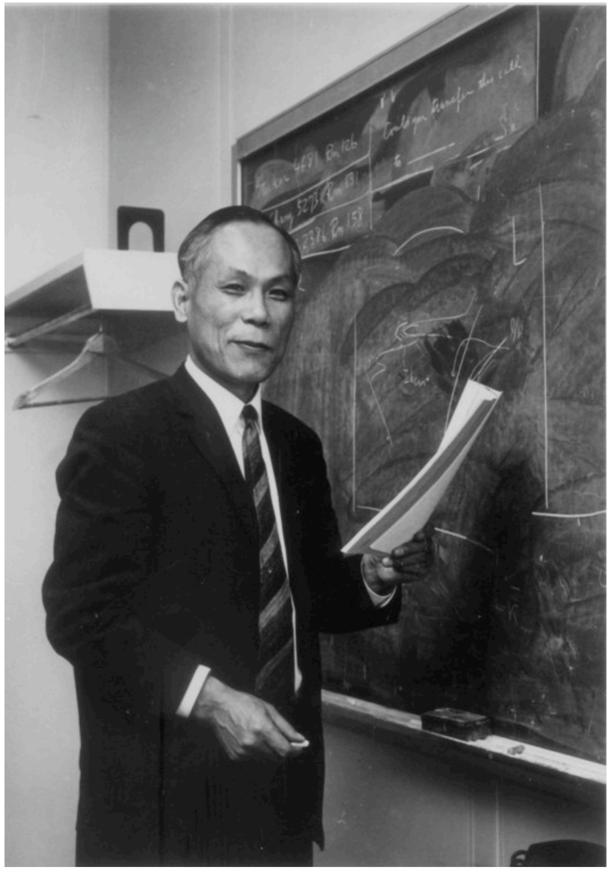
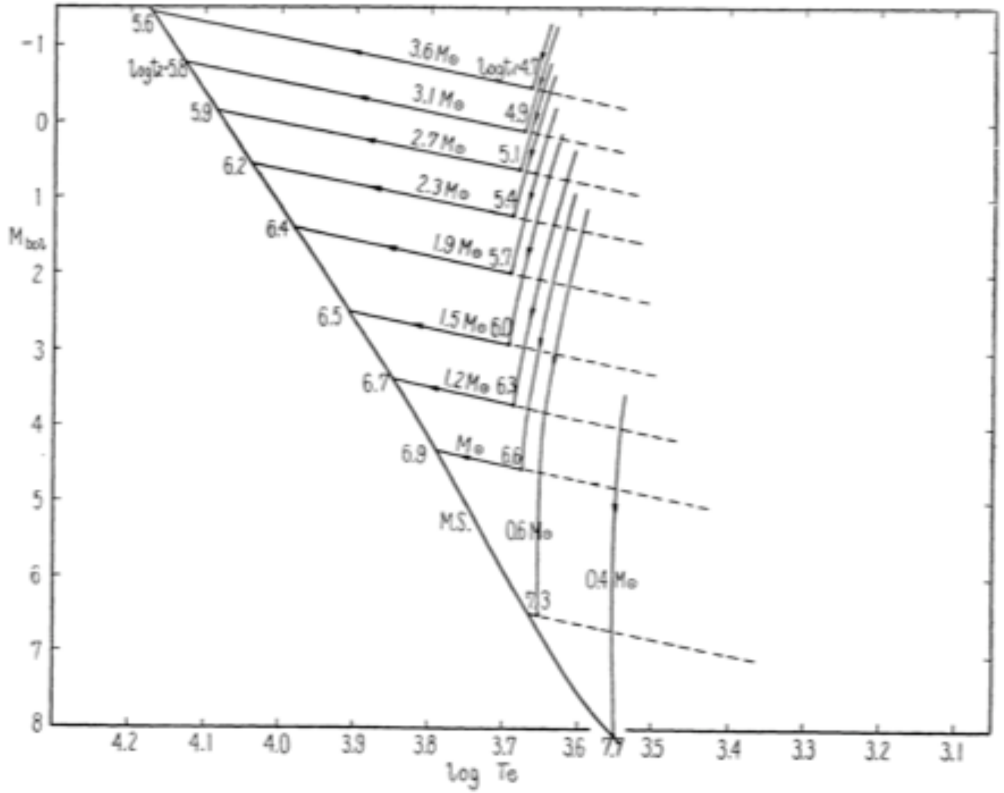


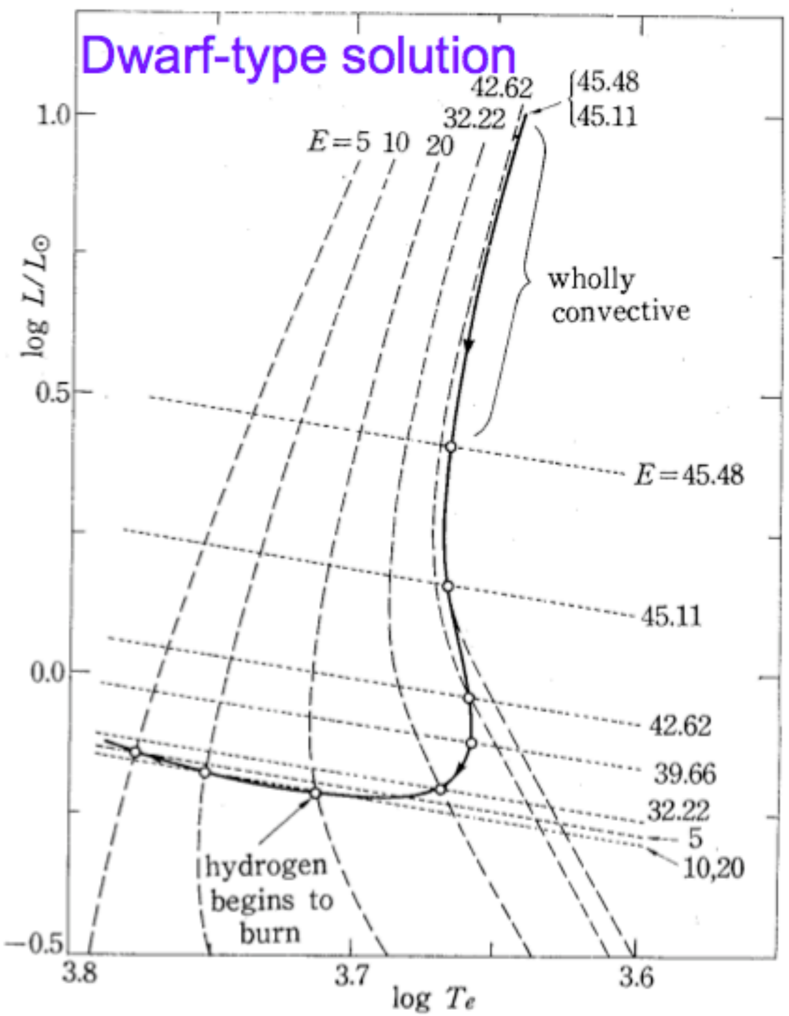


1961-2011:
50(+1) Years of Hayashi Tracks

Francesco Palla - Osservatorio di Arcetri

Kyoto, May 21, 2012

Pre-MS Evolution: classical theory



Hayashi Phase 1961

PMS contraction initially fully convective case: 1 M_0

HHS 1962

lower T_{eff} for larger E

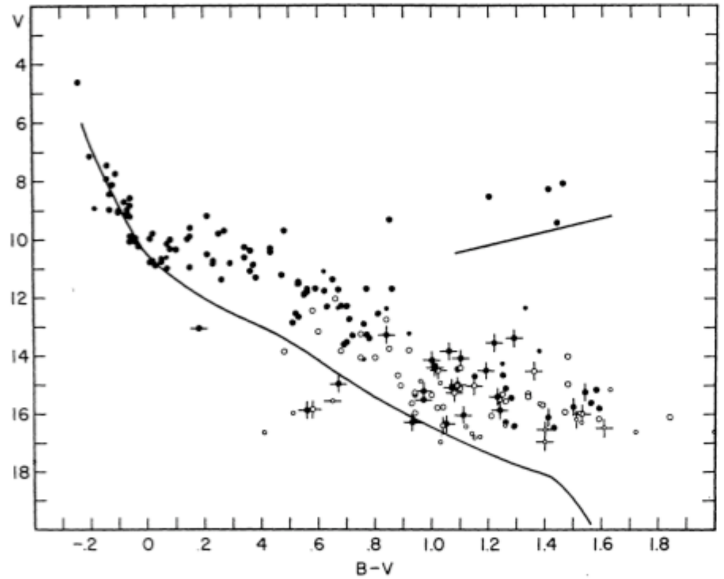
Comparison with Observations

STUDIES OF EXTREMELY YOUNG CLUSTERS. I. NGC 2264

MERLE F. WALKER*
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington, California Institute of Technology
Received May 21, 1956

ABSTRACT

Three-color photoelectric and photographic observations of NGC 2264 have been obtained to $V = 17$, in order to investigate the color-magnitude diagram of an extremely young cluster of stars. The diagram indicates that the cluster possesses a normal main sequence extending from O7 to A0, below which the stars fall above the main sequence. The reality of this effect has been confirmed by spectroscopic observations. The shape of the color-magnitude diagram agrees approximately with that predicted theoretically for clusters which are so young that the fainter stars are still in the process of contracting gravitationally from the prestellar medium and have not yet reached the main sequence. The age of the cluster given by the point where the cluster stars depart from the main sequence is about 3×10^6 years.



Comparison with Observations: NGC 2264

452 C. HAYASHI [Vol. 13,

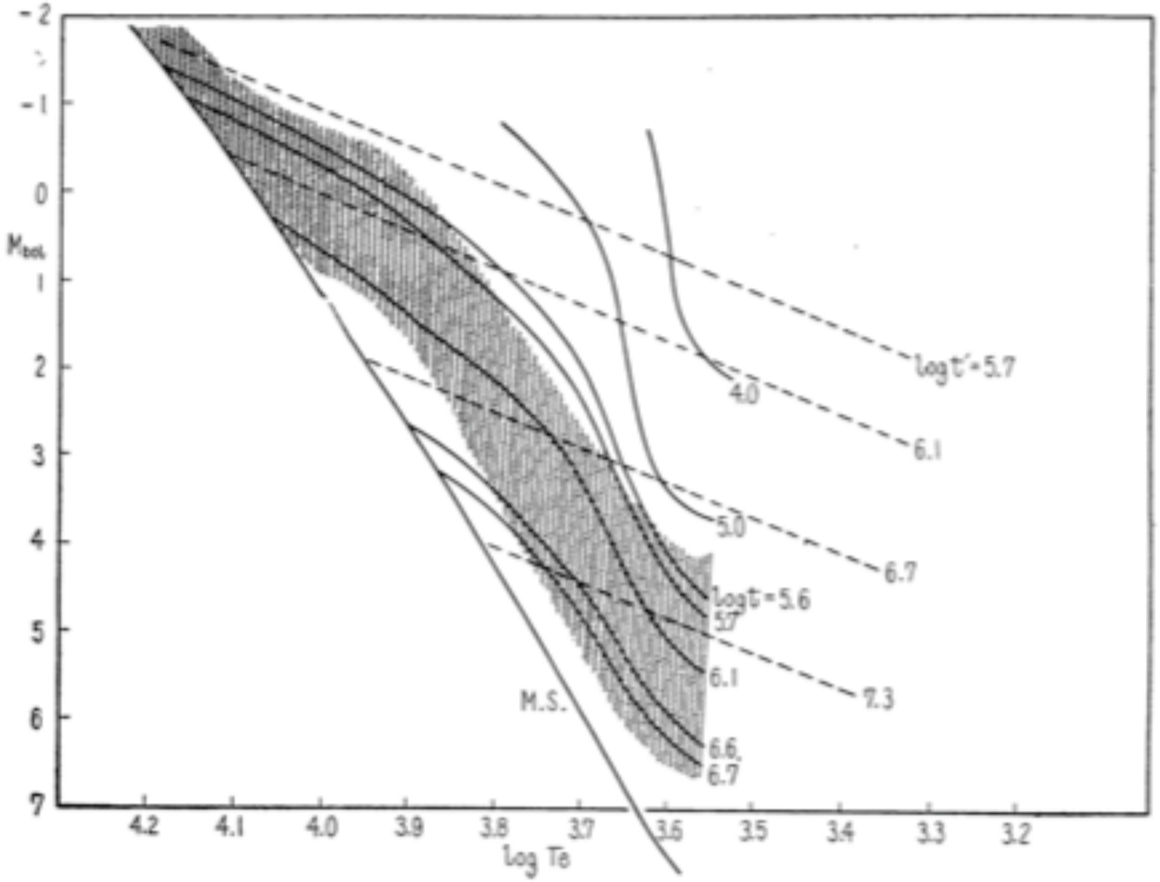


FIG. 3. Curves for constant ages for stars with different masses as compared with the *H-R* diagram of NGC 2264. Solid curves (t in years) and dotted lines (t' in years) correspond to the present calculation and to the results by SALPETER and HENYEY et. al., respectively.

Time Scales: much shorter!

Young Stars!

Pre-MS Evolution: classical theory

- *A PMS star contracts due to heat loss at a rate*

$$L_{surf} = 4\,\pi\,R_*^2\,\sigma\,T_{eff}^{\;4}$$

- *The star is fully convective*

$$S_{int} = constant$$

- *Homologous contraction on a timescale*

$$t_{KH} = GM_*^2 / R_* L \gg t_{sound} \rightarrow \textit{hydro equil.}$$

- *Star is fully convective due large radius*

$$R_* = 60\ (M_*/M_0)\ R_0 \rightarrow L_{surf}(M_*{=}1M_0) \sim 600\ L_0$$

$$L_{surf} \gg L_{rad} = L_0\ (M_*/M_0)^{5.5}\ (M_0/M_*)^{0.5}$$

- *Convection from the surface*

Pre-MS Evolution: M-R relation

- *A protostar of mass M and radius R forms from a cold, static cloud*

$$E_{int}\ (thermal+mechanical) = 0$$

- *The protostars is gravitationally bound with a negative total energy → energy is lost by radiation, dissociation & ionization*

$$\Delta E_{int} = XM_*/m_H\,[\Delta E_{diss}^{H2}/2 + \Delta E_{ion}] + YM_*\,\Delta E_{ion}^{He}/4\,m_H$$

- *The thermal energy is U=-W/2 and the virial theorem*

$$0 = -1/2\ GM_*^2 / R_* + \Delta E_{int} + L_{rad}\,t$$

- *If $L_{rad} = 0$, homologous & adiabatic contraction*

$$R_{max} = GM_*^2 / \Delta E_{int} \sim 60\ R_0\,(M_*/M_0)$$

Pre-MS Evolution: better approach

- *Models of contracting stars: convectively unstable, spatially constant entropy* → *homologous contraction*
- *Thermal evolution is simple*

$$t_{conv} << t_{contr} = t_{KH} = GM_*^2 / R_* L_*$$

- *Over* t_{KH} : $s_{int} \downarrow$ → $T_c \uparrow (\sim R_*^{-1})$
- *Since* $t_{KH} >> t_{sound}$ → *assume hydrostatic equilibrium despite slow quasi-static contraction*
- *Stars are not fully convective: contraction in* t_{KH}, *but non-homologous;* s *varies with* $t_{photon\ diff}$ → *variable!*

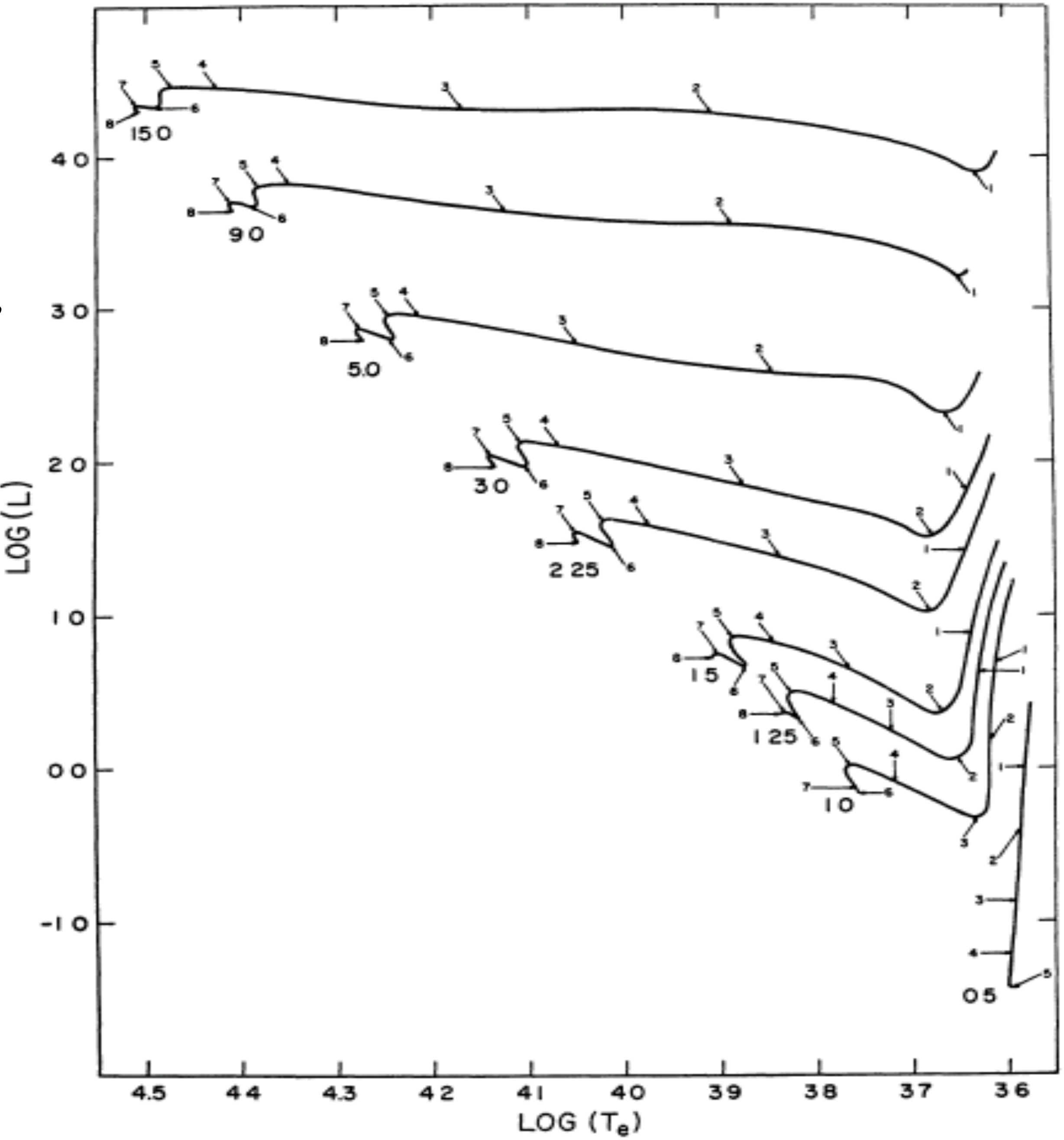
Pre-MS Evolution: standard theory

- *Stars move from the forbidden zone to the border*
- *They descend vertical paths*
- *They join radiative tracks*
- *They reach the Main Sequence*

The classical HR diagram

Iben 1965 ApJ

Stellar Evolution:
I. The approach to
The Main Sequence



Protostar & Pre-MS Evolution

- *Recall Hayashi's assumption*

$$0 = -1/2\ GM_*^2 / R_* + \Delta E_{int} + L_{rad}\, t$$

- *During collapse, gravit. energy ~ radiative energy*

$$R_* << R_{max}$$

- *Set* $M_{acc} = M_*/t$ *and* $L_{rad} \sim L_{acc}$

$$L_{acc} = G\, M_* M_{acc}\ /R_* \sim$$

$$60\ L_0\ (M_{acc}/10^{-5}\ M_0\, yr^{-1})\ (M_*/1\ M_0)\ (R_*/5\ R_0)$$

- $L_{rad} \sim L_{acc}$ *throughout main accretion phase*

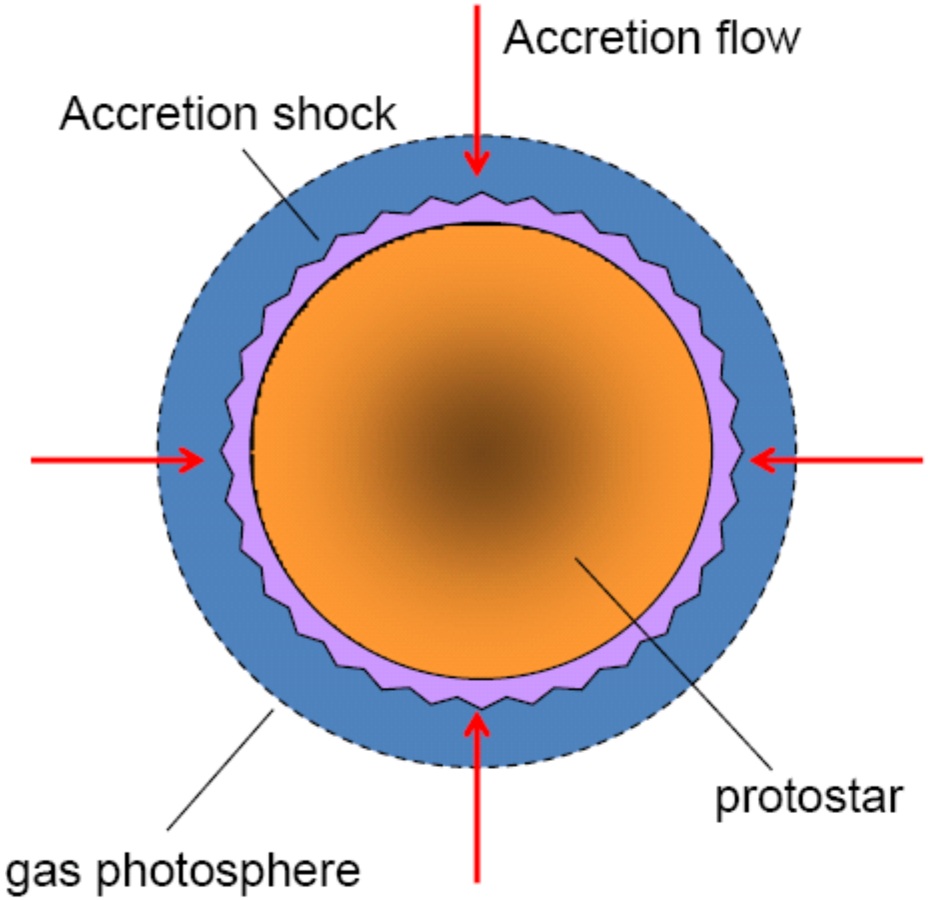
  L_{acc} *generated close to the protostar's surface*

  $L_{acc} > L_{nucl}\ ,\ L_{contraction}$ *for low- and intermediate mass stars*

Models of protostellar evolution

numerically solve the detailed structure of accreting protostars.

(e.g., Palla & Stahler '91, Omukai & Palla '03)



Basic eq.: 4 stellar structure eqs.

Continuity : $\dfrac{\partial r}{\partial m} = \dfrac{1}{4\pi\rho r^2}$

Momentum : $\dfrac{\partial P}{\partial m} = -\dfrac{Gm}{4\pi r^4}$

Energy : $\dfrac{\partial l}{\partial m} = \epsilon_{\rm nuc} + T\left(\dfrac{\partial s}{\partial t}\right)_m$

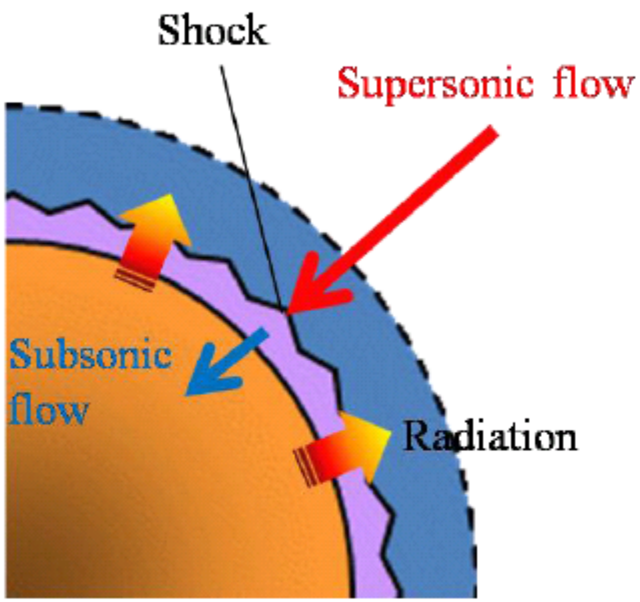
Heat transport : $\dfrac{\partial T}{\partial m} = -\dfrac{T}{P}\dfrac{Gm}{4\pi r^4}\nabla$

connected with outer (steady) accretion flow using shock jump condition

- constant acc. rate: $10^{-6} M_\odot/\mathrm{yr} \le \dot{M} \le 10^{-2} M_\odot/\mathrm{yr}$

Effects of geometry of accretion

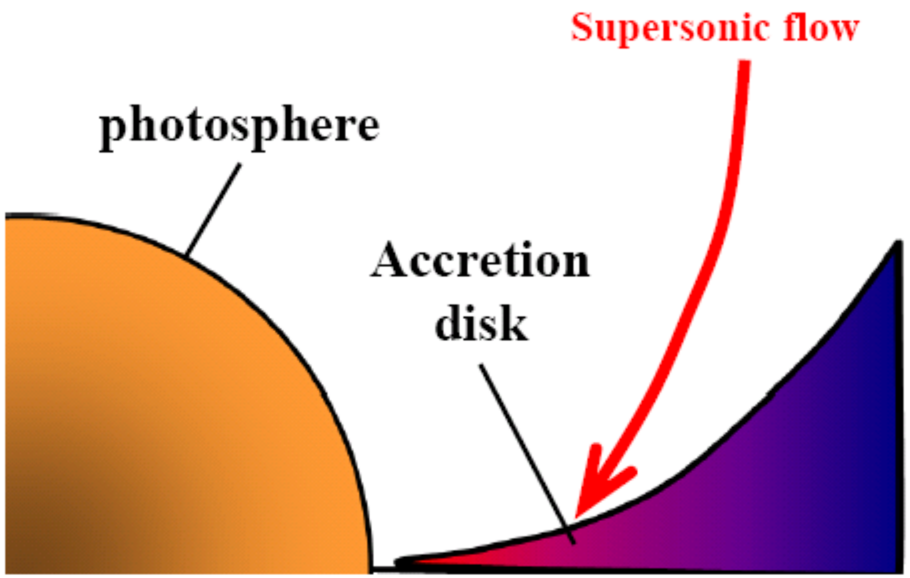
Shock boundary condition



Accretion flow structure is solved, and connected with the protostar by the shock jump condition

High influx of entropy

Photospheric boundary condition



Gas softly accretes to the protostar through the disk. Flow structure is not solved, but ordinary photospheric boundary is adopted.

Low influx of entropy

Protostar & Pre-MS Evolution

- *Protostar: a mass gaining star whose luminosity stems from external accretion*

- *Assume: - that the relation M_p vs R_p determines the initial conditions for PMS contraction*

  - that $t_{PMS} < t_{acc}$

- *Then, follow standard PMS evolutionary tracks…*

Pre-MS Evolution: standard theory

- *Stars move from the forbidden zone to the border*

yes, but HRD much more reduced

- *They descend vertical paths*

yes & not: not all of them do

- *They join radiative tracks*

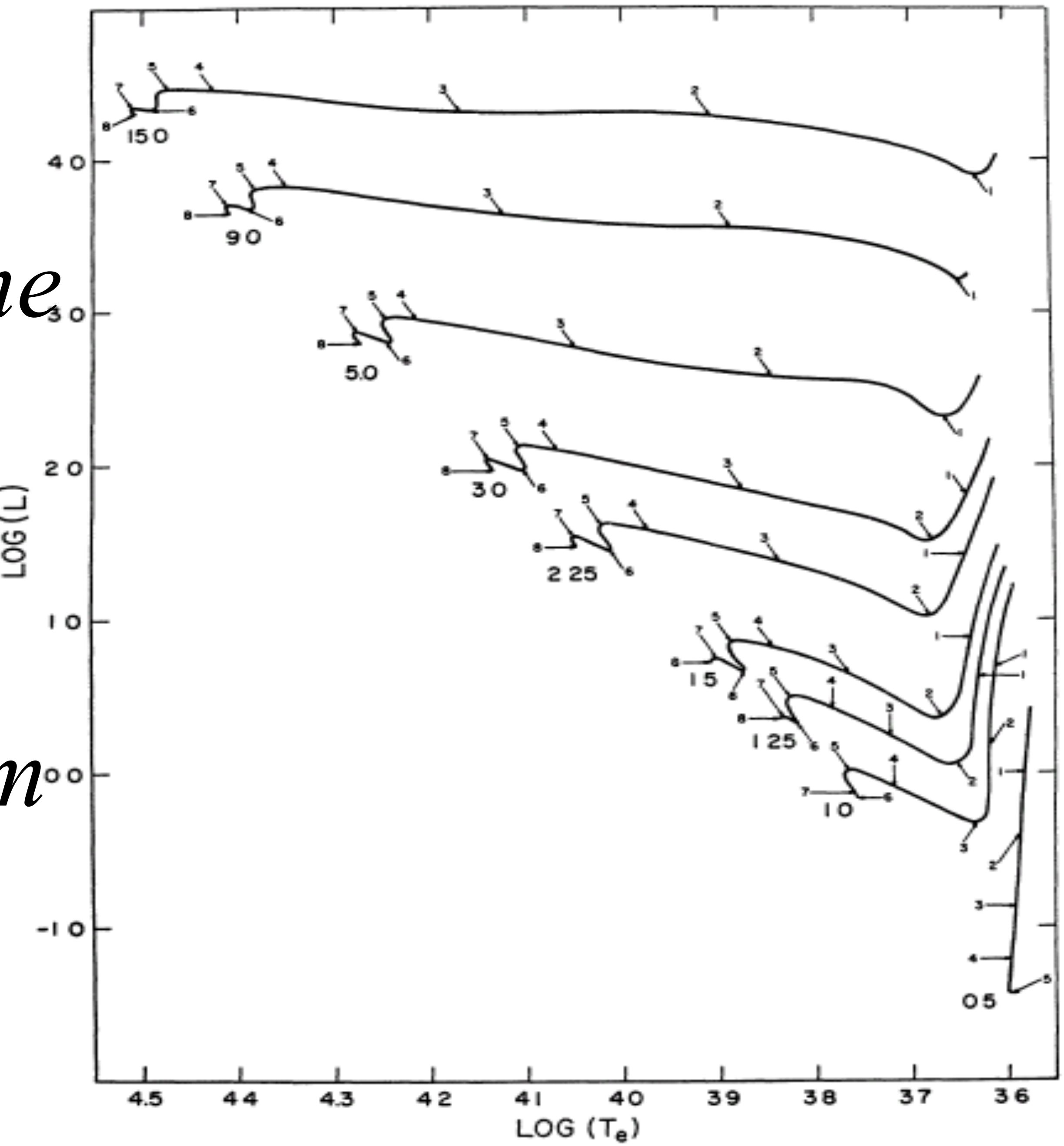
yes, all of them

- *They reach the Main Sequence*

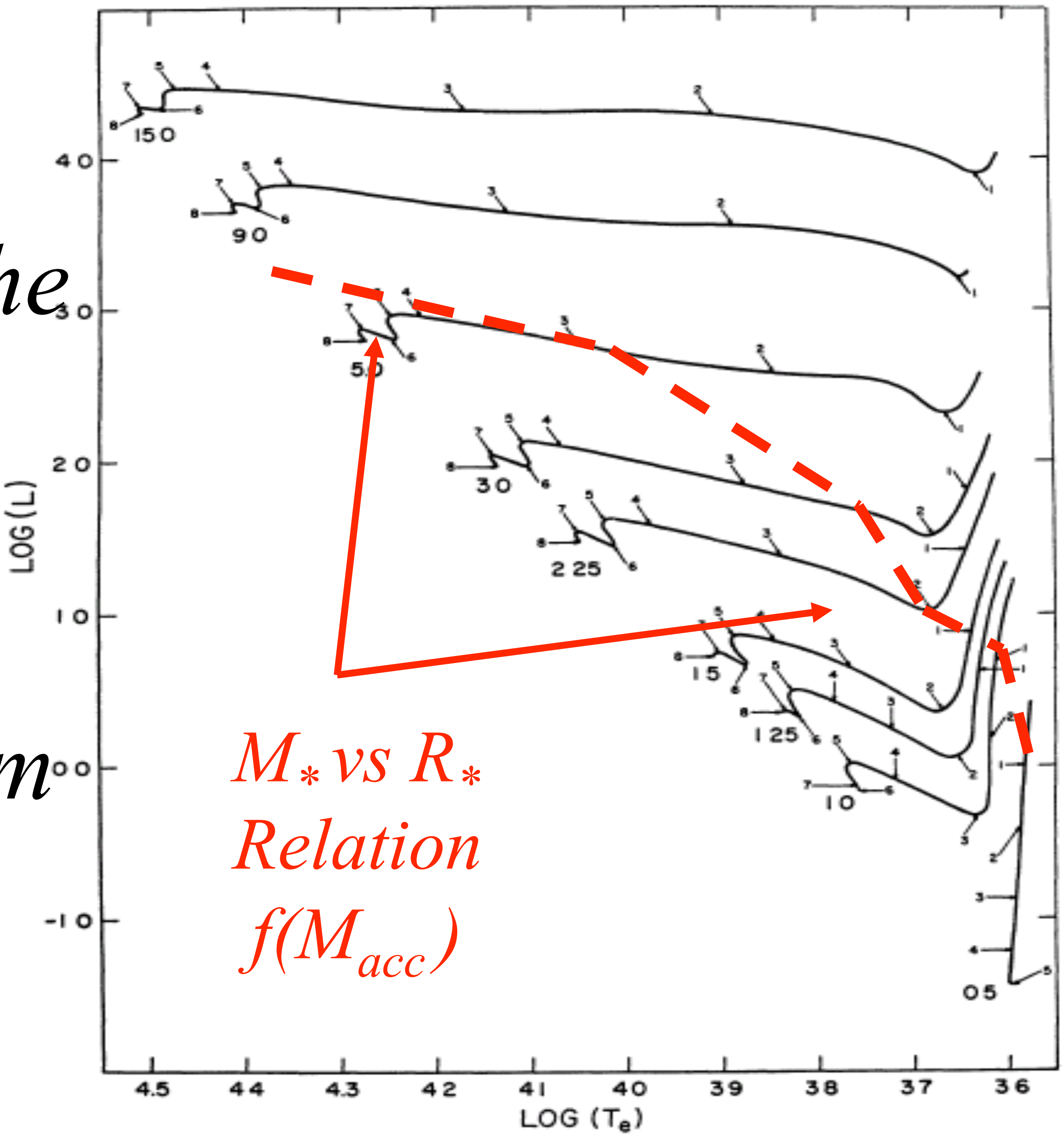
indeed! ... but massive stars are born on the MS

A modern HR diagram

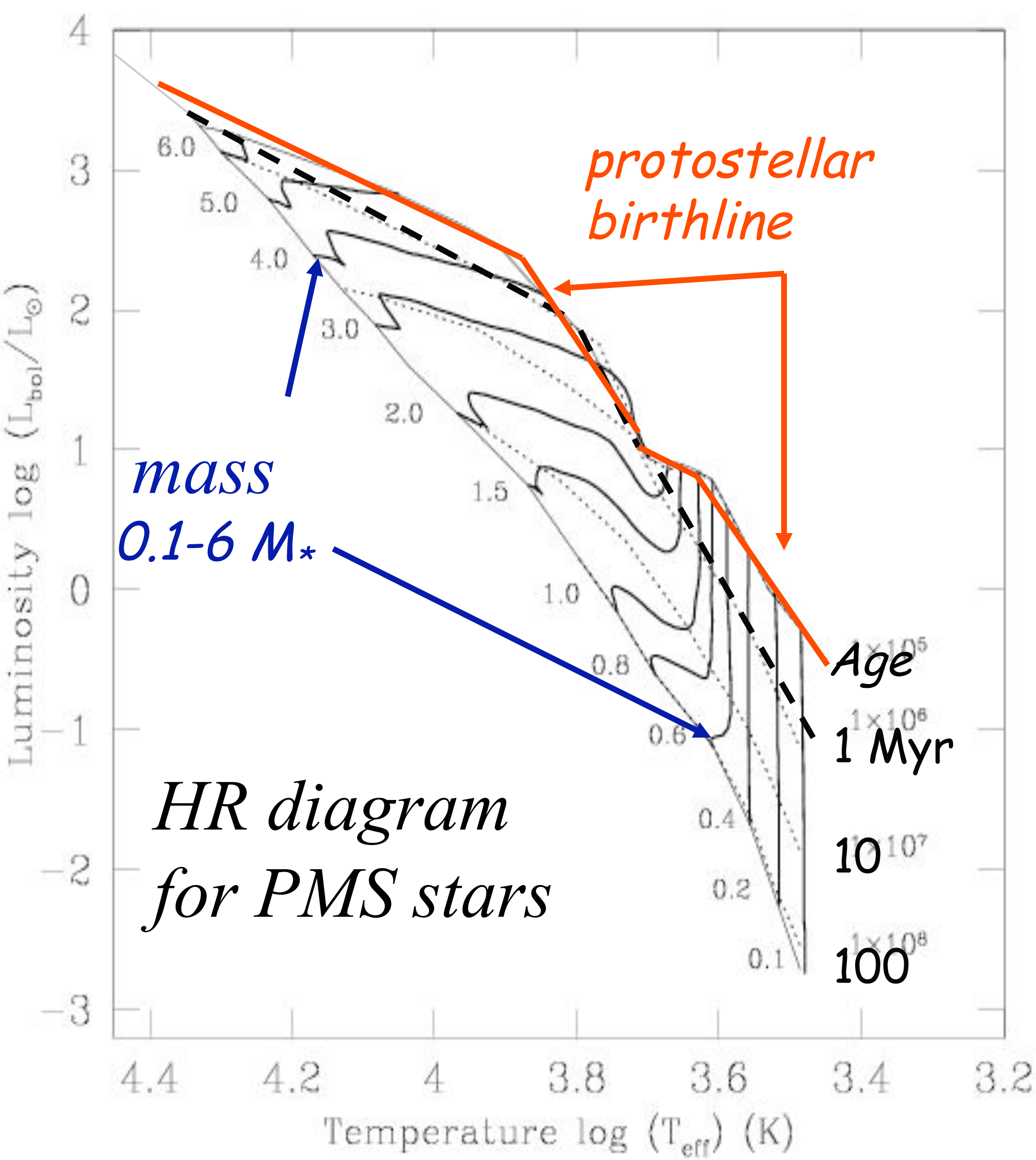
Impact of the M – R Relation on the HR diagram



Impact of the $M-R$ Relation on the HR diagram



PMS evolution: main features



low :<2 M_0

unchanged
no D-MS
tests: Li-depl, binaries

intermediate:~2-8 M_0

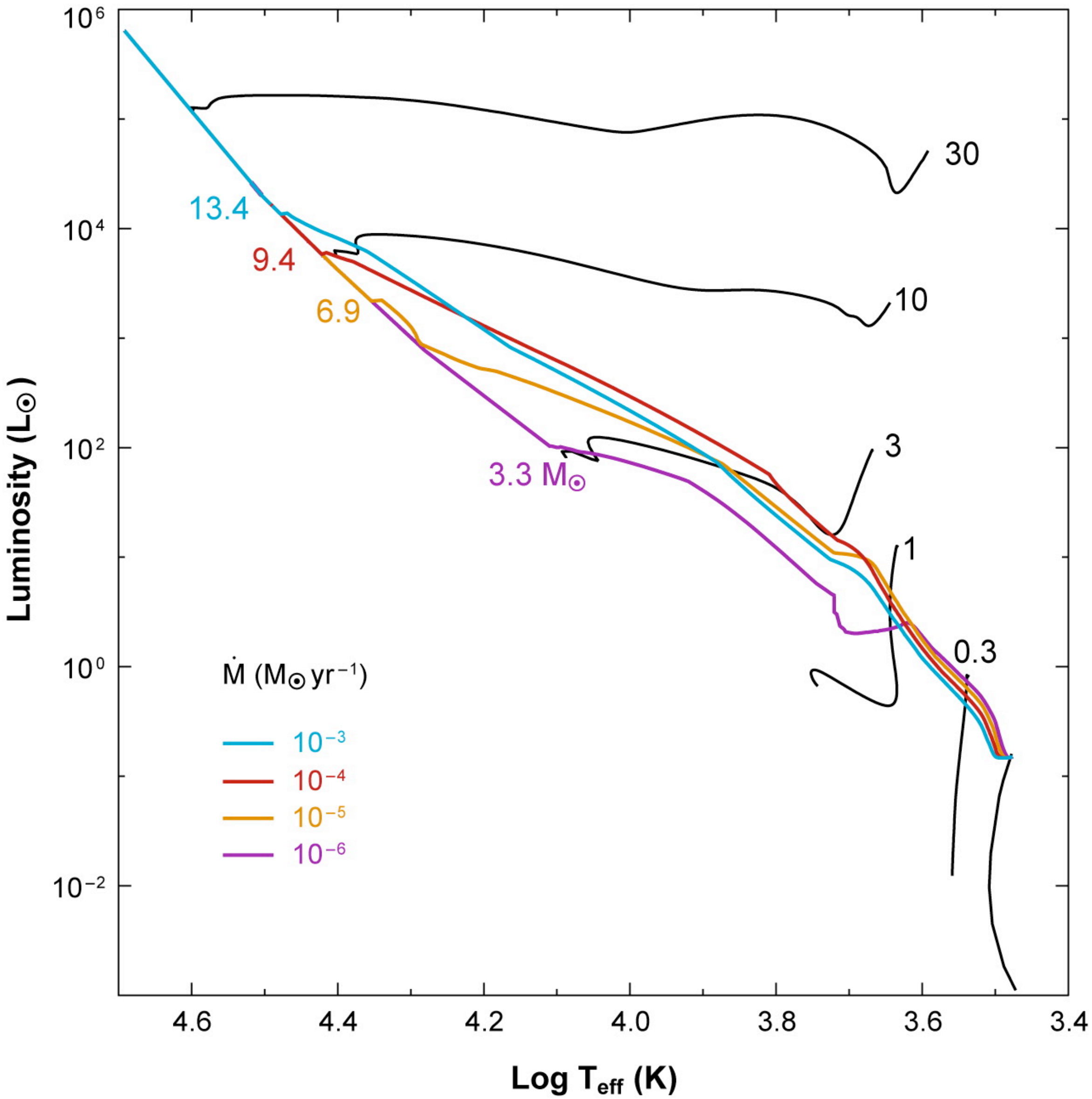
thermal relaxation
no convection
short life time

high: >8 M_0

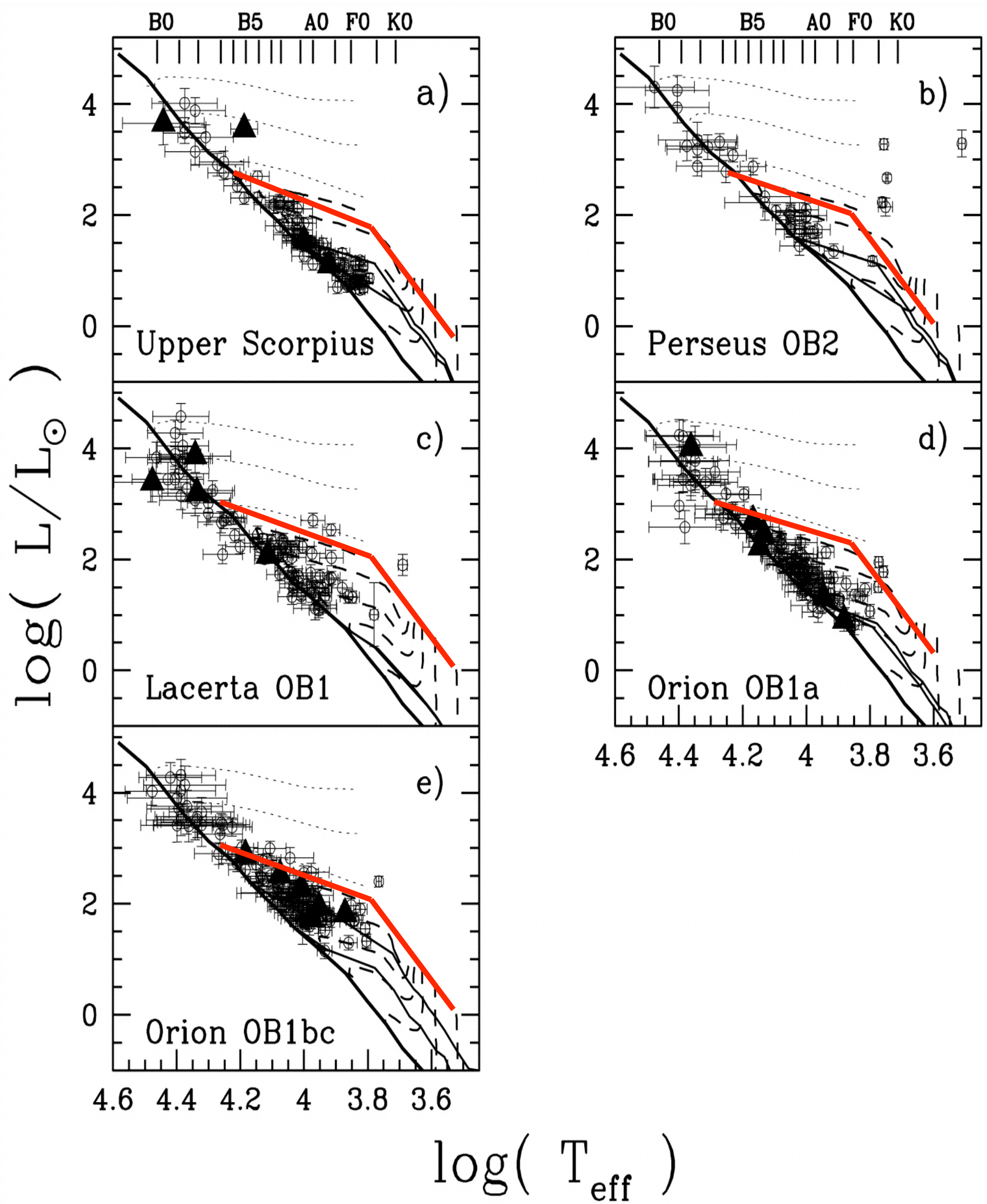
no PMS phase
H-burning
stars on ZAMS

Palla & Stahler 1993,1999

Protostellar models with different accretion rates & the HRD



Zinnecker H, Yorke HW. 2007.
Annu. Rev. Astron. Astrophys. 45:481–563



Census of Herbig stars in nearby OB assoc's:

440 Hipparcos stars d<500 pc,age: 3-16 Myr

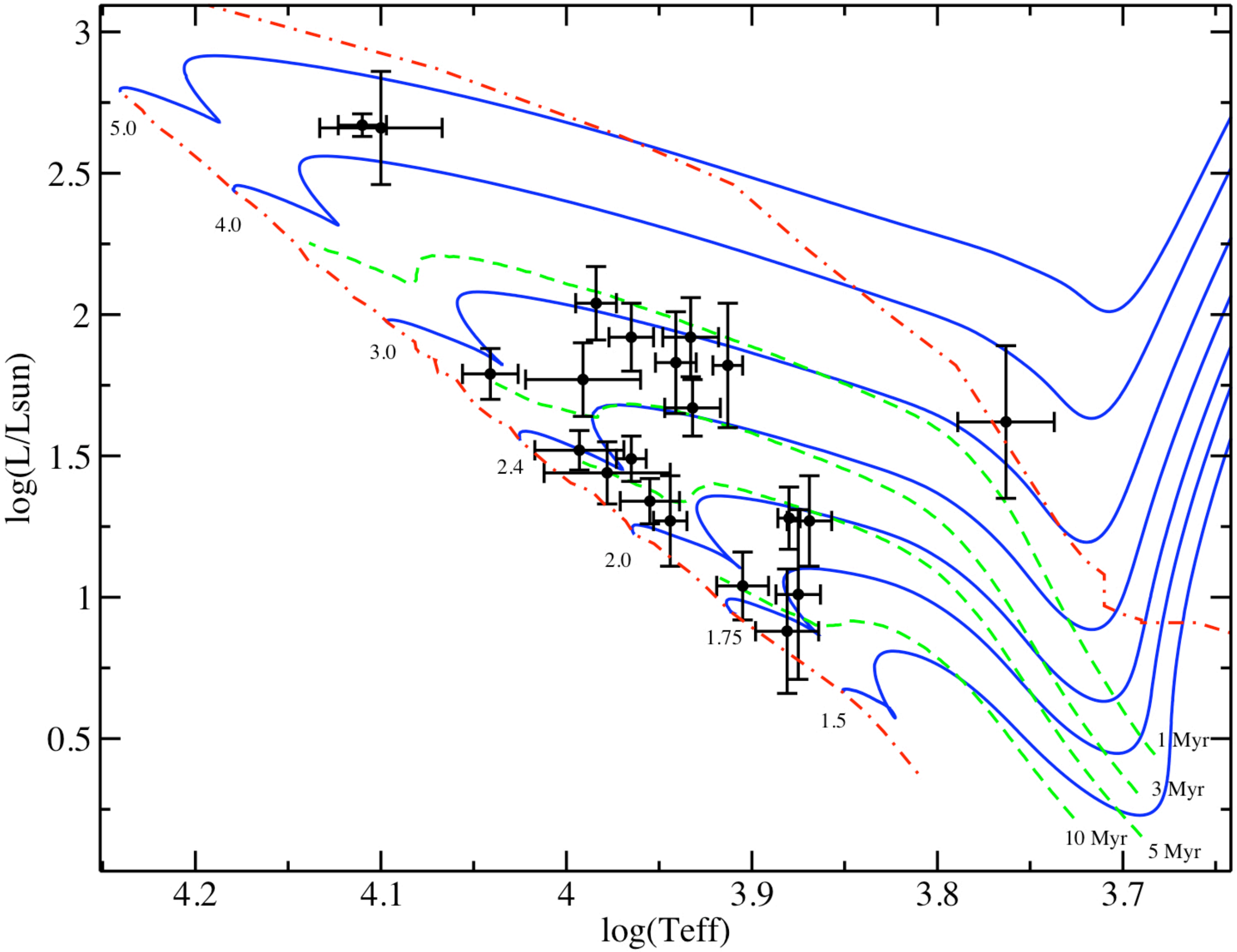
good match with HRD

inner disk frequency lower by factor of ~10 than in low-mass stars: rapid disk evolution

Hernandez + 2005

Sample of Herbig Ae/Be stars

(2011, Bagnulo et al. MNRAS)



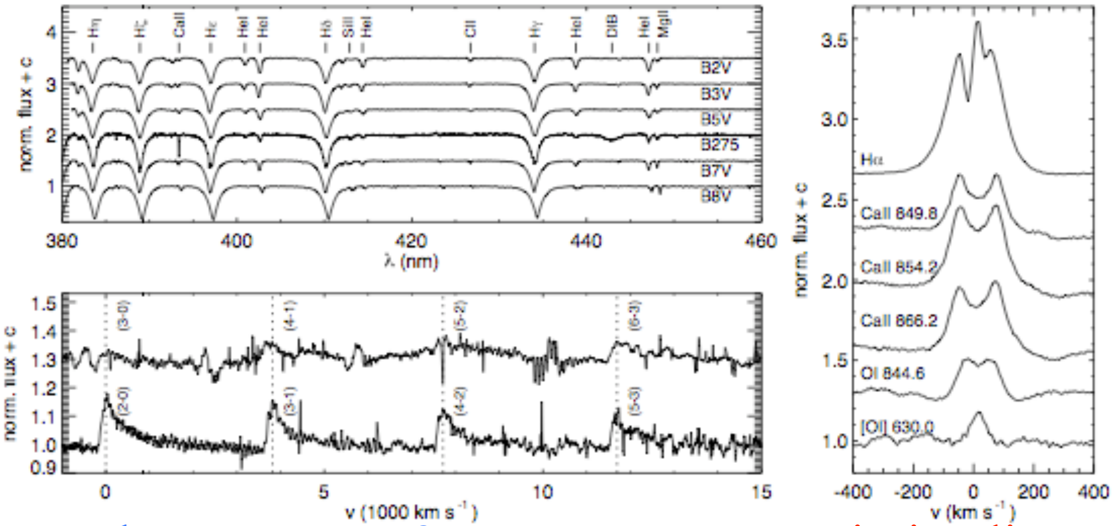
Astronomy & Astrophysics manuscript no. M17˙Xshooter˙revised˙lang
October 27, 2011

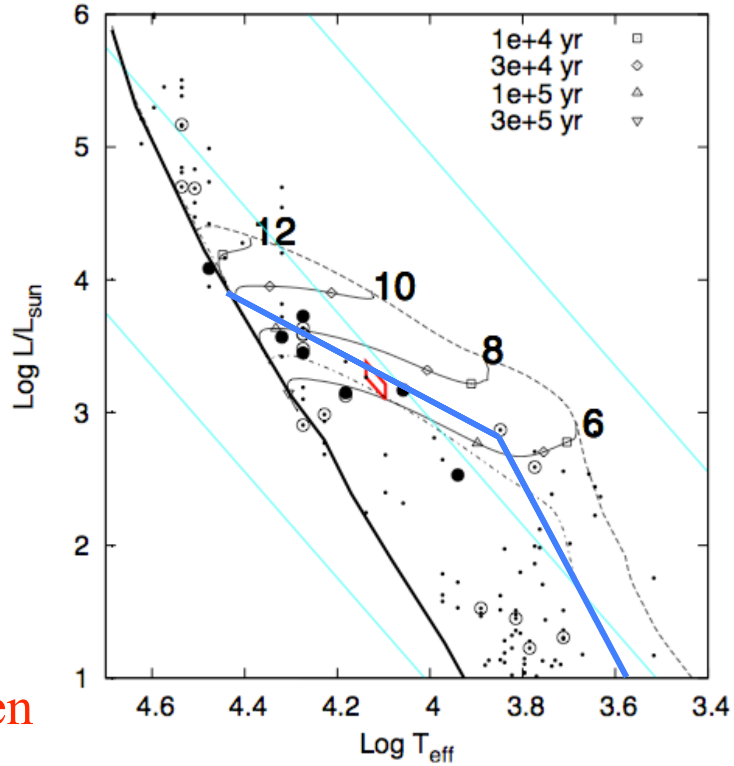
Letter to the Editor

First firm spectral classification of an early-B pre-main-sequence star: B275 in M17*

B.B. Ochsendorf[1], L.E. Ellerbroek[1], R. Chini[2,3], O.E. Hartoog[1], V. Hoffmeister[2], L.B.F.M. Waters[4,1], and L. Kaper[1]

VLT/X-shooter spectrum - SV
V=15.55 mag – K=8.05 mag





Blue spectrum & B-type stars
1st, 2nd overtone CO bands

Emission lines
CaII, OI, Paschen

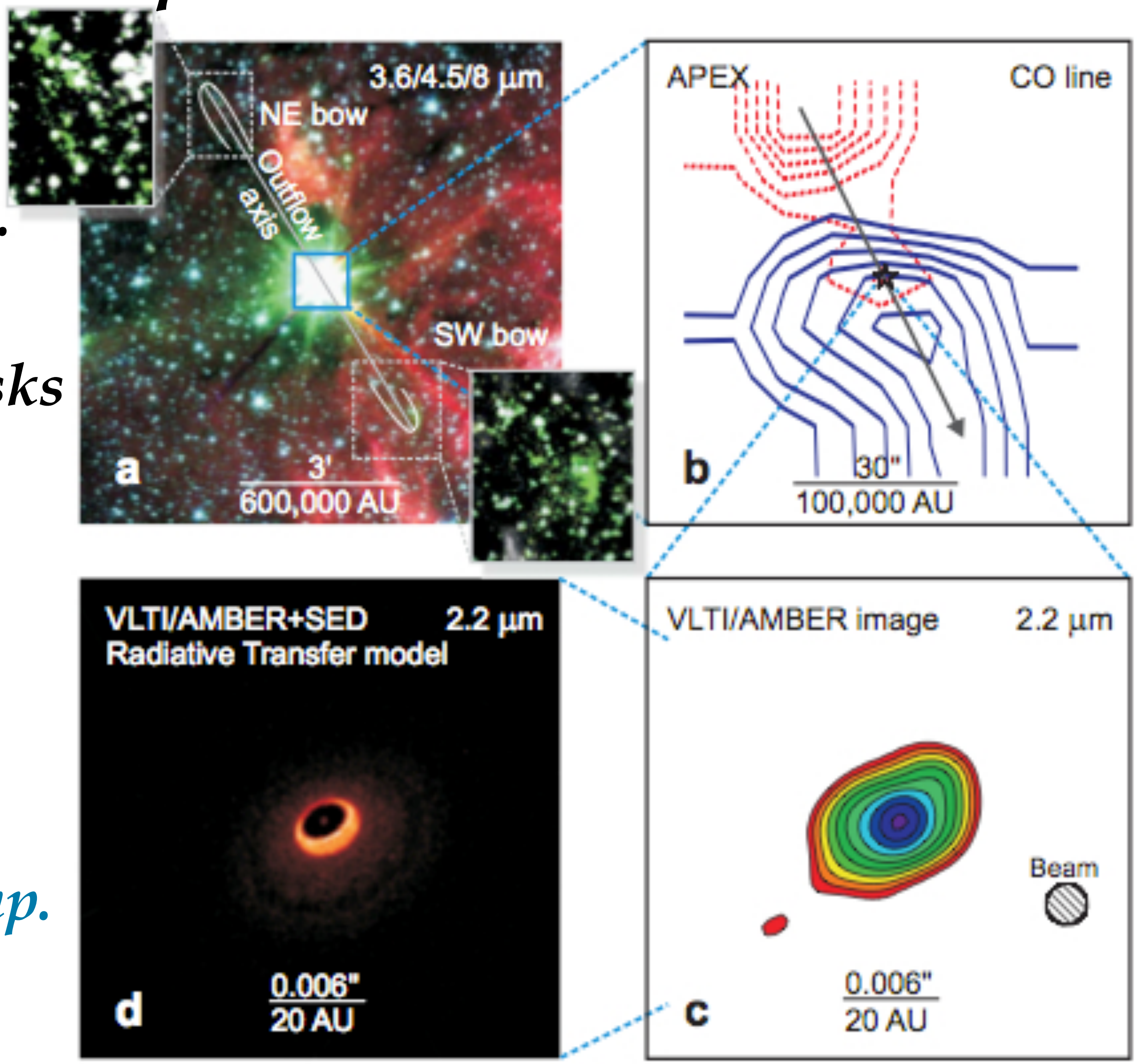
Compact disk around a ~20 M_0 YSO (speckle + AMBER/VLTI)

- *Disk: low degree of asymmetry…*

  problems for self-grav. disks

- *Absence of nearby companion (>10 mas)…*

  problems for mergers, comp. accretion



Kraus+ 10

PMS evolutionary models provide two fundamental astrophysical quantities:

MASS → *IMF*

AGE → *SFH*

Revisiting the Orion Nebula Cluster

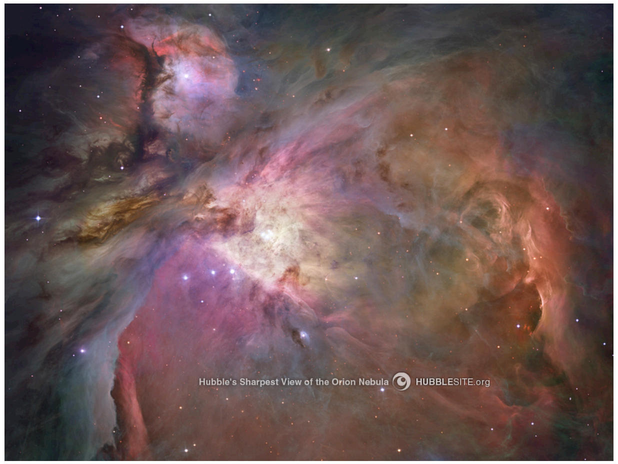
2009-2011

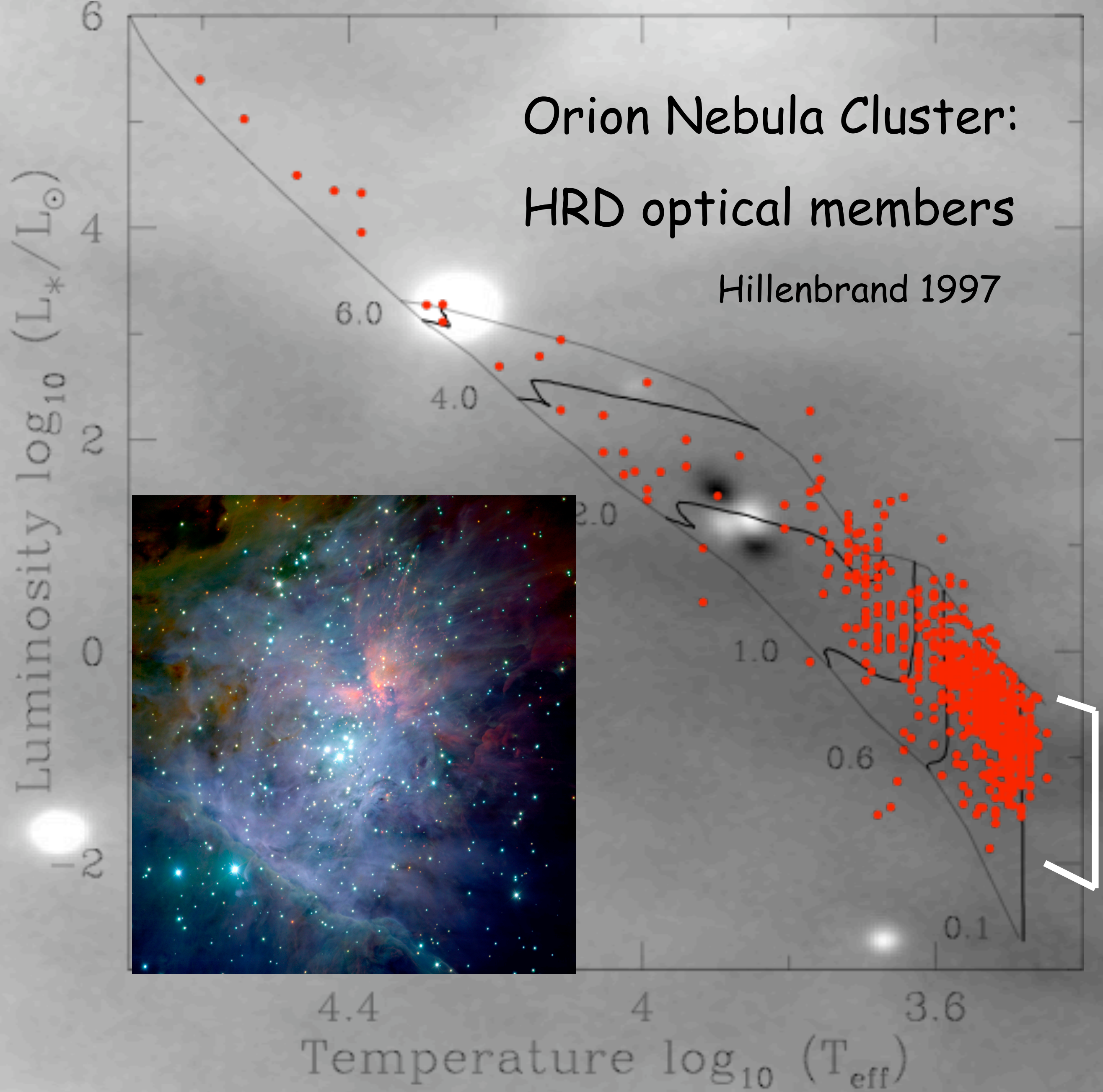
In coll'n: **N. Da Rio**, M. Robberto, L. Hillenbrand, K. Stassun

HST Treasury Program on ONC – PI M. Robberto

→ multicolor visible photomtery w/ highest spatial resolution and sensitivity

Ancillary data: CTIO-NIR & WFI/ESO-optical



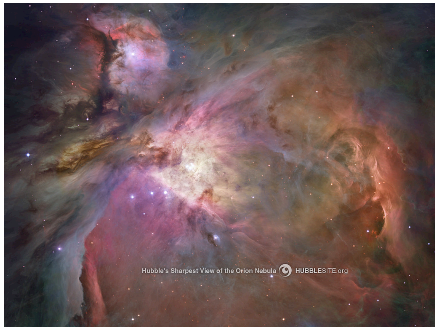


Most stars formed ~1-2 Myr ago

Notice the large ΔL~10

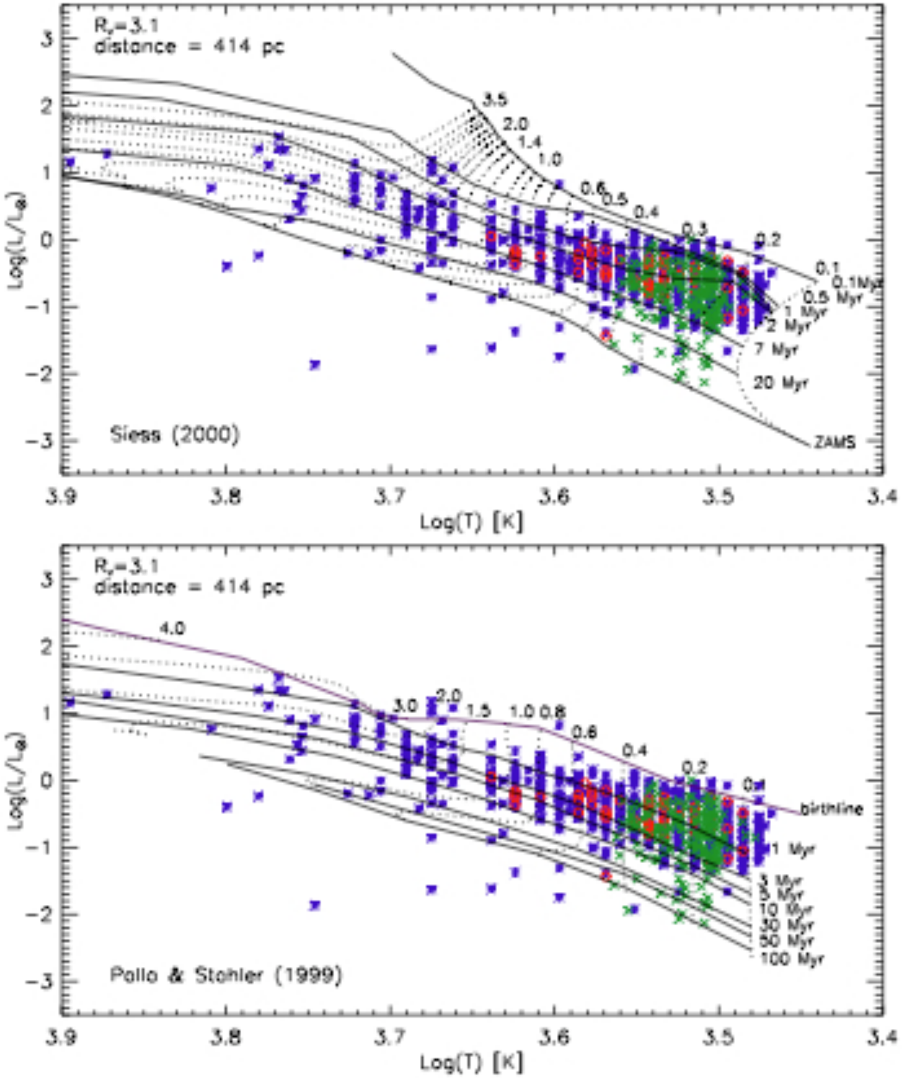
↓

age spread: real or not?



Revisiting the ONC

HST Treasury Program – PI M. Robberto



blue: from H97, excluding stars with membership P<50%

red: stars with new spectral types

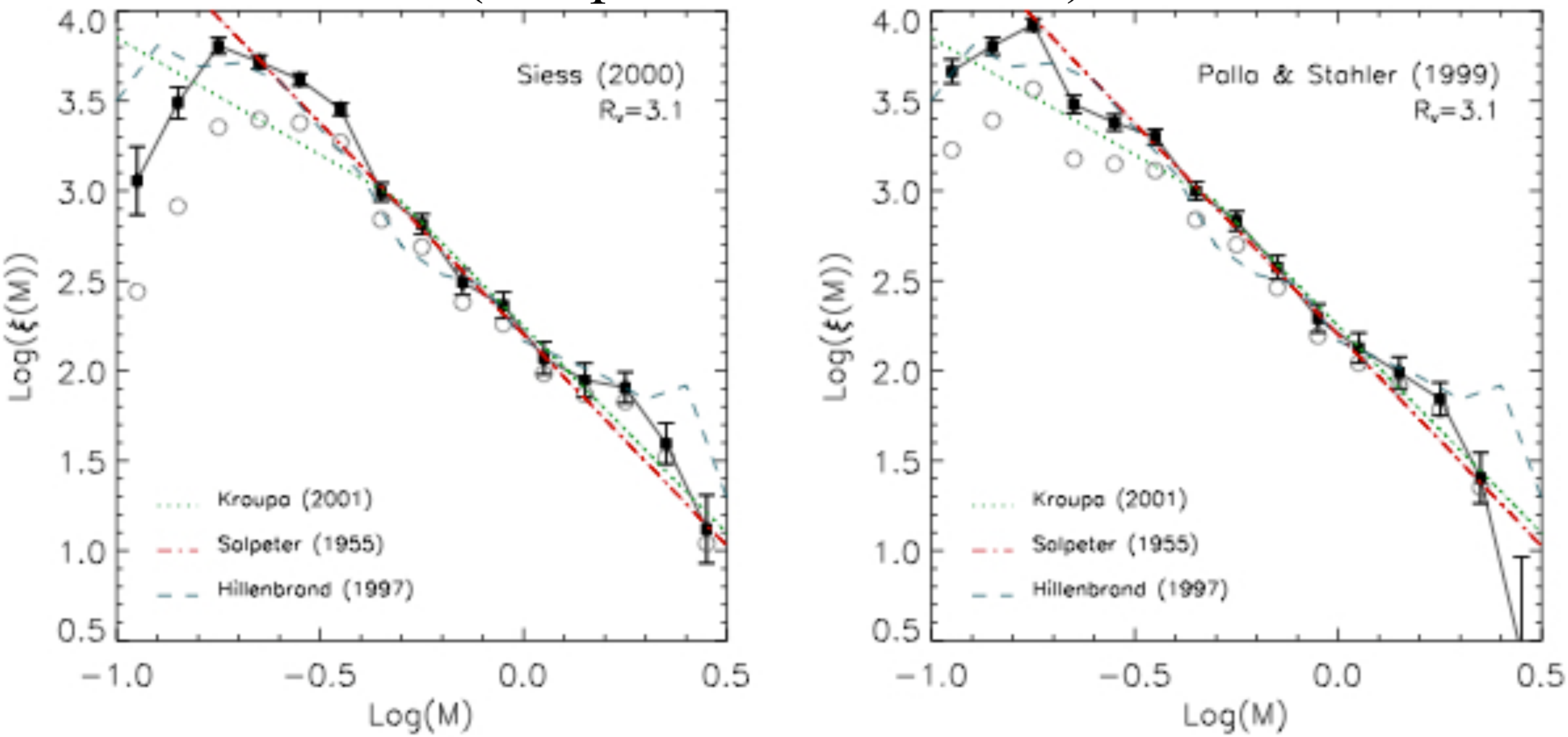
green: M-type with Teff from TiO index

Contamination by fore/background sources with unknown membership: 2-3%

Da Rio+ 10

The Initial Mass Function

(completeness corrected)



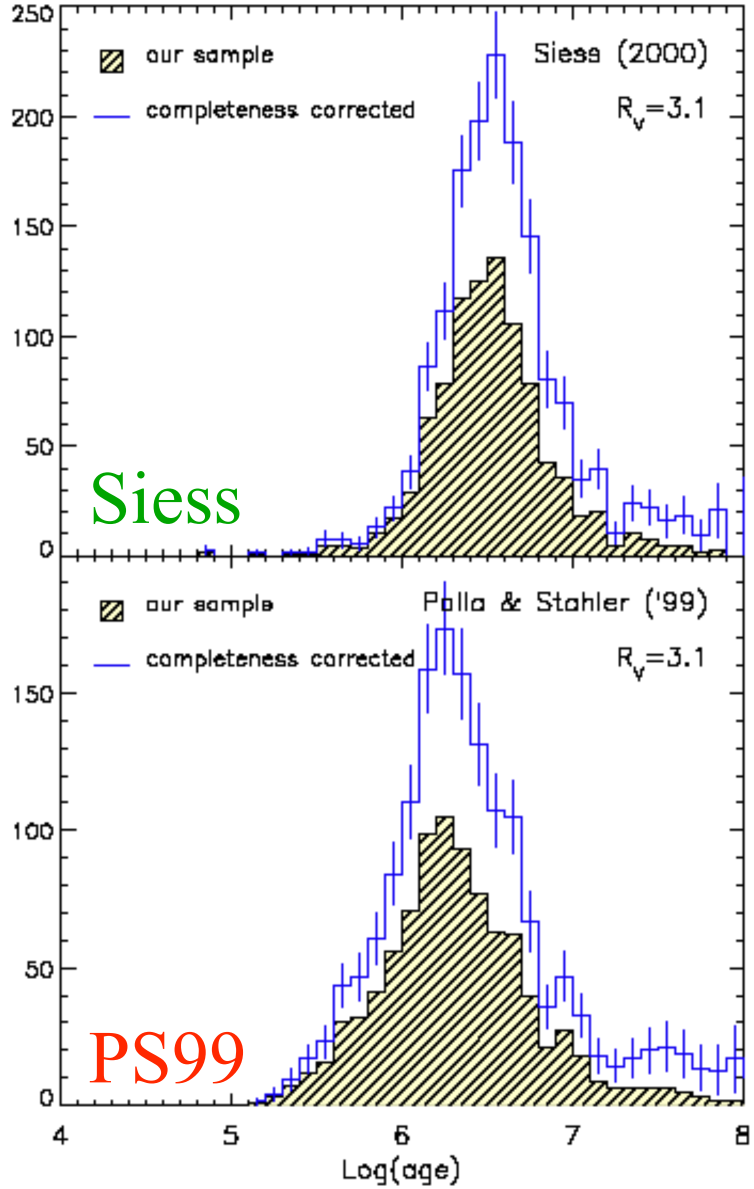
Significant differences for log M<~-0.3, both flatten:

Siess - clear turnover below 0.2 M_0, overabundance @0.2-0.3

PS99 - modest change of slope, agreement with Kroupa IMF

Age distribution

shaded: full sample - blue: completeness corrected



Siess: average ages ~3 Myr
within 1σ: 2.5 – 5 Myr
spread ~0.4 dex

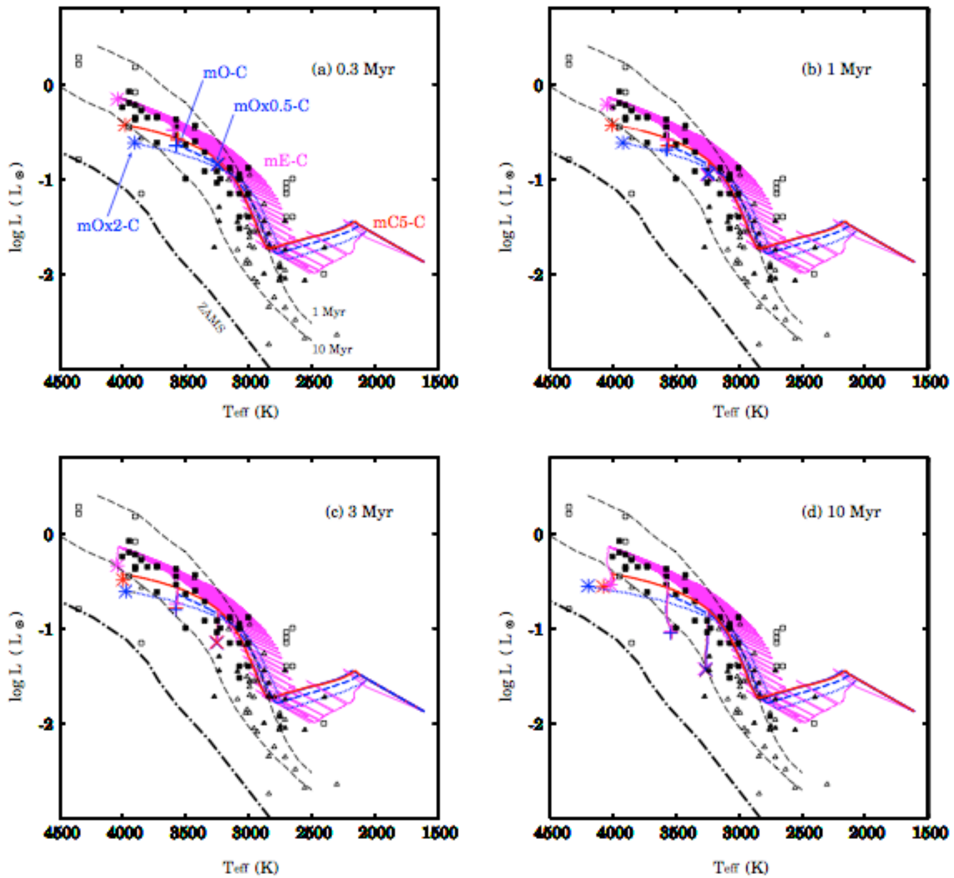
PS99: average ages ~2 Myr
within 1σ: 1.2 – 3.2 Myr
spread ~0.3 dex

Real vs artificial spread
(combined effect…)

The Astrophysical Journal, 738:140 (11pp), 2011 September 10 doi:10.1088/0004-637X/738/2/140

ON THE RELIABILITY OF STELLAR AGES AND AGE SPREADS INFERRED FROM PRE-MAIN-SEQUENCE EVOLUTIONARY MODELS

Takashi Hosokawa[1,2], Stella S. R. Offner[3], and Mark R. Krumholz[4]



Red: constant accretion

Magenta: episodic accretion

Blue: decreasing accretion

★: 0.90 M_0

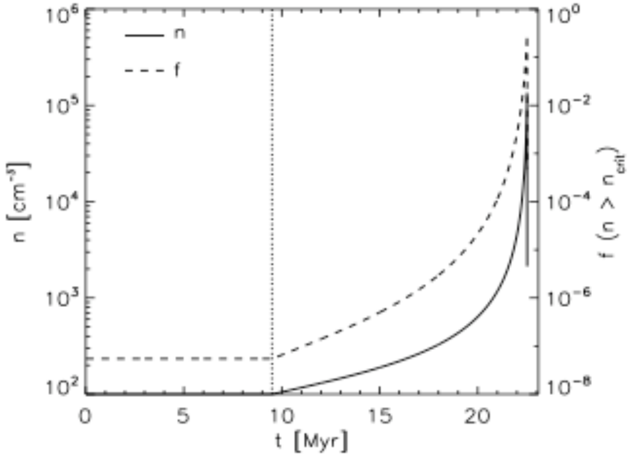
+ : 0.45 M_0

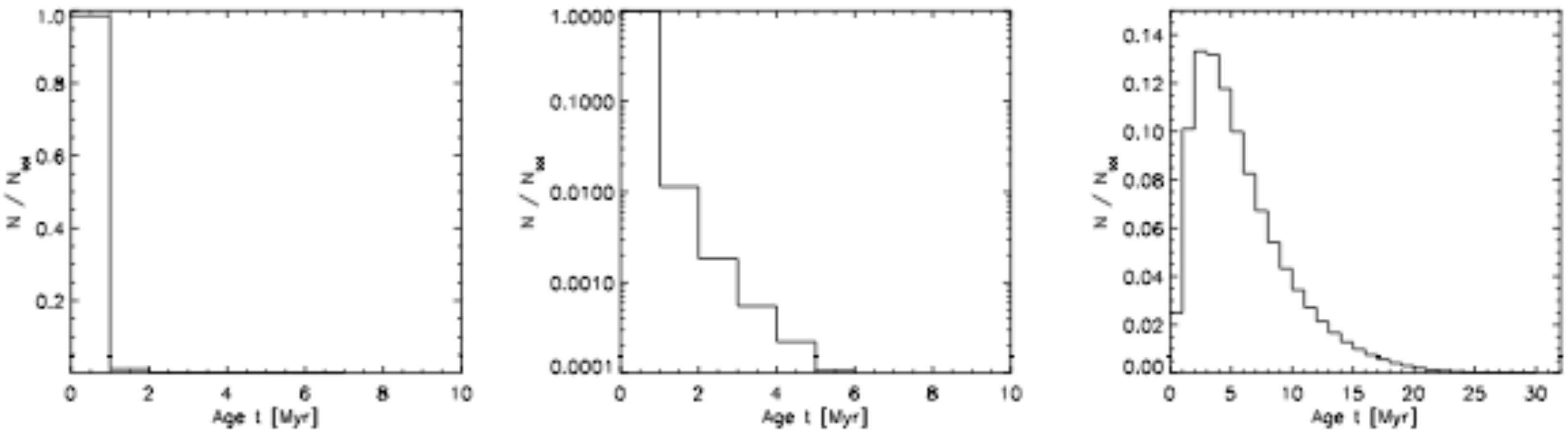
× : 0.23 M_0

An Evolutionary Model for the Star Formation Efficiency in Gravitationally Collapsing Molecular Clouds.

Manuel Zamora-Aviles[1] & Enrique Vázquez-Semadeni[1]

Evolution of the cloud number density and mass fraction





Stellar age distributions for isolated cloud (left) & GMC (right)

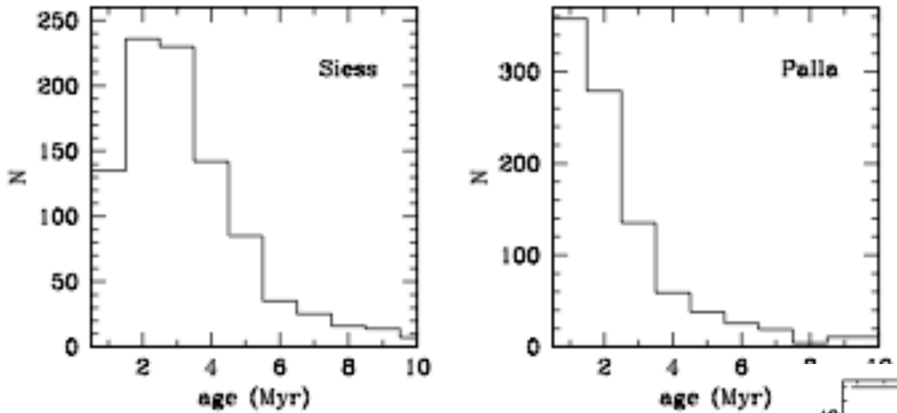
ApJ 2011

Mon. Not. R. Astron. Soc. 000, 1–5 (2011) Printed 27 August 2011 (MN LaTeX style file v2.2)

Rapid Star Formation and Global Gravitational Collapse

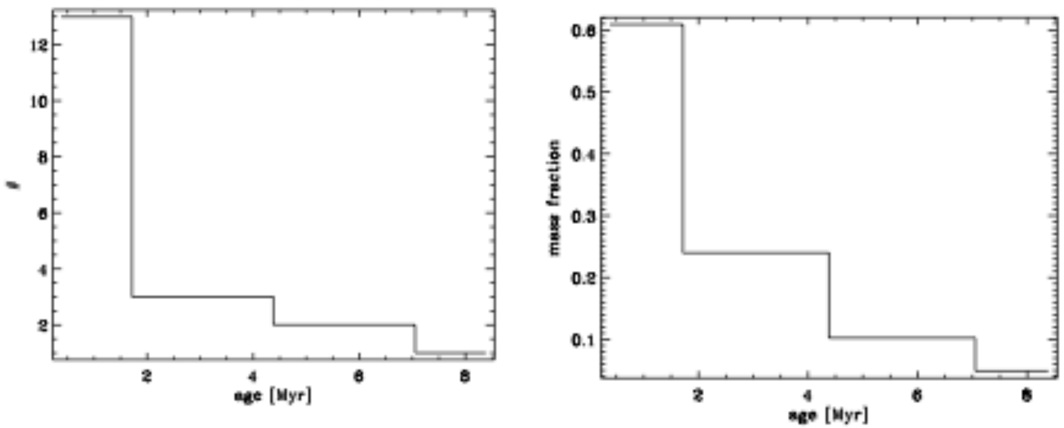
Lee Hartmann[1], Javier Ballesteros-Paredes[2], Fabian Heitsch[3]

local gas densities. We show that two different numerical simulations of dynamic, flow-driven molecular cloud formation and evolution 1) predict age spreads for the main stellar population roughly consistent with observations, and 2) raise the possibility of forming small numbers of stars early in cloud evolution, before global contraction concentrates the gas and the bulk of the stellar population is produced. In general, the existence of a small number of older stars among a generally much-younger population is consistent with the picture of dynamic star formation, and may even provide clues to the time evolution of star-forming clouds.



Results of observations

Results of simulations



Modeling of PMS Evolution

INITIAL CONDITIONS
Initial model
Interaction with surrounding: disk locking

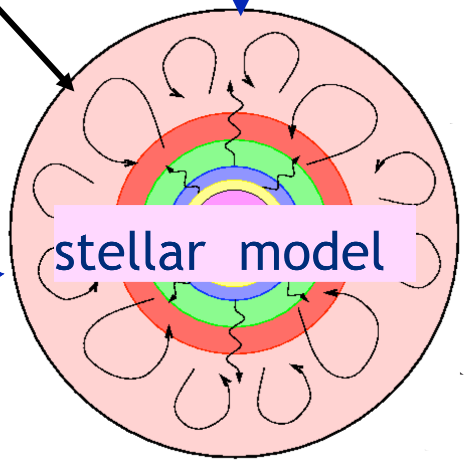
INPUT PARAMETERS
initial mass
initial chemical composition
evolutionary state

Model atmosphere

INPUT PHYSICS

microscopic:
Nuclear reactions
opacities
equation of state
microscopic diffusion

macroscopic: transport and 1D approximation
Convection α
rotation
internal waves
magnetic field and related transports



BOUNDARIES
T-Tau law
Mass loss
Angular moment. loss

NUMERICS

Uncertainties on impact on mass and age accuracies
- some are under control
- some require further work

Popular models

Baraffe & Chabrier 1997, 1998…

Siess 2000

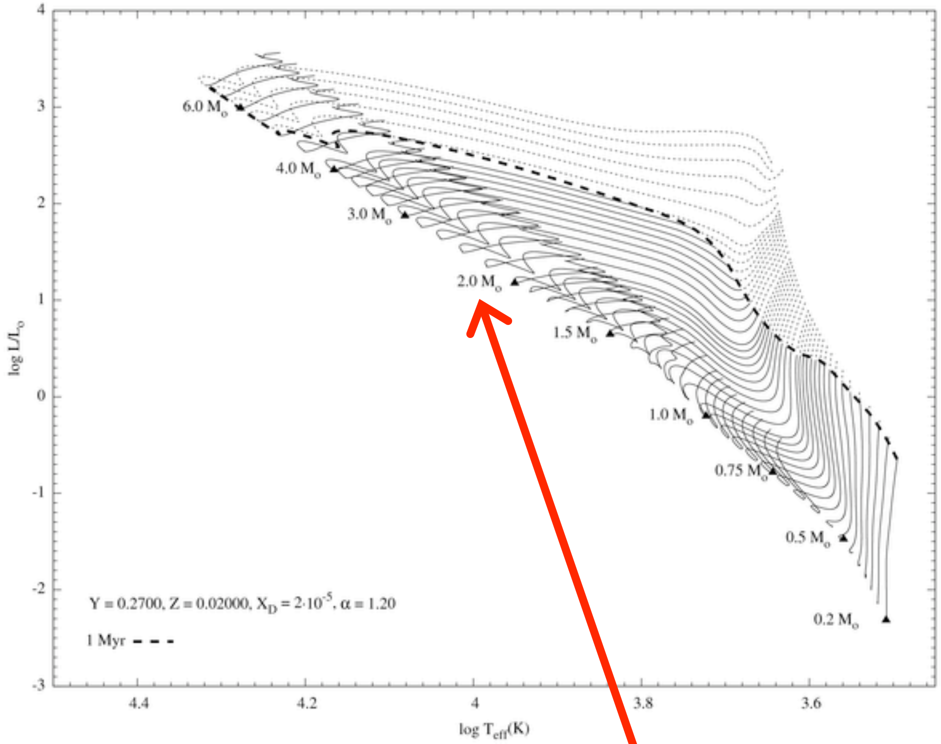
Palla & Sthaler 1993, 1999

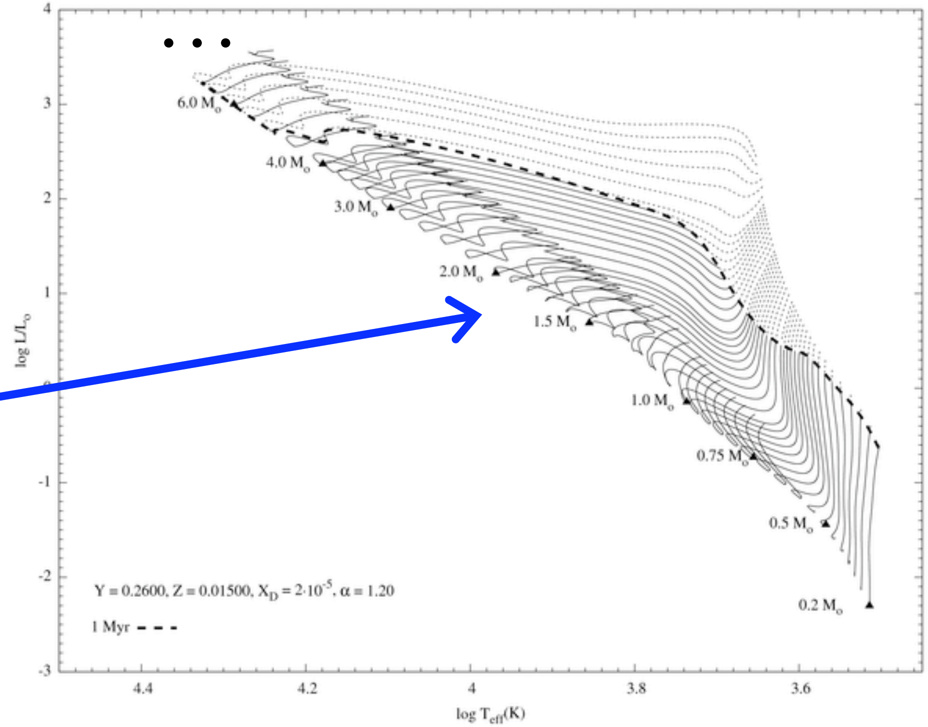
D'Antona & Mazzitelli 1994, 1997, 1998…

Demarque Y^2 2001, 2002,2004

Pisa PMS models (2010-12)

M: 0.2 → 6 M_0
large range of Z





…

Z= 0.02 (solar)
0.01

Measurements of chemical abundances!

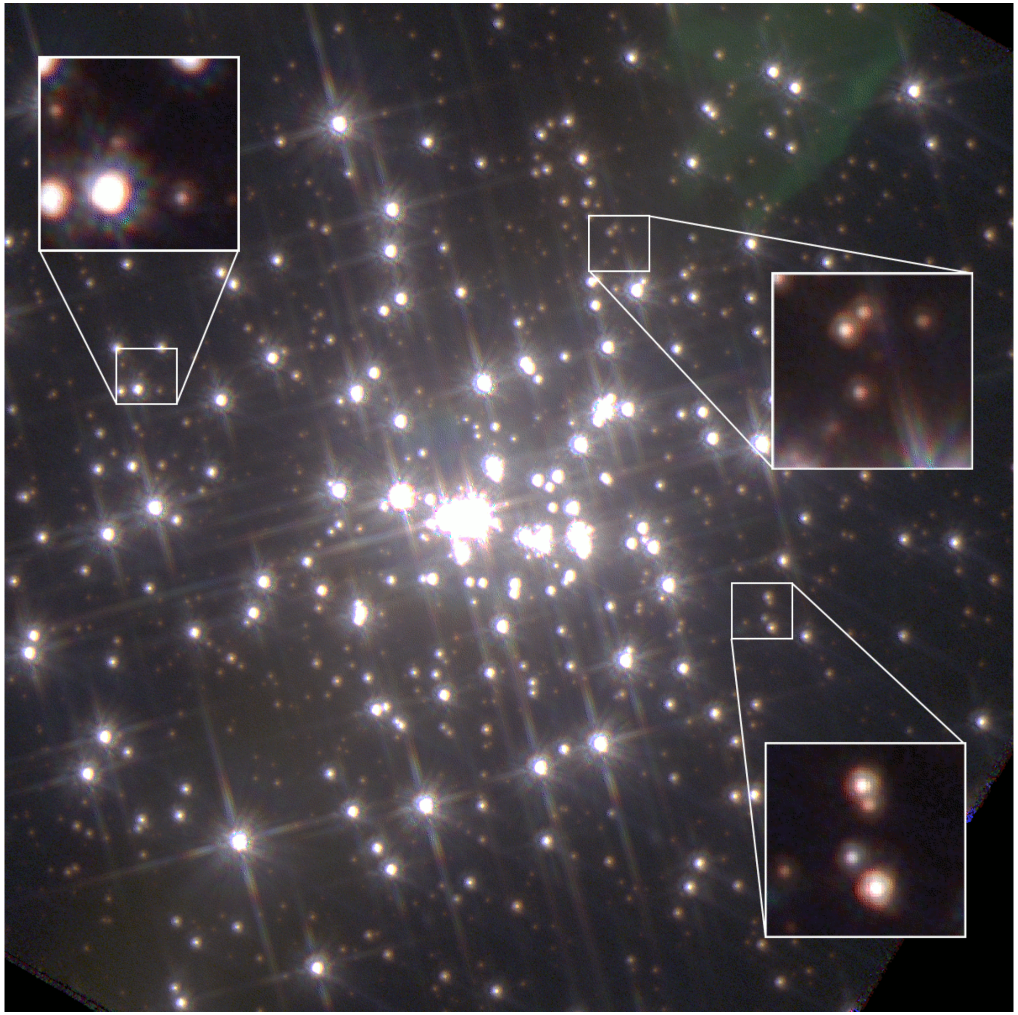
NGC 3603: internal dynamics (1997-2007)

σ_{1D}=4.5±0.8 km/s

Stars with M=1.7-9 Mo
have same vel. disp. →
cluster not virialized…

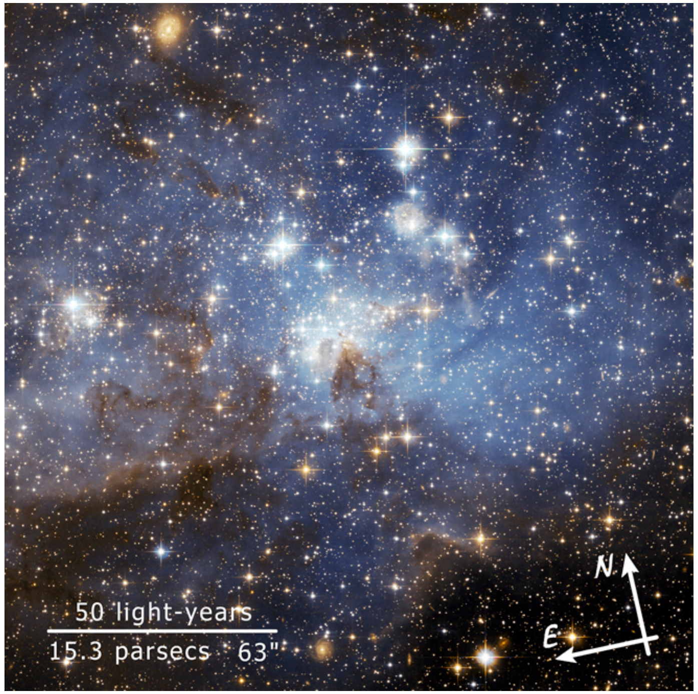
M_{dyn}=17600 Mo vs
M_{cl}=10-16000 Mo

Stars in the r-c gap:
3.5-3.8 Mo



Rochau+ 10

Older 4 Myr stars → previous episode… multiple formation…

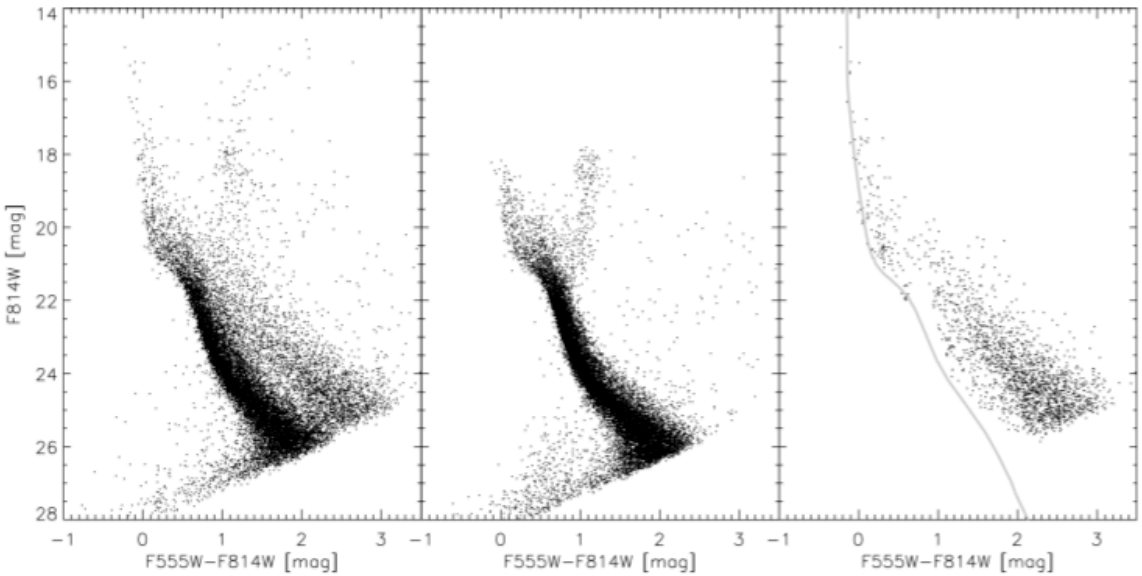


Extragalactic PMS evolution: low-mass stars in SFRs

Only HST has the required sensitivity and f.o.v. coverage: impossible to do repeated imaging, spectroscopy of large samples, X-ray monitoring. Advantages:

1. PMS population easily distinguished from field via CMDs

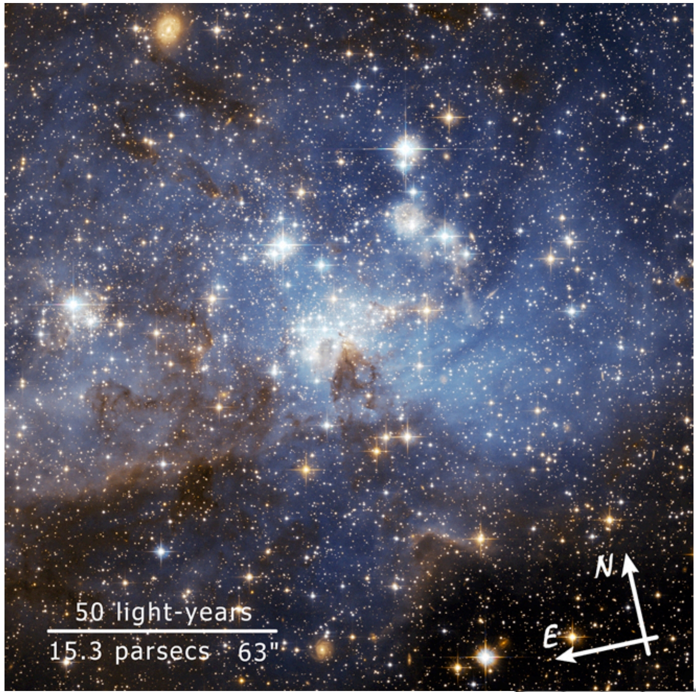
2. Large samples of stars for statistical analyses



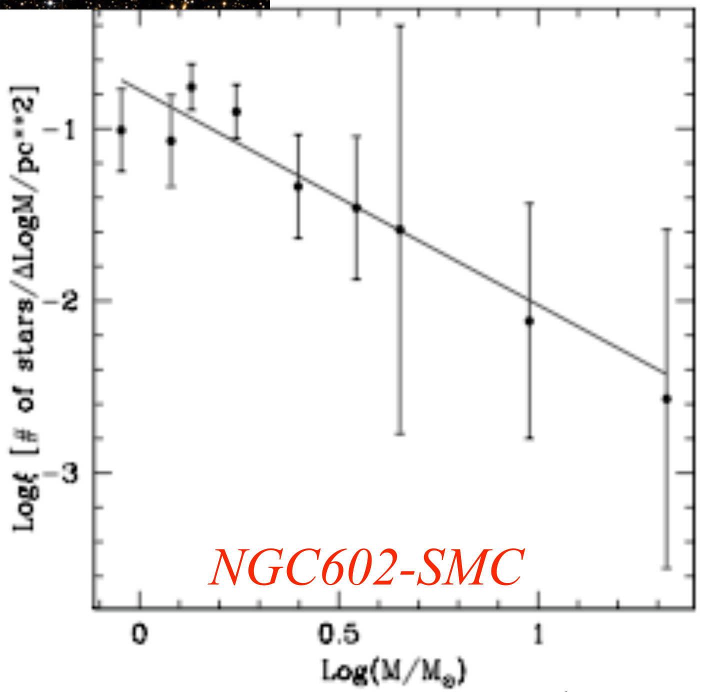
Gouliermis 2012

Getting the ~complete IMFs down to sub-solar masses…

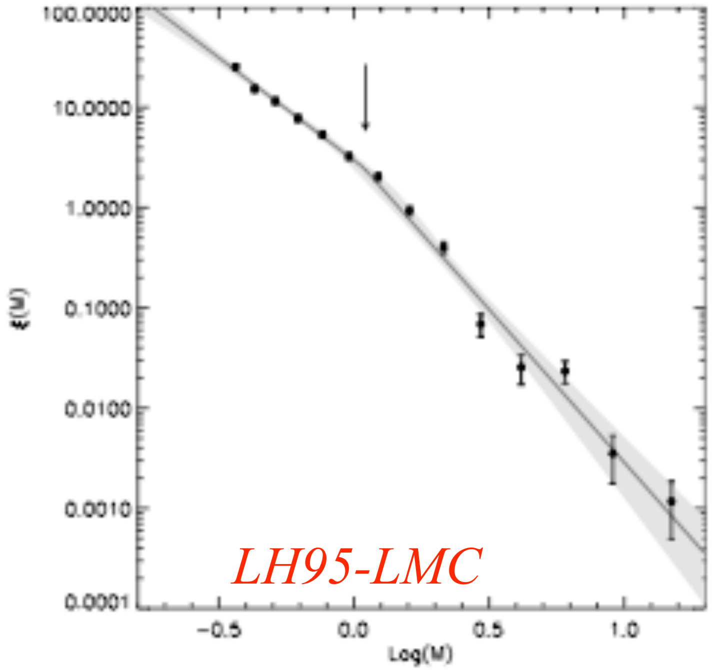
knee at ~1 M_0 and power-laws as in the galactic IMF



Gouliermis 2012



Cignoni et al 2009



Da Rio et al. 2010

Present & Future of PMS Evolution

- Reconstruct Star Formation History of Clusters and Associations & IMF → galactic and extragalactic Local Group and beyond…
- Fundamental quantities: distance, membership, stellar parameters, abundances
- Main issues: coevality vs age spread, IMF, disk evolution, binaries
- Useful diagnostics: Li, surface g, abundances, activity…
- Observations: GAIA-ESO Survey of SFRs/Clusters
  GAIA…

THE ASTROPHYSICAL JOURNAL, **308**:697–705, 1986 September 15

PRIMORDIAL STELLAR EVOLUTION: THE PRE–MAIN-SEQUENCE PHASE

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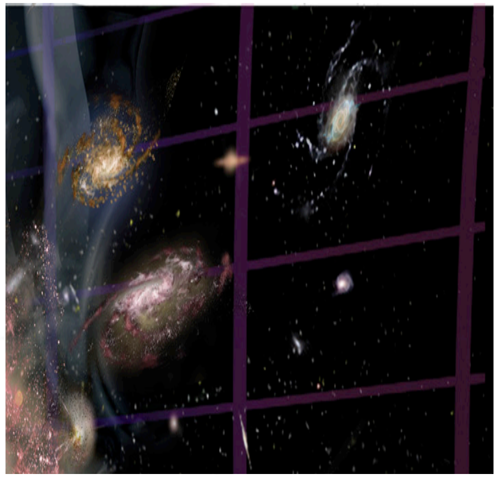
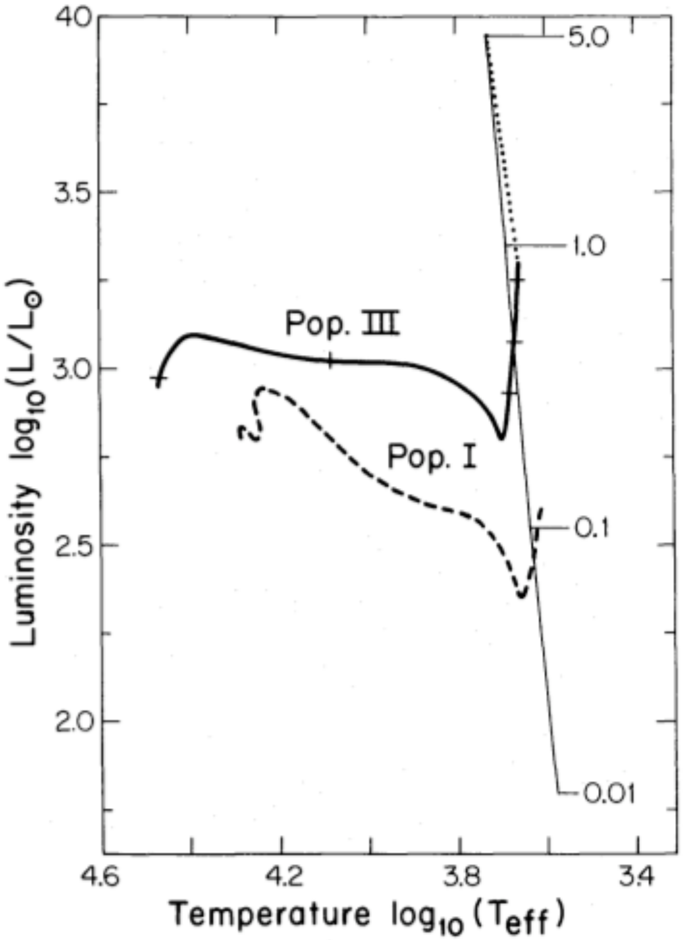
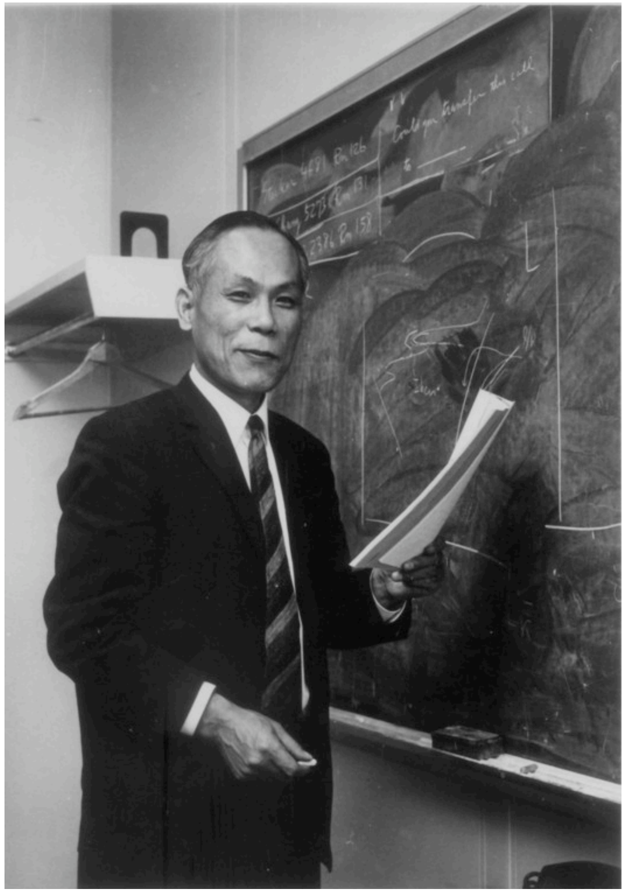
Received 1986 February 18; accepted 1986 March 7







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