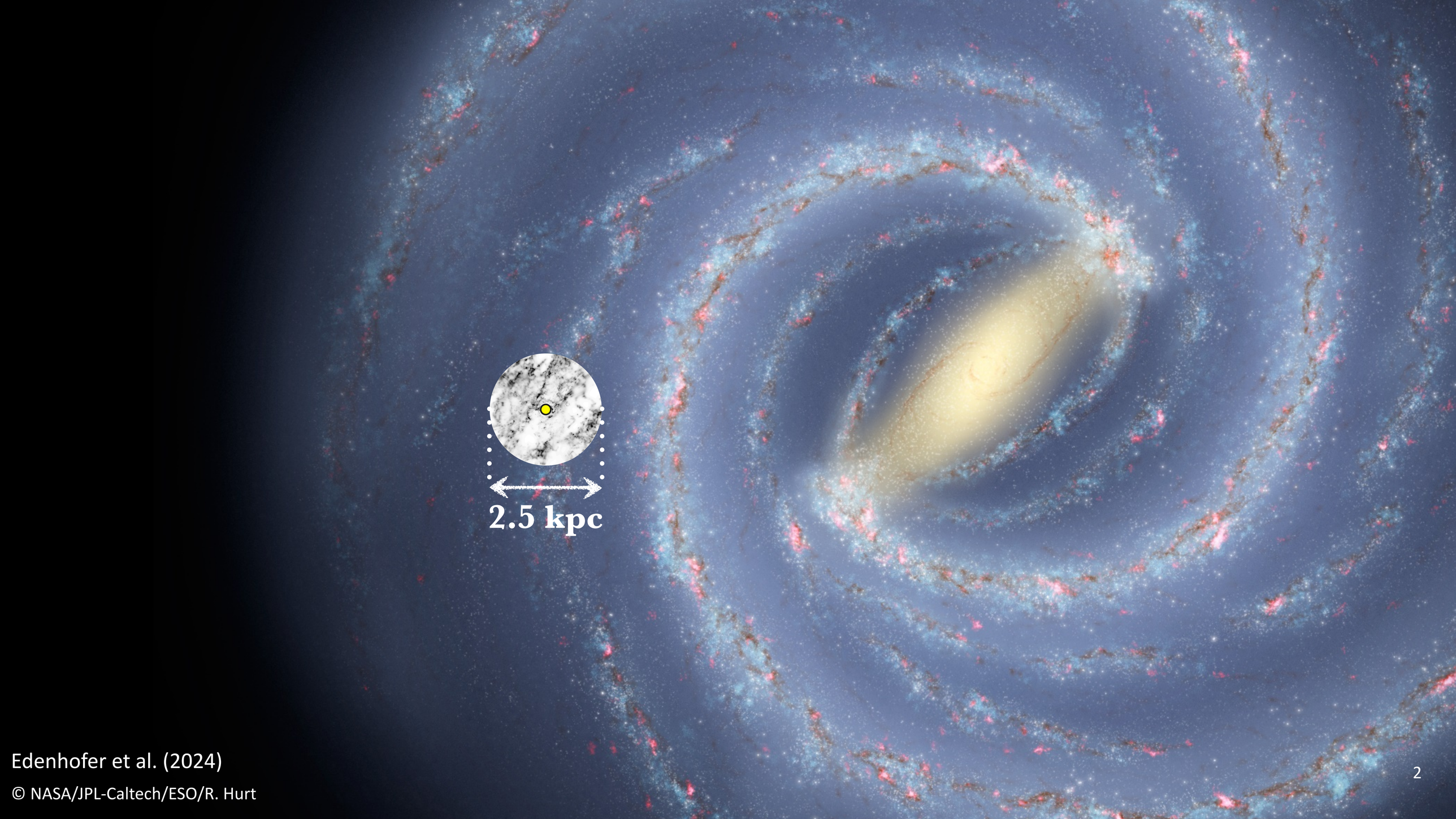
Propagating Star Formation in Sco-Cen

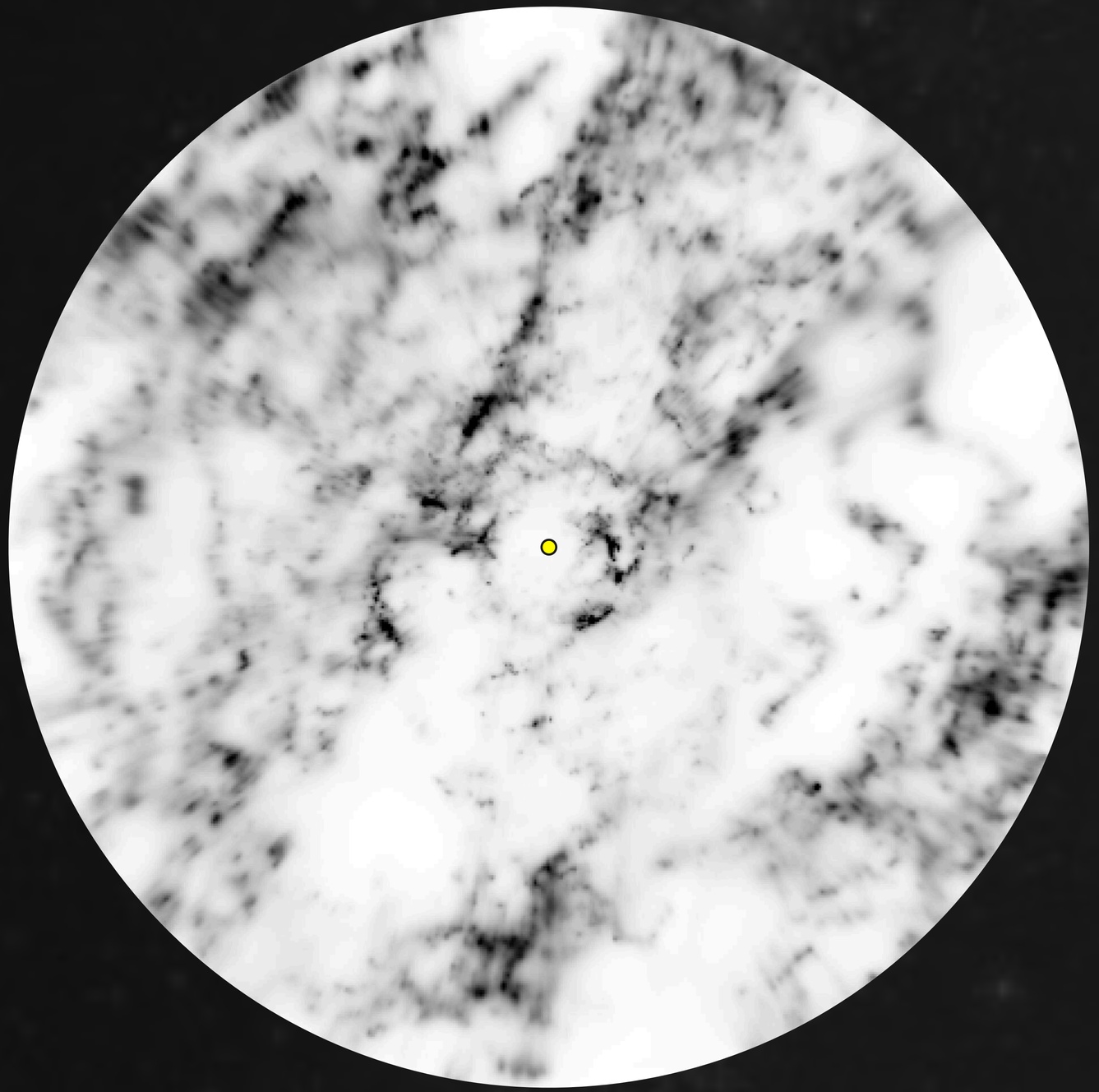
Cluster Chains as Tracers of Stellar Feedback

Sebastian Ratzenböck @CfA

Inter+Stellar | May 13, 2025



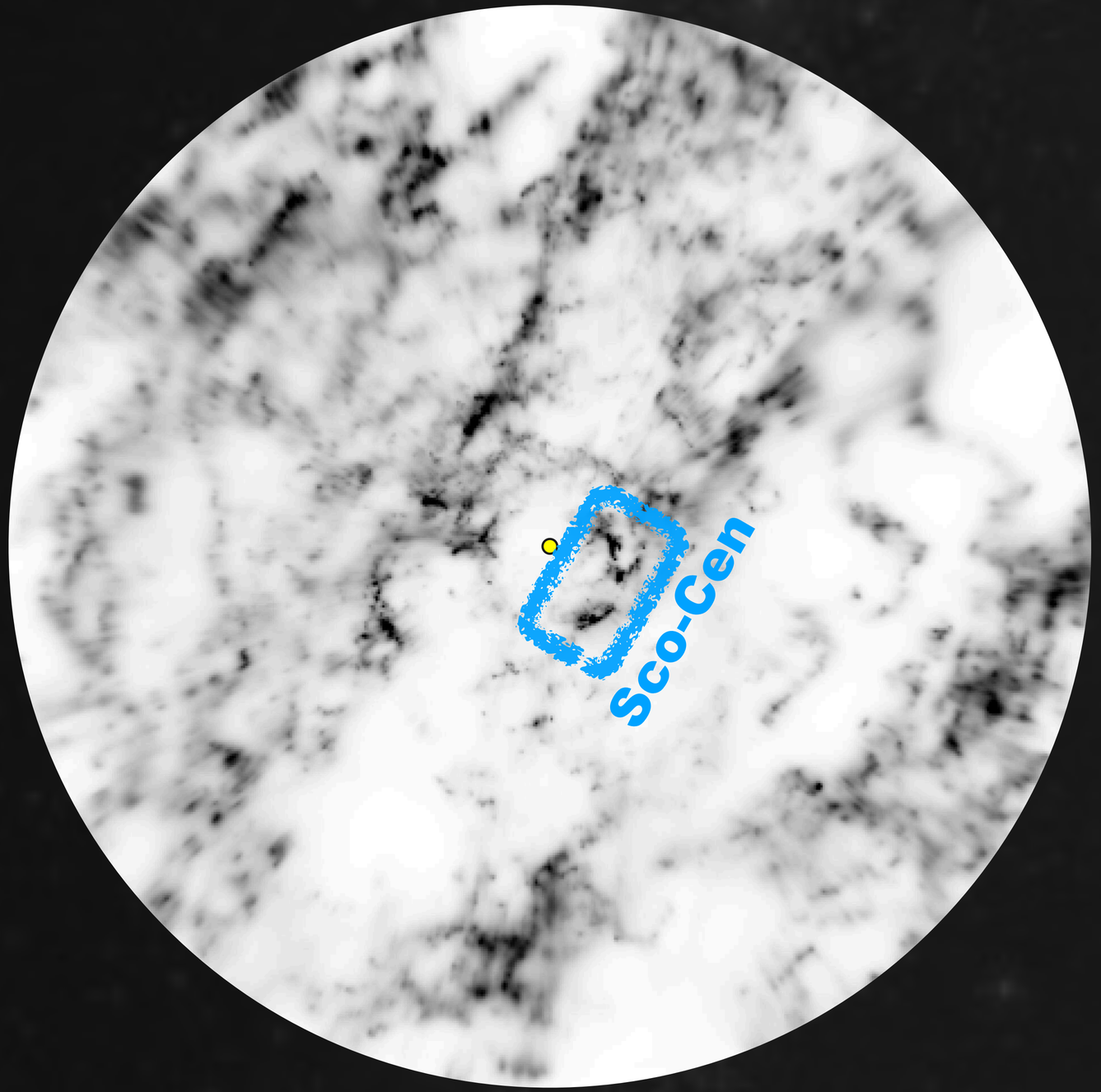
Edenhofer et al. (2024)



Galactic rotation

Galactic center

Edenhofer et al. (2024)



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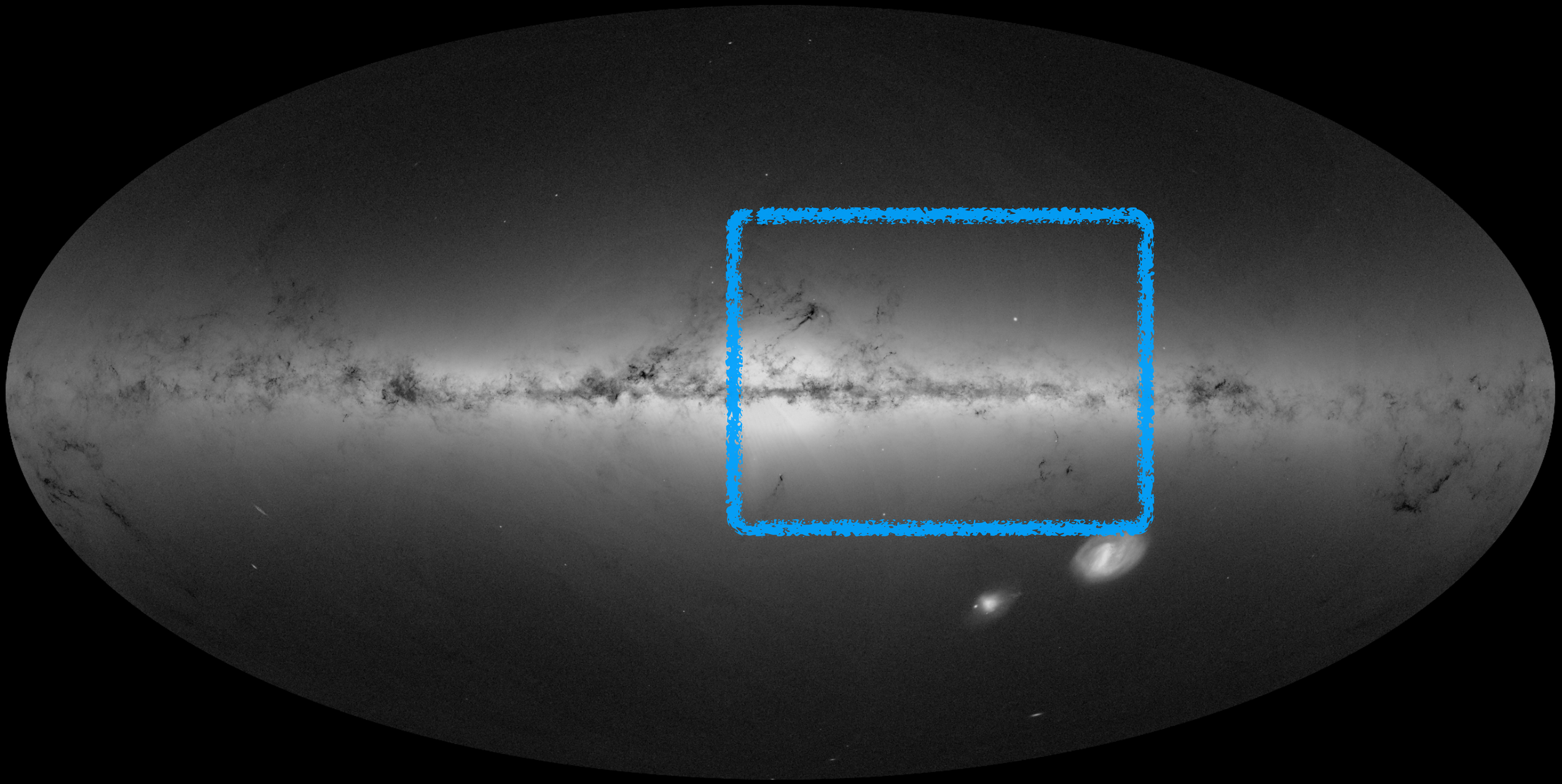
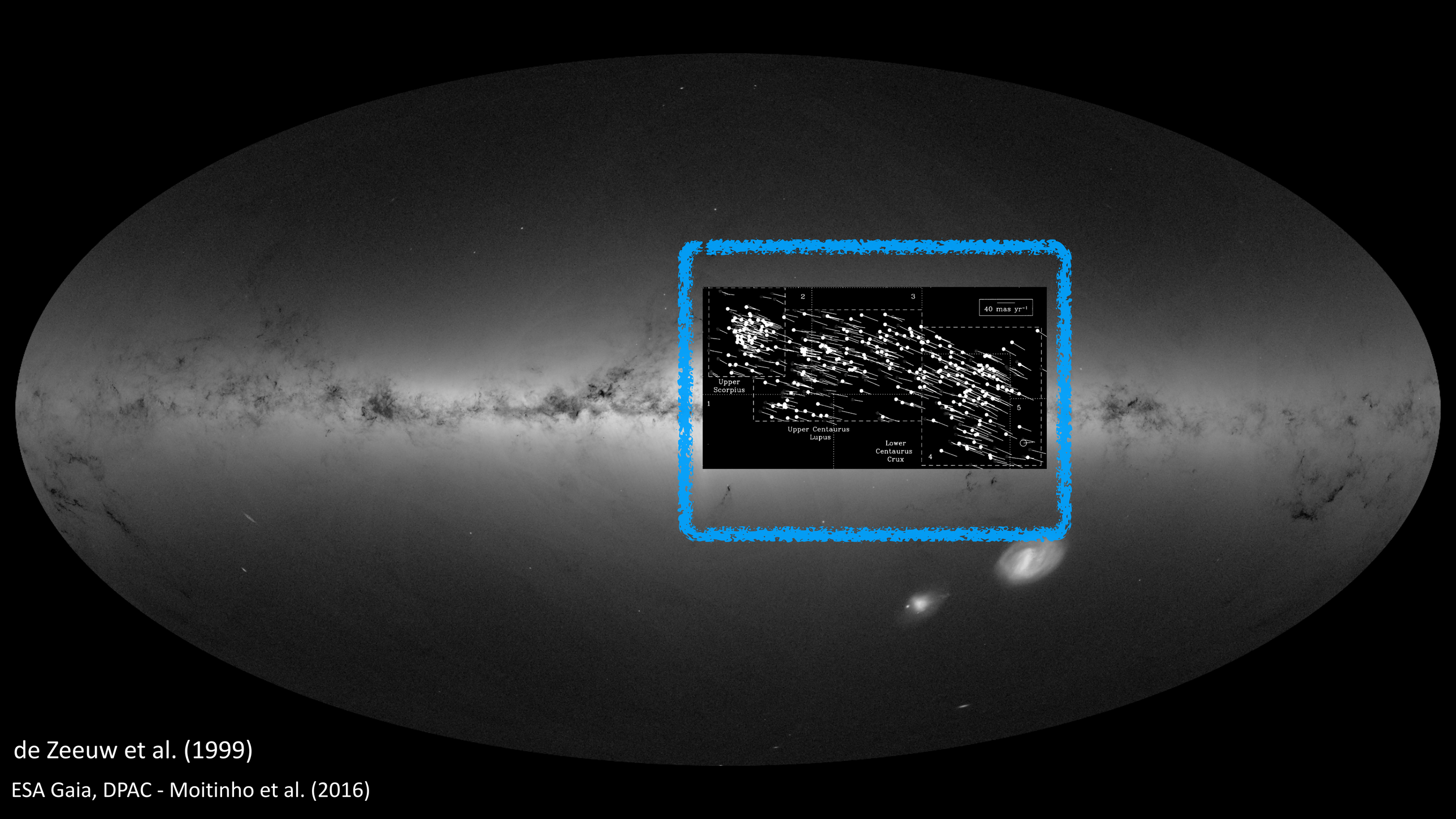


ESA Gaia, DPAC - Moitinho et al. (2016)



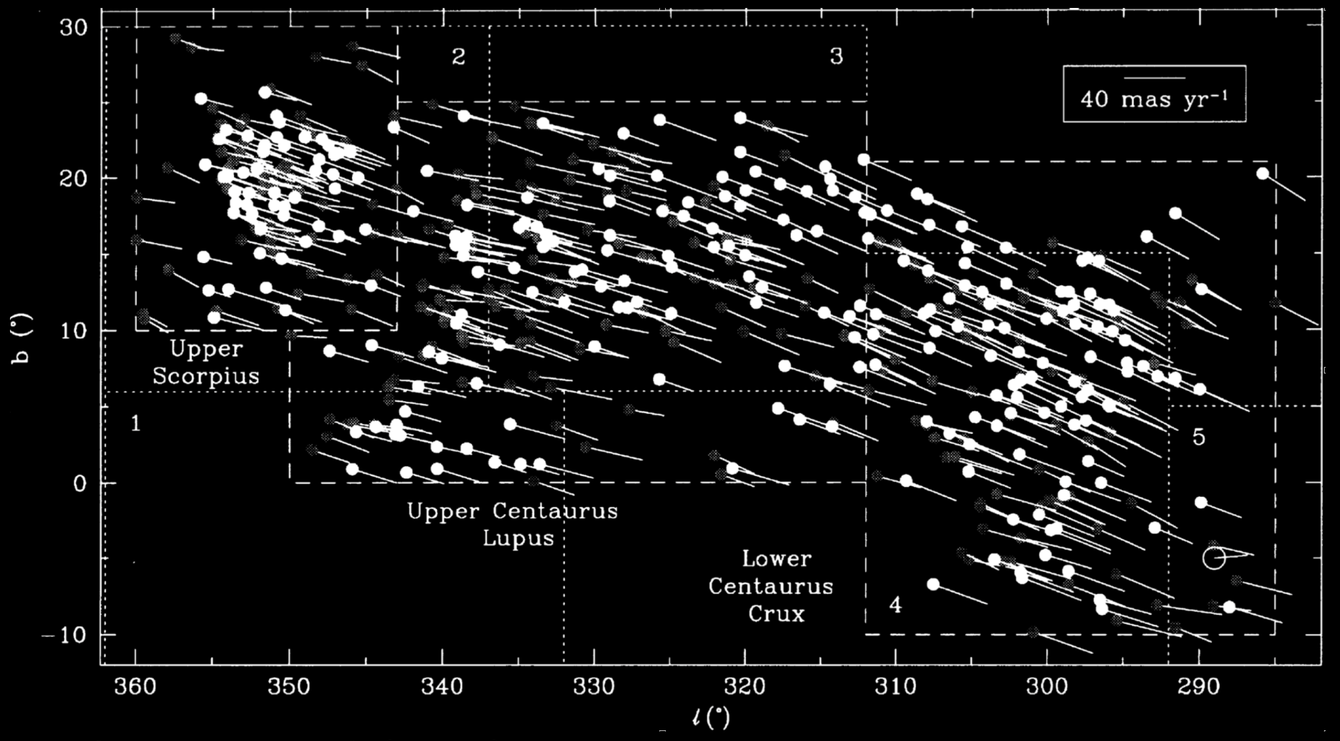
de Zeeuw et al. (1999)

ESA Gaia, DPAC - Moitinho et al. (2016)

Sco-Cen OB association

Nearest large young star laboratory

- Covers ages 1–20 Myr
- Covers mass spectrum from OB → substellar objects
- Lab for star & planet formation, and cluster evolution
  e.g., Preibisch & Mamajek (2008)
- Interaction between the association and ISM
  e.g., de Geus (1992)



de Zeeuw et al. (1999)

Open questions

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- What role does stellar feedback from massive stars (e.g., SN, winds) play in subsequent star formation?

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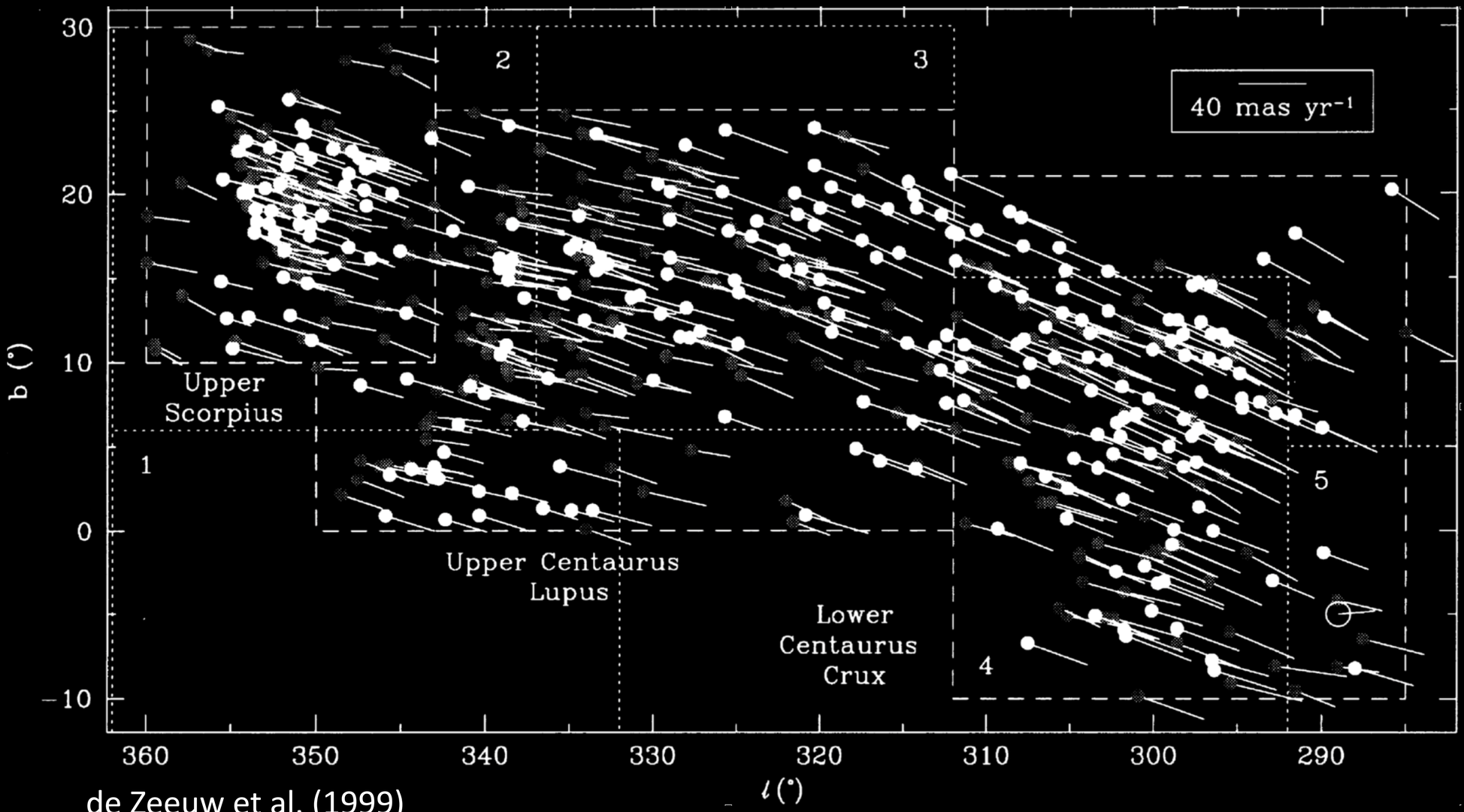
- What are time scales associated with molecular cloud formation, star formation, and cloud dispersal and what drives their disruption?
- What role does stellar feedback from massive stars (e.g., SN, winds) play in subsequent star formation?
- What fraction of stars in OB associations can be directly attributed to feedback-triggered star formation events?

Sco-Cen: star formation history



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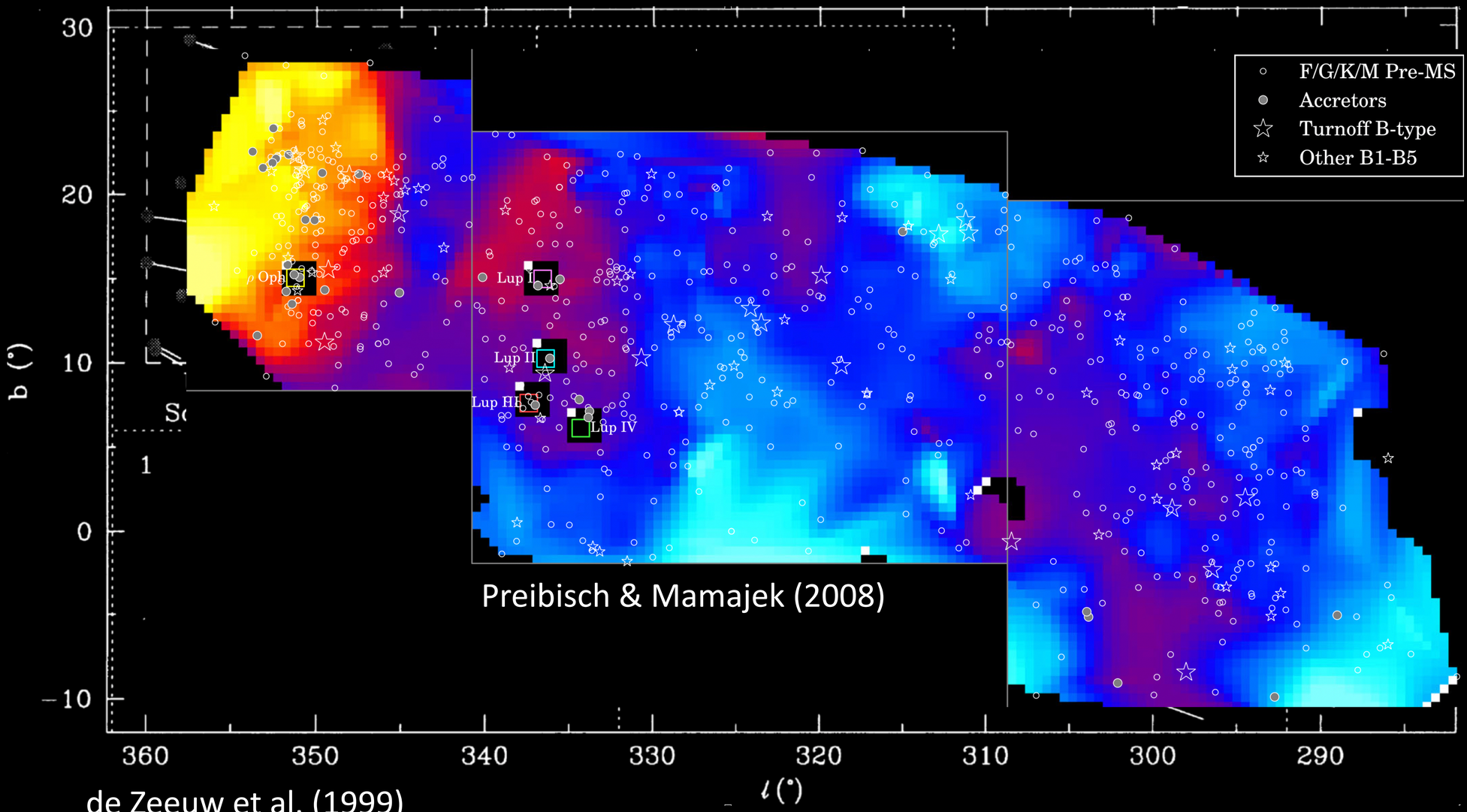
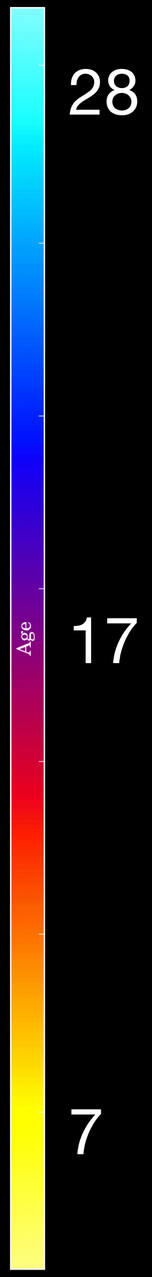


Preibisch & Mamajek (2008)

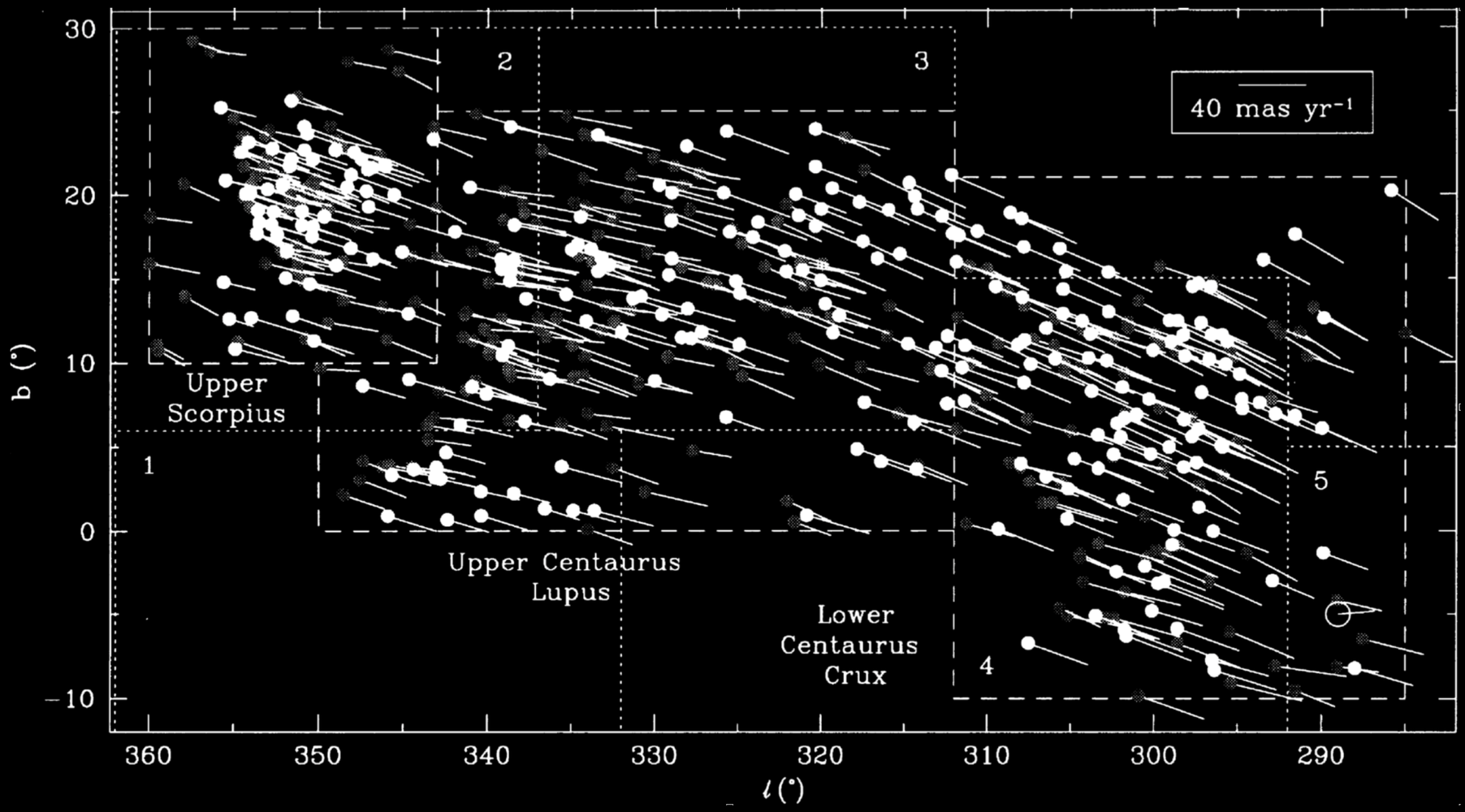
de Zeeuw et al. (1999)



Sco-Cen since Gaia DR2

Reference	Sect.	Data	Studied area
Damiani et al. (2019) [e]	5.2.1	DR2	(l = 360° to 280°, b = 0° to 30°) OR (l = 315° to 280°, b = −10° to 0°) FOV = 2750 deg^2, d < 200 pc
Kerr et al. (2021) [f]	5.2.2	DR2	The whole TLC22 stellar group TLC22 without EOM 1–5 22 EOMs of TLC22 (without EOM 1–5)
Schmitt et al. (2022) [g]	5.2.3	EDR3 and eROSITA	de Zeeuw et al. (1999) borders: US (l = 343° to 360°, b = 10° to 30°) OR UCL (l = 312° to 350°, b = 0° to 25°) OR LCC (l = 285° to 312°, b = −10° to 22°), FOV = 2050 deg^2, d ∼ 60–200 pc
Luhman (2022)	5.2.4	EDR3	l = 2° to 285°, b = −12° to 35°, FOV = 3252 deg^2, d ∼ 90–250 pc
Žerjal et al. (2023)	5.2.5	DR2	l = 40° to 240°, b = −60° to 70°, FOV = 36 400 deg^2, d ∼ 83–200 pc
Squicciarini et al. (2021) [h] (only US, subsample with RVs)	5.2.6	EDR3	α = 236° to 251°, δ = −29° to −16° FOV = 195 deg^2, d ∼ 125–175 pc
Miret-Roig et al. (2022a) [i] (only US, subsample with RVs)	5.2.7	DR3	α = 235° to 252°, δ = −30° to −17° FOV = 221 deg^2, d ∼ 80–200 pc
Briceño-Morales & Chanamé (2023) [j] (only US, subsample with RVs)	5.2.8	EDR3	l = 343° to 360°, b = 10° to 30° FOV = 340 deg^2, d < 200 pc

Post Gaia star formation history



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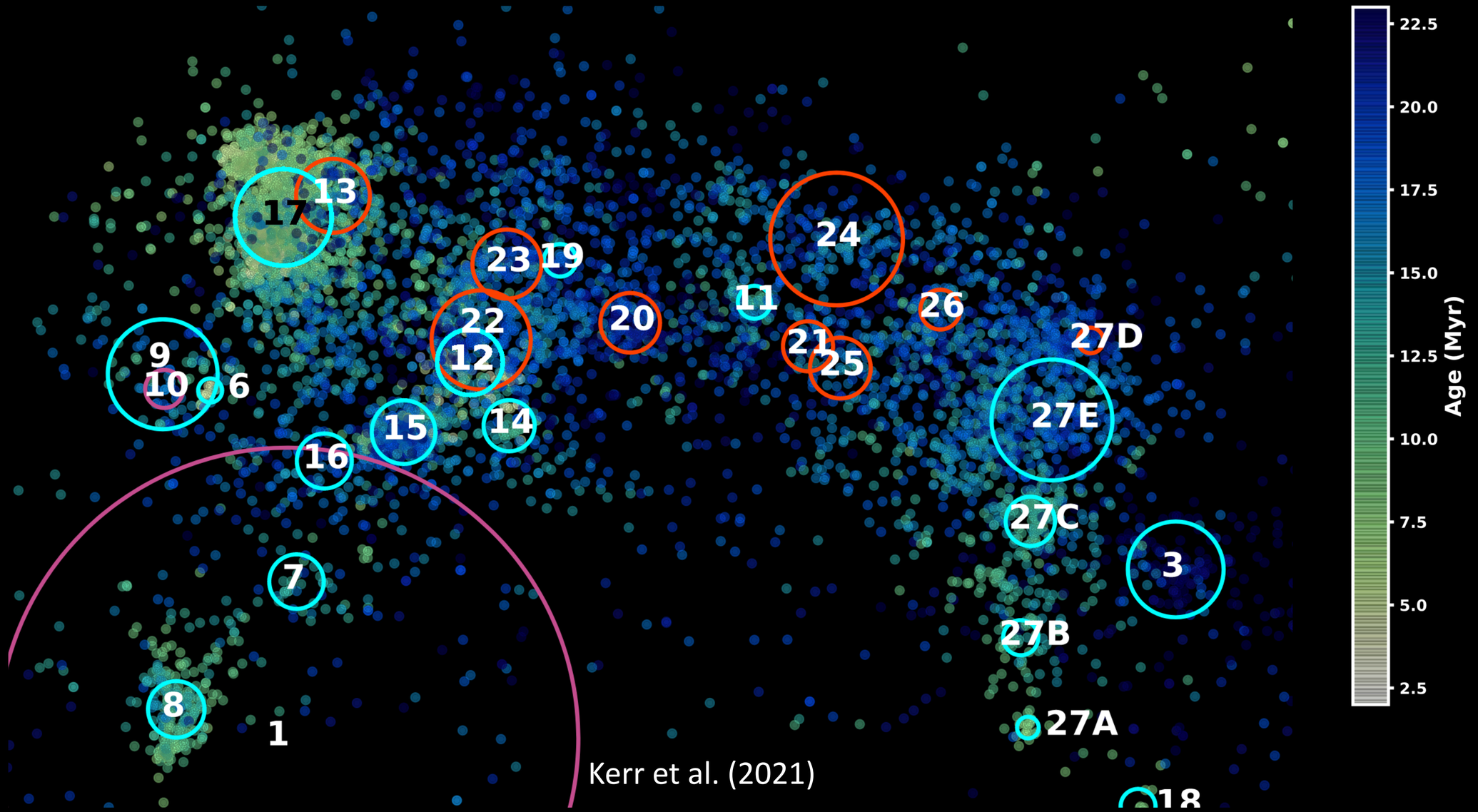
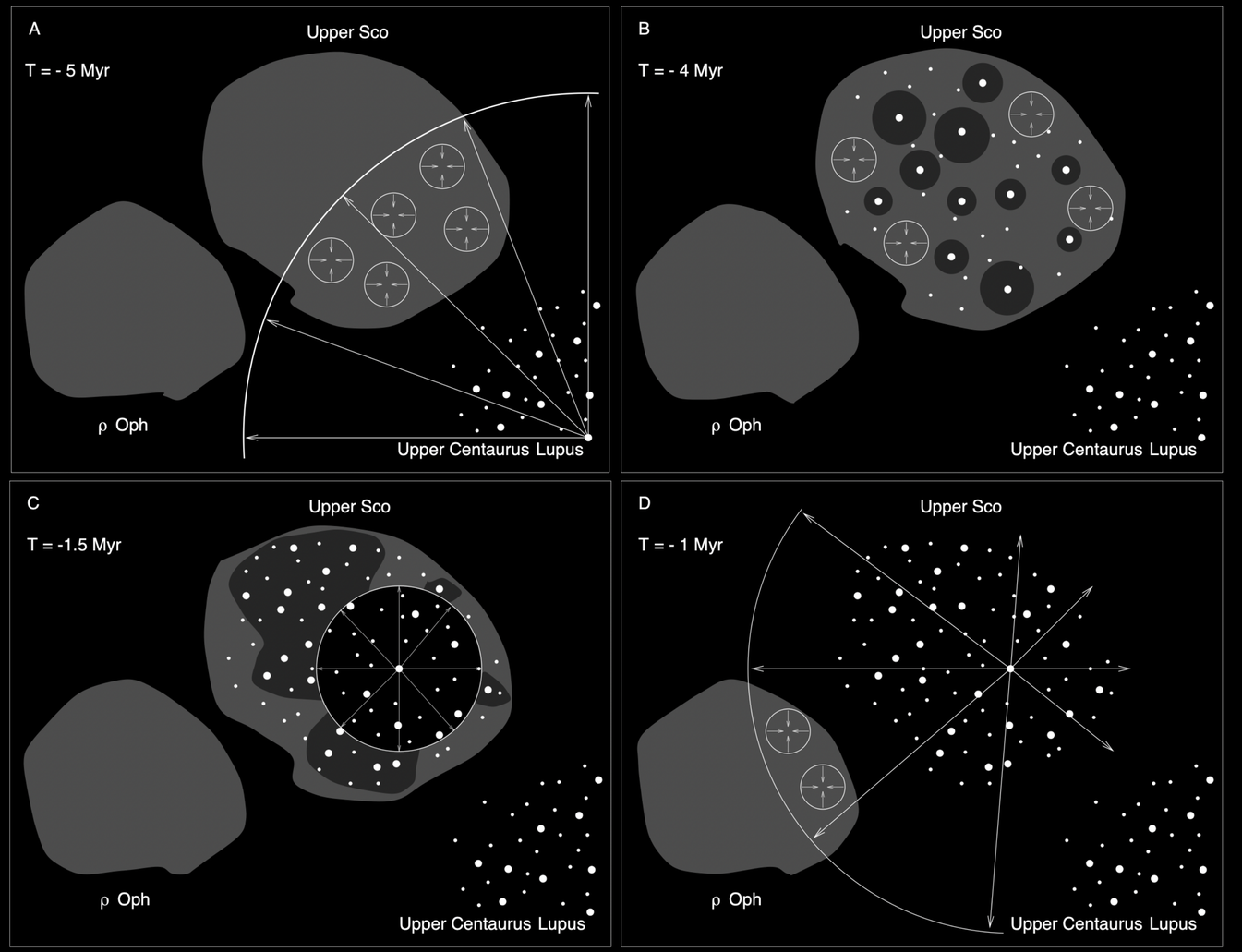
Post Gaia star formation history



Kerr et al. (2021)

Open questions

- *"Star formation histories of associations […] so far have failed to reveal simple patterns of star formation propagation (e.g., triggering)"*
  Wright et al (2022)



Preibisch & Mamajek (2008)

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- *“Star formation histories of associations […] so far have failed to reveal simple patterns of star formation propagation (e.g., triggering)”*
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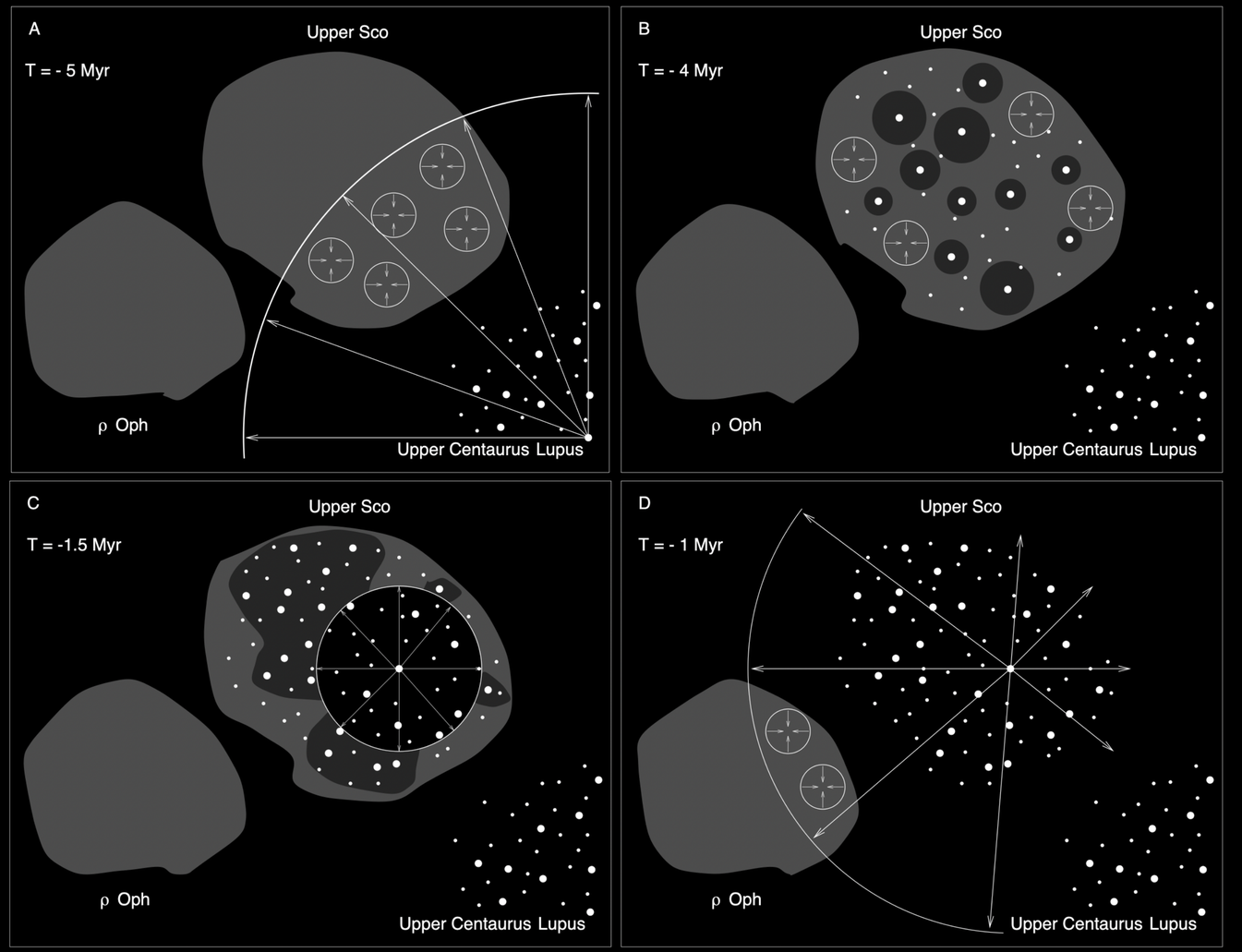
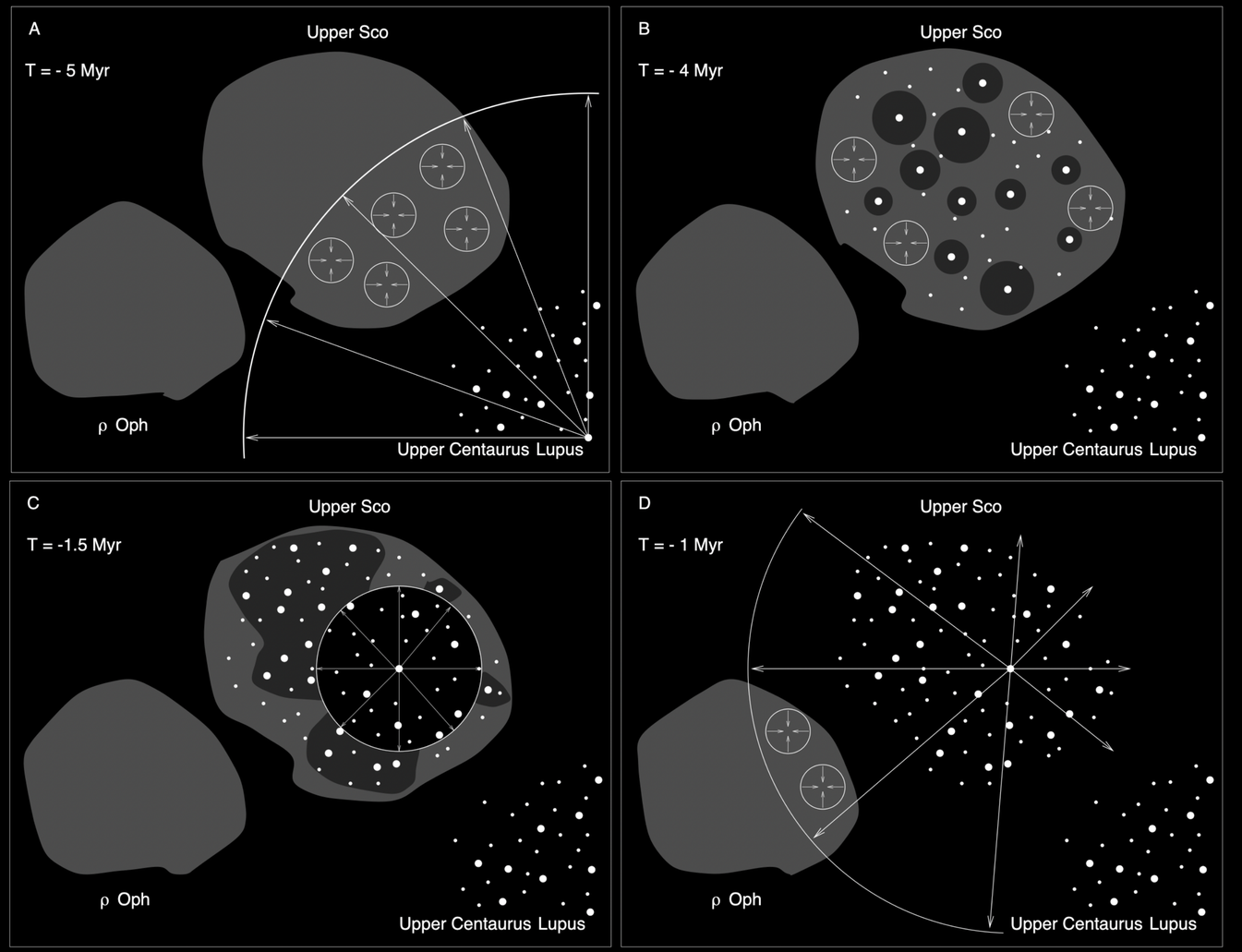
  - Stellar associations quickly disperse — low density



Preibisch & Mamajek (2008)

Open questions

- *“Star formation histories of associations […] so far have failed to reveal simple patterns of star formation propagation (e.g., triggering)”*
  Wright et al (2022)
  - Stellar associations quickly disperse — low density
  - Formed from same molecular cloud complex — velocities & age differences small



Preibisch & Mamajek (2008)

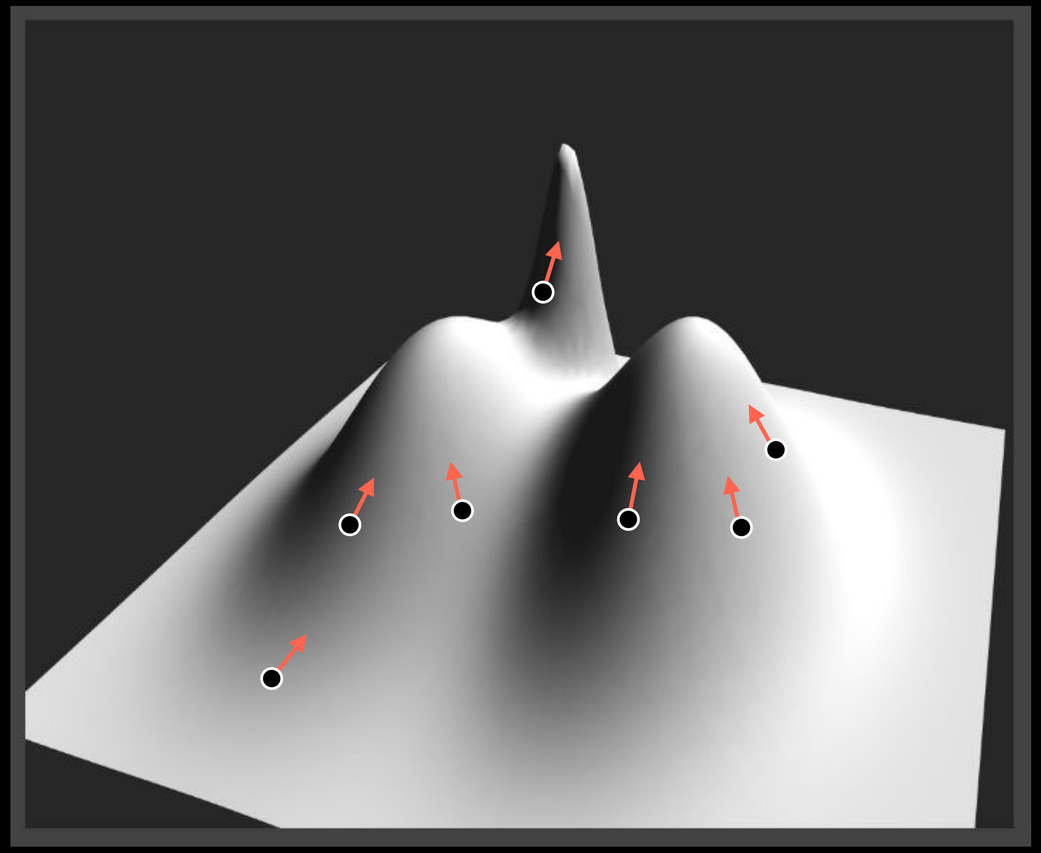
Goal: Apply *SigMA*

Recap: Density based clustering

Nonparametric, density-based clustering

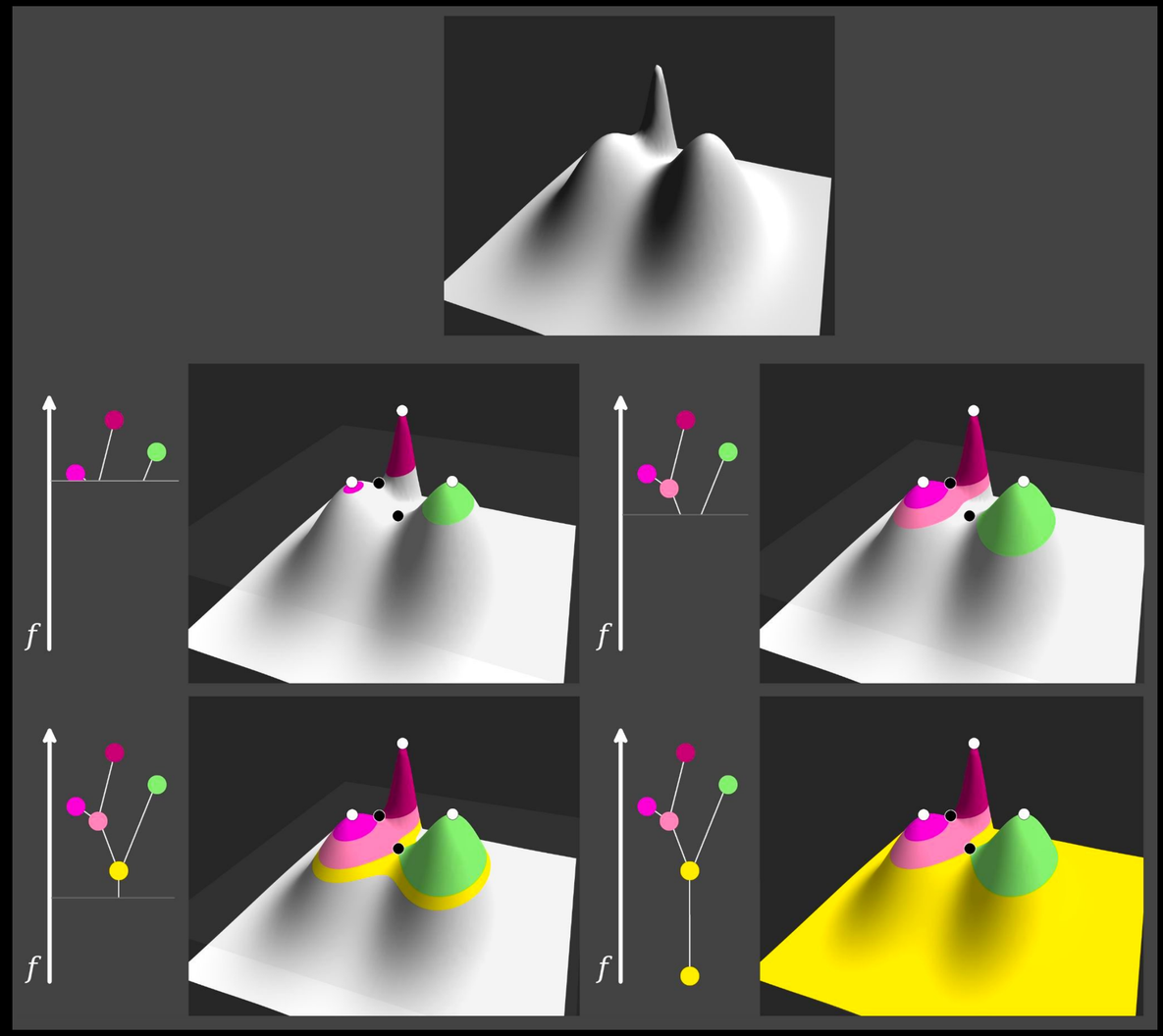
Problem definition

- **Wishart (1969) cluster definition**
  - $\mathbf{x}_i$ associated with modes of f
  - Propagate $\mathbf{x}_i$ along ∇f

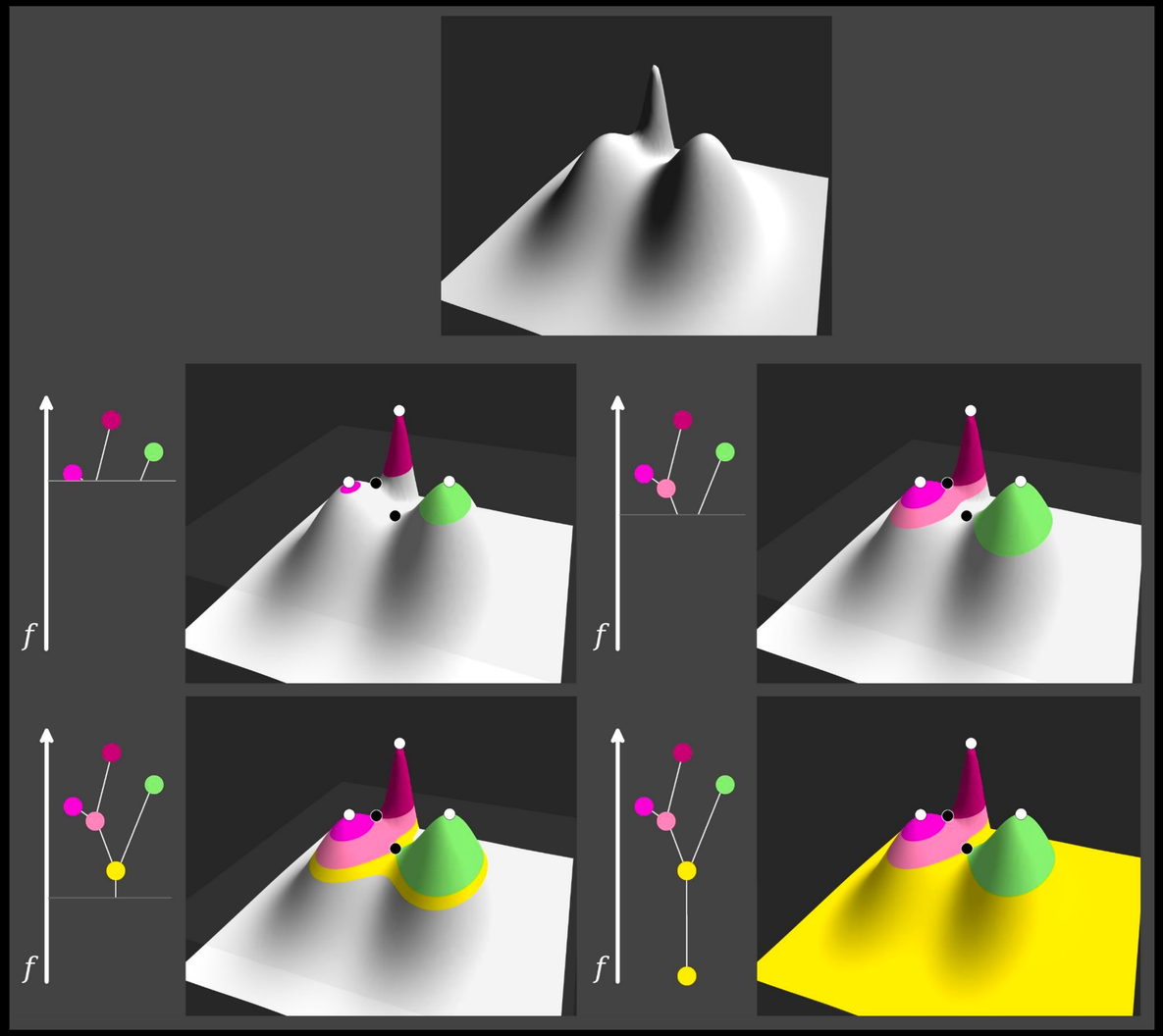


Nonparametric, density-based clustering

- Level set: $L(\lambda) = \{f(\mathbf{x}) \geq \lambda\}$
- **Hartigan (1975) cluster definition**
  - Connected components of $L(\lambda)$
  - Cluster tree: vary λ: $\infty \rightarrow -\infty$

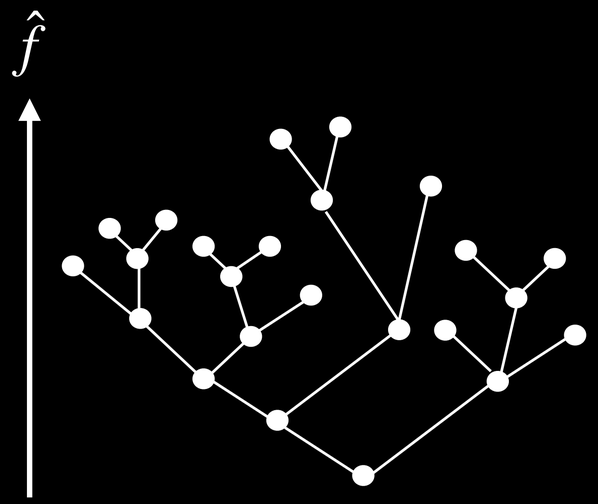


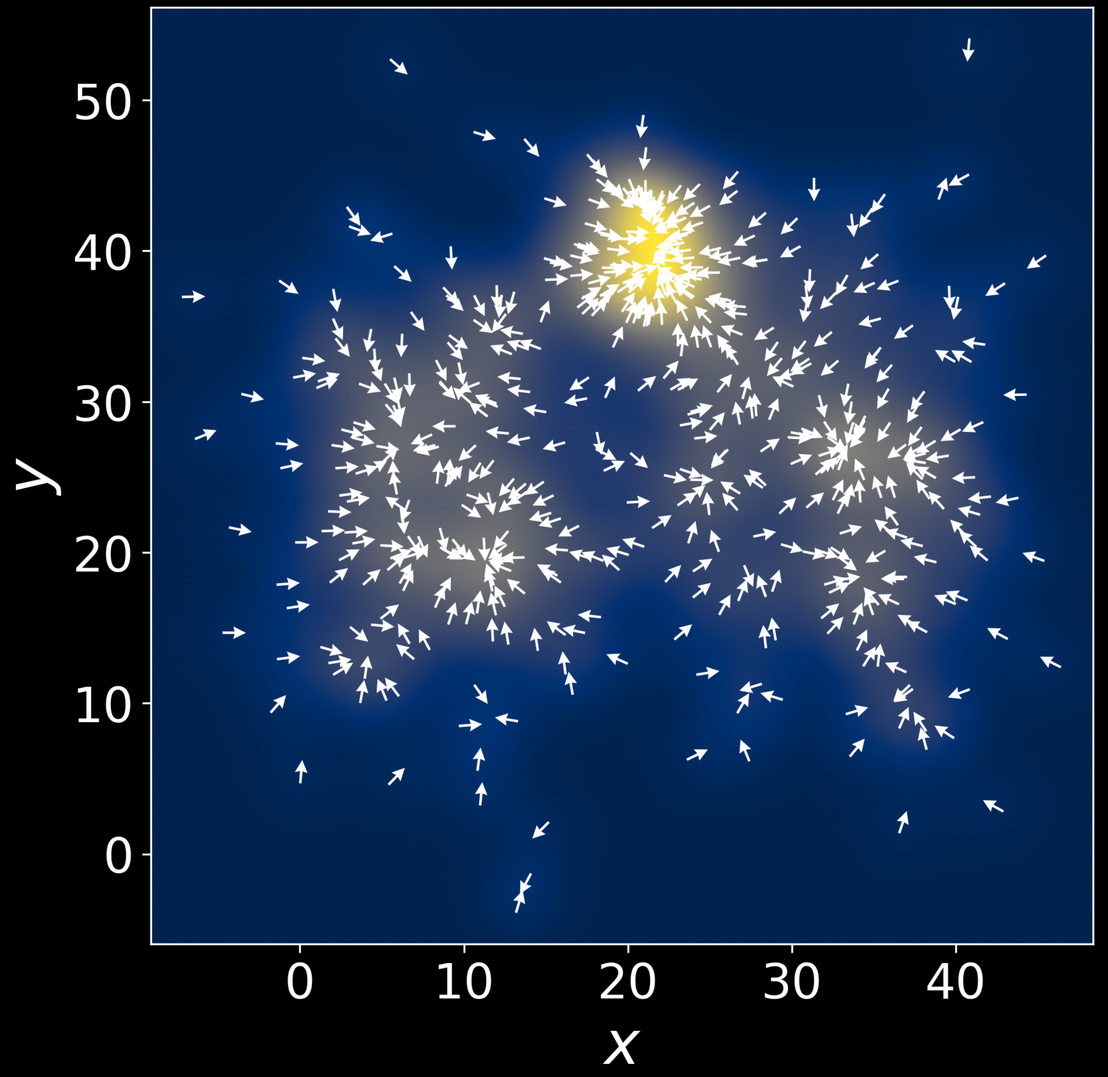
Reality
Estimate density from data



Clustering pipeline: SigMA

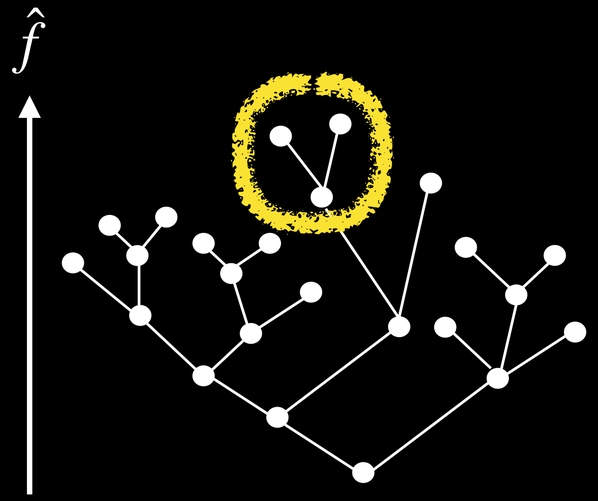
1. Gradient ascent step — cluster tree

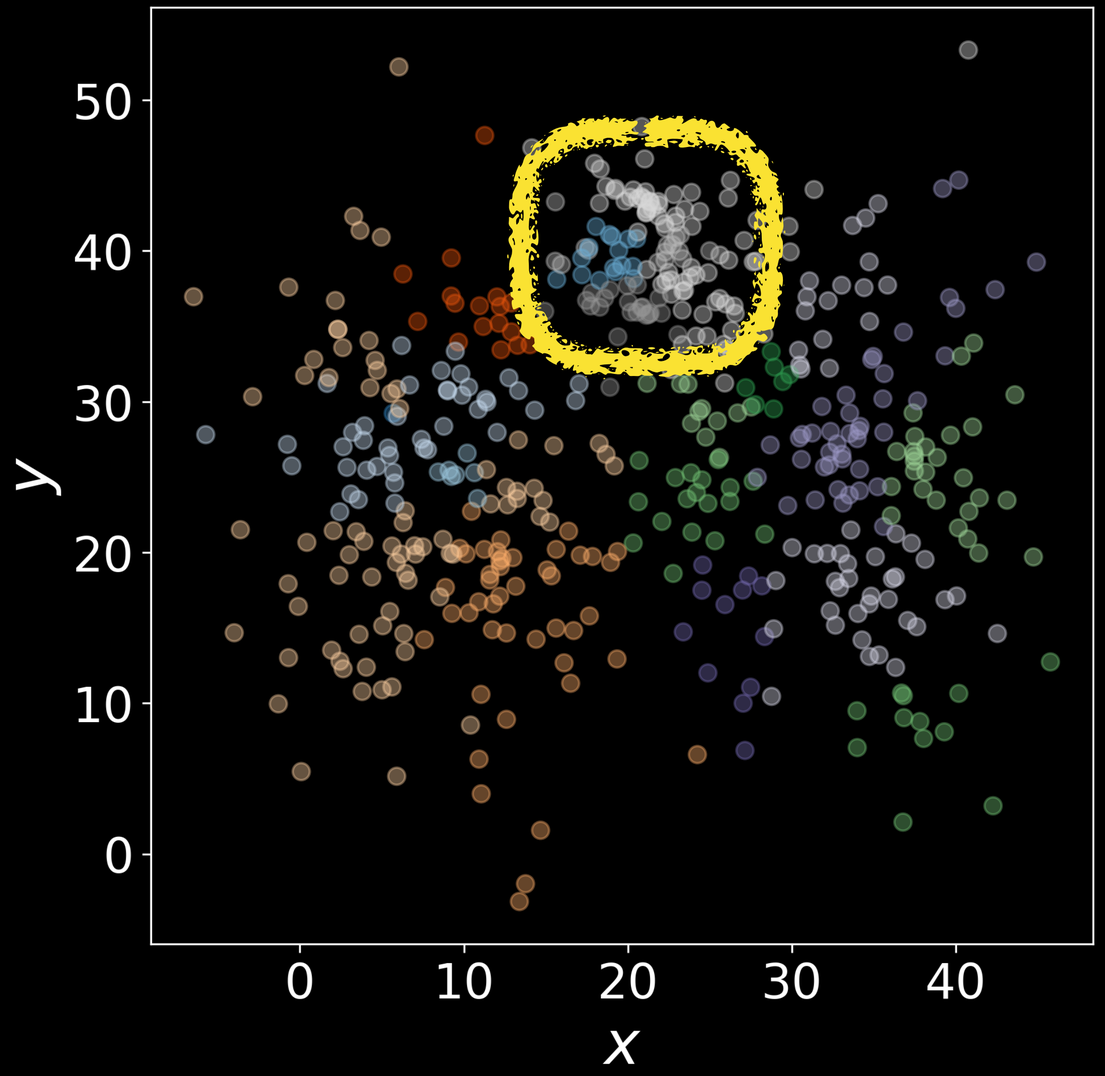




Clustering pipeline: SigMA

1. Gradient ascent step
2. Scan saddle points: $\max \hat{f} \rightarrow \min \hat{f}$





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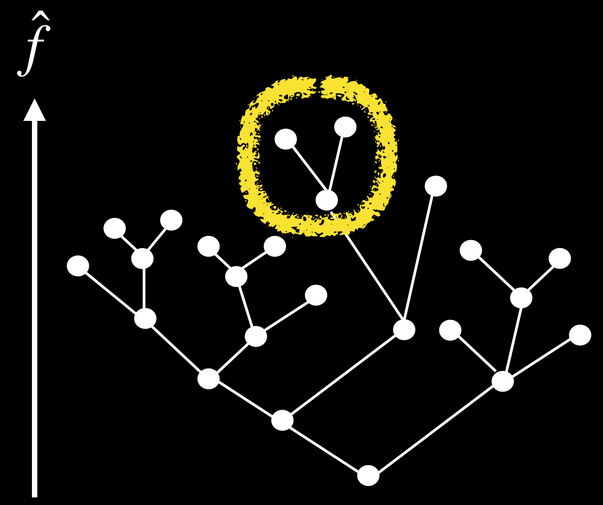
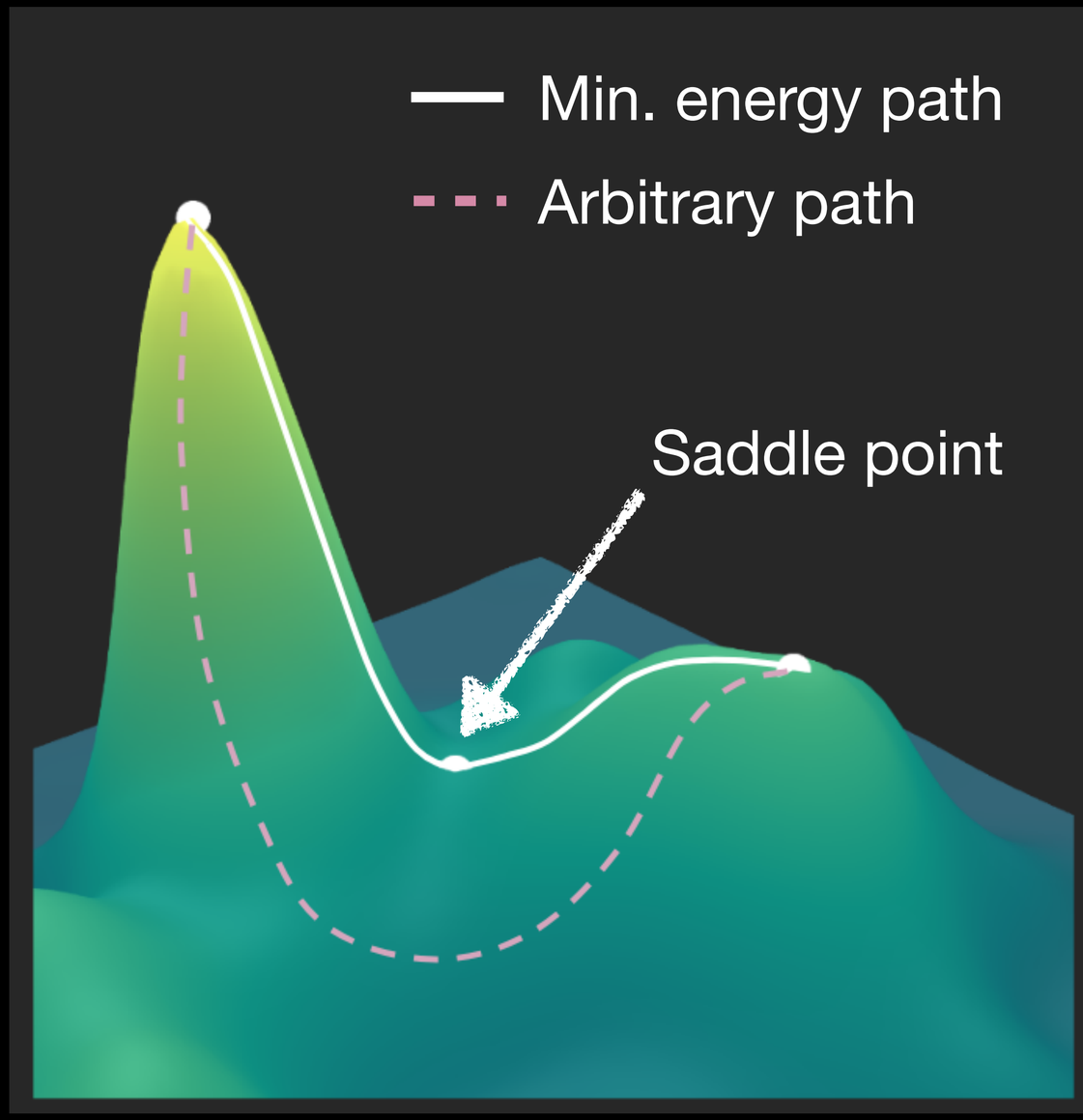
   A. Test modality between modes





Clustering pipeline: SigMA

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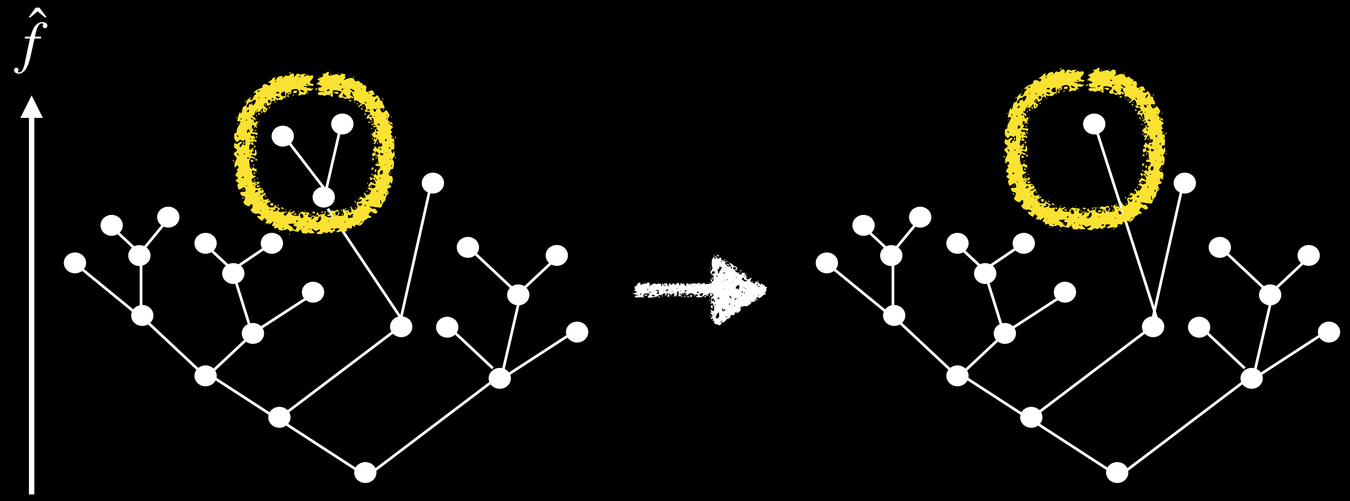

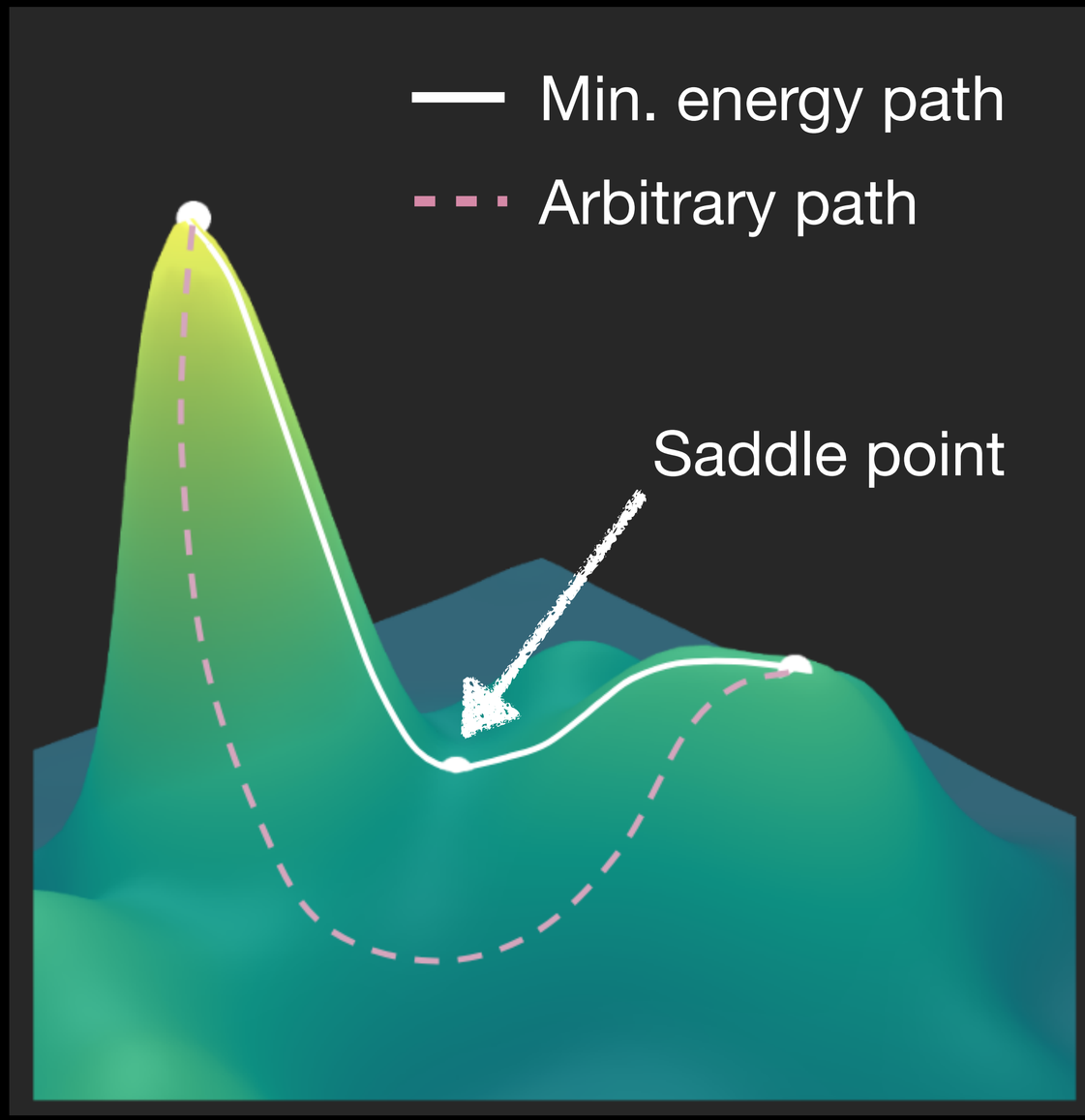

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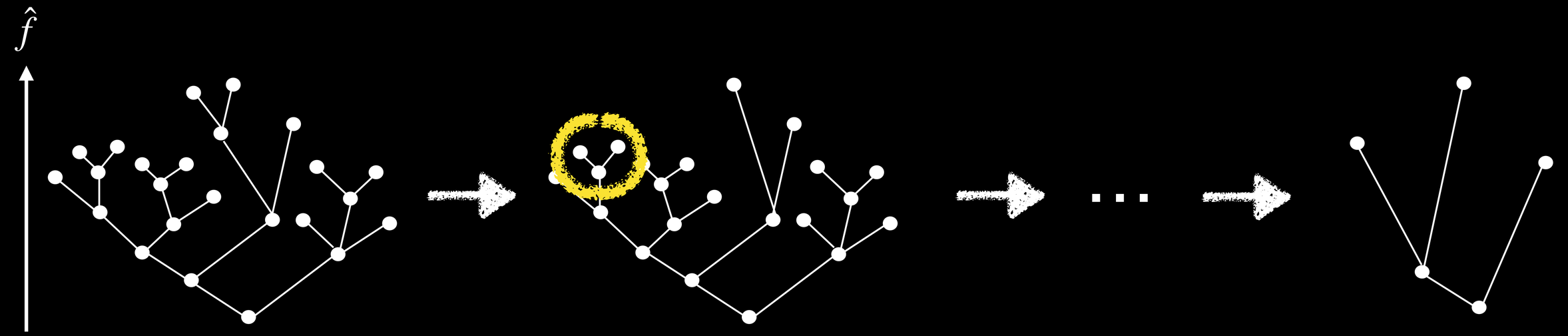
Next saddle point



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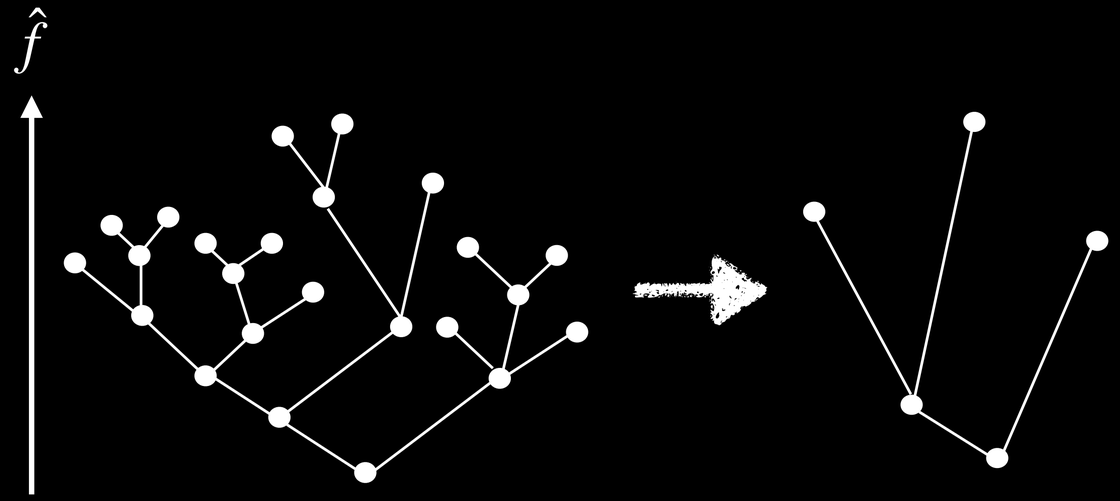
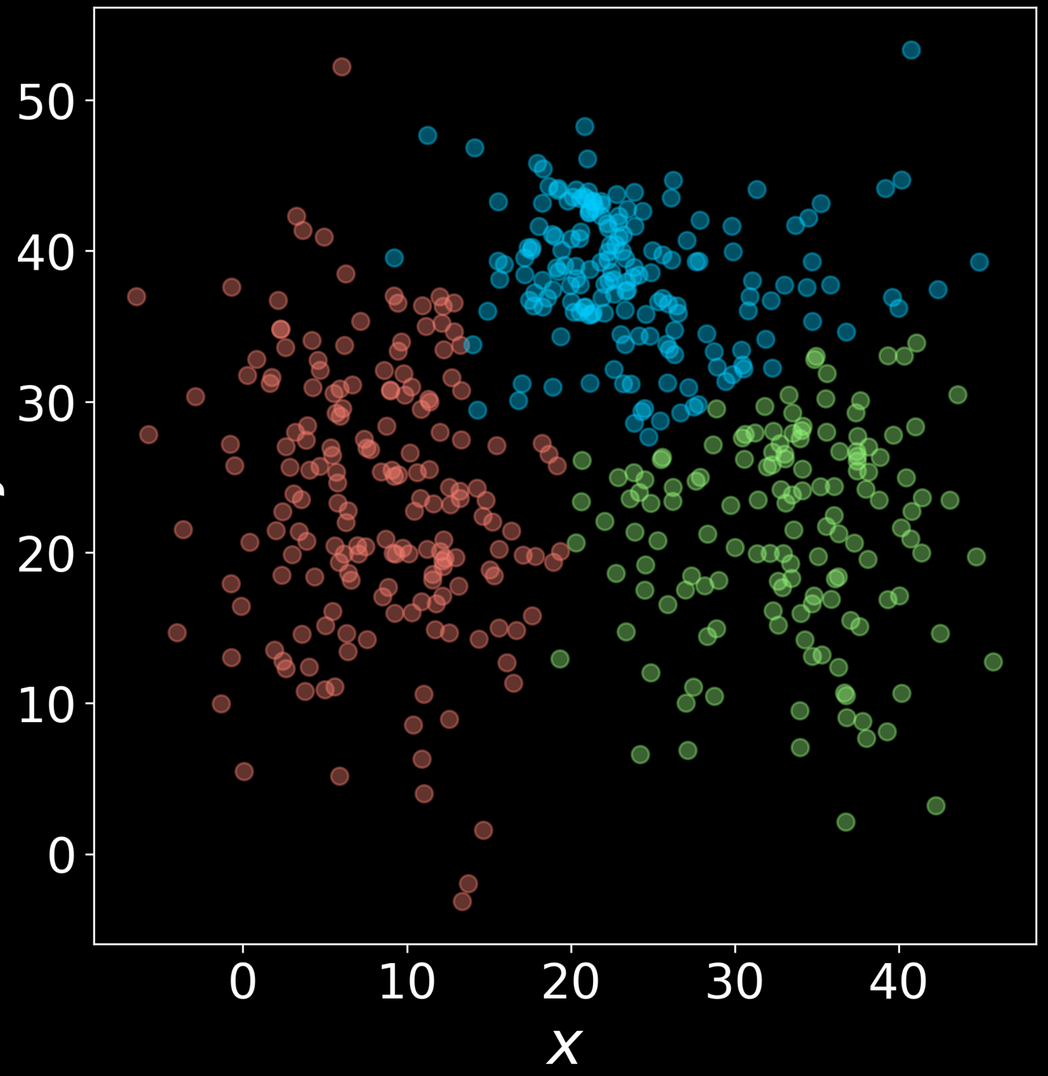
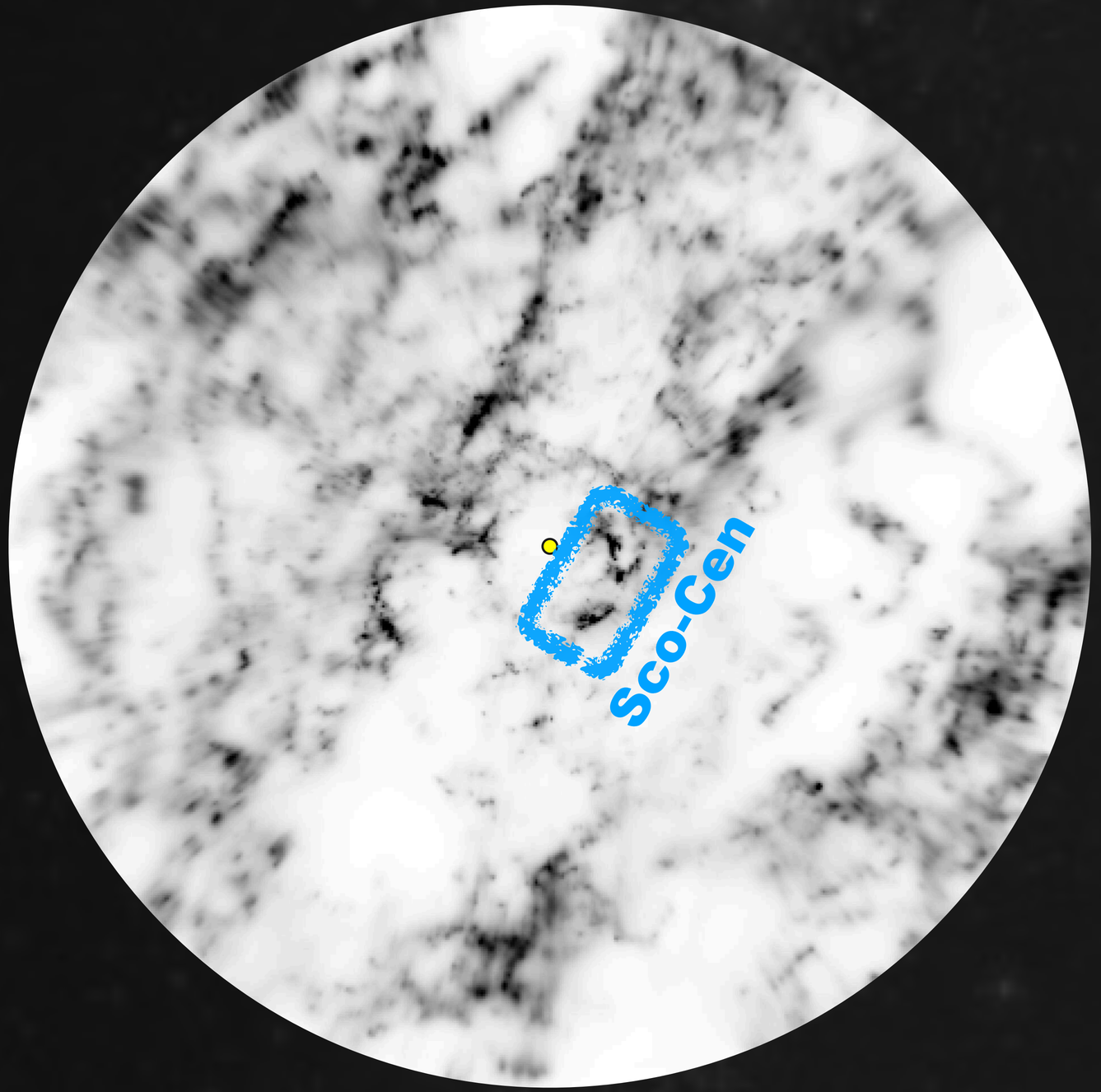




Results



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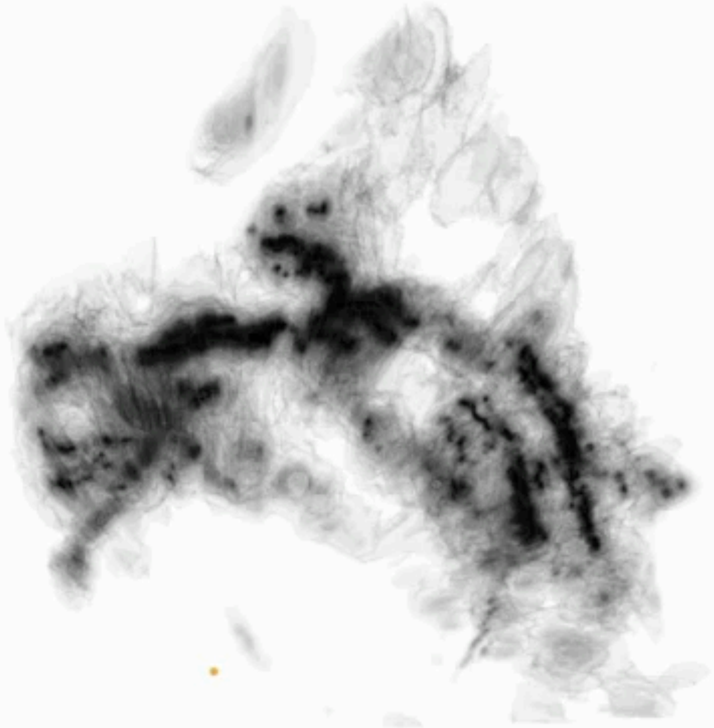
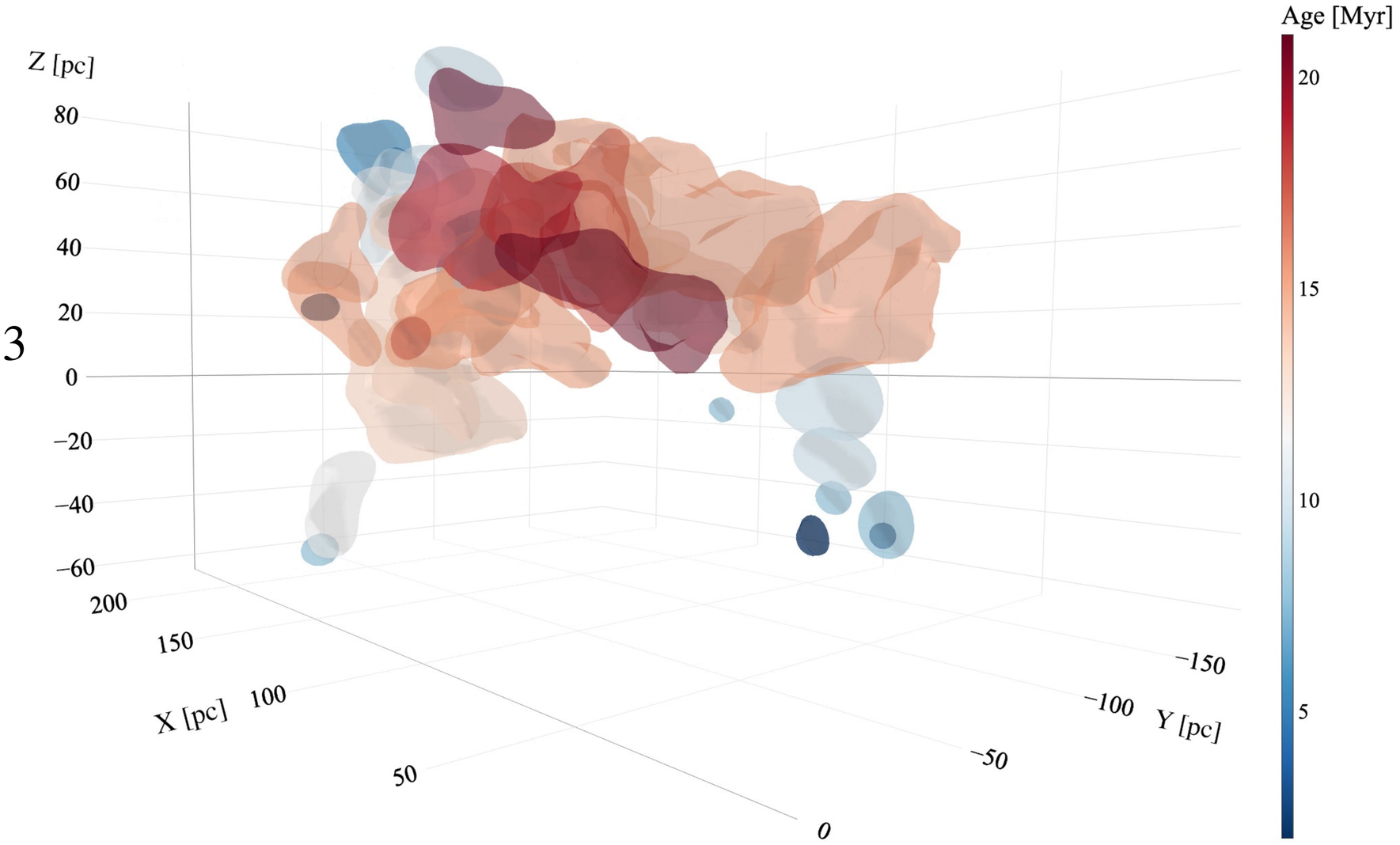
Edenhofer et al. (2024)



Results in Sco-Cen

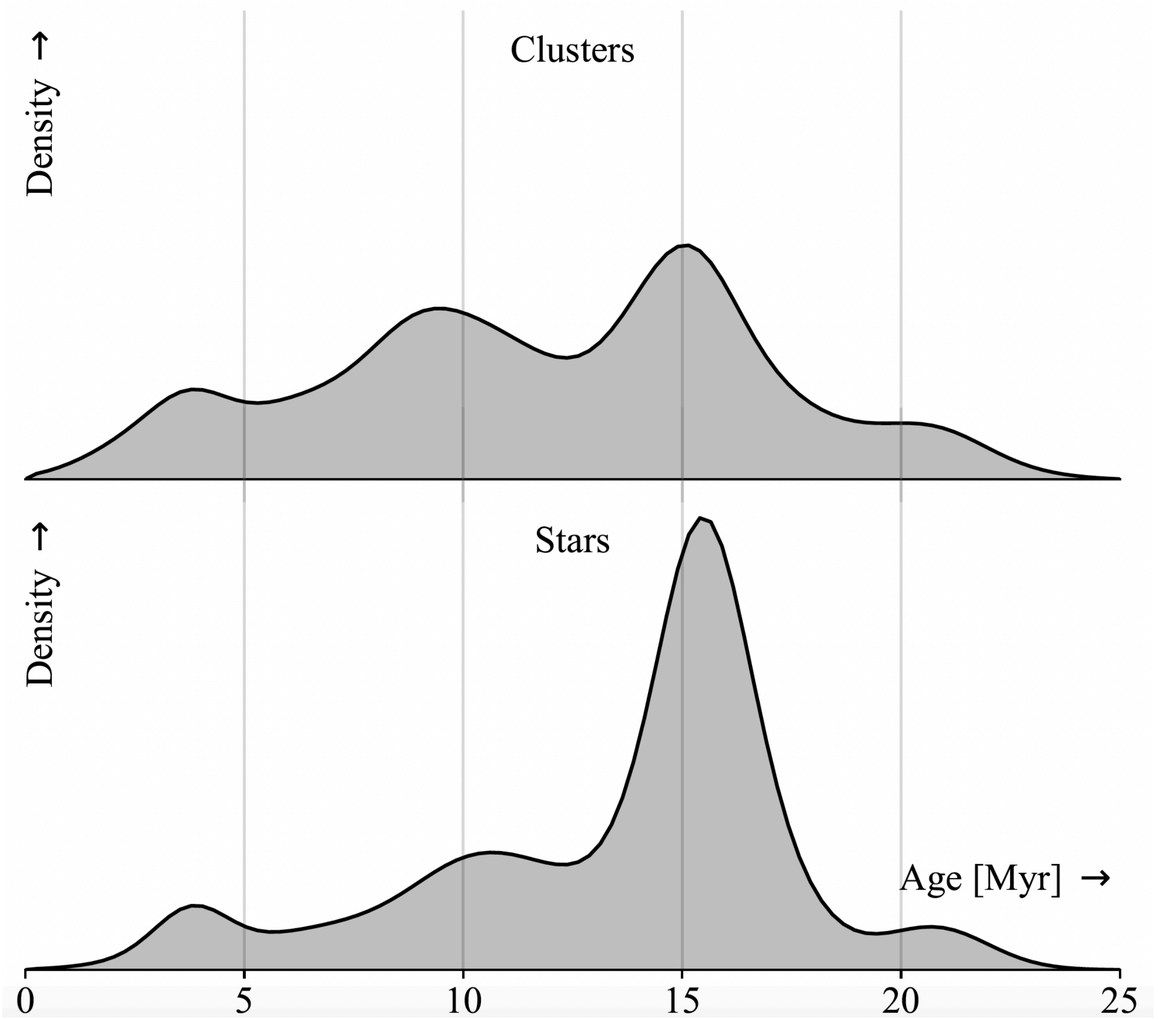
- New substructure
- Resolution
  - $\Delta v \sim 0.5\,\mathrm{km\,s^{-1}}$
  - $0.01\ \mathrm{sources\,pc^{-3}}$
  - $\sigma_{3D} \sim 1\,\mathrm{km\,s^{-1}}$
- High-res spatio-temporal map
  - Age gradients



Ratzenböck et al. (2023b)

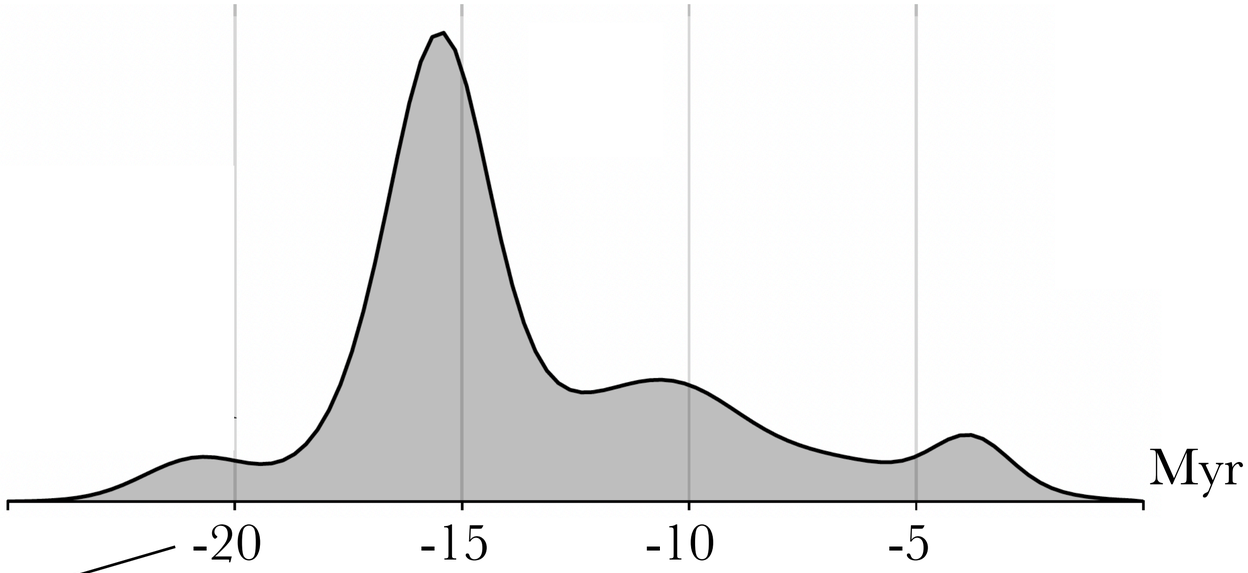
Buildup of Sco-Cen

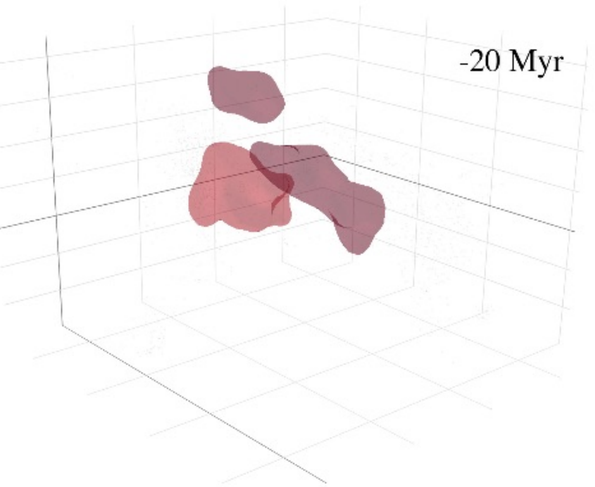
Four episodes of star formation



Buildup of Sco-Cen

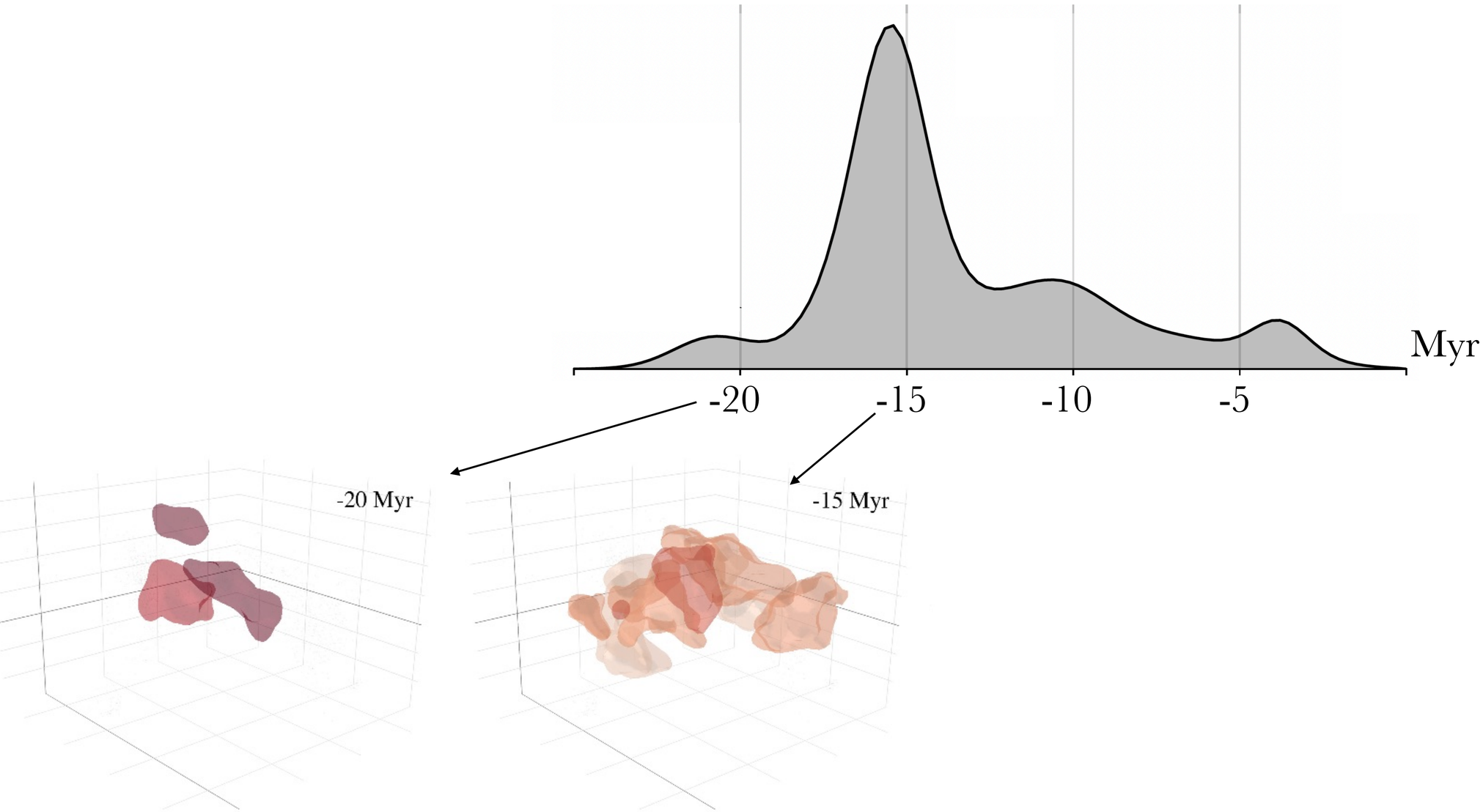
Initial onset of SF





Buildup of Sco-Cen

Maximum SF/CF rate



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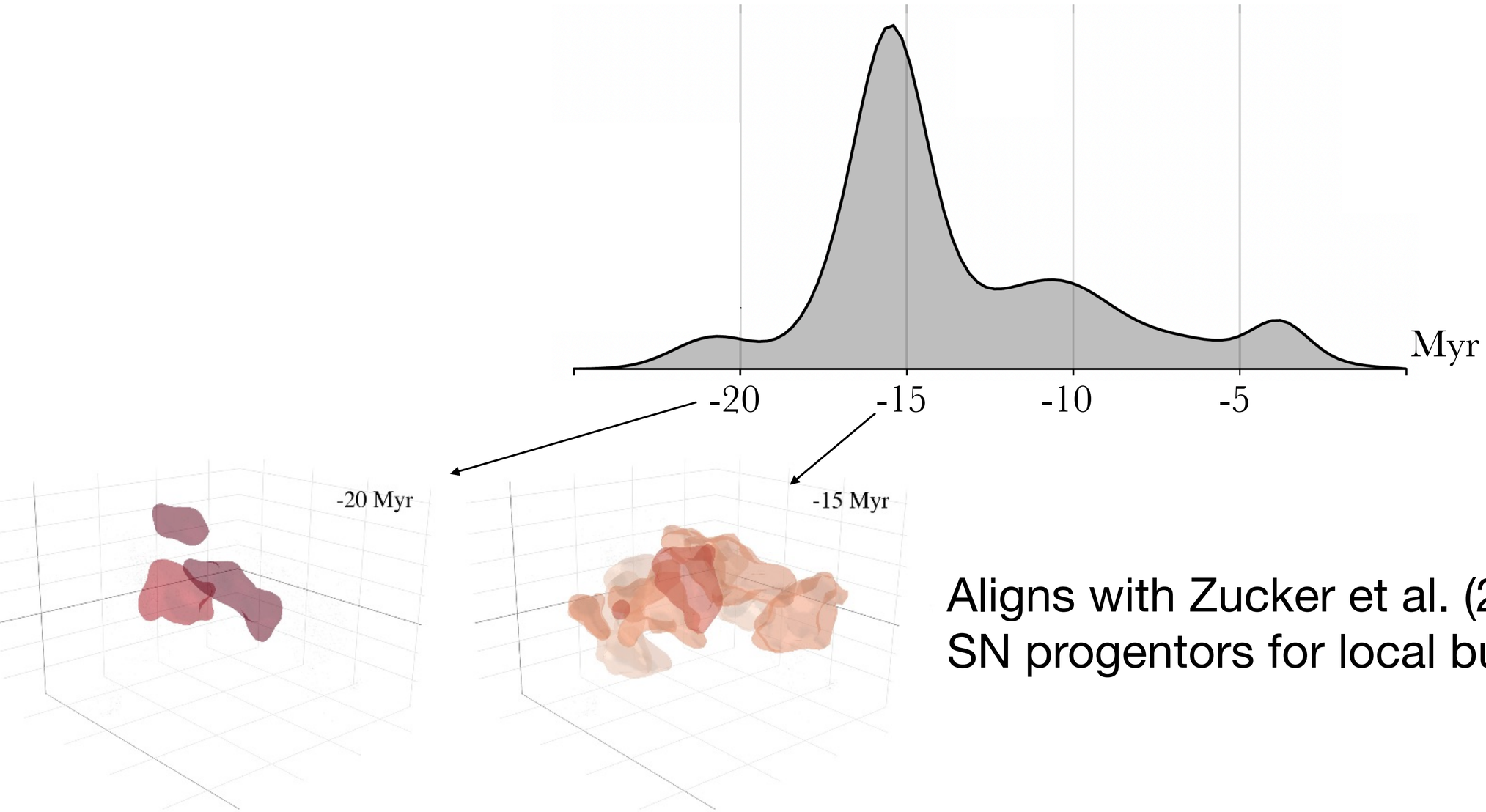
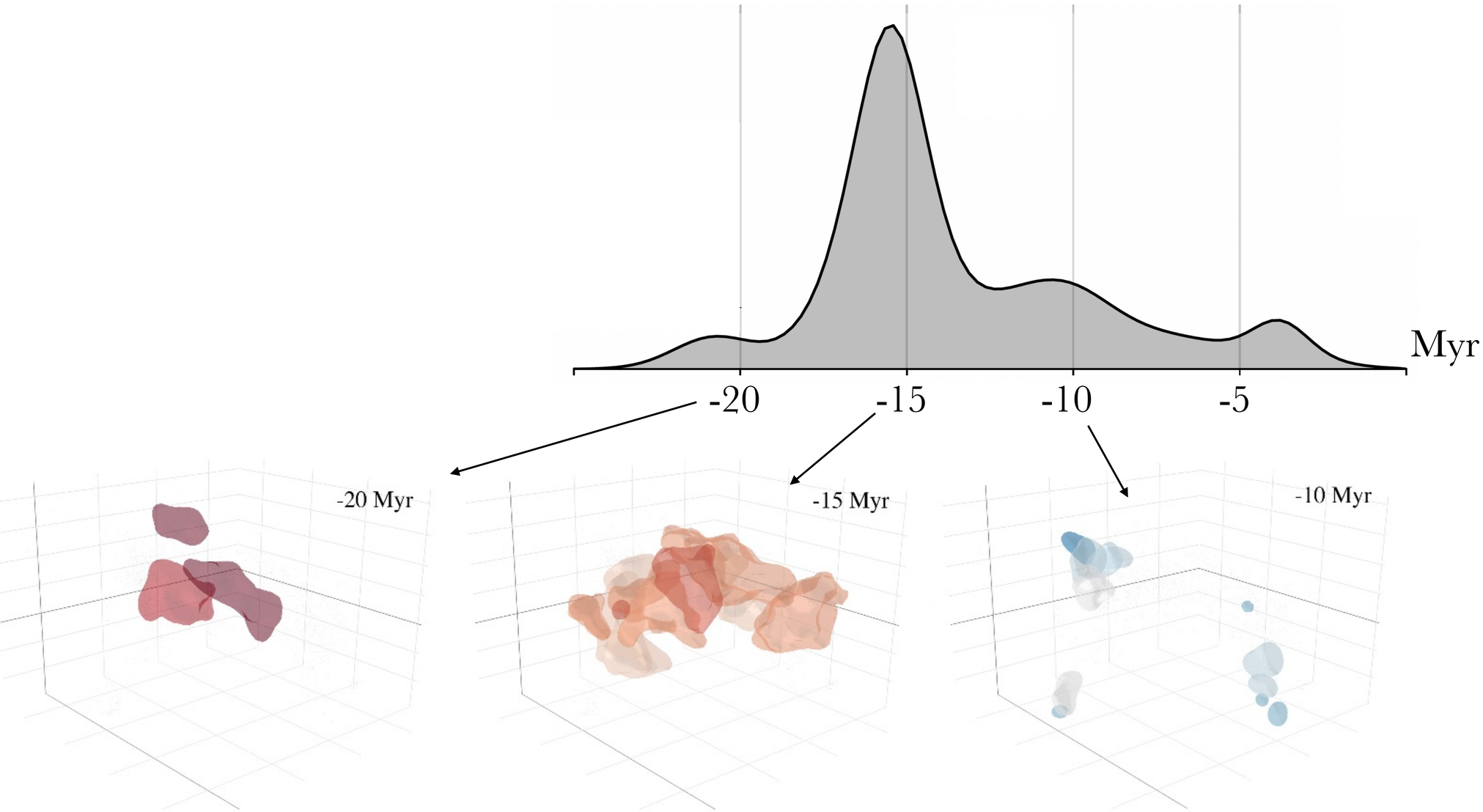


Aligns with Zucker et al. (2022)
SN progentors for local bubble formation

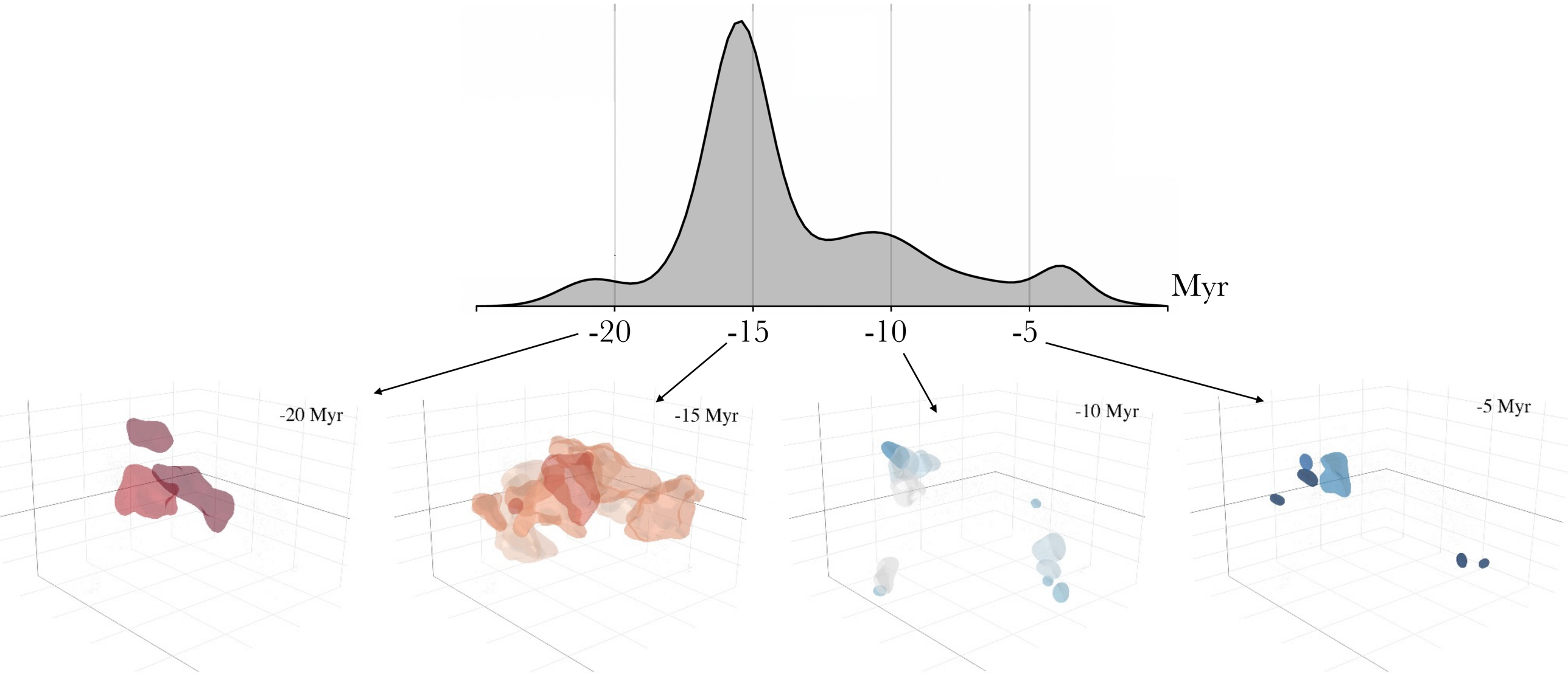
Buildup of Sco-Cen

USco & cluster chains



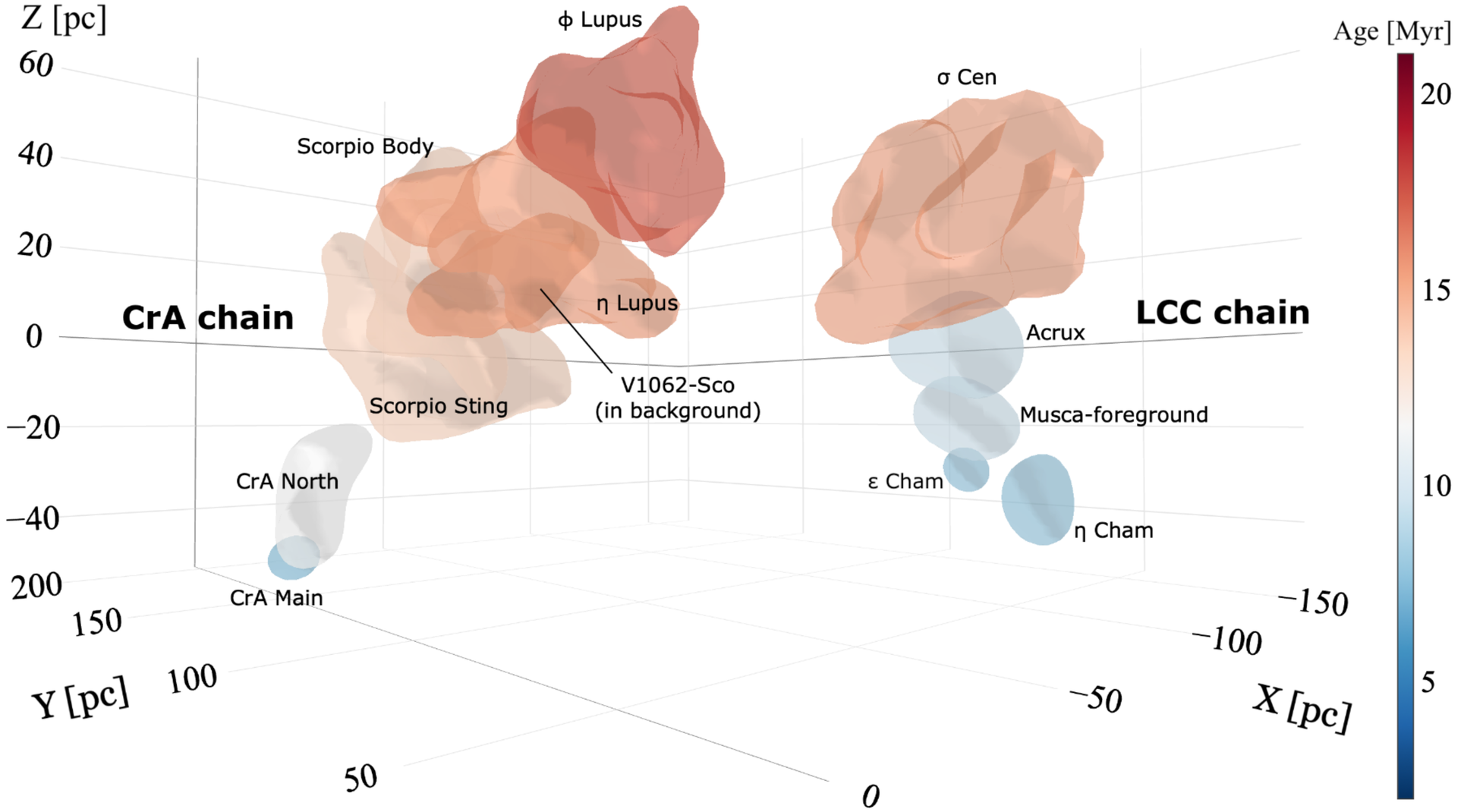
Buildup of Sco-Cen

Recent star formation



Star formation progression

100 pc cluster chains



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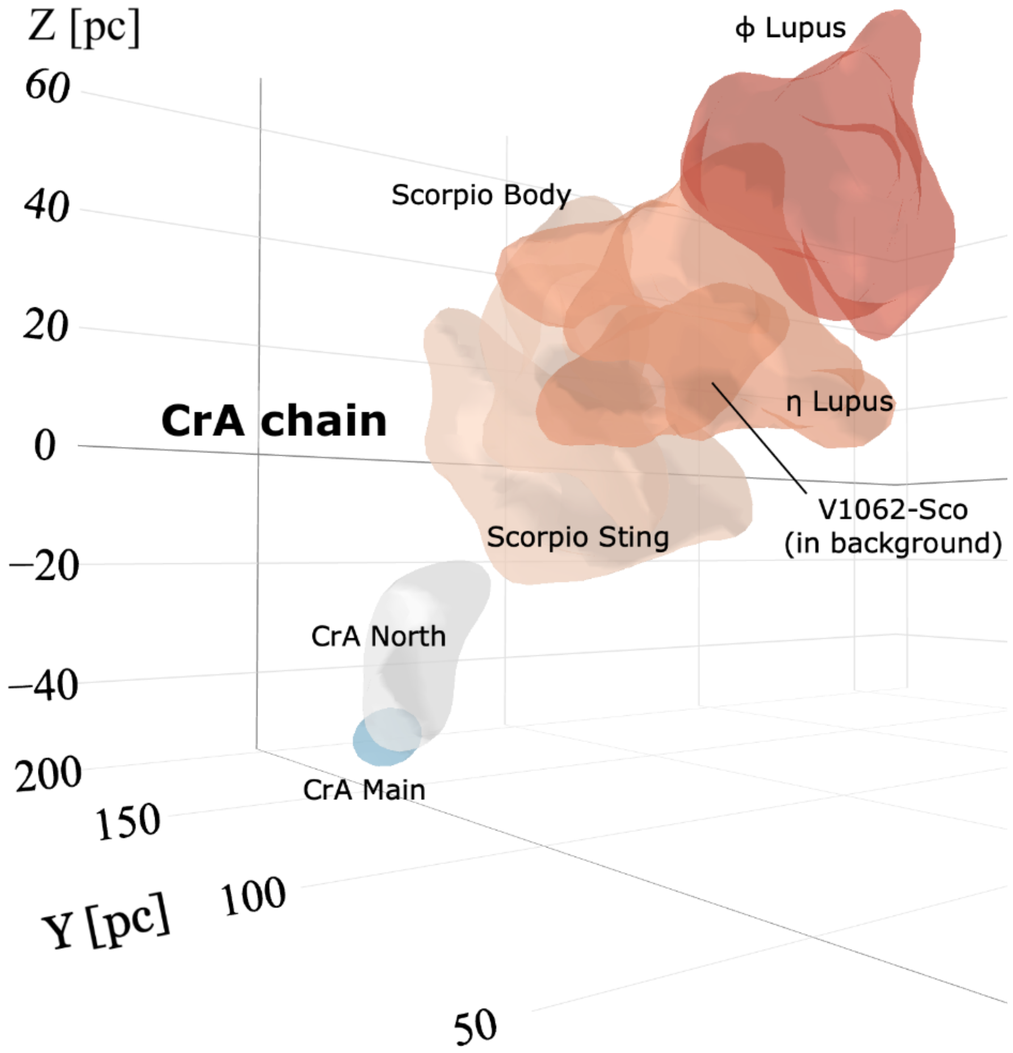

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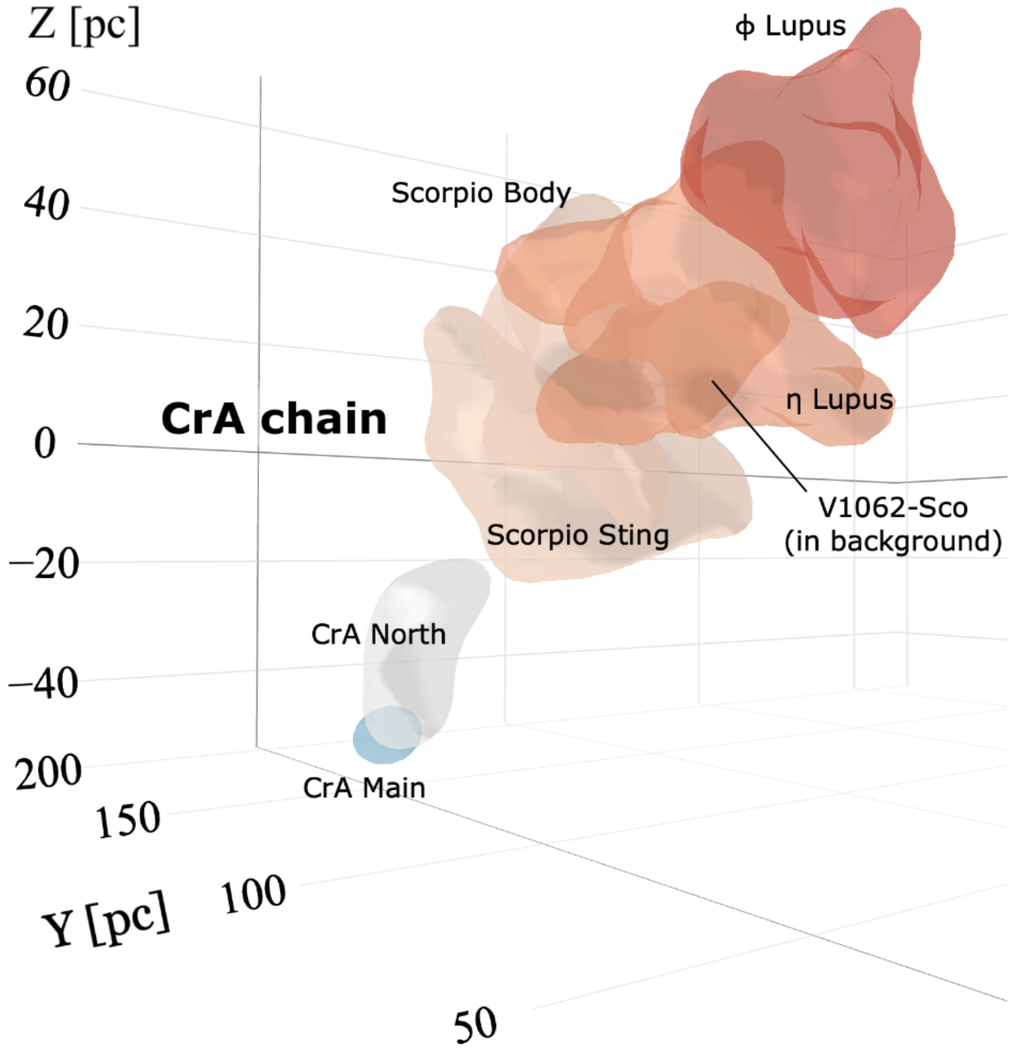

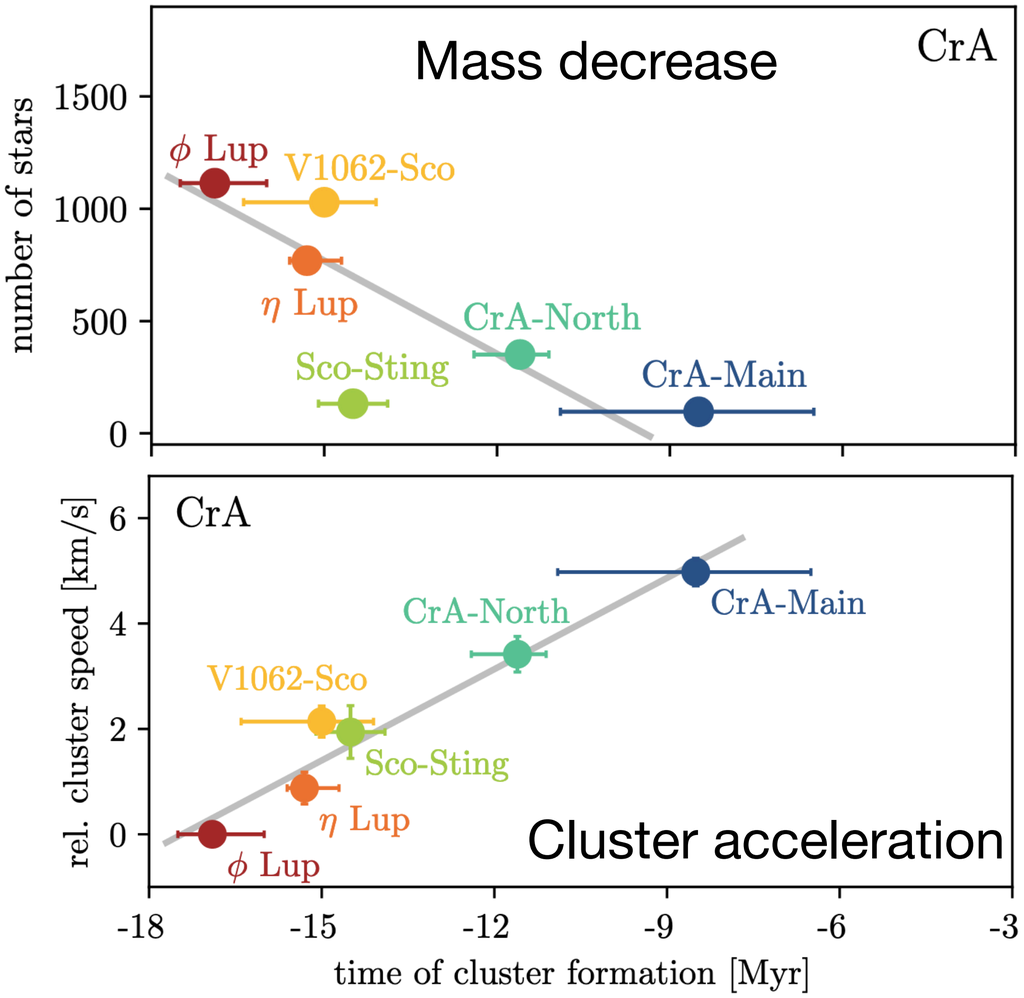

Posch et al. (2025)

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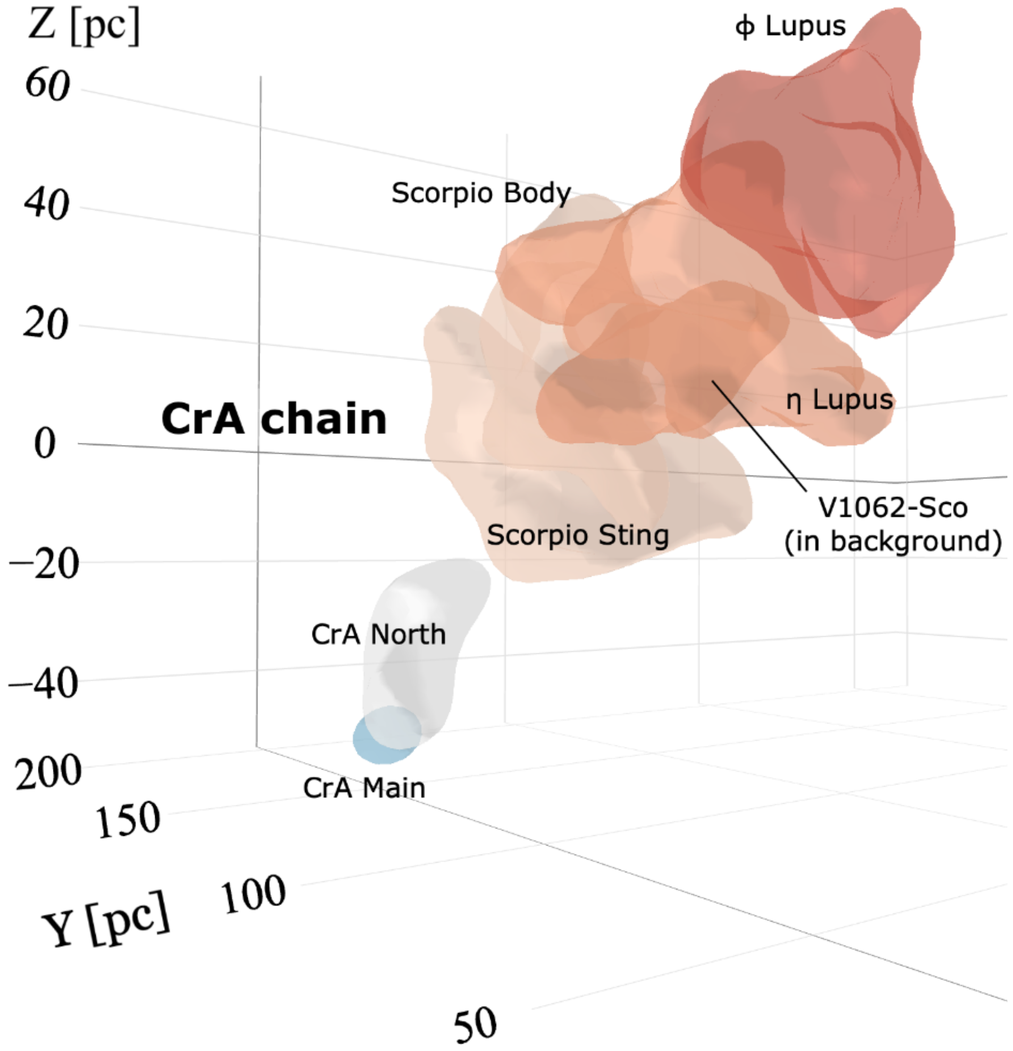

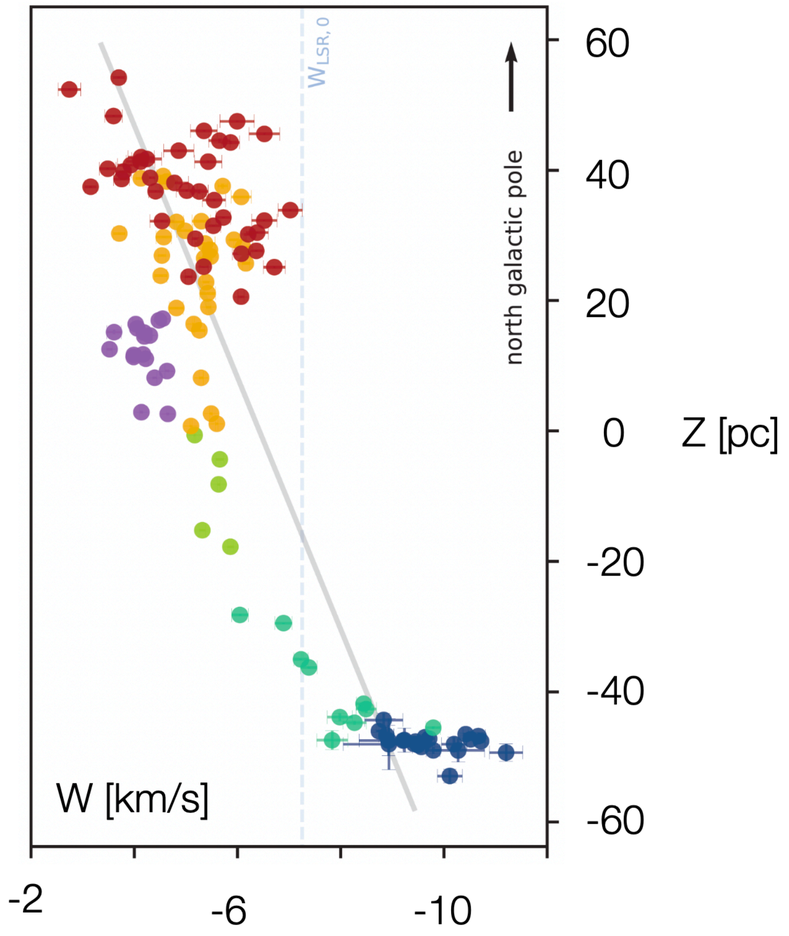

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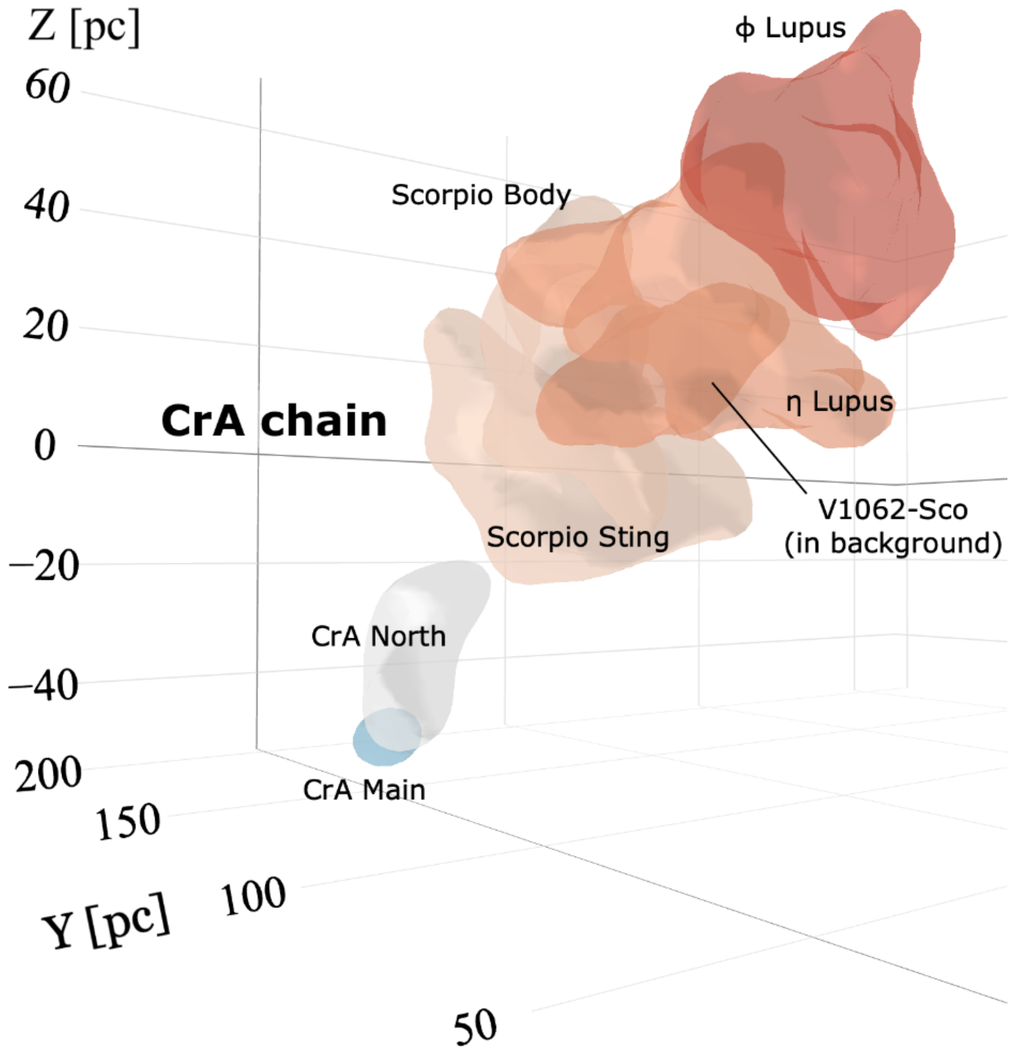
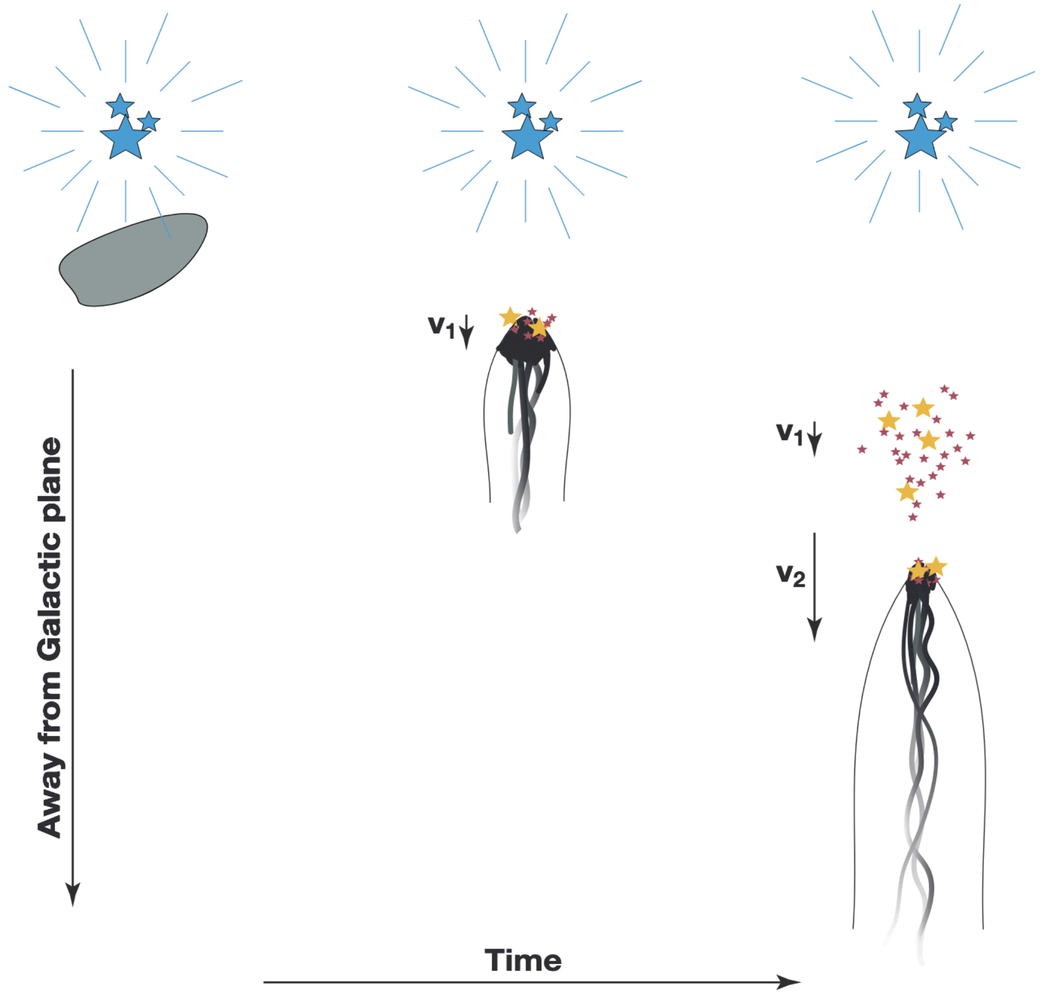
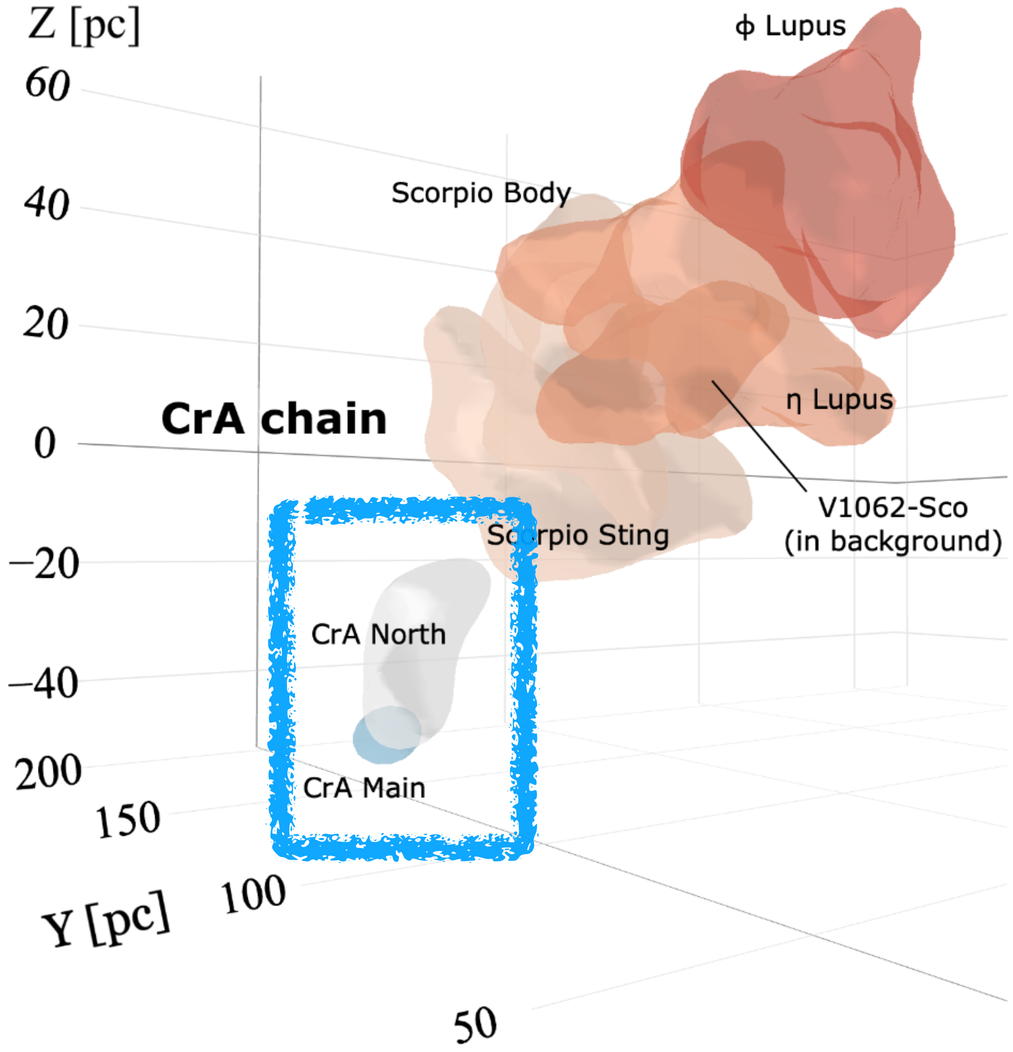


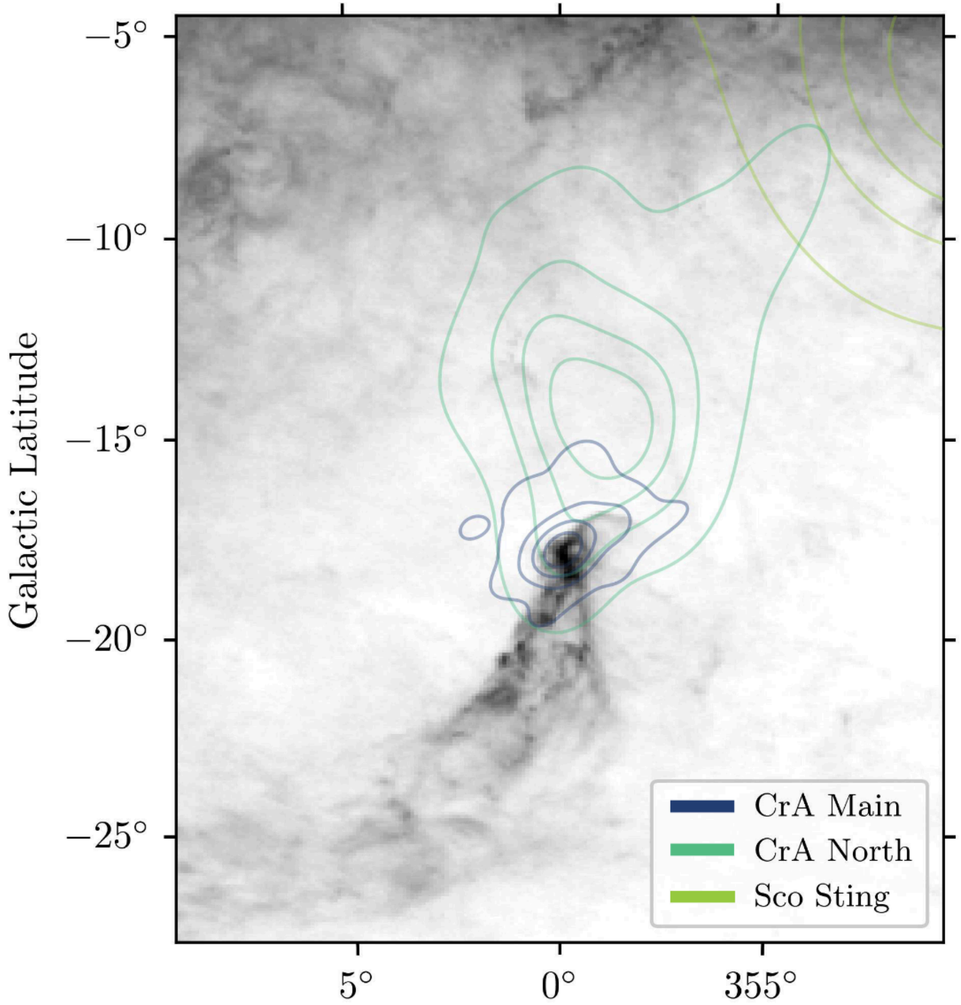


Posch et al. (2023)

Residual gas clouds

Cometary morphologies, containing embedded YSOs





Posch et al. (2023)

Signs of star formation propagation

- Inside-out formation: older massive clusters in center and younger low mass ones toward the outskirts

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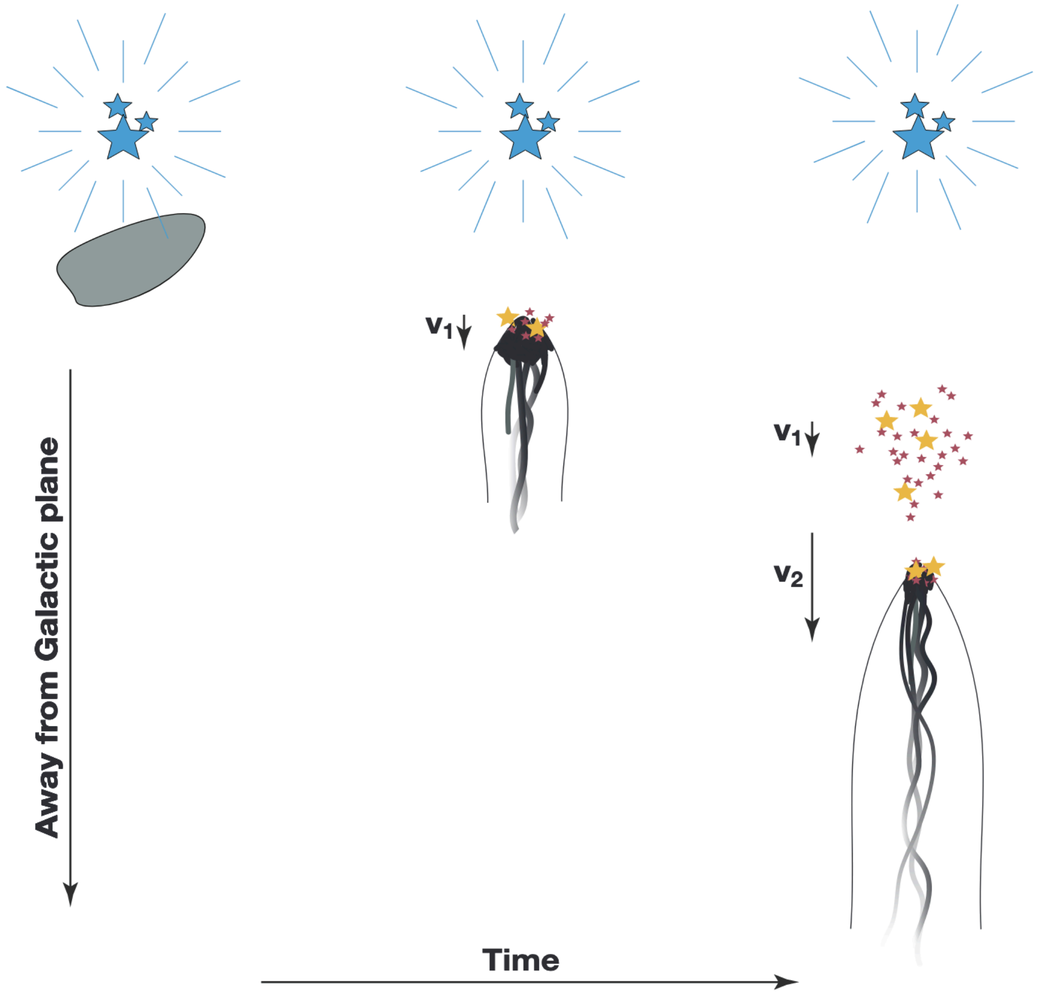
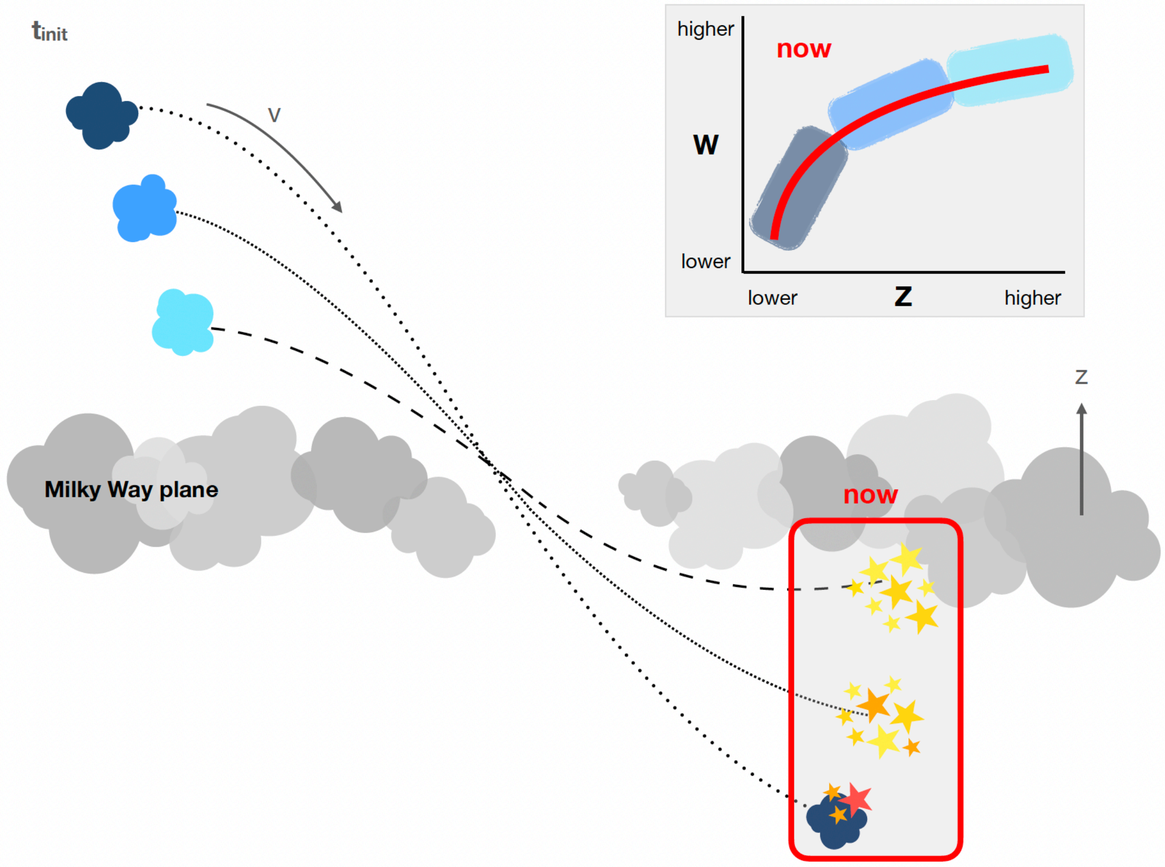
- Velocity imprints of feedback on younger next gen clusters
- Residual gas clouds show compression & shaping from feedback
- ~40% of Sco-Cen formed through triggered star formation, with 35% located in cluster chains

Thank you!

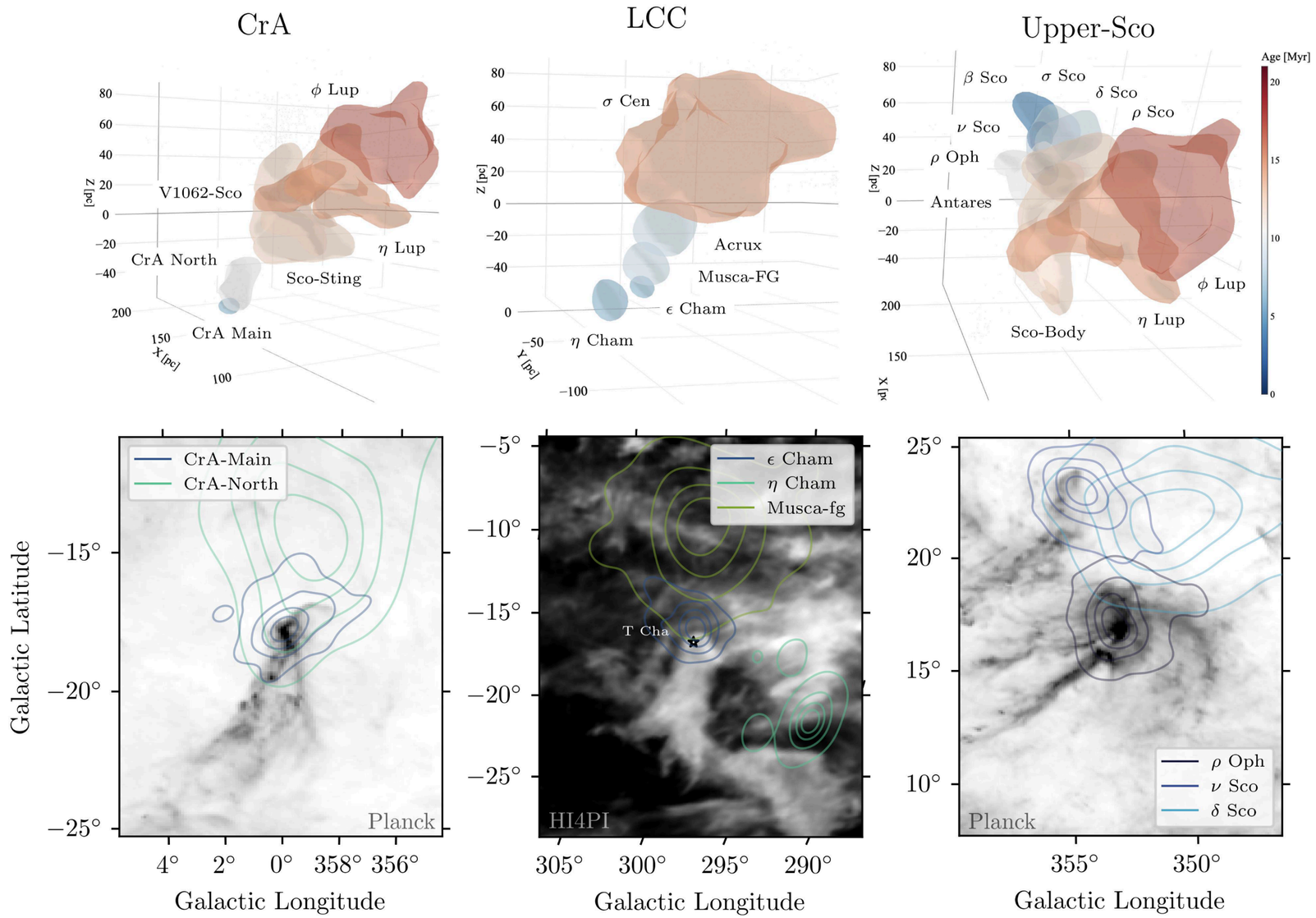
Backup


Away from Galactic plane
Time
v1
v1
v2


tinit
v
Milky Way plane
now
z
higher
now
W
lower
lower
Z
higher

Residual gas clouds

Cometary morphologies, containing embedded YSOs



Momentum analysis

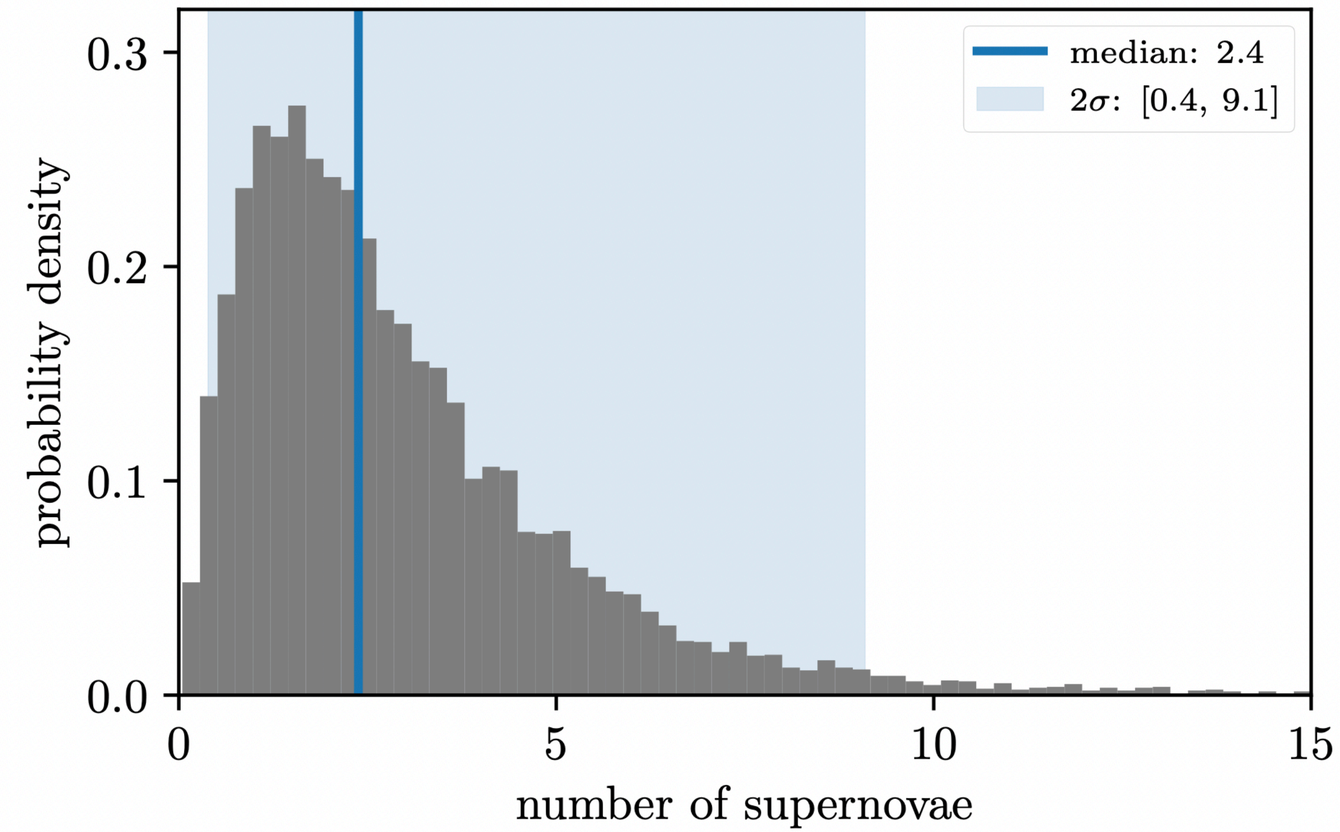


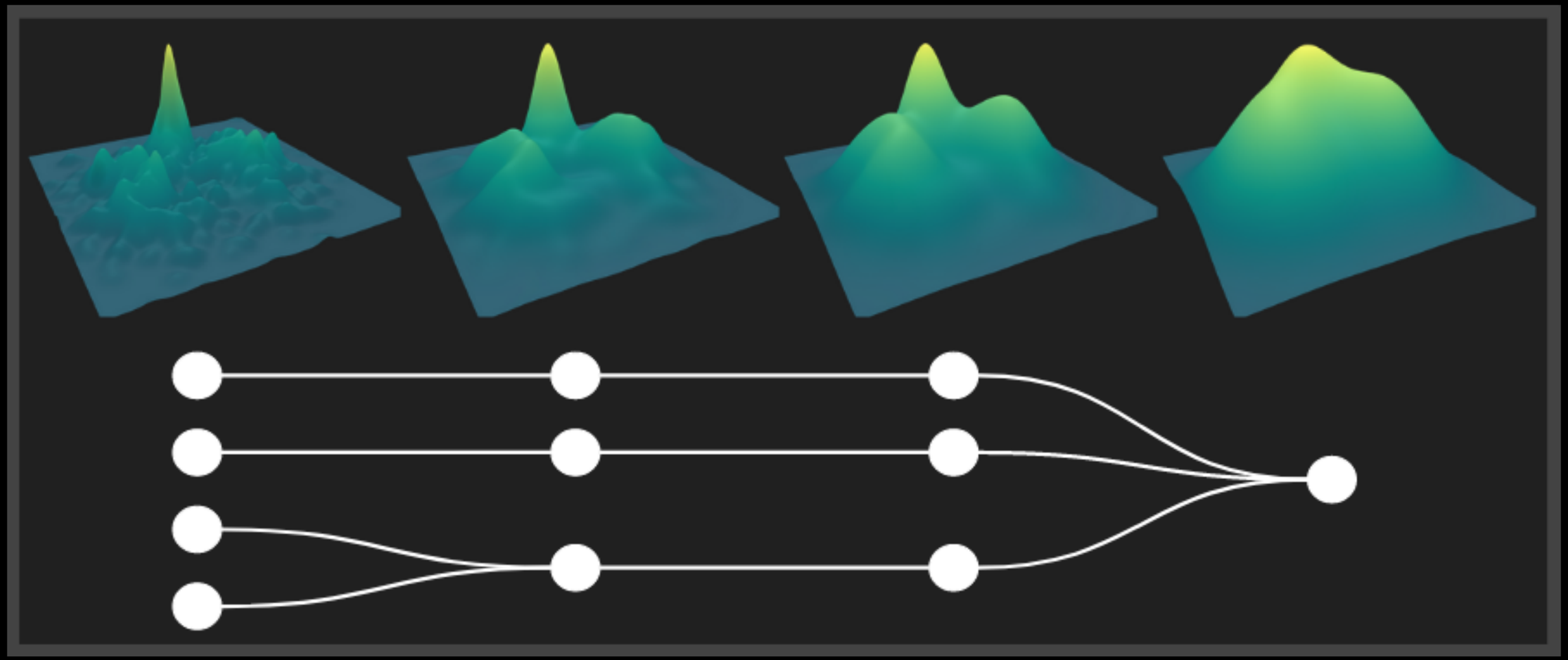
Fig. C.1. Probability distribution of the number of SN explosions needed to explain the current momentum of the CrA molecular cloud. The median number of SNe necessary is about two, with 95% of values lying between 0.4 and 9.1.

How to set parameters?

SigMA(k,α)

Choosing k

$$\hat{T}_n(t) \sim \mathcal{N}(0,1) \iff \log N < k < N^{4/(4+p)}$$



Choosing α

- Many hypotheses tests increases chance of false positives
- Limit proportion of **false positives** among all positives
  - Apply **Benjamini & Hochberg procedure**

➡ Data driven way of choosing significance α

Problem #1

Distance metric

Distance metric

- Mixed meaning of dimensions
- 3 positional features
  - In Cartesian space
- 2 velocity features
  - Measurements “on sky”
  - spherical coordinates

Problem #2

Uncertainties

Time complexity

Density computation (k-d tree)

mode & saddle search (union find)

$$\mathcal{O}(p\,N \log N) + \mathcal{O}(p\,N \log N) + \mathcal{O}(N\,k) + \mathcal{O}(\,|\,\mathcal{S}\,|\,)$$

Graph construction

Cluster tree pruning

Robustness of $\hat{T}_n(t)$