The Orion Nebula Cluster as seen by VLBI

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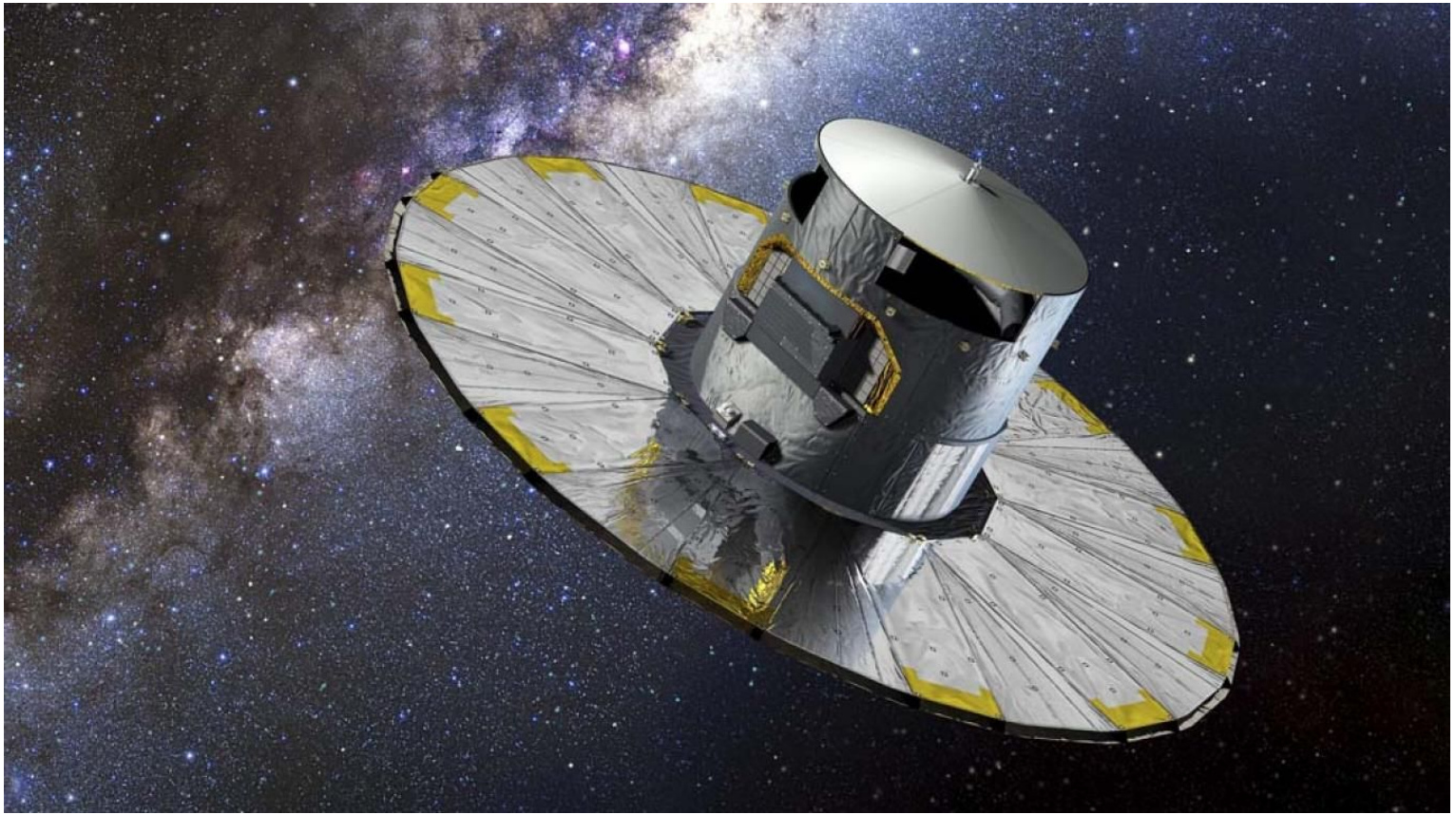
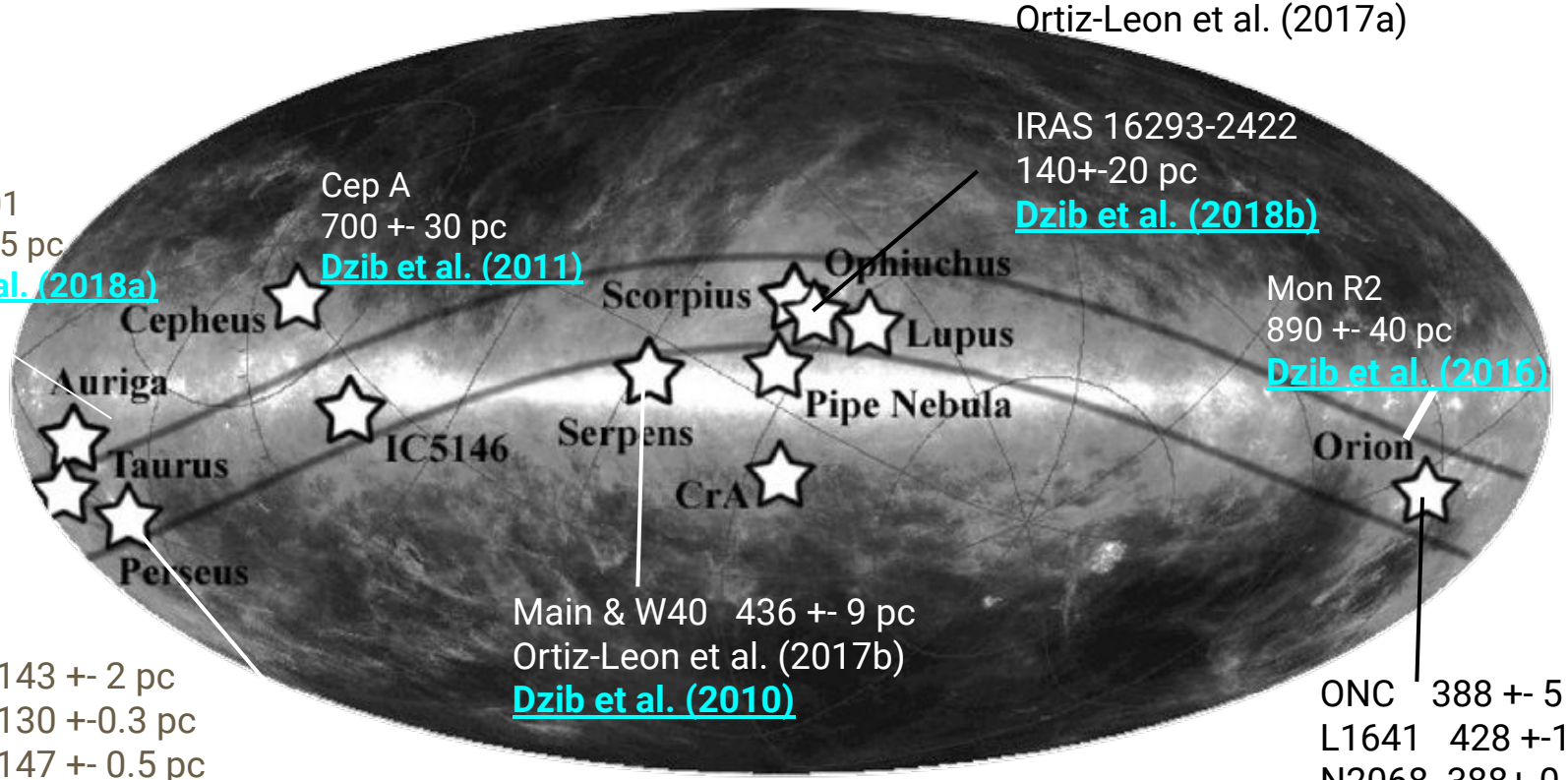
Gaia mission

Launched in December 2013



Gaia Satelite. Credits: ESA.

Distances with VLBA



L1689 147+-3 pc
L1688 137+-1 pc
Ortiz-Leon et al. (2017a)

IRAS 16293-2422
140+-20 pc
Dzib et al. (2018b)

LkHa 101
525 +- 25 pc
Dzib et al. (2018a)

Cep A
700 +- 30 pc
Dzib et al. (2011)

Mon R2
890 +- 40 pc
Dzib et al. (2016)

Main & W40 436 +- 9 pc
Ortiz-Leon et al. (2017b)
Dzib et al. (2010)

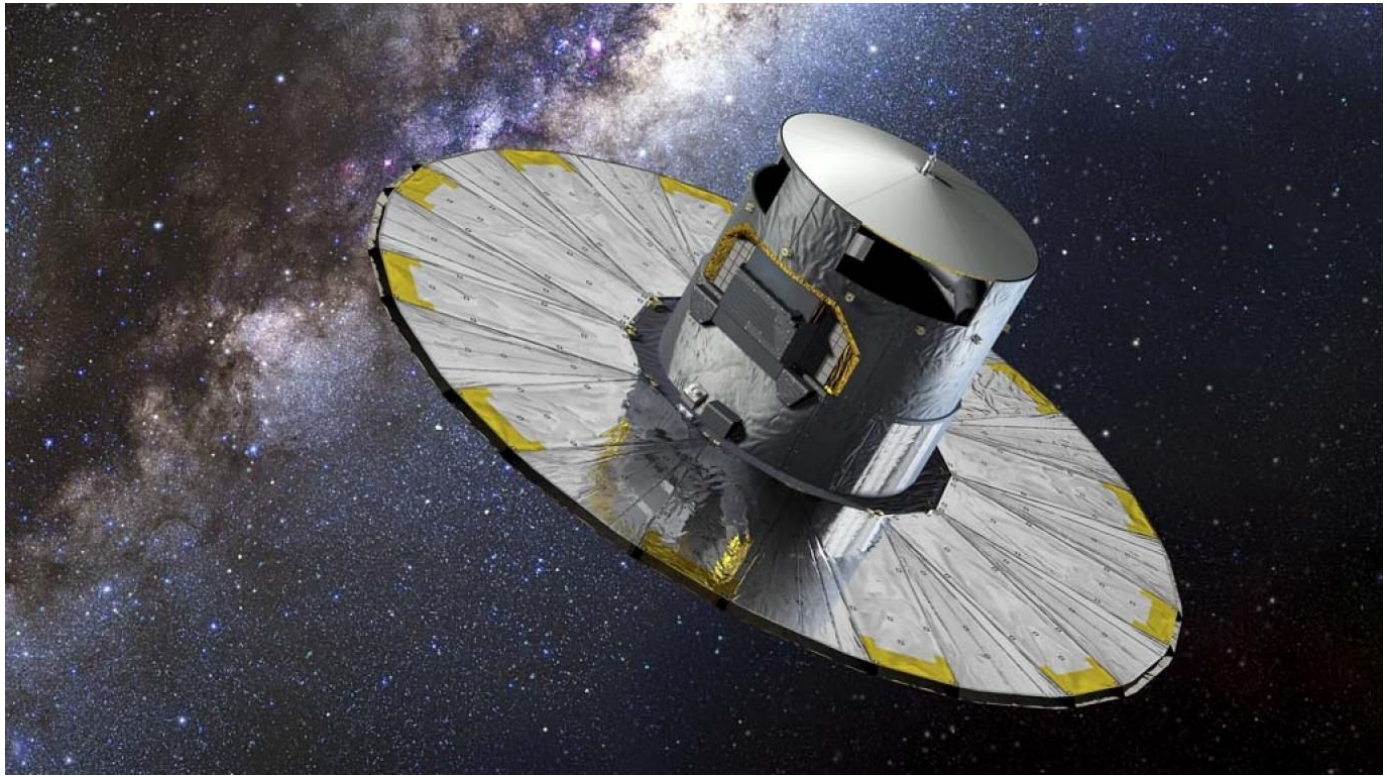
L1513 143 +- 2 pc
L1495 130 +-0.3 pc
L1551 147 +- 0.5 pc
L1534 137 +- 3 pc
Galli et al. (2018)

ONC 388 +- 5 pc
L1641 428 +-10 pc
N2068 388+-0.5 pc
N2024 423 +-15 pc
Kounkel et al. (2017)

Gaia mission

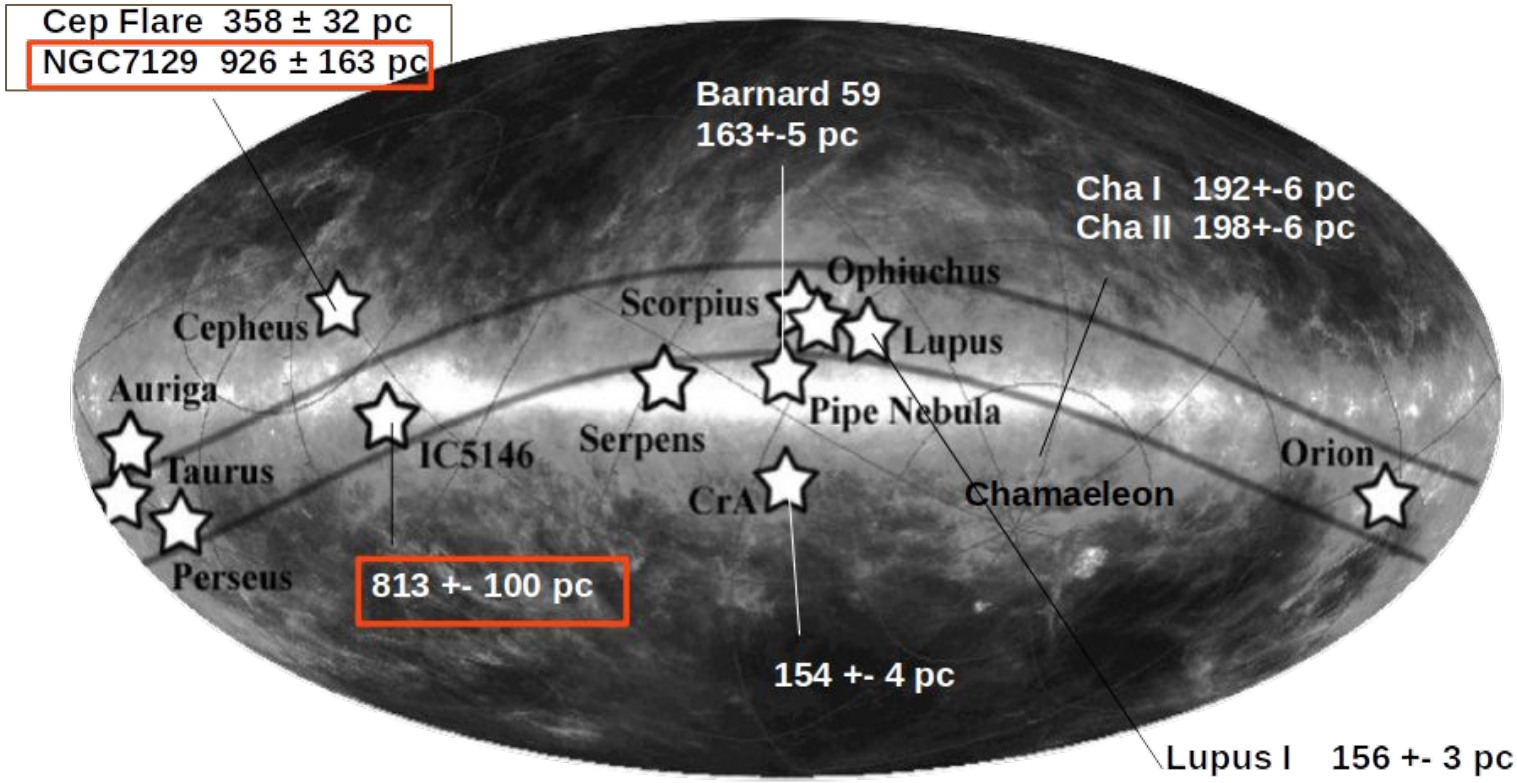
Gaia DR2 (2018)

Astrometry to ~1.5 billions stars



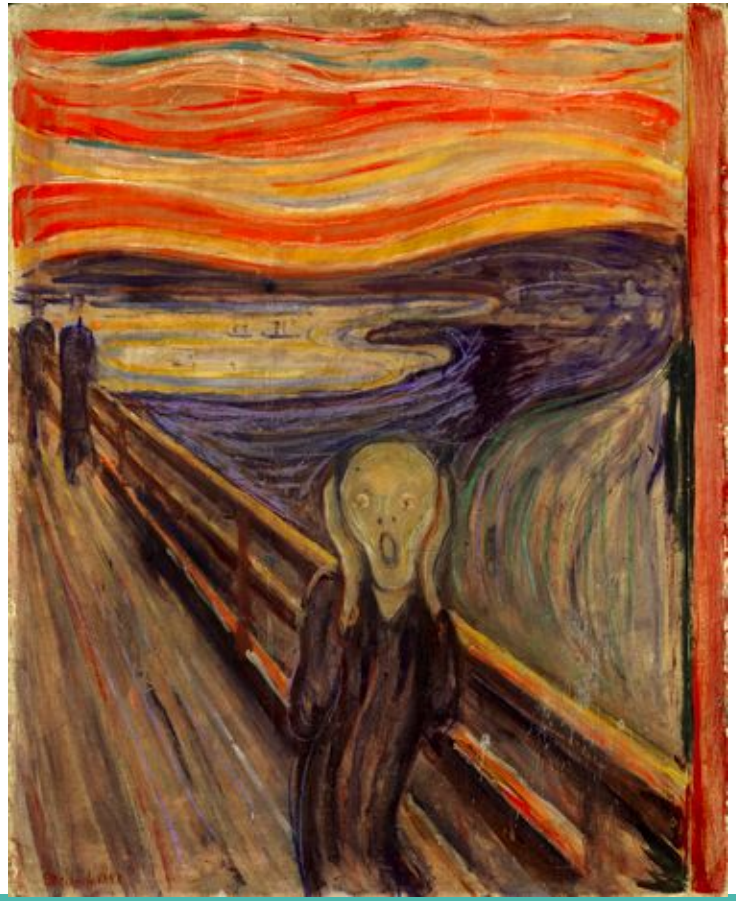
Gaia Satelite. Credits: ESA.

Distances with Gaia DR2



Dzib et al. (2018c, ApJ...867..151D)

What will happen with VLBI stellar astrometry to YSO?



Skrik
Edvard Munch
National Museum and Munch Museum, Oslo, Norway

What will happen with VLBI stellar astrometry to YSO?

- DYNAMO VLBA **(Jazmin's talk)**
- Increase the number of star with VLBI and Gaia astrometries to determine Gaia systematic errors **[Poster #30]**
- Learn other VLBI observation modes
  - M2FINDERS **[Poster #11]**
- Kinematic studies of young clusters.
  - Orion is the perfect target

Motivation

- How stellar clusters evolve?
  - Expanding, contracting, rotating?
  - Bulk motion
- Are there runaway stars?

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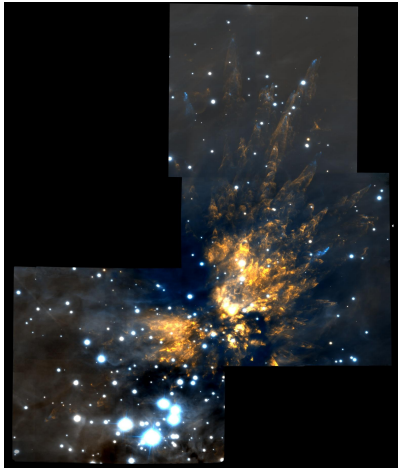
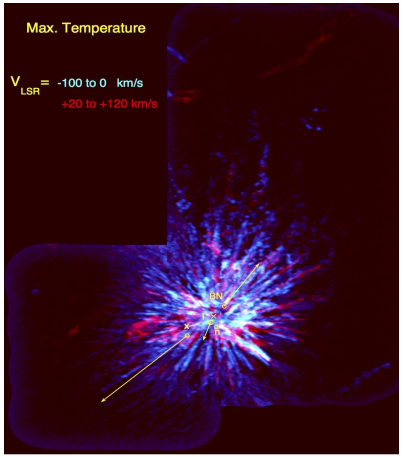
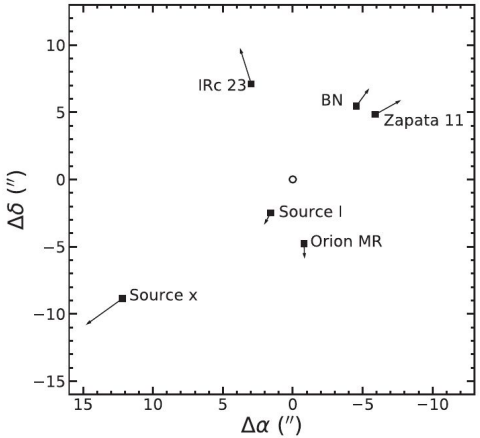




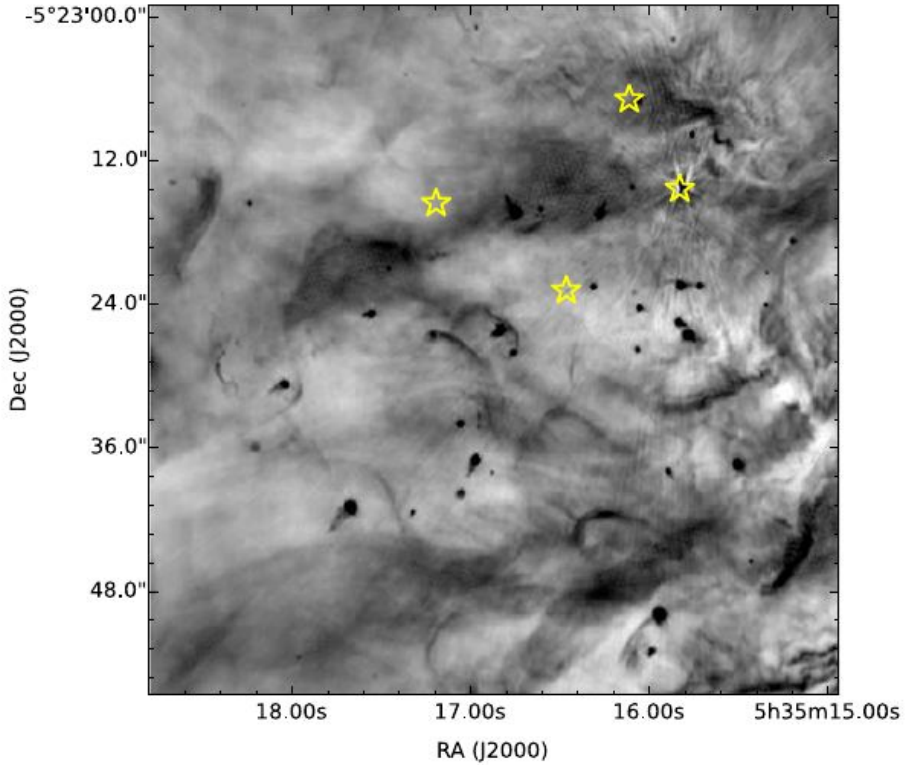
Bally et al. (2011); Zapata et al. (2011)



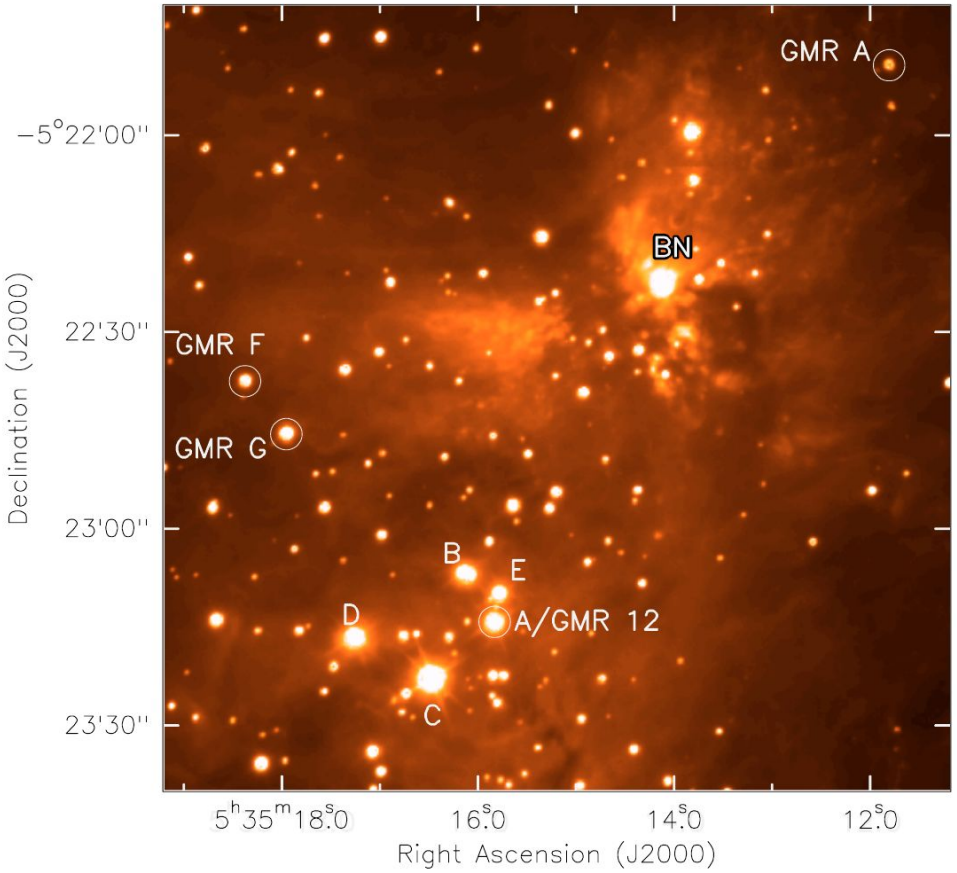
Rodriguez, Dzib et al. (2020)

Orion Nebula Cluster (ONC)

- Nearest (390 pc; Kounkel et al. 2017) region in which recently (<2 Myr) massive stars have formed.
- ~3500 members, and it is the most studied young cluster
- About 600 YSO with radio emission (Forbrich et al 2016, Vargas-Gonzalez et al. 2022)



ONC VLA image from Forbrich et al. (2016)



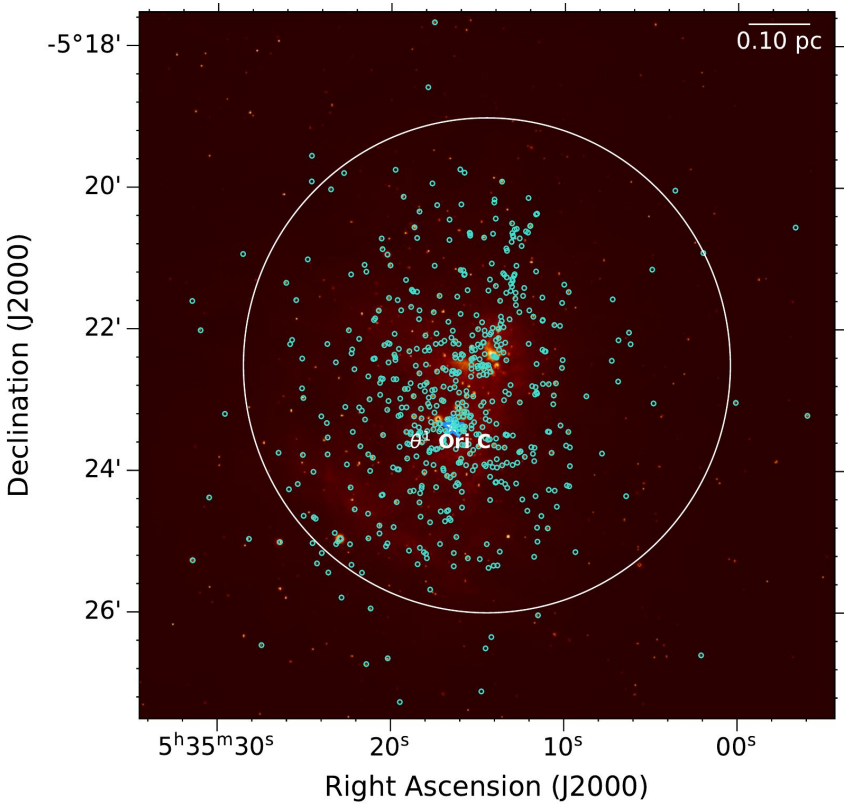
Menten et al. (2007)

1 observation

3 correlation passes

3x more time in correlator than telescope time

VLBA observations of Orion Nebula Cluster

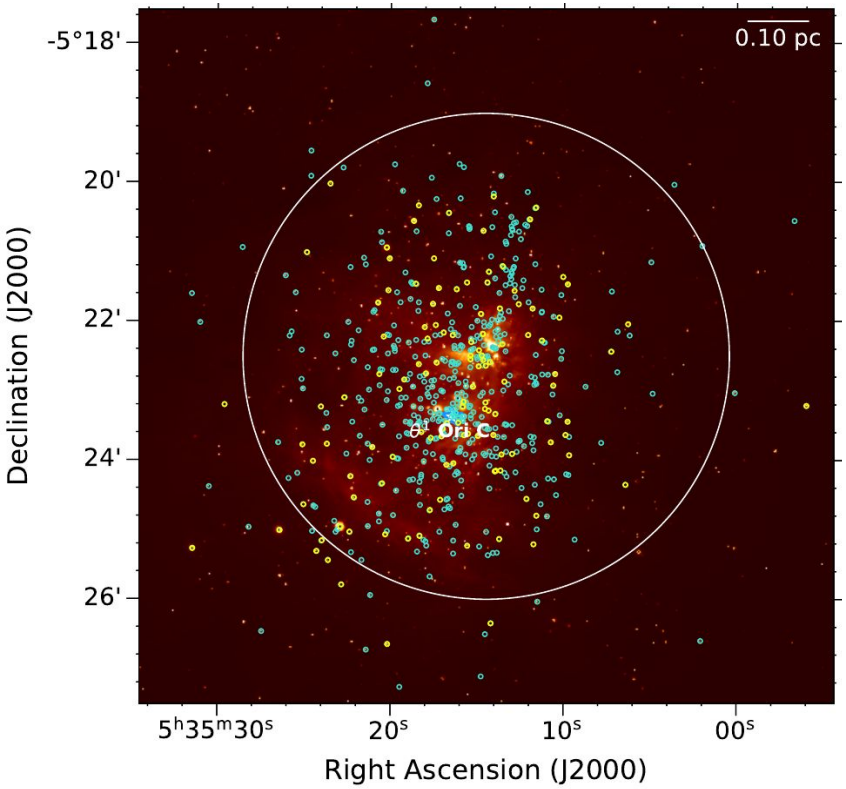


Frequency 7.0 GHz in four epochs

Correlate the position of the 557 radio sources known in the ONC.

- **~2200 independent images**

VLBA observations of Orion Nebula Cluster



Frequency 7.0 GHz in four epochs

Correlate the position of the 557 radio sources known in the ONC.

- ~2200 independent images

Detected 123 (22%) of the radio sources with S/N> 6.5

Detection results: Forbrich, Dzib, et al. (2021)

First astrometric results: Dzib, Forbrich et al. (2021)

Precise position measurements

We look for counterparts in the Gaia DR2 catalog and found 34.

Correcting for astrometry (parallax and proper motions), only 9 sources have separations < 1.5 mas with its Gaia associated source.

The remaining 25 source have separations larger than 4.5 mas=1.8 AU (Binaries?).

Proper motions

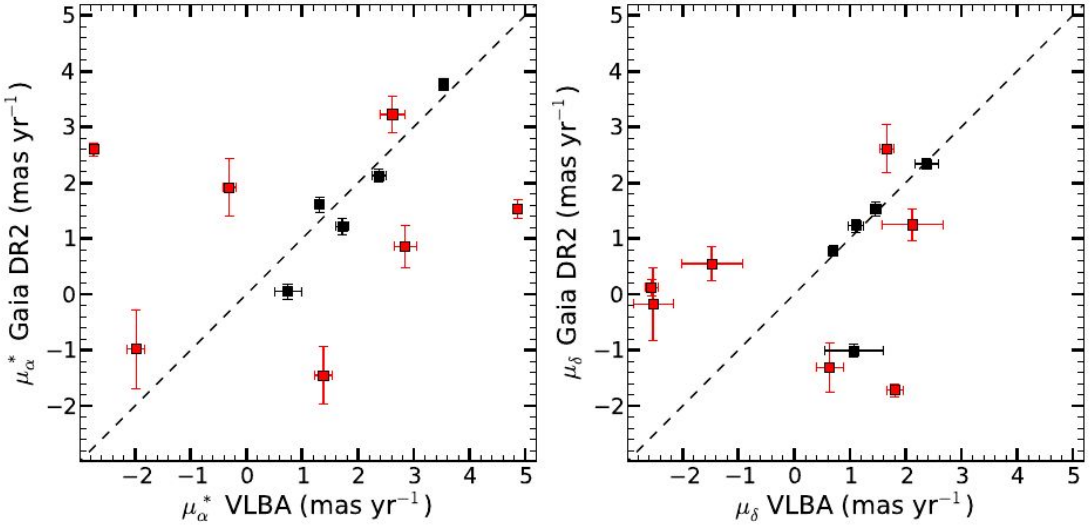


Figure 3. Comparison between VLBA and *Gaia* astrometry. *Left:* Proper motion in right ascension. *Right:* Proper motions in declination. Black symbols indicate sources where the difference in positions between VLBA and Gaia DR2 is less than 1.5 mas, otherwise the symbols are red.

Dzib et al. (2021)

Kinematics of the ONC

Table 5. Kinematics of the Trapezium.

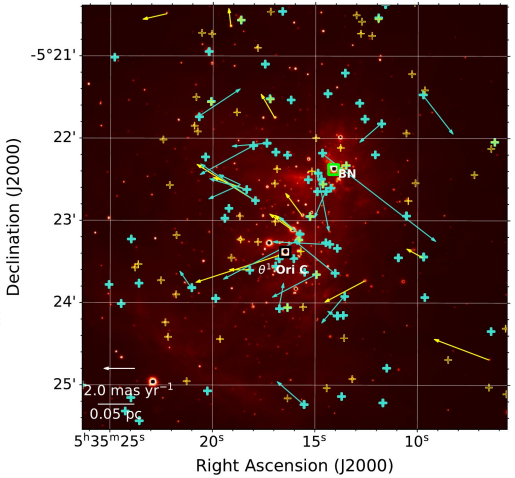
Data set	$\overline{\mu_\alpha^*}$ (mas yr^{-1})	$\overline{\mu_\delta}$ (mas yr^{-1})	σ_{μ_α} (mas yr^{-1})	σ_{μ_δ} (mas yr^{-1})	$\sigma_{v_\alpha}{}^a$ (km s^{-1})	$\sigma_{v_\delta}{}^a$ (km s^{-1})	$\overline{\mathbf{v}\cdot\hat{\mathbf{r}}}$ (km s^{-1})	$\overline{\mathbf{v}\times\hat{\mathbf{r}}}$ (km s^{-1})
VLA[b]	1.0 ± 0.1	-0.8 ± 0.2	1.1 ± 0.1	1.3 ± 0.2	2.1 ± 0.2	2.5 ± 0.4	0.7 ± 0.3	-0.1 ± 0.3
VLBA	1.2 ± 0.1	-0.3 ± 0.3	1.5 ± 0.1	2.1 ± 0.3	2.9 ± 0.2	4.0 ± 0.4	-0.5 ± 1.0	1.7 ± 0.9
Gaia	1.1 ± 0.1	0.2 ± 0.1	0.7 ± 0.1	1.2 ± 0.1	1.3 ± 0.2	2.2 ± 0.2	0.2 ± 2.3	0.8 ± 1.9
VLBA+Gaia[c]	1.15 ± 0.07	0.15 ± 0.10	1.09 ± 0.07	1.29 ± 0.10	2.10 ± 0.14	2.56 ± 0.18	-0.39 ± 0.92	1.54 ± 0.81

NOTE—Columns are (left to right): Proper motions data set, mean of proper motions, proper motion dispersions, velocity dispersions (all these three parameter in right ascension and declination and with their uncertainties), mean of dot and cross products of the unit vector and velocity vectors, both with their uncertainties.

[a] At a distance of 400 pc: 1.0 mas yr^{-1} $\equiv$ 1.9 km s^{-1}.

[b] Values from Dzib et al. (2017).

[c] Values are the variance weighted average from the indpendent results of VLBA and *Gaia* data sets.



Dzib et al. (2021)

And now?

And now?

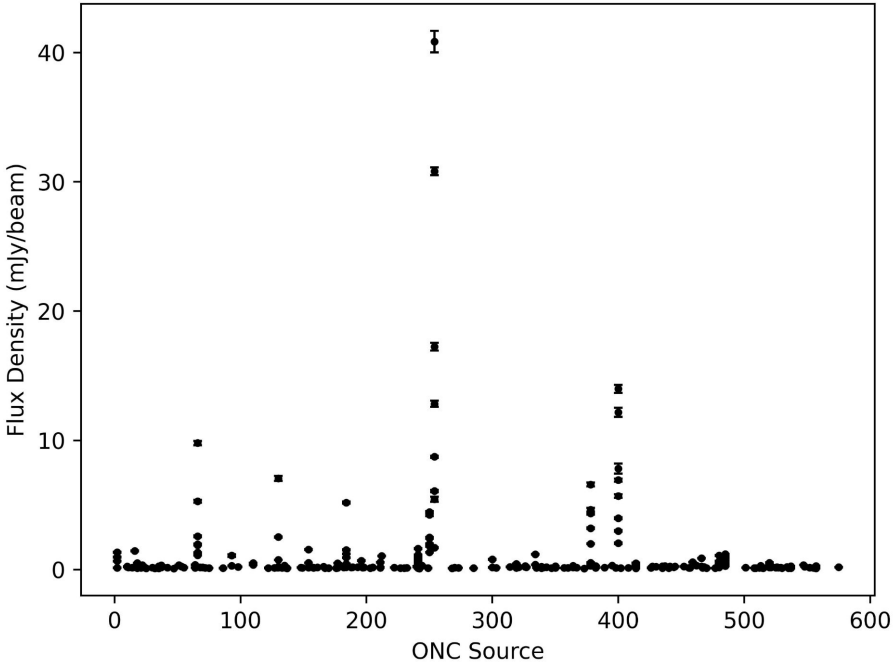
- Four new observations
  - Include 20 more positions for correlation
  - Now using the 4 gbps recording

Ongoing work

Eoin O’Kelly Ph. D. student
University of Hertfordshire

VLBA detections

- 182 unique sources detected; ~32% of the 575 sources imaged.
- The brightest source is ONC254 (Θ^1 Ori A2) which varies in flux density from 1.7 to 40.8 mJy.
-



O'Kelly, Forbrich, Dzib et al. in prep.

VLBA detections

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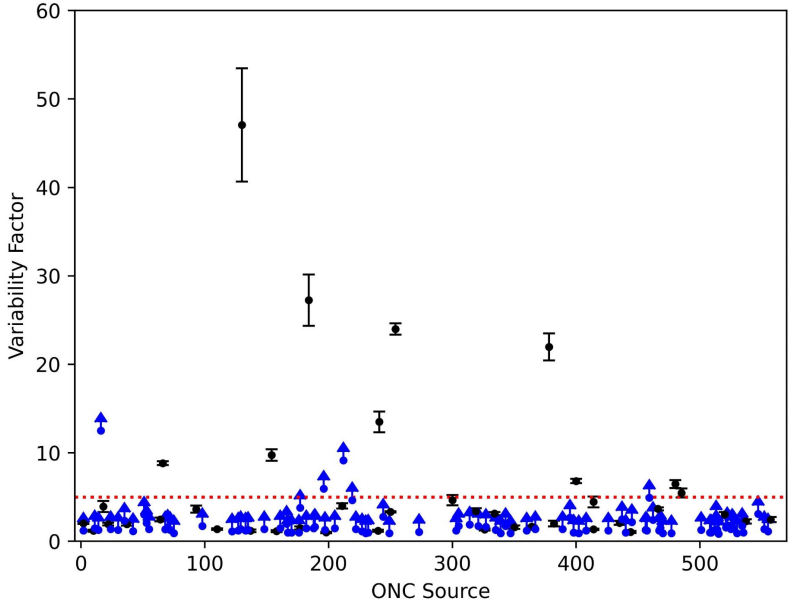
- The brightest source is ONC254 (Θ^1 Ori A2) which varies in flux density from 1.7 to 40.8 mJy.
- Ten sources have a variability factor ($S_{\nu,max}/S_{\nu,min}$) > 5.
- ONC130 VF=47.1 ± 6.4. It is an X-ray flare source (Getman et al 2008).



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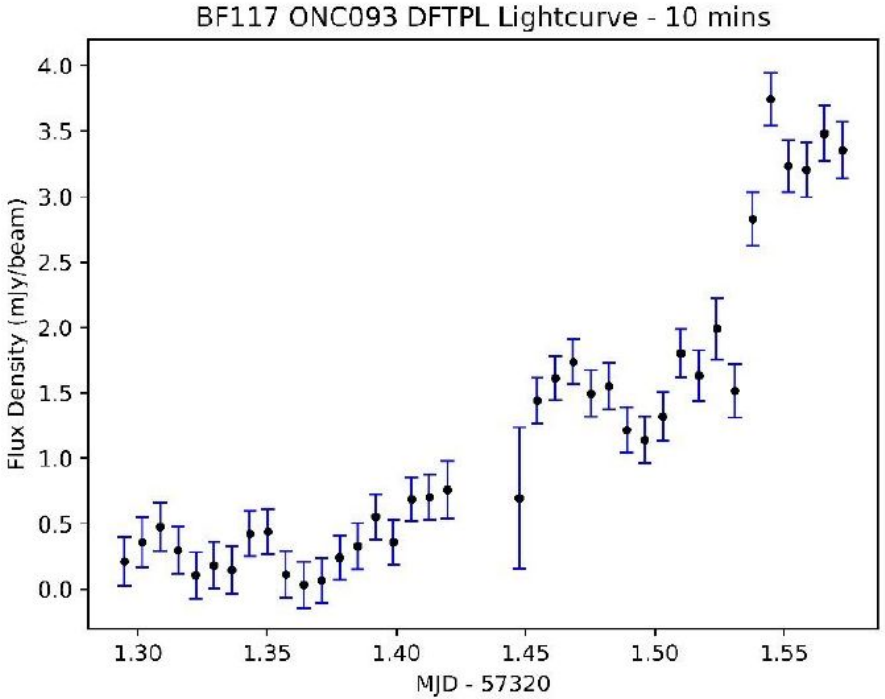
Light curves



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Future work

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  - Comparison with Gaia current and future data releases

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  - VLBA [Particle ejections]
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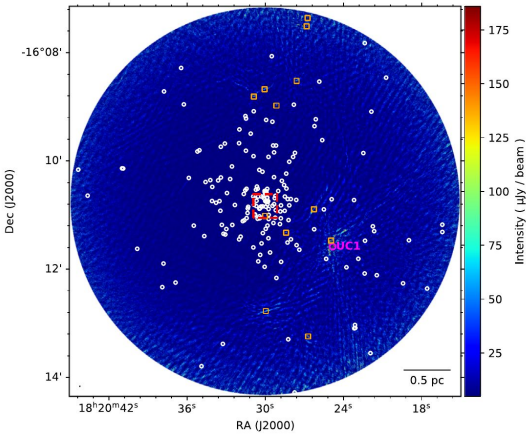
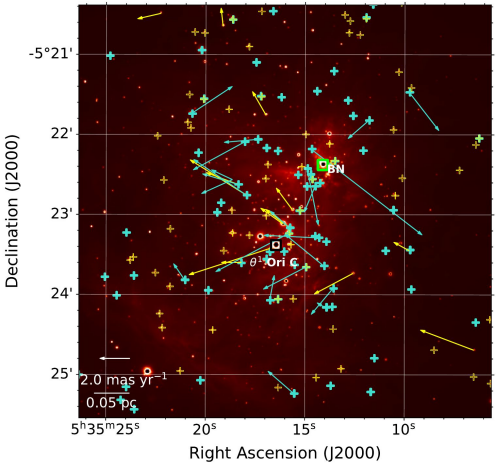
- Other regions



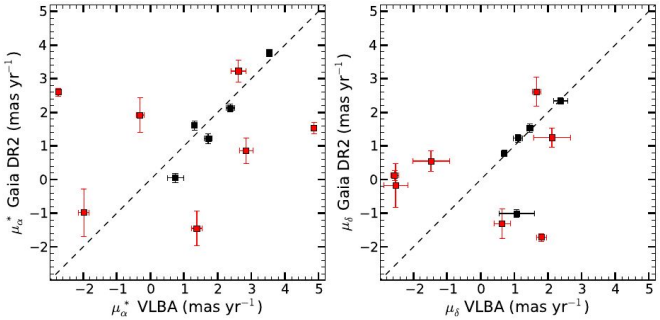
M17: Yanza, Masque, Dzib, et al. (2022)

Vanessa Yanza

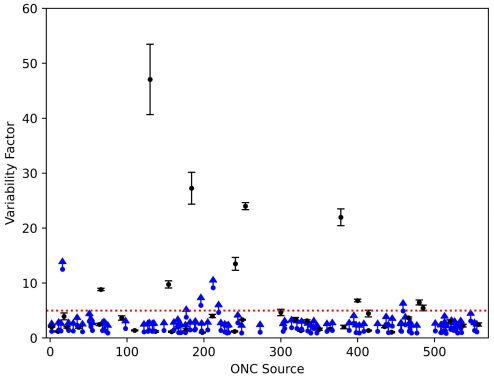
CONCLUSIONS



~200 YSO with nonthermal radio emission (Forbrich et al. 2021; O'Kelly et al. in prep)



Uncovered a population of tight binaries in the ONC (Dzib et al. 2021)



YSOs with non-thermal radio emission show very strong variability

Stellar VLBI astrometry still playing a key role on star formation studies

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