Star cluster physics and stellar population synthesis beyond the Local Group's "comfort zone"

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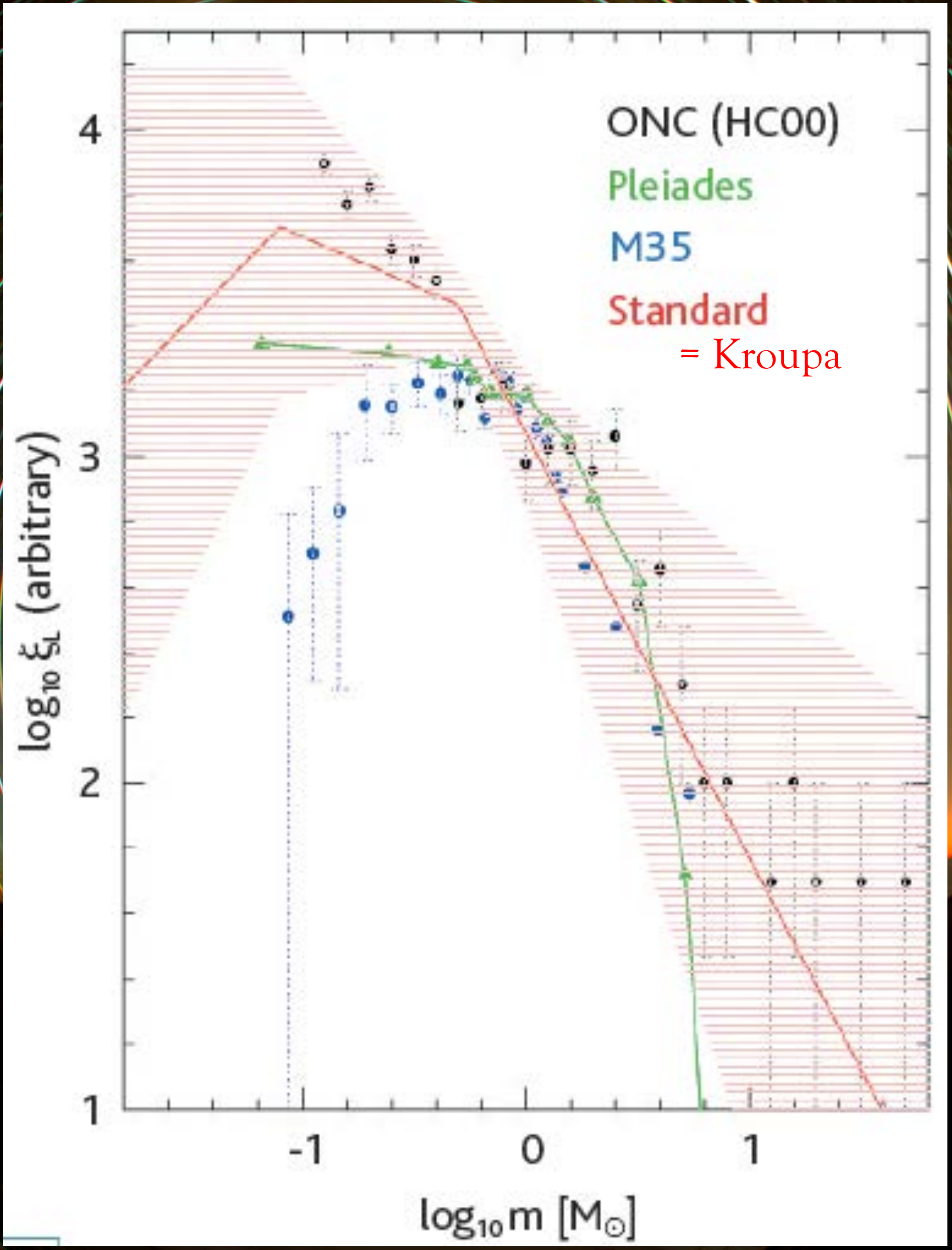
Key questions for TMT

- How does star formation *occur*, *proceed*, and how is it *triggered*?
- What is the importance of the *interactions* of newly born stars with their environment?
- How does the resulting IMF inform our understanding of star formation *as a function of environment*? (if at all!)
- What *range of environments* can we probe *with TMT*?
  - Galactic centres
  - Starburst clusters (e.g., Arches)
  - Low-metallicity environments; different stellar and gas densities
  - Giant elliptical *versus* dwarf galaxies
- How far *down* the IMF can we go?



Universal or not?

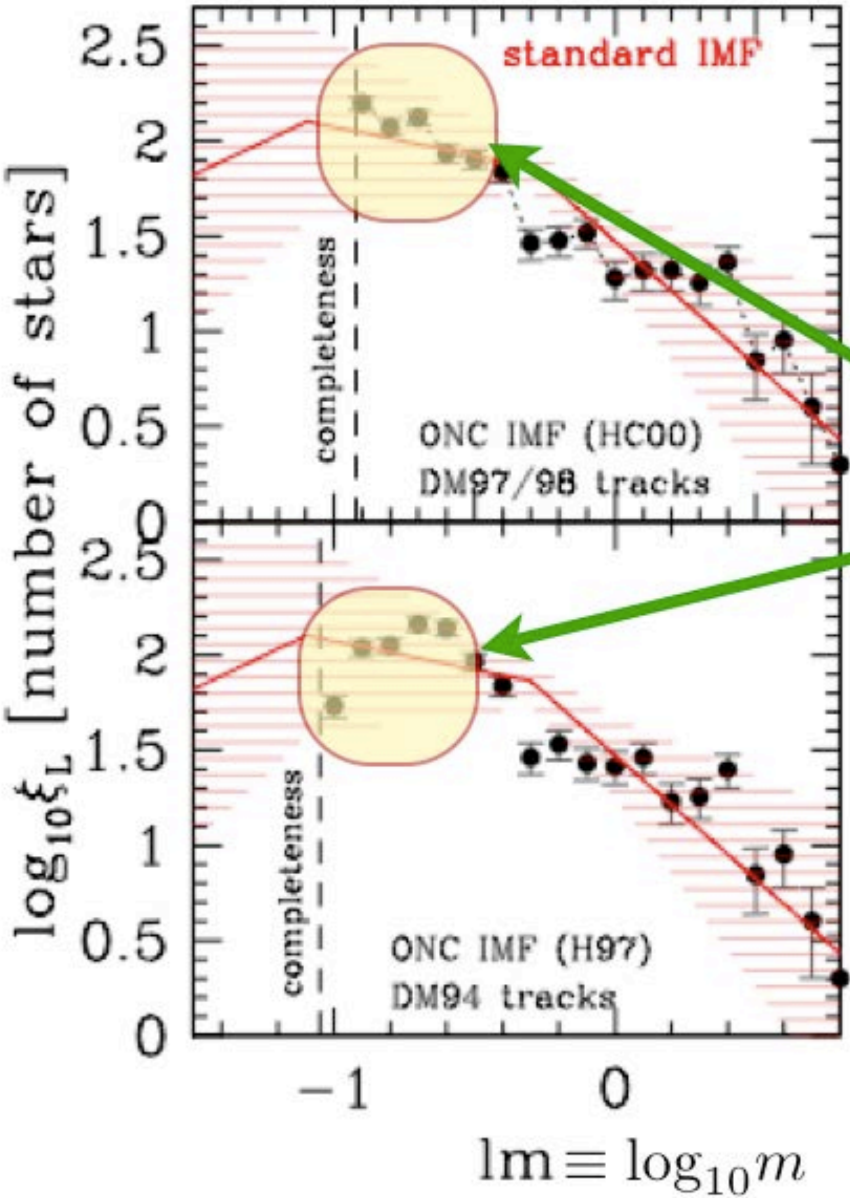
Clustered star formation

- Massive stars *rarely form in isolation*: most stars > 0.5 $M_\odot$ form in *star clusters* (OB/TT to YMCs)
- (Massive) star clusters are records of *episodes of higher-than-average star formation* in their host galaxies
- The massive stars are the primary source of *heavy elements* injected into the ISM (as well as the IGM)
- Need *large aperture* and *diffraction-limited spatial resolution* in the optical and near- to mid-IR to probe to low(er) masses
- *ALMA* provides superb spatial resolution at *complementary*, dust-penetrating (sub)mm wavelengths – probe into the *cores* of the most active, dust-enshrouded star-forming regions
- With TMT and ALMA, we will be able to study the *early evolution* and the *transformation* from the youngest star-forming, cluster-like regions to more mature, partially virialized systems

Science and predicted capabilities

- TMT *L-* and *M*-band imaging, combined with ALMA observations, will enable *determination of the shape of the IMF* over the entire range of masses, from ~100 $M_{\odot}$ to well below 1 $M_{\odot}$

- *Diffraction-limited TMT resolution* will allow us to probe the *brown dwarf regime* at Magellanic Cloud distances, as well as the low-mass (< 1 M¤) stellar regime in a *representative* slice of the Universe:
  - the nearest large spiral galaxies (M31 and M33)
  - the very low-metallicity environments provided by Local Group dwarf galaxies.

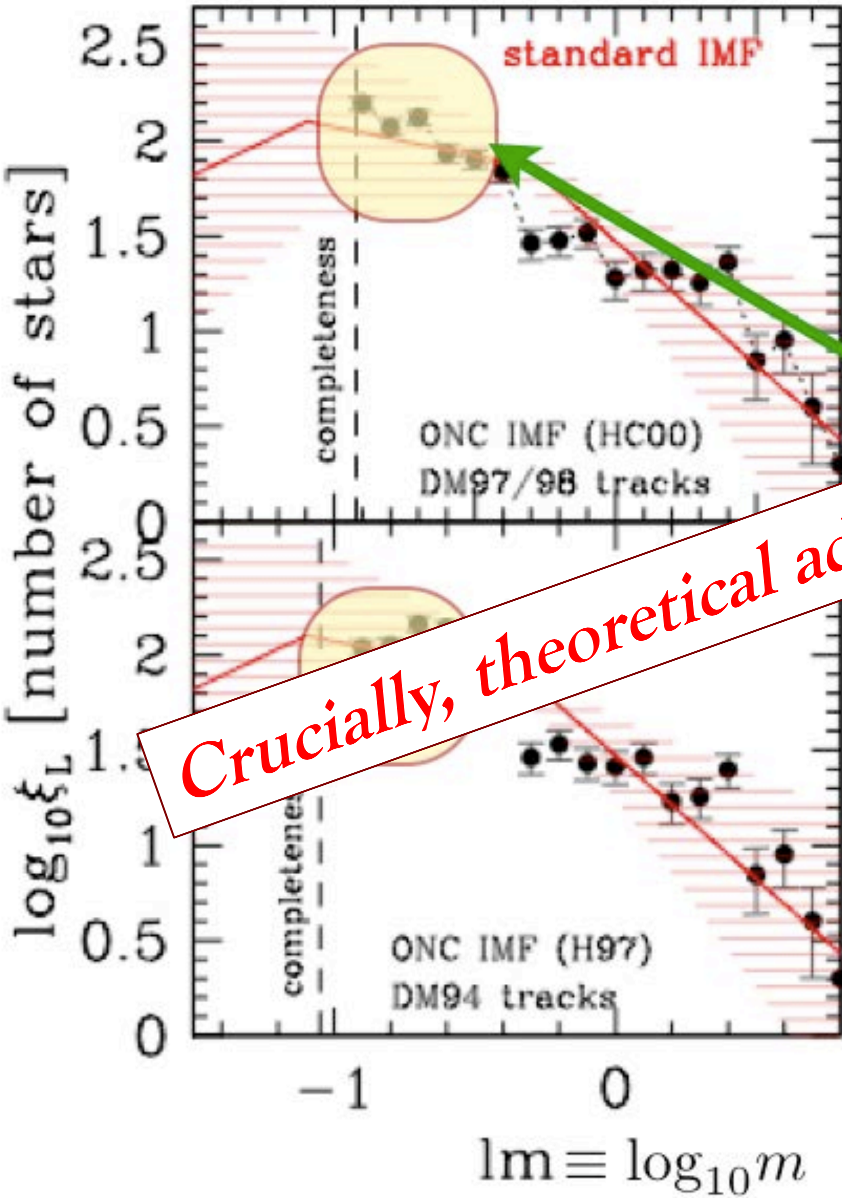


Uncertainties due to pre-main sequence tracks

e.g. the ONC : 1 Myr old

Shape differs for the same data !

(Slide courtesy Pavel Kroupa)



Uncertainties due to pre-main sequence tracks

e.g. the ONC :

...ape differs for the same data !

Crucially, theoretical advancements must keep up!

(Slide courtesy Pavel Kroupa)

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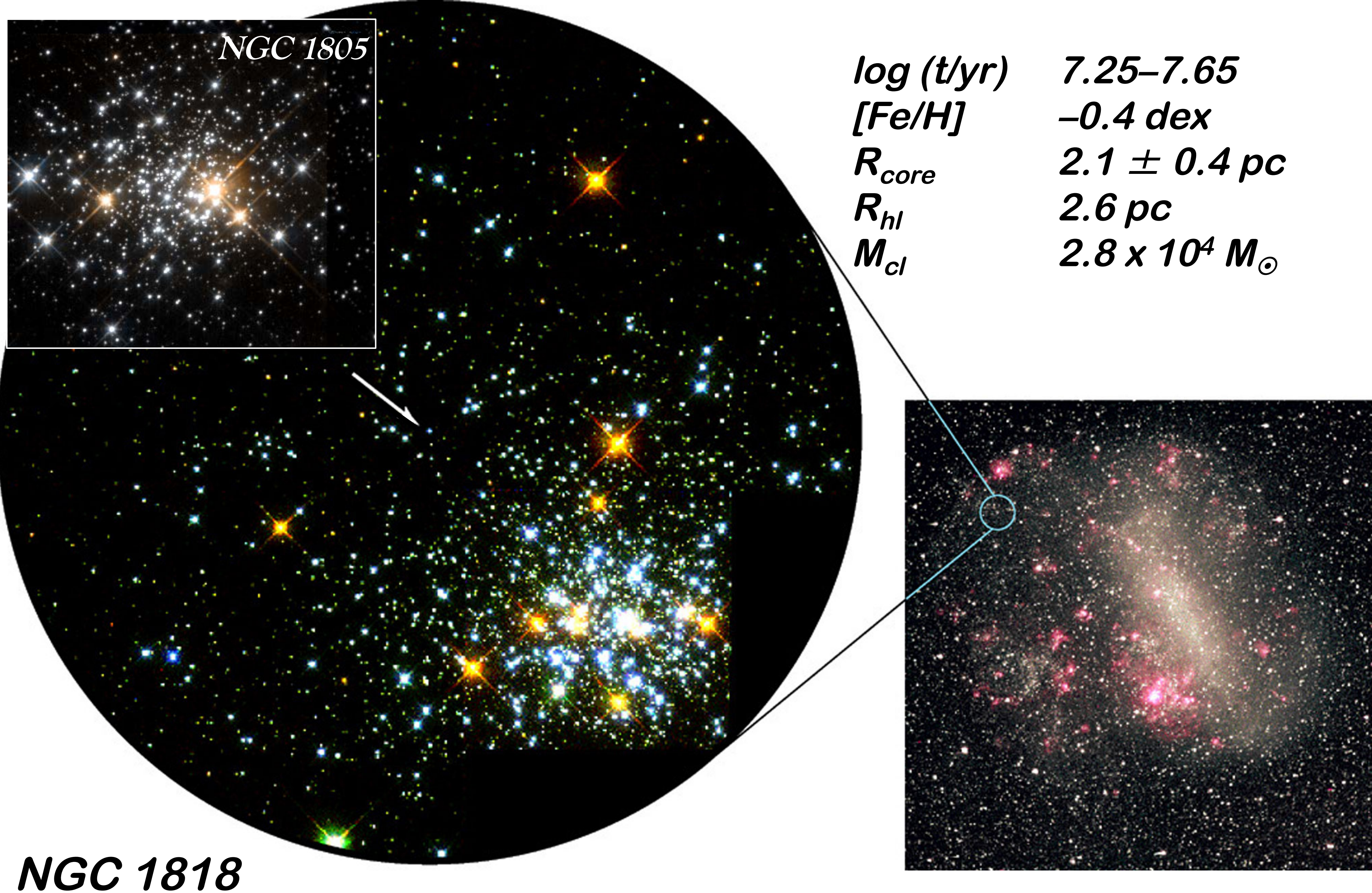
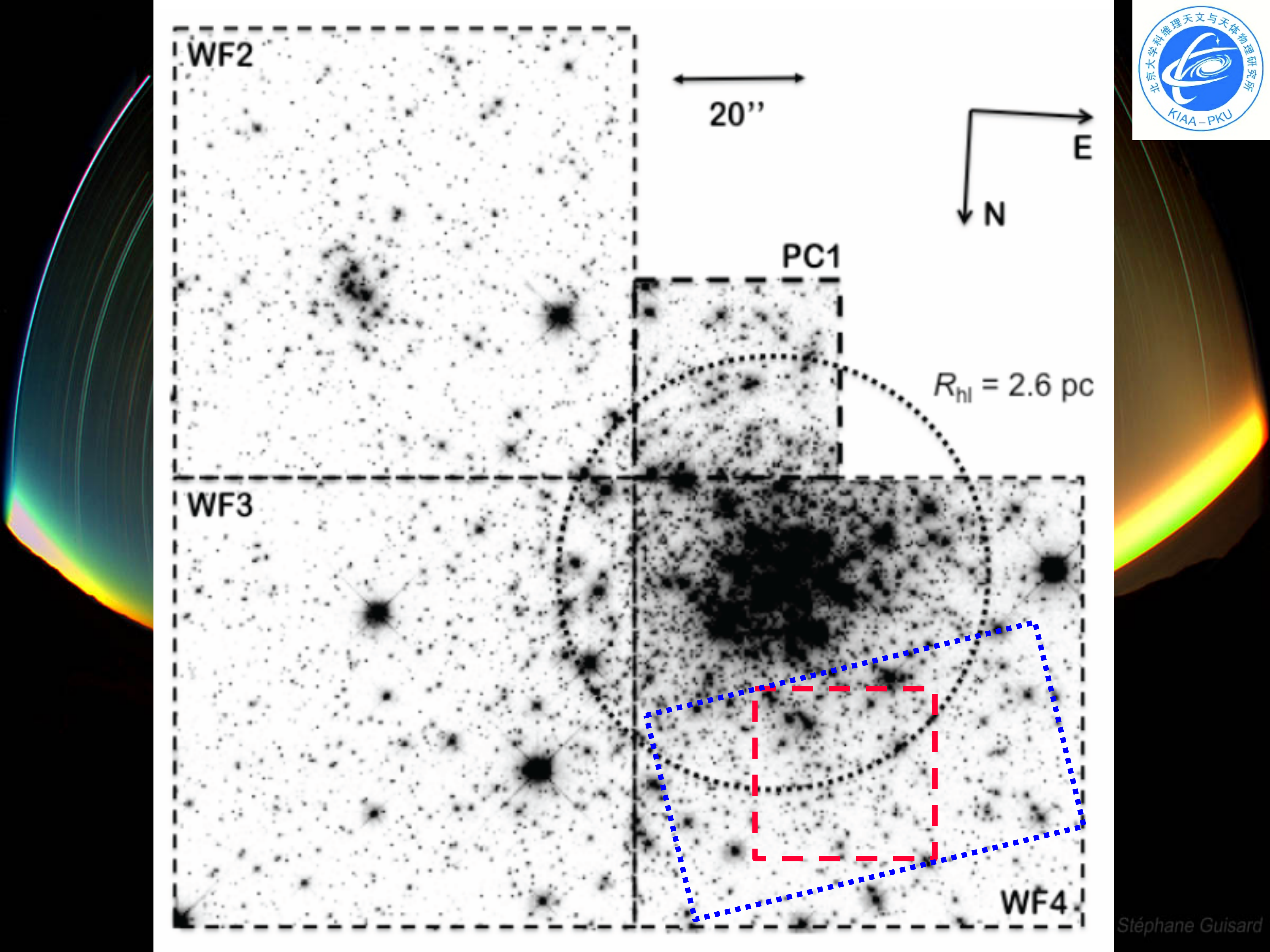
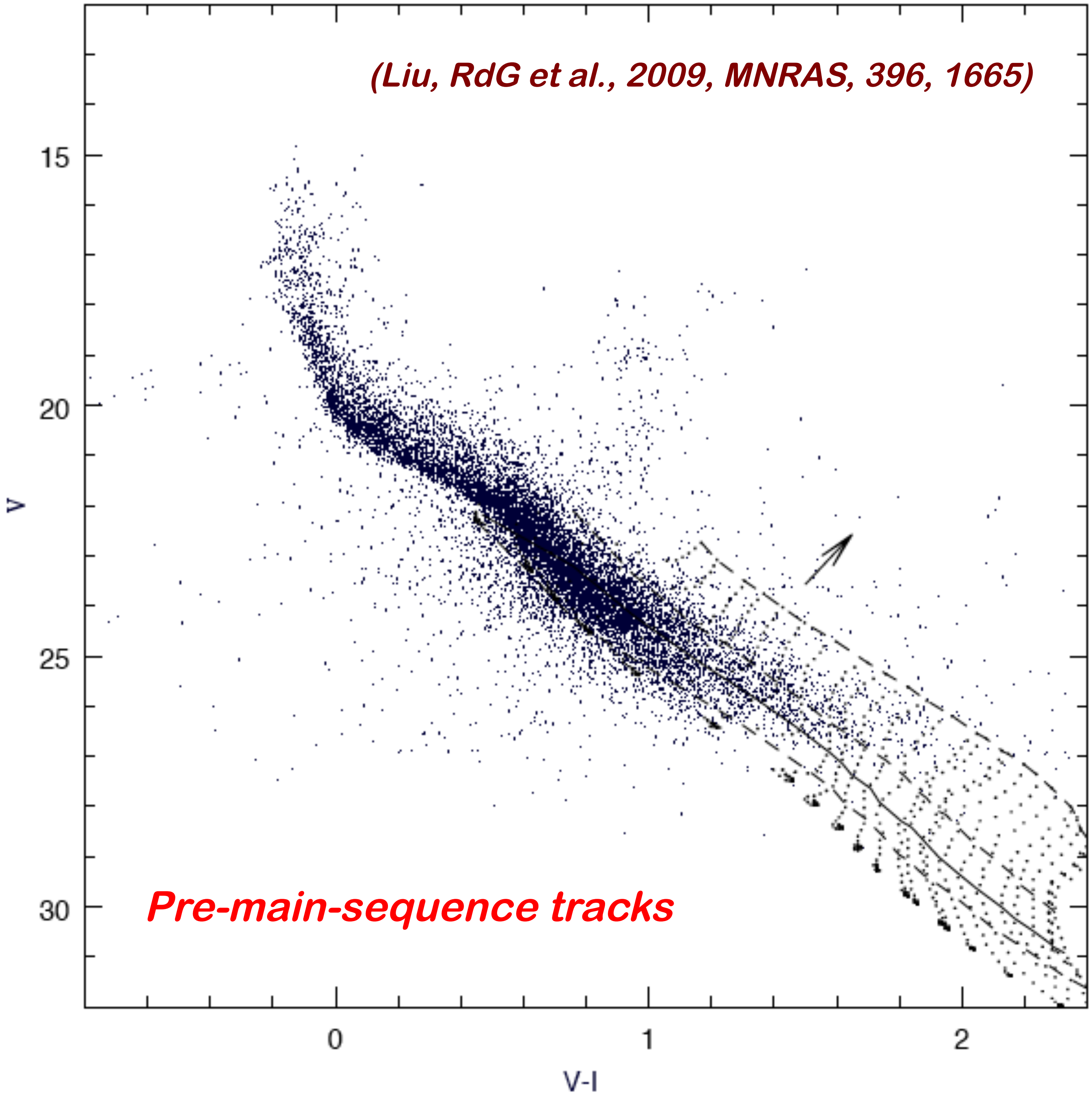
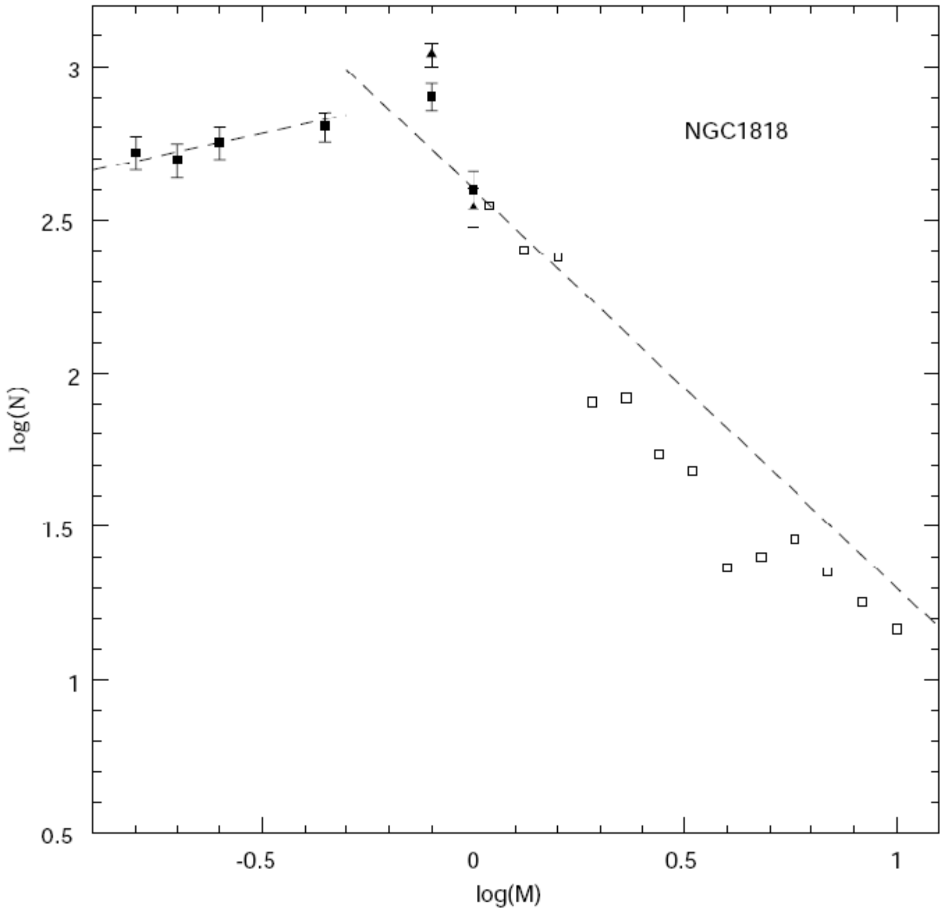

NGC 1805
log (t/yr) 7.25–7.65
[Fe/H] –0.4 dex
R_{core} 2.1 ± 0.4 pc
R_{hl} 2.6 pc
M_{cl} 2.8 x 10^4 $M_\odot$
NGC 1818

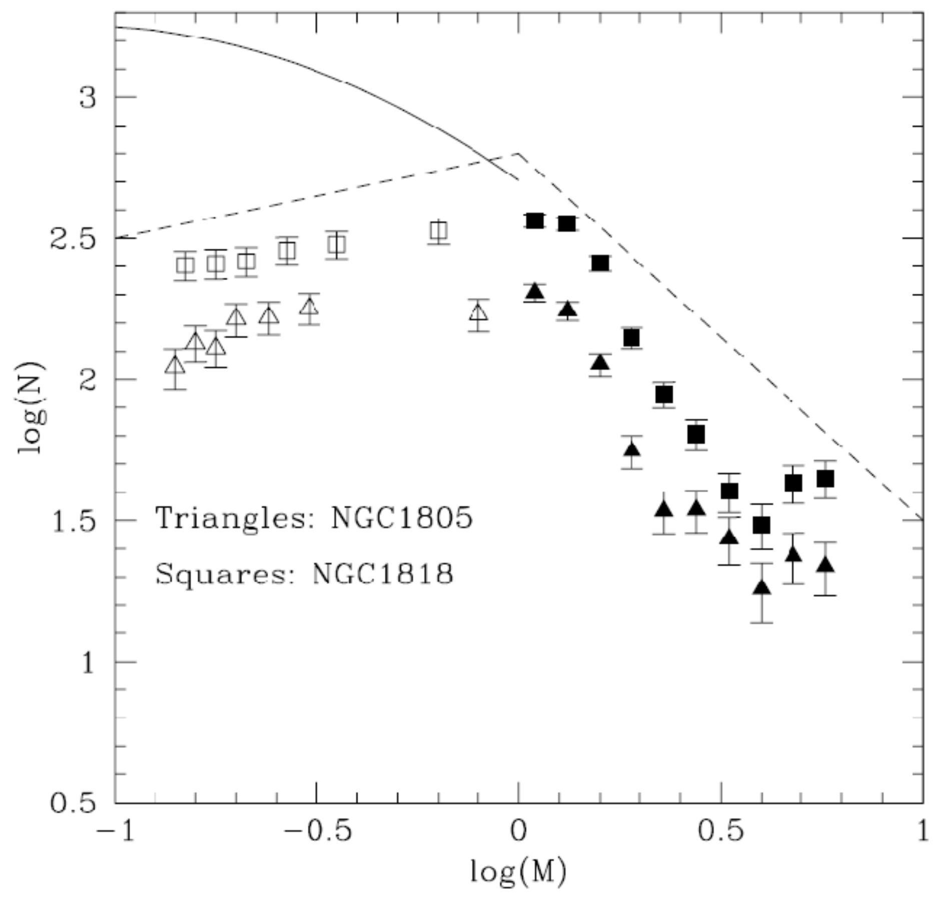

WF2
20''
E
N
PC1
R_{hl} = 2.6 pc
WF3
WF4
Stéphane Guisard


(Liu, RdG et al., 2009, MNRAS, 396, 1665)
Pre-main-sequence tracks
15
20
25
30
V
0
1
2
V-I

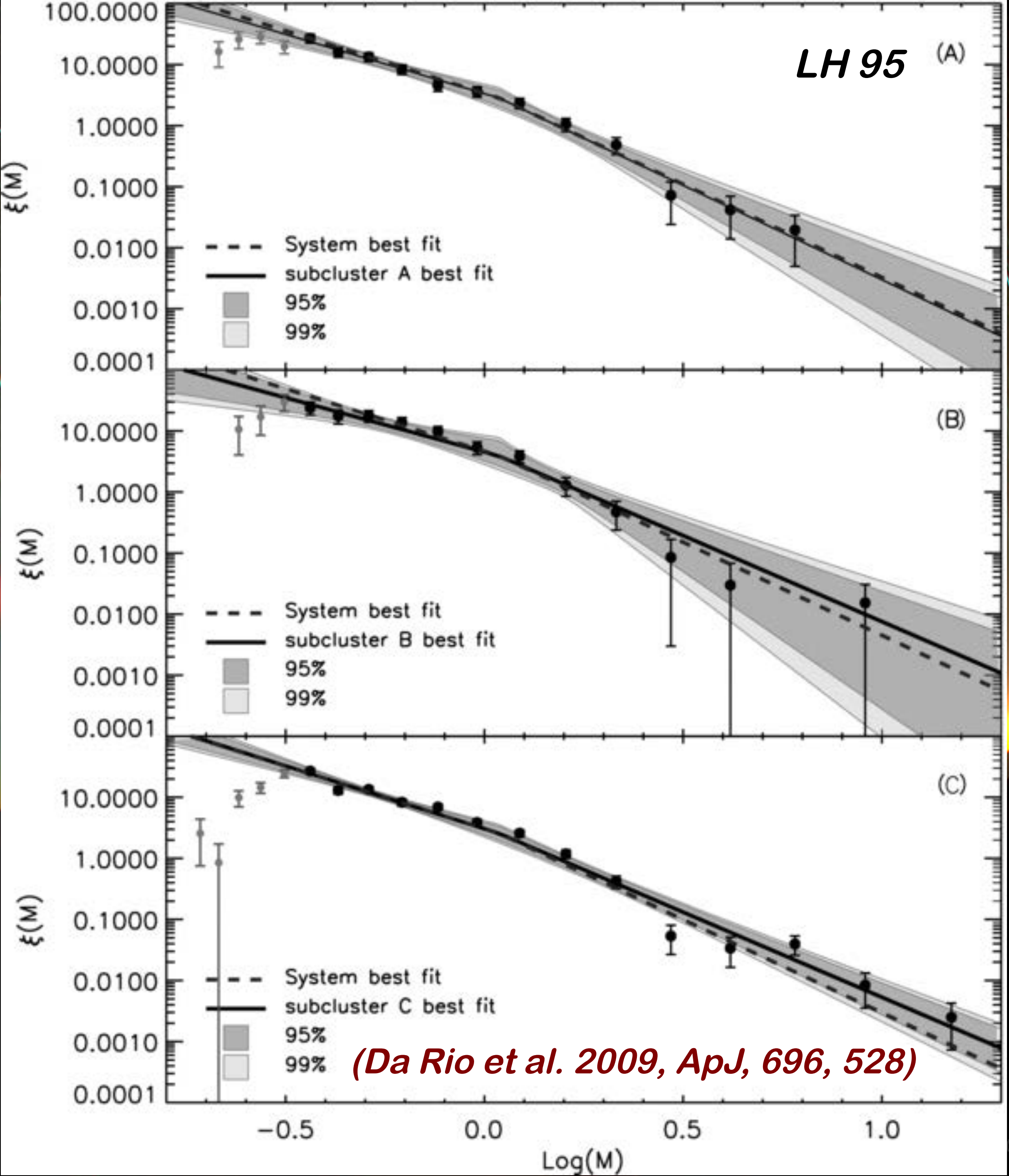


(Liu, RdG et al., 2009, MNRAS, 396, 1665)

(Liu, RdG et al., 2009, A&A, 503, 469)



Metallicity-related differences affecting the shape of the stellar mass distribution probably require significantly lower metallicities to become apparent.

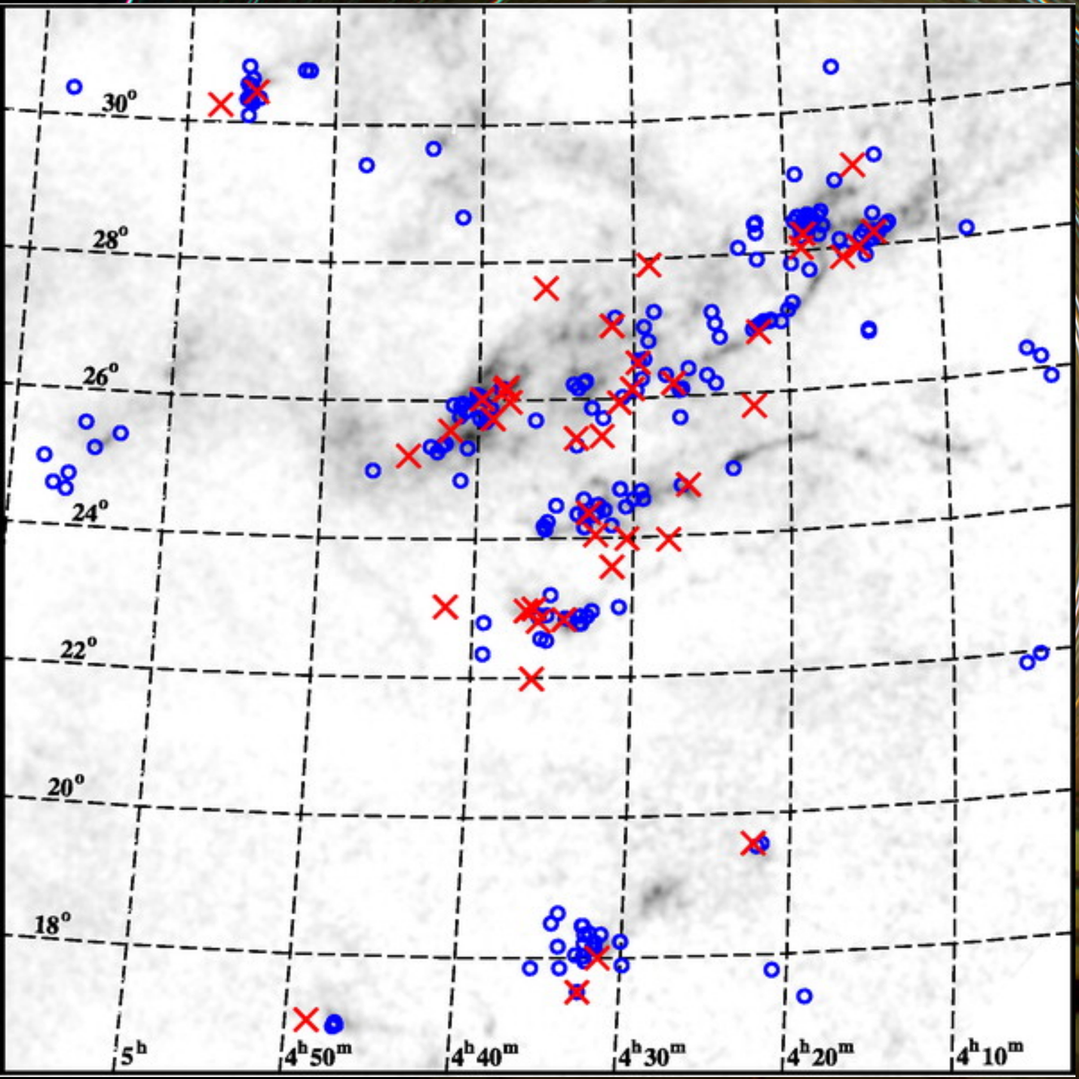


LH 95
(A)
(B)
(C)
ξ(M)
Log(M)
System best fit
subcluster A best fit
subcluster B best fit
subcluster C best fit
95%
99%
(Da Rio et al. 2009, ApJ, 696, 528)

Science and predicted capabilities

- Relationship between emerging stellar masses and local stellar density within a given cluster, which is a potential measure of the ***importance of collisions*** between protostellar cores and mergers in forming high-mass stars
  - Star formation in molecular cloud cores follows a ***spatial distribution*** imprinted by the properties of the prevailing turbulence
  - Numerical simulations of such initial stellar distributions suggest ***rapid subsequent formation of dense cluster cores***, given the expected subvirial dynamical conditions in such environments
  - This suggests that most stars populate cluster-like configurations on very rapid timescales, but ***they do not necessarily form in such a way***

(Luhman 2006, ApJ, 645, 676)



✓ Young embedded clusters are clumpy

← (cf. Taurus)

✓ To erase substructure on short timescales, clusters must initially have a cool virial ratio

(Goodwin & Whitworth 2004; also Girichidis et al. 2012)

Primordial or dynamical mass segregation?

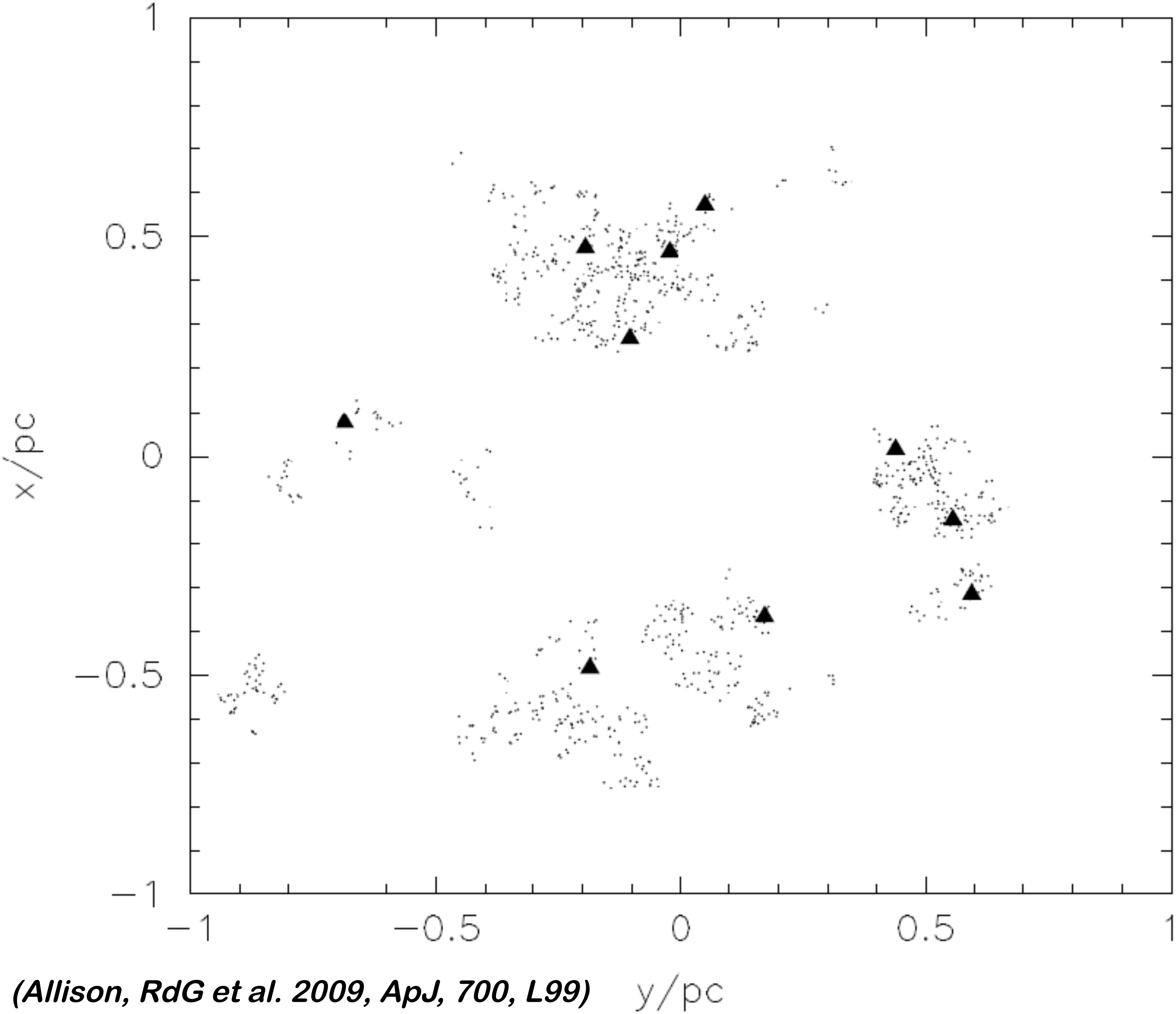
<u>*Initial conditions:*</u>

1. ***Dynamically cool (subvirial) star-forming clumps:** $Q = 0.3$ ($Q = 0.5$ virialised);*

2. ***Substructure:** mimicking clumpy molecular cloud structure – due to supersonic turbulence (fractal dimension = 1.6; uniform sphere: 3.0);*

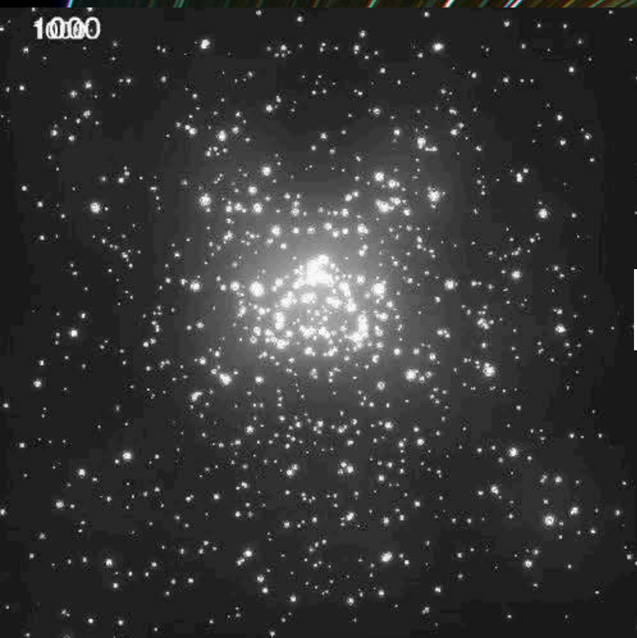
3. ***Kroupa IMF, 1000 stars, 0.08 – 50 $M_{\odot}$.***

(... et al. 2009, ApJ, 700, L99)

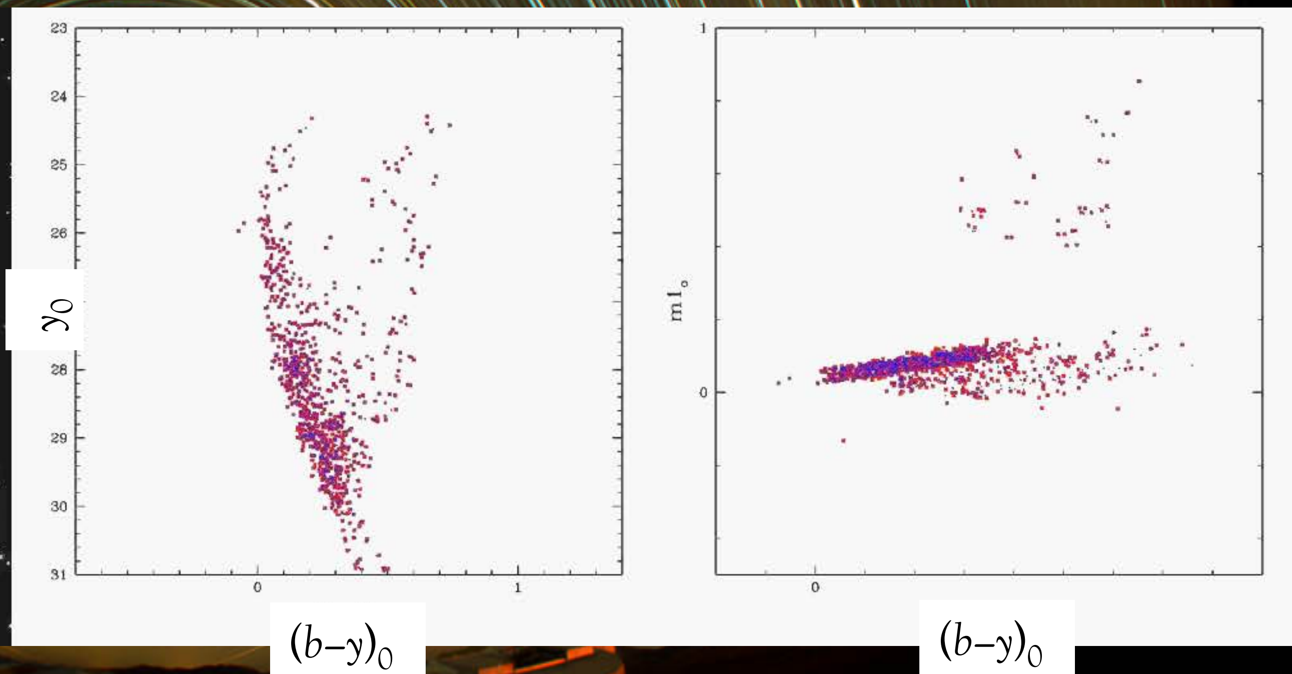


(Allison, RdG et al. 2009, ApJ, 700, L99)

Resolving power beyond the Local Group



(Distance in kpc)

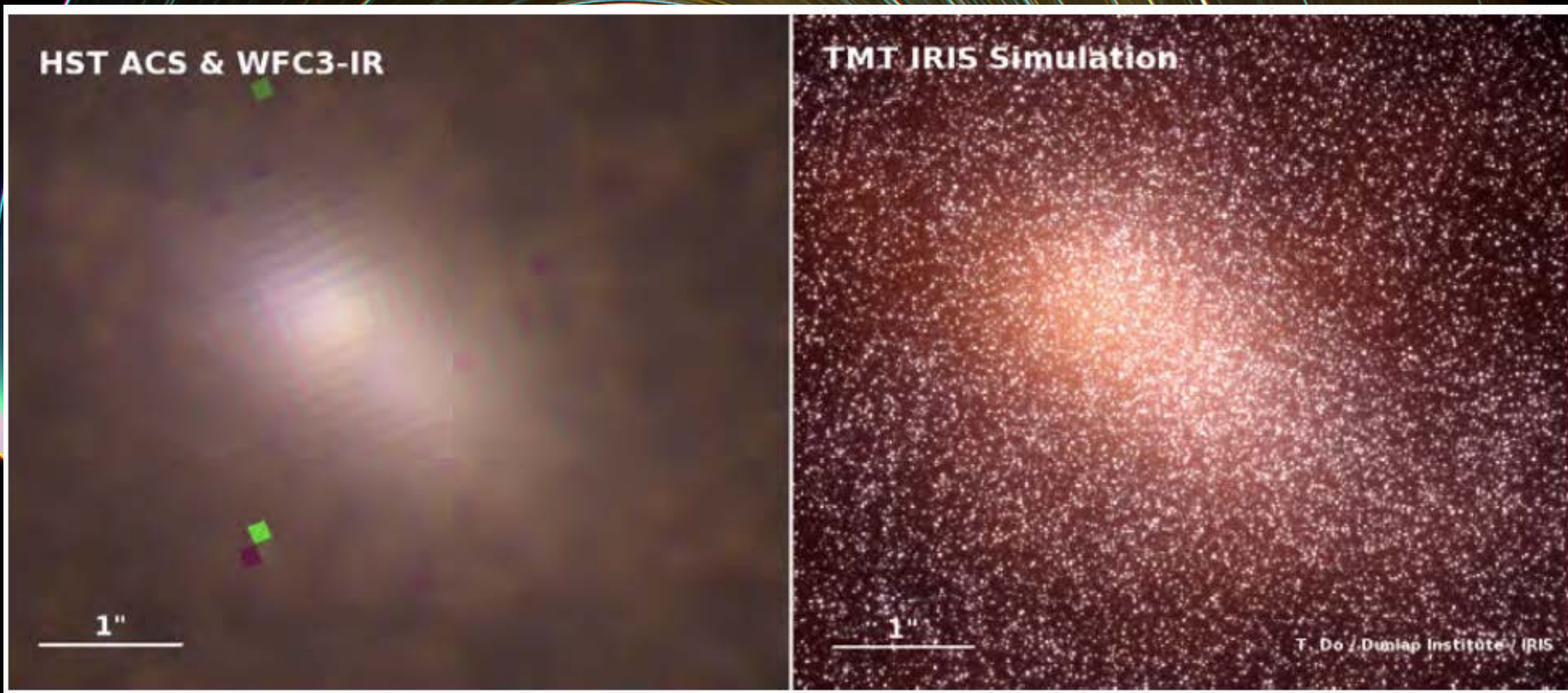


(*Credit*: Euro50 development team/Arne Ardeberg, Lund Obs.)

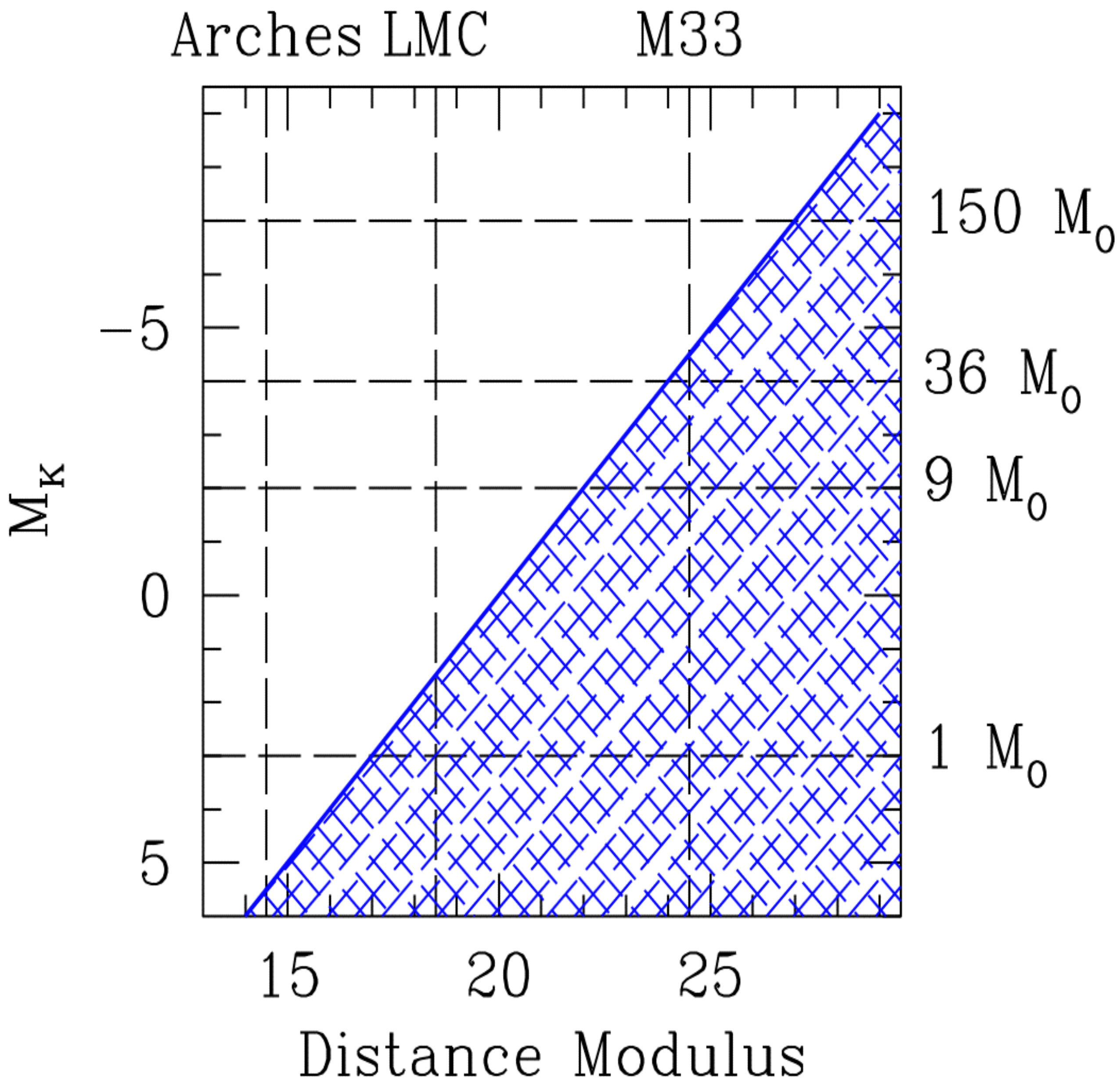
Photometric (imaging) limits

	Limiting K magnitude			Limiting Mass ($M_\odot$)		
Radius (R_e)	LMC	M33	M82	LMC	M33	M82
0.5	>27.5	17	<19.8	~0.01	…	…
1.0	>27.5	18.9	<19.8	~0.01	65	…
2.0	>27.5	22.3	20	~0.01	3	…
5.0	>27.5	27.5	23.9	~0.01	1.1	32

Photometric crowding and photon statistic limits have been computed using the radial profiles of the Arches and R136 clusters, coupled with the crowding limit algorithm given by Olsen et al. (2003). The input luminosity function used for these calculations is a hybrid based on measurements in the Arches cluster (Blum et al. 2001) for the high-mass stars ($\geq 2\ M_\odot$) and measurements in the Trapezium by Hillenbrand & Carpenter (2000) for the low-mass stars ($\leq 3\ M_\odot$).


HST ACS & WFC3-IR
1"
TMT IRIS Simulation
1"
T. Do / Dunlap Institute / IRIS

Spectroscopic limits; S/N > 50



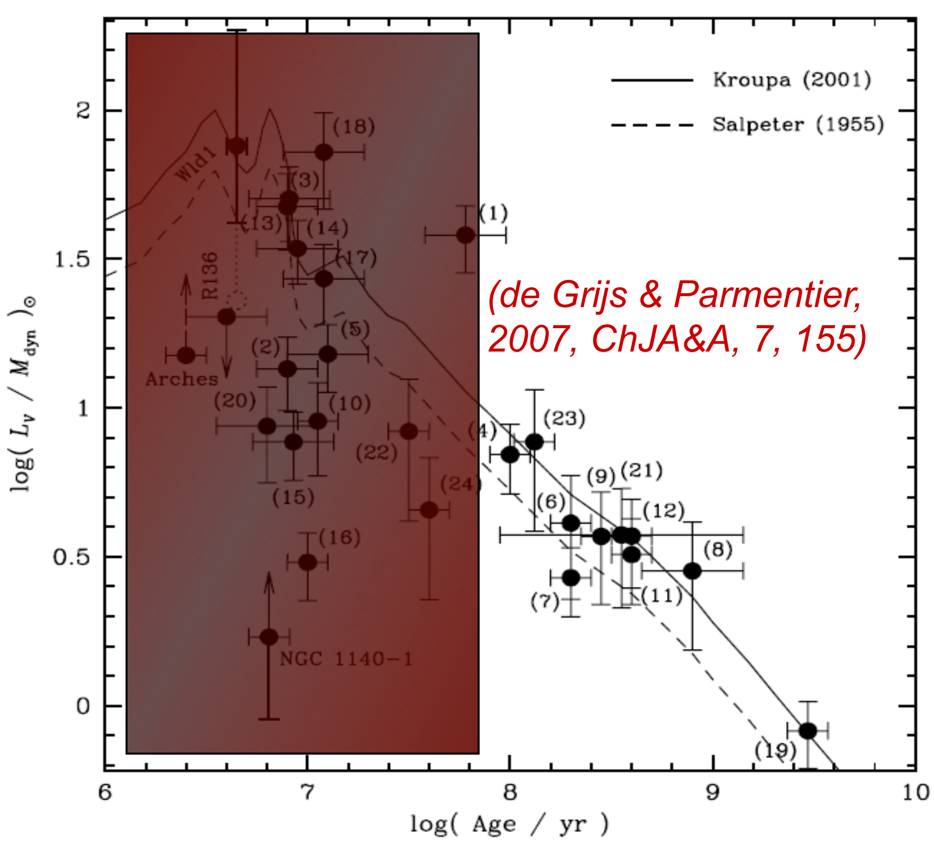
M_K limits in the the non-crowded outer regions of clusters for signal-to-noise ratio = 50 at R = 4000 on IRIS in IFU mode during a 3 hour total exposure time.

At a given distance modulus, stars within the blue area are either not observable or only with lower SNR.

Survival chances to old age

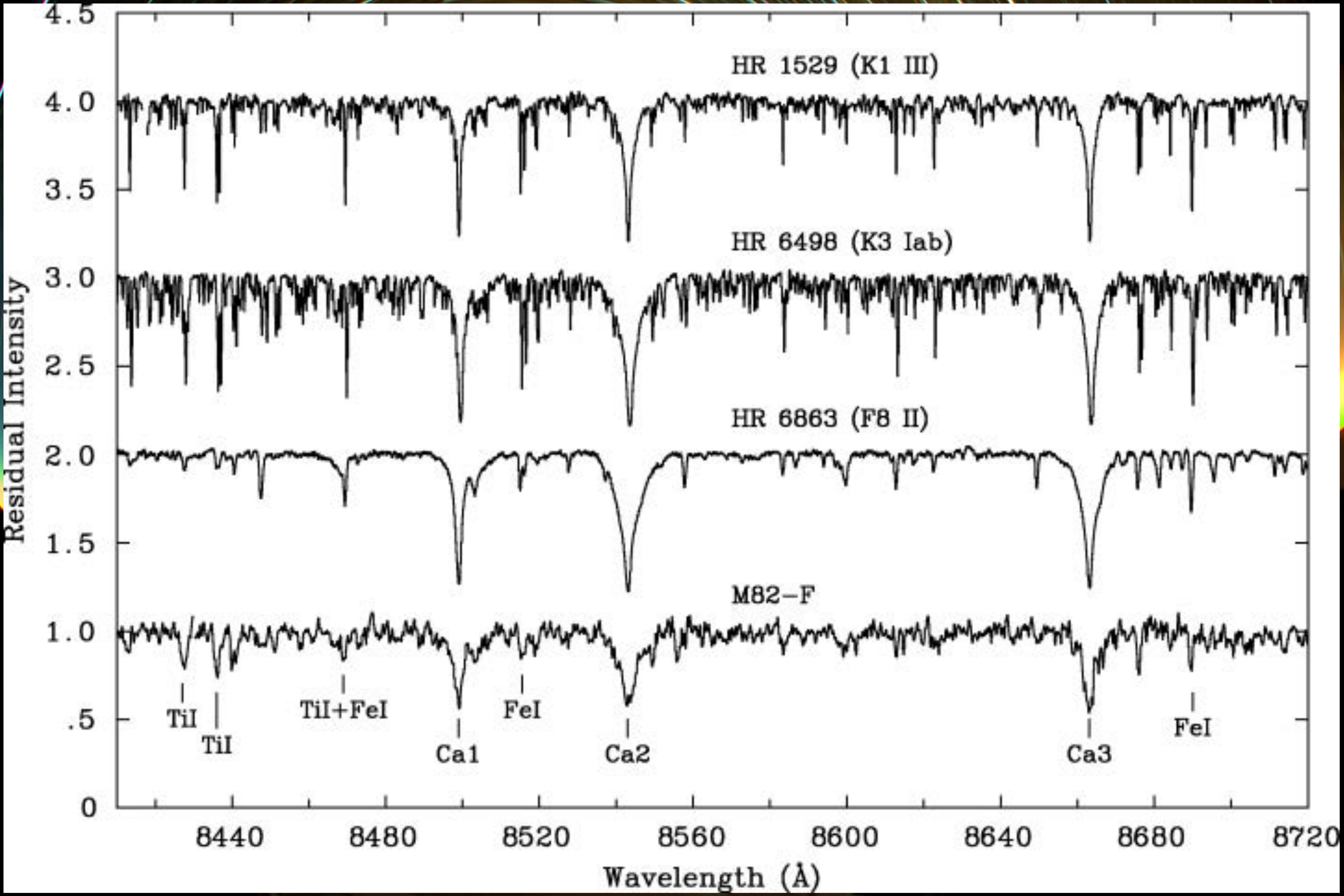
- *Crucially dependent on the IMF!*
- *Confirmation:*
  - *High-resolution spectroscopy*

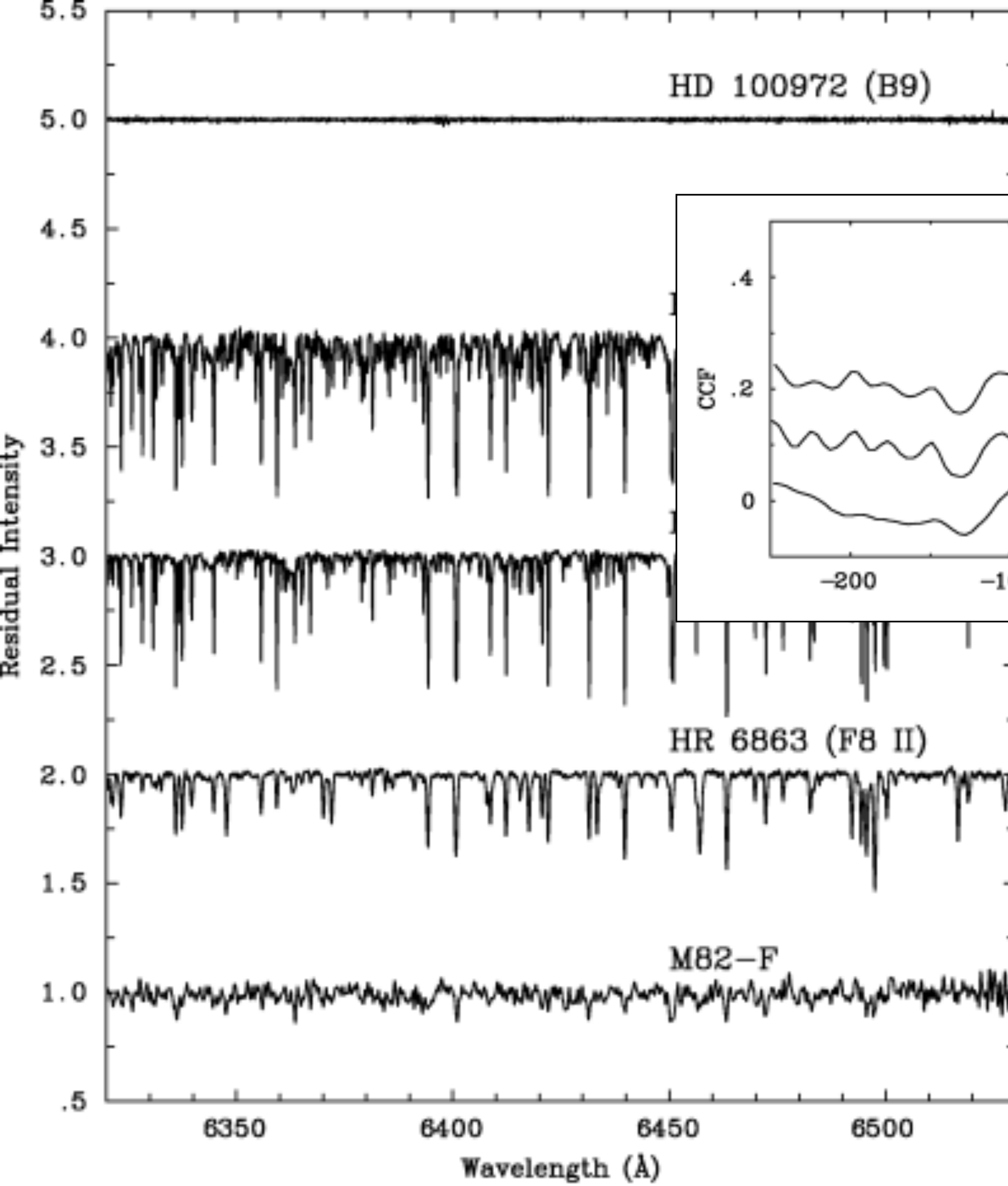
$$M_{\rm dyn} = \frac{\eta \sigma_{\rm los}^2 r_{\rm h}}{G}$$

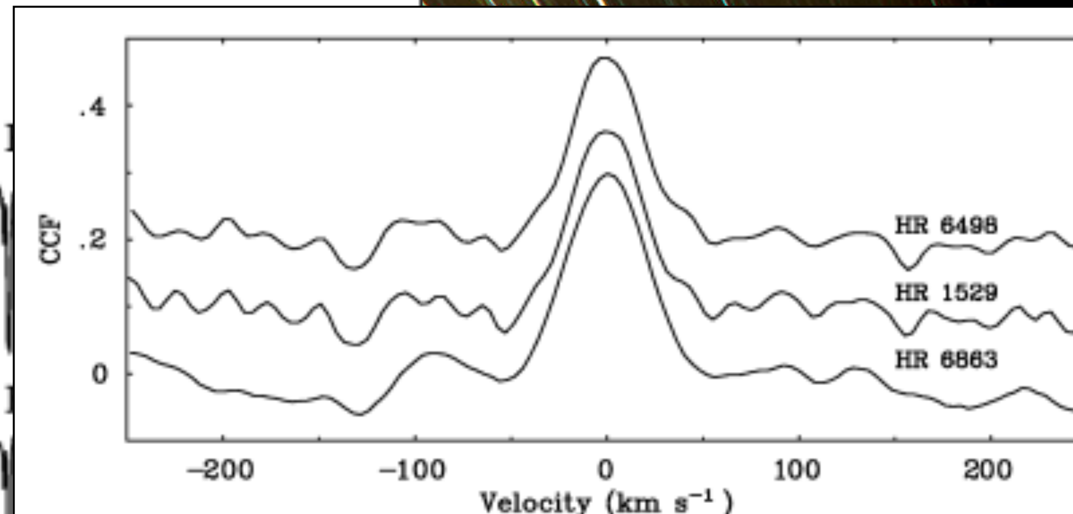


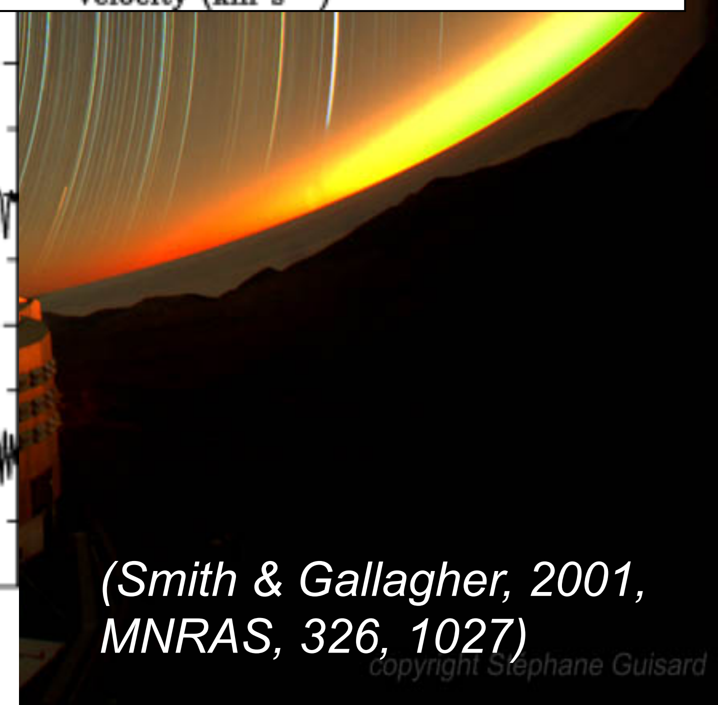
(de Grijs & Parmentier, 2007, ChJA&A, 7, 155)

(Smith & Gallagher, 2001, MNRAS, 326, 1027)









(Smith & Gallagher, 2001, MNRAS, 326, 1027)

Take-home messages

- **Key question to be tackled**: How does star formation ***occur***, ***proceed***, and how is it ***triggered***?
- How does the resulting IMF inform our understanding of star formation ***as a function of environment***?
- TMT *L*- and *M*-band imaging, combined with ALMA data, will enable ***determination of the shape of the IMF*** over the entire range of masses, from ~100 $M_{\odot}$ to << 1 $M_{\odot}$
- TMT's ***high spatial resolution*** at *L* and *M*, combined with ALMA observations probing into the molecular cloud cores, will enable us to conclusively probe the ***earliest conditions*** of star formation (spatial distribution, masses) in a range of ***representative local environments***