3D space motions of molecular clouds

Untangling the star formation history in the Local Milky Way

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DSS RGB

DSS RGB


California
Mon R2
Taurus-Auriga
Orion
Perseus
HFI PLANCK
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California
Mon R2
Taurus-Auriga
Orion
Perseus
Regions are part of the
Radcliffe Wave
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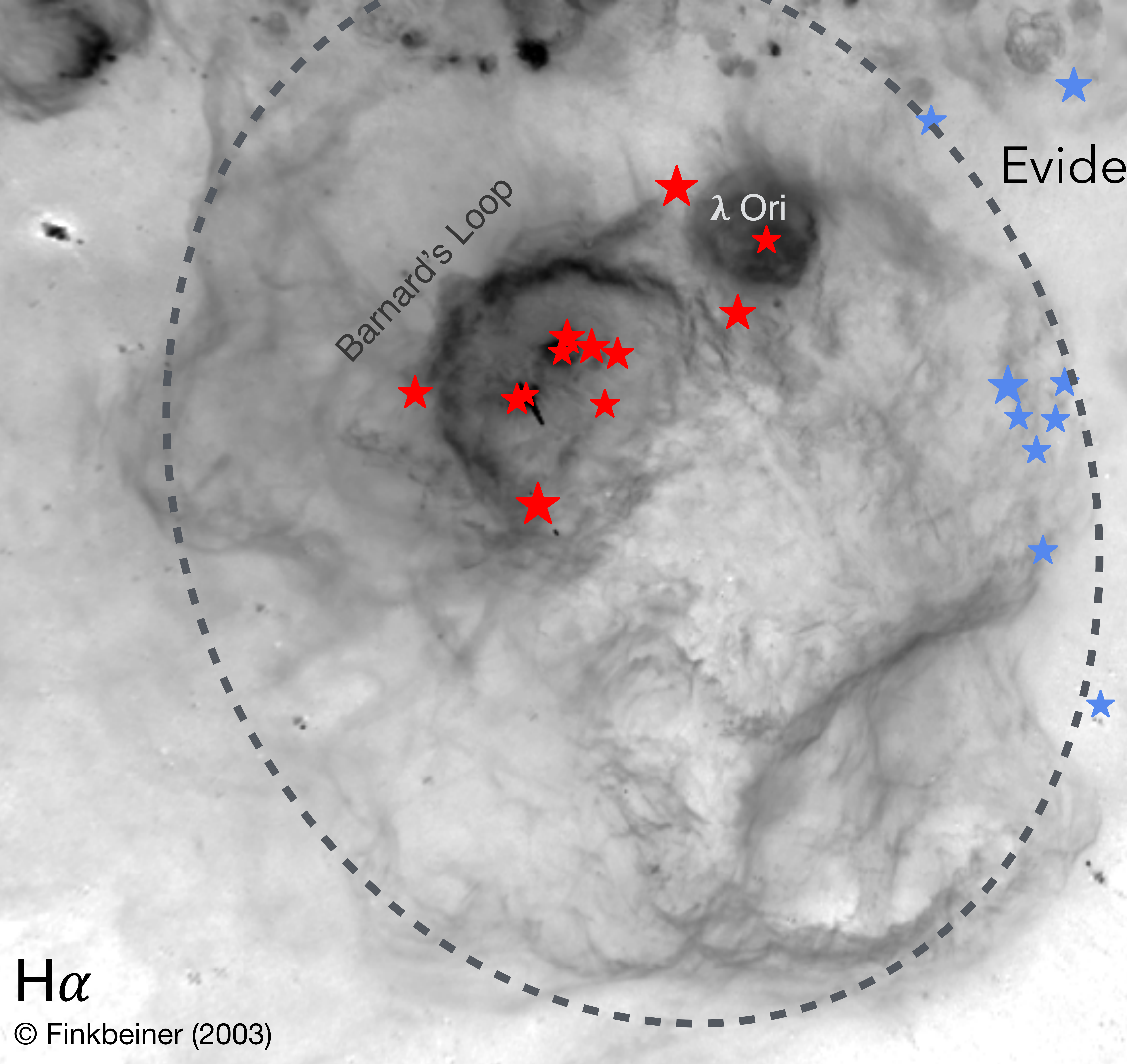

Evidence for massive stellar feedback

Orion-Eridanus Superbubble

Created by ~ 10-20 SNe

Age ~ 4-10 Myr

E.g.

Bally, Langer & Wilson (1987)

Brown et al. (1995)

Lee & Chen (2009)

Ochsendorf et al. (2015)

Pon et al. (2016)

Barnard 1894

O'Dell+1967+2011

Muench+2008

Mathieu+2008


California
Mon R2
Taurus-Auriga
Orion
Perseus
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Orion A 3D shape with Gaia DR2
Großschedl et al. (2018)
Tail
Head
Orion A
~40pc @ 400pc
Closest massive star-forming region, *d* ~ 400 pc *(e.g., Menten+2007)*
~ 3000 YSOs with IR excess *(Großschedl+2019)*
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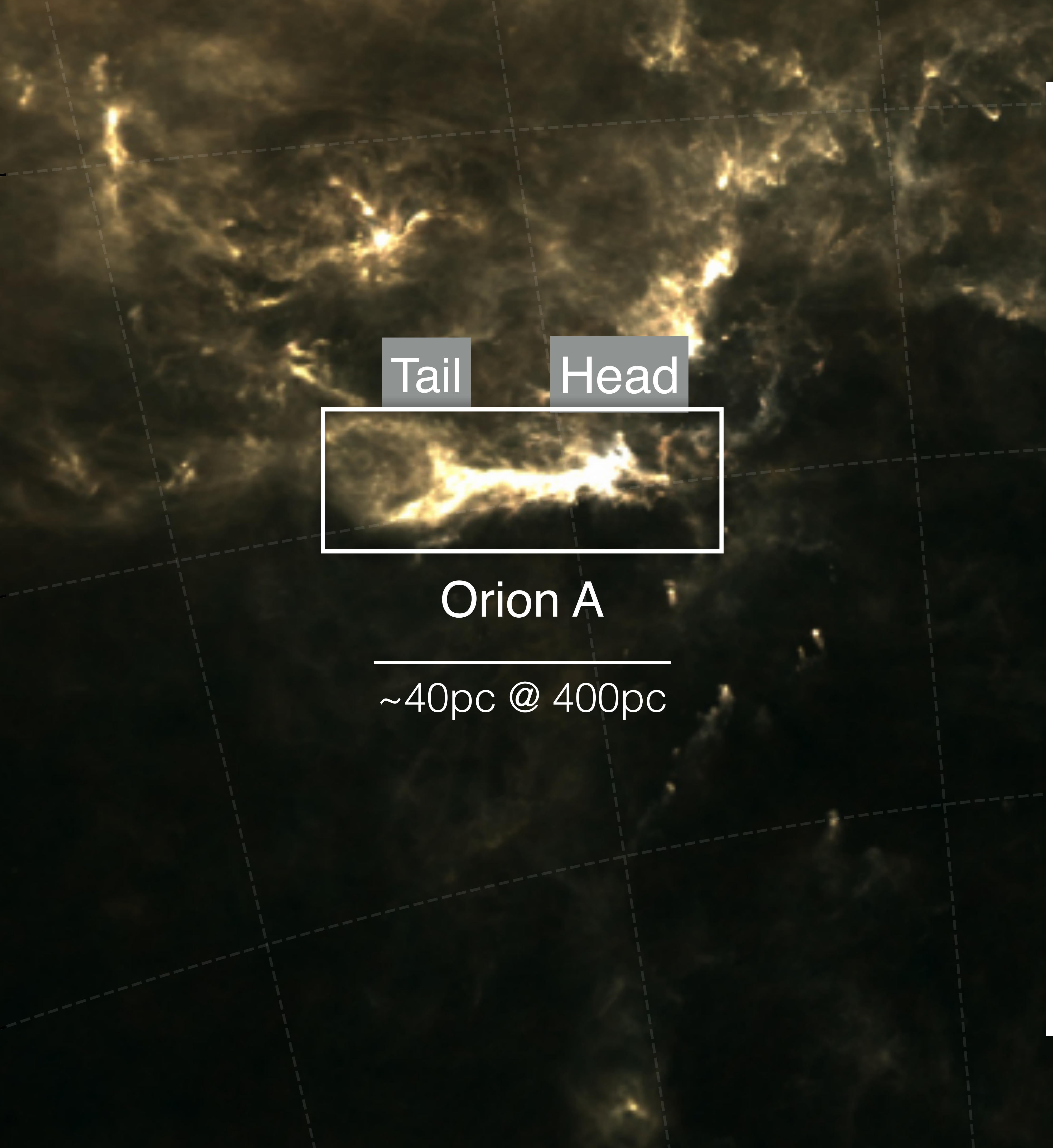
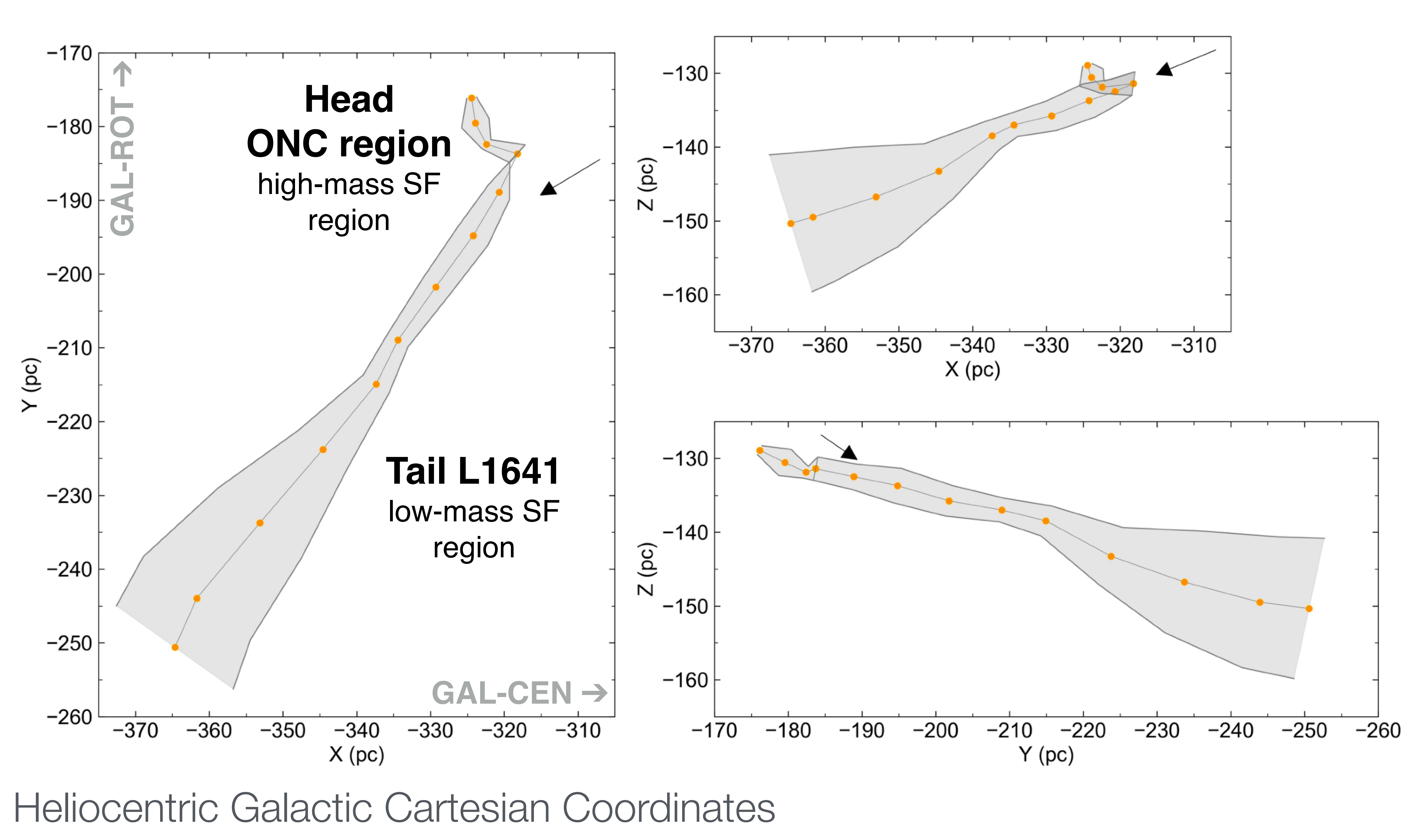
Orion A 3D shape with Gaia DR2
Großschedl et al. (2018)

Using Average YSO distances: Tail ~ 70 deg inclined
Twice as long as previously assumed (~90pc)
(see also Rezaei Kh.+2020)





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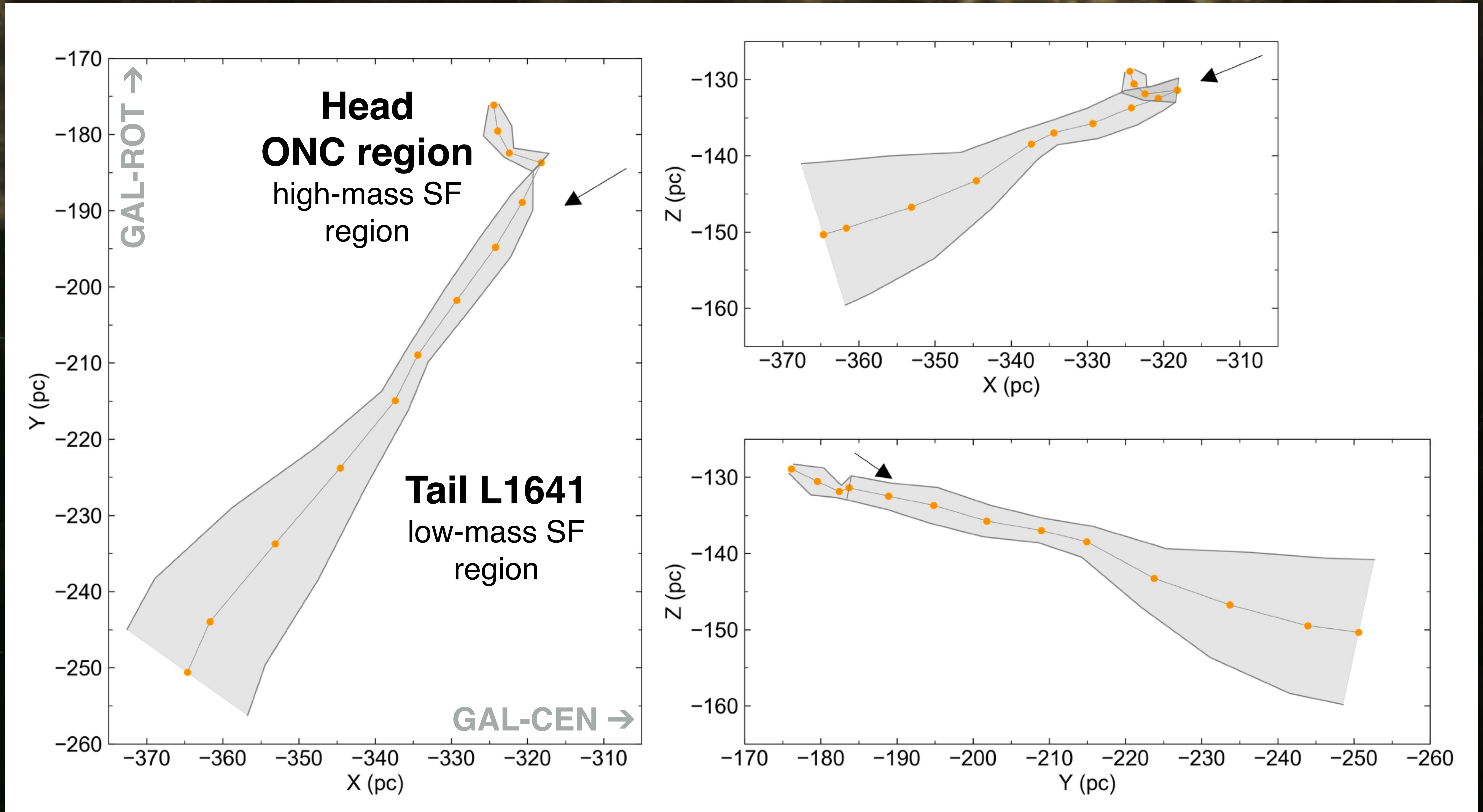
Gaia DR2: Gaia Collaboration+2018
YSOs with IR-excess: Großschedl+19, Megeath+12+16, Furlan+16
Distance estimates see also: Menten+07, Schlafly+14, Kounkel+17+18, Zucker+19+20, Leike+20, Rezaei Kh+20

Orion A 3D shape with Gaia DR2
Großschedl et al. (2018)

Peculiar "**bent head**" – Was the gas **pushed**?
Feedback from previous generations of massive stars?



Heliocentric Galactic Cartesian Coordinates

Gaia DR2: Gaia Collaboration+2018
YSOs with IR-excess: Großschedl+19, Megeath+12+16, Furlan+16
Distance estimates see also: Menten+07, Schlafly+14, Kounkel+17+18, Zucker+19+20, Leike+20, Rezaei Kh+20

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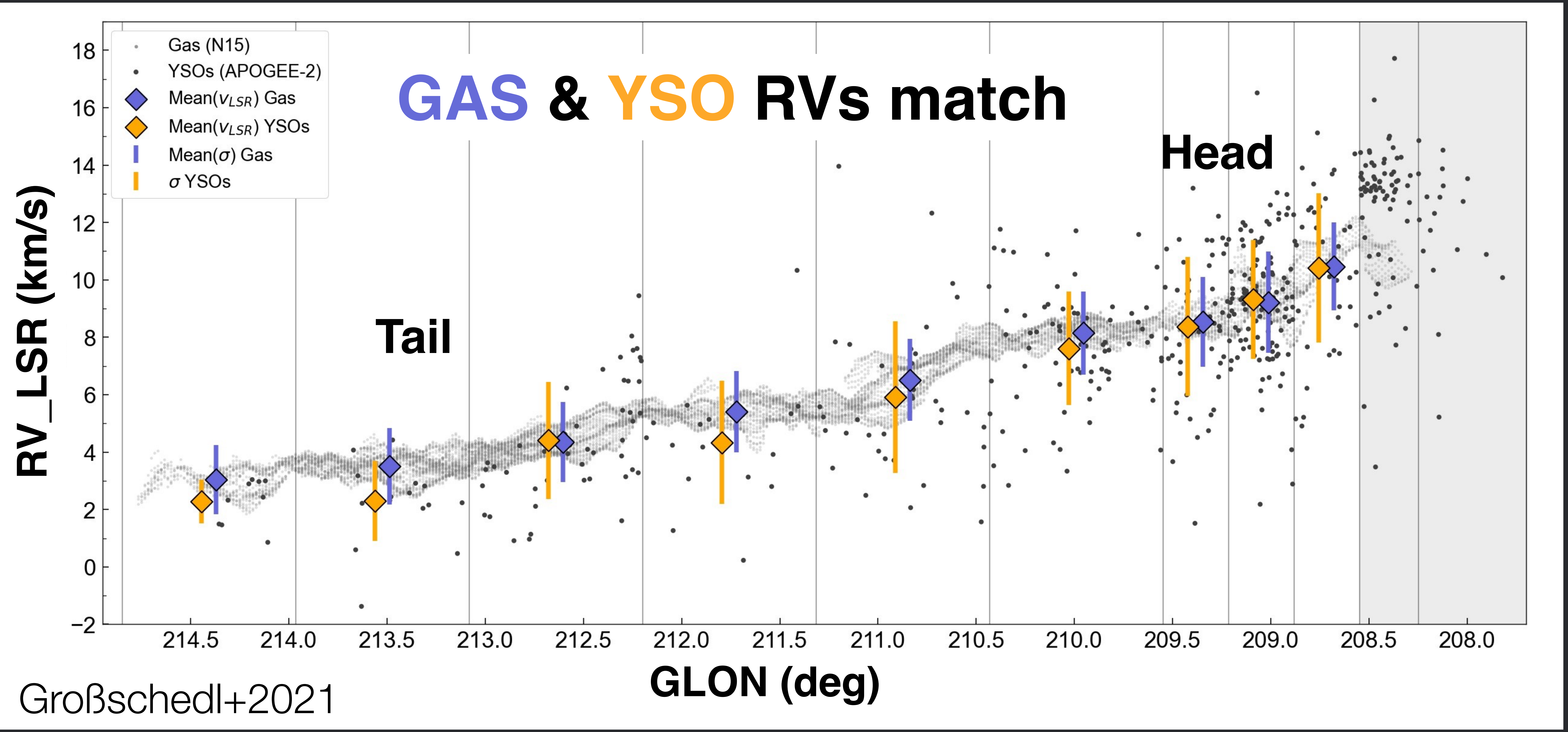
We need
Proper Motions
of the gas

We know
Radial Velocities
of the gas



see also e.g. Hacar+16, Tobin+09

PV-Diagram for Orion A

Gas:
^{12}CO(2-1) 1.Moment map
(Nishimura+2015)

YSOs:
APOGEE-2 SDSS-DR16
(Majewski+2017, Ahumada+2020)

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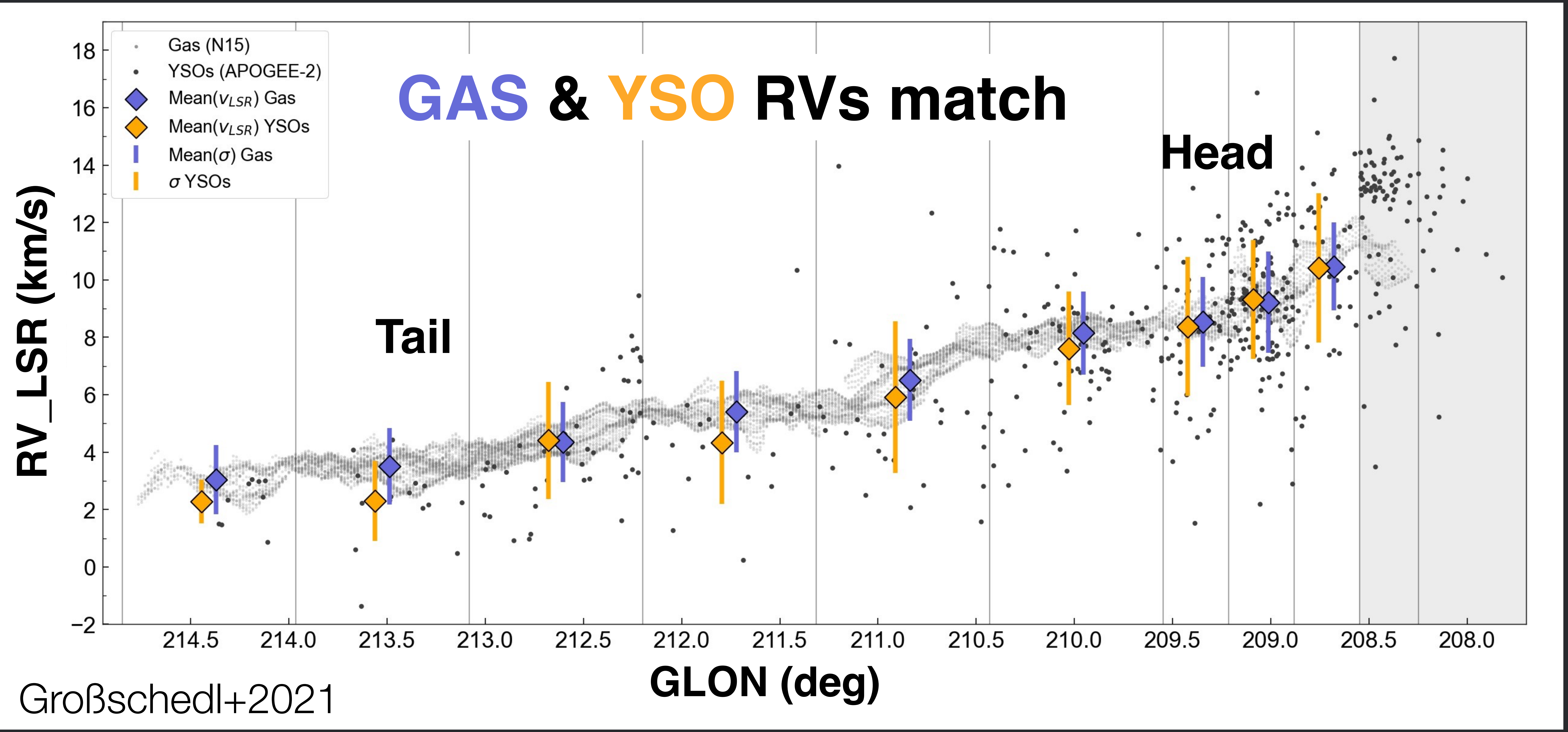

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APOGEE-2 SDSS-DR16
(Majewski+2017, Ahumada+2020)

–> YSOs proper motions can be used
as proxies for cloud proper motions

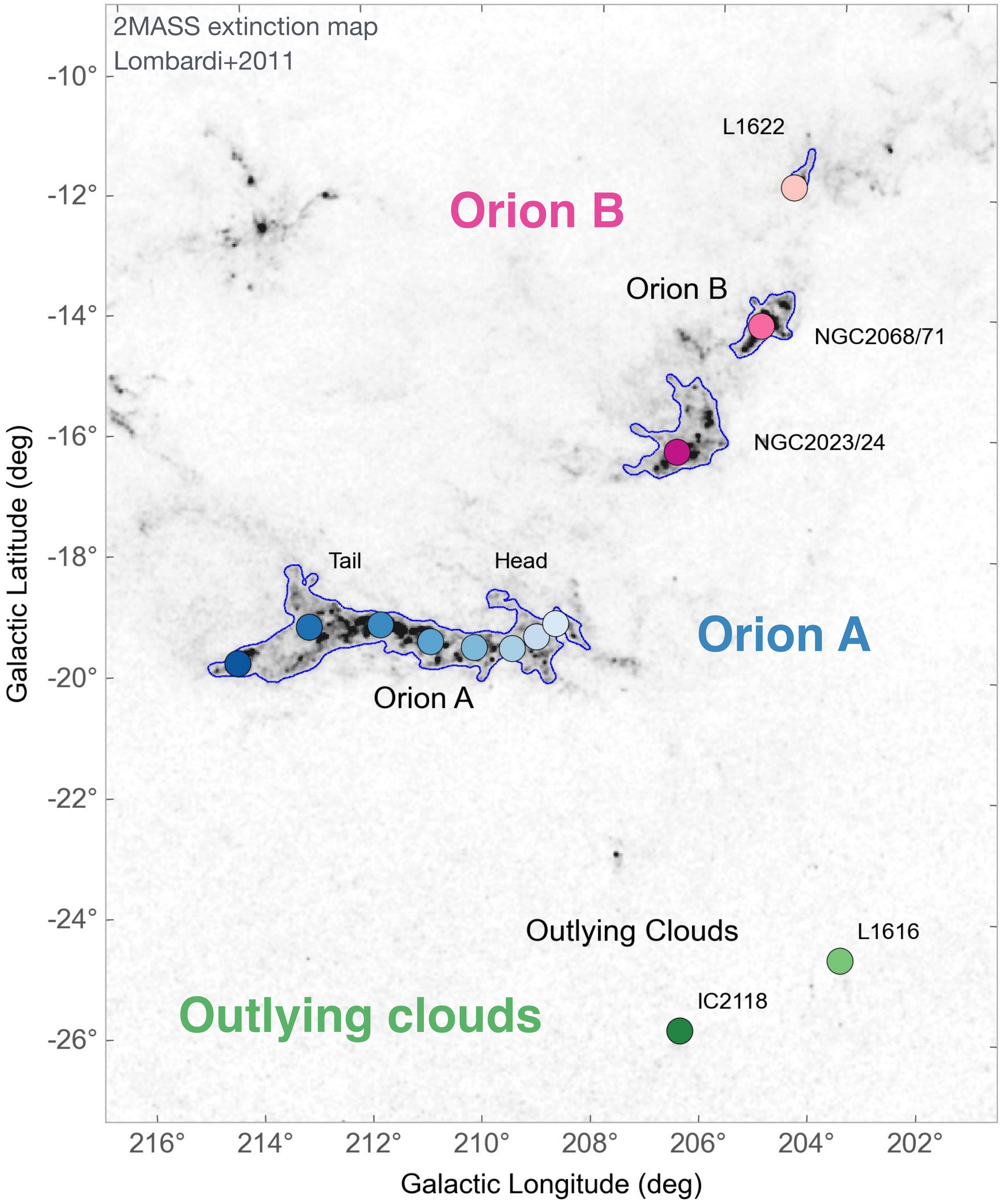
3D space motions of molecular clouds

Großschedl et al. (2021)

YSOs average distances
YSOs average proper motions
Gas radial velocities

6D phase space for 14 sub-regions –>

Data References:
RV data: Nishimura+2015, Maddalena+1986, Dame+2001, Wilson+2005, Park+2004, Alcala+2004, Kun+2001+2008; Kounkel+2017b+2018; SDSS-DR16 APOGEE-2, Majewski+2017+2020
YSO data: Kun+2004+2008, Alcala+2004, Guieu+2010, Megeath+2012+2016, Furlan+2016, Großschedl+2019, Additional WISE-YSO-selections with AllWISE, Cutri+2013;
Gaia DR2 & EDR3, Gaia Collaboration et al.+2018+2020
Other kinematic studies for Orion, e.g.: Kounkel+2018, Zari+2019, Swiggum+2021



3D space motions of molecular clouds

Großschedl et al. (2021)

Visualisation of results in 3D

Get orbital motions for each subregion

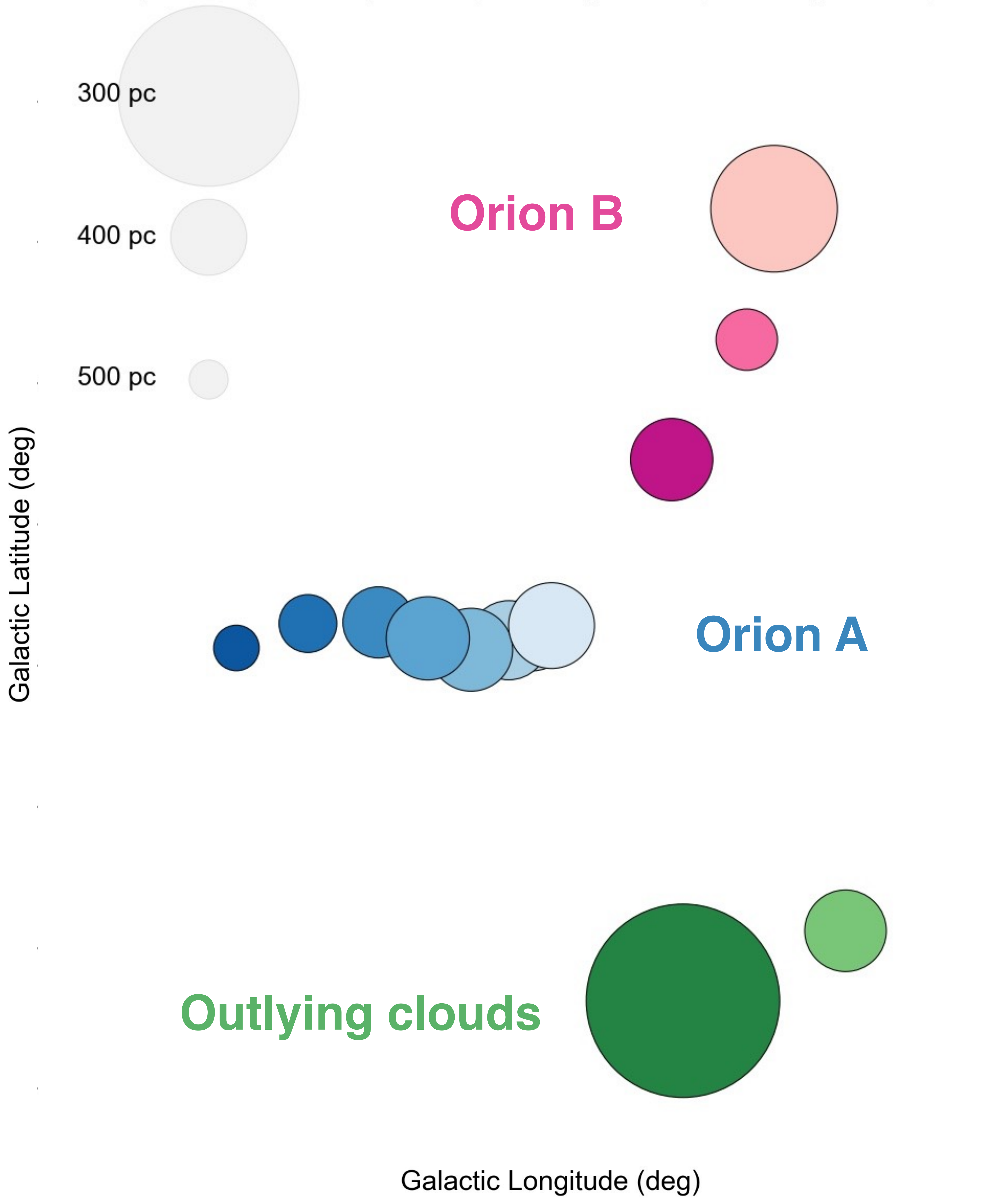
E.g. with Astropy and Galpy
(Milky Way Potential with Disk, Bulk & Halo, *Bovy+2015*)

Investigate distances between regions in space and time

Dynamical age of massive feedback event?

Get relative space motions

chose a central position & rest frame



3D space motions of molecular clouds

Großschedl et al. (2021)

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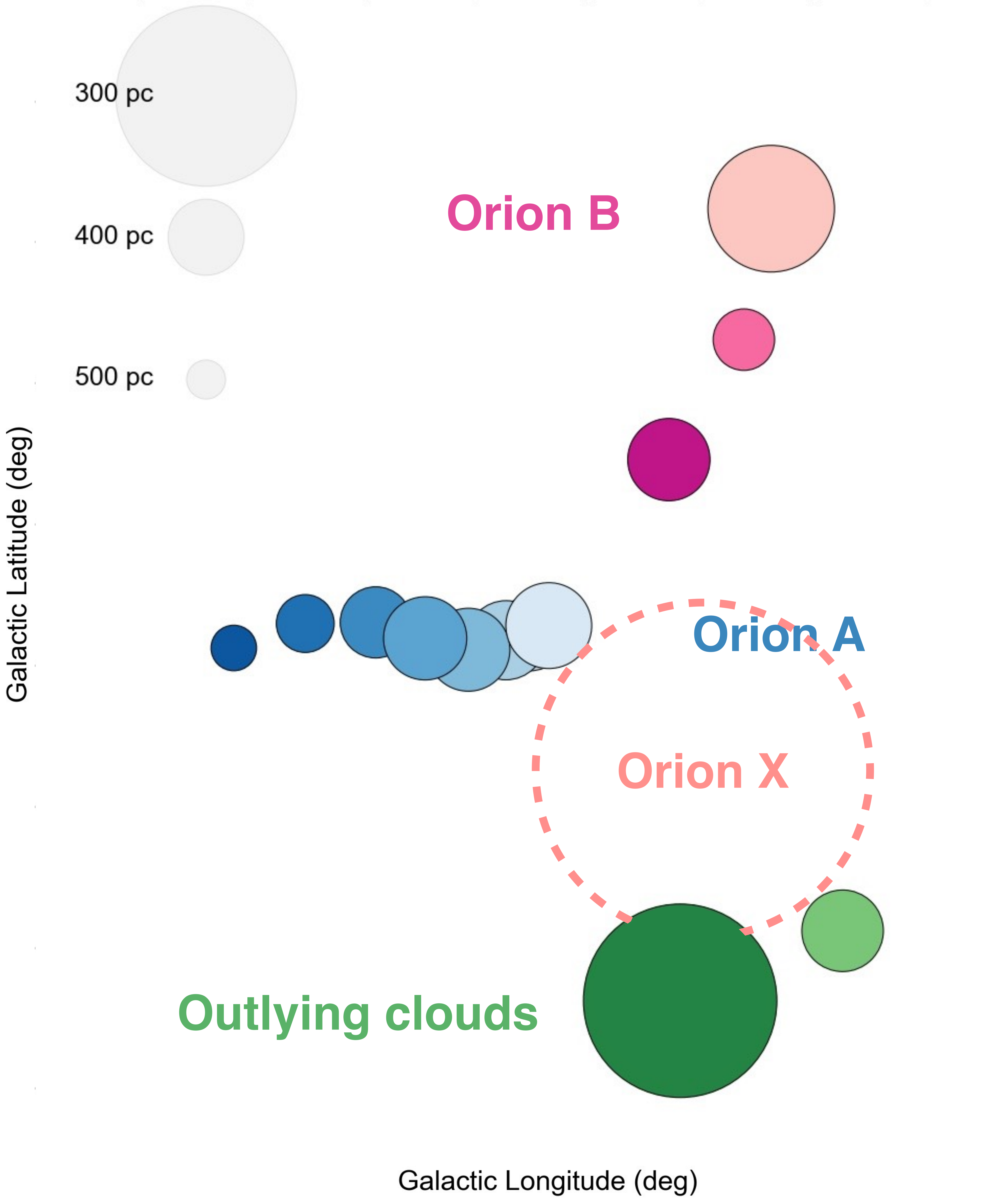
Reference cluster for rest frame:
Cluster Orion X
(Bouy & Alves 2015, Chen+2020)



3D space motions of molecular clouds

Großschedl et al. (2021)

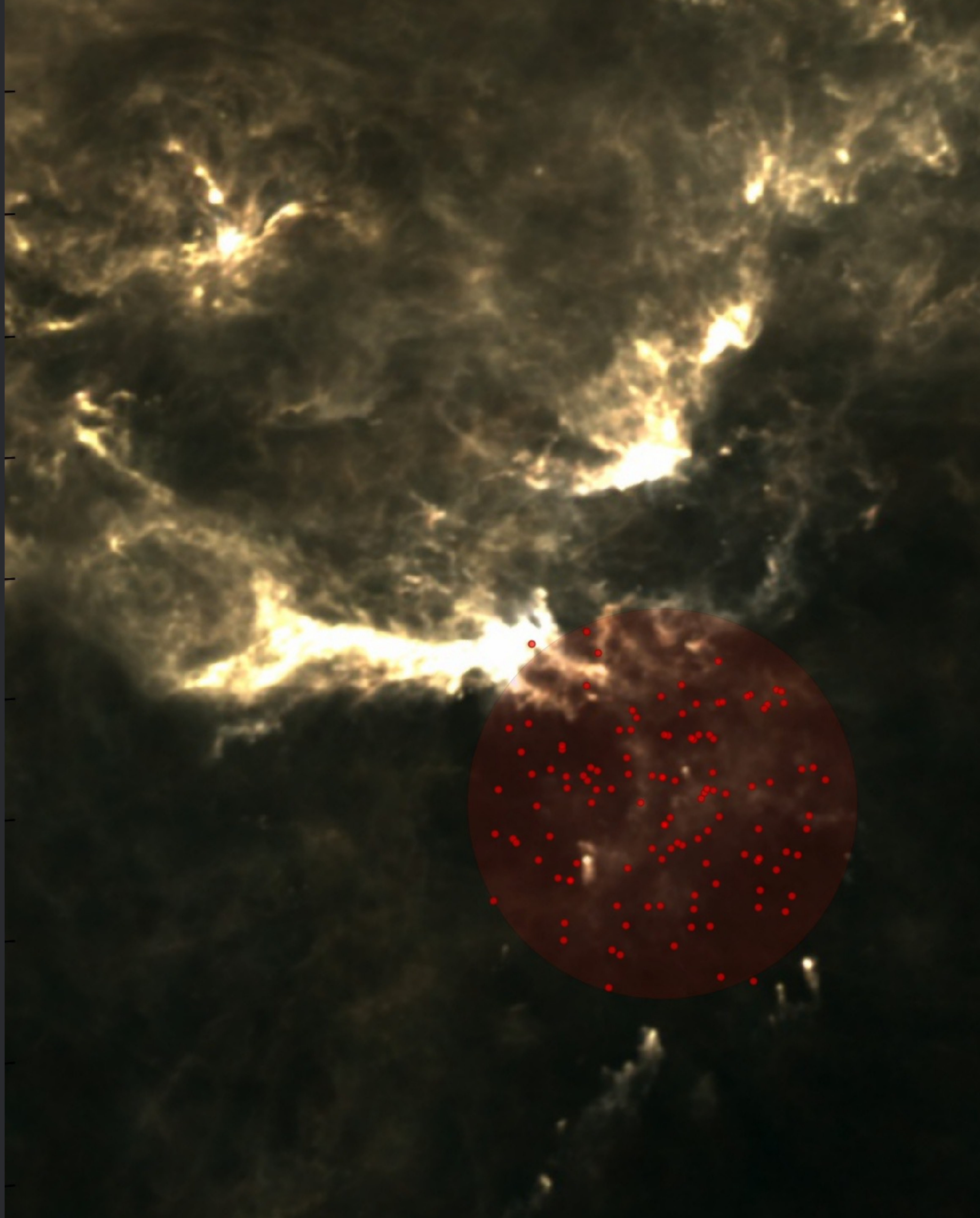
Orion X - stellar group

Bouy & Alves 2015, Chen+2020

possible progenitor cluster of massive stellar feedback in this region

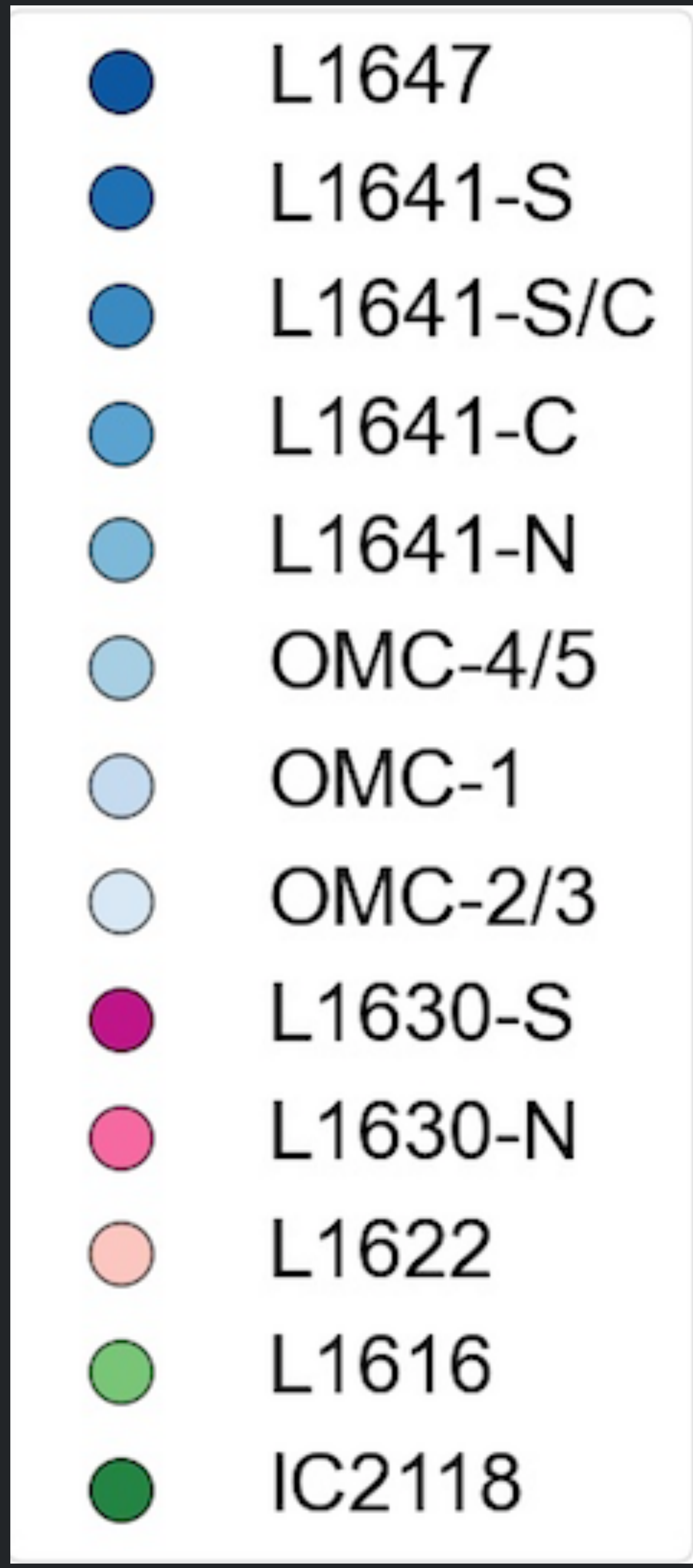
Age ~ 10 Myrs

Extent ~ 40 pc



Cartesian **front** view

Orion-centred Galactic Cartesian coordinates with $\mathbf{X'_{Orion}}$ pointing toward Orion X

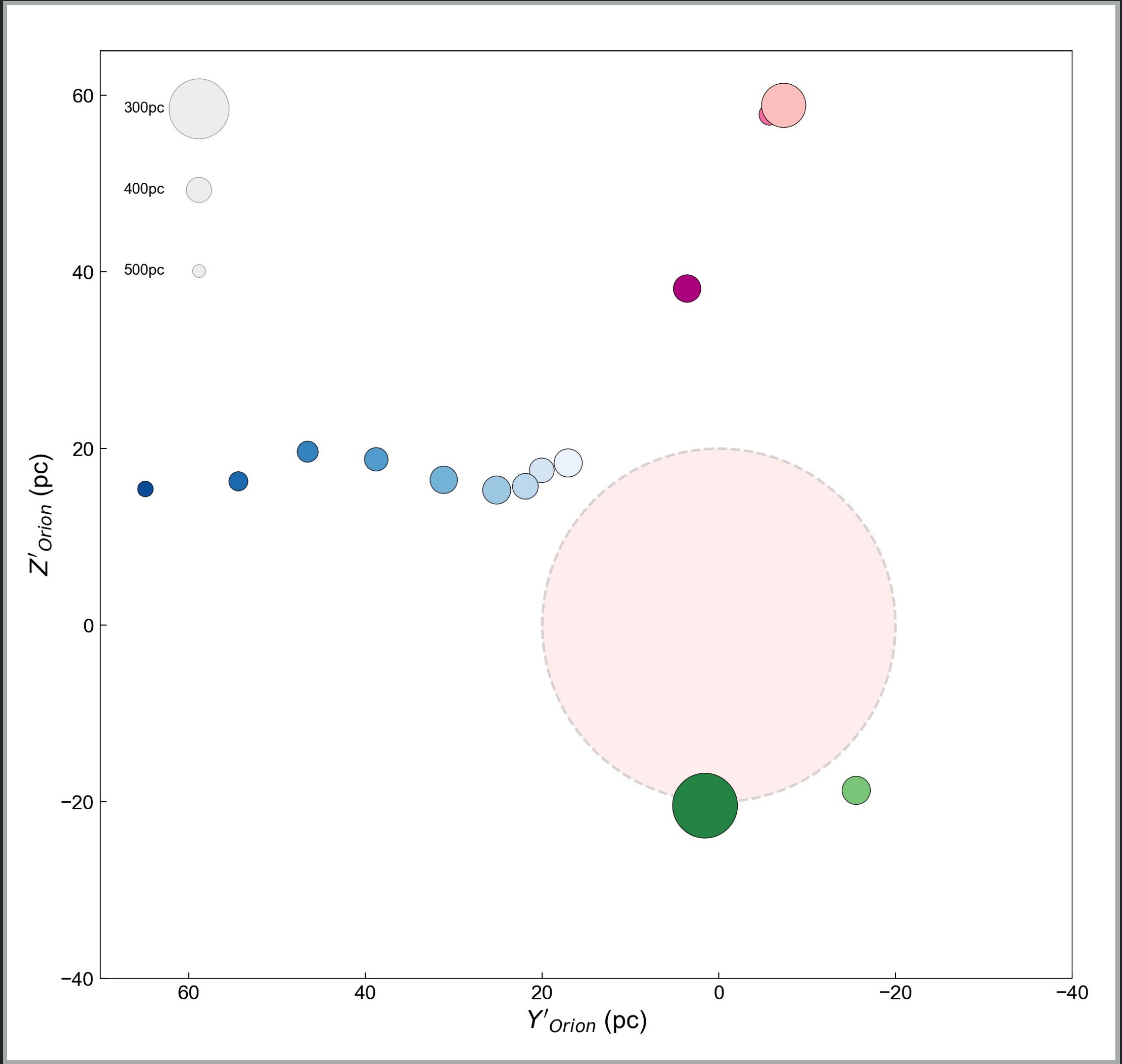


red filled circle: Orion X cluster extent

Orion A

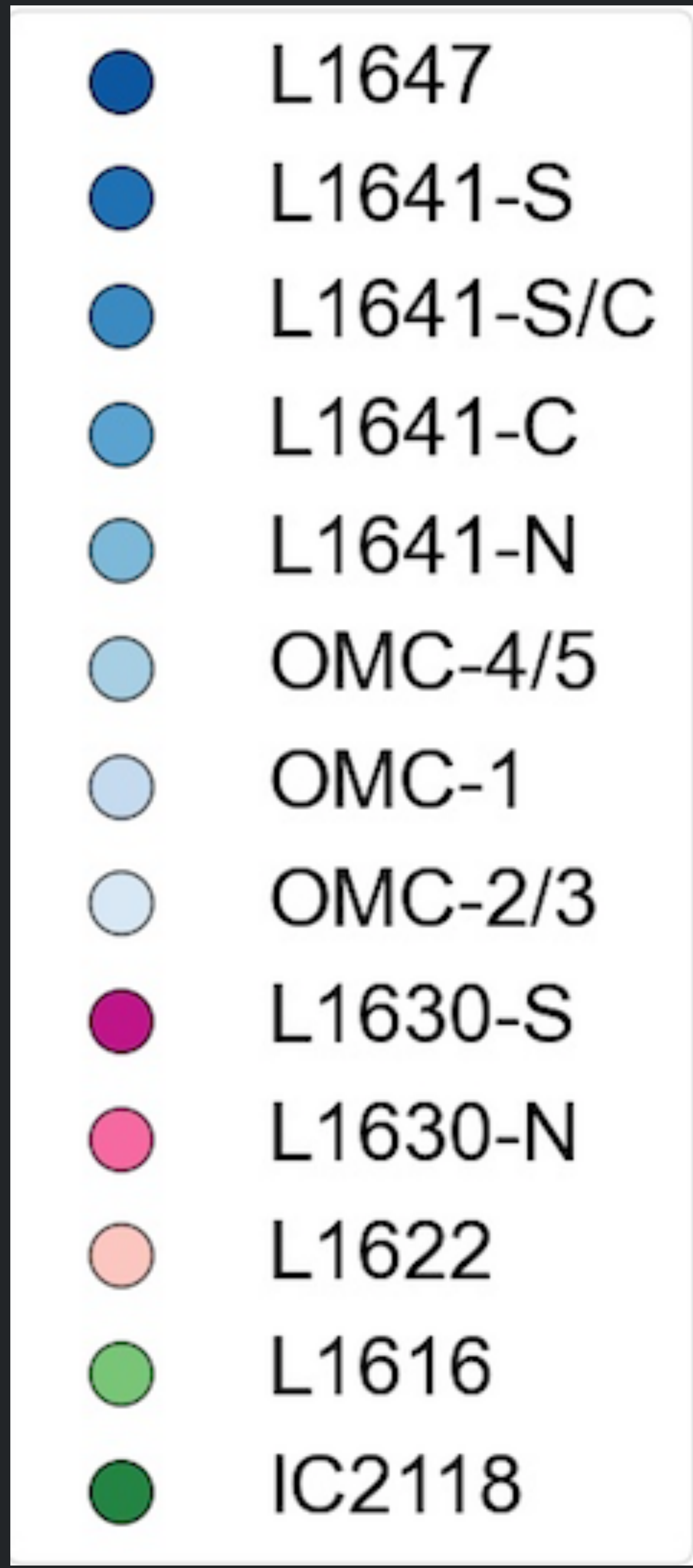
Orion B

Outlying clouds



Cartesian **top-down** view

Orion-centred Galactic Cartesian coordinates with **X'_{Orion}** pointing toward Orion X



red filled circle: Orion X cluster extent

Orion A

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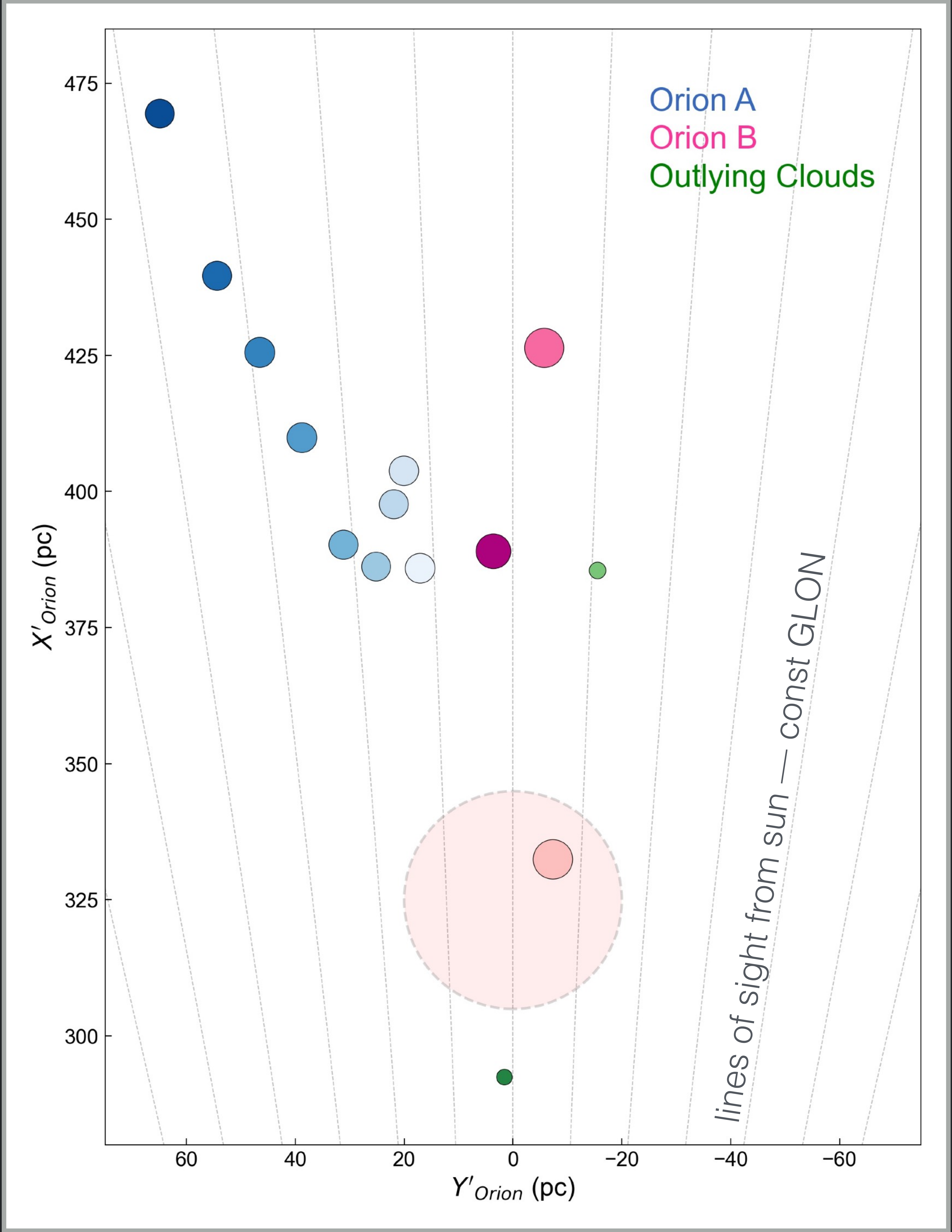
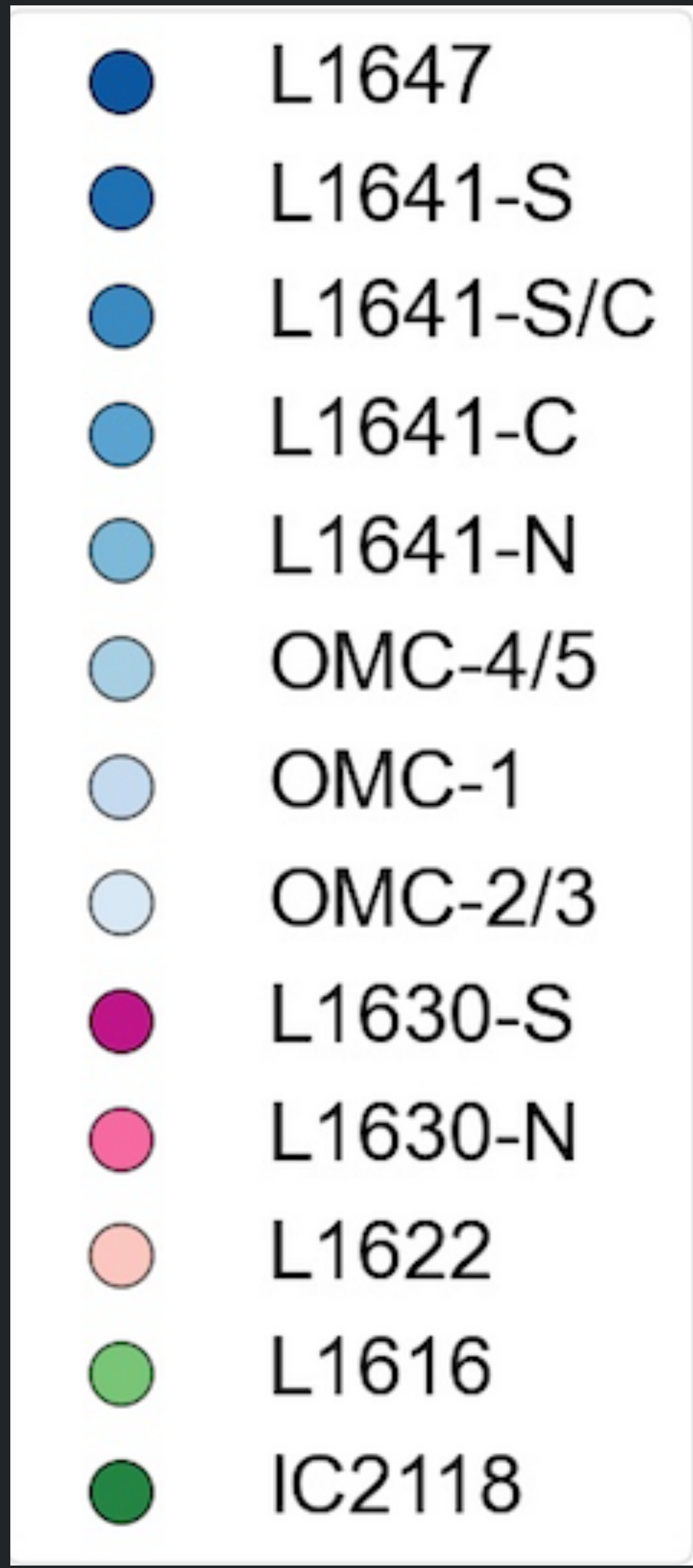
Outlying clouds



Cartesian **side** view

Orion-centred Galactic Cartesian coordinates with **X′**



red filled circle: Orion X cluster extent

Orion A

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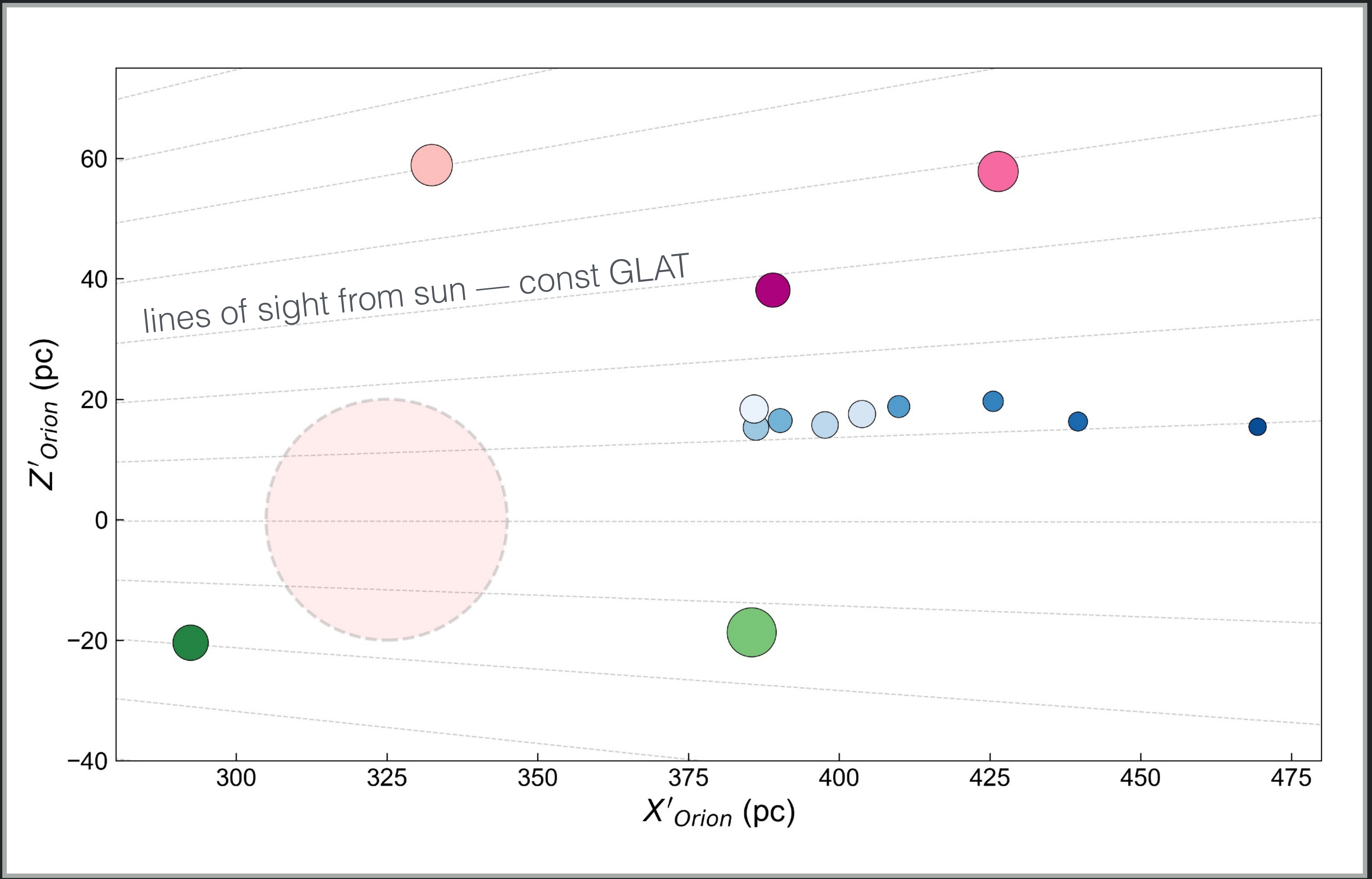


Cartesian **side** view

Time-lapse **MOVIE** -7 to +7 Myr motions relative to **Orion X**

Minimum distance between regions ~ 6 Myr ago

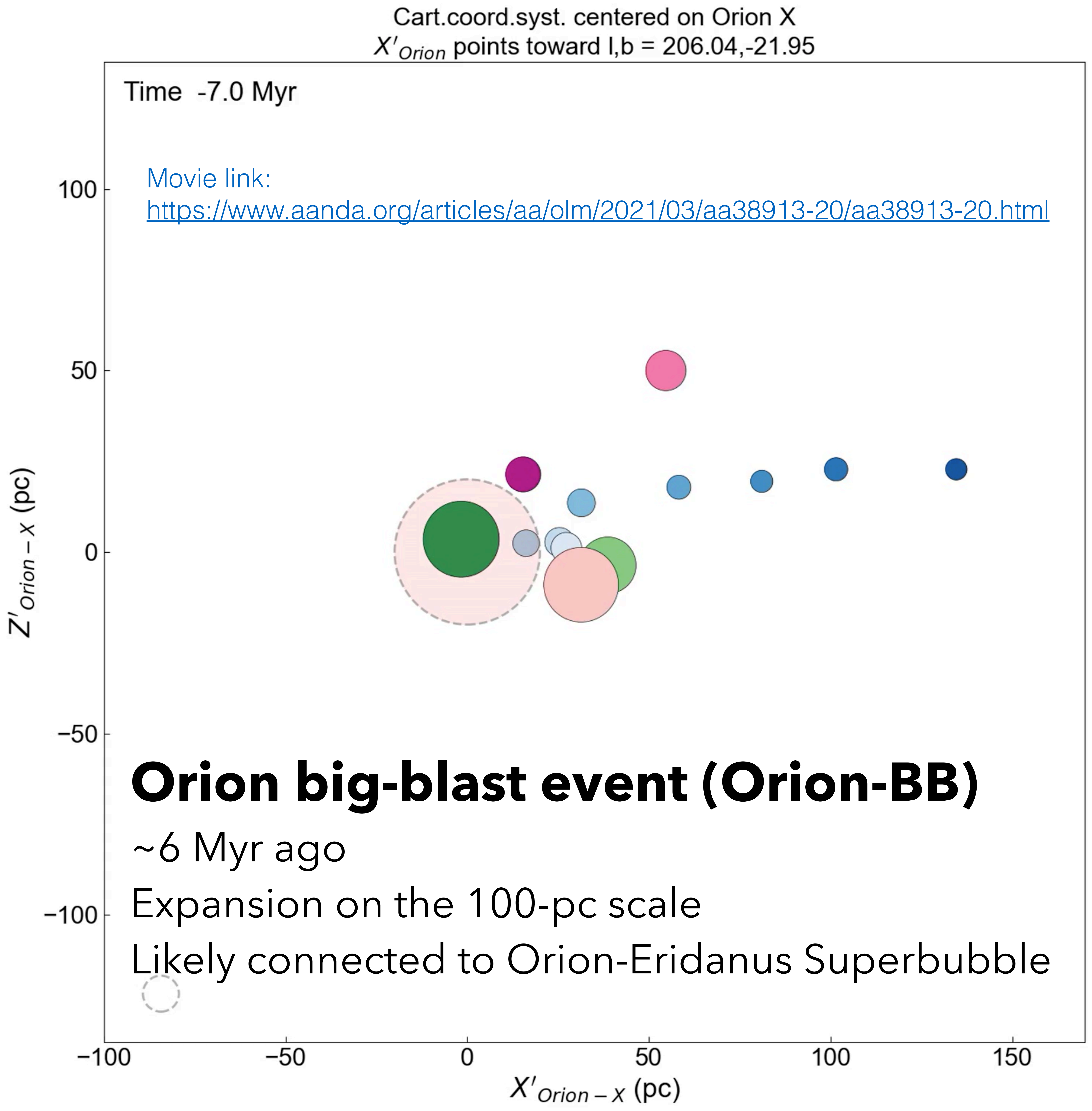
	L1647
	L1641-S
	L1641-S/C
	L1641-C
	L1641-N
	OMC-4/5
	OMC-1
	OMC-2/3
	L1630-S
	L1630-N
	L1622
	L1616
	IC2118

red filled circle: Orion X cluster extent

Orion A

Orion B

Outlying clouds



Orion big-blast event (Orion-BB)

~6 Myr ago

Expansion on the 100-pc scale

Likely connected to Orion-Eridanus Superbubble

Momentum Analysis : $p = mv$ ($M_\odot$ km s^{-1})

v* – *Velocities

3D motions of the cloud parts

m* – *Masses

Mass estimates
from Herschel or extinction maps

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$\boldsymbol{v_{rel}}$ Velocity relative to three chosen rest velocities:

- relative to Orion X (cluster)
- relative to Orion A's Tail (L1641-S/C)
- relative to OBP-Near (cluster)

Momentum Analysis : $p = mv$ ($M_\odot$ $km\ s^{-1}$)

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Compare to Simulations

e.g. ***Walch & Naab (2015)***

Radial momentum output of one SN in ambient fractal medium with n_0=100 cm^{-3}

Momentum Analysis : compared to *Walch & Naab (2015)*

Numerical simulation setup : FC (fractal+cooling, n_0=100 cm^{-3}), FCI (+ionization)

What can we learn from Orion?

Orion is a benchmark to study the impact of feedback on the ISM in 6D phase space

- Orion clouds expand radially on 100-pc scale
- Pushed by Orion big-blast event (Orion-BB) ~ 6 Myr ago
- Likely connected to the origin of the Orion-Eridanus Superbubble


Orion-Eridanus Superbubble
E.g.
Bally, Langer & Wilson (1987)
Brown et al. (1995)
Lee & Chen (2009)
Ochsendorf et al. (2015)
Pon et al. (2016)
Hα
© Finkbeiner (2003)


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© Finkbeiner (2003)

Local Bubble

Zucker et al. 2022, Nature

Image © Leah Hustak, STScI

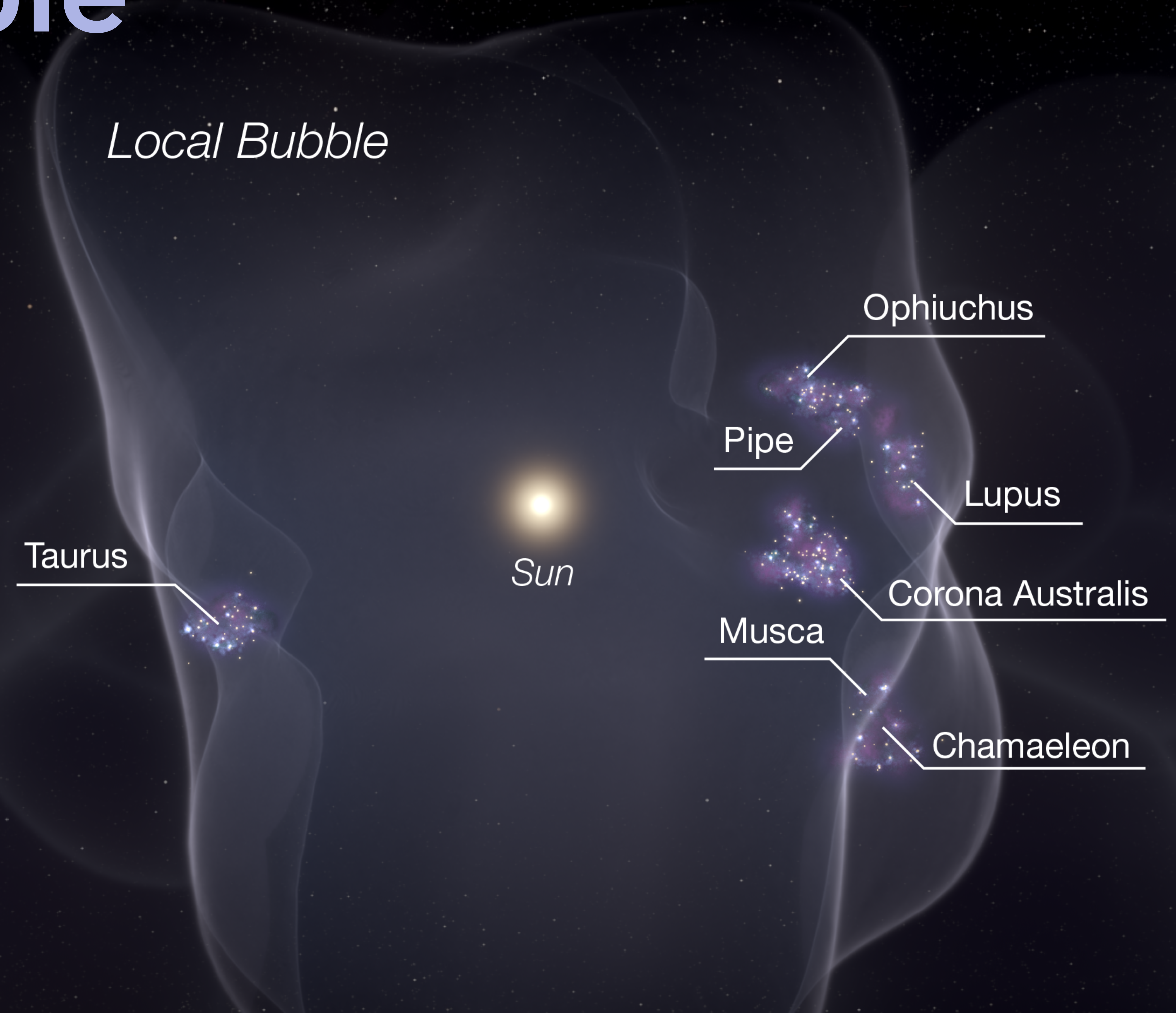
Local Bubble

Zucker et al. 2022, Nature

Image © Leah Hustak, STScI

Star-forming regions at the surface of the bubble

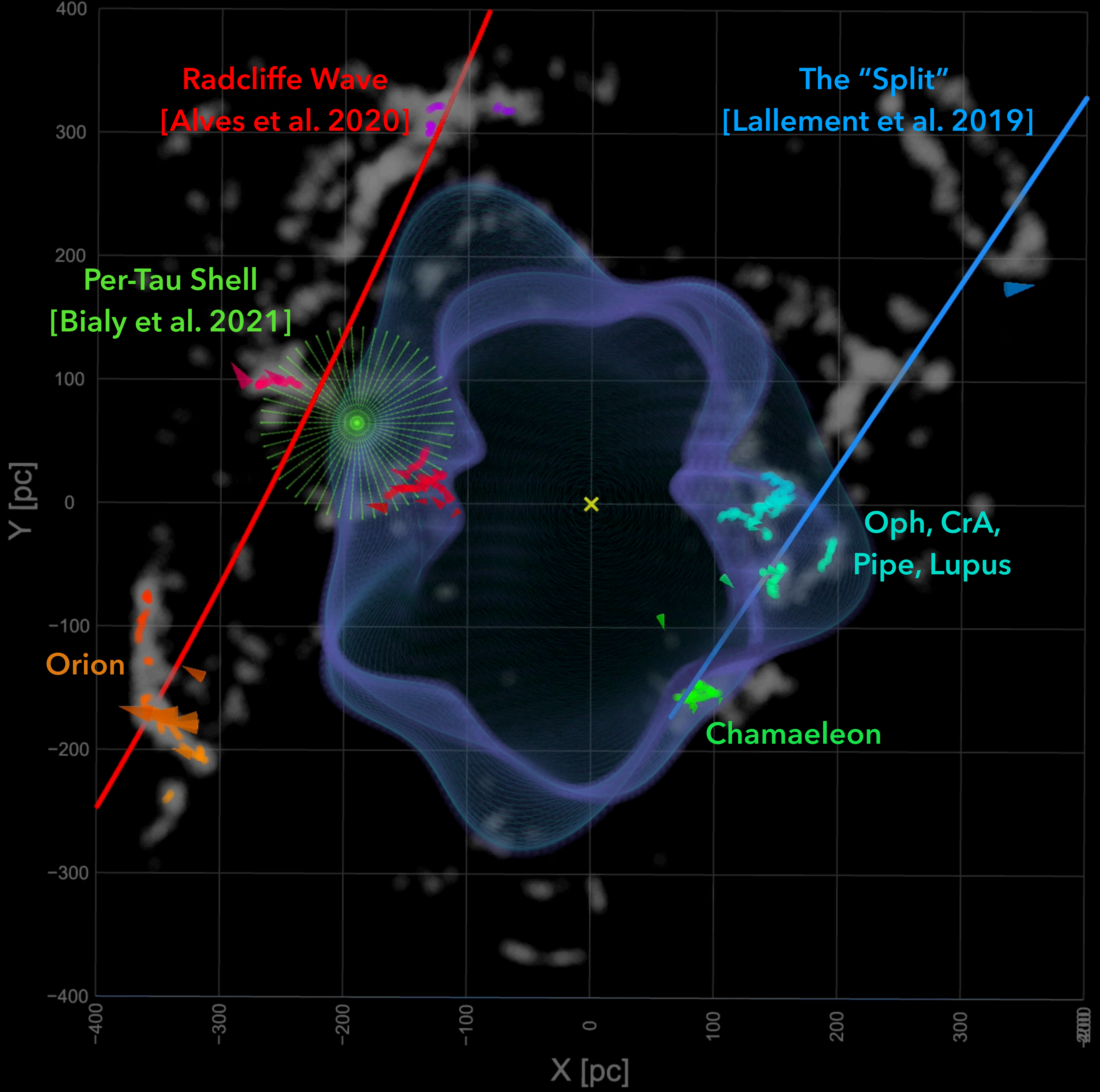
Bubble Origin: 10–20 SNe from UCL and LCC started ~14 Myr ago



We have known about the Local Bubble for 50 years

e.g. Lucke 1978, Sanders 1977, Cox & Reynolds 1987, Frisch et al. 2011

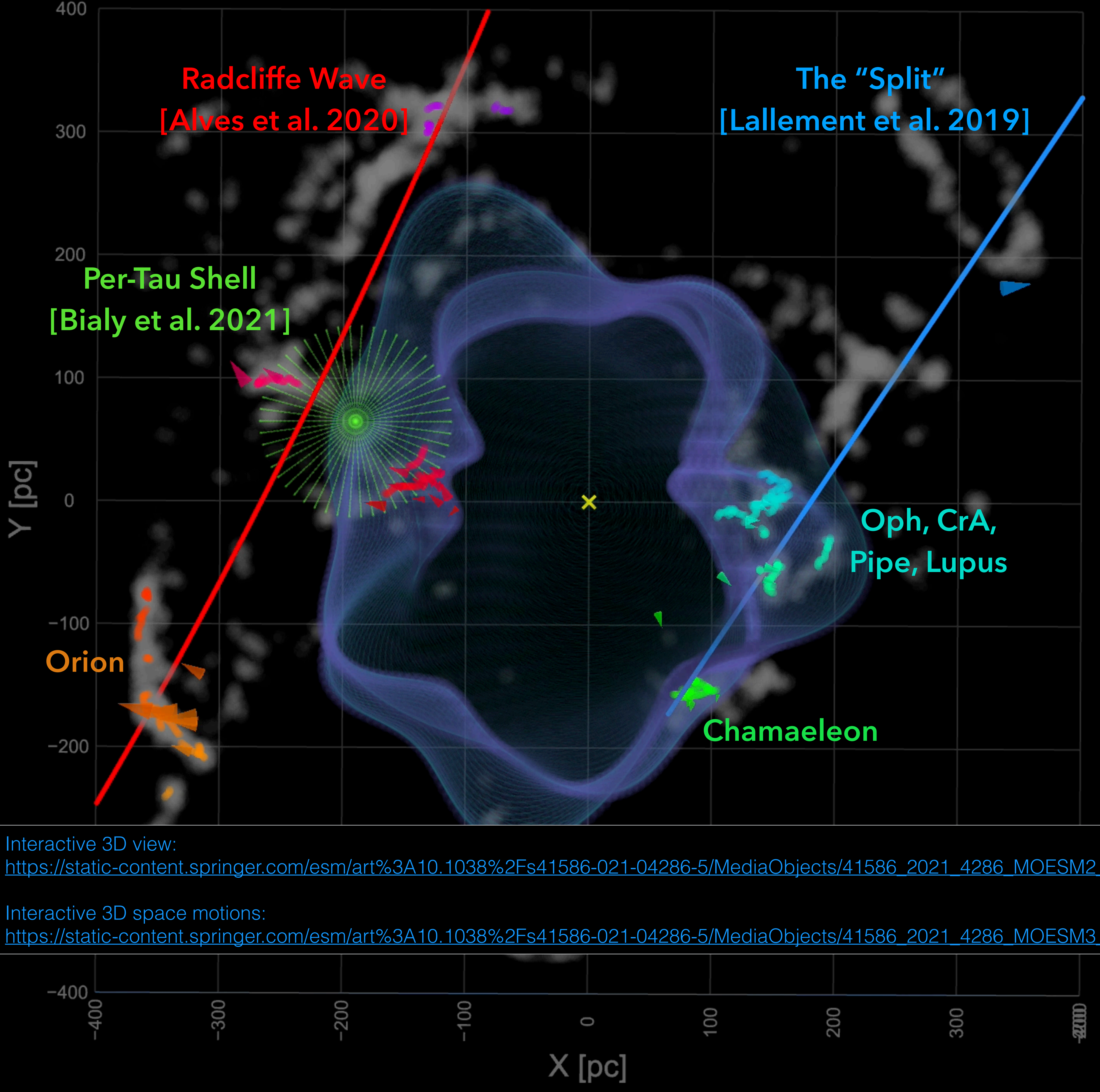
Local Bubble *Zucker et al. 2022, Nature*



- *All nearby star-forming regions (<200 pc) lie on the surface of the Local Bubble*
- *"6D" observational evidence that supernovae can sweep up gas into dense clouds that ultimately form new star*
- *Sun being centred in bubble by "luck" suggests that bubbles must be pervasive across the Galaxy*
- *Implying "bubbly" Milky Way*

Lallement+2019, Pelgrims+2020, Leike+2020, Zucker+2021

Local Bubble *Zucker et al. 2022, Nature*



Interactive 3D view:
https://static-content.springer.com/esm/art%3A10.1038%2Fs41586-021-04286-5/MediaObjects/41586_2021_4286_MOESM2_ESM.html

Interactive 3D space motions:
https://static-content.springer.com/esm/art%3A10.1038%2Fs41586-021-04286-5/MediaObjects/41586_2021_4286_MOESM3_ESM.html

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Lallement+2019, Pelgrims+2020, Leike+2020, Zucker+2021

Takeaways

We are now able to address long standing questions using the 6D phase space

Improved reconstruction of star formation histories

Bubbles everywhere?

Massive stellar feedback likely plays a crucial role in regulating star formation in the Milky Way