Gravitational theory and the tidal tails of open star clusters

"From star clusters to field populations: survived, destroyed and migrated clusters"
Villa Galileo
Florence
Nov. 20-23, 2023

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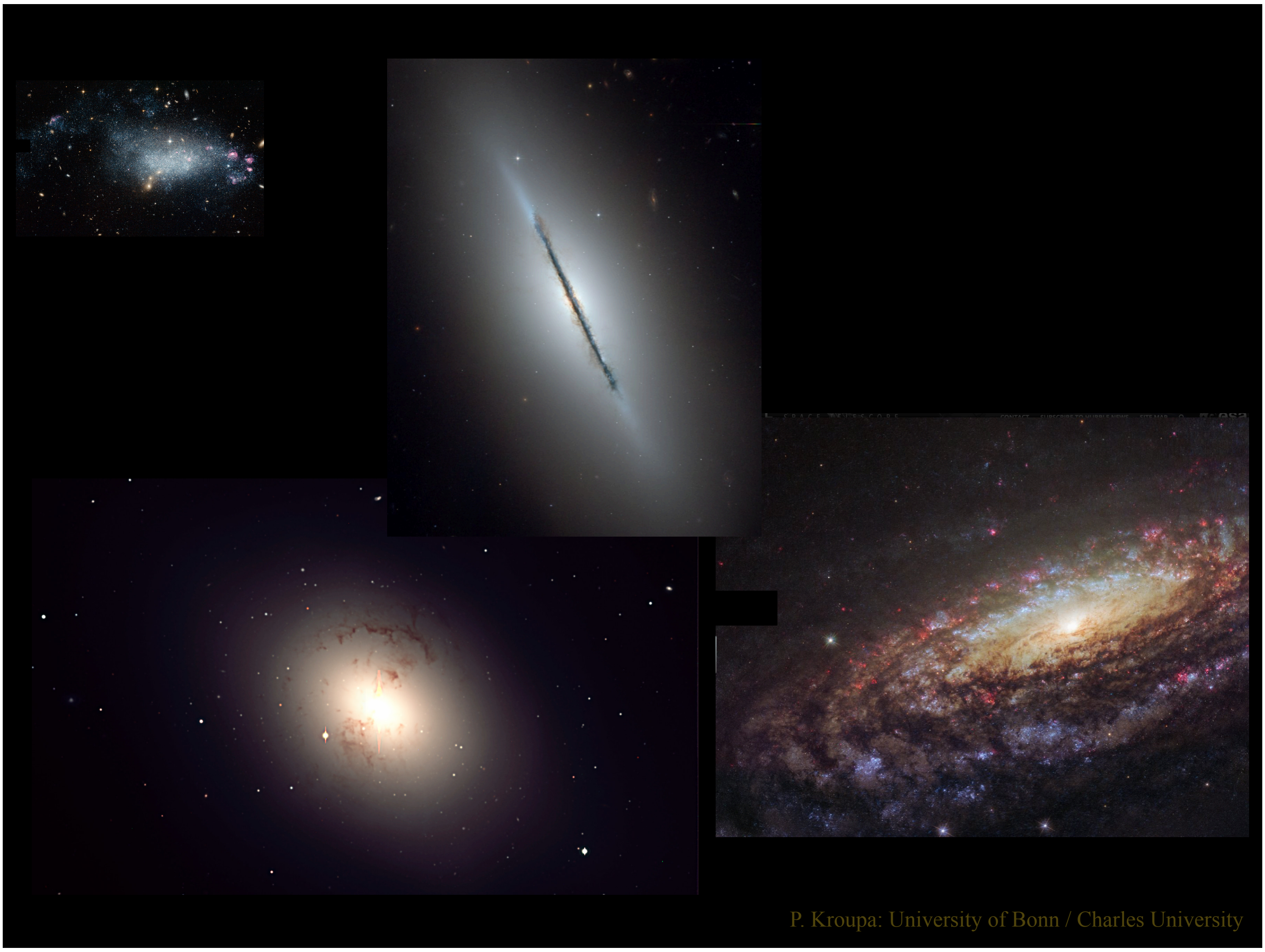
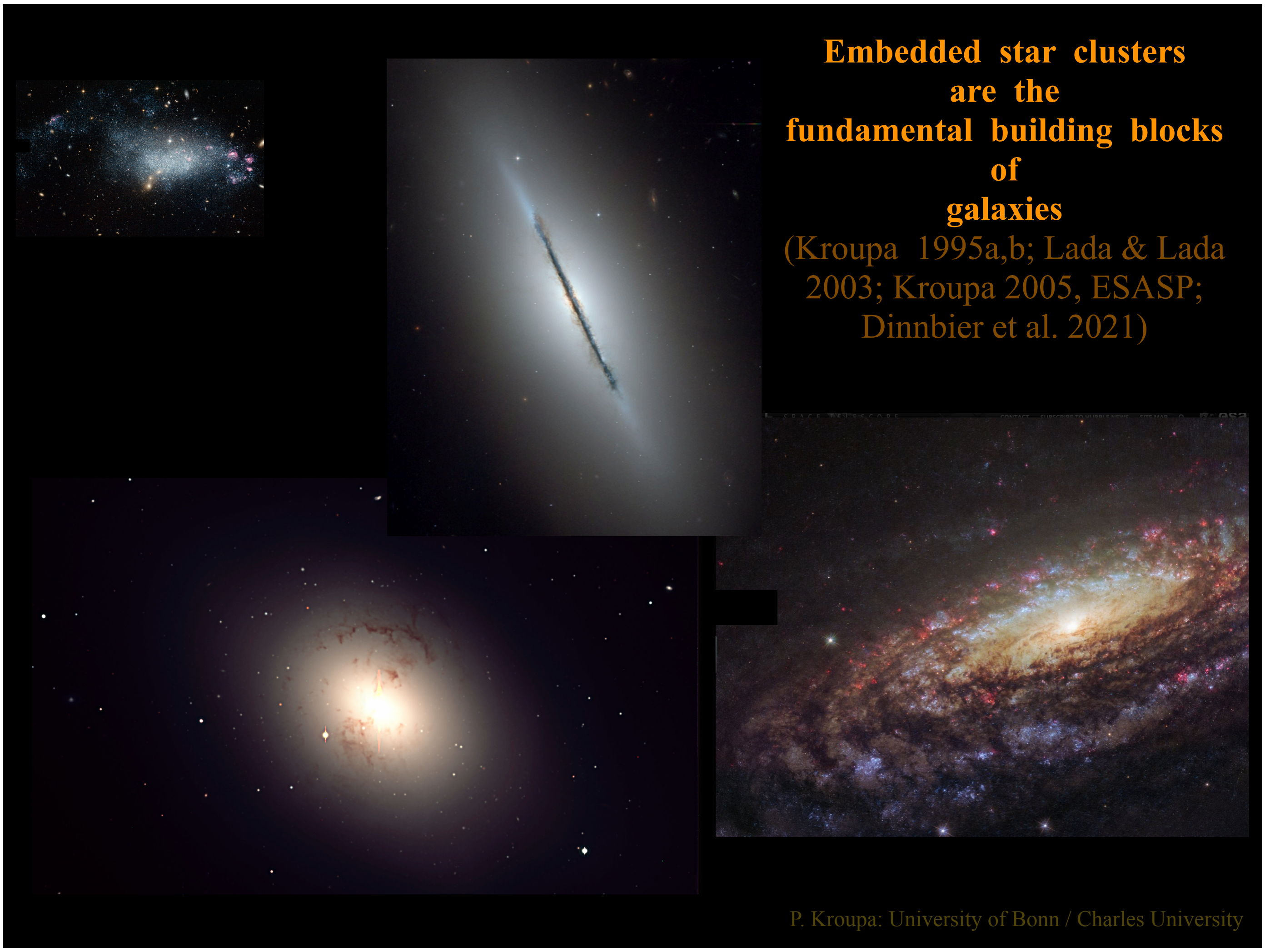
Problem :
calculate
the stellar and binary
populations
in
galaxies of different types

Are they statistically the same ?


P. Kroupa: University of Bonn / Charles University


Embedded star clusters
are the
fundamental building blocks
of
galaxies
(Kroupa 1995a,b; Lada & Lada
2003; Kroupa 2005, ESASP;
Dinnbier et al. 2021)
P. Kroupa: University of Bonn / Charles University

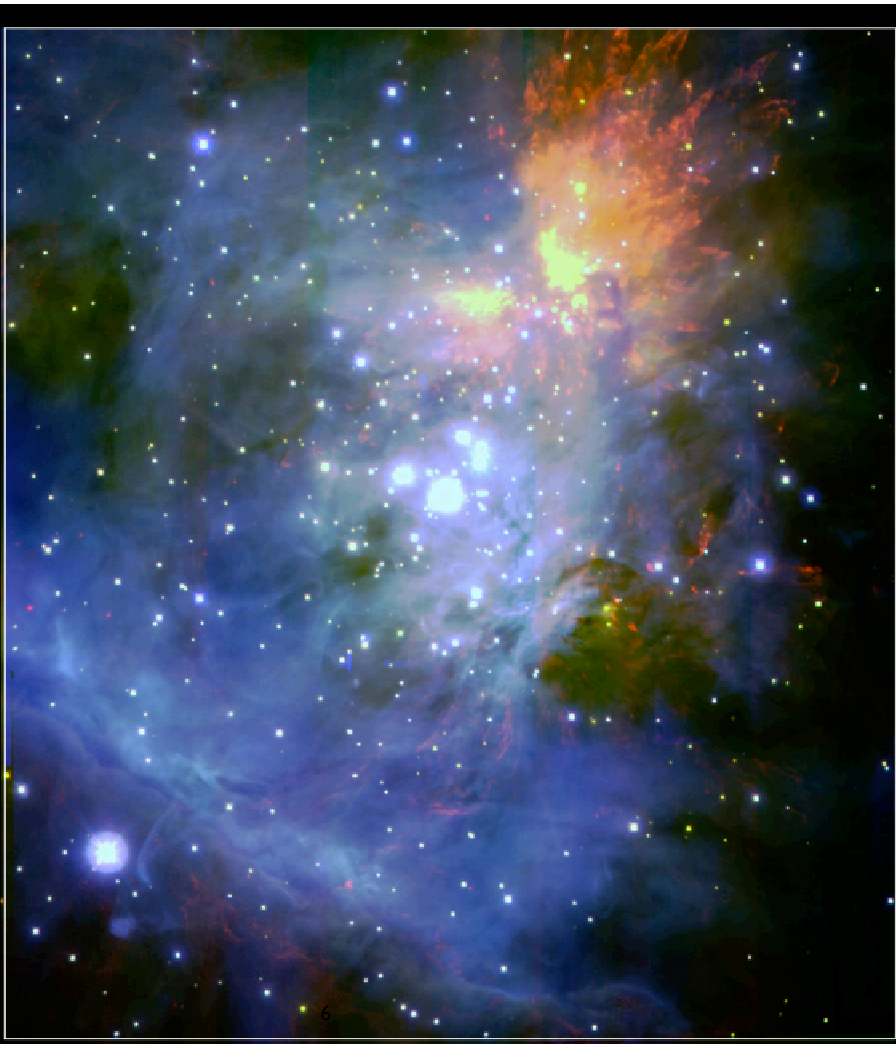
The Galileo Conjecture

Stars form in
embedded clusters,

some evolve to

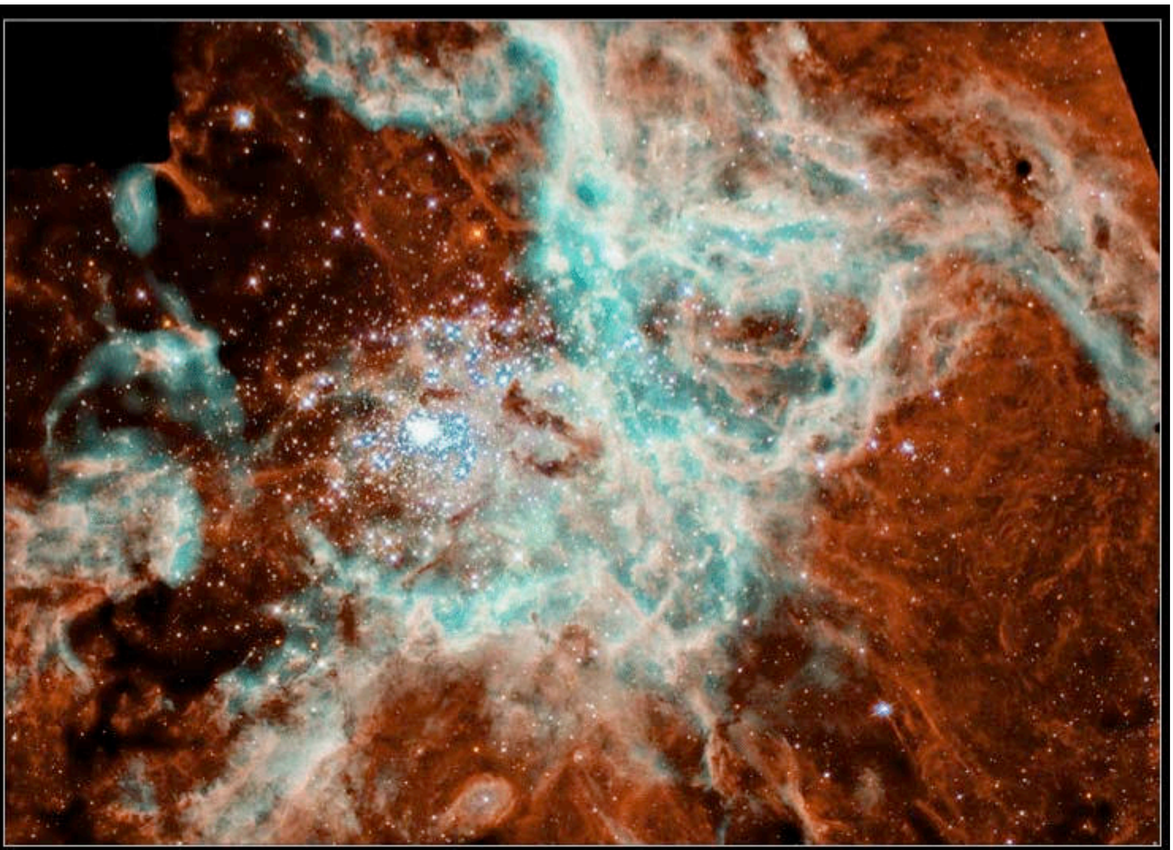
open clusters

Example:
The Orion Nebula Cluster



0.5kpc away
1 Myr old
10^3 Msun heavy
2 pc across

50kpc away
2 Myr old
10^5 Msun heavy
2 pc across



30 Doradus in the Large Magellanic Cloud
Hubble Space Telescope • WFPC2

NASA, N. Walborn (STScI), J. Maíz-Apellániz (STScI), and R. Barbá (La Plata Observatory, Argentina) • STScI-PRC01-21

Here we entertain the Alison-Sills-Approximation (ASA):

The 

model

The Galileo conjecture: *all stars are born in embedded star clusters*

The calculation is thus adding-up what each embedded star cluster provides e.g. the total mass in all stars formed in the time δt :

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e.g. the total mass in all stars formed in the time δt : $M_{\mathrm{tot},\delta t} = SFR\,\delta t$

$\xi_{\mathrm{ecl}}(M_{\mathrm{ecl}})\,dM_{\mathrm{ecl}}$ # of embedded clusters with stellar mass $M_{\mathrm{ecl}} \in [M_{\mathrm{ecl}}, M_{\mathrm{ecl}} + dM_{\mathrm{ecl}}]$

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$M_{\mathrm{ecl}}\ \xi_{\mathrm{ecl}}(M_{\mathrm{ecl}})\,dM_{\mathrm{ecl}}$ stellar mass in these embedded clusters

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$$M_{\mathrm{tot},\delta t} = \int_{M_{\mathrm{ecl,min}}}^{M_{\mathrm{ecl,max}}(SFR)} M_{\mathrm{ecl}} \;\; \xi_{\mathrm{ecl}}(M_{\mathrm{ecl}})\, dM_{\mathrm{ecl}}$$

All stellar mass formed in time δt

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$$\Omega_{\mathrm{dyn}}^{M_{\mathrm{ecl}},r_{\mathrm{h}}}(t_{\mathrm{freeze}})\left[D_{\mathrm{in}}\right]\quad \xi_{\mathrm{ecl}}(M_{\mathrm{ecl}})\, dM_{\mathrm{ecl}}$$

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More generally, for a "product" coming out of the forming population of embedded clusters :

$$D^{r_{\mathrm{h}}}_{\mathrm{GF},\delta t} = \int_{M_{\mathrm{ecl,min}}}^{M_{\mathrm{ecl,max}}(SFR)} \Omega_{\mathrm{dyn}}^{M_{\mathrm{ecl}},r_{\mathrm{h}}}(t_{\mathrm{freeze}})\left[D_{\mathrm{in}}\right]\ \ \xi_{\mathrm{ecl}}(M_{\mathrm{ecl}})\, dM_{\mathrm{ecl}}$$

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The time δt is the life-time of molecular clouds, $\delta t \approx 10\,\mathrm{Myr}$

Weidner et al. 2004; Schulz et al. 2015, 2016

$$D^{r_h}_{GF,\delta t} = \int_{M_{ecl,min}}^{M_{ecl,max}(SFR)} \Omega^{M_{ecl},r_h}_{dyn}(t_{freeze})[D_{in}] \quad \xi_{ecl}(M_{ecl})\, dM_{ecl}$$

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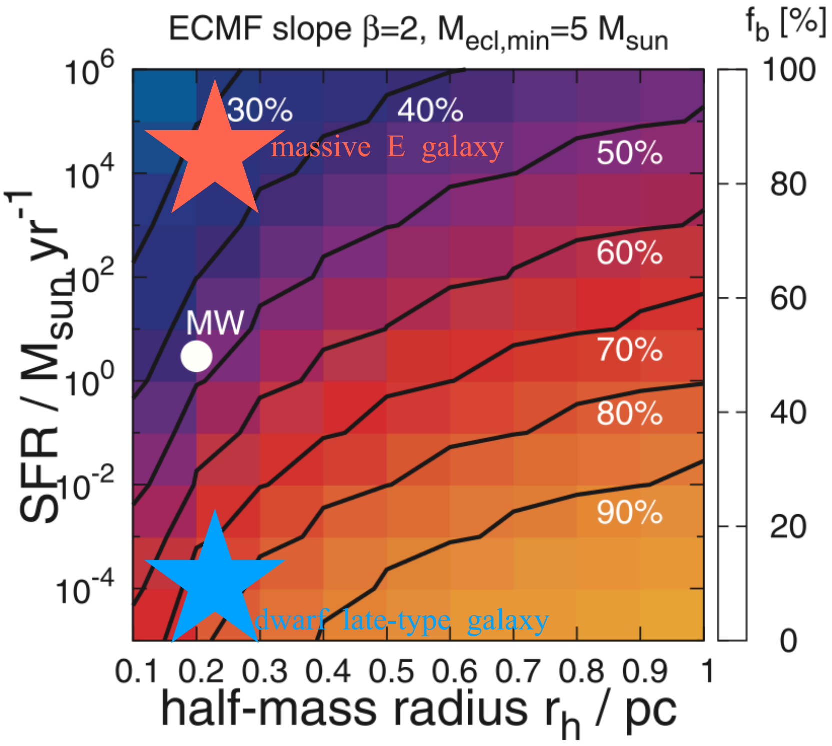

Marks & Kroupa 2011

Thus we have the *prediction* :

massive E galaxies : $f_b \approx 0.30$

MW-type galaxies : $f_b \approx 0.55$

dwarf late-types : $f_b \approx 0.80$

Period-distribution functions of pre-main sequence binaries and of field stars are unified, as are mass-ratio and eccentricity distributions

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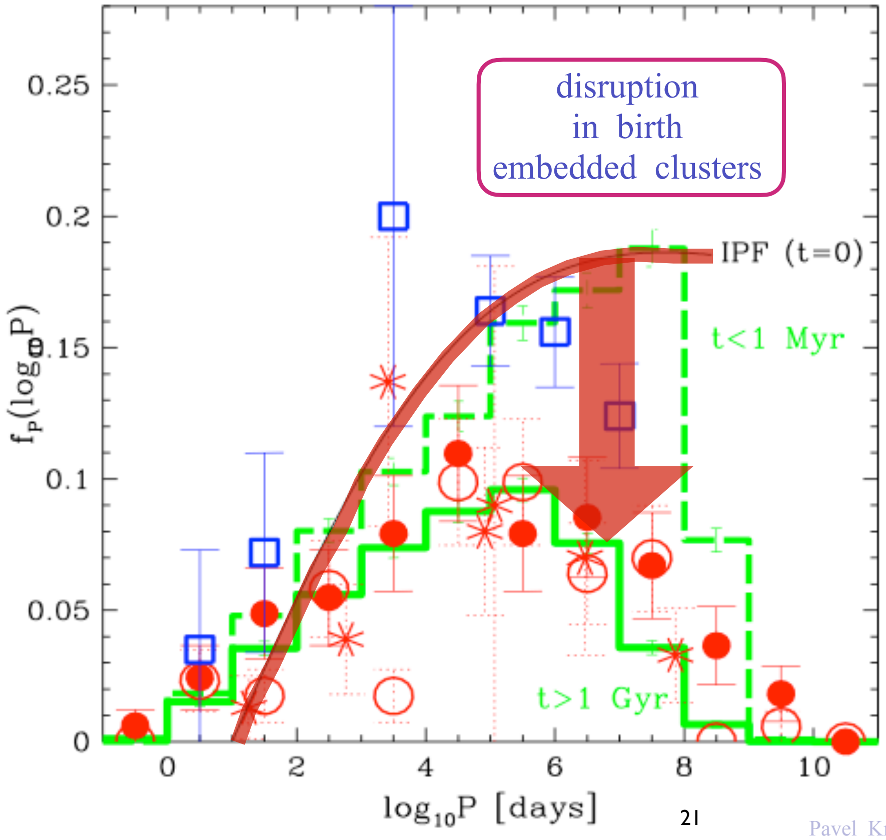
Kroupa 2011, IAU



***All stars form as binaries with the canonical birth binary population*:**

$$f_{P,\mathrm{birth}} = 2.5\,\frac{lP-1}{45+(lP-1)^2}$$

with $lP_{\max} = 8.43$

with subsequent pre-main sequence adjustments (*eigenevolution*) for $P < 10^3\,\mathrm{d}$ systems

Kroupa 1995b; Belloni et al. 2017

Pavel Kroupa: University of Bonn / Charles University Prague

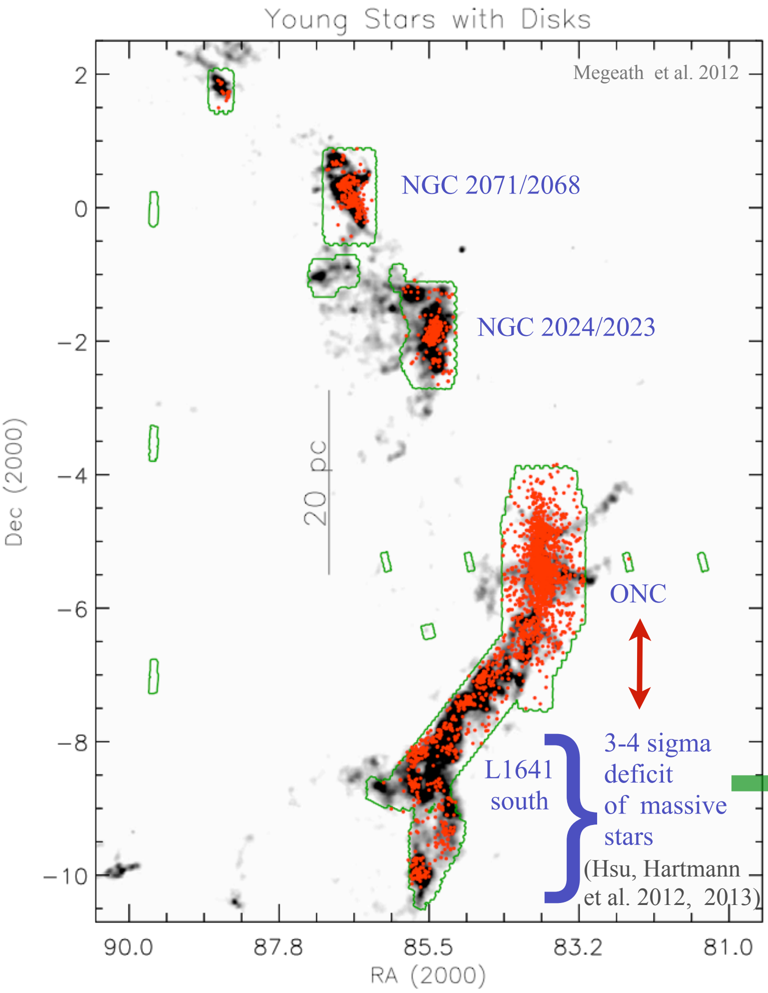
To do these calculations, we need the distribution functions defining a stellar population at birth

$$D^{r_h}_{\mathrm{GF},\delta t} = \int_{M_{\mathrm{ecl,min}}}^{M_{\mathrm{ecl,max}}(SFR)} \Omega^{M_{\mathrm{ecl}},r_h}_{\mathrm{dyn}}(t_{\mathrm{freeze}})\left[D_{\mathrm{in}}\right]\ \xi_{\mathrm{ecl}}(M_{\mathrm{ecl}})\,dM_{\mathrm{ecl}}$$

IMF = IMF(Z, rho)

✔

Marks et al. 2012



Lack of O stars

Many small / low-mass groups or clusters do not yield the same IMF as one massive cluster

stochastic IMF in each group is ruled out.

The $m_{\rm max}(M_{\rm ecl})$ *relation*

Weidner & Kroupa 2005, 2006; Weidner et al. 2010

Yan, Jerabkova et al. 2023

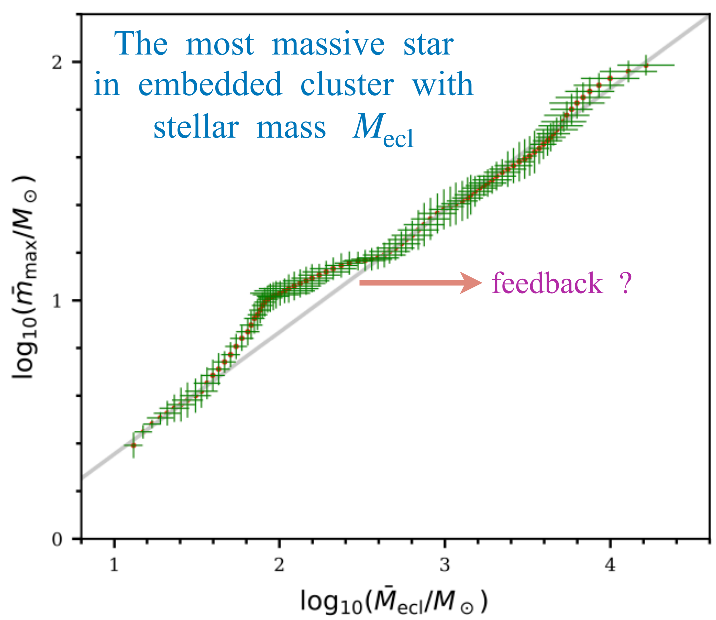


Fig. 6. Average position of the observational data for the groups of ten nearest points in the $m_{\rm max}-M_{\rm ecl}$ relation. The linear grey line highlights that the clusters with a mass of between $10^{1.8}\,M_\odot = 63\,M_\odot$ and $10^{2.6}\,M_\odot = 400\,M_\odot$ depart from the linear relation.

physical maximum stellar mass ?

$$m_{\rm max,*} \approx 150\,M_\odot$$

(Weidner & Kroupa 2004; Figer 2005; **Oey & Clarke** 2005, Koen 2006; Maiz Appelaniz et al. 2007)

To do these calculations,
we need the distribution functions defining a stellar population at birth

$$D^{r_\mathrm{h}}_{\mathrm{GF},\delta t} = \int_{M_\mathrm{ecl,min}}^{M_\mathrm{ecl,max}(SFR)} \Omega^{M_\mathrm{ecl},r_\mathrm{h}}_\mathrm{dyn}(t_\mathrm{freeze})\left[D_\mathrm{in}\right] \quad \xi_\mathrm{ecl}(M_\mathrm{ecl})\, dM_\mathrm{ecl}$$

IMF = IMF(Z, rho)

Marks et al. 2012

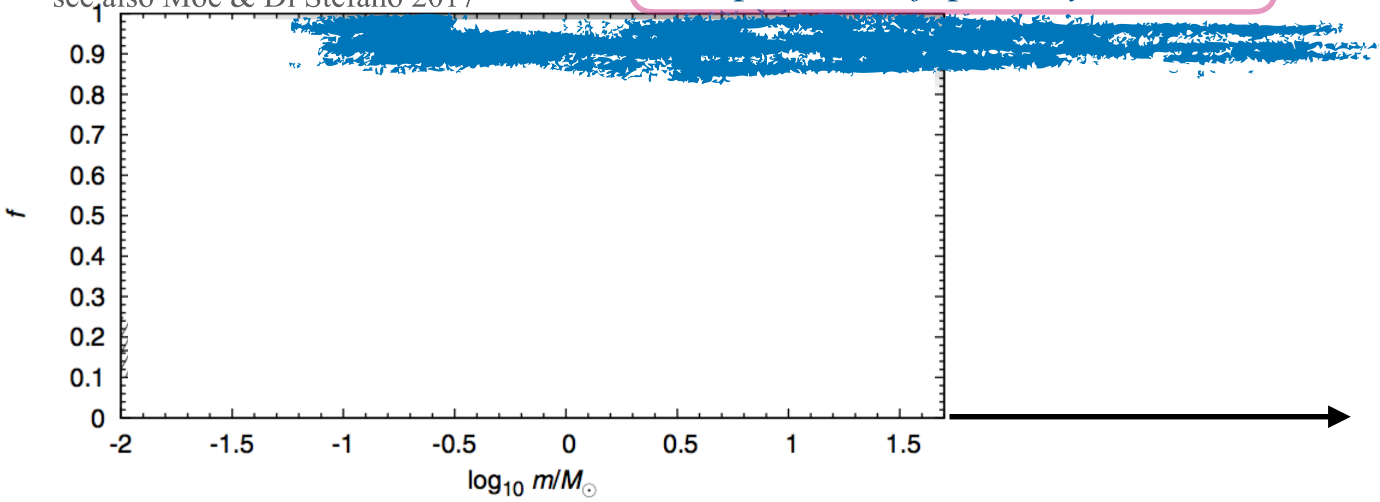
Initial binary-star
distribution
functions
(periods, mass ratios, eccentricities)

Kroupa 1995a,b;
Belloni et al.

The binary fraction in dependence of primary mass

initial (<1Myr) binary fraction is *independent of primary mass* !!

Thies et al. 2015, ApJ
see also Moe & Di Stefano 2017



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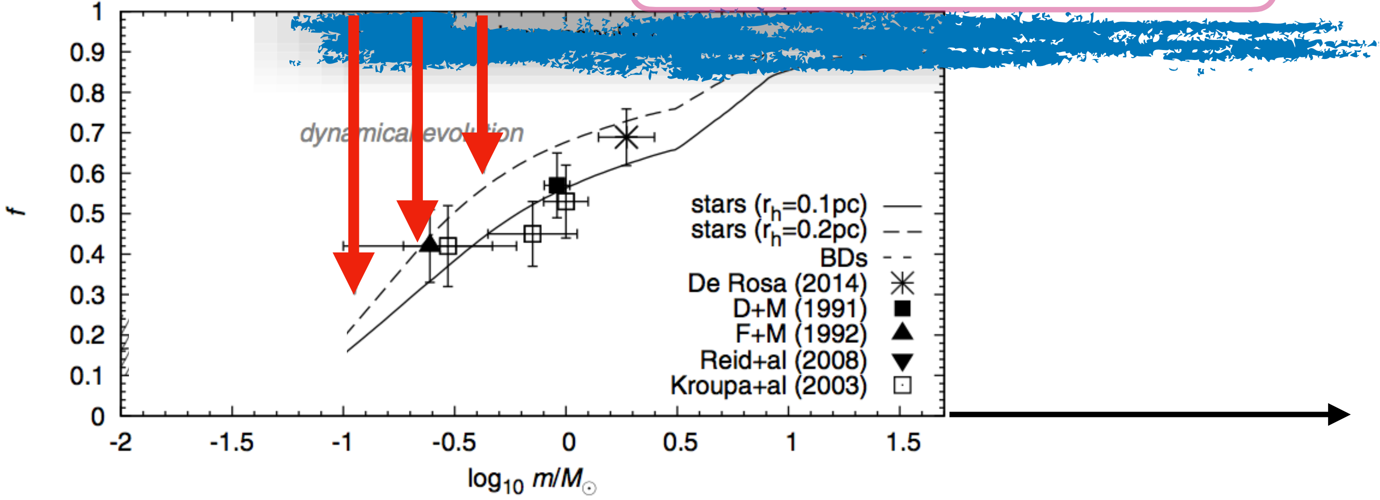

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most massive embedded cluster forming in a galaxy ✔
Weidner et al. 2004

least-massive embedded cluster forming in a galaxy ✔
Weidner et al. 2004

IMF = IMF(Z, rho) ✔
Marks et al. 2012

Initial binary-star distribution functions (periods, mass ratios, eccentricities) ✔
Kroupa 1995a,b; Belloni et al. 2017

Initial half-mass radii of embedded clusters ✔
Marks & Kroupa 2012

Initial mass function of embedded clusters ✔
Weidner et al. 2004; Schulz et al. 2015, 2016

The embedded clusters,
must expand significantly

to reach the radii of
open clusters

By fitting Nbody models to well-observed star clusters,
universal numbers emerge

		M_{ecl}
Small embedded clusters in Taurus-Aurigae	Kroupa et al. 2003	$\approx 10\, M_\odot$
Orion Nebula Cluster (ONC) and Pleiades	Kroupa et al. 2001	$\approx 10^3\, M_\odot$
NGC 3603	Banerjee & Kroupa 2013; 2014; 2015; 2017; 2018	$\approx 10^4, M_\odot$
R136	Banerjee & Kroupa 2013; 2014; 2015; 2017; 2018	$\approx 10^5, M_\odot$

$\tau_{gas} \approx \dfrac{r_h}{10\mathrm{pc/Myr}}$ gas flows out at sound speed

$\Delta\tau_{gas} \approx 0.6\,\mathrm{Myr}$ embedded + UCHII region lifetime

$SFE \approx \dfrac{1}{3}$ star-formation efficiency in embedded cluster

ONC

Pleiades $(\approx 1/3\ N)$
$+$ *EP* $(\approx 2/3\ N)$

≈ 100 Myr

We thus have

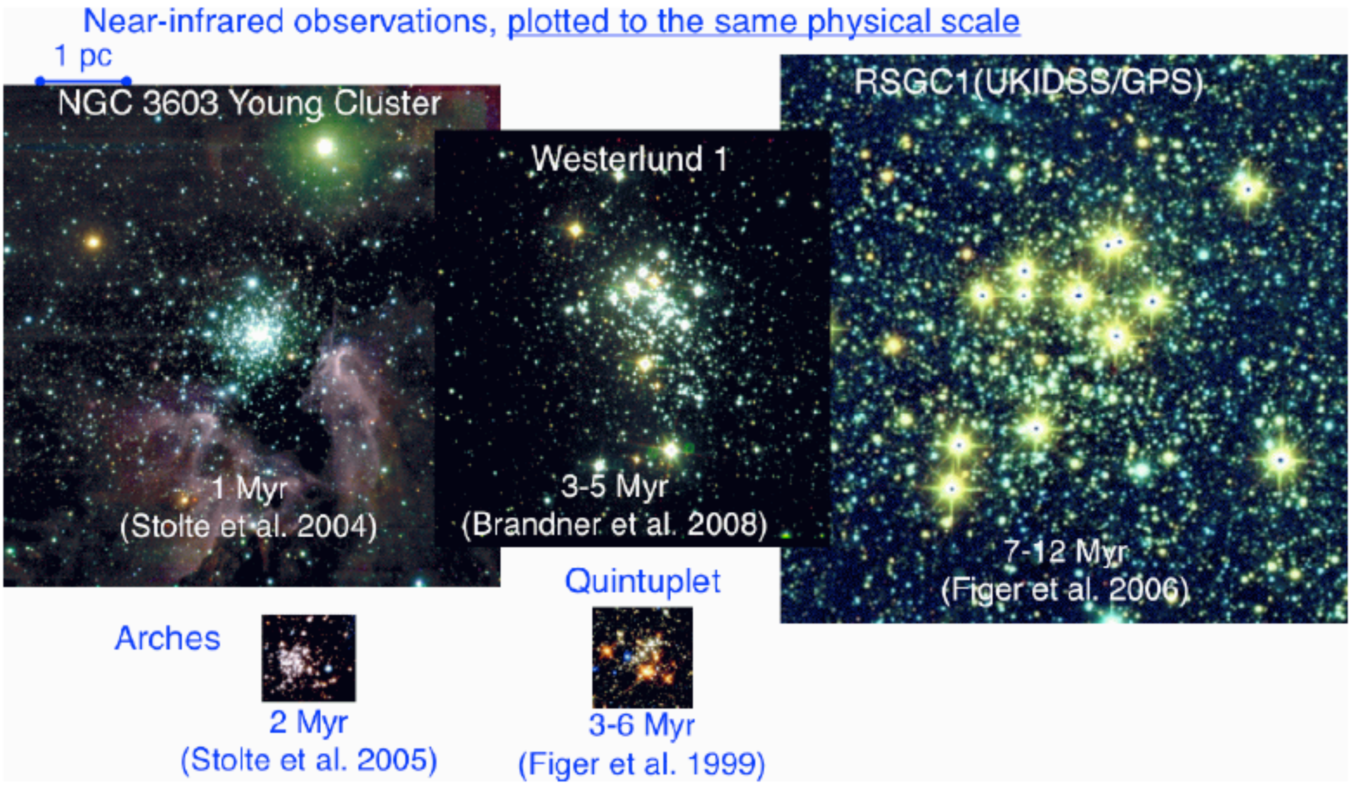
ONC → *Pleiades* → *Hyades*

≈ 99 Myr ≈ 500 Myr

(Kroupa, Aarseth & Hurley 2001; Portegies Zwart etal. 2001; Kroupa 2005)

with an *inflation* in *R* .

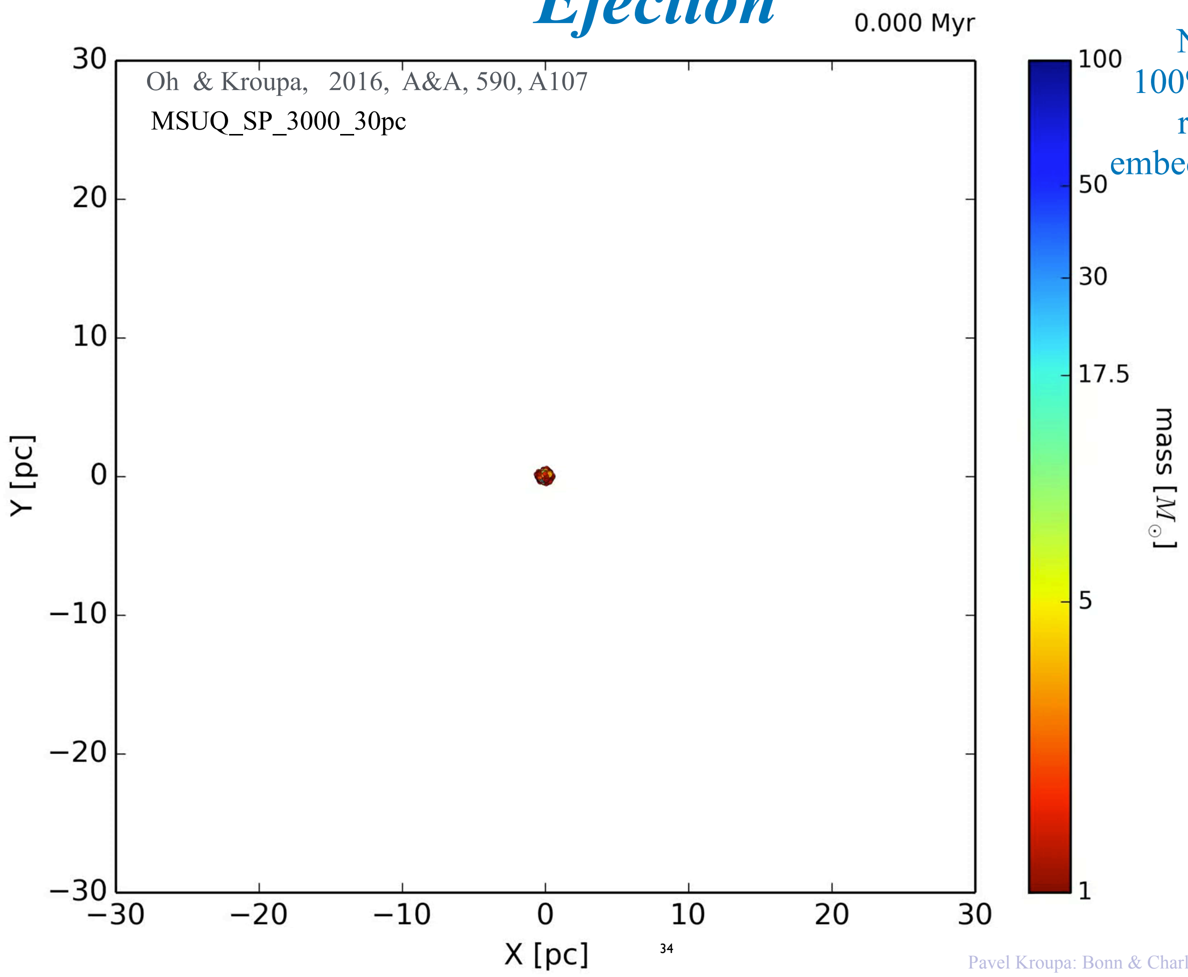
Brandner, astro-ph/0803.1974 Banerjee & Kroupa 2017



$$\dot{M}_{\text{cluster}} < 0$$

How do star clusters
loose their stars ?

Ejection

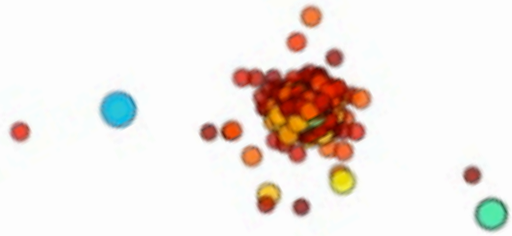


Nbody6
100% binaries
realistic
embedded cluster

Ejection

Oh & Kroupa, 2016, A&A, 590, A107

MSUQ_SP_3000_30pc Nbody models



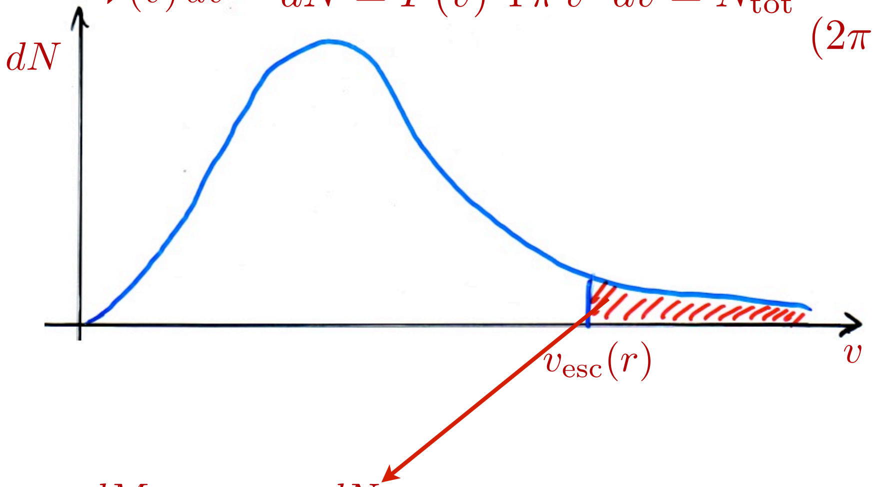
Monoceros R2 cluster (Carpenter et al. 1997, AJ 114, 198)

Evaporation

Assume, for simplicity : the cluster consists of single stars of equal mass m.

At a given radius r in the cluster the stars have, approximately, a *Maxwell-Boltzmann* distribution of speeds :

$$\mathcal{V}(v)\,dv = dN = F(v)\,4\,\pi\,v^2\,dv = N_{\rm tot}\,\frac{1}{(2\pi\,\sigma^2)^{\frac{3}{2}}}\,e^{-\frac{v^2}{2\,\sigma^2}}\,4\,\pi\,v^2\,dv$$



$$\frac{dM_{\rm cl}}{dt}(t) = m\,\frac{dN}{dt}(t)$$

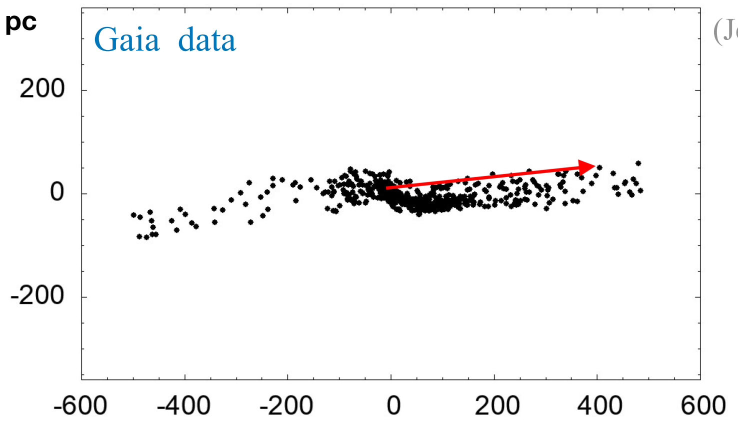
Evaporated stars
leave their
open clusters
through
tidal tails

New method developed by Tereza Jerabkova in 2021 allowing *the tidal tails of open clusters* to be mapped to their tips.

The Jerabkova Compact Convergent Point (CCP) method.

(Jerabkova et al. 2021)

https://www.cosmos.esa.int/web/gaia/iow_20221026



(Jerabkova et al. 2021)

Hyades

(Kroupa, Jerabkova et al. 2022)

The asymmetry in number of stars between leading and trailing tail is a 6.5sigma deviation from Newtonian predictions.

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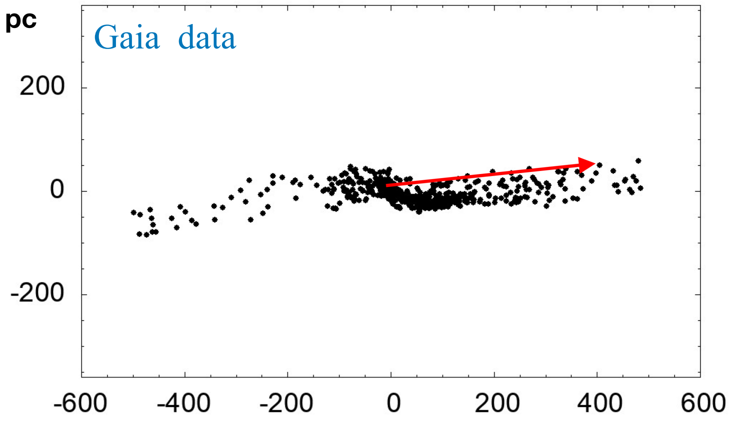

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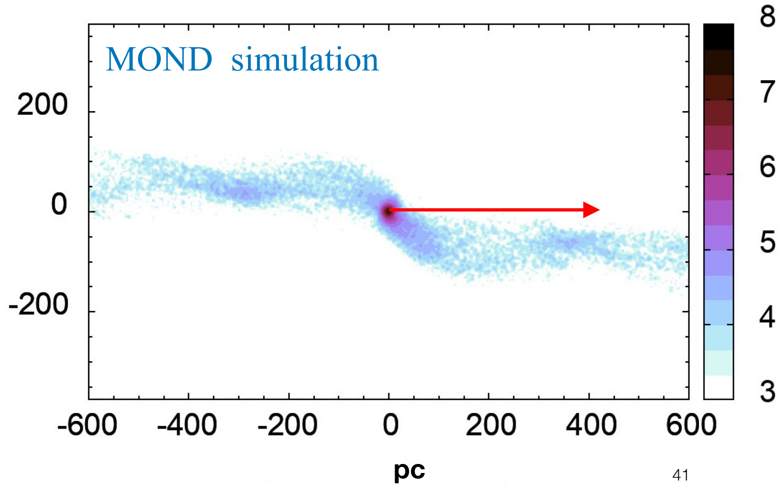
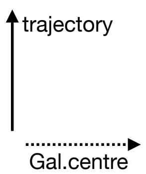


The asymmetry in number of stars between leading and trailing tail is a 6.5sigma deviation from Newtonian predictions.

Evaporation in Newtonian and Milgromian gravitation



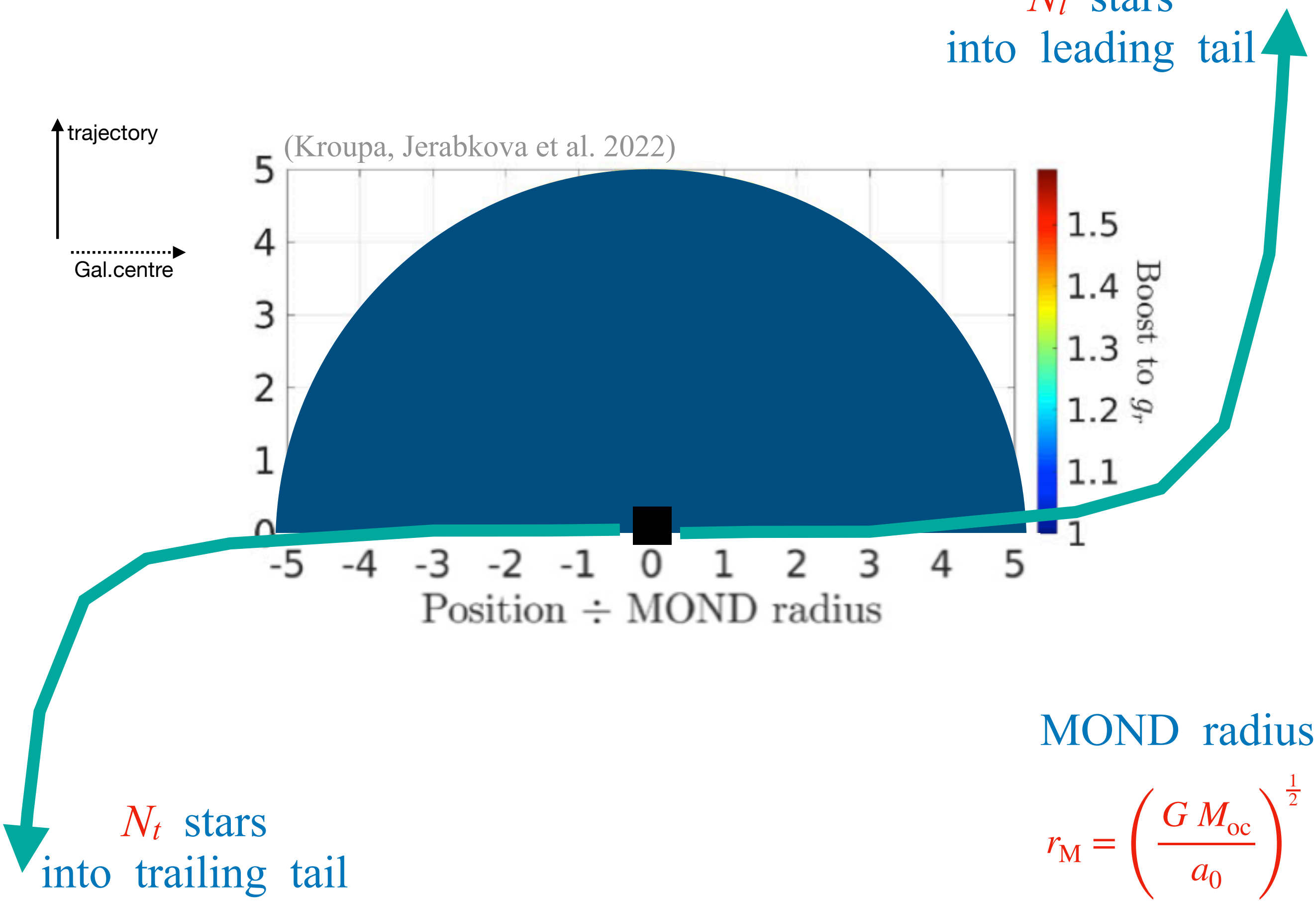
(Kroupa, Jerabkova et al. 2022)

open star cluster

MOND radius :

$$r_M = \left(\frac{G\, M_{oc}}{a_0} \right)^{\frac{1}{2}}$$

Newtonian case



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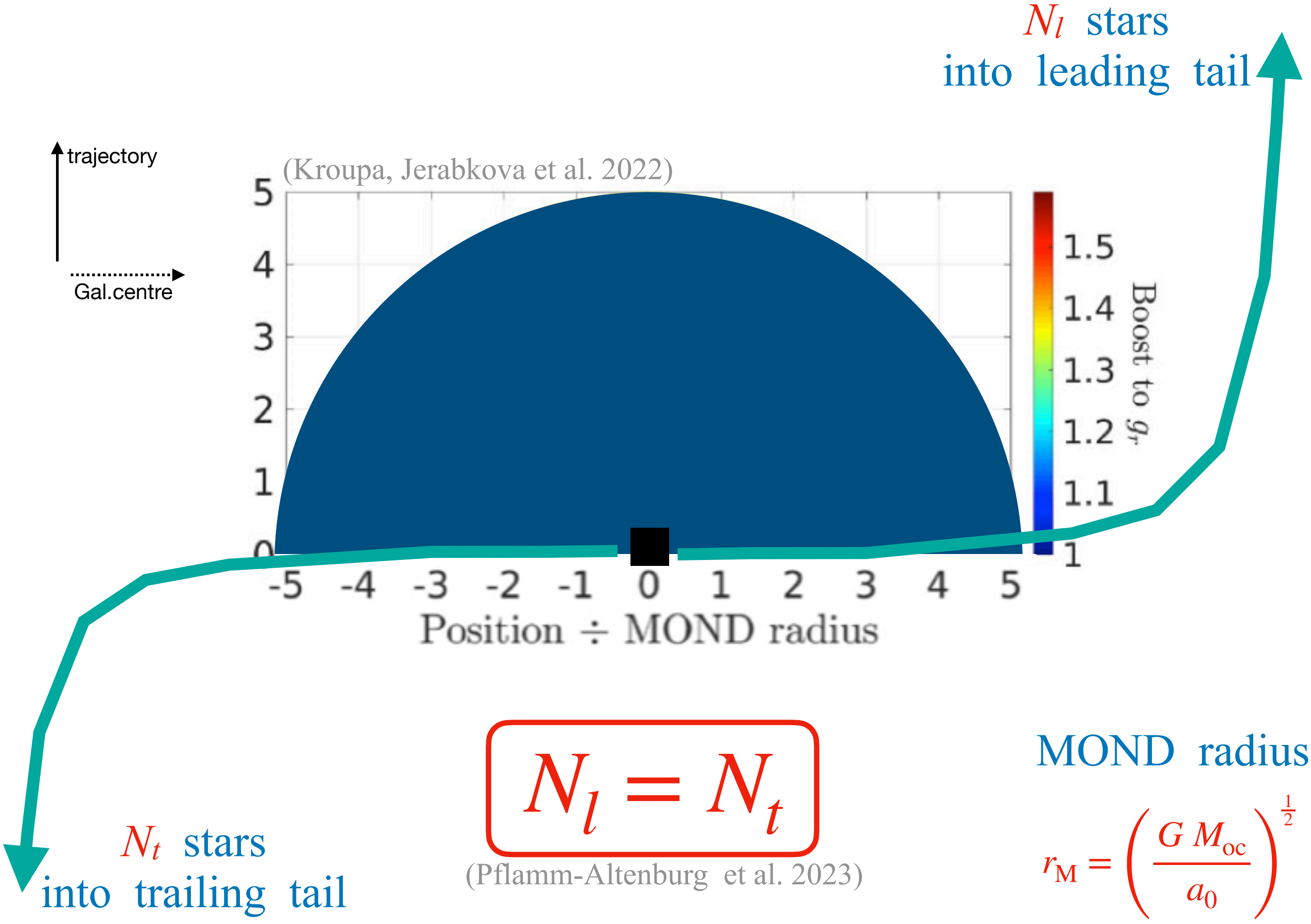


$$N_l = N_t$$

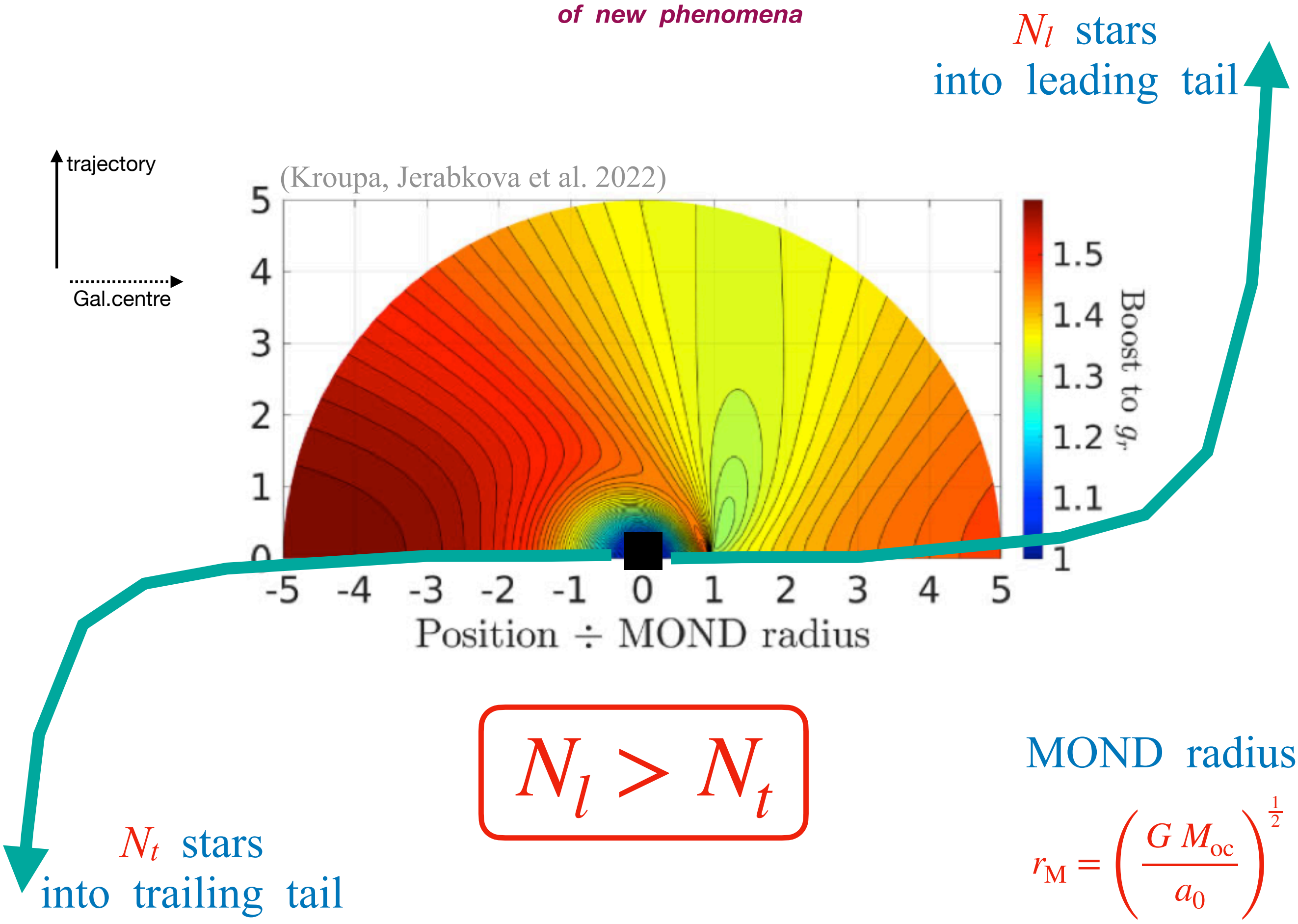
(Pflamm-Altenburg et al. 2023)

MOND radius :

$$r_{\rm M} = \left(\frac{G\,M_{\rm oc}}{a_0}\right)^{\frac{1}{2}}$$

MOND predictions

of new phenomena



$$N_l > N_t$$

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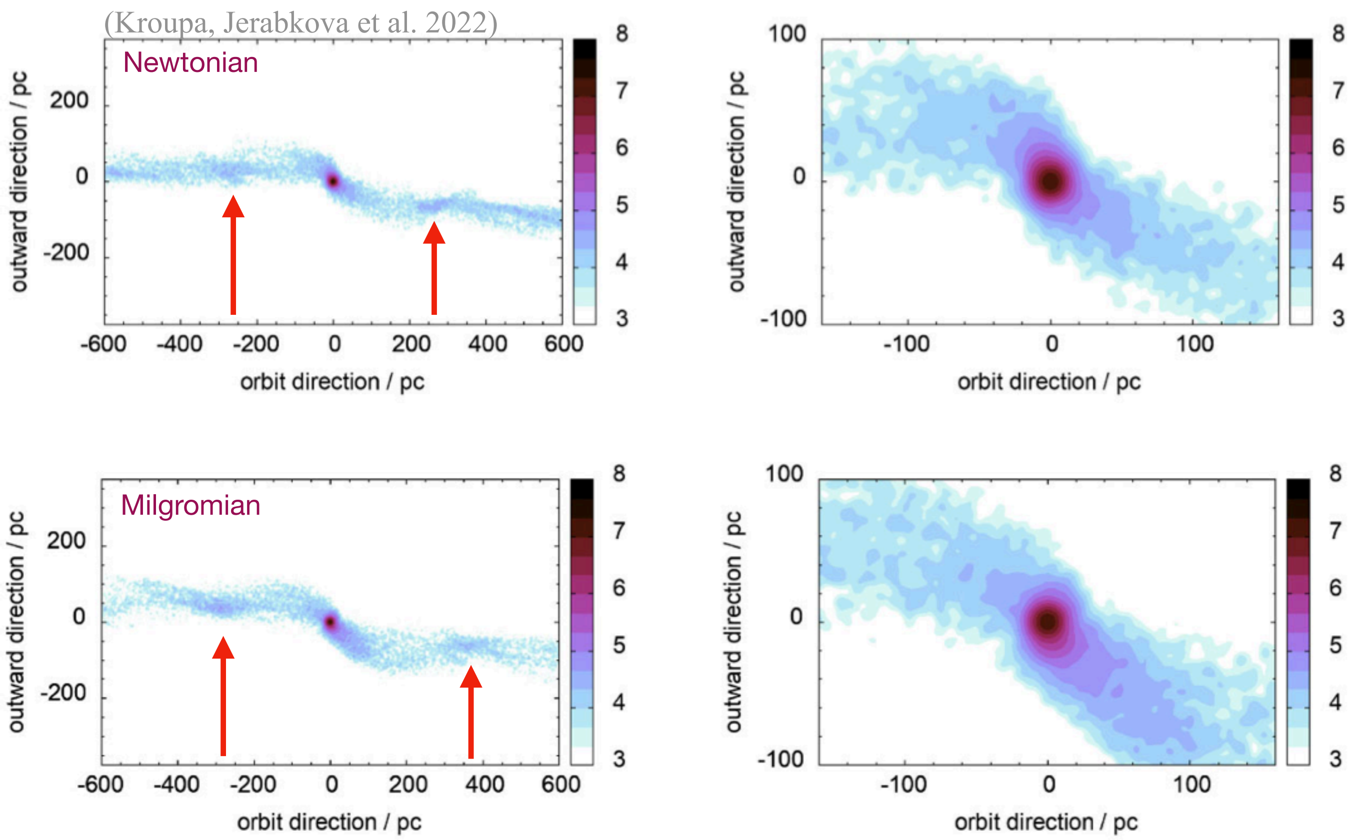
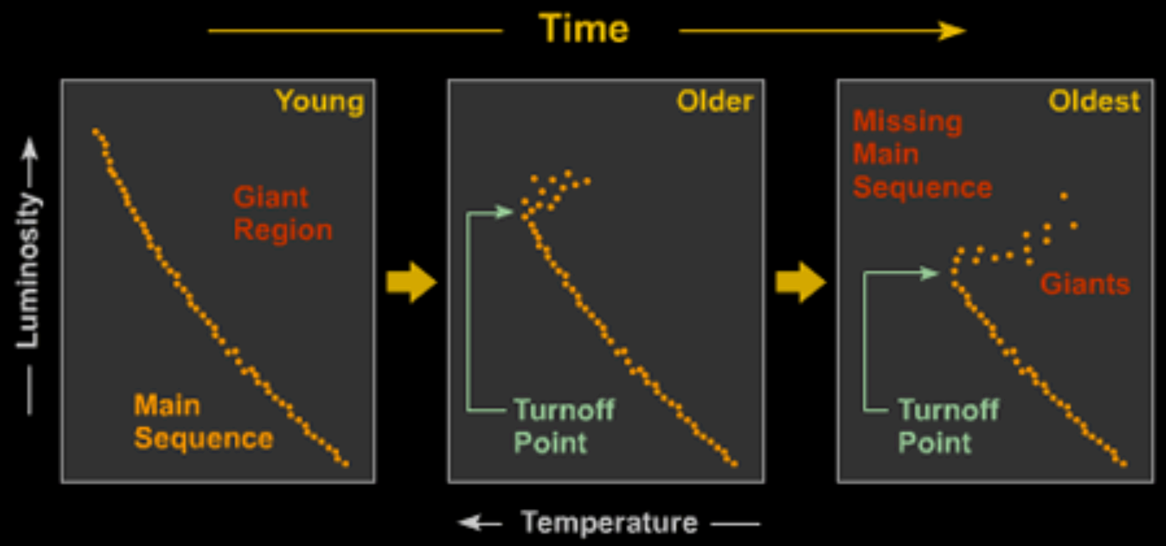


Leading Kuepper-overdensity further from cluster in Milgromian case

Age-dating methods
of
open star clusters

Astrophysical age-dating



(Image credit: Brooks/Cole Thomson Learning)

Pavel Kroupa: Bonn & Charles University, Prague

New age-dating methods
of
open star clusters

See also yesterday's talk on
dynamical and evaporative age-dating
by Nuria Miret Roig

Age-dating with tidal tails

The Dinnbier method

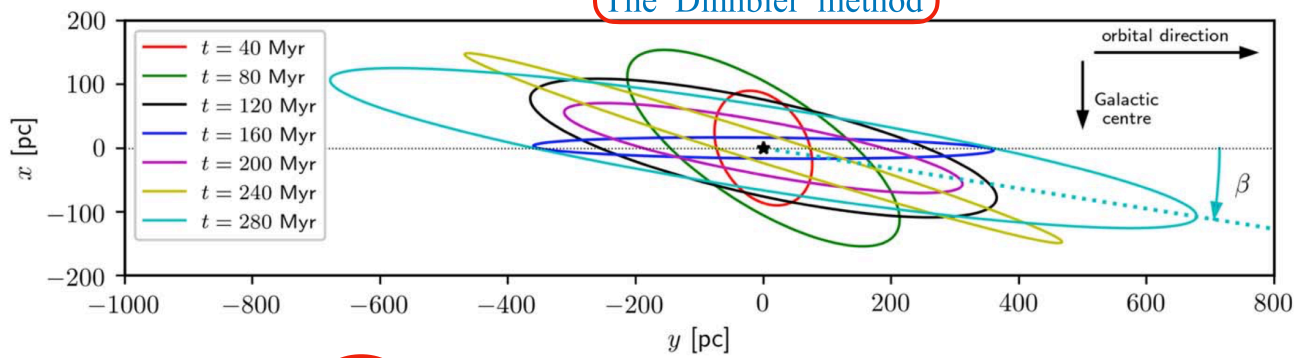
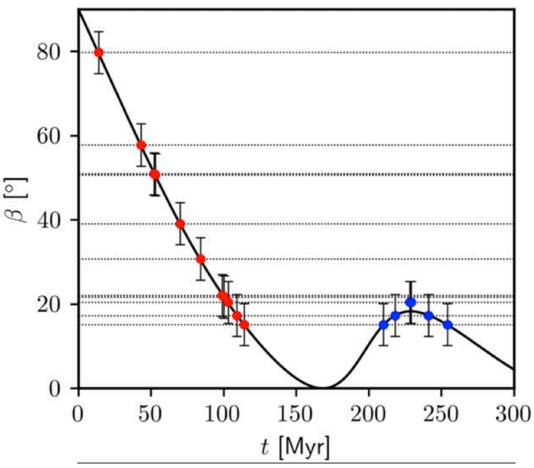
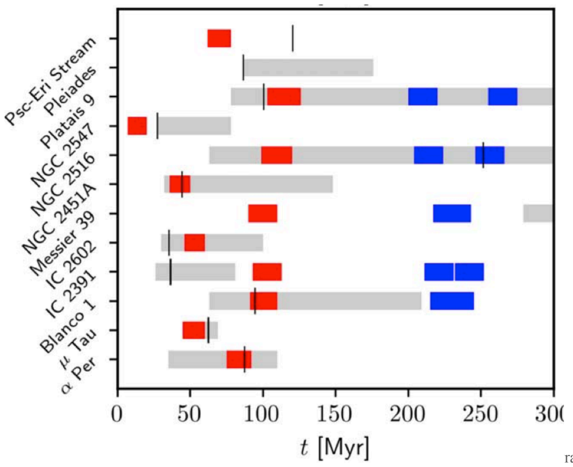


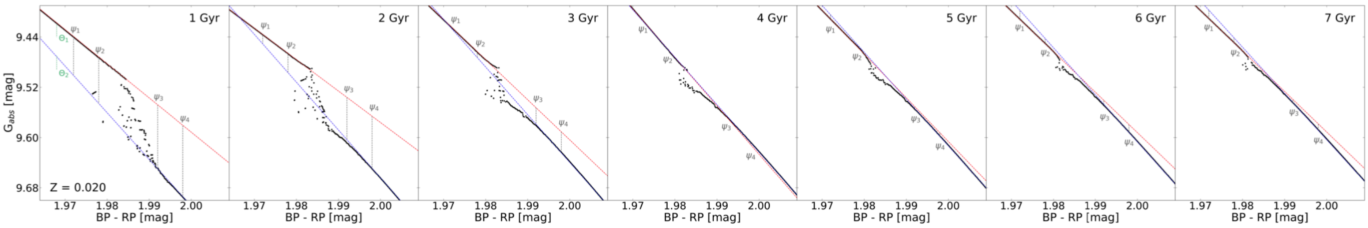
Figure 1. The orientation and shape of tidal tail I as calculated according to Equations (1) and (2) for stars escaping at $\tilde{v}_{e,I} = 2$ km s^{-1} and for the conditions at the solar circle. The age of the tail is indicated by the color. The star cluster is located at the center of the coordinate system (the black star), and it orbits the Galaxy in the direction indicated at upper right. As the cluster and tail age, the direction of the long axis of the tidal tail changes from pointing almost toward the Galactic center (at $t = 40$ Myr) to the direction of the cluster motion (at $t = 160$ Myr), and with increasing tilt again afterward. Also note that the shape and aspect ratio of the tidal tail undergo complicated changes with time. The dotted cyan line shows the definition of the tail tilt angle β.

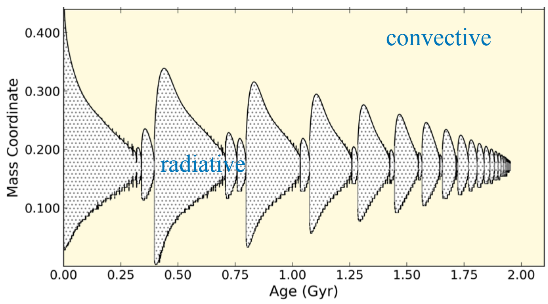




Age-dating with the *kissing instability* in Mdwarf stars

(Mansfield & Kroupa 2021; 2023)





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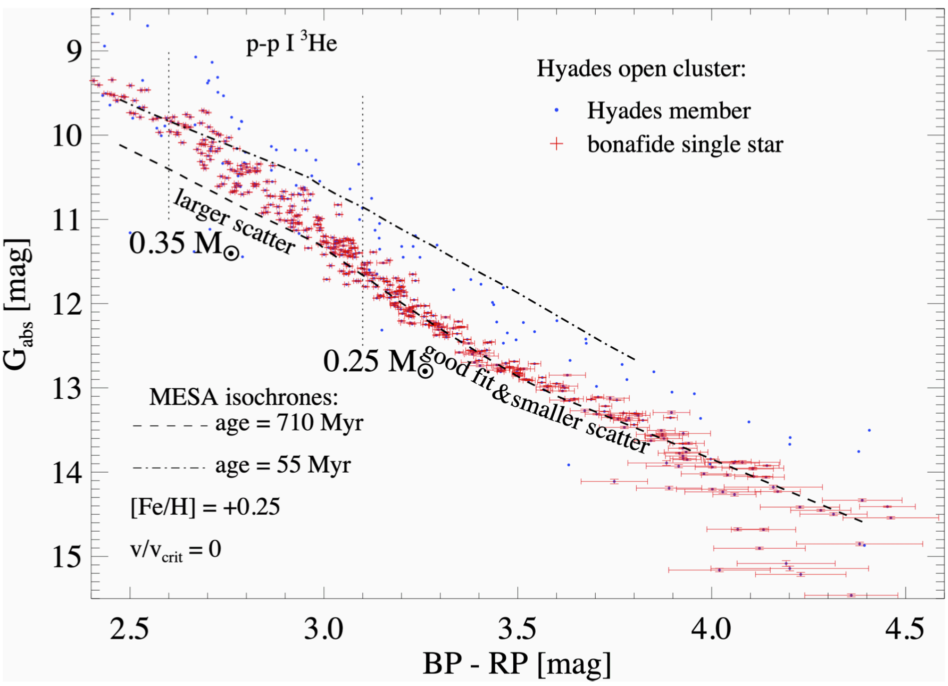
4 *W. Brandner, P. Calissendorff, and T. Kopytova* 2023



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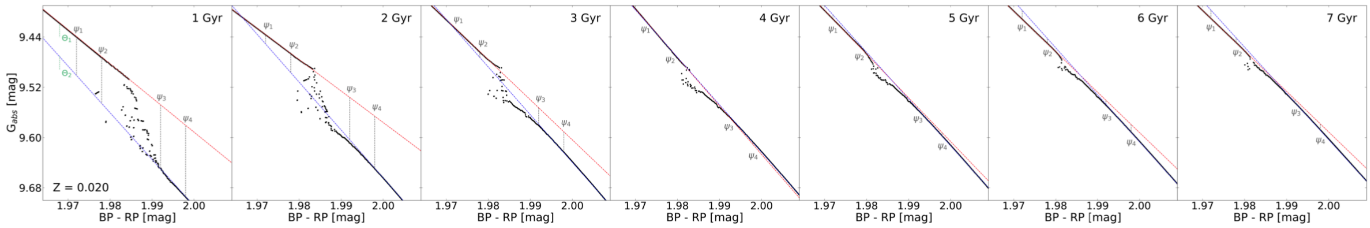

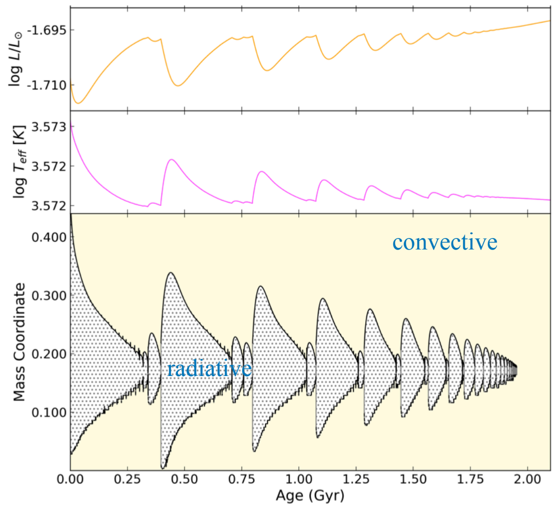

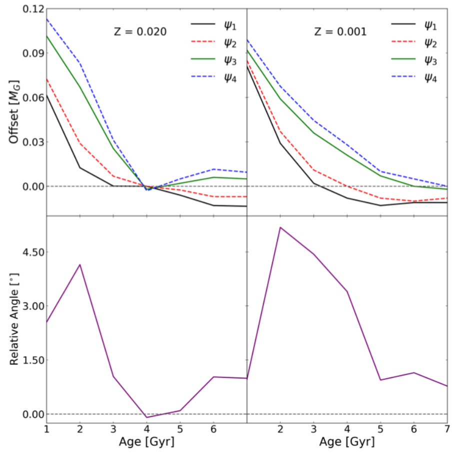

Figure 10. The offsets Ψ_i (*top*), and the relative angle (*bottom*) between the upper and lower parts of the MS shown in Fig. 9.

Conclusions

Can compute stellar and binary populations in whole galaxies

For this initial distribution functions reasonably well known

Need : all stars form as binaries in embedded clusters (The Galileo Conjecture)

---> *yesterday's talk by Franta Dinnbier*

New Jerabkova CCCP method to map extended tidal tails of open clusters ---> *talk by Henri Boffin*

Tidal tails asymmetric ===> Milgrom, and not Newton

---> *talk by Jan Pflamm-Altenburg*

Age-dating: tidal tail I angle (The Dinnbier method)
and kissing instability in Mdwarfs

END