

# XXI Simposio Peruano de Física



## La compleja historia de formación estelar en la región IC1396

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# ¿Cúmulos?

Aglomeraciones 1 pc.

HD206267

Laboratorios ideales para estudiar la formación estelar

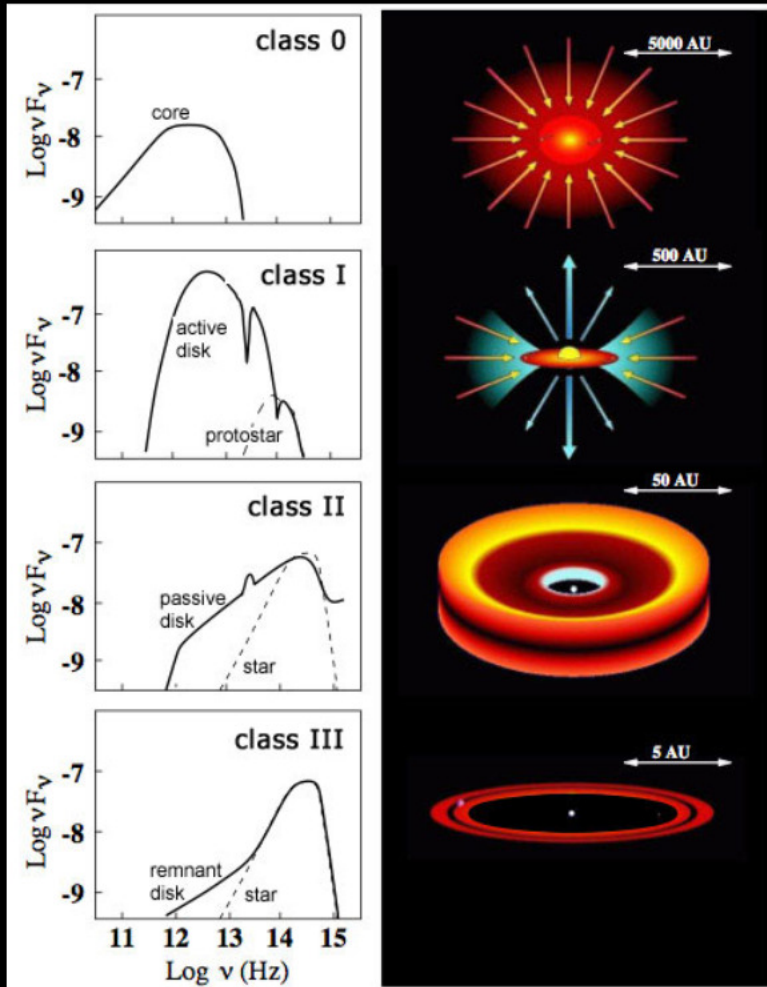
Todas las estrellas están a la misma **distancia**

Todas las estrellas tienen la misma **edad**

Todas tienen la misma **historia de formación**

Mosaico WISE (W4=22.19  $\mu\text{m}$ ) T=90-700 K

# Young Stellar Objects (YSOs)



Tomado de la tesis Andrea Isella (2006)

**Colapso "Clump"  
pre-estelar (0.1-0.2  
pc)**

**Protoestrella (material  
coexiste infall-outflow)**

**Formación del disco  
protoplanetario**

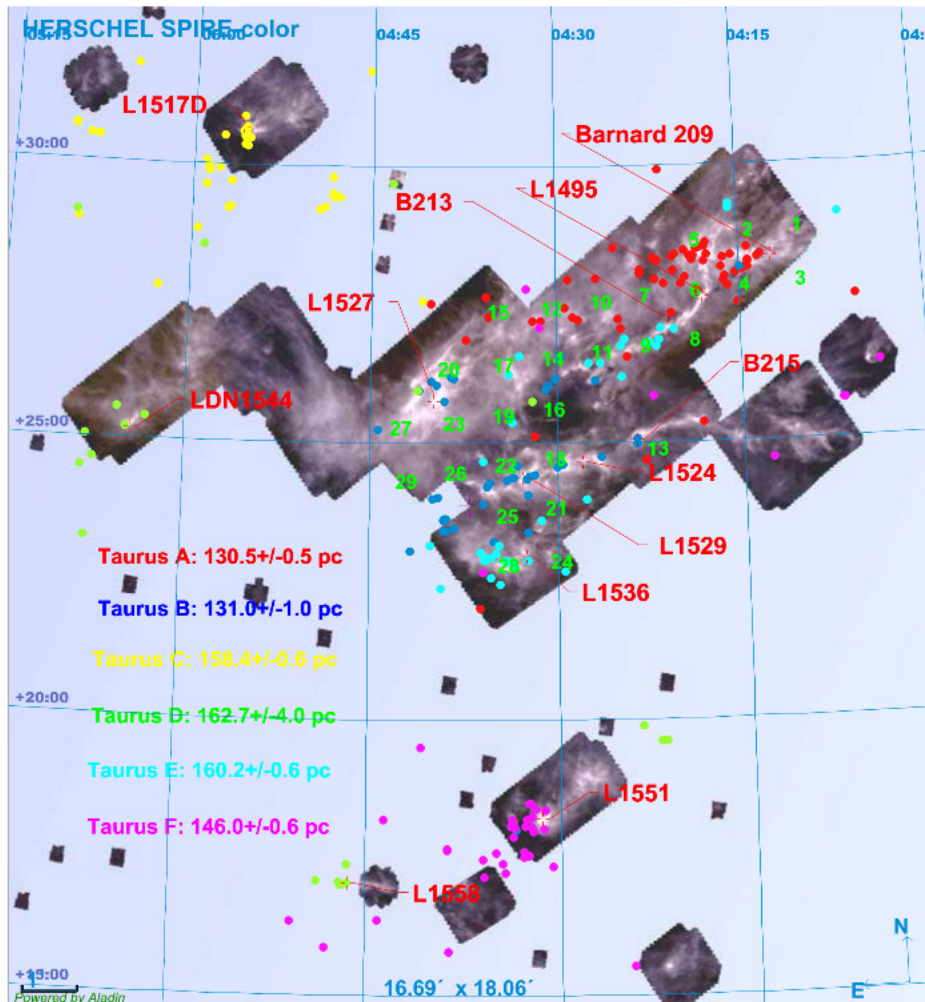
**Estrella PMS con un  
sistema planetario**

Formación de cúmulos en estructuras filamentosarias (Dale et al 2012)  
Regiones de formación estelar (e.g. André et al 2010)

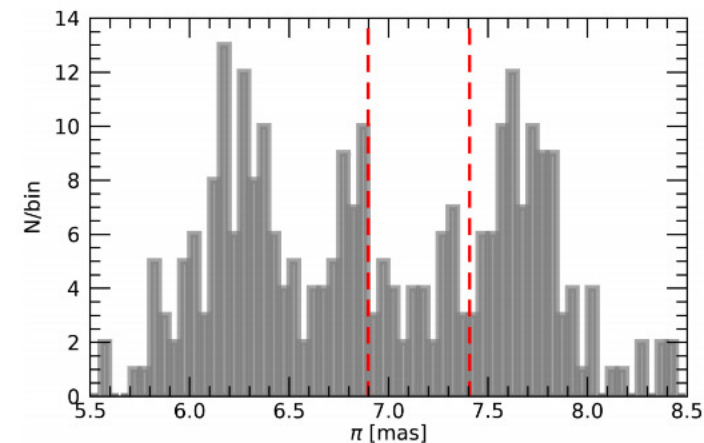


# Región de Taurus

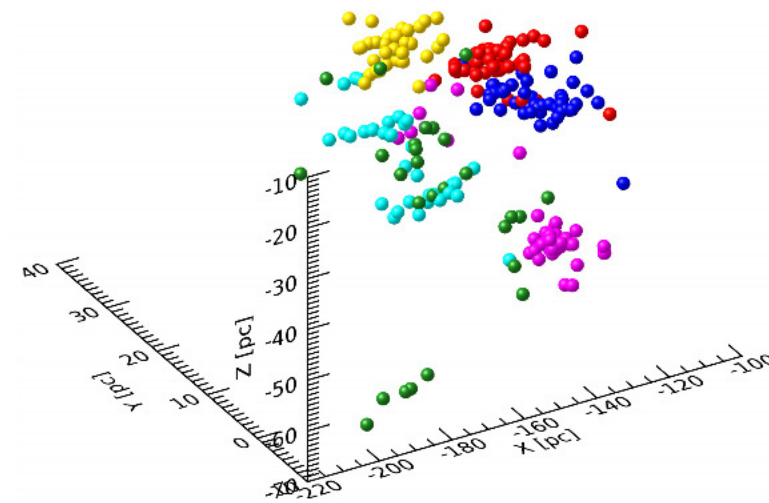
A&A 638, A85 (2020)



**Fig. 6.** *Herschel* RGB color composition using all public SPIRE observations from the *Herschel* Science Archive at 250  $\mu\text{m}$  (blue), 350  $\mu\text{m}$  (green), and 500  $\mu\text{m}$  (red). The filled circles represent the most probable members of Taurus A (in red), Taurus B (in blue), Taurus C (in yellow), Taurus D (in green), Taurus E (in cyan) and Taurus F (in magenta). With *Taurus Main* we refer to the Taurus complex excluding the clouds L1517D, LDN 1551 and L1558. The green numbers which appear only on *Taurus Main* correspond to the distances in parsec computed in those positions by Zucker et al. (2019). In red we indicate the names of the clouds in the region. At 150 pc the size of  $1^\circ$  corresponds to 2.6 pc.



**Fig. 1.** Histogram of the parallaxes of the Taurus members. The dashed red lines indicate the range in parallax commonly adopted in the literature.



**Fig. A.1.** Three-dimensional spatial distribution of the multiple populations. The color code is as in Fig. 4. An animation with different orientation of this plot is available [online](#).

[Roccatagliata et al 2020 A&A, 638, 85]

# IC1396

## Región H II

Mosaico WISE (W4=22.19  $\mu\text{m}$ ) T=90-700 K

HD206267

- Parte de la Burbuja de Cefeo (Patel et al 1998) a 945 pc (Sicilia-Aguilar et al 2019)
- Ionizada (O5+O9, Maíz Apellániz y Barbá 2020)
- Cúmulo joven Tr37 (e.g Patel et al 1998). A 870 pc (Contreras et al 2002)
- Cientos de miembros de la región --> YSOs (emisión rayos-x, NIR, variabilidad, detección de exceso en el IR que indica discos)



# Gaia DR3: Compleja historia de formación estelar de IC1396

Astrometría para 1500 millones de estrellas  
Magnitud  $G=21$

[Pelayo-Baldárrago, SA, et al 2023, A&A 669.22]

# Caracterizando IC1396 con GAIA

## Selección miembros confiables

- Selección rigurosa de KM (incertezas)
  - KM + 2 nuevos miembros → 1538
- **Criterios:**
  - $f < 0.25$  (Bailer-Jones 2015)
  - $\text{RUWE} < 1.4$  (Lindgren, L. 2018)
  - $w = 0.6 - 1.6$  mas
- **KM confiables → 578 (53% KM)**
- Metodo: colección KM\* y conjunto inicial subcumulos
  - Caracterización – paralaje y cinemática KM
  - Conjunto inicial subcumulos: Identificación visualmente (7 parametros astrometricos)

\* Marschall and van Altena, 1987; Kun and Pasztor, 1990; Contreras et al., 2002; Mercer et al., 2009; Morales-Calderon et al., 2009; Sicilia-Aguilar et al., 2004, 2005, 2006a; Barentsen et al., 2011; Nakano et al 2012; Getman et al 2012; Rebull et al 2013; Sicilia-Aguilar et al 2013c, 2019; Meng et al, 2019.

## Función: Maximum likelihood

Significación → estructura subcúmulos → ML

Método: Franciosini et al 2018, Roccatagliata et al 2020, Lindegren et al 2000

$$P_{i,j} = f s_j \frac{L_{i,j}}{L_i}$$

$$L_{i,j} = (2\pi)^{2/3} |C_{i,j}|^{1/2} \exp\left[-\frac{1}{2}(a_i - a_j)^T C_{i,j}^{-1} (a_i - a_j)\right]$$

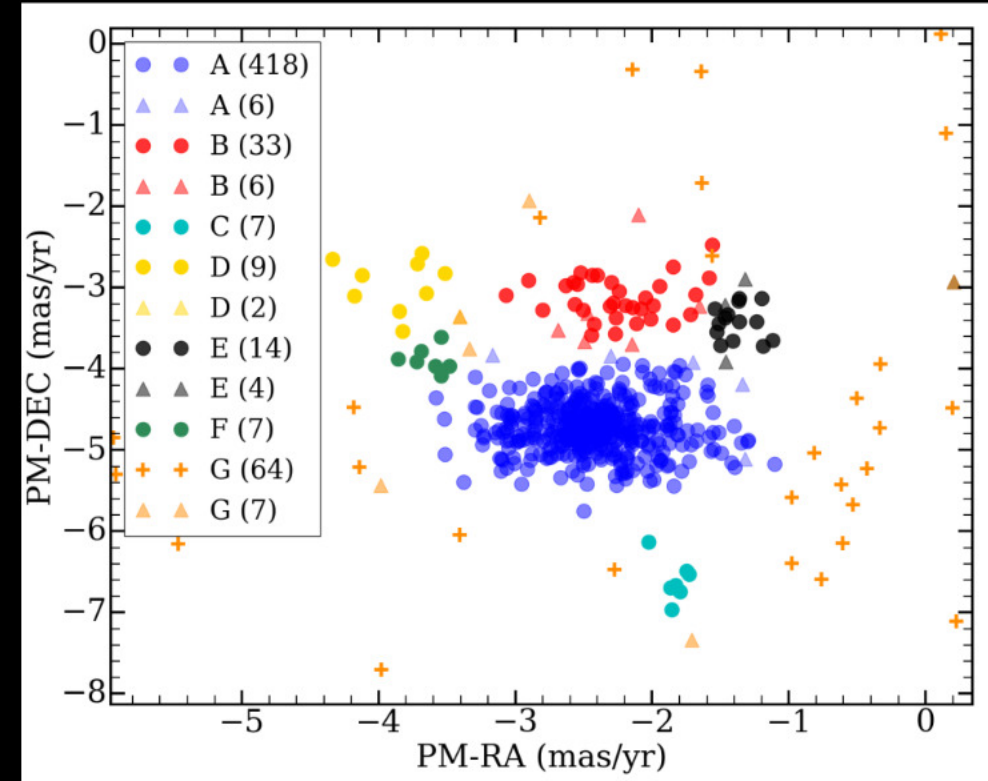
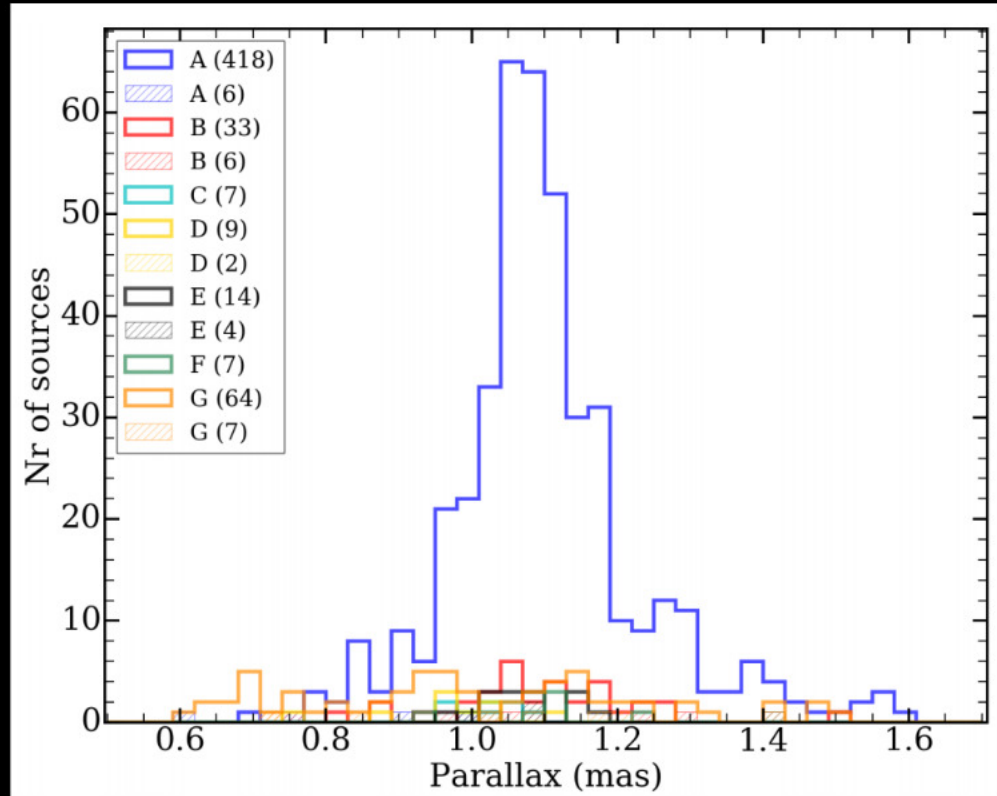
$$L_i = \sum_{j=1}^n f s_j L_{i,j}$$

In Eq. (2),  $a_{ij} = (a_i - a_j)$  is the vector that represents the difference between the astrometric parameter of the star vs each subcluster, and  $(a_i - a_j)^T$  is the transposed vector. Therefore,

$$a_i - a_j = \begin{bmatrix} \varpi_i - \varpi_j \\ \mu_{\alpha,i} - \mu_{\alpha,j} \\ \mu_{\delta,i} - \mu_{\delta,j} \end{bmatrix} \quad (\text{C.1})$$



# Análisis de Máxima probabilidad para los miembros conocidos.



- Se utilizó un espacio multidimensional de gaussianos para representar el espacio de la paralaje y el movimiento propio para los miembros conocidos.
- Siguiendo la técnica de Roccatagliata et al. 2019 se encontró 578 KM (*Know members*) con buena astrometría de un total 1538 candidatos
- Encontrando 7 poblaciones **[Pelayo-Baldárrago, SA, et al 2023, A&A 669.22]**



# Resultados: Análisis de Máxima probabilidad para los miembros conocidos.

**Table 7.** Results of the maximum likelihood analysis using the *Gaia* EDR3 data, showing the best-fit subcluster positions and standard deviations in parallax-proper motion space.

Subcluster/ Population	EDR3						Nr. of Stars	Distance (pc)
	$\varpi$ (mas)	$\sigma_{\varpi}$ (mas)	$\mu_{\alpha}$ (mas yr <sup>-1</sup> )	$\sigma_{\mu_{\alpha}}$ (mas yr <sup>-1</sup> )	$\mu_{\delta}$ (mas yr <sup>-1</sup> )	$\sigma_{\mu_{\delta}}$ (mas yr <sup>-1</sup> )		
A	1.101±0.006	0.130	-2.432±0.020	0.412	-4.719±0.015	0.308	418	908±73
B	1.098±0.022	0.128	-2.251±0.063	0.360	-3.131±0.044	0.252	33	911±75
C	1.002±0.013	0.035	-1.835±0.034	0.091	-6.603±0.091	0.241	7	998±61
D	0.963±0.030	0.090	-3.876±0.087	0.260	-2.954±0.100	0.301	9	1038±48
E	1.075±0.016	0.060	-1.374±0.036	0.133	-3.424±0.054	0.201	14	931±62
F	1.092±0.032	0.085	-3.632±0.046	0.121	-3.883±0.054	0.143	7	916±46
G	0.997±0.029	0.229	-1.909±0.645	5.159	-3.124±0.524	4.192	64	1003±70

**Notes.** The parallax and proper motion errors are listed here as the standard errors in the mean for each parameter, which define the mean properties of each subcluster. The  $\sigma_{\varpi}$ ,  $\sigma_{\mu_{\alpha}}$ , and  $\sigma_{\mu_{\delta}}$  are the standard deviation or the intrinsic dispersion of the astrometric parameters. Note the large scatter in the parameters of population G, which renders it unusable to identify new members. The final column shows the average distance for each group and its error.

# Analisis de membresía para los nuevos miembros (NM)

Distancia de Mahalanobis  $\approx$  Probabilidad gaussiana

i→ estrellas

j→ subcumulos

Pij

NM→ 95% → 334

M. E. Pelayo-Baldárrago et al.: Star formation history of IC1396

**Table 6.** Samples used with *Gaia* EDR3 data from our IC1396 stellar member analysis.

Sample	Nr. sources	Criteria	Code <sup>(*)</sup>
KM plus 2 new spectroscopic members	1538	Listed in the literature +Spectroscopy	KM
KM used for the maximum likelihood analysis	578	Fractional parallax error ( $f < 0.25$ ) RUWE $< 1.4$ . Parallax (0.6–1.6 mas)	–
New members obtained from the Mahalanobis distance	334	Errors magnitude $< 0.05$ mag Errors proper motion $< 0.1$ mas yr <sup>-1</sup> Age cut (0.1–10 Myr)	NM

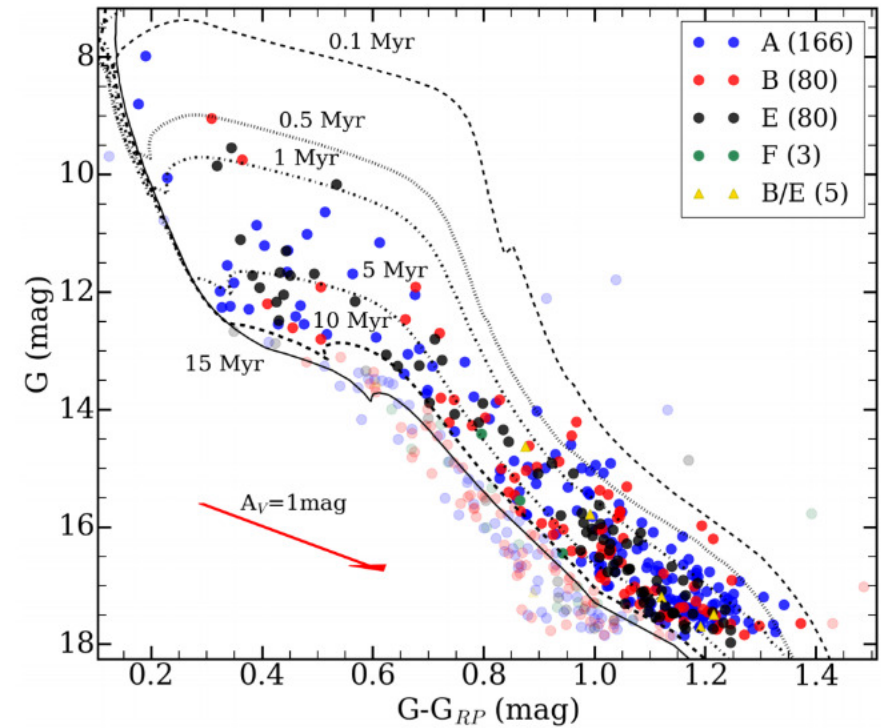
**Notes.** <sup>(\*)</sup>The code will be used throughout the paper for a better understanding of the sample used in the analysis.



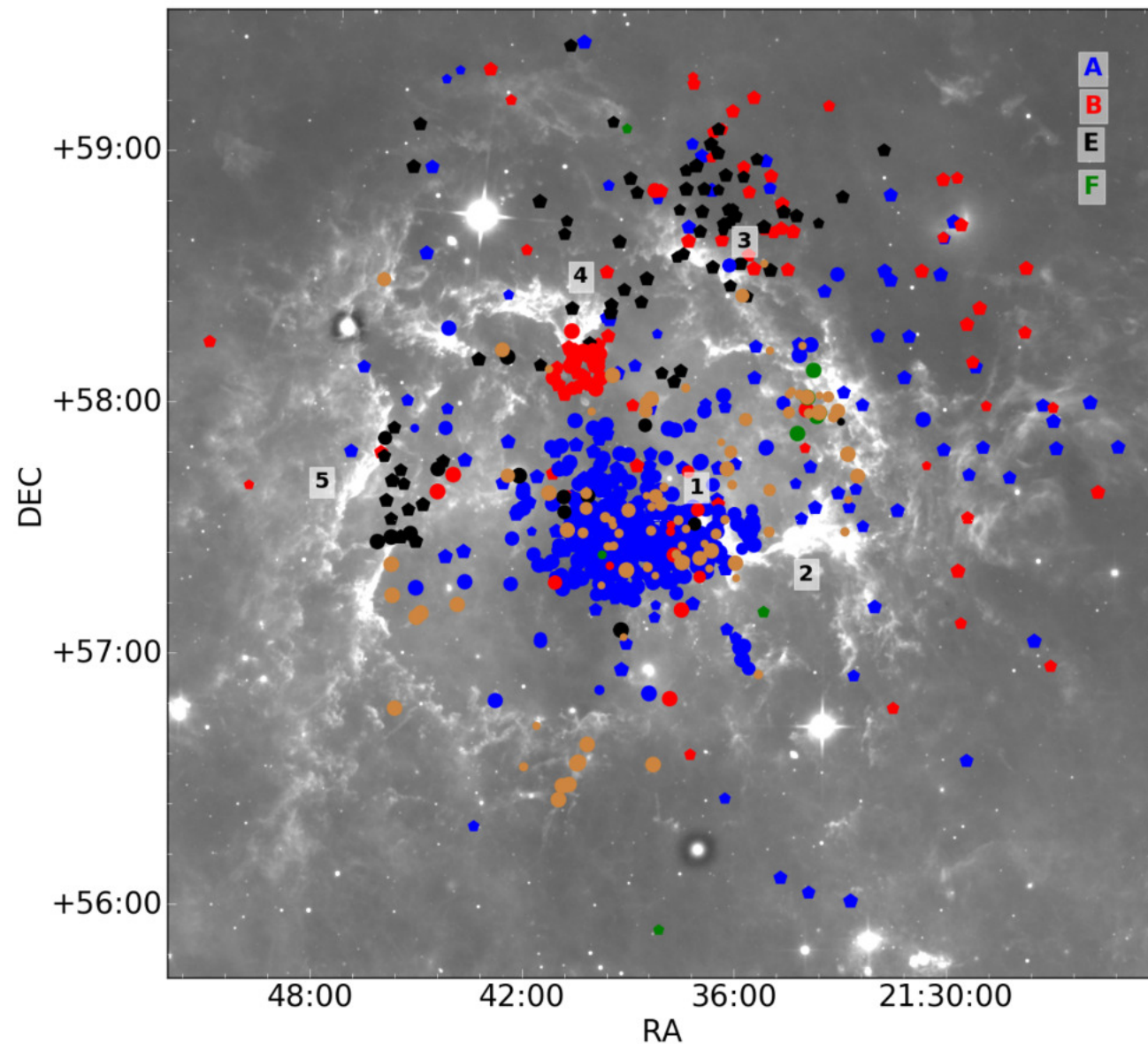
# Resultados de membresía para los 4 subcúmulos encontrados

Group	Maximum likelihood		Mahalanobis result		
	KM	KM	NM	NM	Total
	Total	0.1–10 Myr	Total	0.1–10 Myr	Rejected
A	418	388	234	166	15%
B	33	25	148	80	42%
E	14	11	92	80	14%
F	7	4	16	3	70%
B/E	–	–	7	5	–
Total	472	428	497	334	

**Notes.** *Column 1:* Subclusters obtained from the maximum likelihood considered in the Mahalanobis analysis. *Columns 2 and 3:* Total known members (KM) per cluster and those between the 0.1 Myr and 10 Myr isochrones. *Columns 4 and 5:* Total new members (NM) from the Mahalanobis analysis and those between the 0.1 Myr and 10 Myr isochrones. *Column 6:* Percentage of sources outwith the 0.1–10 Myr isochrones, including both the known and new members.



**Fig. 6.** Color-magnitude diagram for the new members obtained from Mahalanobis distance analysis with the *Gaia* EDR3 data. The 334 new members between 0.1 and 10 Myr are in full color, candidates with ages  $>10$  Myr are rejected and shown in semi-transparent color. The theoretical PMS tracks have been corrected for a distance of 925 pc and a lower limit of extinction of  $A_V = 1$  mag to reject foreground stars. Five members are plotted as triangles and belong to both subclusters B and E. We note there is an empty space between the 10 Myr and 15 Myr isochrones, which reinforces the criterion of considering as members only those up to 10 Myr. A vector extinction is indicated by a red arrow.



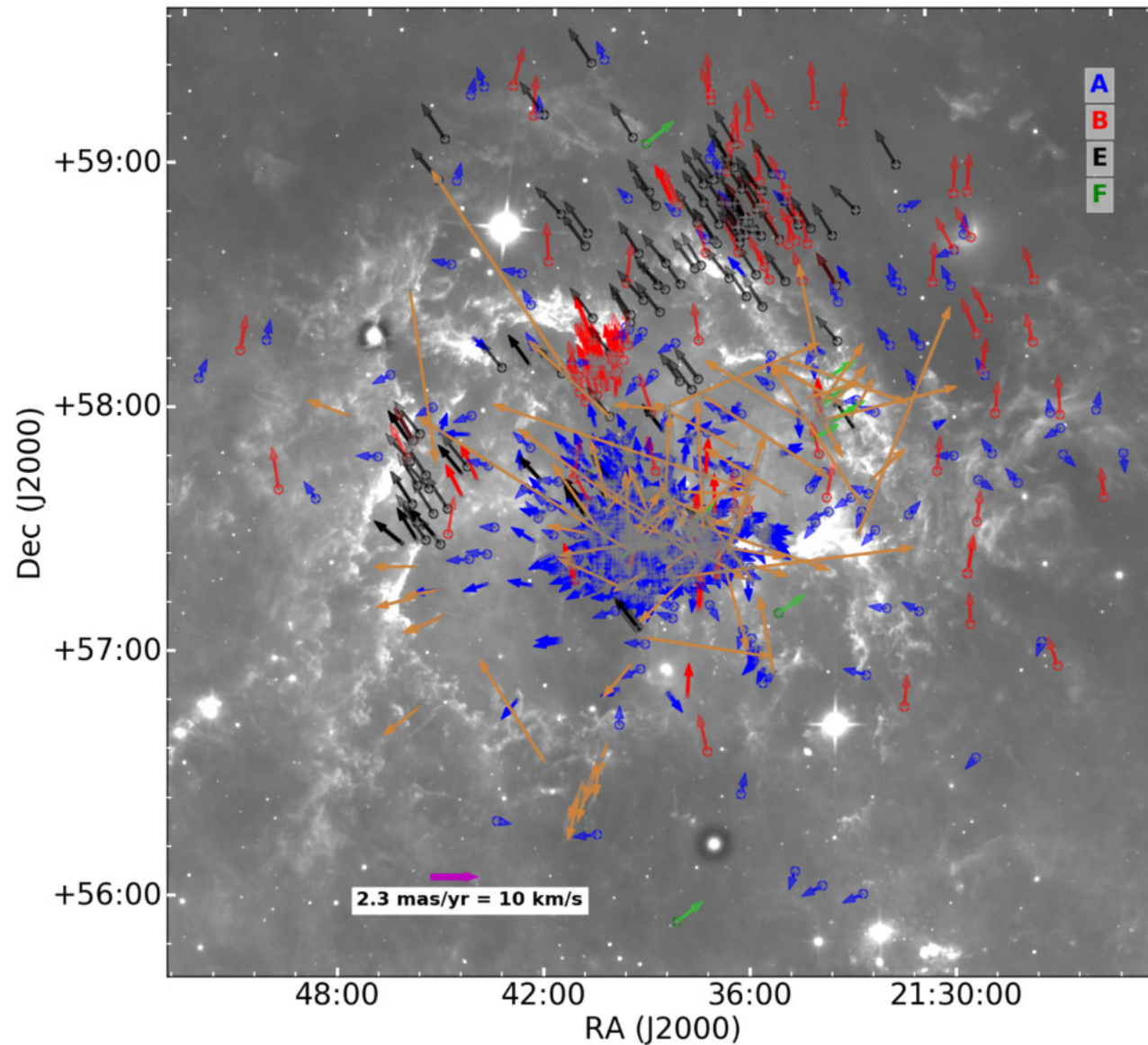
**Fig. 7.** Spatial distribution of the known (full-color circles) and new (pentagon) members. The colors represent the four subclusters (A, B, E, F, see legend). Orange circles mark the rest of the known members not belonging to any subcluster. The age of members (derived in Sect. 5.1) is represented by the symbol sizes, with the youngest members having large symbols ranging from 0.1 to 20 Myr. Black numbers indicate the main BRCs, 1=IC1396 A, 2=IC1396 B, 3=IC1396 D, 4=IC1396 N, 5=IC1396 G. The background image is a  $\sim 4^\circ \times \sim 4^\circ$  mosaic built from WISE 22.19  $\mu\text{m}$ .

# Estructura de IC1396

KM: círculos  
NM: pentagonos

[Pelayo-Baldárrago, SA,  
et al 2023, A&A 669.22]





**Fig. 9.** Map of the velocity dispersion in proper motion of known and new members. The arrows mark the direction and size of the proper motion vectors relative to the average proper motions of subcluster A. They are color-coded by subcluster (see legend). Known members not associated with any subcluster are shown in orange. The long orange arrows are mostly from the extended population G. New members are marked by open circles. The magenta arrow in the *bottom left corner* indicates the physical velocity scale (at 925 pc).

# Dispersión de la velocidad

Estructura de velocidad: Velocity Structure analysis tool (VSAT, Arnold & Goodwin 2019)

[Pelayo-Baldarrago, SA, et al 2023, A&A 669.22]

# Conclusiones

- Gaia DR3 revela una **compleja historia de formación estelar** revelando varias poblaciones claramente distintas en velocidad pero no en distancia. Además de la distribución espacial de los miembros --> **PROCESOS DE FORMACIÓN MULTIEPISODIOS**
- GAIA DR3 se confirma una distancia de  $925 \pm 73$  pc
- Se identificaron 4 subcúmulos nuevos y una población extendida
- Se encontró 334 nuevos miembros asociados a los cúmulos
- Región NO ESTA LIGADA gravitacionalmente y se está expandiendo como un todo

**Tenemos un nuevo entendimiento de la formación estelar, la estructura y cinemática de la región y en general de los cúmulos de alta masa**