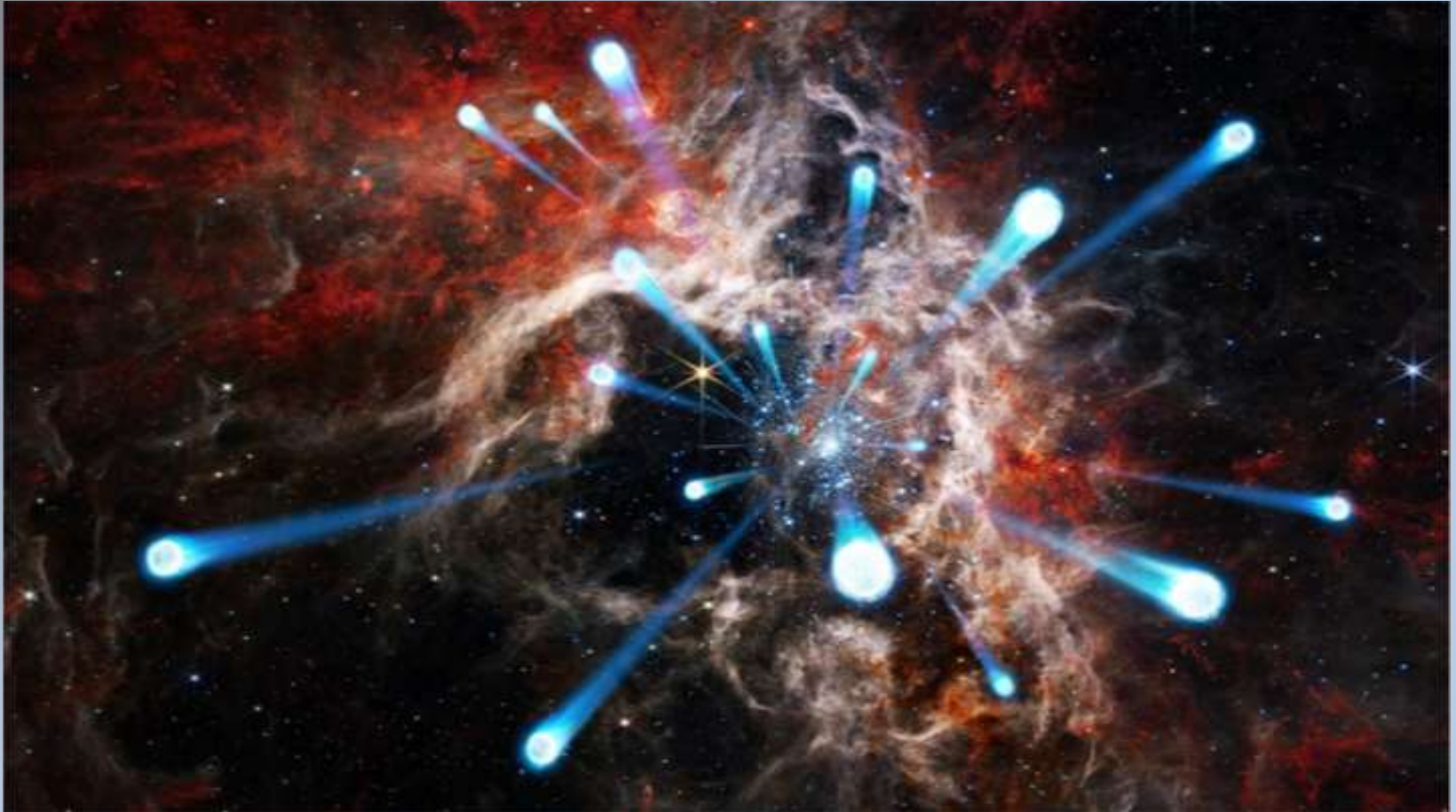


*Runaways*: zware sterren die met supersonische snelheid door ons Melkwegstelsel razen



prof. dr. Lex Kaper  
Anton Pannekoek Instituut, Universiteit van Amsterdam

# Vorming, evolutie en dood van zware sterren

- Zwaar (10 tot  $>100 M_{\text{zon}}$ ), heet en lichtkrachtig, massaverlies door sterwind, leven kort ( $3 - 50 \times 10^6$  jr), en eindigen hun leven in een supernova explosie.
- Vaak in dubbelster systeem.
- Eindproduct: neutronenster of zwart gat.
- Belangrijkste bron van impuls en energie in Melkweg.
- Chemische verrijking insterstellaire midden.
- *First Stars* waren waarschijnlijk (heel) zware sterren.



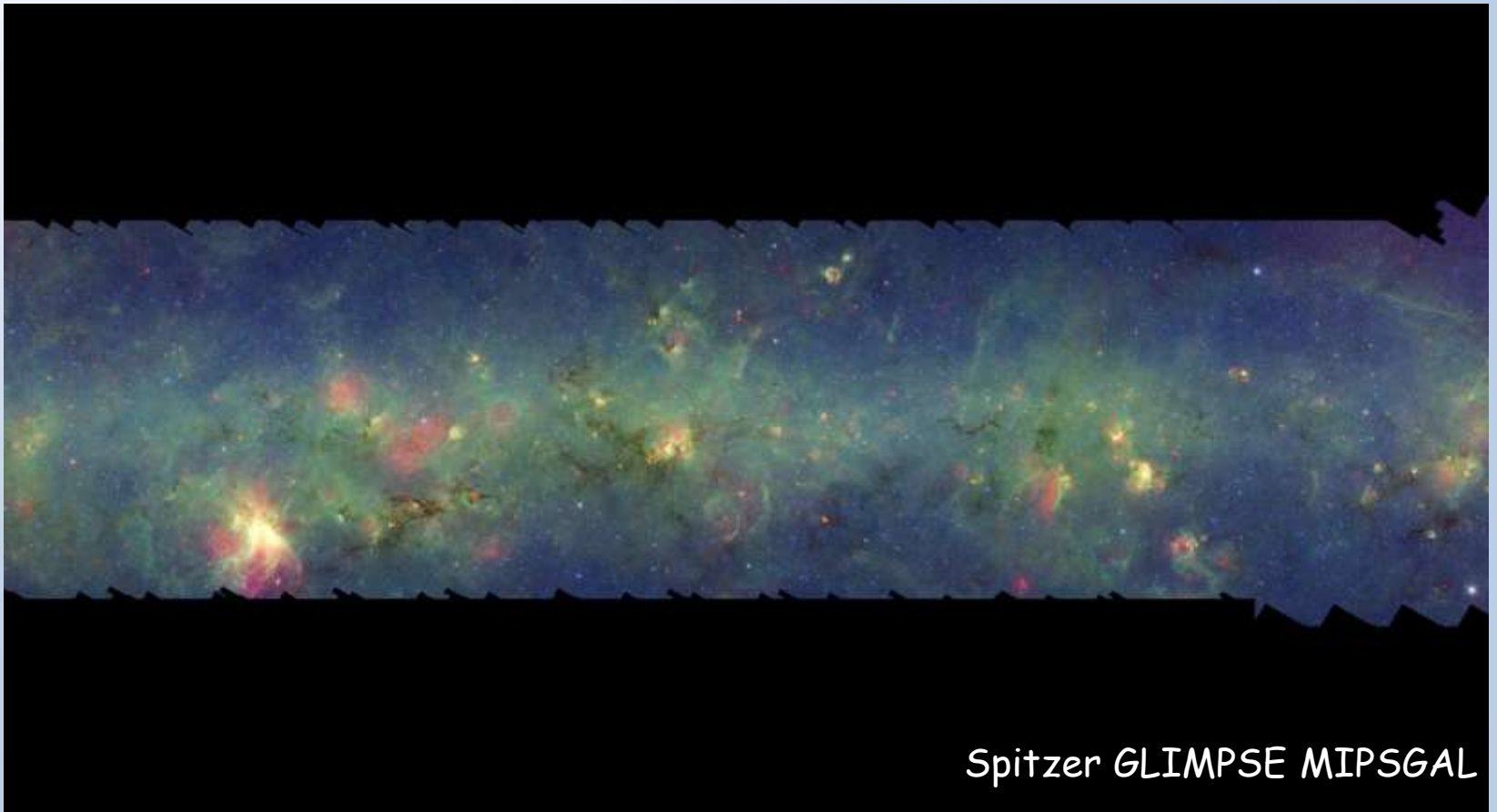
Carina region (JWST)



Crab nebula (VLT)

# Feedback van zware sterren

- Bakens van stervorming (H II gebieden, SN resten)
- Belangrijke bijdrage aan de dynamische en chemische evolutie van een melkwegstelsel.

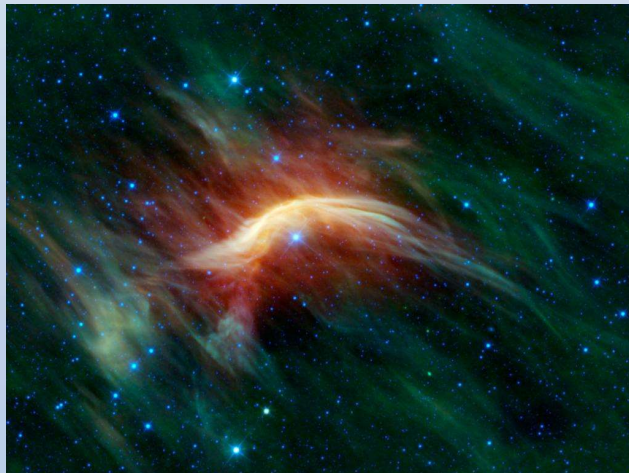


Spitzer GLIMPSE MIPS GAL



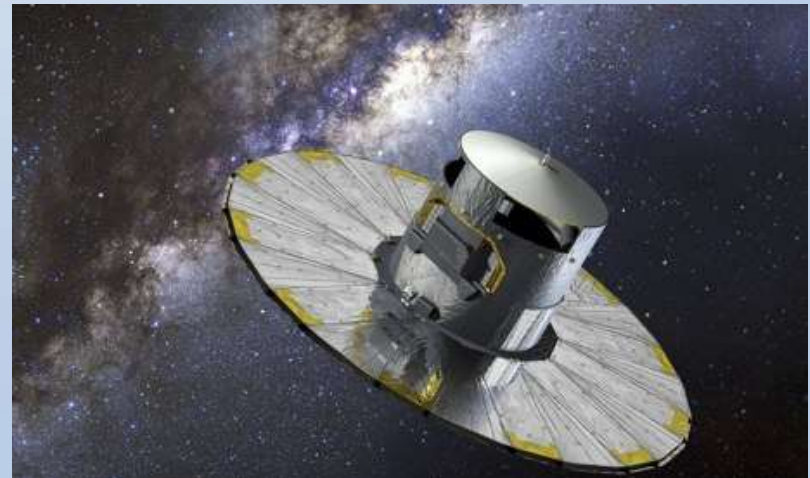
# Outline

- Astrometrie met de *Gaia* satelliet (2014 - 2025)
- *Runaway* sterren (Blaauw 1961: hoge ruimtesnelheid  $v > 30$  km/s met oorsprong in OB associatie)
- Twee scenario's:
  - Lancering uit cluster via botsingen (Poveda et al. 1967)
  - Supernova in een dubbelstersysteem (Blaauw scenario)
- Consequenties:
  - Zware sterren verlaten het Melkwegvlak
  - Produceren een boeggolf
  - Ontploffen op grote hoogte boven het Melkwegvlak



ζ Oph  
O9.5 V

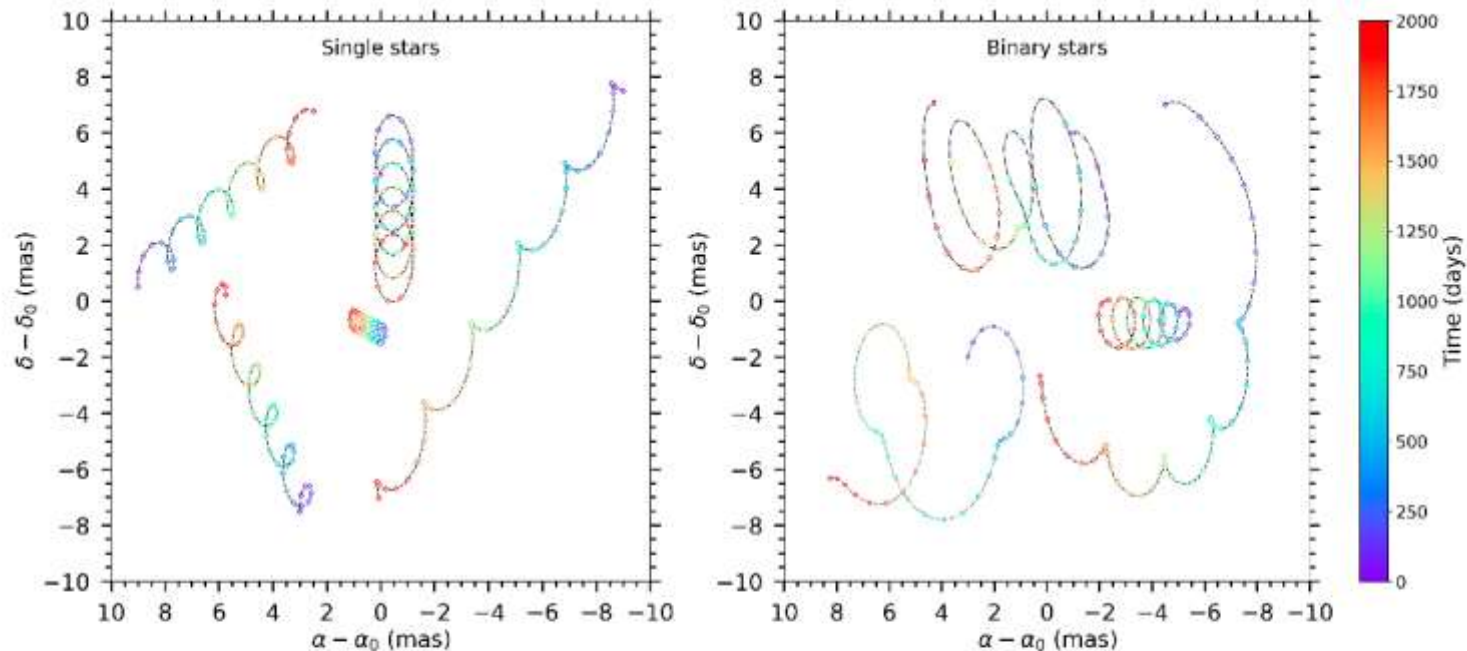
*Gaia*



# Astrometrie



# Parallax en eigenbeweging



**Figure 1.10:** Change in position across the sky due to the effect of parallax, proper motion and binary orbital motion. The stars are coloured according to the time since the first measurement, and the total time is equivalent to the length of the nominal mission of 66 months ( $\sim 2000$  days) of *Gaia*. The colour-bar for both panels is given on the right. *Left:* Change in position for single stars with various different proper motions and parallaxes. For a relatively low proper motion, the change in position of the star appears to circle out a helix. For a relatively large proper motion, the star traces out a wobbly pattern. *Right:* The effect of binary orbital motion superimposed on top of the effects of parallax and proper motion. All primaries in the binary systems are assumed to orbit a dark companion, such as a black hole or neutron star. Depending on the orbital parameters, the stars in binary systems can appear to move across the sky in a peculiar manner.

# Cluster lidmaatschap

Sterren in een cluster bewegen op een bijna identieke manier door de ruimte en vormen zo een coherente structuur in de 6-dimensionale fase ruimte:  $(x, y, z, v_x, v_y, v_z)$

We gebruiken deze eigenschap om clusterleden te identificeren.

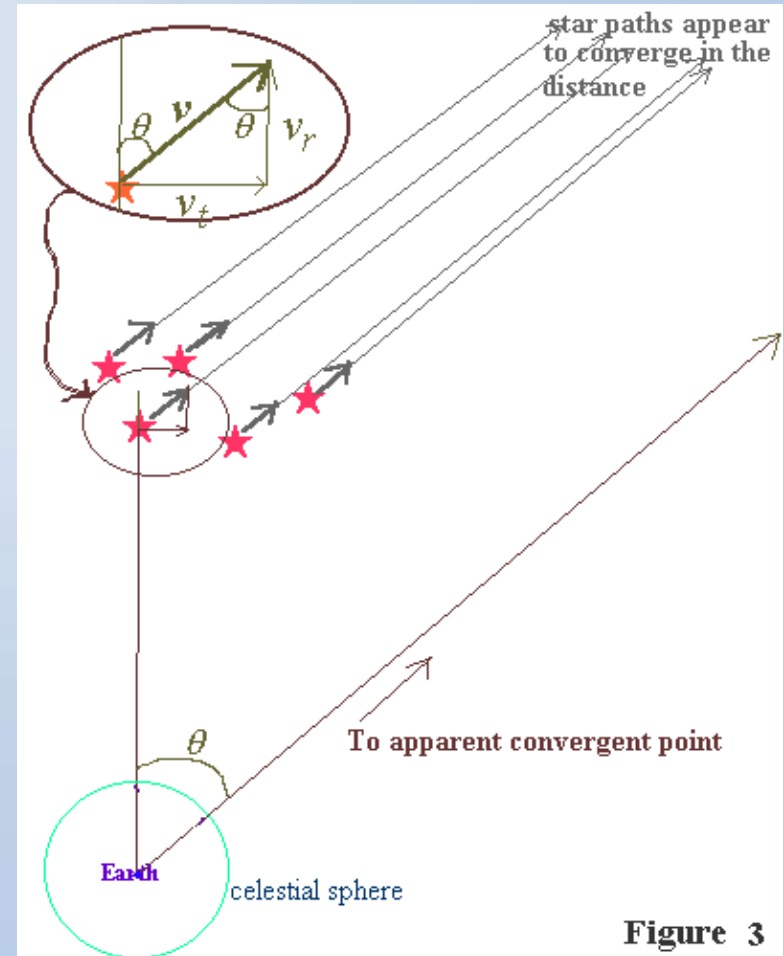
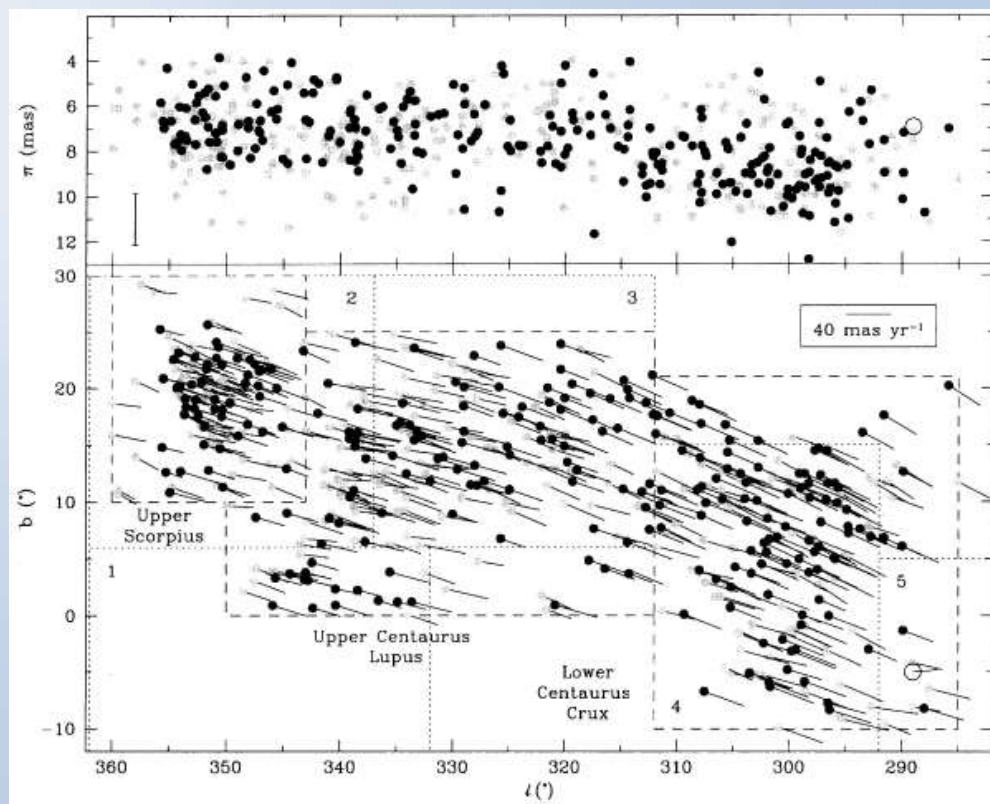


Figure 3

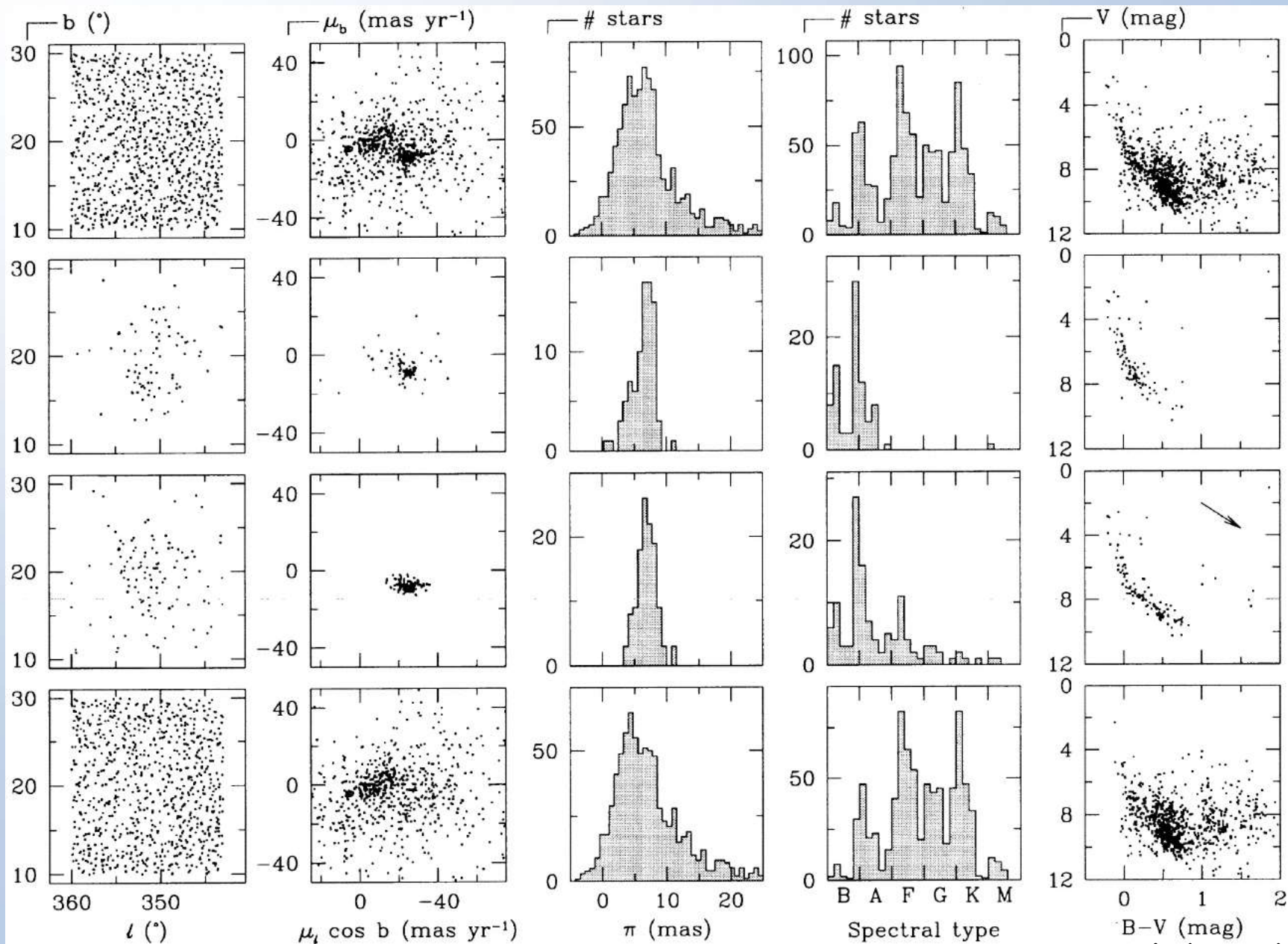


# Sco OB2 (*Hipparcos*)

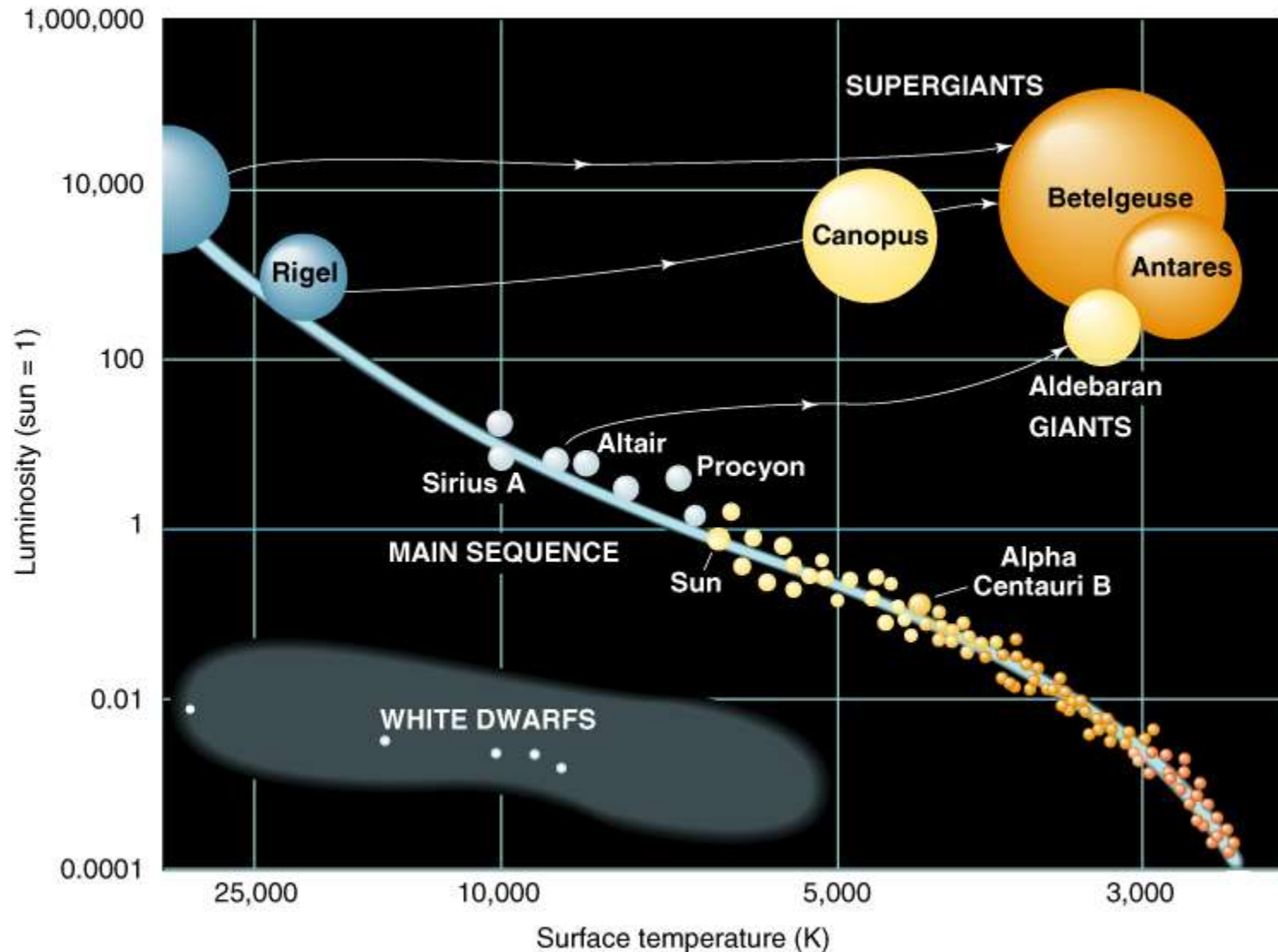




# Upper Sco

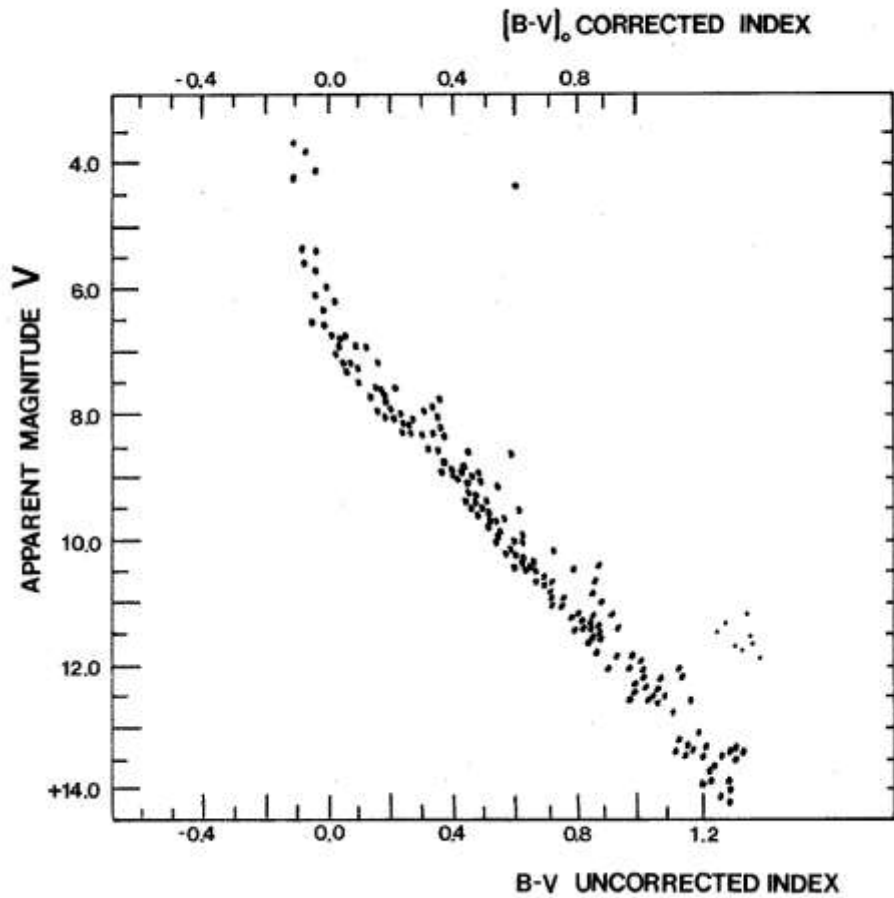


# Hertzprung - Russell diagram



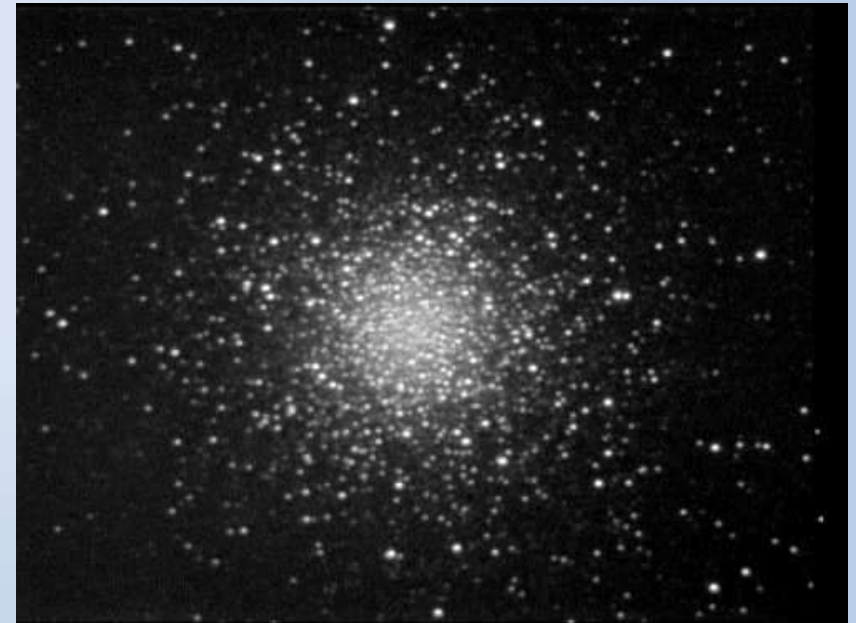
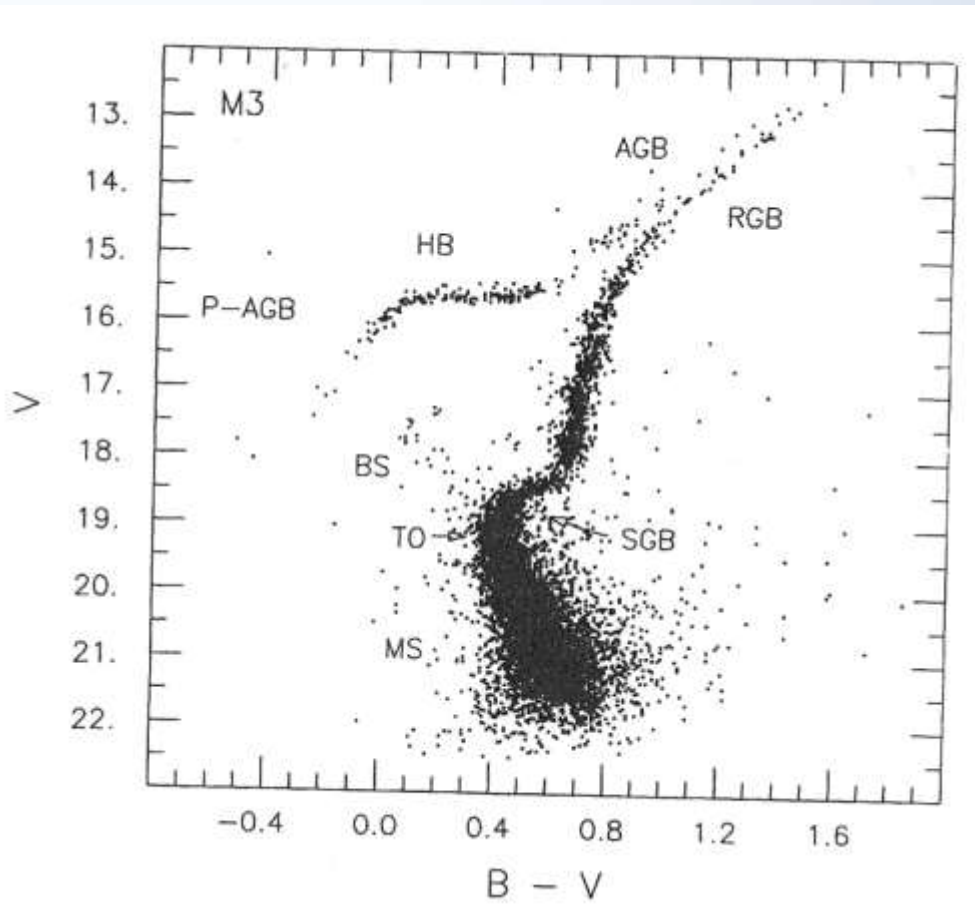
# HRD jonge sterrenhoop

M45 (Pleiades)



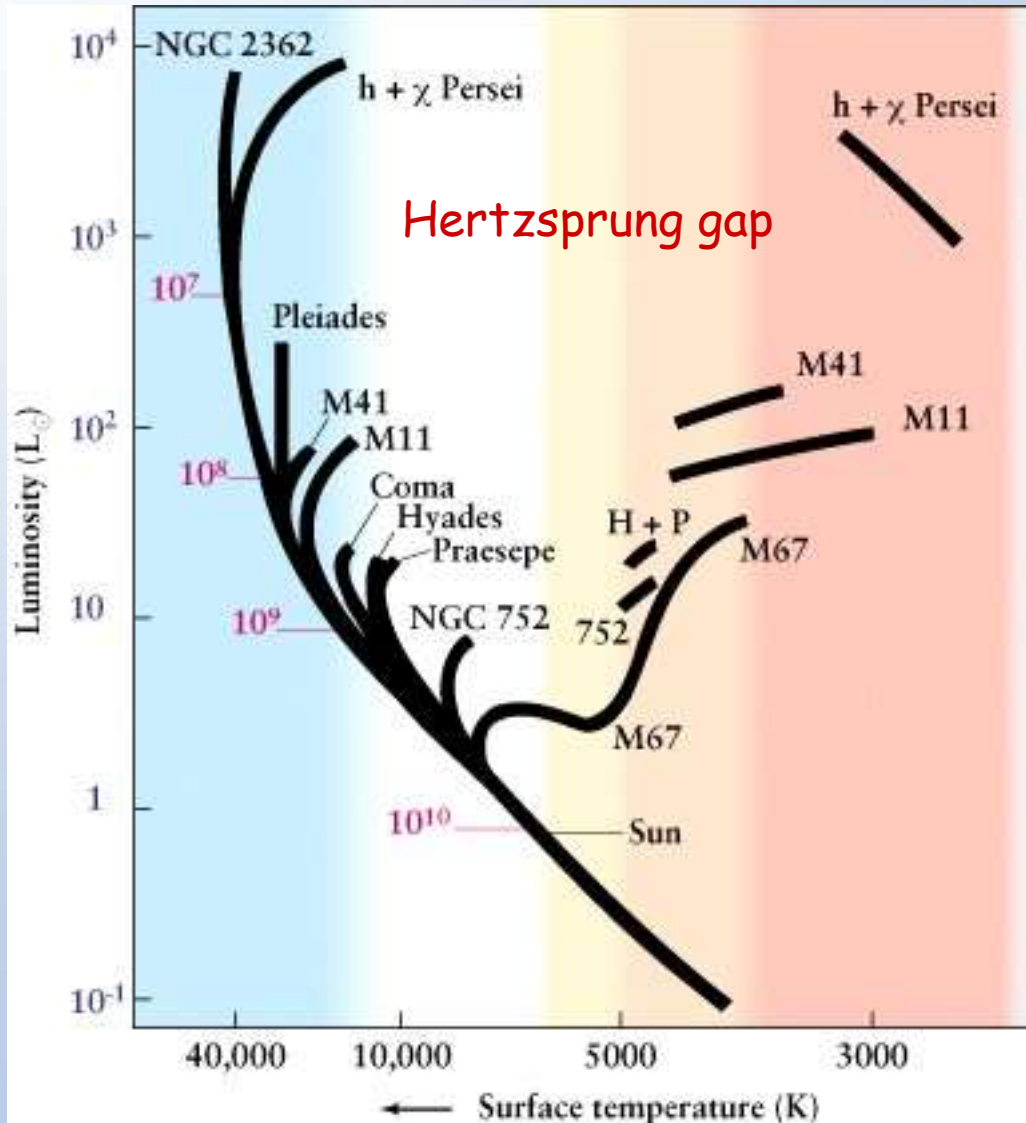


# HRD oude sterrenhoop



M3

# HRD sterrenhopen (turn-off point)



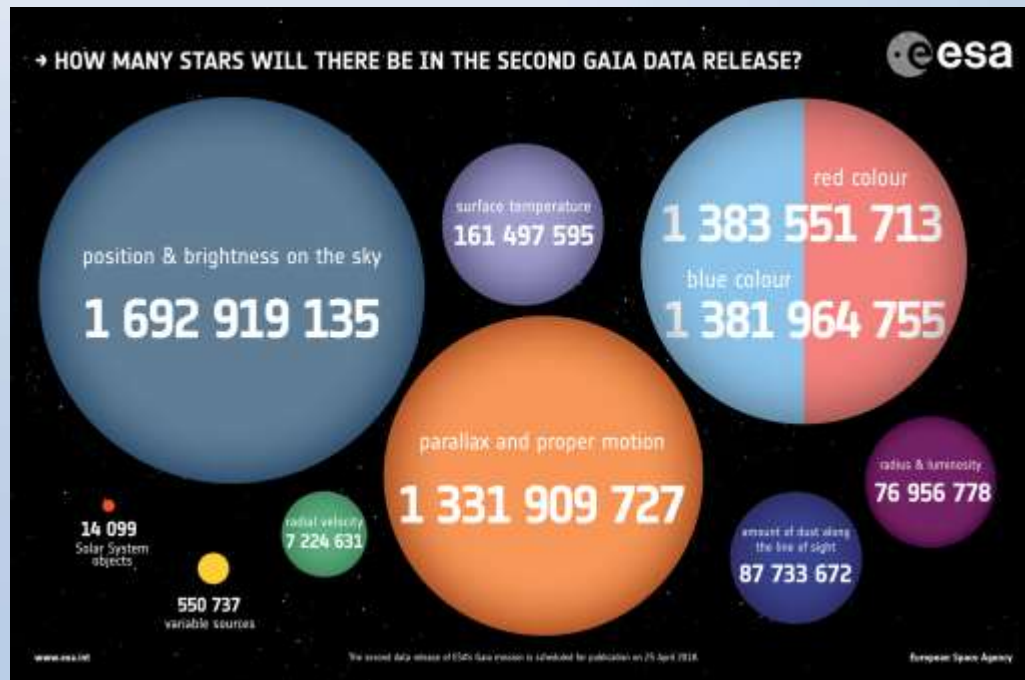
# *Gaia* kaart van de Melkweg (2014 - 2025)

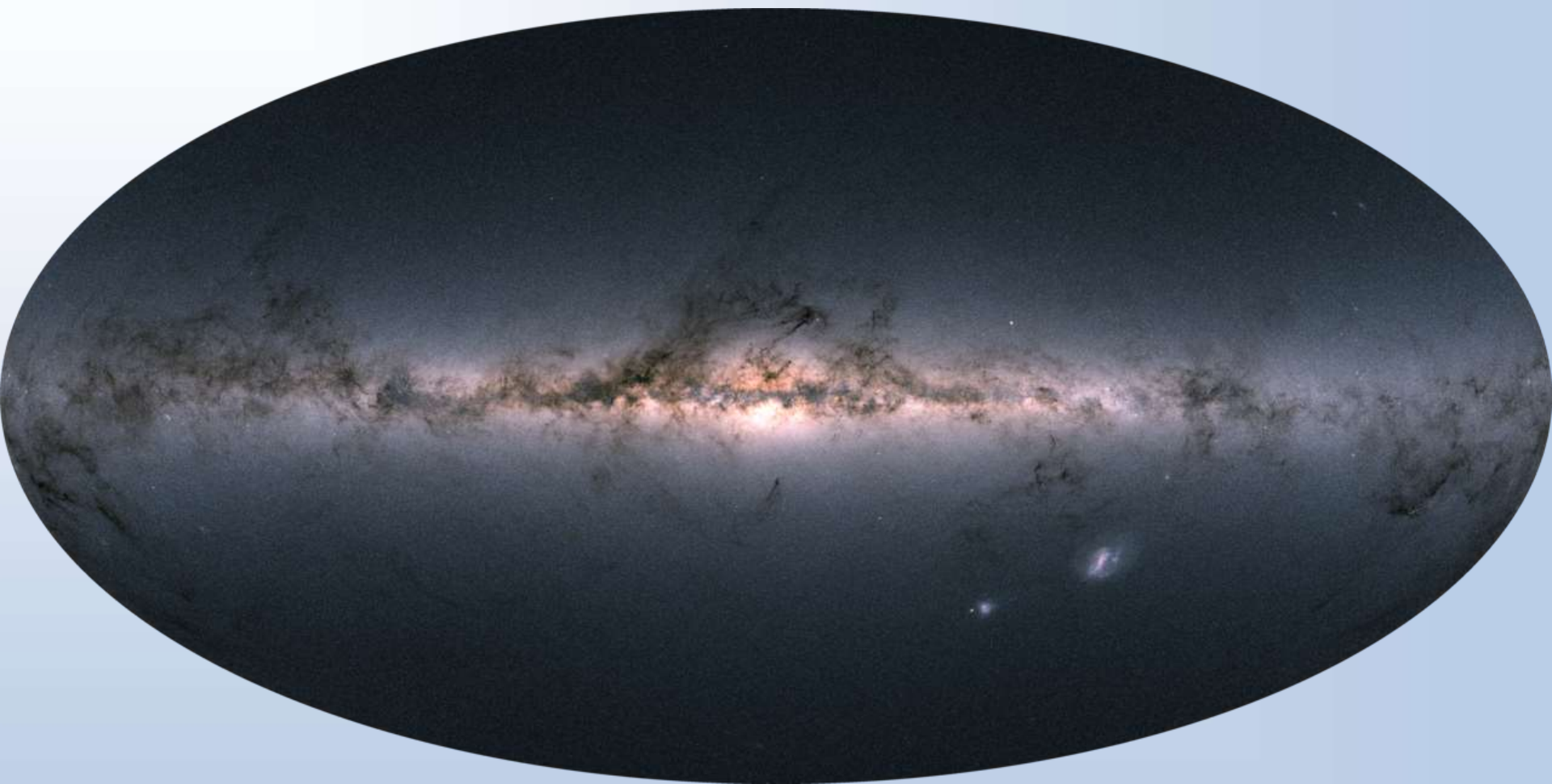




# Gaia vs Hipparcos

	N	V	Positie (arcsec)
Brahe (1550)	$10^3$	6	1
Kapteyn (1900)	$10^6$	10	0.01
<i>Hipparcos</i> (1990)	$10^6$	11	0.001
<i>Gaia</i> (2025)	$10^9$	20	0.00001

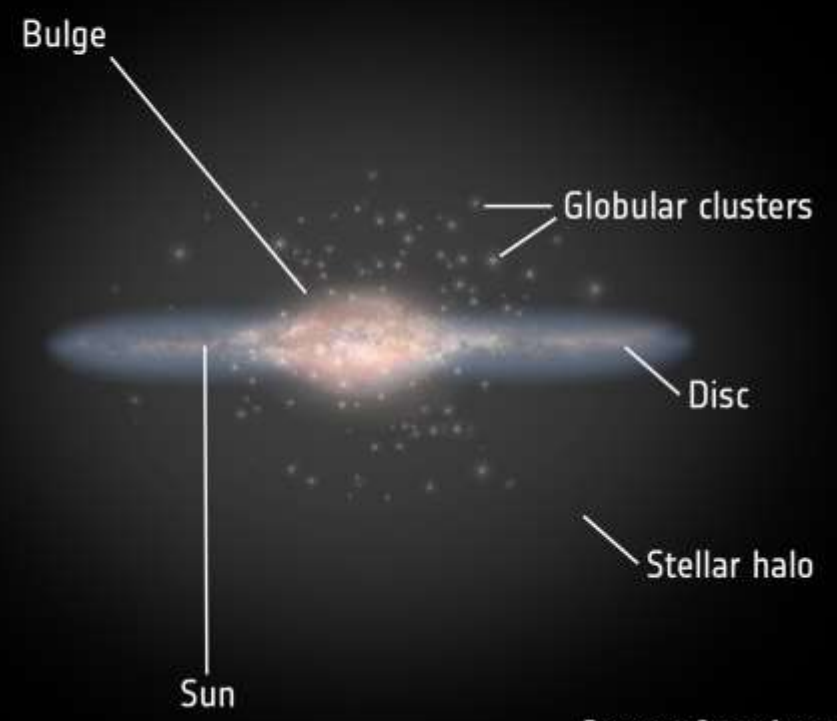




# → ANATOMY OF THE MILKY WAY



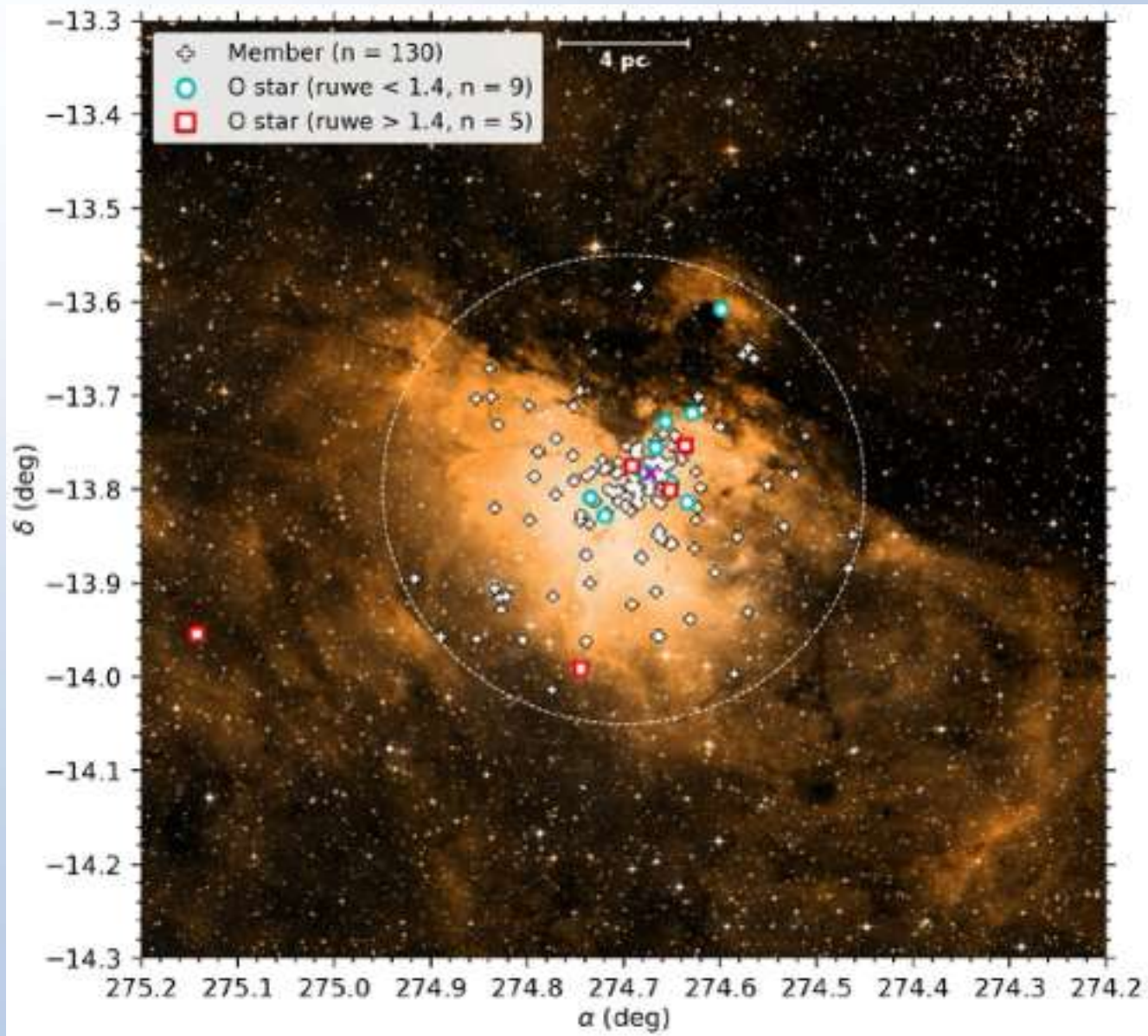
[www.esa.int](http://www.esa.int)

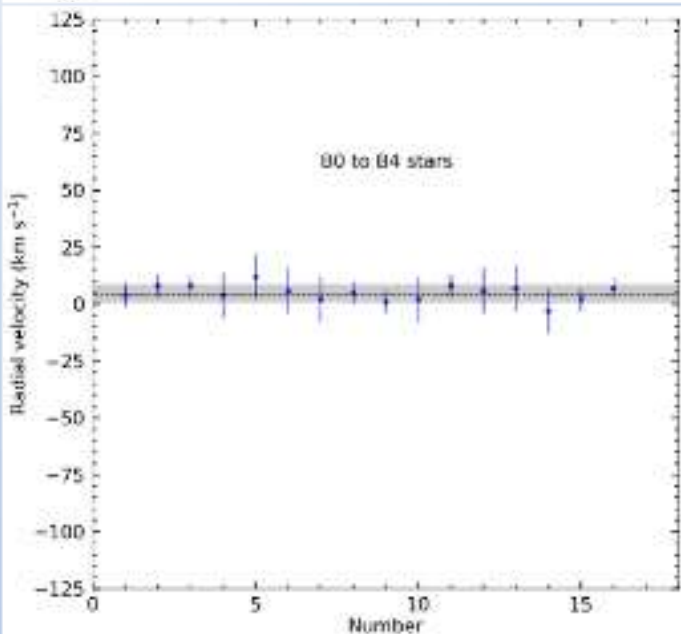
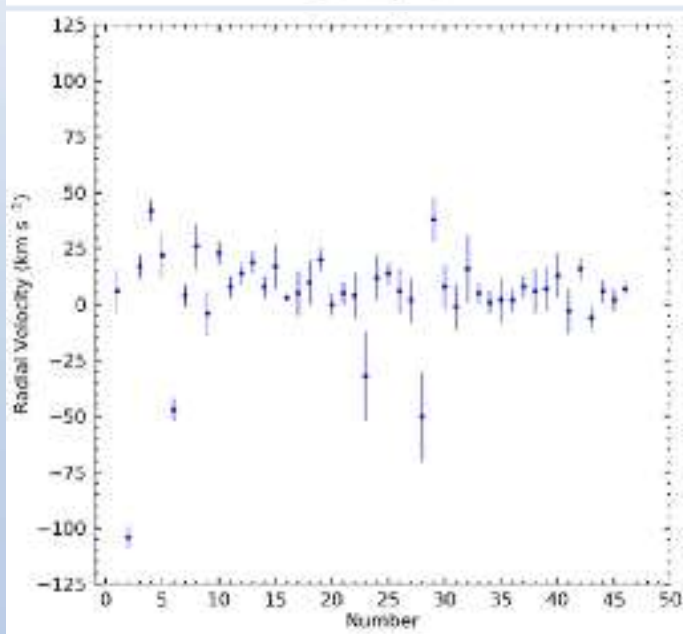
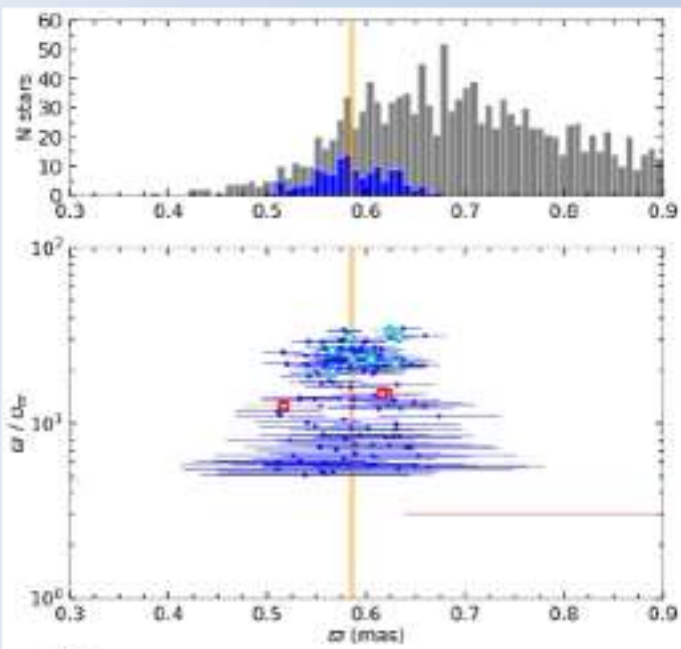
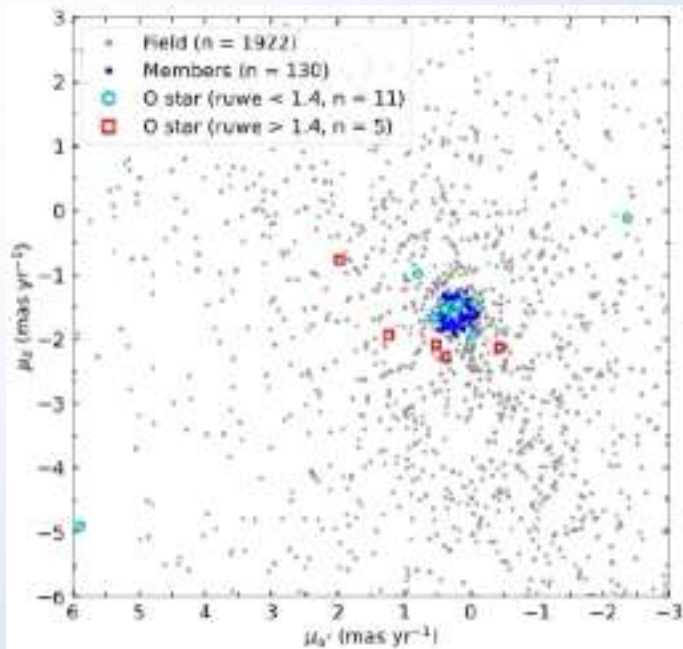


European Space Agency

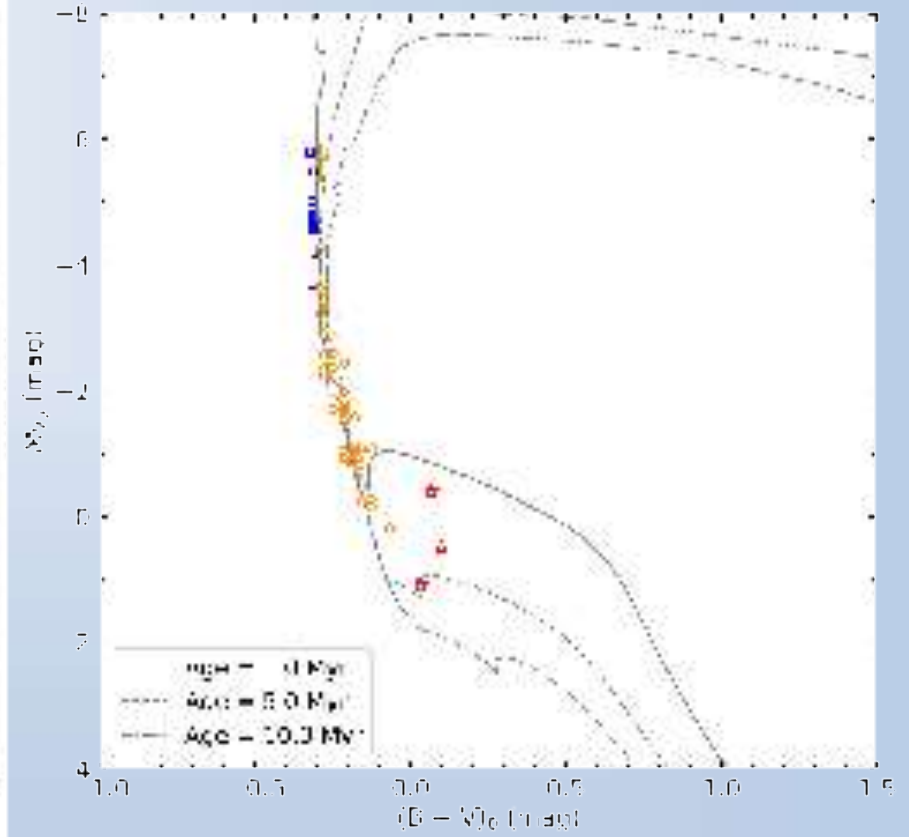
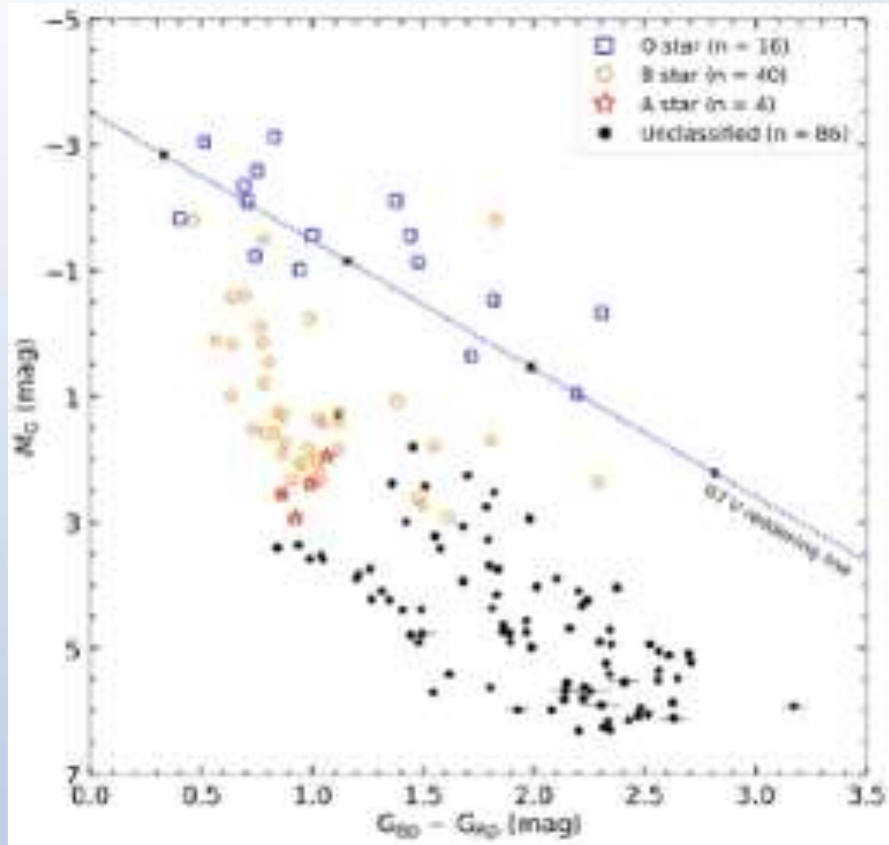


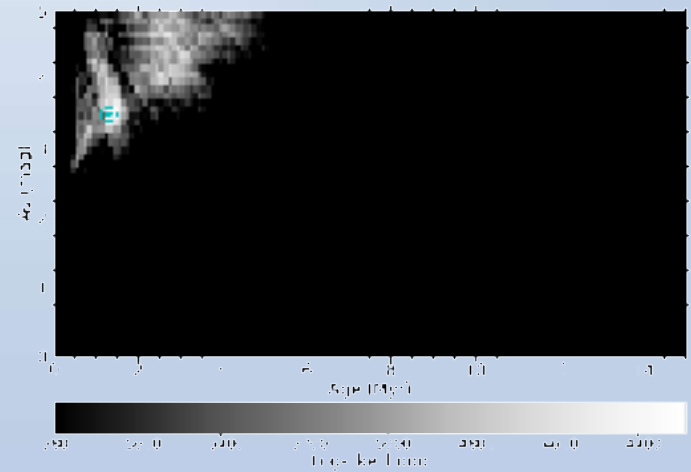
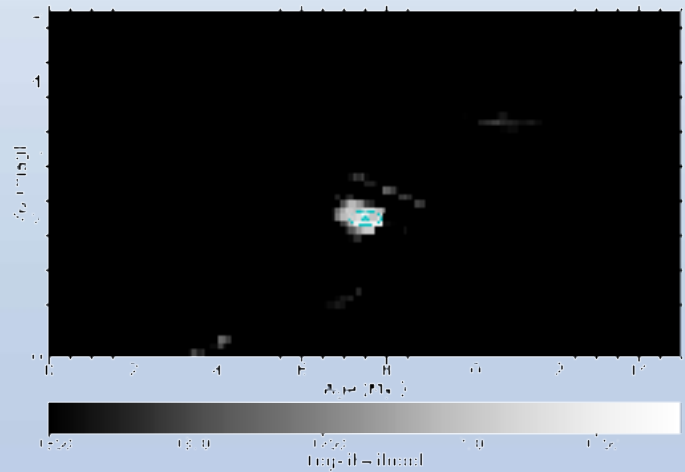
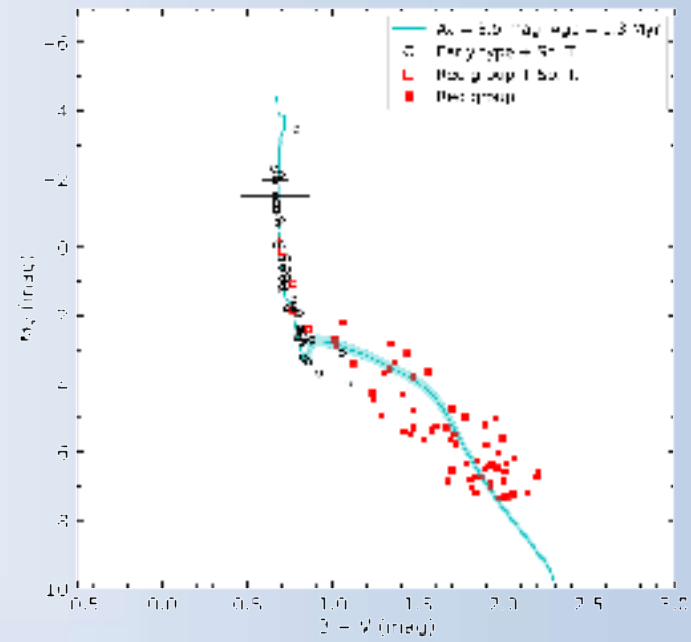
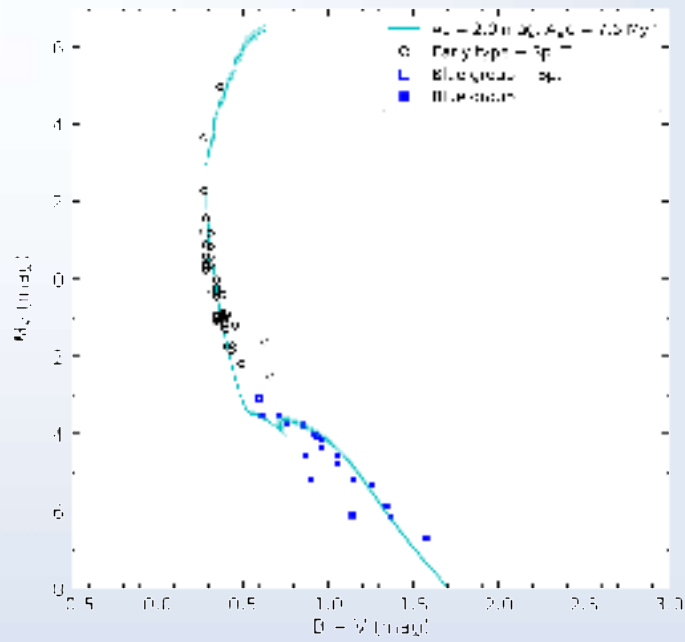
# NGC6611 (M16) using *Gaia* DR3





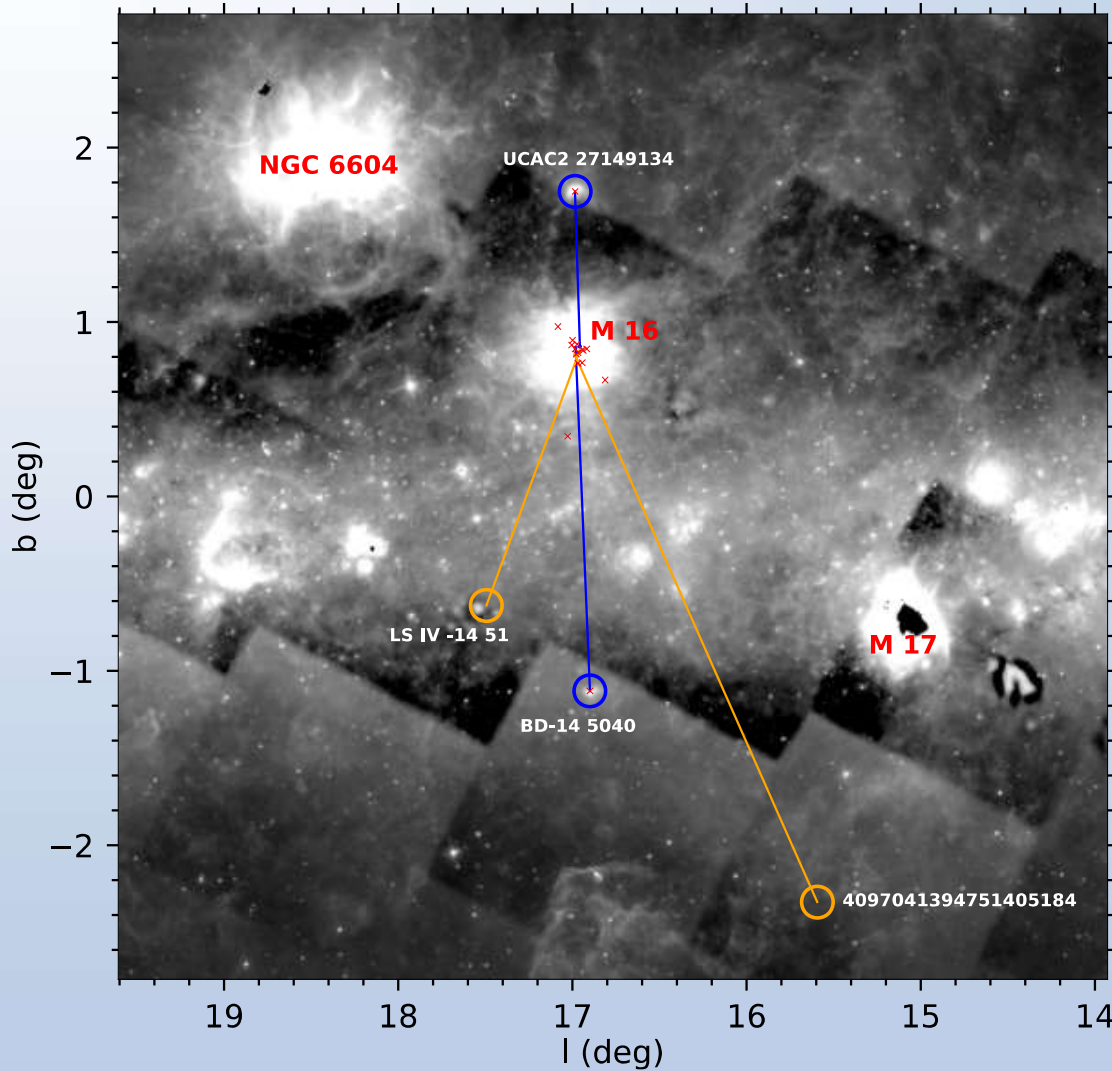
# M16: twee populaties







# Runaways afkomstig uit M16



# Runaway sterren

- Ruimte snelheid  $> v_{esc}$  (tot een aantal 100 km/s)
- Frequentie: 20% O sterren, 2.5% B0 - B0.5 sterren
- Afkomstig uit OB associatie / cluster

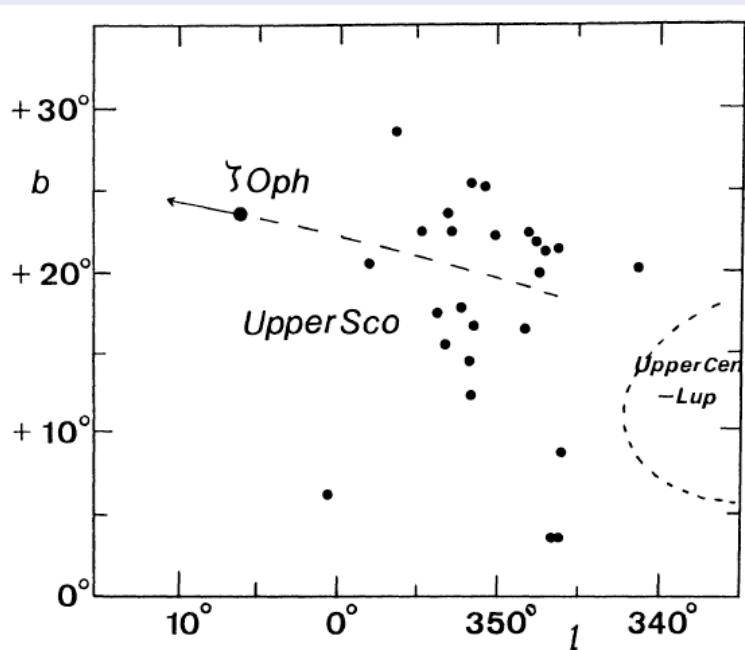
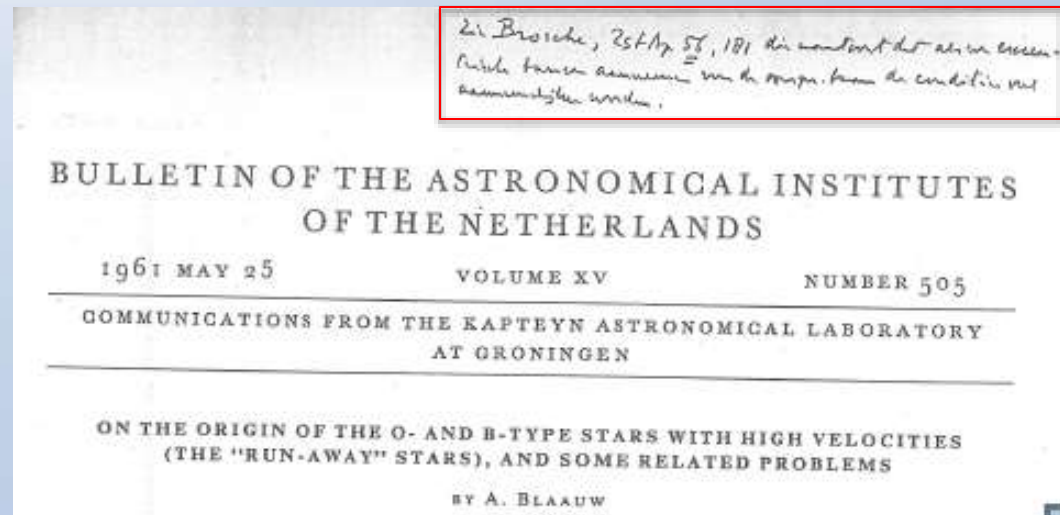


Fig. 1 Runaway  $\zeta$  Oph with parent Upper Sco; see text

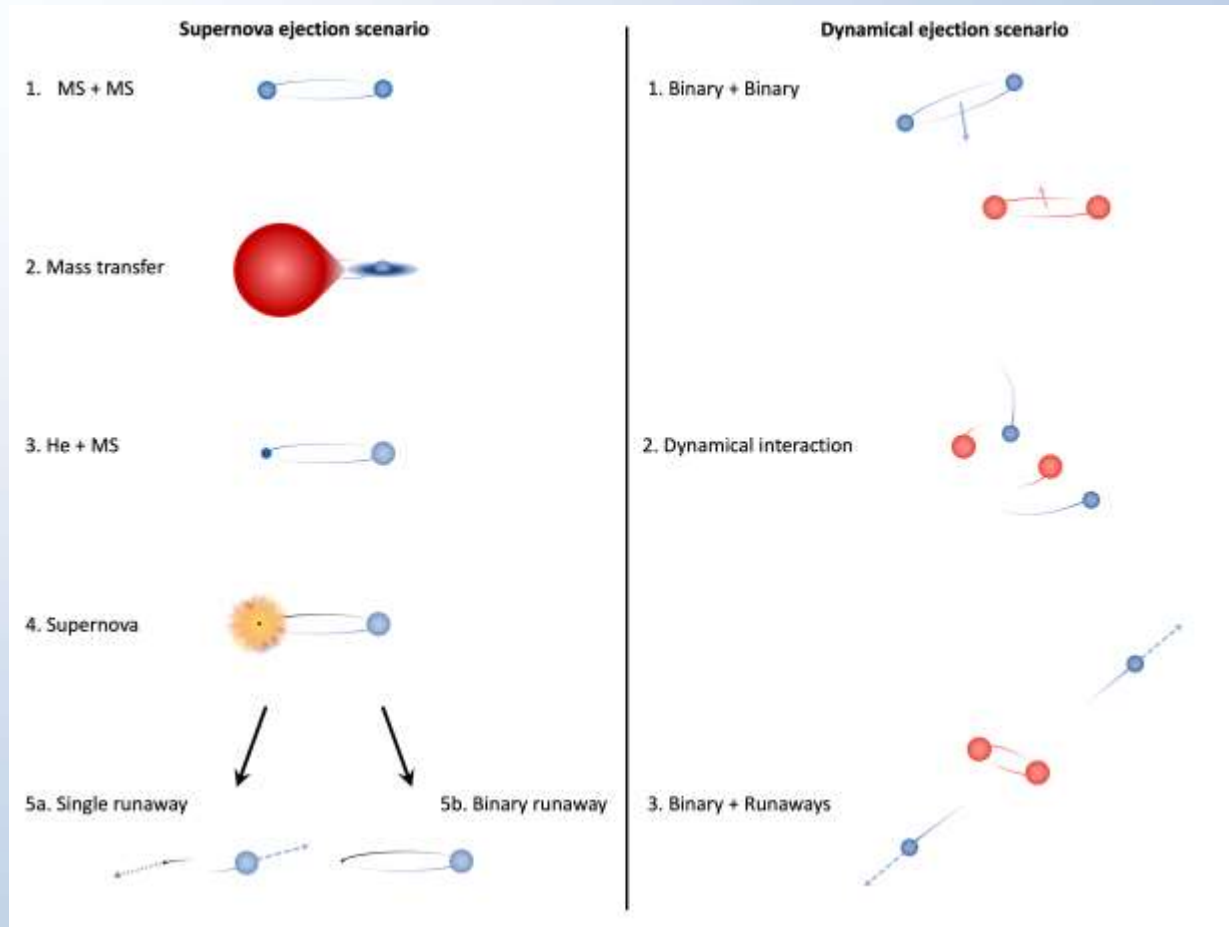
Jan Oort (ESO library)



# Adriaan Blaauw bezoekt Paranal (2010)



# Twee scenario's om *runaways* te produceren



Supernova explosie in een dubbelstersysteem

Via botsingen: enige scenario actief in jonge clusters (< 3 Myr)



# Dynamische ejectie

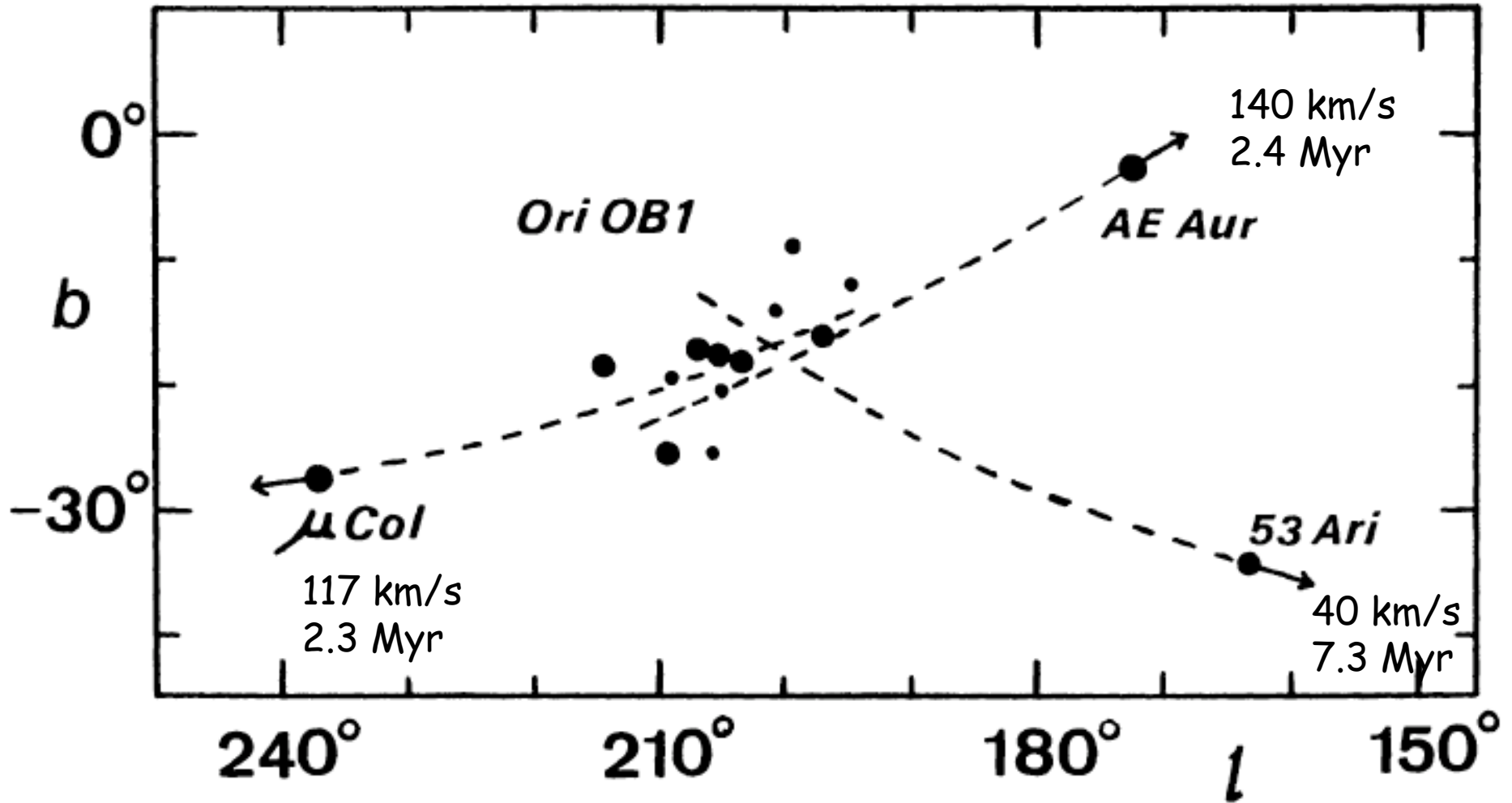


Fig. 3 Runaways  $\mu$  Col, AE Aur and 53 Ari with parent Ori OB1; see text

Blaauw (1992)

# Hipparcos

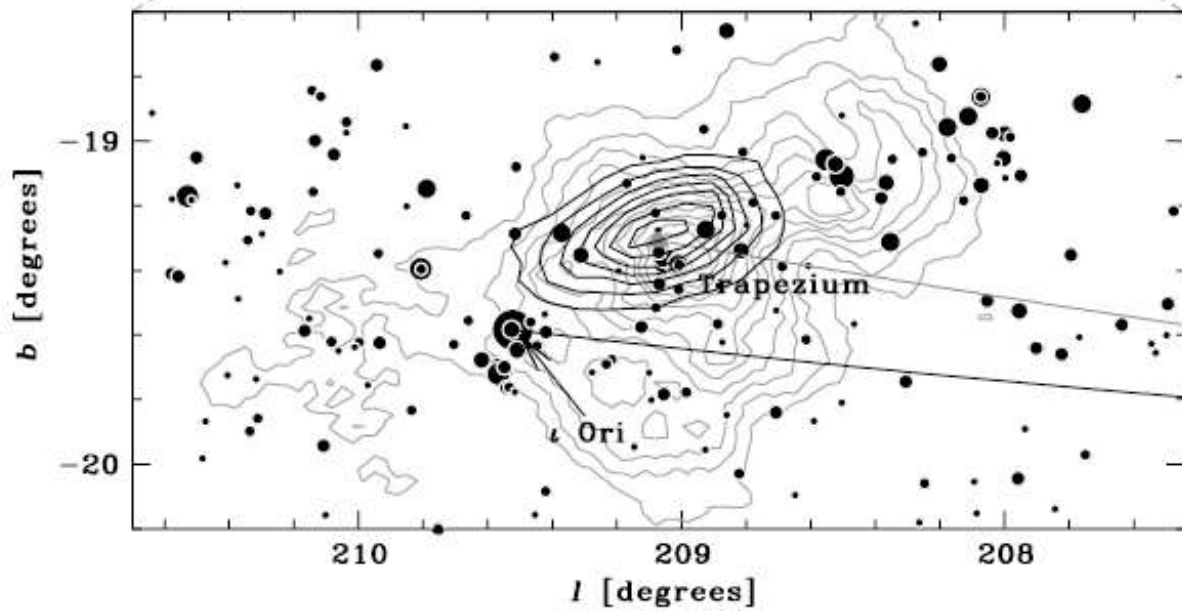
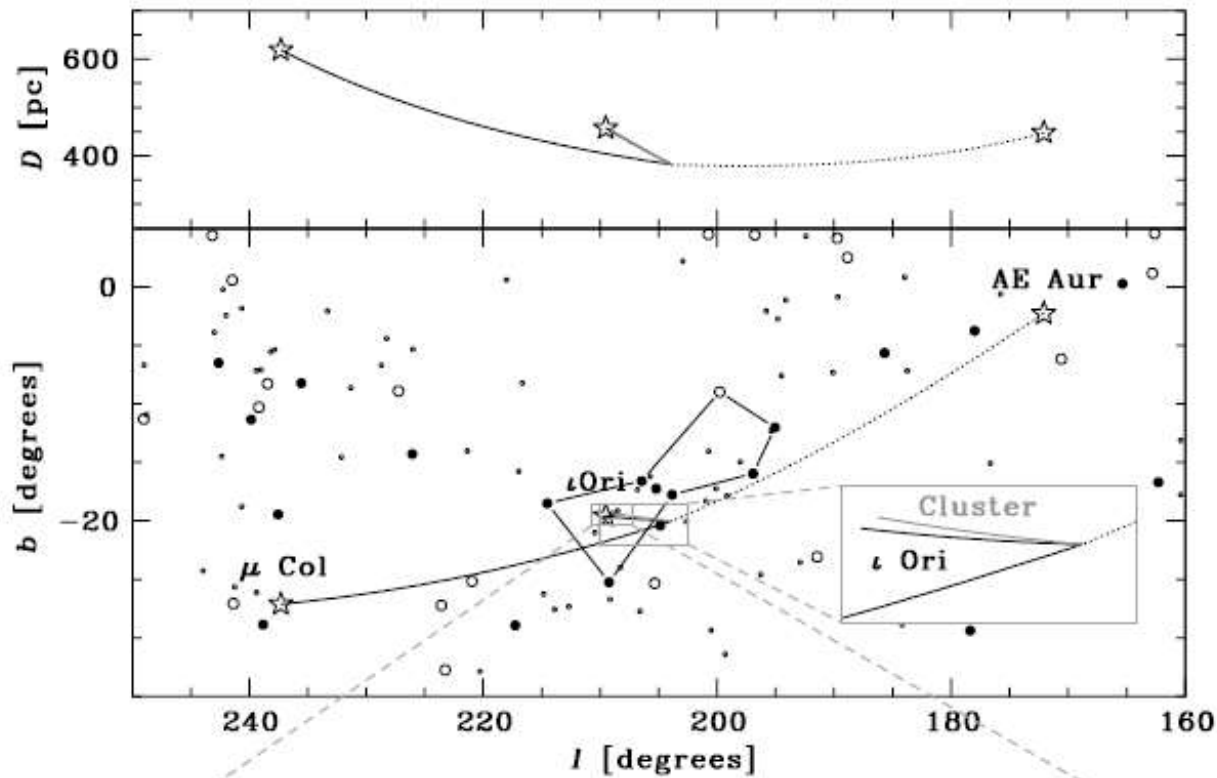
Gereconstrueerde banen AE Aur en  $\mu$  Col wijzen naar oorsprong in Trapezium  $\sim 2.5$  Myr geleden.

Kinem. leeftijd = leeftijd cluster

Dubbel-dubbel interactie ( $\iota$  Ori)

Partnerruil?  
(Gualandris et al. 2004)

Hoogerwerf et al. 2001



# Supernova in een zware dubbelster

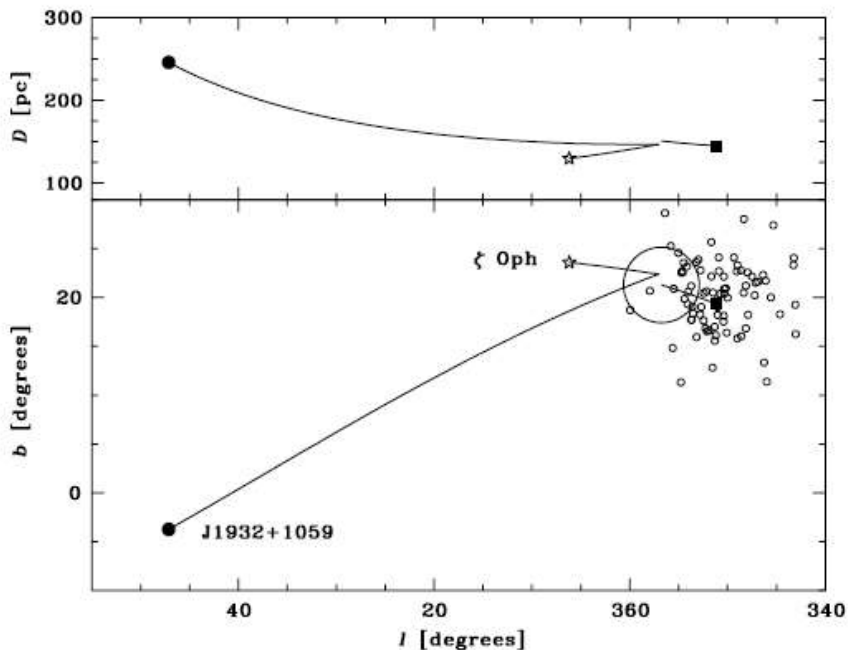


Fig. 6. The orbits of  $\zeta$  Oph, PSR J1932+1059, and Upper Scorpius. The present positions are denoted by a star for the runaway, a filled circle for the pulsar, and by a filled square for the association. The *top* panel shows the distance vs. Galactic longitude of the stars. The *bottom* panel shows the orbits projected on the sky in Galactic coordinates. The small open circles in the bottom panel denote the present-day positions of the O, B, and A-type members of Upper Scorpius, taken from de Zeeuw et al. (1999). The large circle denotes the position of the association at the time of the supernova explosion, and has a 10 pc radius. This figure assumes a set of space motions consistent with the common origin hypothesis

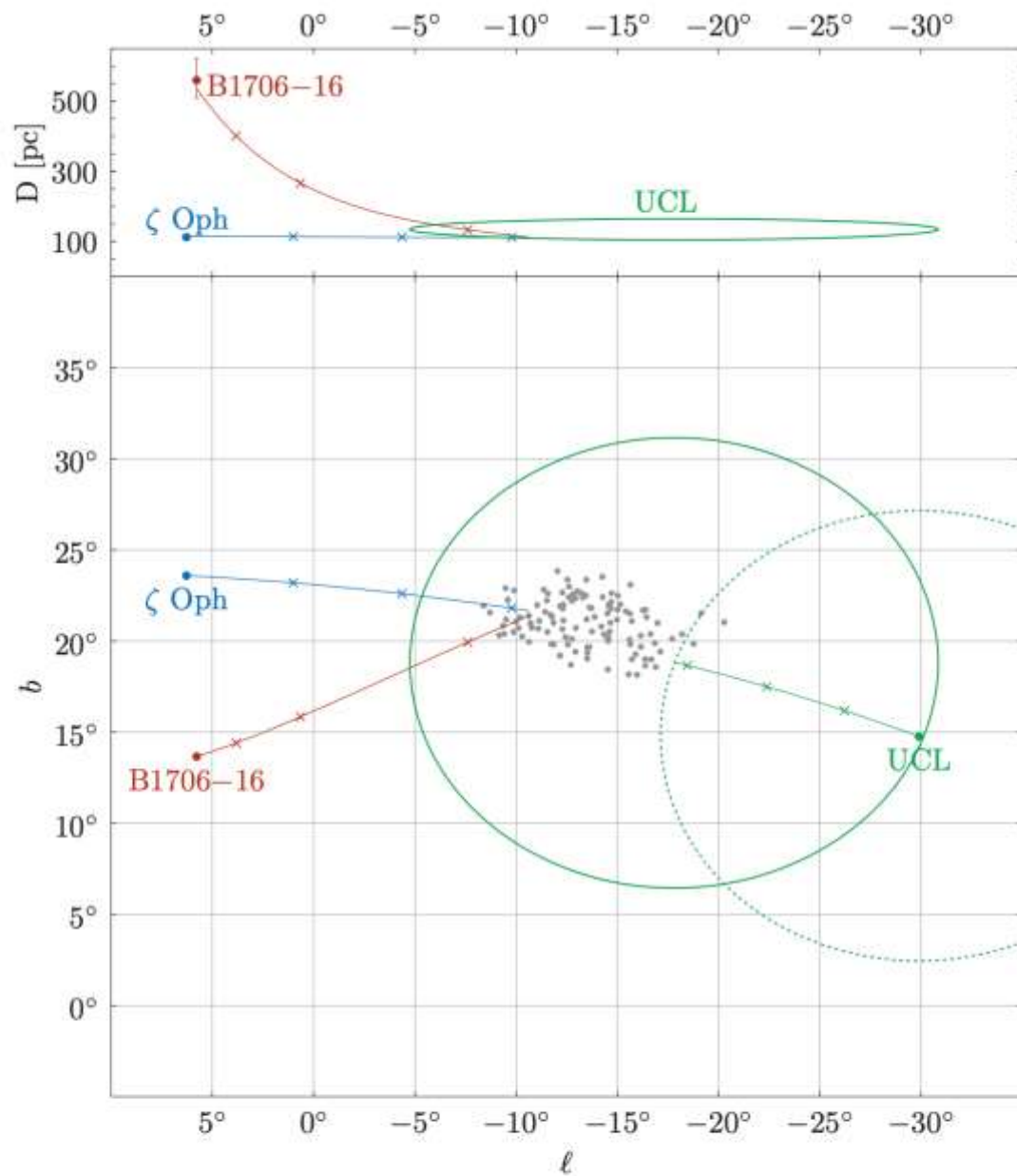
$\zeta$  Oph en pulsar 1932+1059  
kruisten  $\sim 1$  Myr ago in  
Upp Sco (age  $\sim 5$  Myr):

Ontbinding dubbelster  
tijdens de supernova die  
de pulsar produceerde.

Kinematische leeftijd  $\ll$   
leeftijd geboorte cluster

$$v_{\text{kick}} (\text{pulsar}) = 240 \text{ km/s}$$

Hoogerwerf et al. (2000)



**Figure 2.** Close approaches between PSR B1706-16 and  $\zeta$  Oph. Lower panel: For the closest approach between PSR B1706-16 and  $\zeta$  Oph (best case) projected on sky (Galactic longitude  $\ell$  versus latitude  $b$  at epoch of date), we show the flight paths (coloured lines) starting at their current positions (left), marked by small crosses after each 0.5 Myr of flight time, ending 1.58 Myr before present at the closest approach within 0.5 pc (centre). UCL is shown as full circle for 1.58 Myr ago and as dotted circle for the present time. The grey dots show all 117 close approaches within 10 pc inside UCL (Table 5), mean flight time  $1.78 \pm 0.21$  Myr, mean distance at closest approach  $107 \pm 4$  pc. Upper panel: distance  $D$  versus Galactic longitude  $\ell$  for the past flight paths (best case); the lines from  $\zeta$  Oph and the pulsar do not start exactly at their nominal positions (dots), because we show here the distances which were used as input in that particular run (best case among 3 million runs by varying the input using their measurement uncertainties). See also Tables 3-5 and Figs 3 and 4.



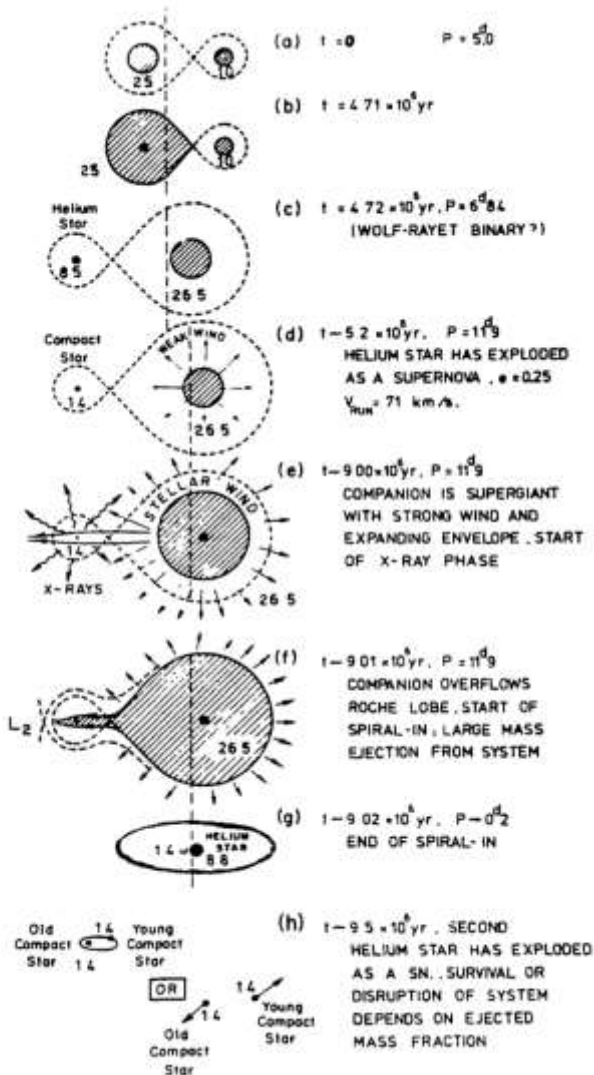
$\zeta$  Oph O9.5 V

Wind bow shock (WISE)

Neuhauser et al. (2020):  
*A nearby recent supernova that ejected the runaway star  $\zeta$  Oph, the pulsar PSRB1706-16, and  $^{60}\text{Fe}$  found on Earth*



# Dubbelster evolutie met massa overdracht



Zware dubbelster: zwaarste ster evolueert het snelst → fase van massa overdracht → massa ratio invertteert → systeem kan gebonden blijven na supernova → krijgt een grote snelheid

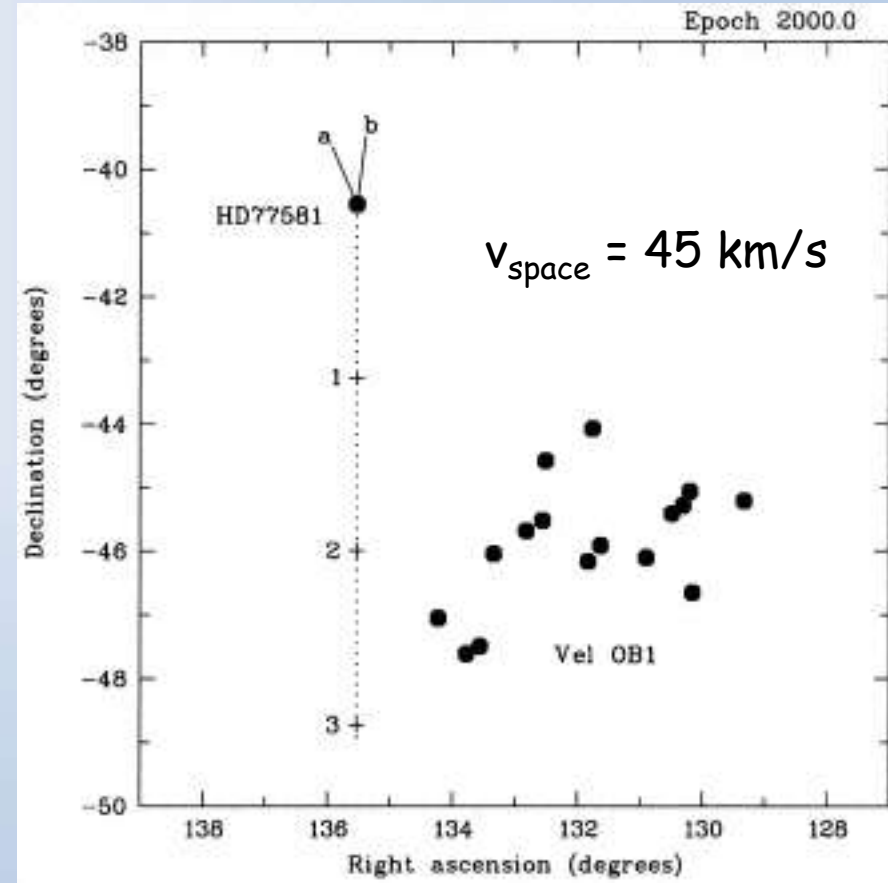
→ *high-mass X-ray binary* wordt runaway

Dubbele pulsar (of ontbonden)

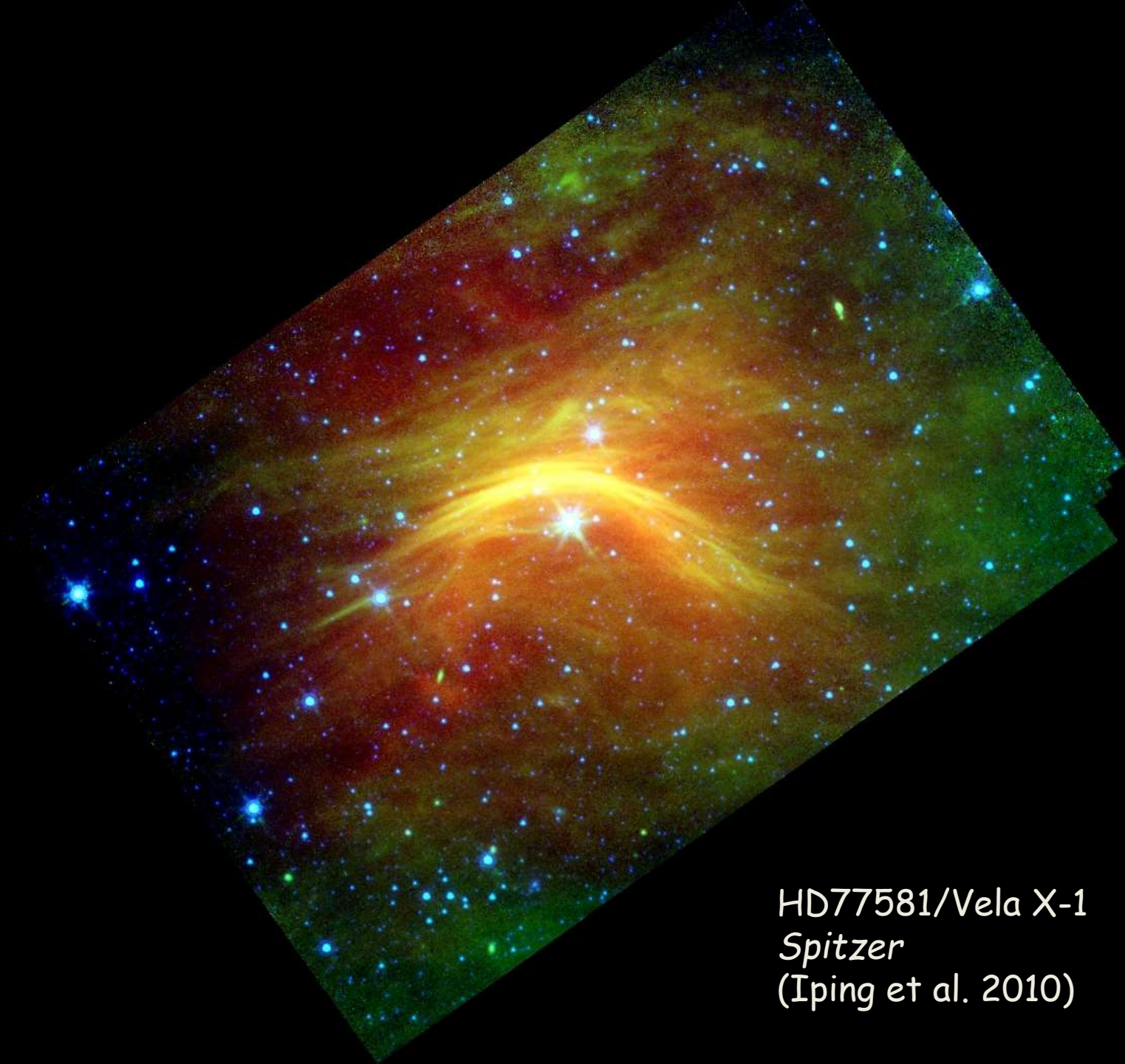
# HD77581/Vela X-1



Kaper et al. (1997)

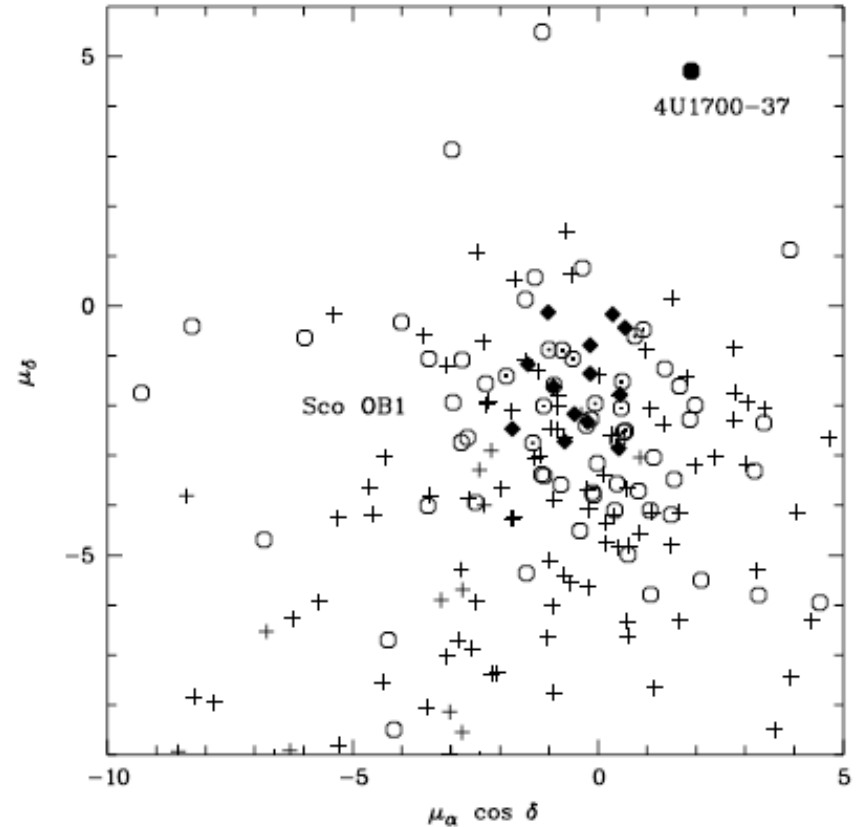
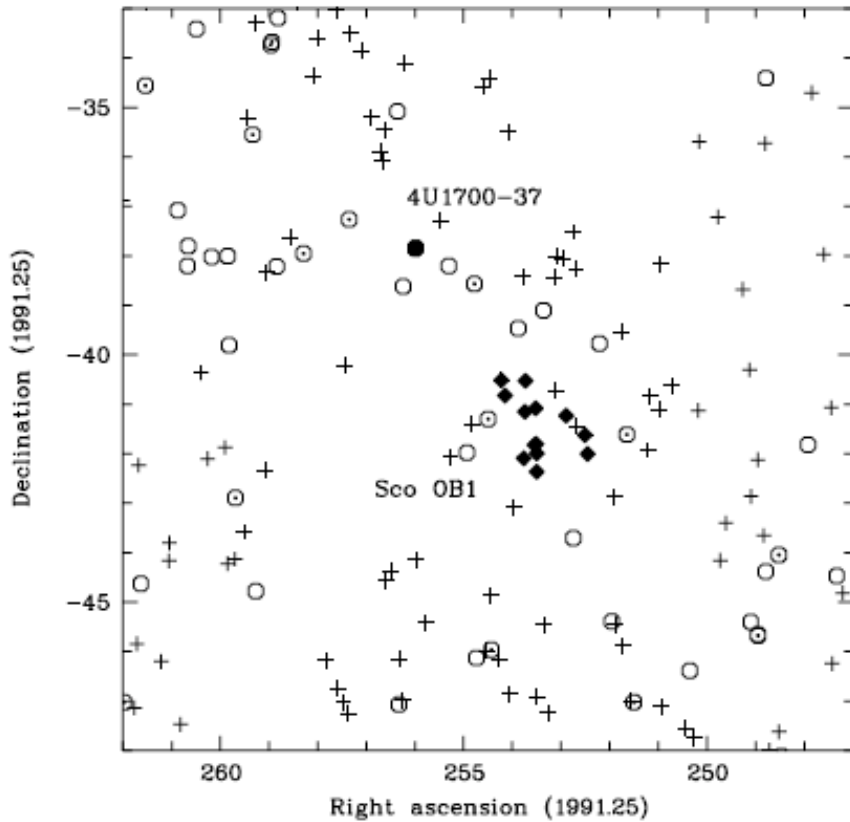


Van Rensbergen et al. (1996)



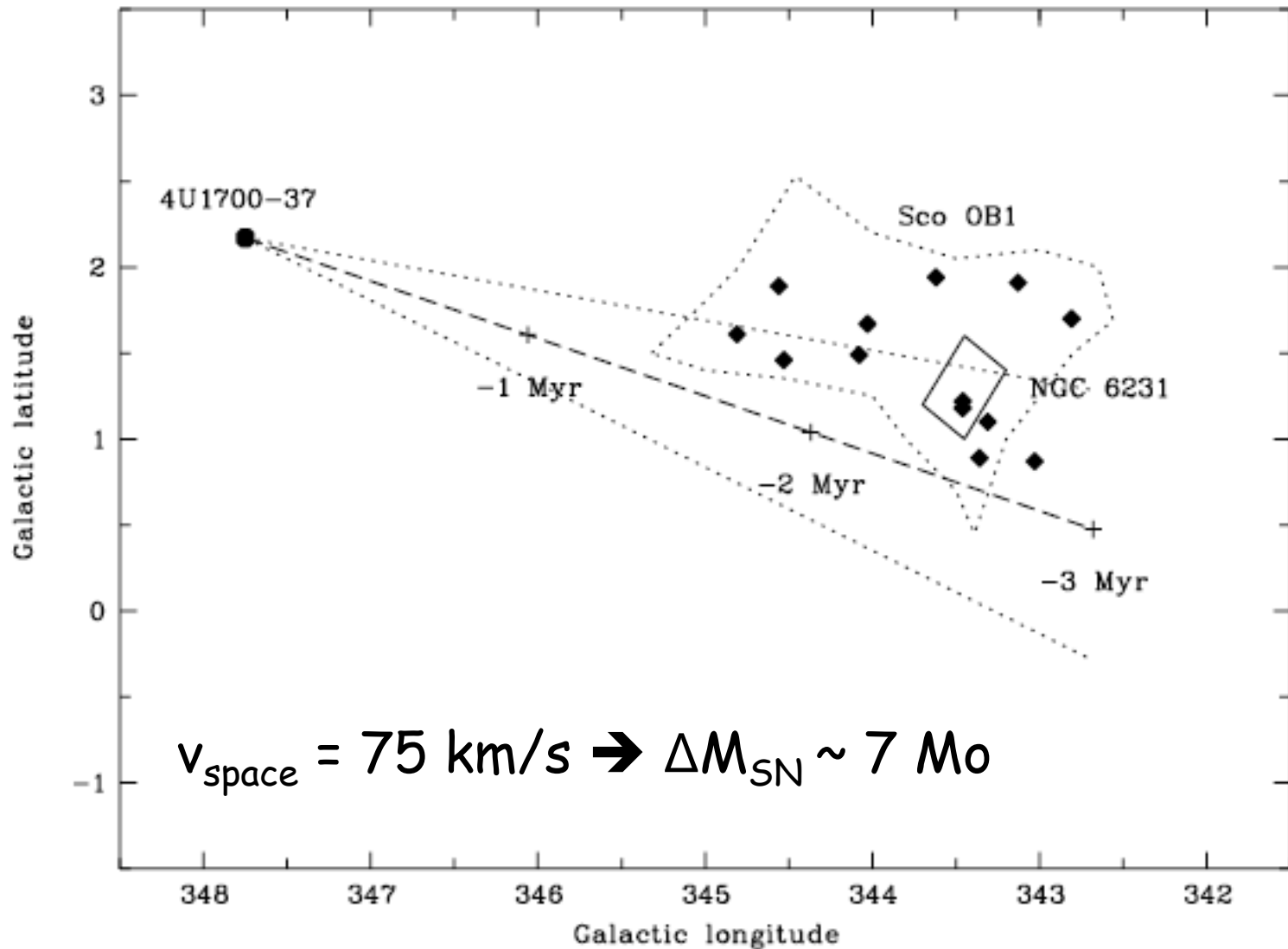
HD77581/Vela X-1  
*Spitzer*  
(Iping et al. 2010)

# HD153919 / 4U1700-37



*Hipparcos* data HD153919 and Sco OB1 (Ankay et al. 2000)

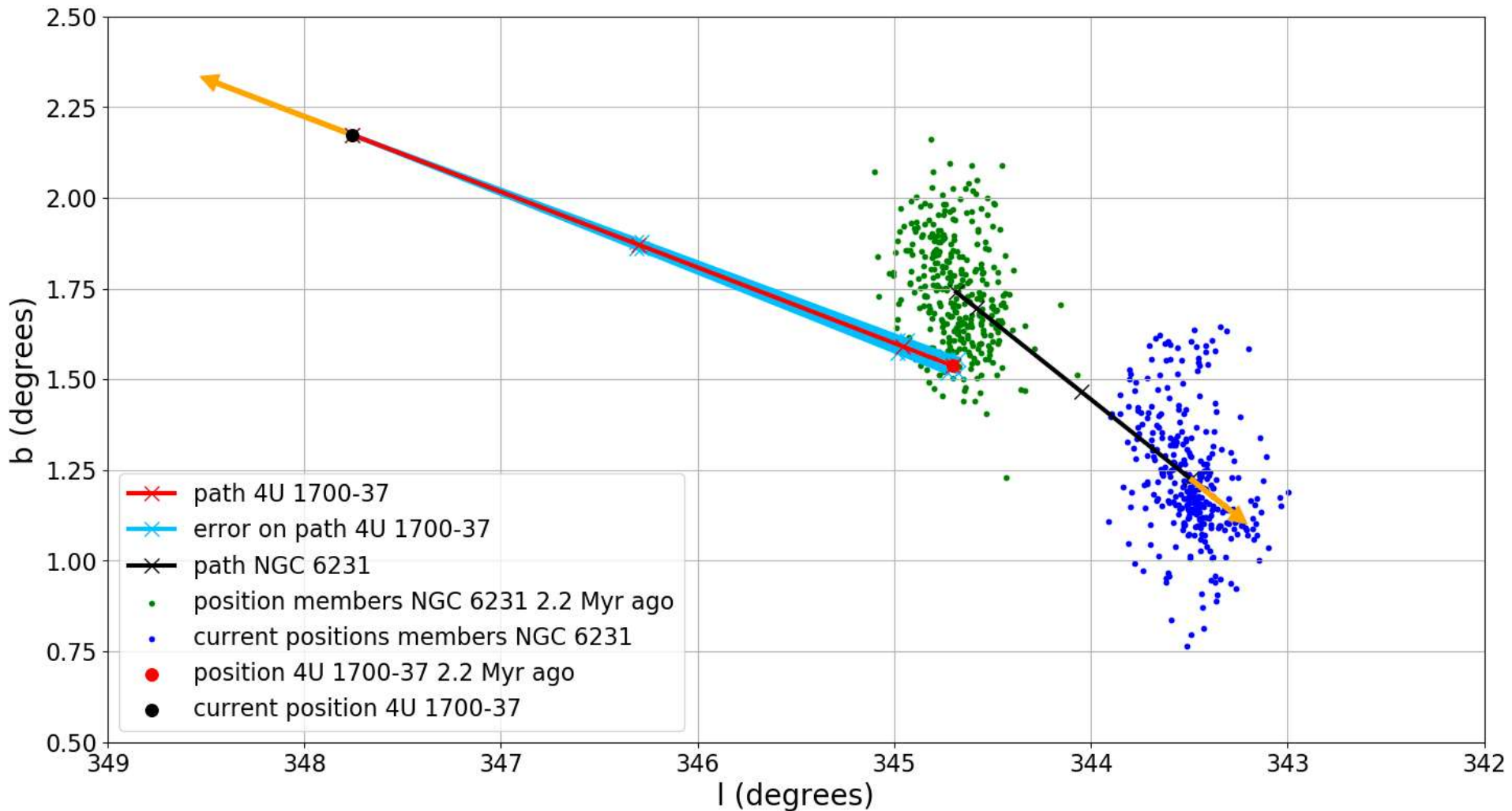




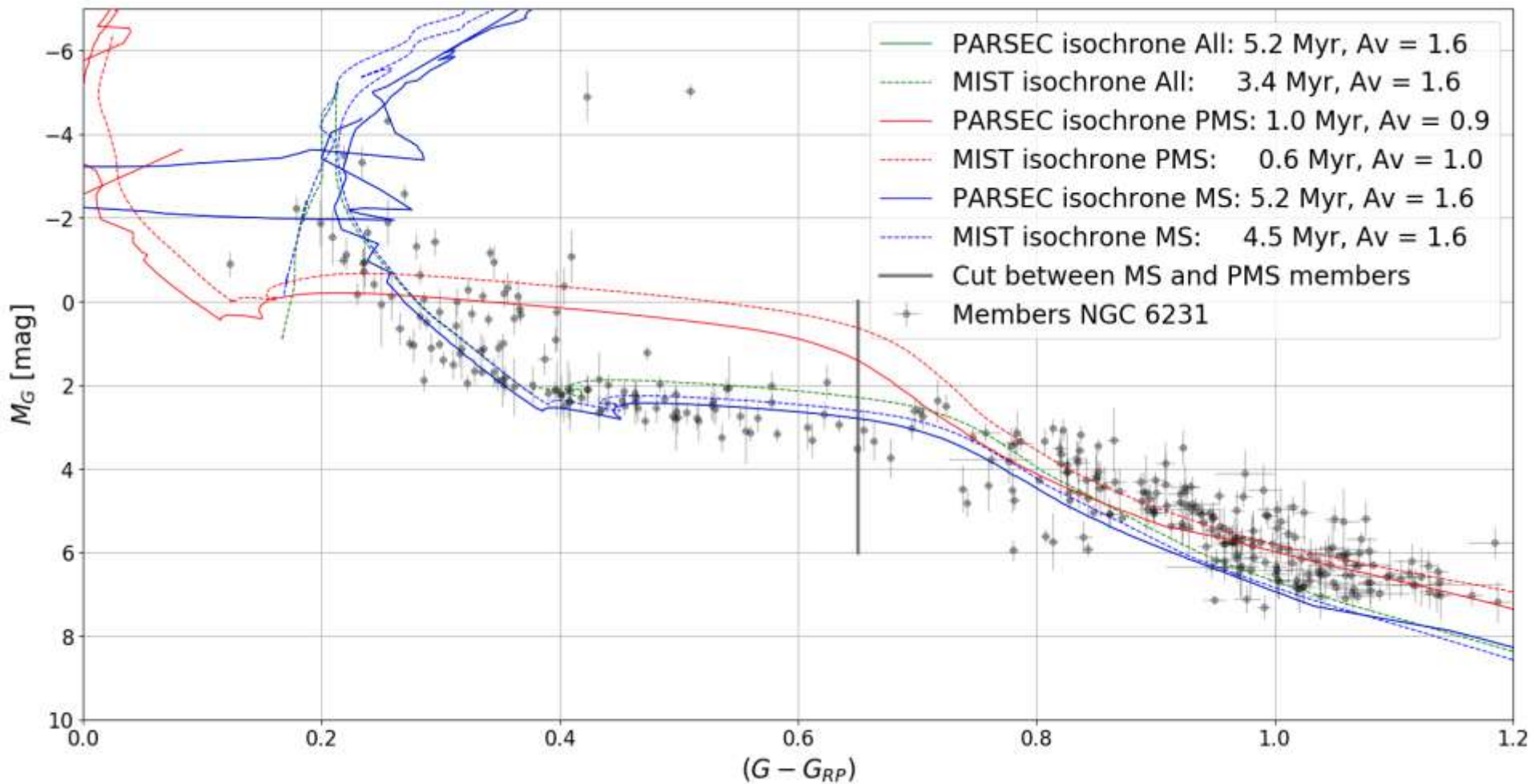
Sco OB1:  $\sim 8 \text{ Myr} \rightarrow M_{\text{turn-off}} \sim 25 M_{\odot}$

NGC6231:  $\sim 4 \text{ Myr} \rightarrow M_{\text{turn-off}} \sim 40 M_{\odot}$

# Nieuwe analyse *Gaia* (Vincent van der Meij, Difeng Guo et al. 2021)



# Leeftijdsbepaling NGC6231



# Evolutionaire geschiedenis 4U1700-37



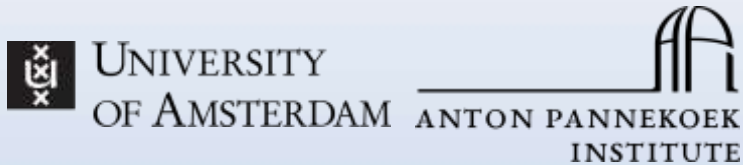
- O6.5Iaf+ supergiant plus neutronenster / zwart gat verliet NGC6231 2.2 Myr geleden met een snelheid van 63 km/s
- Huidige leeftijd NGC62131 is 4.7 +/- 0.4 Myr
- Turn-off massa NGC6231 ten tijde van supernova impliceert dat de exploderende ster een massa had > 60 Mzon
- Tijdens de SN werd 7 Mzon verloren: compact object is meest waarschijnlijk een (zware) neutronenster.



Two waves of massive stars running away from the young cluster R136

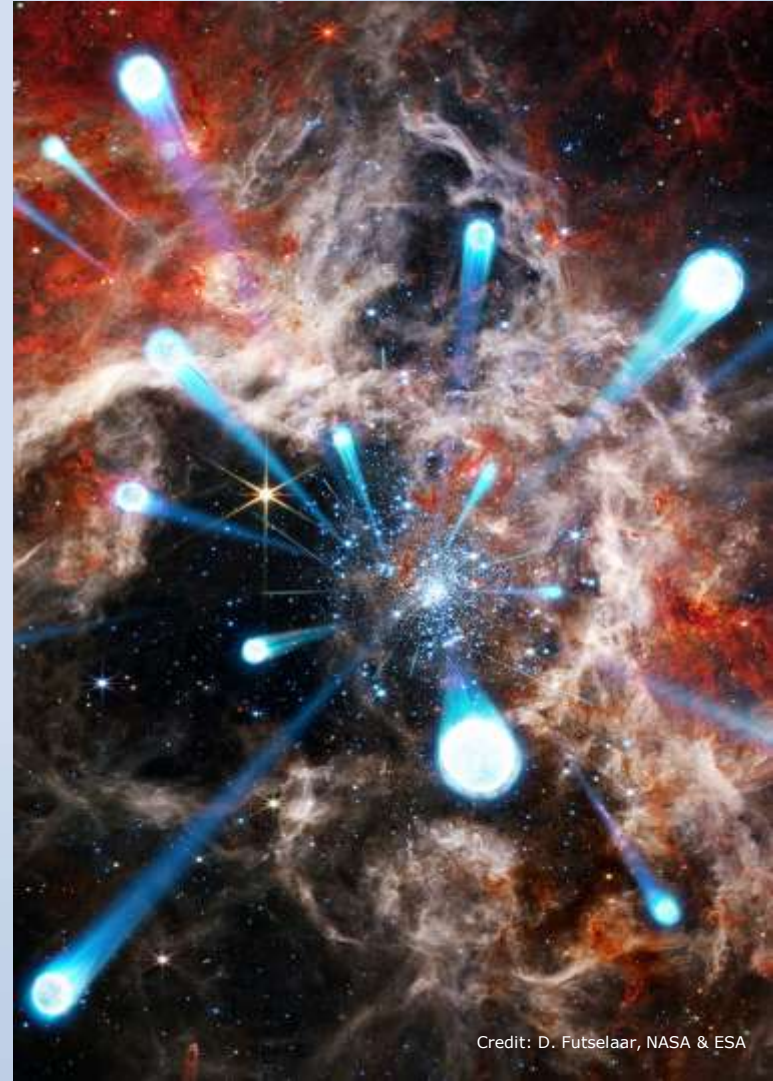
Mitchel Stoop

University of Amsterdam

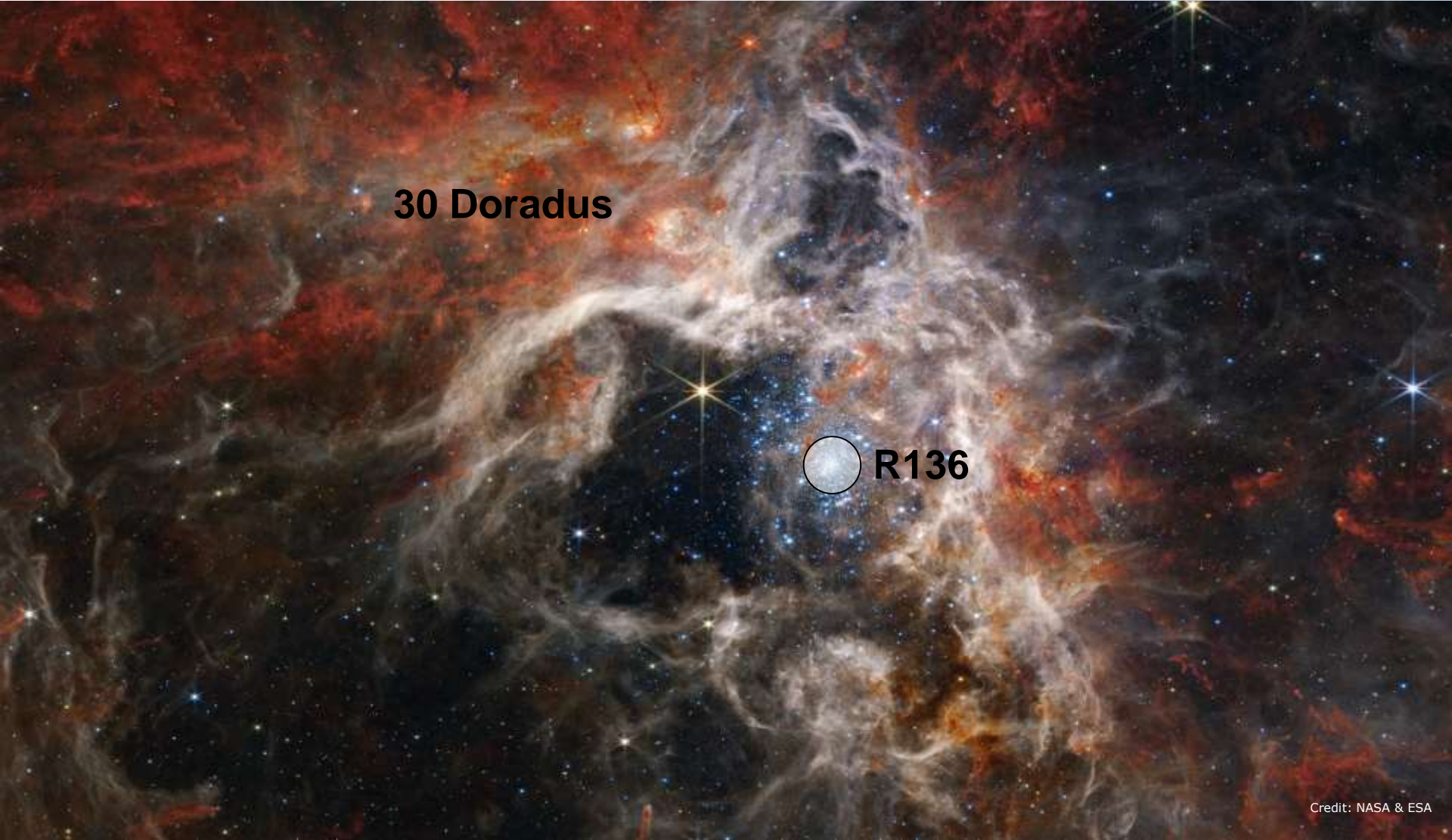


Stoop *et al.* (2024), *Nature* 9 oktober (online)

Alex de Koter, Lex Kaper, Sarah Brands, Simon Portegies Zwart, Hugues Sana, Fiorenzo Stoppa, Mark Gieles, Laurent Mahy, Tomer Shenar, Difeng Guo, Gijs Nelemans, Steven Rieder



Credit: D. Futselaar, NASA & ESA



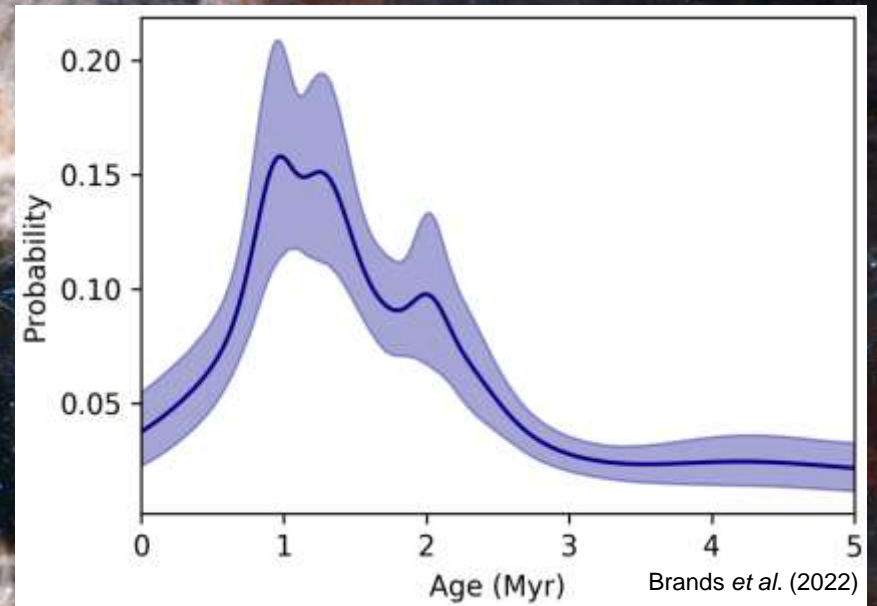
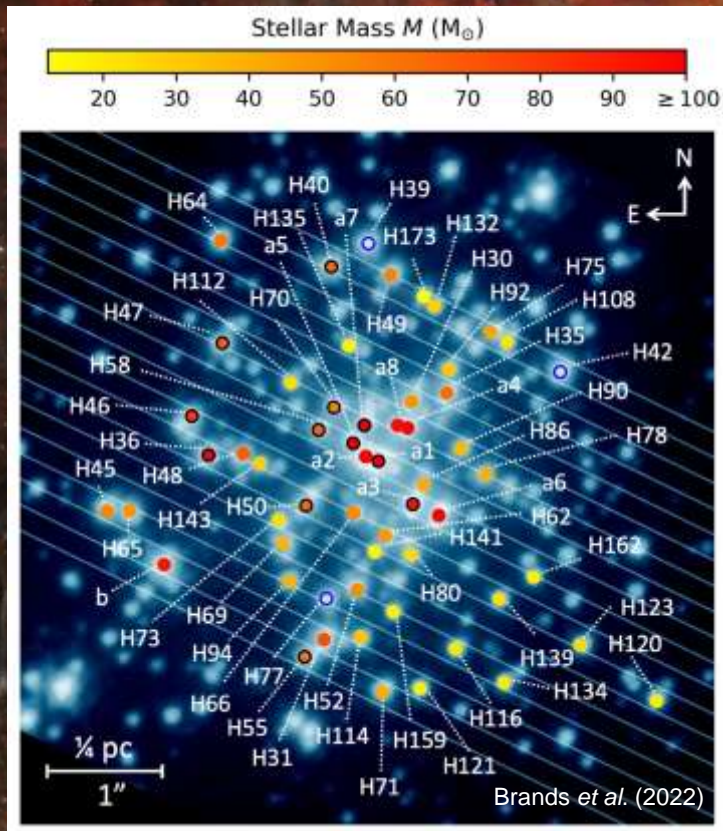
30 Doradus

R136

Credit: NASA & ESA

Tarantula nevel in LMC (opname JWST)



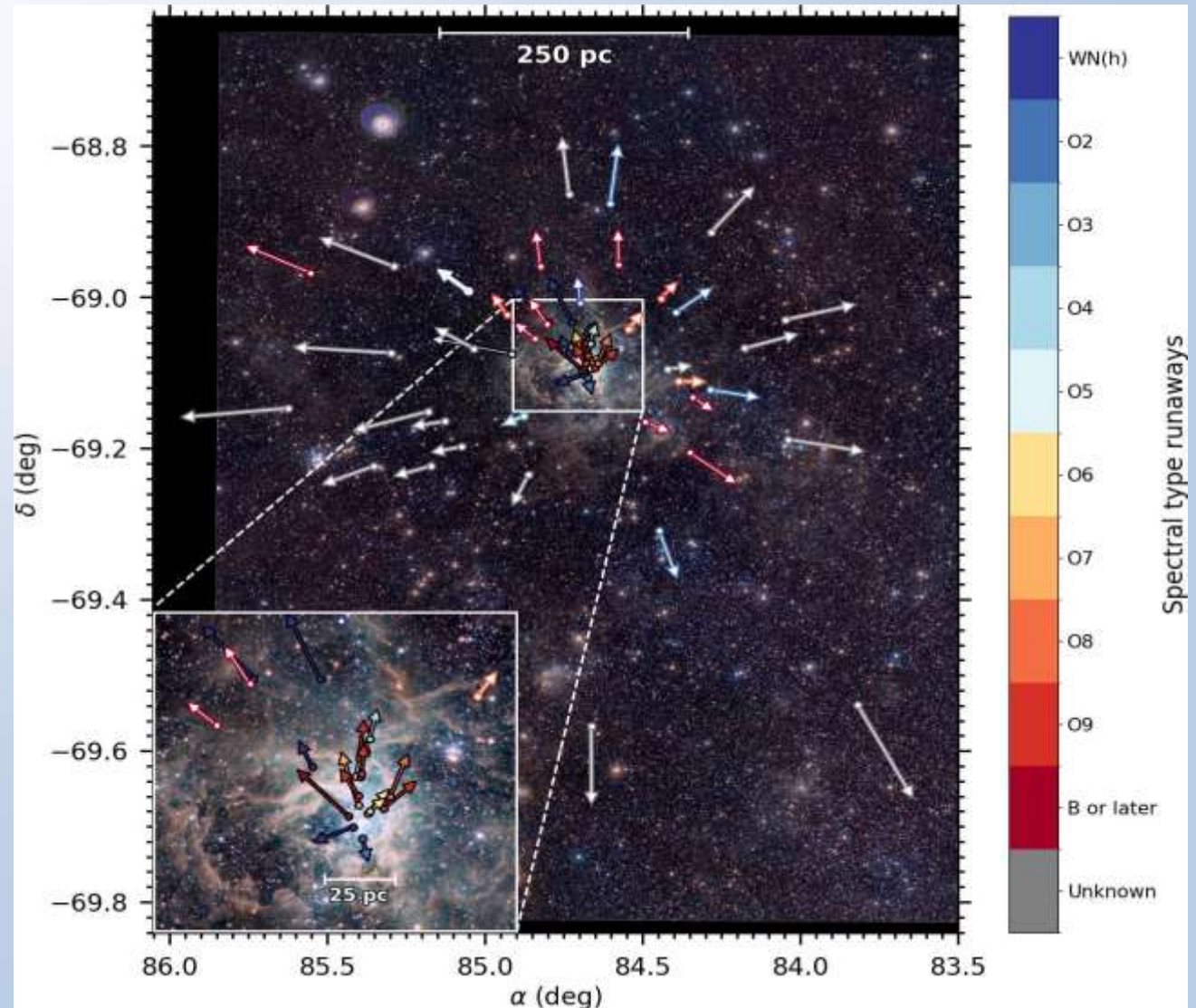


# R136: cluster in de Grote Magelhaense Wolk

55 runaways!

Spectraal type:

- 5 WN(h)
- 6 O2/3 type
- 6 O4-6 type
- 11 O7-9 type
- 9 B of later type
- 18 onbekend





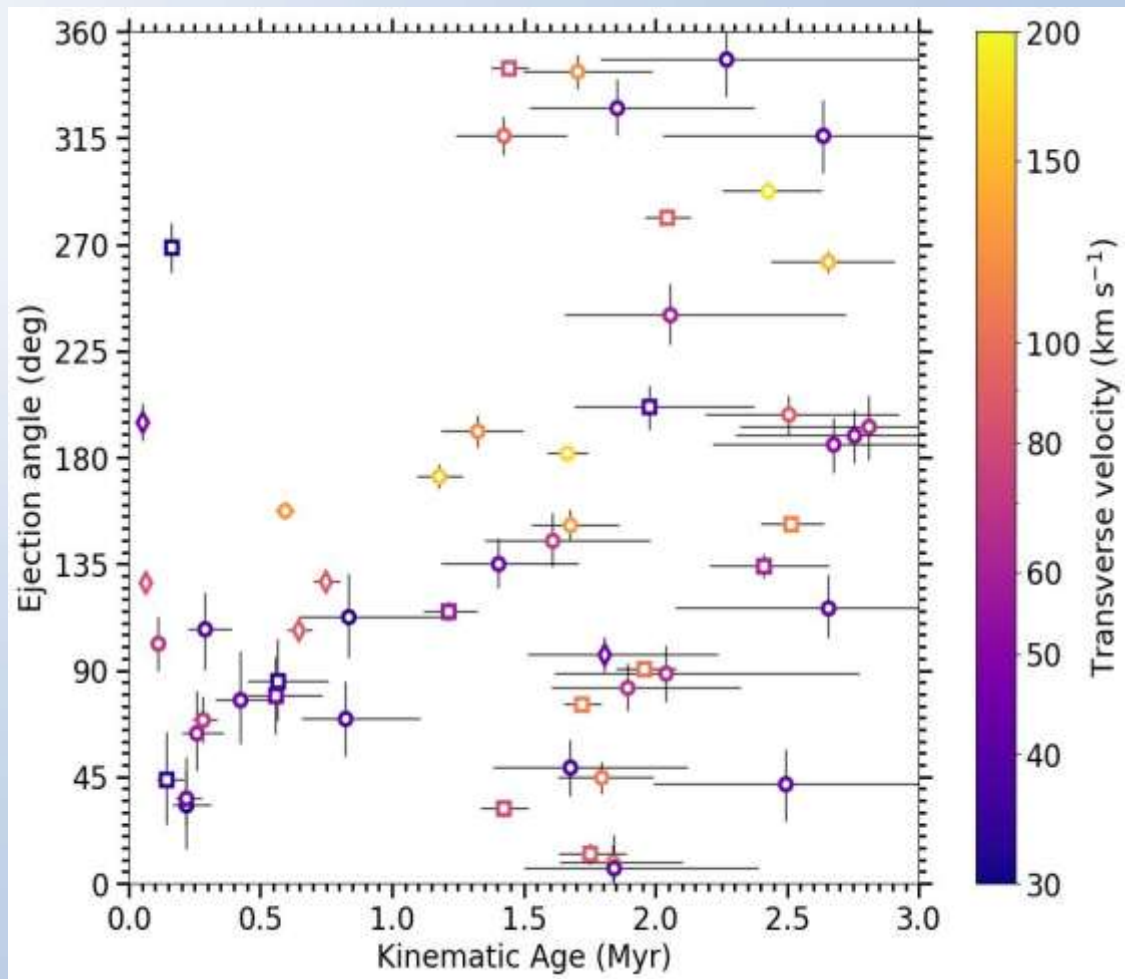
# Richting van lancering

$t_{\text{kin}} > 1.0$  Myr:

- Symmetrisch / isotroop

$t_{\text{kin}} < 1.0$  Myr:

- Asymmetrisch / anisotroop
- $> 3\sigma$  waarschijnlijk

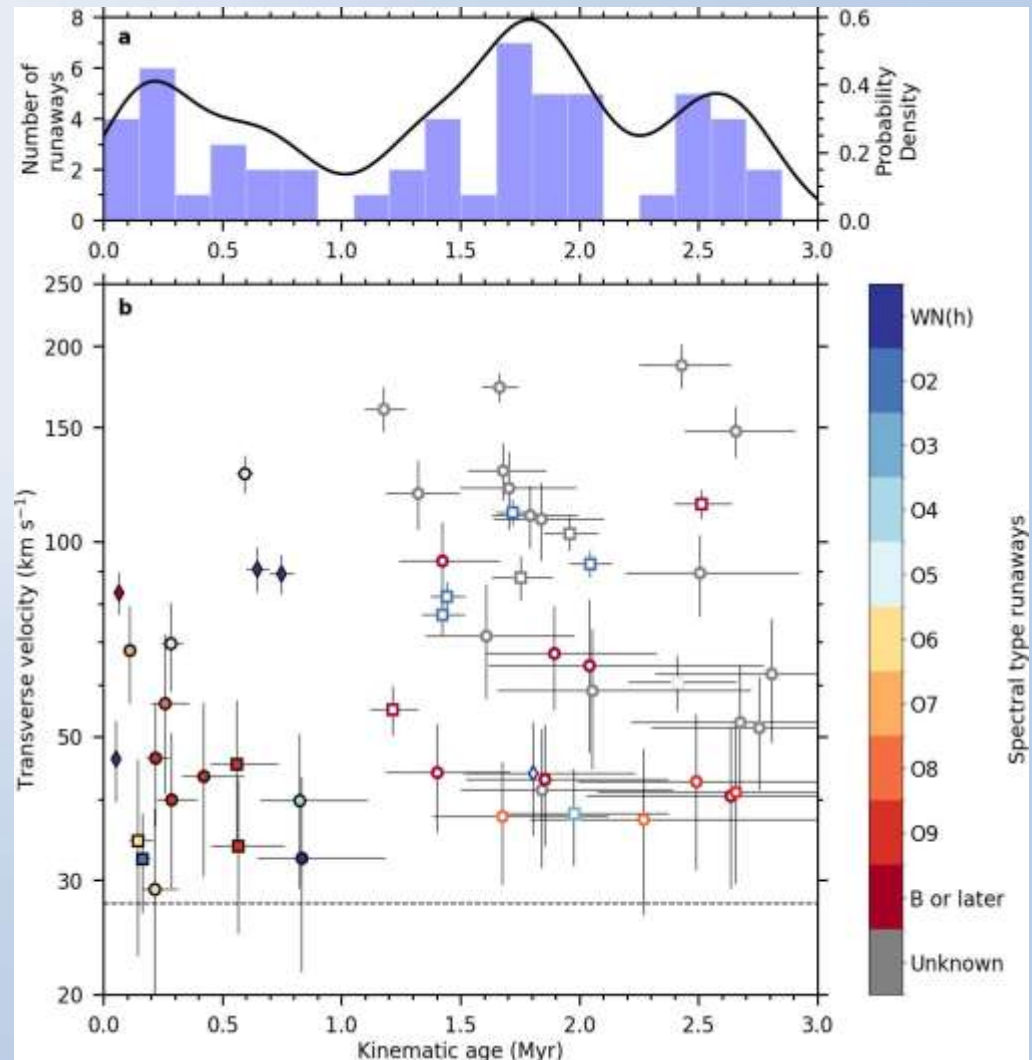


# Kinematische leeftijd

Runaways met  $v_T$  tot  $200 \text{ km s}^{-1}$

$t_{\text{kin}}$  distributie:

- Piek rond 0.2 Myr
- Dip rond 1.0 Myr
- Piek rond 1.8 Myr
- $2.5\sigma$  betrouwbaarheid



# Evolutionaire leeftijd ( $\tau_{evo}$ )

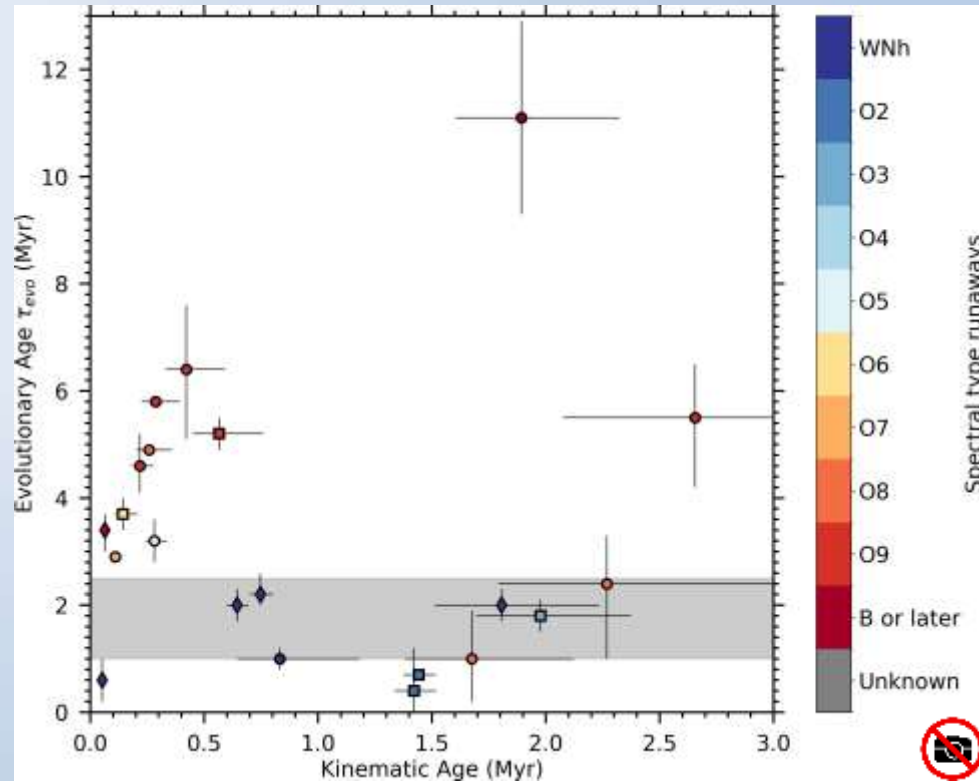
21 van de 55 *runaways* hebben  $\tau_{evo}$

$t_{kin} < 1.0$  Myr:

- $\tau_{evo}$  tussen 3 - 7 Myr

$t_{kin} > 1.0$  Myr:

- $\tau_{evo}$  tussen 0 - 2.5 Myr



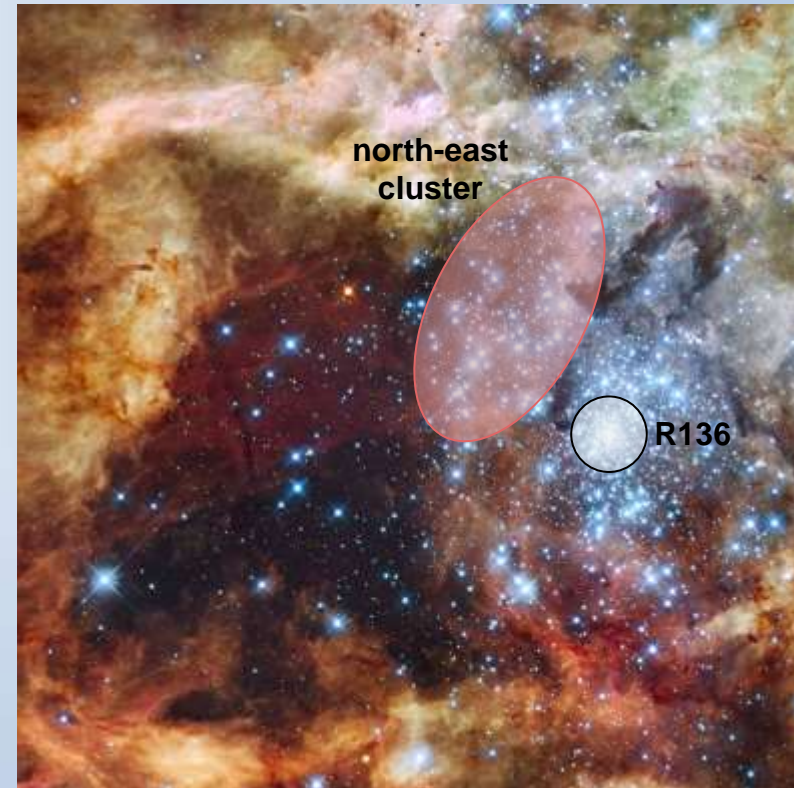
# R136 - noord-oostelijke cluster

$t_{\text{kin}} < 1.0$  Myr:

- Gelanceerd in een voorkeursrichting
- Evolutionair ouder (3 - 7 Myr old)
- Specifiek moment (0.2 - 0.8 Myr ago)

Wijst op een eerdere interactie van R136 met de noord-oostelijke cluster

Sabbi *et al.* (2012): 2-5 Myr old sub-cluster

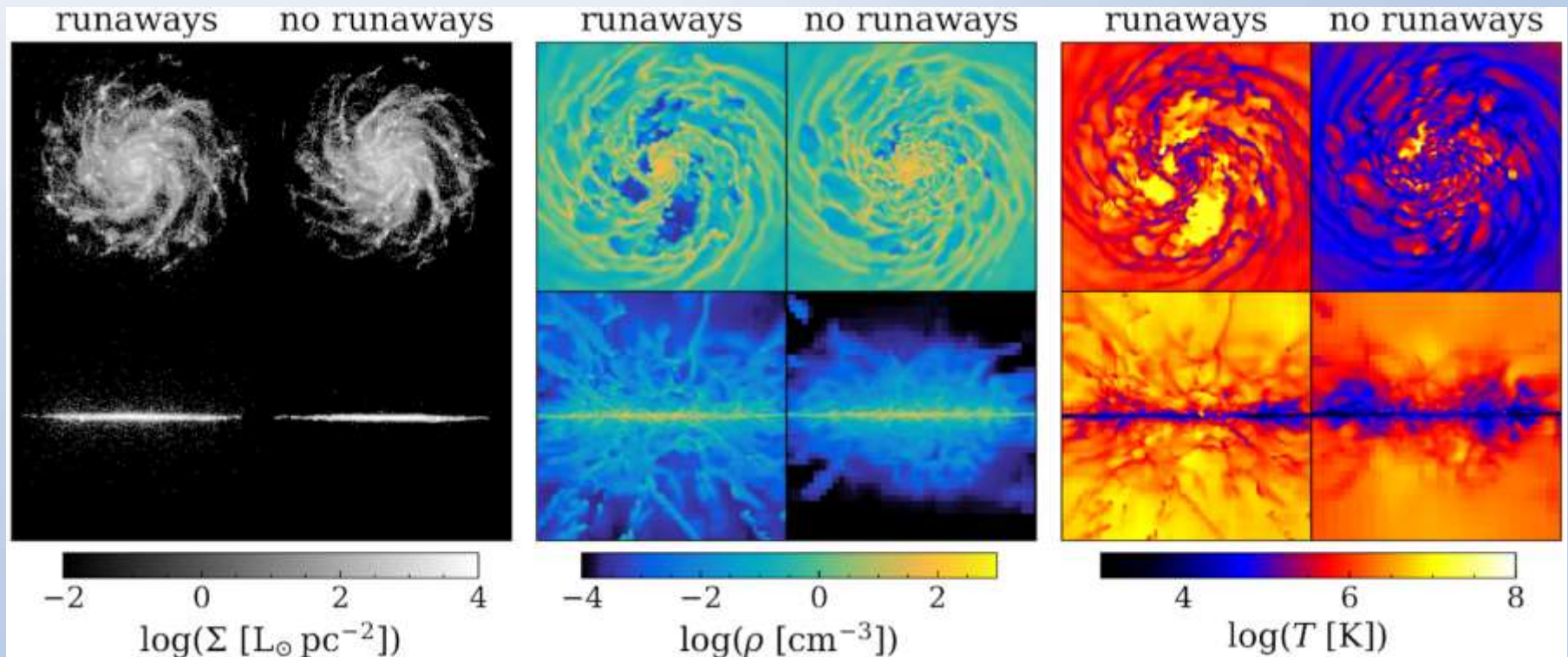


Stoop et al. (2024)



# Hoe runaways materiaal uit stelsel blazen

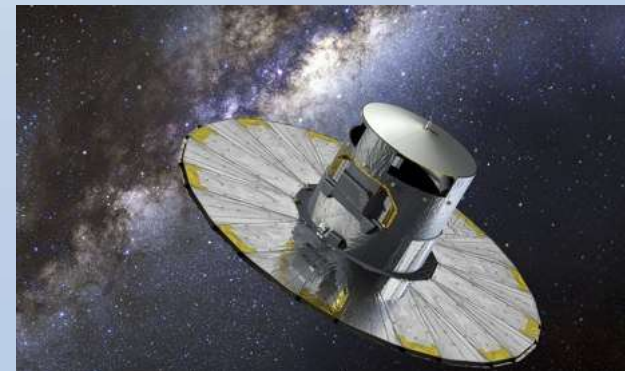
- Runaways reizen honderden parsec voordat zij als supernova ontploffen in het lege ISM
- Hydrodynamische simulaties spiraalstelsel: 10% runaway fractie
- Tien keer zo sterke galactische uitstroom!



# Conclusies



- *Runaways* verschaffen belangrijke informatie over de oorsprong en evolutie van zware sterren en de dynamische evolutie van sterclusters.
- Zij hebben een grote invloed op de dynamische en chemische evolutie van een melkwegstelsel.
- Botsingen van sterren veroorzaken de lancering van een belangrijke fractie van de zware sterren die in de cluster geboren zijn.





# Wind bow shock



$\zeta$  Oph O9.5 V

WISE (3 - 22  $\mu\text{m}$ )