Star formation in nearby molecular clouds

Marco Lombardi
(University of Milan)

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with

Joao Alves, Jan Forbrich, Josefa Großschedl,
Birgit Hasenberger, Charles Lada, & Stefan Meingast

Molecular clouds show filamentary structures

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Number counts and NIR extinction

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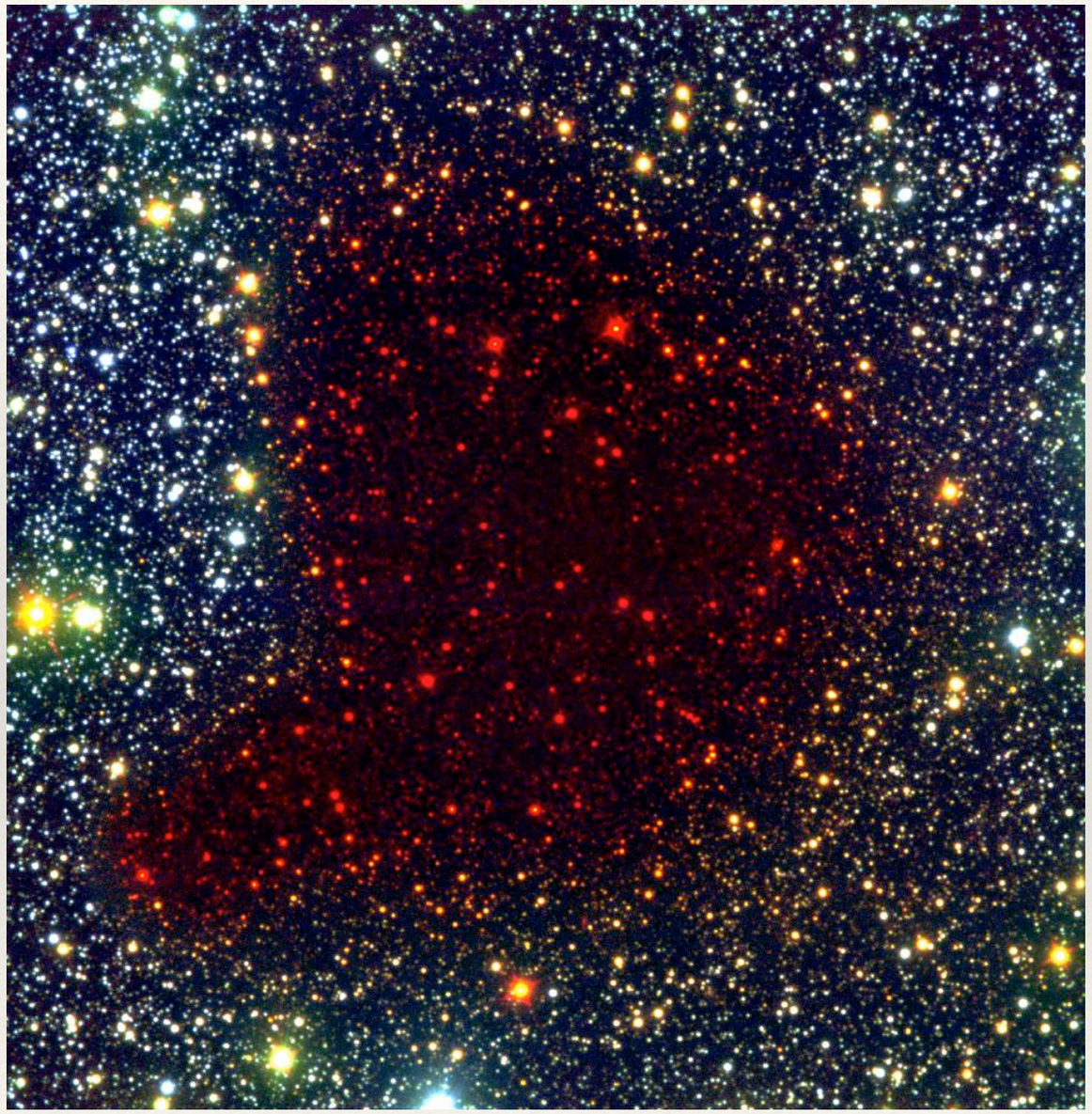
Alves et al. (2000)

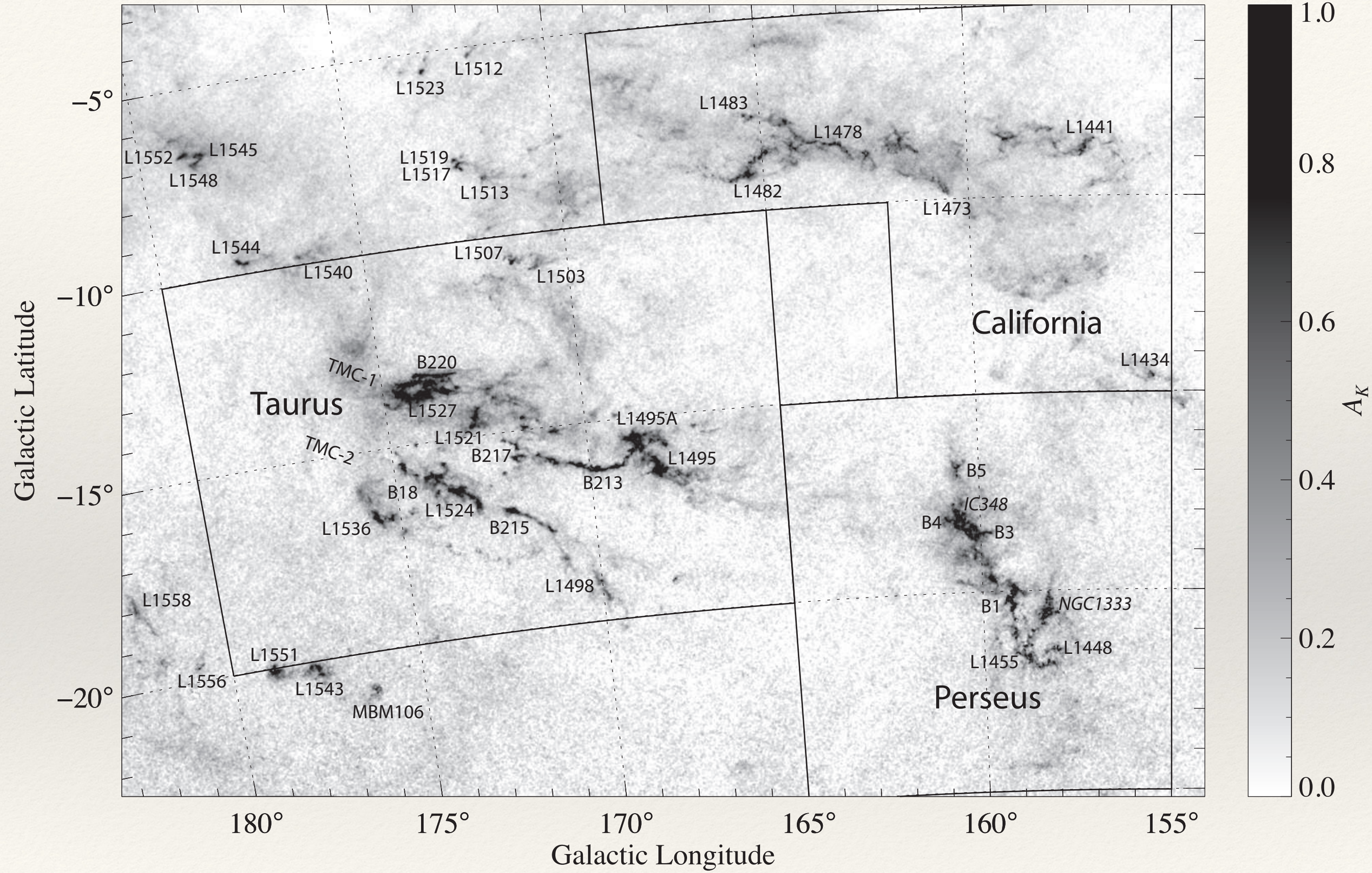
Number counts and NIR extinction

VLT (BVI)



VLT + NTT (BIK)

Alves et al. (2000)



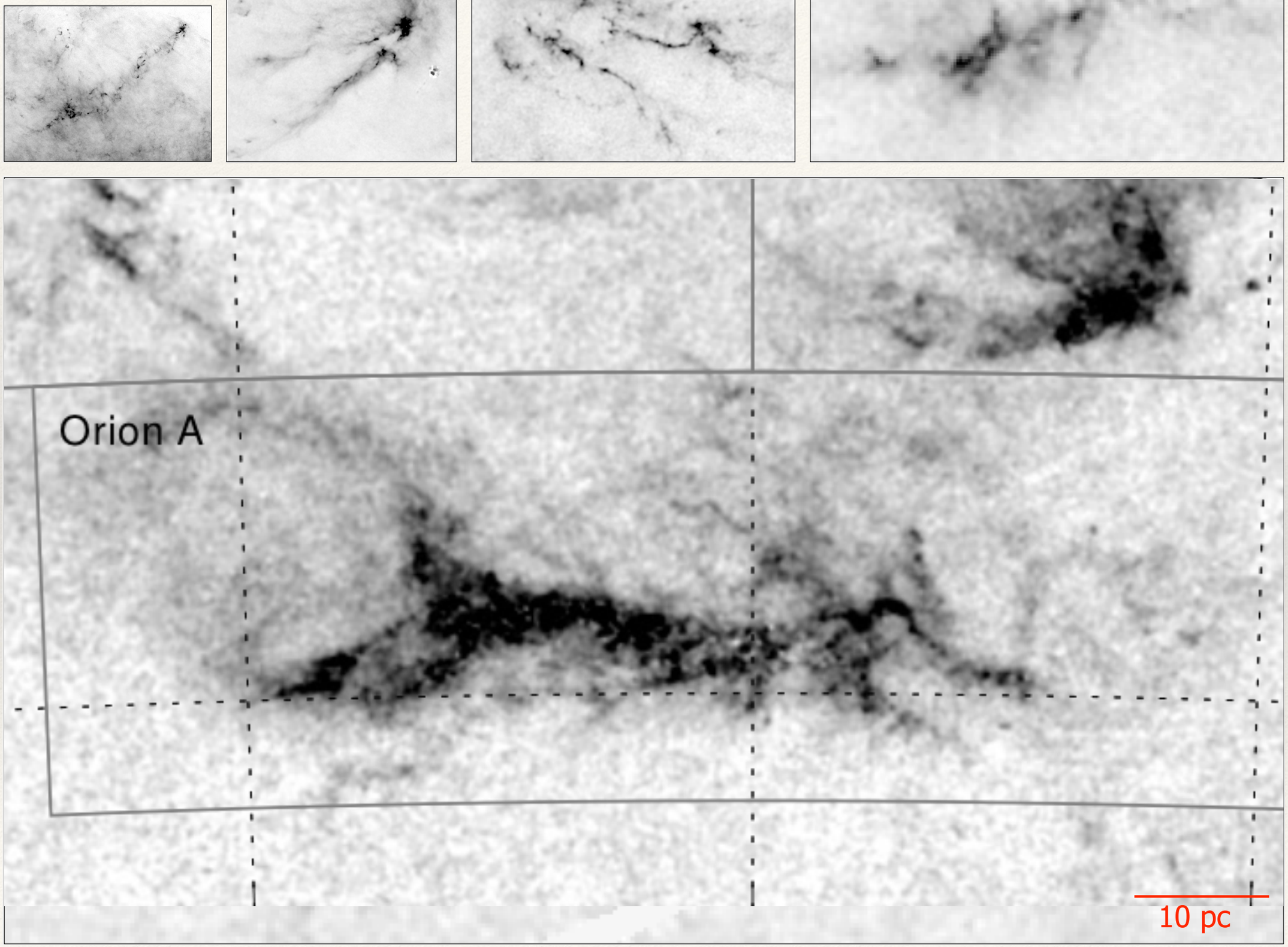
2MASS extinction map (Lombardi et al. 2010)

Perseus

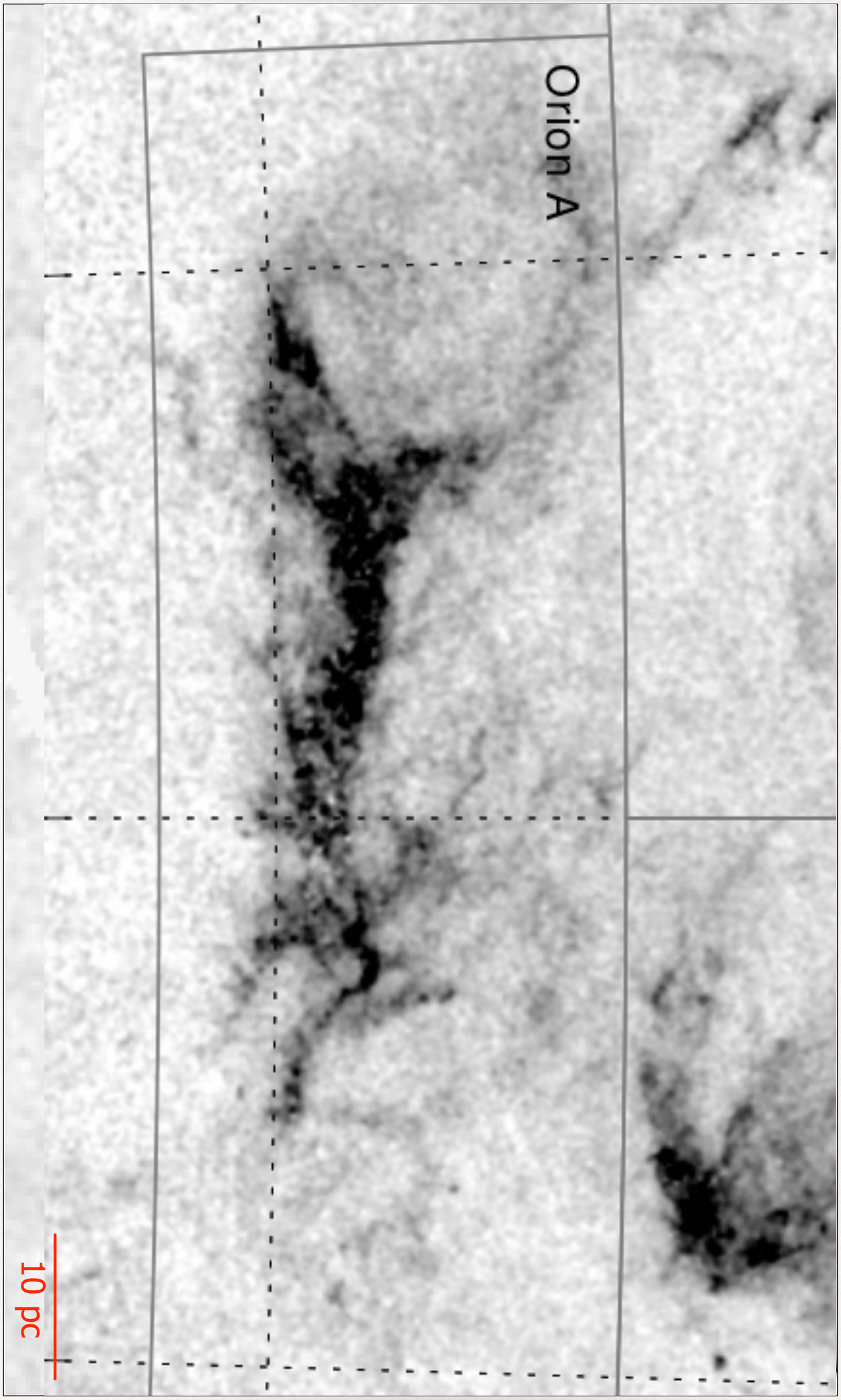
Taurus

Ophiuchus

Pipe



Lombardi • Alves • Lada (2006-2012)
NICER, NICEST



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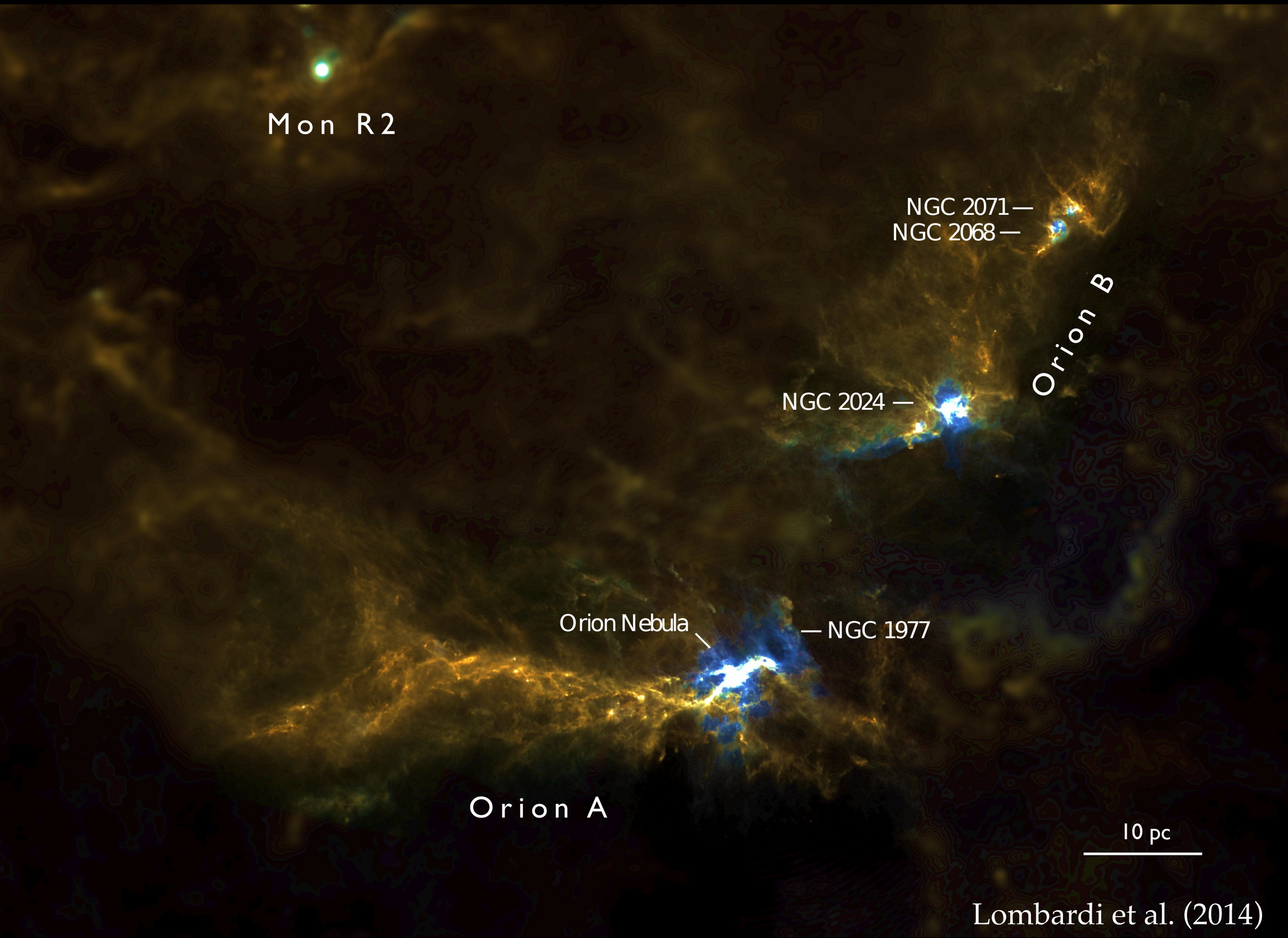

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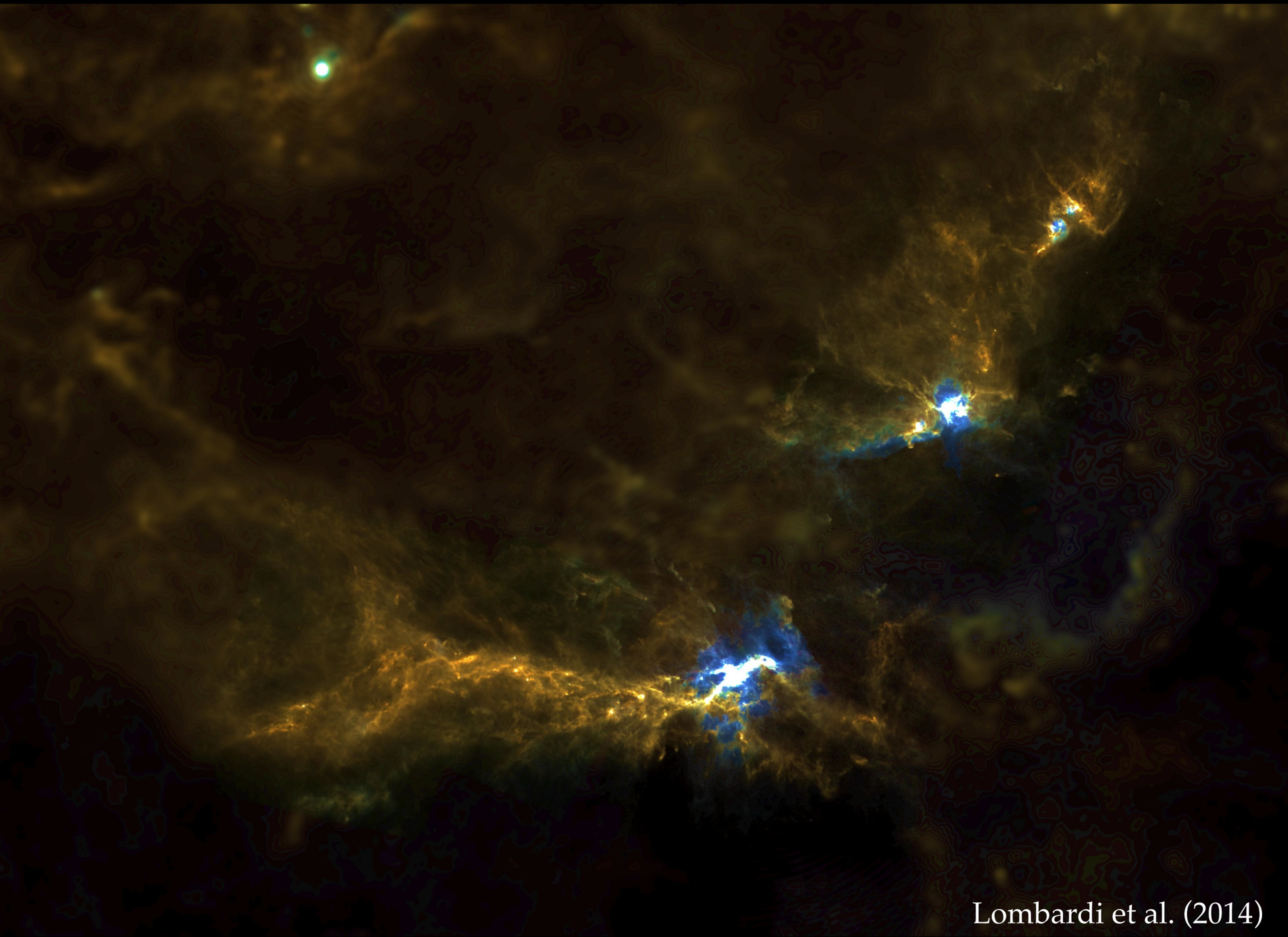

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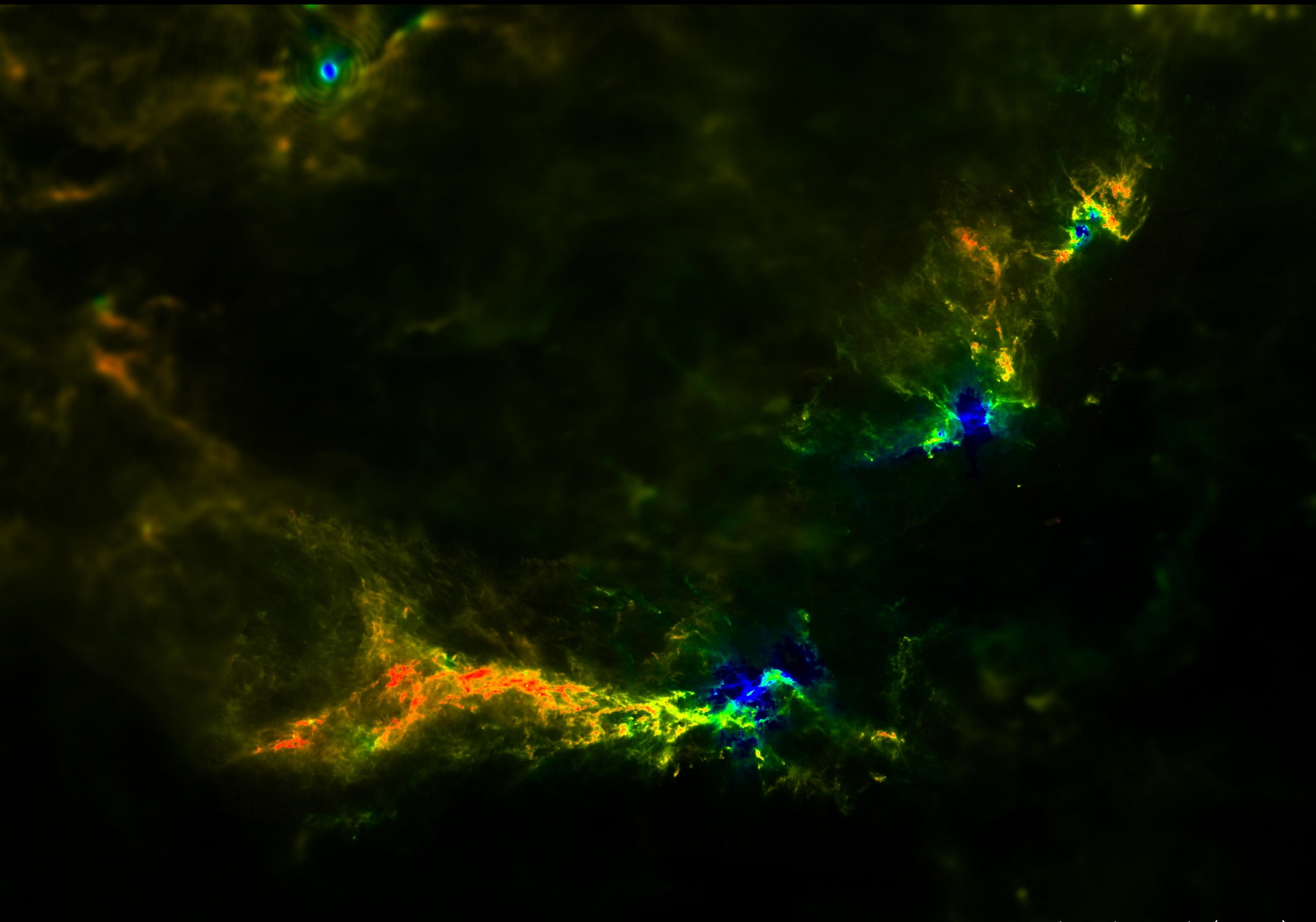

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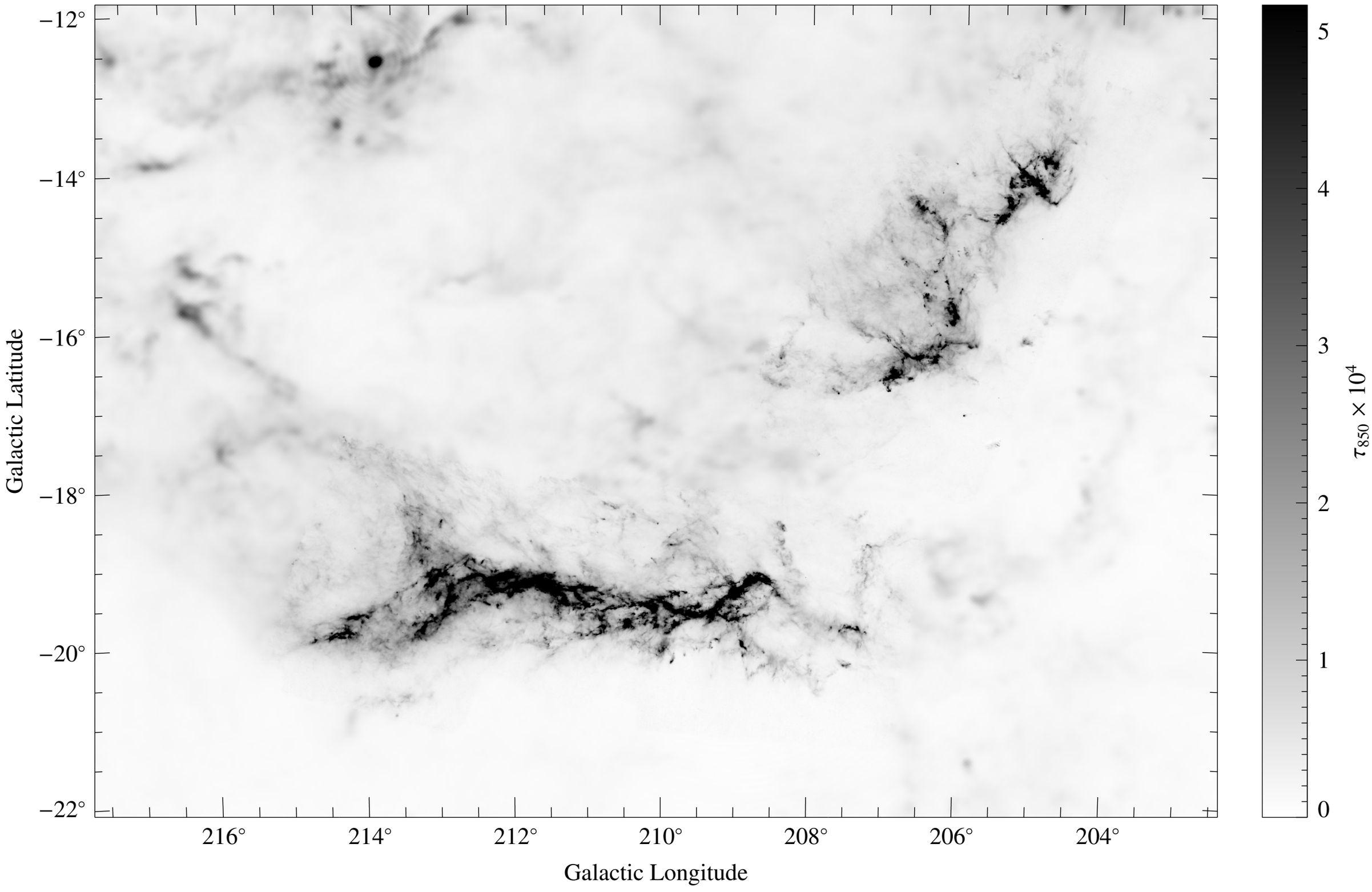

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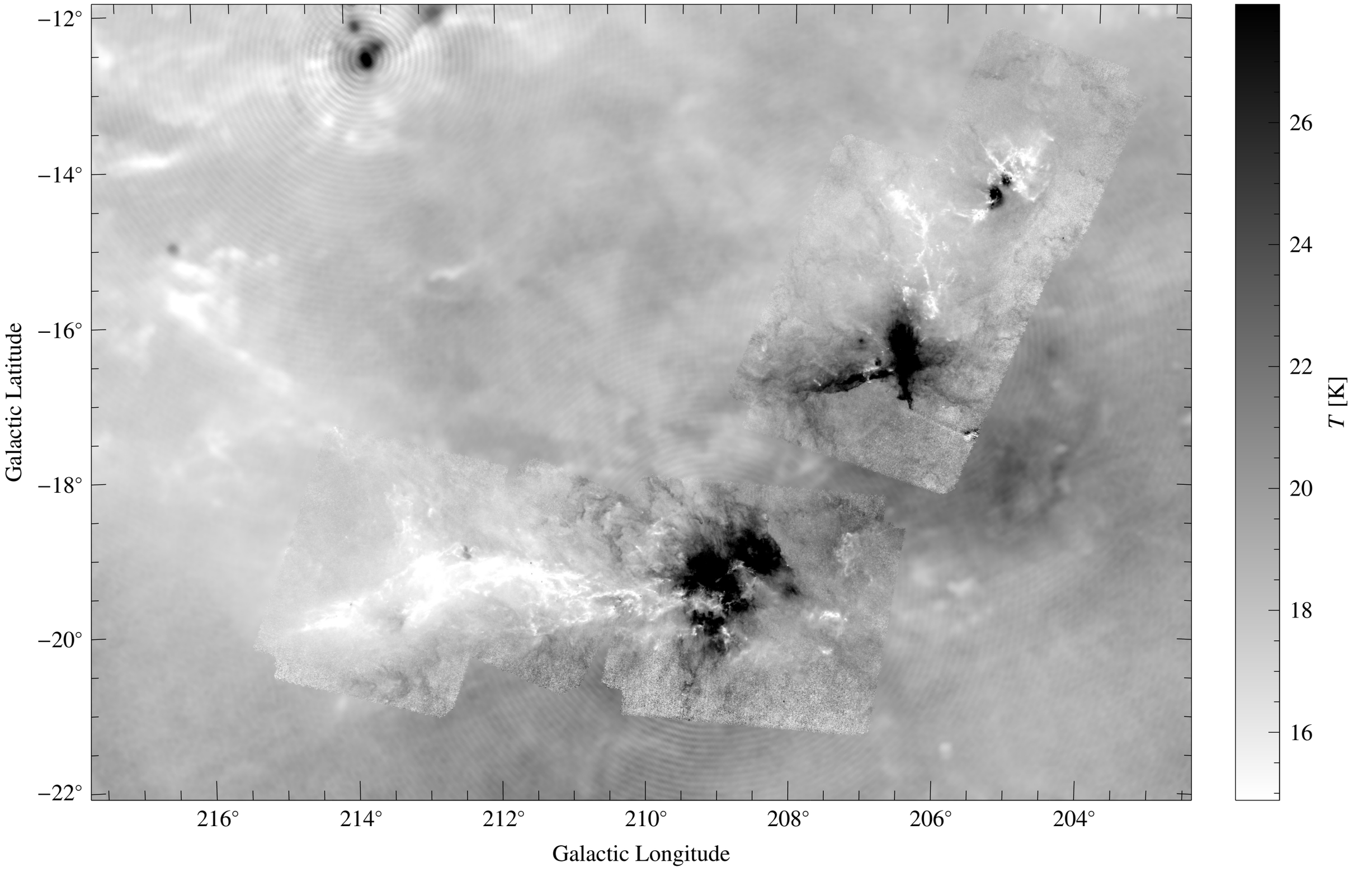


Lombardi et al. (2014)

NIR extinction

- Probably the **most robust** technique (e.g., Goodman 2008)
  - **insensitive** (in the NIR) to the physical properties of the **dust grains** (Indebetouw et al. 2005; Ascenso et al. 2013)
  - relies on a well established **dust-to-gas ratio** (Savage & Mathis 1979; Lilley 1955; Bohlin et al. 1978)
    - used to **calibrate** others methods (X-factor for molecular line emission, opacity for dust emission)
- Limited by the angular **density of background sources**
  - Need for **deep observations** and **suitable methods** for analyzing them (Meingast et al. 2017, Lombardi 2018)

VISIONS public survey

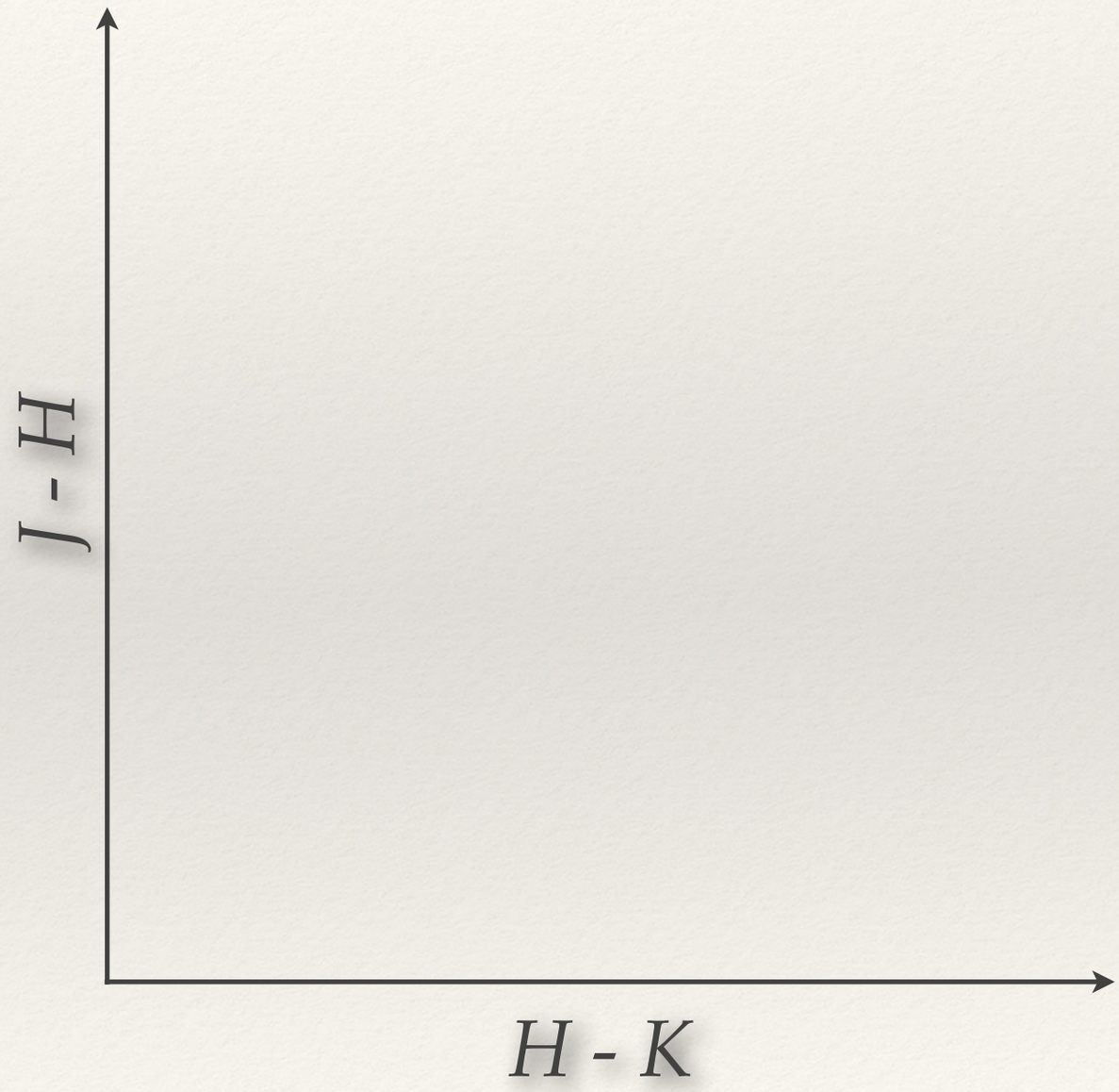
PI: Joao Alves

- ~550 sq deg in nearby molecular clouds
- YSOs identification, characterization, proper motion
- IMF, CMF, cluster formation, wide binaries
- Resolved KS relation (down to 0.1 pc)
- 3D structure, shape, and orientation of clouds (Gaia)
- Dust properties, jets,

http://visions.univie.ac.at

The NICER technique

- Un-reddened stars occupy a small region in the color-color plane
- Reddened stars are shifted in this plane
- Best extinction estimate obtained from colors and errors of each star
- Need for a **control field** with negligible extinction for calibration



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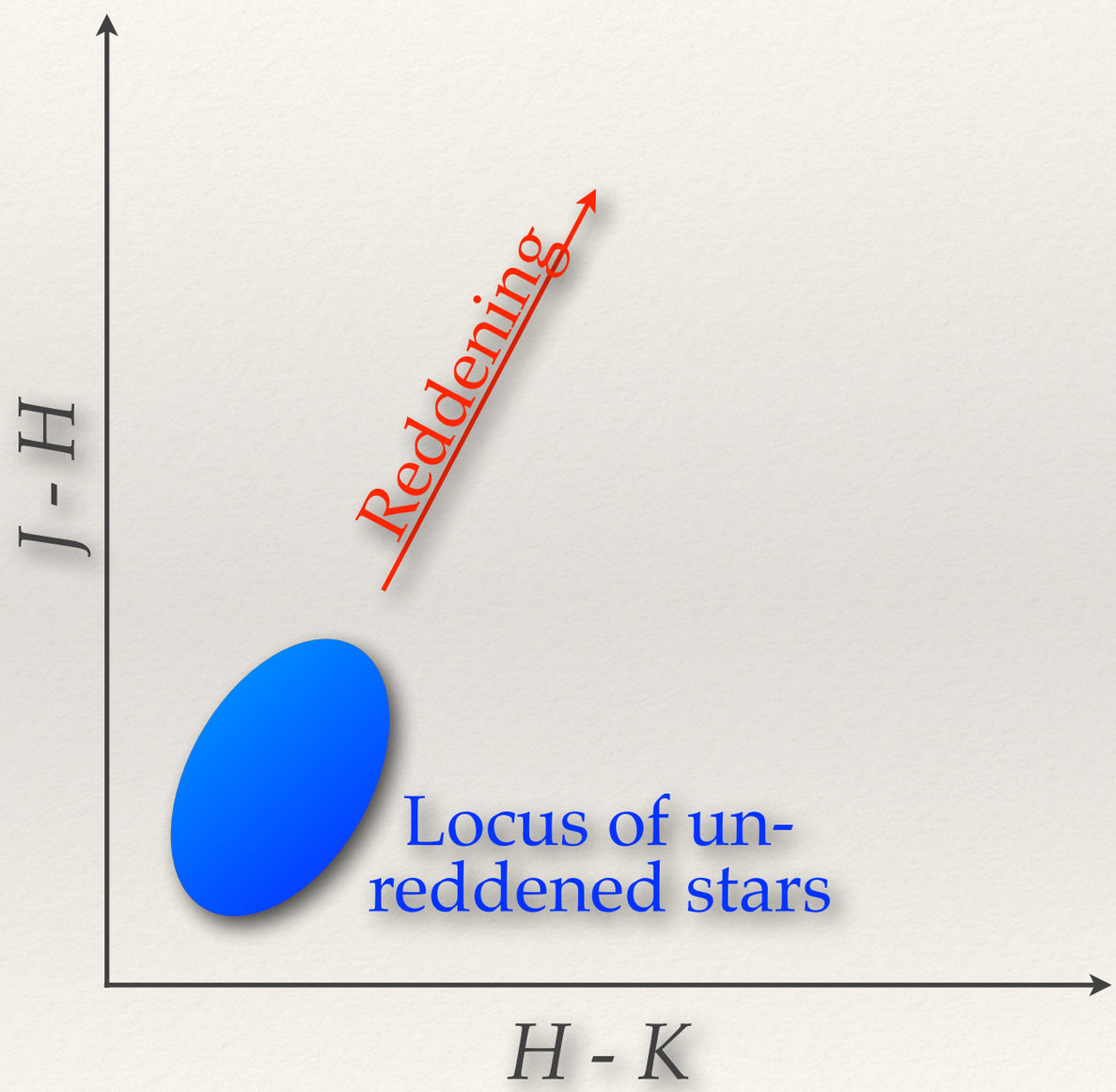

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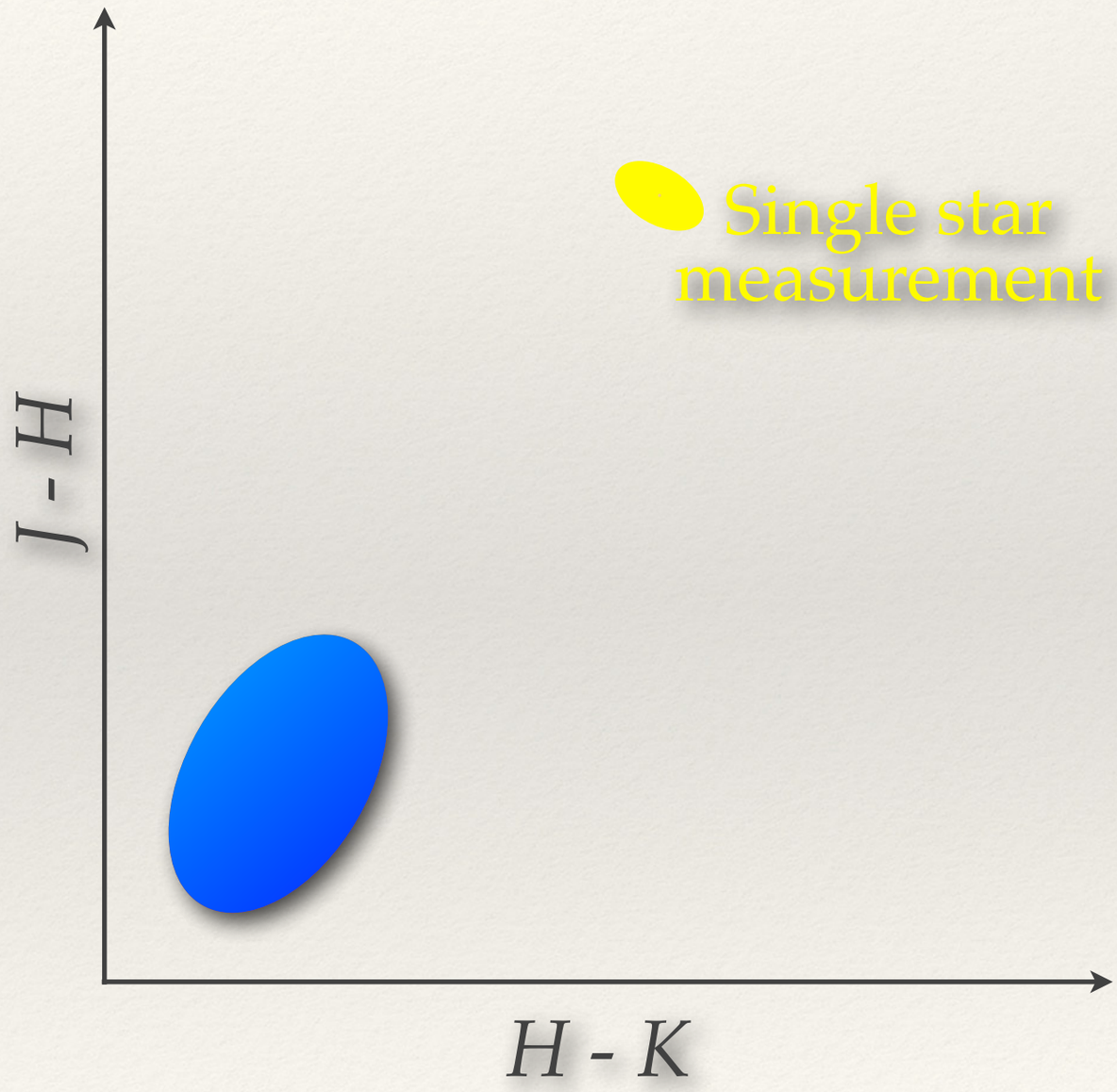

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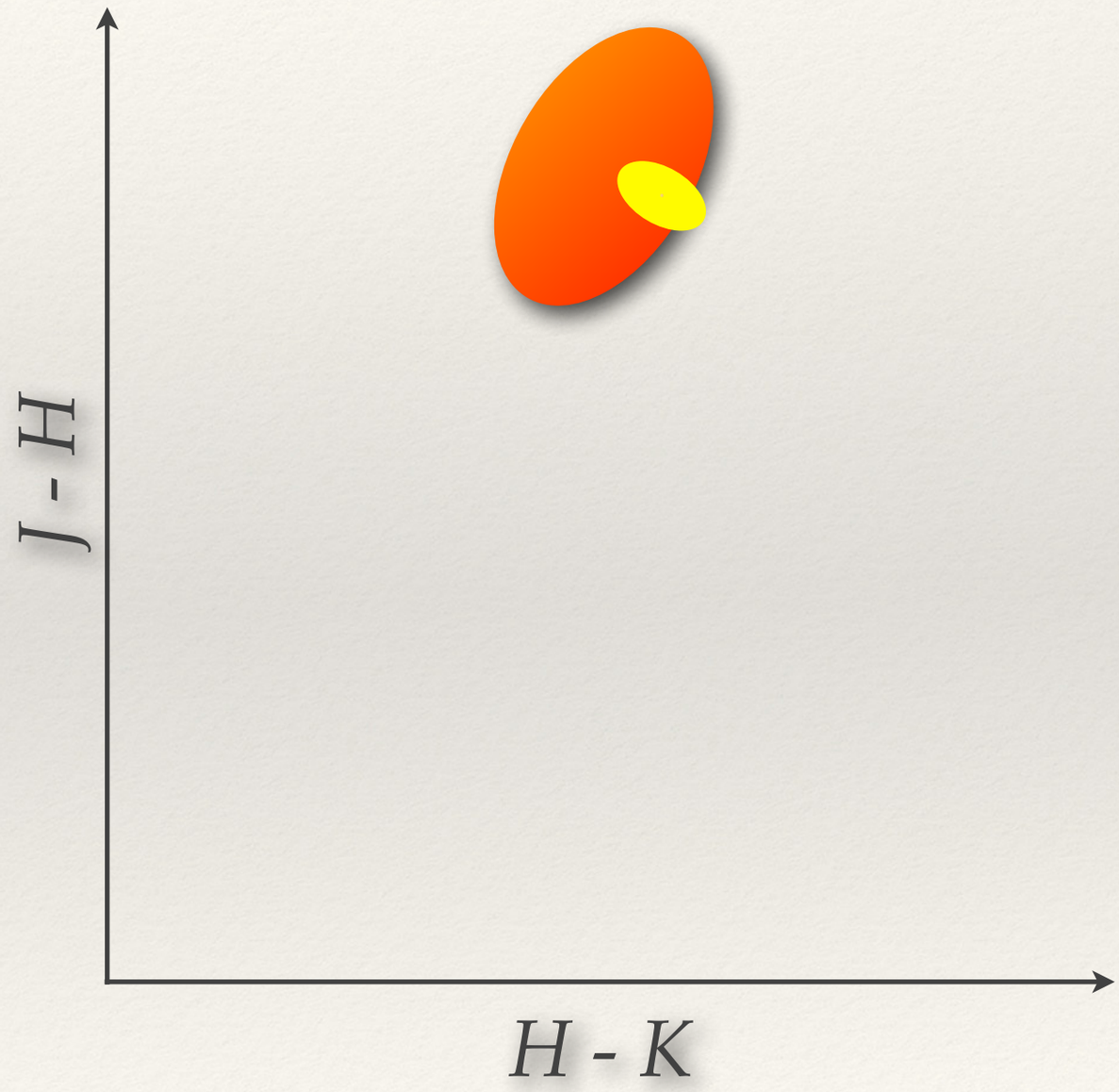

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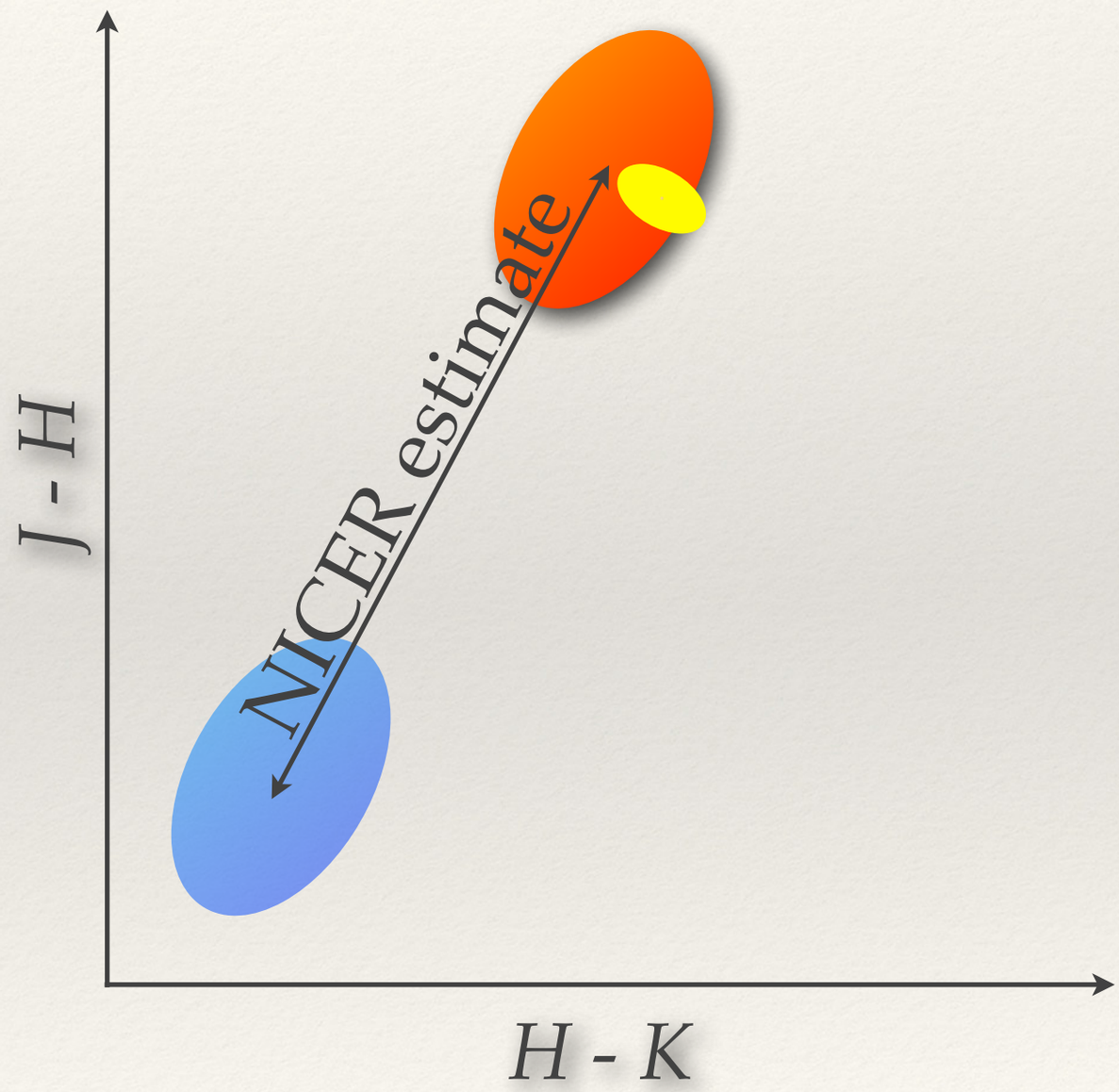
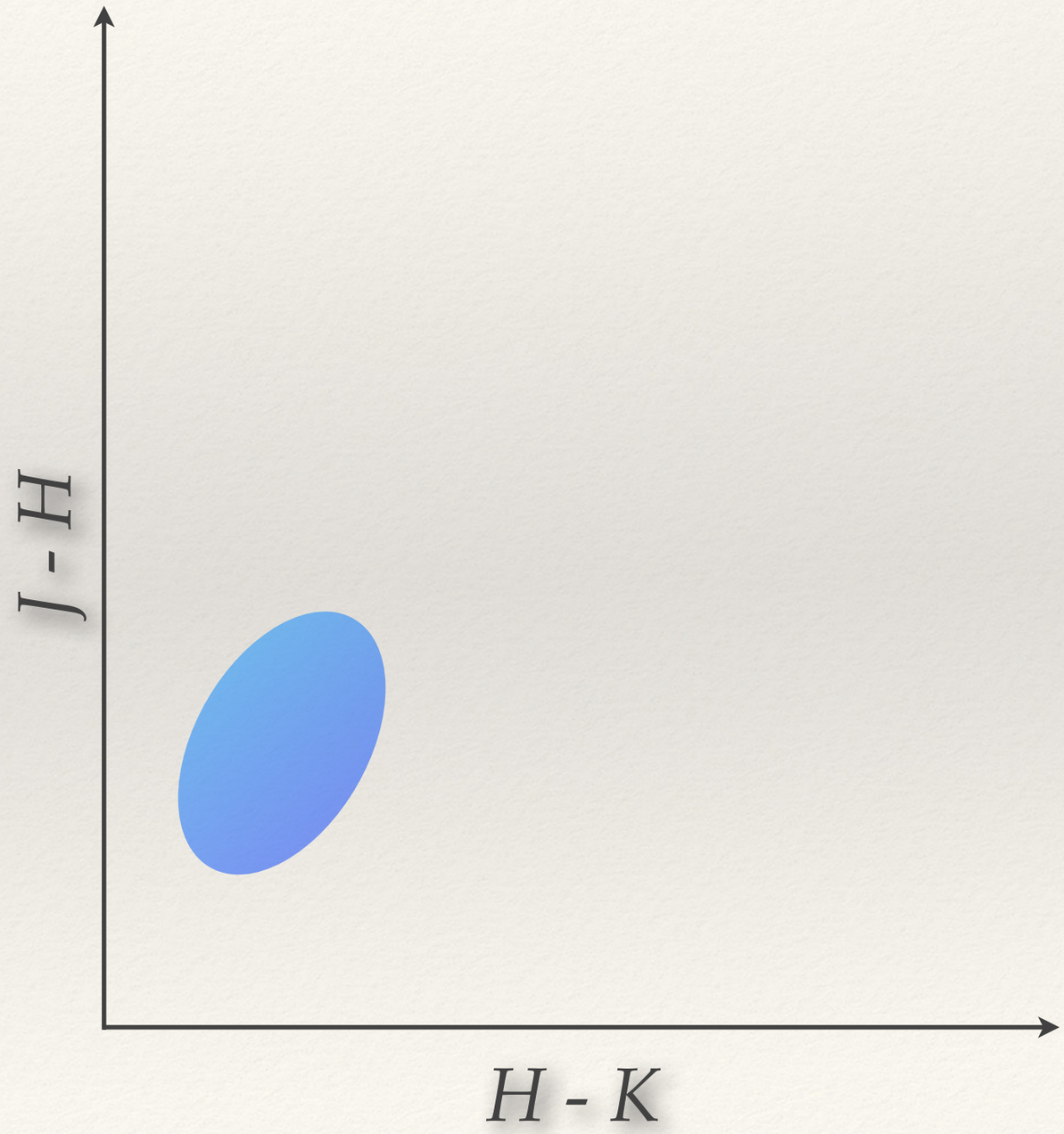


Extinction with deep data



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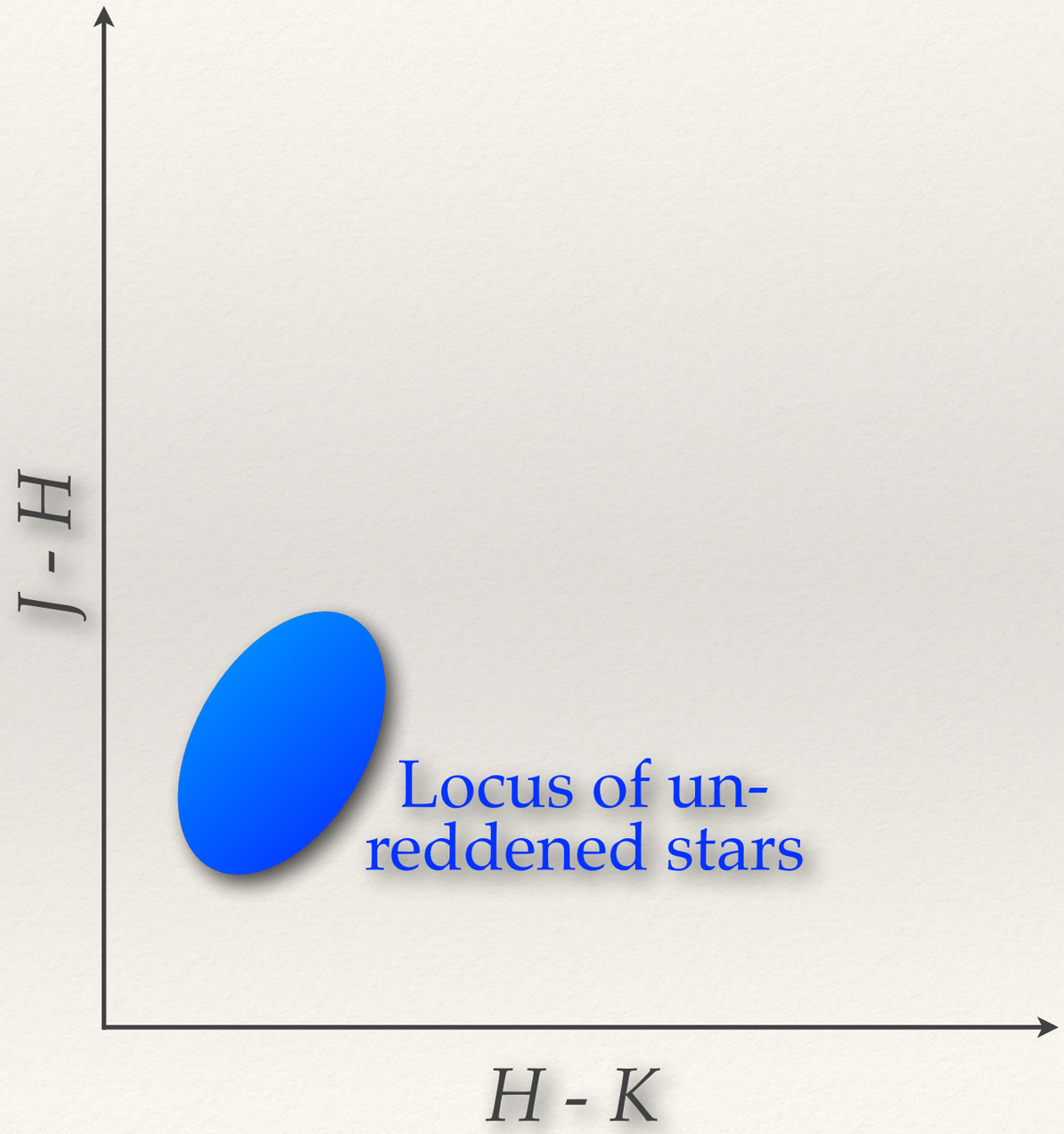

Extinction with deep data

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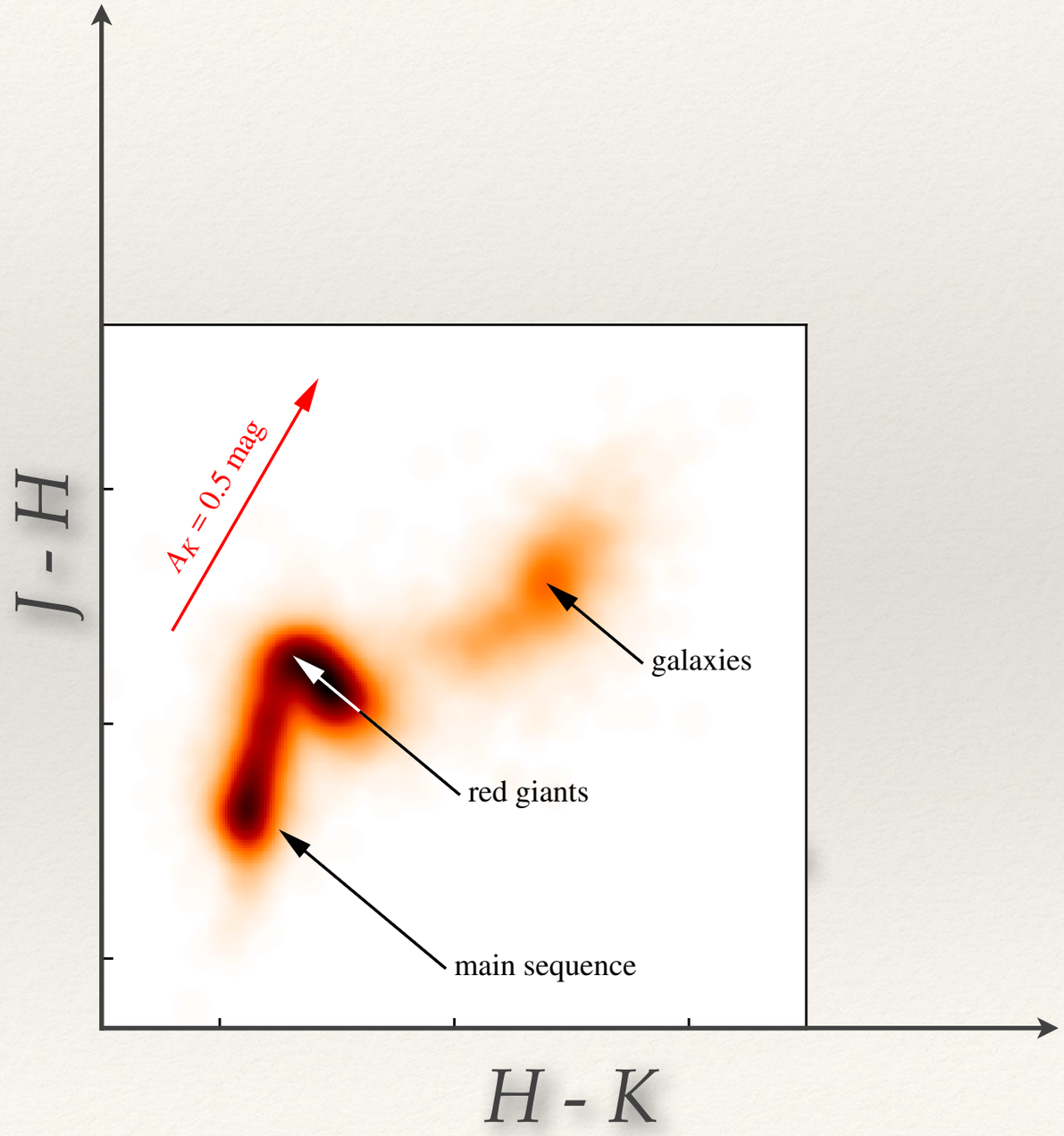

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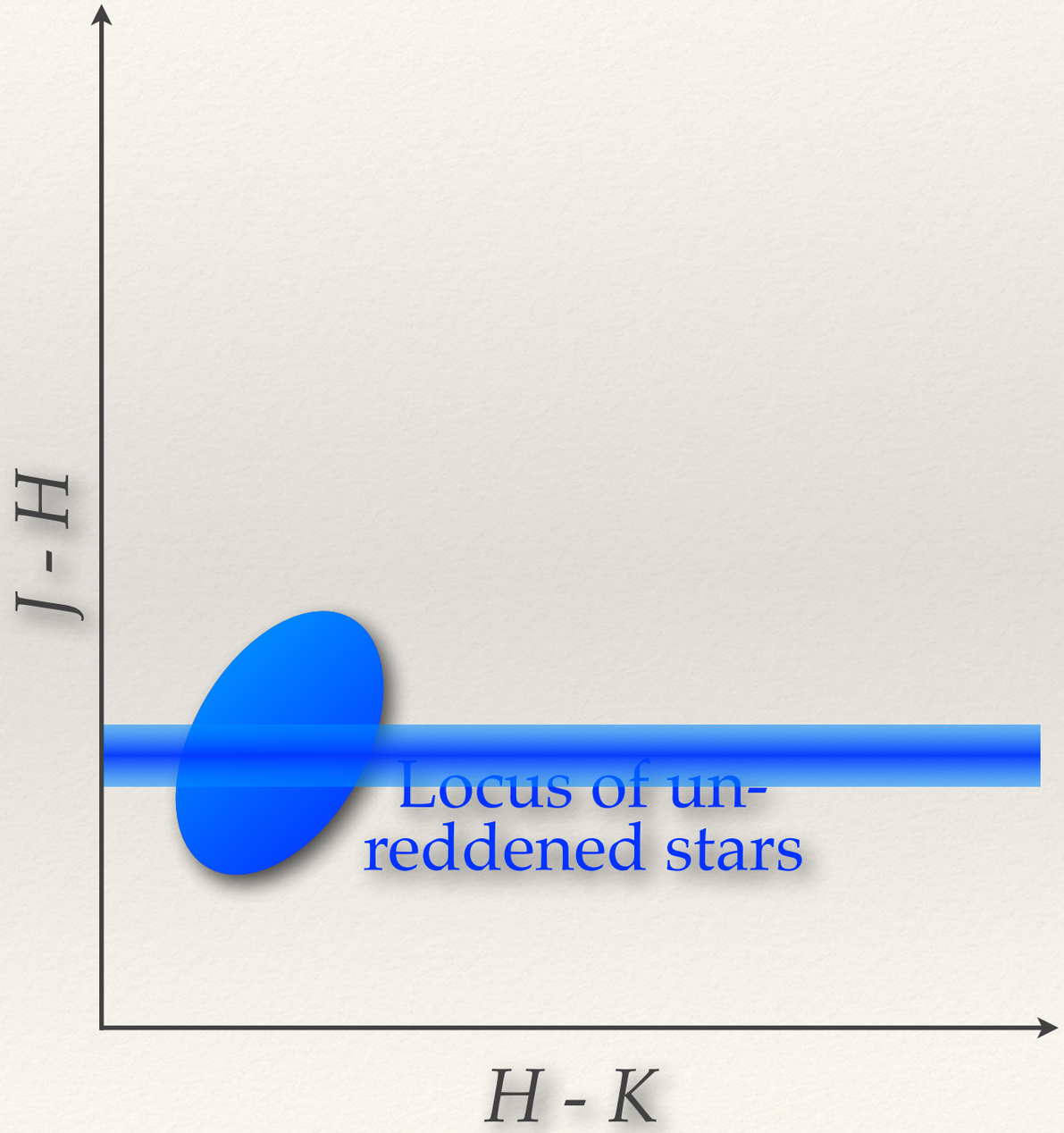

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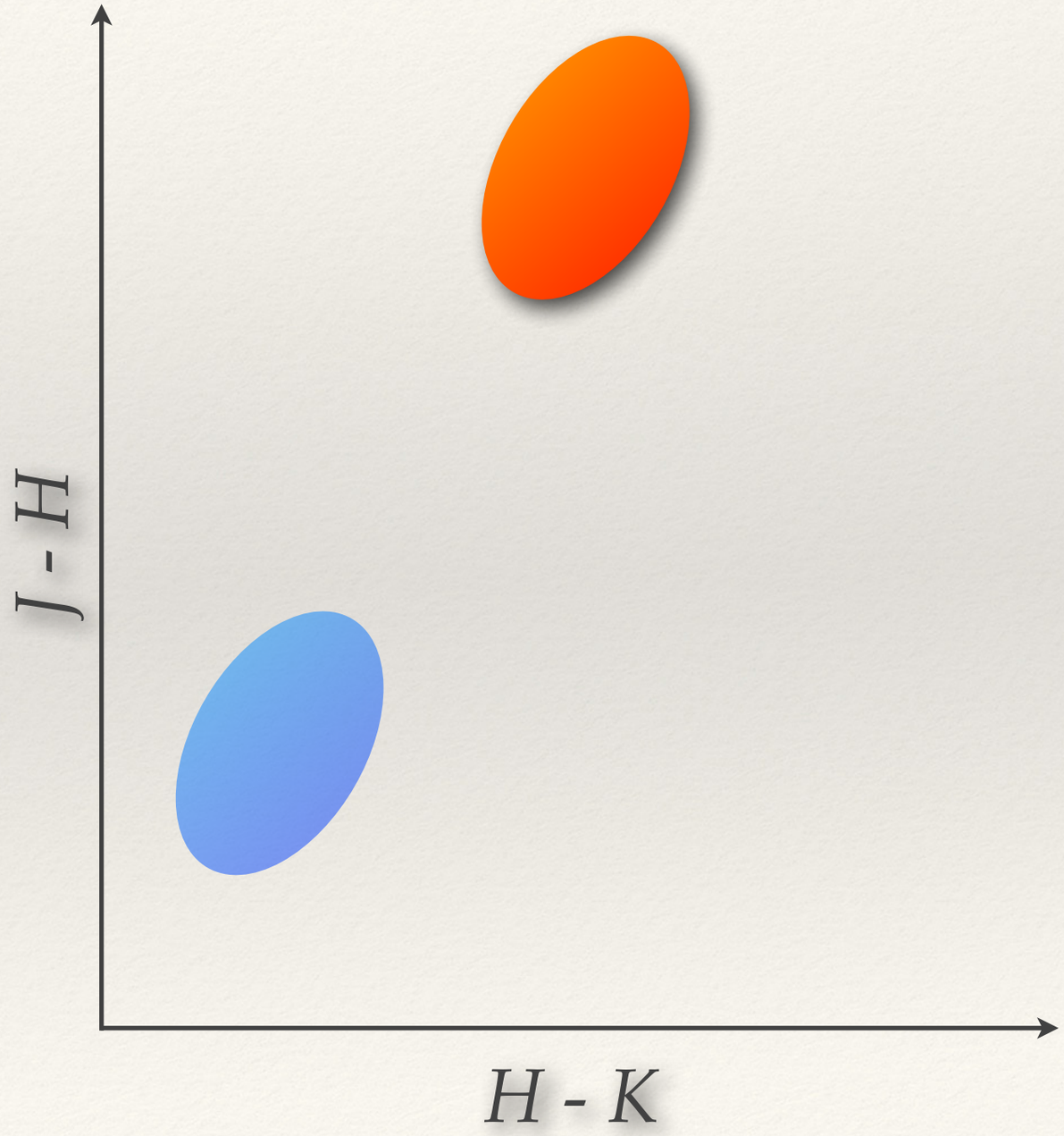

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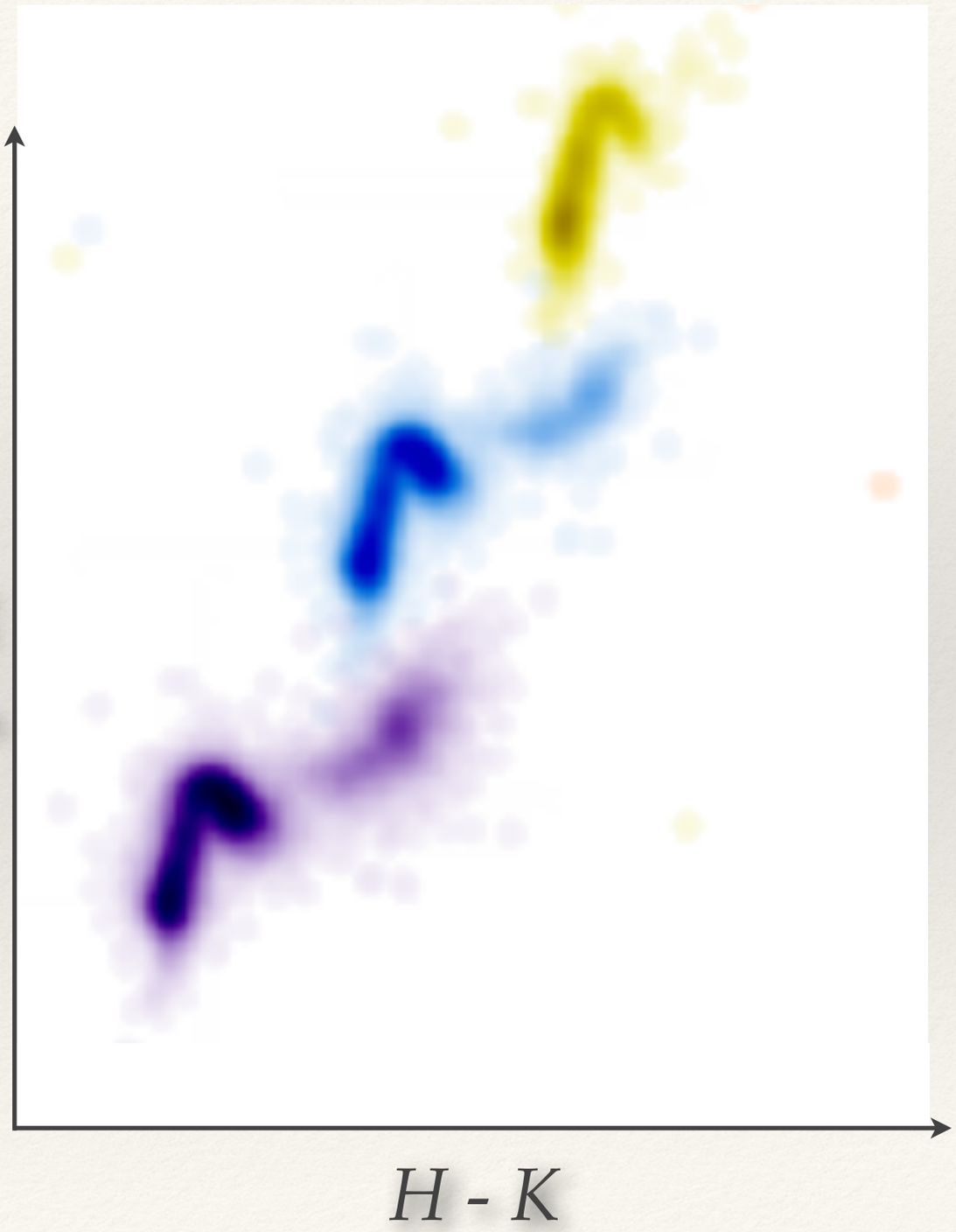

XNICER

(Lombardi 2018)

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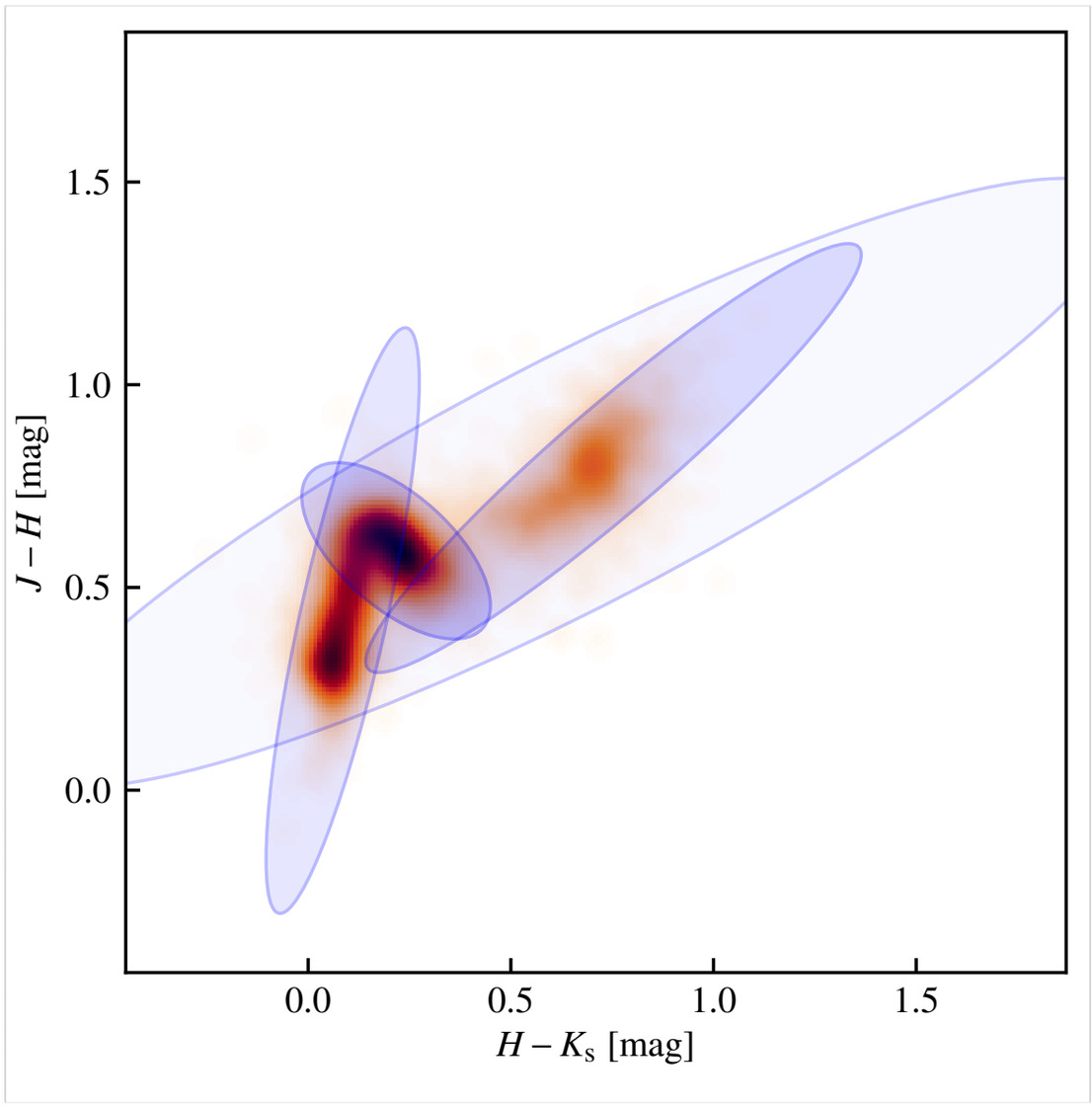

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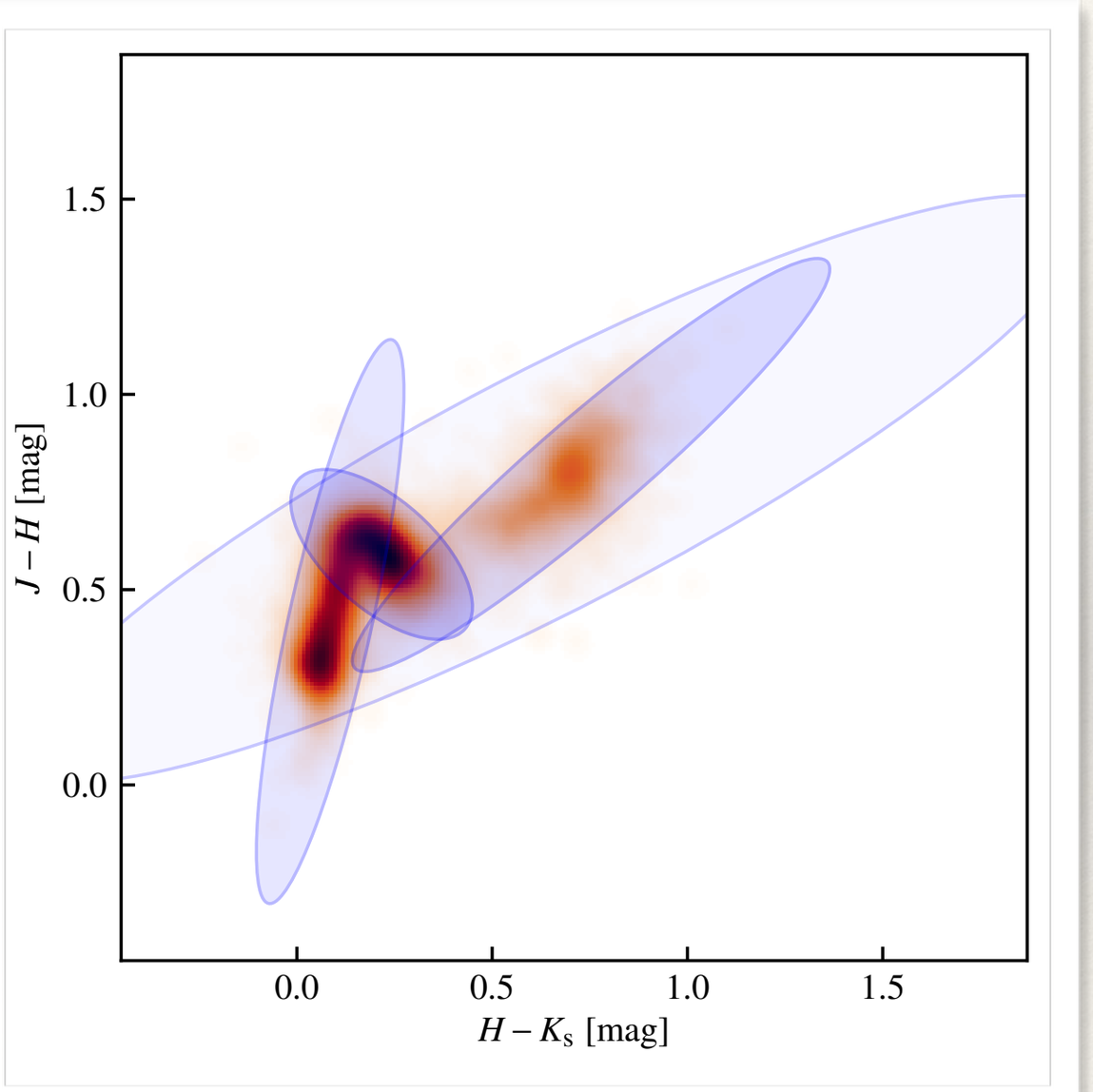

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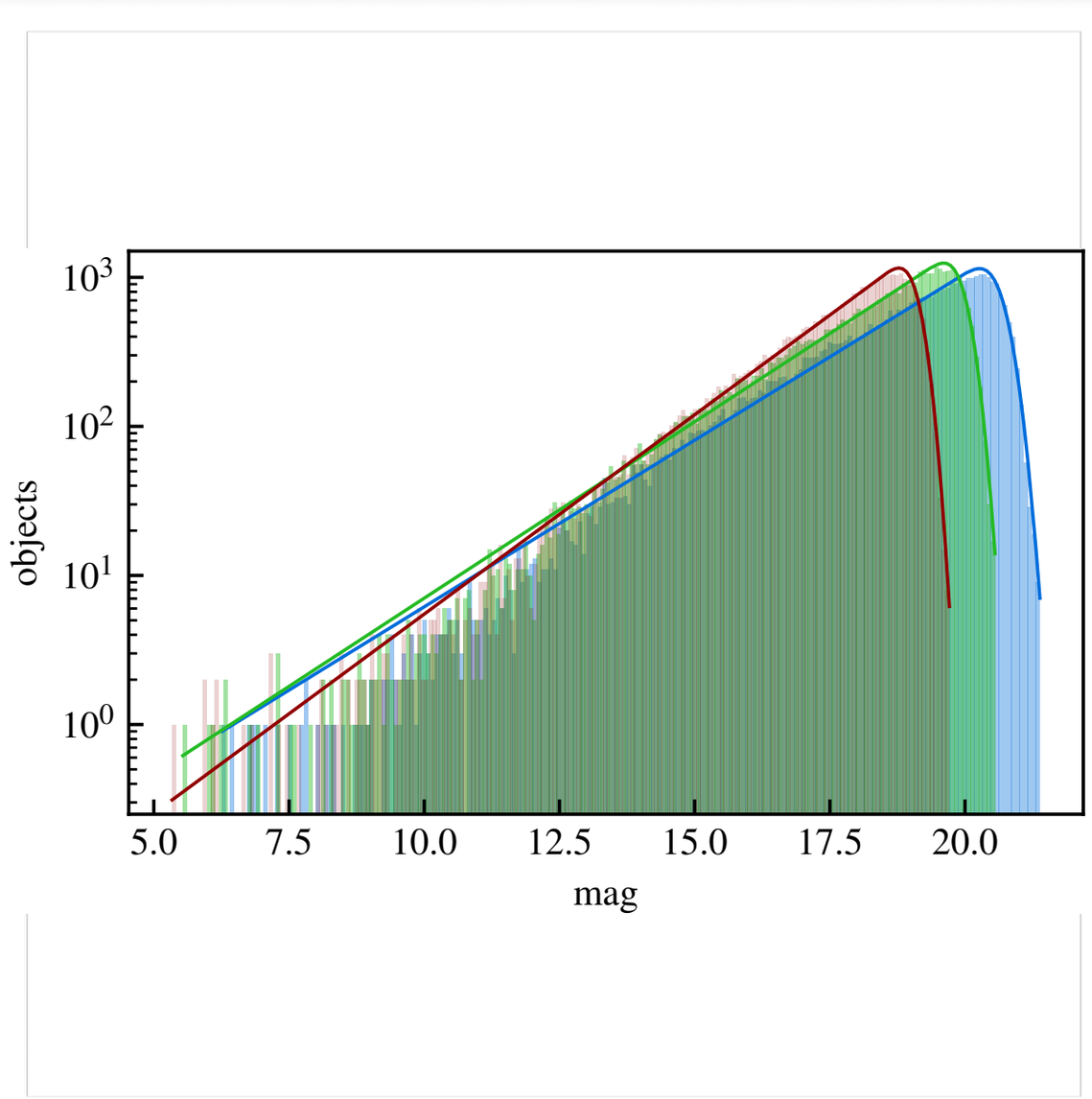

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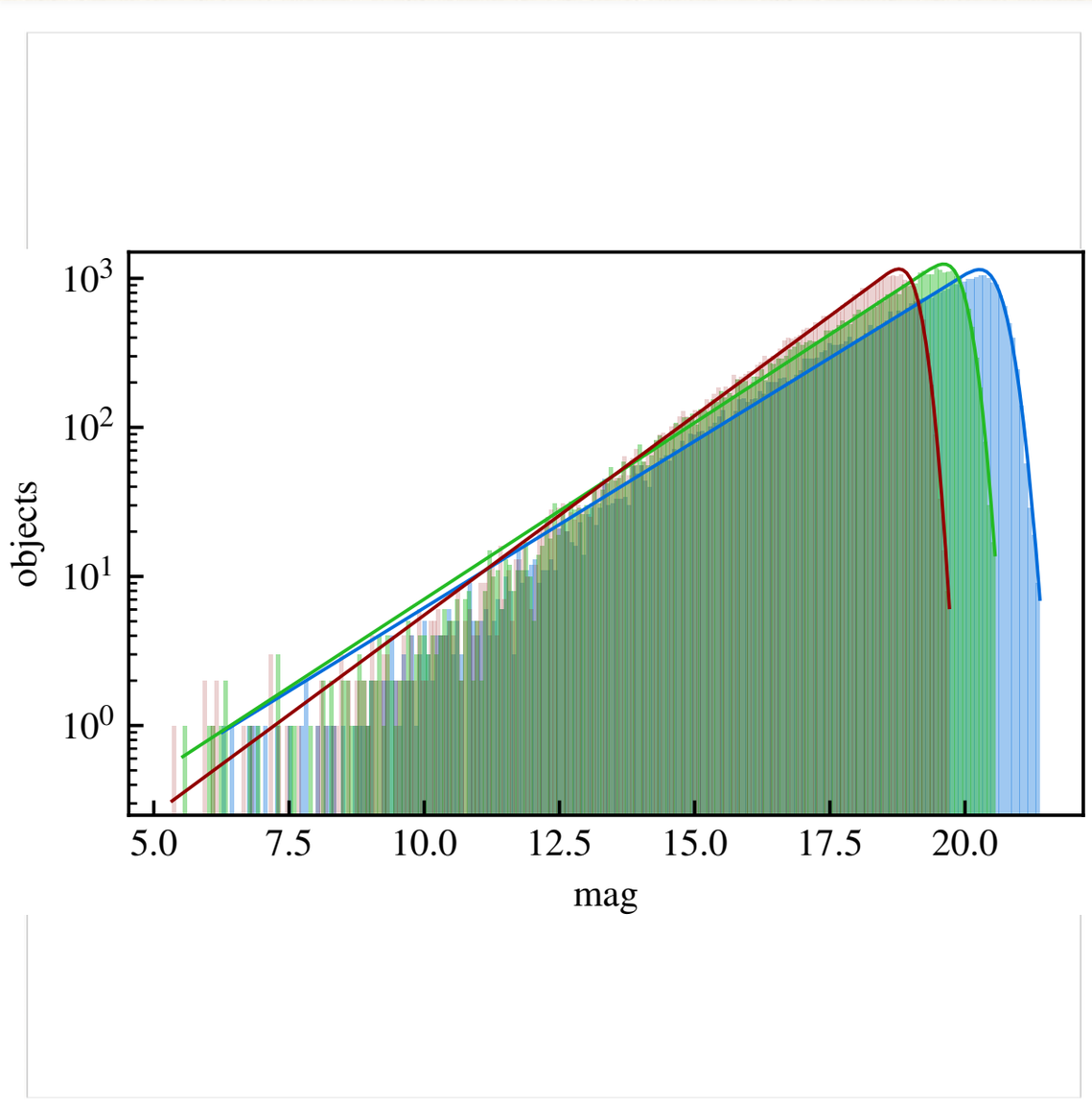
- Big **noise improvement** wrt NICER on VISION (~50% noise reduction)



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- Python code freely available: `github.com/astrozot/xnicer`

```
741                 raise ValueError(
742                     'Selection must be a one-dimensional array')
743             if selection.shape[0] != n_objs:
744                 raise ValueError(
745                     "Color and selection must have the same number of objects")
746         if projections is not None:
747             if projections.ndim != 3:
748                 raise ValueError(
749                     'Projections must be a three-dimensional array')
750             if projections.shape[0] != n_objs:
751                 raise ValueError(
752                     "Color and projections must have the same number of objects")
753             if projections.shape[1] != n_cols or projections.shape[2] != n_cols:
754                 raise ValueError(
755                     "Wrong shape for the projection matrix")
756         if log_probs is not None:
757             if log_probs.ndim != 1:
758                 raise ValueError(
759                     'Log probabilities must be a one-dimensional array')
760             if log_probs.shape[0] != n_objs:
761                 raise ValueError(
762                     "Color and log-probabilities must have the same number of objects")
763         if log_class_probs is not None:
764             if log_class_probs.ndim != 2:
765                 raise ValueError(
766                     'Log probabilities for classes must be a two-dimensional array')
767             if log_class_probs.shape[0] != n_objs or \
768                 log_class_probs.shape[1] != len(class_names):
769                 raise ValueError(
770                     'Wrong size of log-probabilities for classes')
771         elif class_names is not None:
772             raise ValueError('If class names are provided, log probabilities '
773                 'for classes must be provided too')
774         # Saves the results
775         self.n_objs = n_objs
776         self.n_cols = n_cols
777         self.cols = cols
778         self.col_covs = col_covs
779         if selection is not None:
780             self.selection = selection
781         else:
782             self.selection = np.arange(n_objs)
```

Fact 1.
Stars form inside molecular clouds

LH 95 in LMC (ACS/HST, Dimitrios Gouliermis)

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Stars form in the densest parts of molecular clouds

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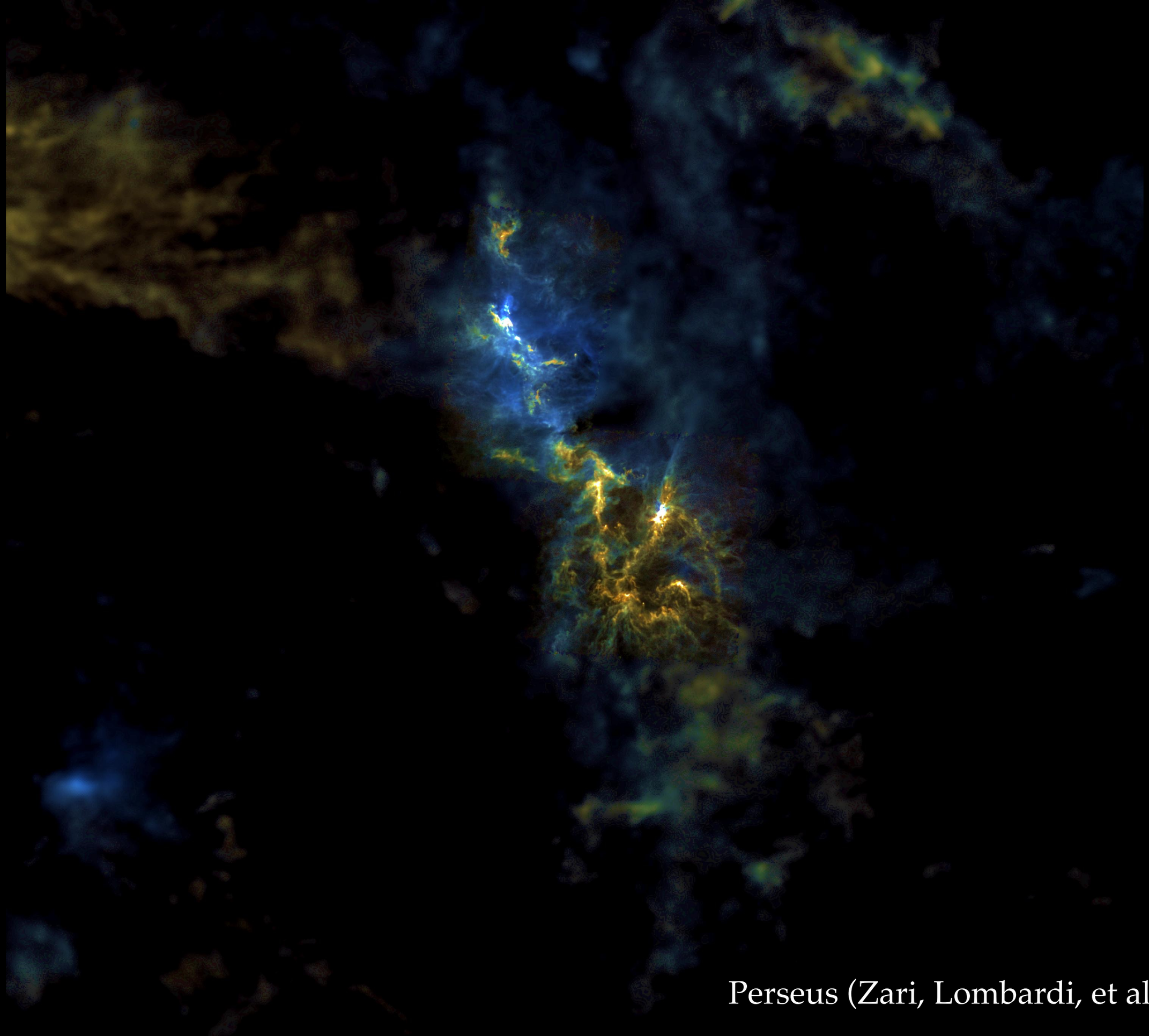
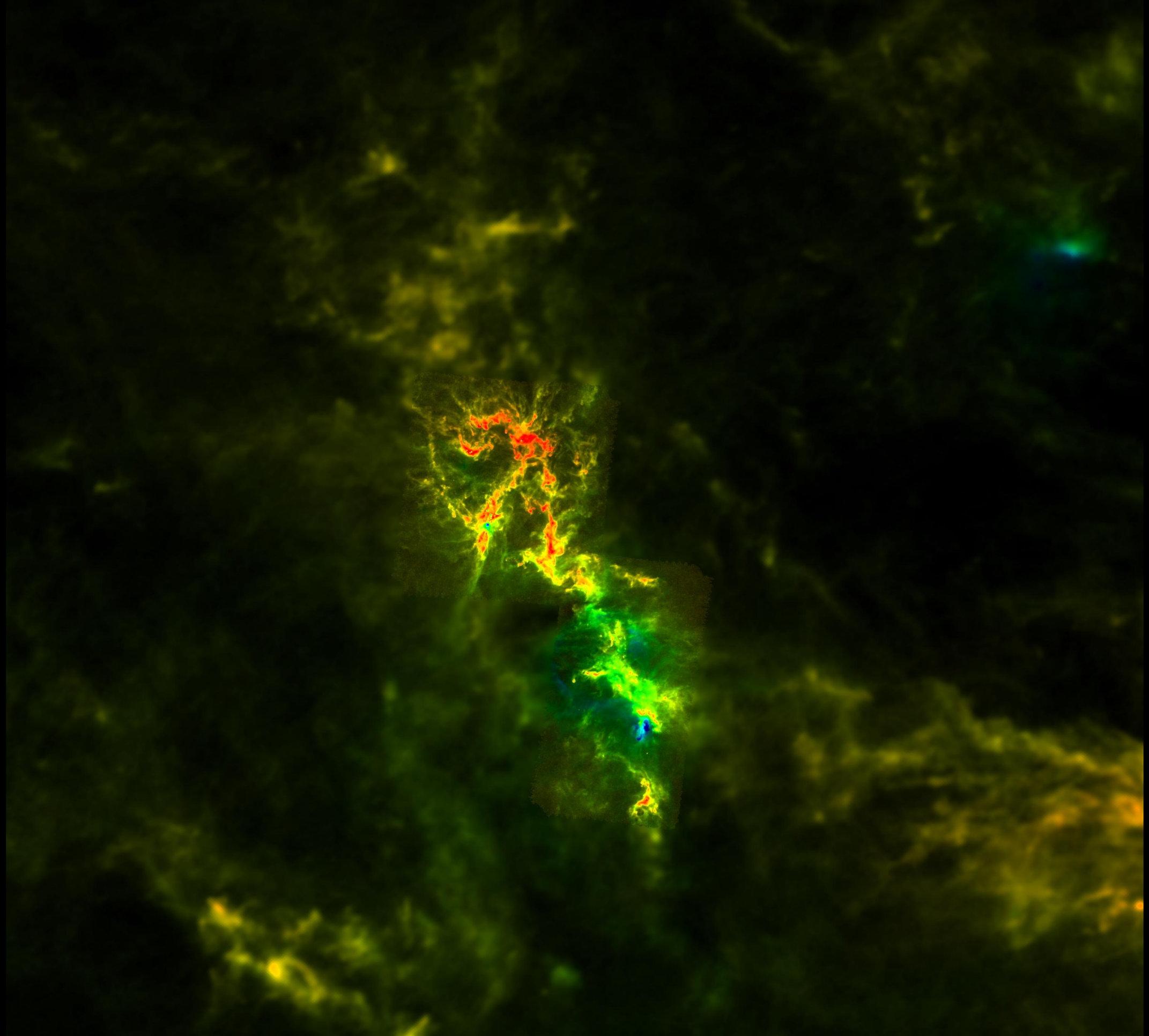
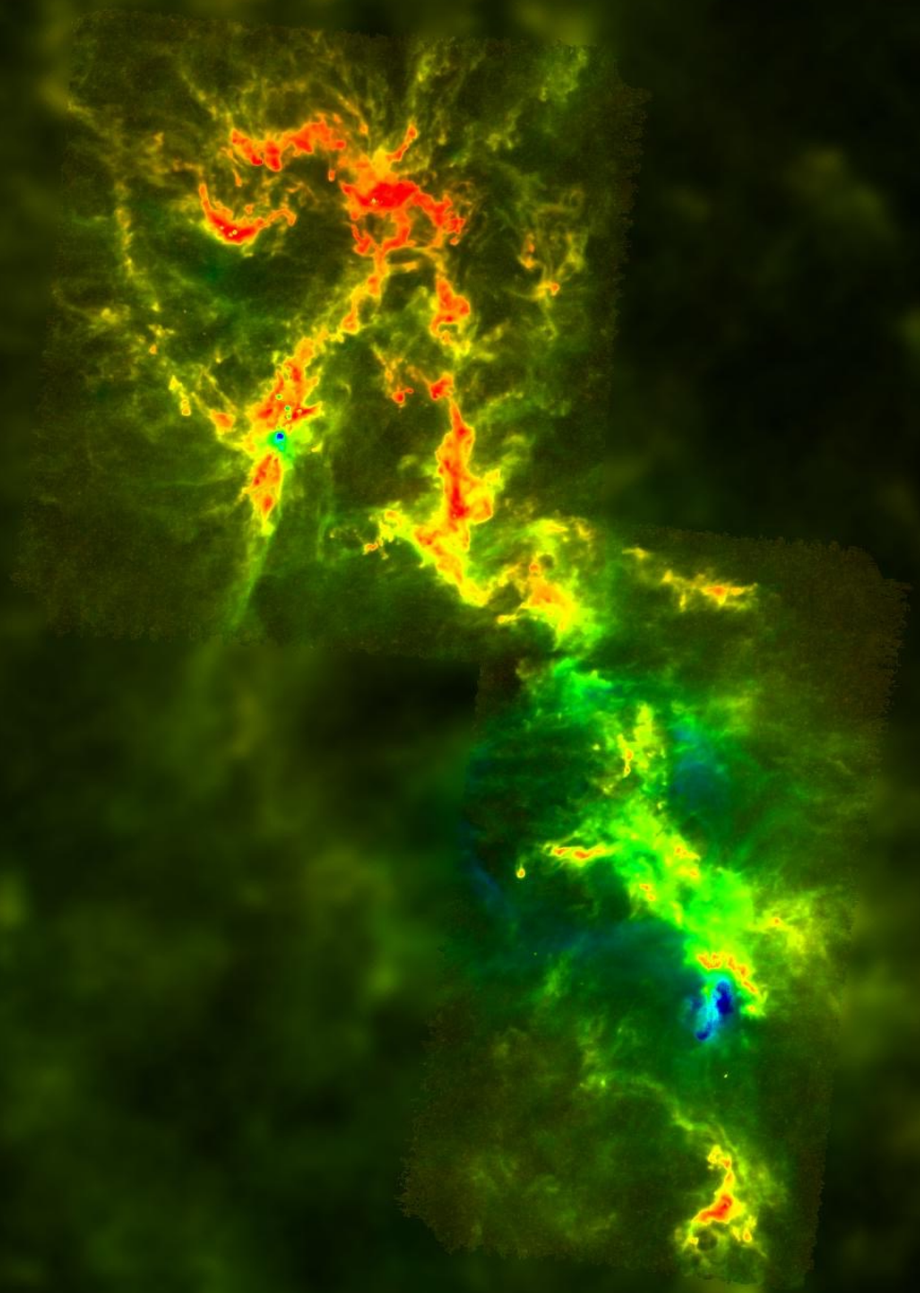
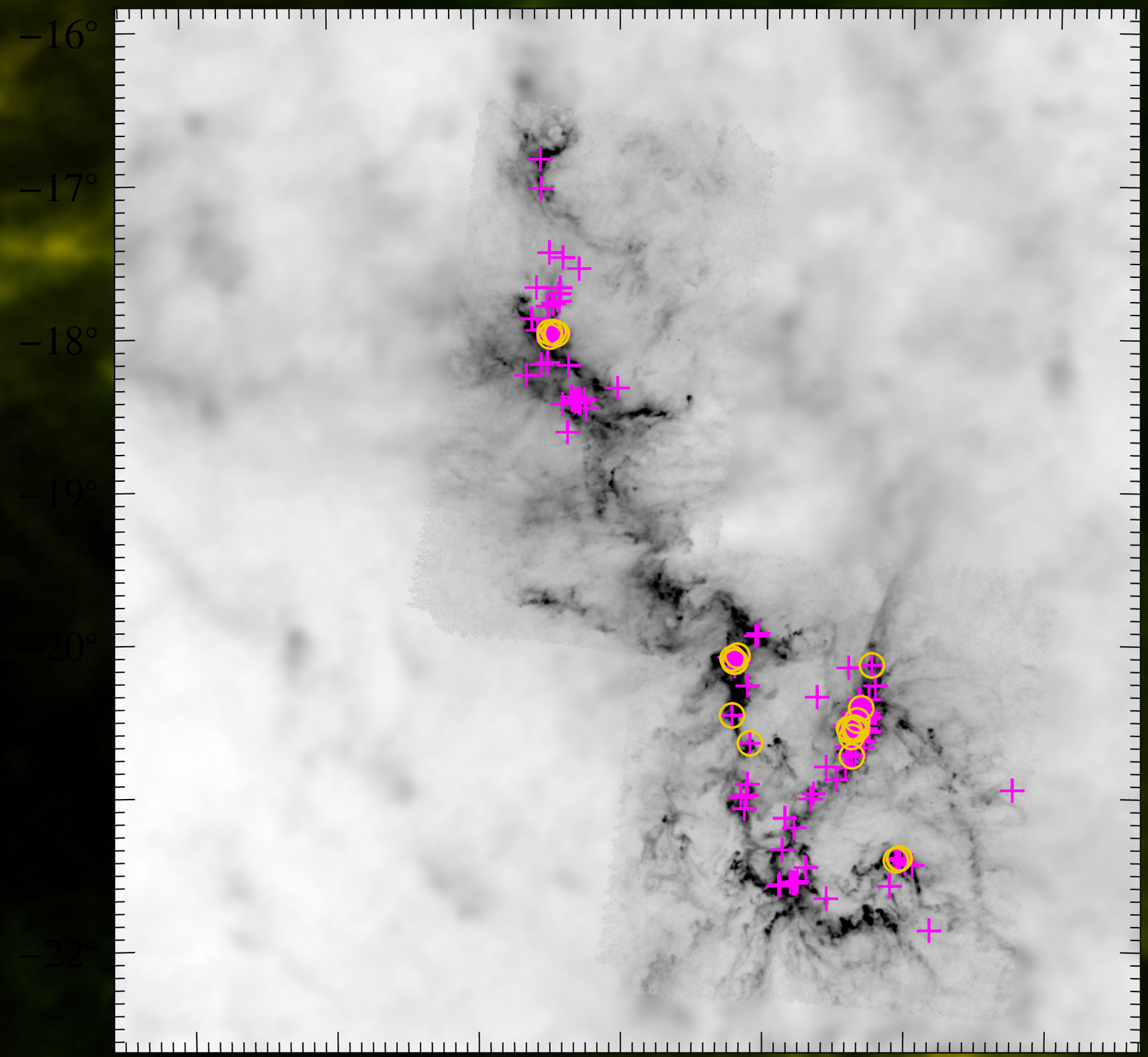


Perseus (Zari, Lombardi, et al. 2016)



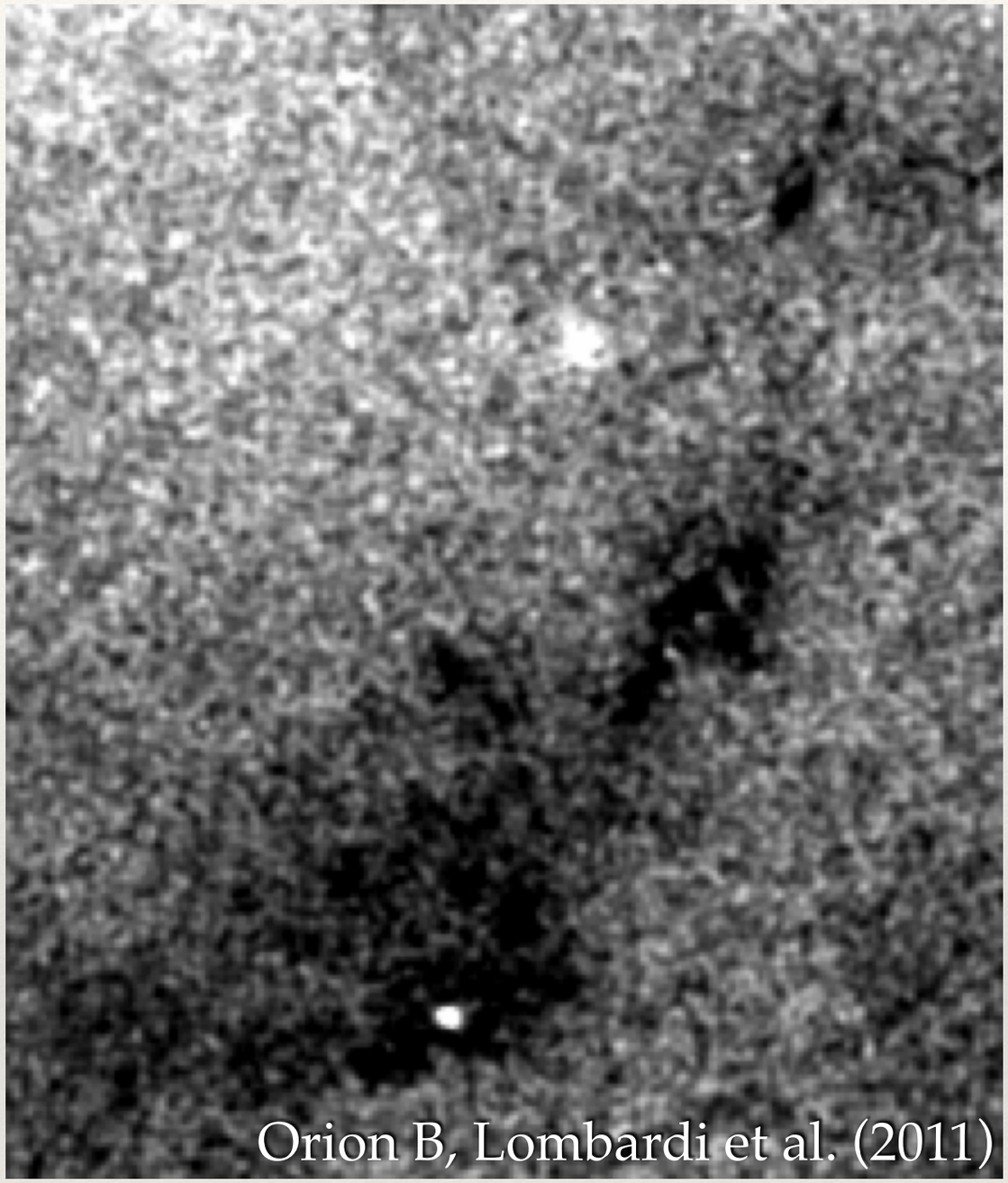



−16°
−17°
−18°
−19°
−20°
−22°
163°
162°
161°
160°
159°
158°
157°
Galactic Latitude
Galactic Longitude

Embedded clusters

- Stars form in the **densest regions** of molecular clouds…
- …mostly in **clusters** (Lada & Lada 2003)
- Early evolution of stars (infant mortality) responsible for shaping molecular clouds (e.g. Geyer & Burkert 2001)
- …which in turn are responsible for making more stars
- We need to study star formation and clusters in their early stages

2MASSS density map



Cluster identified as **star overdensities** (e.g. von Hoerner 1963, Gutermuth et al. 2009)

Often *non-trivial* for young, embedded ones

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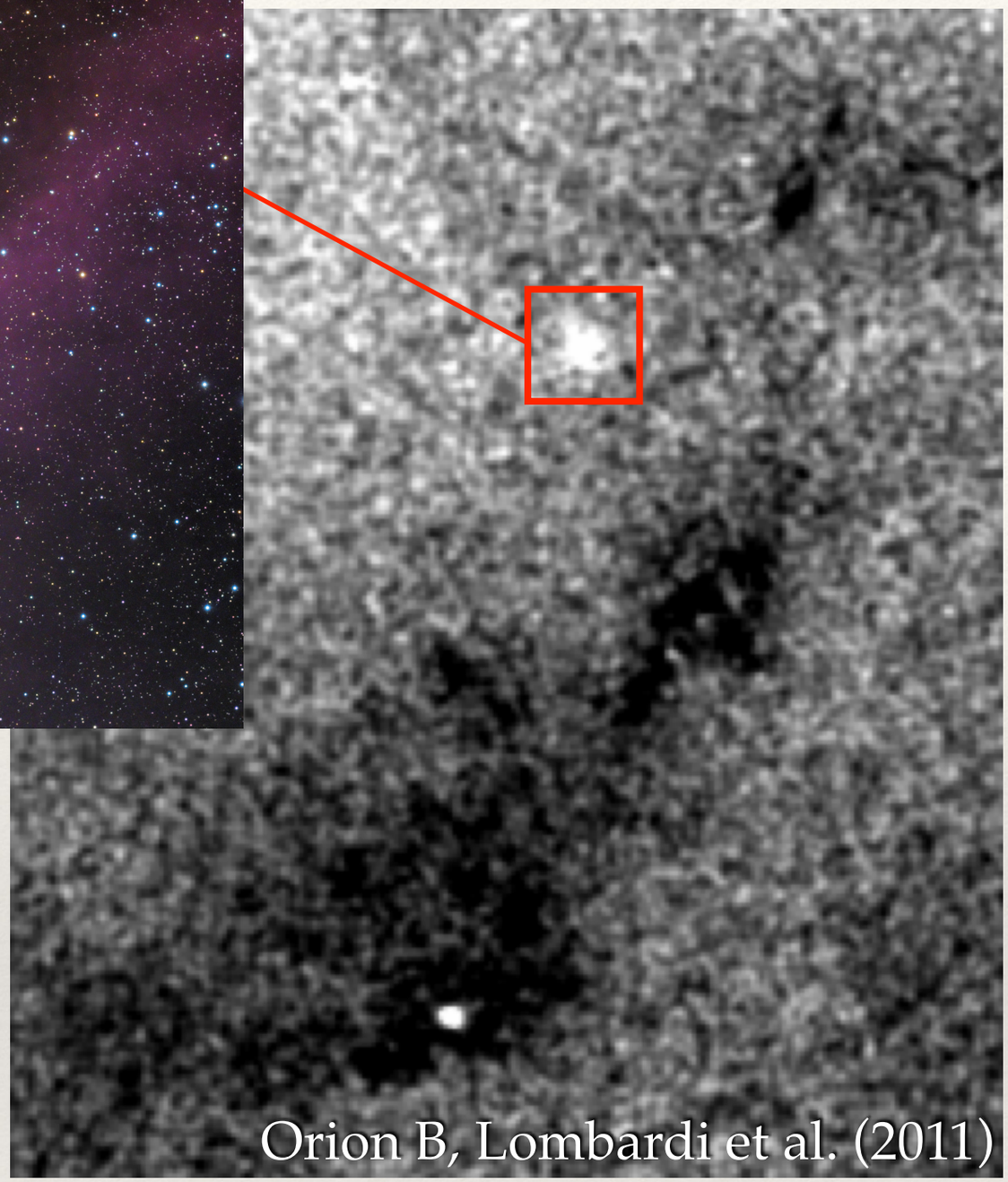

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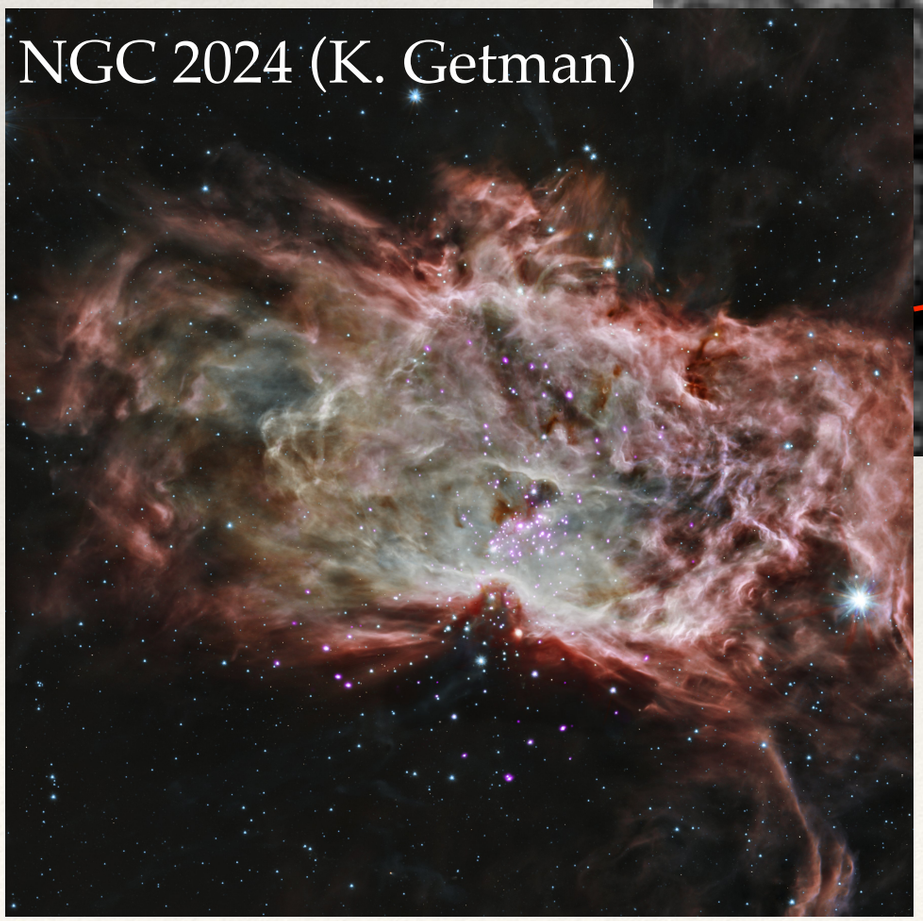

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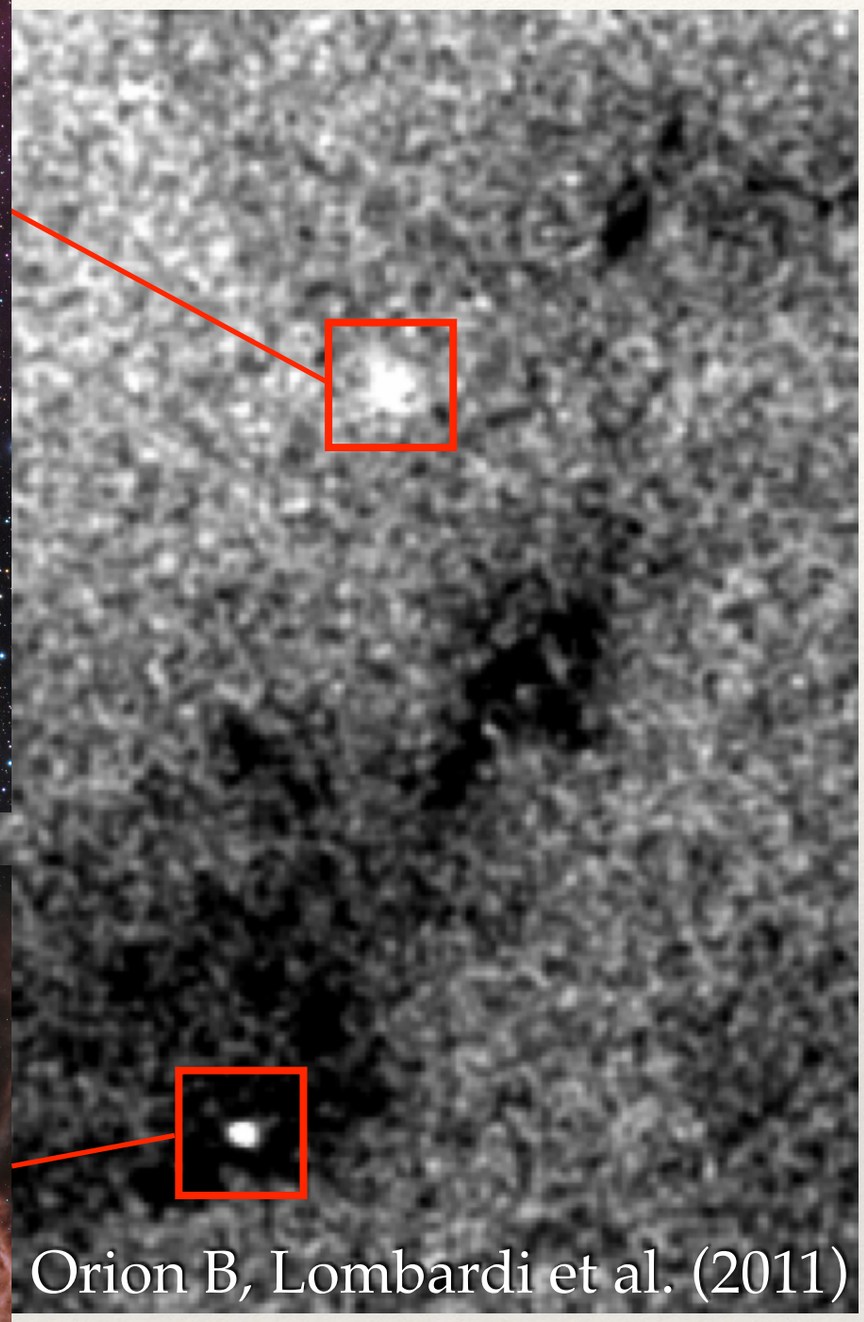

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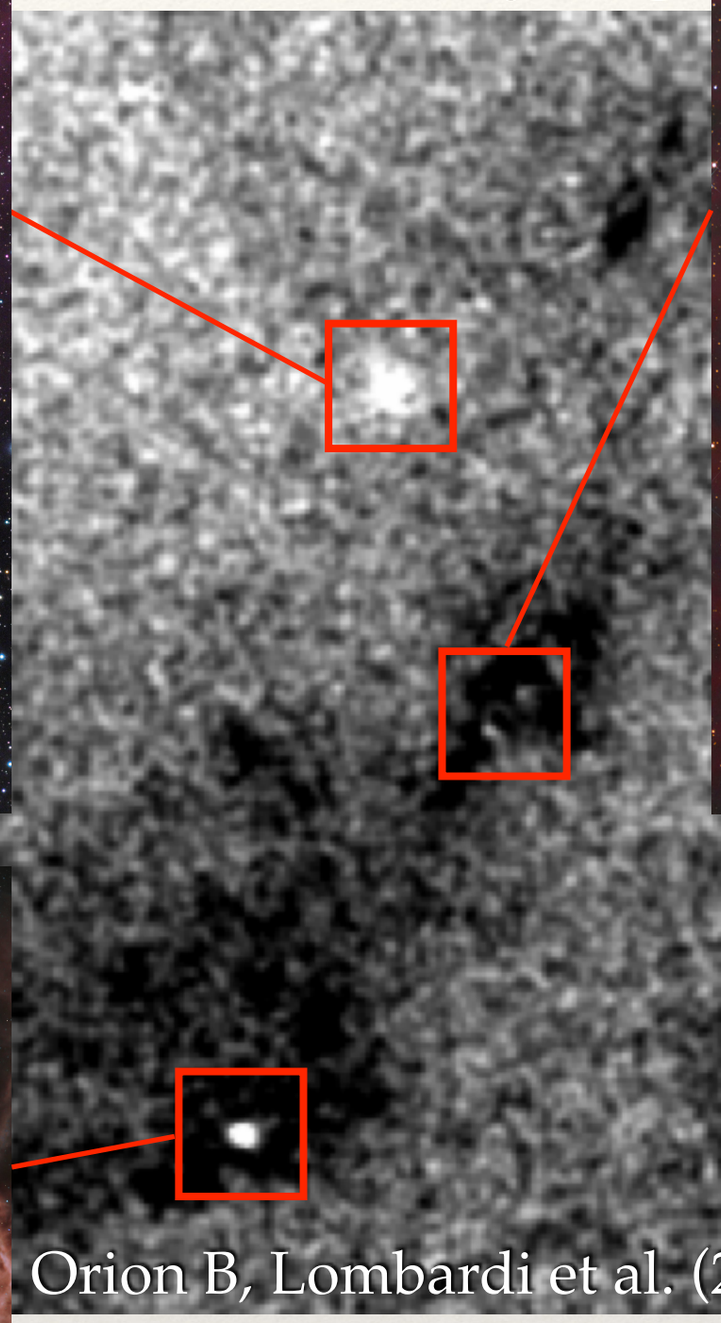

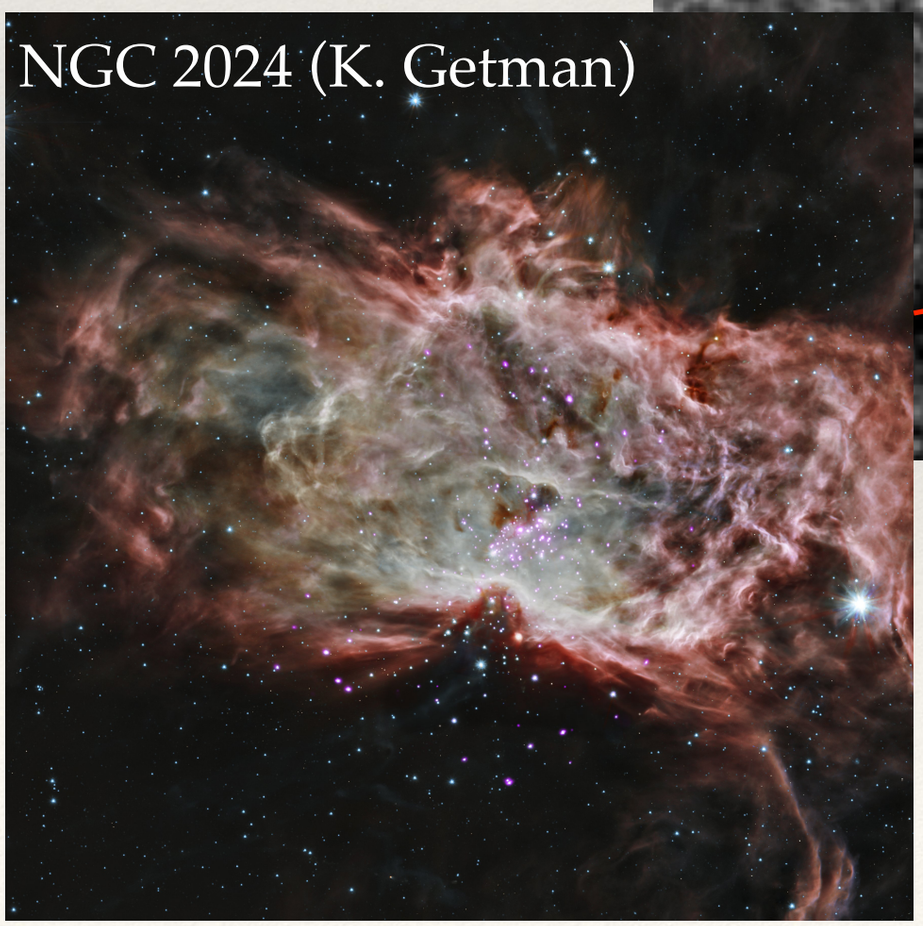

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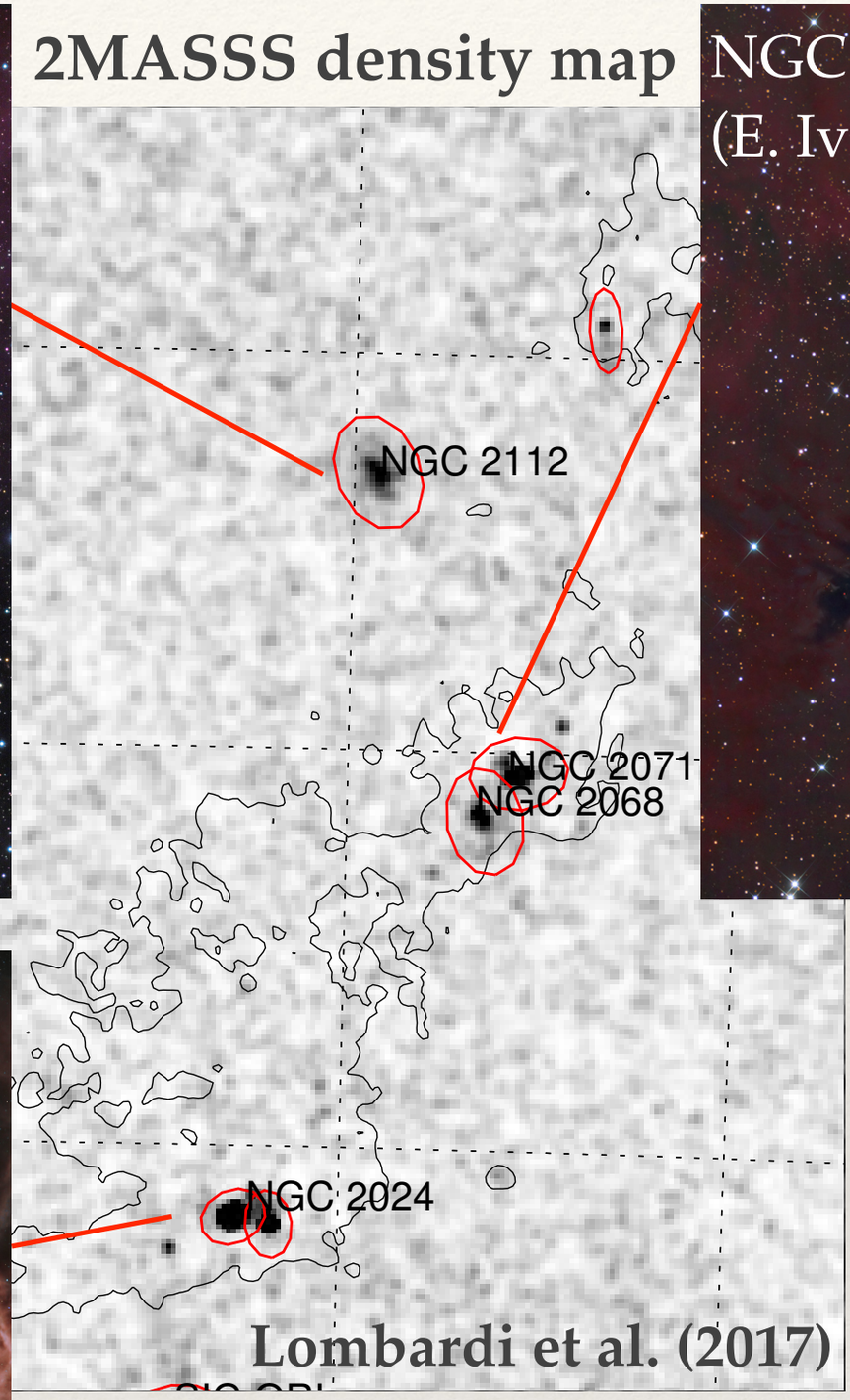

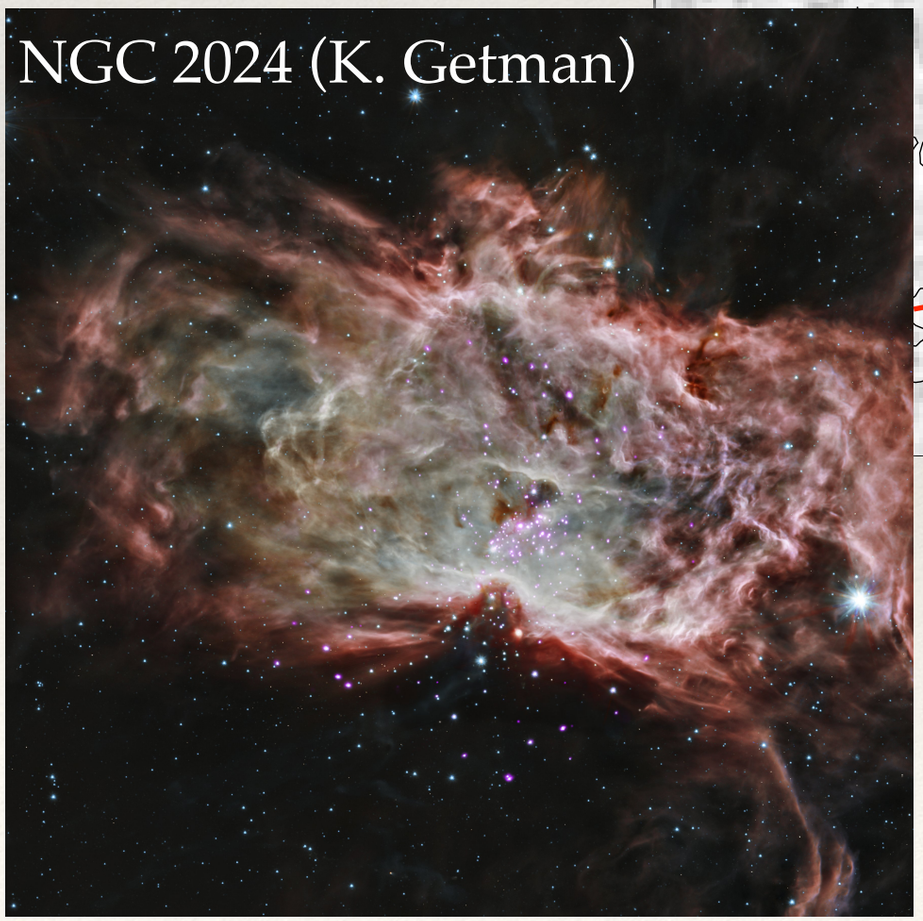

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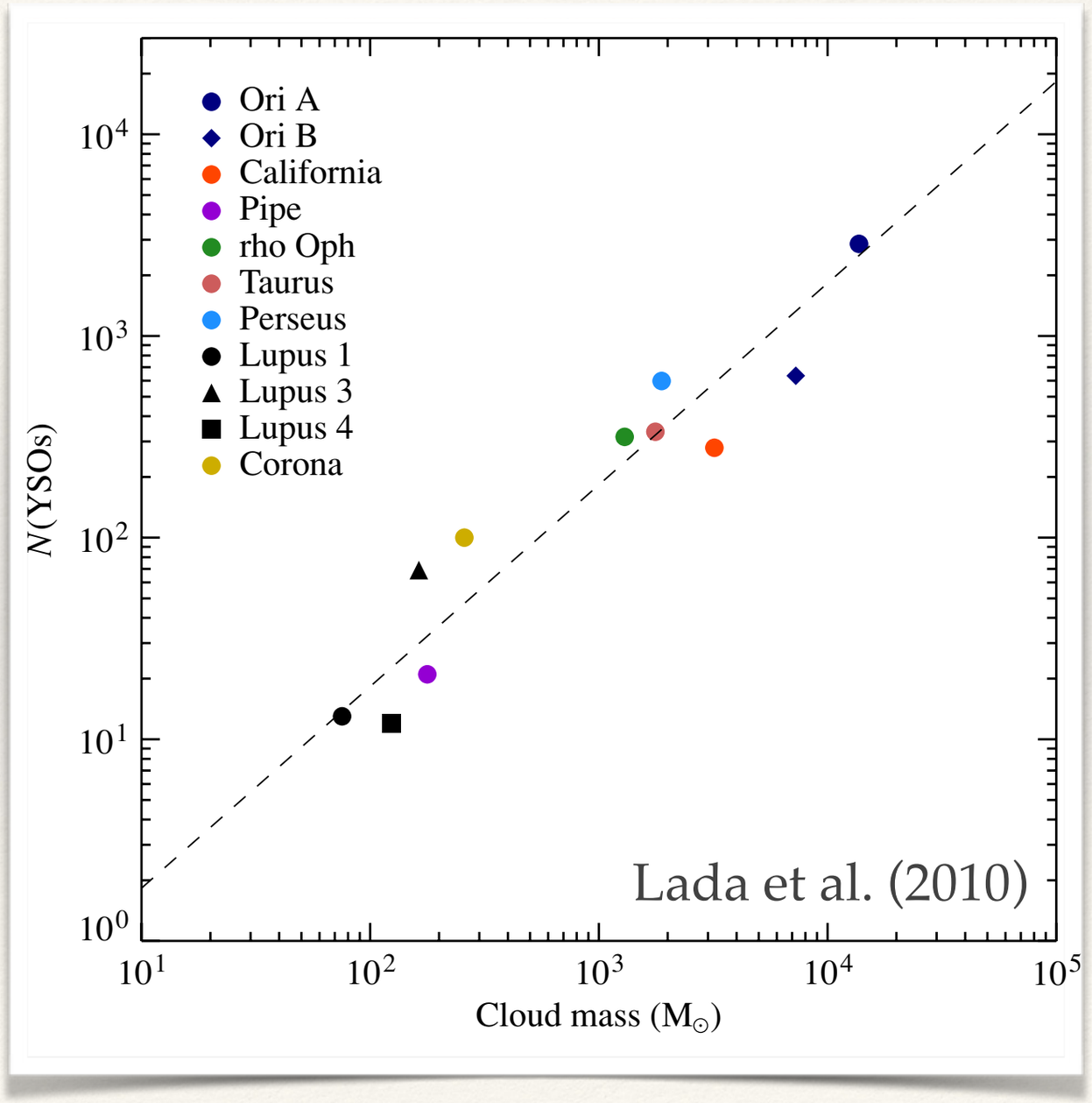
SFR best correlates with dense gas



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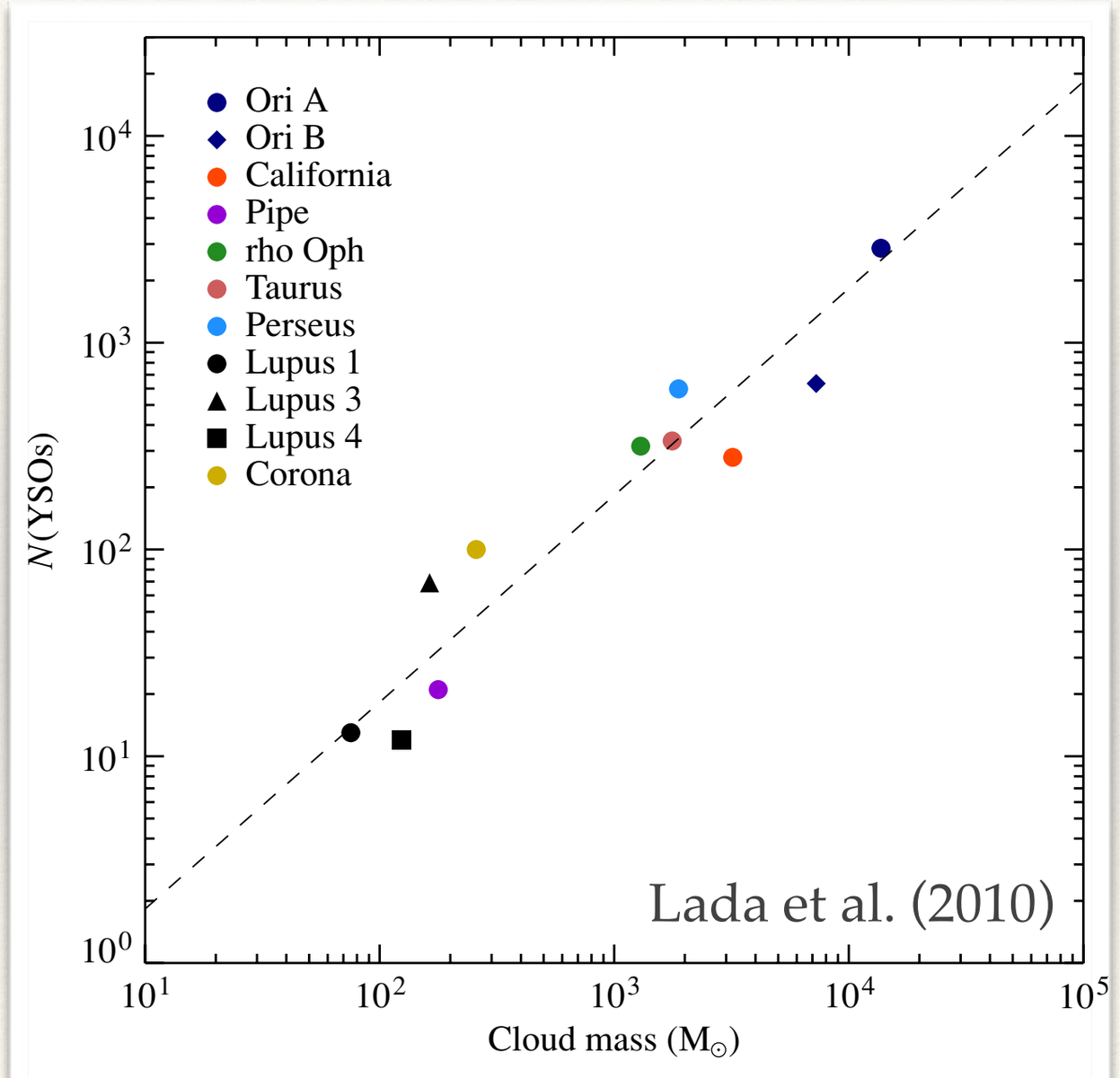
- YSOs form at high ($A_K > 0.8$ mag) column density (presumably high densities)



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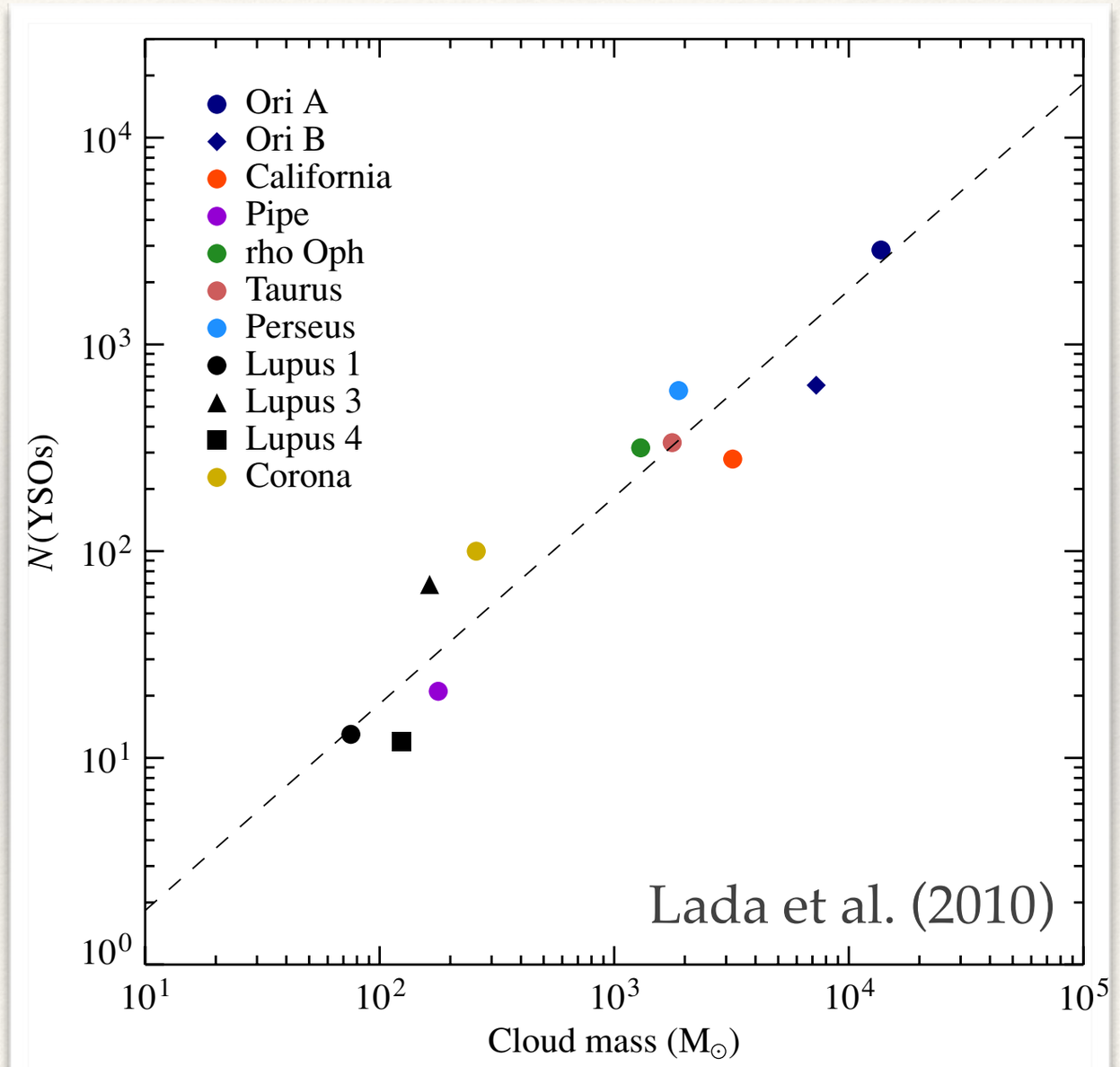

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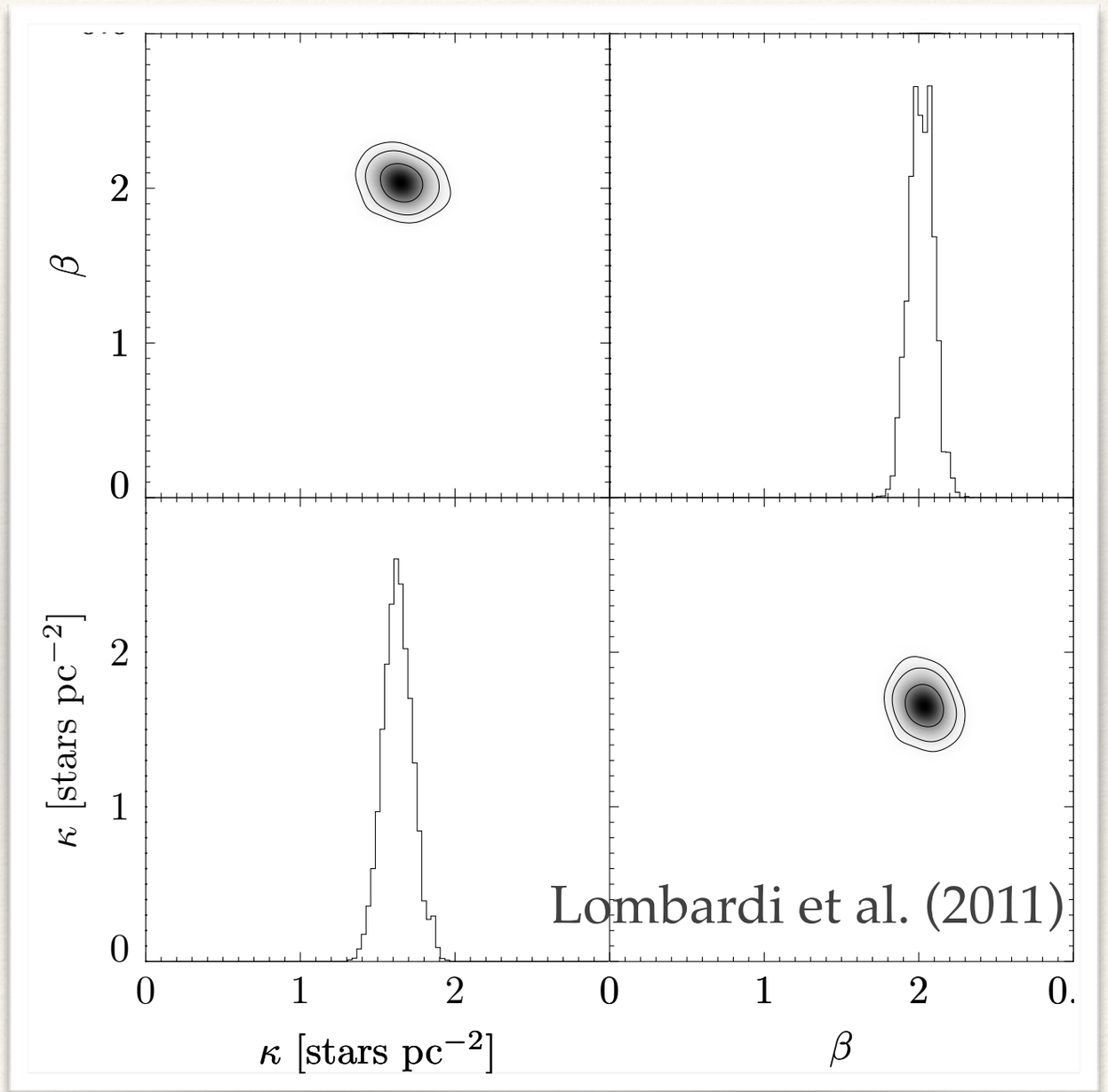
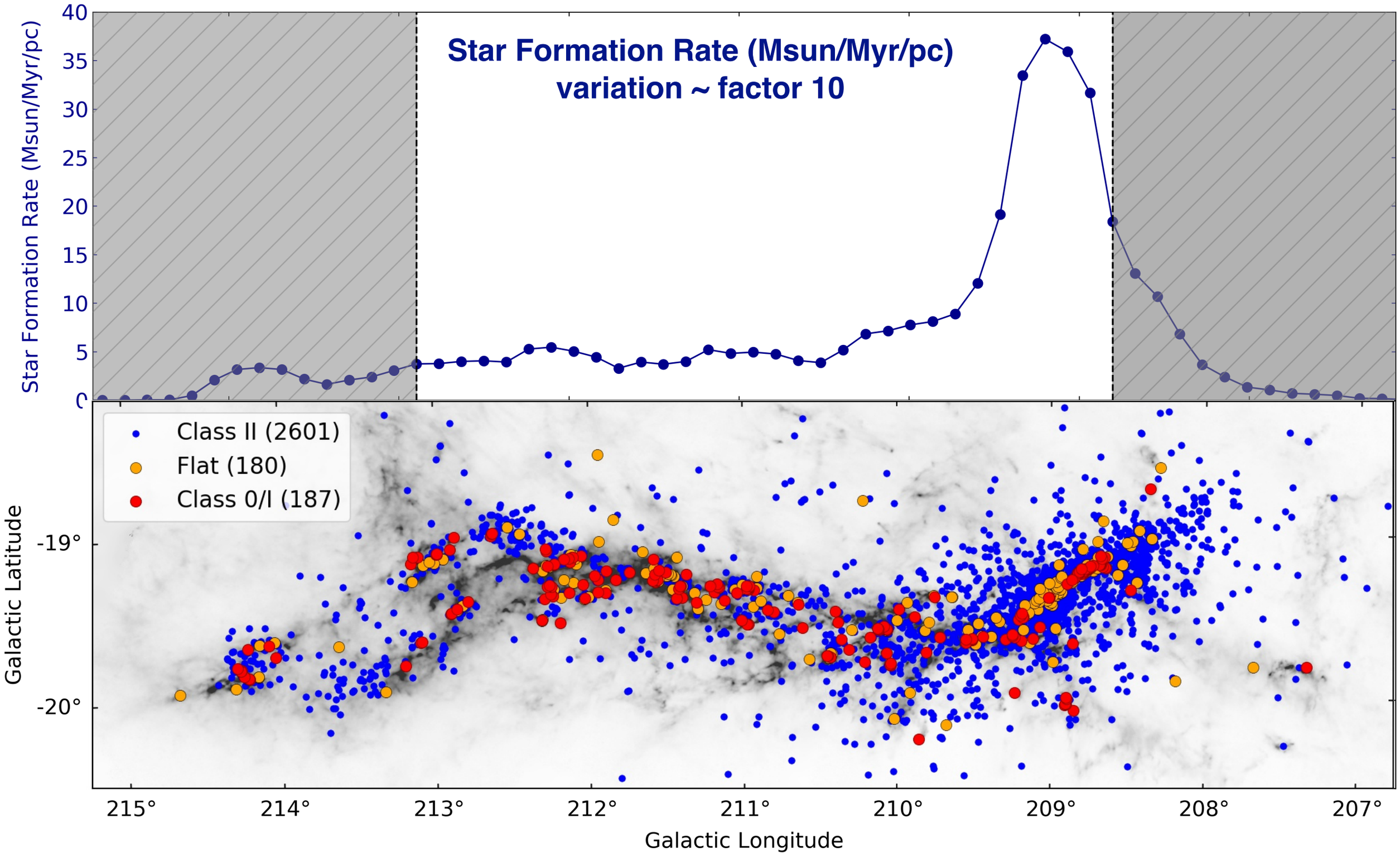
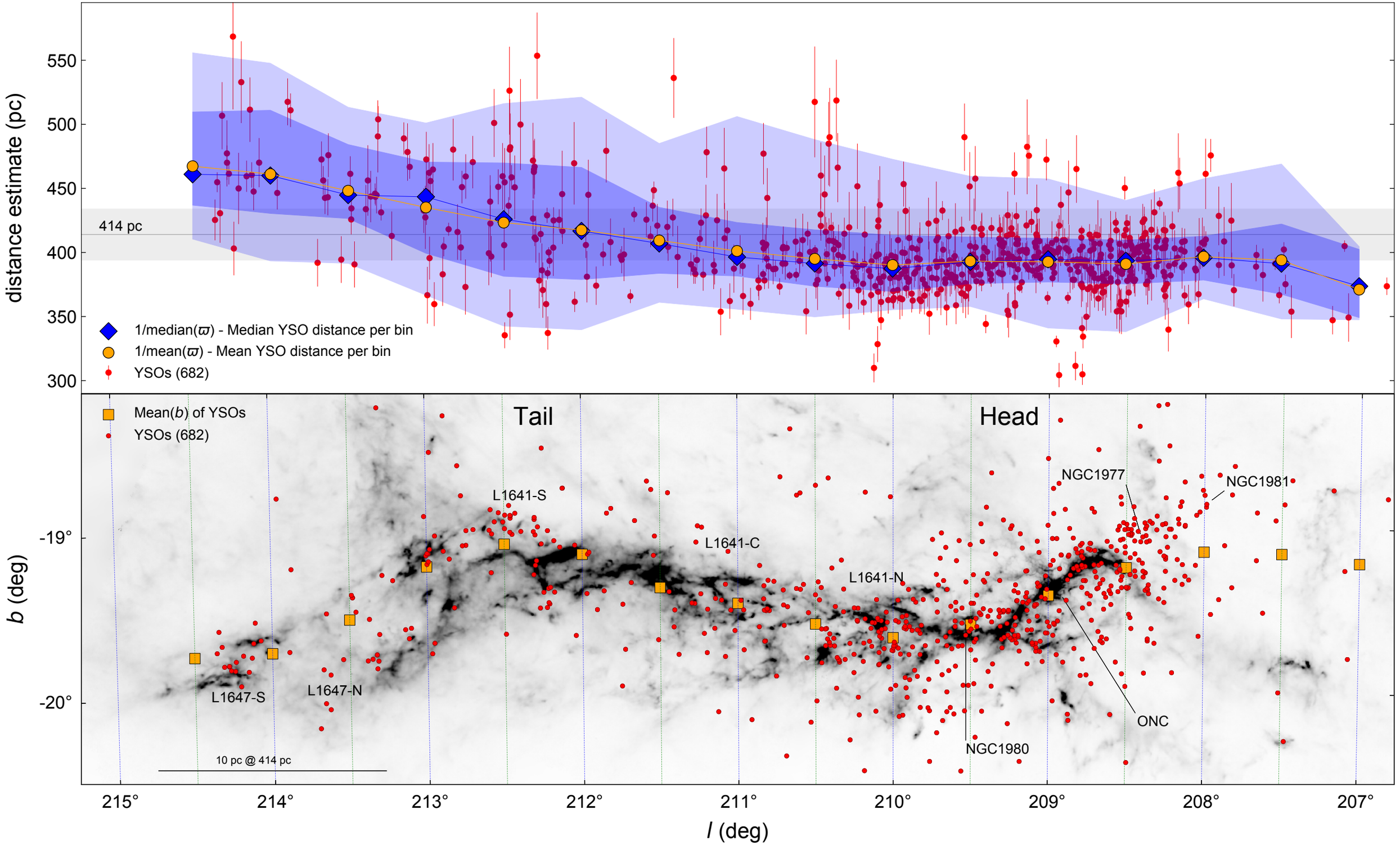
- Related to the resolved Schmidt-Kennicutt relation: SFR ∝ $A_K{}^{\beta}$ (Lombardi et al. 2011), with $\beta = 2$–3





SFR changes along the cloud by a factor ~10, following dense gas (YSO catalogs from Evans et al. 2003, Megeath et al. 2012, Großschedl et al. 2019)



Orion in 3D using Gaia DR2 parallaxes of YSOs: bent head, in total the cloud is 90 pc long! (Großschedl et al. 2018)

Fact 2.
Molecular clouds have log-normal PDFs

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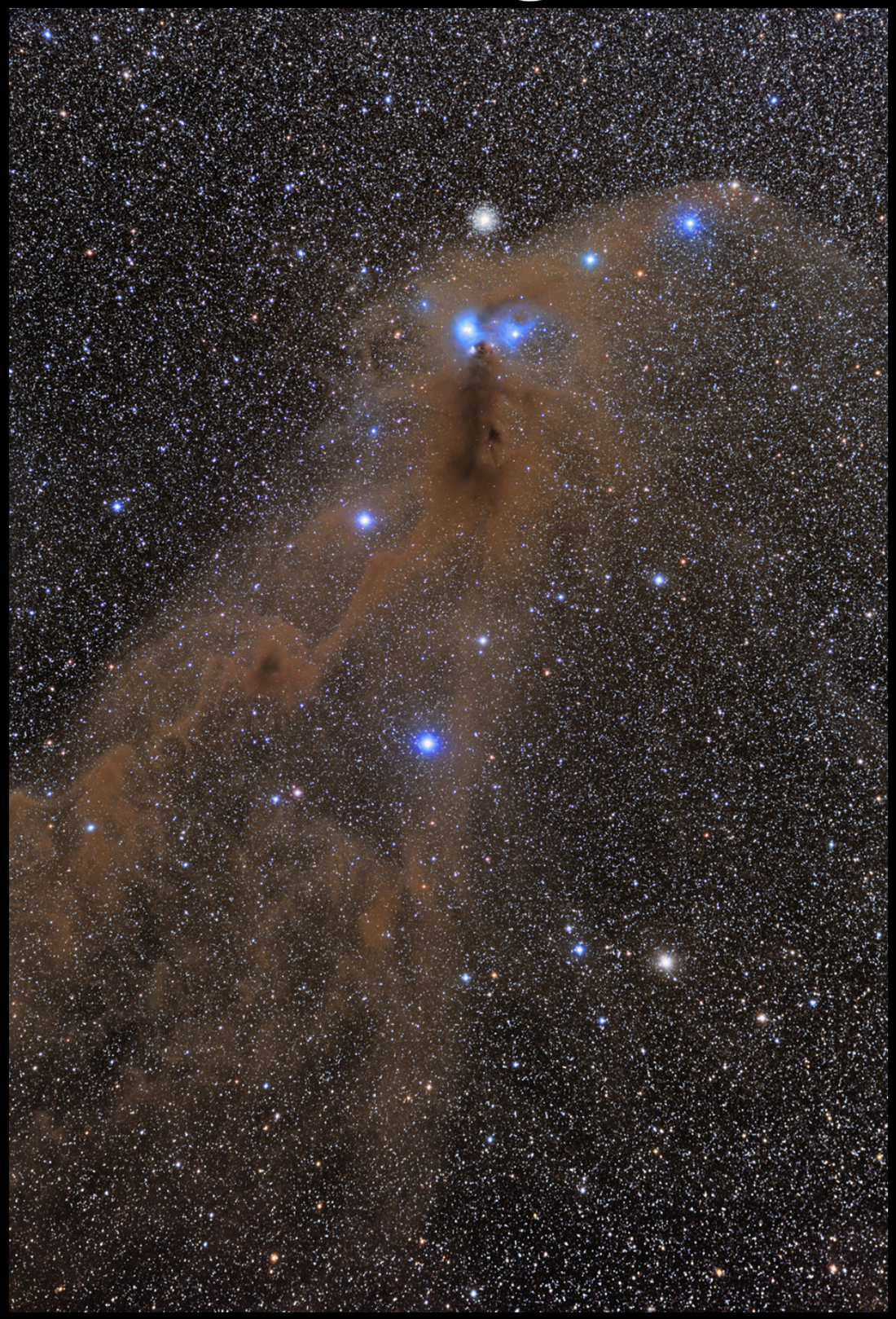
Log-normality of PDFs



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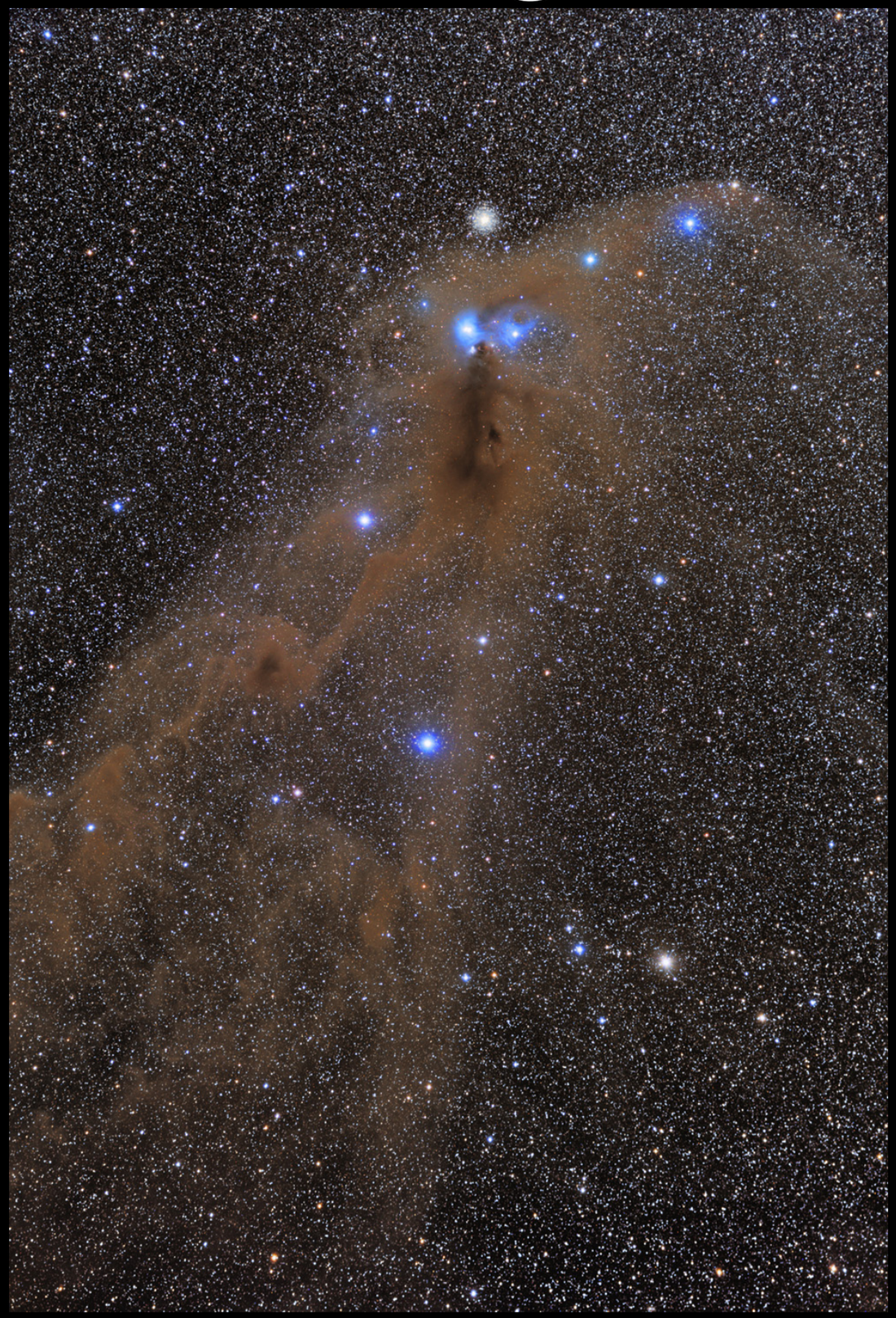

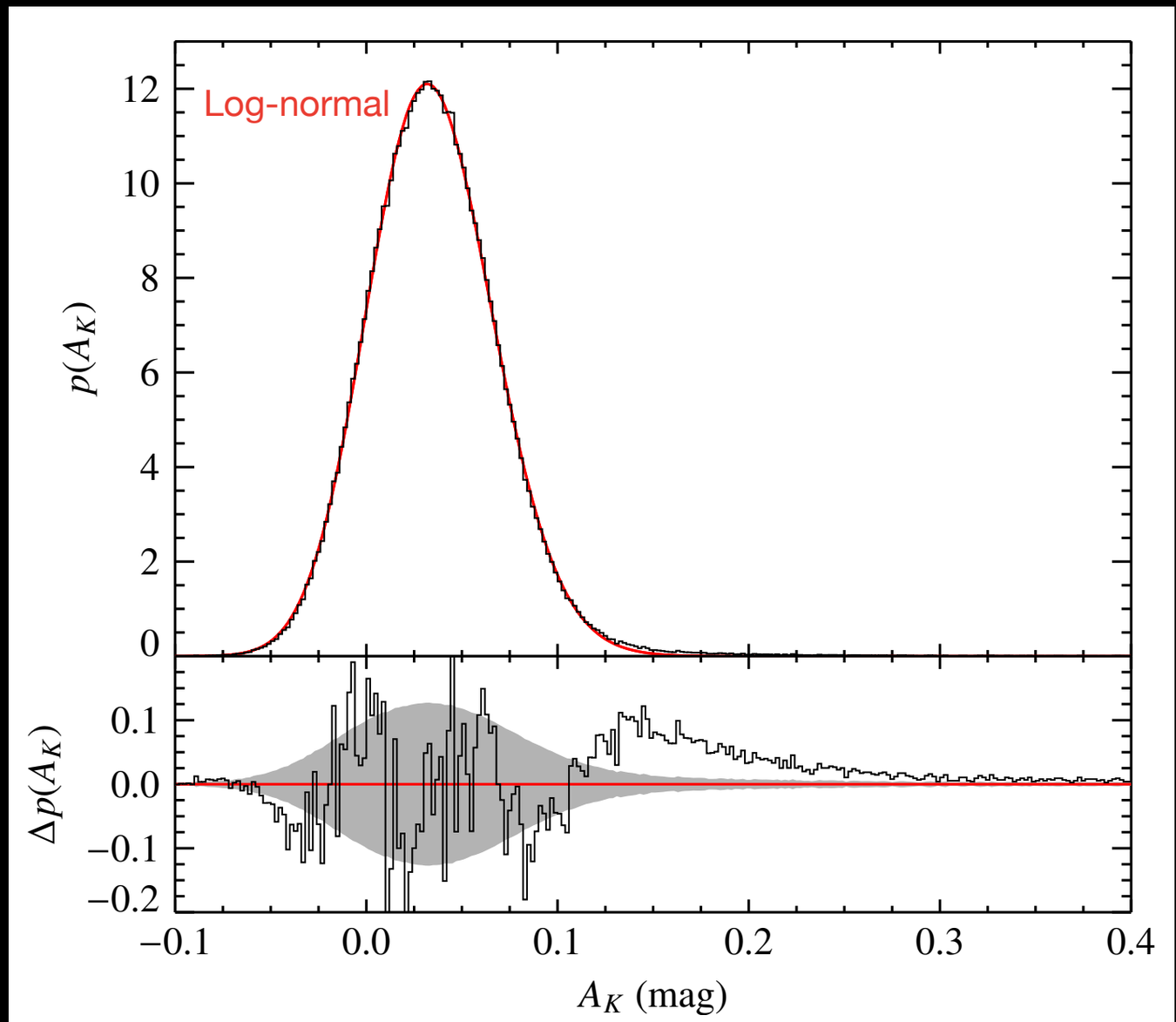

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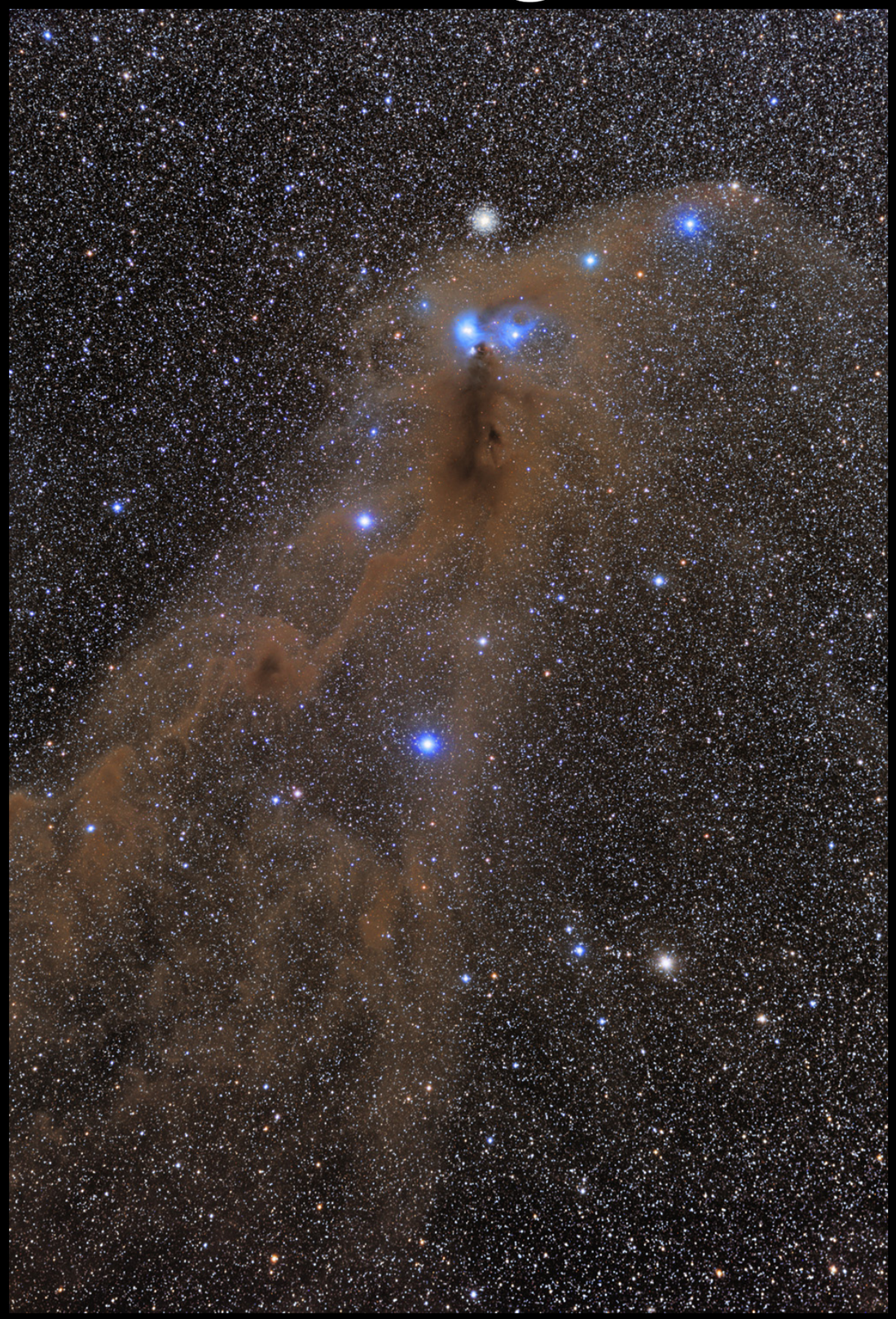

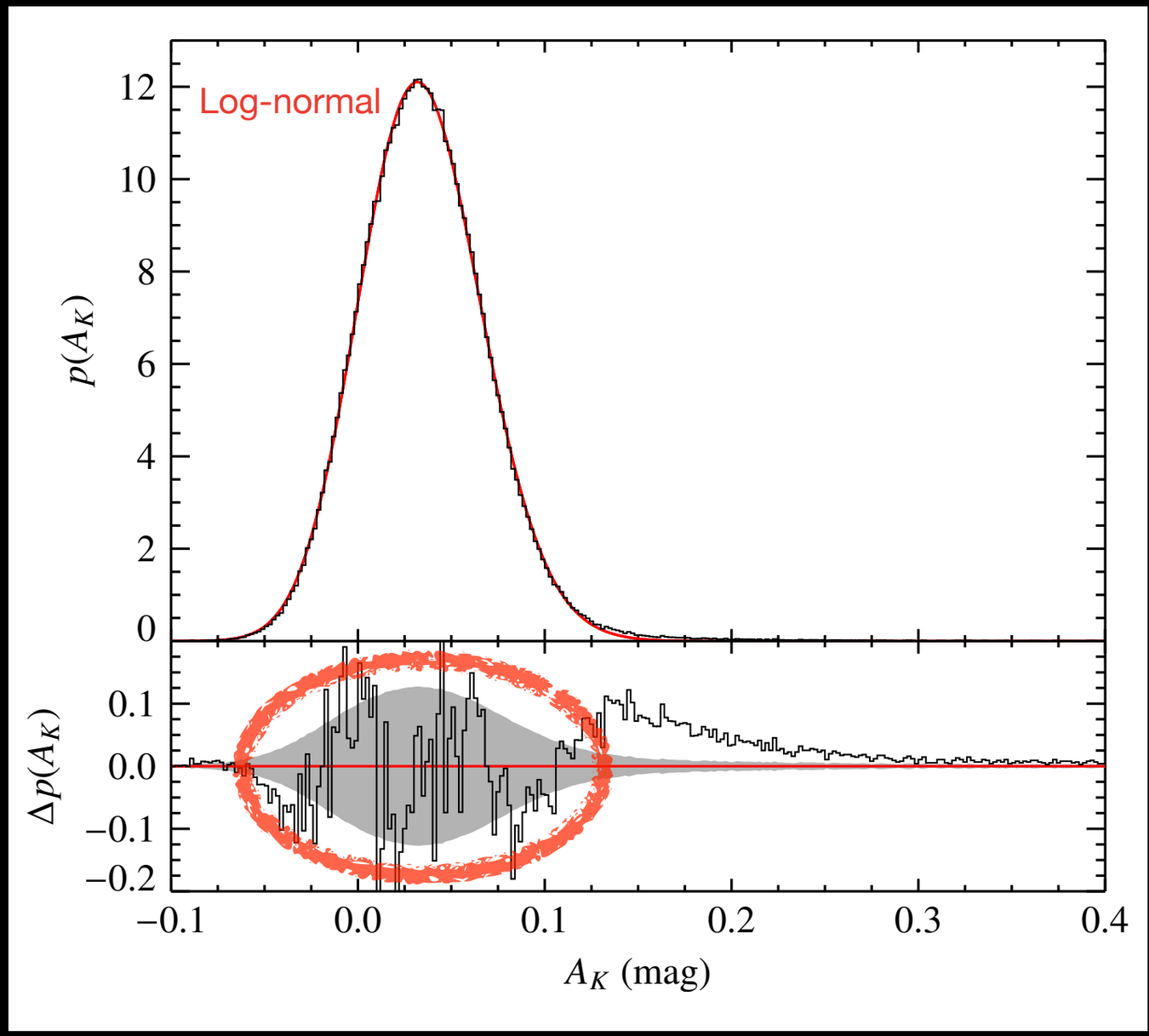

Systematic residuals in the entire fitting region. Maybe Herschel will do better?

Alves et al. (2014)

Herschel PDFs of local clouds

- PDFs are hardly symmetric in log-log
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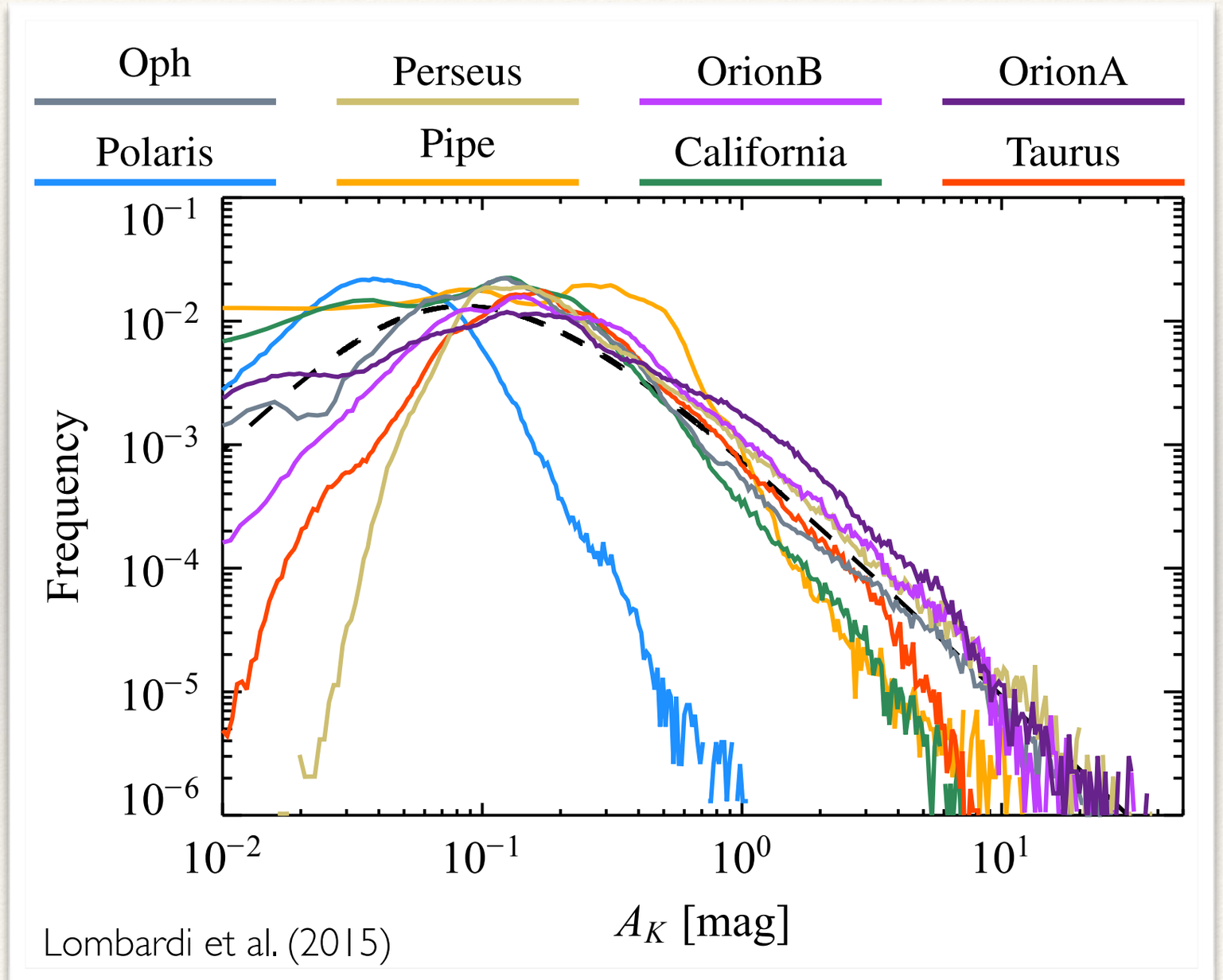

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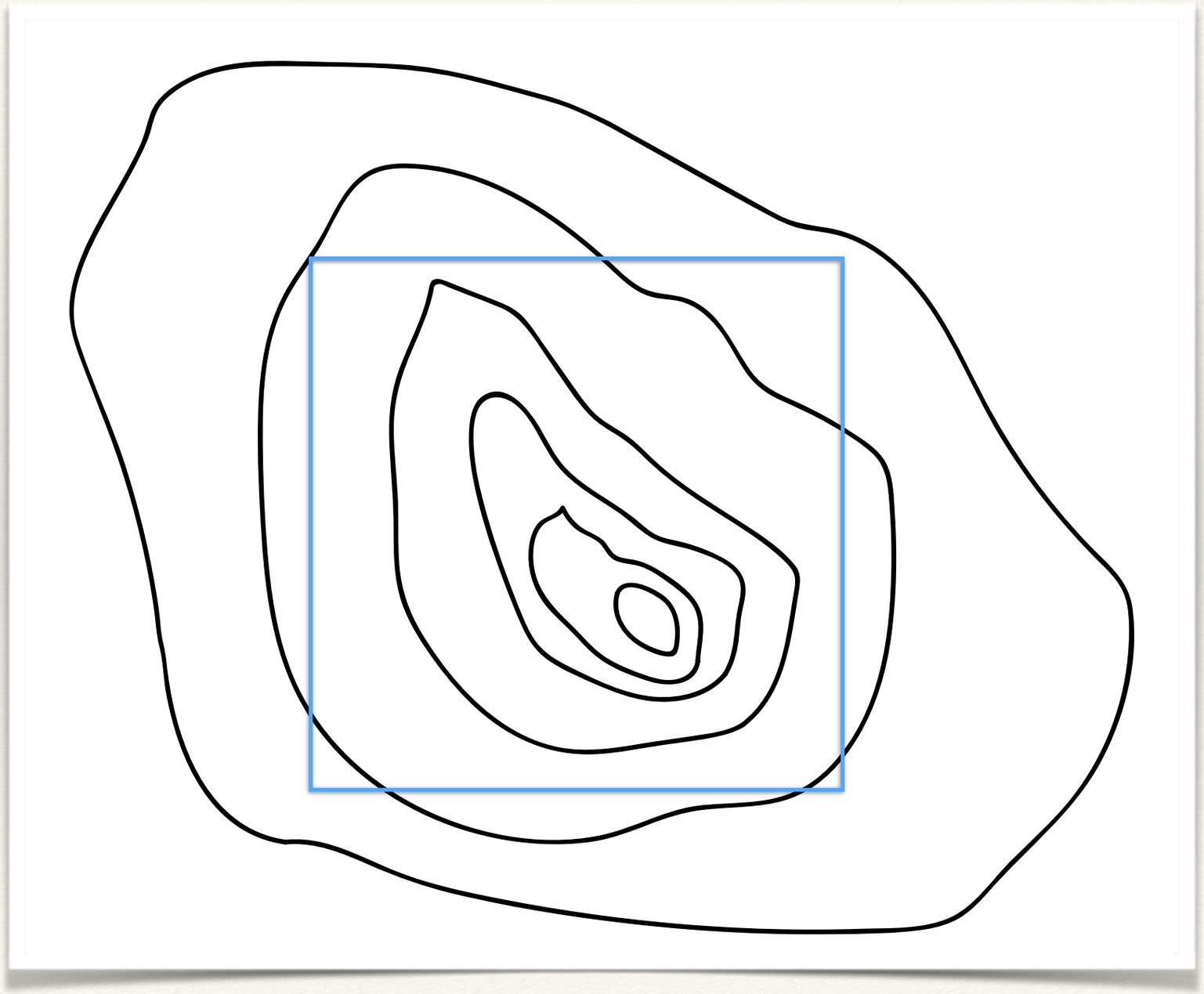

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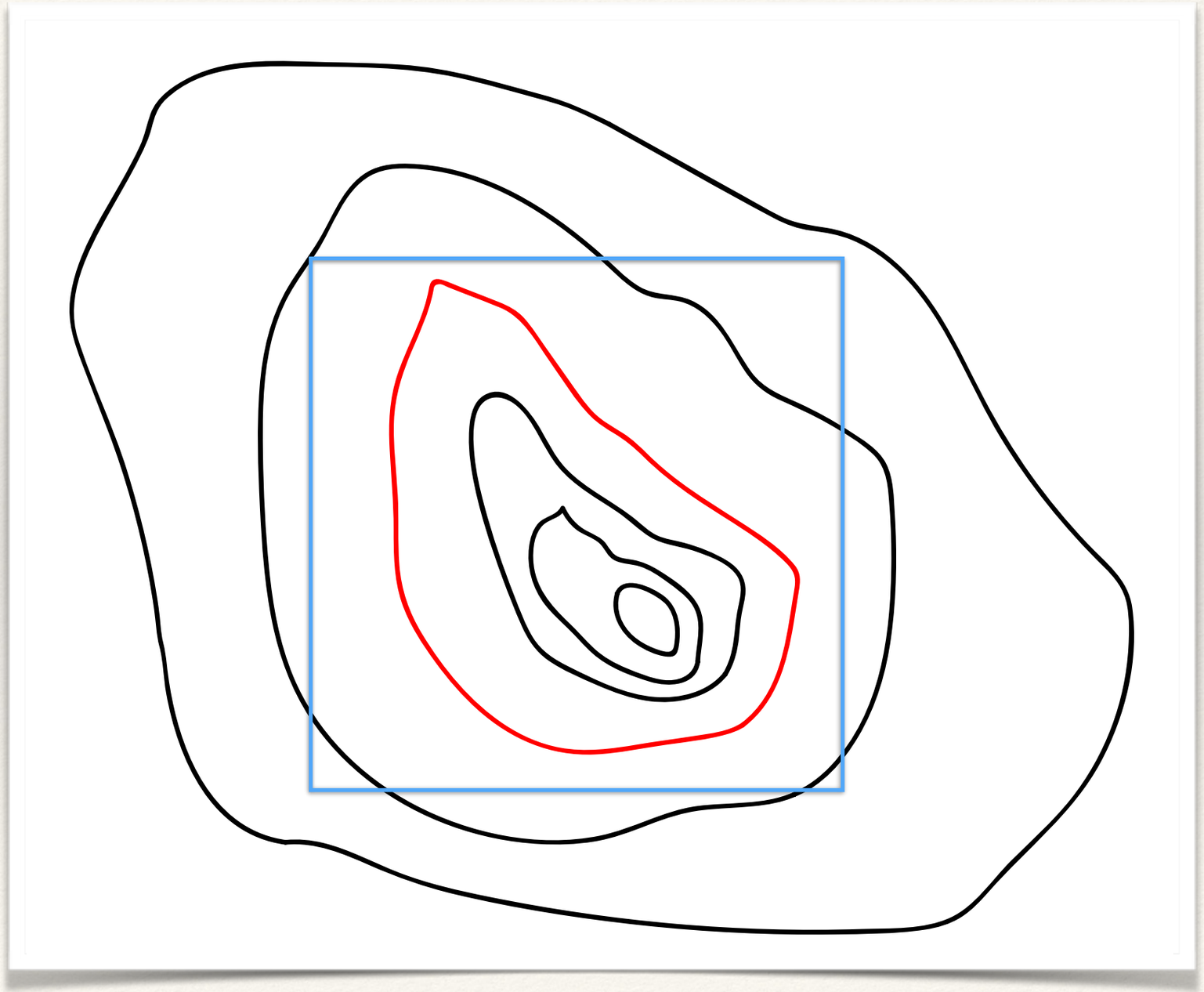

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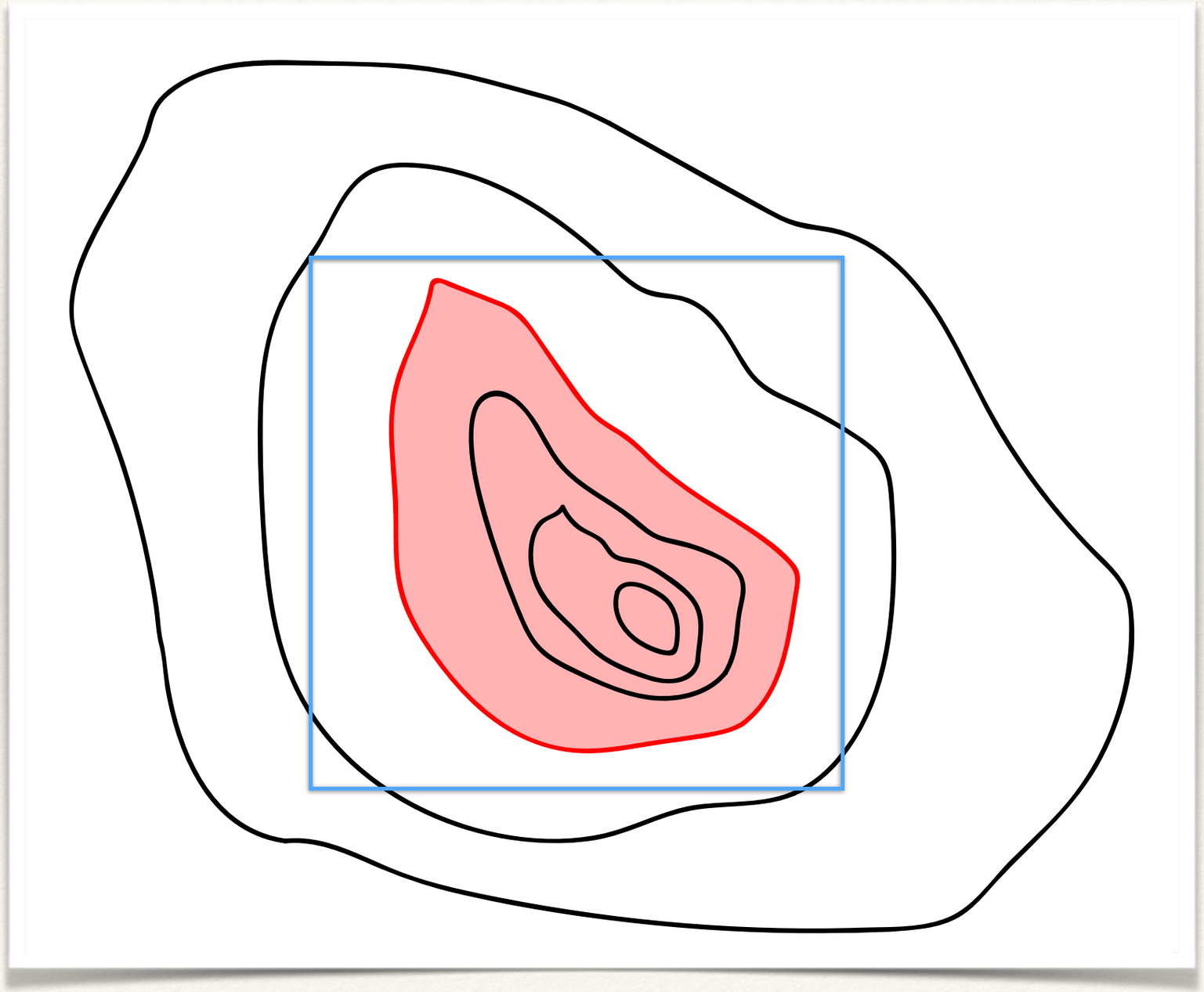
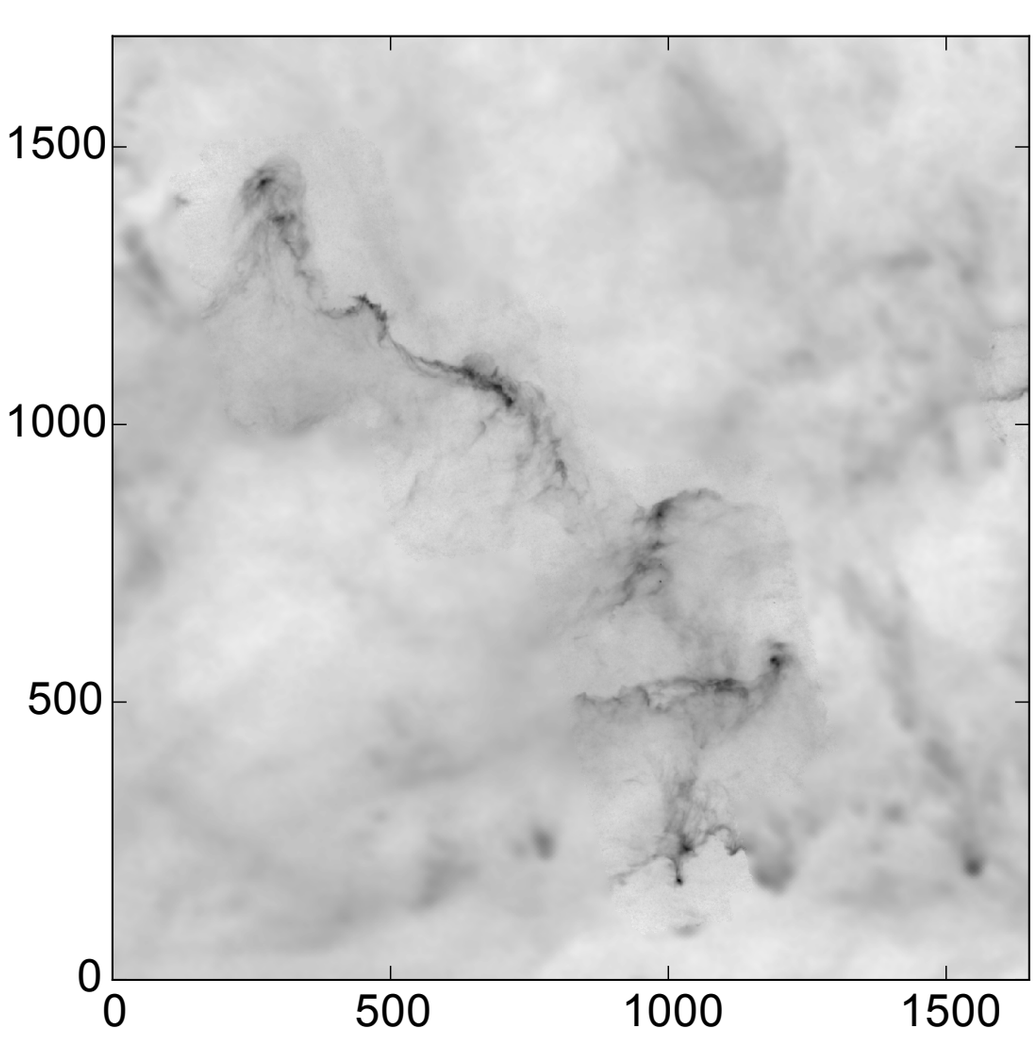
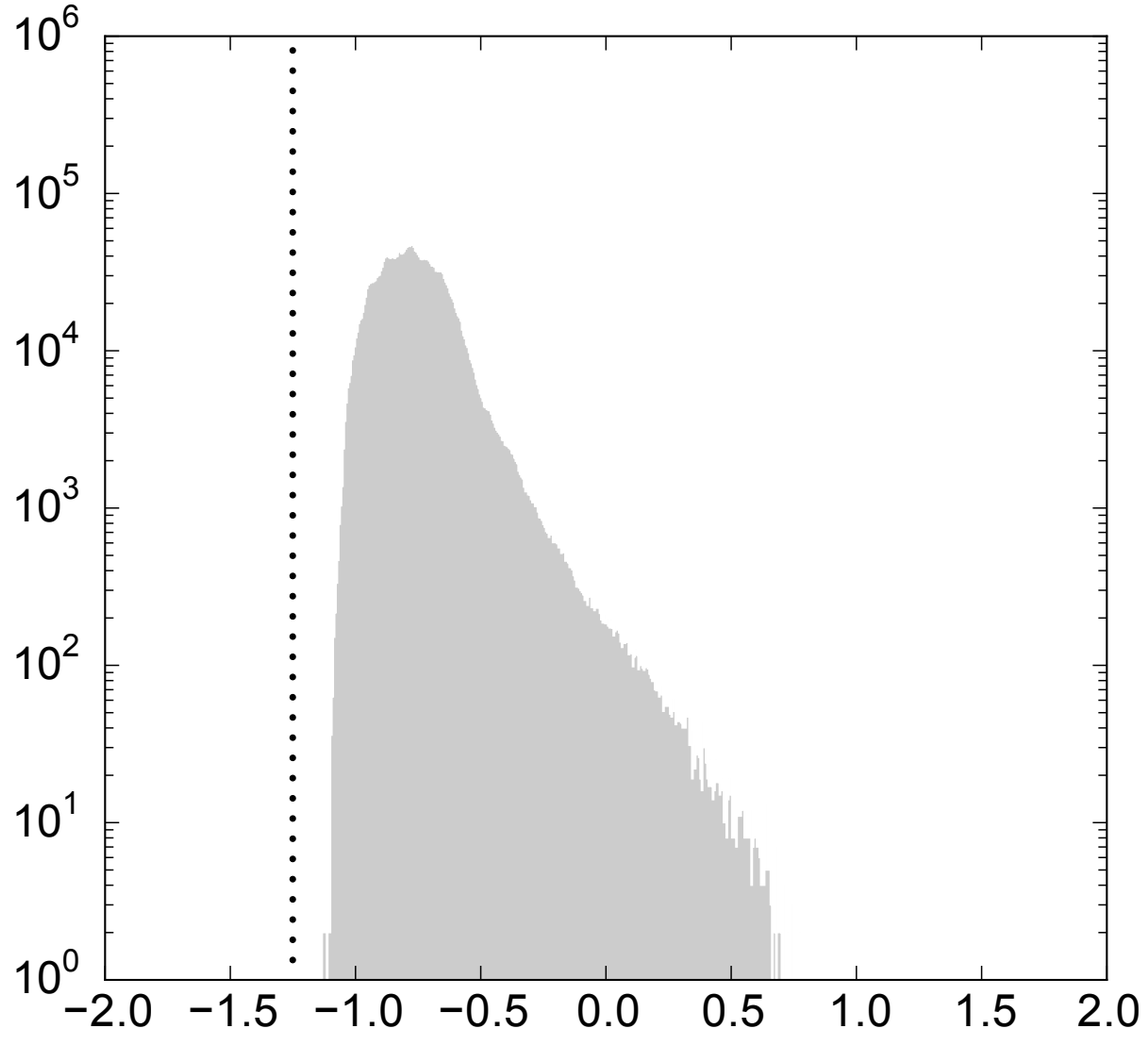


PDFs completeness

Ophiuchus North (Planck + Herschel)





Alves, Lombardi, Lada (2017)

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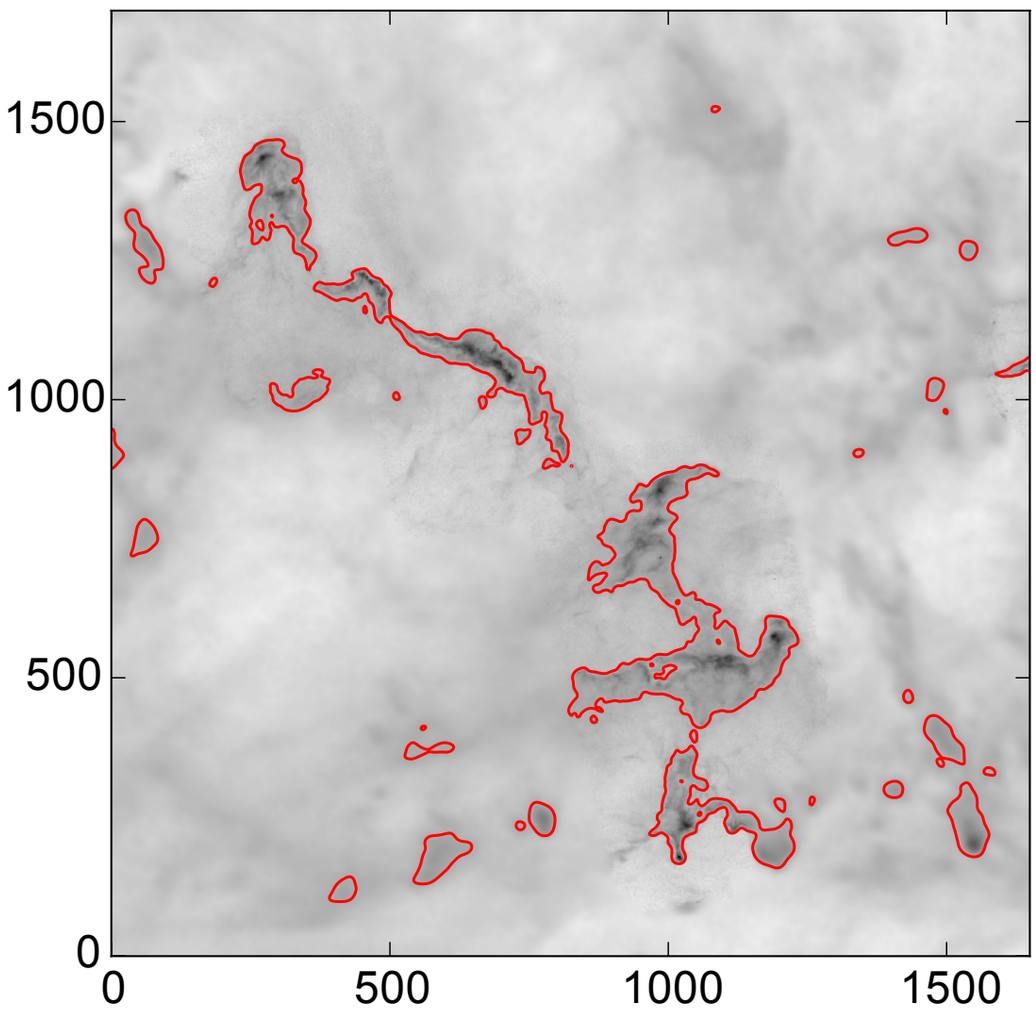

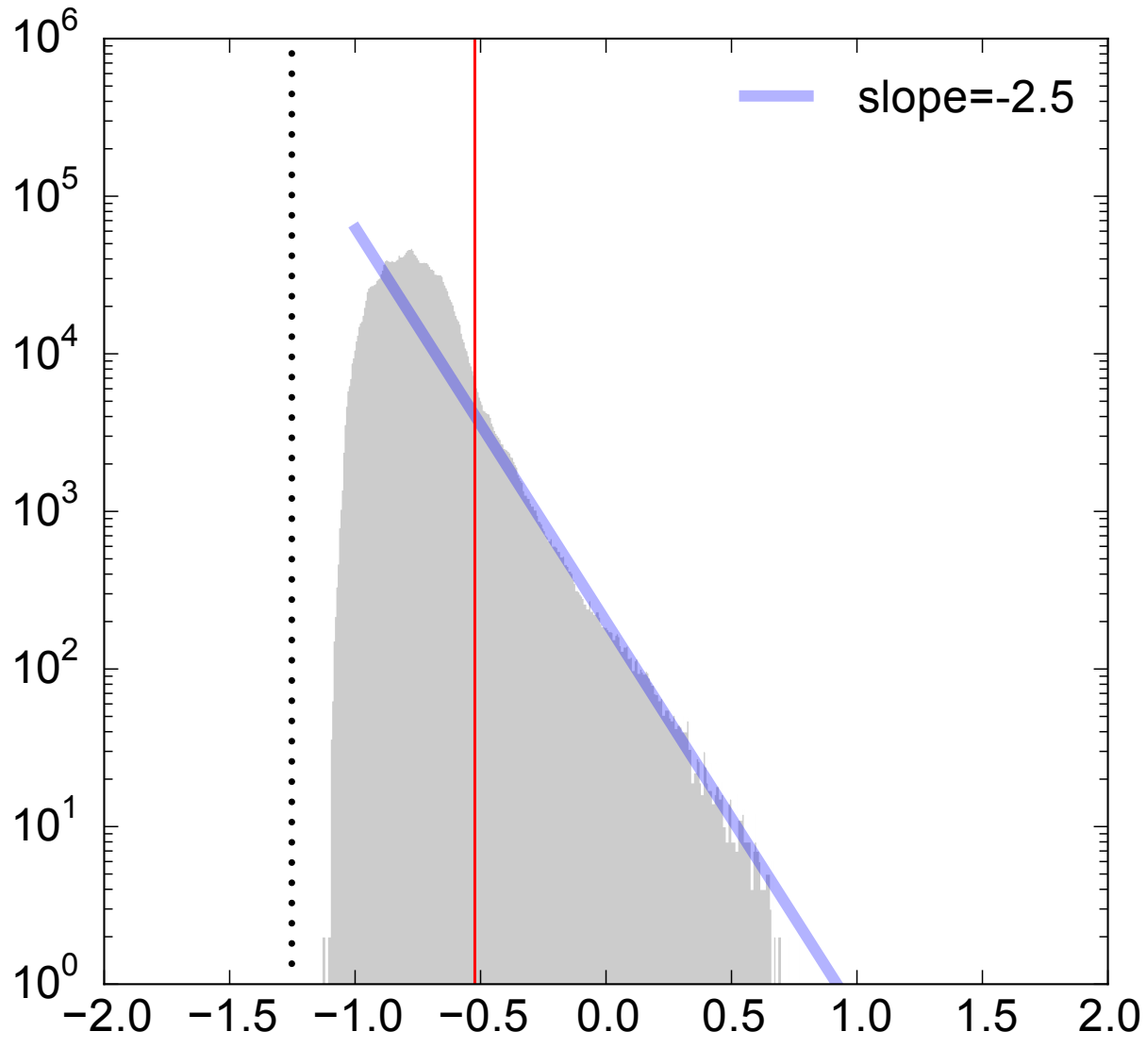

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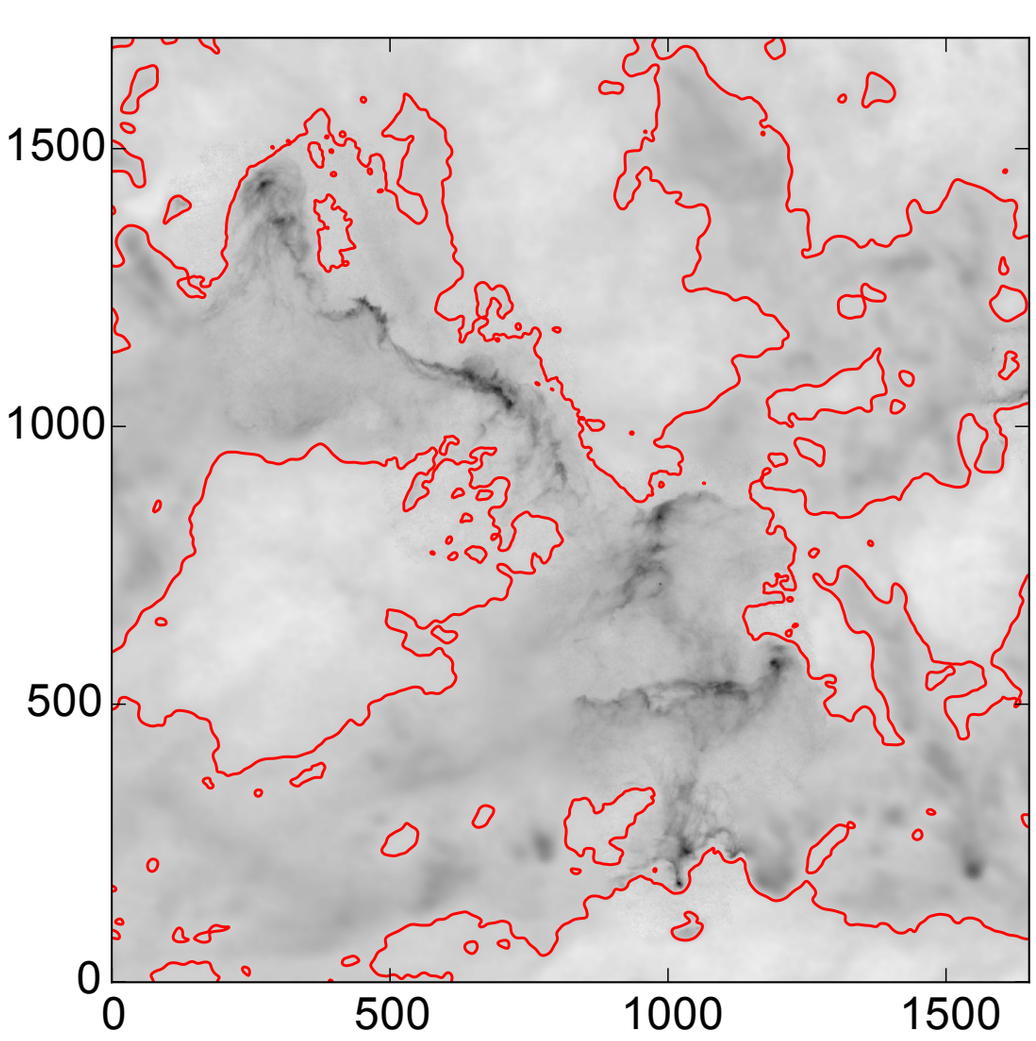

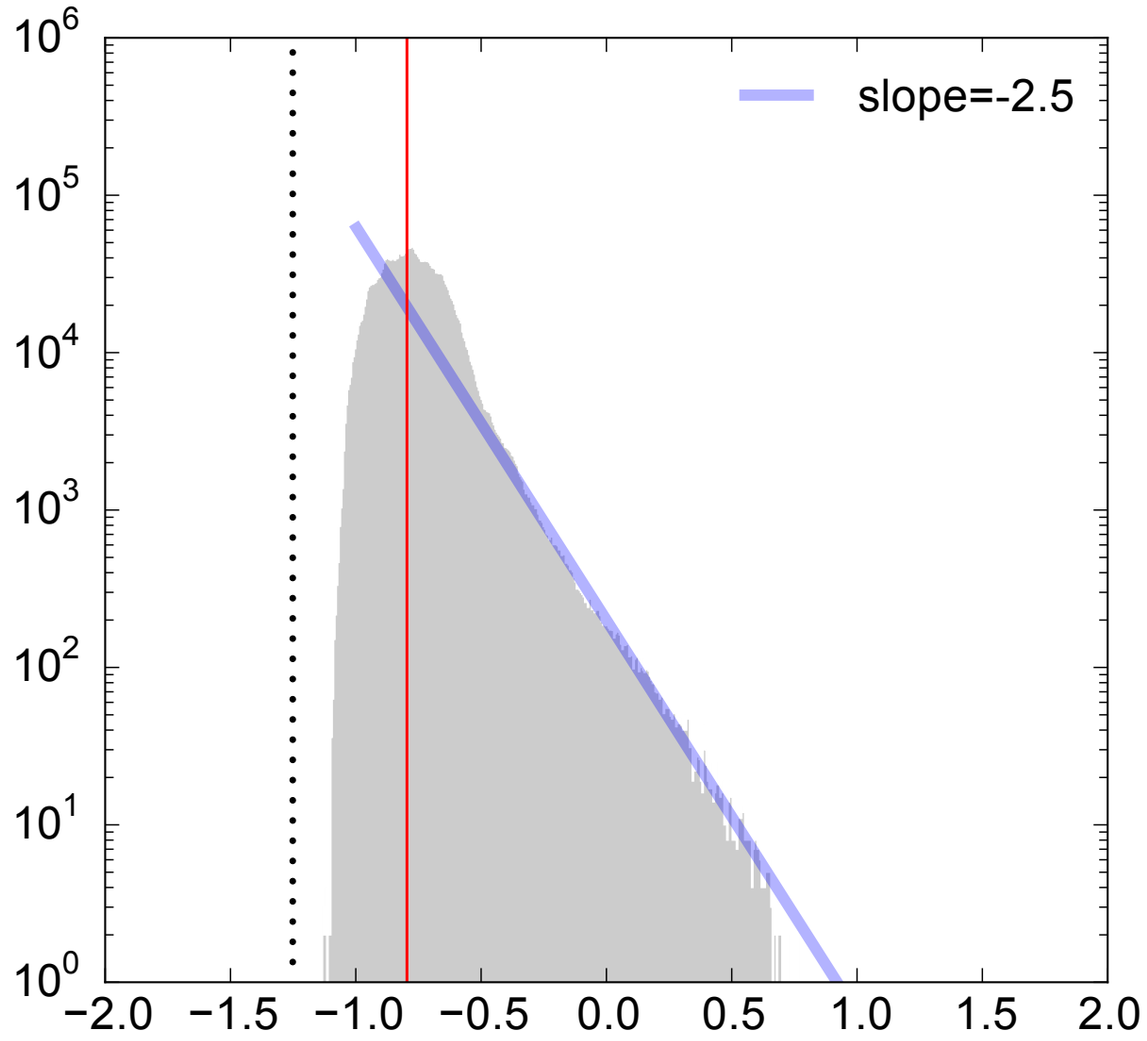

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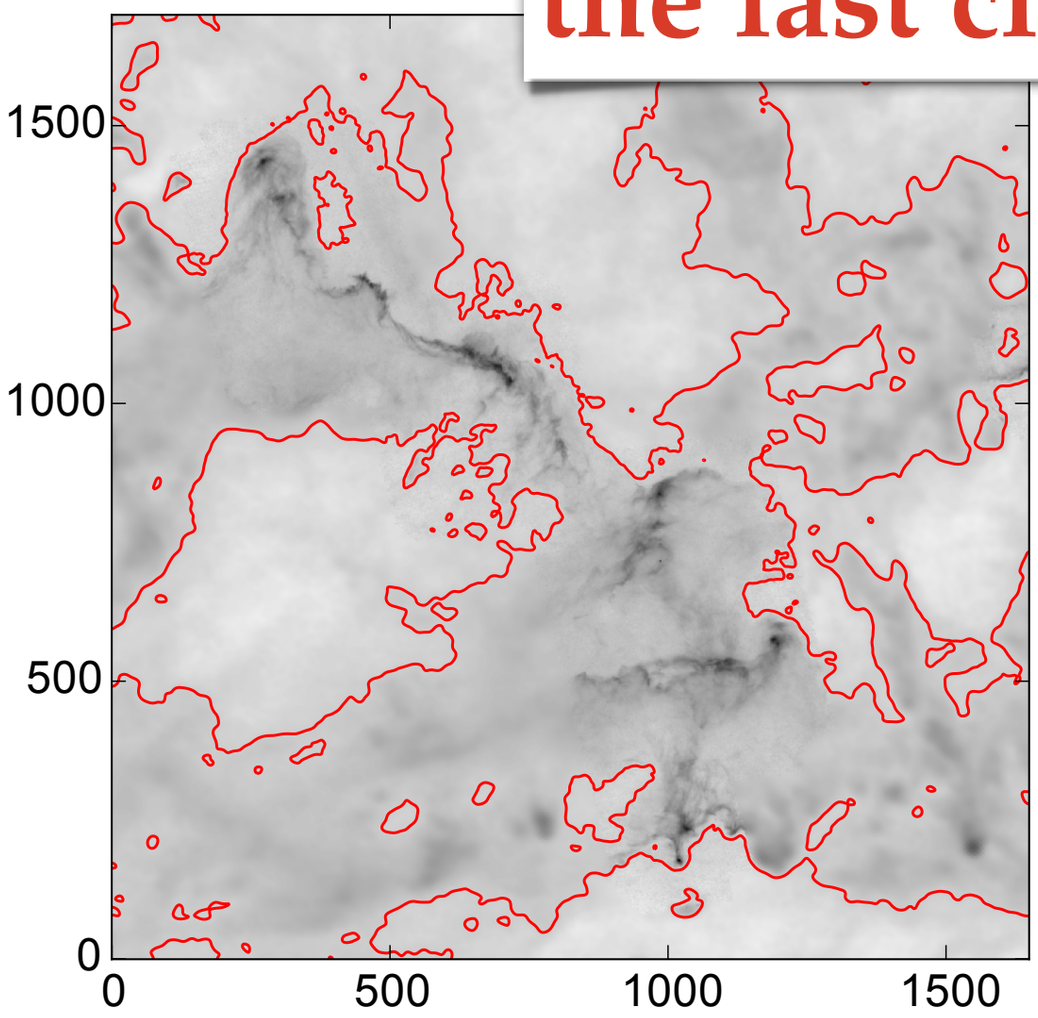
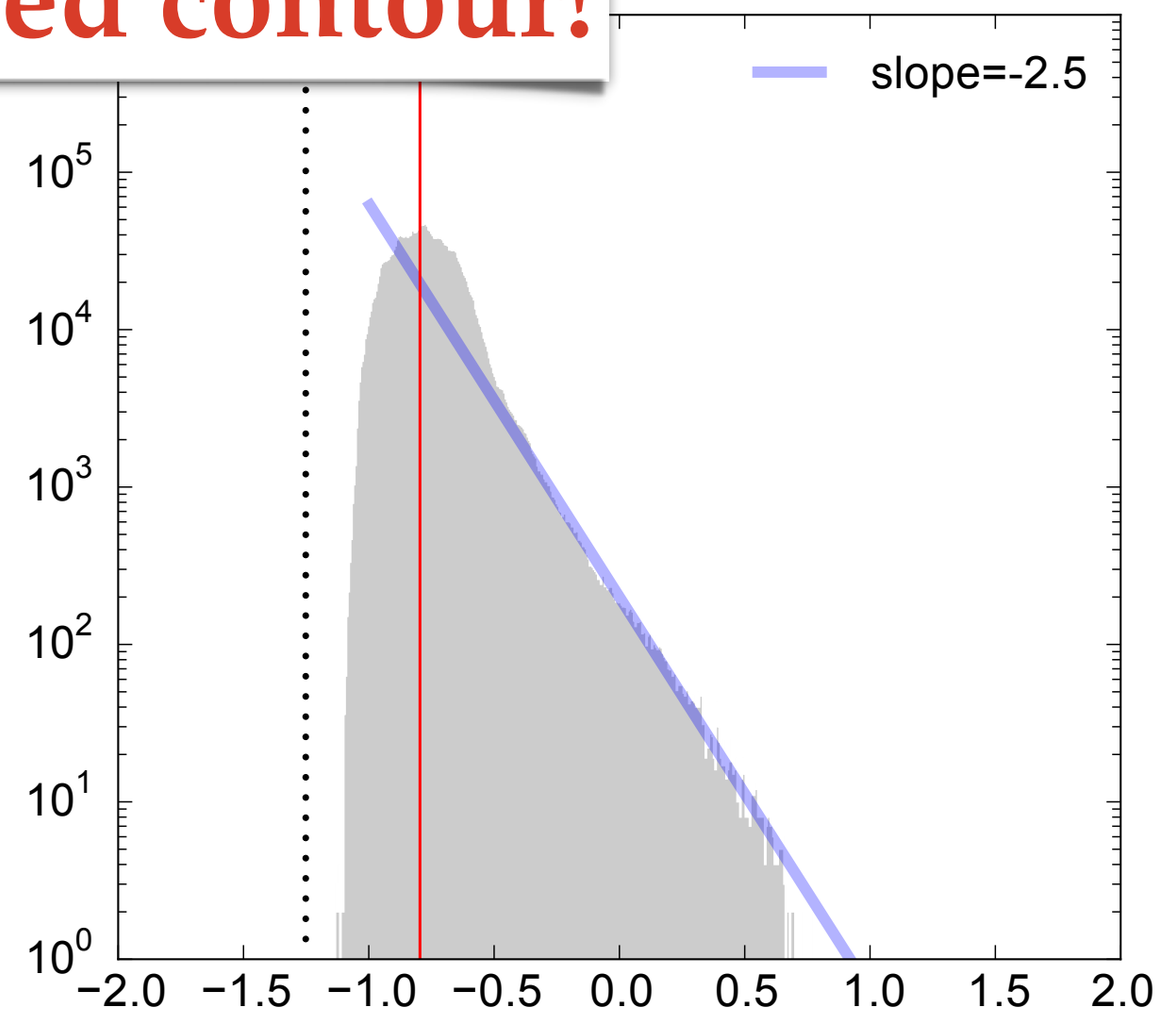
Completeness set by the last closed contour!





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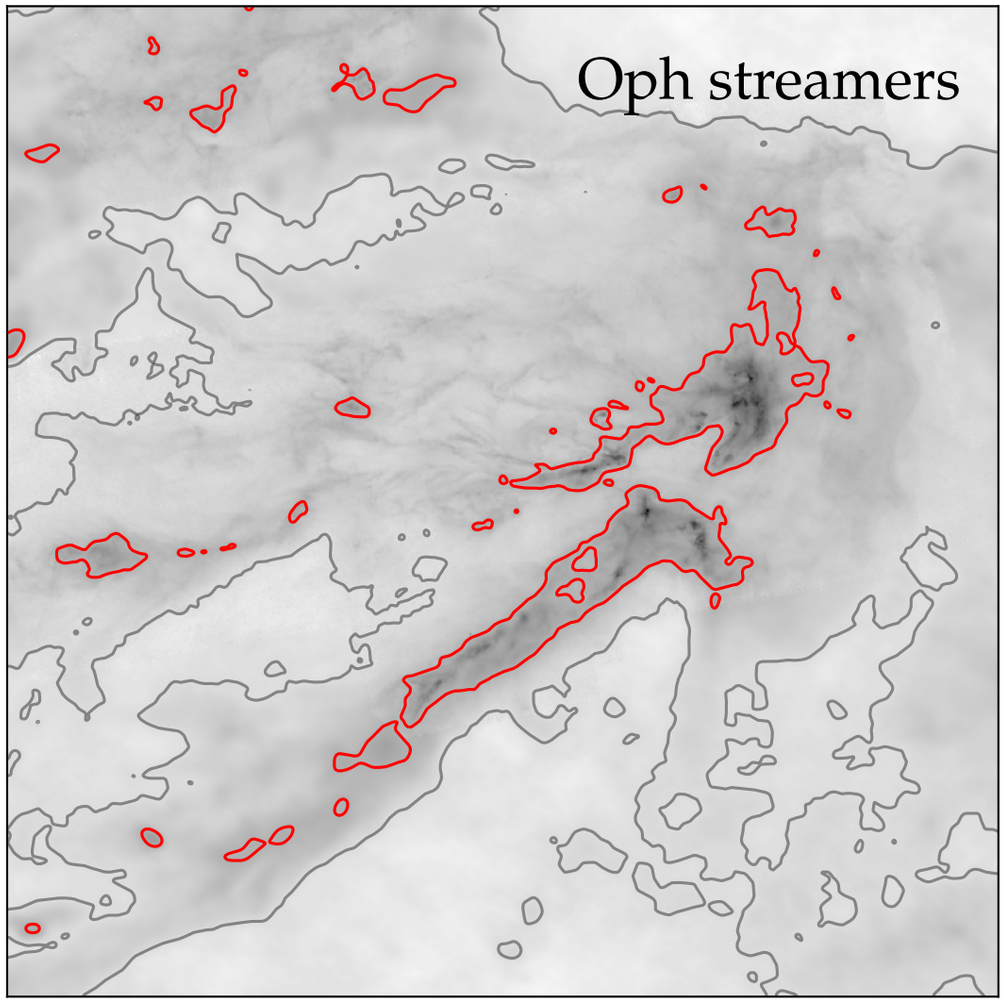
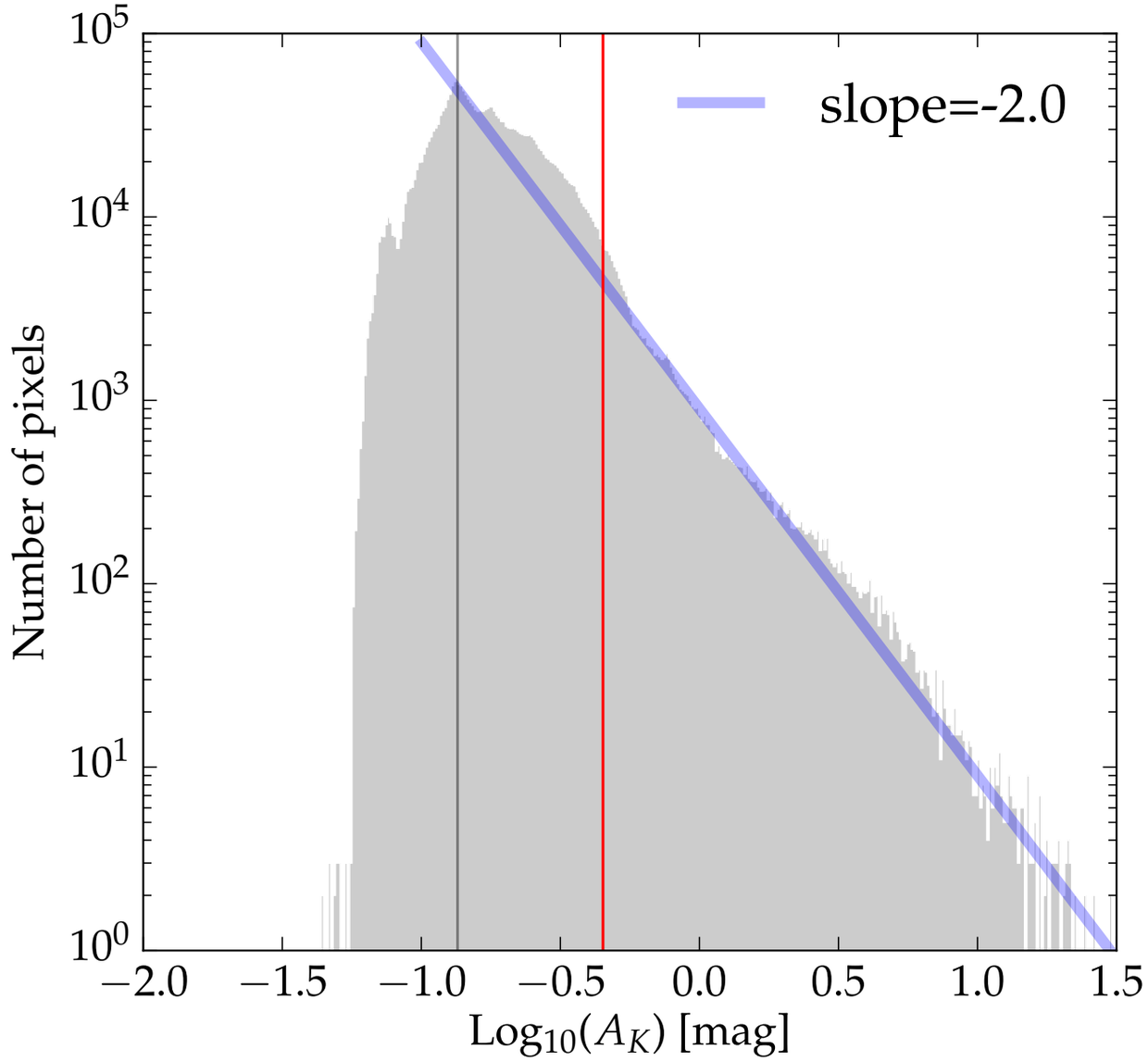
What we really know about PDFs





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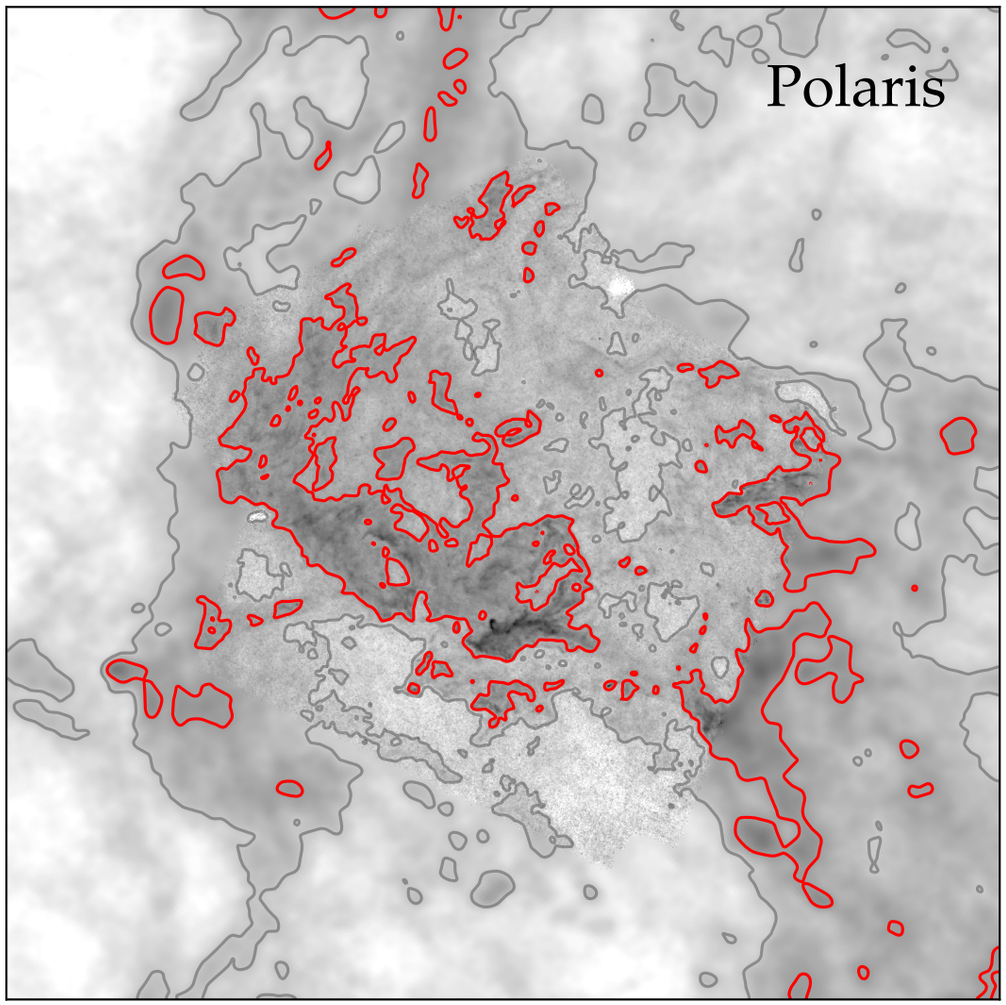

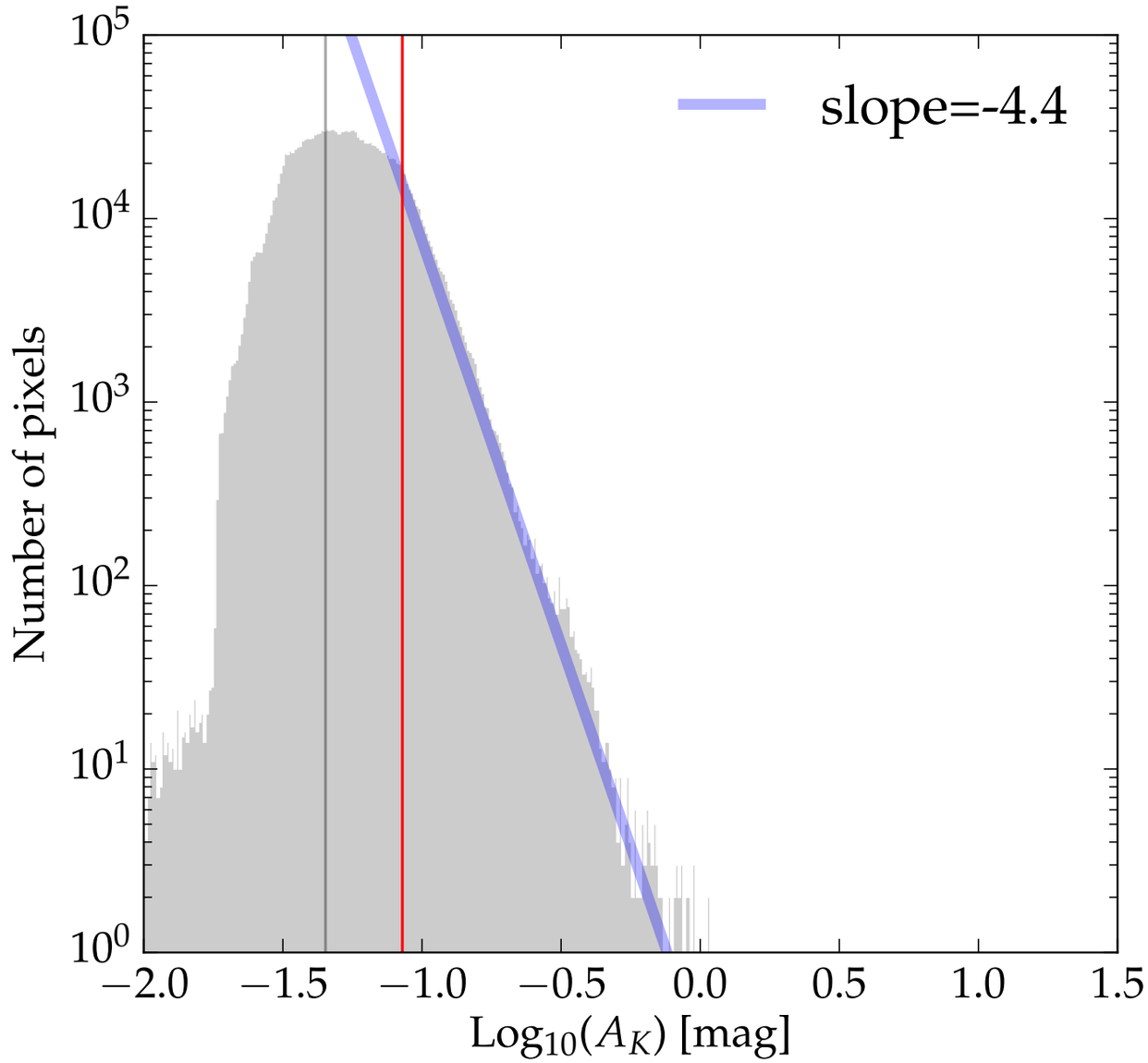

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3. Local clouds our best chance to understand the scaling relations http://www.interstellarclouds.org/html

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- Projection effects (in most cases…) do not significantly alter this expectation (Vázquez-Semadeni & García 2001)

Extinction and color excess

- Brightness

$$m_{\rm obs} = -2.5\log(F_\star e^{-\tau})$$
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$$A_K \propto E(H-K) \propto E(J-H)$$

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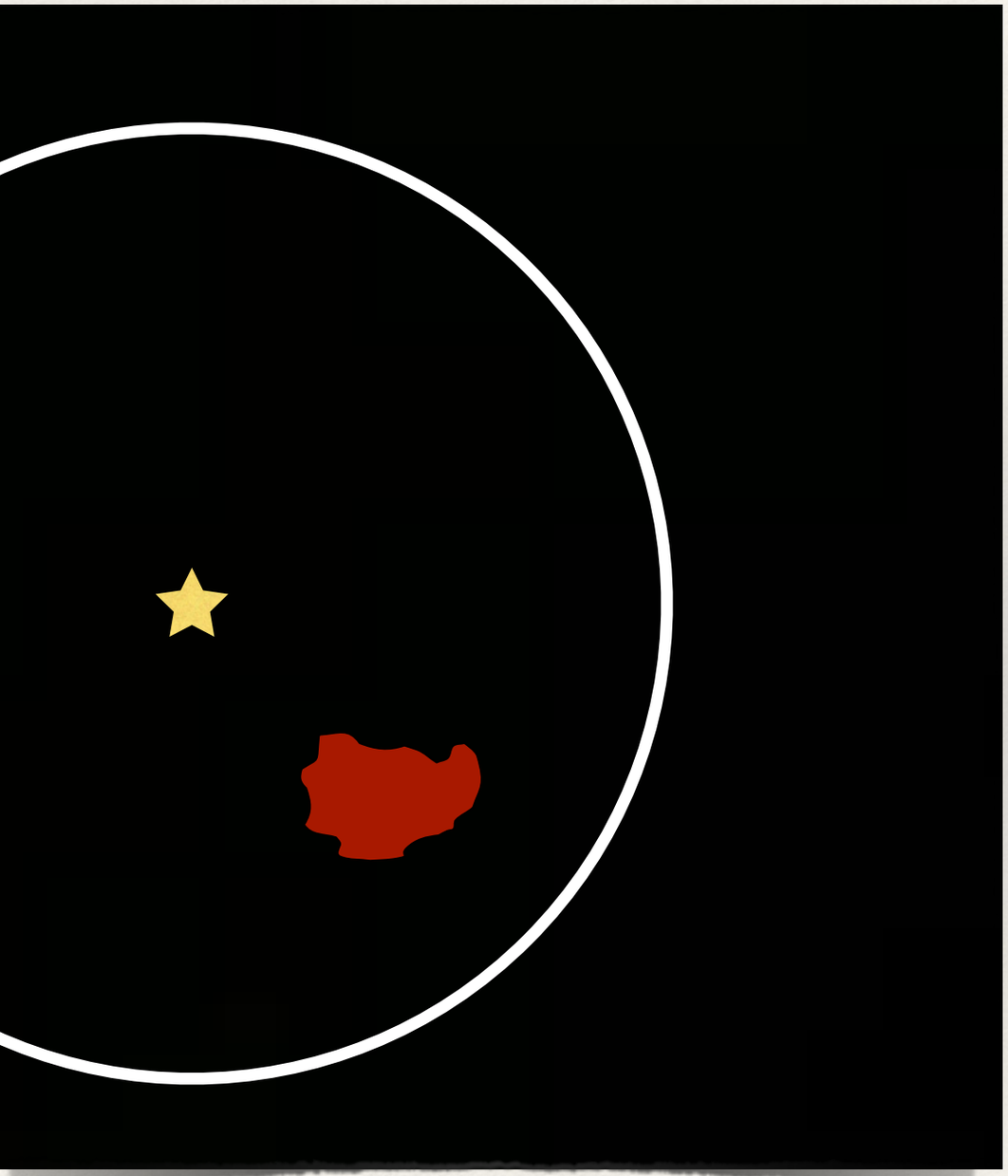

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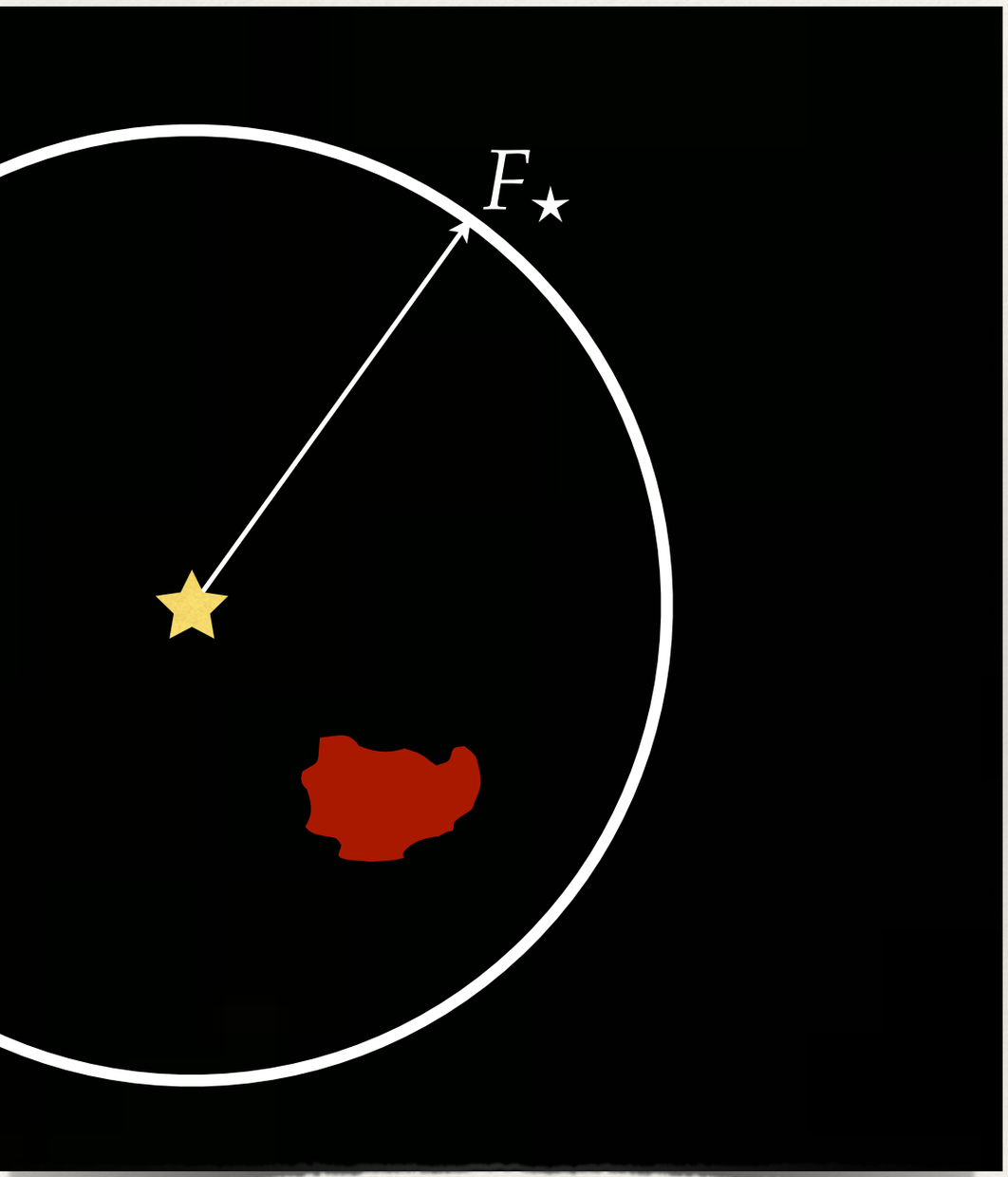

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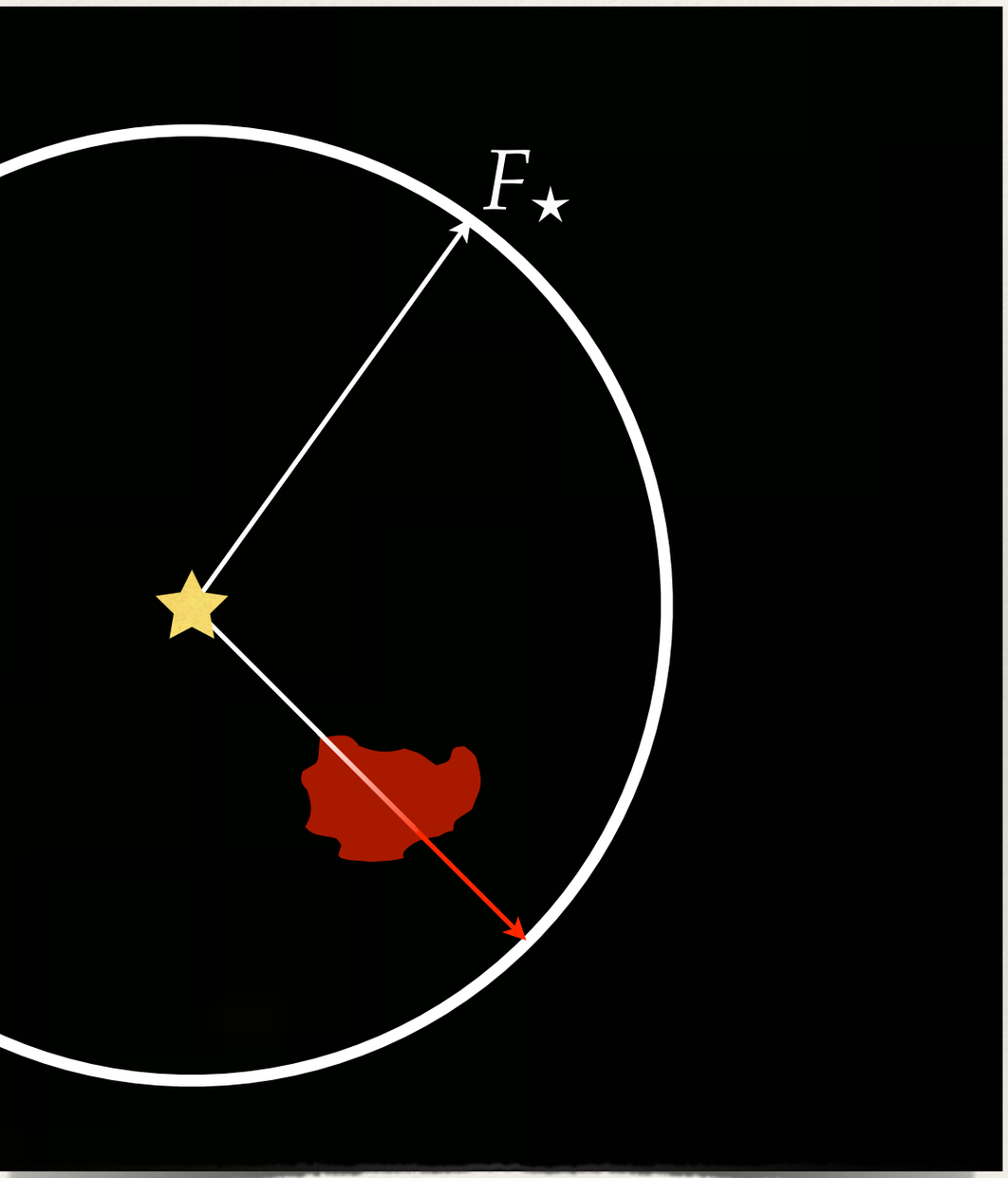

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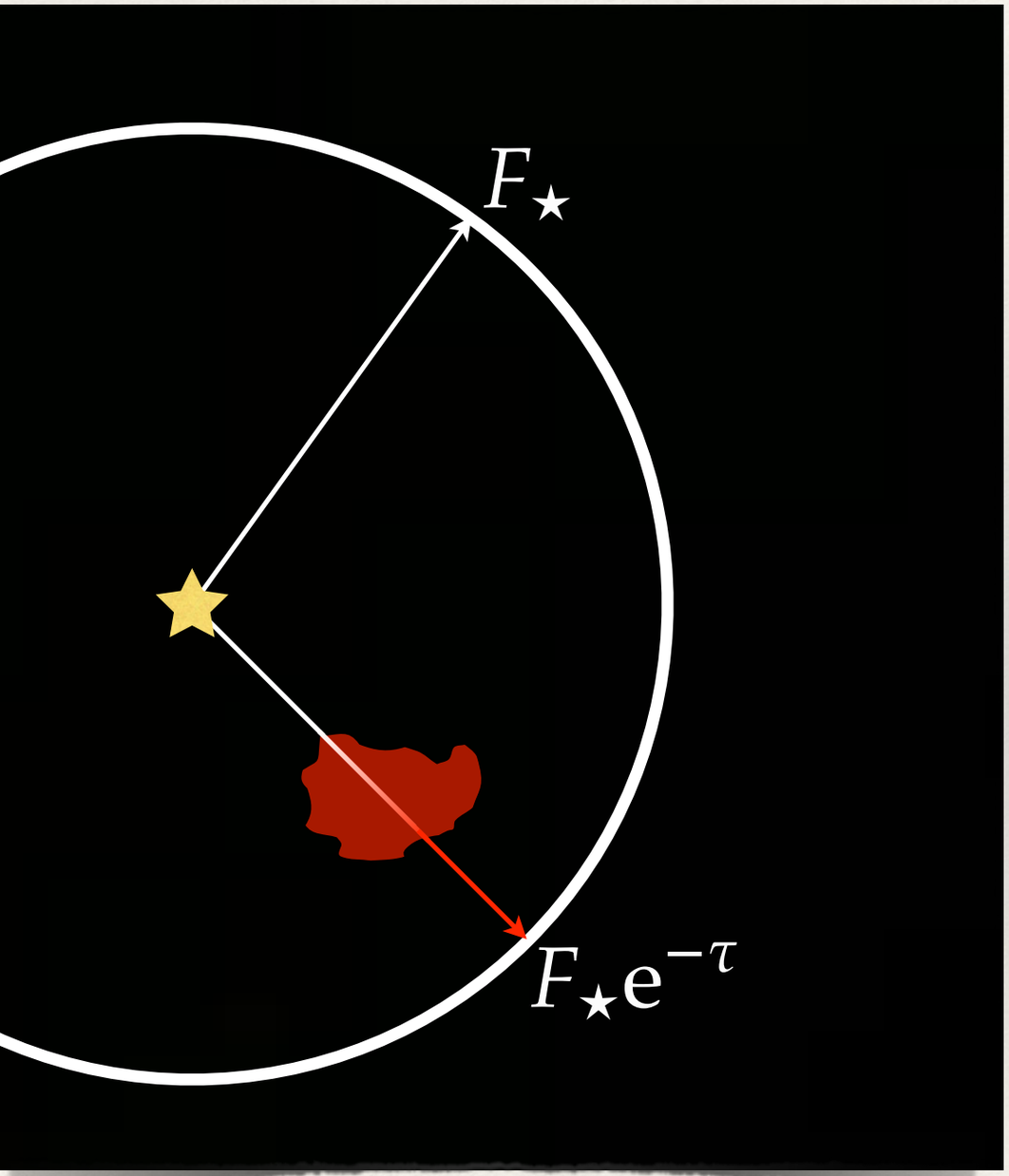

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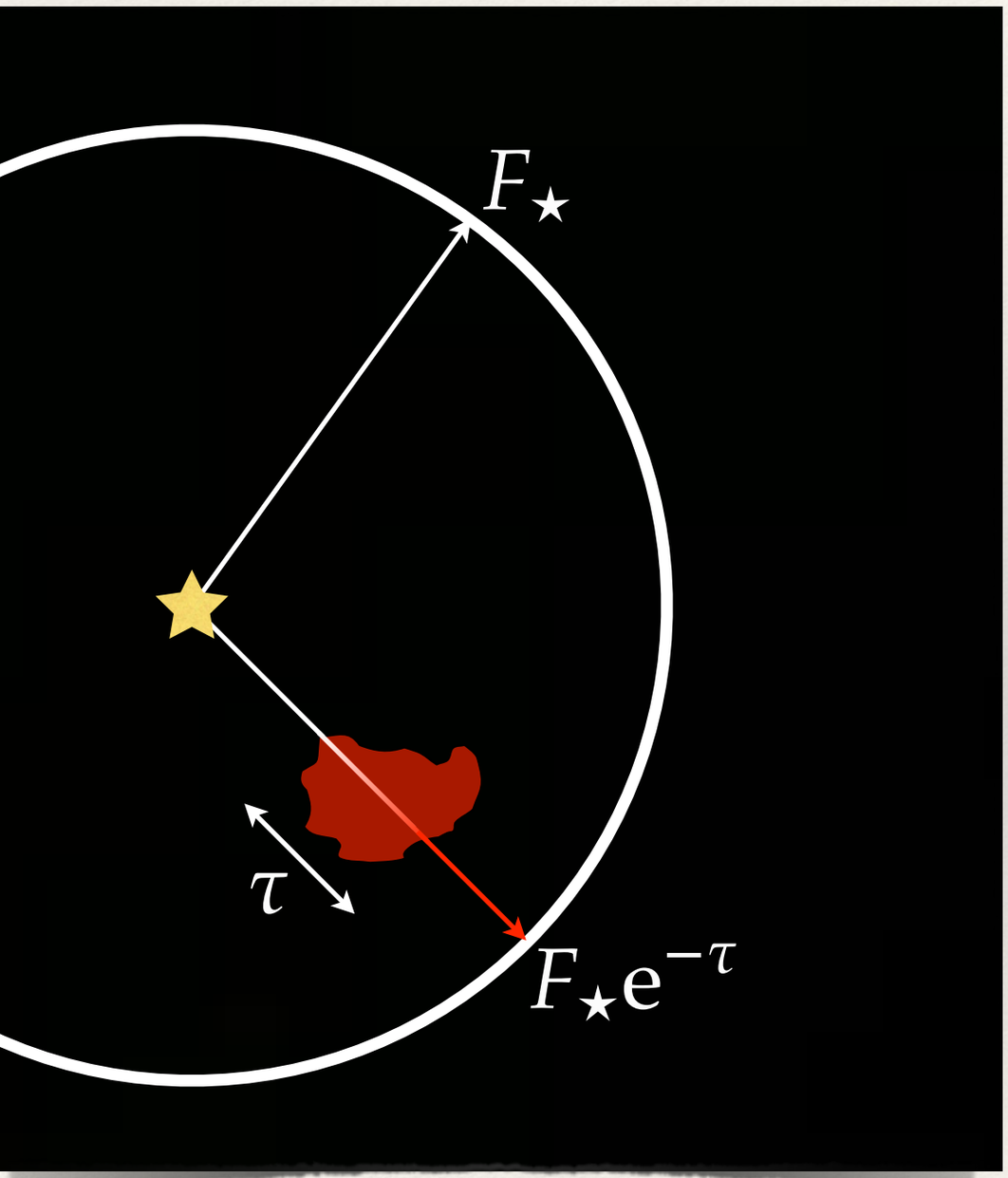

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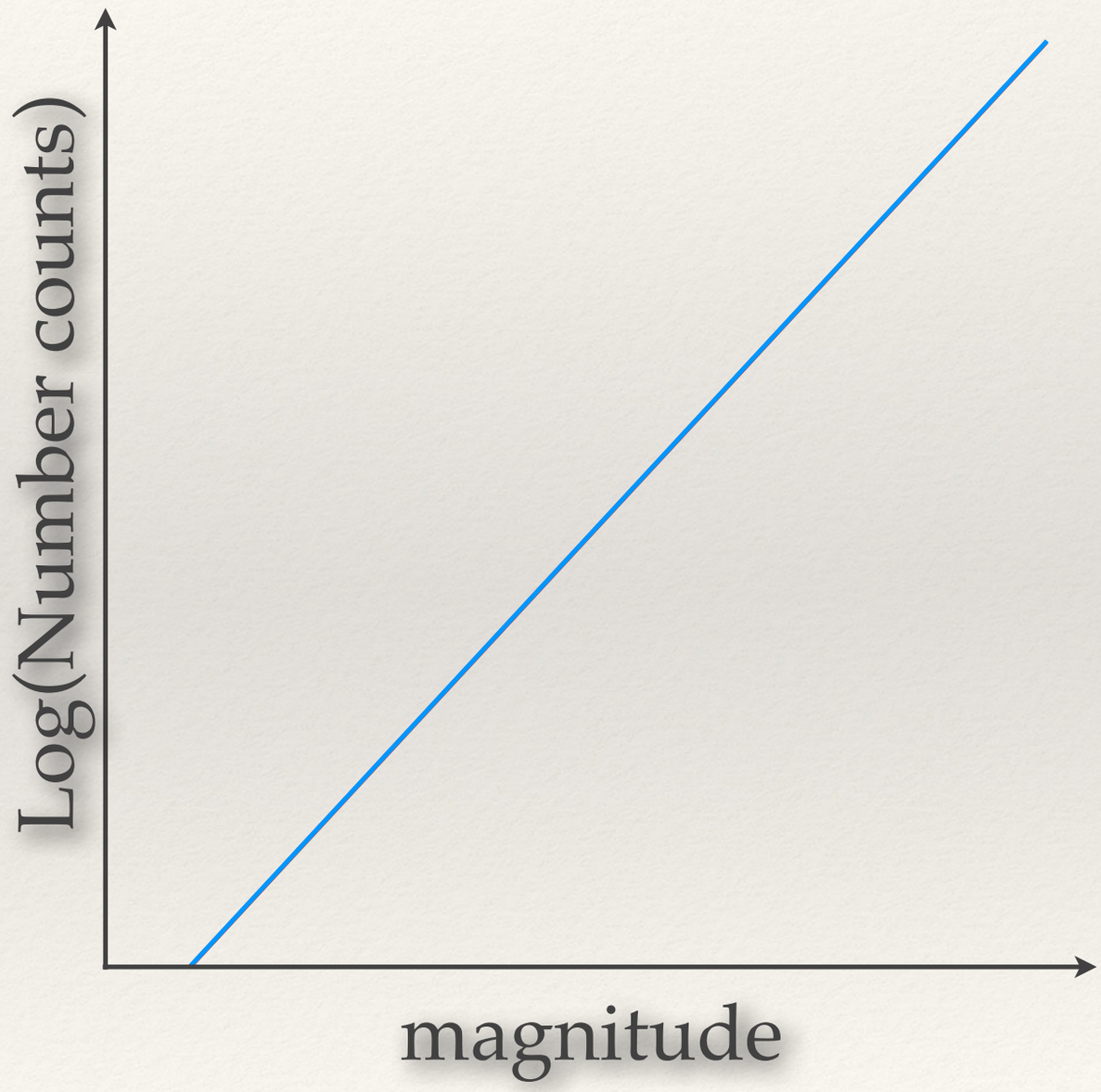

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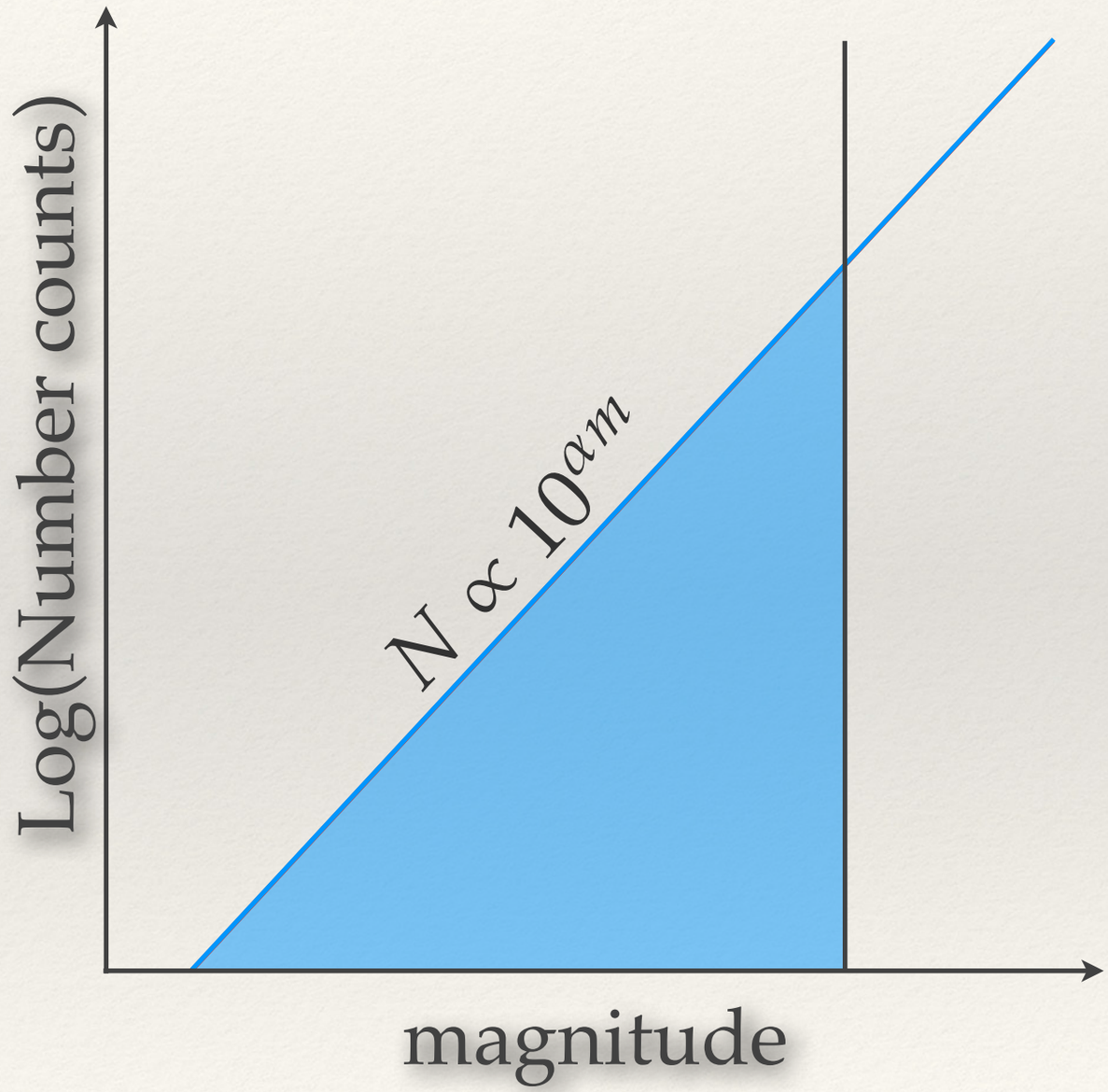

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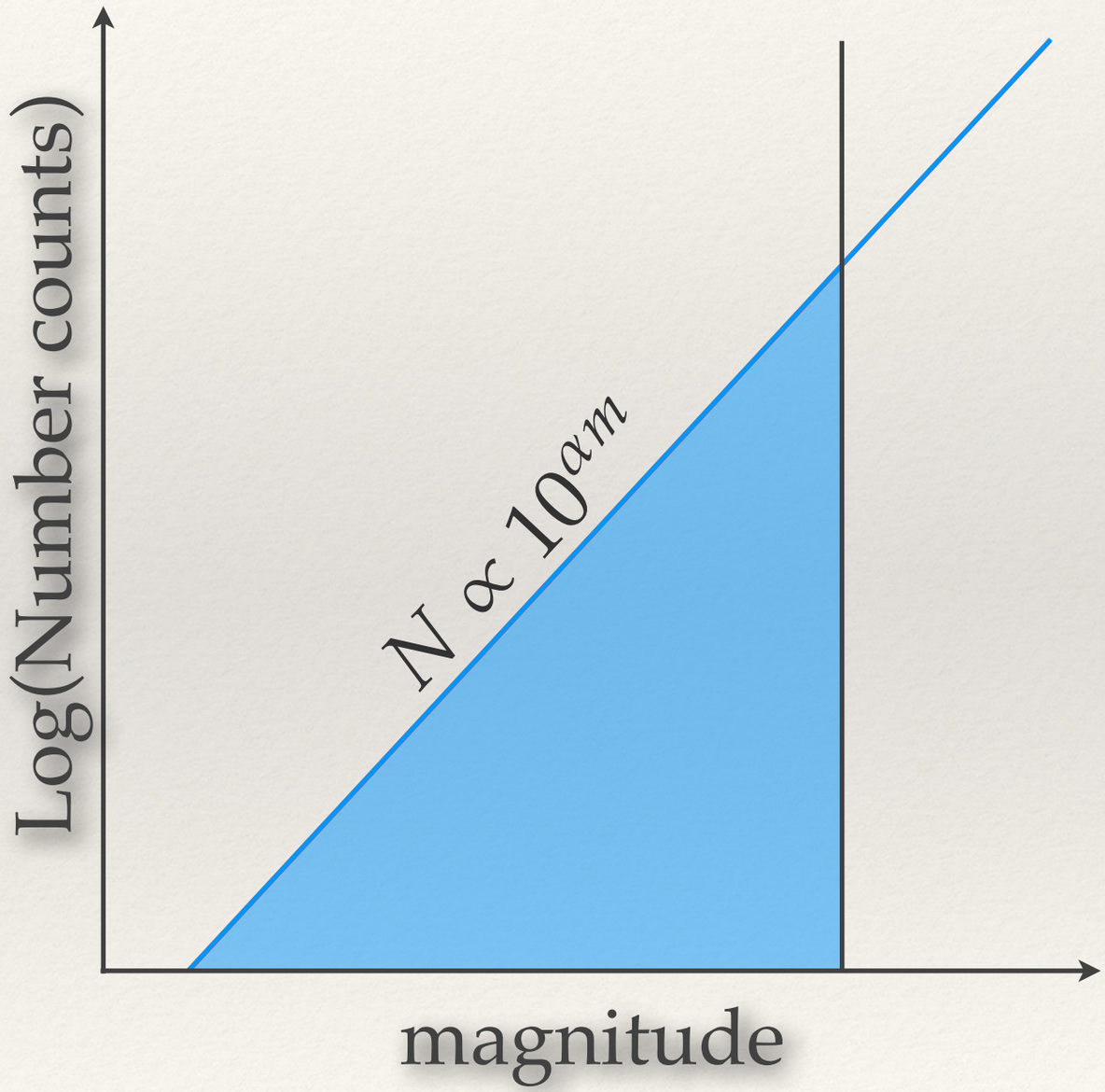

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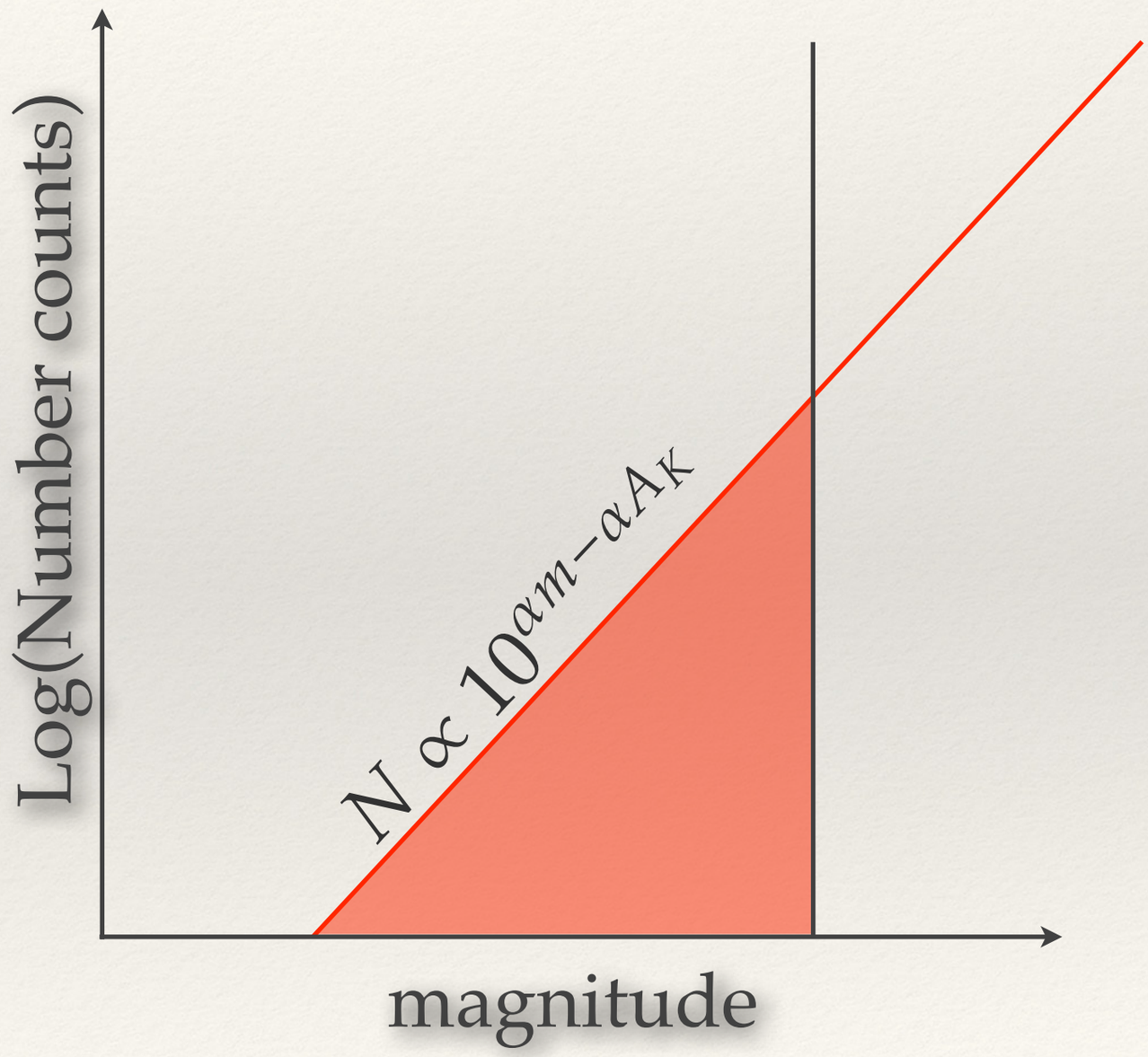

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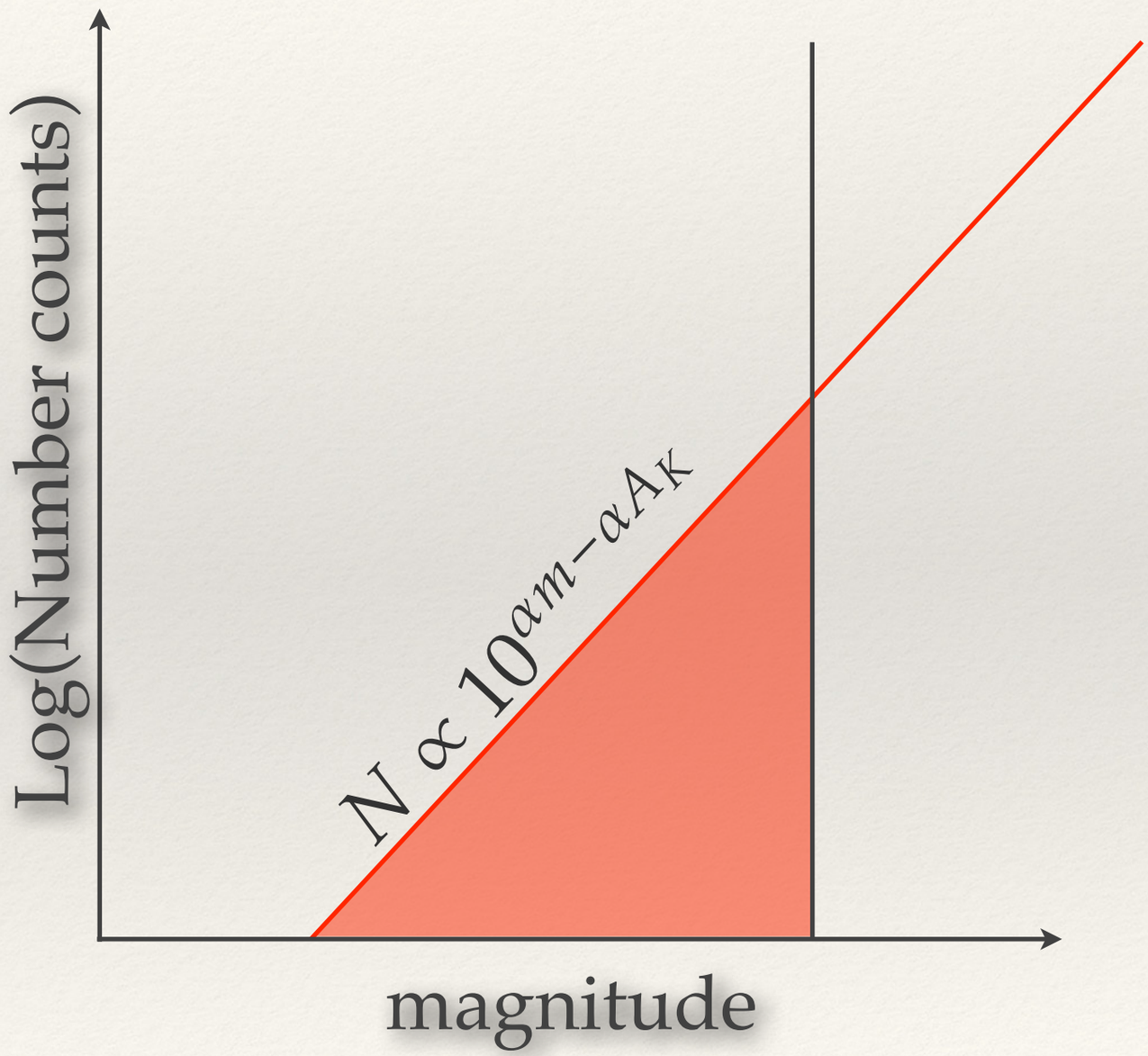

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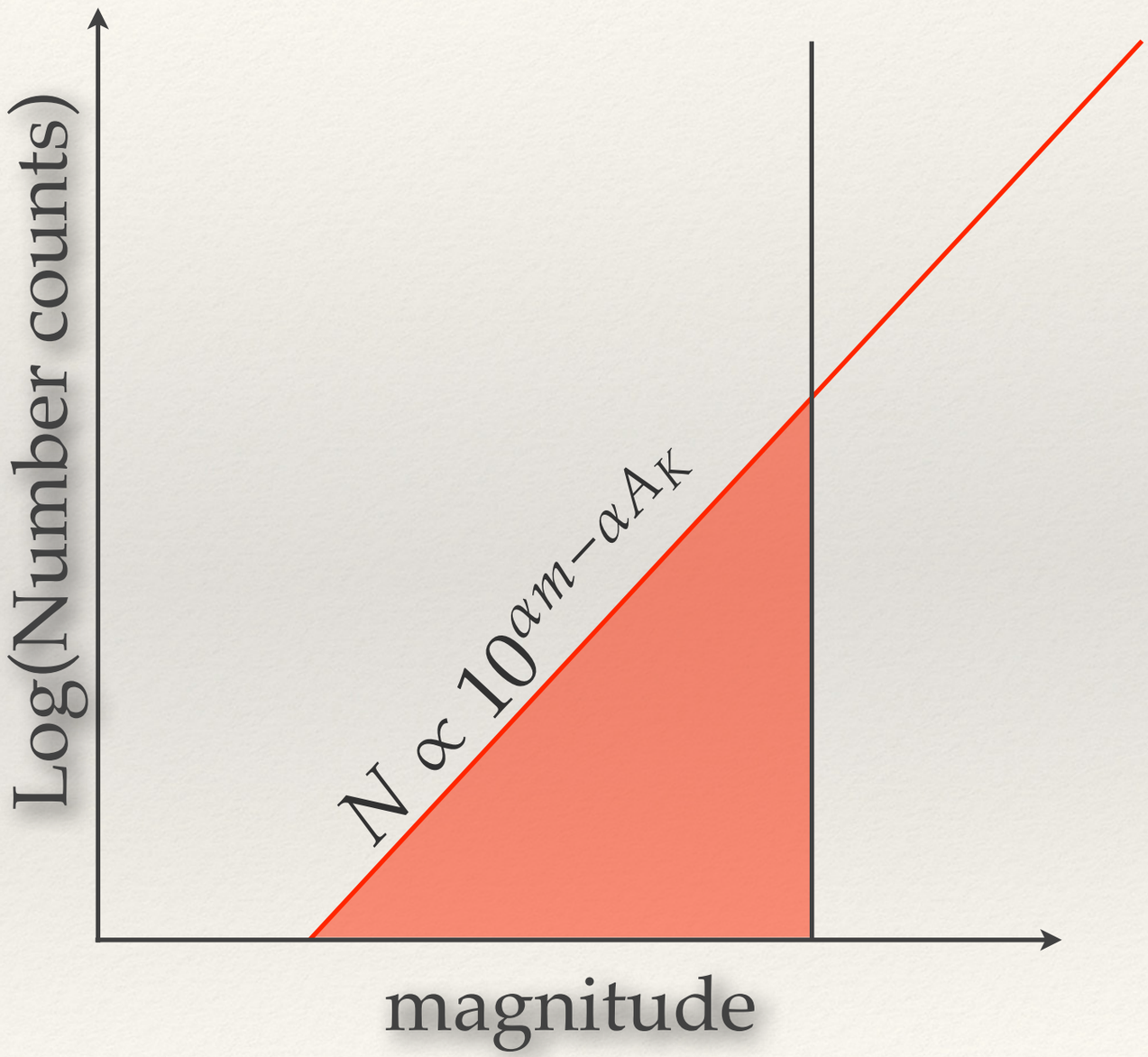

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Lombardi (in prep.)

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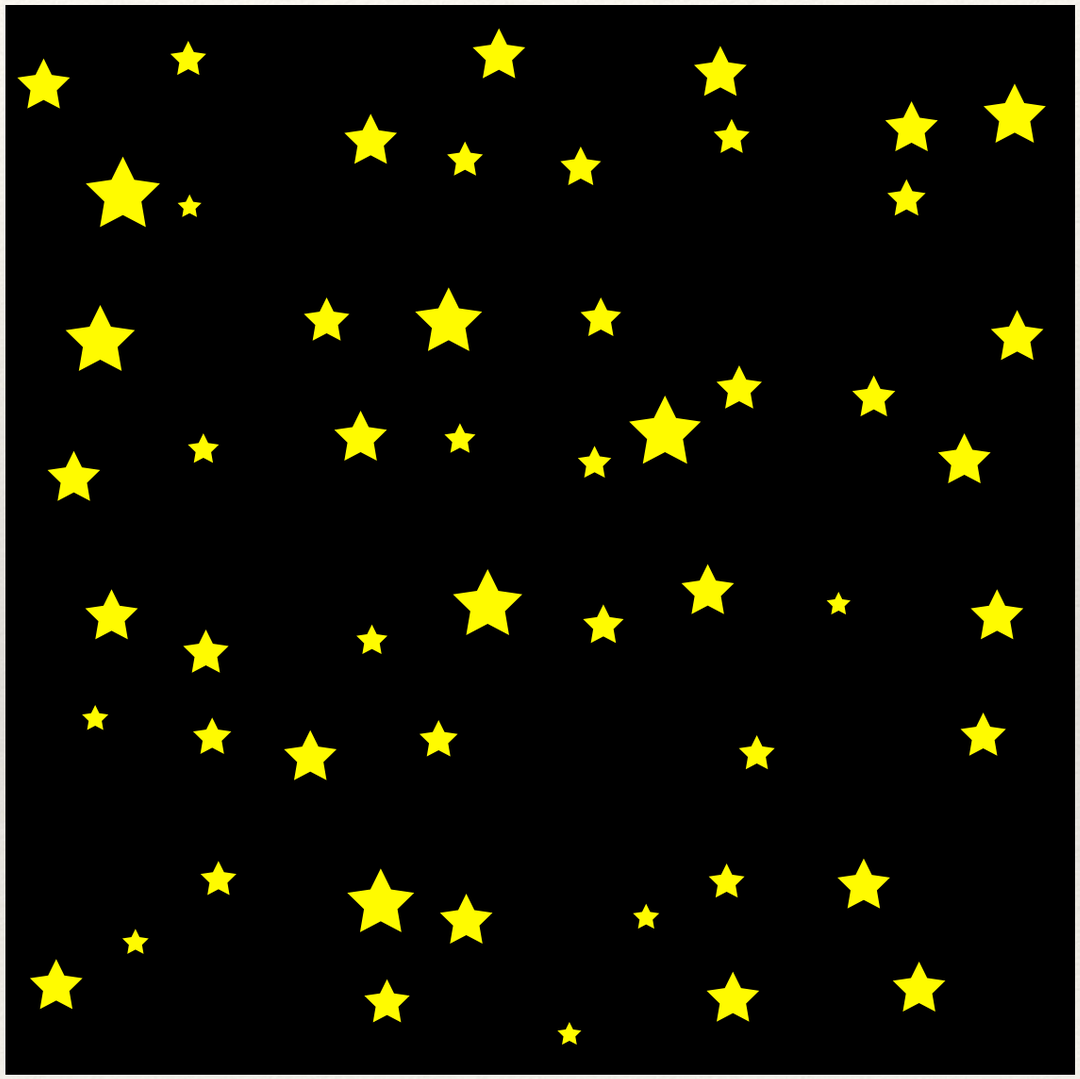

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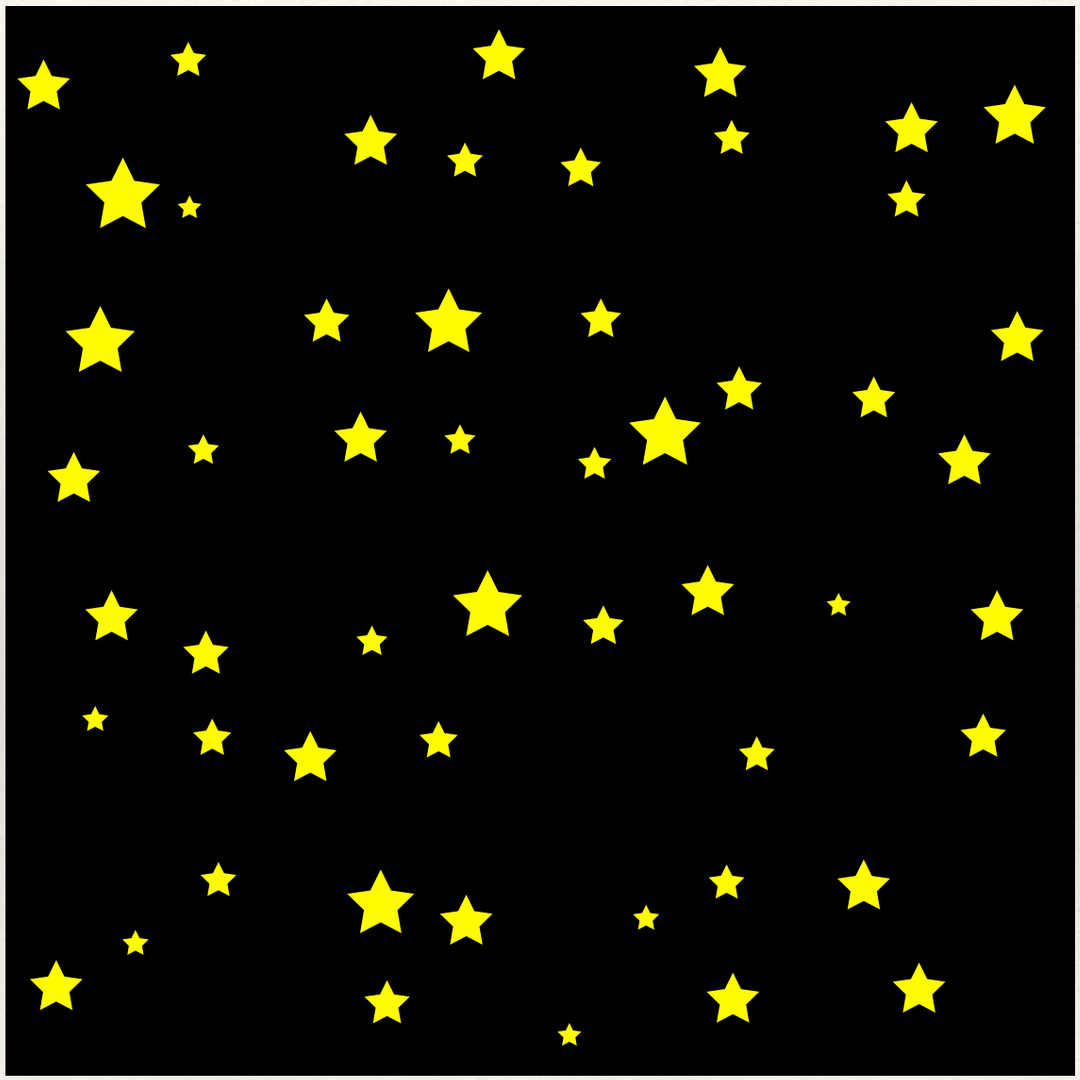

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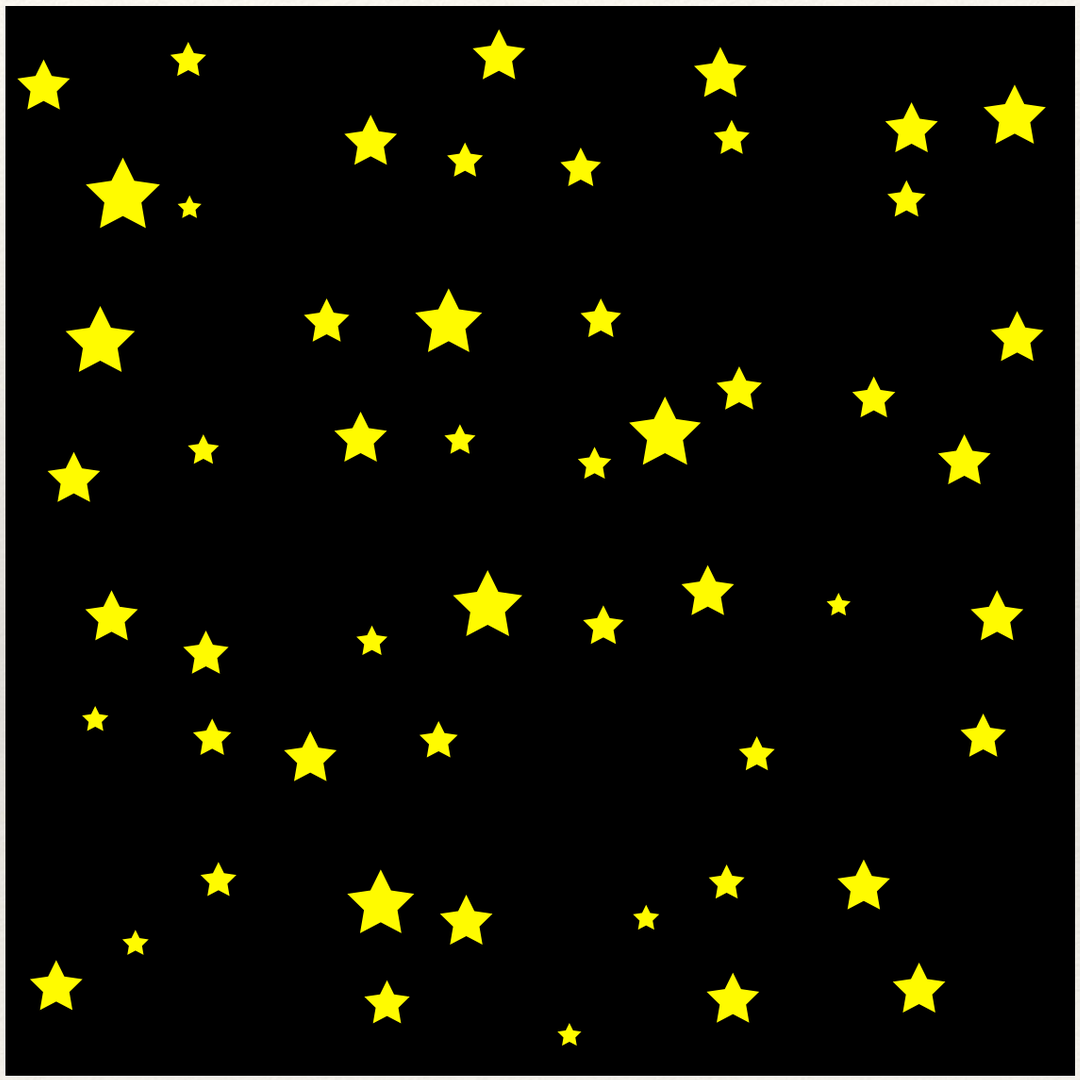

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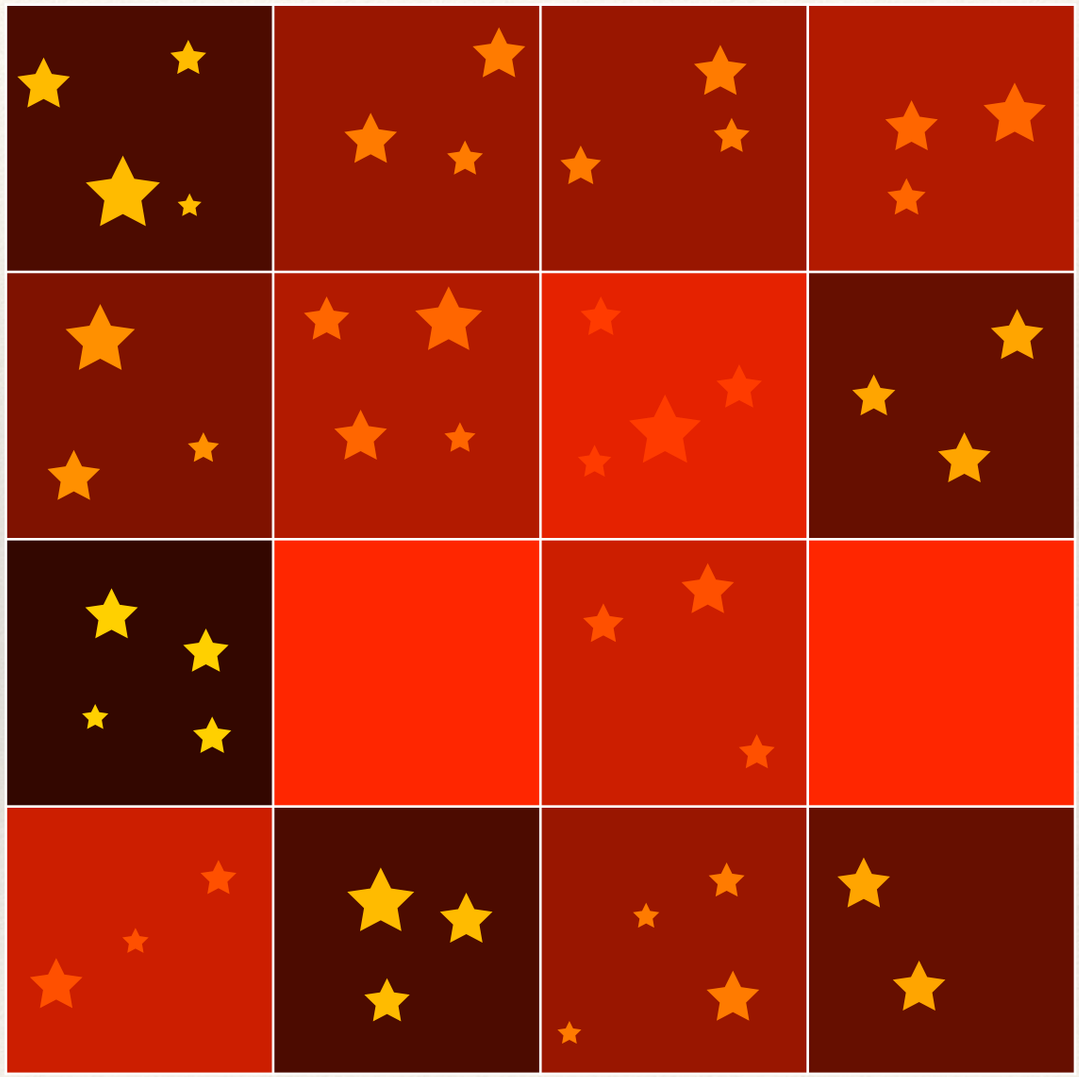

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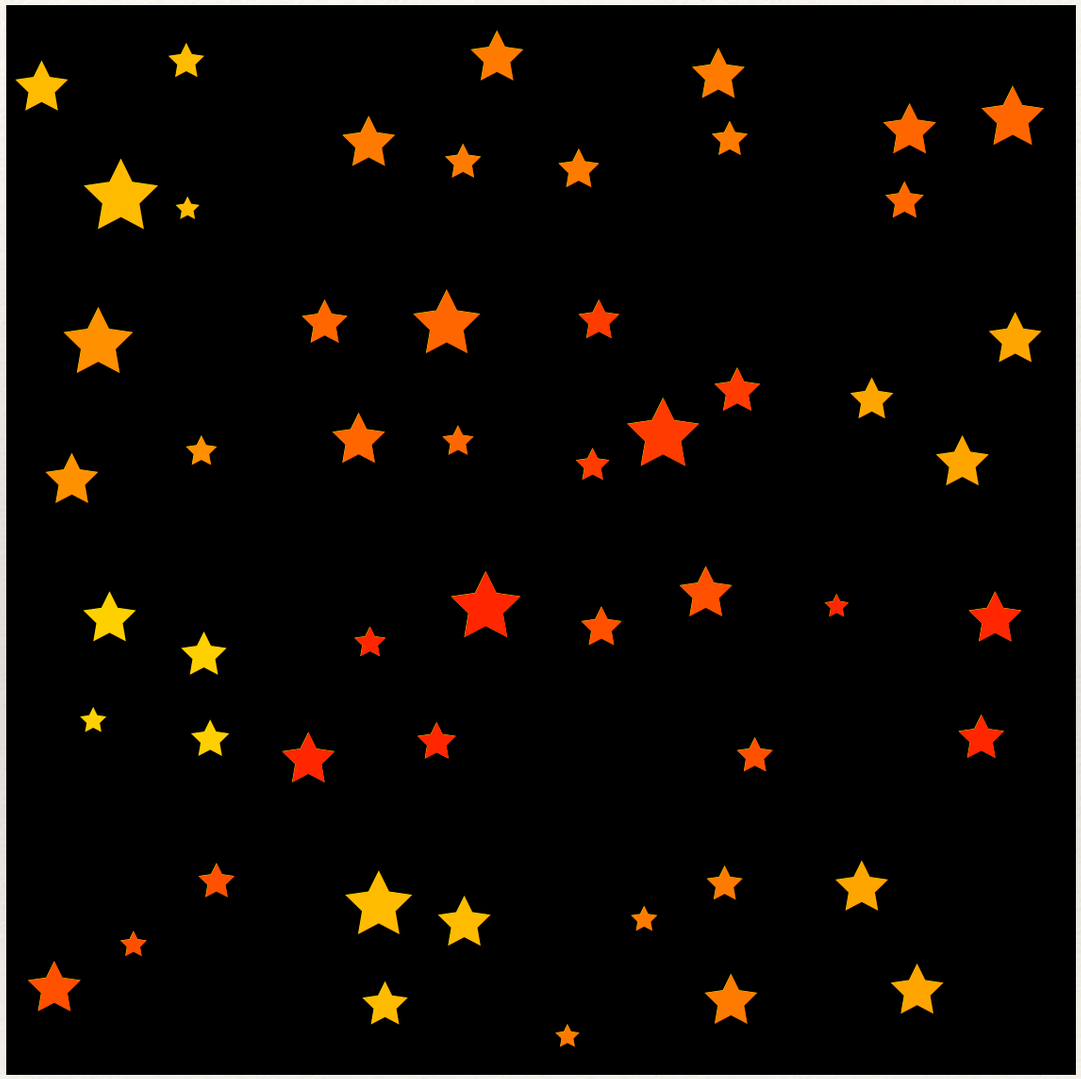

XNICEST: unresolved substructures

Lombardi (in prep.)

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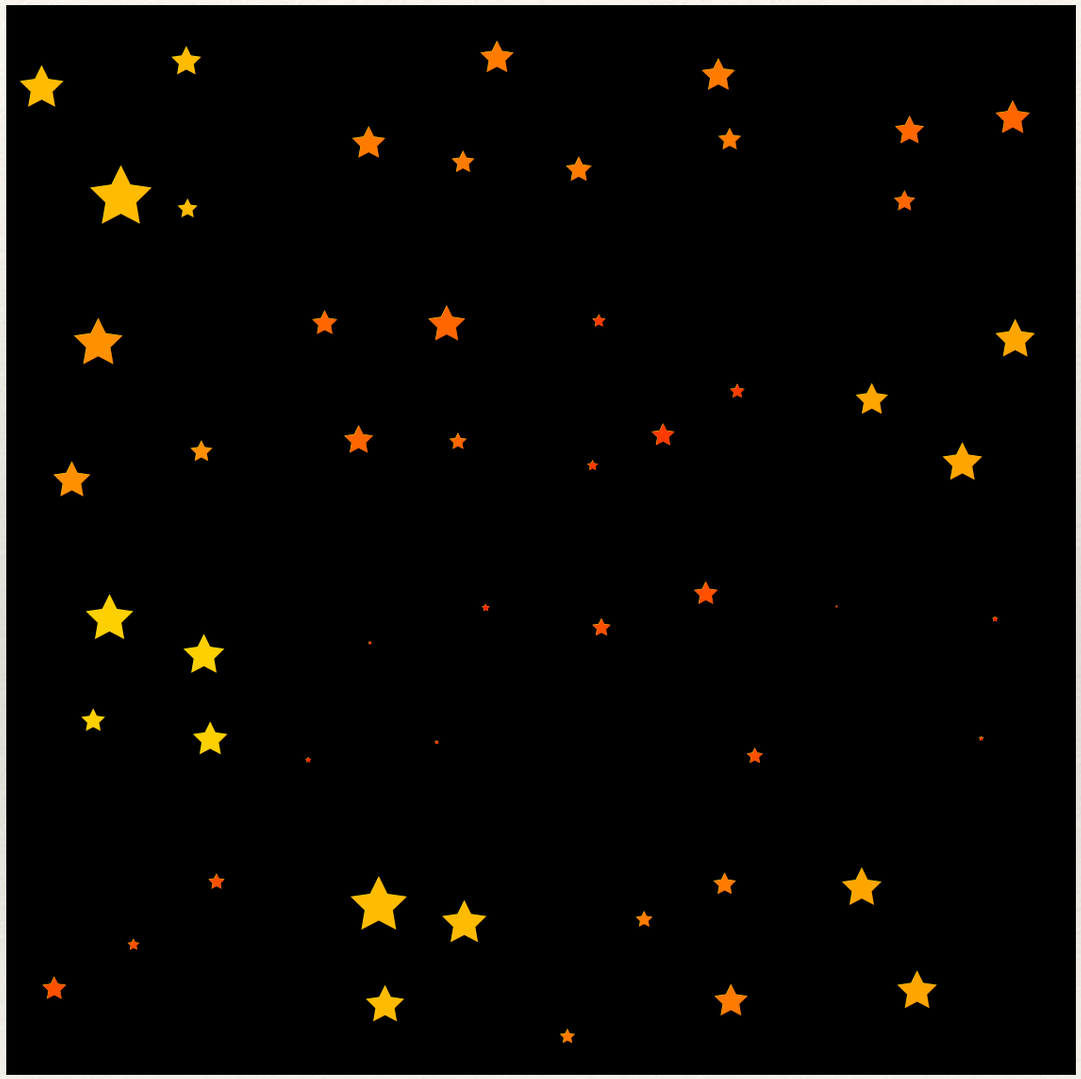

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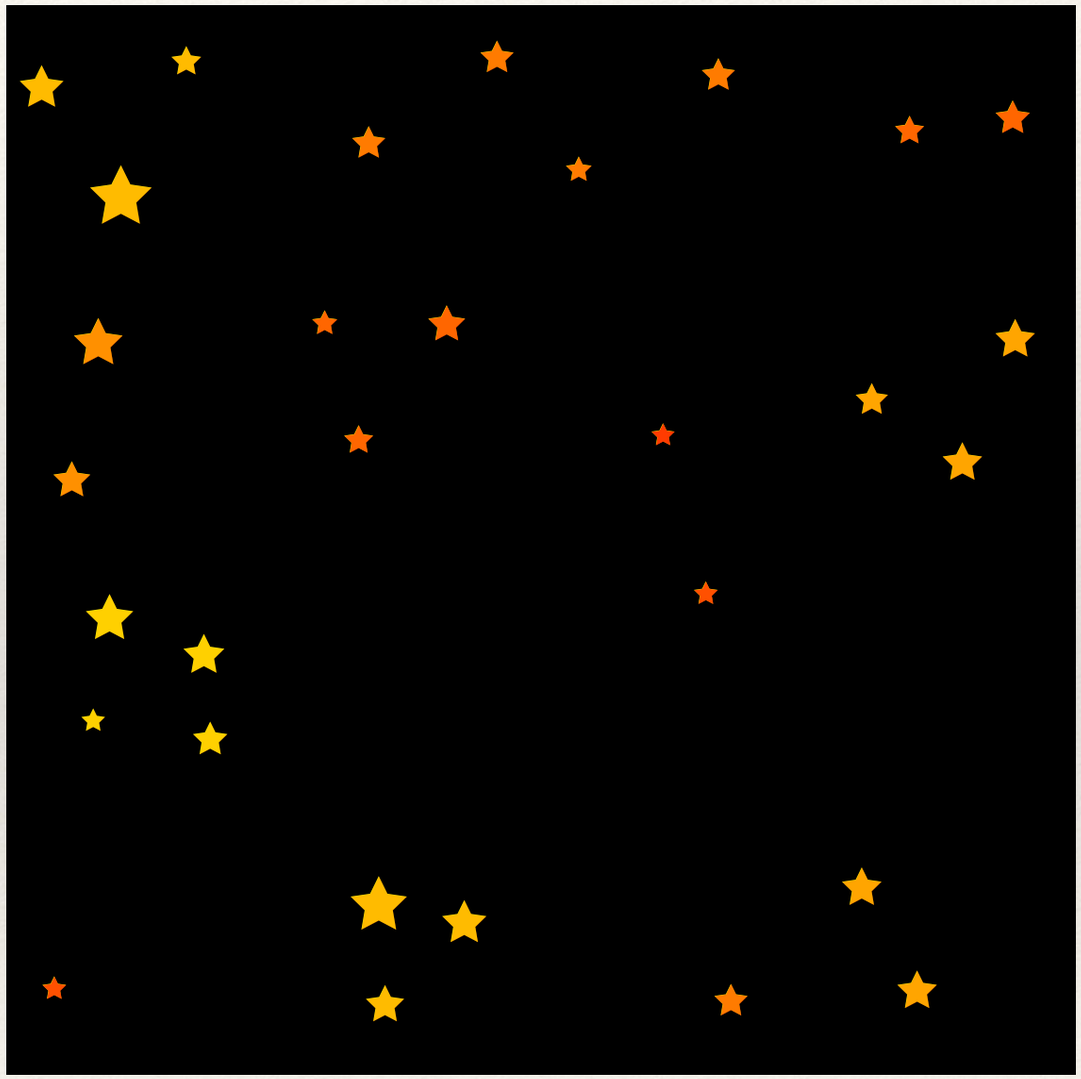

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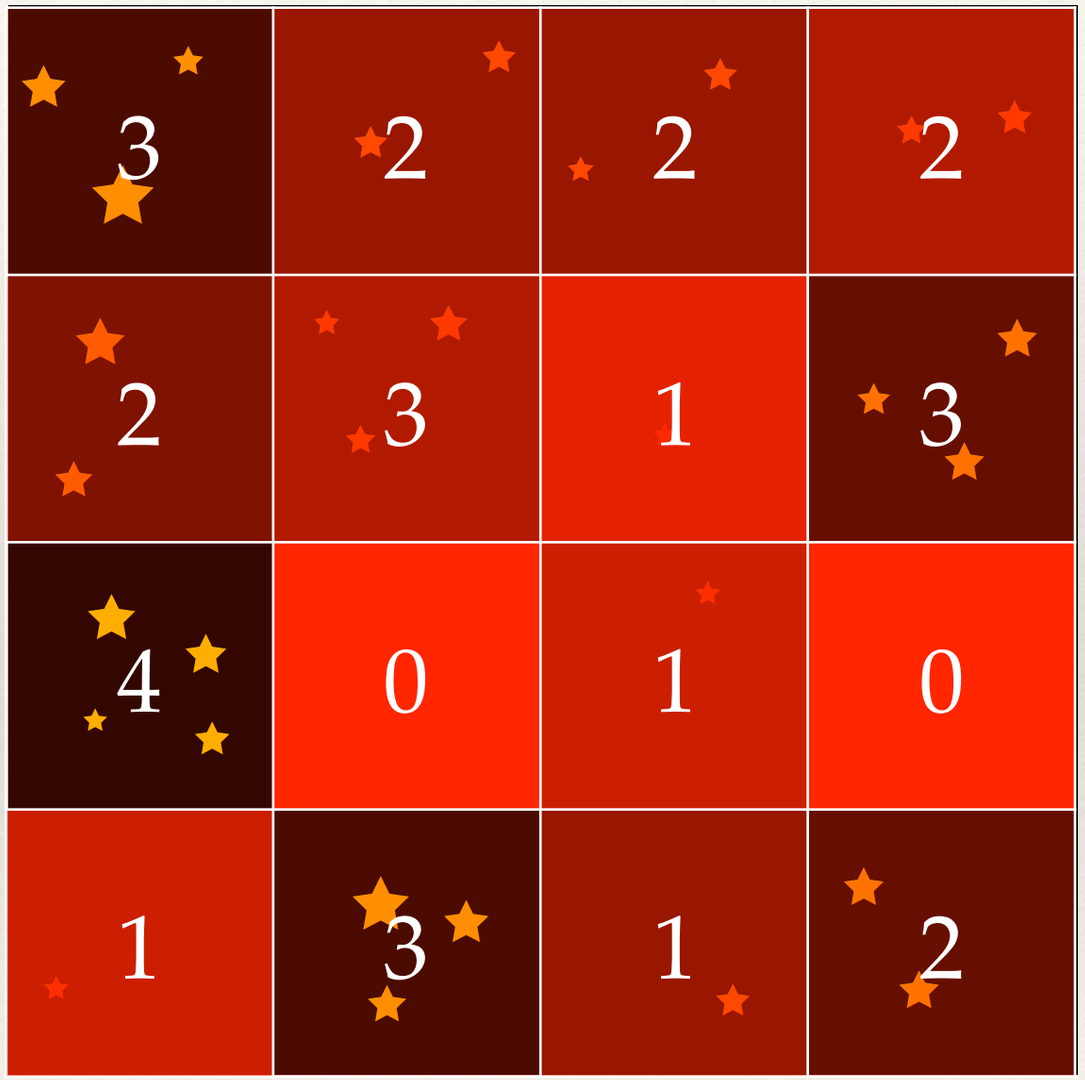

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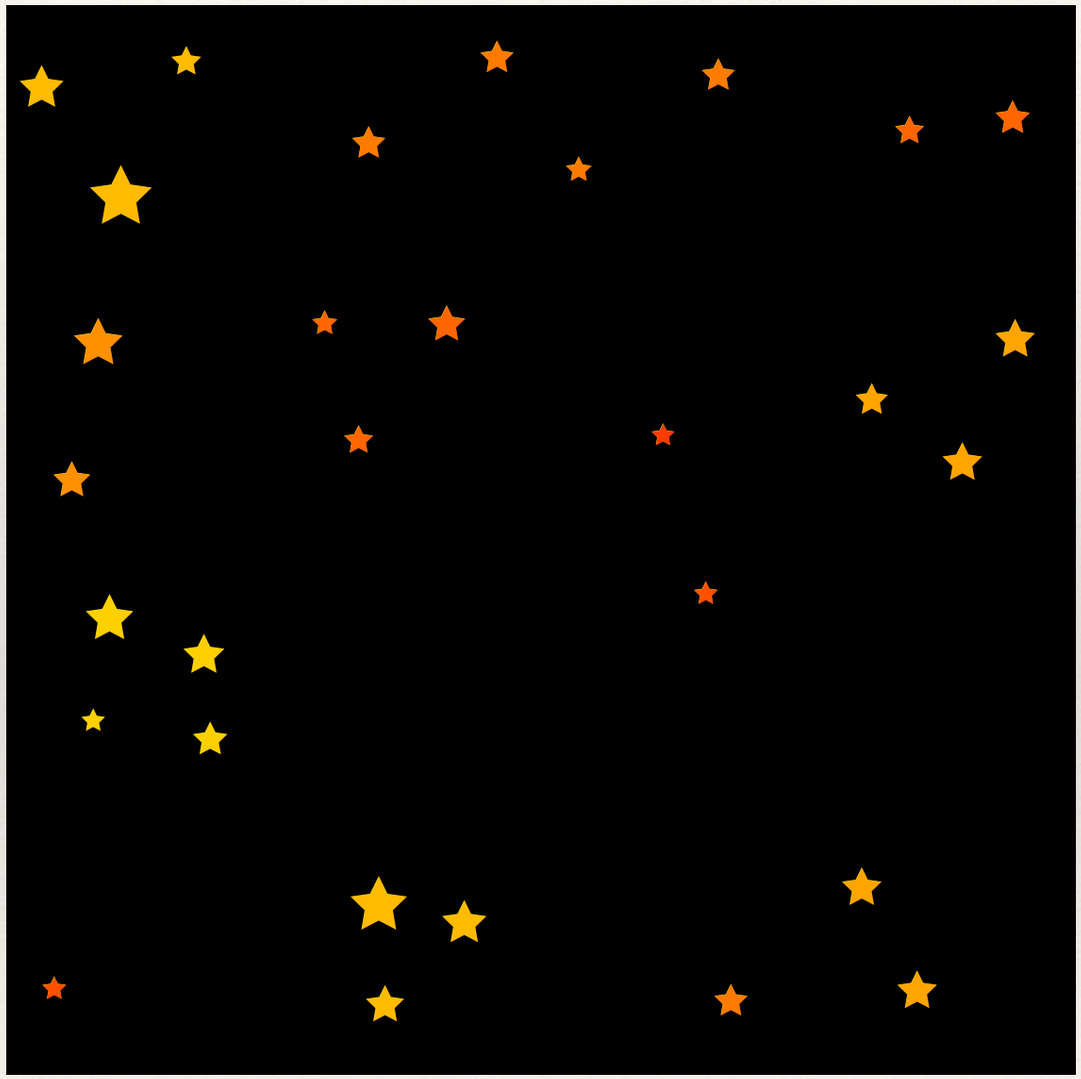

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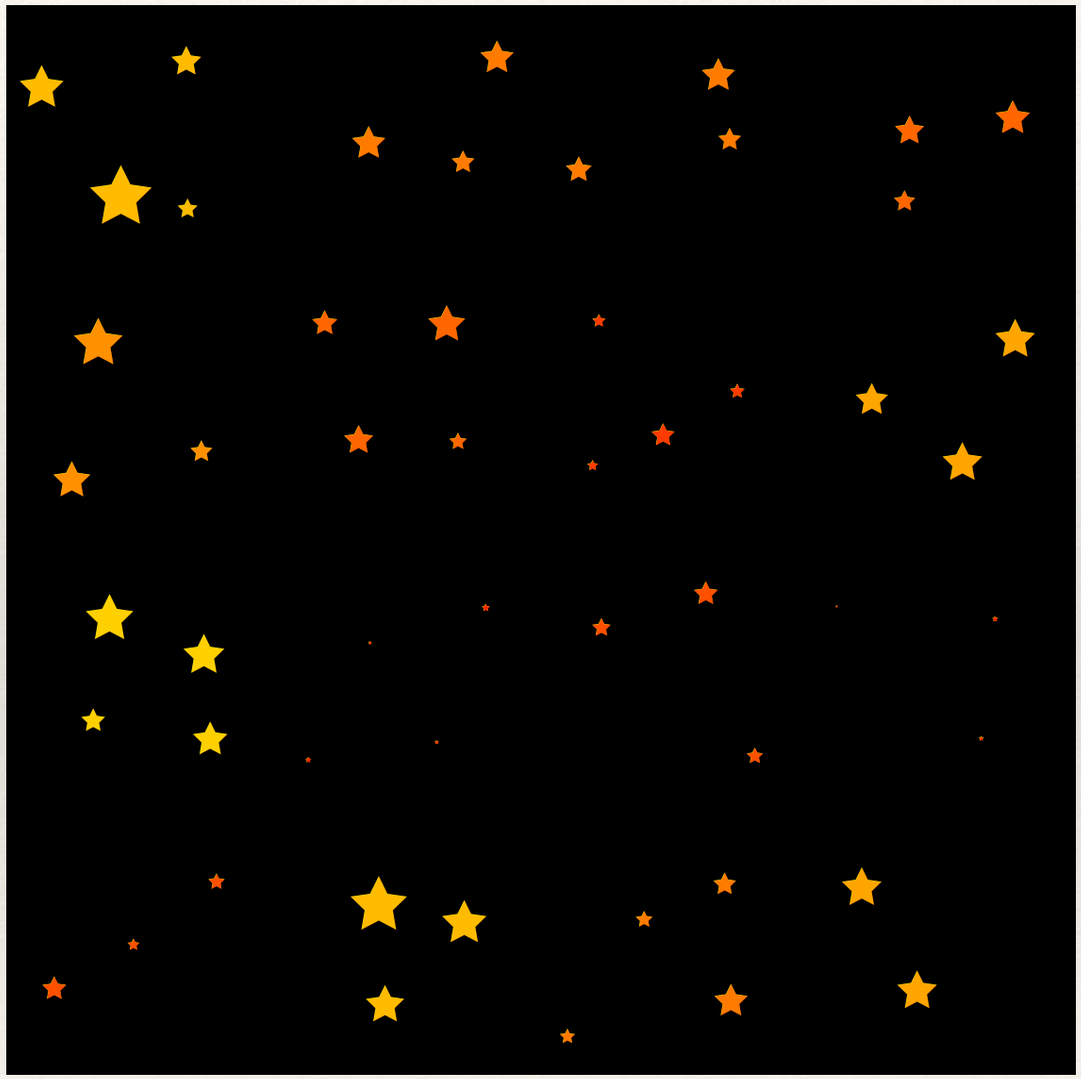

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- Solution: weight each star by the inverse of its detection probability (Lombardi 2009)