# A Galactic-scale gas wave in the Solar Neighborhood

João Alves, Catherine Zucker, Alyssa A. Goodman, Joshua S. Speagle, Stefan Meingast, Thomas Robitaille, Douglas P. Finkbeiner, Edward F. Schlafly, and Gregory M. Green

Haochang Jiang (蒋昊昌)

2021. 10. 15, DoA student seminar

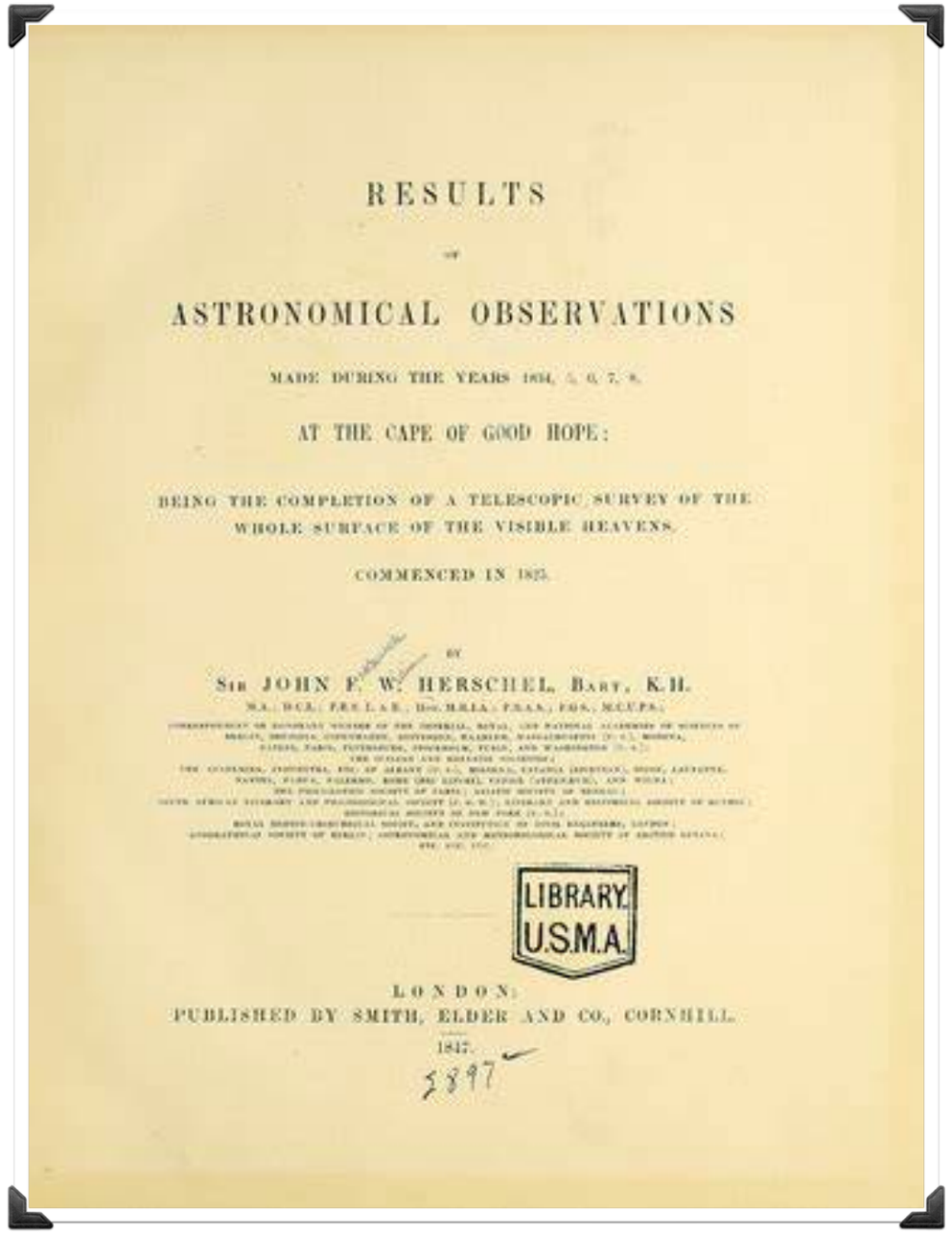
We are all in the gutter, but some of us are looking at the stars.

— Oscar Wilde (1854-1900)

# 1847

## Sir John Frederick William Herschel

- bright stars in south sky inclined with the milk way equator



RESULTS

OF

ASTRONOMICAL OBSERVATIONS

MADE DURING THE YEARS 1834, 5, 6, 7, 8,

AT THE CAPE OF GOOD HOPE:

BEING THE COMPLETION OF A TELESCOPIC SURVEY OF THE WHOLE SURFACE OF THE VISIBLE HEAVENS,

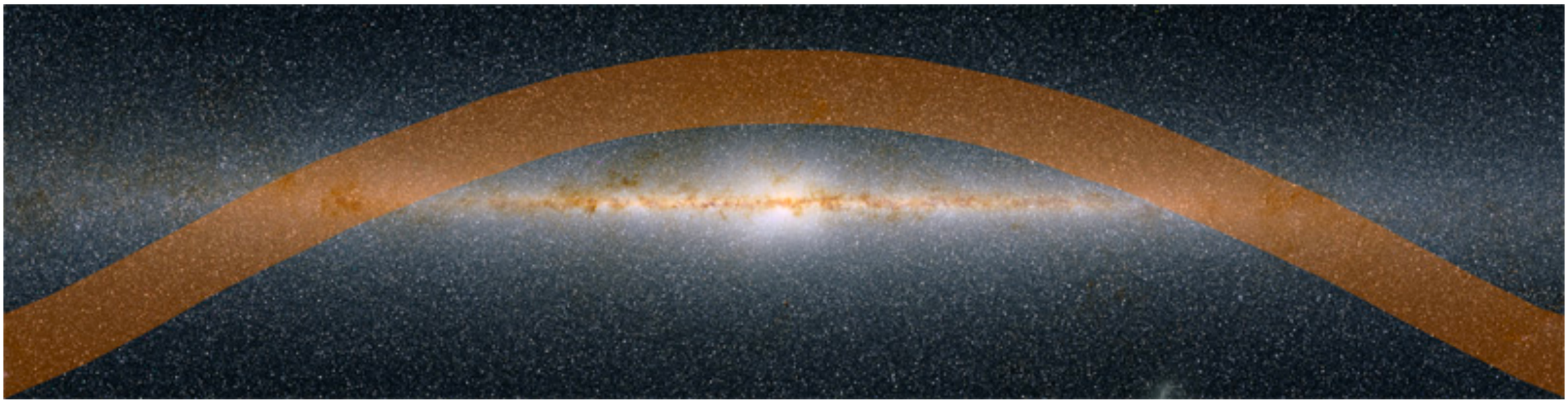
COMMENCED IN 1825.

BY

SIR JOHN F. W. HERSCHEL, BART, K.H.



LONDON:
PUBLISHED BY SMITH, ELDER AND CO., CORNHILL.
1847.

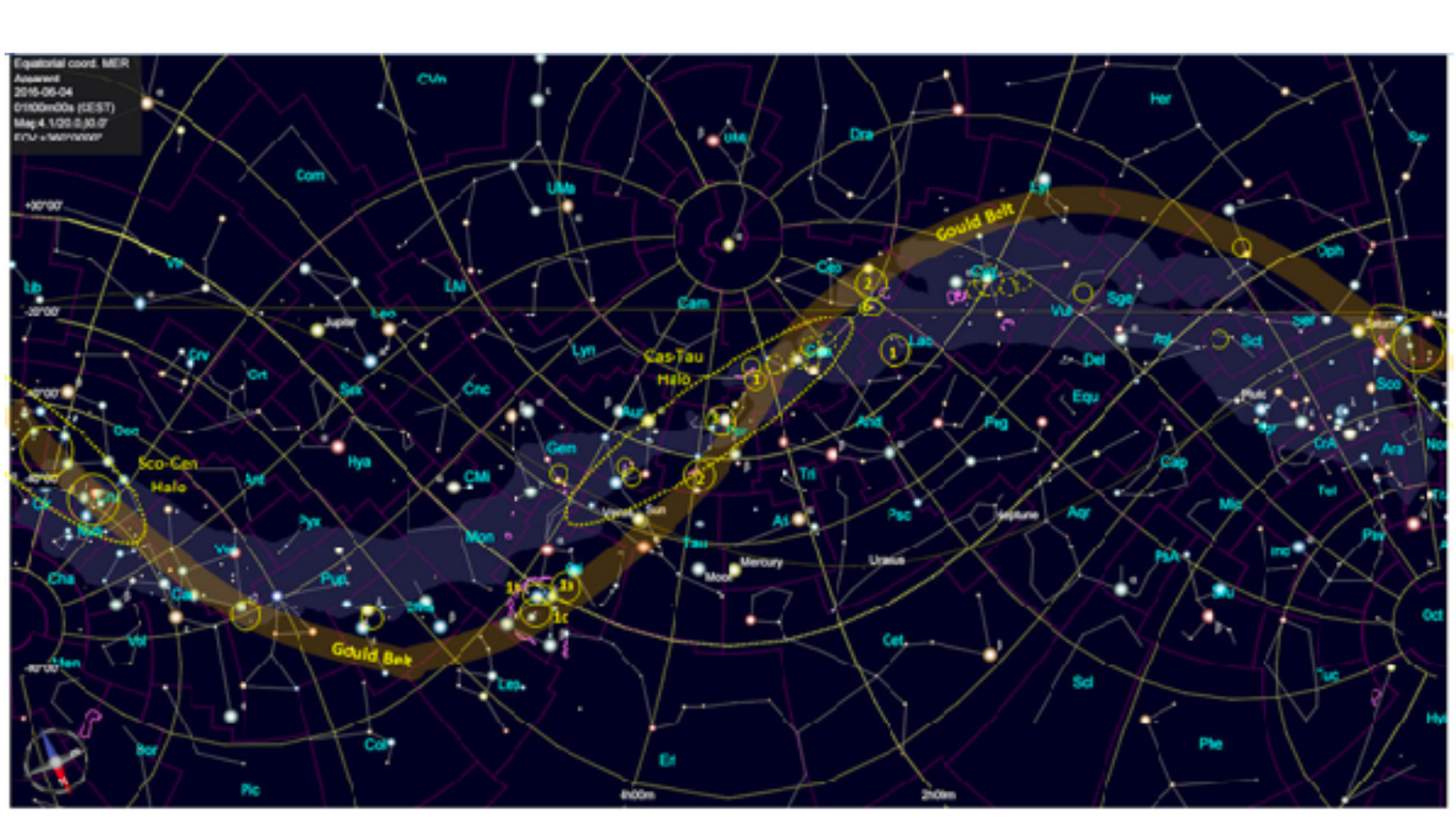



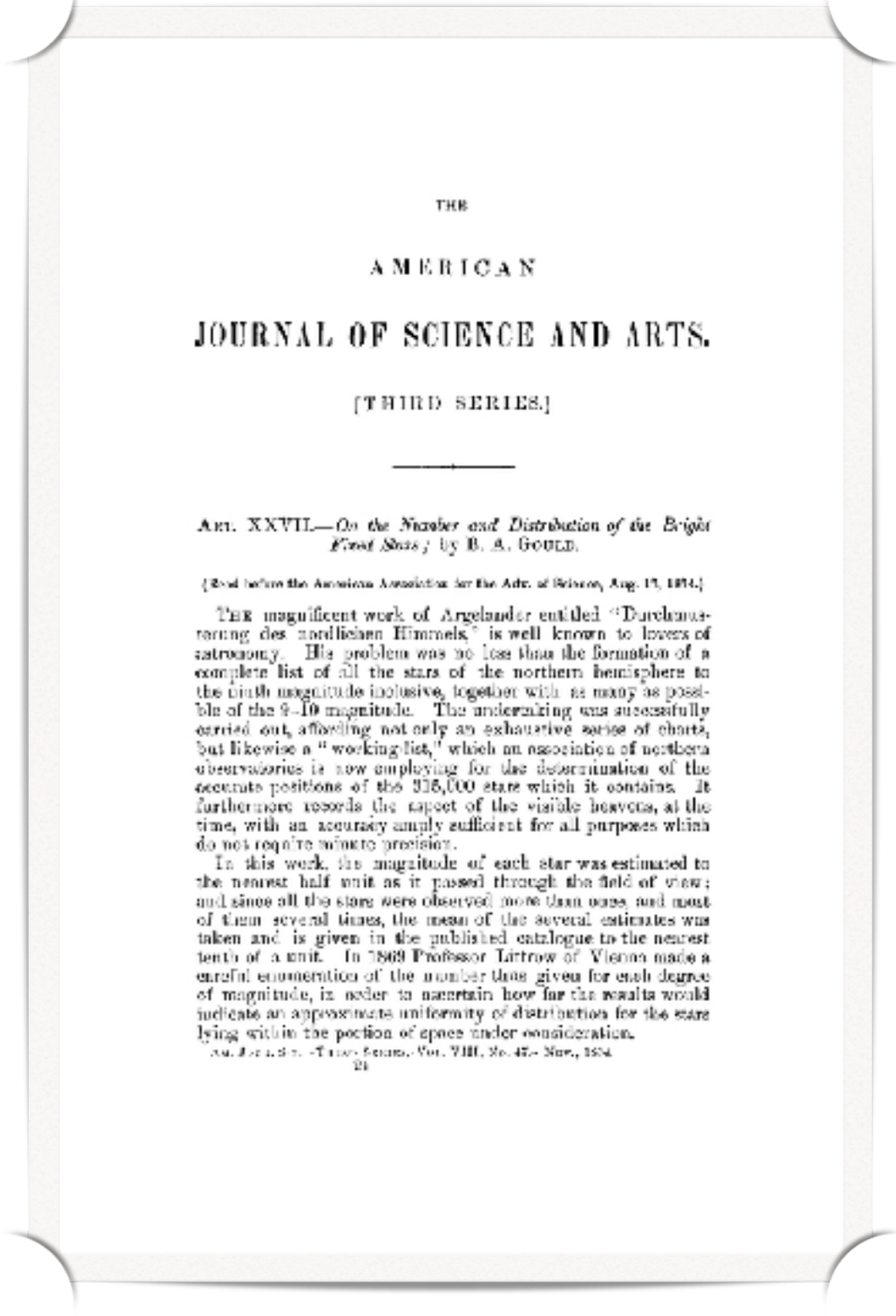
# 1874

*“On the Number and Distribution of the Bright Fixed Stars”*

## B. A. Gould

- determined the coordinates



THE

AMERICAN

JOURNAL OF SCIENCE AND ARTS.

[THIRD SERIES.]

ART. XXVII.—*On the Number and Distribution of the Bright Fixed Stars*; by B. A. GOULD.

[Read before the American Association for the Adv. of Science, Aug. 17, 1874.]

THE magnificent work of Argelander entitled "Durchmusterung des nordlichen Himmels," is well known to lovers of astronomy. His problem was no less than the formation of a complete list of all the stars of the northern hemisphere to the tenth magnitude inclusive, together with as many as possible of the 9–10 magnitude. The undertaking was successfully carried out, affording not only an exhaustive series of charts, but likewise a "working-list," which an association of northern observatories is now employing for the determination of the accurate positions of the 324,000 stars which it contains. It furthermore records the aspect of the visible heavens, at the time, with an accuracy amply sufficient for all purposes which do not require minute precision.

In this work, the magnitude of each star was estimated to the nearest half unit as it passed through the field of view; and since all the stars were observed more than once, and most of them several times, the mean of the several estimates was taken and is given in the published catalogue to the nearest tenth of a unit. In 1869 Professor Littrow of Vienna made a careful enumeration of the number thus given for each degree of magnitude, in order to ascertain how far the results would indicate an approximate uniformity of distribution for the stars lying within the portion of space under consideration.

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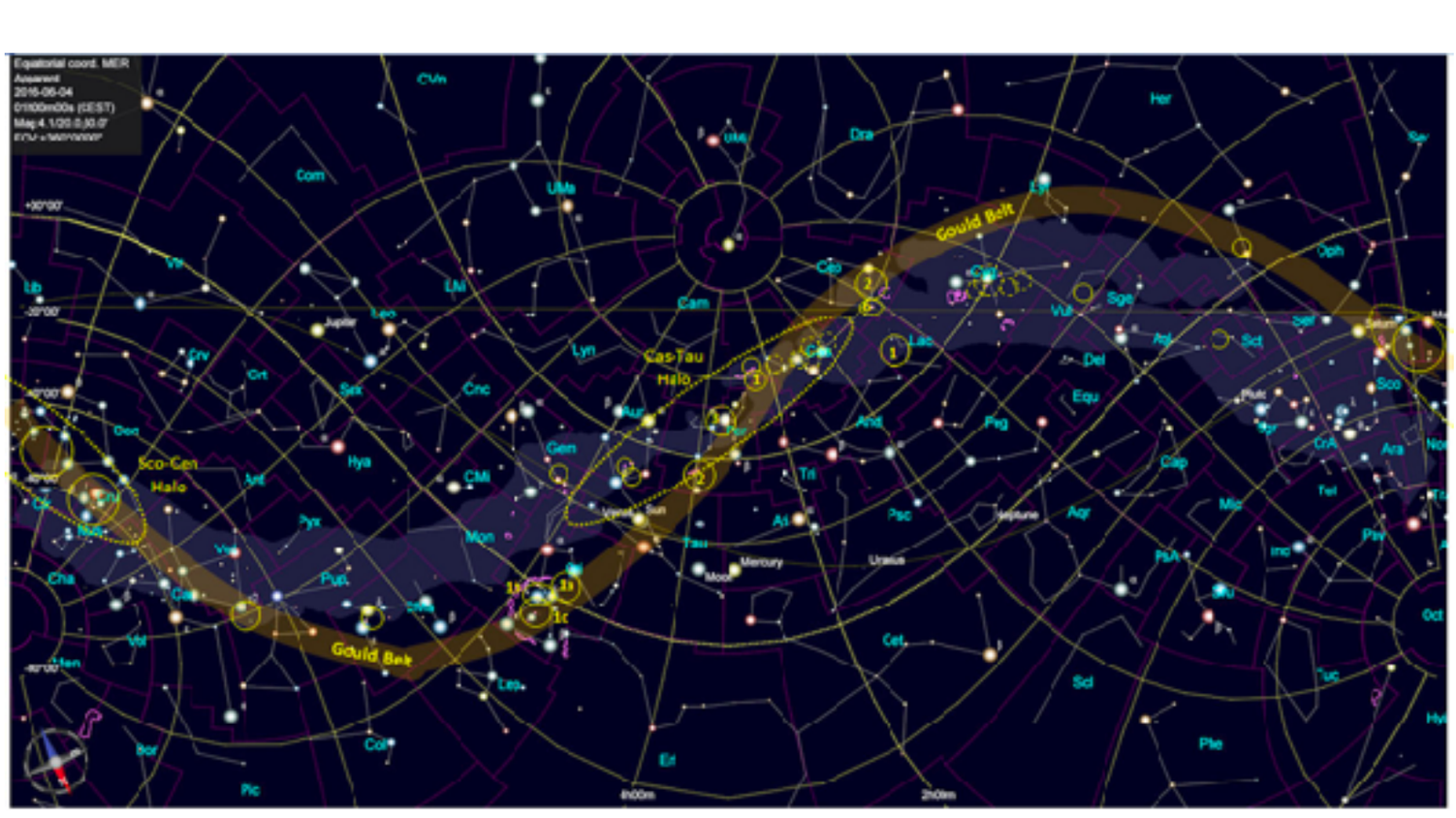


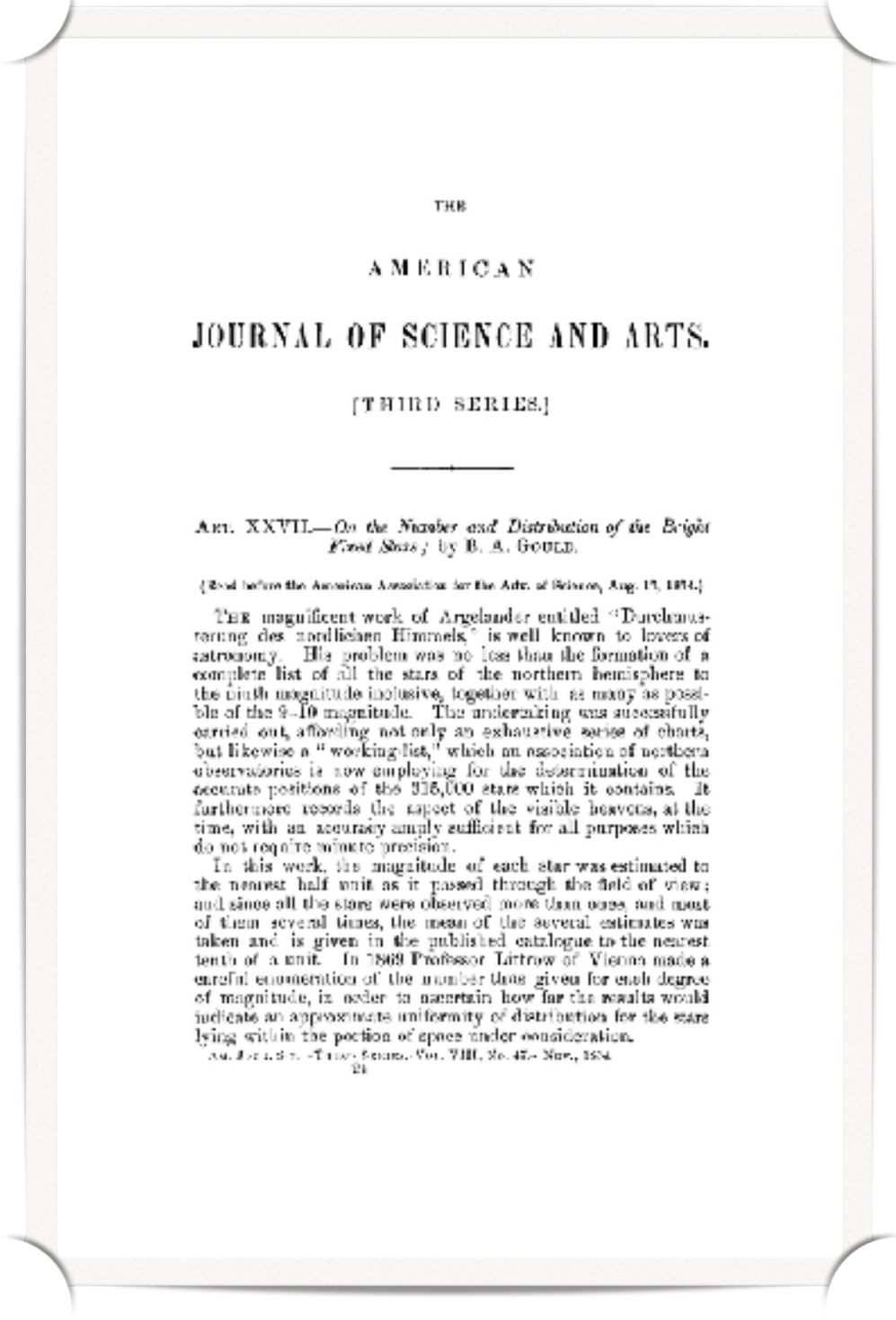

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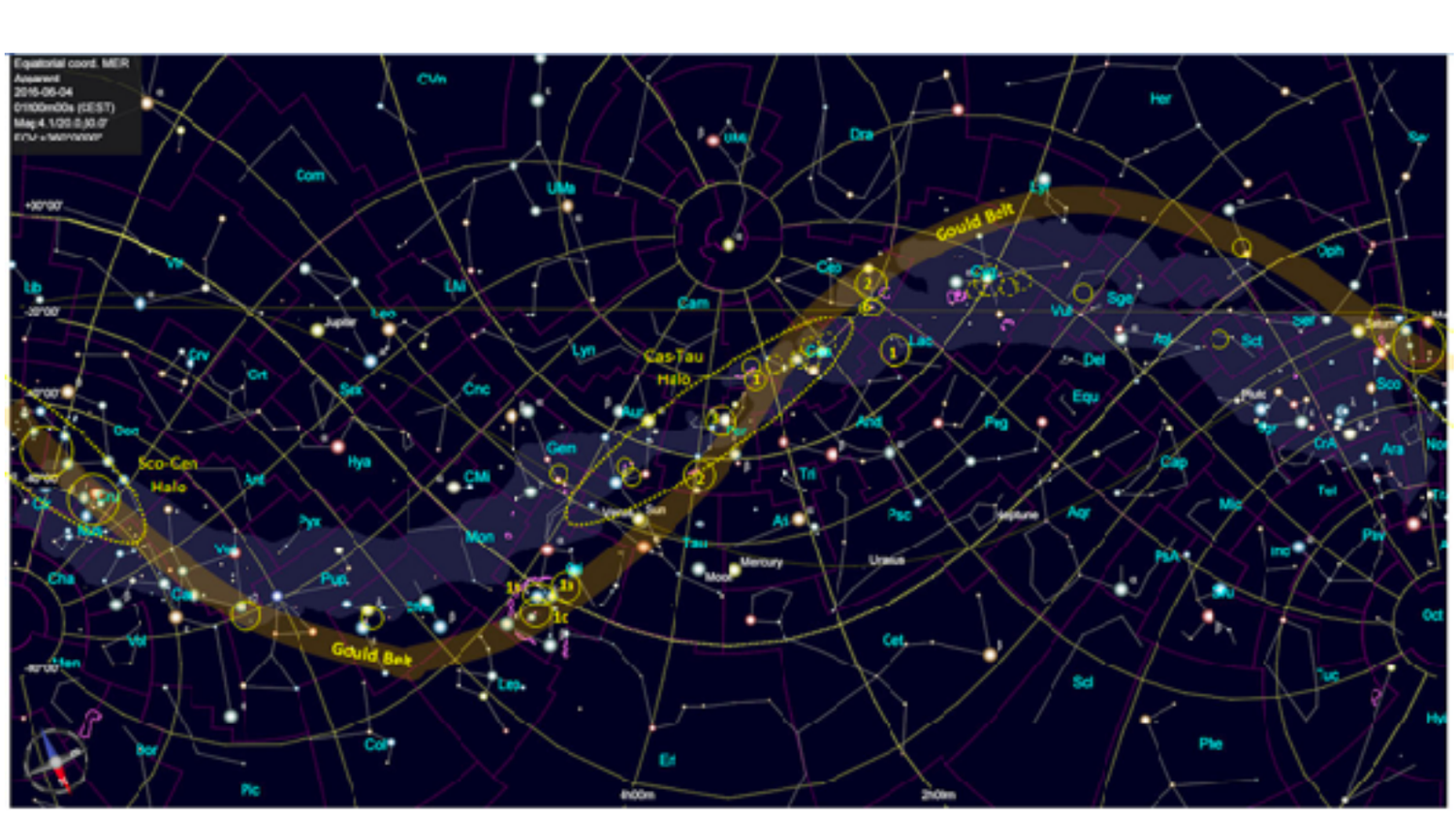


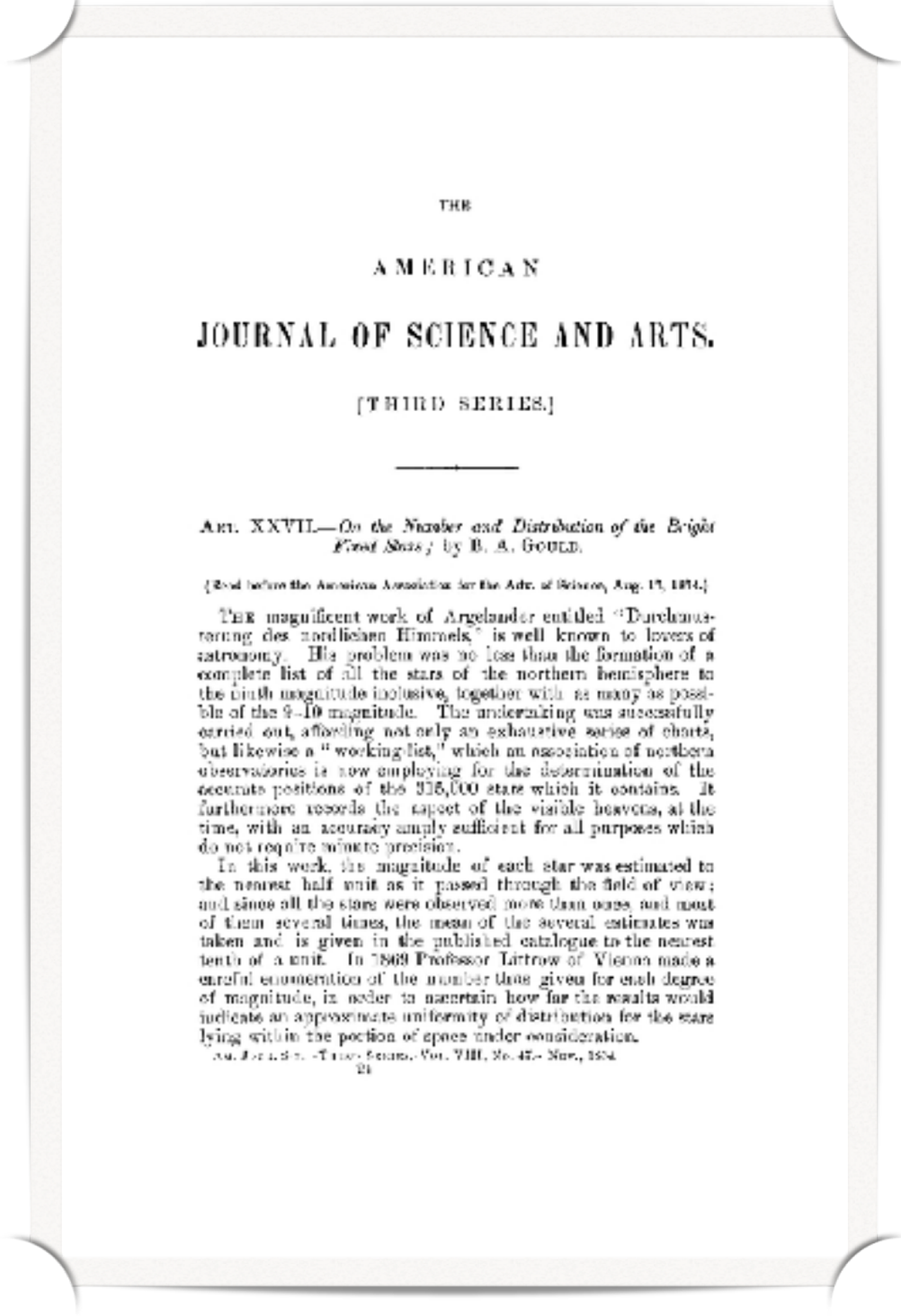

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*Herschel’s publication citations: 445*

# 1919

Harlow Shapley

- the close (to 1 kpc) bright stars form a unique separate subsystem — Local system

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Harlow Shapley

- the close (to 1 kpc) bright stars form a unique separate subsystem — Local system

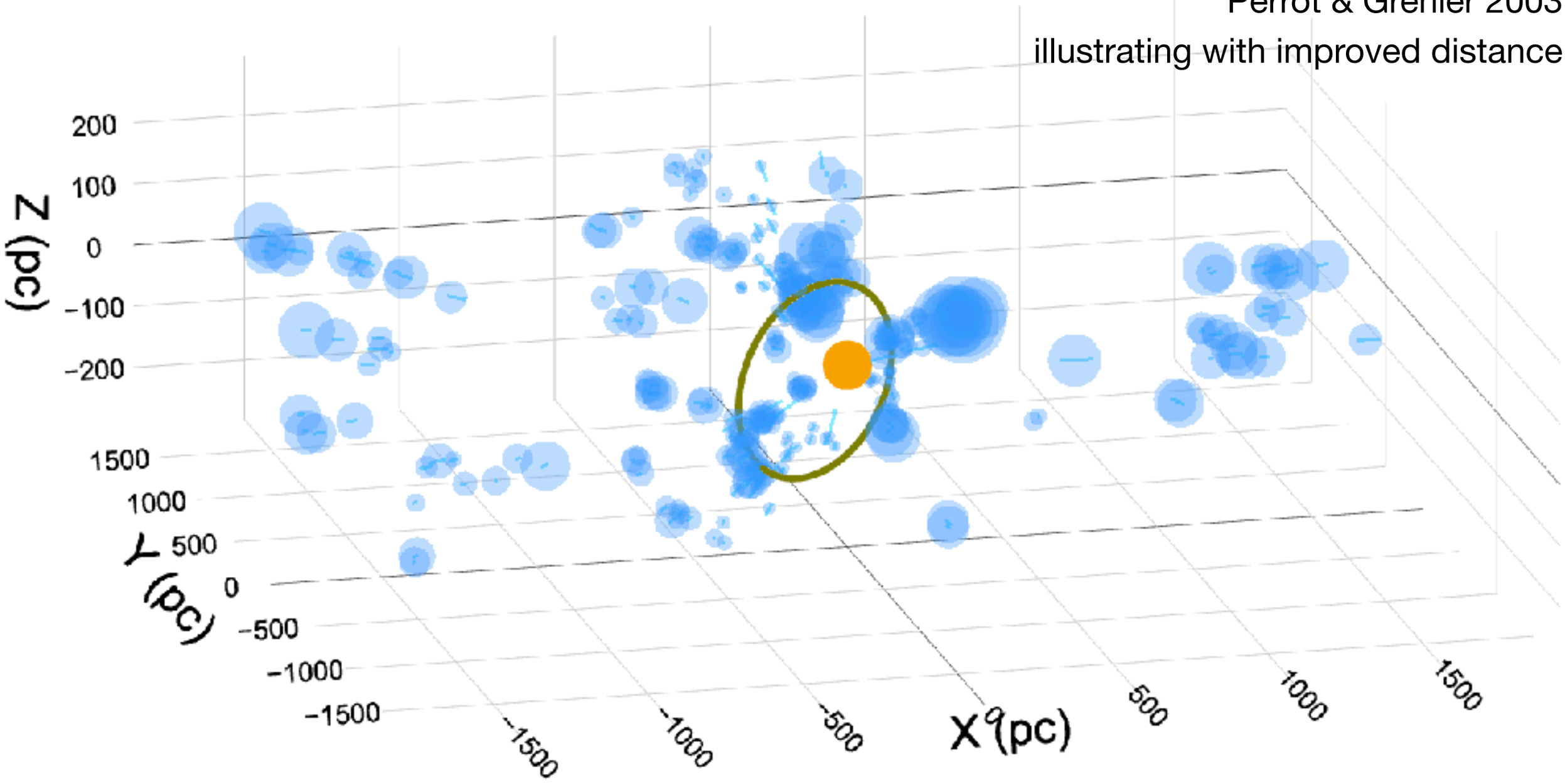
- “From a modern standpoint, the term “Local system” is more substantive, ……the presence of **cold atomic HI**, **molecular H2**, and high temperature coronal **gas** and **dust**.”

Bobylev 2014

# Major Cloud Catalog

Perrot & Grenier 2003

illustrating with improved distance




Gould's Belt show off as a ring in 3D map

# How to form the Gould Belt?

- **Supernova explosion**

- Evolution of arm

- High-v cloud

# Supernova explosion

Gould's Belt is the **result of the expansion of extremely hot gas**

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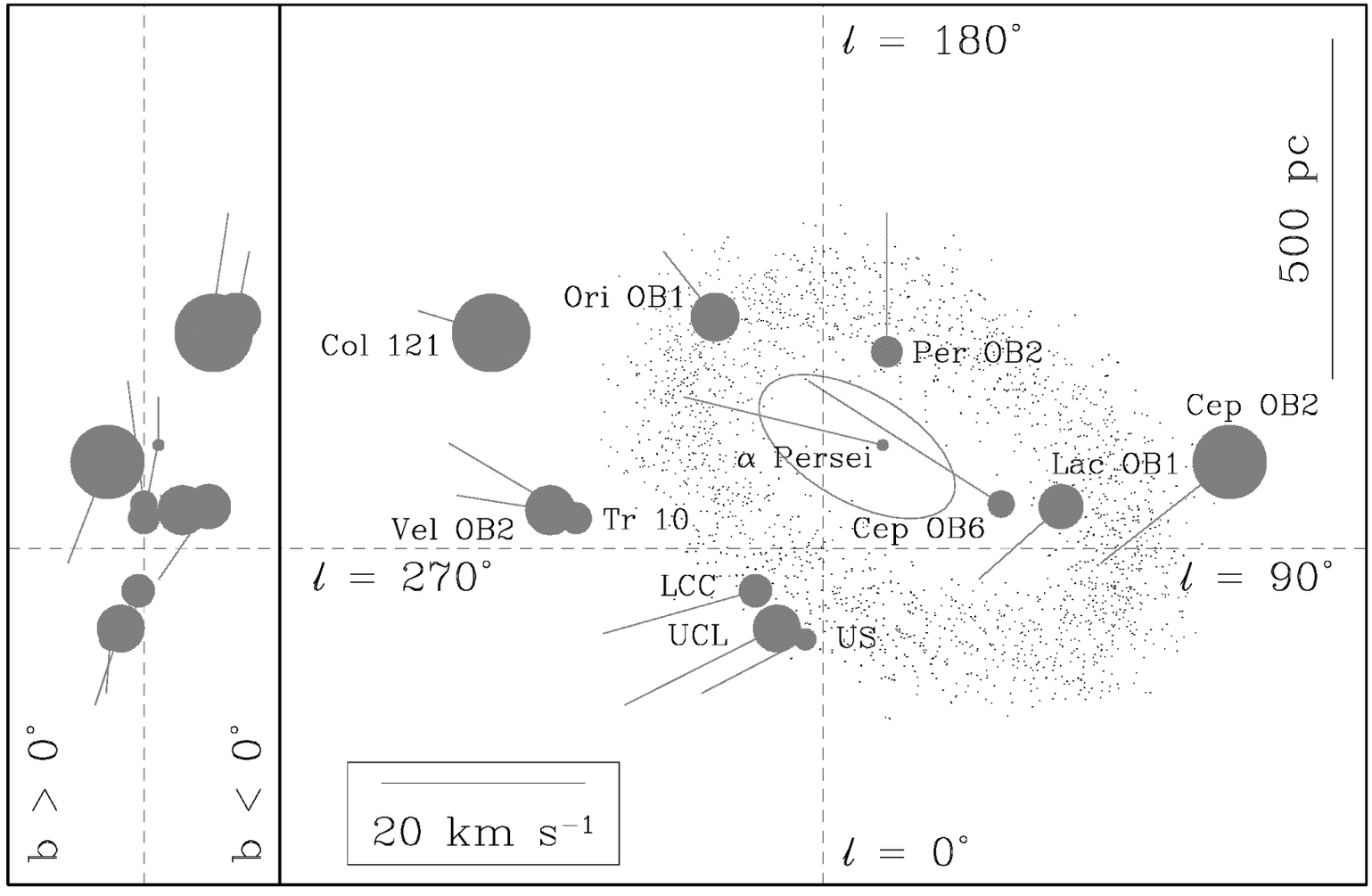


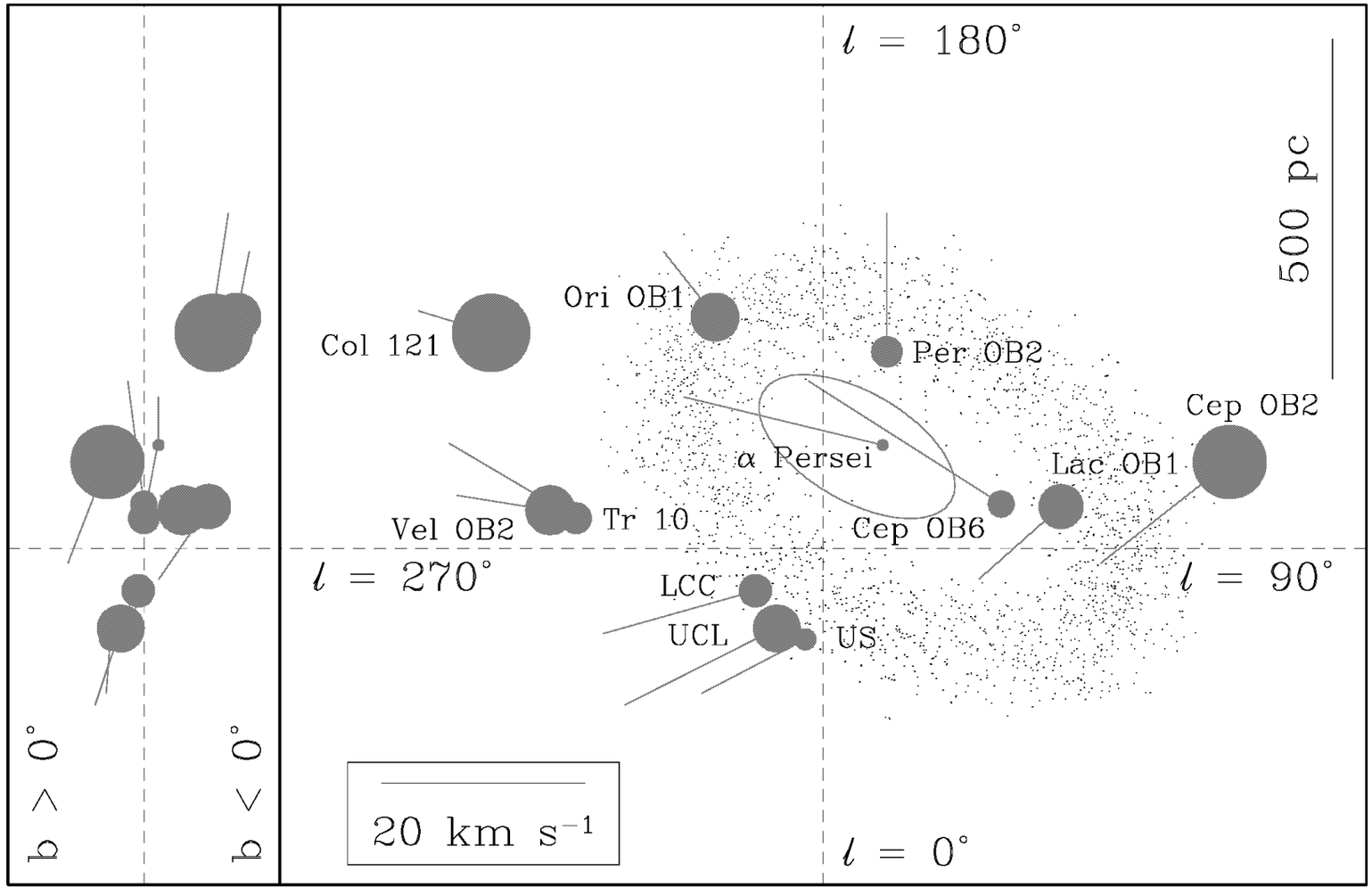

Blaauw 1965

*the distribution of the nearest OB associations*

de Zeeuw et al. 1965
re-plot by Bobylev 2014

# Supernova explosion

Gould's Belt is the **result of the expansion of extremely hot gas**




Blaauw 1965

*the distribution of the nearest OB associations*

the model is not complete

de Zeeuw et al. 1965
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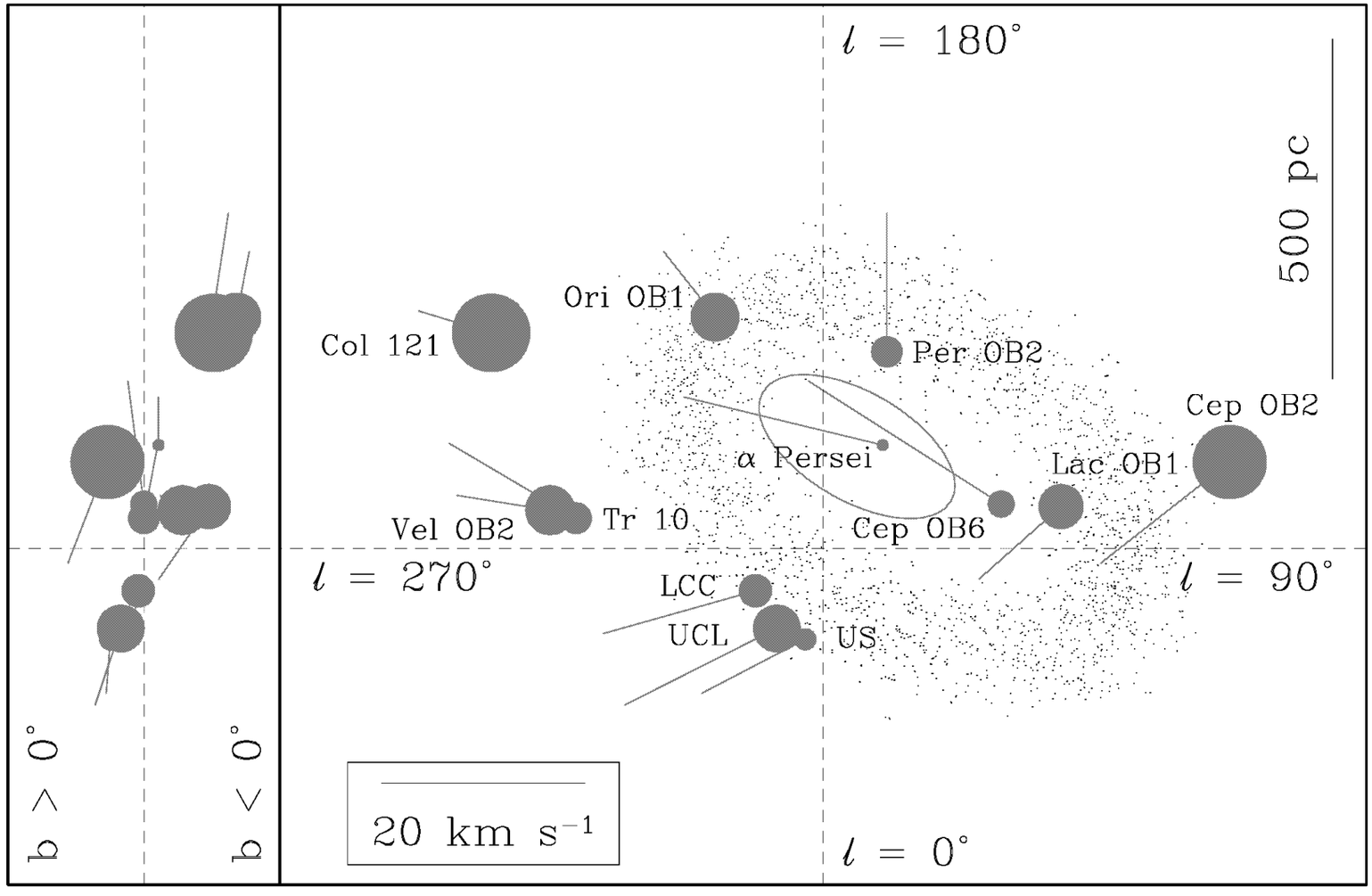


Olano 1982

*gas dynamic model*

initial $v_{expansion}$ ≈20 km/s

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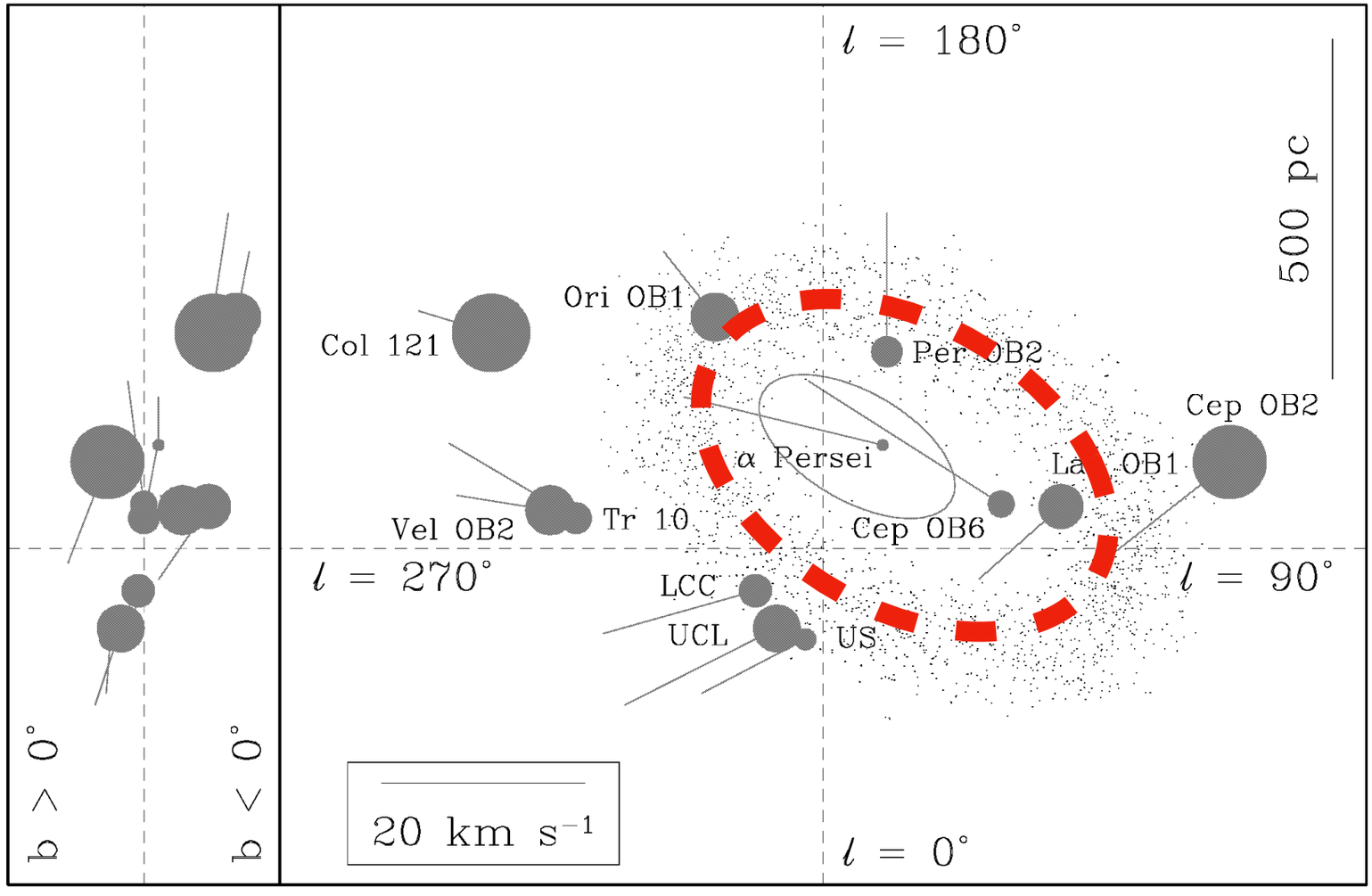


Olano 1982

*gas dynamic model*

initial $v_{expansion}$ ≈20 km/s

$l_0 = 131^\circ$ , $R_0 = 166$ pc

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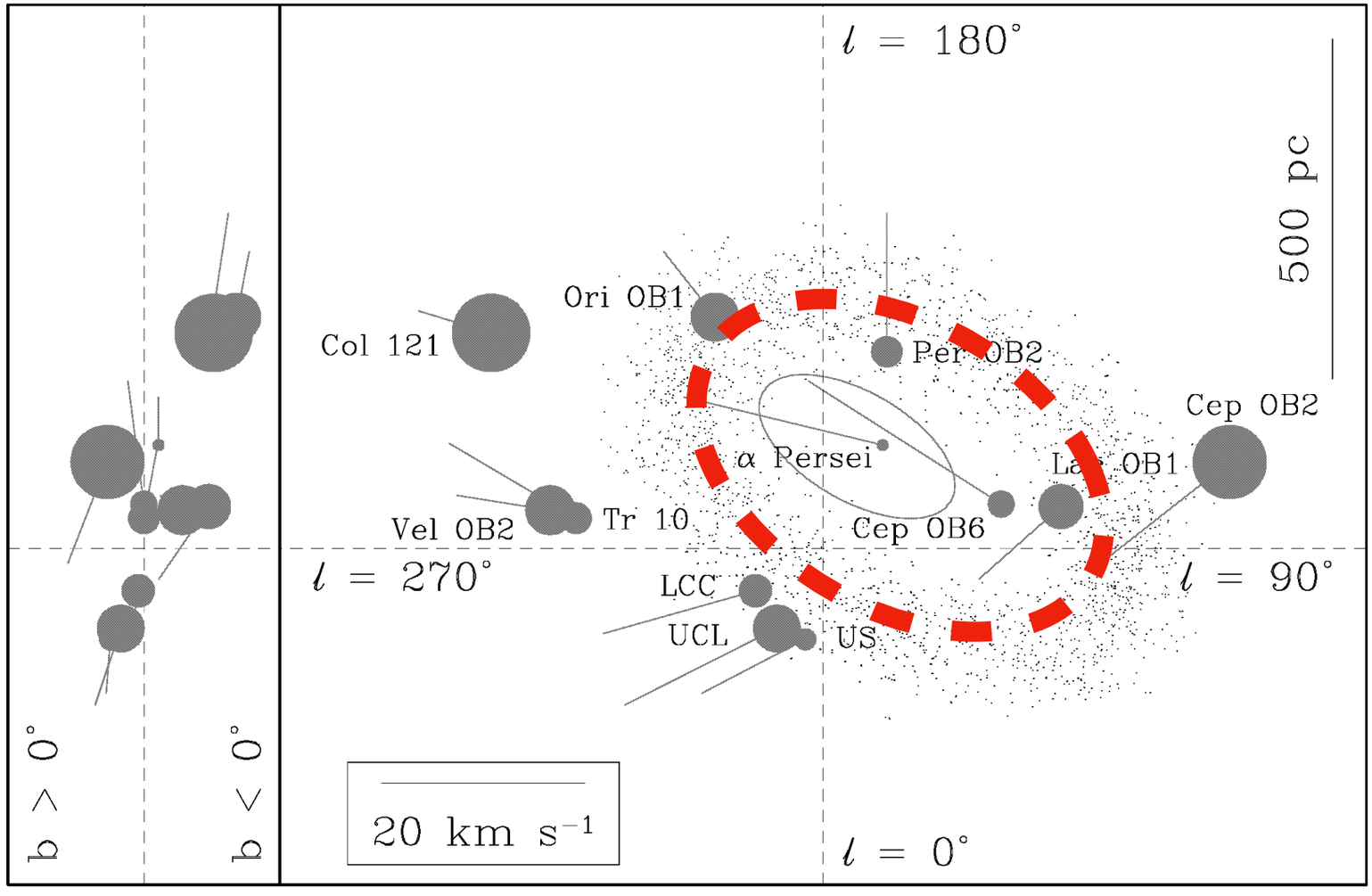
# Supernova explosion

Gould's Belt is the **result of the expansion of extremely hot gas**




Lindblad 2000; Bobylev 2004, 2006

*intrinsic differential rotation*

$\omega_0 = -24$ km/s/kpc

$l_0 = 127^\circ$ , $R_0 = 166$ pc
the flat shape

de Zeeuw et al. 1965
re-plot by Bobylev 2014

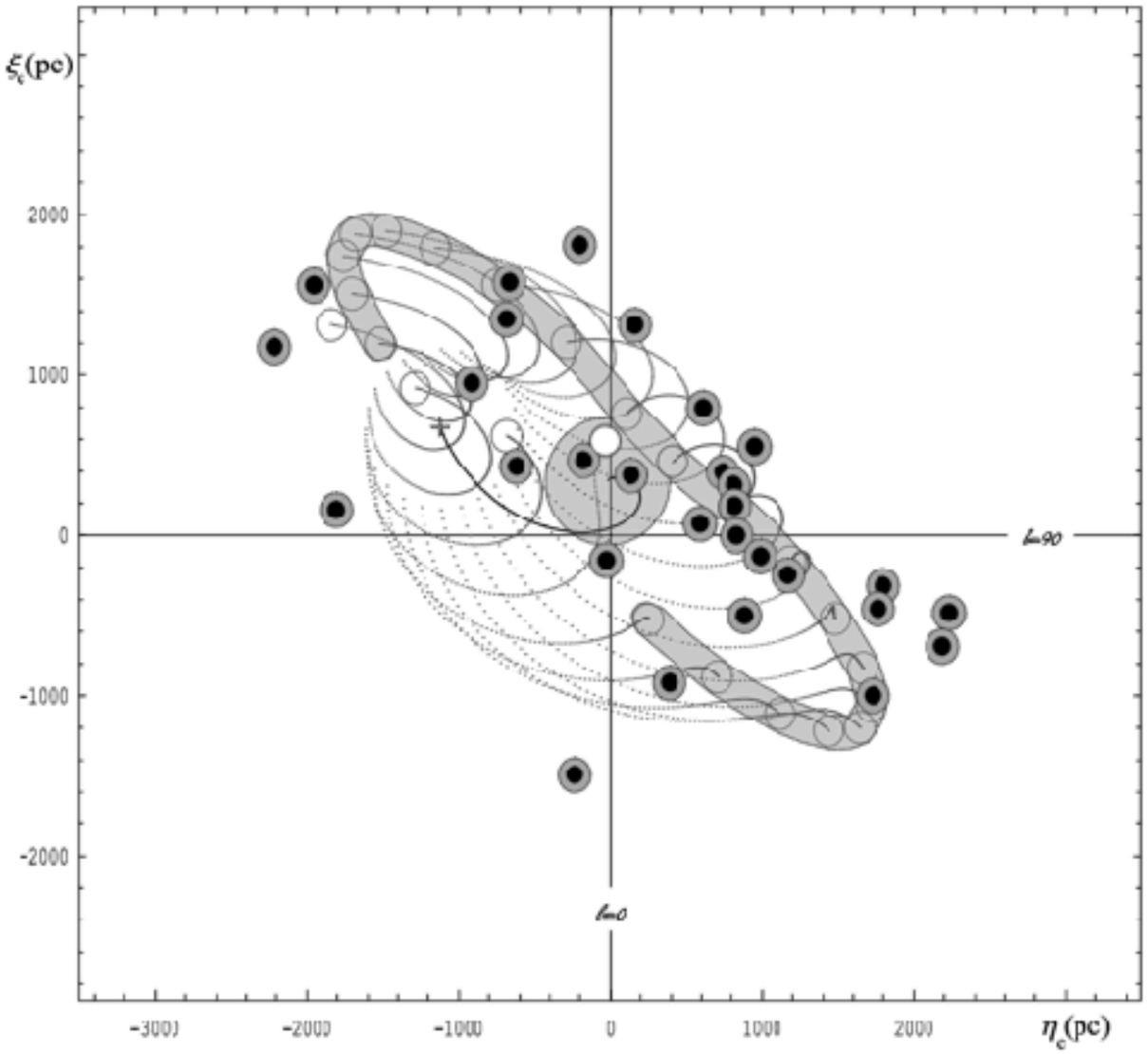
# Supernova explosion

Many remained problems:

- older associations should lie further from center than younger ones, but not observed
- complex of molecular clouds in Taurus lies inside the expanding ellipse
- still very hard to explain the shape of Gould's Belt - expansion is more likely from a line, than a point center
- .....

# Evolution of arm

- A gas cloud collide with a spiral density wave of Orion arm. The central regions of this parent cloud compressed to the Gould belt.

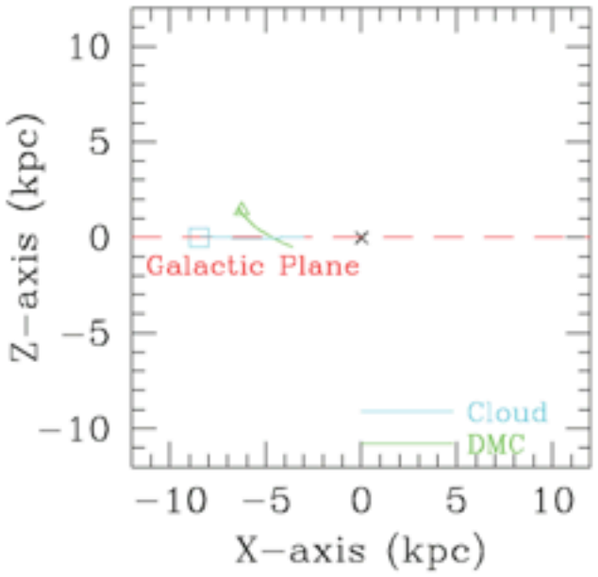


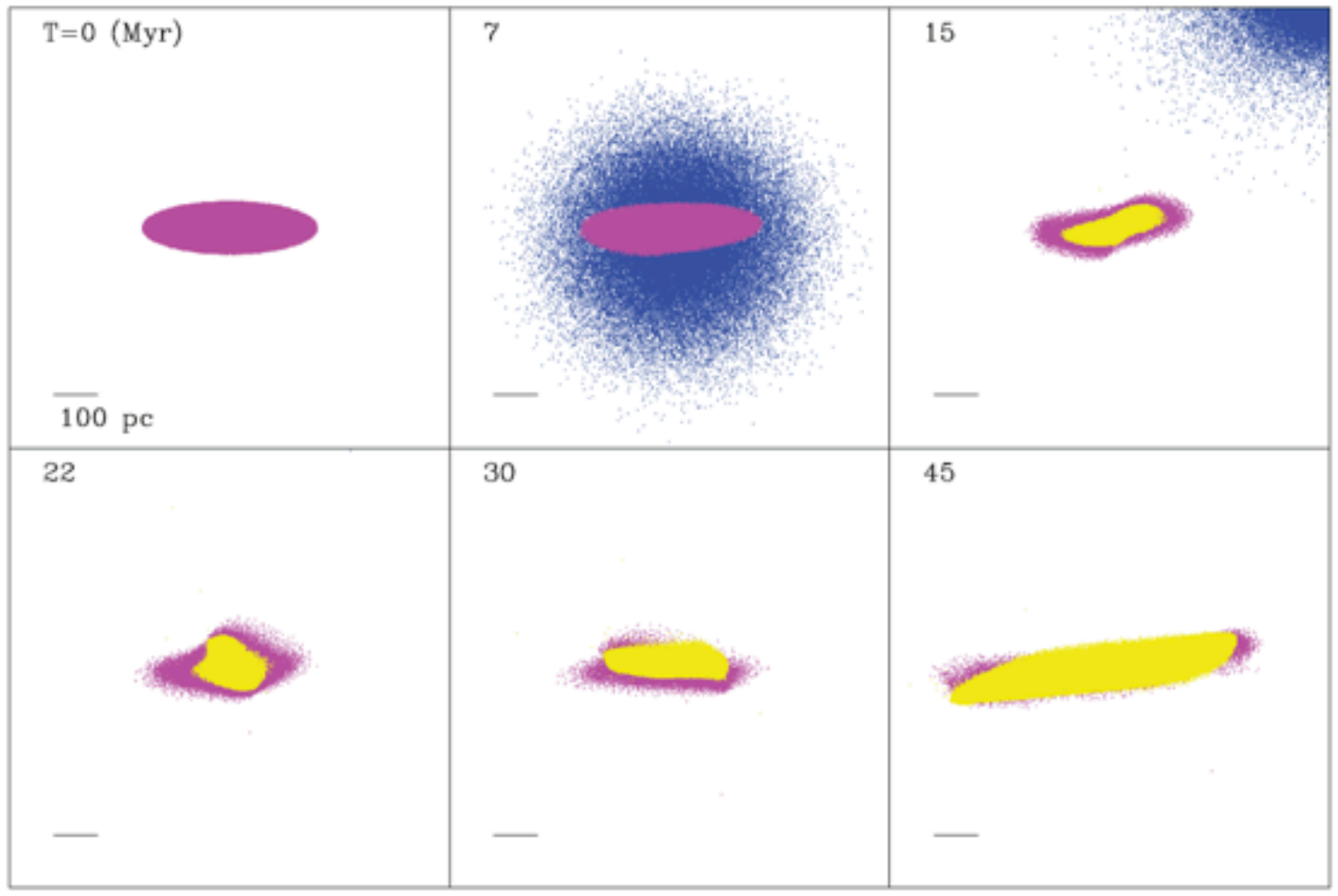

Olano 2001

# High-v clouds

- A High-v cloud beyond galactic plane collide onto it. The resulted symmetric gas cloud elongates into an ellipse.

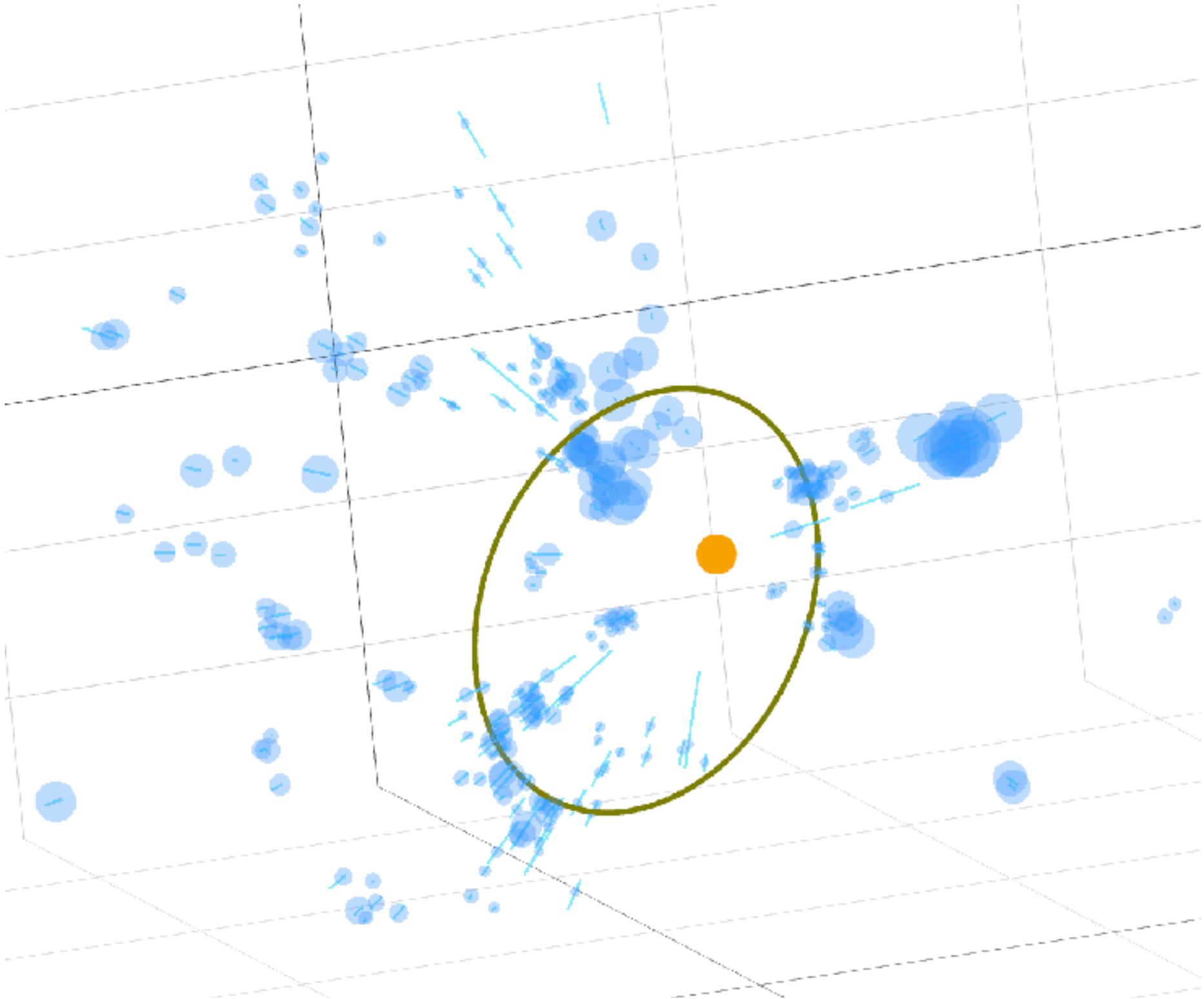
Lepin & G. Duvert 1994; Comeron & Torra 1992; Bekki 2009



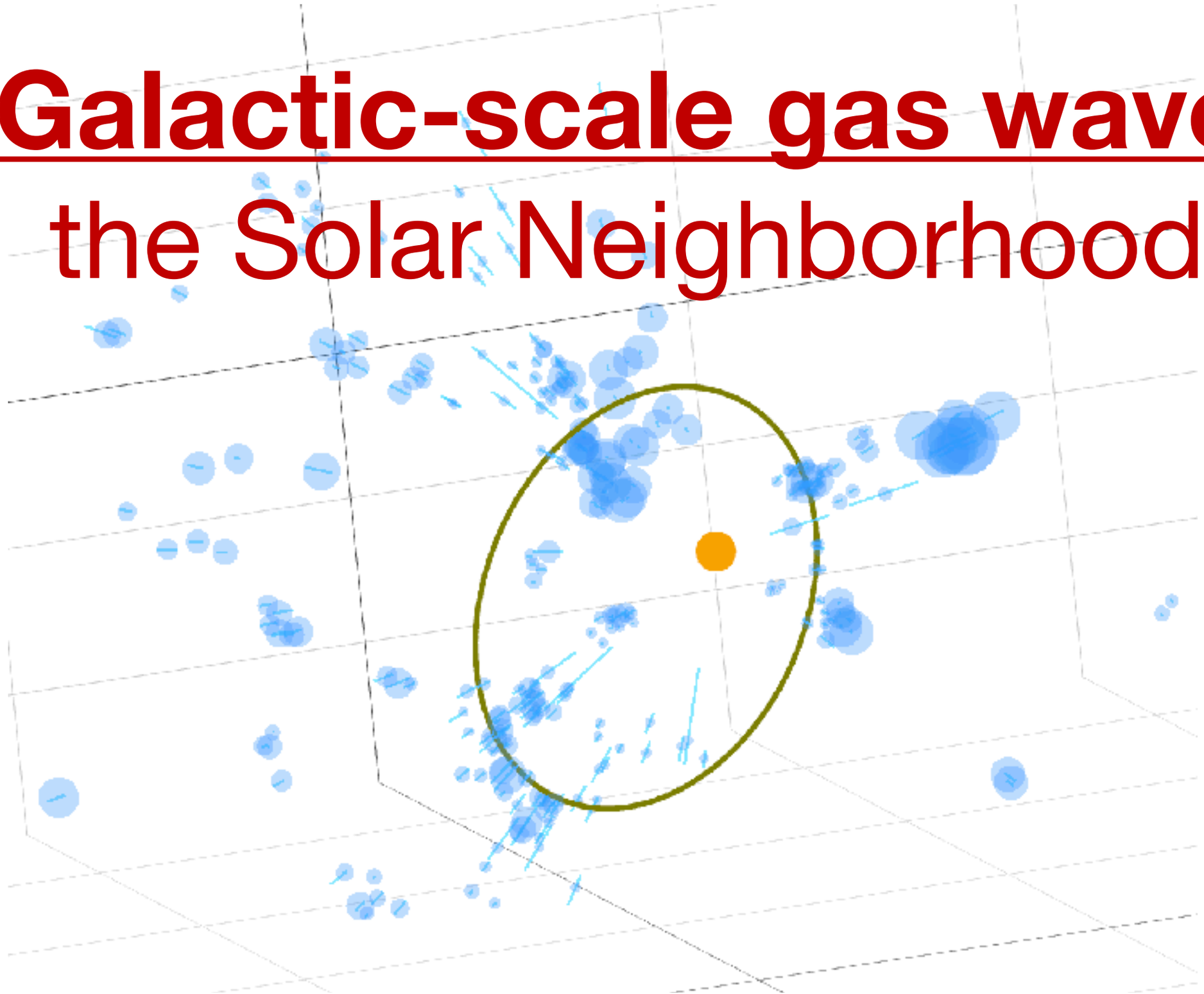

Bekki 2009

# Gould's Belt?

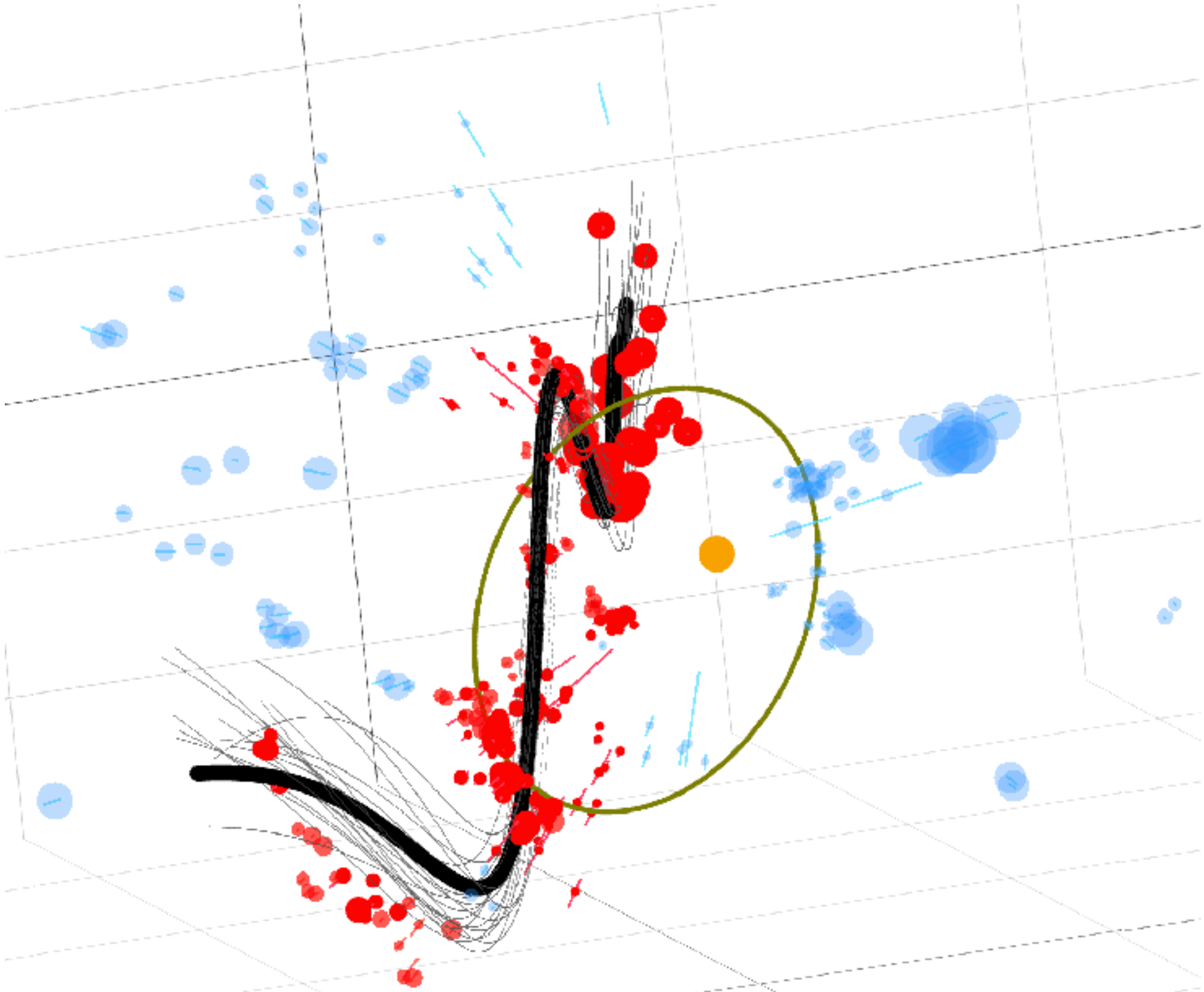


Gould's Belt?

# **A Galactic-scale gas wave** in the Solar Neighborhood

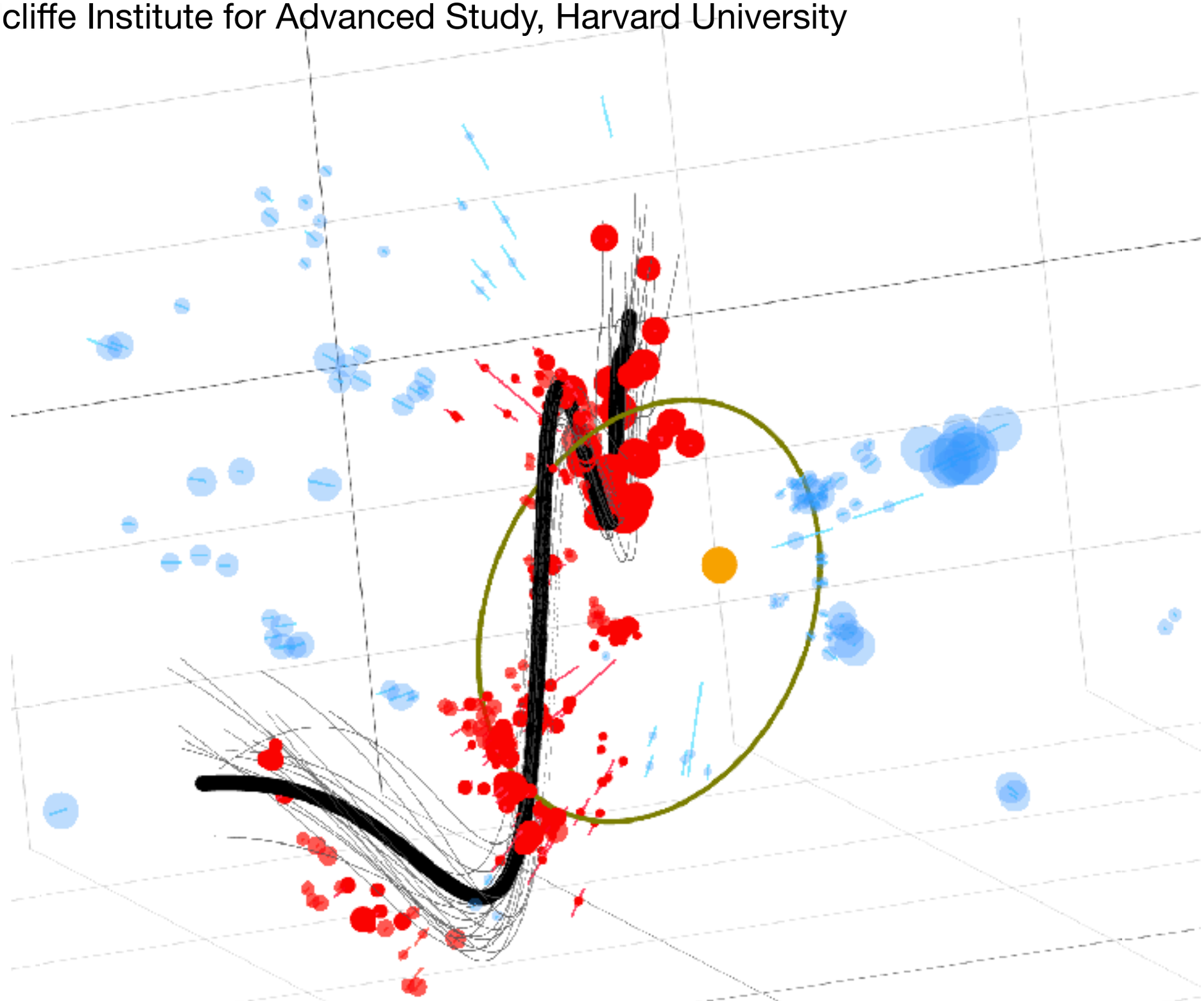


# Radcliffe Wave!



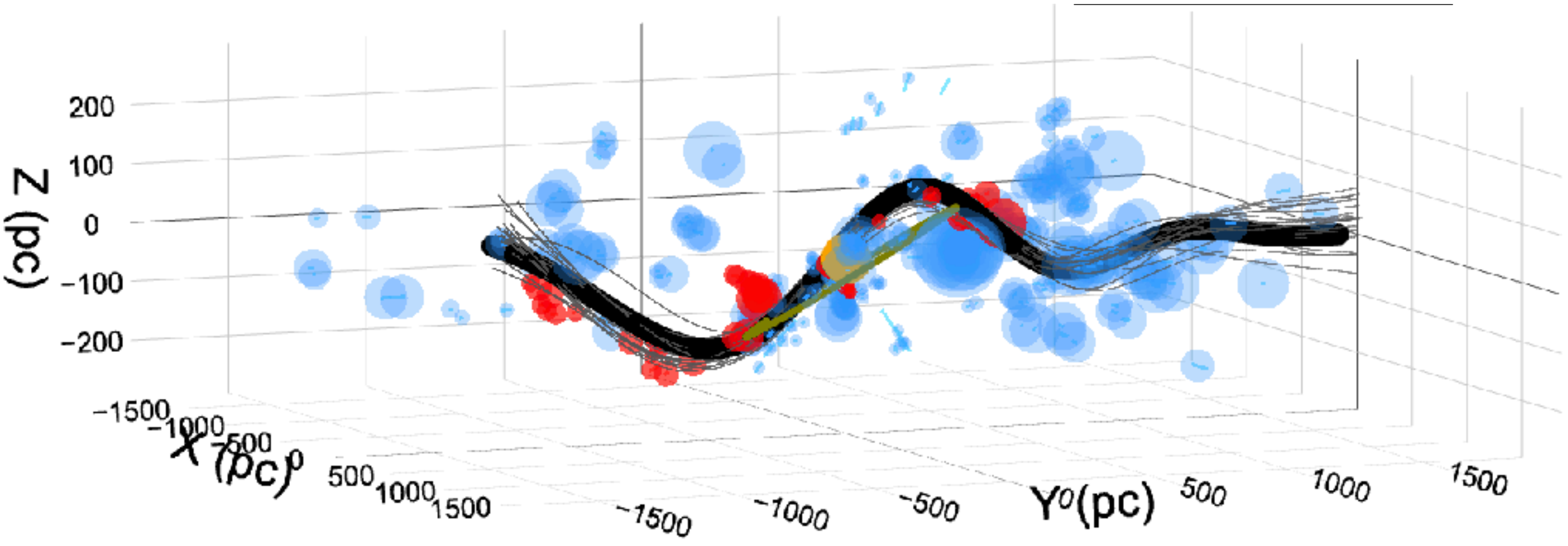
# Radcliffe Wave!

* Radcliffe Institute for Advanced Study, Harvard University



# Take home message

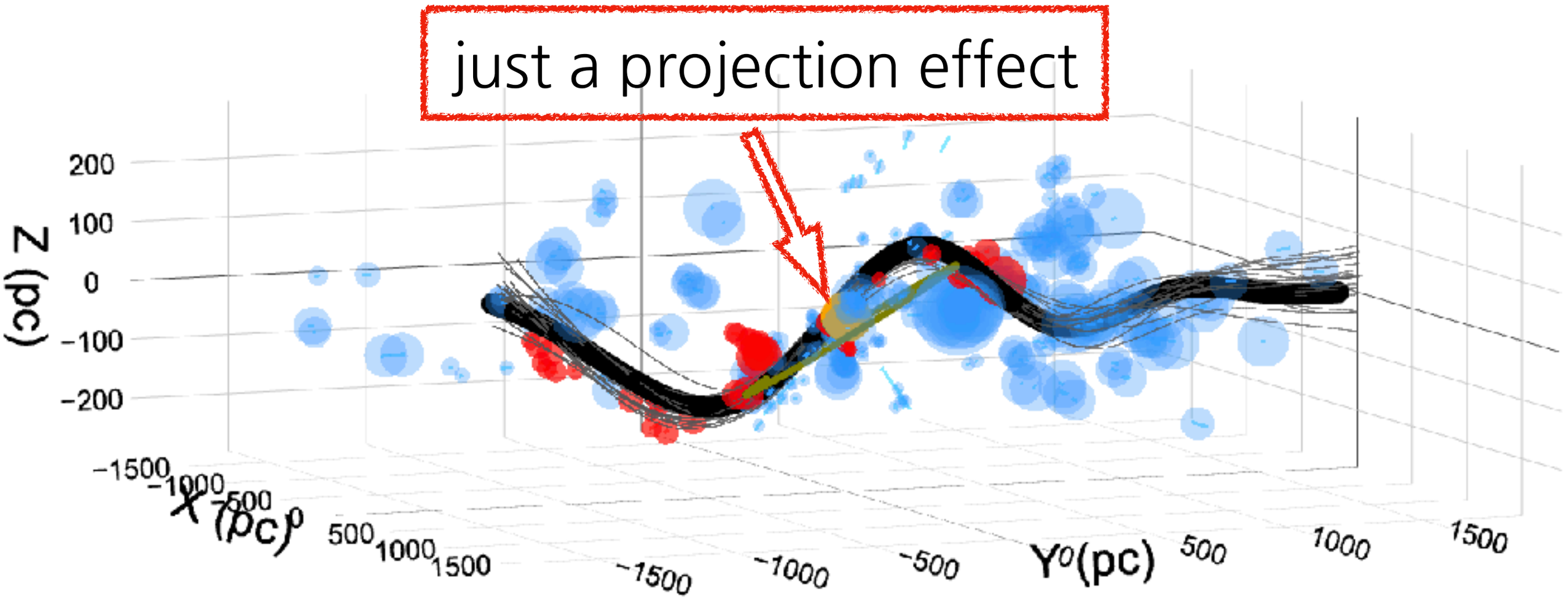
| Name | Median with 95% CI |
|---|---|
| Length | $2.7 \pm 0.2$ kpc |
| Scatter | $60 \pm 15$ pc |
| Amplitude | $160 \pm 30$ pc |
| Mass | $\geq 3 \times 10^6$ $M_\odot$ |




The authors find a narrow and coherent dense gas structure, disputing the Gould Belt model

# Take home message

just a projection effect

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# Mapping the solar neighborhood

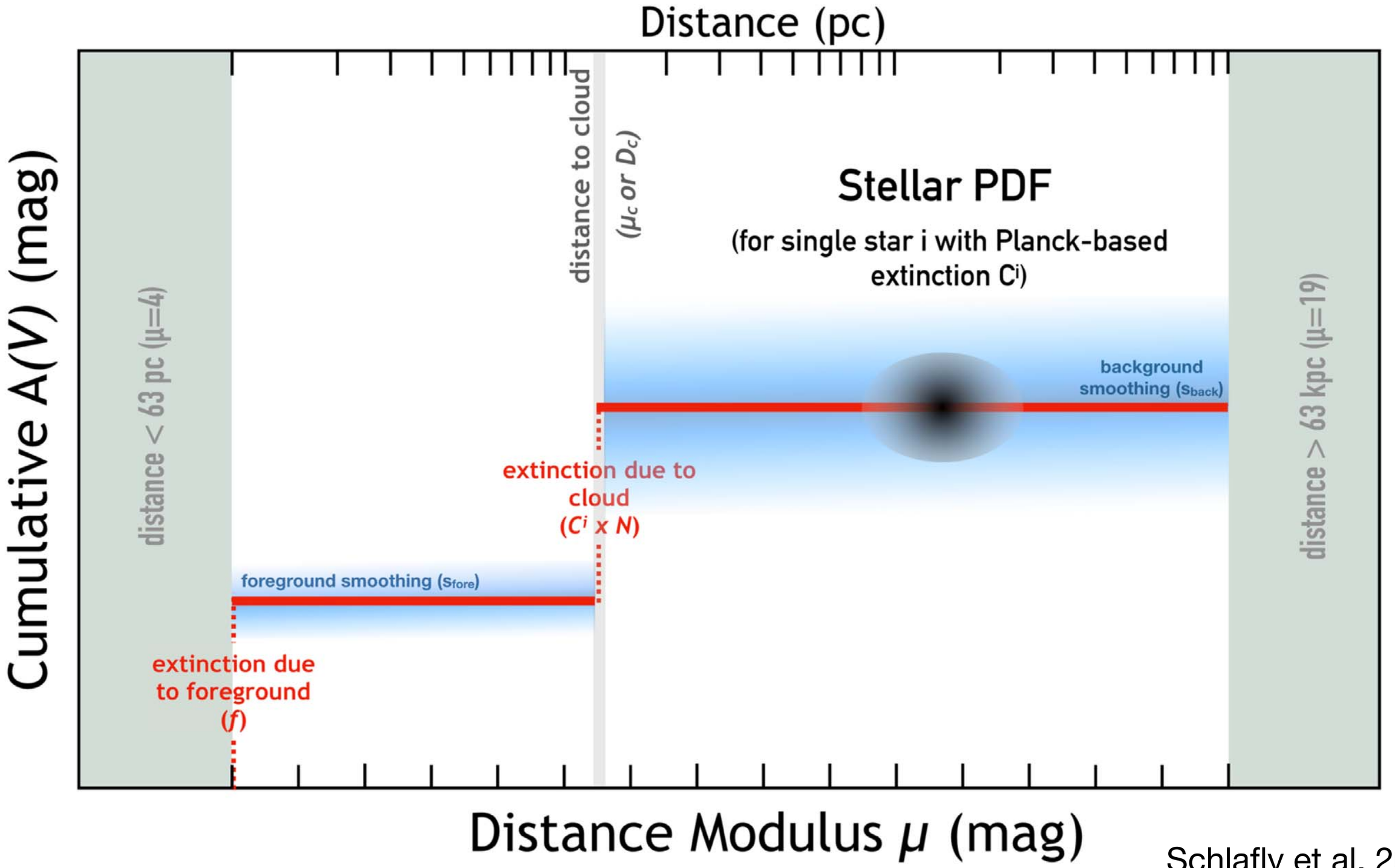
Chambers et al. 2016

- Pan-STARRS1 survey - photometry

- Gaia astrometric survey - parallaxes

Brown et al. 2018

# Mapping the solar neighborhood




Schlafly et al. 2014
Zucker & Speagle et al. 2019

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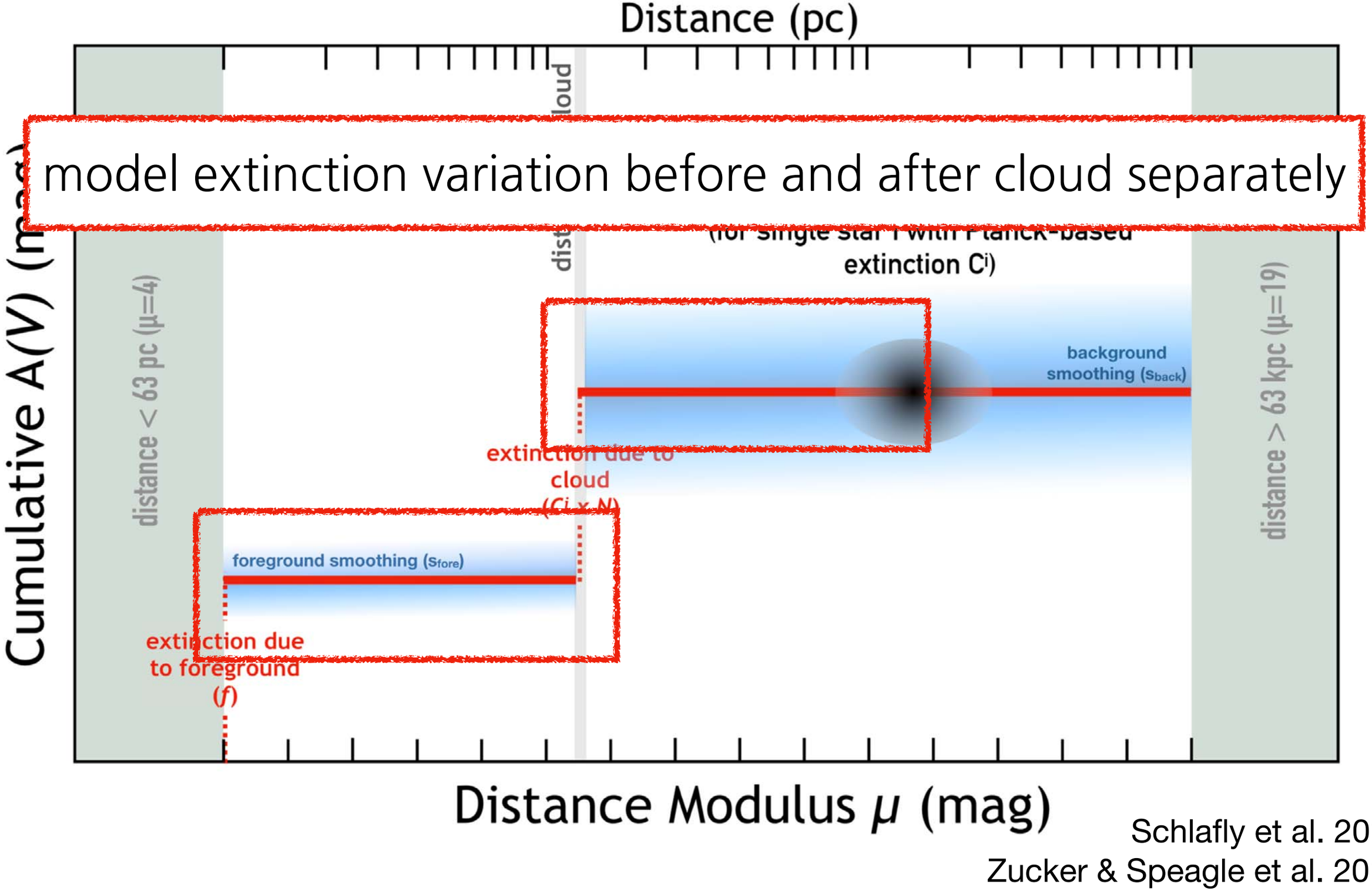


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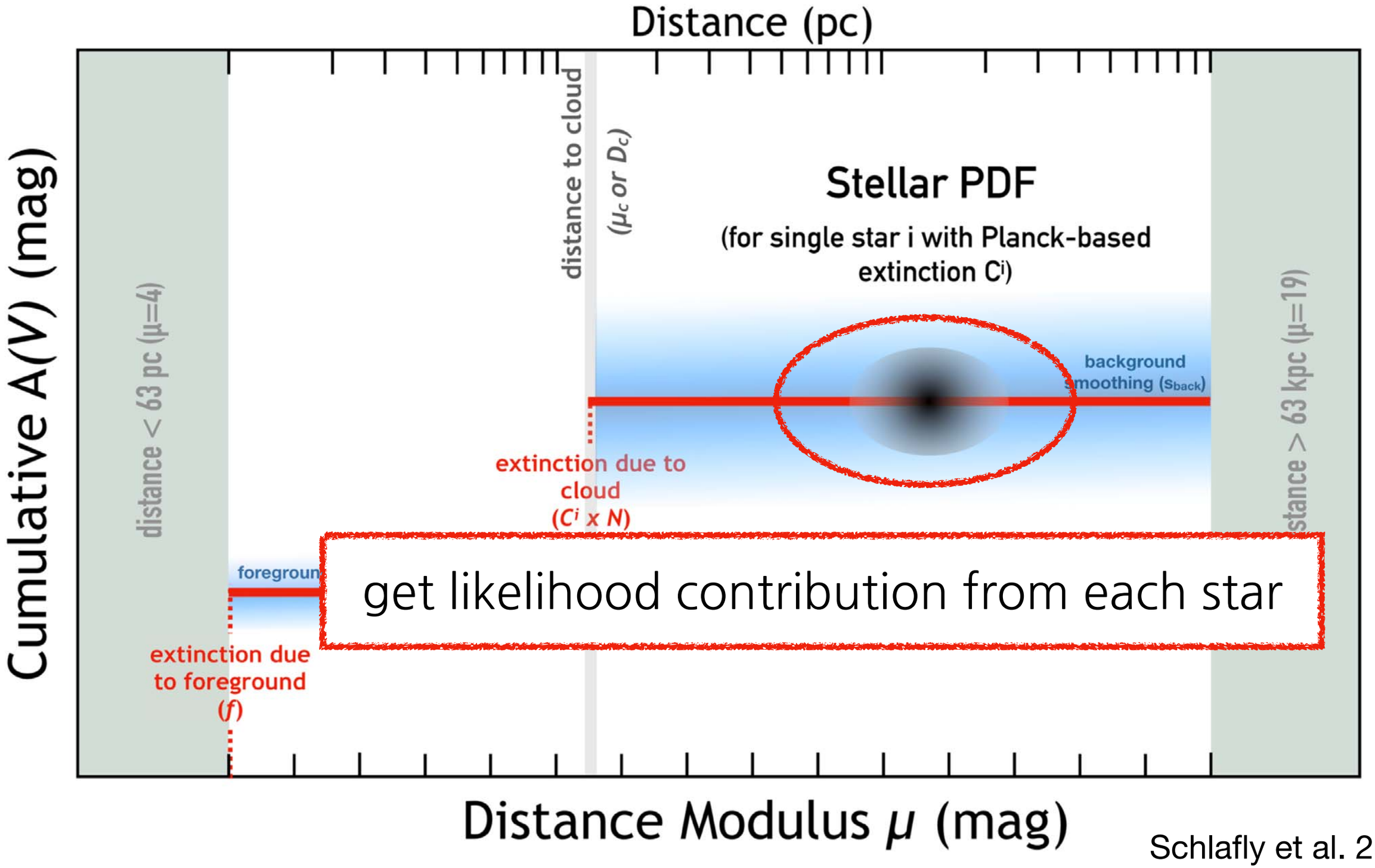


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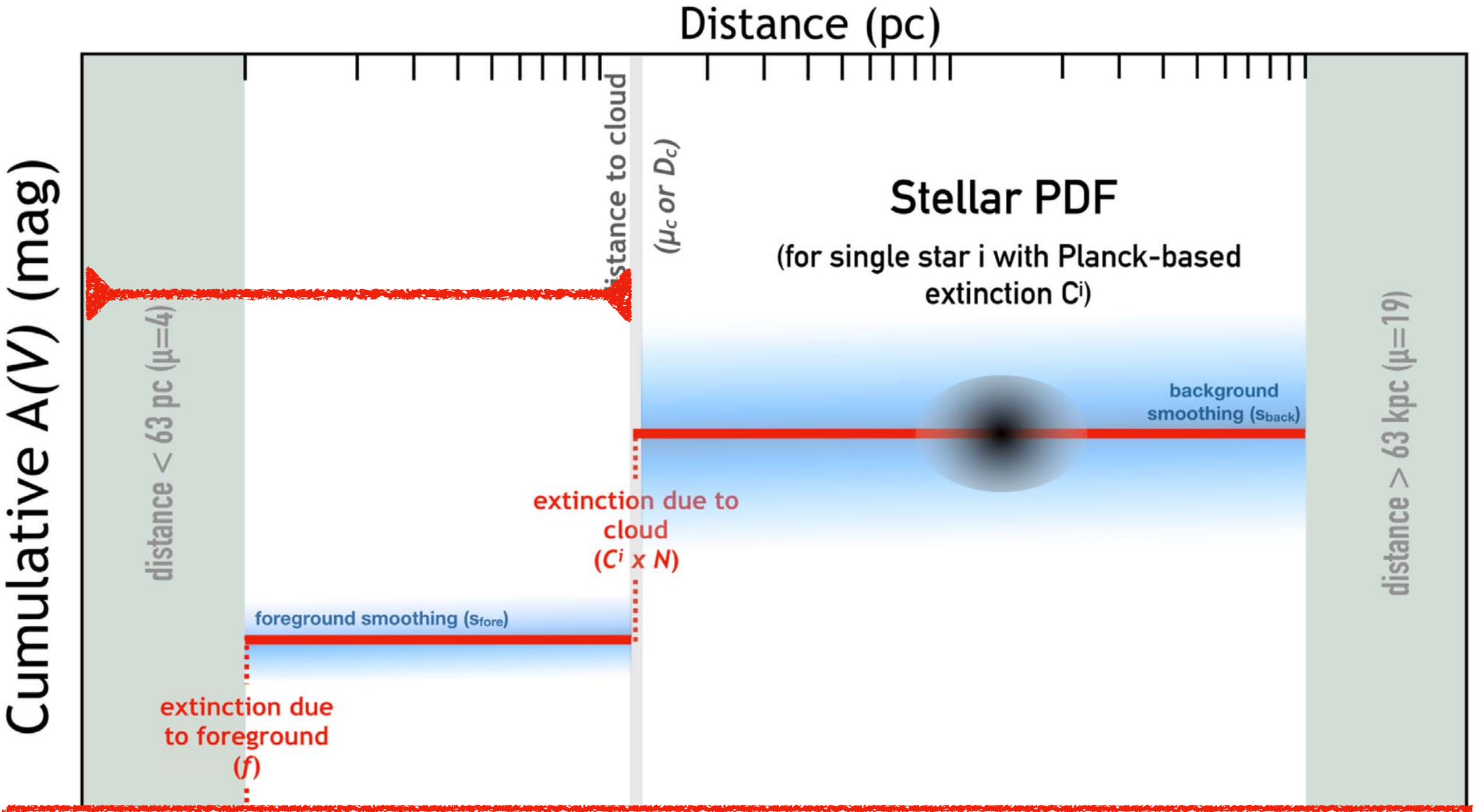
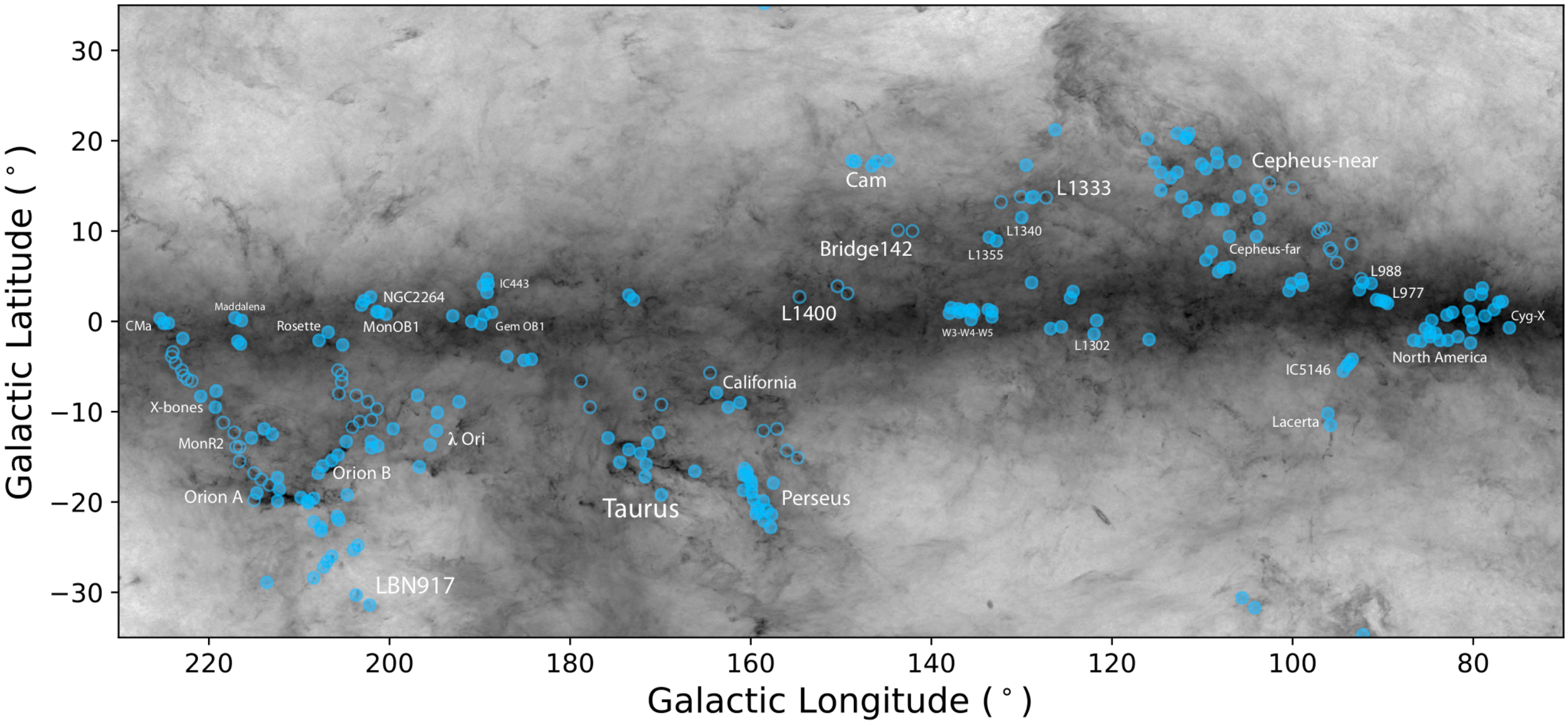



accurate distances to the Local Molecular Clouds



2014
2019

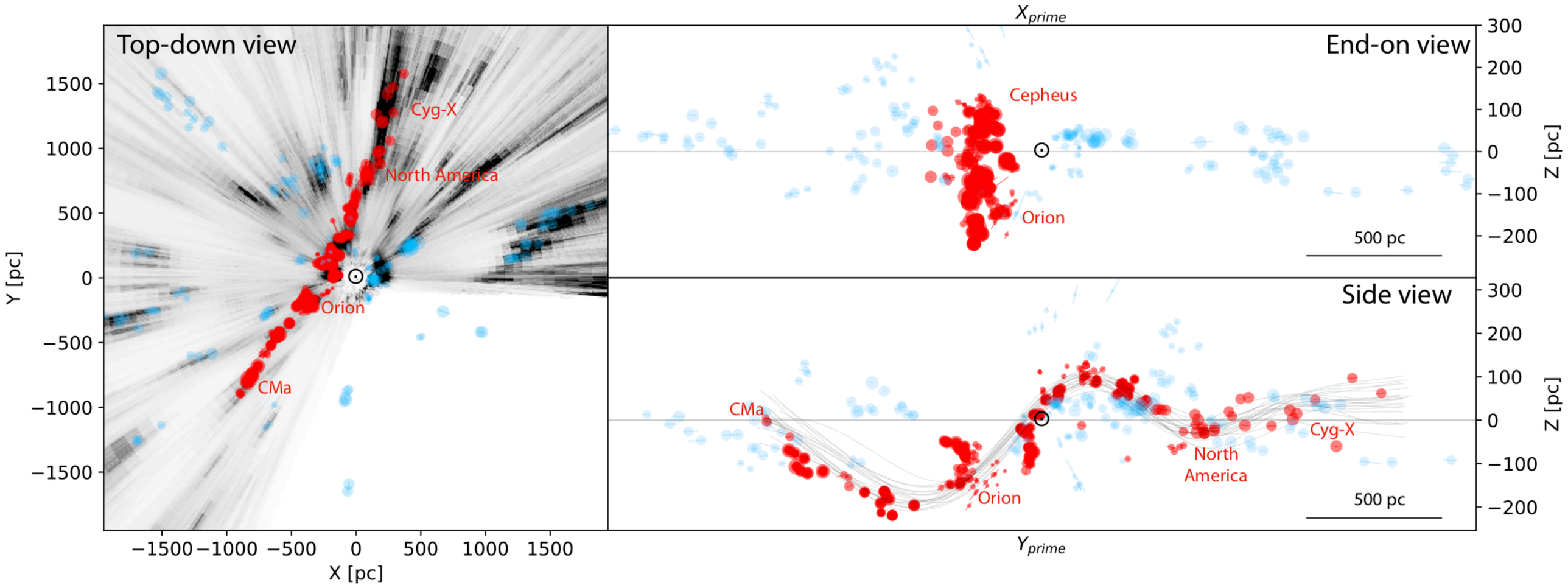
# Target list of lines of sight




not only cloud, but also bridges in between

# View of Radcliffe Wave

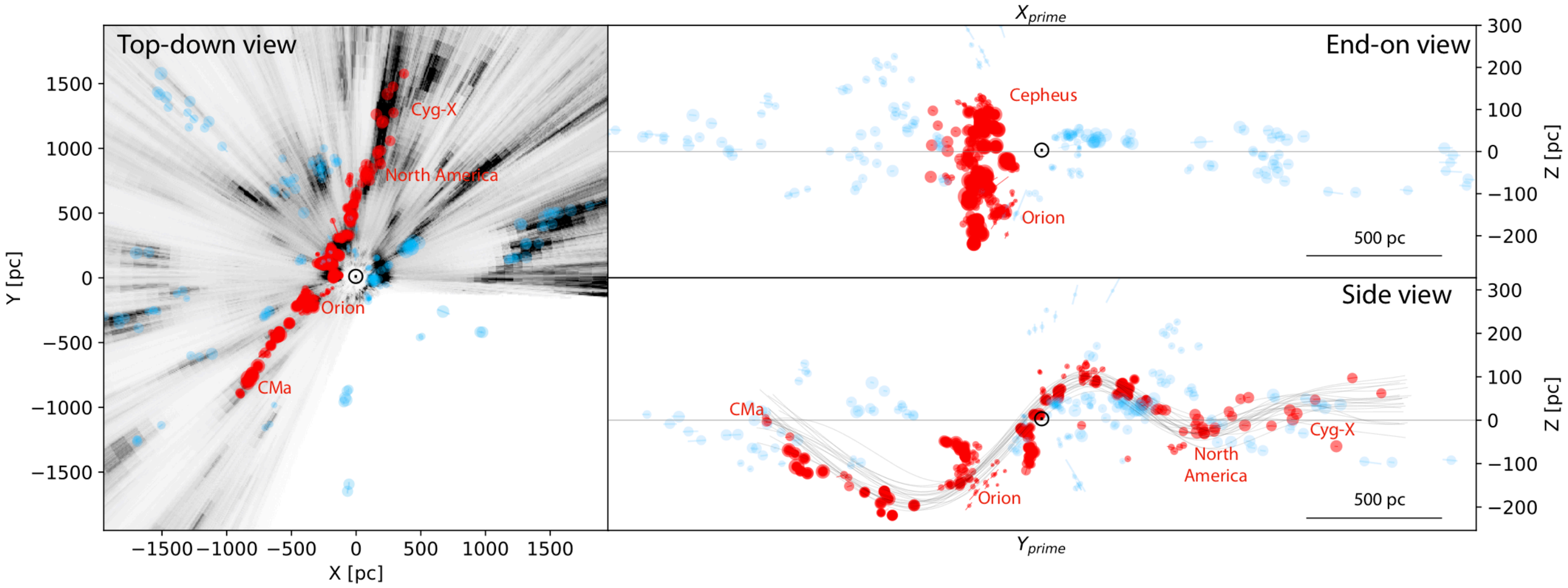
3D interacitve plot




$$\Delta z(t) = A \times \exp\left[-\delta\left(\frac{d(t)}{\mathrm{kpc}}\right)^2\right] \times \sin\left[\left(\frac{2\pi d(t)}{P}\right)\left(1 + \frac{d(t)/d_{\max}}{\gamma}\right) + \phi\right]$$

# View of Radcliffe Wave

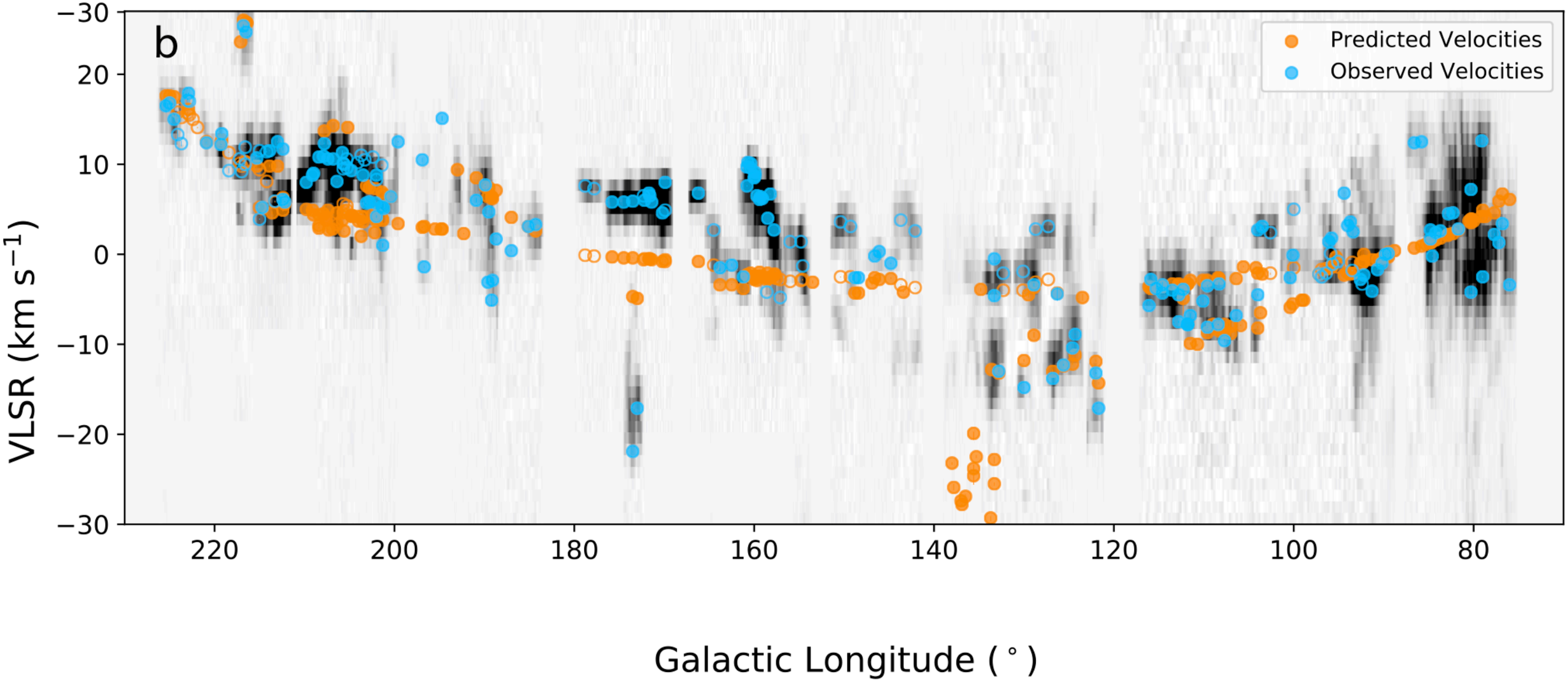
3D interacitve plot




$$\Delta \left[ \left( \frac{d(t)}{\quad} \right)^2 \right] \left[ \left( \frac{2\pi d(t)}{\quad} \right) \left( \frac{d(t)/d_{\max}}{\quad} \right) \phi \right]$$

Radcliffe Wave is spatially coherent

# Position-velocity diagram



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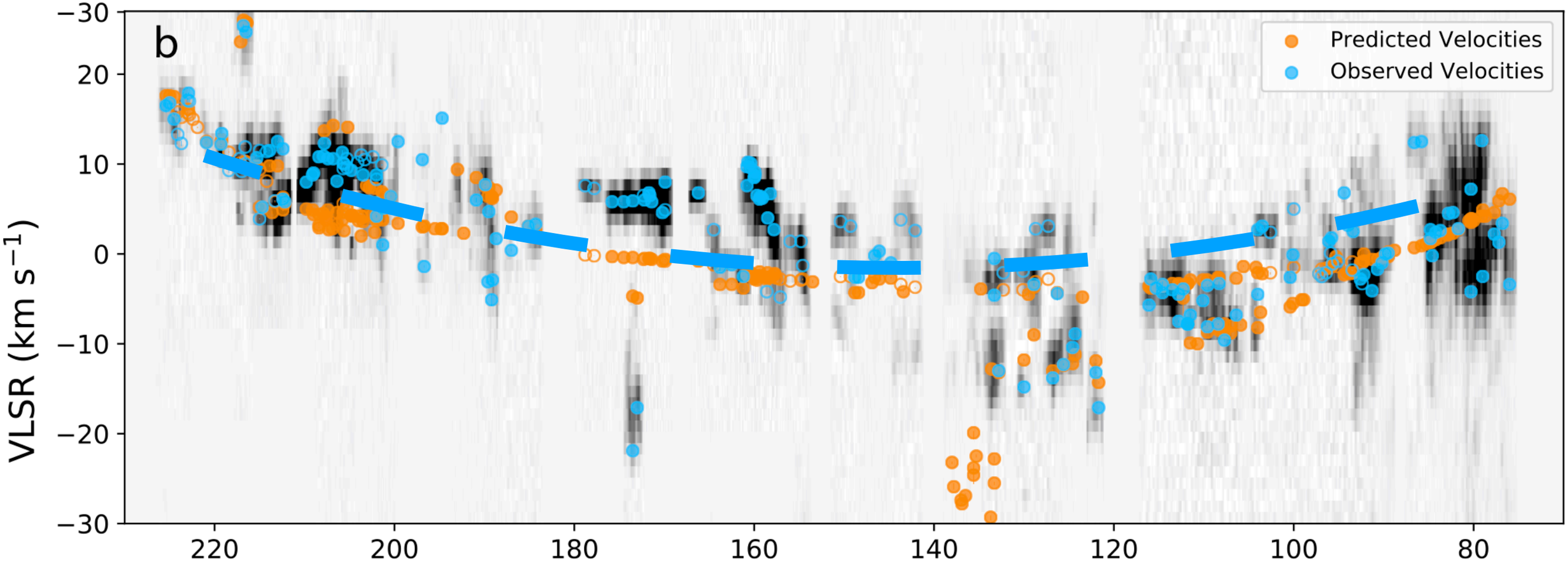
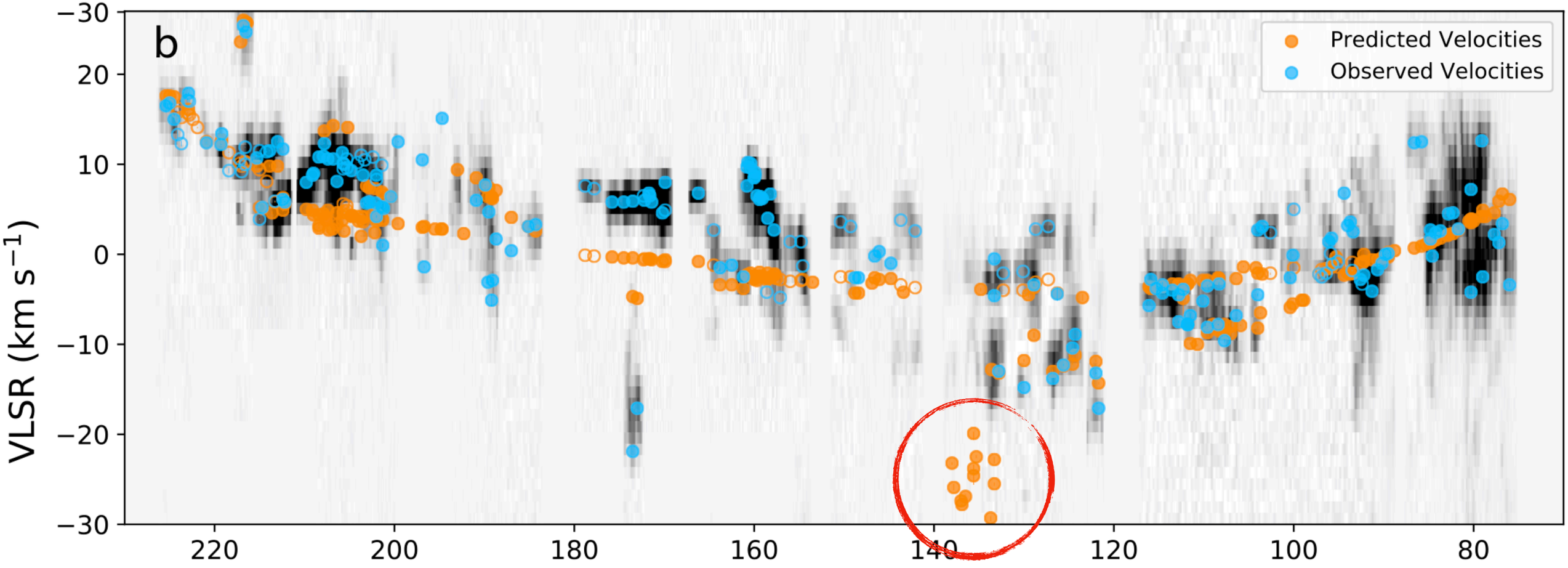


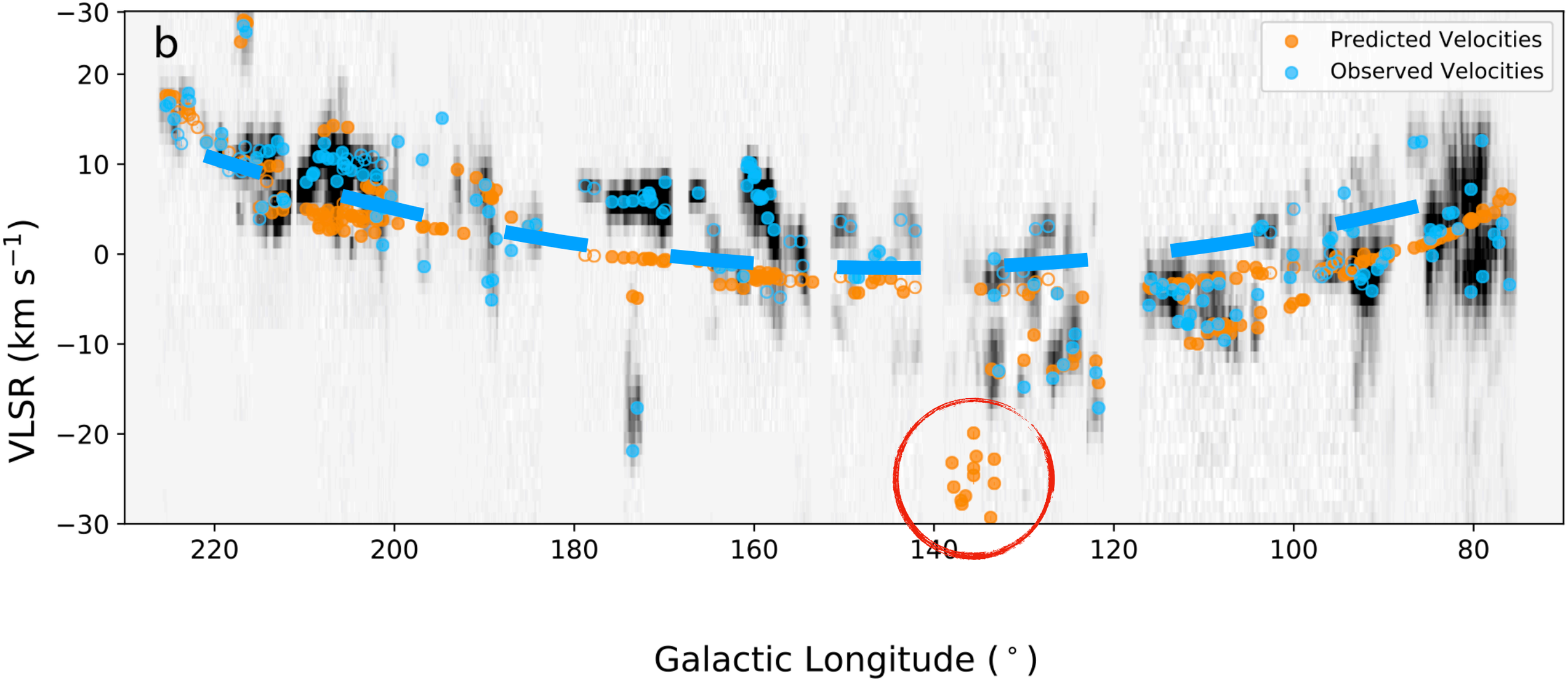

meet the quasi-linear arrangement

# Position-velocity diagram




"universal" Galactic rotation curve

# Position-velocity diagram




Radcliffe Wave is kinematically coherent

# Comments

- For this moment, the Radcliffe wave model is not necessary and/or able to fully rule out the Gould's Belt hypothesis.

- More quantifying kinematical analysis may help us to better understand the wave structure

- For example, is the vertical librating true?

- New Gaia data release may learn us a revolutionary picture about our solar neighborhood

# Summary

- A narrow and both spatially and kinematically coherent wave-like 2.7 kpc arrangement of dense gas is find

- The prevailing view of the local ISM based on the peculiarity known as the Gould's Belt need to be updated

# Potential questions

- Formation theory of the Radcliffe wave
- Can it explain all of side effects associated with Gould's Belt as well?
- How to explain the "Split" on the other side?
- What do we expect for larger scales?
- How will it influence our understanding about star formation?

# Formation of Radcliffe wave

- Too large and too straight to be the feedback of a previous generation of massive stars

- Outcome of a large-scale Galactic process of gas accumulation

  - a shock front in a spiral arm

  - gravitational settling and cooling on the MW plane

Formation of Radcliffe wave

# A minimum-hypothesis explanation for the “Radcliffe Wave”:

Robert Fleck

2020Natur.583E..24F

Formation of Radcliffe wave

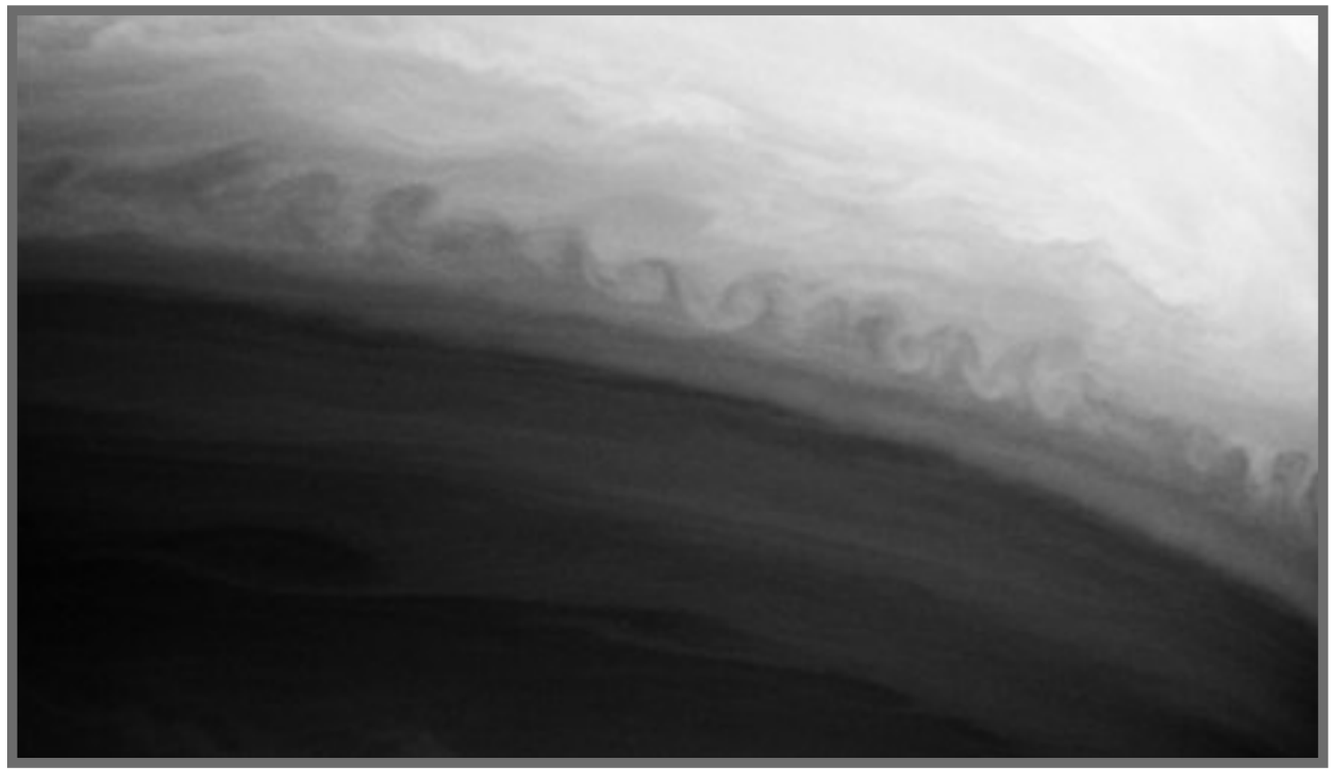
# A minimum-hypothesis explanation for the “Radcliffe Wave”: KH instability

Robert Fleck

2020Natur.583E..24F

# Formation of Radcliffe wave

A KH instability rendered visible by clouds, known as fluctus



A KH instability on the planet Saturn, formed at the interaction of two bands of the planet's atmosphere

Credit: Wikipedia
Kelvin–Helmholtz instability