

The dynamics of young clusters from the Gaia-ESO Survey

Rob Jeffries Keele University, UK



- Overview of the Gaia-ESO Survey
- The precision of dynamical measurements (radial velocities)
- Focus on young clusters

Survey Co-PIs: Gerry Gilmore & Sofia Randich

350+ Co-Is
(mostly, but not only,
from Europe)
90+ institutes



www.gaia-eso.eu

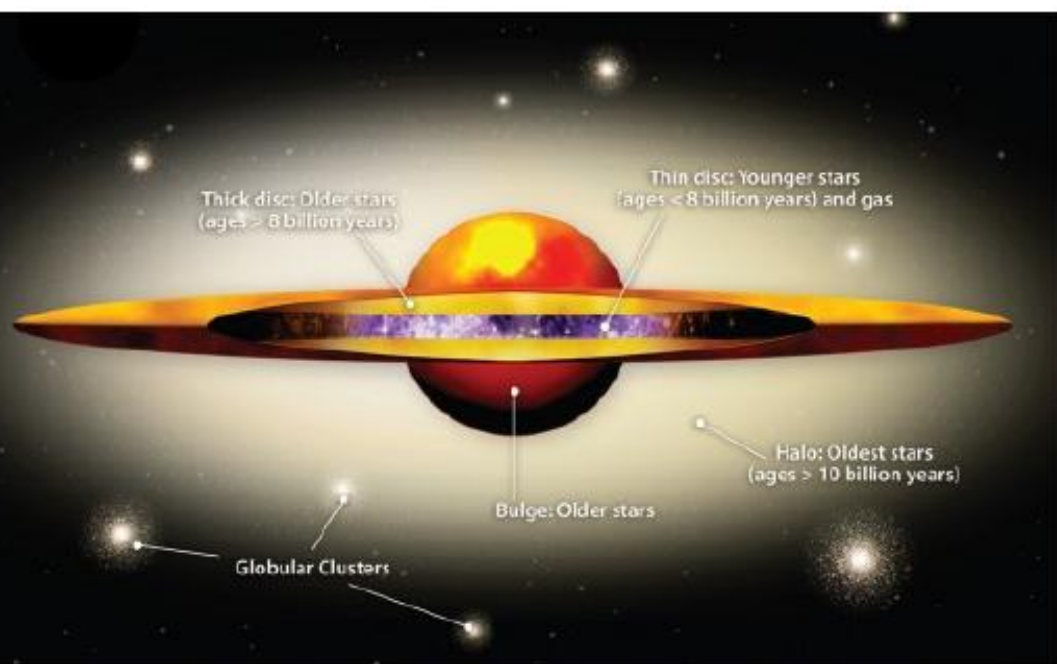
1 The Gaia-ESO Survey

Co-PIs: Gerry Gilmore¹³⁷⁰, Sofia Randich¹³³⁵
 CoIs: M. Asplund¹⁴⁹⁰, J. Binney¹⁶¹¹, P. Bonifacio¹⁵⁸⁸, J. Drew¹⁶⁶⁸, S. Feltzing¹⁴⁷³, A. Ferguson¹⁶⁴⁹, R. Jeffries¹¹³², G. Micola¹²⁴⁴, I. Negueruela⁷⁶⁰⁹, T. Prusti¹²⁷⁶, H.-W. Rix¹⁴⁶⁹, A. Vallenari¹³⁴³, U. Abbas¹³⁴⁶, D. Aden¹⁴⁷³, V. Adibekyan¹²⁰⁰, C. Aerts¹³⁹⁹, L. Affer¹²⁴⁴, J.-M. Aieala¹³⁴⁰, E. Alfaro¹³⁹², C. Allende Prieto¹³⁹³, G. Altabilla⁷⁵³⁰, J. Alves¹⁶⁰⁰, T. Antoja¹⁴²², A. Aparicio¹³⁹³, F. Arenou¹⁵⁸⁵, C. Argiroffi¹⁶⁸³, A. Asensio Ramos¹³⁹³, C. Babusiaux¹⁵⁸⁸, C. Bailer-Jones¹⁴⁸⁹, L. Balaguer-Núñez¹⁸²¹, G. Barentsen¹⁶⁶⁸, A. Bayo¹²⁶³, B. Barbuy¹⁸²⁸, G. Barisevicius¹¹⁷⁶, D. Barrado y Navascués¹⁰⁶⁸, C. Battistini¹⁴⁷³, I. Bellas-Verdés¹⁵⁵⁵, M. Bellazzini¹³²⁹, V. Belokurov¹³⁷⁰, T. Bensby¹⁴⁷³, M. Bergemann¹⁴⁹⁰, G. Bertelli¹³⁴³, K. Biazzo¹³⁴⁰, O. Biemayne¹⁵⁸², S. Blanco Curesma¹⁵⁹², J. Bland-Hawthorn²⁰⁴⁴, R. Blomme¹⁶⁵⁰, C. Boeche²¹¹², S. Bonito¹³⁴⁴, S. Boudresault¹³⁹³, J. Bourvier¹⁴⁴⁹, A. Bragaglia¹³³⁷, I. Brandao¹²⁰⁰, A. Brown¹⁷¹⁶, E. Brugaletta¹⁸⁷⁴, J. de Bruijne¹²⁷⁸, M. Burleigh¹²⁴⁴, J. Caballero⁸⁵⁴⁵, E. Caffau²¹¹², F. Calura¹³³⁷, T. Cantat¹³⁴³, R. Capuzzo-Dolecetta¹⁸⁵⁷, M. Caramazza¹³⁴⁴, G. Carraro¹²⁶¹, L. Casagrande¹⁴⁹⁰, S. Casewell¹²⁴⁴, S. Chapman¹³⁷⁰, C. Chiappini¹¹³⁵, Y. Chorniy¹³⁷⁶, N. Christlieb¹⁹⁸², M. Cignoni⁷⁵³⁰, G. Cocozza⁷⁵³⁰, M. Colles¹⁰¹⁷, R. Collet¹⁴⁹⁰, M. Collins¹⁴⁶⁹, M. Correnti¹³²⁹, M. Cottaar¹³⁷¹, E. Covino¹³⁴⁰, D. Crnojević¹⁶⁴⁹, M. Cropper¹²⁴², P. Cruz Gamba¹⁰⁶⁸, M. Cunha¹²⁰⁰, F. Damiani¹³⁴⁴, M. David¹²³⁵, A. Delgado¹³⁹², E. Delgado-Mena¹²⁰⁰, R. Dorda Laforet⁷⁶⁰⁹, S. Duffau²¹¹², S. Van Eck¹³⁵⁸, B. Edvardsson⁶¹⁸¹, J. Eldridge¹³⁷⁰, H. Enke¹¹³⁵, K. Eriksson⁶¹⁸¹, N.W. Evans¹³⁷⁰, L. Eyer¹³⁷⁷, B. Famaey¹⁵⁸², M. Fellhauer¹⁸²⁴, I. Ferreras¹²⁴², F. Figueras¹⁸²¹, G. Fiorentino¹⁴²², E. Flaconnio¹³⁴⁴, C. Flynn²⁰⁴⁴, D. Folha¹²⁰⁰, E. Franciosini¹³³⁵, P. Francois¹⁵⁸⁸, A. Frasca¹³⁴¹, K. Freeman¹¹³⁹, Y. Fremat¹⁶³⁰, E. Friel¹³⁵⁵, B. Geensieck¹²⁴¹, P. Galindo¹⁰⁶⁸, J. Gameiro¹²⁰⁰, F. Garzon¹³⁹³, M. Gebran⁵⁷⁴¹, S. Geier⁵⁶⁷⁷, D. Geisler¹⁸²⁴, O. Gerhard¹⁴⁹⁶, B. Gibson¹¹⁹⁷, M. Gieles¹³⁷⁰, A. Gomboc¹⁸⁹⁵, A. Gomez¹⁵⁸⁸, C. Gonzalez-Fernandez⁷⁶⁰⁹, J.I. Gonzalez Hernandez¹³⁹³, E. Gosset¹³⁵⁹, E. Grebel²¹¹², R. Greimel¹⁴²³, M. Groenewegen¹⁶⁵⁰, J. Groh¹⁴⁹⁴, F. Grundahl¹³⁶⁸, P. Gruyters⁶¹⁸¹, M. Guarcello¹³¹², B. Gustafsson⁶¹⁸¹, P. Hadrawa¹¹¹⁶, T. Hansen¹⁹⁸², D. Hatzidimitriou¹⁵⁵⁹, N. Hambly¹⁶⁴⁹, P. Hammersley¹²⁵⁶, C. Hansen²¹¹², M. Haywood¹⁵⁸⁸, U. Heber⁵⁶⁷⁷, U. Heiter⁶¹⁸¹, E. Held¹²⁴³, A. Helmi¹⁴²², G. Hensler¹⁸⁹³, A. Herrero¹³⁹³, V. Hill¹⁵⁹¹, S. Hodgkin¹³⁷⁰, N. Huelamo⁸⁵⁴⁵, A. Huxor²¹¹², R. Ibata¹⁵⁸², M. Irwin¹³⁷⁰, H. Jacobson¹⁴⁸¹, R. Jackson¹¹³⁹, P. Jofre¹⁵⁹², R. de Jong¹¹³⁵, P. Jonker¹⁶⁶⁰, S. Jordan²¹¹², C. Jordi¹⁸²¹, A. Jorissen¹³⁵⁸, N. Kacharov¹²⁴⁴, D. Katz¹⁵⁸⁸, D. Kawata¹²⁴², S. Keller¹¹⁷⁹, N. Kharchenko¹¹¹⁵, R. Klement¹⁴⁸⁹, A. Klutseh¹⁸⁹³, J. Knude¹⁸⁹⁶, A. Koch¹²⁴⁴, O. Kochukhov⁶¹⁸¹, M. Kontizas¹⁵⁶⁰, S. Koposov¹³⁷⁰, G. Kordopatis¹³⁷⁰, A. Korn⁶¹⁸¹, A. de Koter¹⁶¹⁴, P. Koubsky¹¹¹⁶, A. Lanzafame¹⁸⁷⁴, R. Lallemand¹⁵⁸⁸, C. Lardo¹³³⁷, P. de Laverny¹²⁹¹, F. van Leeuwen¹³⁷⁰, B. Lemasle¹⁴²², G. Lewis²⁰⁴⁴, K. Lind¹⁴⁹⁰, H.P.E. Lindstrom¹⁹⁸⁶, A. Lobel¹³⁵⁹, J. Lopez Santiago¹⁸⁹³, P. Lucas¹⁶⁶⁸, H. Ludwig²¹¹², T. Lueftinger¹⁸⁹², L. Magrini¹³³⁵, L. Mahy¹³⁵⁹, J. Maiz Apellaniz¹³⁹², J. Maklonsdo¹⁶⁰¹, M. Mapelli¹³⁴³, G. Mareconi¹²⁶¹, A. Marino¹⁴⁹⁰, S. Marinoni¹³³⁷, C. Martayan¹²⁶¹, S. Martell¹⁰¹⁷, I. Martinez-Valpuesta¹⁴⁹⁶, T. Masseron¹³⁵⁸, G. Matijevic¹⁹⁹⁵, R. McMahon¹³⁷⁰, S. Messina¹²⁴¹, M. Meyer¹³⁷⁷, A. Miglio¹³⁵⁹, S. Mikolaitis¹³⁷⁶, I. Minchev¹¹³⁵, D. Minniti¹⁸⁰¹, A. Moitinho⁸⁸⁴⁸, Y. Momany¹²⁶¹, L. Monari¹²⁶¹, M. Montalto¹²⁰⁰, M.J. Monteiro¹²⁰⁰, R. Monier⁵⁶⁹⁵, D. Montes¹⁸⁹³, A. Mora¹³⁵⁰, E. Moras¹⁴⁴⁹, T. Morel¹¹⁵⁹, J. Muijcos⁵⁶⁸⁸, N. Mowlavi¹⁵⁸³, A. Mucciarelli⁷⁵³⁰, U. Munari¹²⁴³, R. Napiwotzki¹⁶⁶⁸, N. Nardetto¹⁵⁹¹, T. Naylor¹¹³⁰, Y. Naze¹³⁵⁹, G. Nelemans¹⁶³⁸, S. Okamoto¹⁶¹⁶, S. Ortolani⁶³¹¹, G. Pace¹²⁶⁰, F. Palla¹³³⁵, J. Palous¹¹¹⁶, E. Pancino¹³³⁷, R. Parker¹³⁷⁷, E. Paurzen¹⁸⁹³, J. Penarrubia¹⁸²⁸, I. Pillitteri¹³¹², G. Piotto¹²⁴³, H. Posbie¹⁵⁸⁸, L. Prisinzano¹³⁴⁴, N. Przybilla¹²⁵¹, L. Puspitarini¹⁵⁸⁸, E. Puzeras¹³⁷⁶, A. Quirrenbach²¹¹², S. Ragaini⁷⁵³⁰, P. Re Fiorentin¹³⁴⁶, J. Read¹³⁷⁷, M. Read¹⁶⁴⁹, A. Recio-Blanco¹⁵⁹¹, C. Reyle¹⁵⁹², J. De Ridder¹³⁴⁴, N. Robiehon¹⁵⁸⁸, A. Robin¹⁵⁸², S. Roeser²¹¹², D. Romano¹³³⁷, F. Royer¹⁵⁸⁸, G. Ruehtj¹⁴⁹⁰, C. Ruhland¹⁶⁶⁸, A. Ruzicka¹¹¹⁶, S. Ryan¹⁶⁶⁸, N. Ryde¹⁴⁷³, G. Sacco¹⁶⁴⁵, H. Sans N. Santos¹²⁰⁰, J. Sanz Forcada⁸⁵⁴⁵, L.M. Sarro Baro⁵⁶⁸⁸, L. Sbordon¹⁸⁶², E. Schilbach²¹¹², S. Schmeja²¹¹², O. Schnurr¹¹³⁵, R. Schoenrich¹⁴⁹⁰, R.D. Scholz¹¹³⁵, G. Seabroke¹²⁴², P. Sestito¹⁸⁹³, S. Sharma²⁰⁴⁴, G. De Silva¹⁰¹⁷, R. Smiljanic¹²⁵⁸, M. Smith¹⁶¹⁶, J. Sobek¹⁵⁹¹, E. Solano⁸⁵⁴⁵, R. Sordo¹³⁴³, C. Soubiran¹⁴⁴⁴, S. Sousa¹²⁰⁰, A. Spagna¹²⁴⁶, L. Spina¹¹³⁵, M. Steffen¹¹³⁵, M. Steinmetz¹¹³⁵, B. Stelzer¹³⁴⁴, E. Stempels⁶¹⁸¹, H. Tabernero¹⁸⁹³, G. Thauvaisiene¹³⁷⁶, F. Thevenin¹⁵⁹¹, J. Torra¹⁸²¹, M. Tosi¹²³⁷, E. Tolstoy¹⁴²², M. Tsantaki¹²⁰⁰, C. Turon¹⁵⁸⁸, M. Valentini¹³⁵⁹, M. Walker¹³¹², N. Walton¹³⁷⁰, J. Wambsgans²¹¹², C. Worley¹⁵⁹¹, N. Wright¹⁶⁶⁸, K. Venn²⁰⁶¹, J. Vink¹¹¹¹, R. Wyse¹⁴¹⁹, S. Zaggia¹³⁴³, W. Ziegler¹⁸⁹³, M. Zoccali¹⁸⁹¹, J. Zorec¹³⁶¹, D. Zucker¹⁴⁷⁷, T. Zwitter¹⁸⁹⁵

GAIA-ESO SURVEY IN A NUTSHELL



- Large Public Spectroscopic Survey – FLAMES
- 300 (240+60) nights over 5 (4+1) years;
- 12/2011 (P88) - 9/2016 (P97)++; Visitor Mode

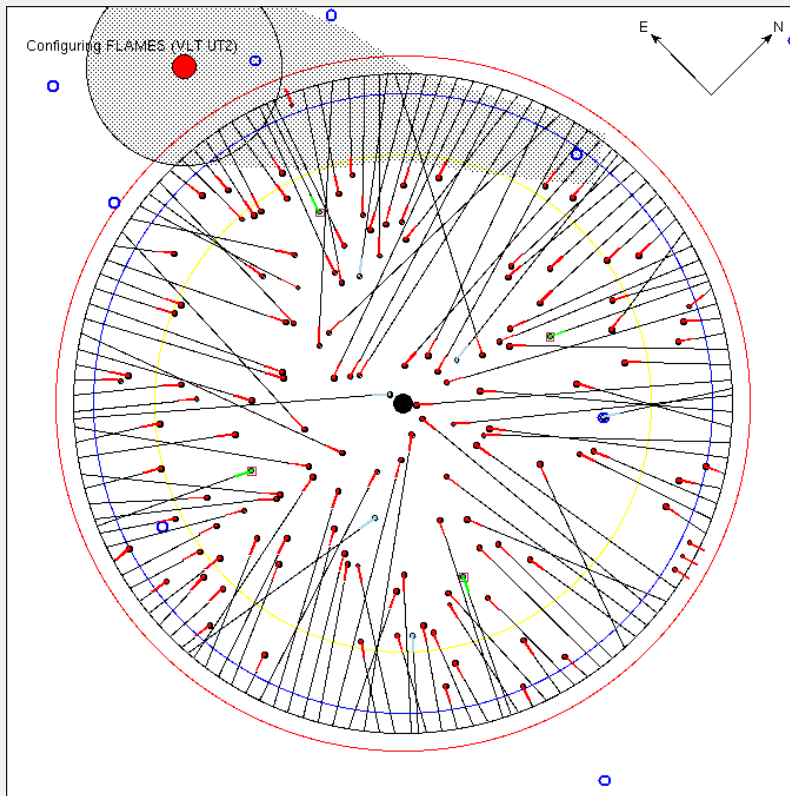


>10⁵ stars.

All populations
of the MW:

- Halo
- Bulge
- Thick & Thin discs
- Open clusters

GAIA-ESO SURVEY IN A NUTSHELL



Giraffe, 132 fibers
 $R=16000-25000$, $H3...H21$
 $403-476...848-900$
 $V < 19$, $S/N > 10-15$

UVES, 6/8 fibers $R=42,000$,
 $520/580$ nm
 $416-617/475-678$
 $V < 16.5$, $S/N > 30$

GAIA-ESO SURVEY IN A NUTSHELL



Giraffe and UVES spectra → Products

- RVs (+variability), $v \sin i$
- T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, $[\text{X}/\text{Fe}]$ (Li, α , Fe-, s-,...)
- stellar properties (activity, M_{acc} , $\dot{M}$, etc.)

Uniform analysis:

→ homogeneous overview

Open Cluster Science



Cluster formation and dynamics:

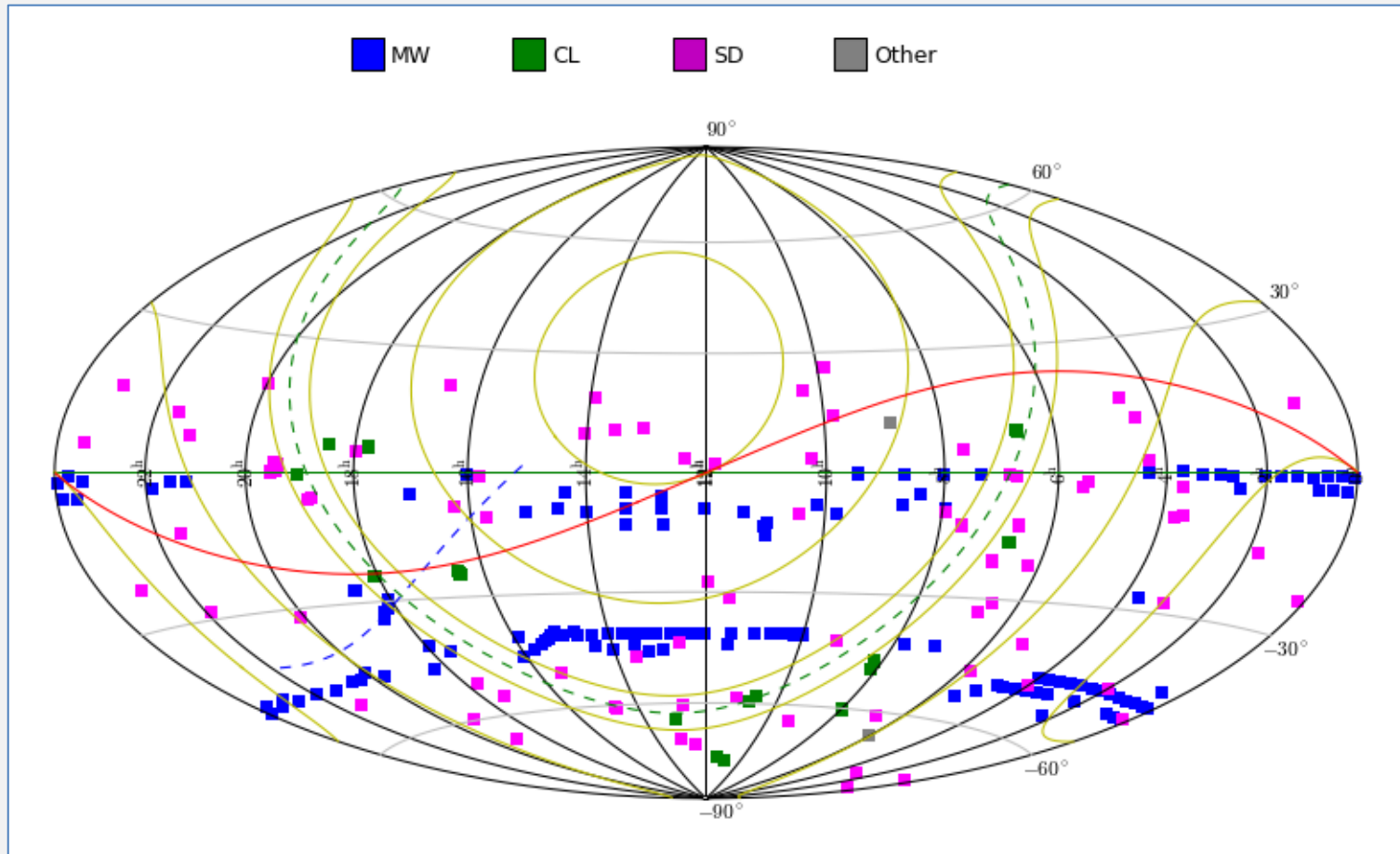
complement Gaia astrometry

Stellar evolution and stellar ages:

calibrate and refine models

Thin Disc : chemical evolution as a
function of age and Galacto-centric radius

Survey Progress



Roughly **50%** of what we hoped for has now been achieved
>10K Giraffe spectra, ~1K UVES spectra in open clusters

Survey Progress

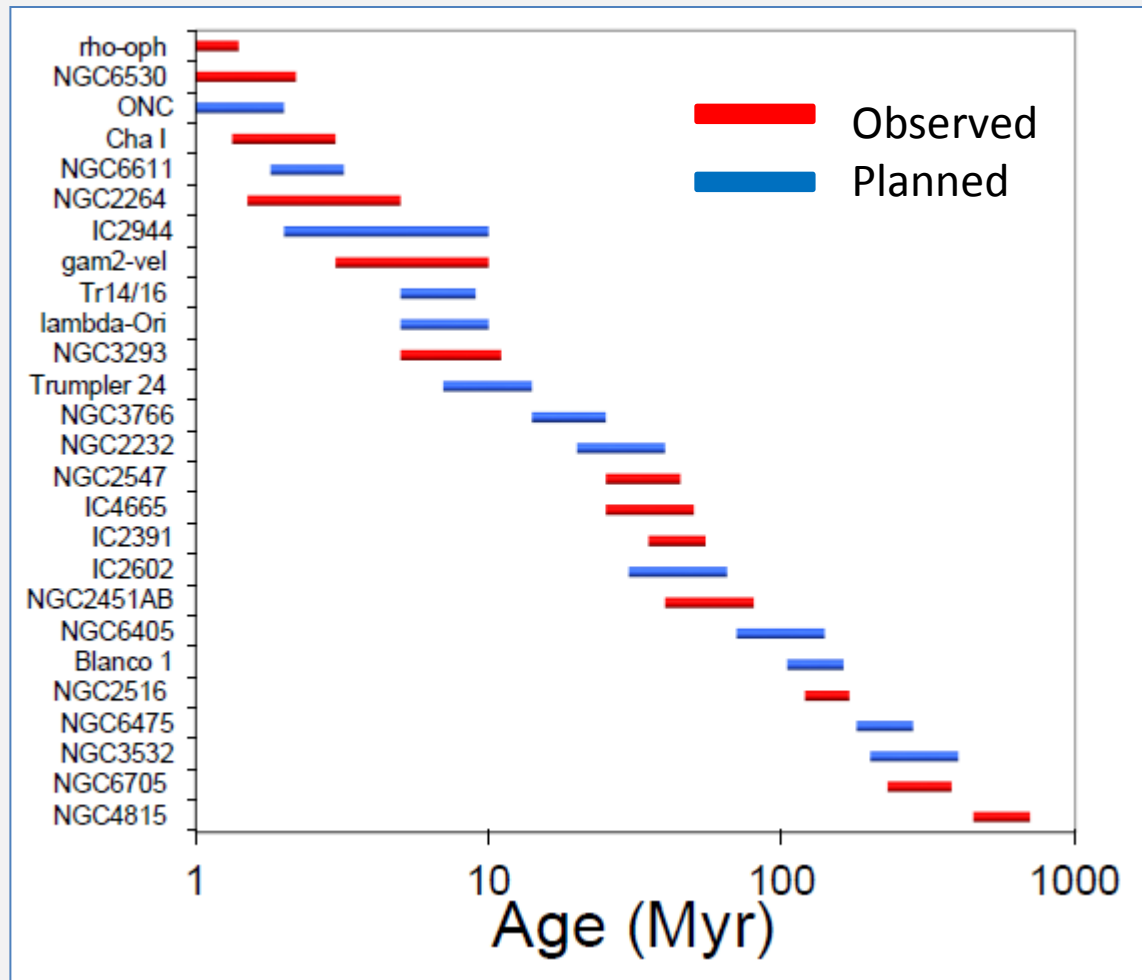


11 young (<200 Myr)
clusters have been
observed so far (+
several older clusters)

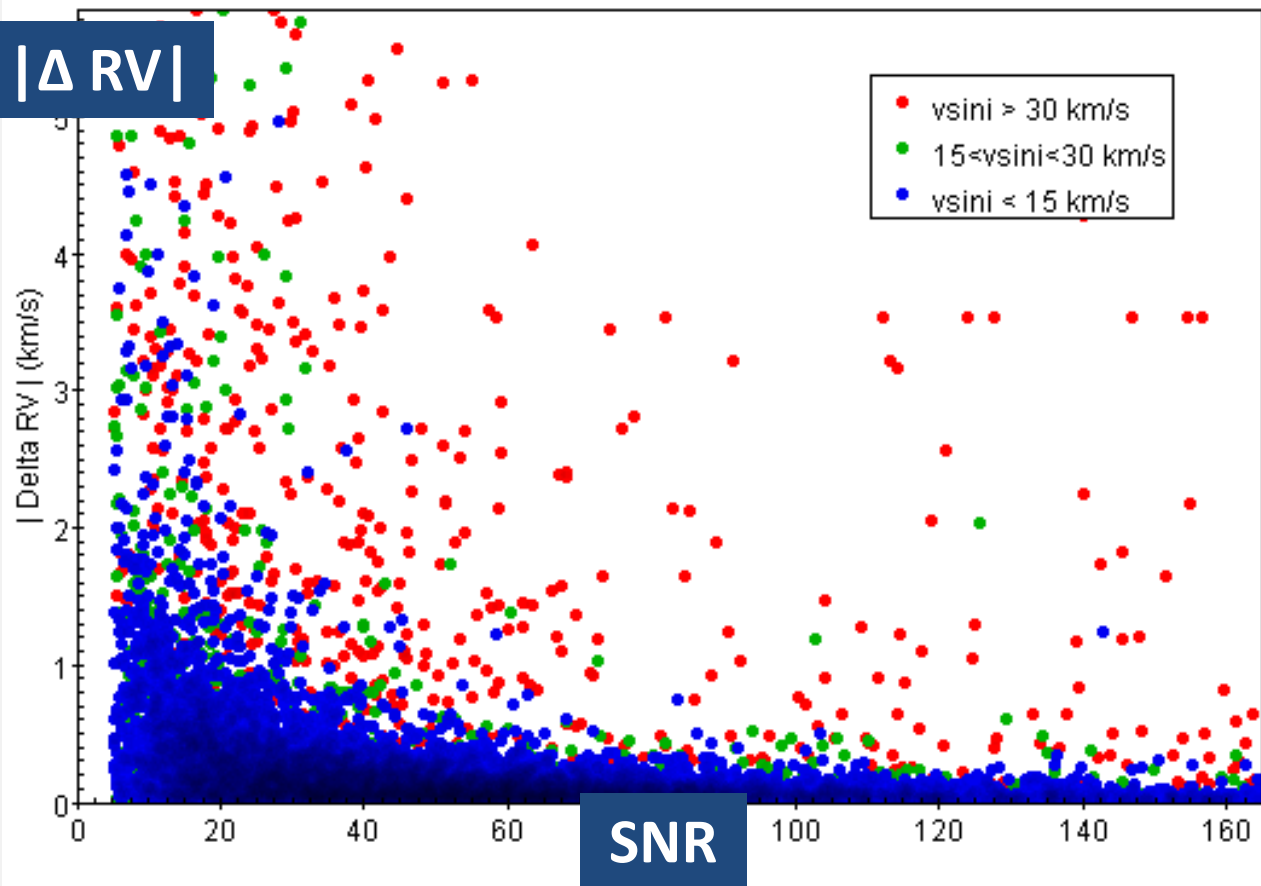
iDR2 data now available
from first 18 months

About 7k spectra in 8
clusters

Most taken with HR15
setup: **647-697nm**



The radial velocity precision of the Giraffe spectra



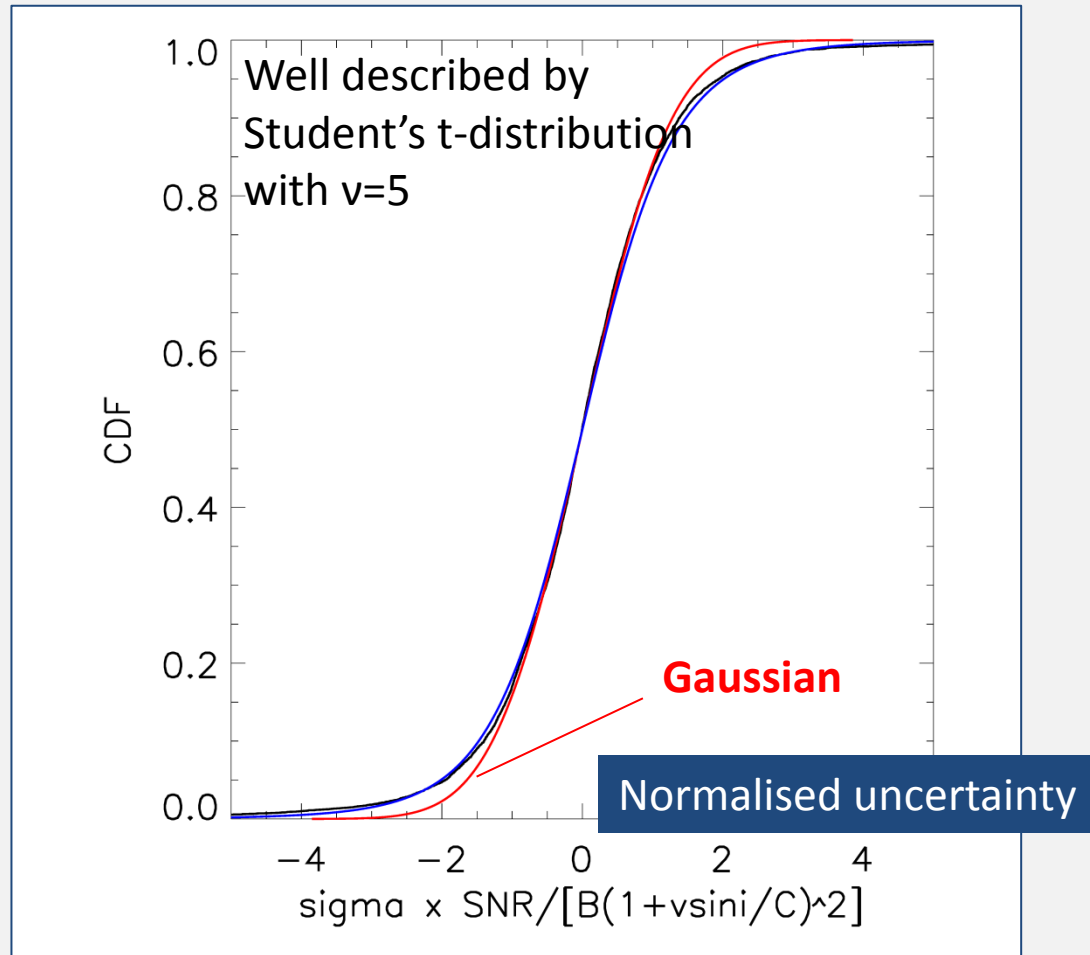
RVs calculated at
CASU (Jim Lewis and
Sergey Koposov)

Analyse short-term
repeats at Keele
(Richard Jackson)

Semi-empirical
model – uncertainty
depends on SNR and
 $v \sin i$

$$\sigma = B[1 + (v \sin i / C)^2] / \text{SNR}$$

Non-Gaussian wings in the uncertainty distribution



$$\sigma = B[1 + (v \sin i / C)^2] / \text{SNR} ; B=5.44, C=22.2 \text{ km/s}$$

Evidence for an additional systematic RV uncertainty



Average values:

A=0.25 km/s

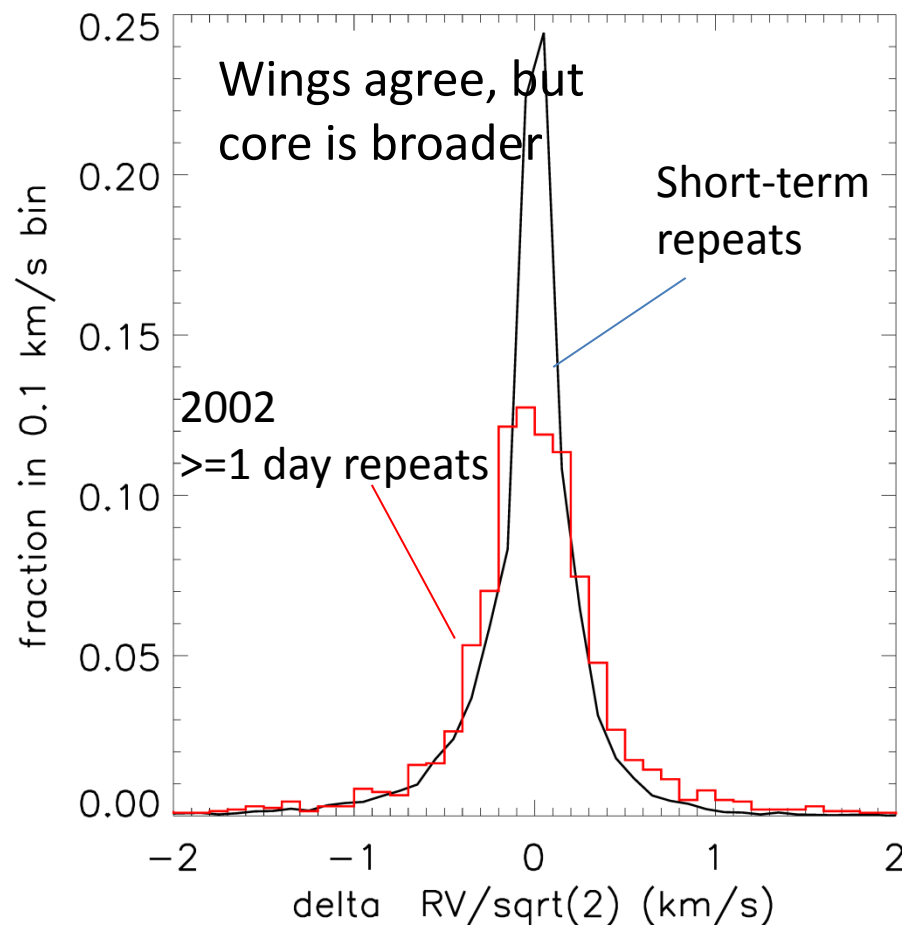
Minimum uncertainty in
single RV

B=5.44 km/s

SNR important if <20

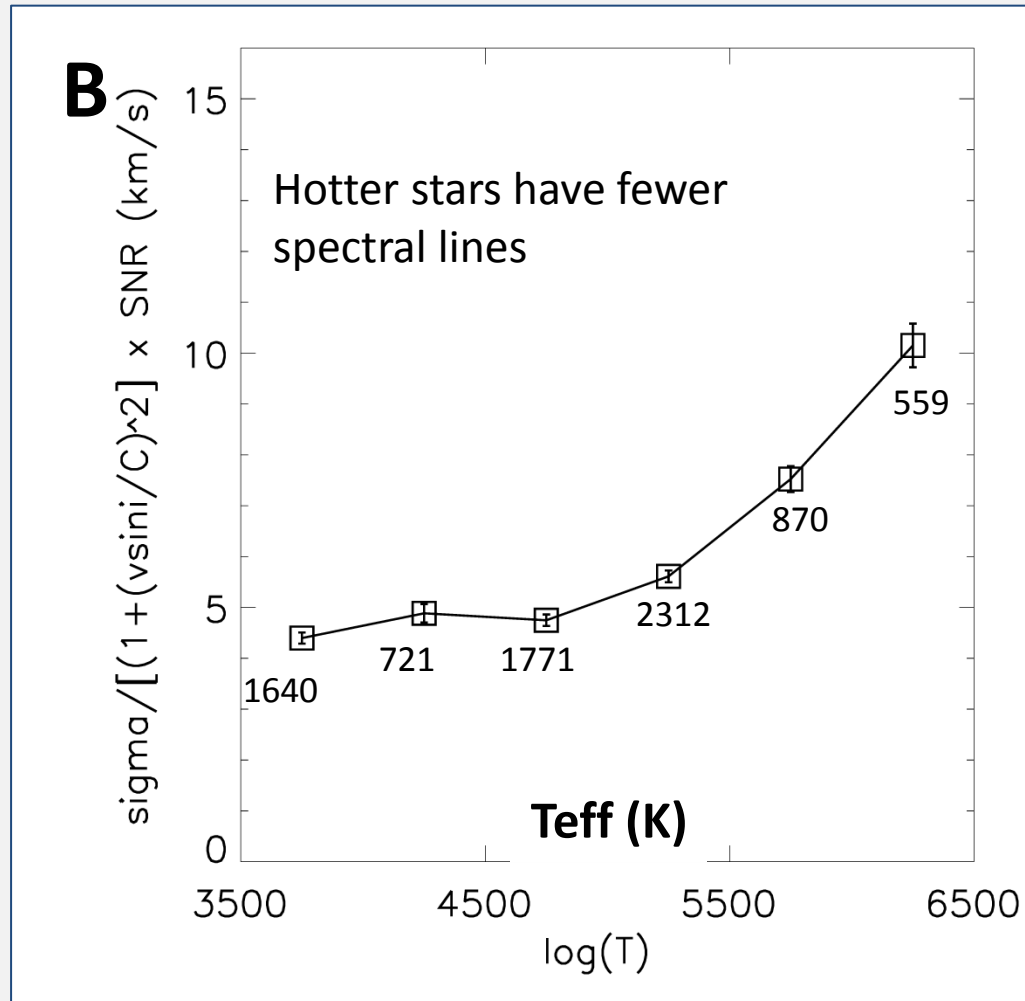
C= 22.2 km/s

vsini important at this value



$$\sigma^2 = \underline{A}^2 + B^2 [1 + (vsini/C)^2]^2 / SNR^2$$

Uncertainty depends on stellar effective temperature

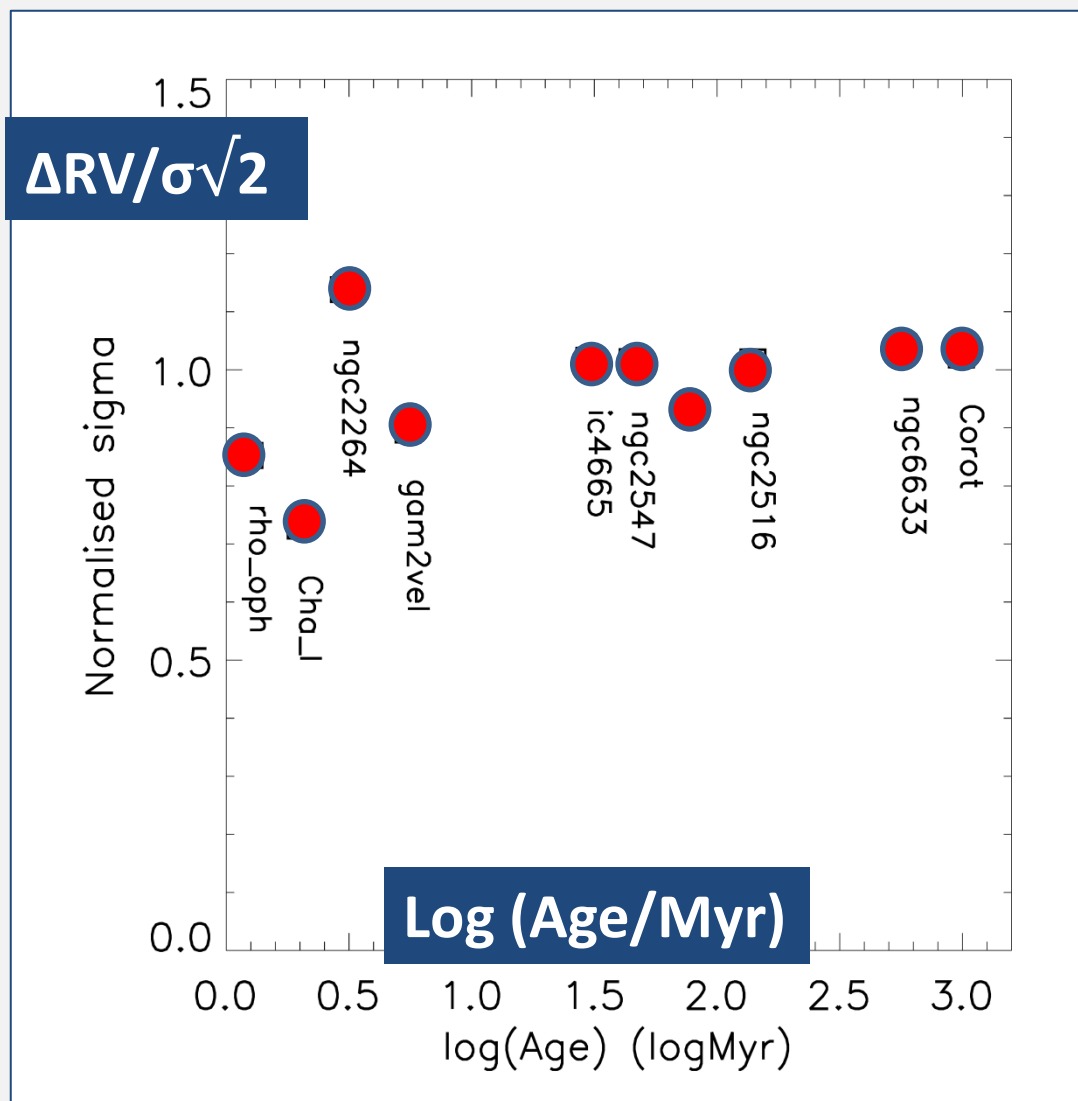


$$\sigma^2 = A^2 + B^2 [1 + (v \sin i / C)^2]^2 / \text{SNR}^2$$

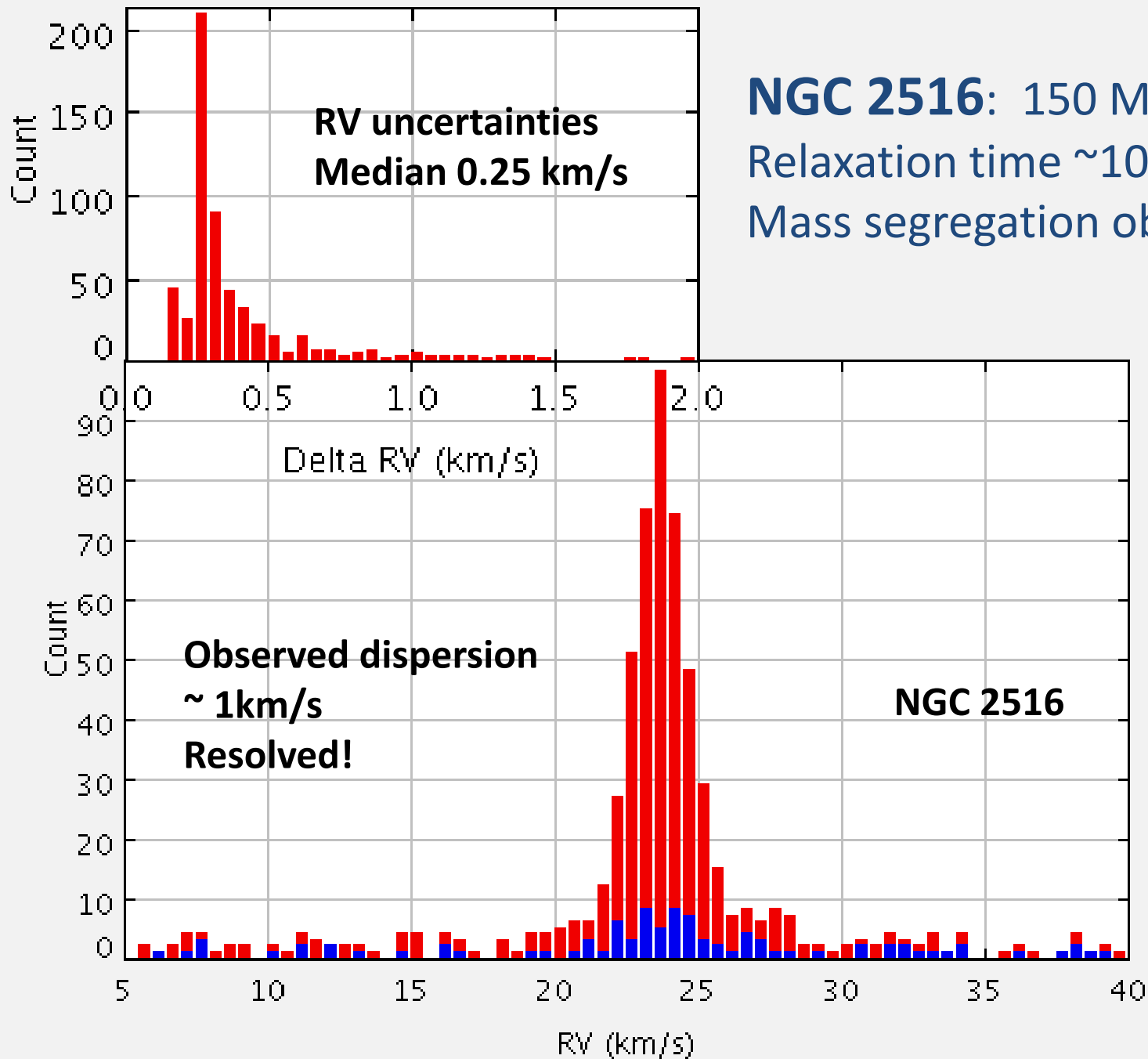
No evidence for any specific age dependence



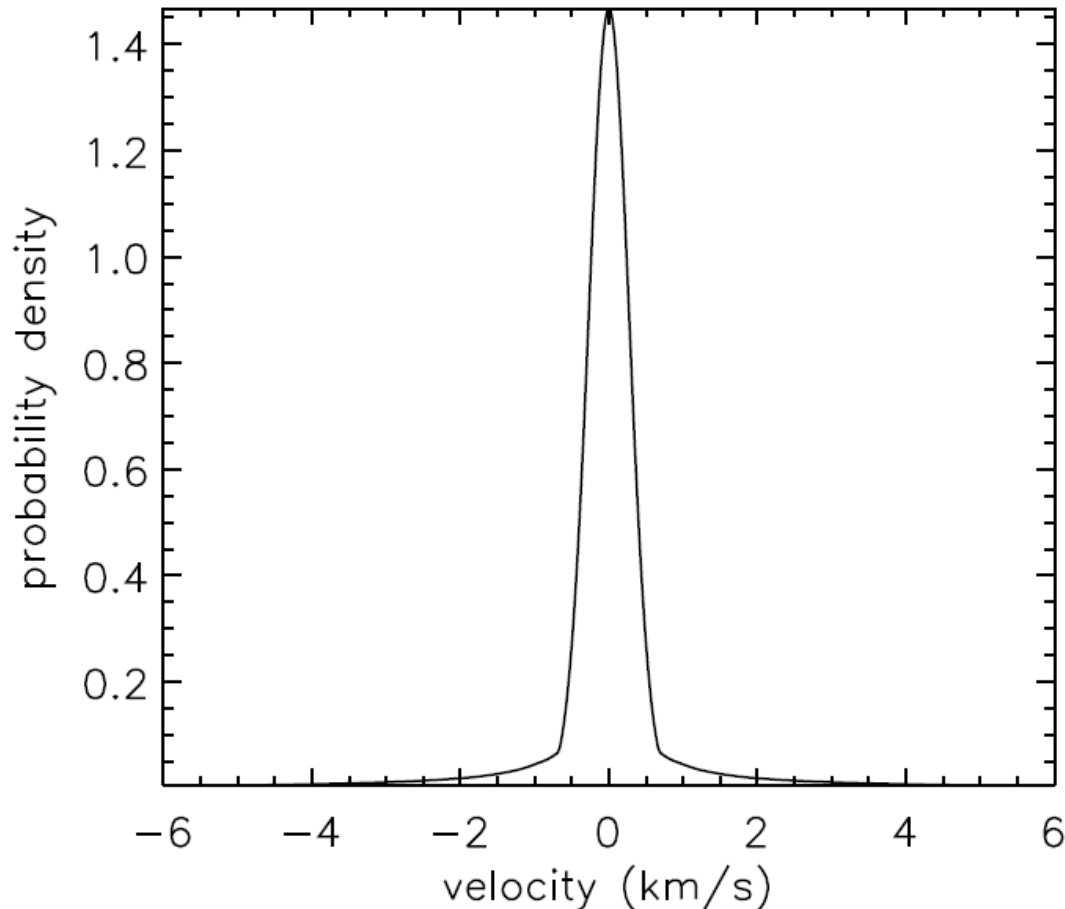
RV differences
normalised by
estimated
uncertainty



NGC 2516: 150 Myr
Relaxation time ~ 100 Myr
Mass segregation observed



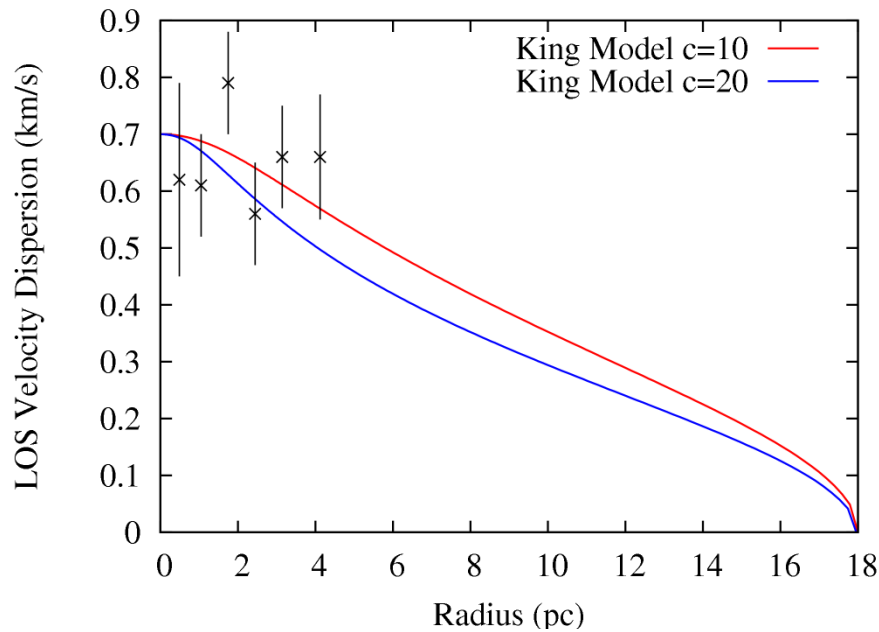
Maximum likelihood modelling accounts for uncertainties and binaries



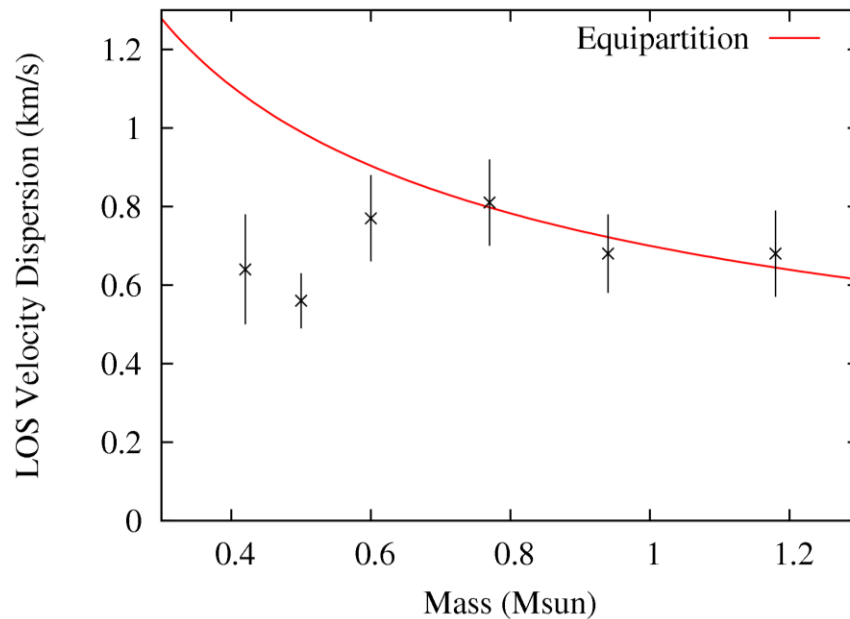
Binary model
convolved with
normal distribution
($\sigma=0.31$ km/s)

Binary parameters
from Raghavan et al.
2010; $f=0.46$

Convolve this with intrinsic velocity models and fit
with maximum likelihood



Line of sight velocity dispersion (just) consistent with King model fits to spatial density

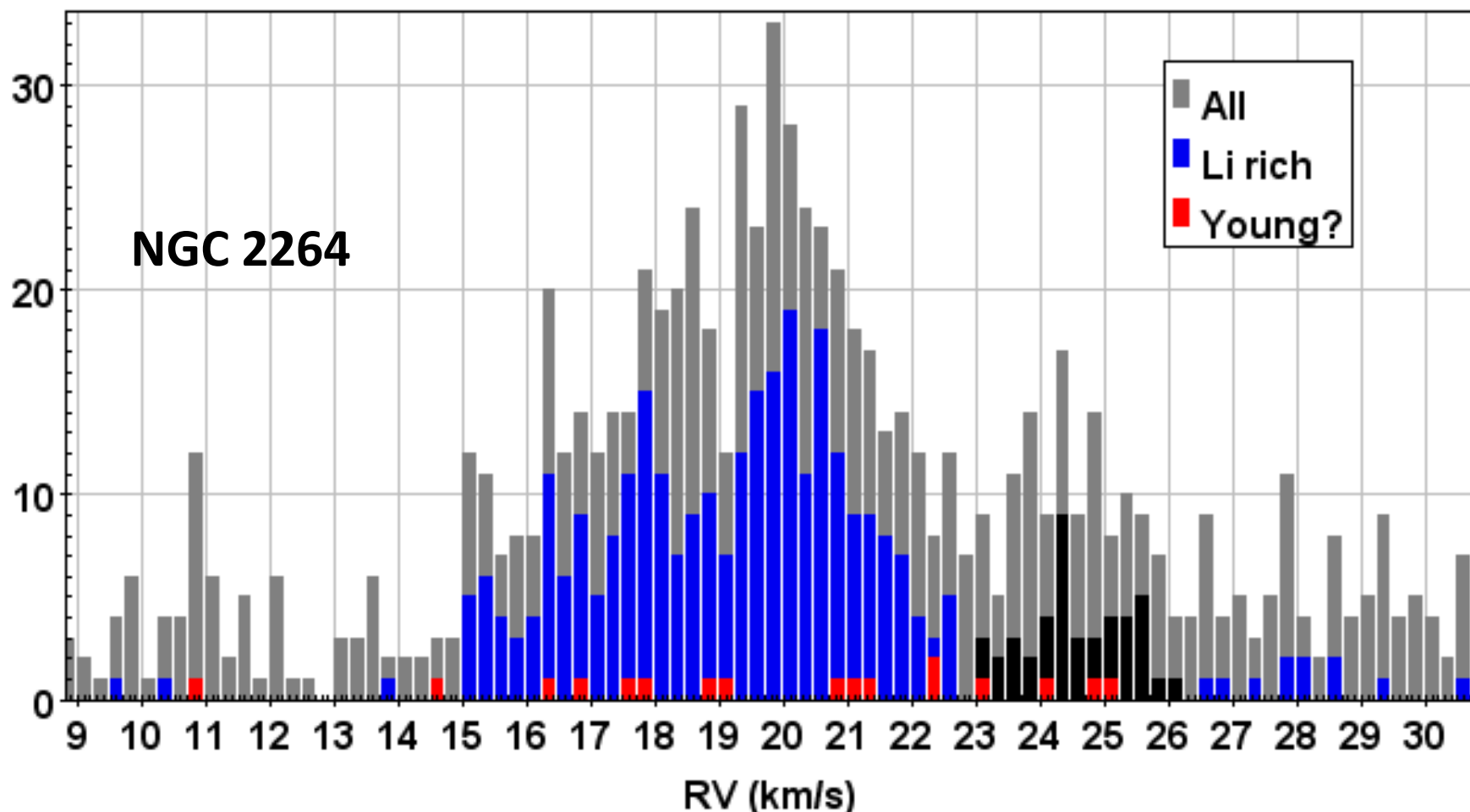


No equipartition is apparent, despite mass segregation?

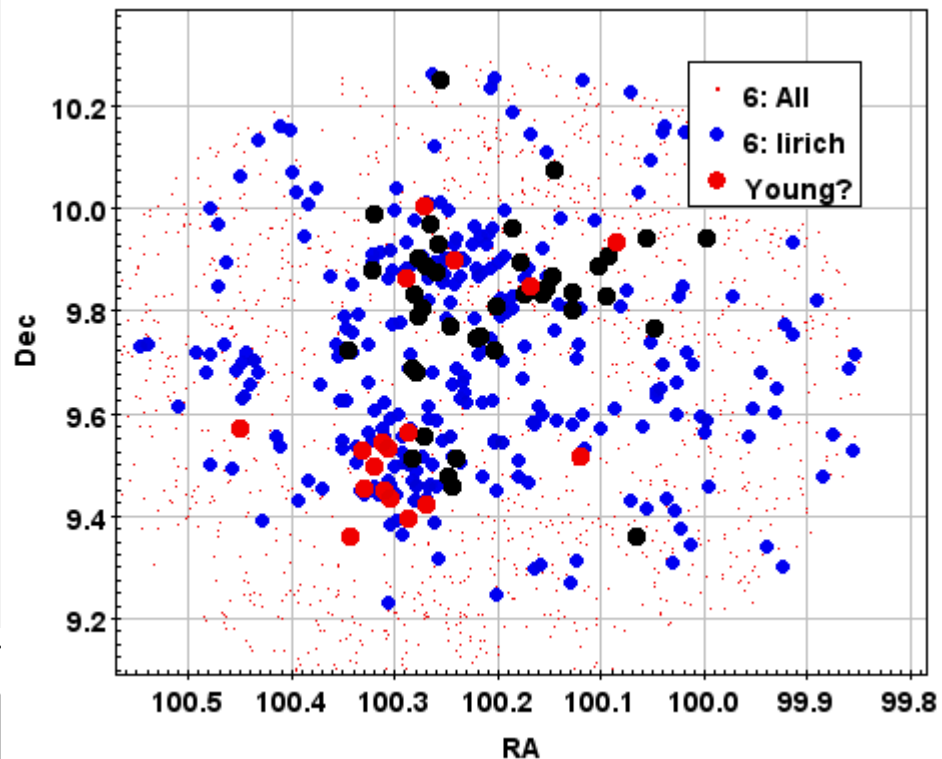
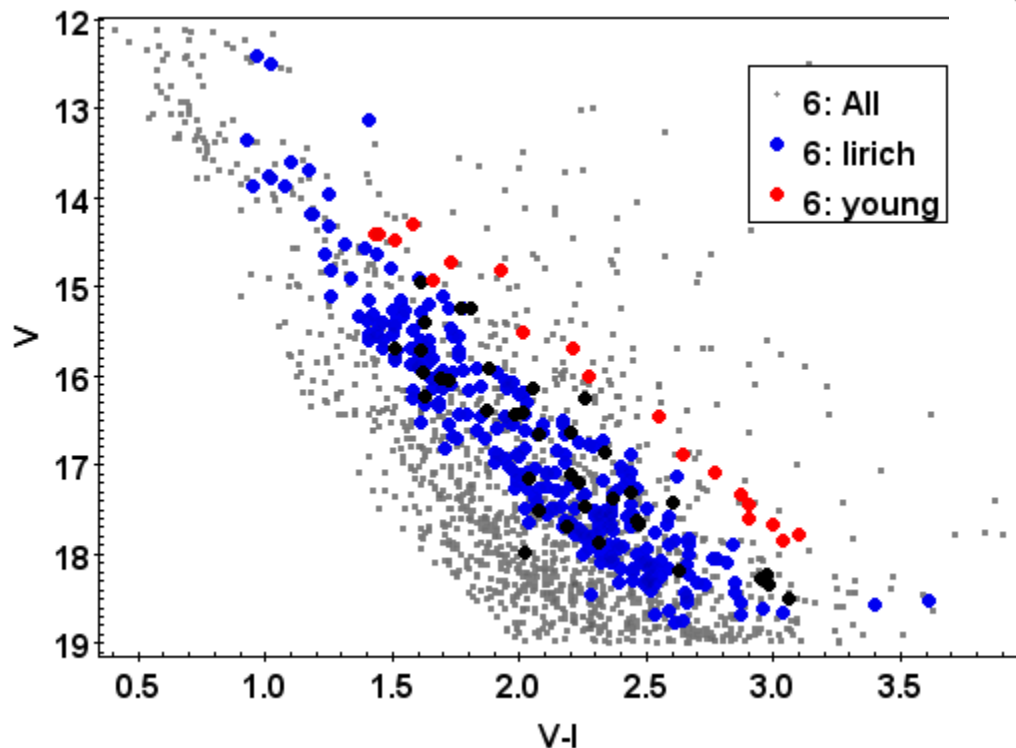
Virial mass is 3 times measured mass!

NGC 2264: Young cluster/association ~ 5 Myr

Complex, resolved RV structure



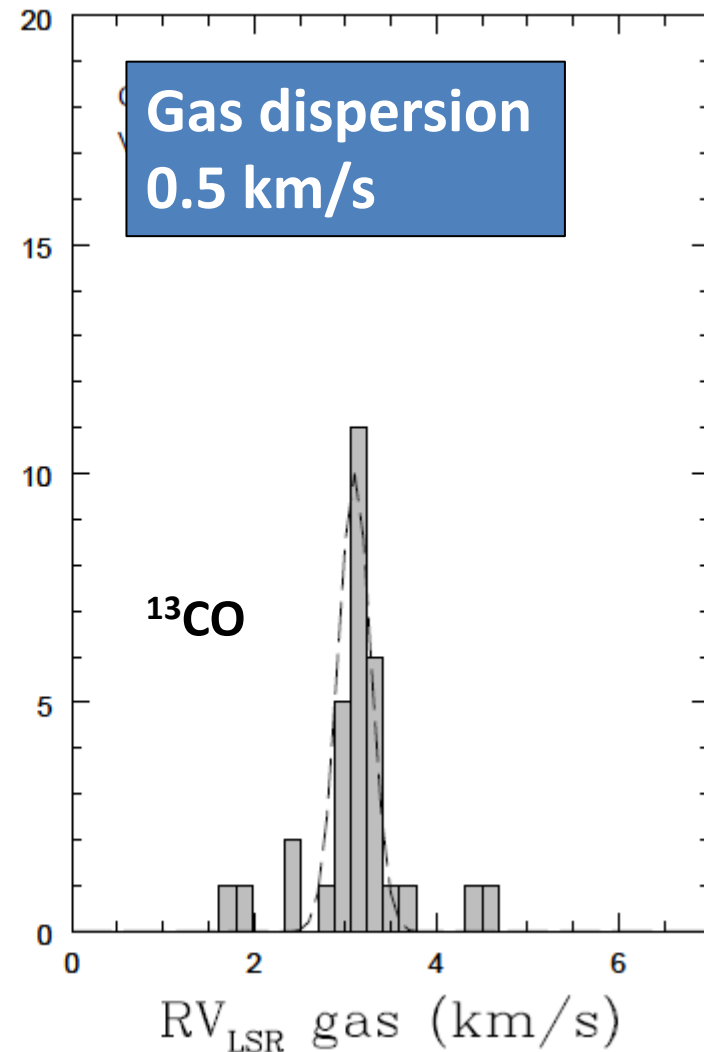
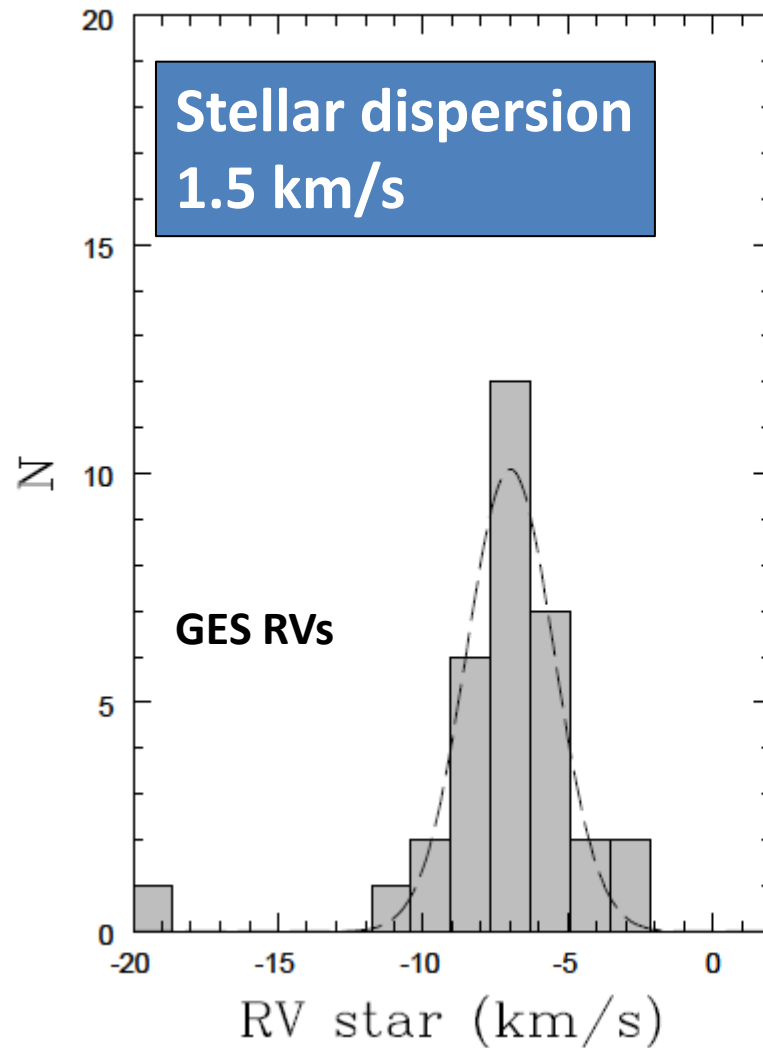
- “Young “ stars in CMD – different spatial population, but dispersed kinematics.
- Detached kinematic population is less widely distributed.



- 1802 individual stars to play with!
- Median RV uncertainty of Li-rich stars is 0.33 km/s

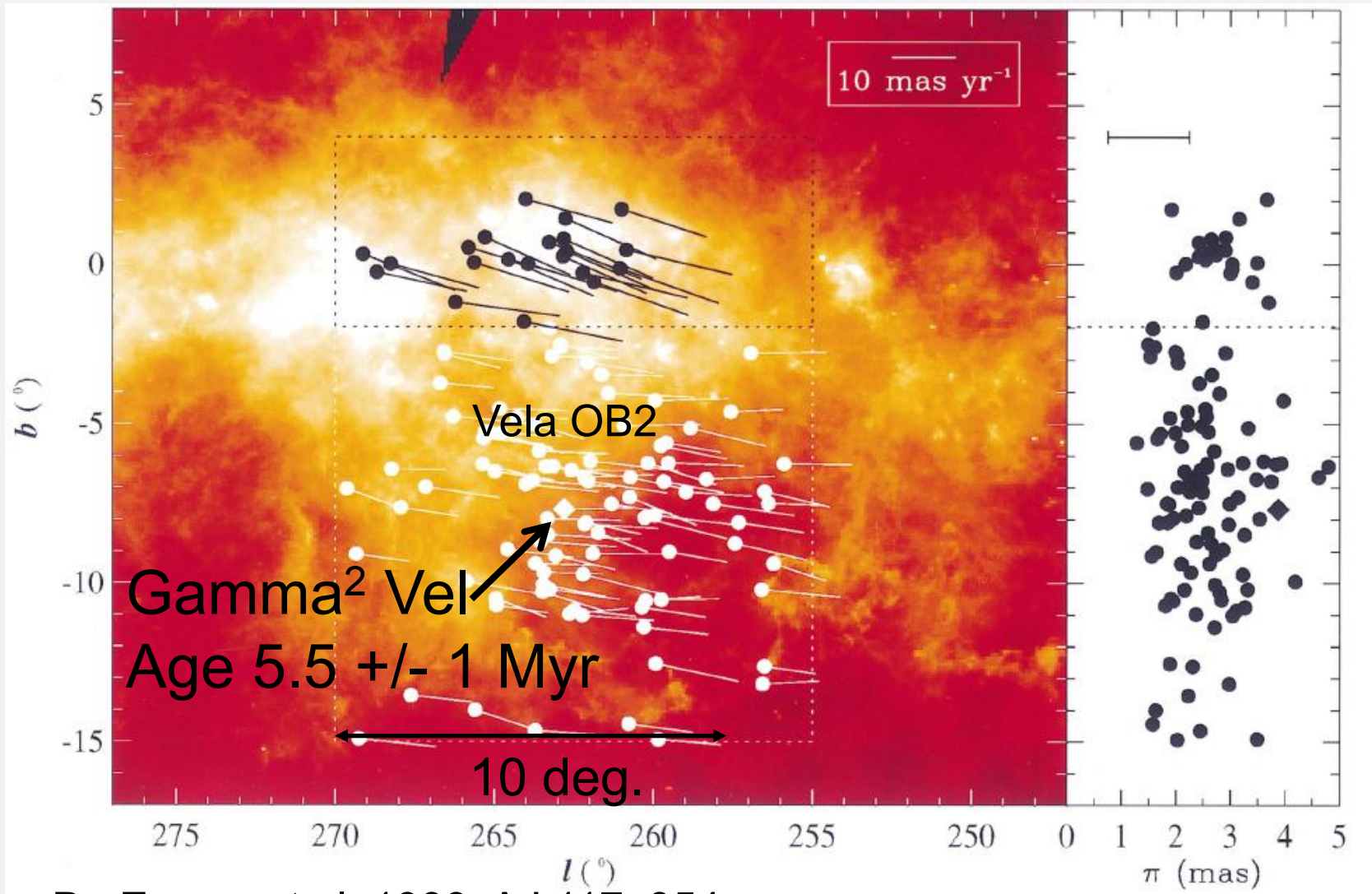
Rho Ophiuchus: 1 Myr cluster

Partly embedded in parental gas



Courtesy of: Rigliaco, Wilking et al. 2014 in prep.

Gamma² Vel (WC8+O8III) – similar distance and co-moving with Vela OB2 B-stars and surrounding low-mass PMS stars Jeffries et al. 2009, MNRAS, 393, 538

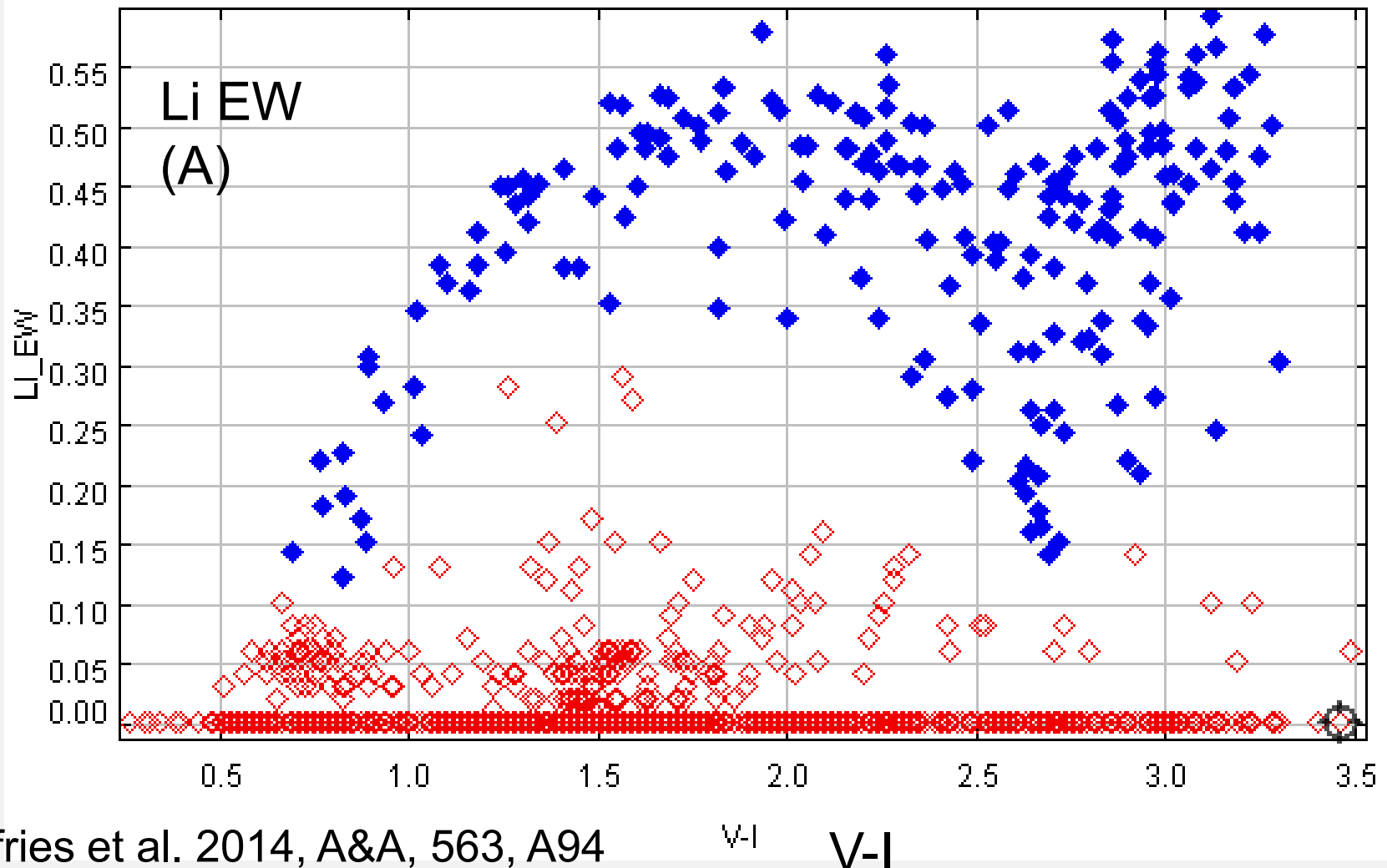


De Zeeuw et al. 1999, AJ 117, 354

Selecting a sample in the GES

1802 observations of 1242 individual targets

Li offers a kinematically unbiased selection of members

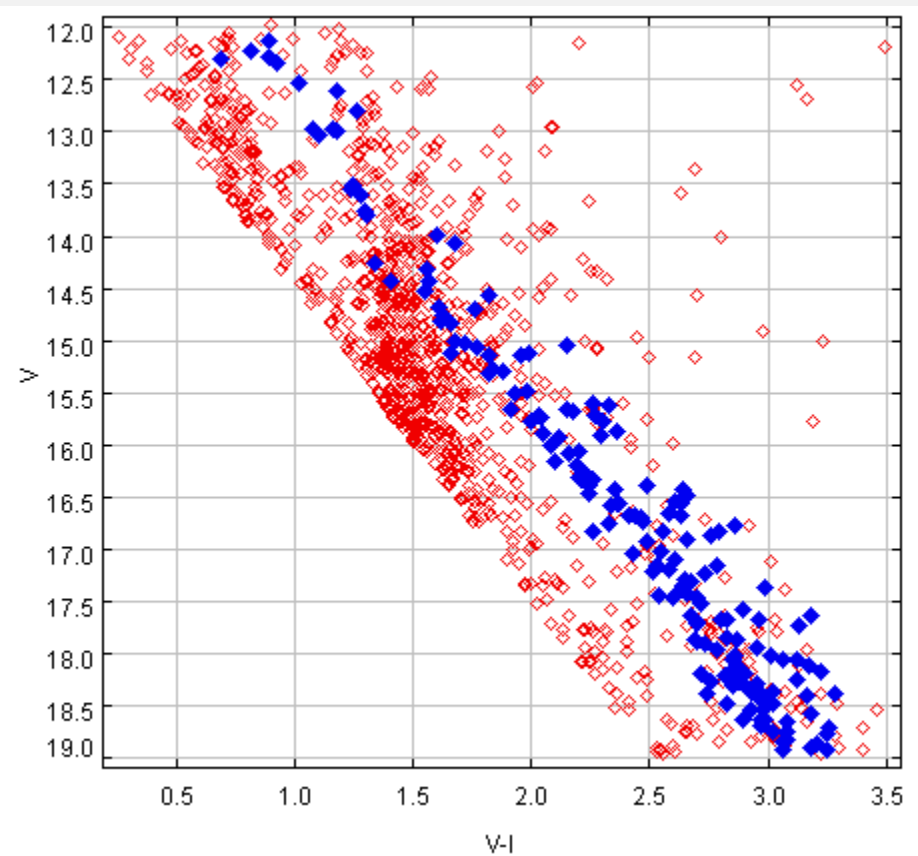
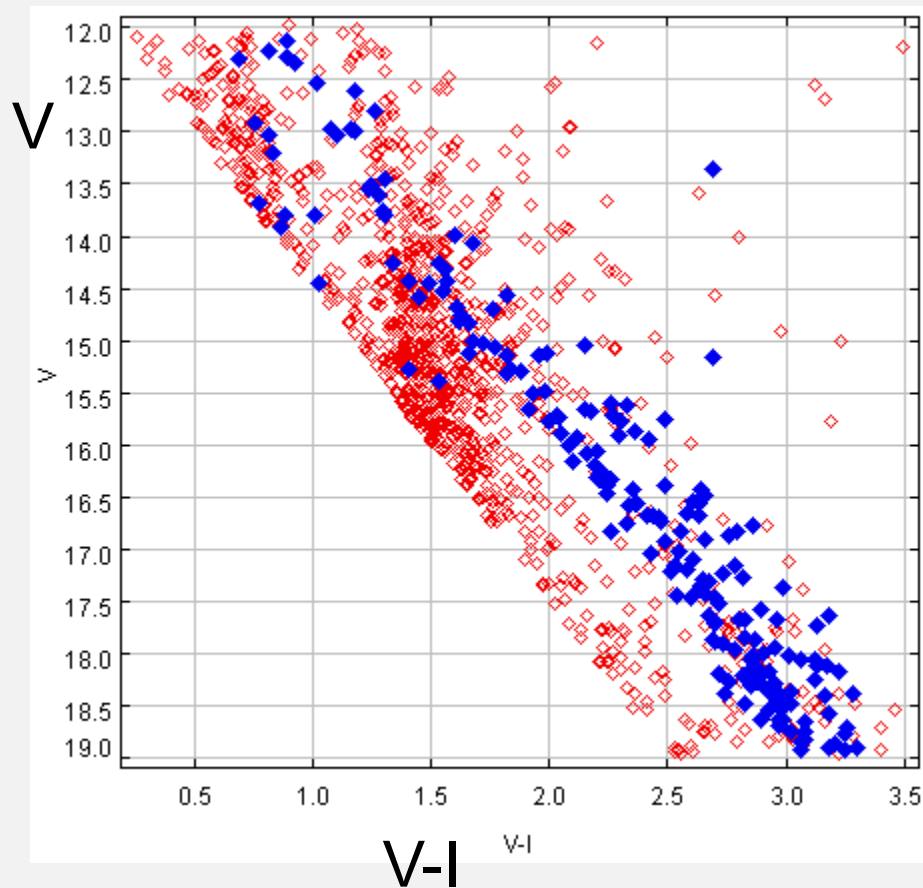


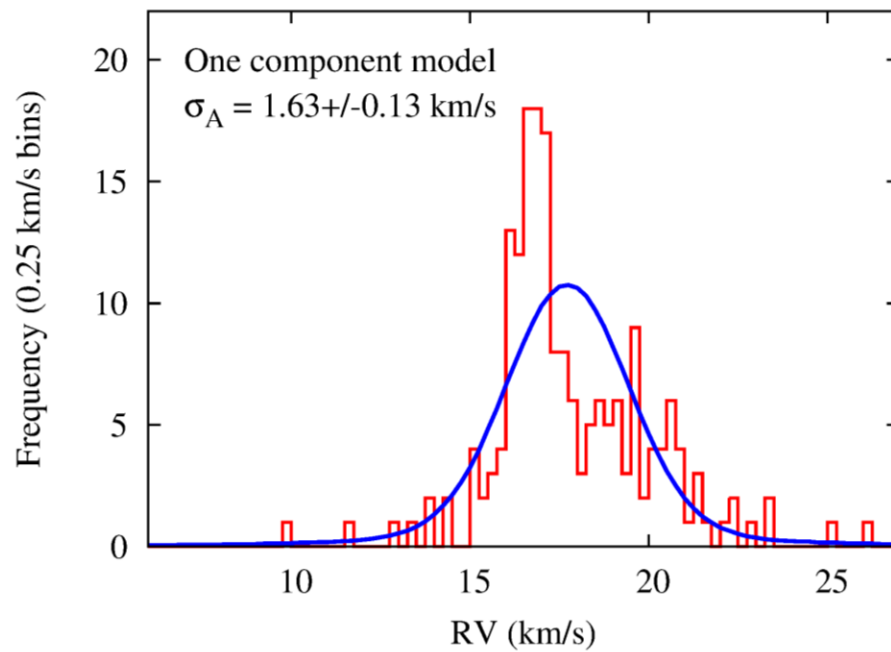
Selecting a sample

1802 observations of 1242 individual targets

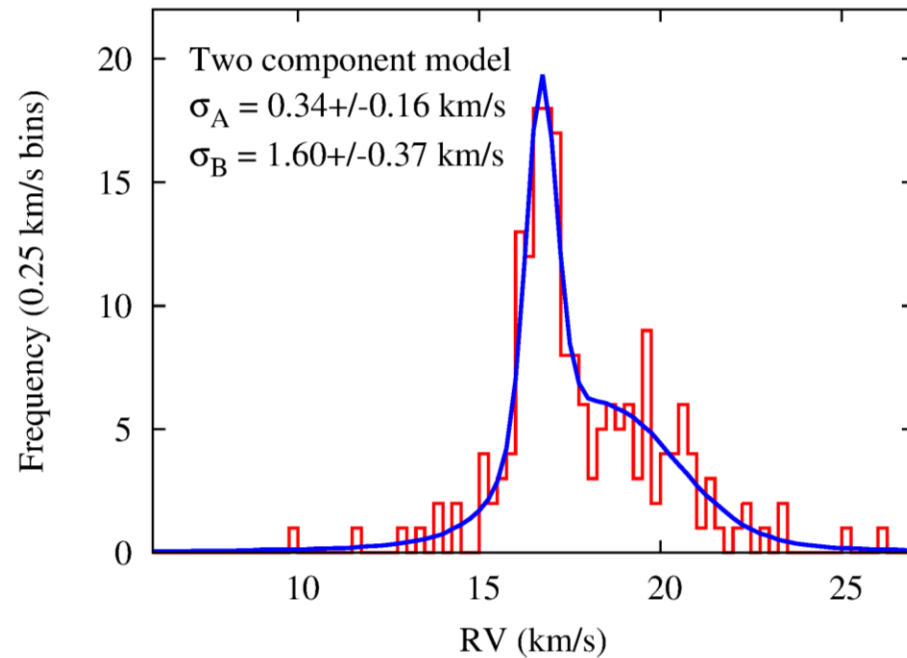
203 Li-selected

179 “clean” objects with
 $\text{SNR} > 20$, $0 < \text{RV} < 40 \text{ km/s}$





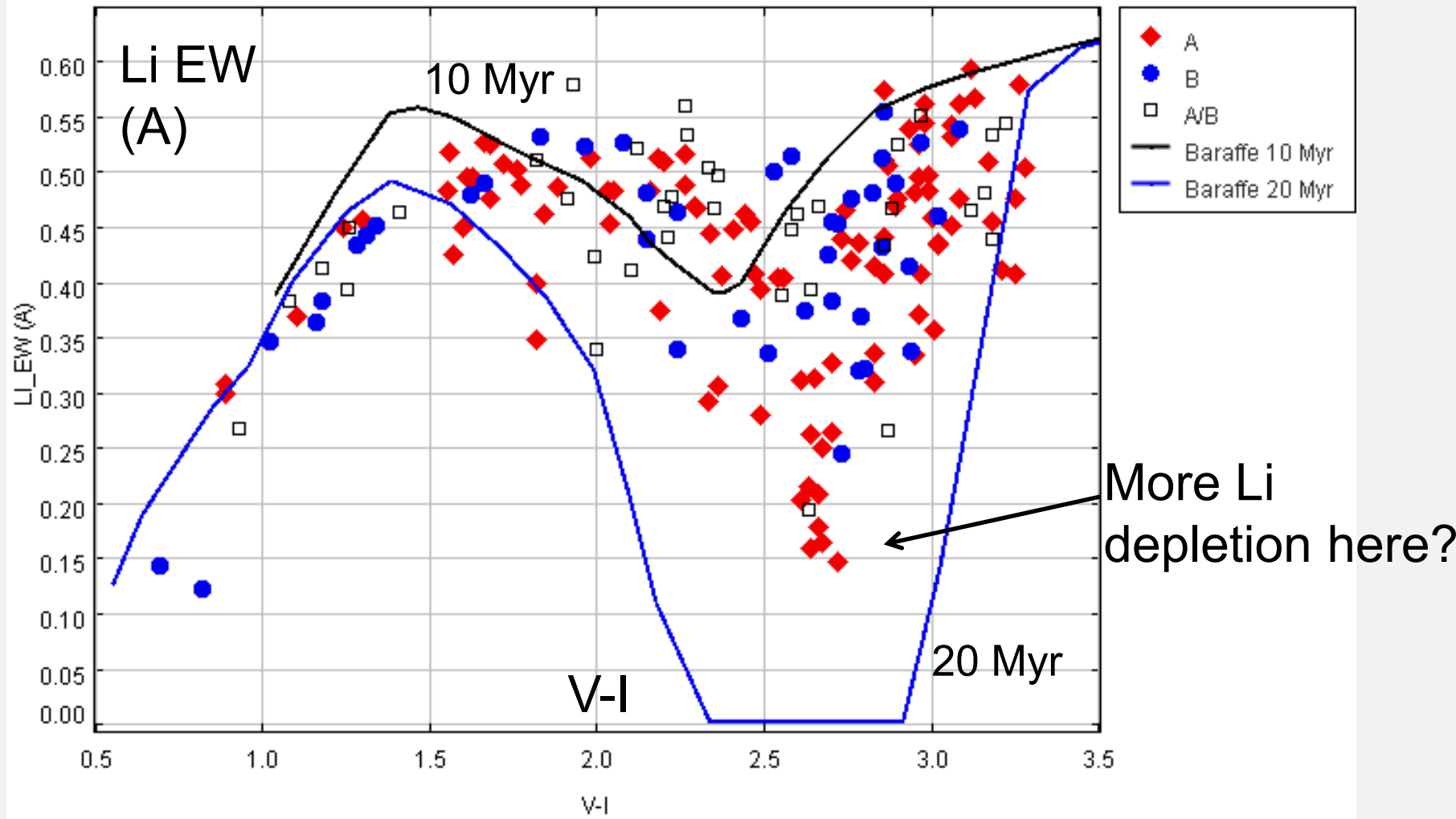
Single component –
poor fit



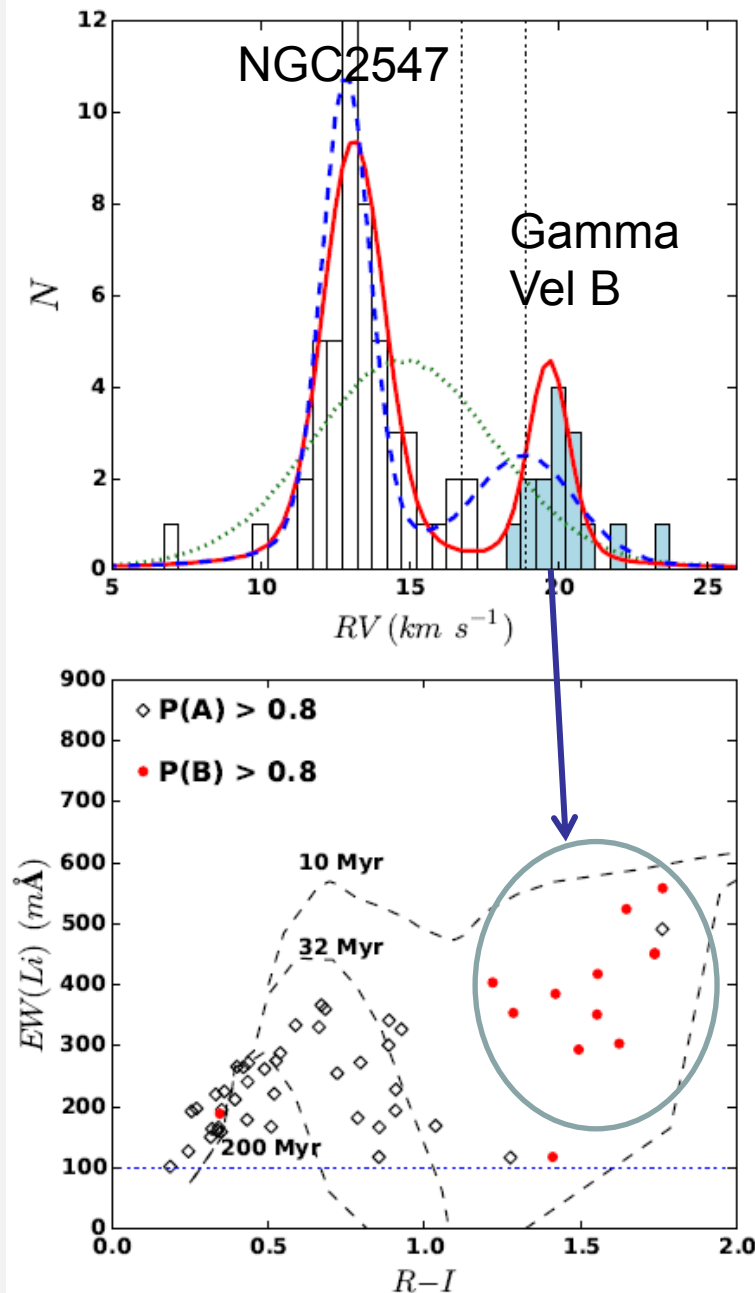
Two-component fit

$\sigma_A = 0.34 \text{ km/s}$ (virial eqbm.)
 $\sigma_B = 1.60 \text{ km/s}$ (unbound)
 $\Delta RV = 2 \text{ km/s}$

A difference in Li depletion?



Population A appears OLDER than Population B, perhaps by a few Myr (and older than 10 Myr).



NGC 2547: age 35 Myr

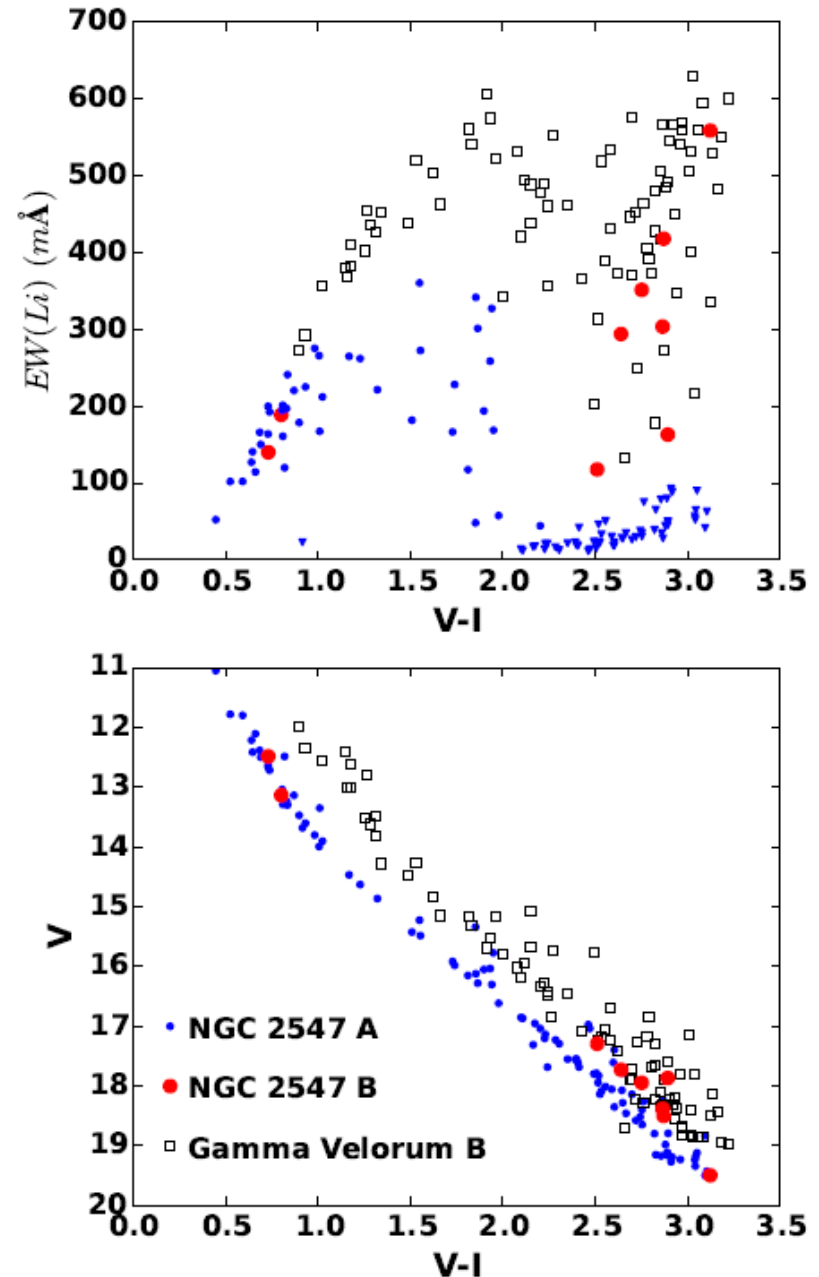
2 degrees South of
Gamma Vel

Kinematically separate population
has Li-rich stars, so < 20 Myr.

Identify with Gamma Vel B

Sacco et al. 2014 in prep.

- Second population matches Gamma Vel B in the CMD and in terms of Li depletion
- Evidence for an extended Vela OB2 population
- But why only low-mass stars?



The dynamics of young clusters from the Gaia-ESO Survey



- Gaia-ESO 50% complete, has observed 11 young clusters/SFRs
- RV precision ~ 0.3 km/s; well characterised
- Cluster kinematics are resolved
- Some key results so far:
 - No equi-partition in NGC 2516
 - RV/spatial/age structure in NGC 2264/ Υ Vel
 - Stellar/gas dispersion discrepancy in ρ Oph