Gas expulsion processes.

Connection between gas kinematics and young star kinematics.

Fraction of clusters that remain bound.



[Povich et al 2019]

d ~2.7kpc

Age spreads and sequencing of star formation.

IMF and evidence for variations.

Mass segregation.

Multiplicity fractions and binary parameters.

Planet formation processes and timescales.

Addressing these questions requires understanding stellar properties!

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)

WHAT ARE WE TRYING TO INFER?

AGE:

- How old is that star / disk / planet?
- How do stars evolve, e.g. M(t) at early times or L(t), Teff(t), R(t), etc., or R(M) vs t
- How do disks evolve and form planets?
- How do planets evolve, e.g.
  - M(t) at early times or L(t), Teff(t), R(t), etc., or R(M) vs t
  - dynamically, in a planetary/debris system

- 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.

WHAT ARE WE TRYING TO INFER?

TEMPERATURE as a basic stellar characteristic, often a proxy for mass

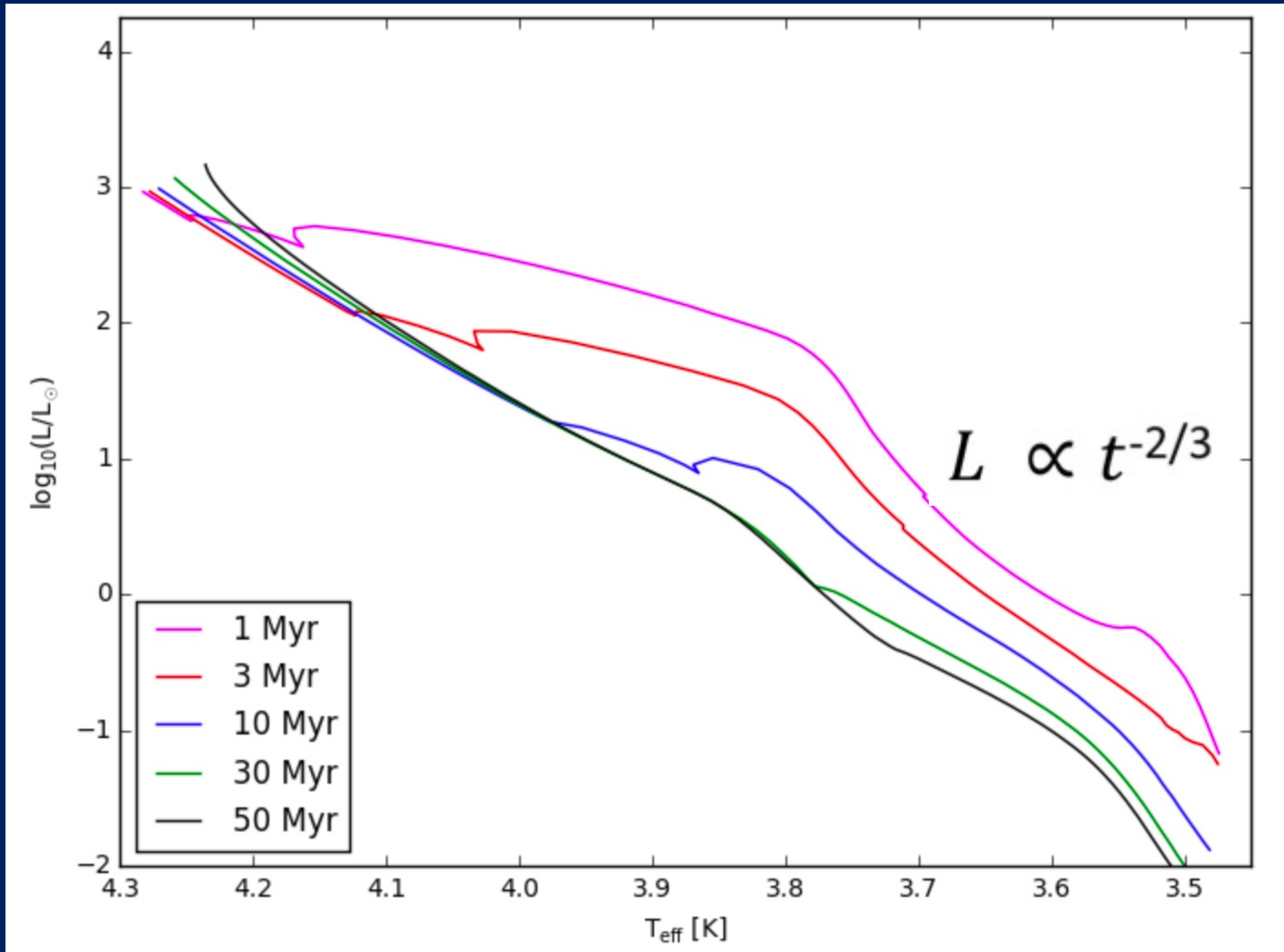
MASS e.g. for assessing M_2/M_1 from RV measurements

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

LUMINOSITY e.g. for interpreting an L_{IR}/L_* measurement

(more stellar parameters later)

STELLAR CONTRACTION THEORY - HRD



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

They remain our most useful tool however.

Amard et al. 2019

PRE-MAIN SEQUENCE EVOLUTIONARY TRACKS STILL CARRY SYSTEMATICS BETWEEN MODEL SETS

- interior physics
- atmosphere
- “birthline” effects

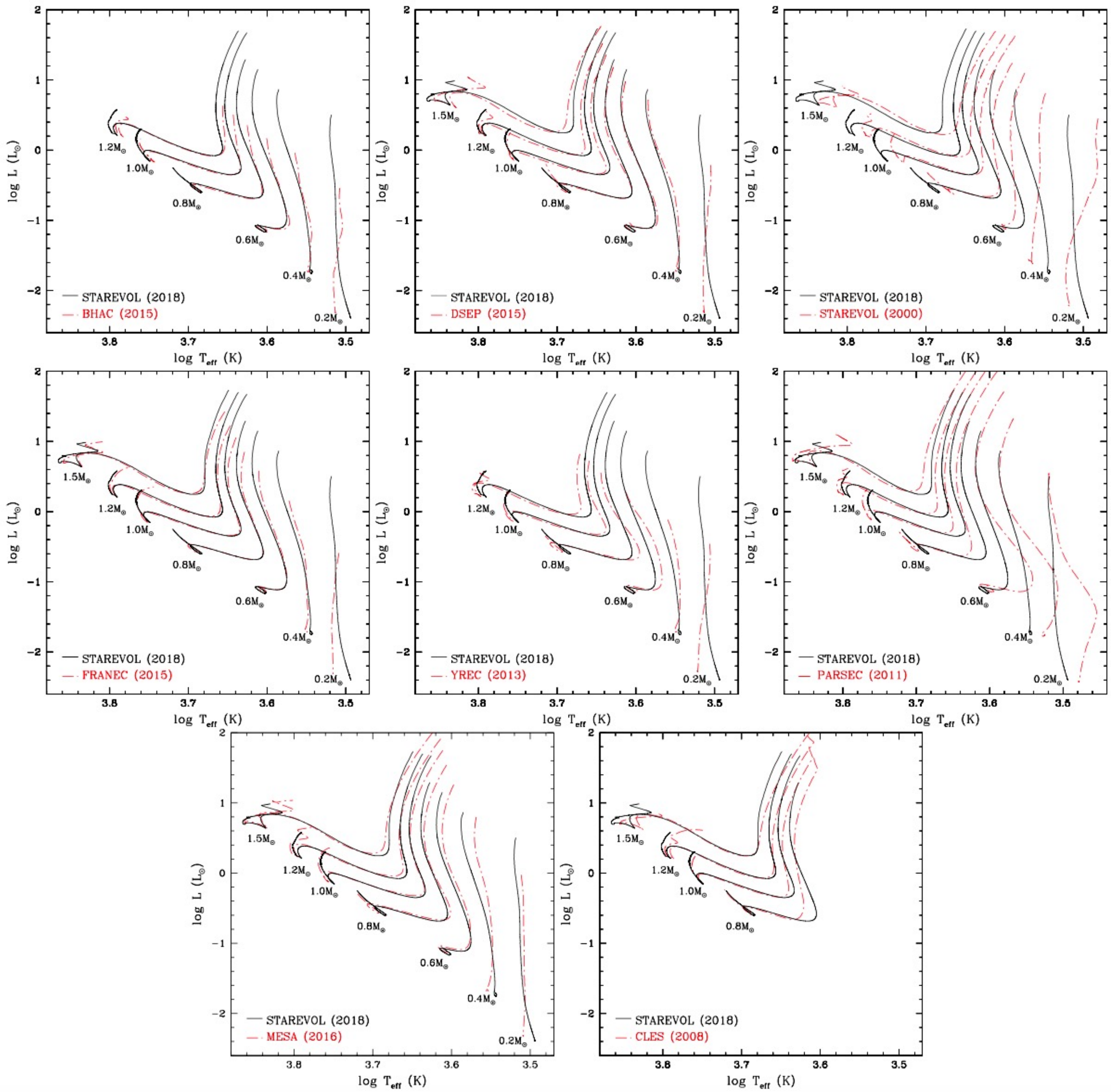
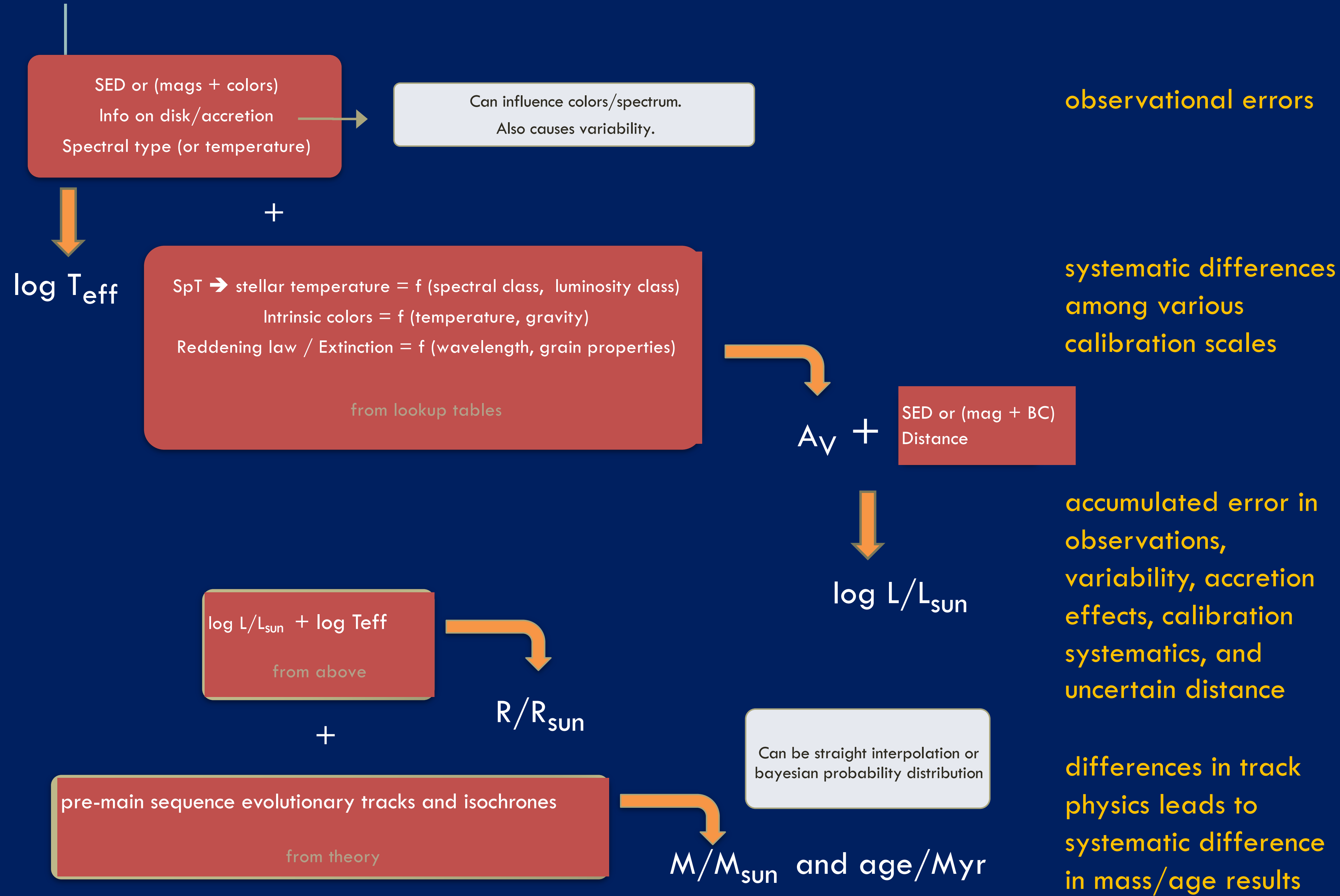
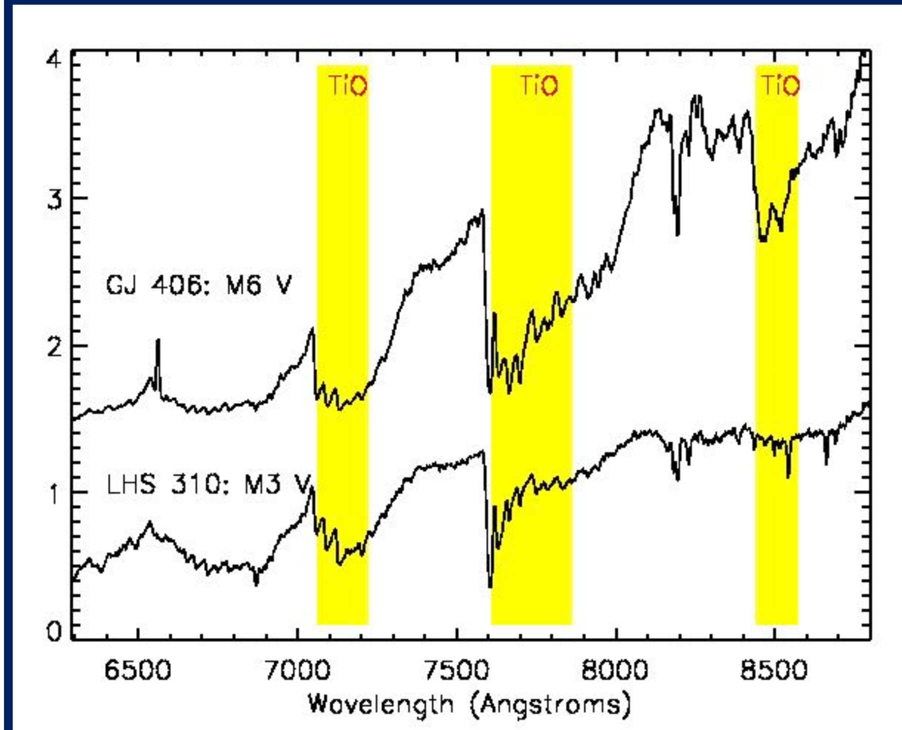
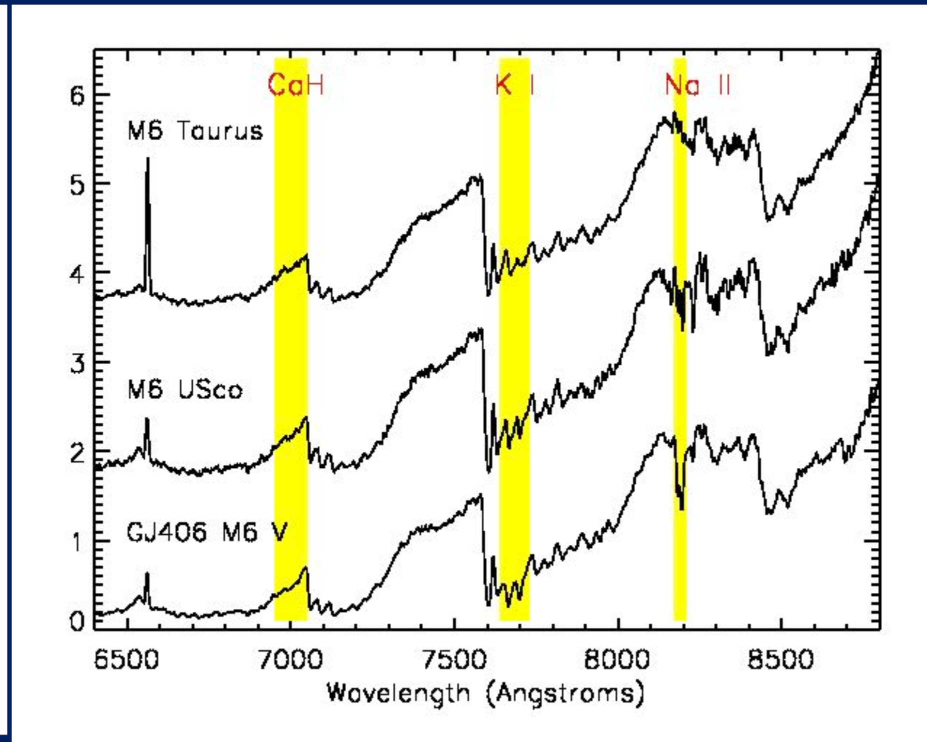


Fig. 3. Comparison of our standard solar metallicity models with other available grids as described in Table 4 and indicated on each panel.

FLOWCHART FOR YOUNG STAR HRD



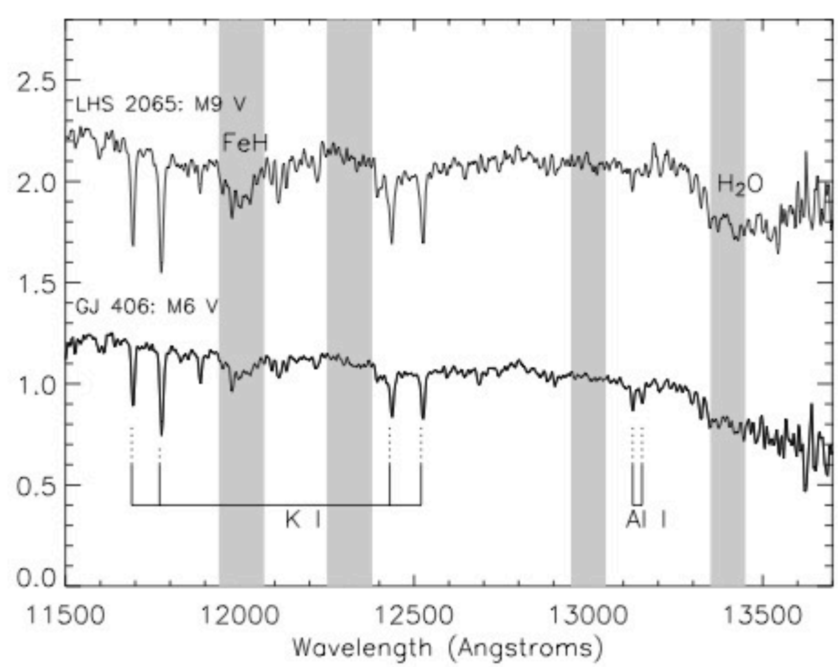


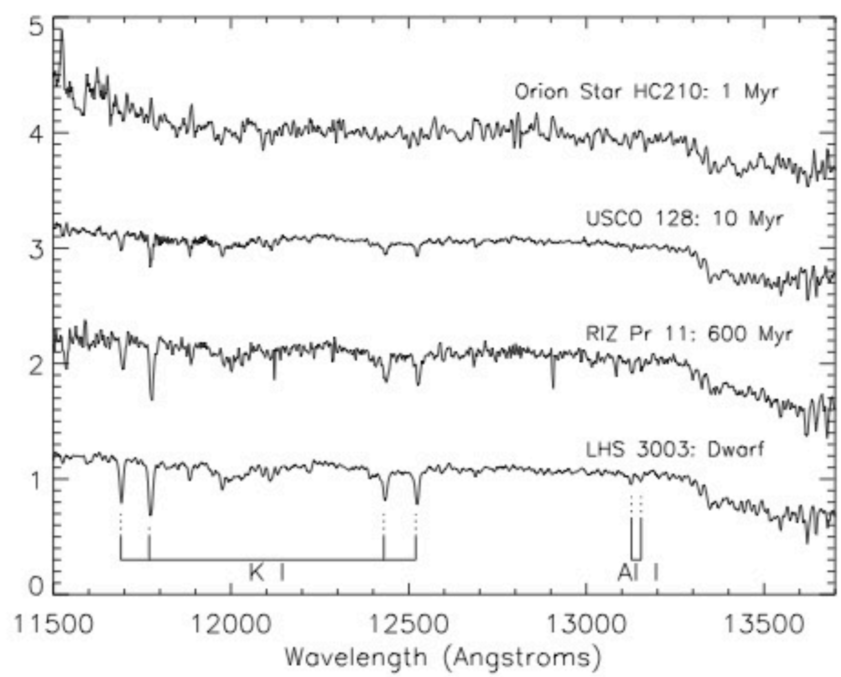


(molecular) temperature indicators

(atomic & molecular) gravity indicators

red optical spectra



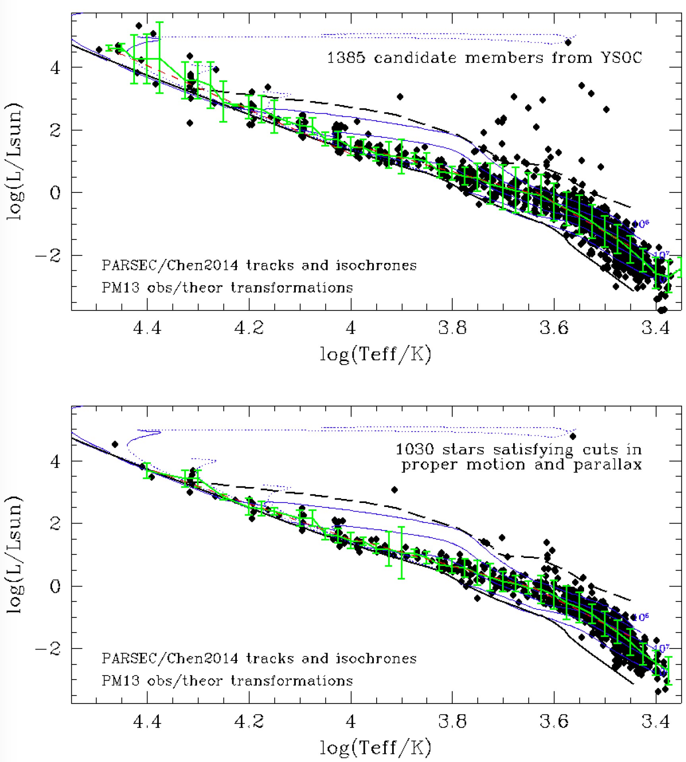


near-infrared spectra

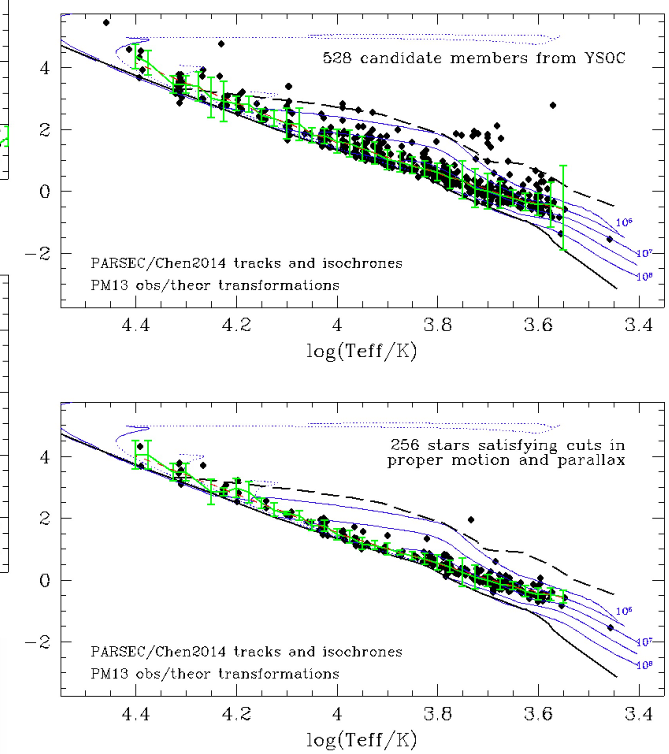
REQUIRING KINEMATIC MEMBERSHIP AND USING INDIVIDUAL PARALLAXES REDUCES LUMINOSITY SPREADS

ScoCen complex

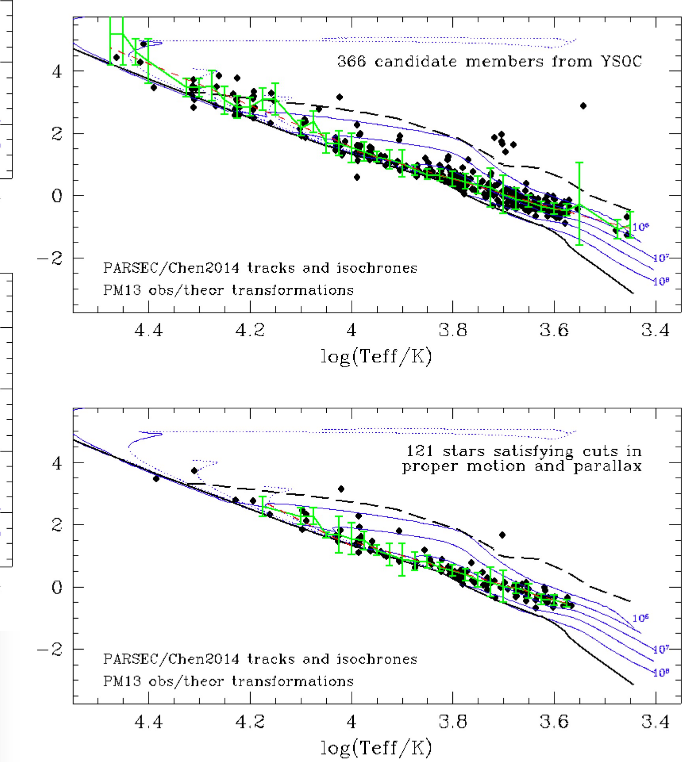
Upper Scorpius



Upper Centaurus-Lupus (UCL)



Lower Centaurus-Crux (LCC)



REQUIRING KINEMATIC MEMBERSHIP AND USING INDIVIDUAL PARALLAXES REDUCES LUMINOSITY SPREADS

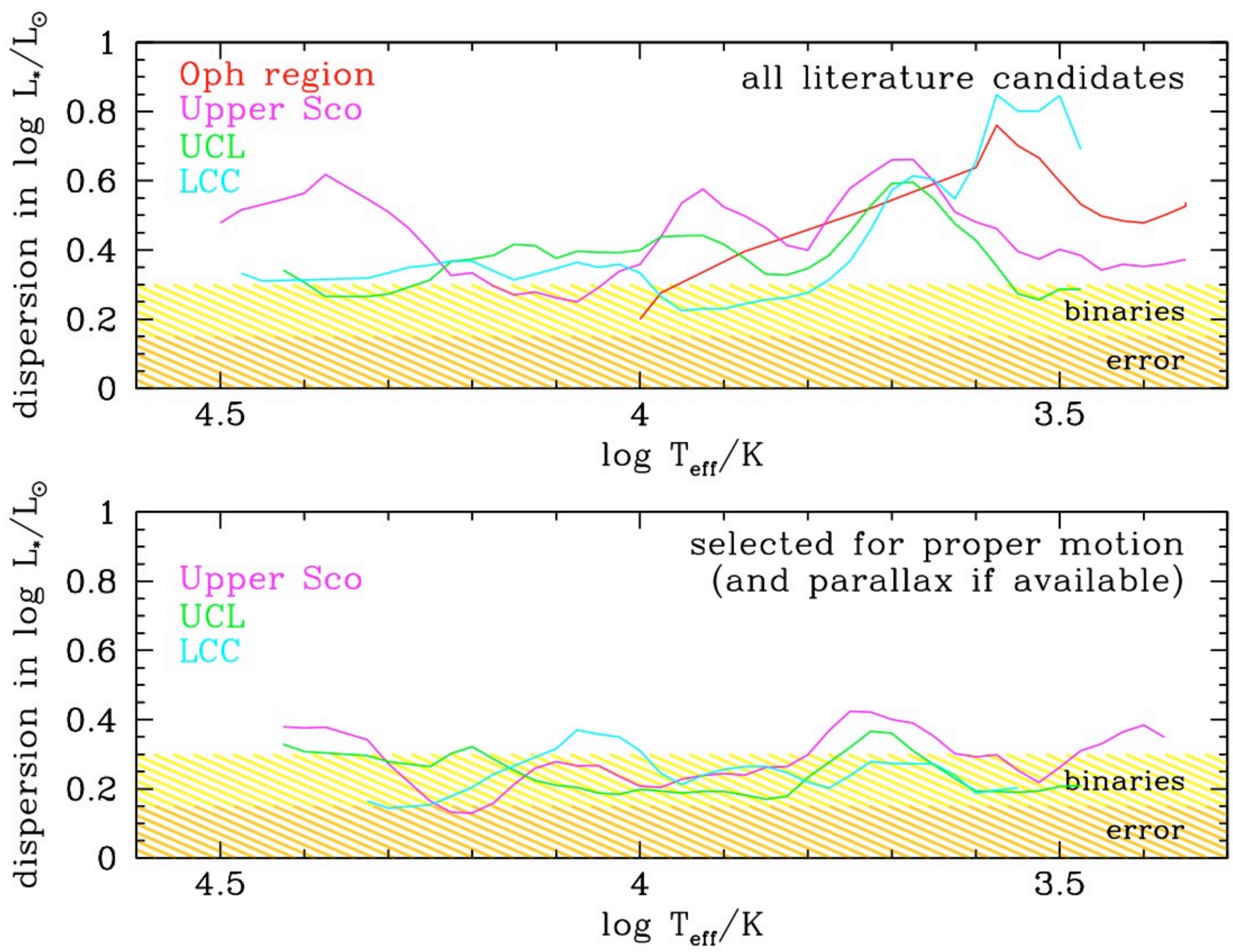


Figure 8. Dispersion in log $L/L_{\odot}$ with log T_{eff}. Pre-Gaia values are in the top panel, and post-Gaia values in the bottom. Although there is a reduction in the luminosity spreads when individual parallaxes are used, the luminosity spreads do not reach the maximum spread expected from propagation of various error sources (gold hatched region). The yellow hatched region extends to the maximum effect from equal-mass binaries.

ScoCen complex

Implications for cluster age spreads and star formation histories.

Hillenbrand et al. in preparation

HOWEVER, IT'S NOT QUITE THAT EASY

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?

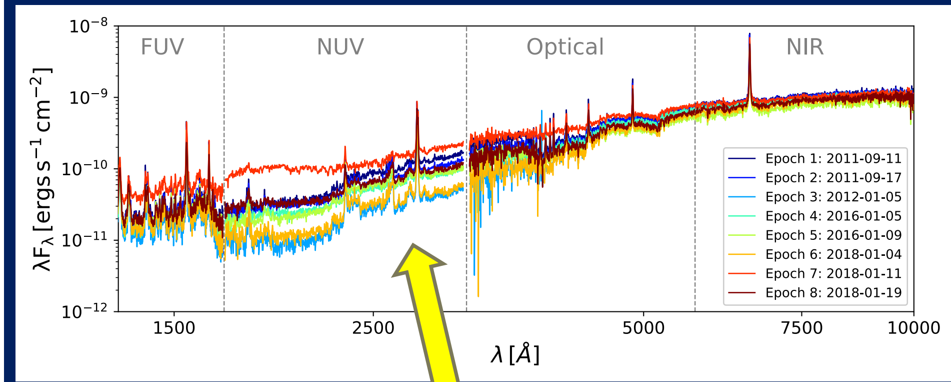
Median RMS values in the ONC:

<0.19> mag at 0.8 um

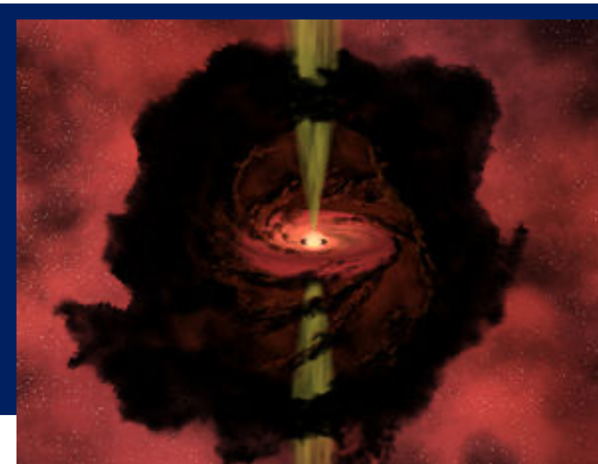
<0.14> mag at 1.2, 1.6, 2.2 um

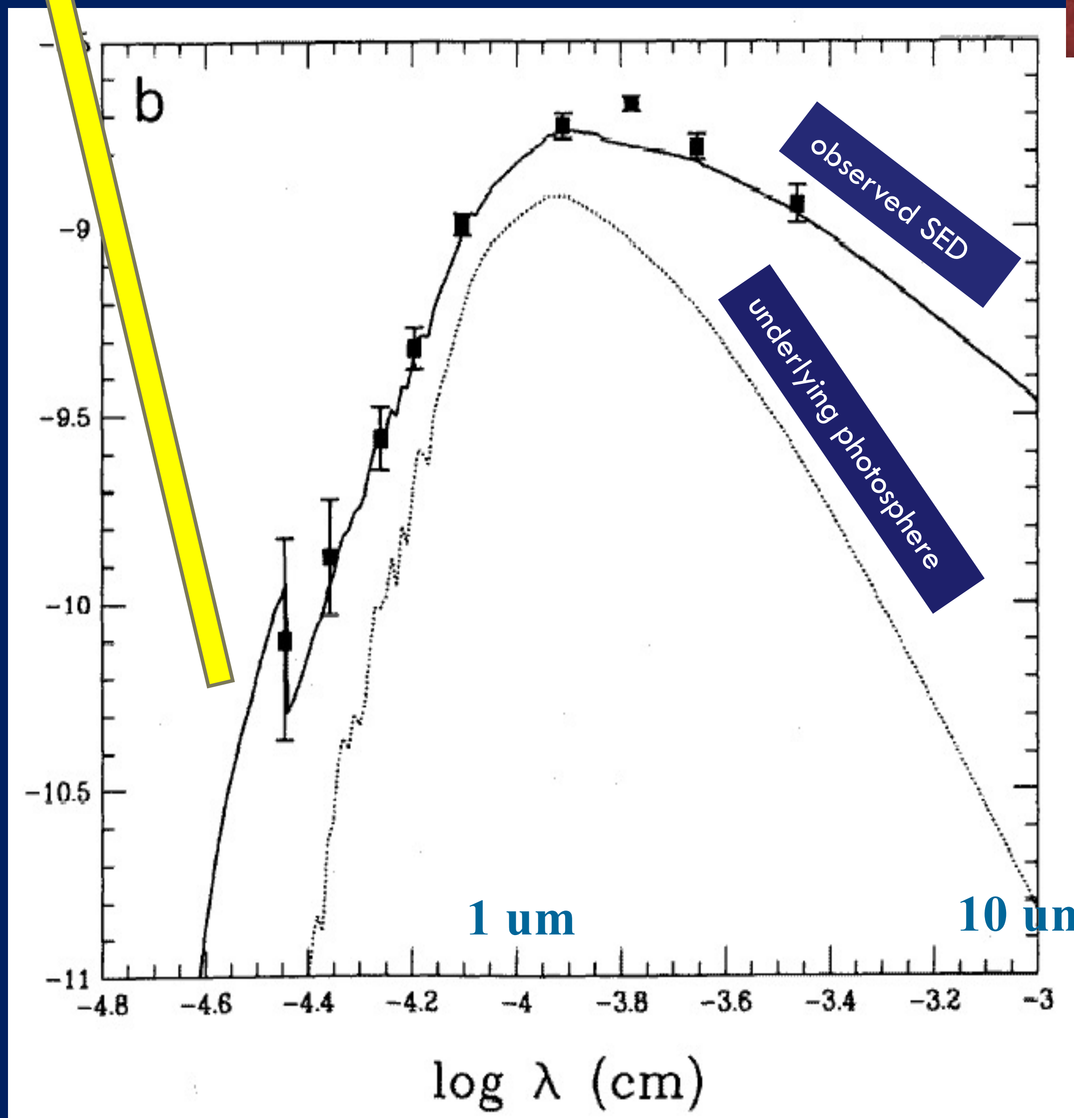
<0.07> mag at 3.6, 4.5 um

High variability tail extends to >2 mag!



[Robinson et al. 2019]





SPECTRAL TYPES PLUS VEILING

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

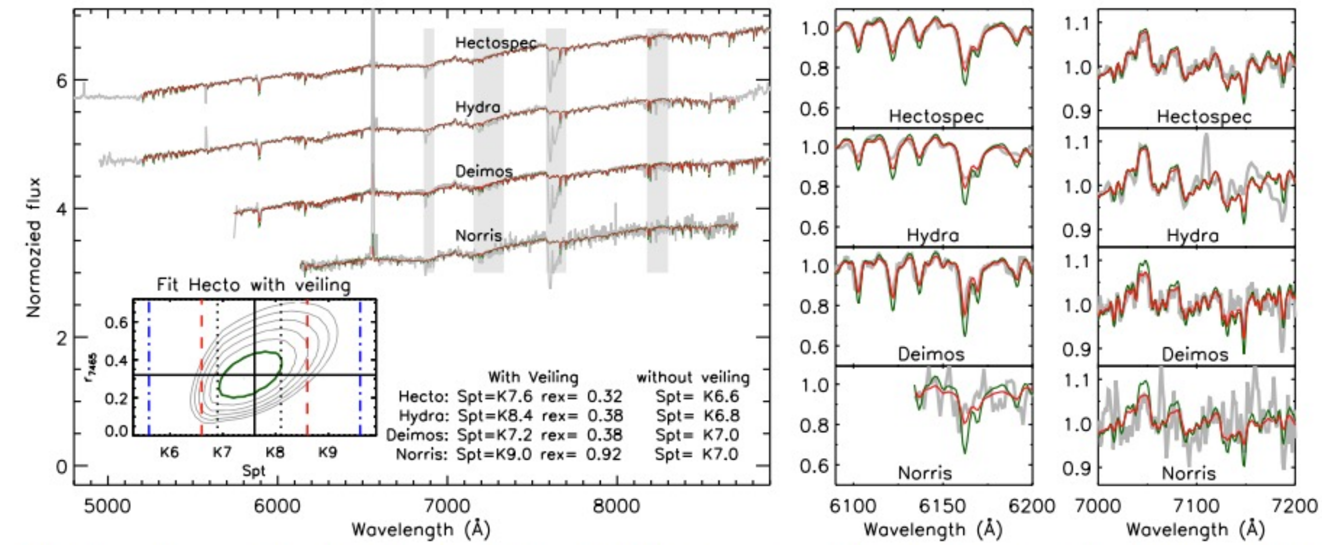


Figure 2. Illustration of our spectral template fitting method for Source ID 103, which was observed with all the four spectrographs used in this study. Left: best-fit X-shooter empirical spectral templates (red including veiling in the template model and green without veiling) overplotted on the observed 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^{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

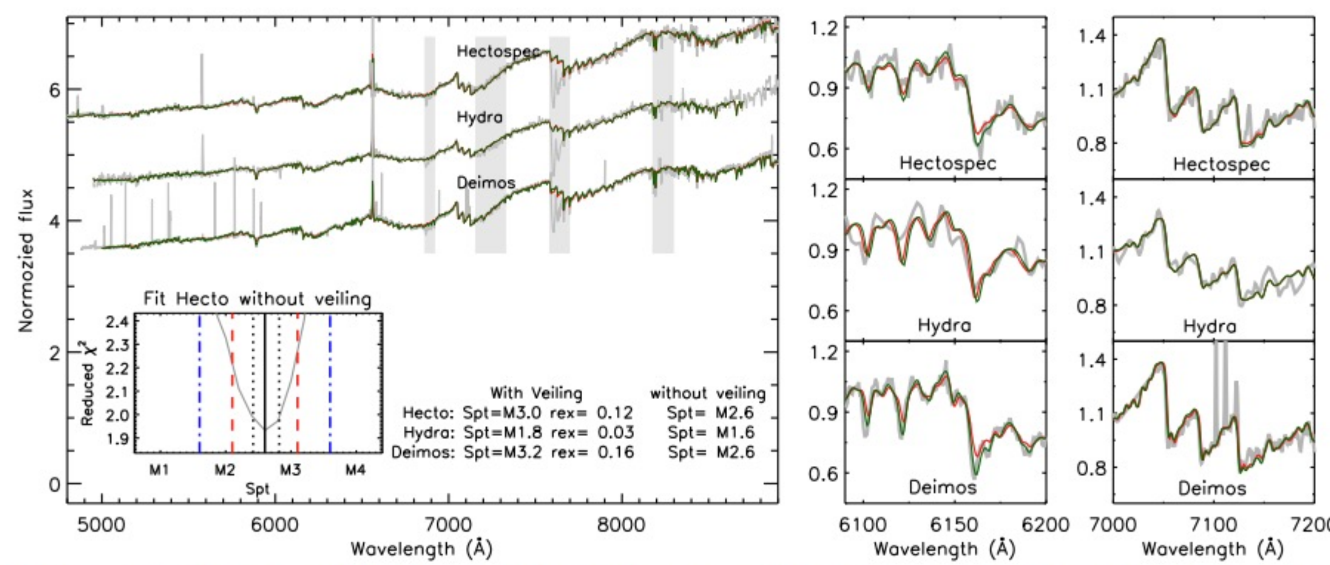


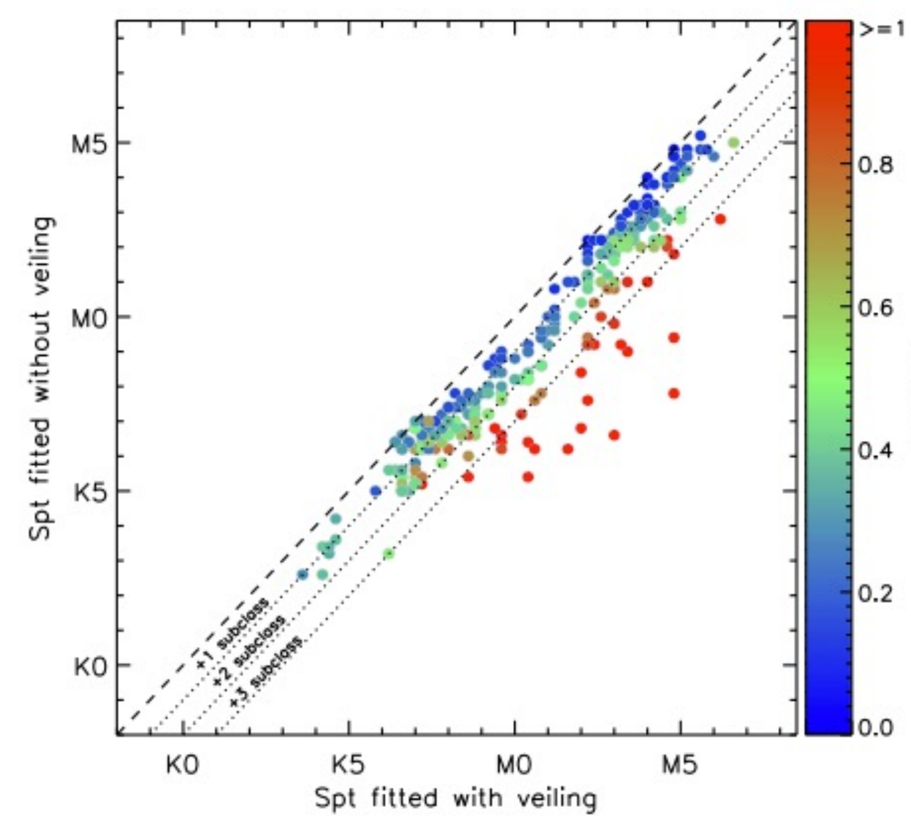
Figure 3. Same as Figure 2, but for Source ID 232. In this case the nonveiled model (green) is the preferred fit to the observed spectrum (gray). In the left panel, the inset shows the distribution of reduced χ^2 derived from fitting the Hectospec spectrum with X-shooter templates having different SpT.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

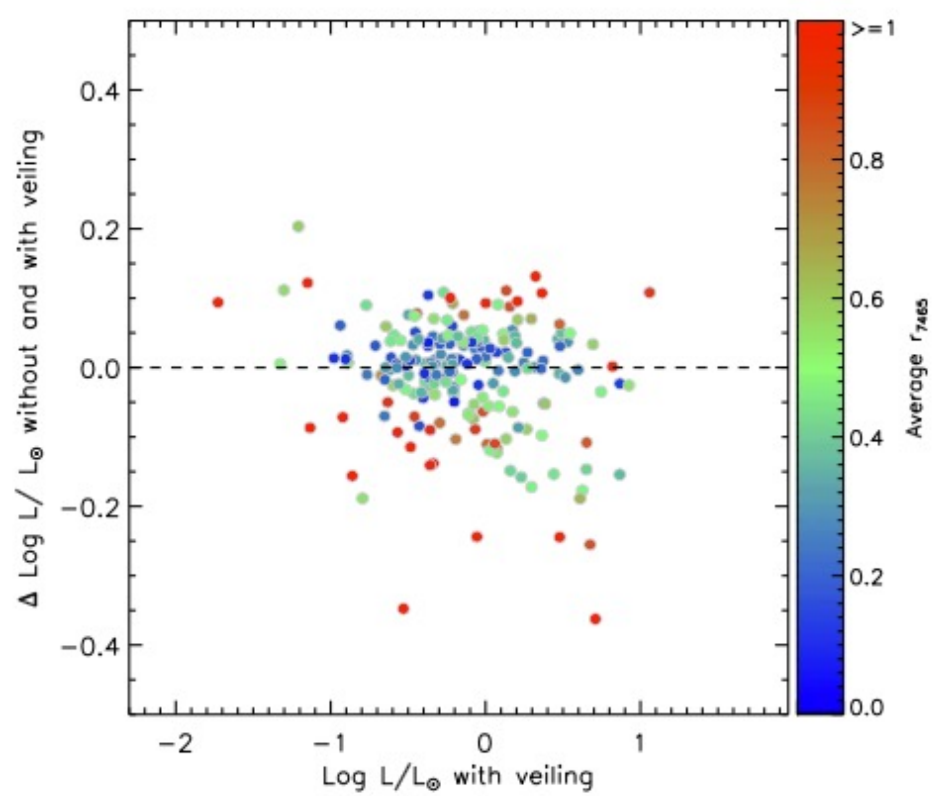
[Fang et al. 2020]

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]

HOW ACCURATE ARE THE HRDS (VARIABILITY)

Similar Δ(log L) = 0.3 dex luminosity spread for all variability amplitudes.

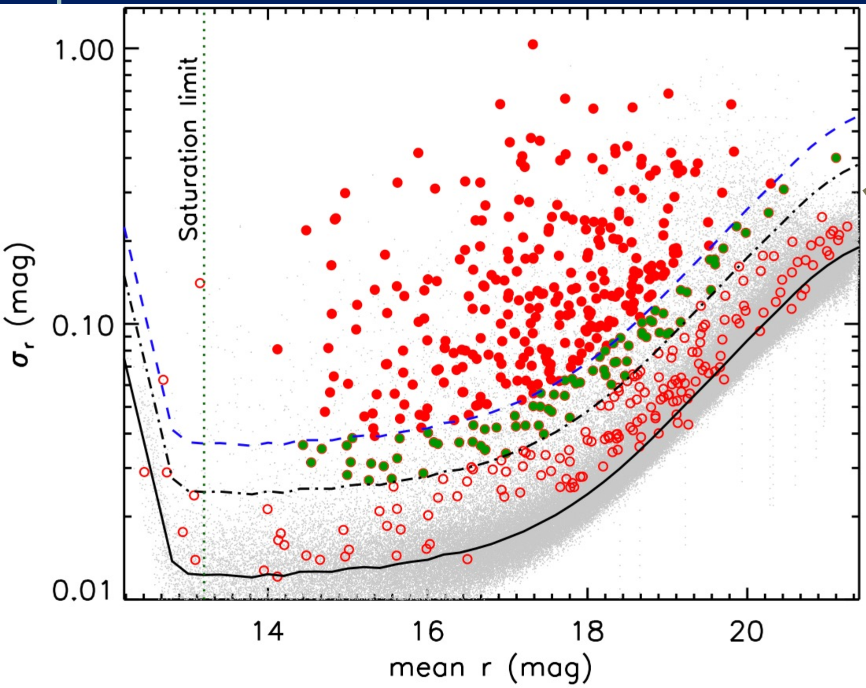


Figure 14. Photometric variability statistic σ_r vs mean magnitude $\bar{r}$ for all stars in the NAP field with distance less than 2 kpc. The underlying distribution is shown as small gray-color dots. The black solid line marks $\bar{\sigma}_r$ within individual magnitude bins, while the black dash-dotted line indicates $2\times\bar{\sigma}_r$ and the blue dashed line $3\times\bar{\sigma}_r$. Our identified YSOs are shown as red circles: red-filled circles are for strongly variable stars, green-filled circles for moderately variable stars, and open circles for stars with low variability.

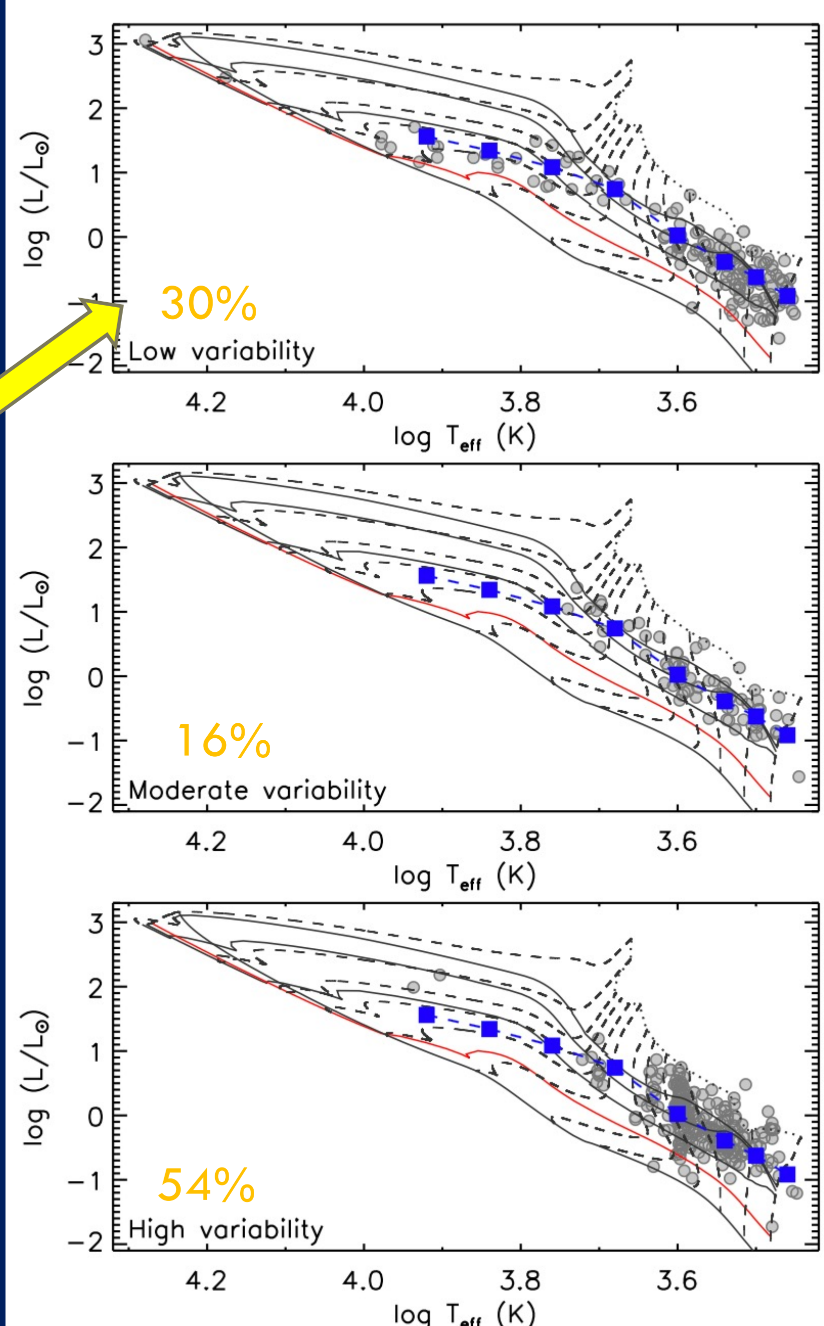
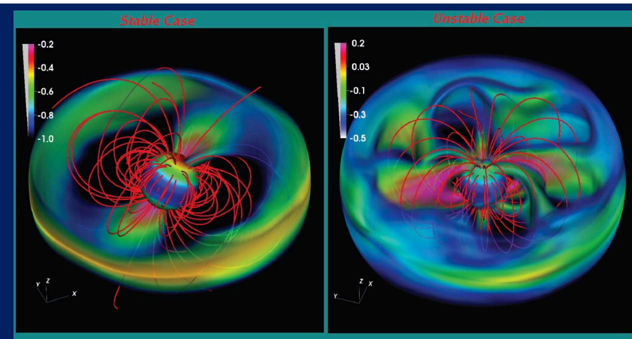


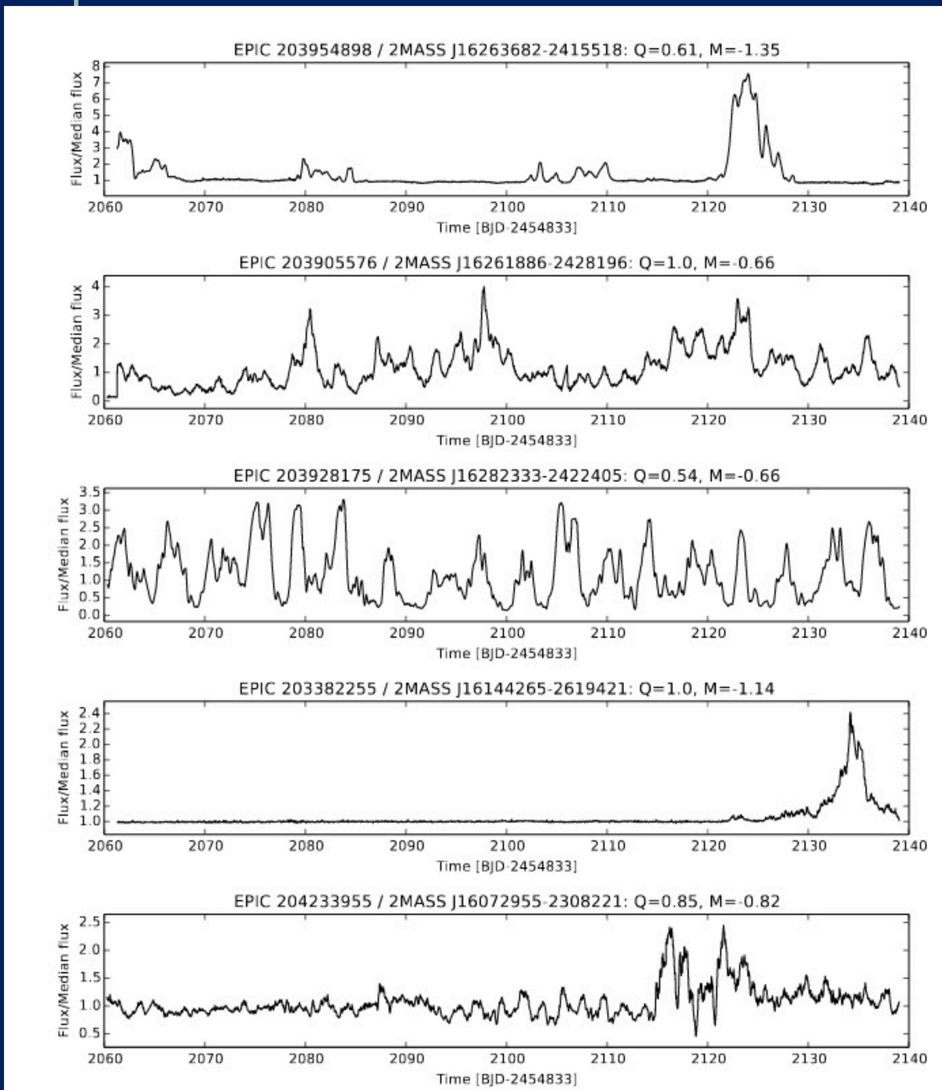
Figure 20. H-R diagram for young stars with photometric variability data and showing variability at low (top panel), moderate (middle panel), or high (bottom panel) levels. The evolutionary tracks are the same as in Figure 12.

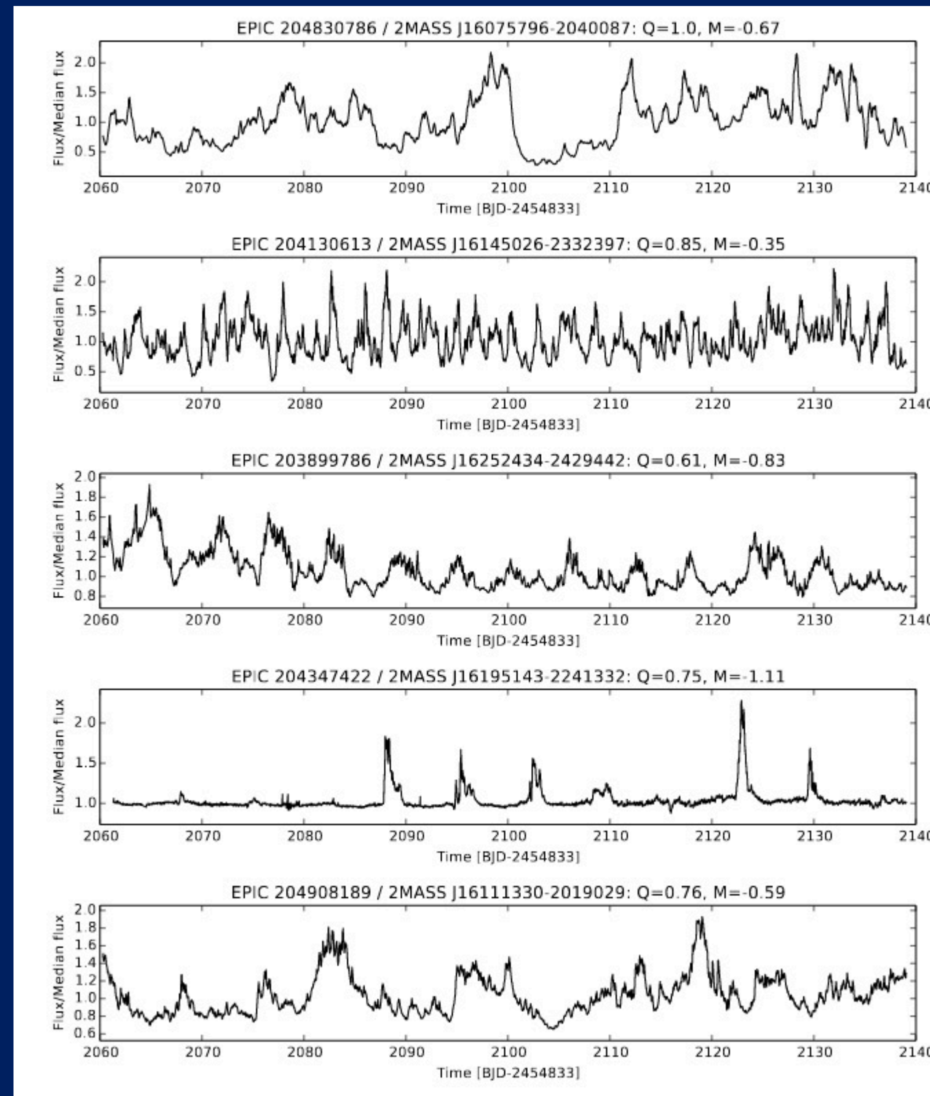
[Fang et al. 2020]

A CONTINUUM OF ACCRETION BURST BEHAVIOR



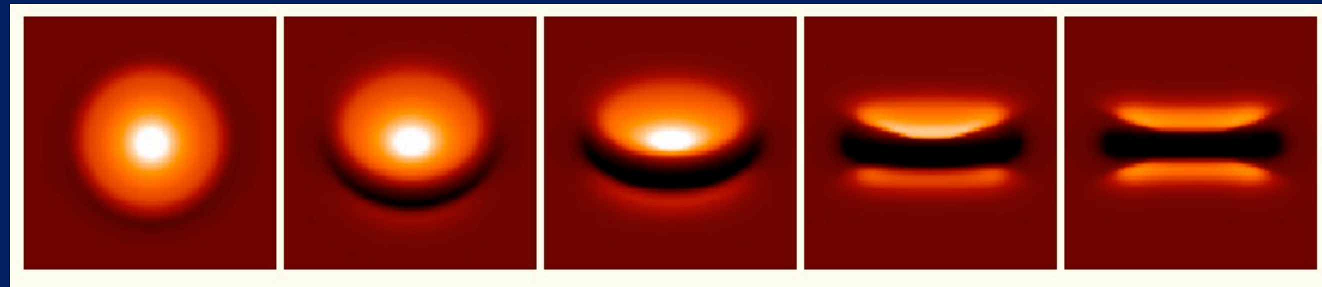
~15% of objects with disks are "bursty" with both aperiodic and quasi-periodic behavior.





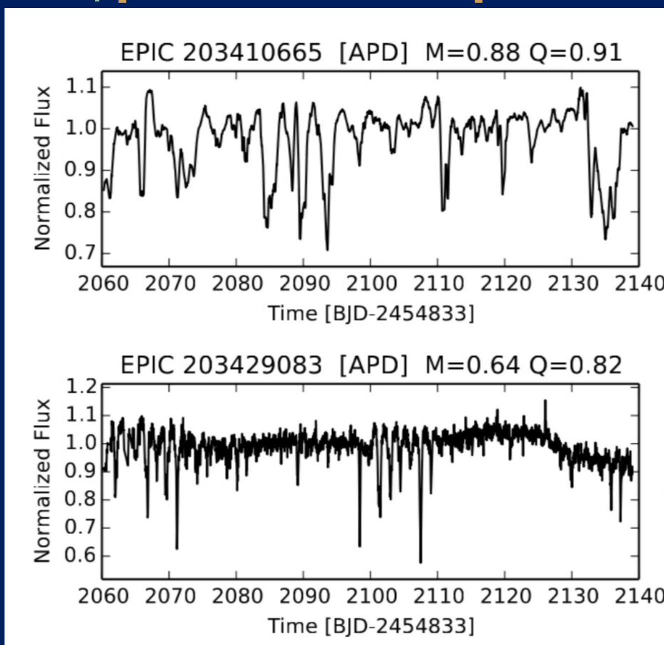
[Cody et al. 2017]

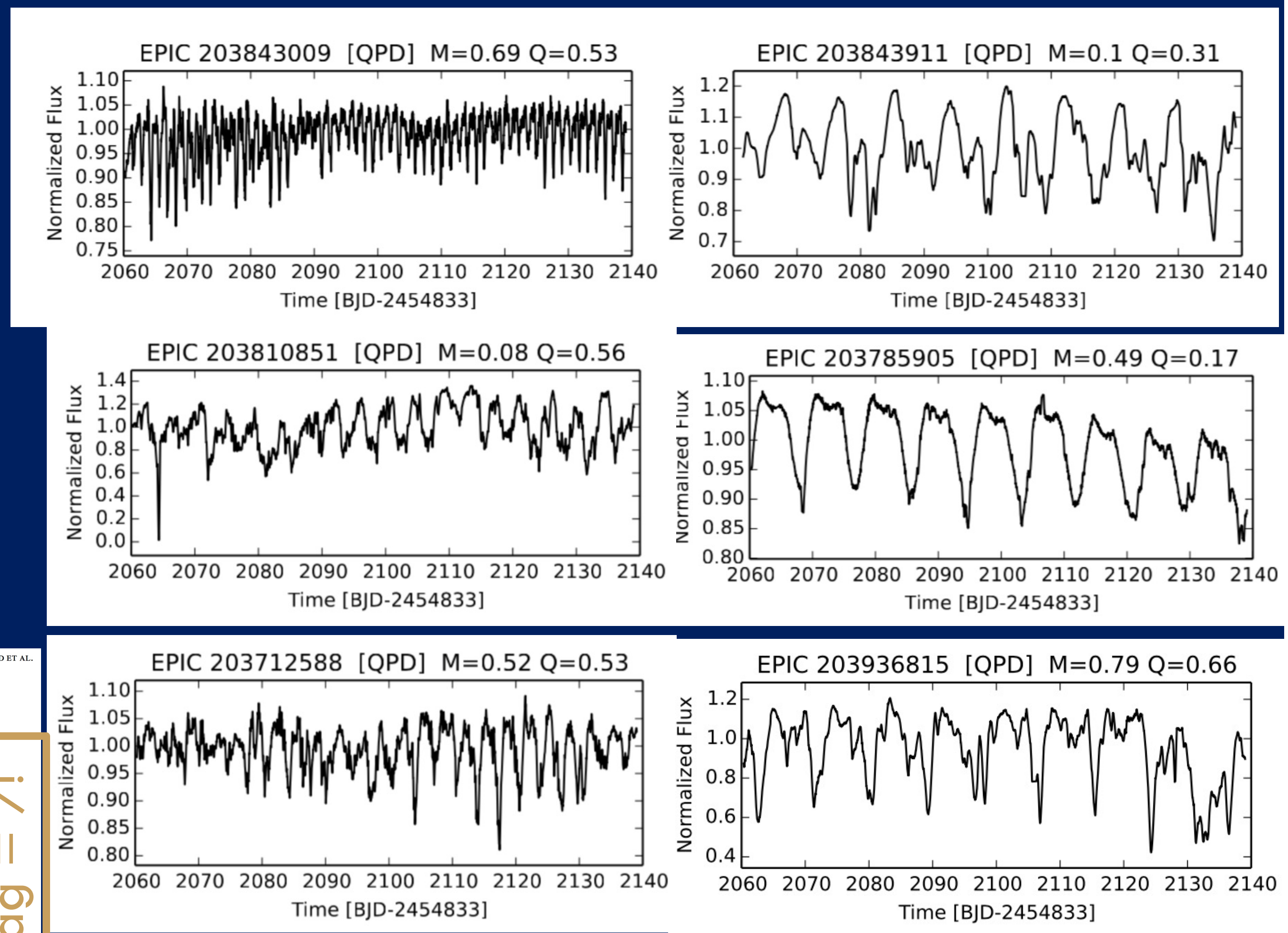
ALSO A CONTINUUM OF DIPPING/FADING BEHAVIOR



Quasi-periodic Examples

Aperiodic Examples





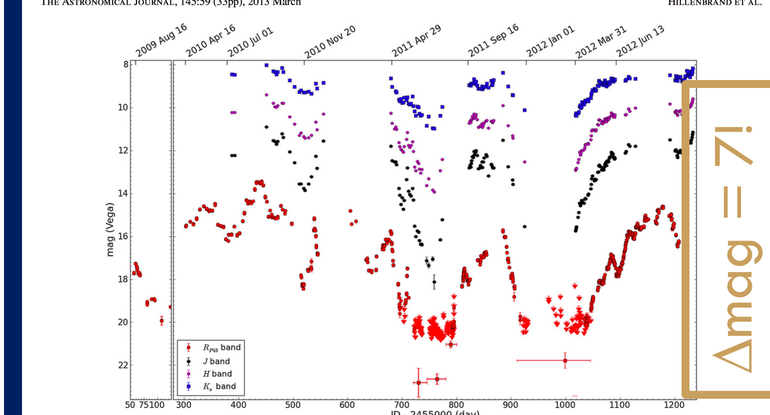


Figure 1. Multi-wavelength light curve of PTF 10nvg with UT dates indicated above the figure. From bottom to top the data streams represent variability in the R band (red; data from PTF) and in the J, H, and K bands (black, purple, and blue respectively; data from PAIRITEL). Error bars are shown, but 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 PTF images (red squares, in the 21–23 mag range); horizontal error bars indicate the time range of measurements included in each stack.

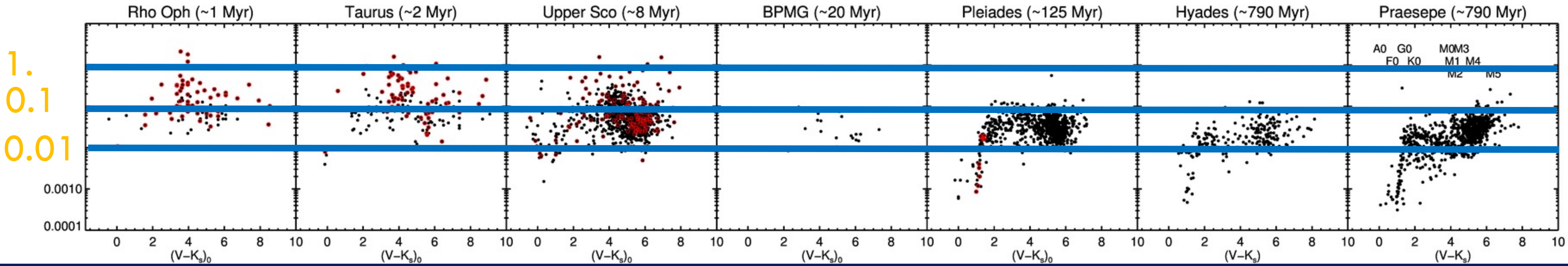
Δmag = 7!

[Cody and Hillenbrand 2018]

see also Ansdell 2016 and Hedges 2018

VARIABILITY AMPLITUDES DECLINE WITH AGE

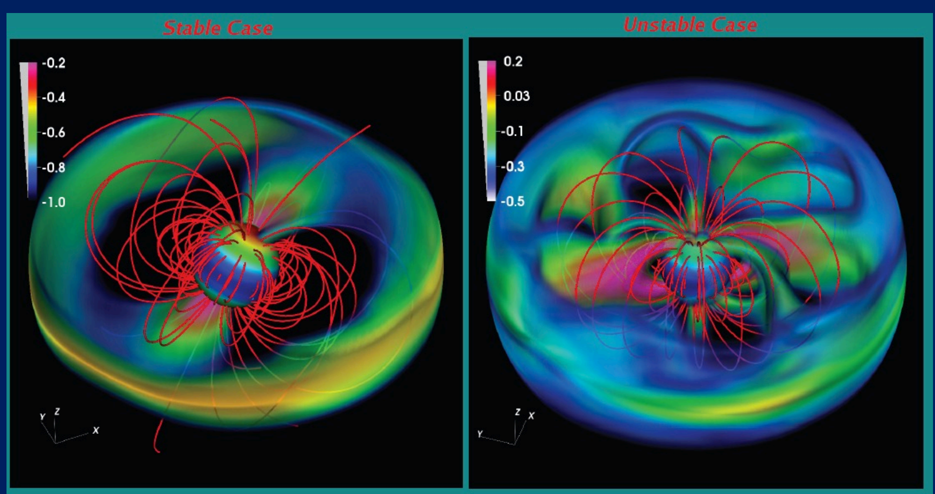
1 Myr   10 Myr   100 Myr   1 Gyr



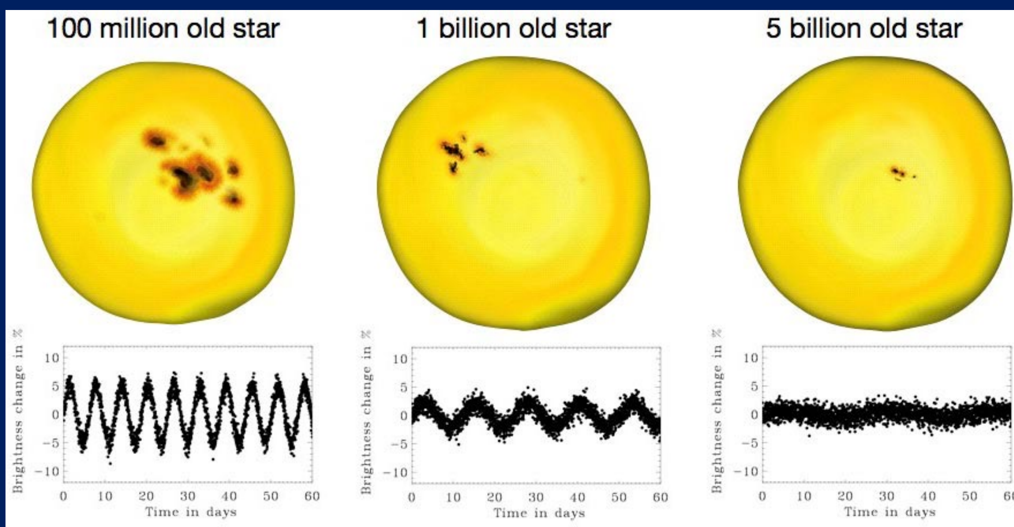
Rebull et al.

accretion and high levels of activity
with amplitudes ~0.1 – 1 mag

activity and spots
with amplitudes ~0.01-0.1 mag



graphic by M. Romanova



graphic by S. Meibom

ALL STARS ARE VARIABLE AT SOME LEVEL -- BUT YOUNG STARS DO STAND OUT

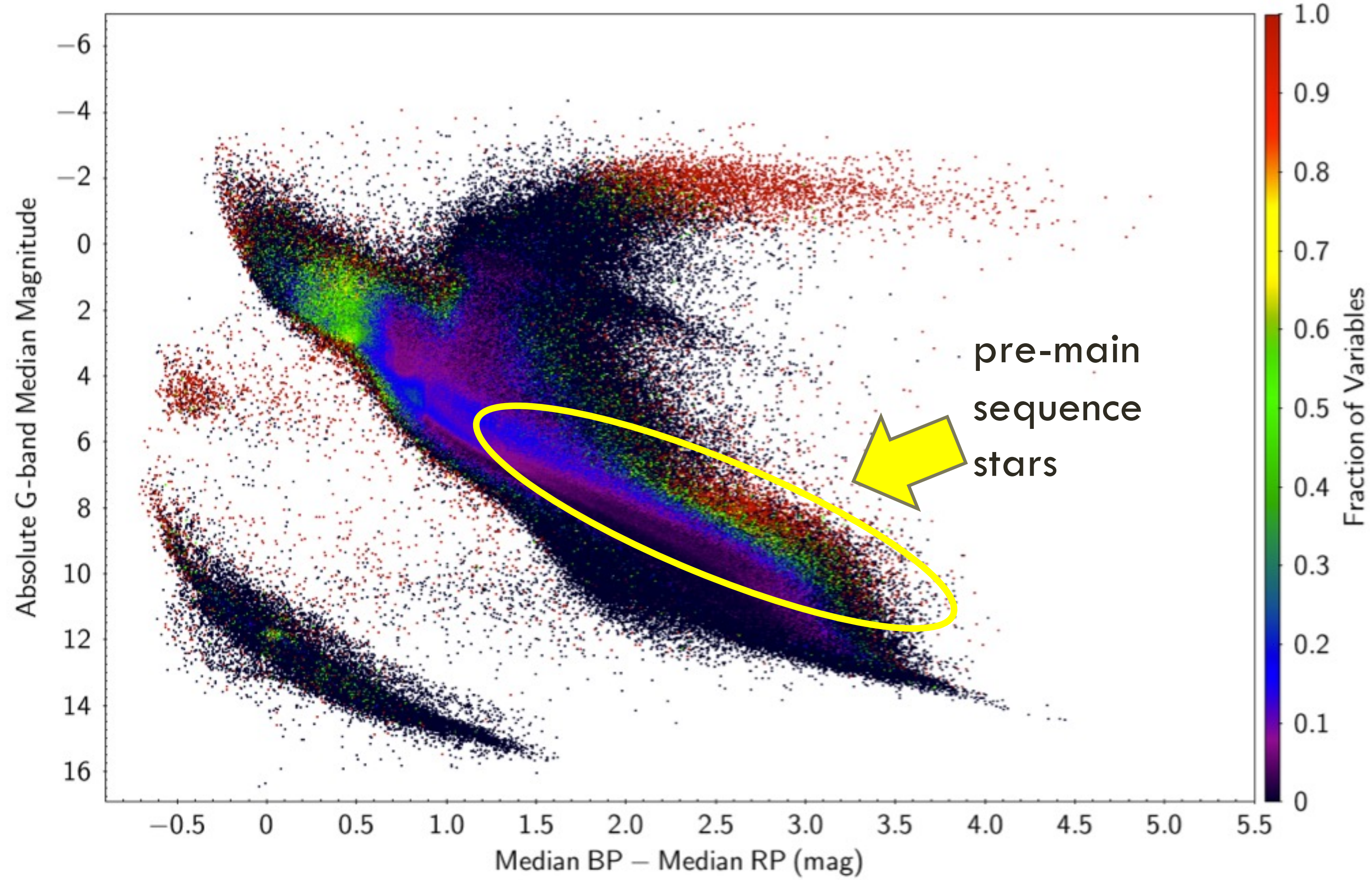


Fig. 8. Variable object fraction in the CaMD shown as a colour scale as labelled. This figure is not based on variable objects from the literature. Instead, variability is detected directly using *Gaia* data and employing supervised classification for sources with at least 20 observations in the

[Eyer et al. 2019]

A FEW MAIN MESSAGES THUS FAR

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.

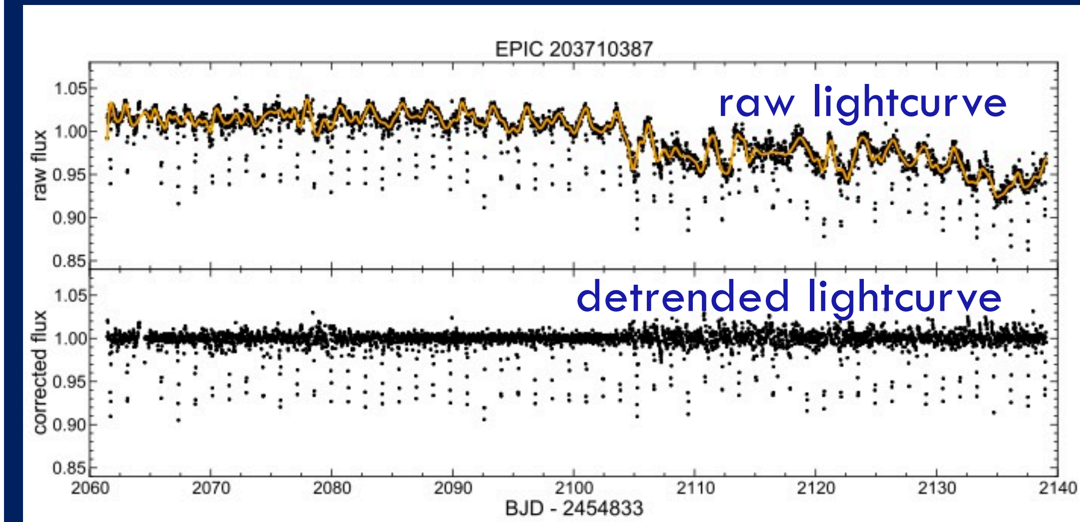
- not readily explained by observational errors or photometric variability or distance spreads

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

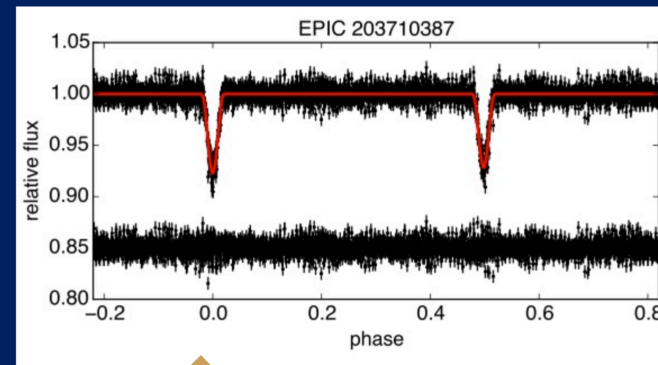
- still missing ingredients in evolutionary theory – currently thought to be accretion history

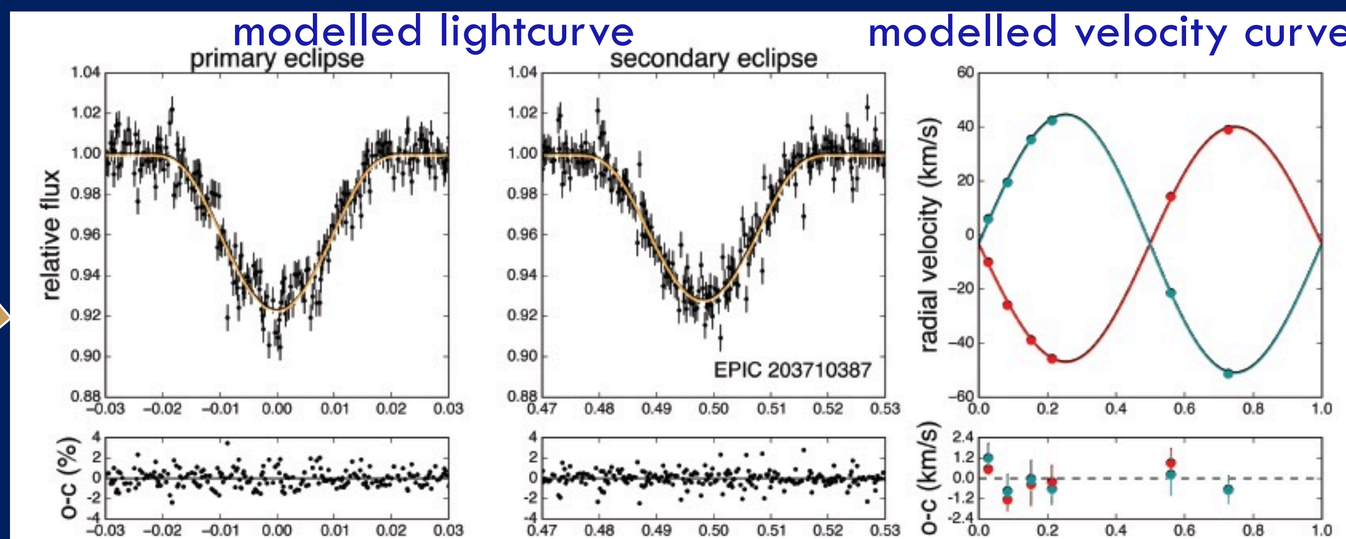
There is an important check on the models, which is to measure M,R directly.

YOUNG DOUBLE-LINE ECLIPSING BINARIES



phased lightcurve





$M_1 = 0.118 \pm 0.003\ M_\odot$

$M_2 = 0.108 \pm 0.003\ M_\odot$

$R_1 = 0.42 \pm 0.01\ R_\odot$

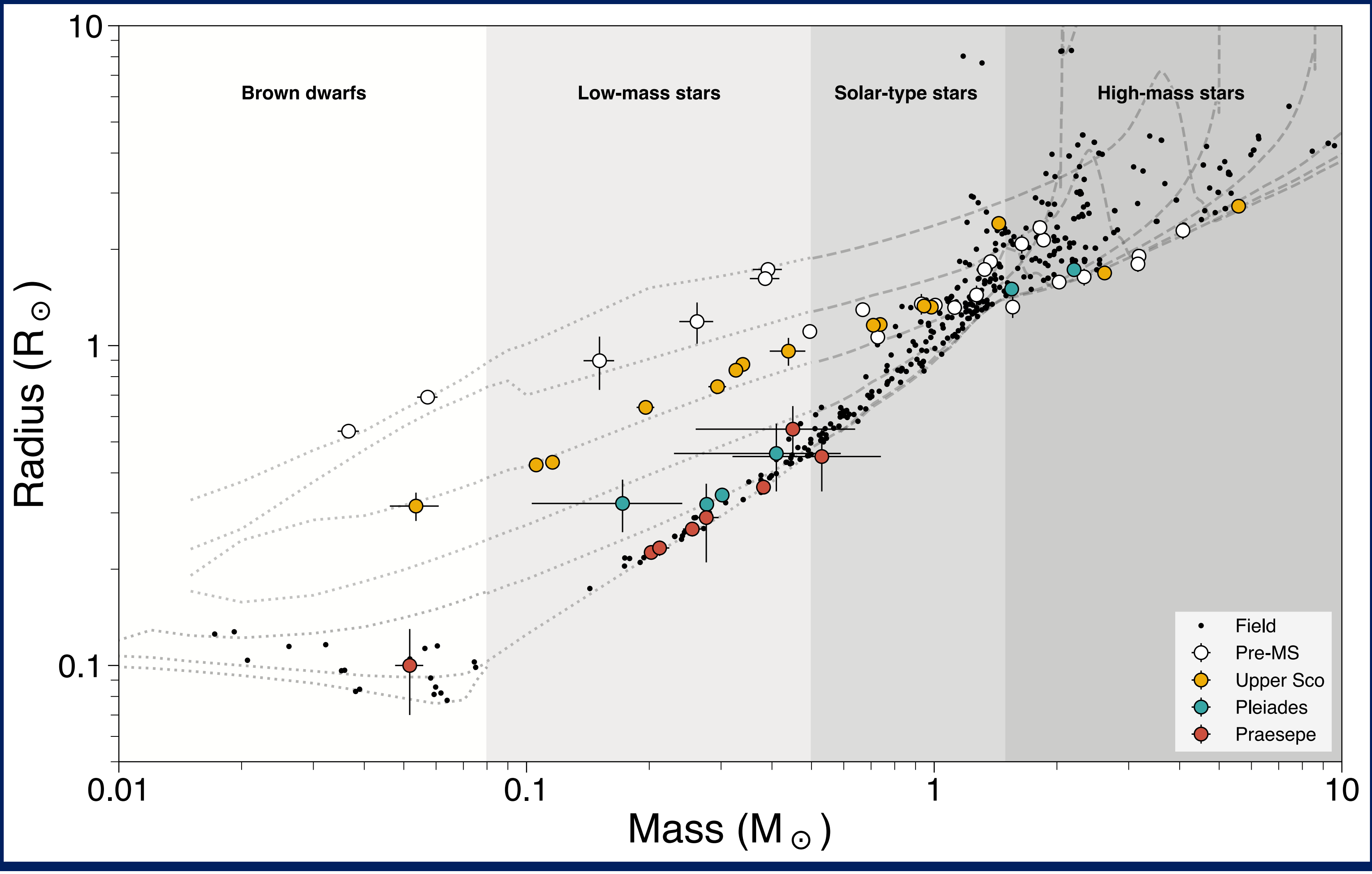
$R_2 = 0.45 \pm 0.01\ R_\odot$

lowest mass
stellar benchmark

[David et al. 2016]

FUNDAMENTALLY DERIVED MASS AND RADIUS

- Cluster member DLEBS 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 & Hillenbrand 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).

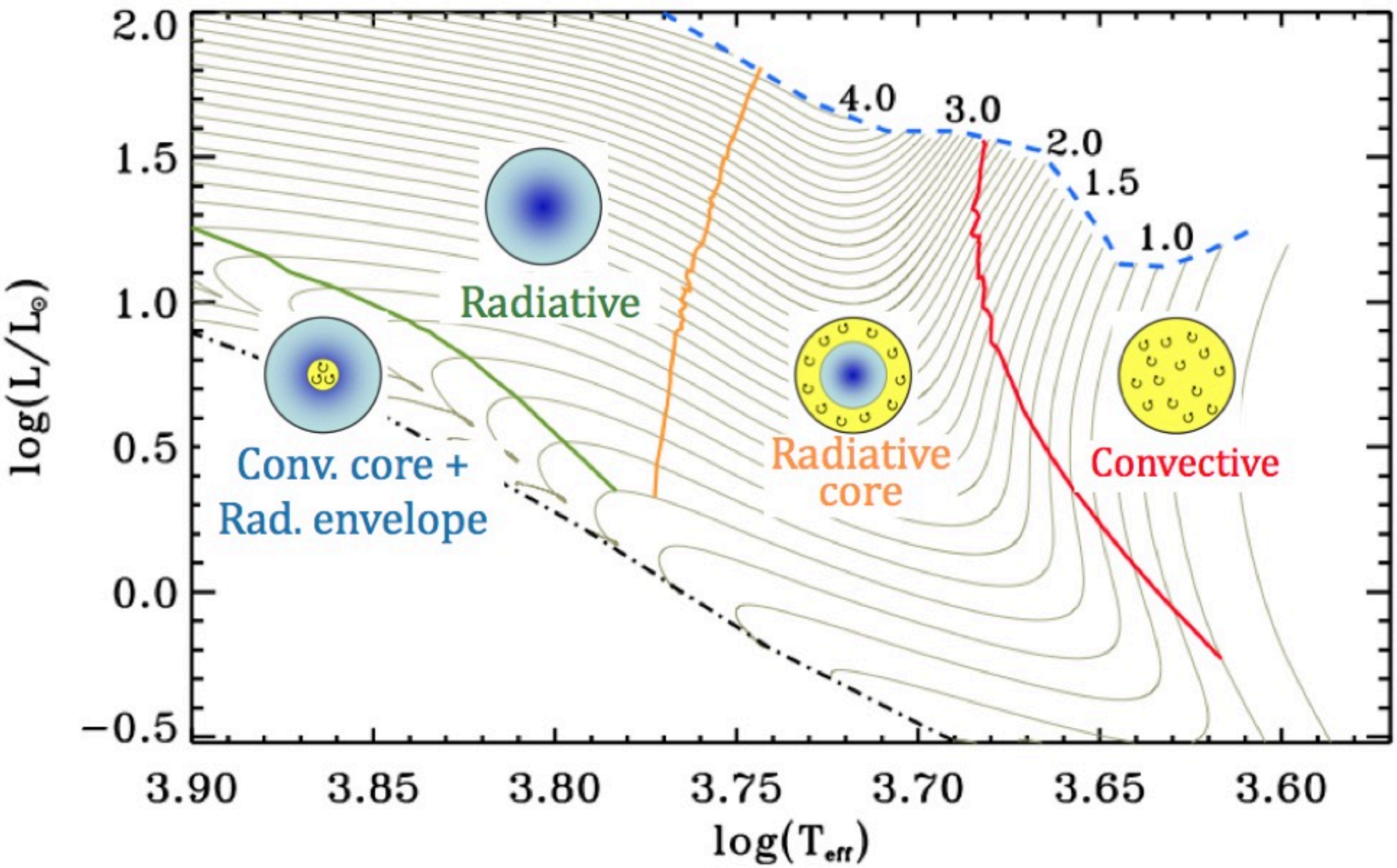


Figure 1. H-R diagram showing Behrend & Maeder (2001) pre-main sequence evolutionary tracks for stellar masses up to $4\,M_{\odot}$. The dashed blue line marks the position of the birthline. All stars with masses less than $3.5\,M_{\odot}$ will undergo a stage along their pre-main sequence evolution in which they have either partially or fully convective interiors. A star with a mass of $1.5\,M_{\odot}$ or more will be subject to several fundamental changes in their internal structure, having a fully convective interior near the birthline, to developing a radiative core, to becoming fully radiative and finally developing a convective core just before reaching the Zero Age Main Sequence (black dot-dashed line).

PRE-MS EVOLUTIONARY THEORY

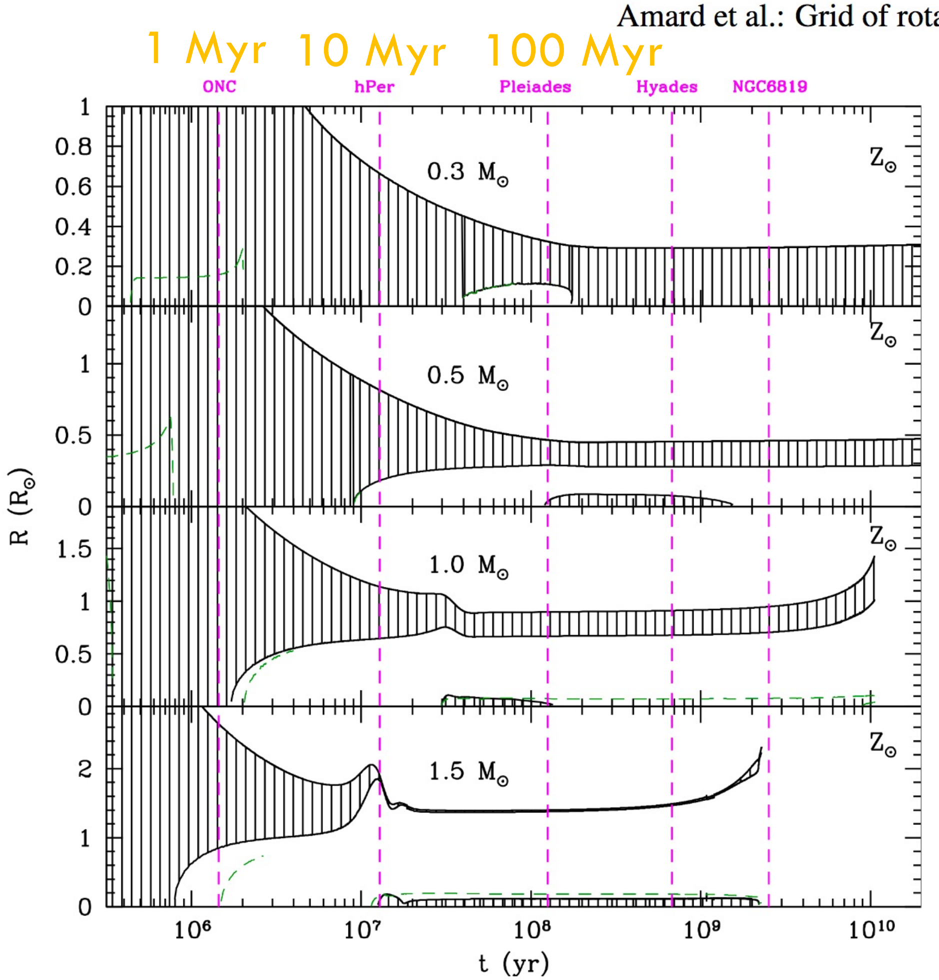


Fig. 5. Kippenhahn diagram showing the evolution of the internal structure of the non-rotating solar metallicity models of 0.3 (top), 0.5, 1.0 and 1.5 $M_\odot$ (bottom) from the PMS up to the end of the main sequence. The upper line represents the surface radius and hatched areas refer to convective regions. The green line displays the H-burning limit. The five pink vertical lines indicate the ages of open clusters used as markers of the evolution.

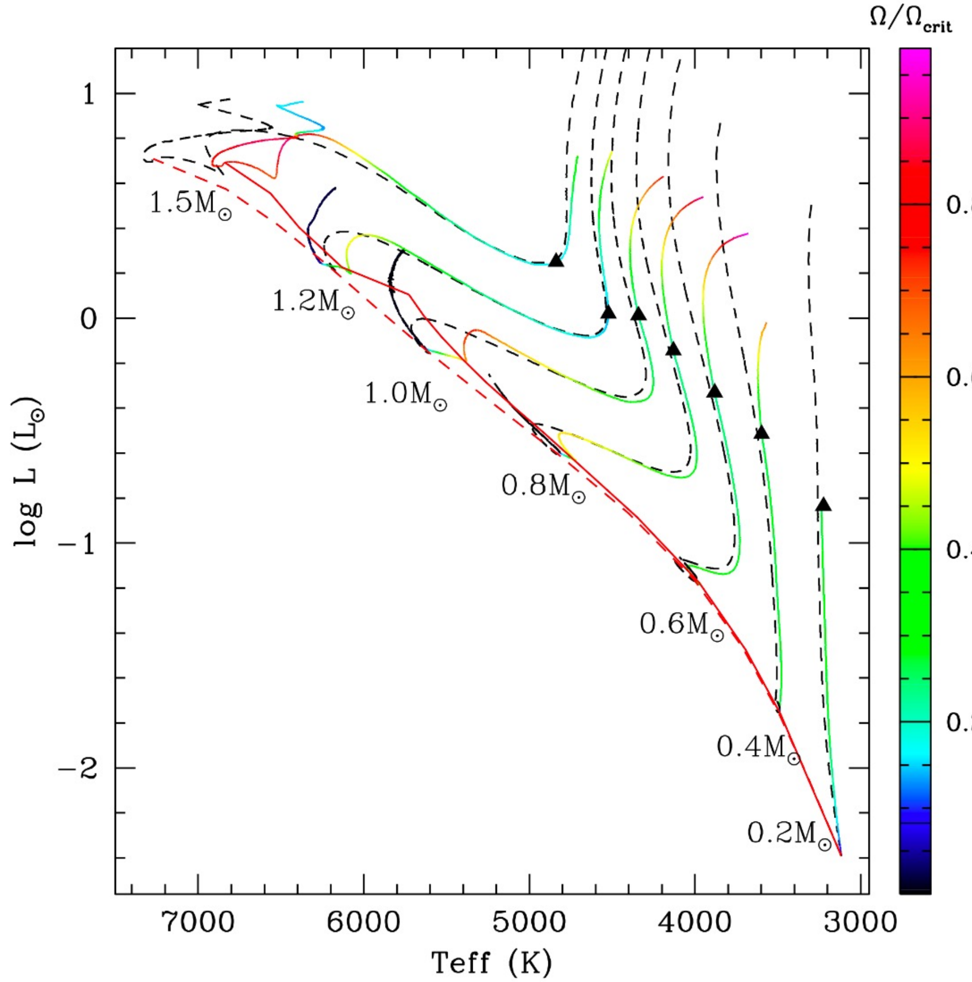
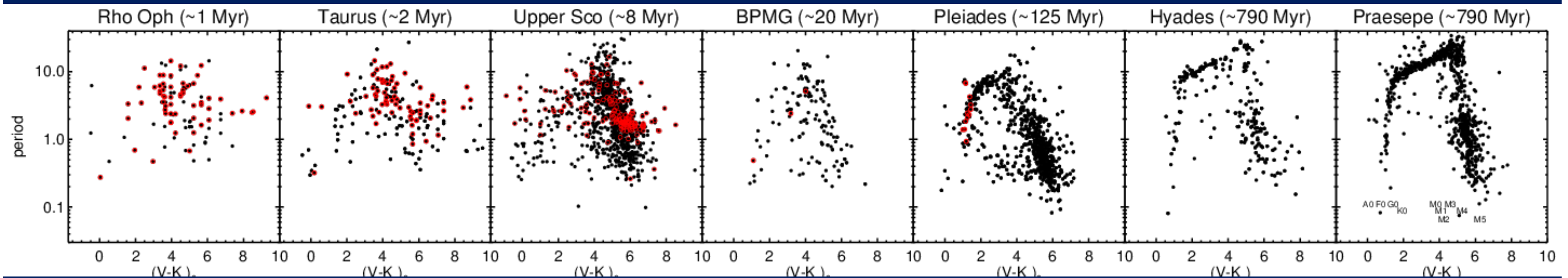


Fig. 4. HR diagram of solar metallicity models without (dashed black line) and with rotation (solid colored lines; here we show the fast rotators). The values of the surface velocity normalized to the break-up value (Ω/Ω_{crit}) increase from blue to red as shown on the right color bar. The black triangles indicate when the rotating models are released from their disc. The red lines indicate the standard (dashed) and rotating (solid) ZAMS.

PERIOD-AGE EVOLUTION VS STELLAR COLOR (MASS)

Rebull et al. 2016, 2017, 2018, 2019…



- Youngest stars have rotation regulated by "disk locking" – <u>no</u> period-mass relation.
- Once free of disk, spin-up en route to the main sequence (30 Myr @1 Msun).
- On main sequence, spin-down due to angular momentum loss via winds.

- Mass effects:
  - A,F stars have no dynamo and therefore no spots, so no measured periods.
  - G,K, and early M stars exhibit age-dependent period-mass relationship.
  - late M stars (fully convective) remain rapidly rotating for at least ~1 Gyr.

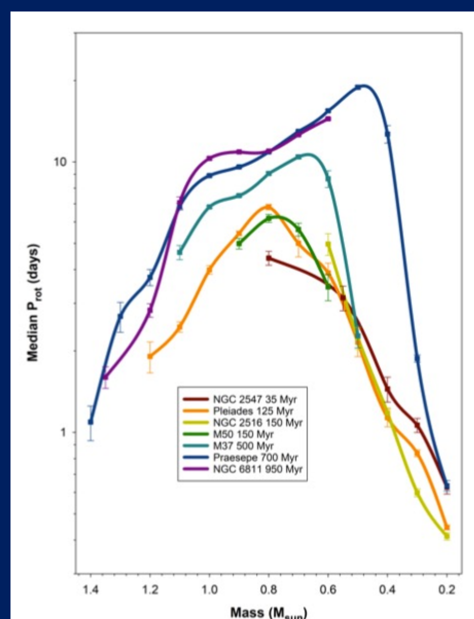
ON THE MAIN SEQUENCE STARS SPIN DOWN AS THEY AGE DUE TO WINDS

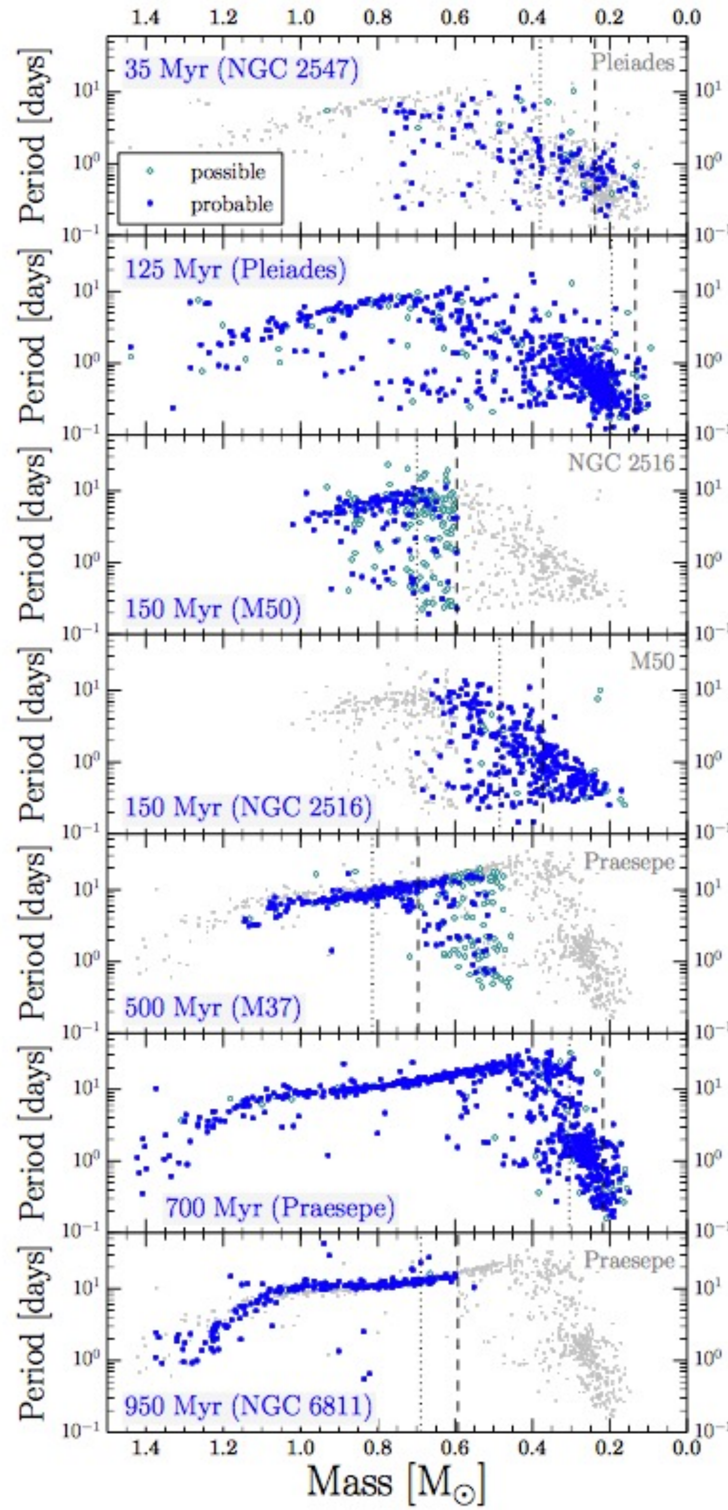
rough mass-dependency.

roughly monotonoic spin-down above 0.5 Msun.

however, some stars are slow to catch on, and remain rapid rotators far longer than their presumably co-eval cluster peers.

below 0.5 Msun, a wide range of rotation rates is maintained up to 1Gyr or more.





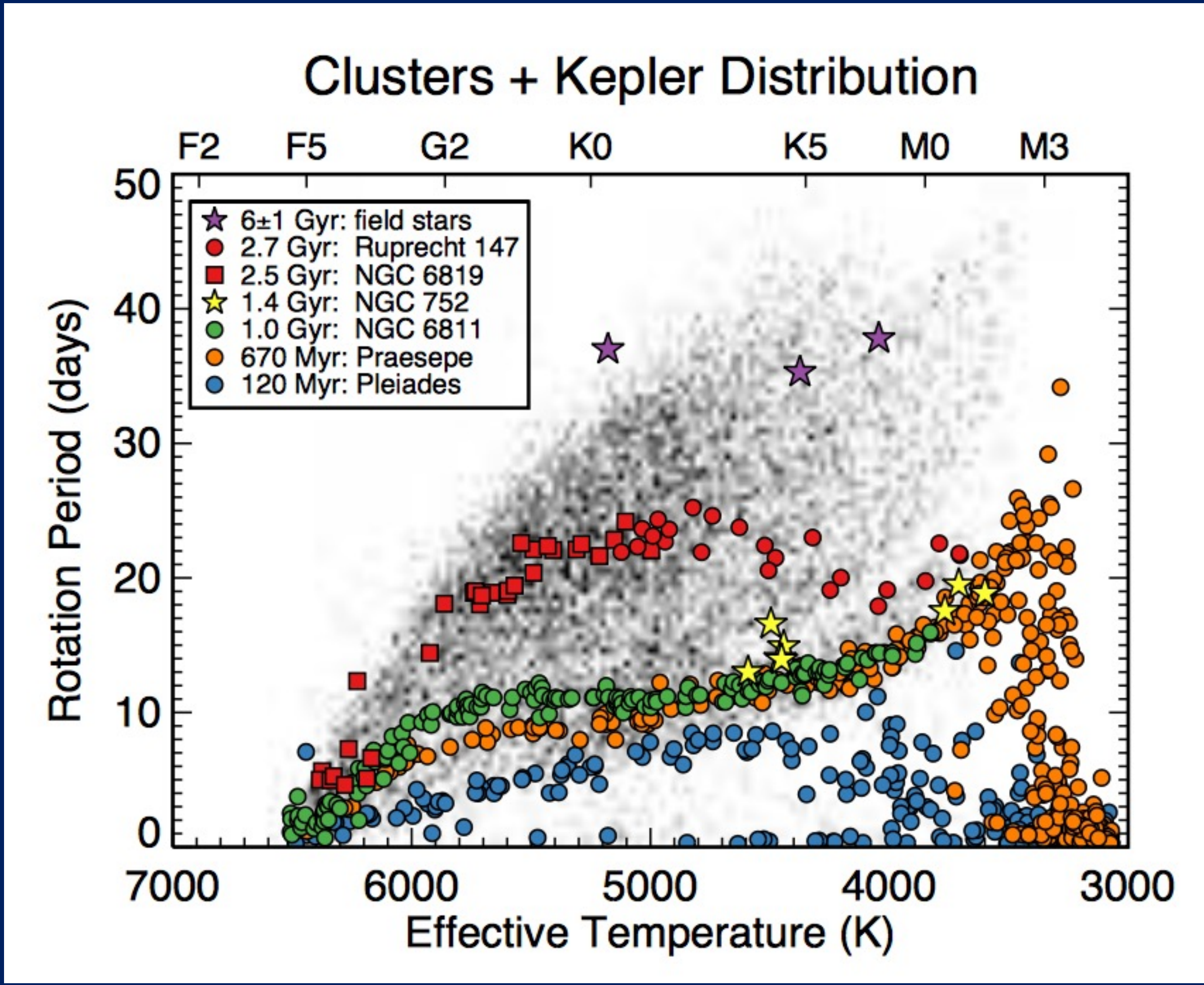
[Godoy-Rivera et al. 2021]

AGES FROM PROBES OF ANGULAR MOMENTUM

measurements:

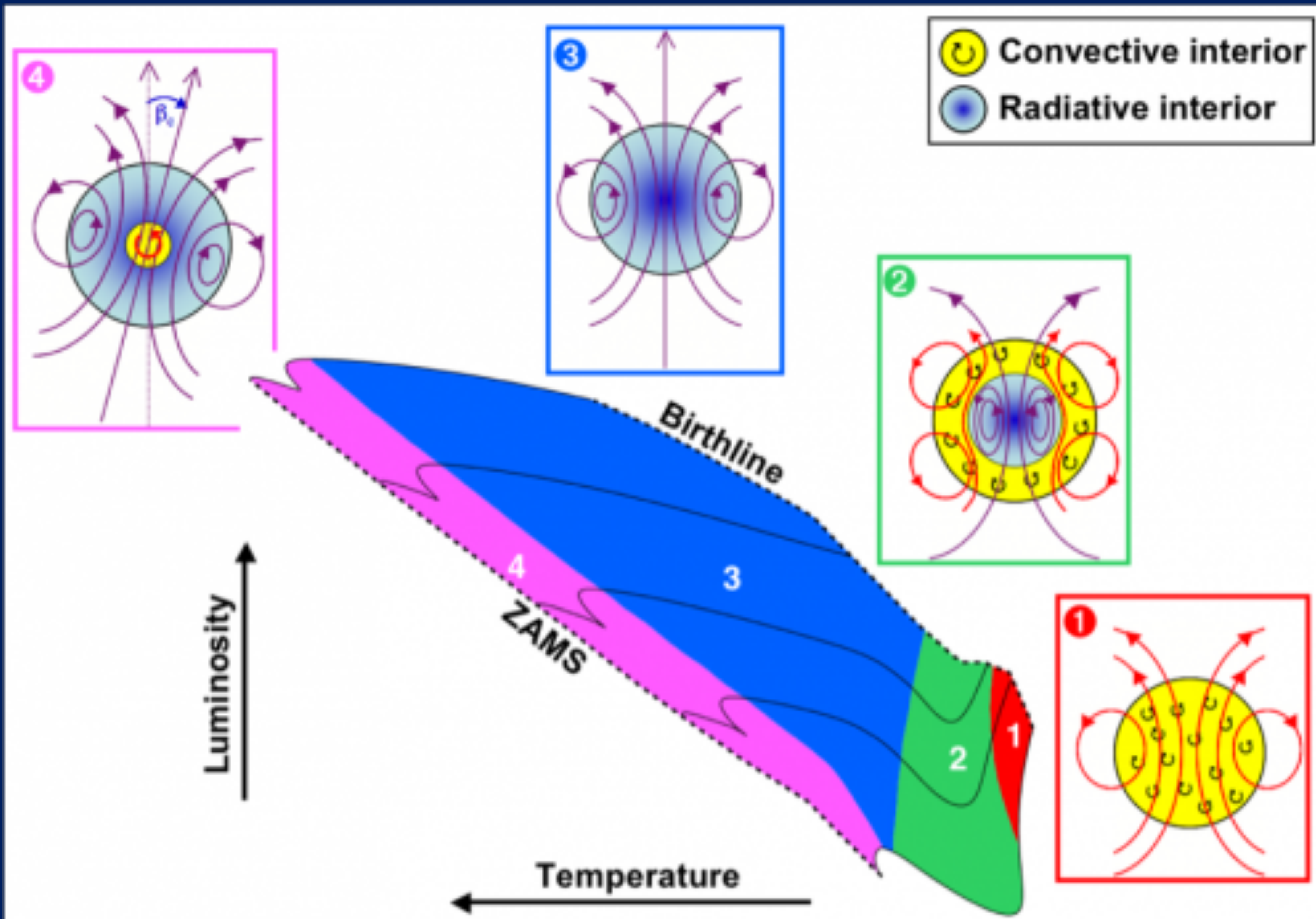
- time series photometry
  ➔ period

- high dispersion spectrum
  ➔ rotational velocity



[Curtis et al 2020]

STELLAR SURAFCE ACTIVITY ALSO CHANGES WITH MASS/AGE



Alecian et al.

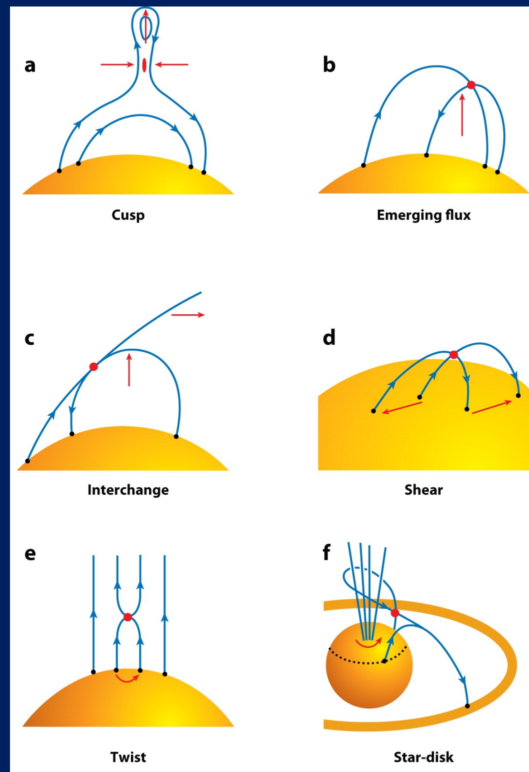
PROBES OF "ACTIVITY"

Xray luminosity

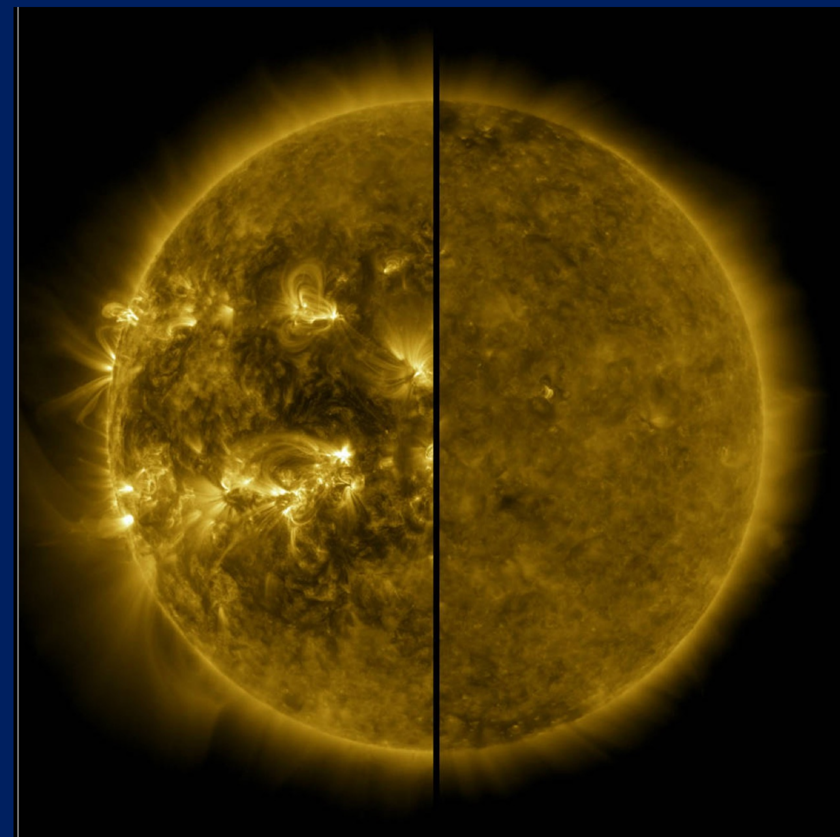
UV continuum excess

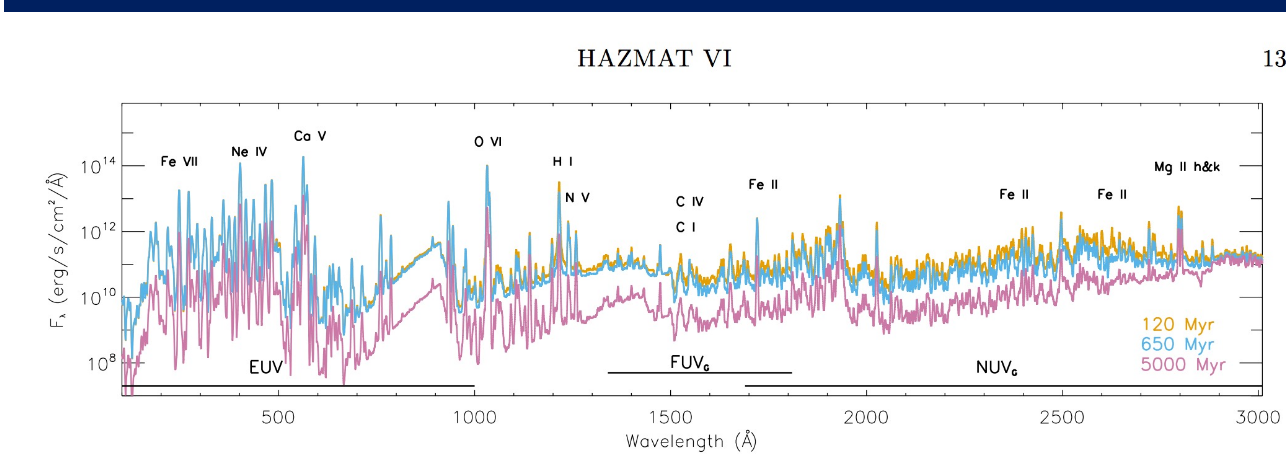
Chromospheric lines

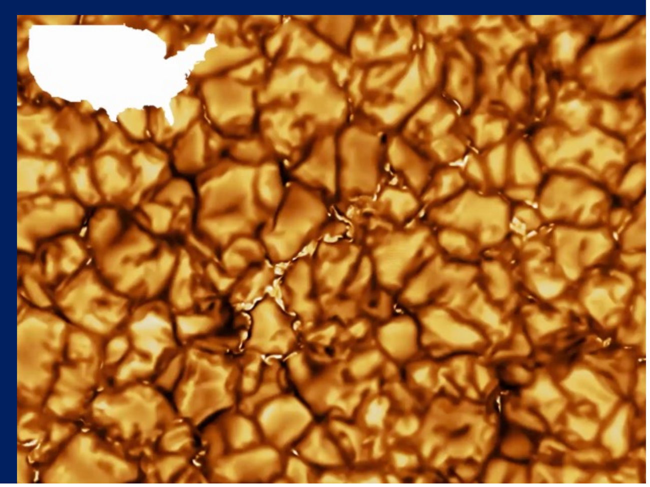
Flaring



Benz AO, Güdel M. 2010.
Annu. Rev. Astron. Astrophys. 48:241–87







ACTIVITY-AGE RELATIONS → P(AGE)

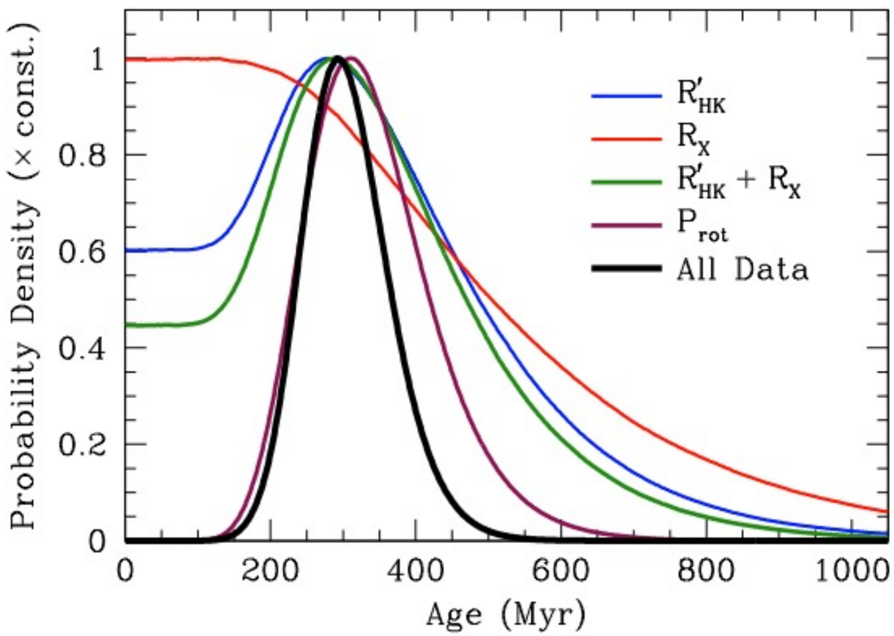


FIG. 2.— The calculation of an age probability distribution for a target, HIP 107350, without a reliable moving group age. HIP 107350 has an exceptional array of secondary age indicators, which enable a good constraint on its age. Most other stars without kinematic ages have much broader posterior probability distributions.

Brandt et al. (2014)

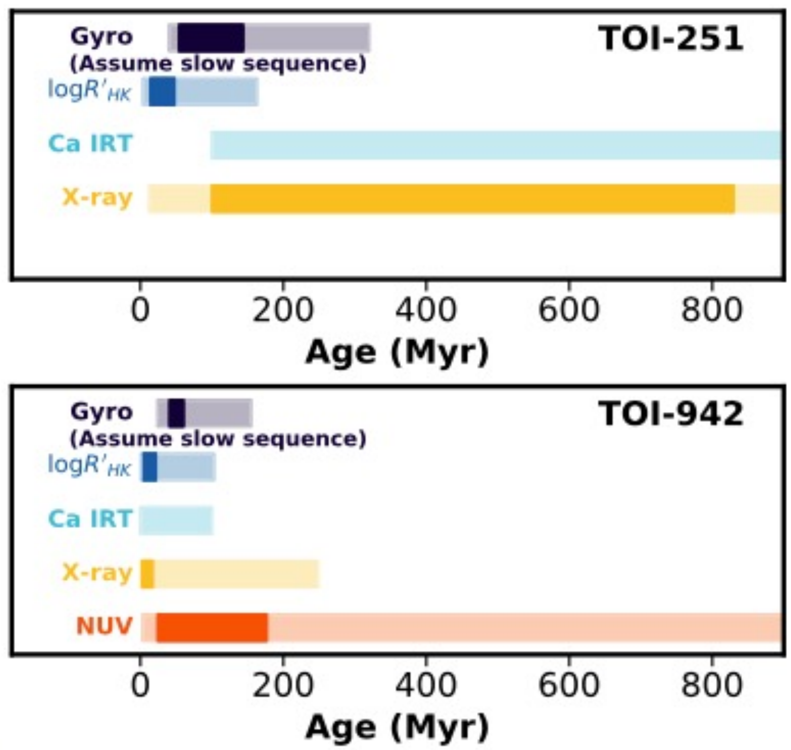


Figure 18. Summary of the age–activity indicators for TOI-251 and TOI-942. The 1σ (darker) and 3σ (lighter) age ranges from gyrochronology and spectroscopic and photometric activity indicators are marked. We adopt a final age estimate for TOI-251 of 40–320 Myr and for TOI-942 of 20–160 Myr.

Zhou et al. (2021)

MAGNETIC FIELD MEASUREMENTS

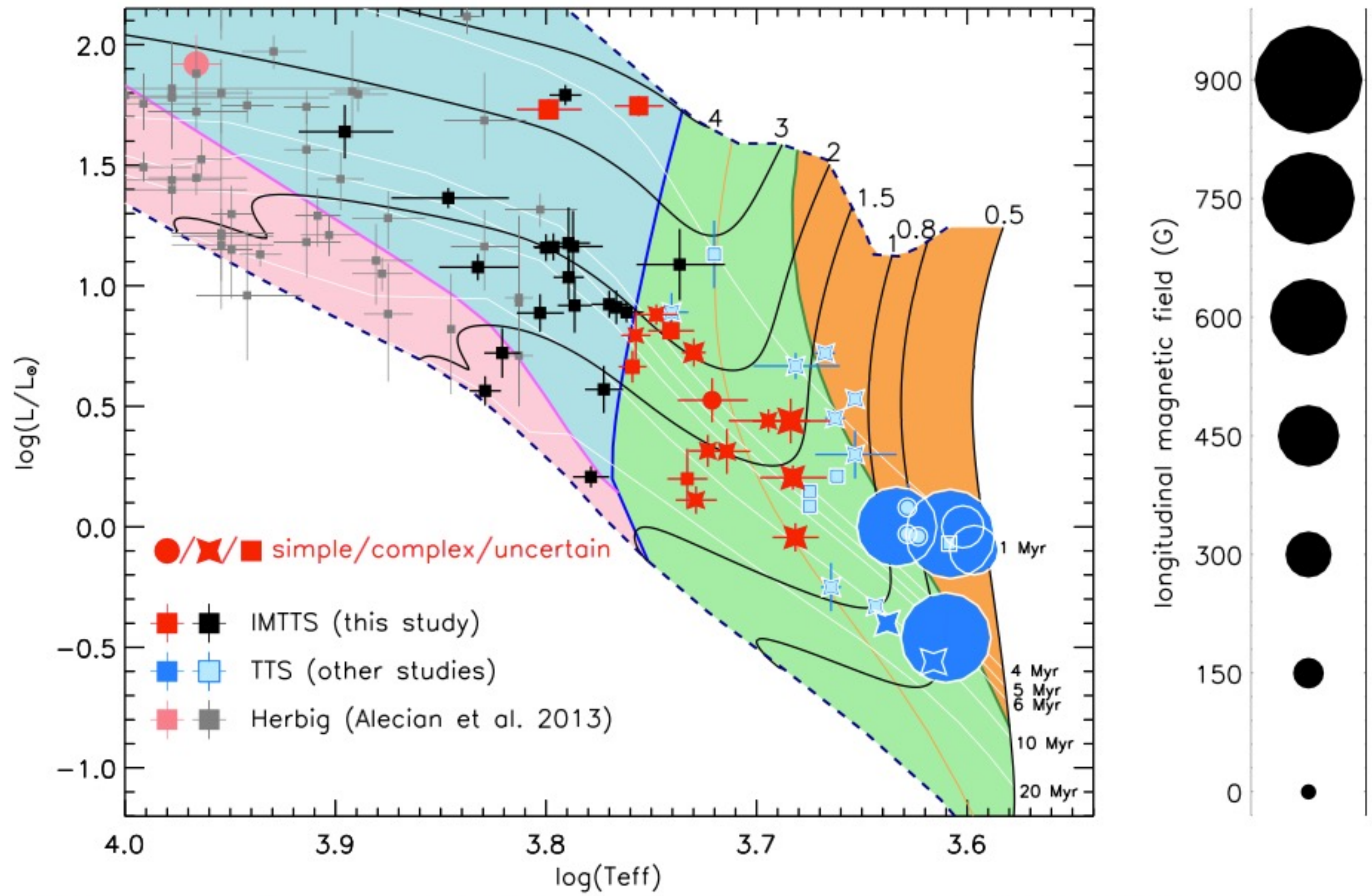


Fig. 1. HR diagram compiling the positions of IMTTS from this study (red and black symbols), and of IMTTS and LMTTS (blue symbols), and HAeBes (faded symbols) from other studies. Black and gray symbols are stars in which no magnetic field has been detected. Red and blue symbols are stars for which a magnetic field has been detected: stars represent complex magnetic topologies, circles represent simple magnetic topologies, and squares represent undefined magnetic topologies. The sizes of the red and dark blue symbols are proportional to the maximum absolute value of the longitudinal magnetic field measurements for each star. A light blue symbol means no such measurement is available. The youngest magnetic HAeBe star (HD 190073) is indicated on the top-left corner as an isolated red circle. The shaded areas have the following meaning; orange: fully convective; green: radiative core + convective envelope; blue: fully radiative; and pink: convective core + radiative envelope. The evolutionary tracks (solid black line, ranging from 1.0–4.0 $M_\odot$), isochrones (solid white line) and ZAMS (lower dashed line) are from the CESAM code, while the birthline (upper dashed line) is from Behrend & Maeder (2001). The numbers above each evolutionary track are the stellar mass in solar units. The numbers beside each isochron is the stellar age. The thin orange line is the location where $R_{\text{conv.env.}}/R_\star = 40\%$.

Villebrun et al. 2019

K2-33; David et al (2016)

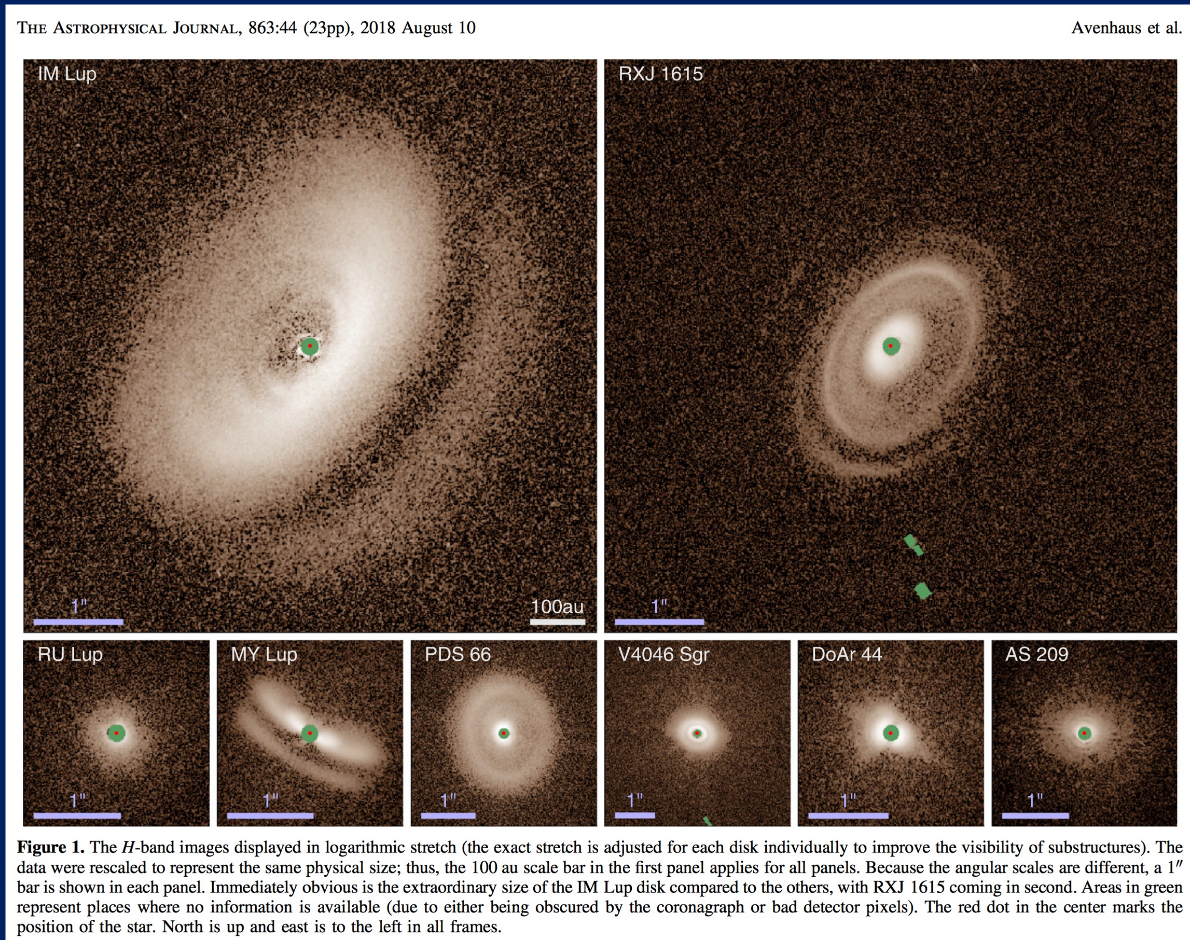
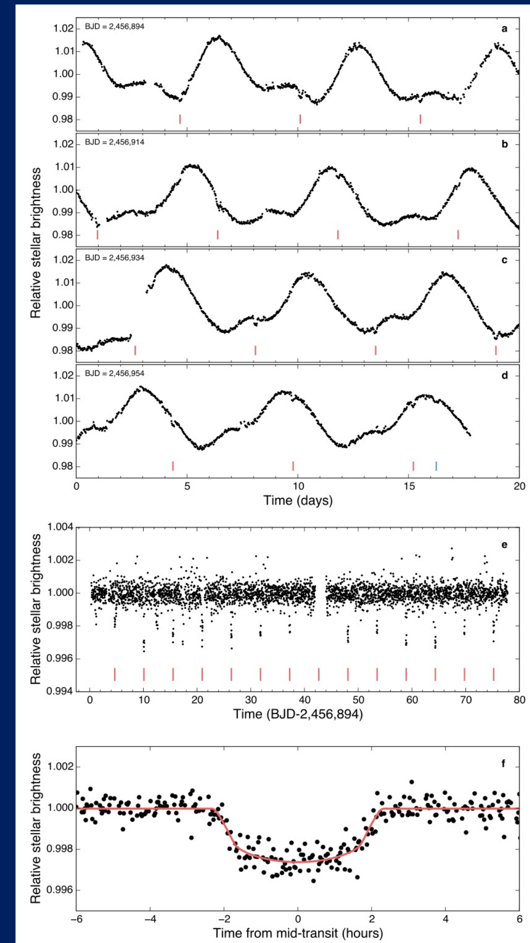

The Astrophysical Journal, 863:44 (23pp), 2018 August 10 Avenhaus et al.

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.



CLOSING REMARKS