Star Formation with the Hubble Space Telescope

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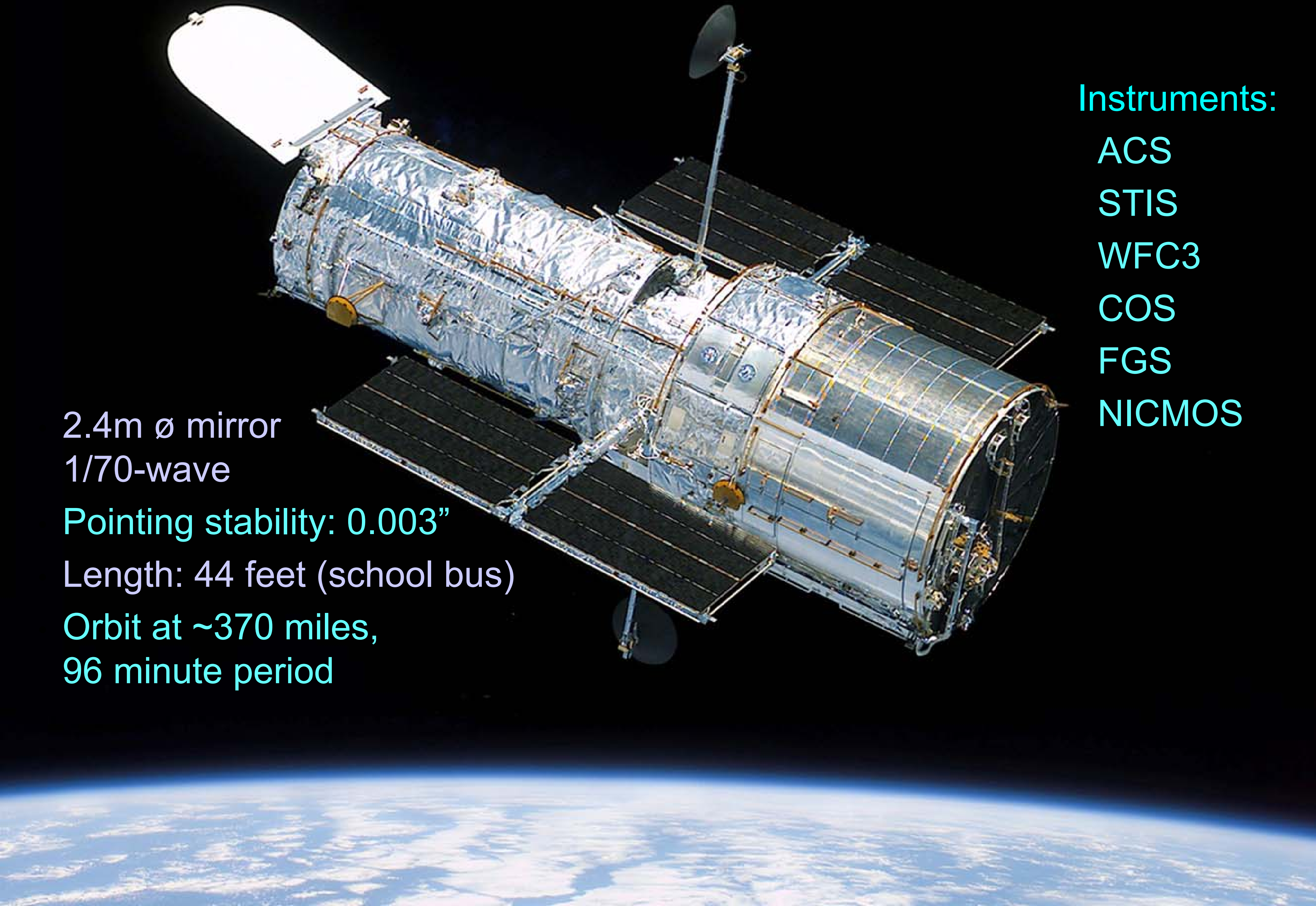
Outline

- Young stars, star formation phenomenology
  - Massive/low mass stars in clusters
  - Dark clouds
  - Jets
  - Disks
- Orion Nebula as a prototype: open problems
  - Disk photoevaporation
  - Orion cluster: IMF, age, mass accretion
- Large/Small Magellanic Cloud
  - Mass accretion and star formation history

The Hubble Space Telescope



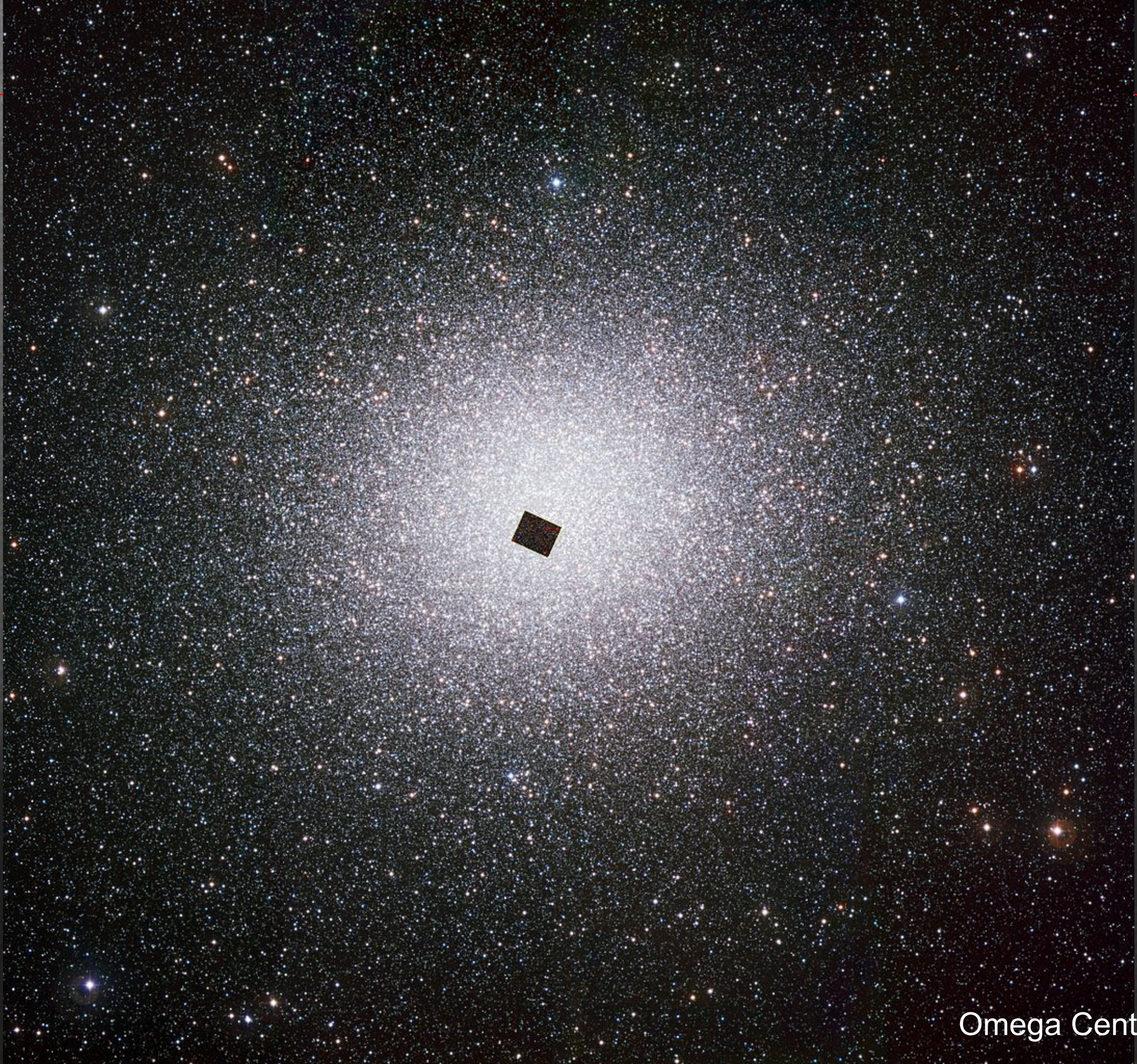
Instruments:
- ACS
- STIS
- WFC3
- COS
- FGS
- NICMOS

2.4m ø mirror
1/70-wave

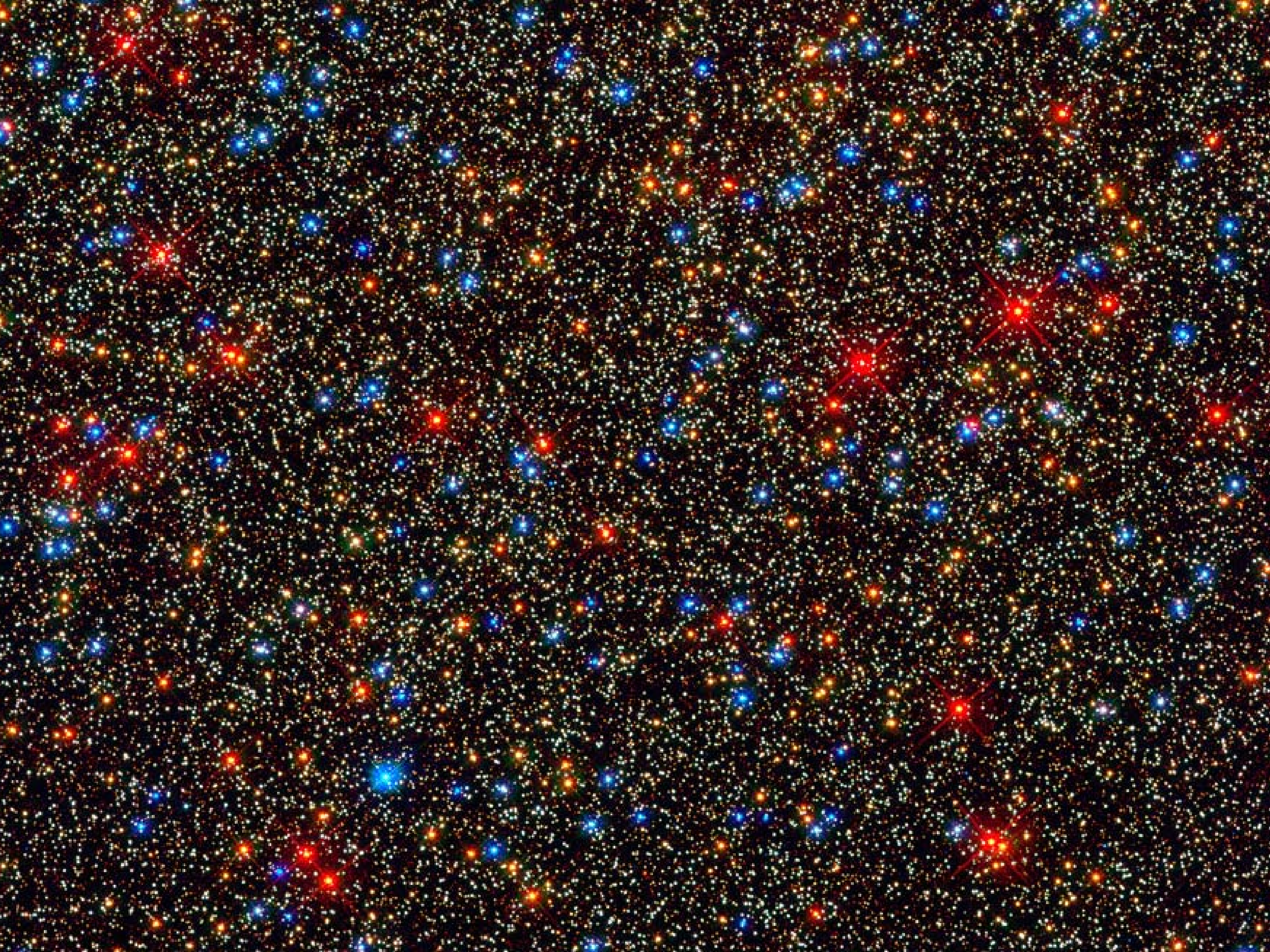
Pointing stability: 0.003”

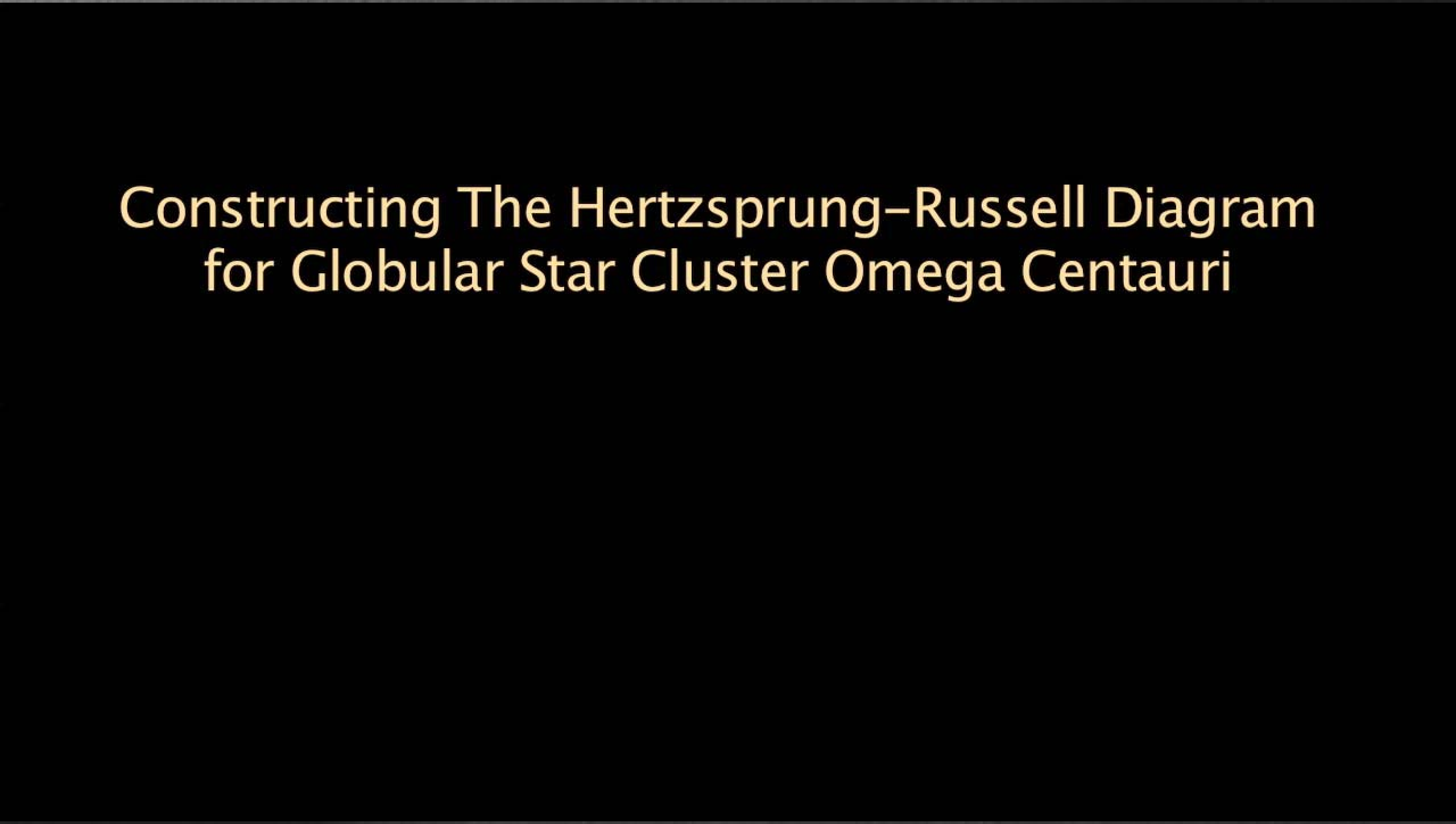
Length: 44 feet (school bus)

Orbit at ~370 miles,
96 minute period

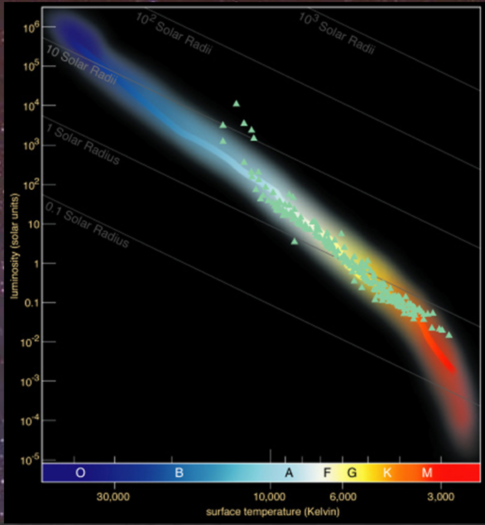


Omega Centauri





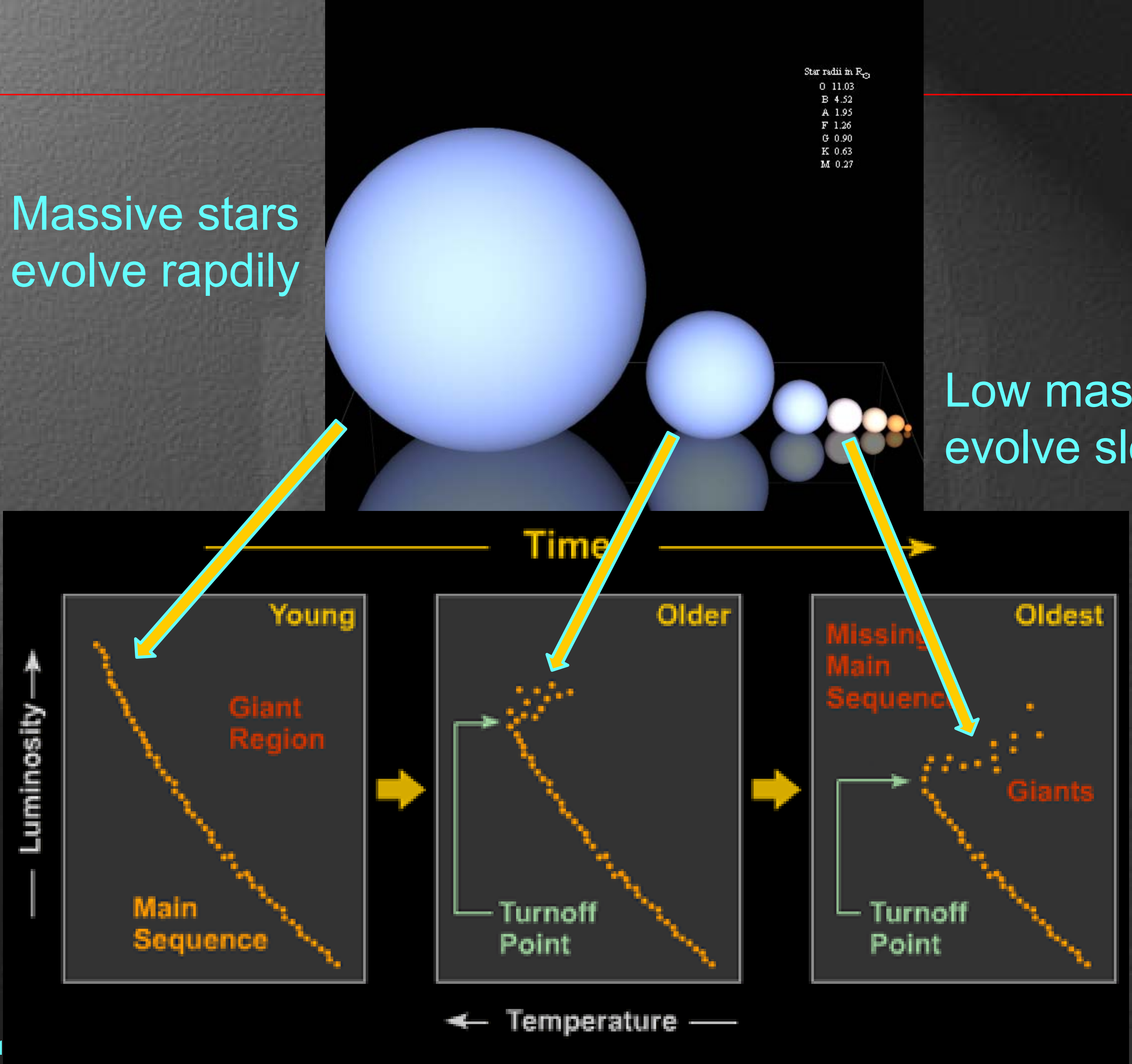
Constructing The Hertzsprung-Russell Diagram
for Globular Star Cluster Omega Centauri


10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
luminosity (solar units)
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)

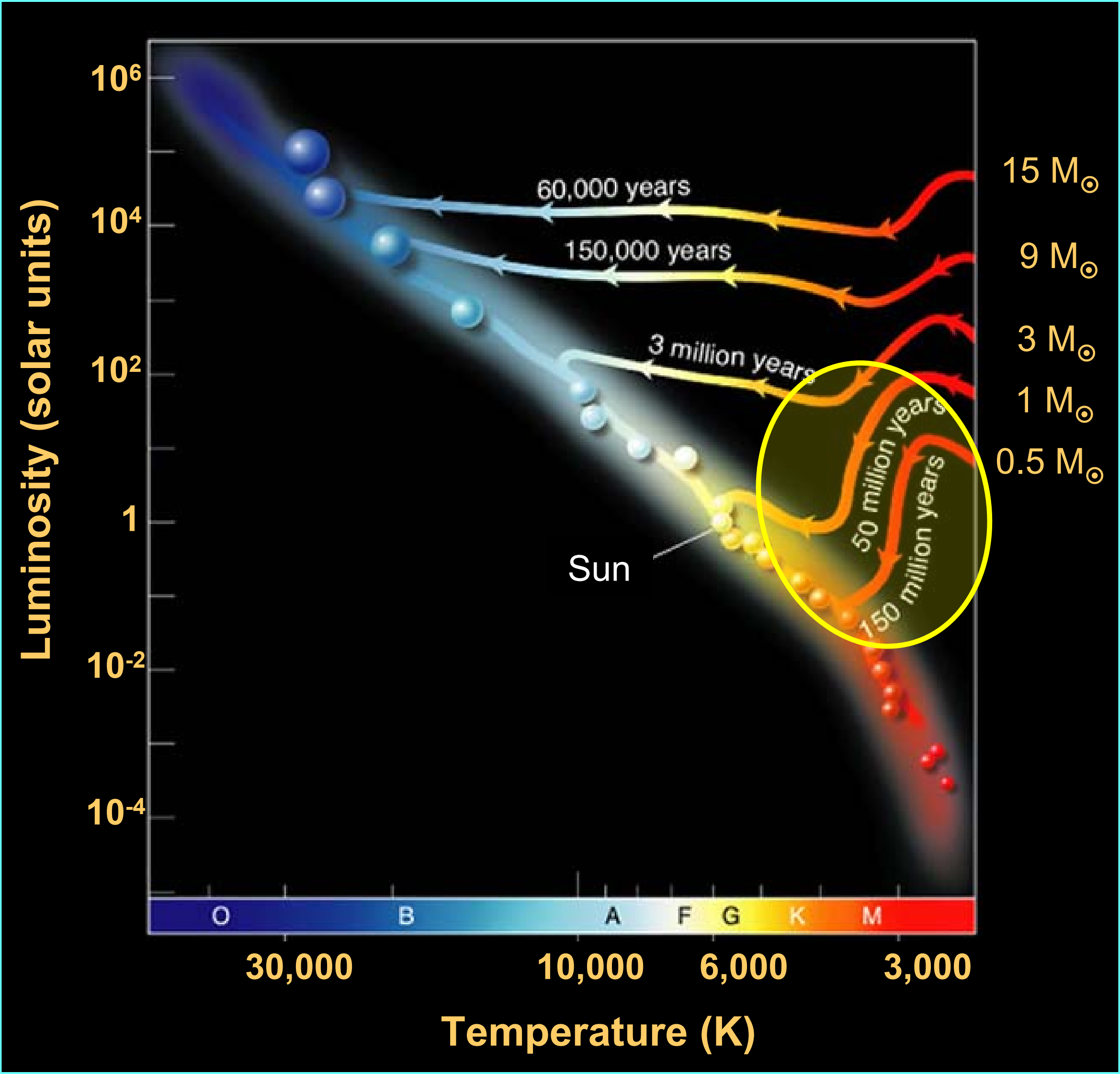
Pleiades

Massive stars evolve rapdily

Low mass stars evolve slowly



Pre Main Sequence

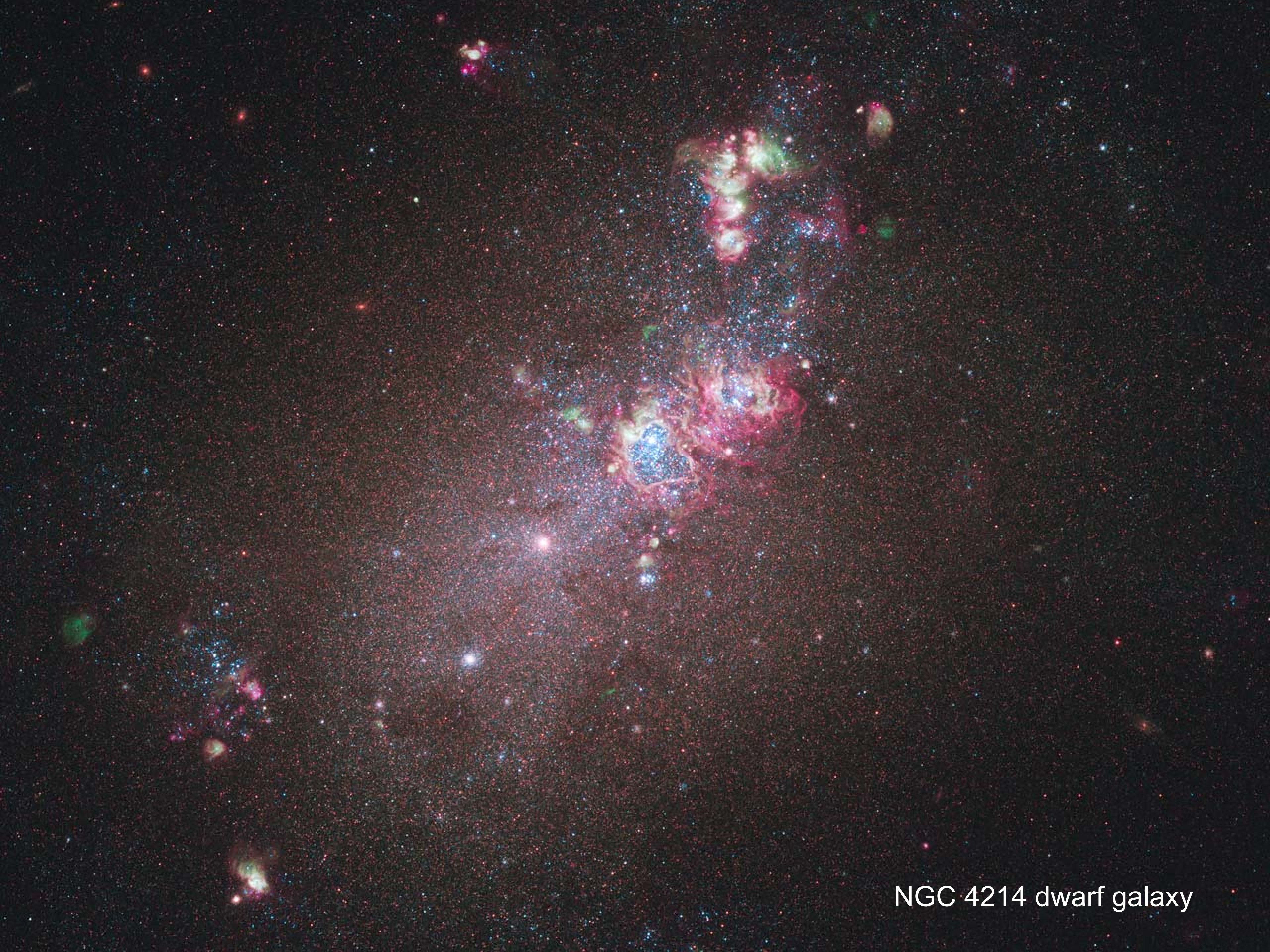


Orion Nebula
region

NGC 2024 and Horsehead

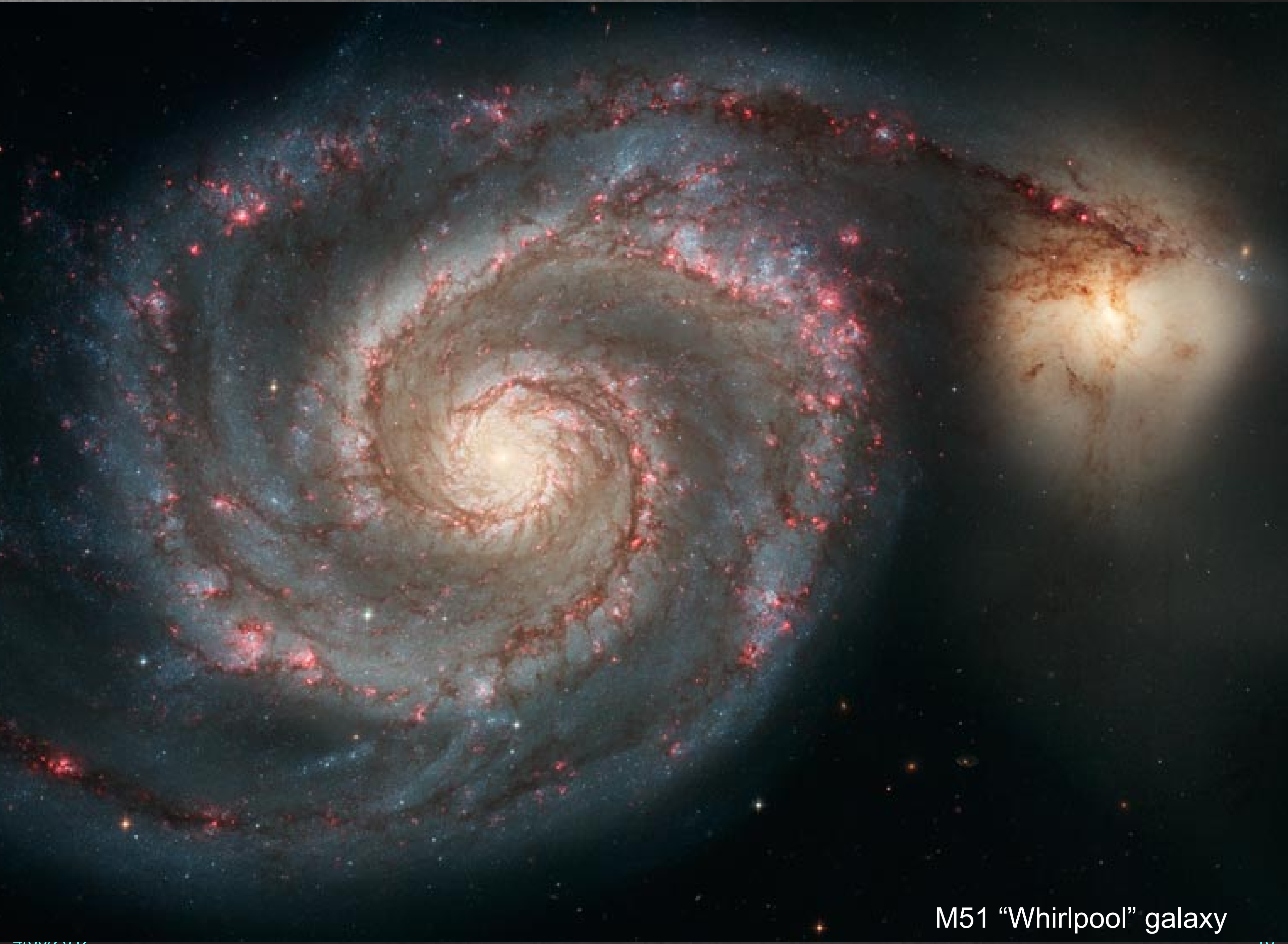

Pismis 3
NGC 2546
Pismis 5
Zeta Pup
Ru 56
NGC 2626
Collinder 197
NGC 2671
Gum 17
Trumpler 10
vDB-Ha 56
Lambda Vel
vDB-Ha 34
NGC 2659
Location of Pulsar (PSR B0833-45)
NGC 2736
(Pencil Nebula)
Dun 65
IC 2395
Gum 35
NGC 2547

Vela region

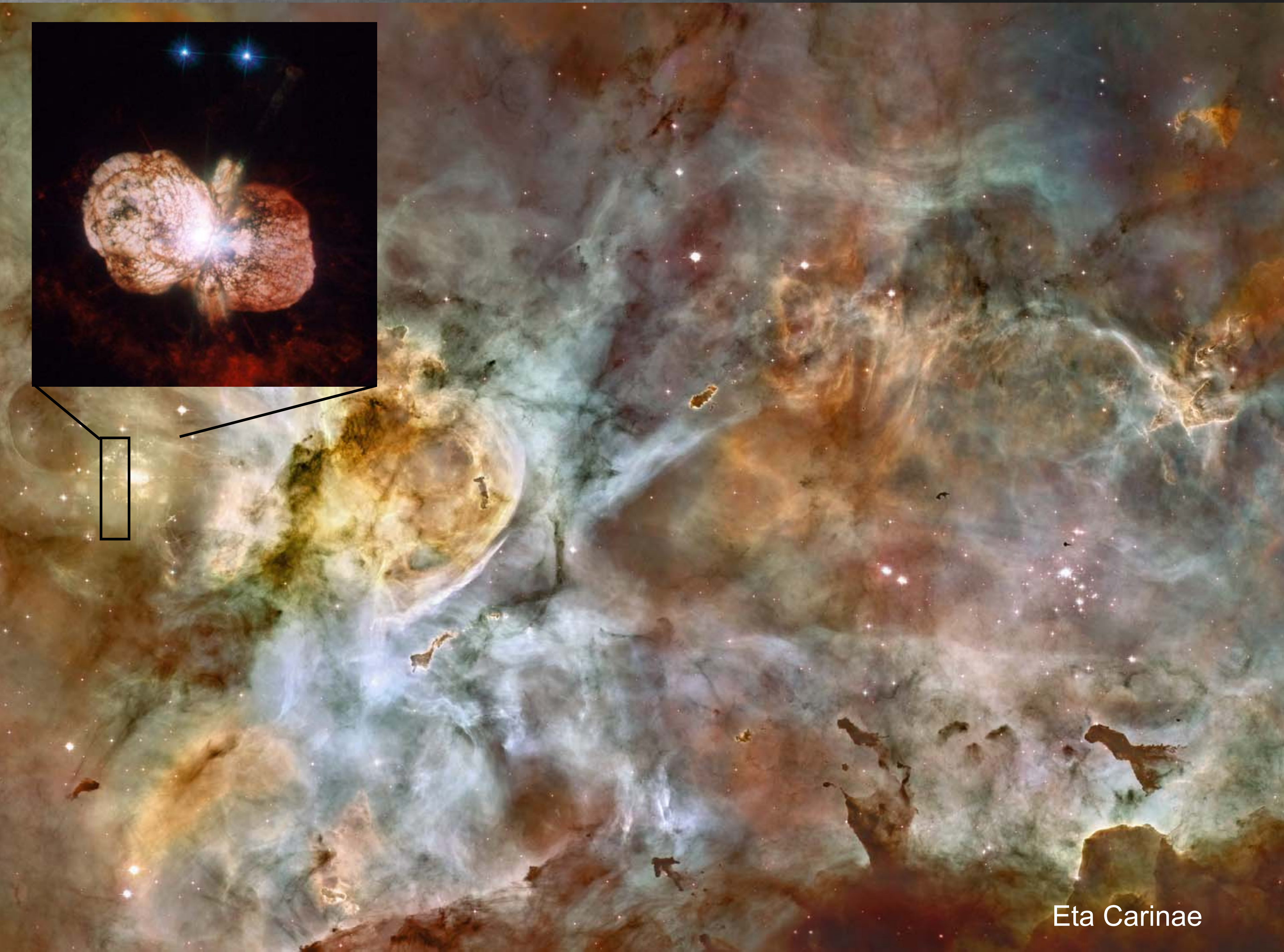


NGC 4214 dwarf galaxy

NGC 2403



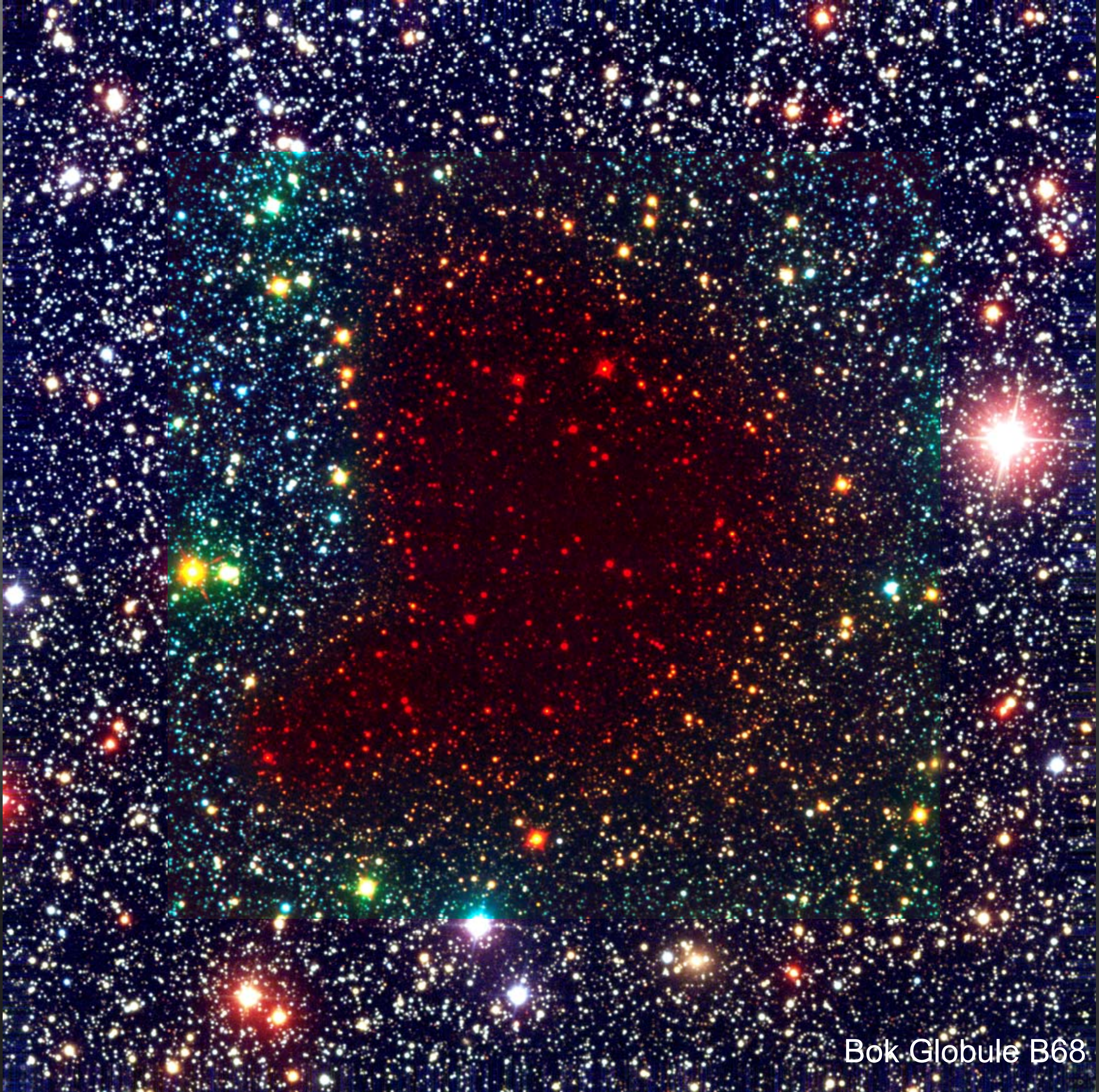
M51 “Whirlpool” galaxy



Eta Carinae

Carina

Carina

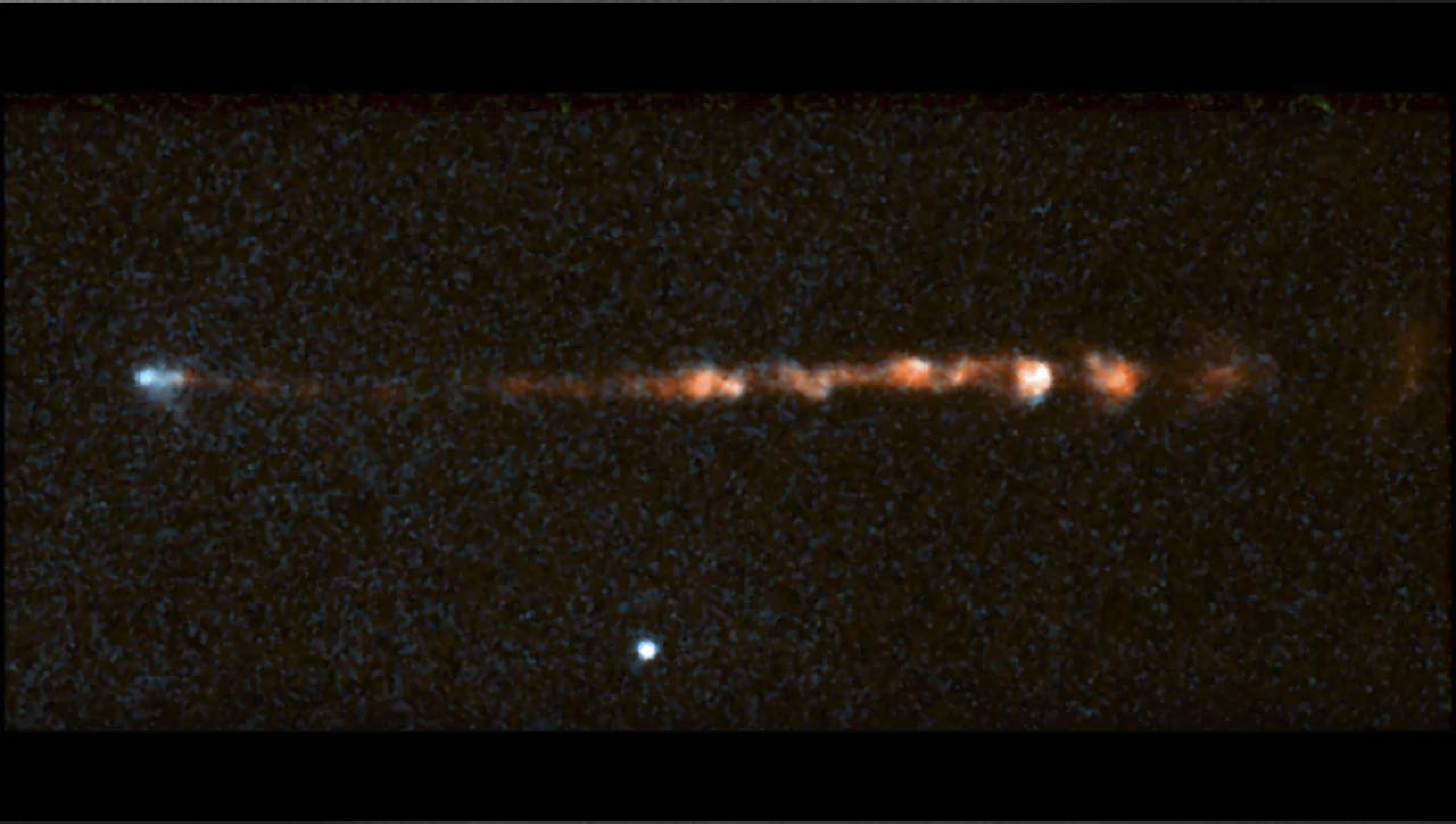


Bok Globule B68

Jet in Carina

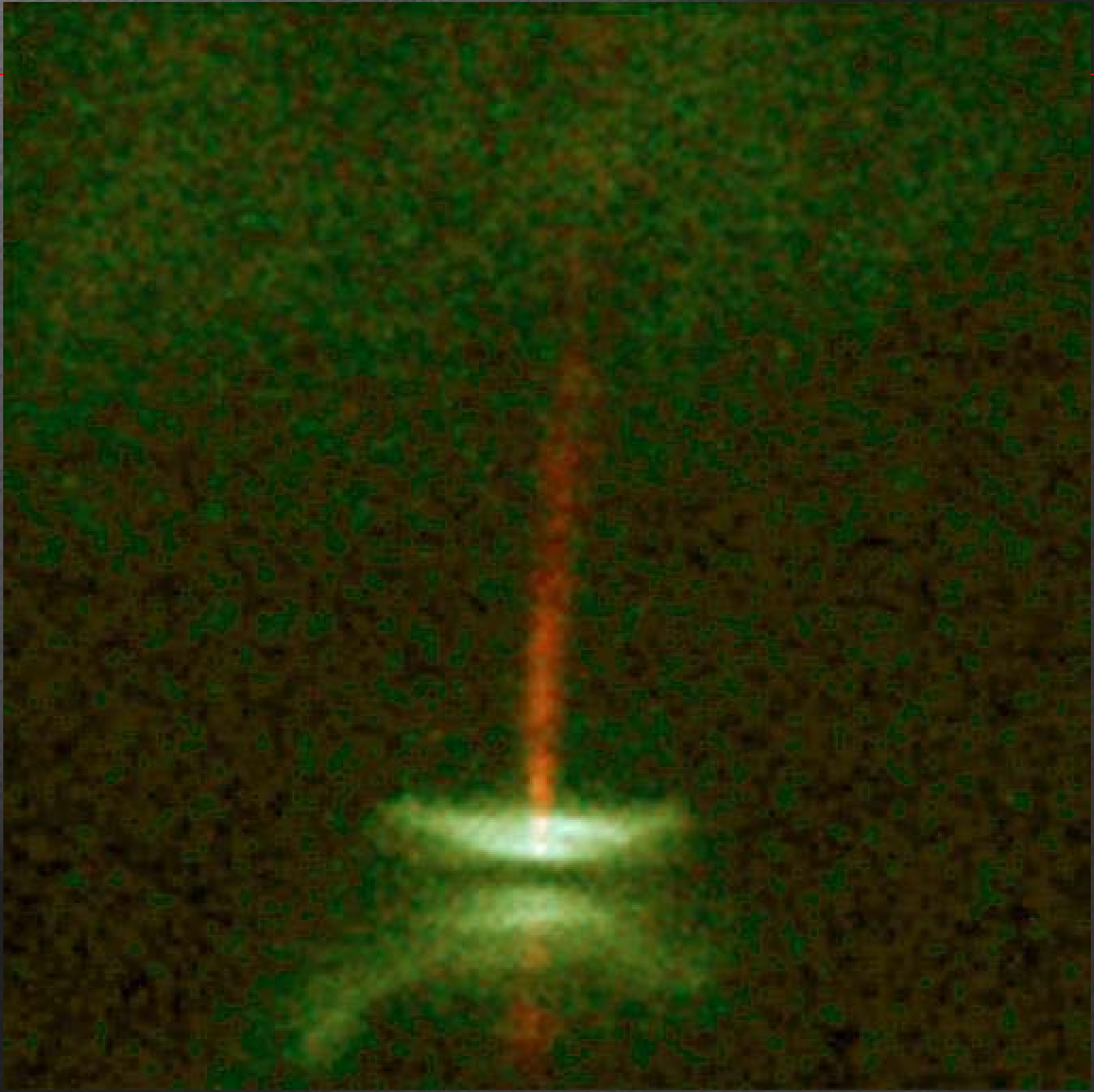
Jet in Carina

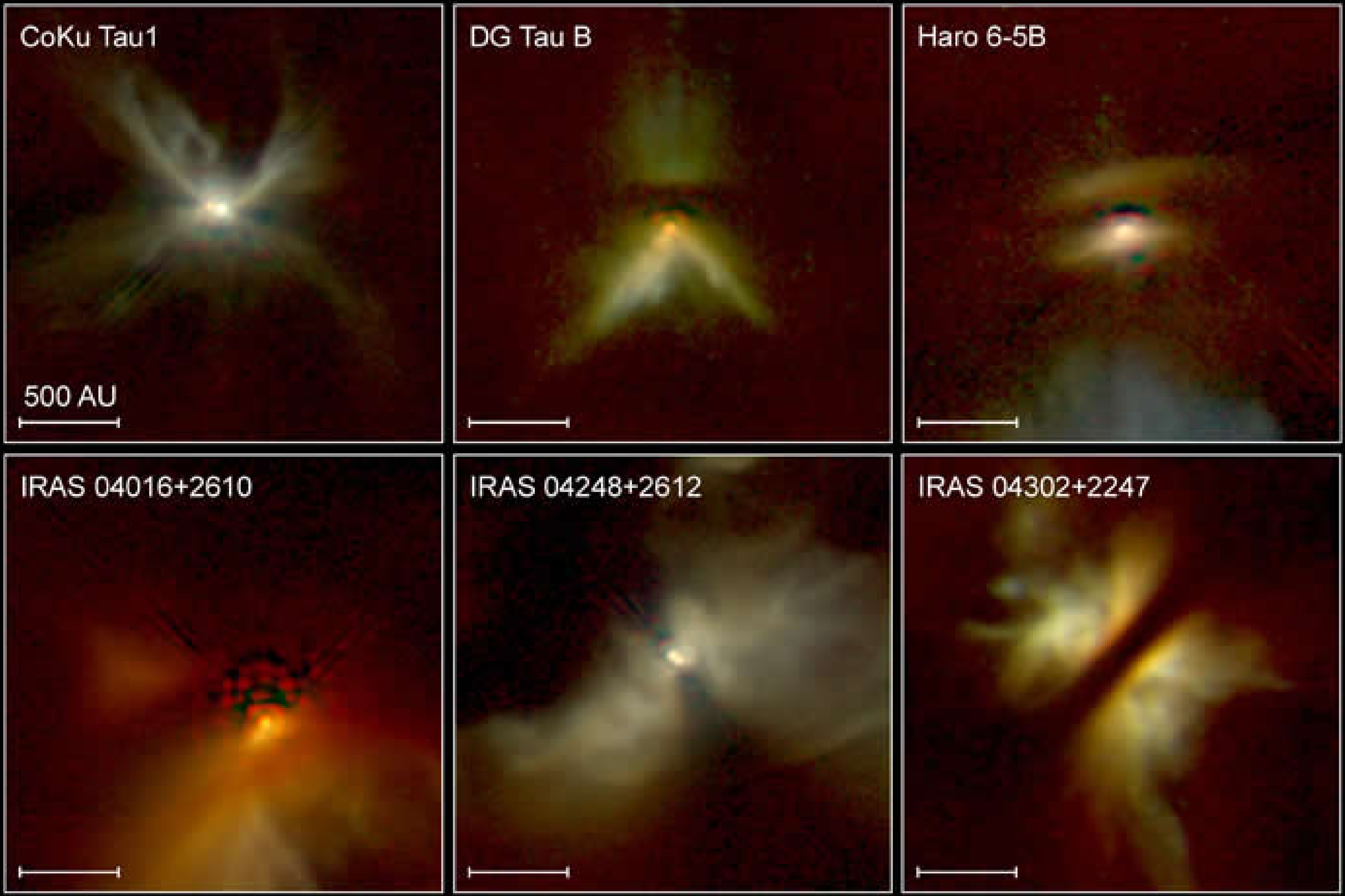
HH 46/47 in Taurus



HH34 in Taurus

HH 2 in Taurus

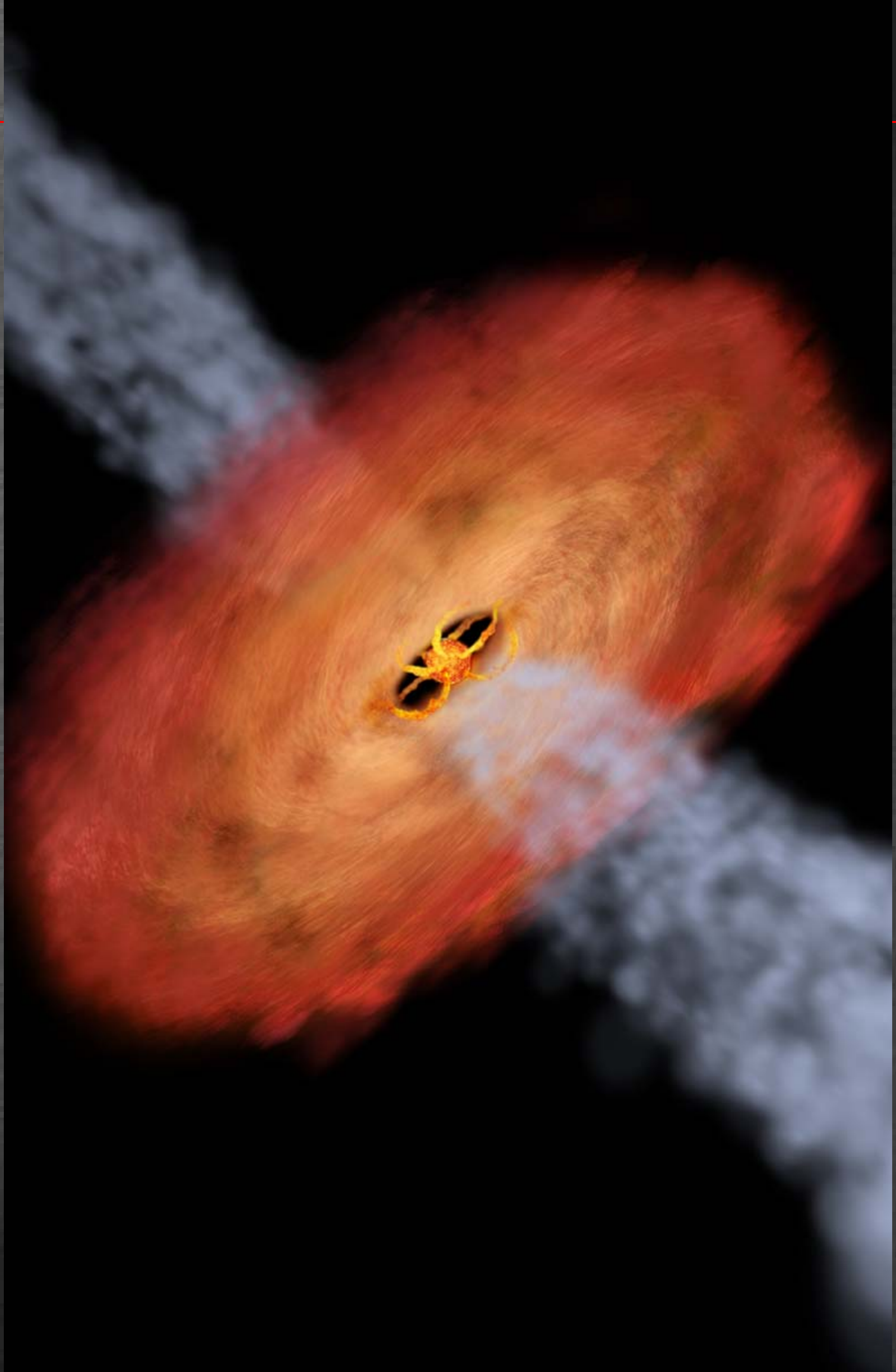




Young Stellar Disks in Infrared

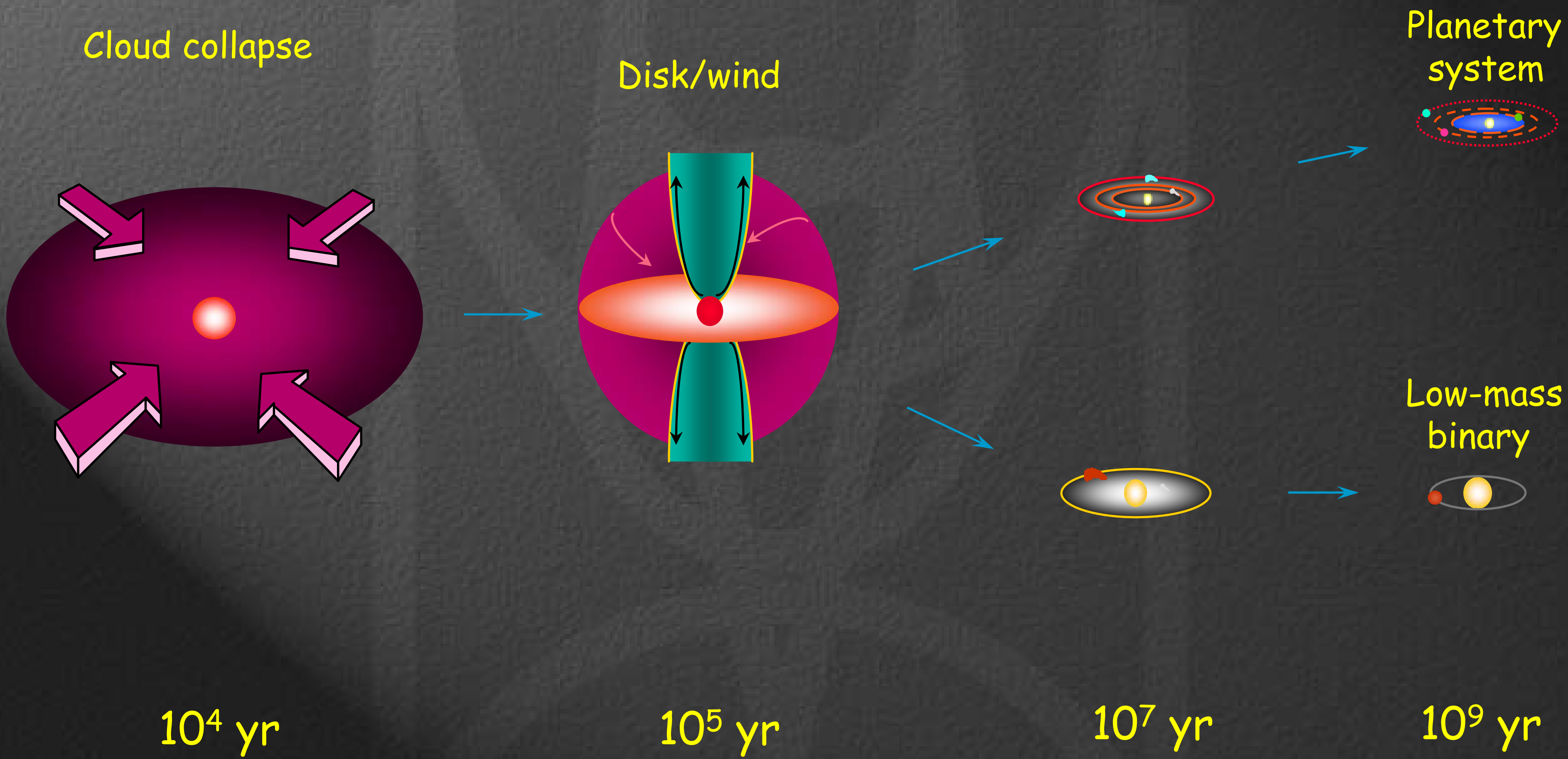
Hubble Space Telescope • NICMOS

PRC99-05a • STScI OPO • D. Padgett (IPAC/Caltech), W. Brandner (IPAC), K. Stapelfeldt (JPL) and NASA



Circumstellar disk
(cartoon)

Star formation: the current paradigm



Cloud collapse

Disk/wind

Planetary system

Low-mass binary

10^4 yr

10^5 yr

10^7 yr

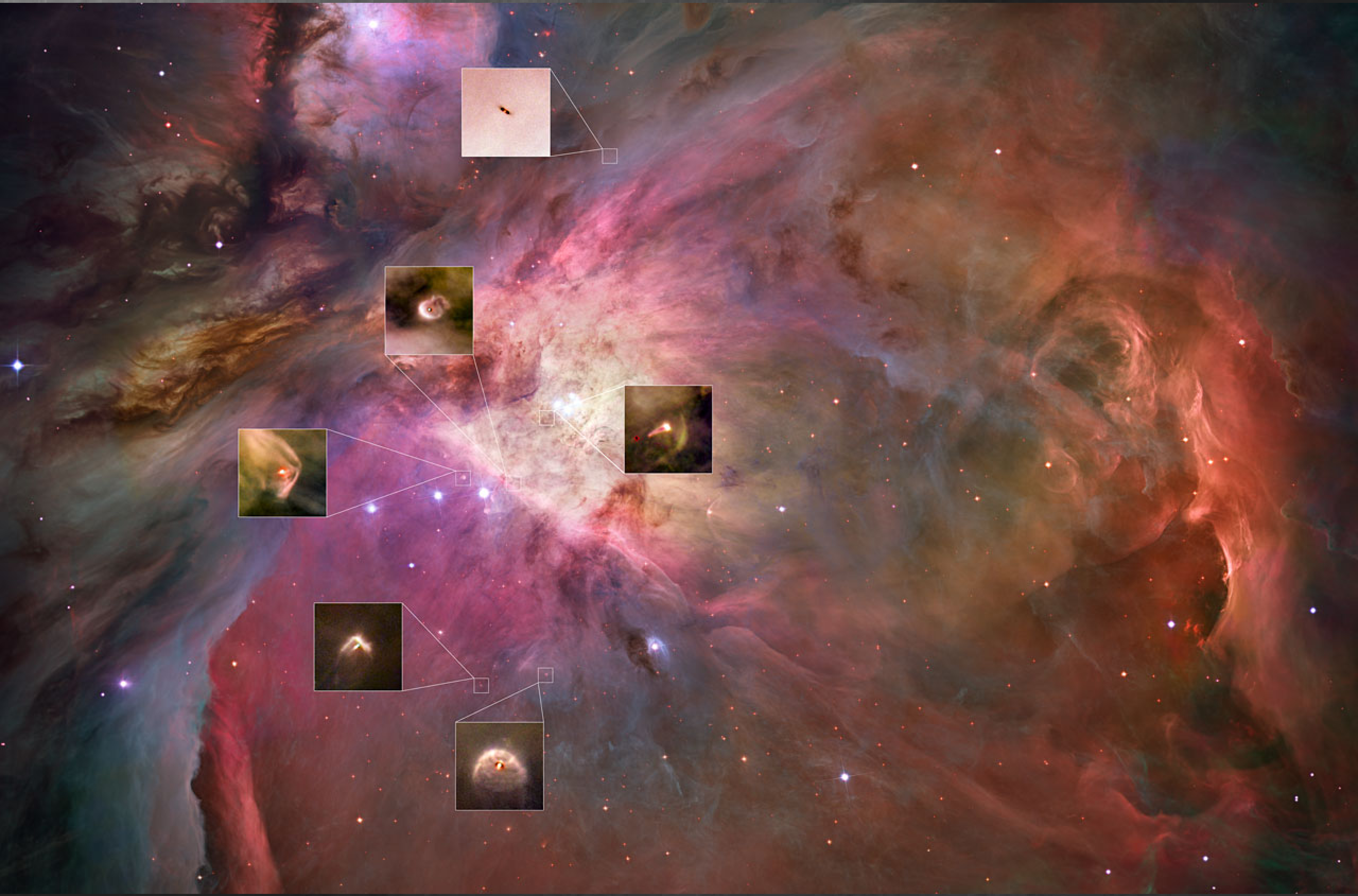
10^9 yr

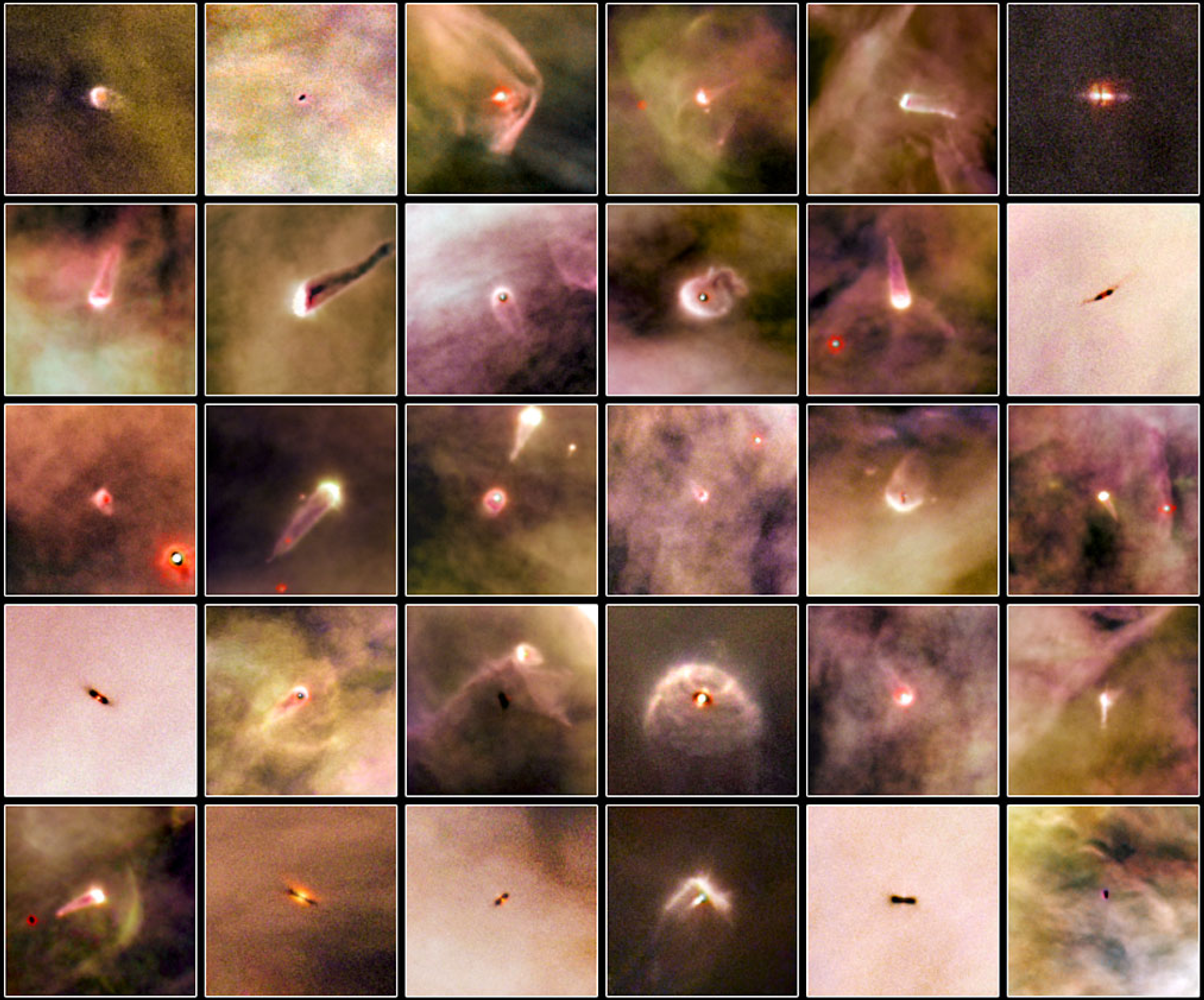
Orion Nebula

May 8, 2006

HST/WFPC2:
Irradiated proto-planetary disks

Proplyds in Orion





The Astrophysical Journal, 687: L83–L86, 2008 November 10

EVIDENCE FOR A PHOTOEVAPORATED CIRCUMBINARY DISK IN ORION[1]

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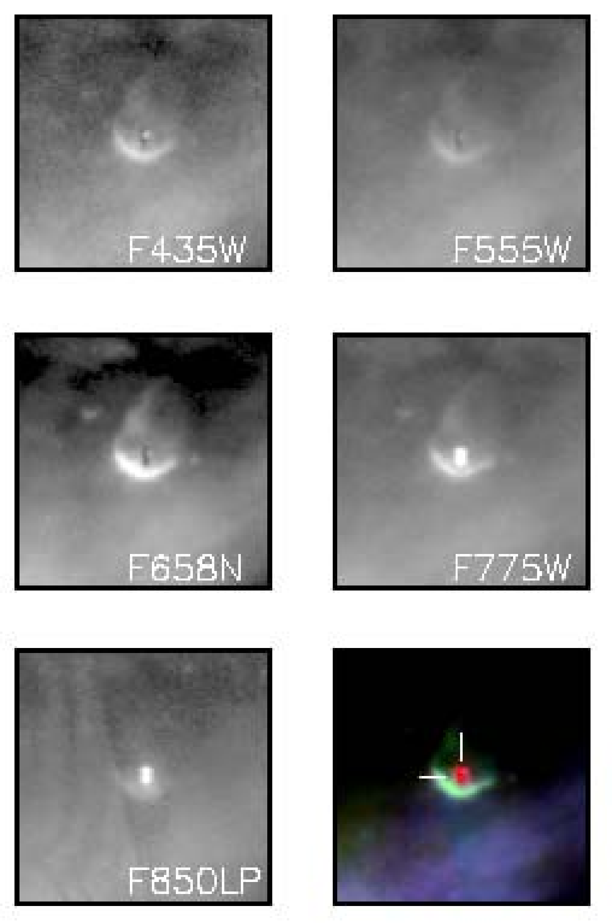
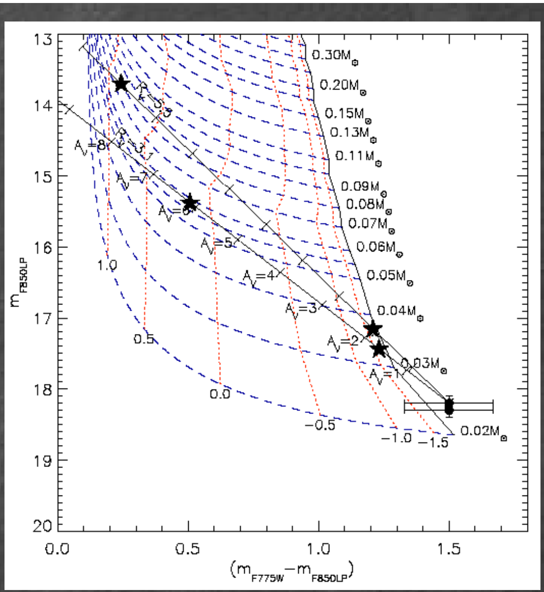
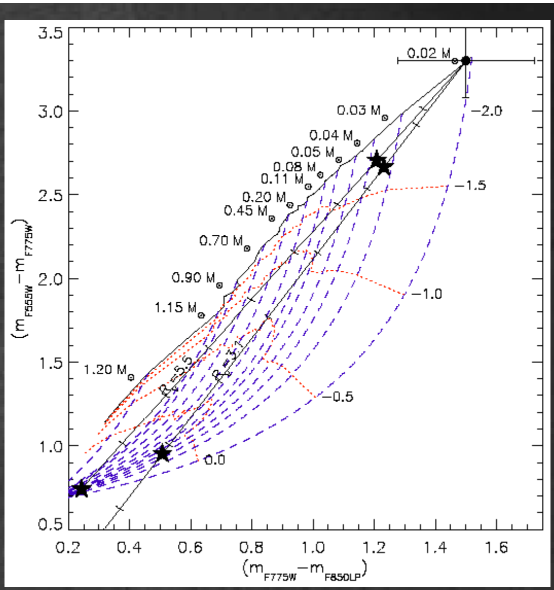
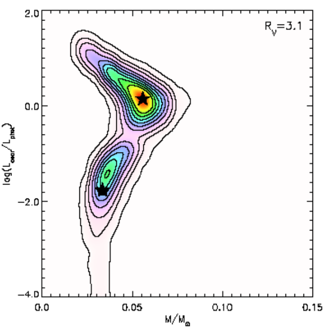
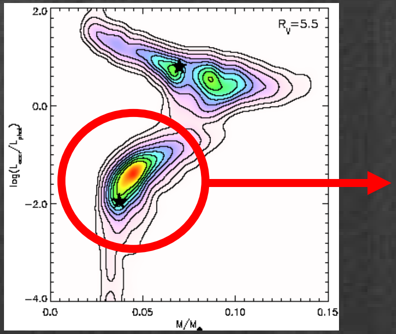








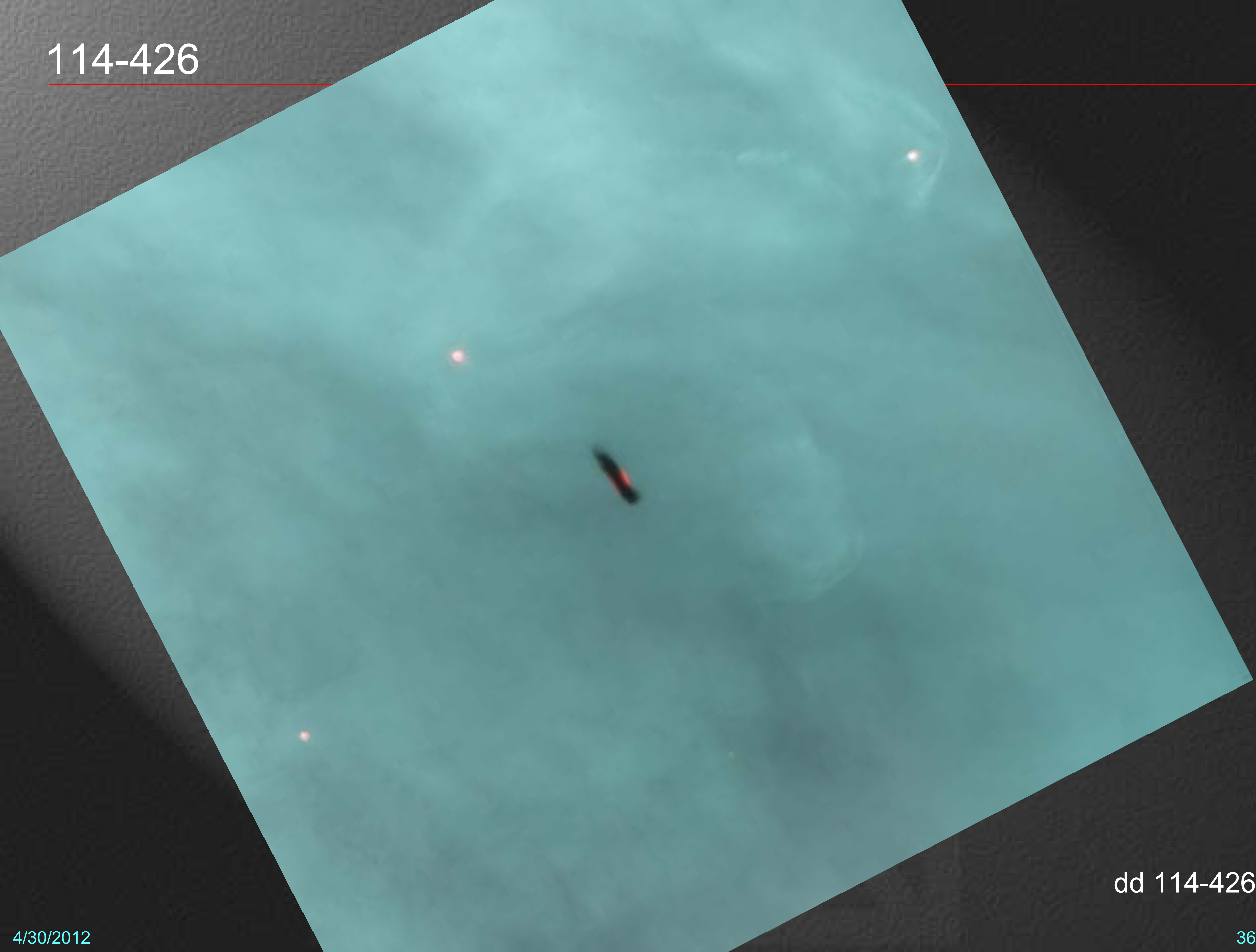


$M = 0.04\ M_\odot$

$\mathrm{Log}M_{acc}$=-10.3

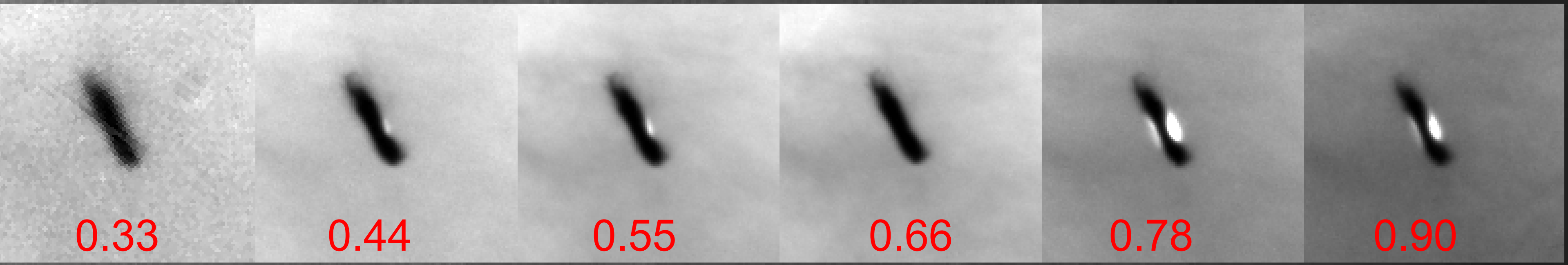
A_V 2

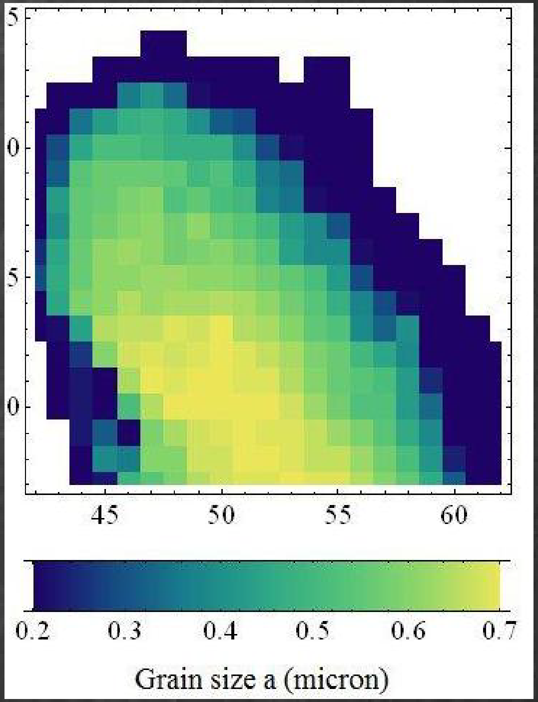
114-426



dd 114-426

New results on 114-426: grain size

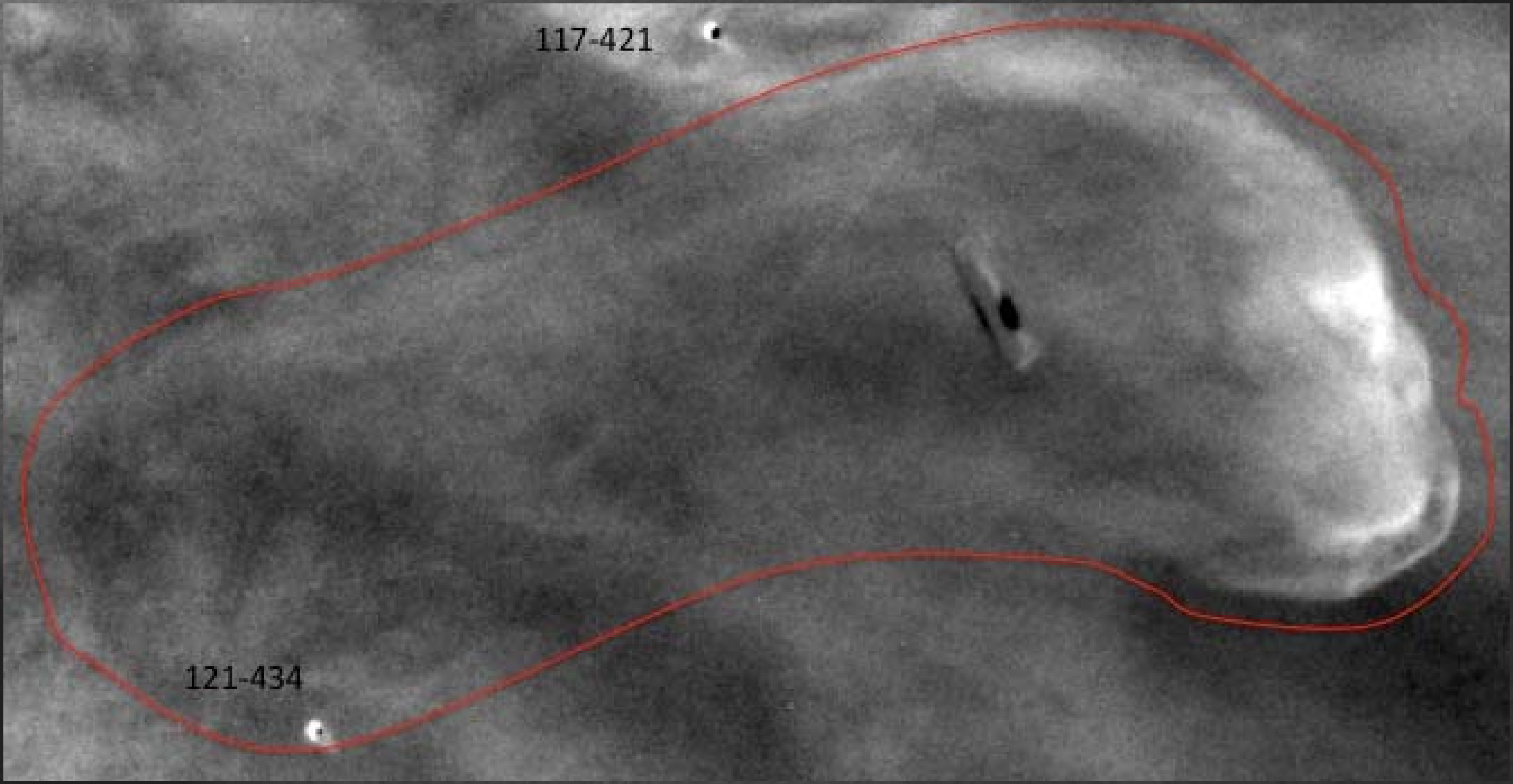




Miotello et al. 2012 (to be submitted)

Dark filaments….

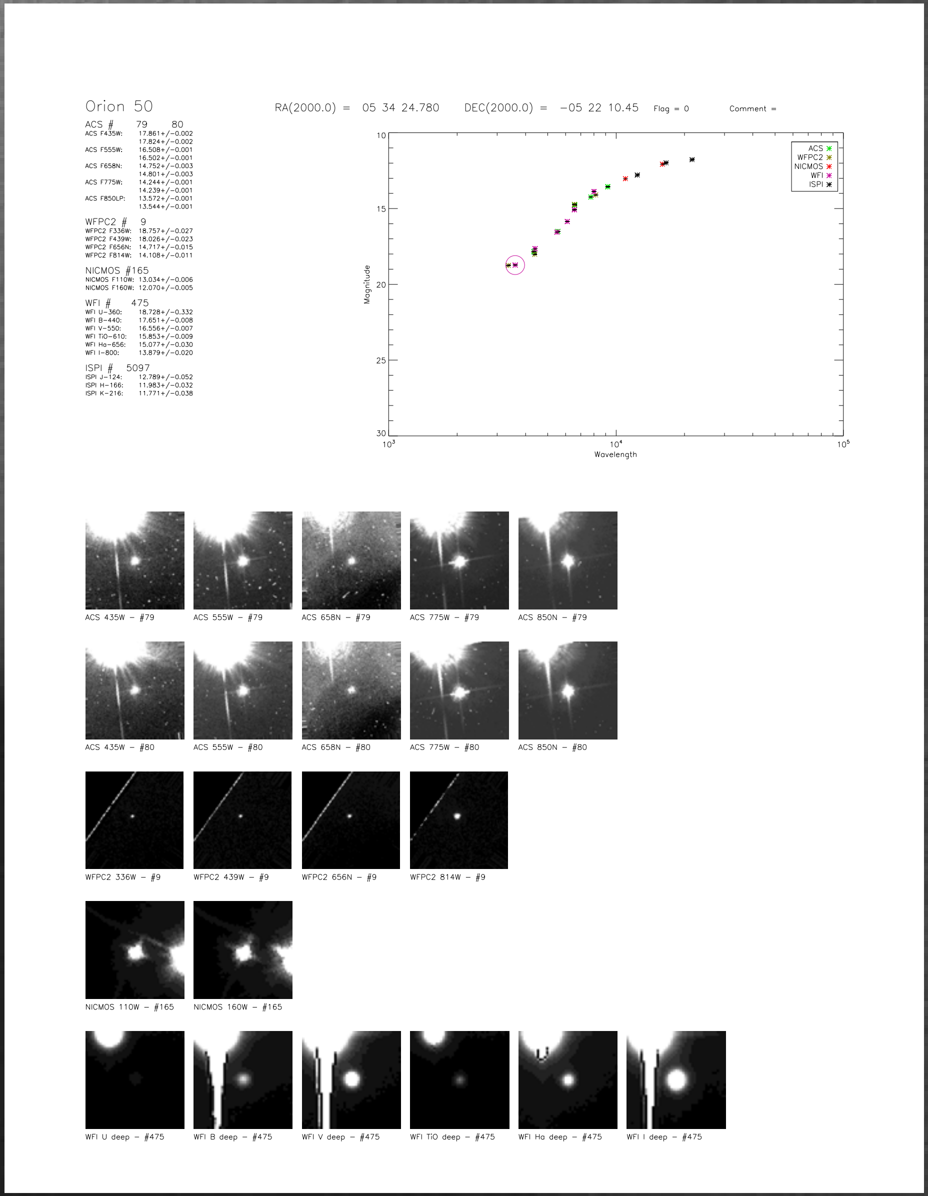
and a large cloud…



also indicate that 114-426 is photoeaporated by the diffuse FUV field

Photoevaporation time-scale ~10^4 yr

The Orion Nebula cluster



Orion 50

RA(2000.0) = 05 34 24.780 DEC(2000.0) = −05 22 10.45 Flag = 0 Comment =

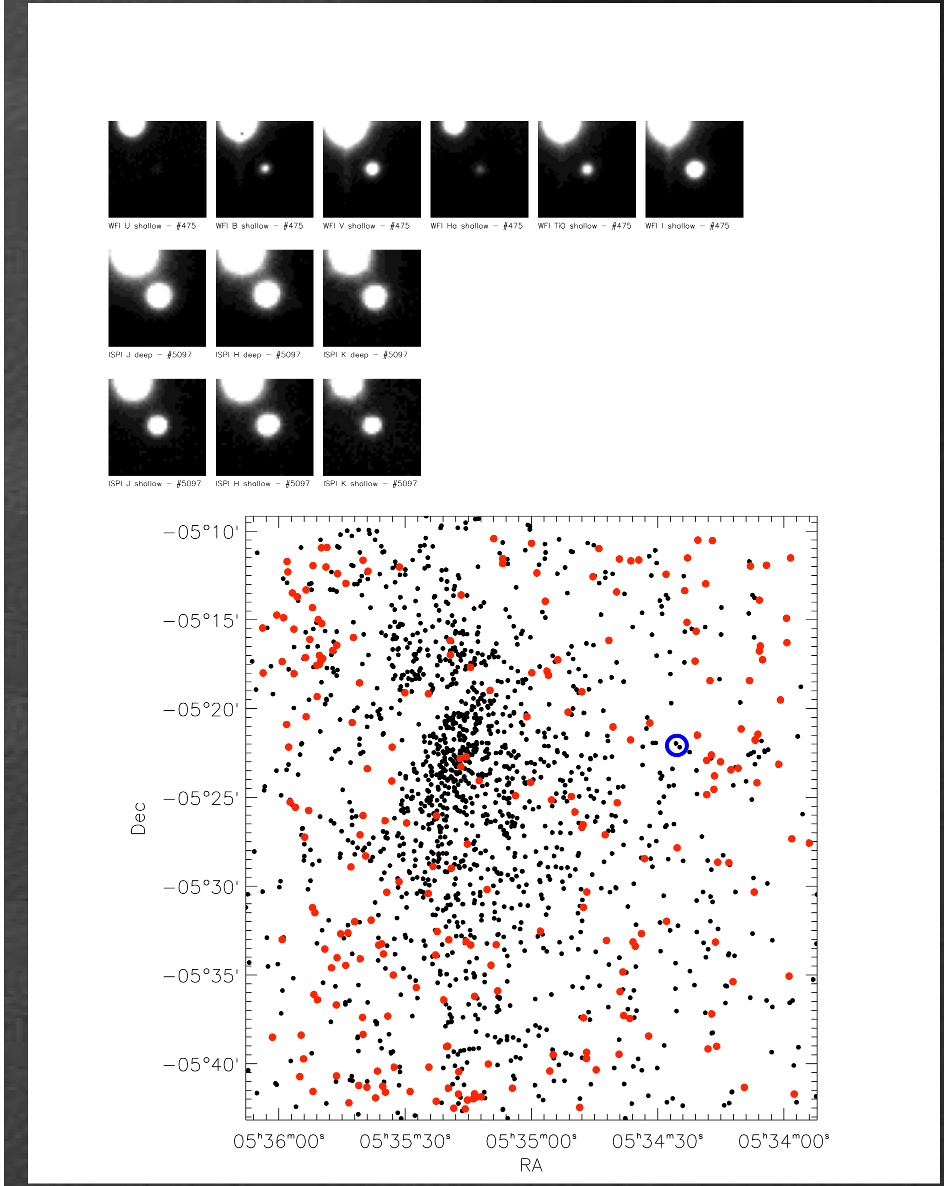
ACS # 79 80
ACS F435W: 17.861+/−0.002
17.824+/−0.002
ACS F555W: 16.508+/−0.001
16.502+/−0.001
ACS F658N: 14.752+/−0.003
14.801+/−0.003
ACS F775W: 14.244+/−0.001
14.239+/−0.001
ACS F850LP: 13.572+/−0.001
13.544+/−0.001

WFPC2 # 9
WFPC2 F336W: 18.757+/−0.027
WFPC2 F439W: 18.026+/−0.023
WFPC2 F656N: 14.717+/−0.015
WFPC2 F814W: 14.108+/−0.011

NICMOS #165
NICMOS F110W: 13.034+/−0.006
NICMOS F160W: 12.070+/−0.005

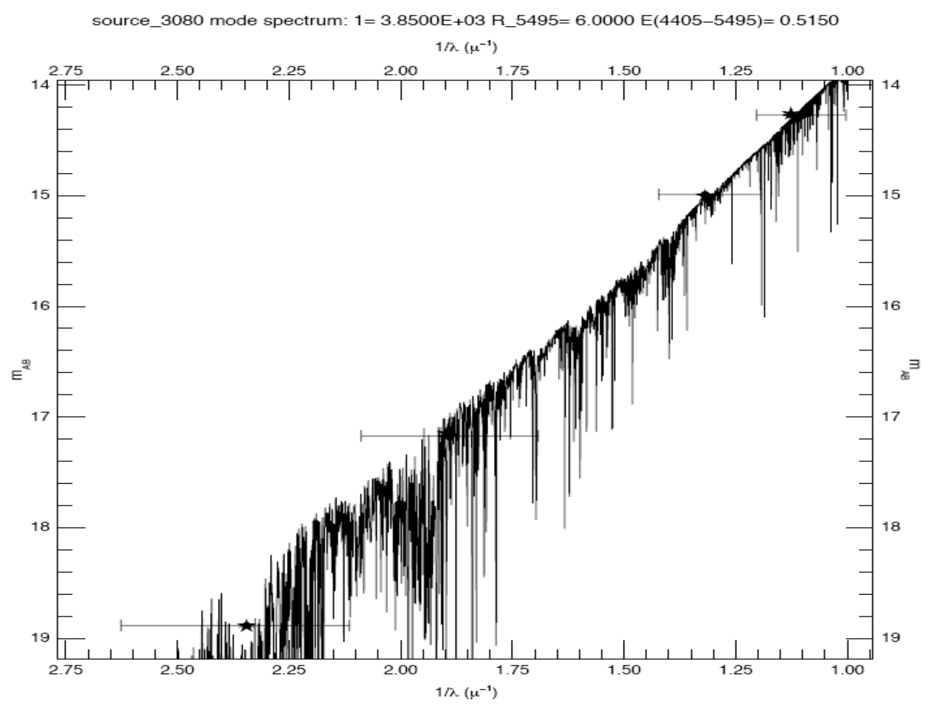
WFI # 475
WFI U−360: 18.728+/−0.332
WFI B−440: 17.651+/−0.008
WFI V−550: 16.556+/−0.007
WFI TiO−610: 15.853+/−0.009
WFI Hα−656: 15.077+/−0.030
WFI I−800: 13.879+/−0.020

ISPI # 5097
ISPI J−124: 12.789+/−0.052
ISPI H−166: 11.983+/−0.032
ISPI K−216: 11.771+/−0.038



Spectral Energy Distribution

Using a bayesian code we can derive the extinction toward each source for a given reddening law.



If we know the extinction, we know the absolute luminosity of the star (distance also needed!)

HR Diagram

Photmetric sample: 2793 ACS and WFI sources with at least 3-band photometry

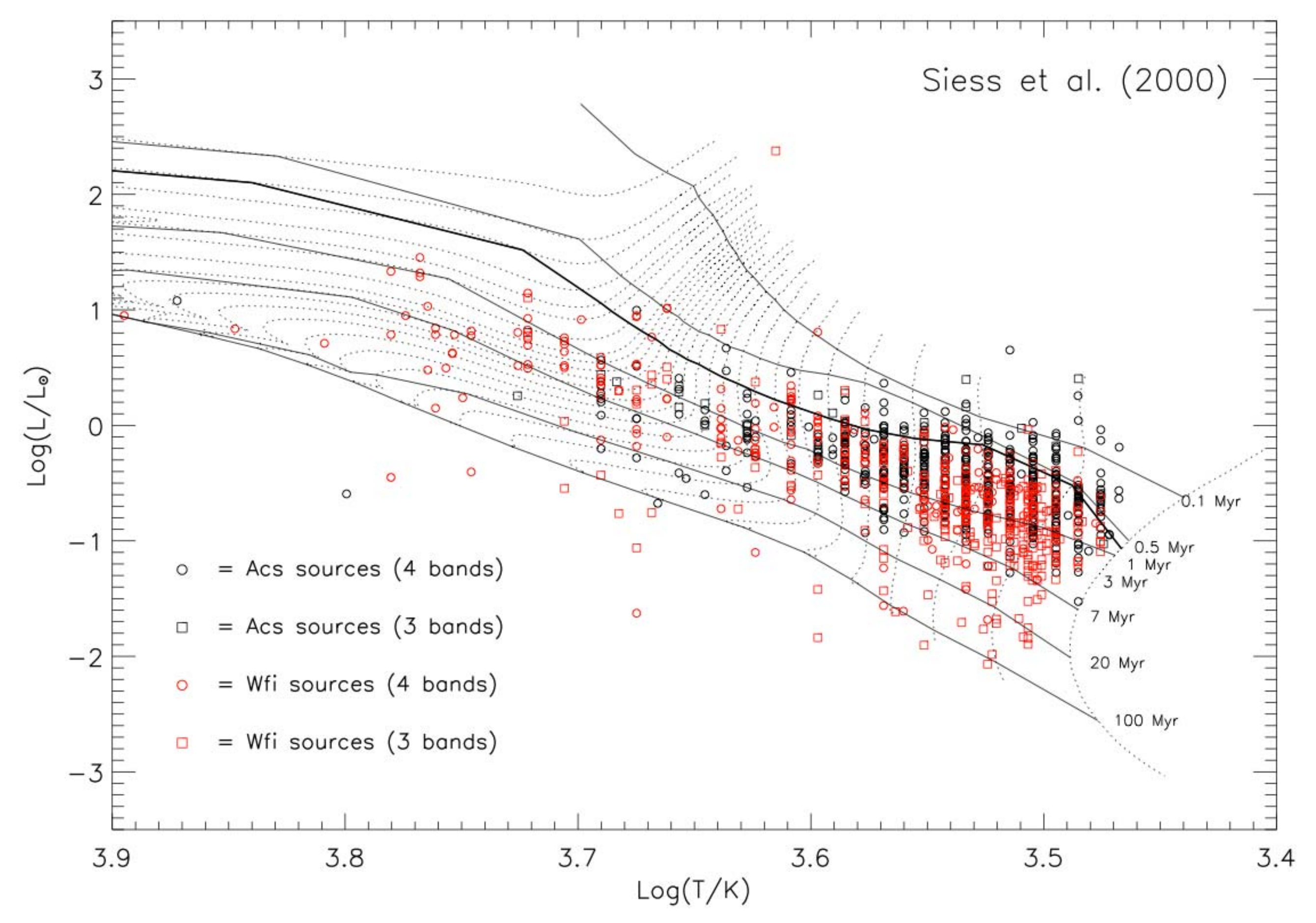
of which:

- 807 stars with spectral type from Hillenbrand (1997)

- 100 stars with spectral type from a follow-up to the study of Stassun et al. (1999)

- 150 stars with spectral type from Da Rio et al. (2009)

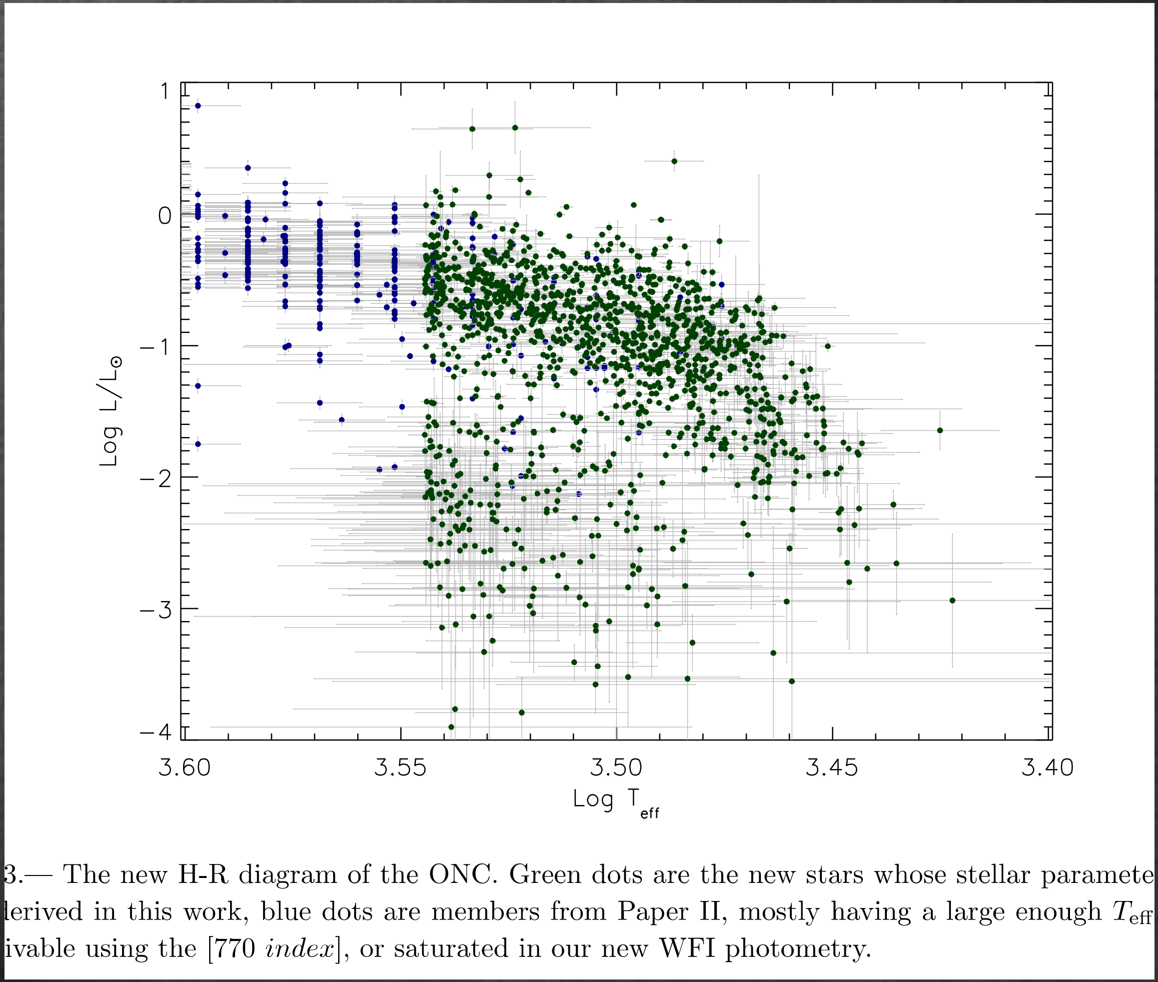
1057 stars with spectral type and photometry in three bands at optical wavelength



Manara et al. 2012, ApJ Submitted

Another view, down into the brown dwarf regime

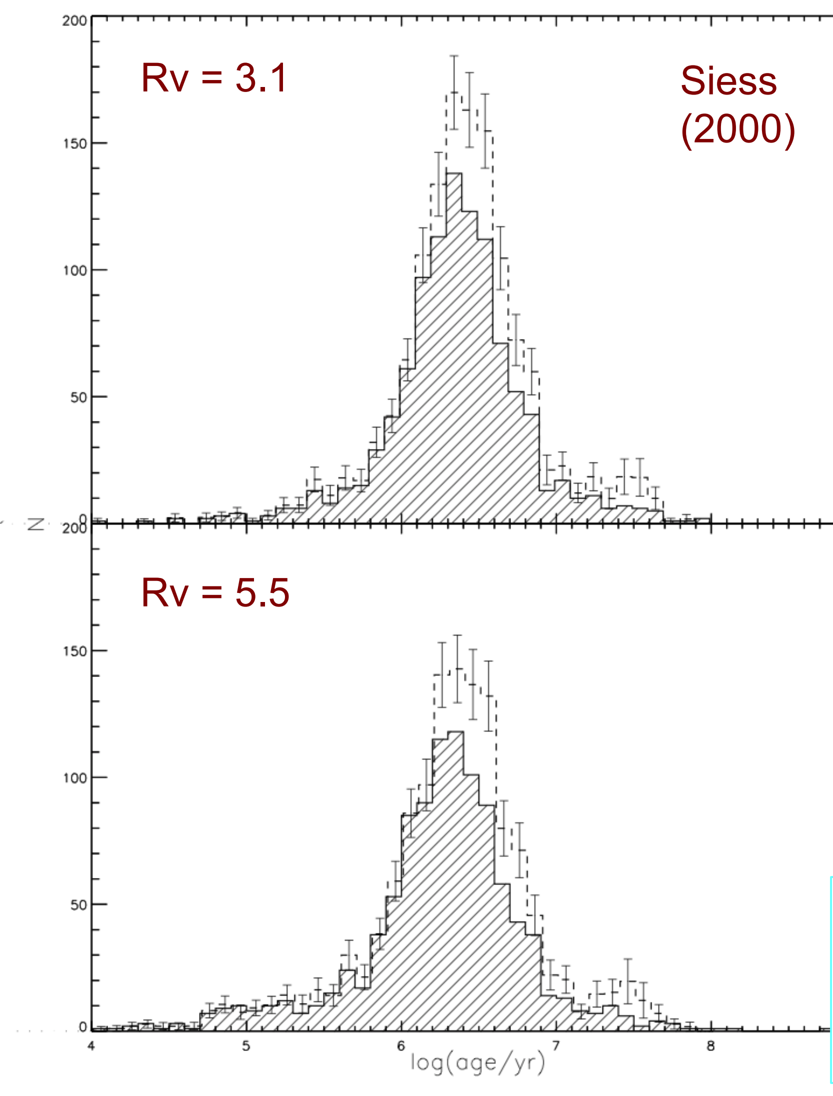
1750 sources down to 0.02 Msun



3.— The new H-R diagram of the ONC. Green dots are the new stars whose stellar paramete lerived in this work, blue dots are members from Paper II, mostly having a large enough $T_{\rm eff}$ ivable using the [770 *index*], or saturated in our new WFI photometry.

Da Rio et al. 2012, ApJ

A large age spread!

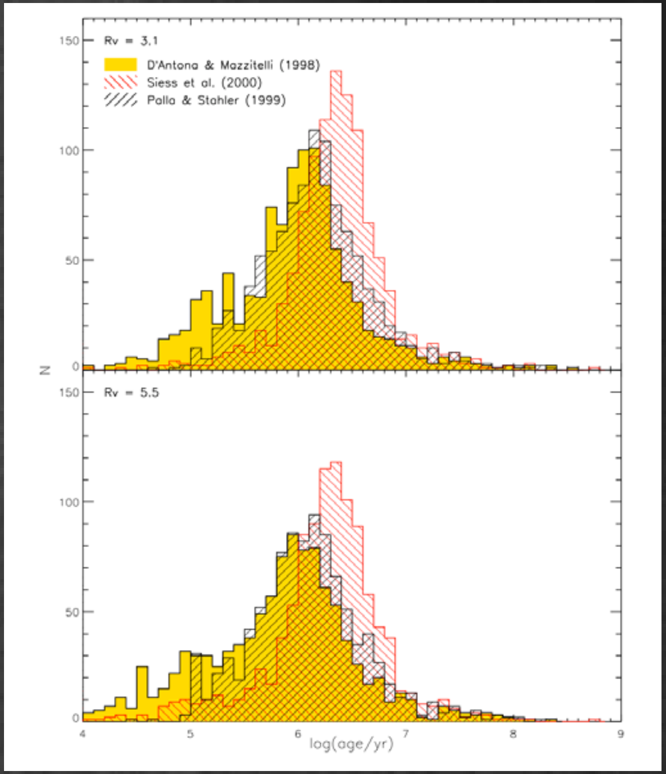


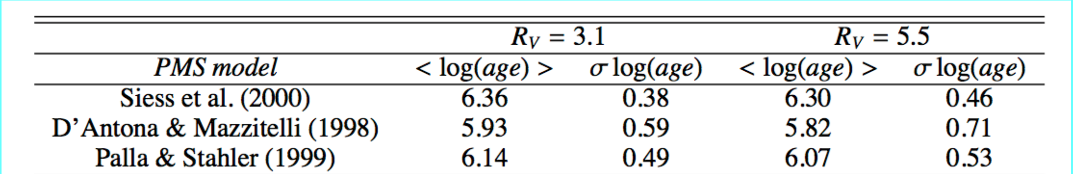
Taking into account uncertainties on

- spectral type
- distance
- extinction
- variability
- unresolved binaries
- accretion

we get

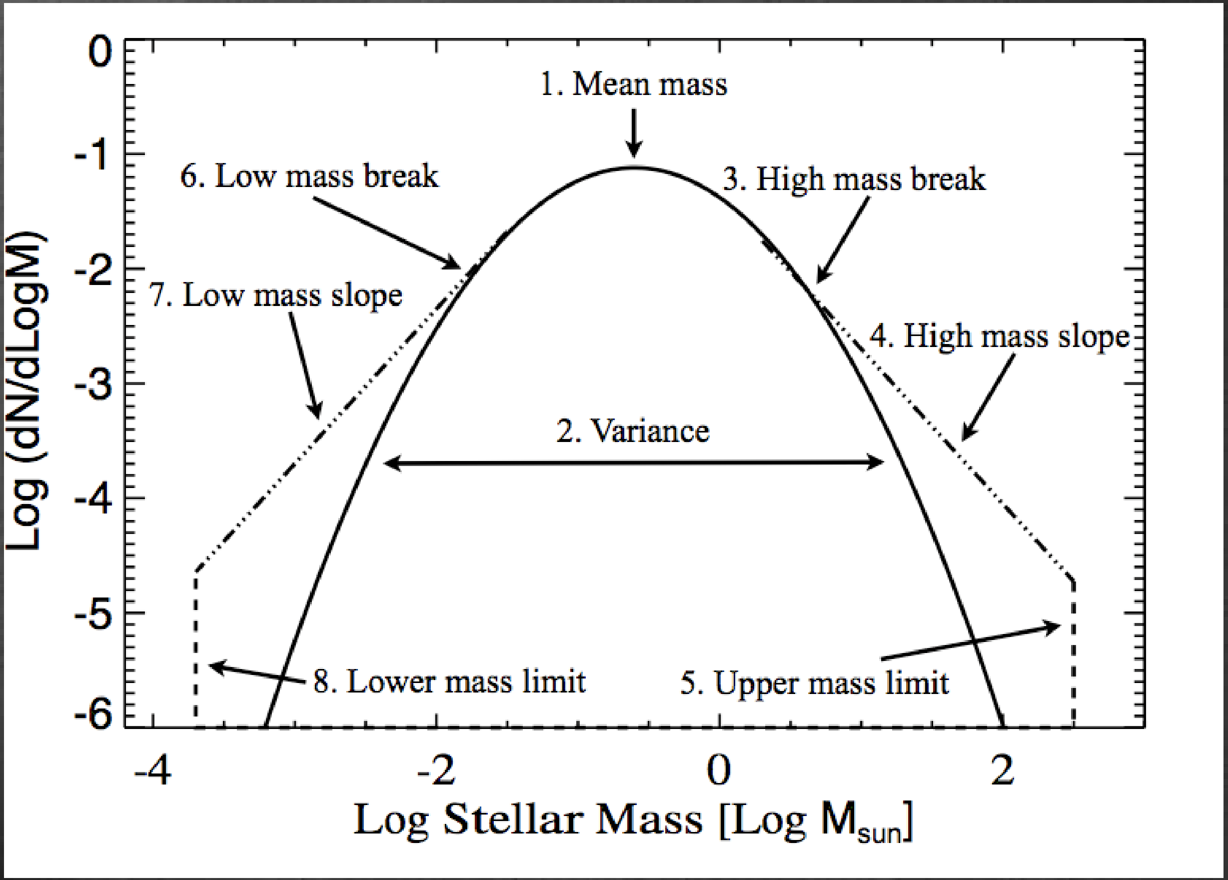
$\sigma(\log L) = 0.10$
$\sigma(\log t) = 0.15$





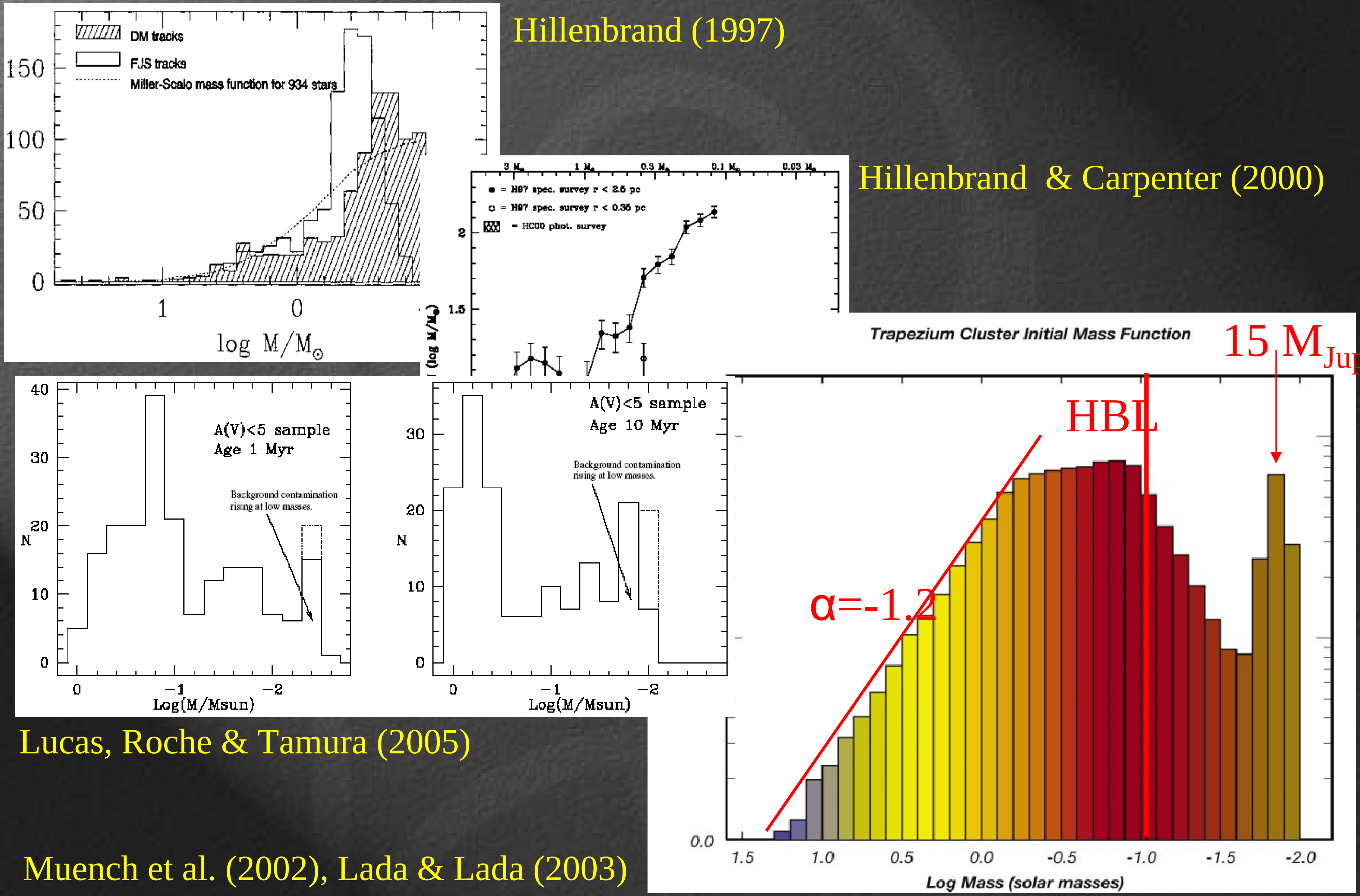
	$R_V = 3.1$		$R_V = 5.5$	
PMS model	$< \log(age) >$	$\sigma \log(age)$	$< \log(age) >$	$\sigma \log(age)$
Siess et al. (2000)	6.36	0.38	6.30	0.46
D'Antona & Mazzitelli (1998)	5.93	0.59	5.82	0.71
Palla & Stahler (1999)	6.14	0.49	6.07	0.53

What is the shape of the IMF?



Bastian, Covey & Meyer 2010

Initial Mass Function



Hillenbrand (1997)

Hillenbrand & Carpenter (2000)

Lucas, Roche & Tamura (2005)

Muench et al. (2002), Lada & Lada (2003)

Steep decrease in the number of brown dwarfs

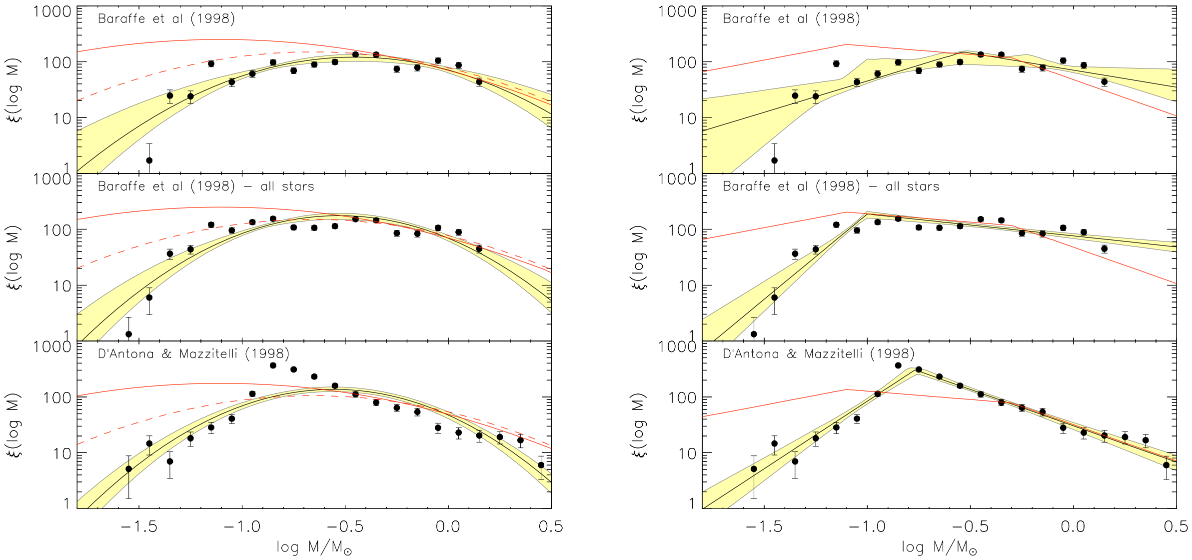
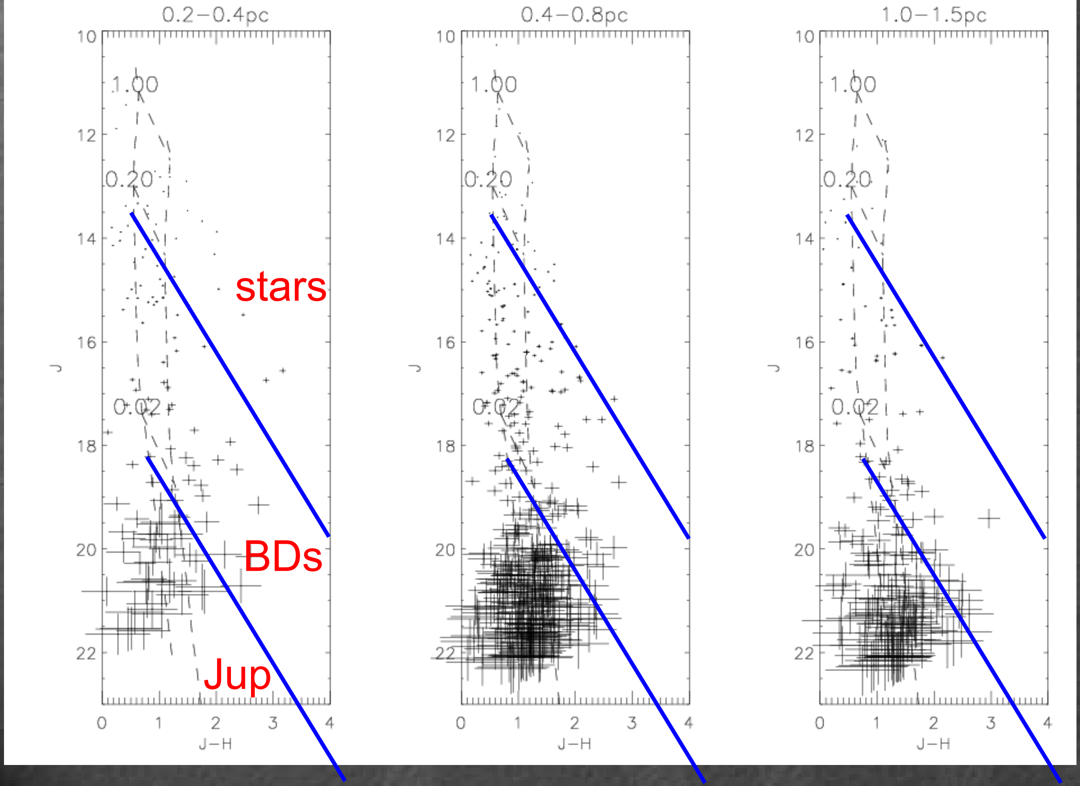
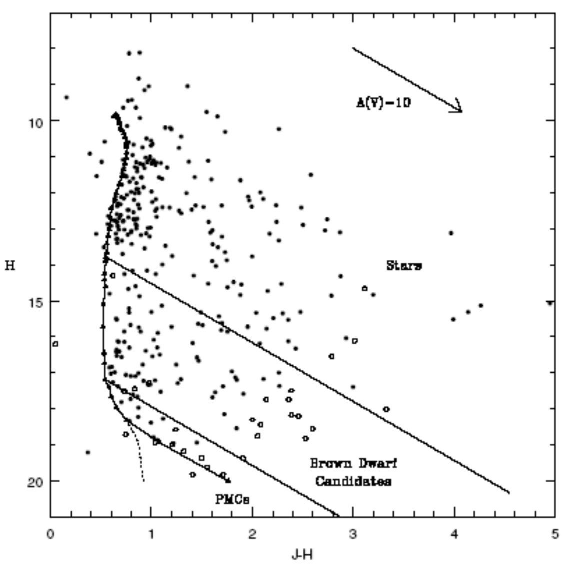


Fig. 18.— The measured IMF for the ONC, fitted with a log-normal distribution (left panel) or a two-phase power law (right panel). The top and bottom panels represent the mass distributions obtained assuming Baraffe et al. (1998) and D'Antona & Mazzitelli (1998) models respectively, whereas the center panels show the result assuming Baraffe models and including also stars located above the 1 Myr, whose mass has been extrapolated from their $T_{\rm eff}$ (see text). The shaded areas enclose the 90% confidence interval for each fit. The red curves represent the IMF of Chabrier (2003) (left panel) and Kroupa (2001) (right panel); the red dashed line is the Chabrier (2003) system IMF.

Da Rio et al. 2012

NICMOS Color-Magnitude Diagram (Andersen et al. 2011)





Lucas, Roche & Tamura (2005)

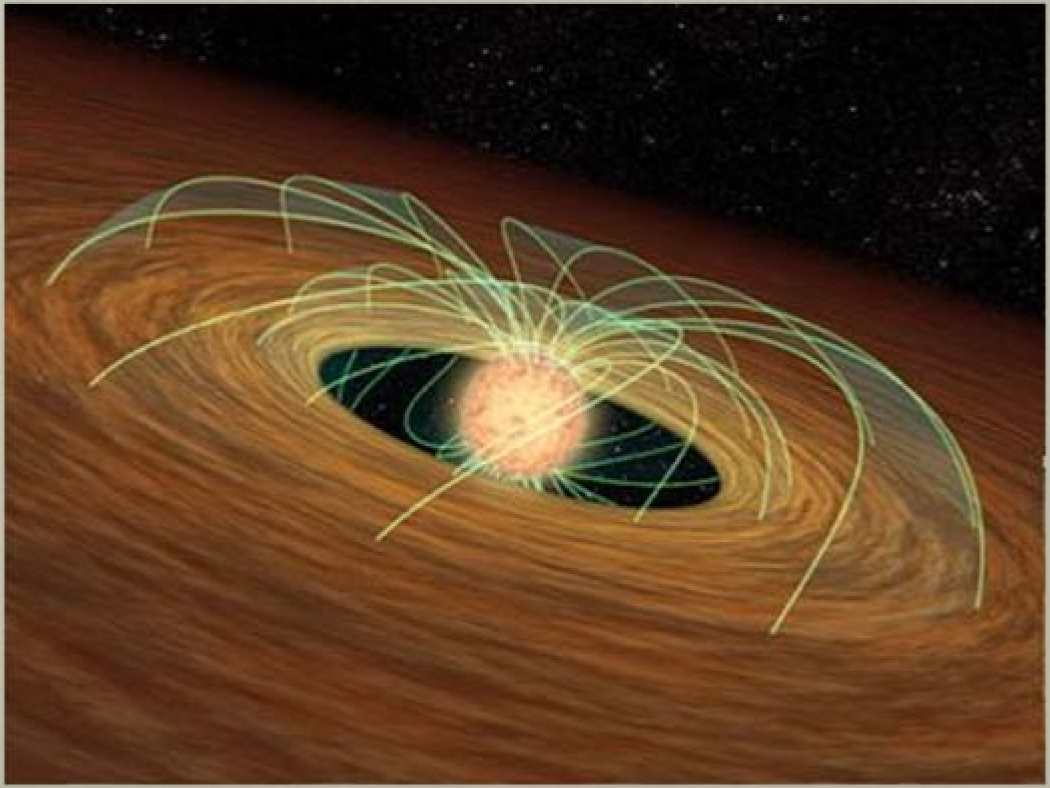
- Myr isochrone of Baraffe et al.
- Reddened with Av=5
- $1M_\odot$,$0.2M_\odot$ and $0.02M_\odot$ tracks

2174 sources in 160.7sq. arcmin

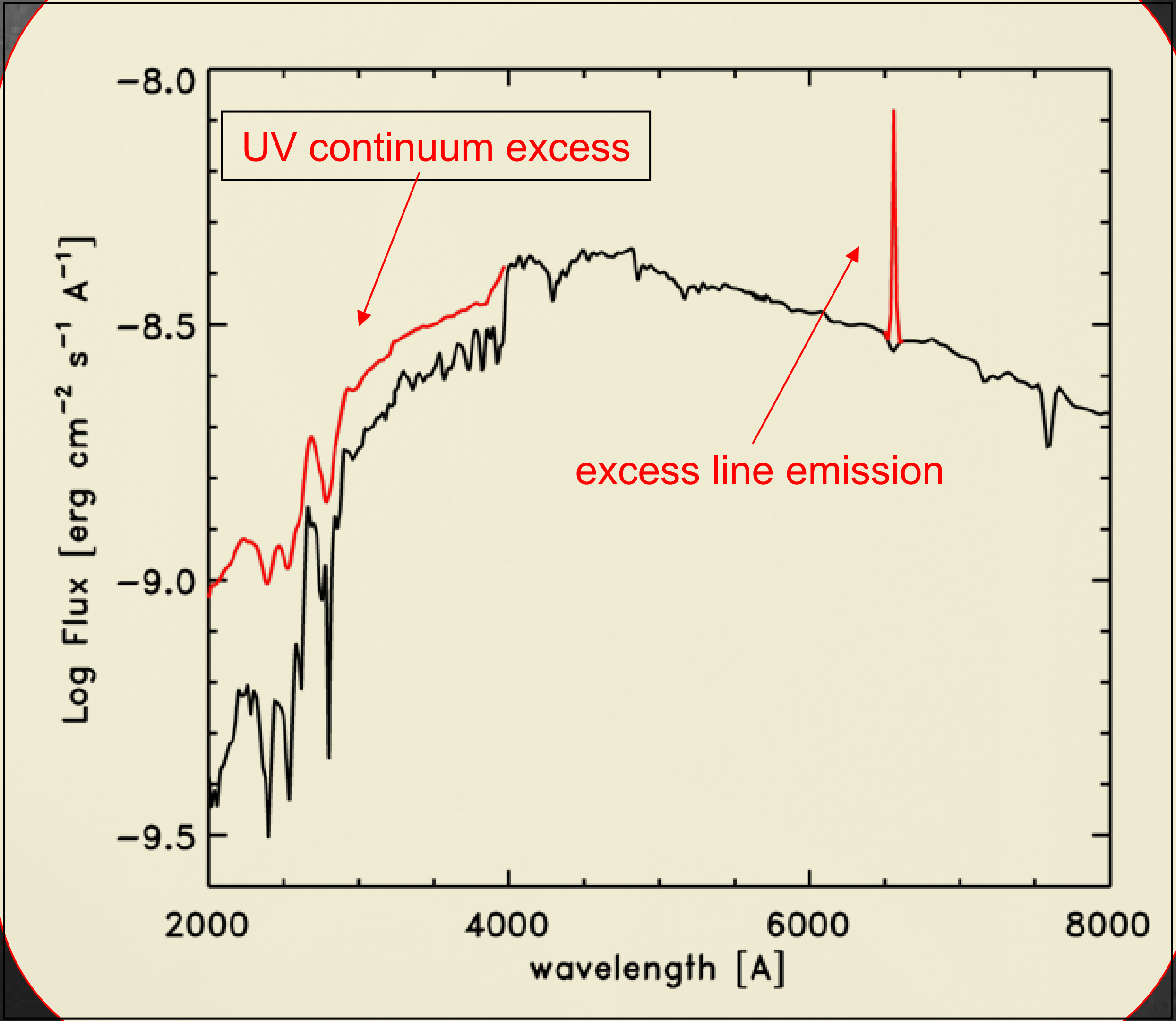
N(0.08-1.0)/N(0.03-0.8)=2.4±0.2 → Flat low mass IMF

(e.g. Allen et al. 20005, ApJ 625,385)

Accretion from circumstellar disc



Accretion from circumstellar disc



UV continuum excess

excess line emission

Mass Accretion Rate

- **Hα luminosity $L_{H\alpha}$ gives accretion luminosity L_{acc} via relationship calibrated using spectroscopic data** (e.g. Dahm 2008)

$$\mathrm{Log}\ (L_{acc}) = \mathrm{Log}\ (L_{H\alpha}) + (1.72 \pm 0.47)$$

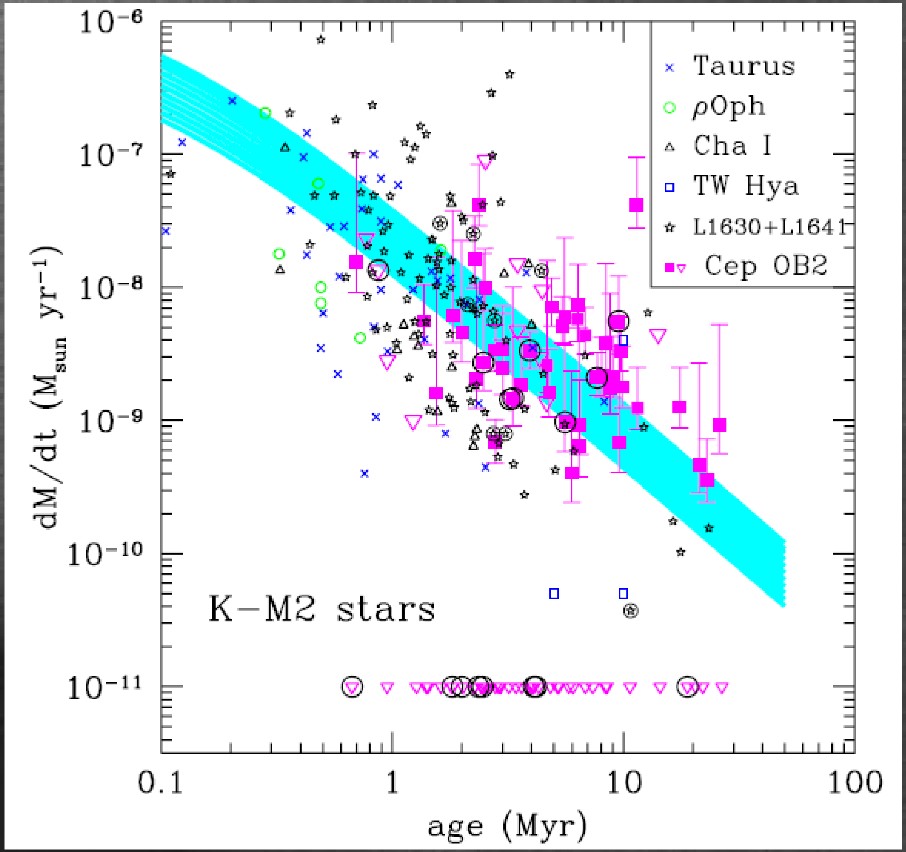
- **Mass $M_\star$ radius $R_\star$ and age $t_\star$ from PMS isochrones in HR diagram**

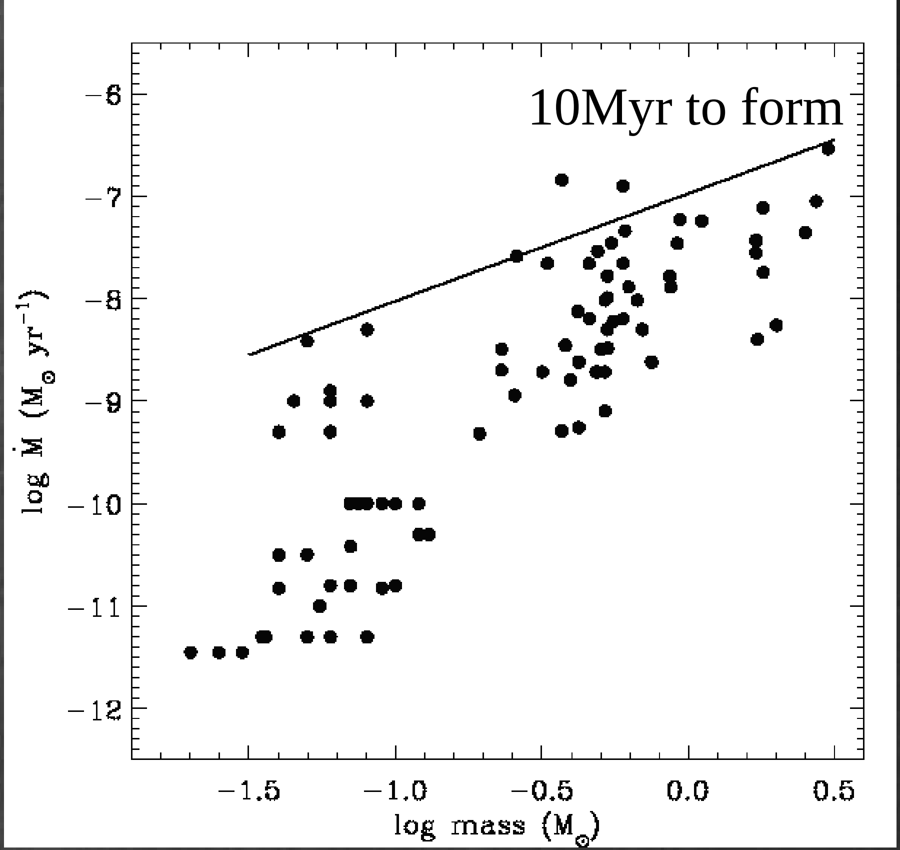
- **Free fall equation gives mass accretion rate $\dot{M}$**

$$L_{acc} \simeq \frac{GM_*\dot{M}}{R_*}\left(1 - \frac{R_*}{R_{in}}\right)$$

- **We can study how star formation has proceeded in space and time**

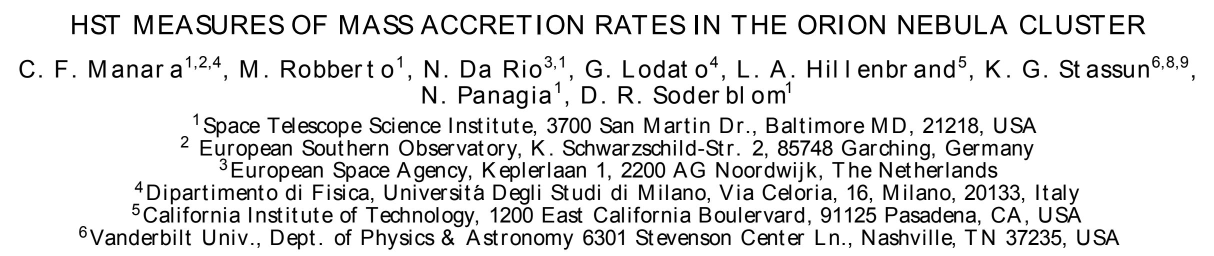
Mass accretion





Hartmann et al. 1998,
Robberto et al. 2004,
Calvet et al. 2005,2008,
Fedele et al. 2010,
Sicilia-Aguilar et al. 2010

Calvet et al. 2004,
Muzerolle et al. 2003, 2005,
Natta et al 2004, 2006,
Hartmann et al. 2006,
Rigliaco et al. 2011



HST MEASURES OF MASS ACCRETION RATES IN THE ORION NEBULA CLUSTER

C. F. Manara[1,2,4], M. Robberto[1], N. Da Rio[3,1], G. Lodato[4], L. A. Hillenbrand[5], K. G. Stassun[6,8,9],
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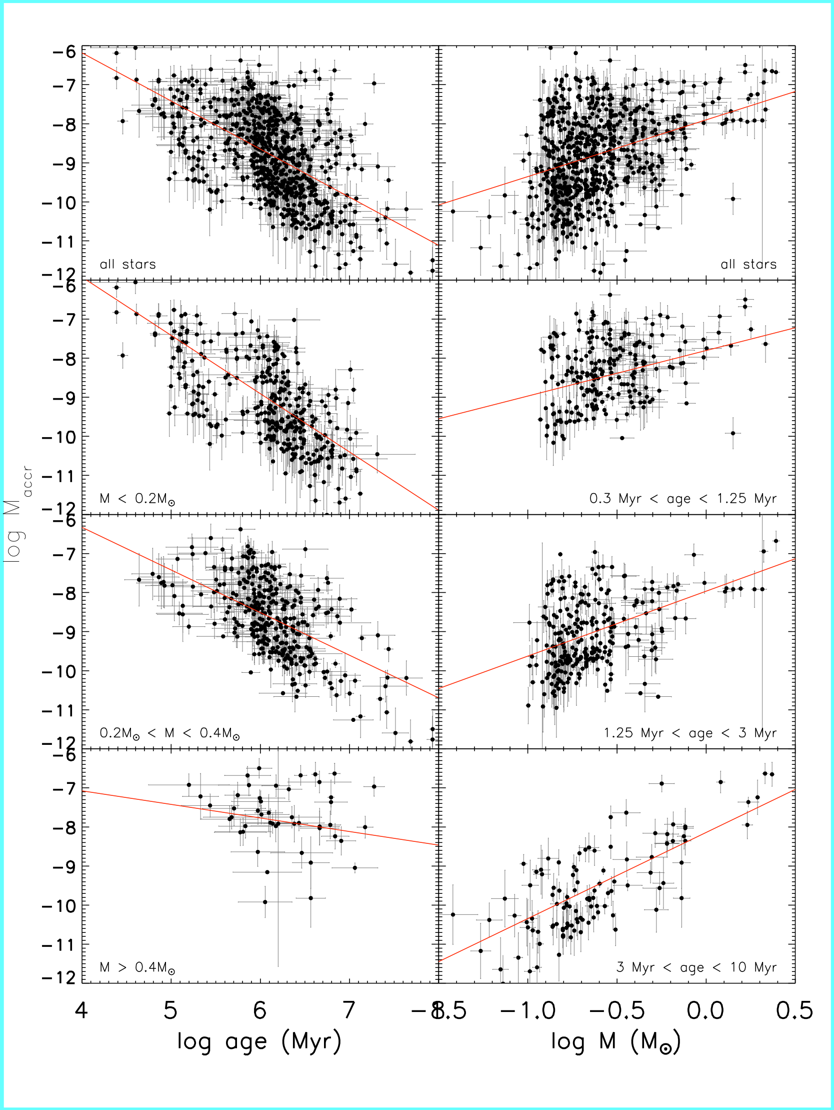
[3]European Space Agency, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands
[4]Dipartimento di Fisica, Universitá Degli Studi di Milano, Via Celoria, 16, Milano, 20133, Italy
[5]California Institute of Technology, 1200 East California Boulervard, 91125 Pasadena, CA, USA
[6]Vanderbilt Univ., Dept. of Physics & Astronomy 6301 Stevenson Center Ln., Nashville, TN 37235, USA



How about other environments?

- Most stars in the Universe formed at redshift z~2, when metallicity was lower, 1/10 – 1/3 solar, like in the nearby Magellanic Clouds, but …

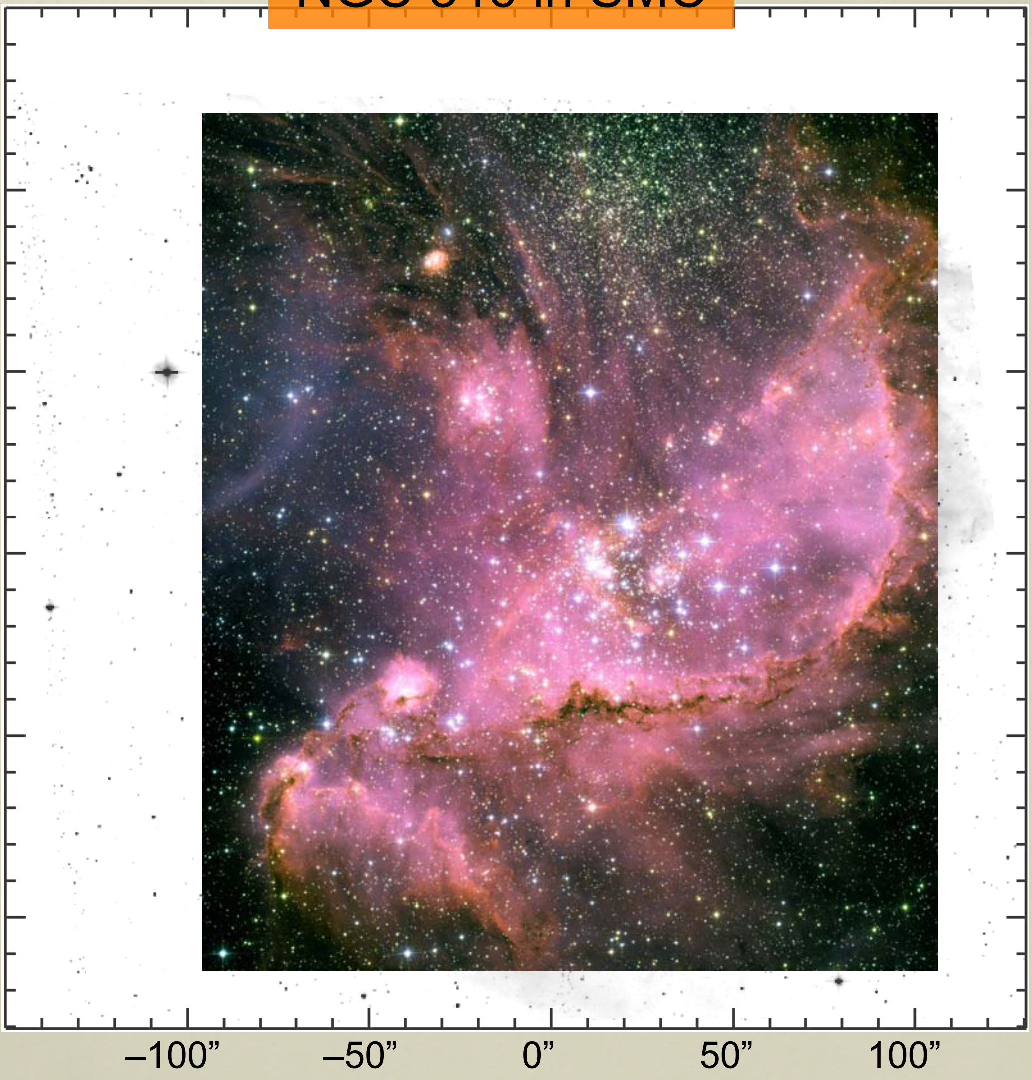
- Spectroscopy of individual stars in MCs hampered by crowding, VLT/Flames observations attempted, but limit is angular resolution

- New simple method combines broad- (V, I) and narrow-band (H_α) photometry and allows us to:
  - ✓ identify all objects with Hα excess emission
  - ✓ derive their accretion luminosity and mass accretion rates
  - ✓ for hundreds of stars simultaneously!

(De Marchi, Panagia & Romaniello 2010, ApJ, 715, 1
De Marchi, Panagia, Romaniello et al. 2011, ApJ, 740, 11
Spezzi, De Marchi, Panagia et al. 2011, MNRAS, submitted)

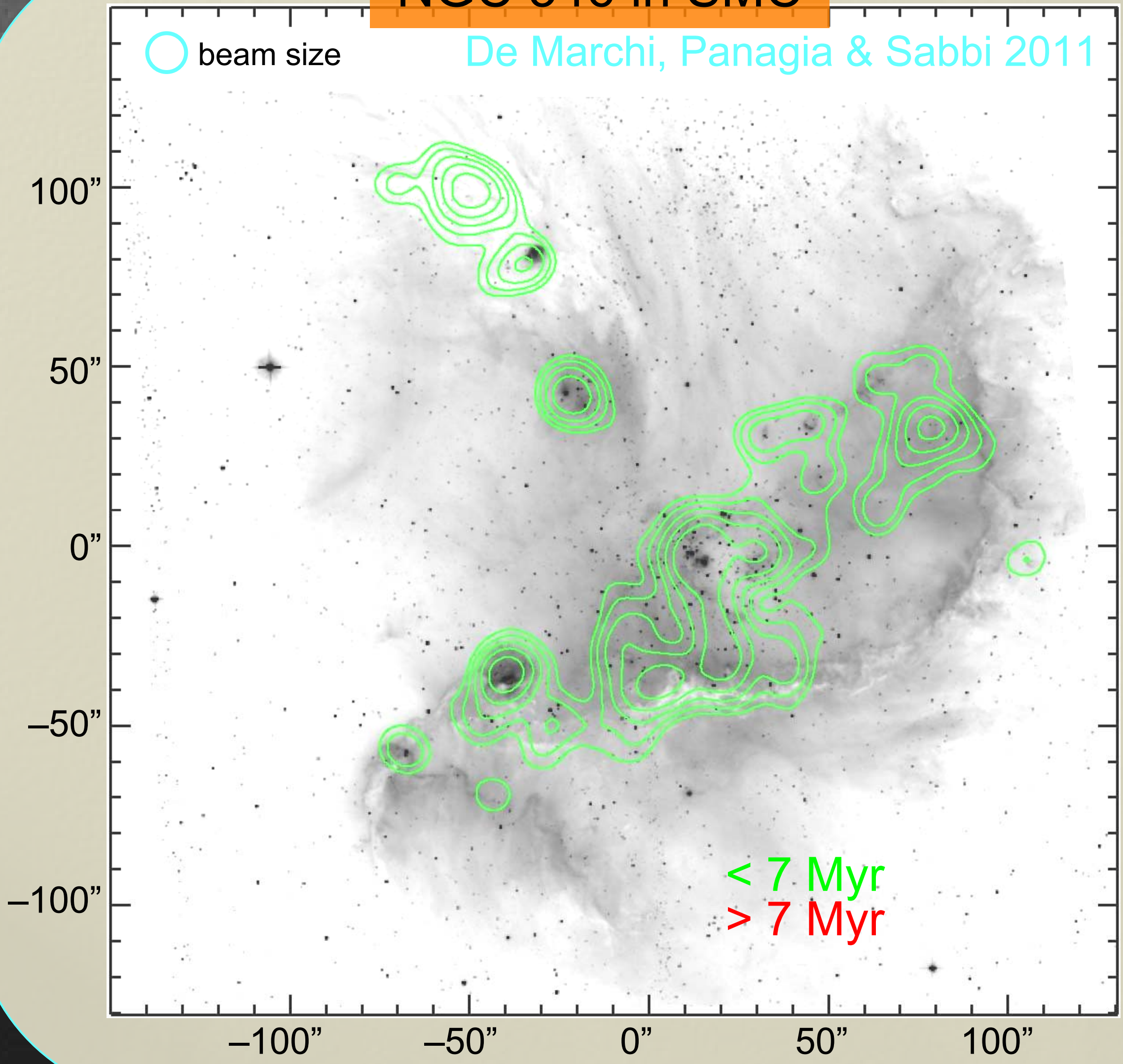
Multiple but unrelated generations

NGC 346 in SMC



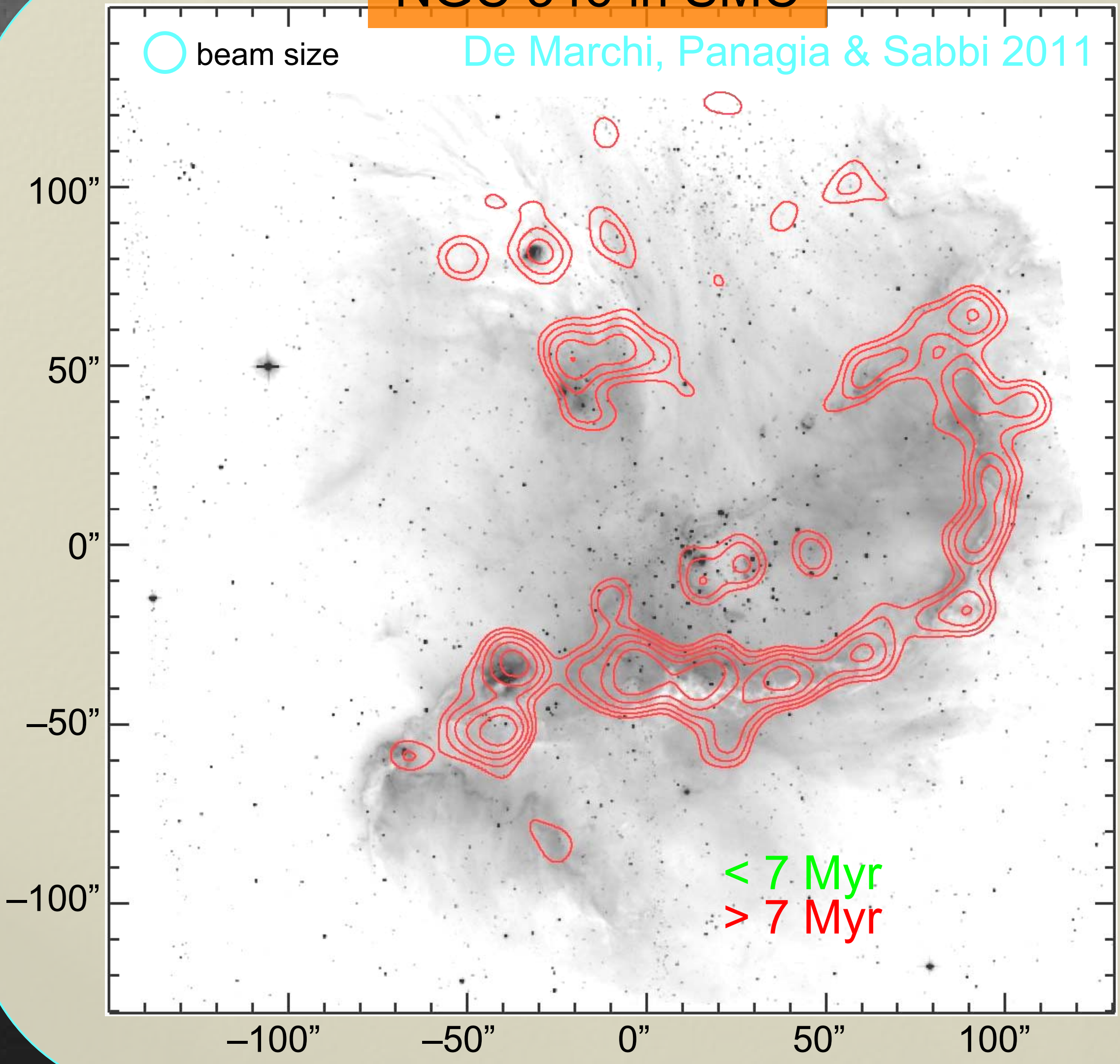
Multiple but unrelated generations

NGC 346 in SMC



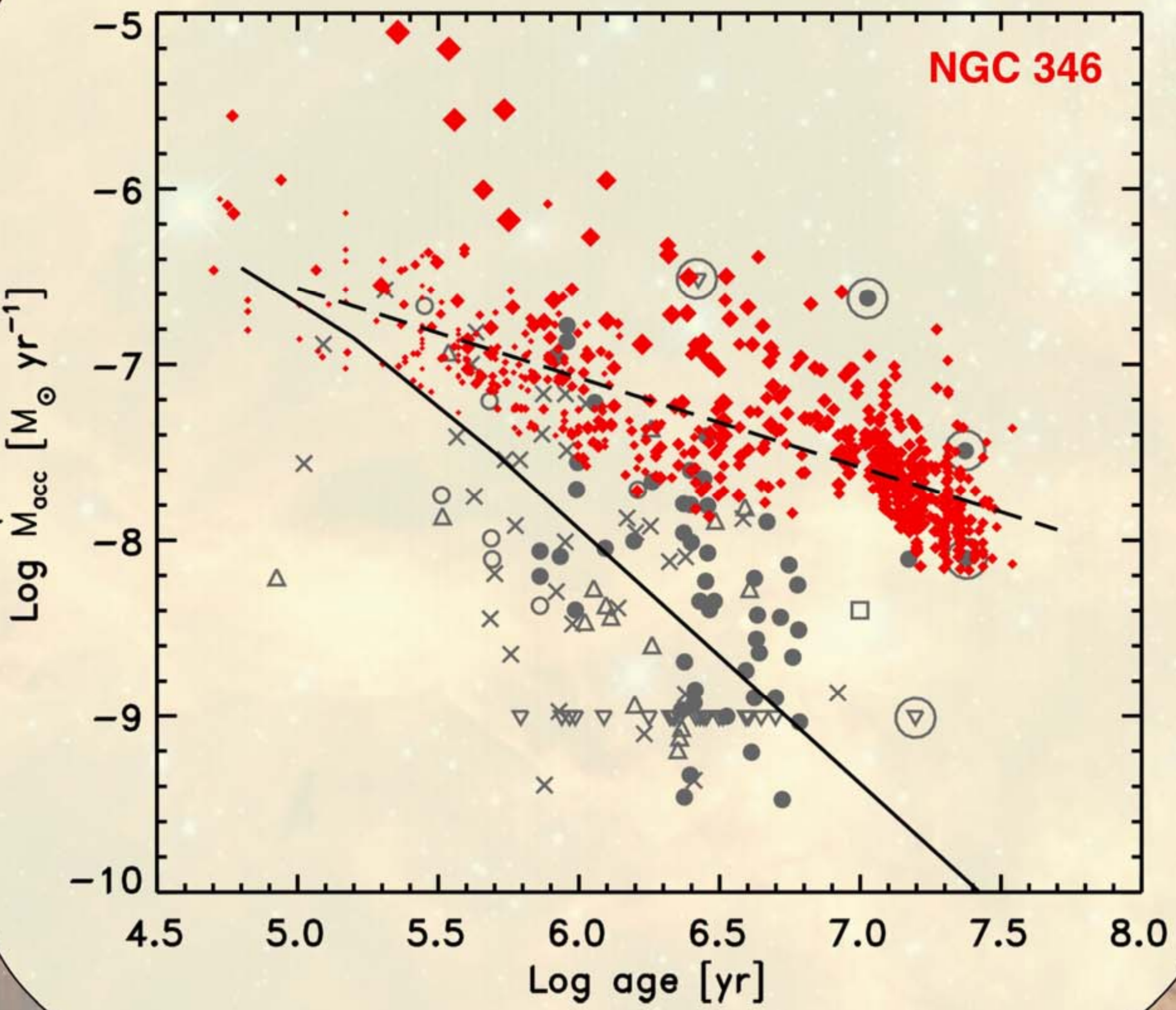
Multiple but unrelated generations

NGC 346 in SMC

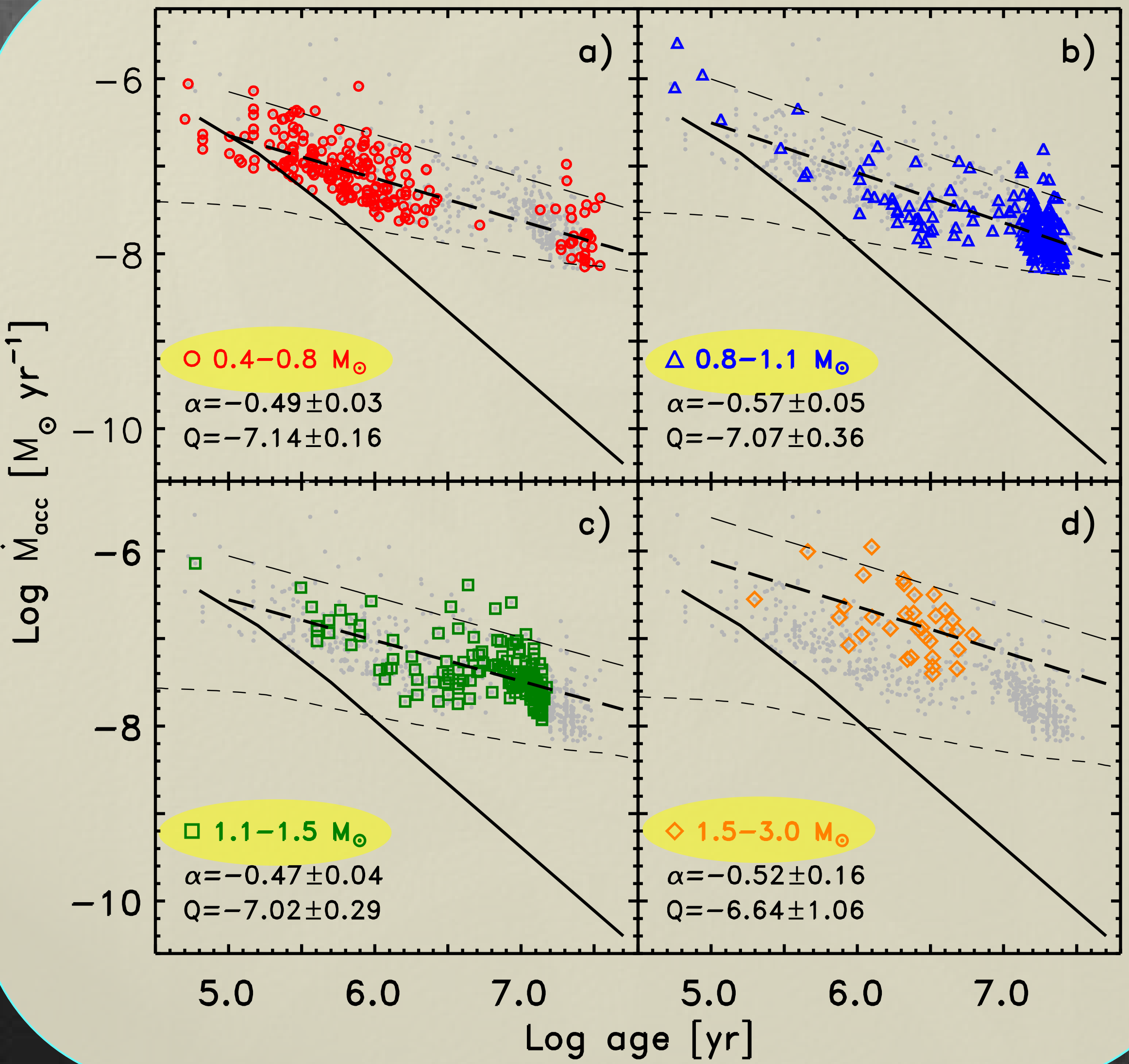


Accretion evolution with time

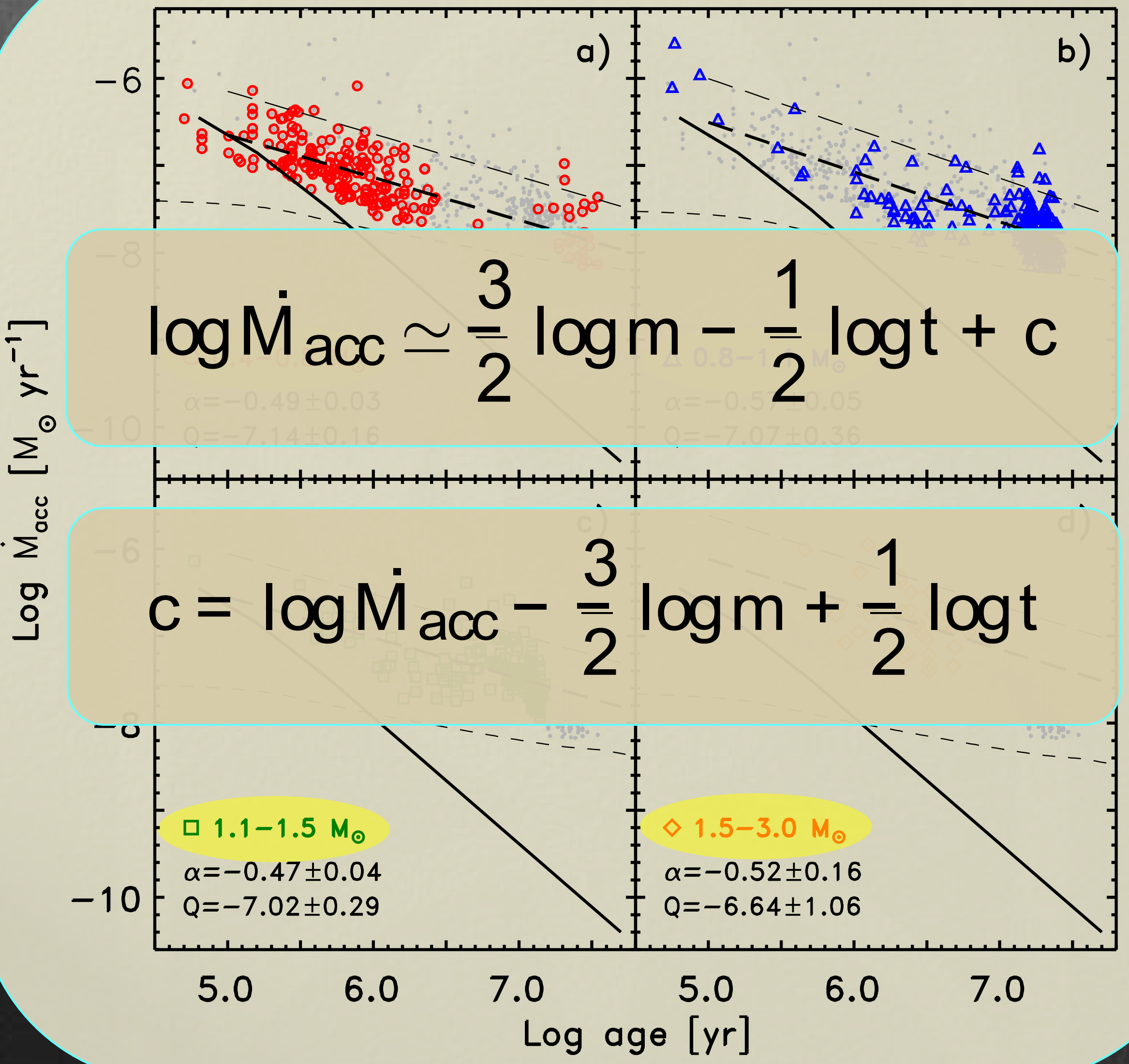
De Marchi et al. 2011a



Accretion evolution with time & mass



Accretion evolution with time & mass

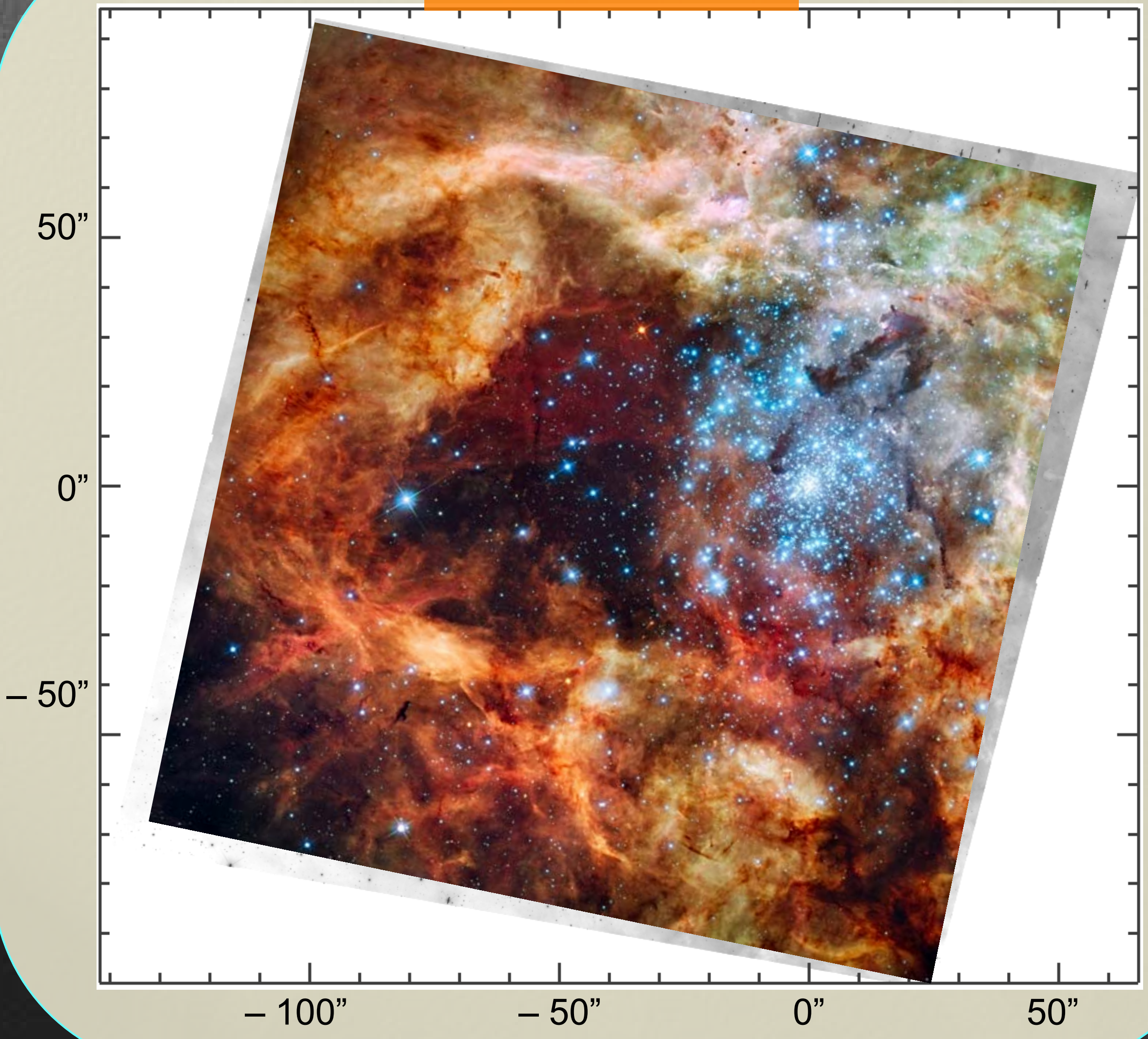


$$\log \dot{M}_{acc} \simeq \frac{3}{2} \log m - \frac{1}{2} \log t + c$$

$$c = \log \dot{M}_{acc} - \frac{3}{2} \log m + \frac{1}{2} \log t$$

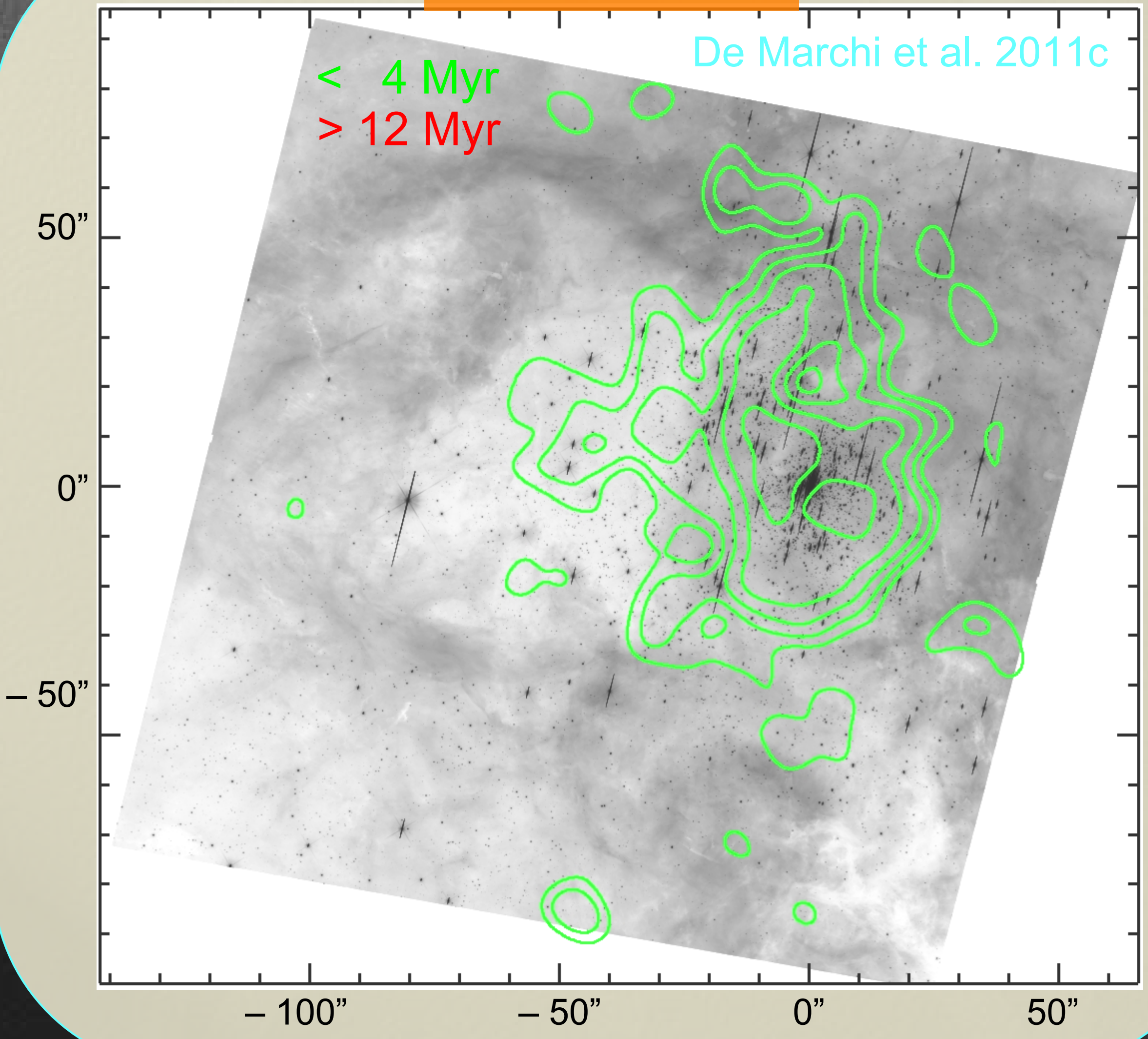
Multiple but unrelated generations

30 Dor in LMC



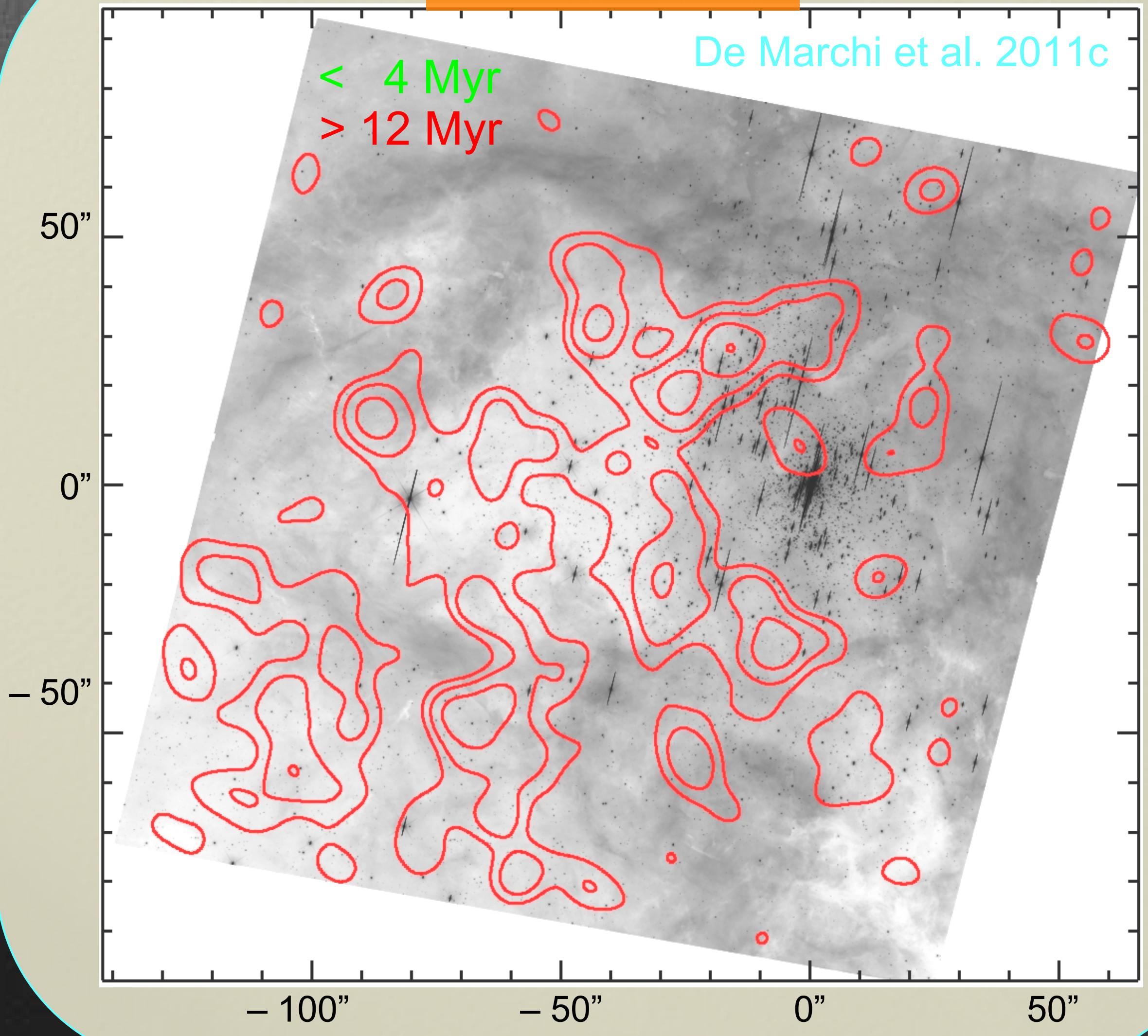
Multiple but unrelated generations

30 Dor in LMC

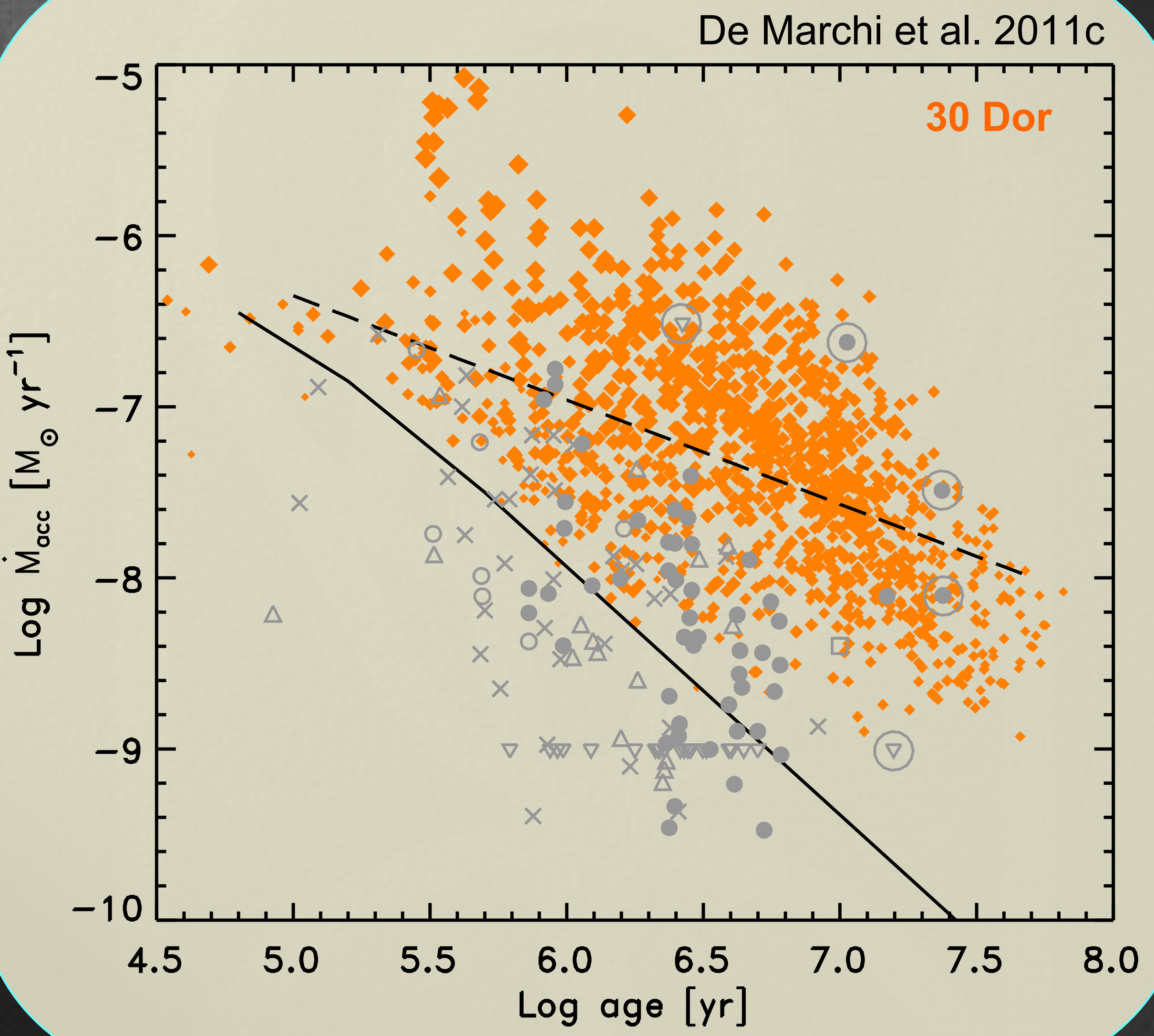


Multiple but unrelated generations

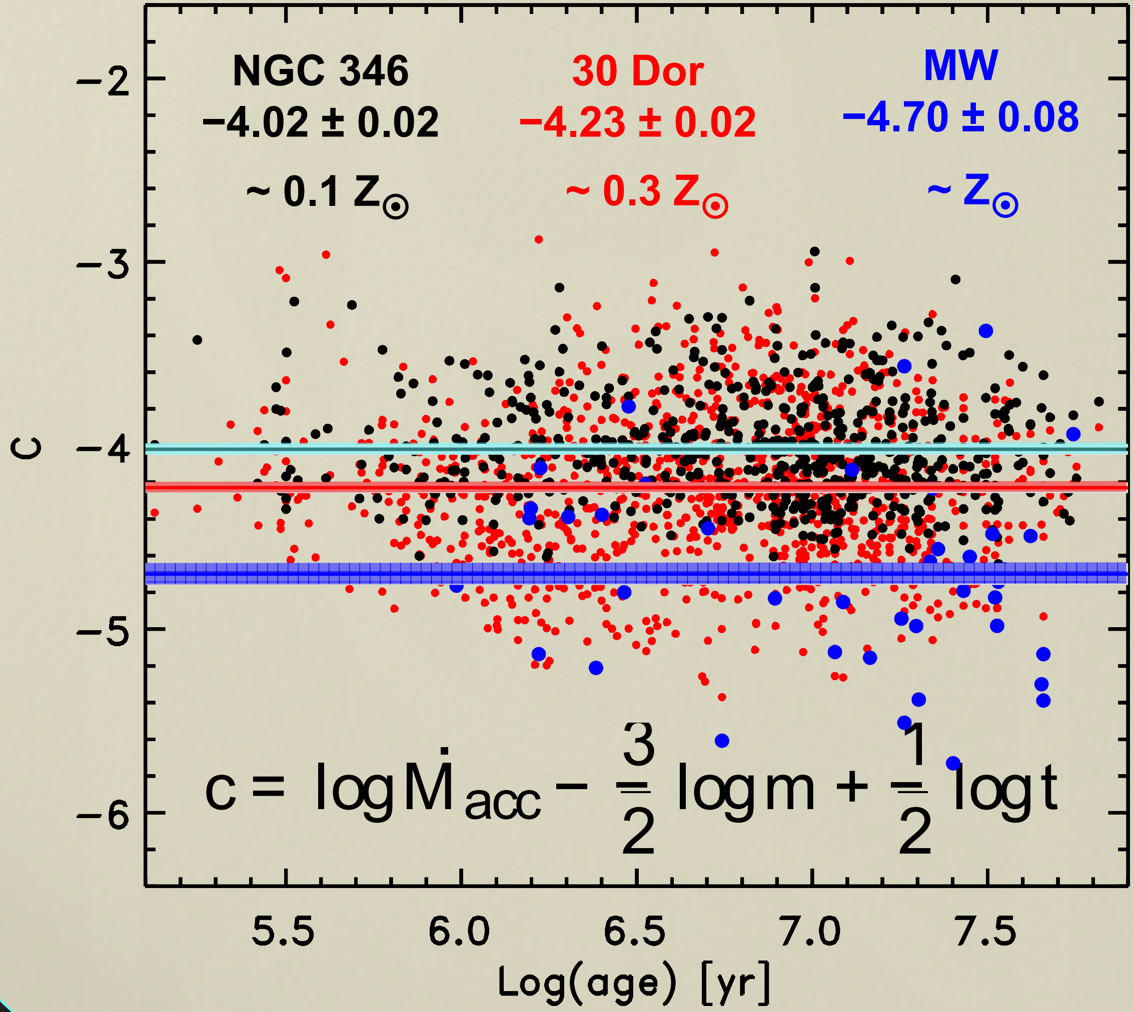
30 Dor in LMC

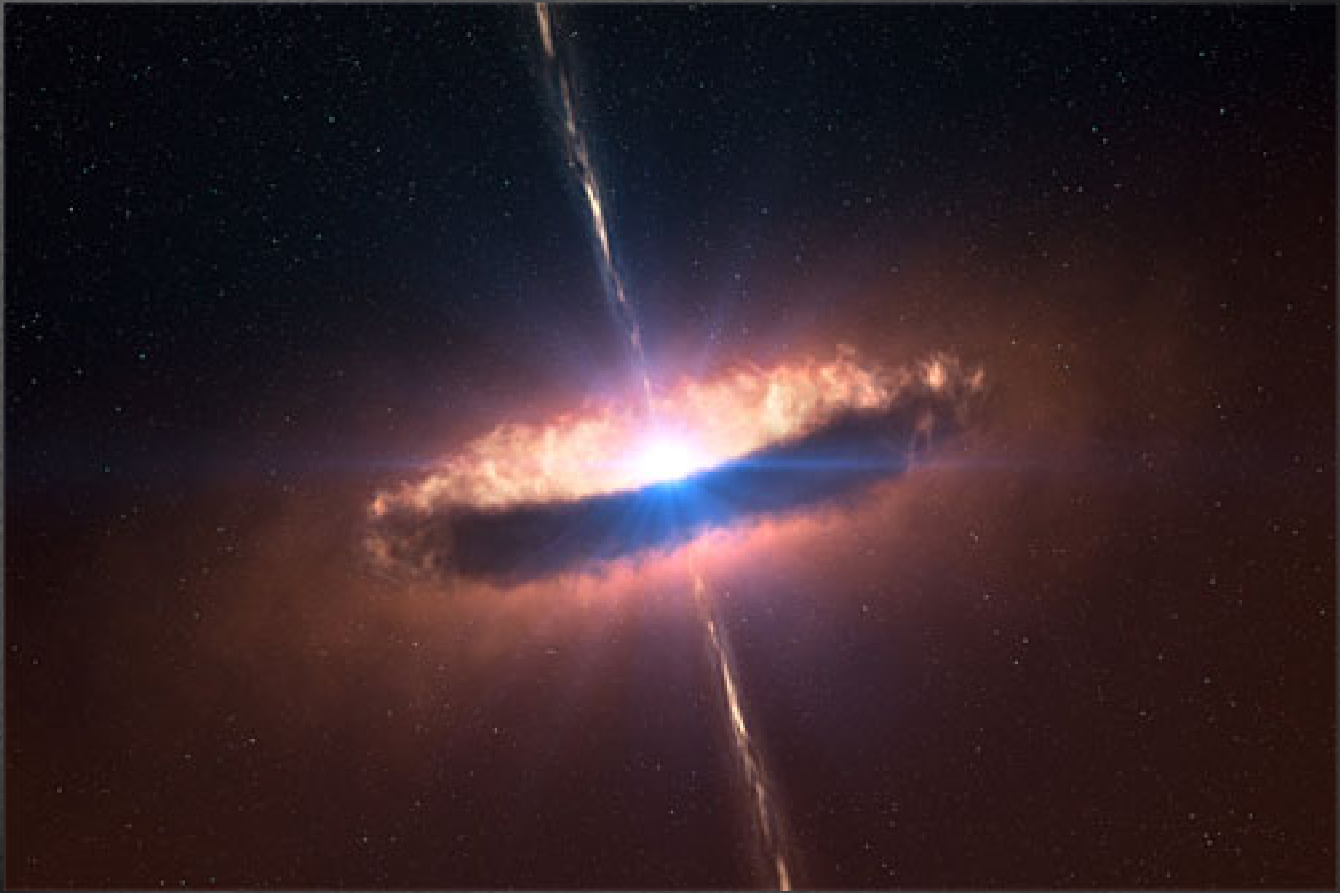


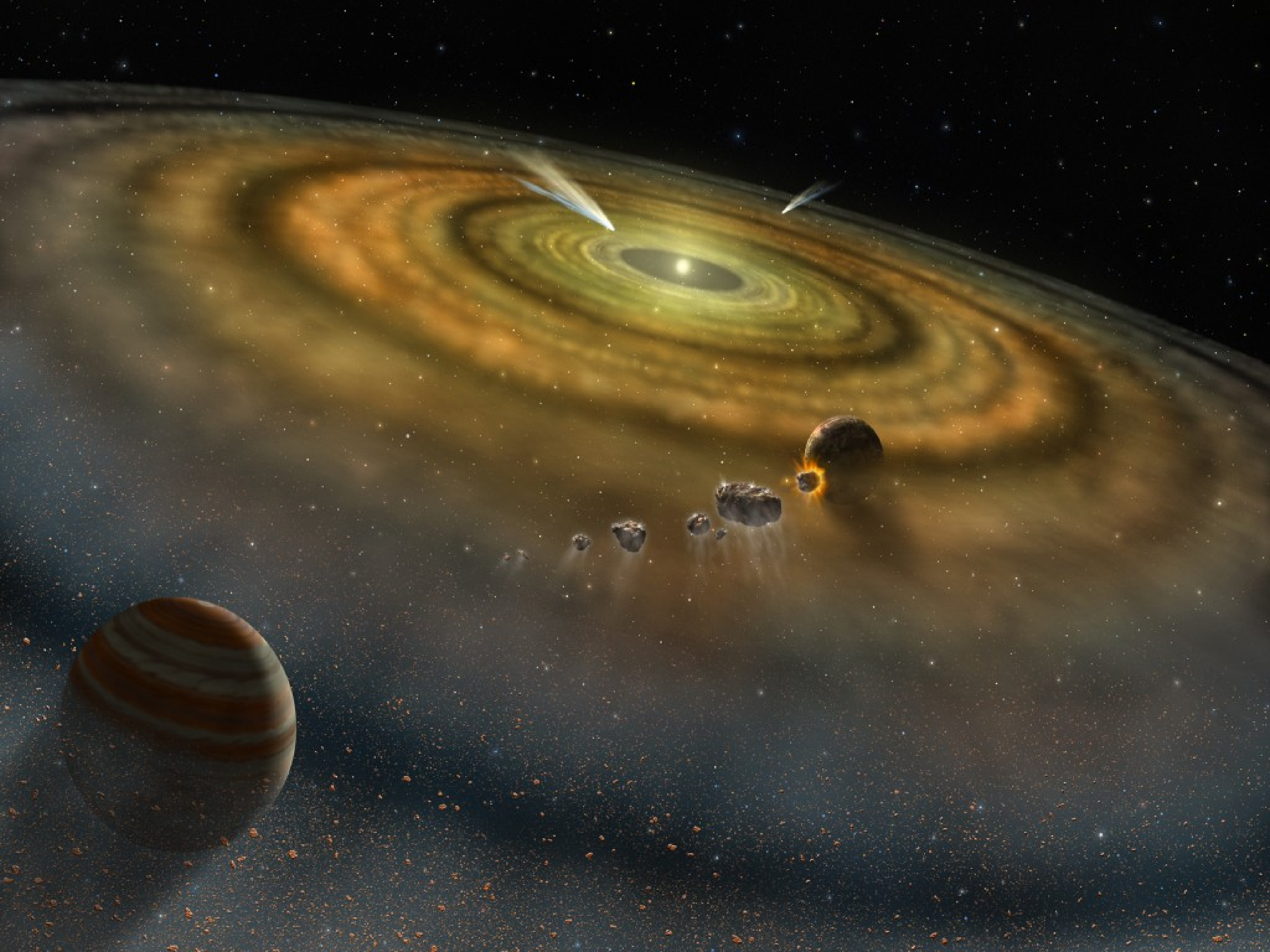
Accretion evolution with time



Accretion rate and metallicity







JAMES WEBB SPACE TELESCOPE (launch 2018)