Filaments, surface density and scaling laws in star and structure formation

Marco Lombardi, University of Milan

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Marco Lombardi, University of Milan

with

Joao Alves, University of Vienna &
Charles Lada, CfA, Harward

Penitenziagite

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Meingast et al. (2015)

$Z=Z_{\odot}$
134606 yr
Matthew Bate
University of Exeter


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- Each tracer has its own benefits and limitations!

Extinction Primer

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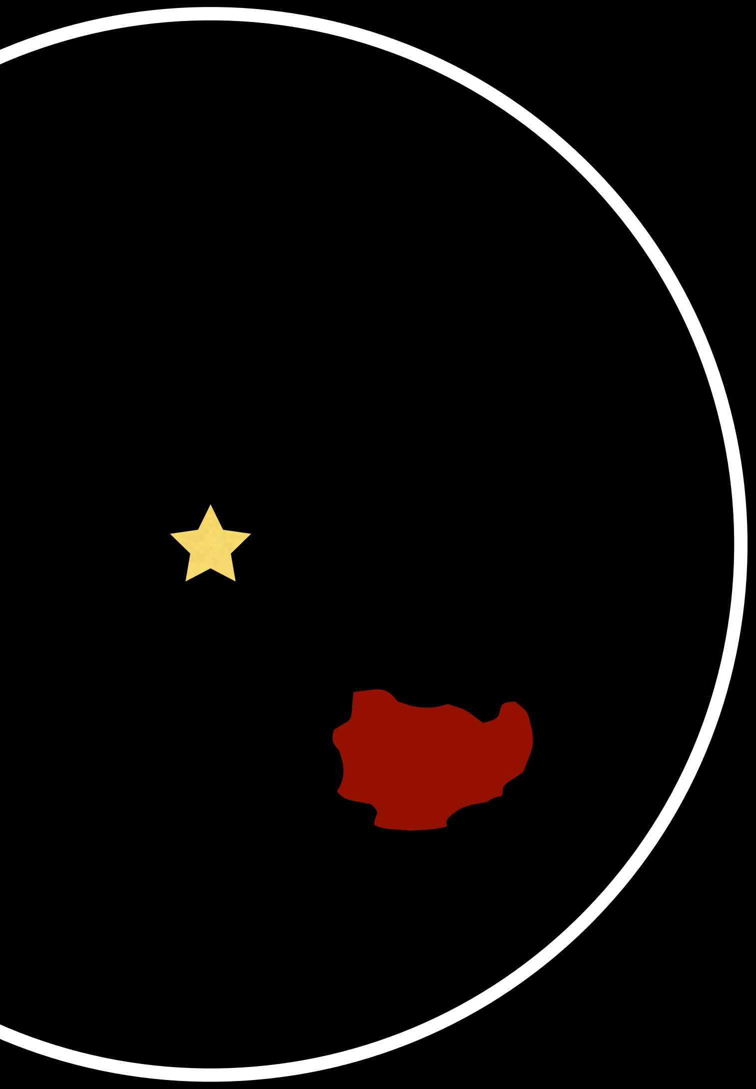

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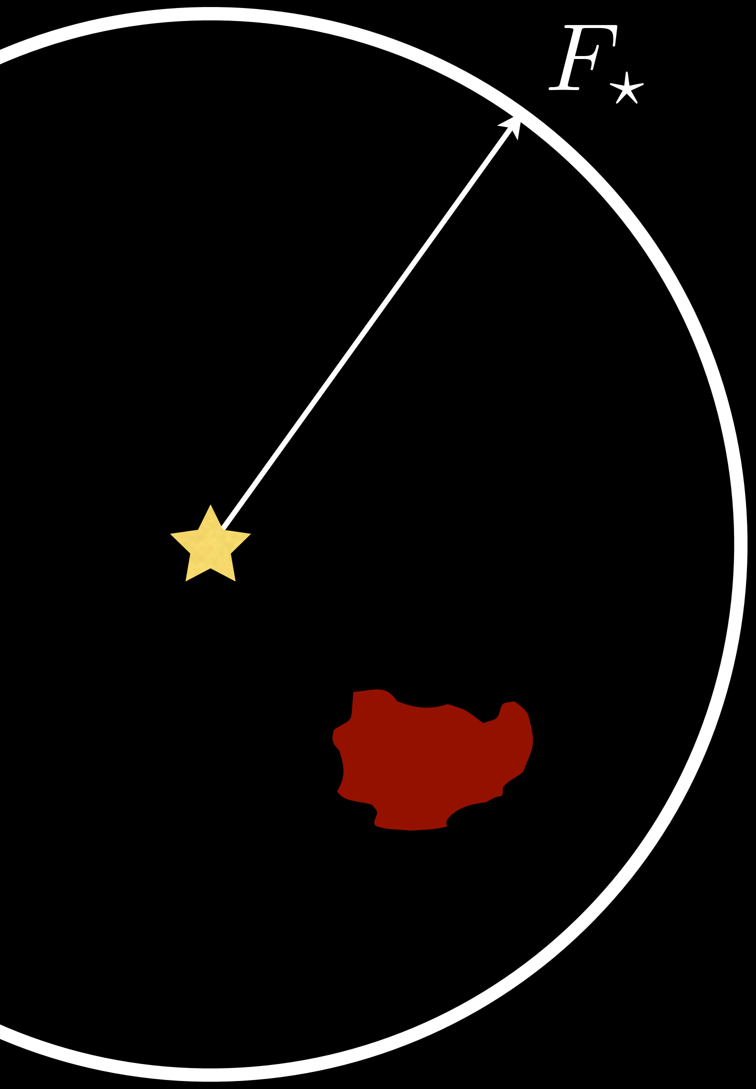

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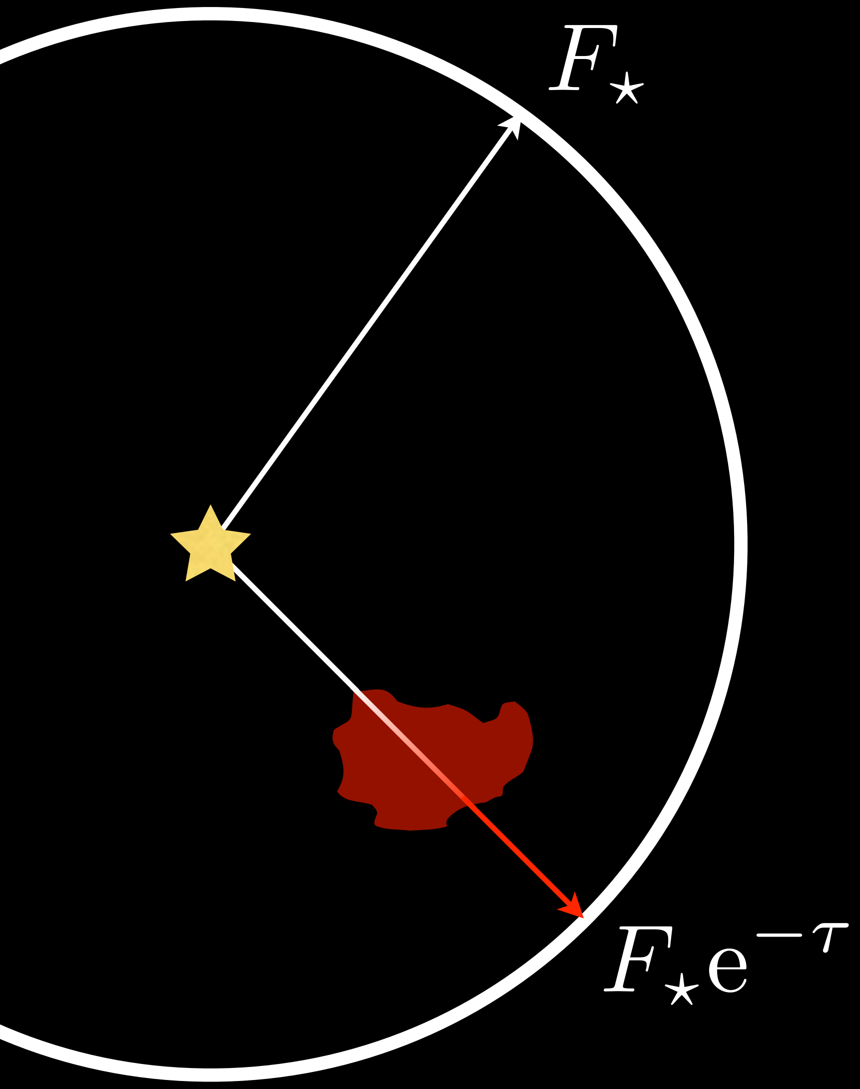

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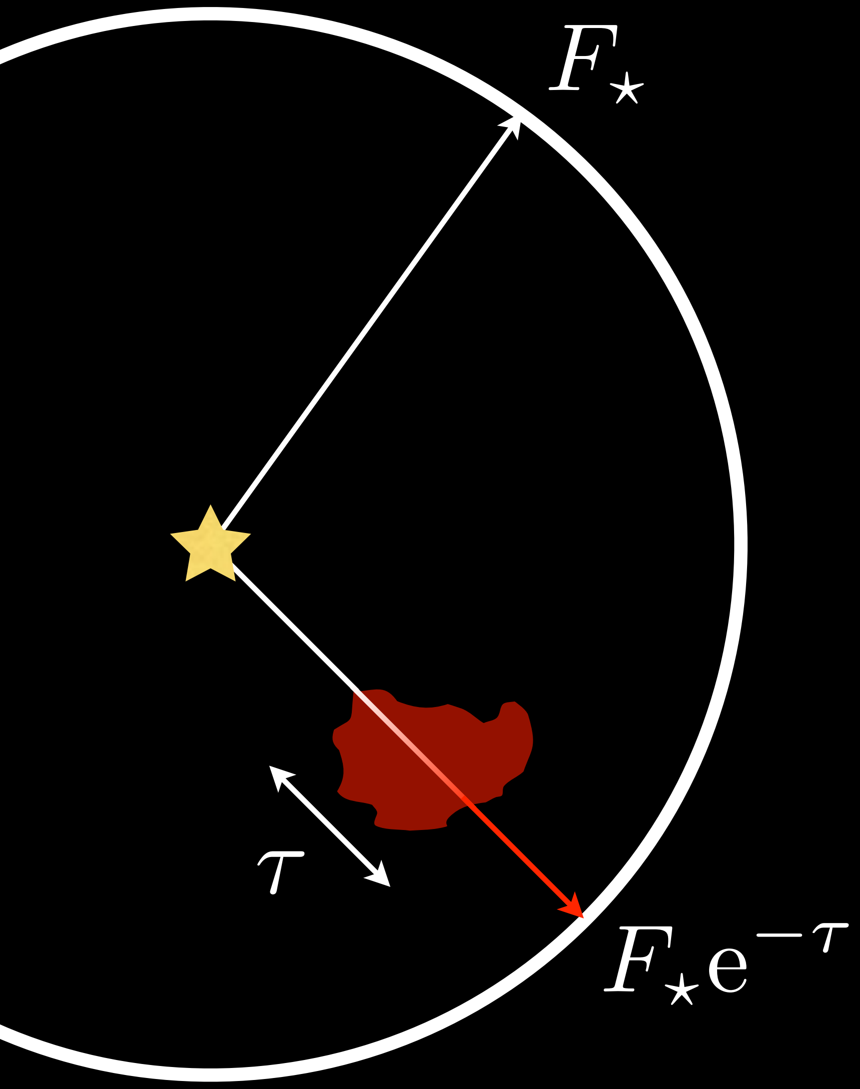

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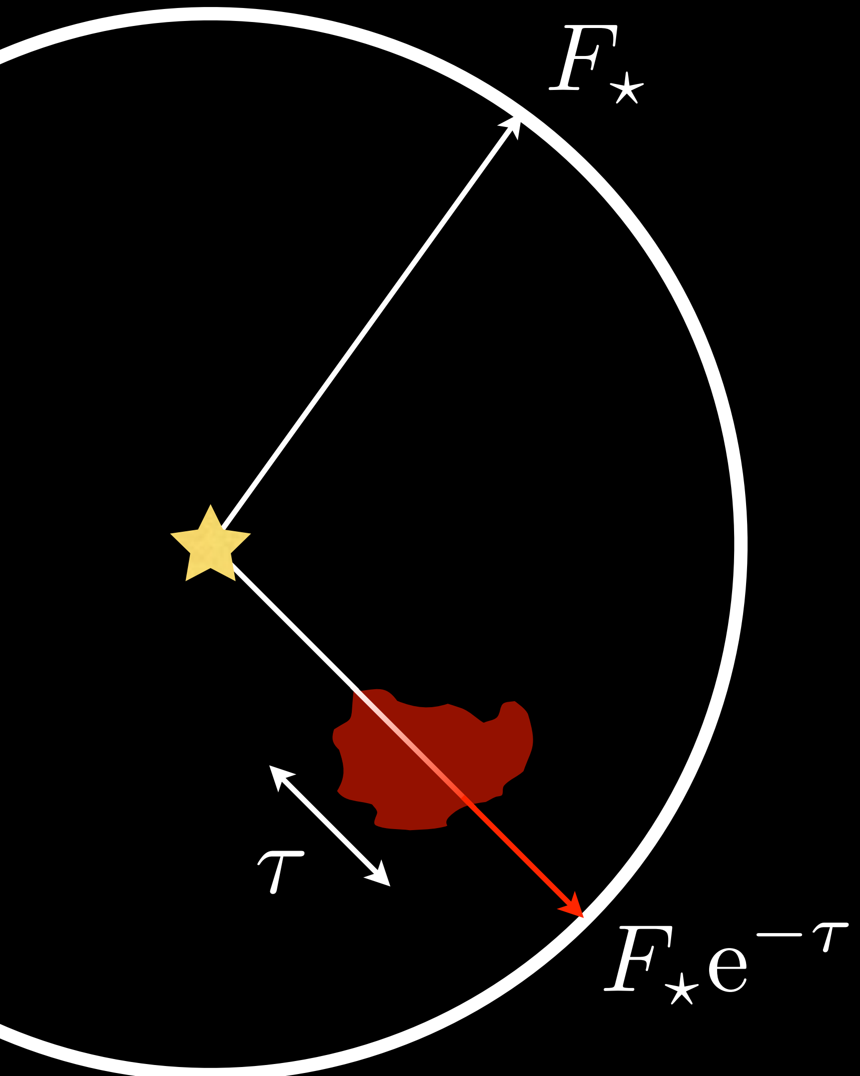
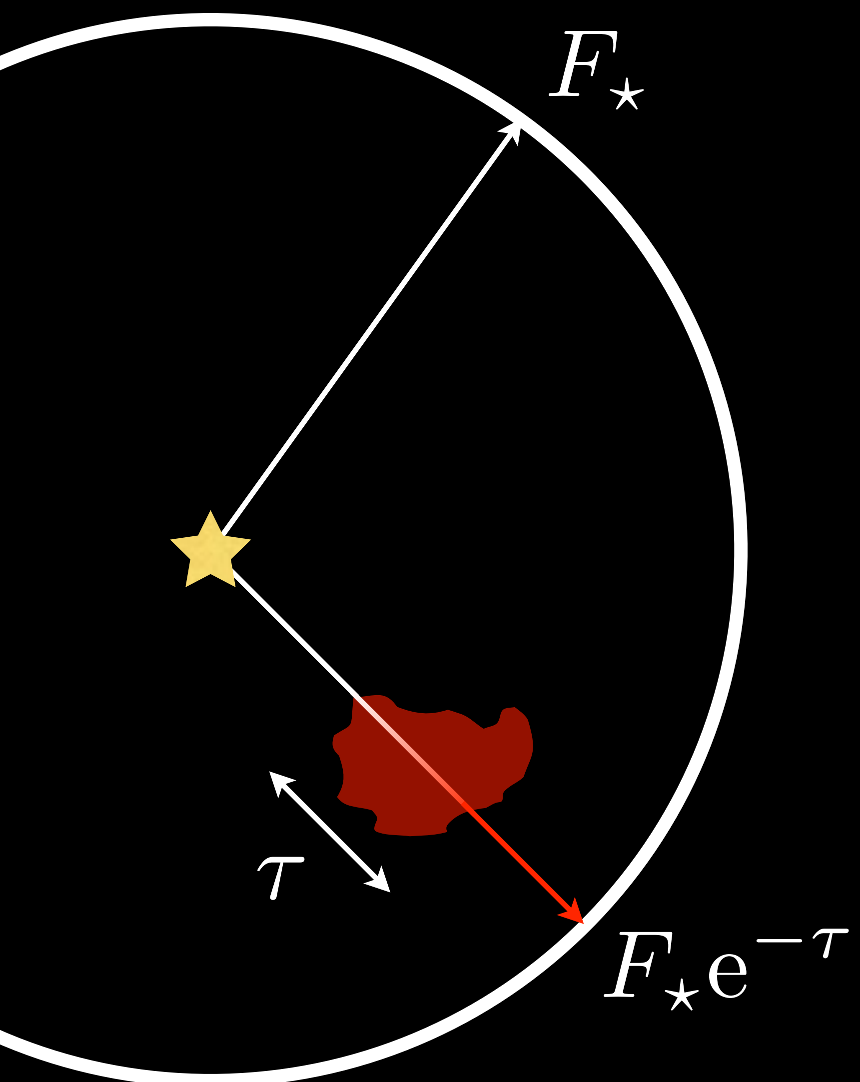


Brightness

$$m_{\mathrm{obs}} = -2.5 \log \left(F_\star \mathrm{e}^{-\tau} \right)$$

$$= -\underbrace{2.5 \log F_\star}_{m_\star} + \underbrace{2.5\, \tau \log \mathrm{e}}_{A_{\mathrm{V}}}$$

Extinction Primer



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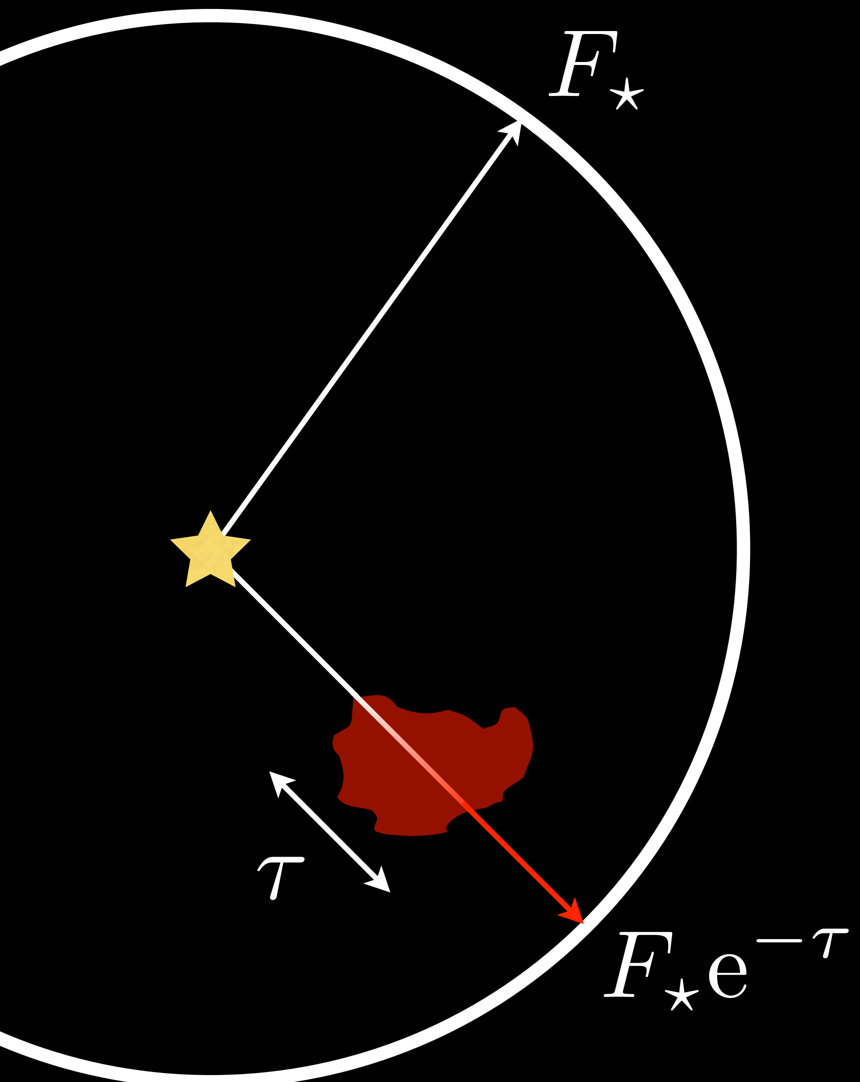

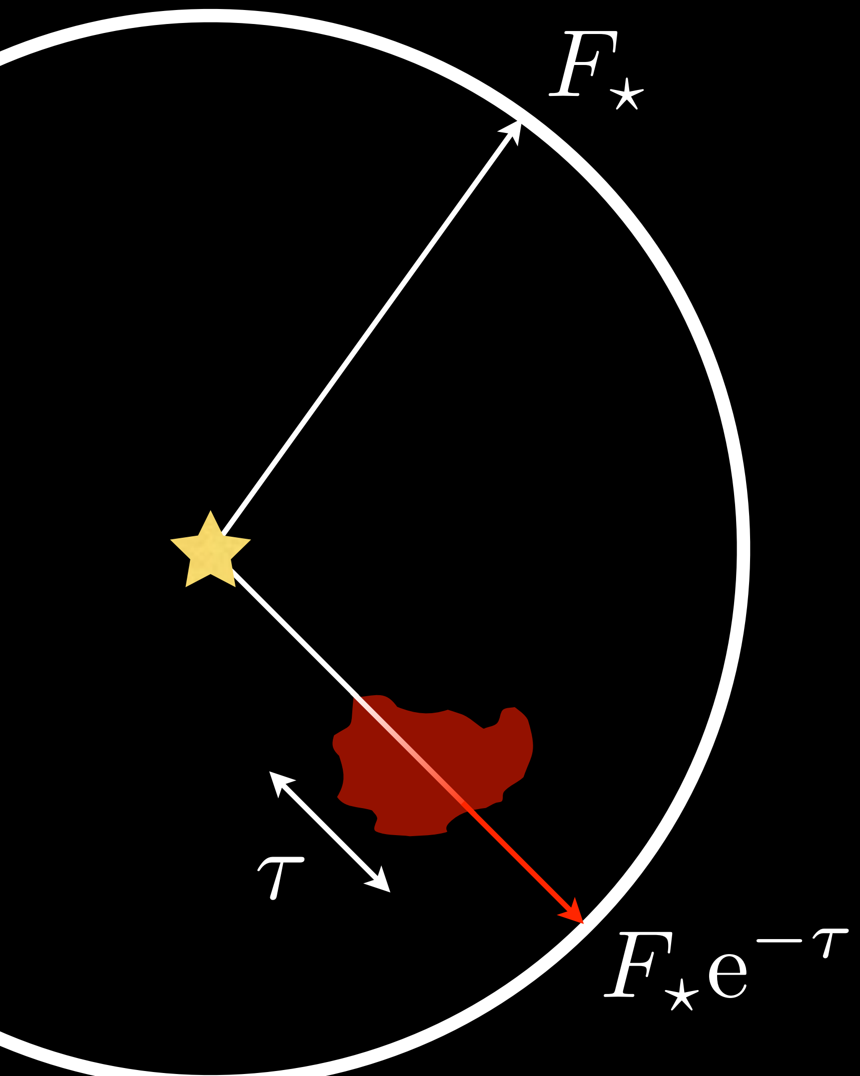

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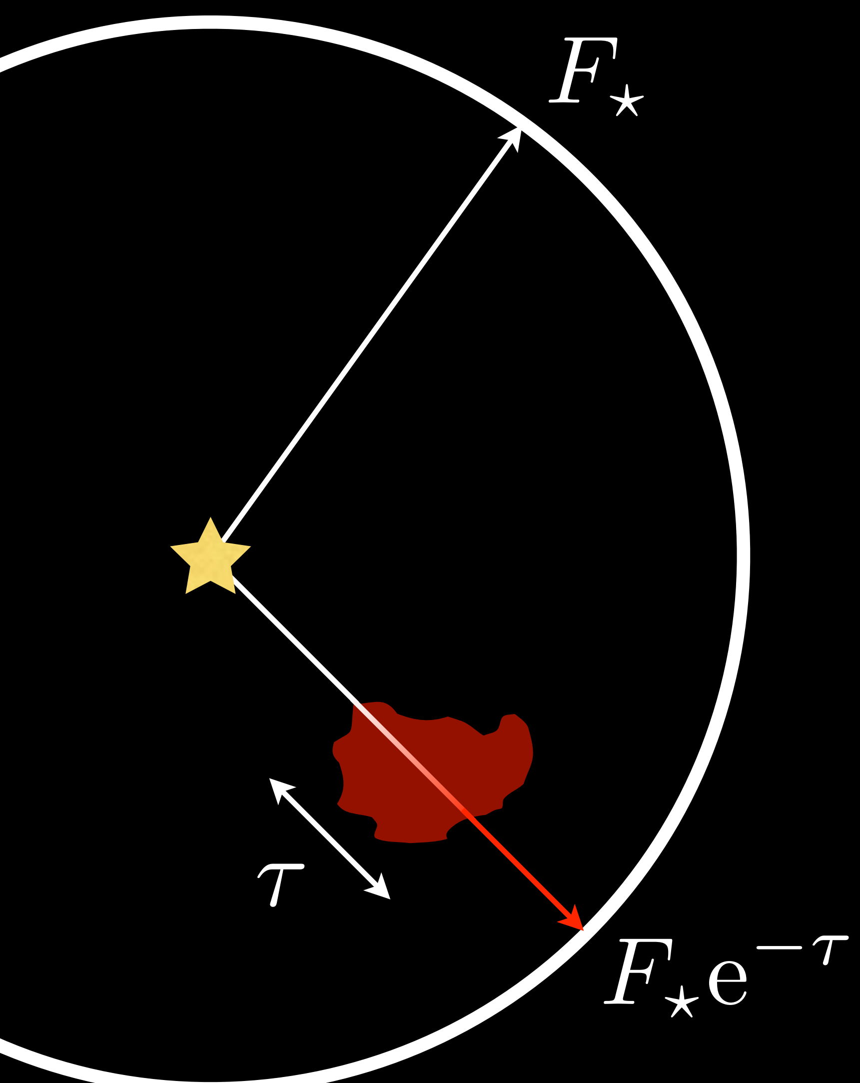
$$\Delta m = m_{\lambda_1} - m_{\lambda_2}$$



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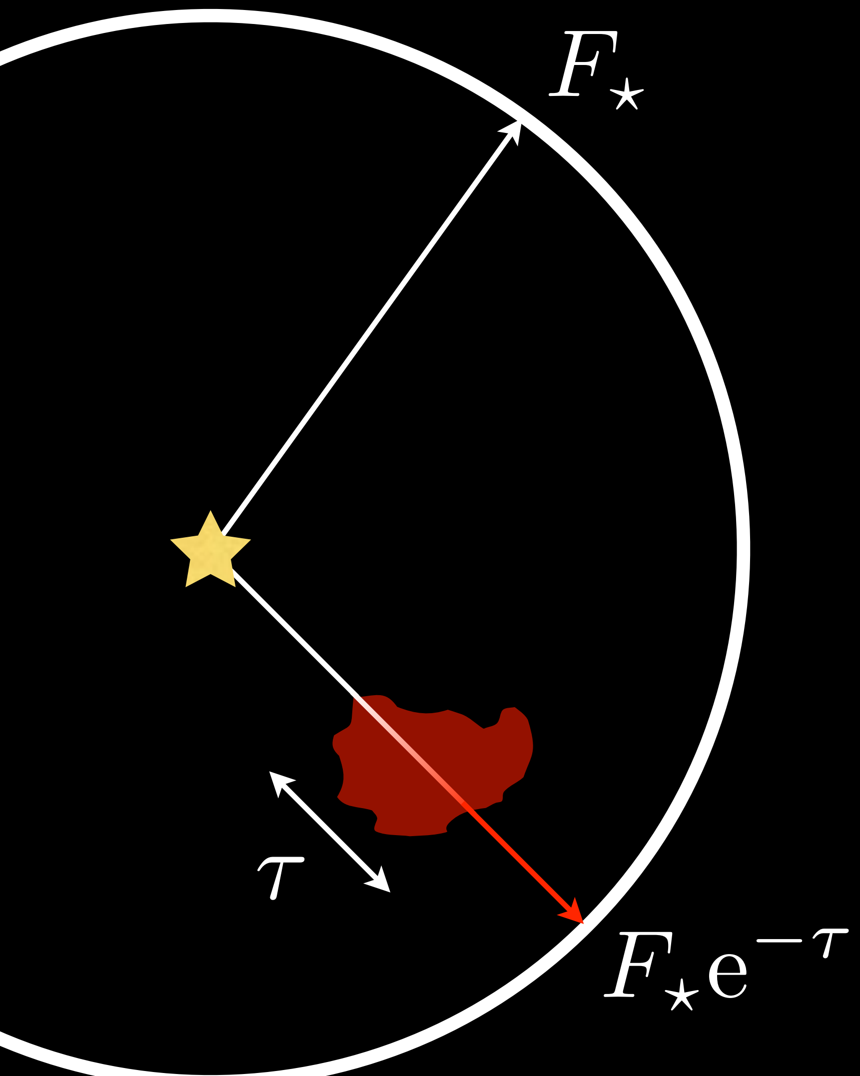

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$R_{1,2}$ parametrizes our knowledge (or ignorance) on the dust properties at the two frequencies λ_1 and λ_2

Making extinction maps

Alves et al. (2014)

Making extinction maps

- Take a cloud

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Making extinction maps

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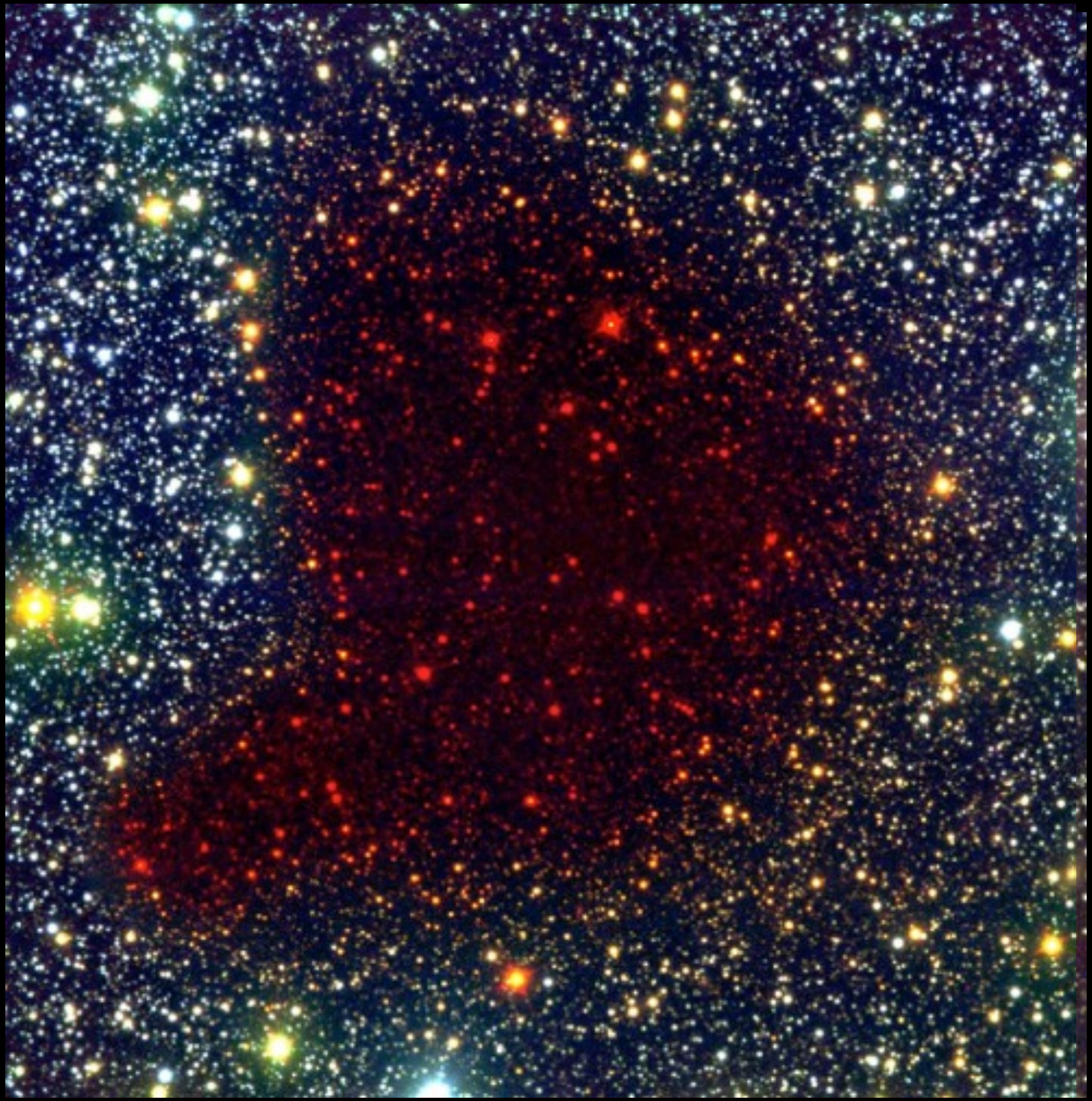
- Observe in the NIR



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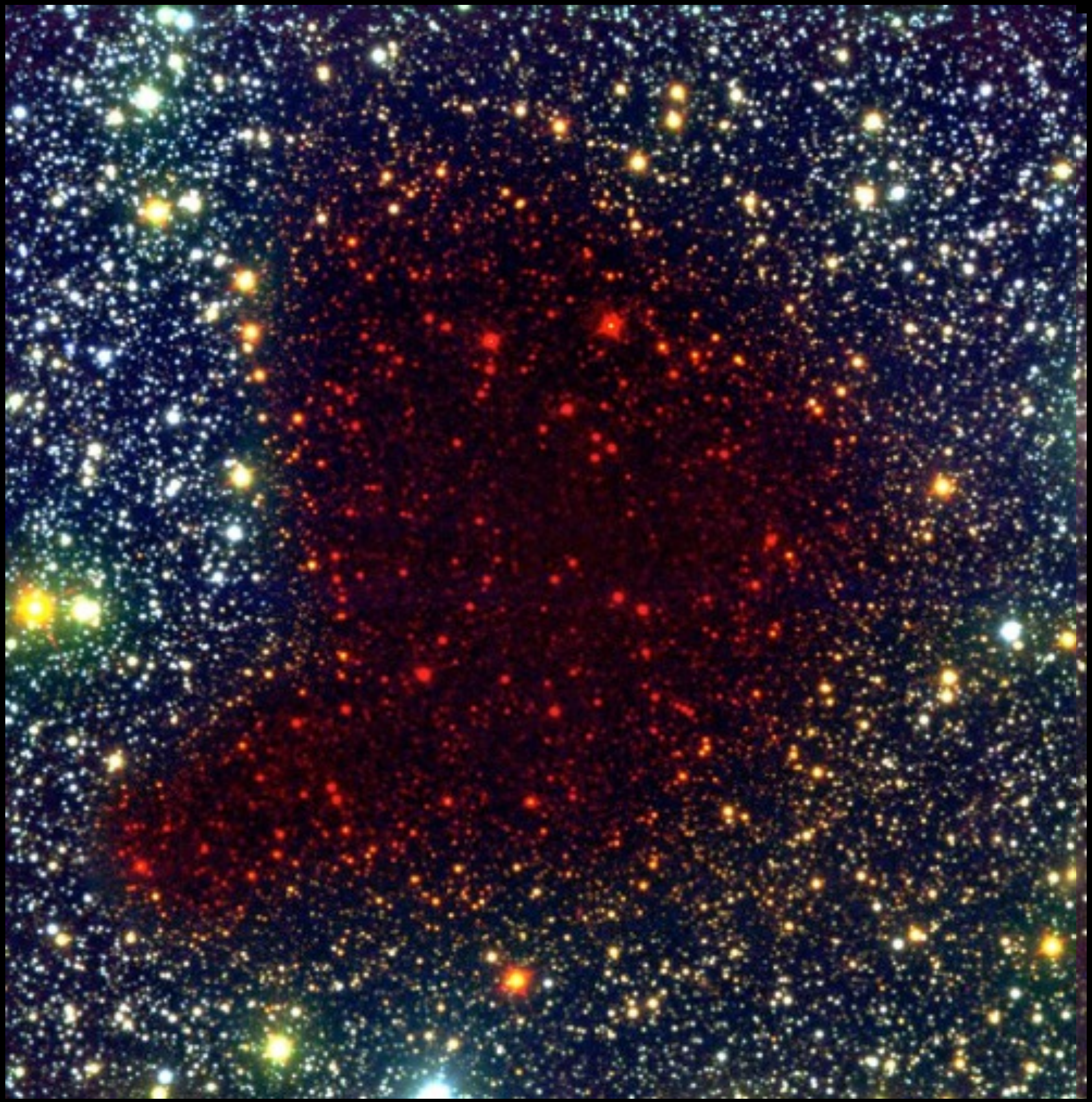

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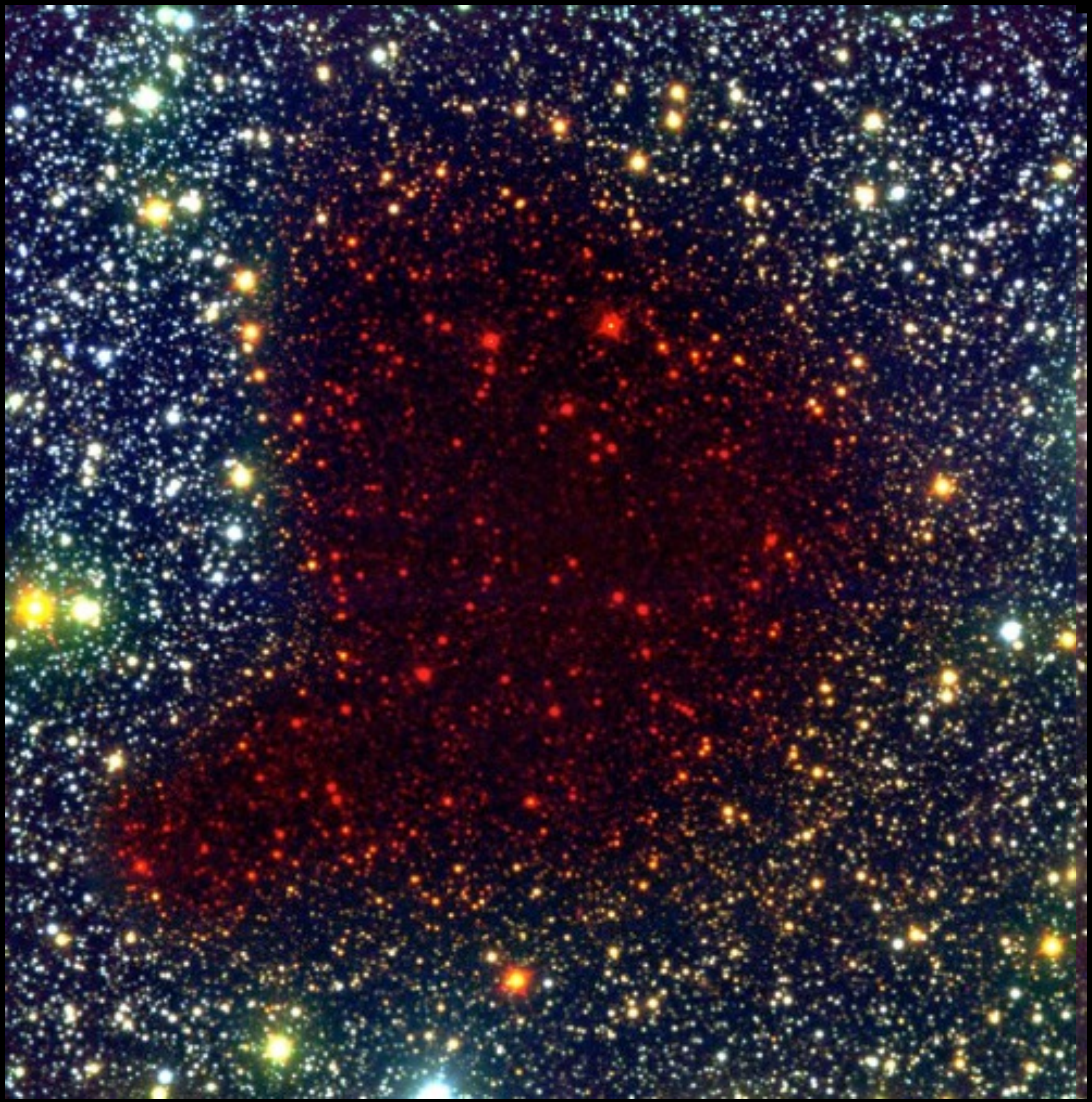

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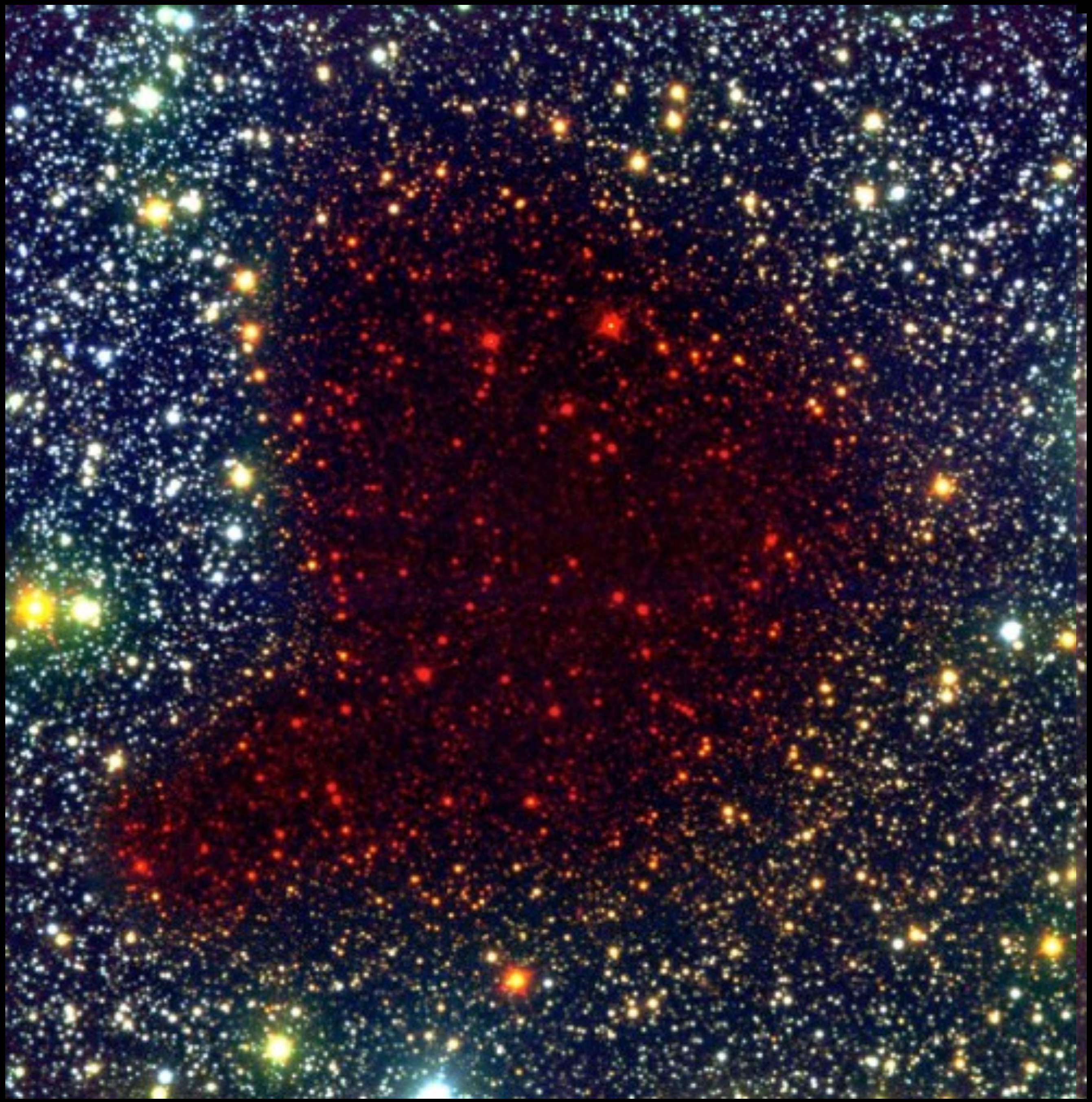

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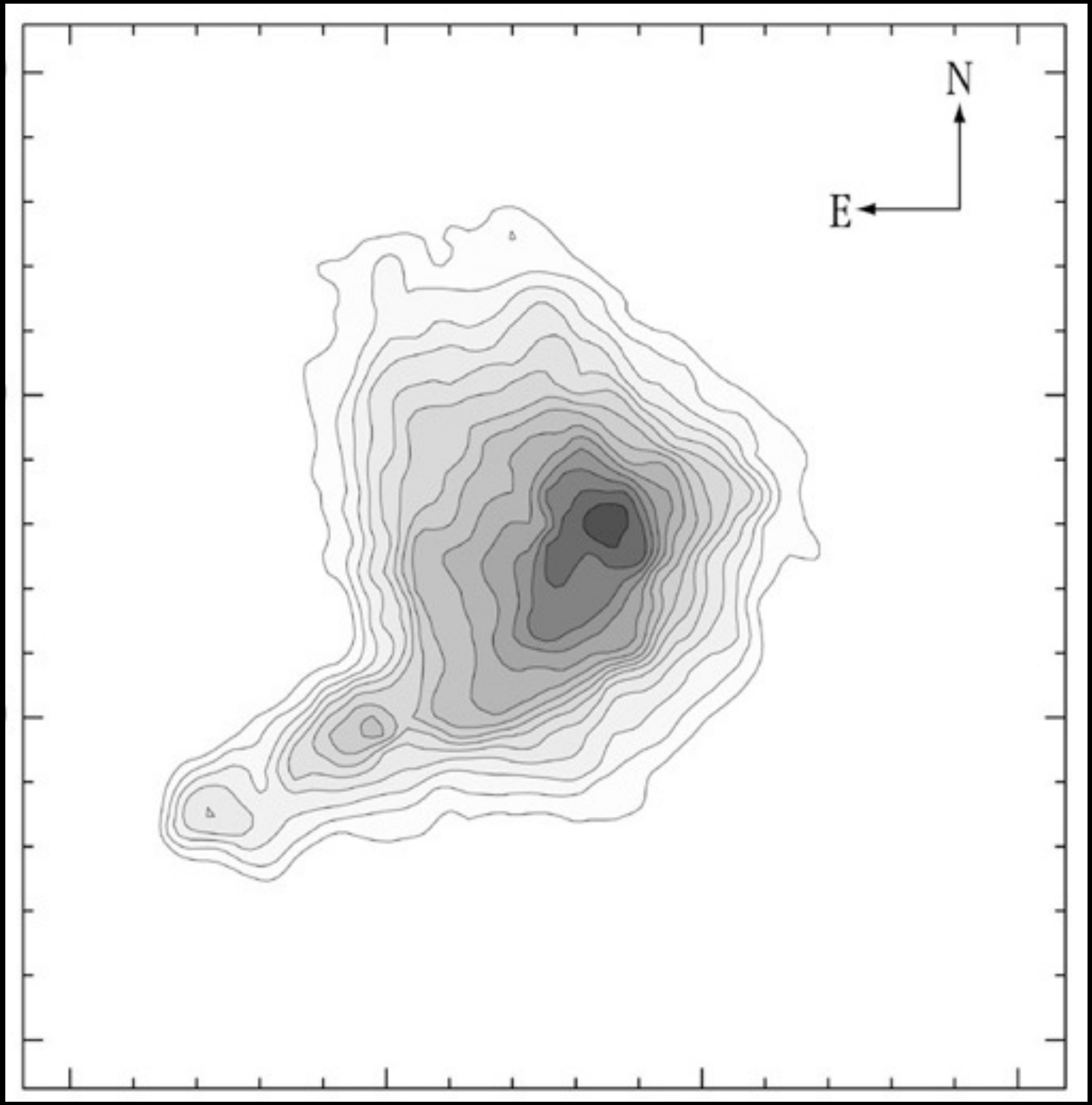

Alves et al. (2014)

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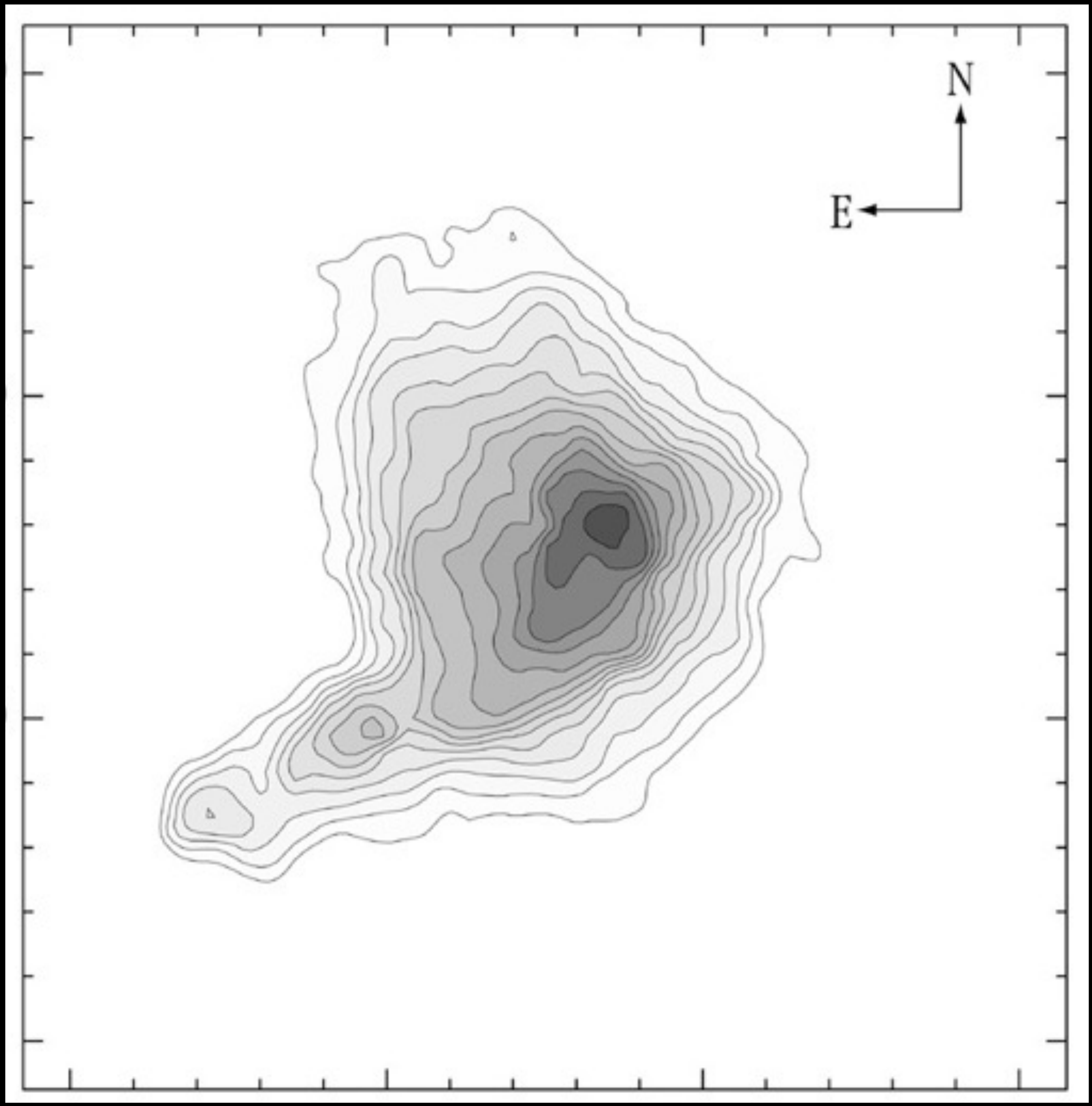
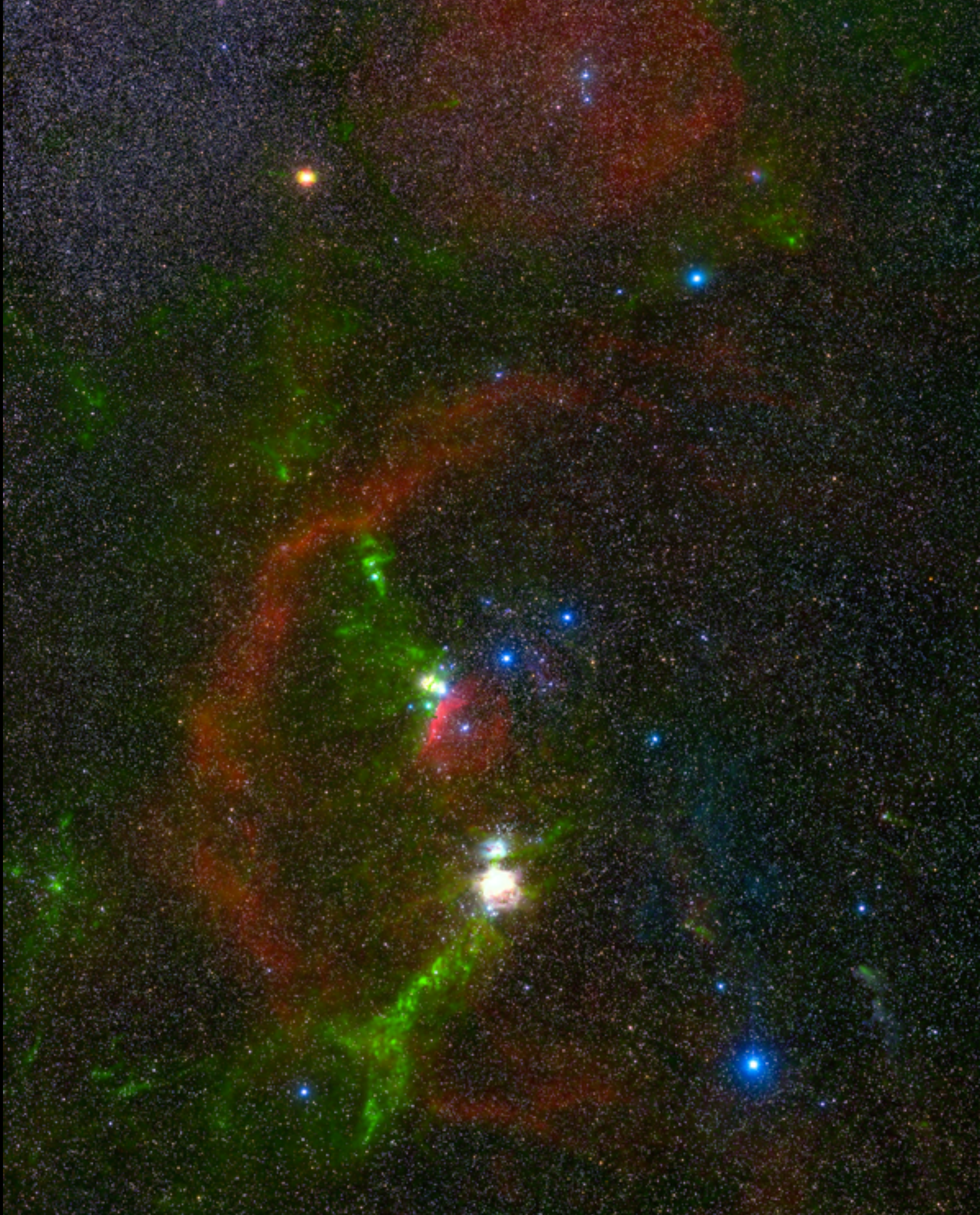
- Make a smooth map
- Convert extinction into gas column density



Alves et al. (2014)

Lombardi et al. (2011)



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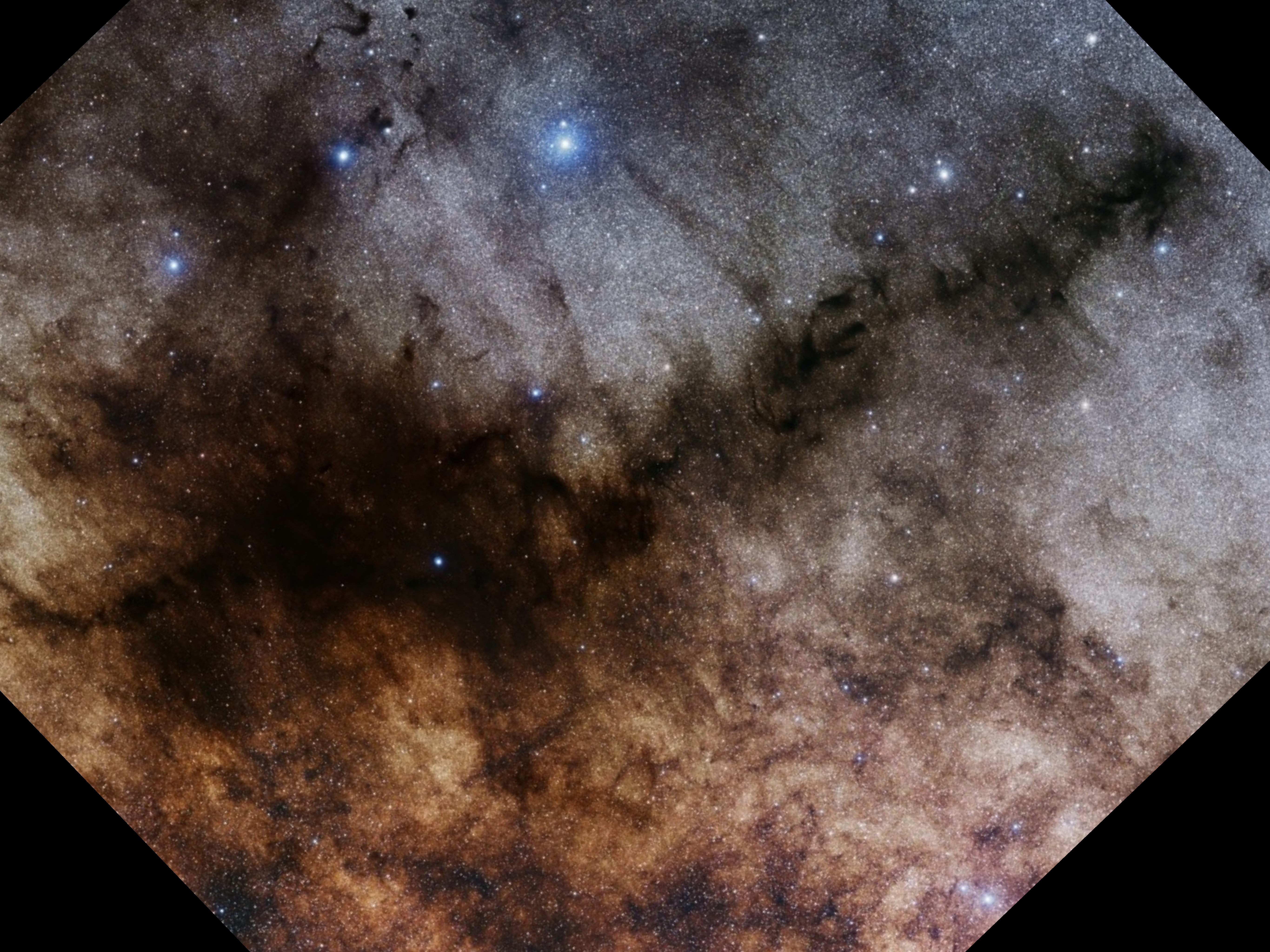
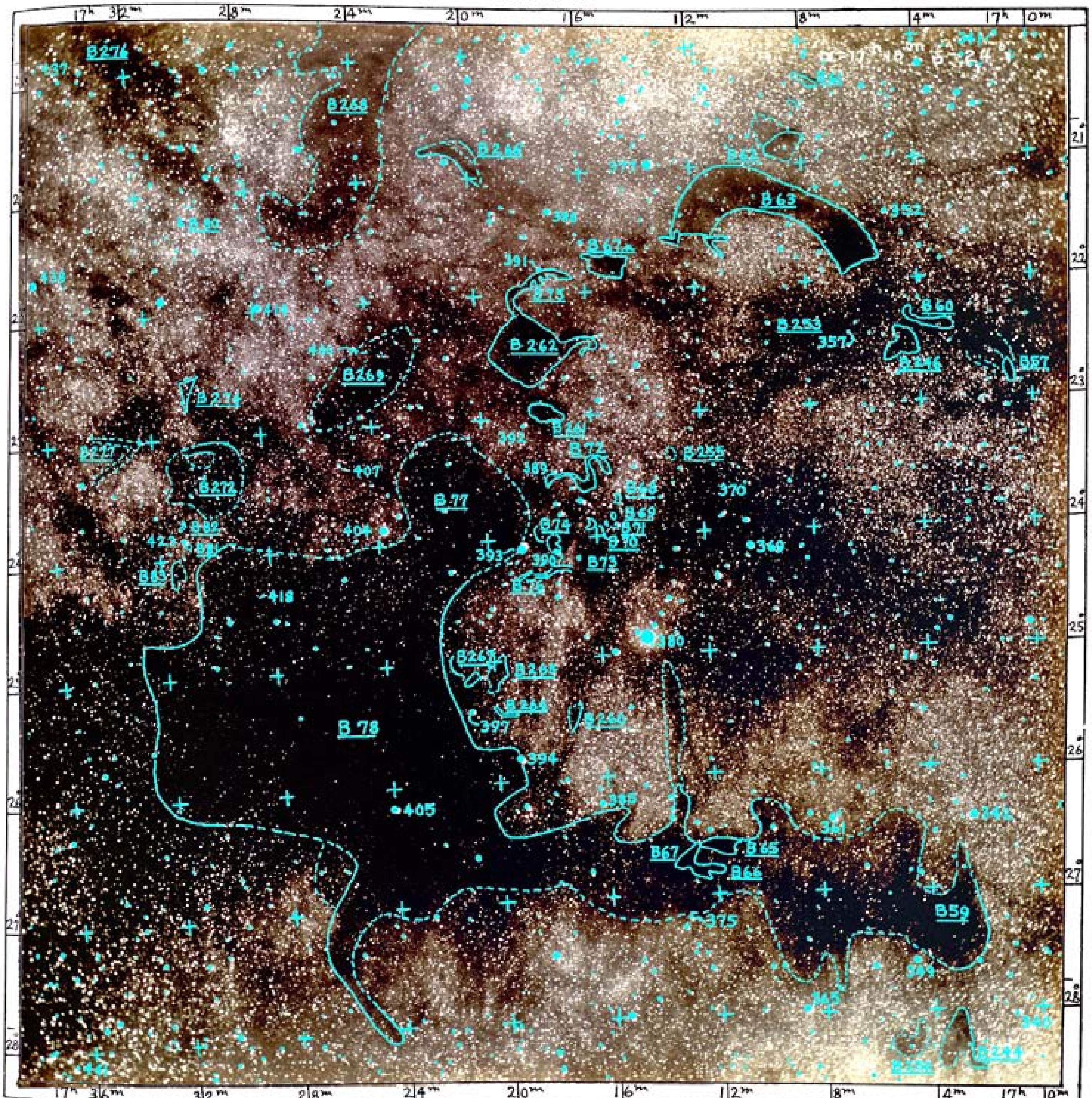
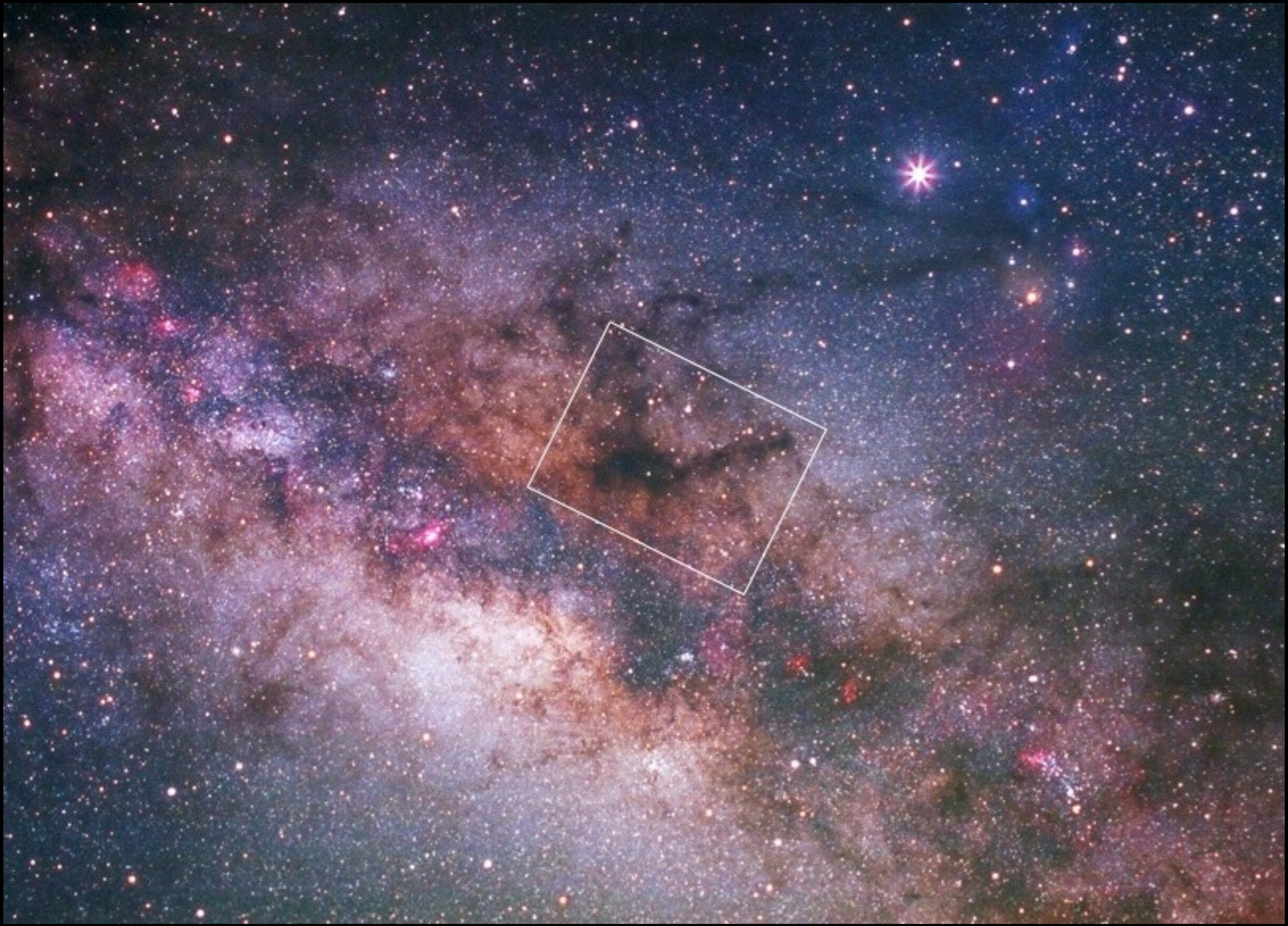


Barnard photographic atlas (1919)

CHART 20

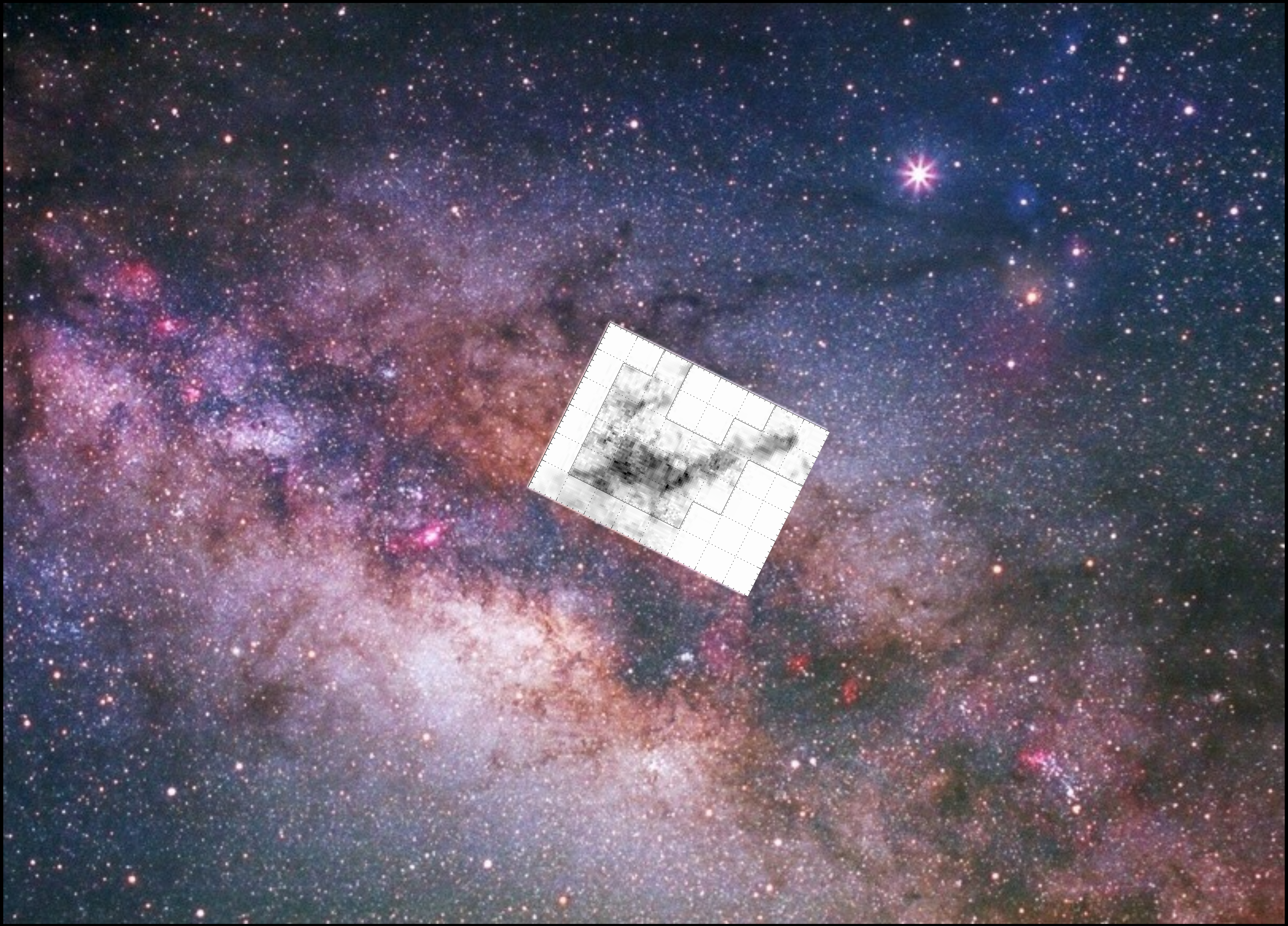


DARK MARKINGS NEAR THETA OPHIUCHI $\alpha = 17^h18^m0^s$ $\delta = -24°10'$



The Pipe Nebula

Lombardi et al. (2006)



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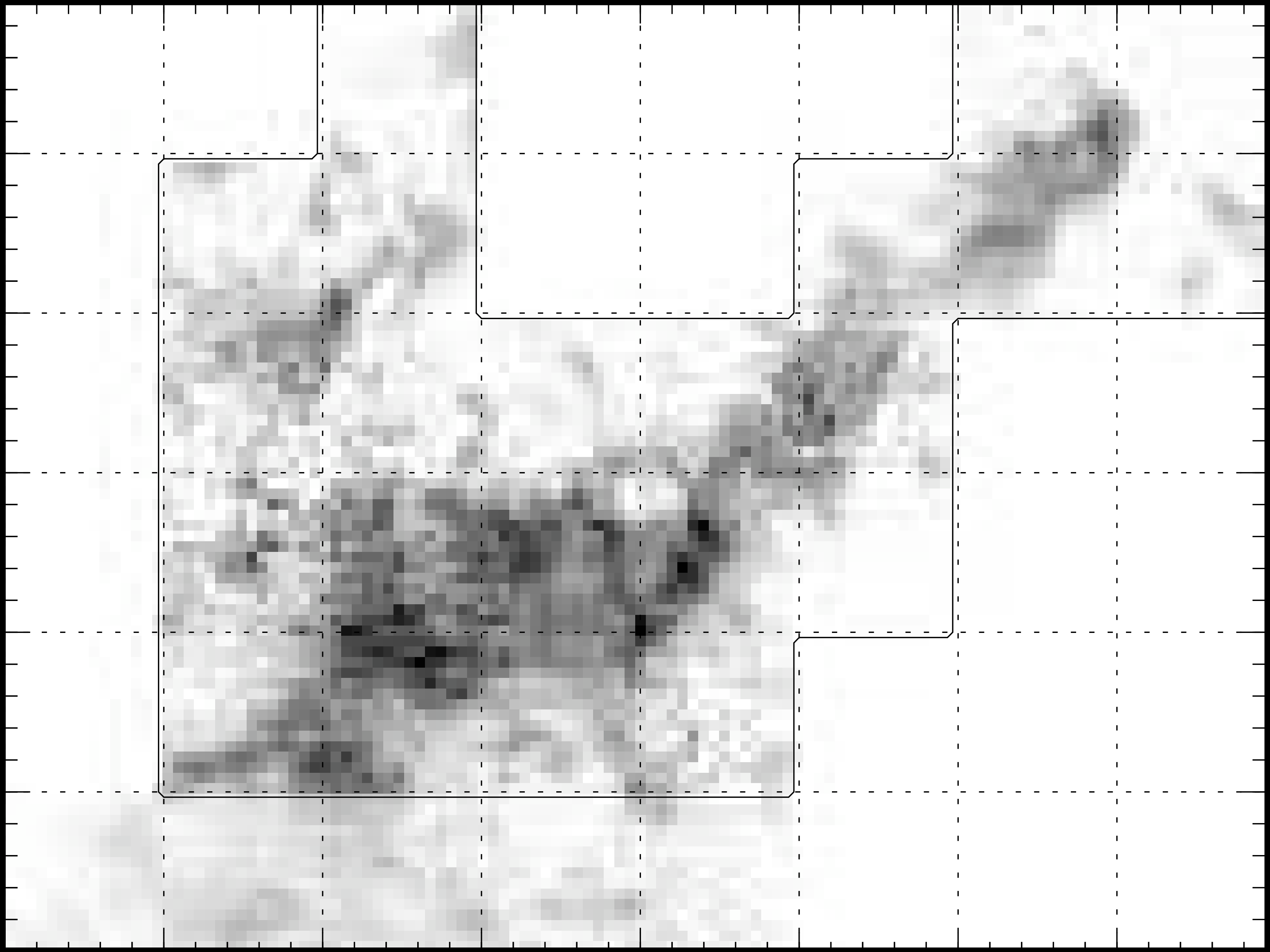

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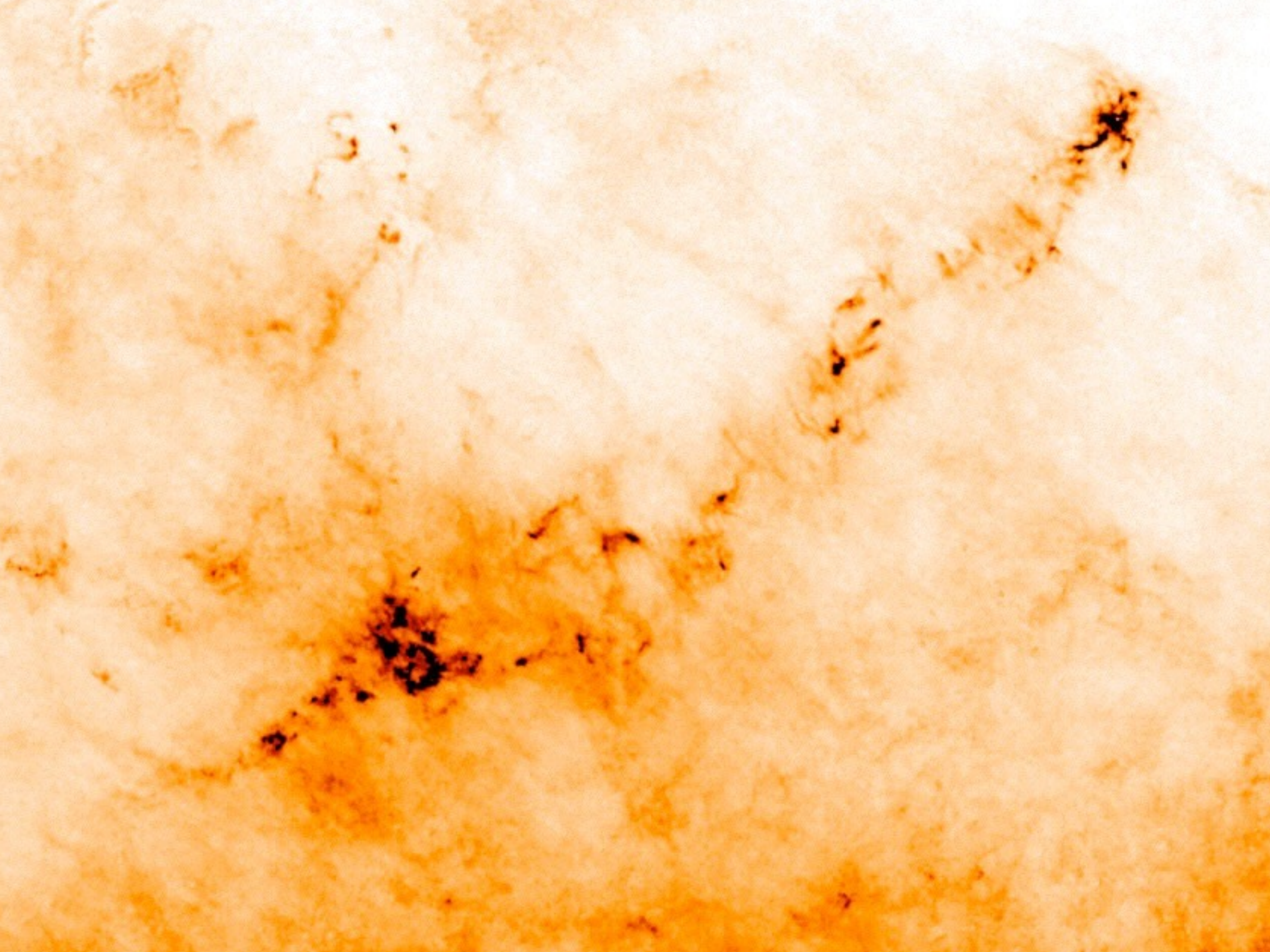
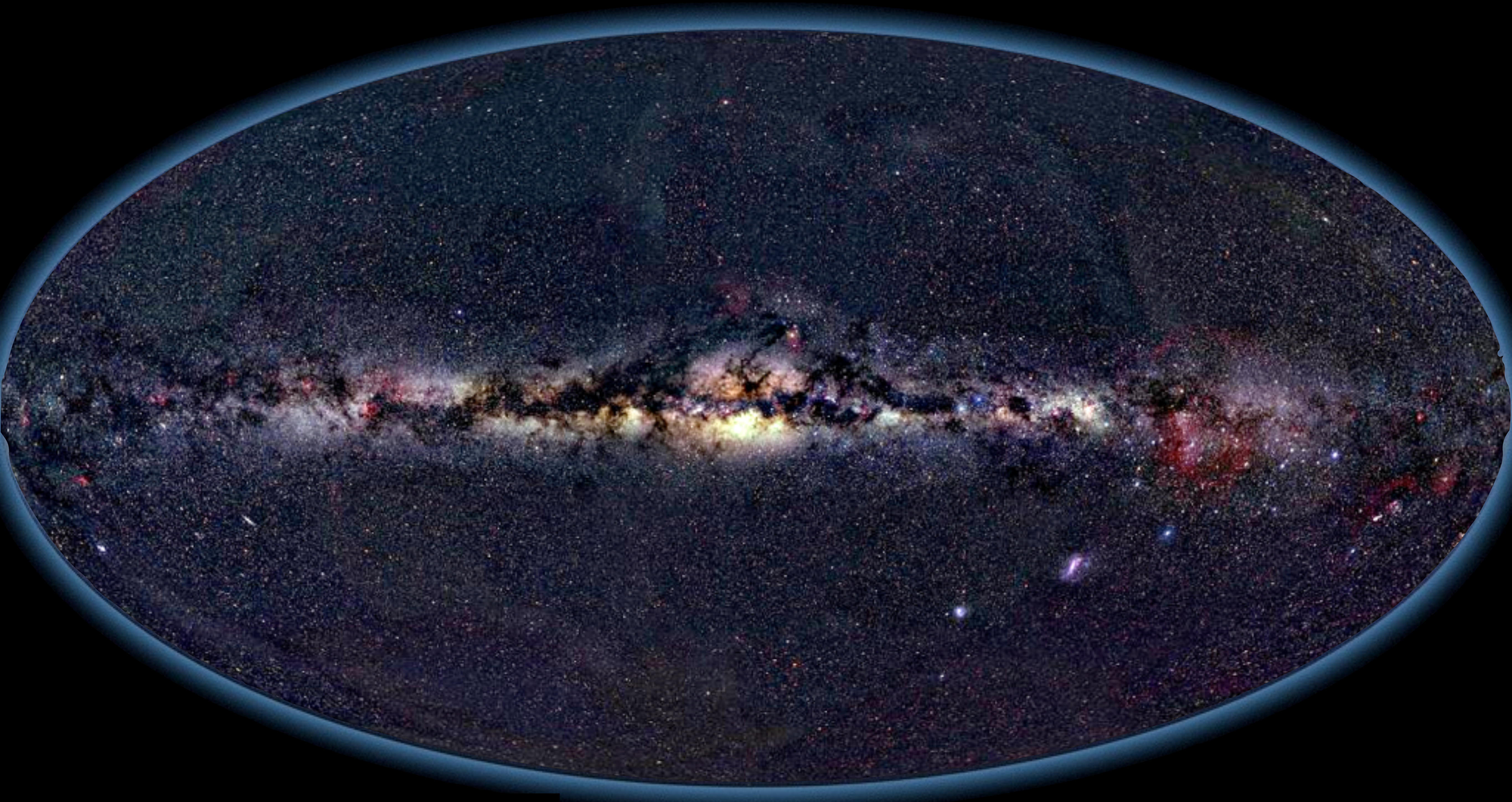
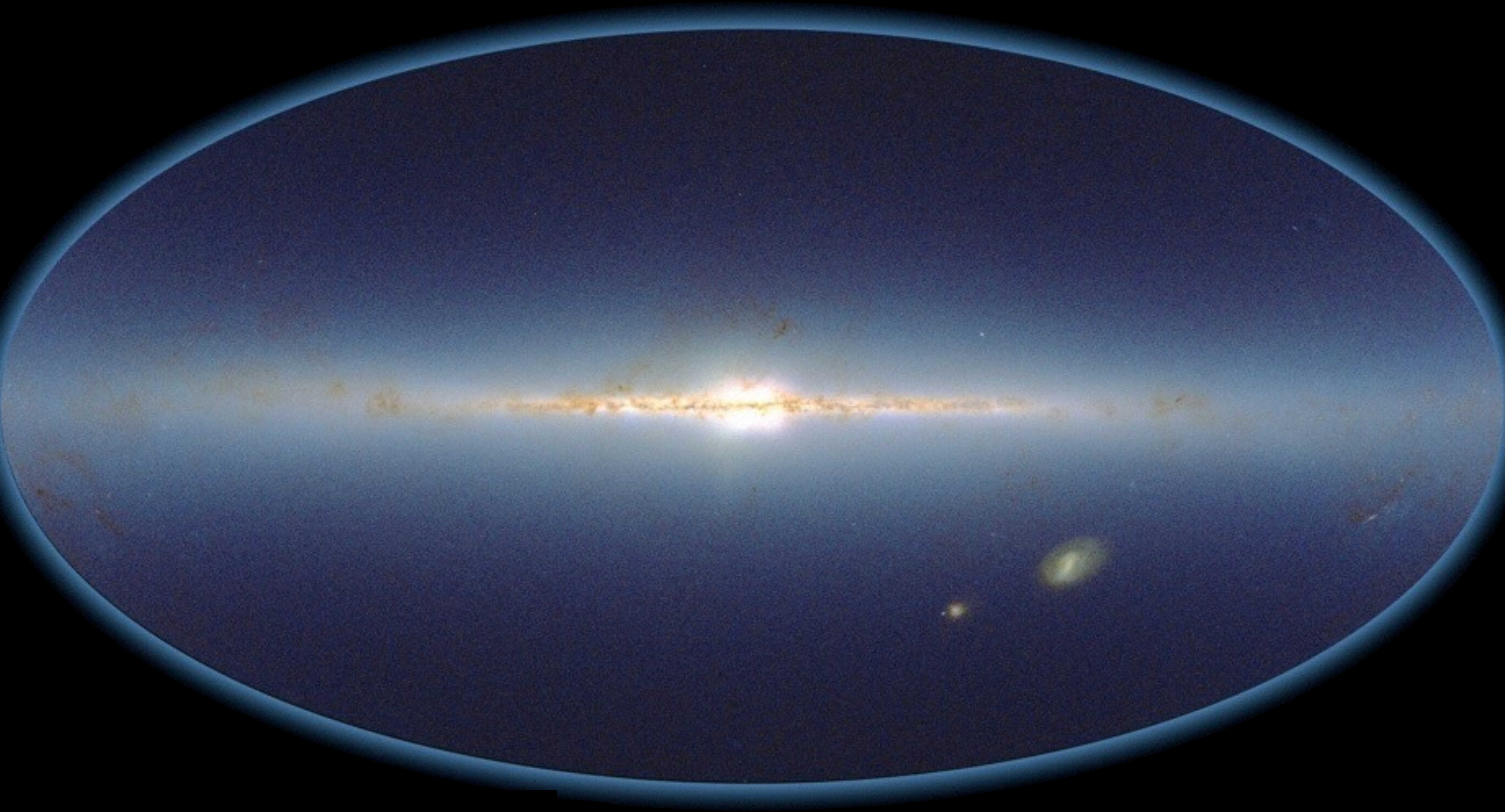


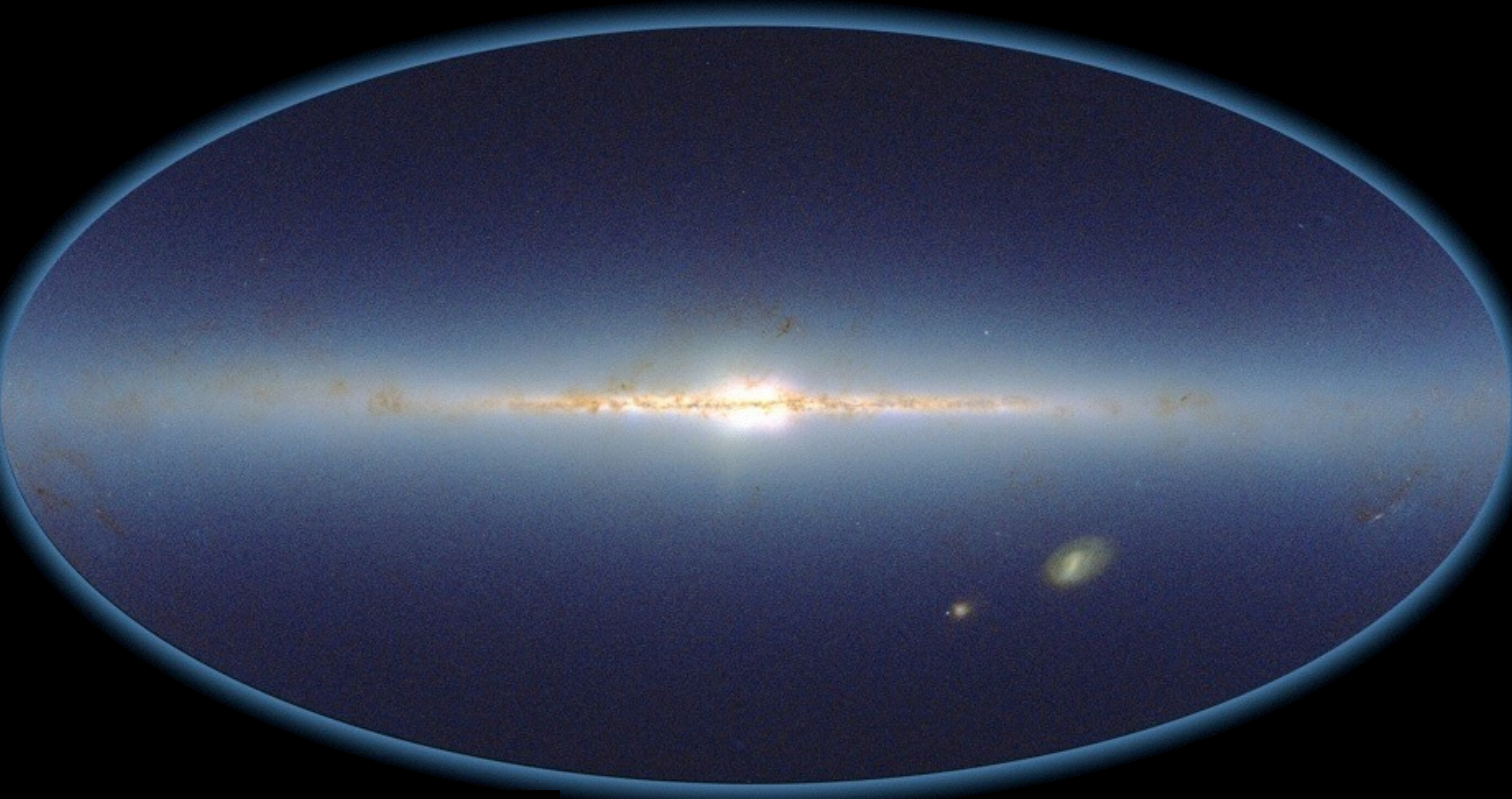


A. Mellinger



2MASS

Gould belt



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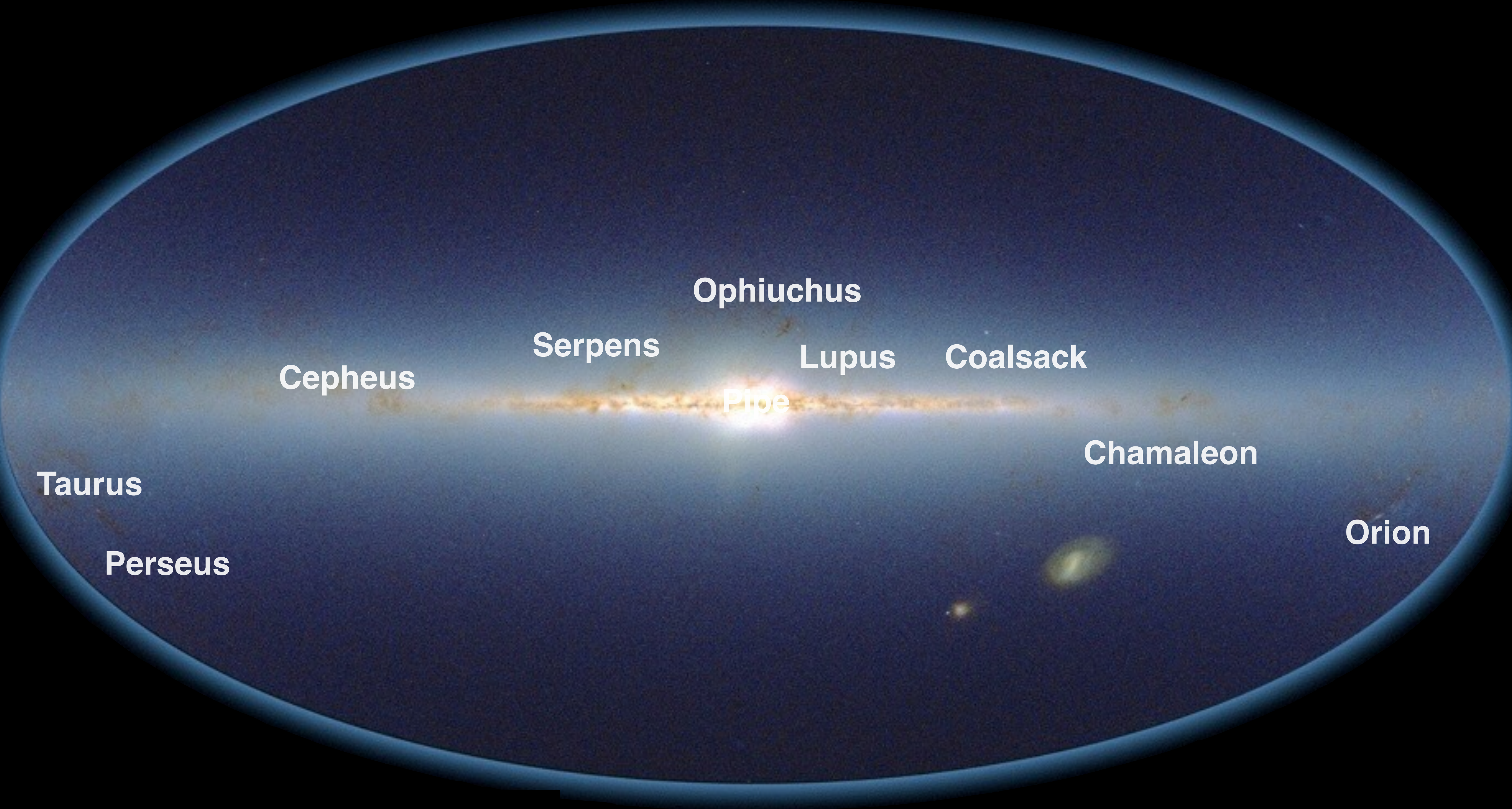

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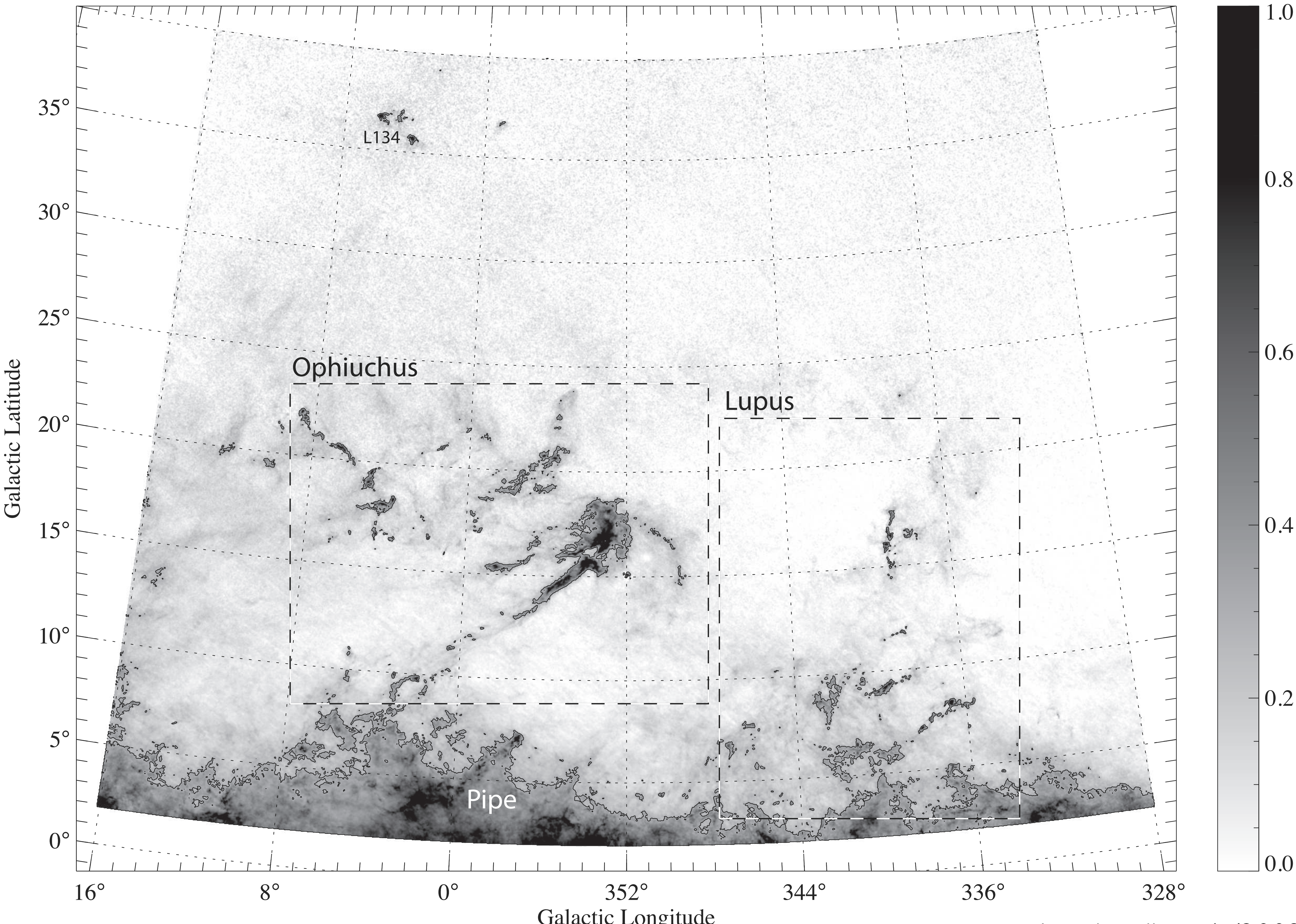
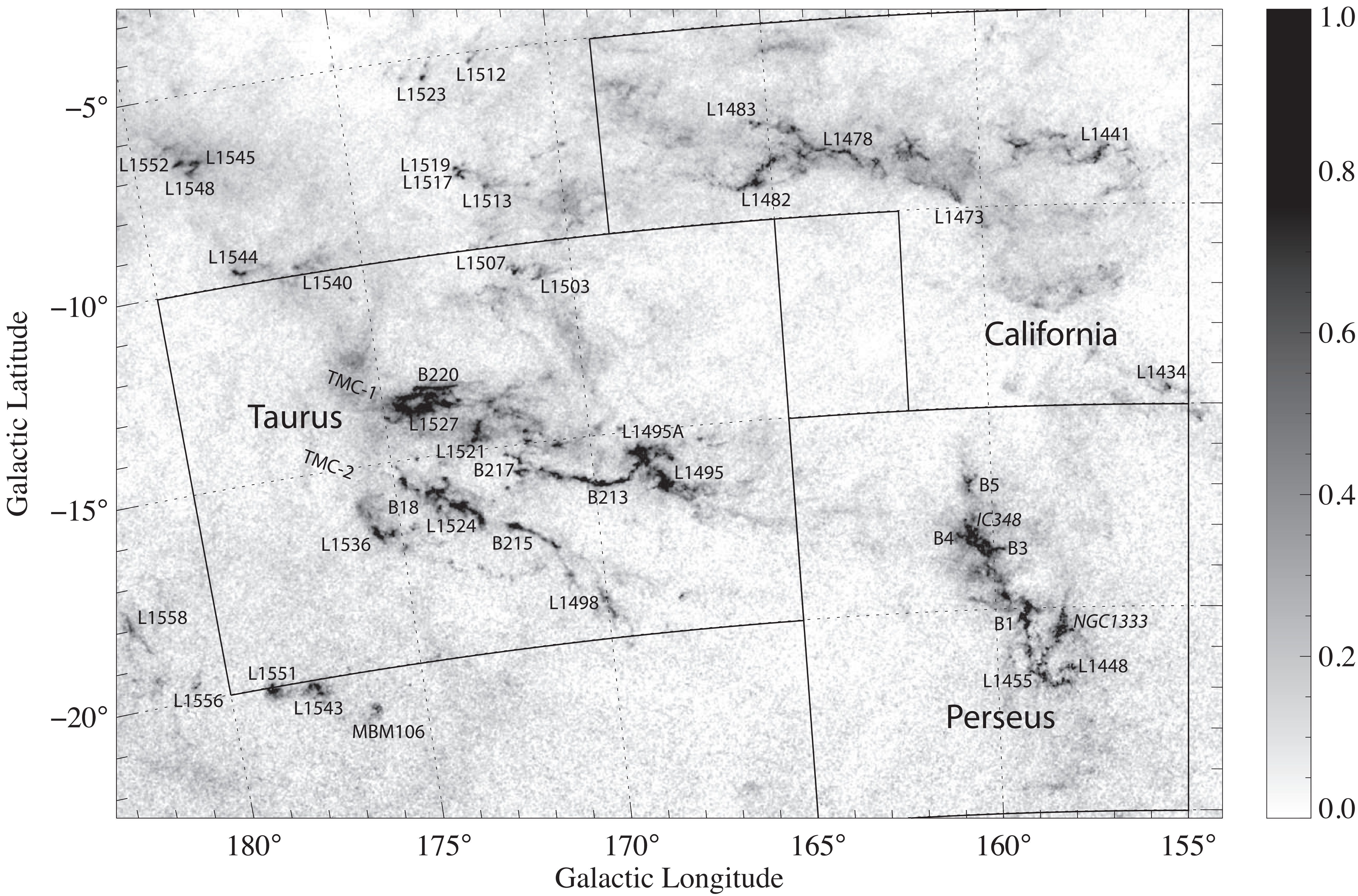


Lombardi et al. (2009)



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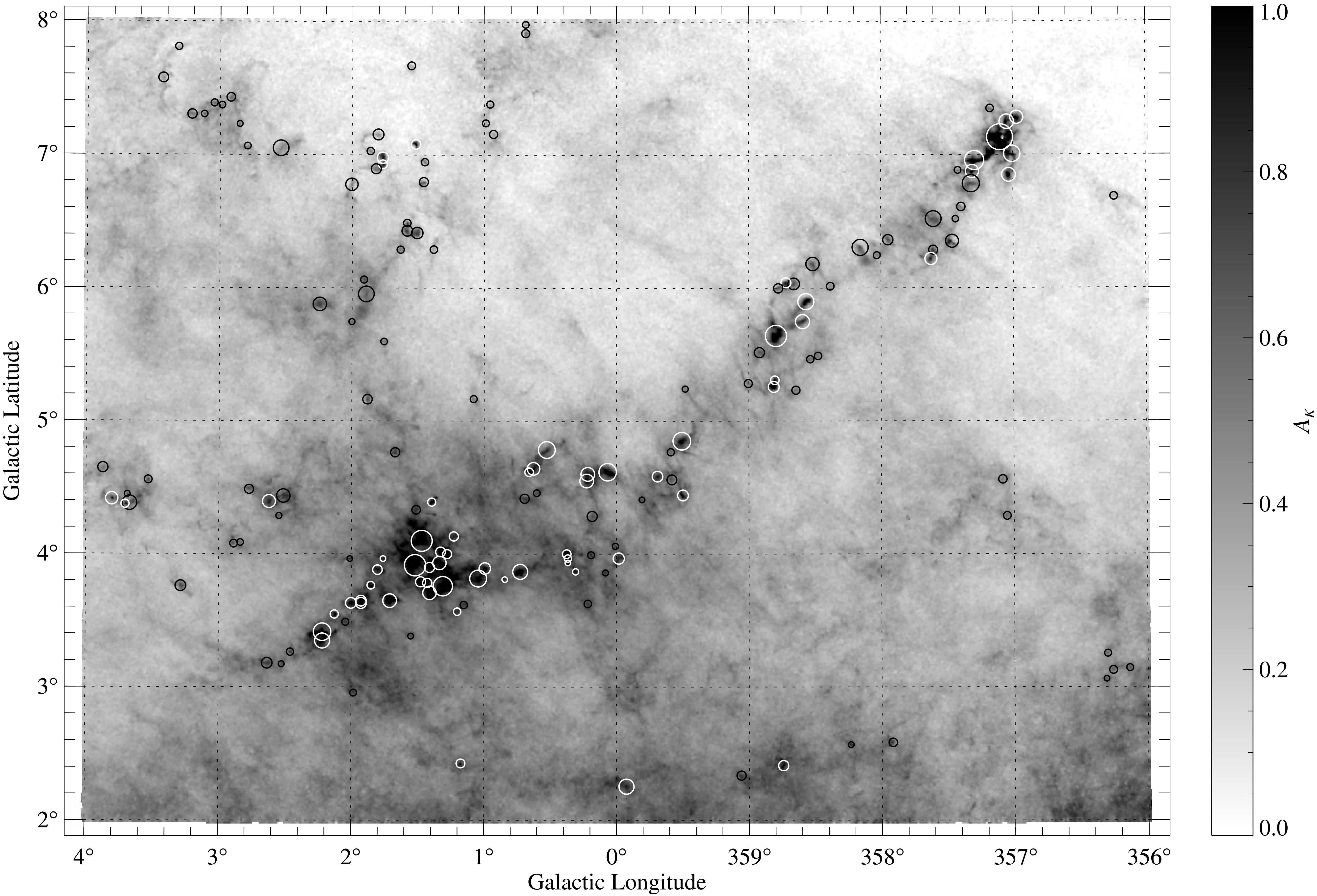

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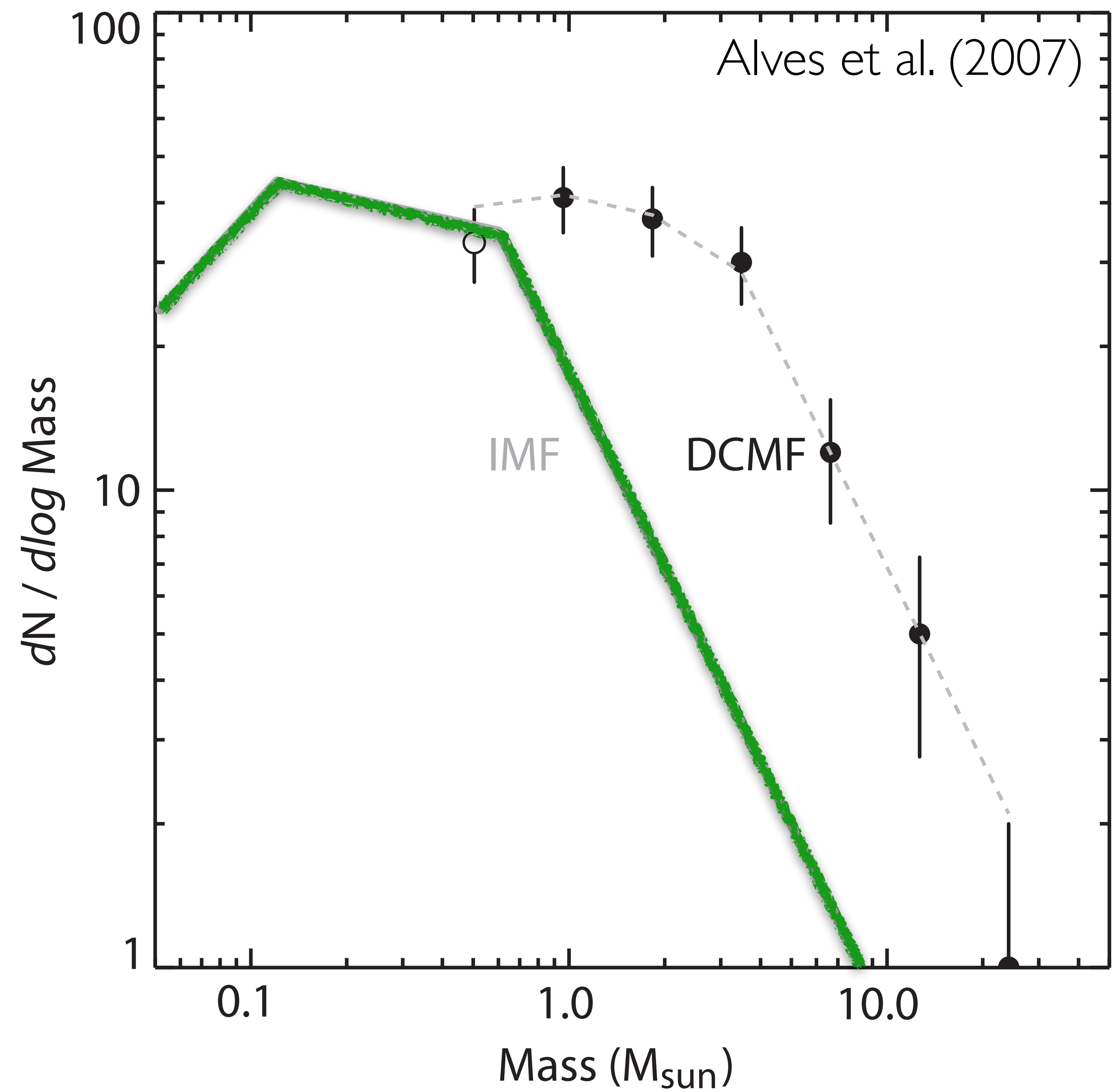
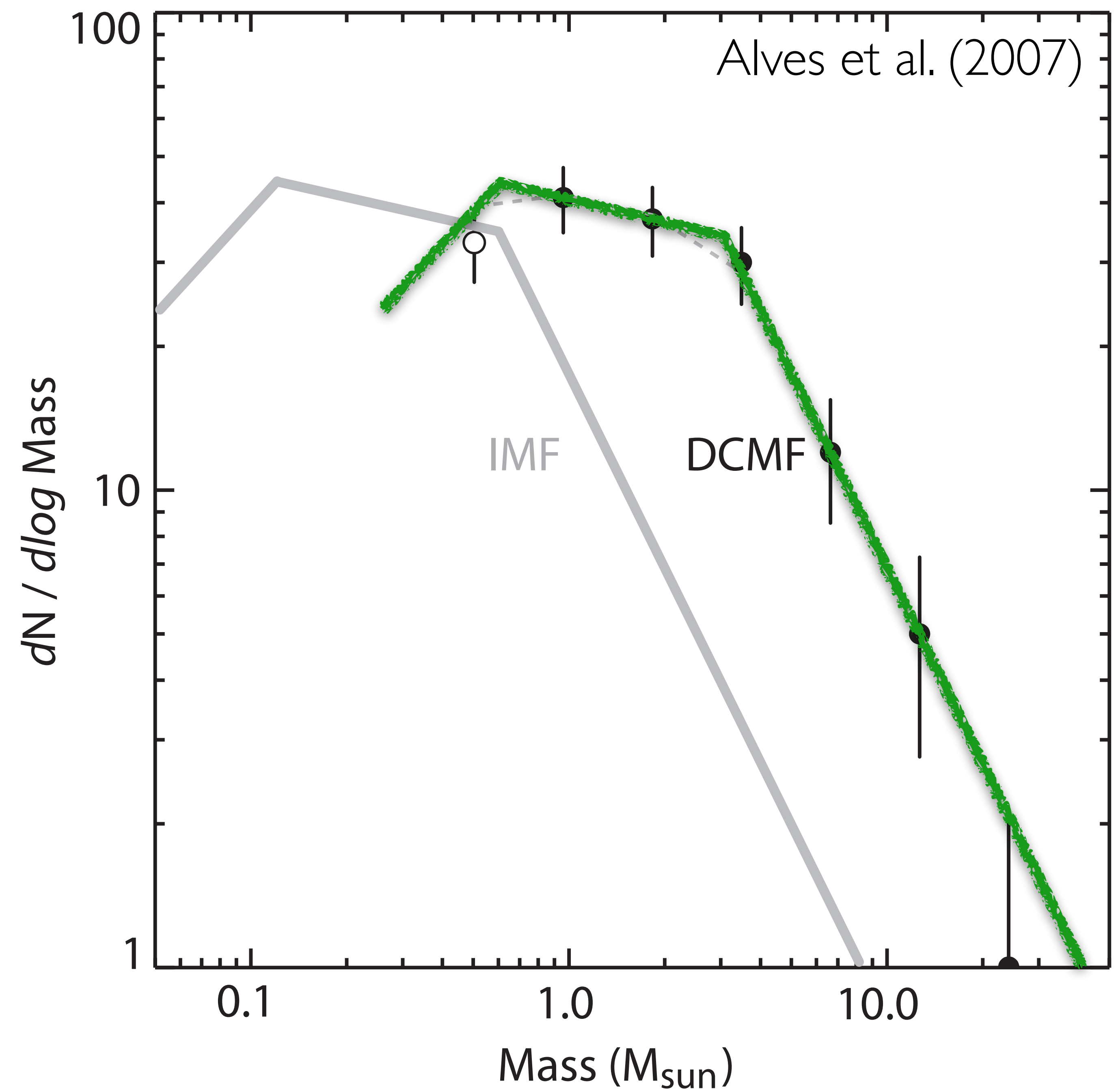
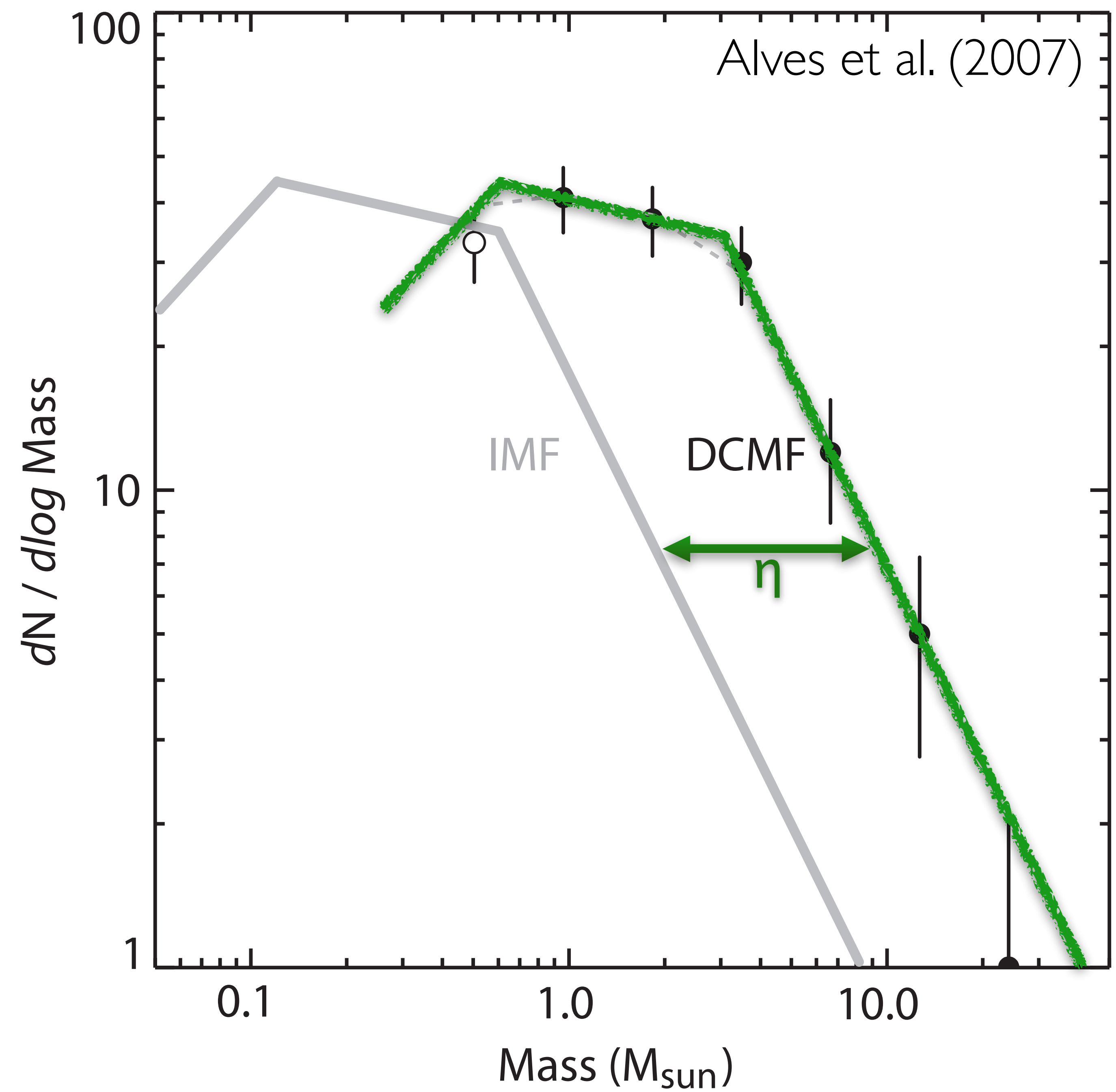


Alves et al. (2007)
IMF
DCMF
100
10
1
0.1
1.0
10.0
dN / dlog Mass
Mass (Msun)

- The dense core mass function (DCMF) has the same shape as the IMF



- The dense core mass function (DCMF) has the same shape as the IMF
- The difference can be interpreted as a star formation efficiency



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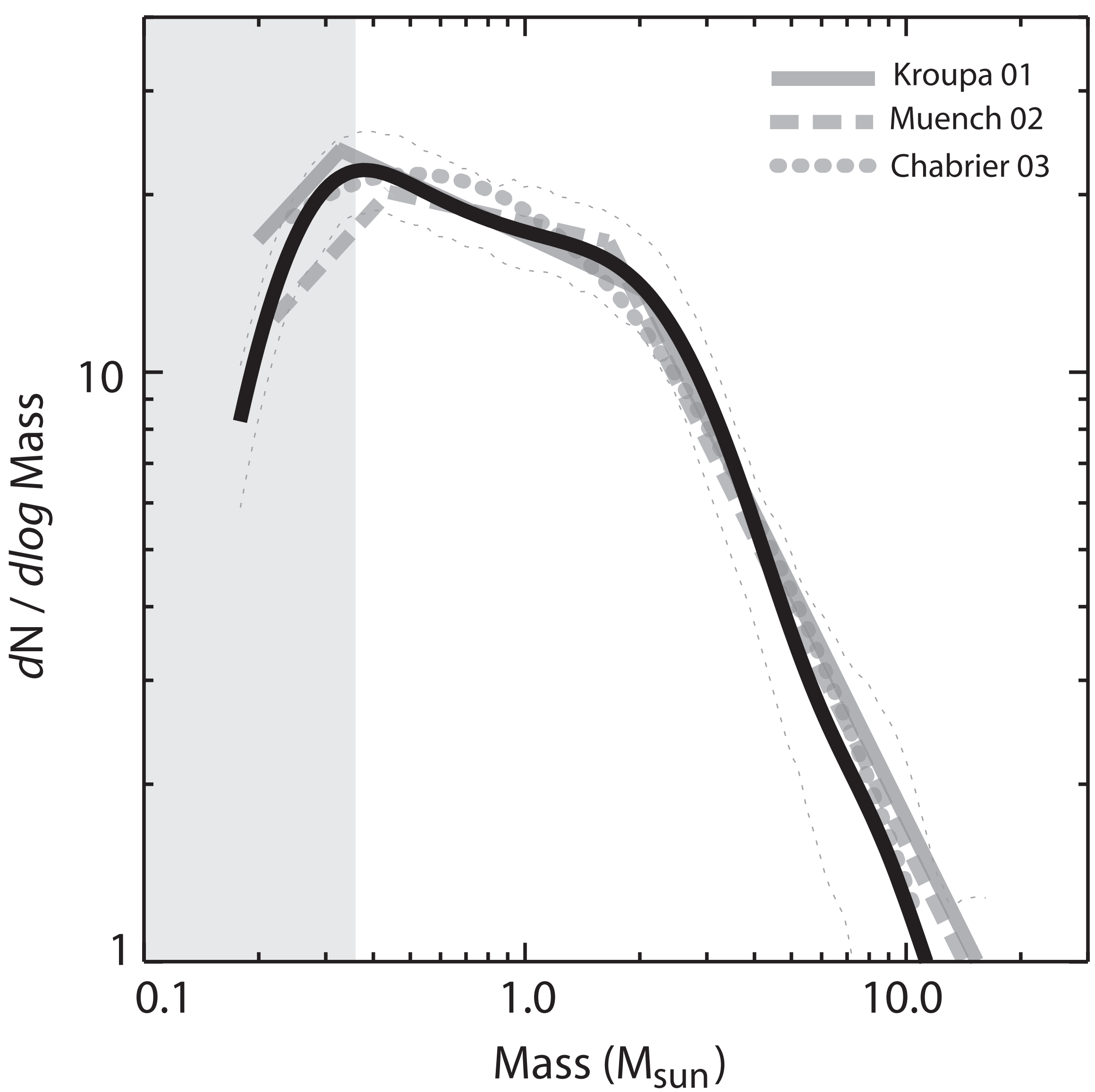

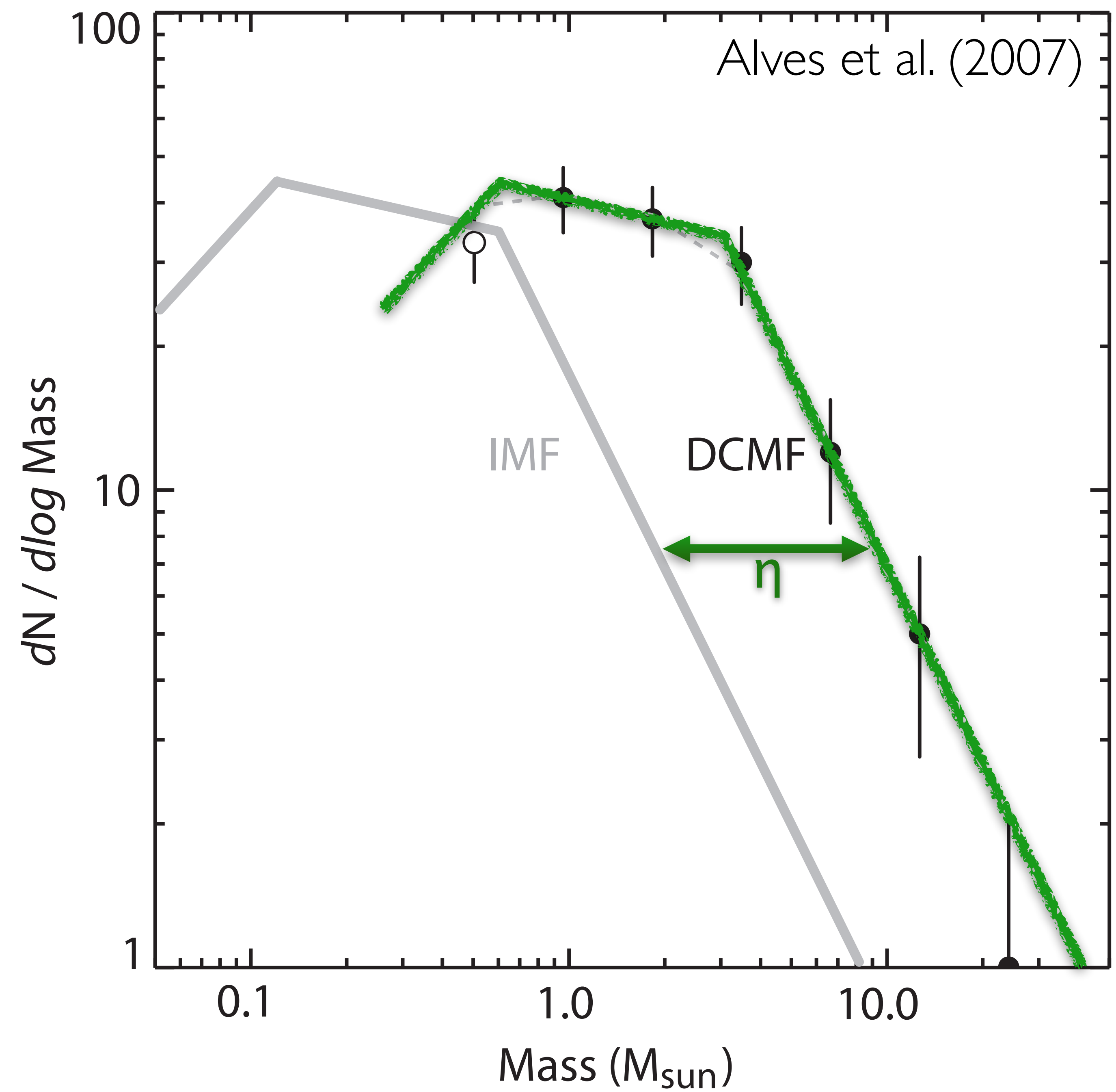

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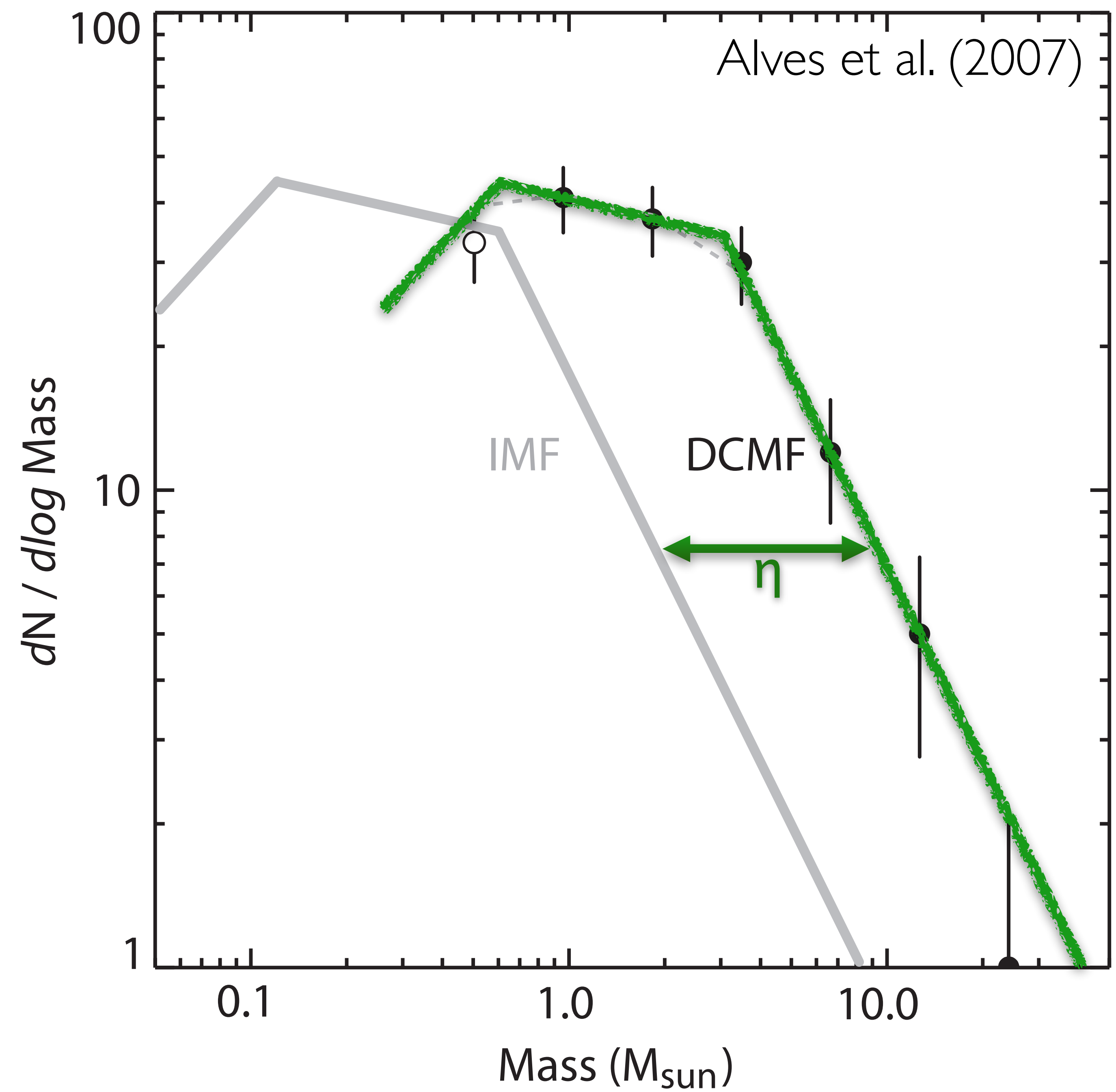
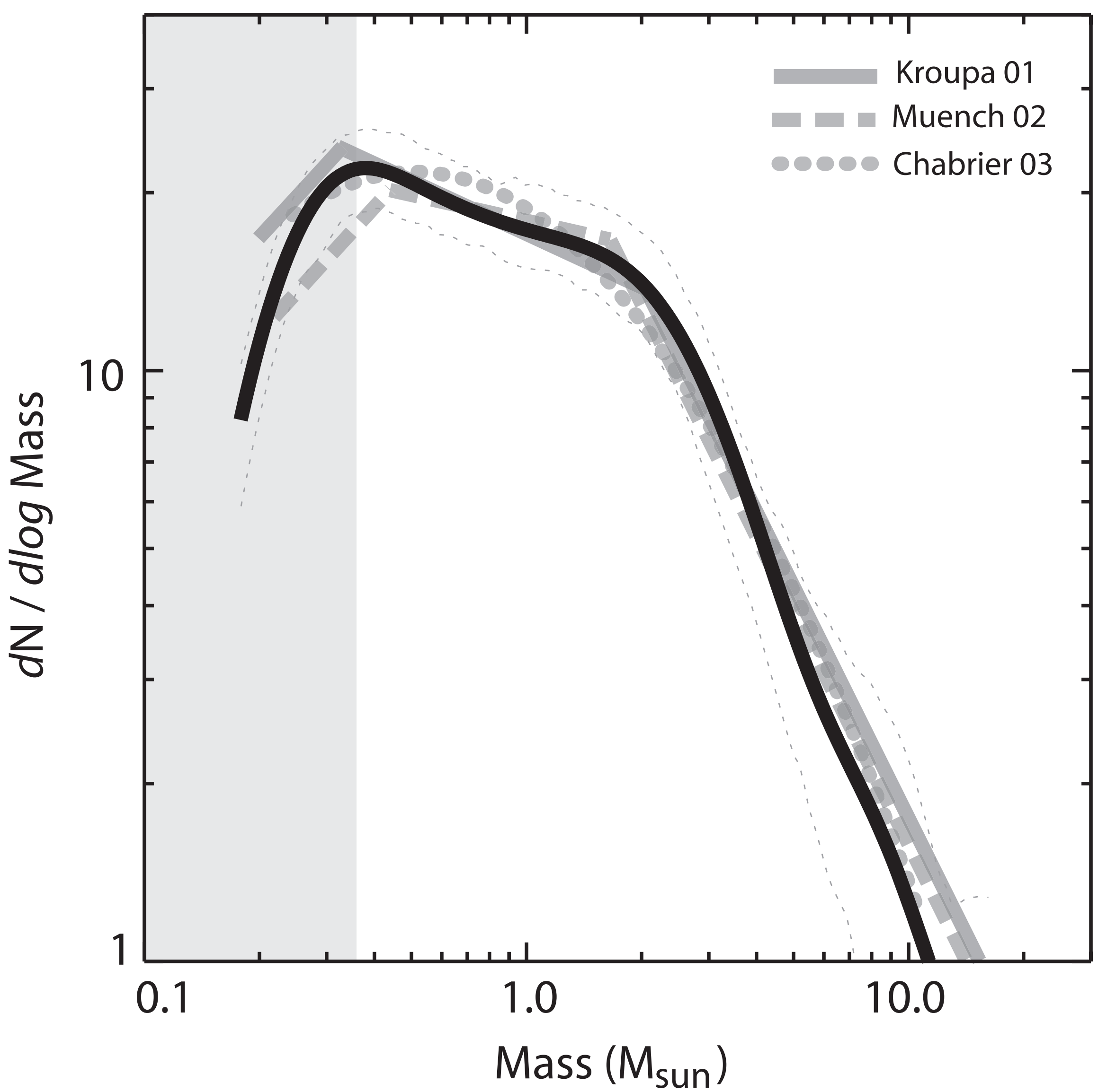
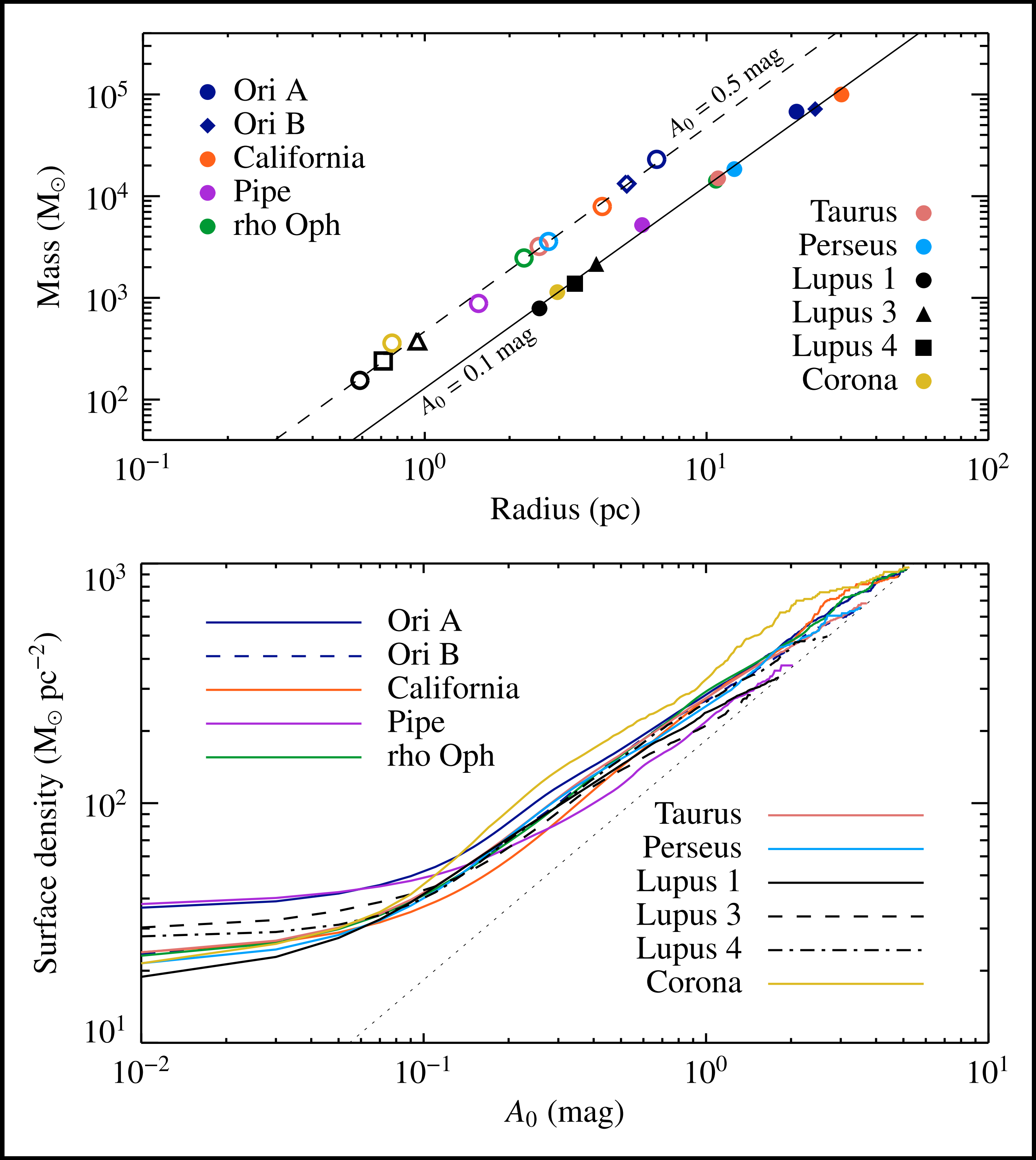




- Things might be more complicated (e.g., one core might fragment)

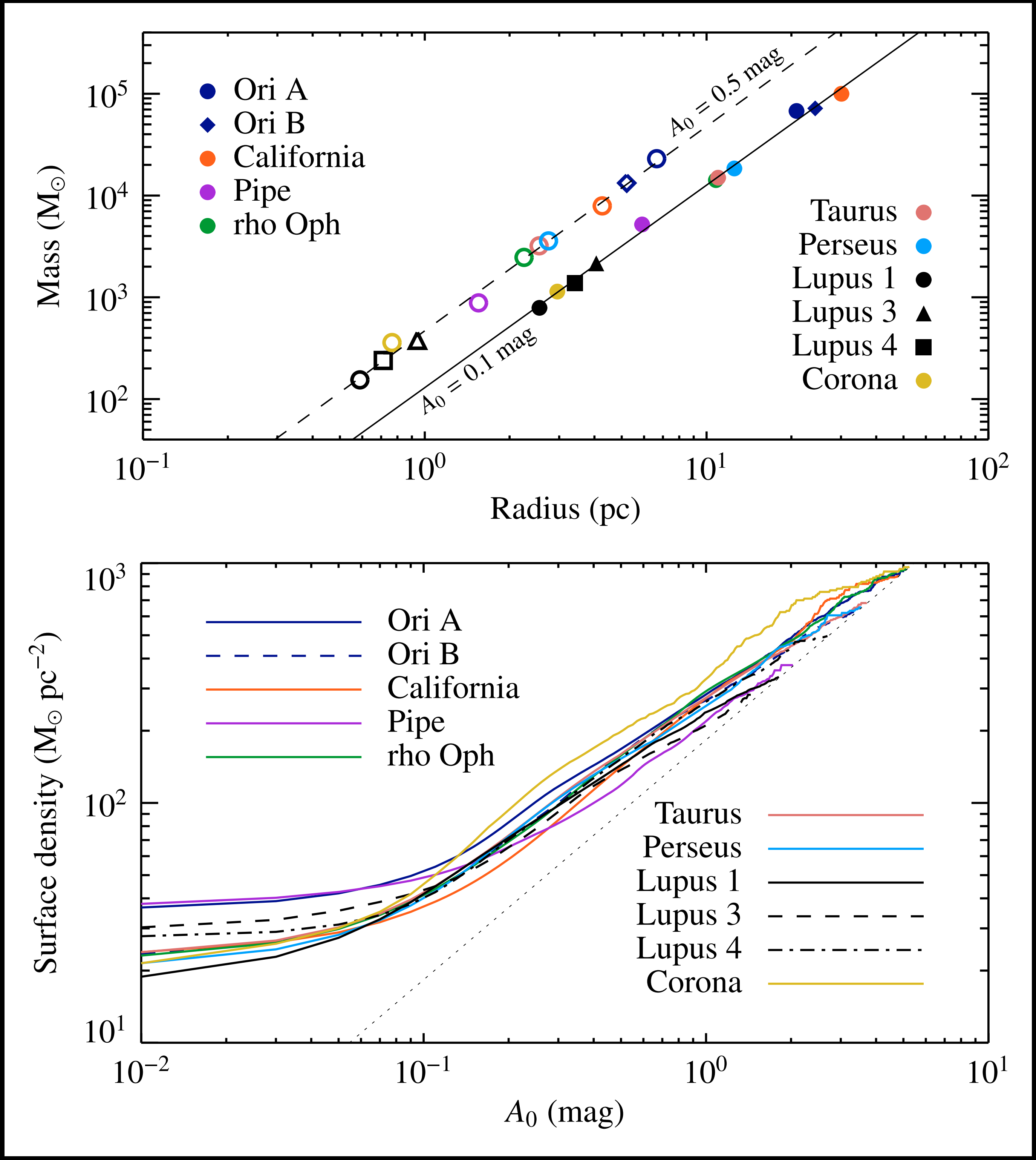
Larson’s 3rd law



Lombardi et al. (2010)

Larson's 3rd law

- The mass of molecular clouds scales as $M \propto R^2$



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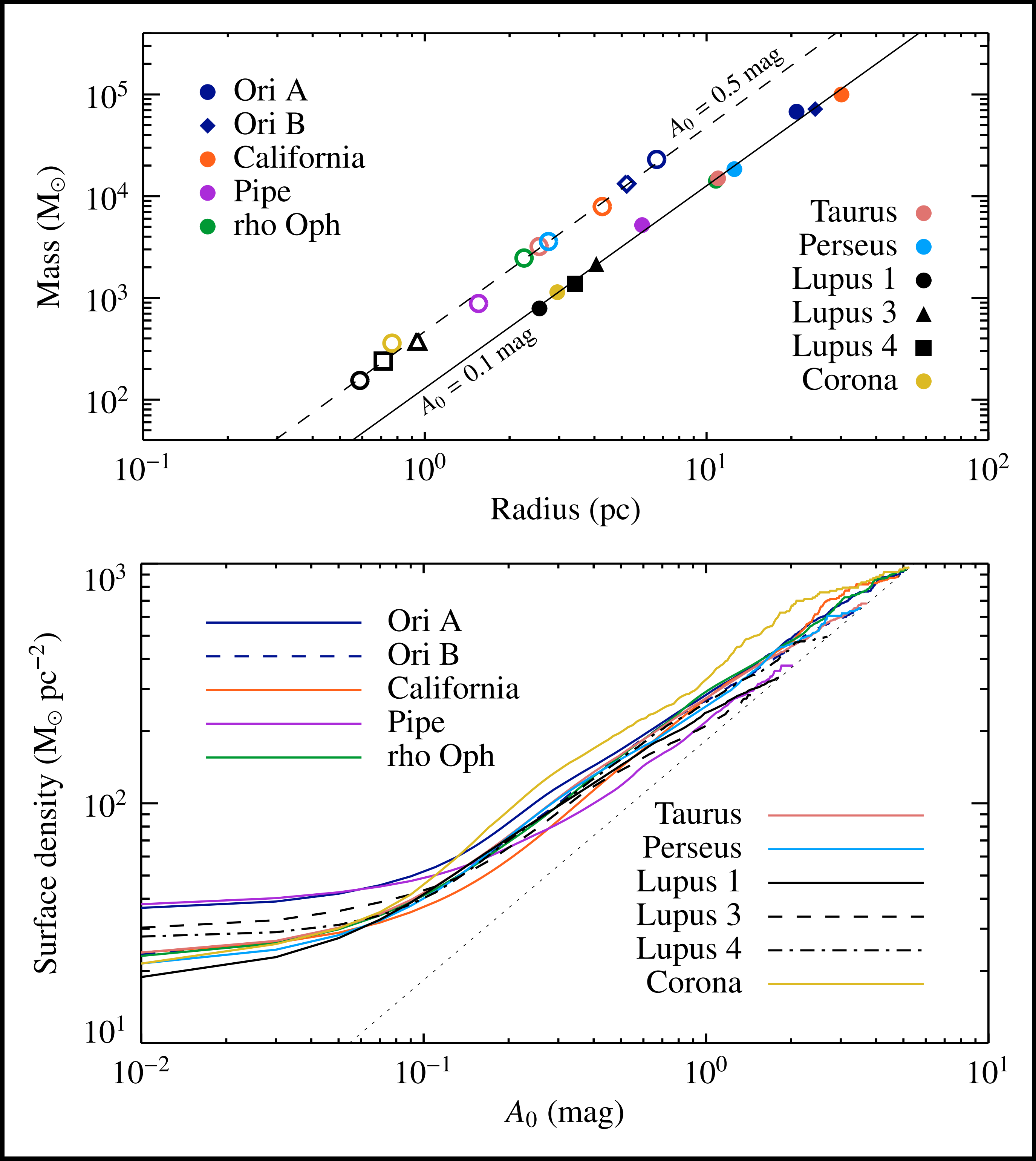

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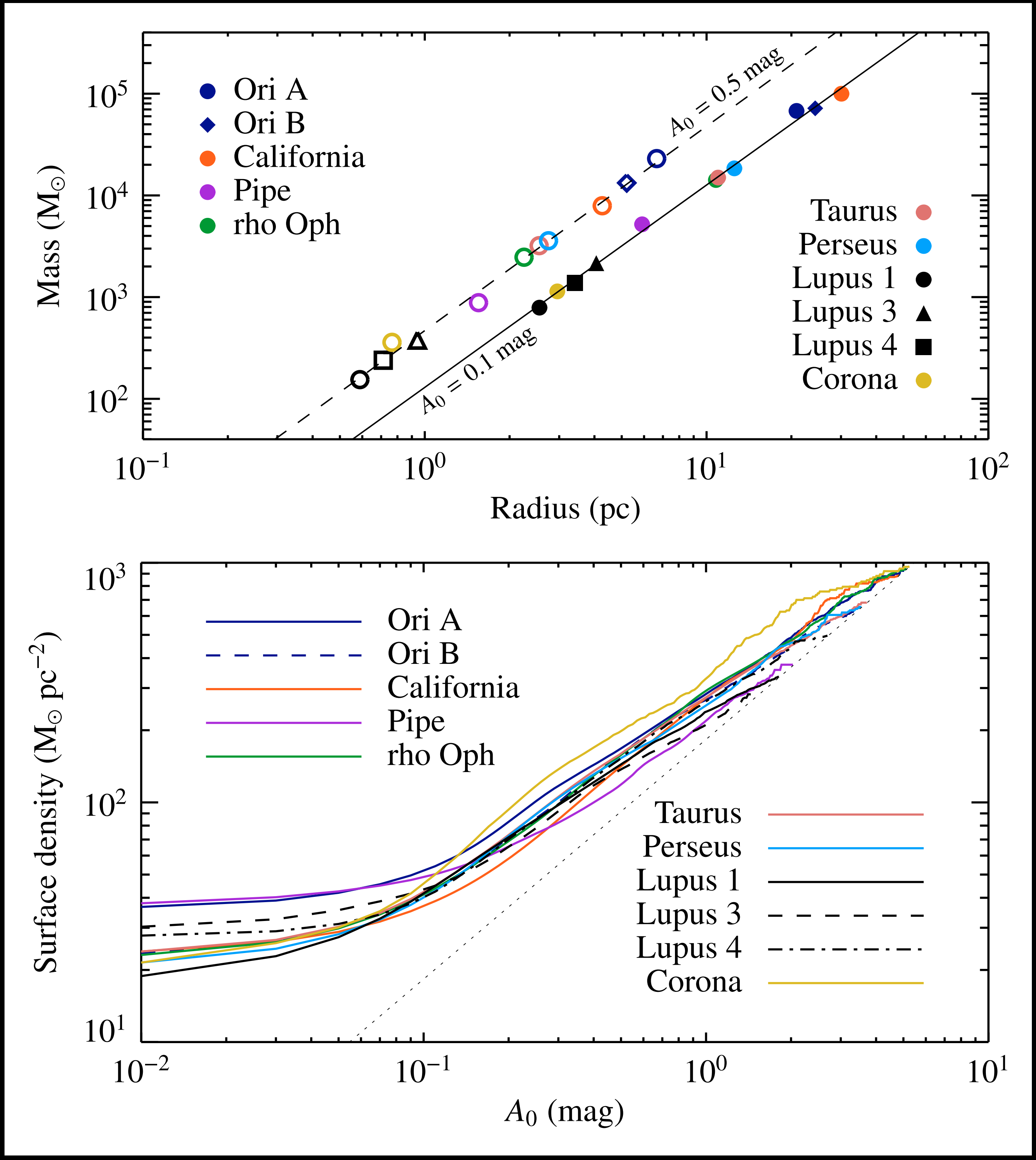

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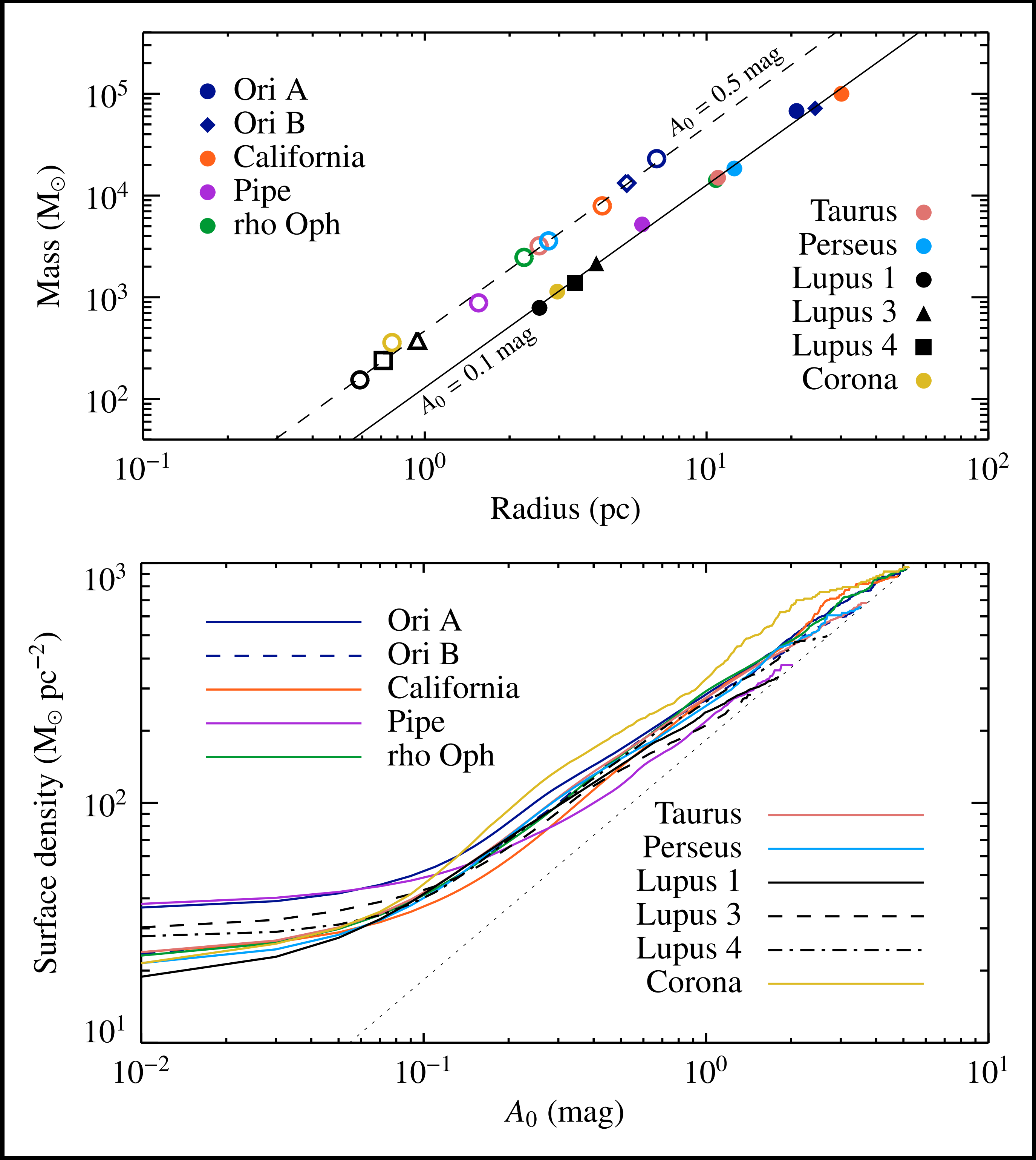
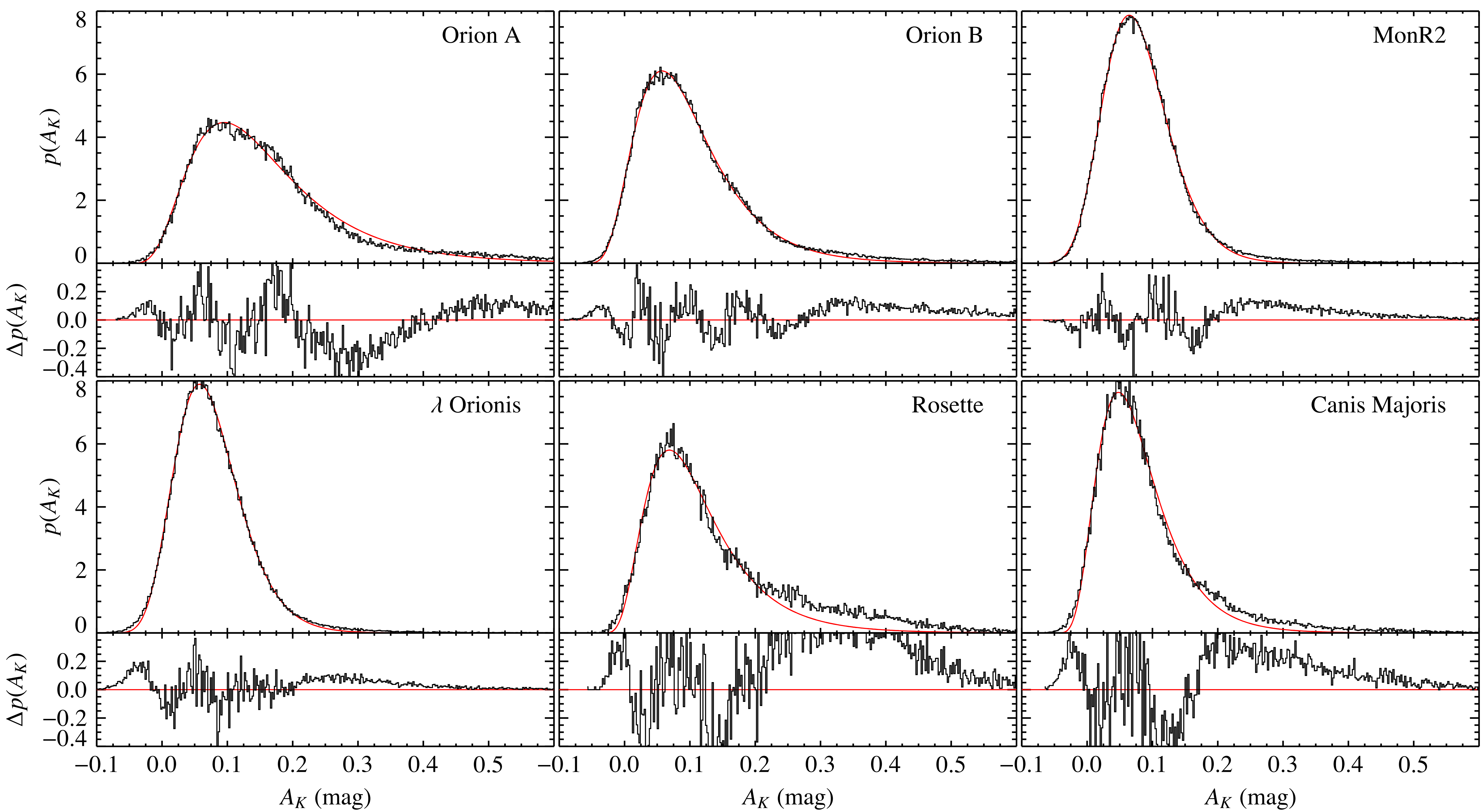
- Makes sense to study the PDF of molecular clouds



Lombardi et al. (2010)

Log-normal fits to cloud projected density distributions



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Magritte

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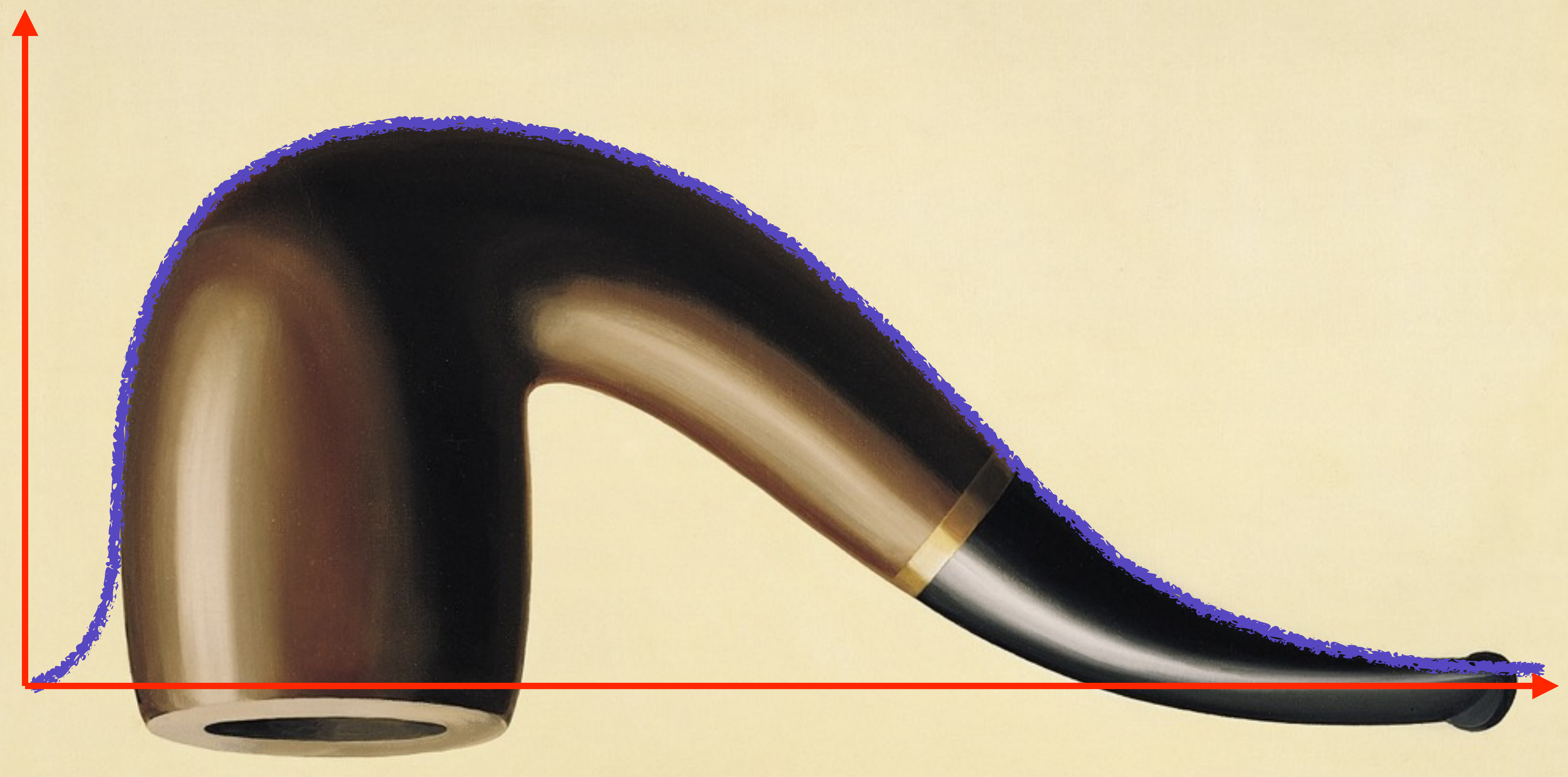

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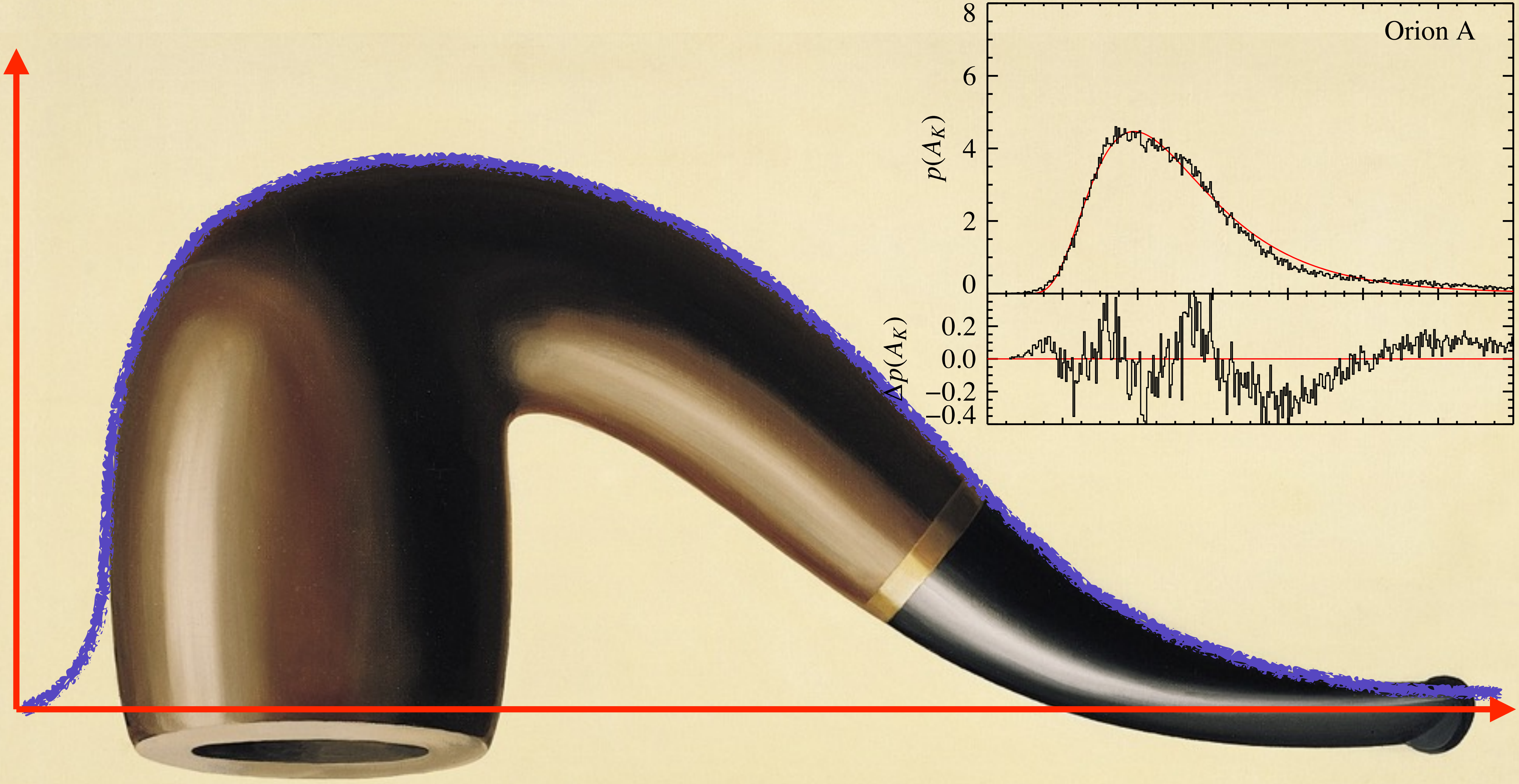
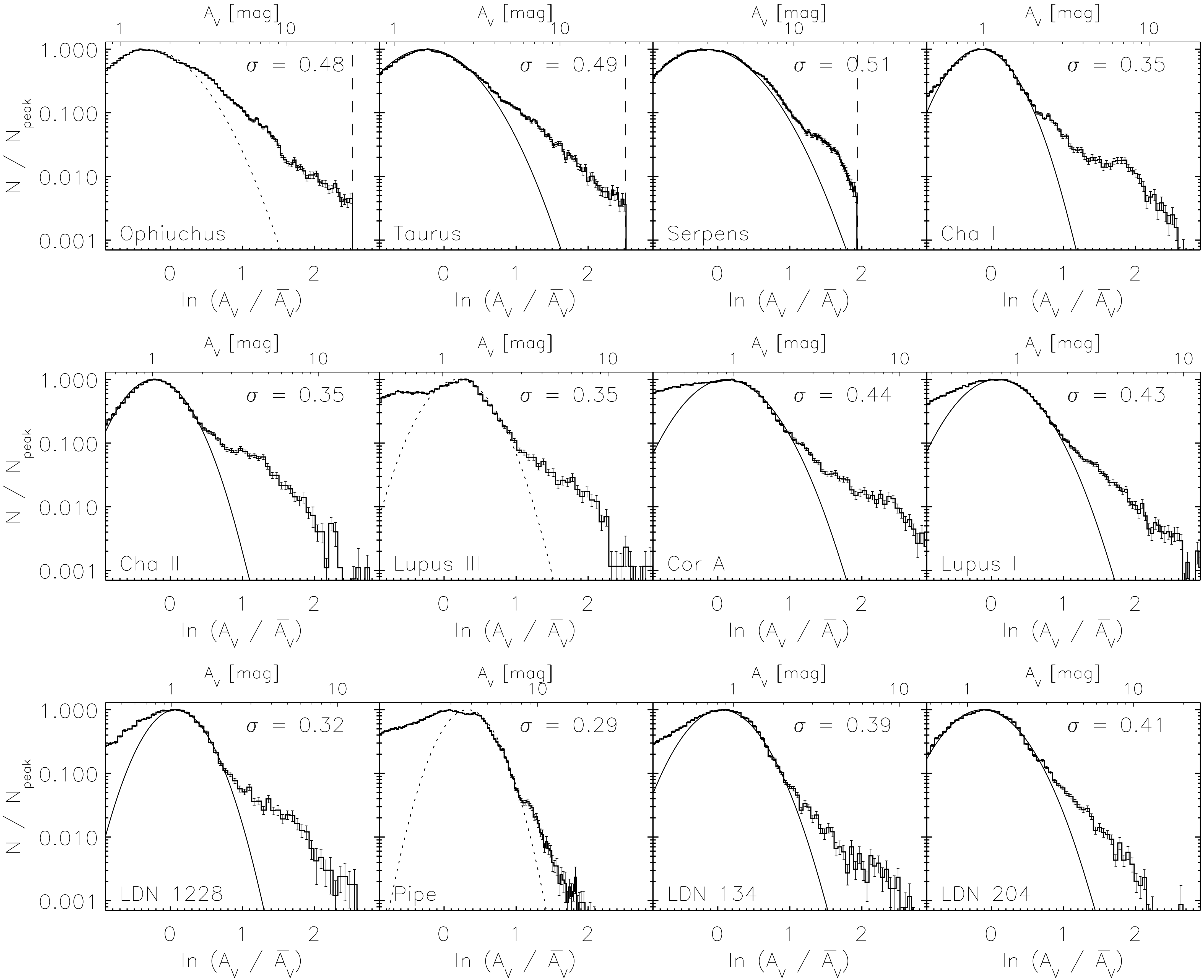


Log-normals everywhere!



Kainulainen et al. (2009; see also 2014)

Why we like log-normals

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$$\frac{\partial \boldsymbol{u}}{\partial t} = -(\boldsymbol{u} \cdot \boldsymbol{\nabla})\boldsymbol{u} - \cancel{\frac{1}{M^2}\frac{\nabla P}{\rho}} + \cancel{\frac{J^2}{M^2}}\boldsymbol{g}$$

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Why we like log-normals

- Log-normal distributions are expected for ρ (Vázquez-Semadeni 1994, Padoan et al. 1997, Scalo et al 1998…)
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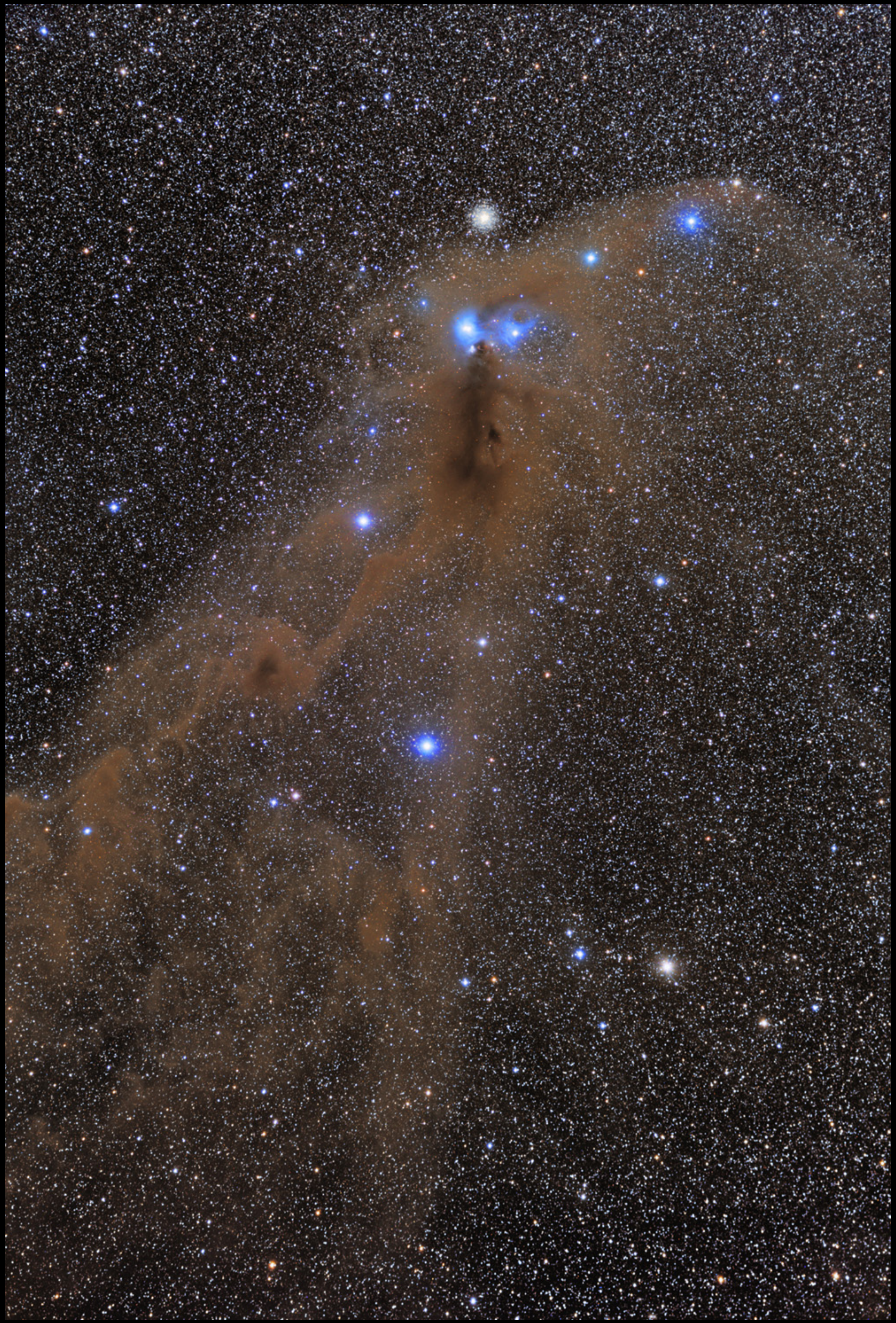
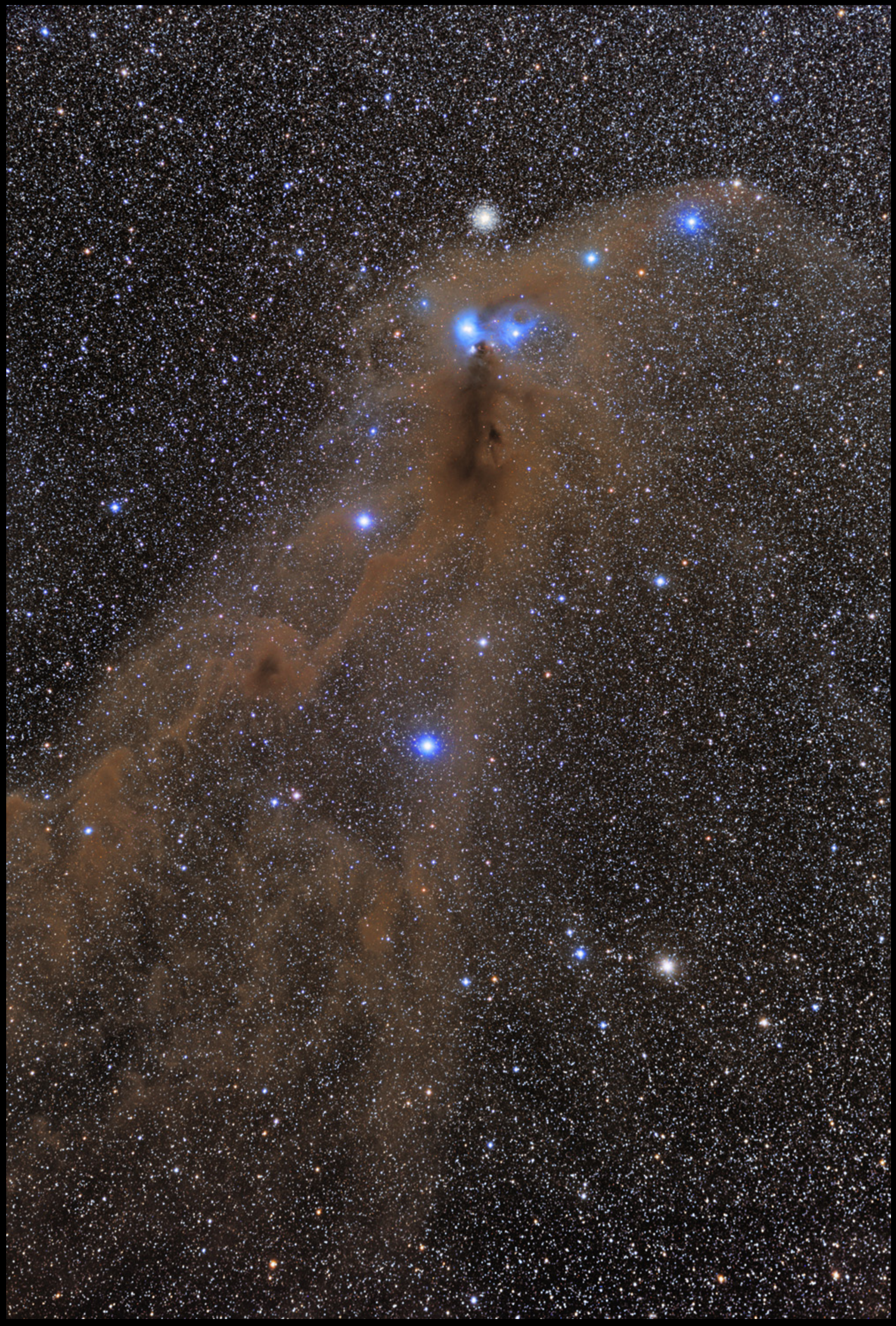
  - Relative changes of ρ are equally expected
  - Central limit theorem predicts a log-normal
- Projection effects (in most cases…) do not significantly alter this expectation (Vázquez-Semadeni & García 2001)

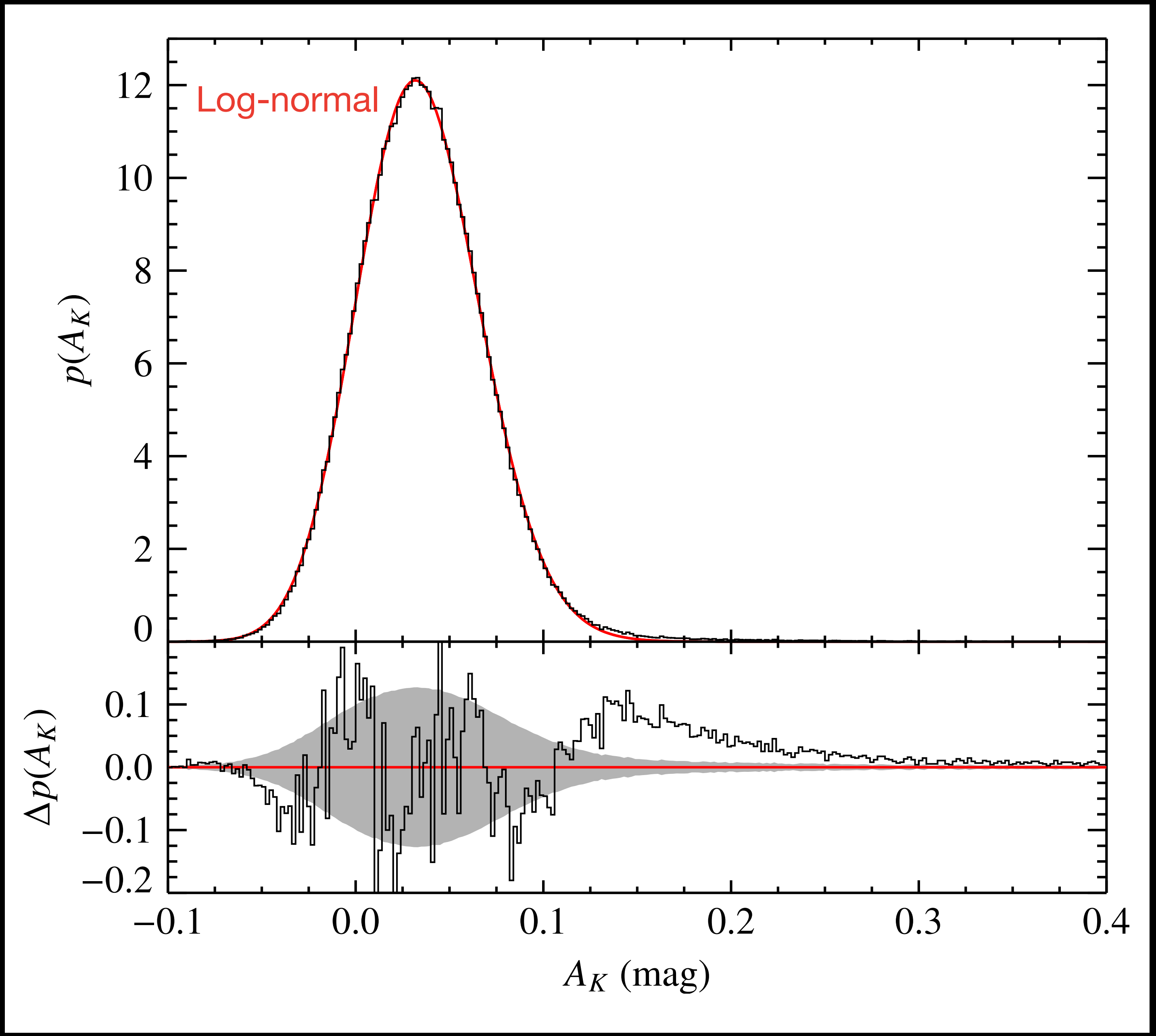
The end of a dream



Alves et al. (2014)

The end of a dream

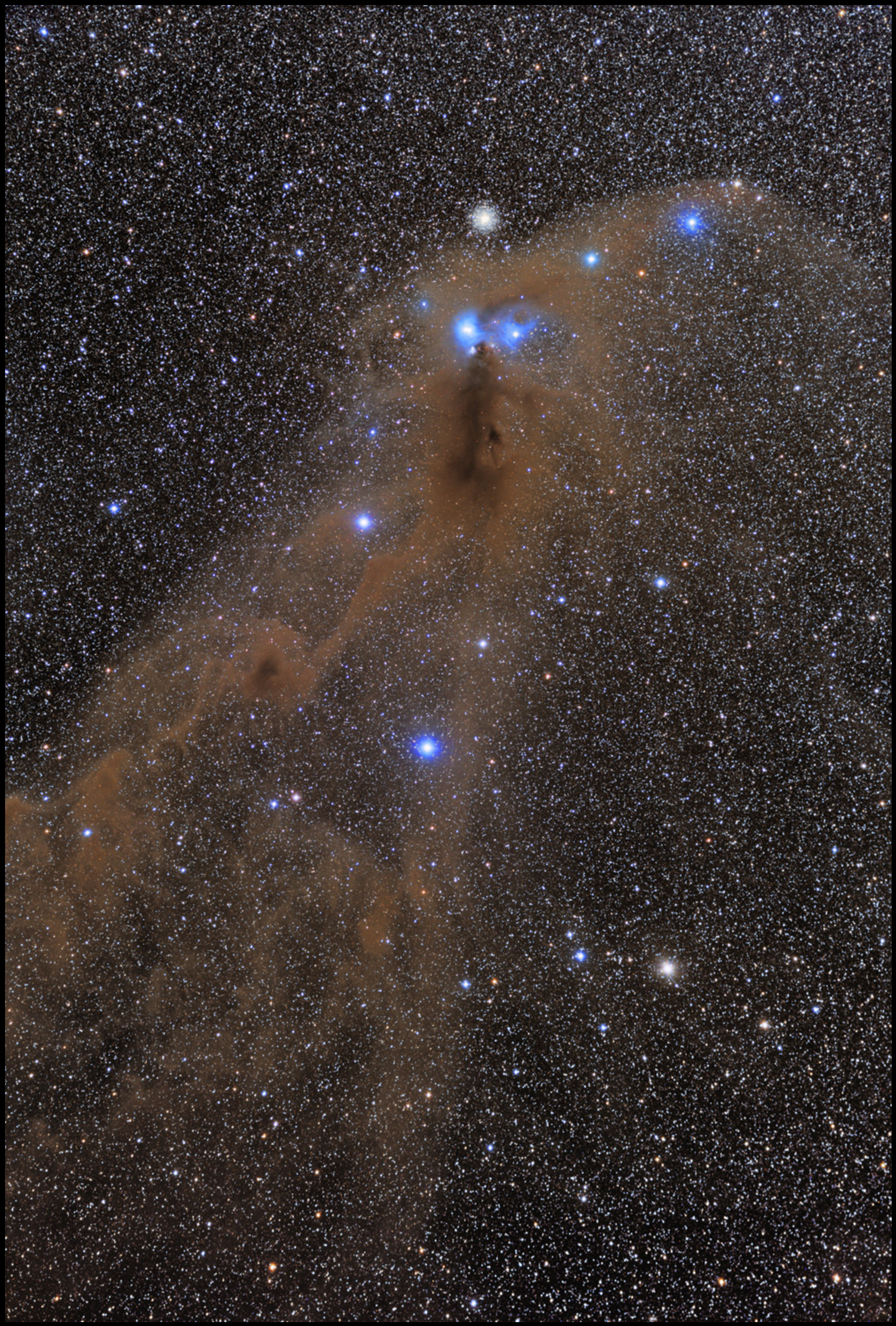


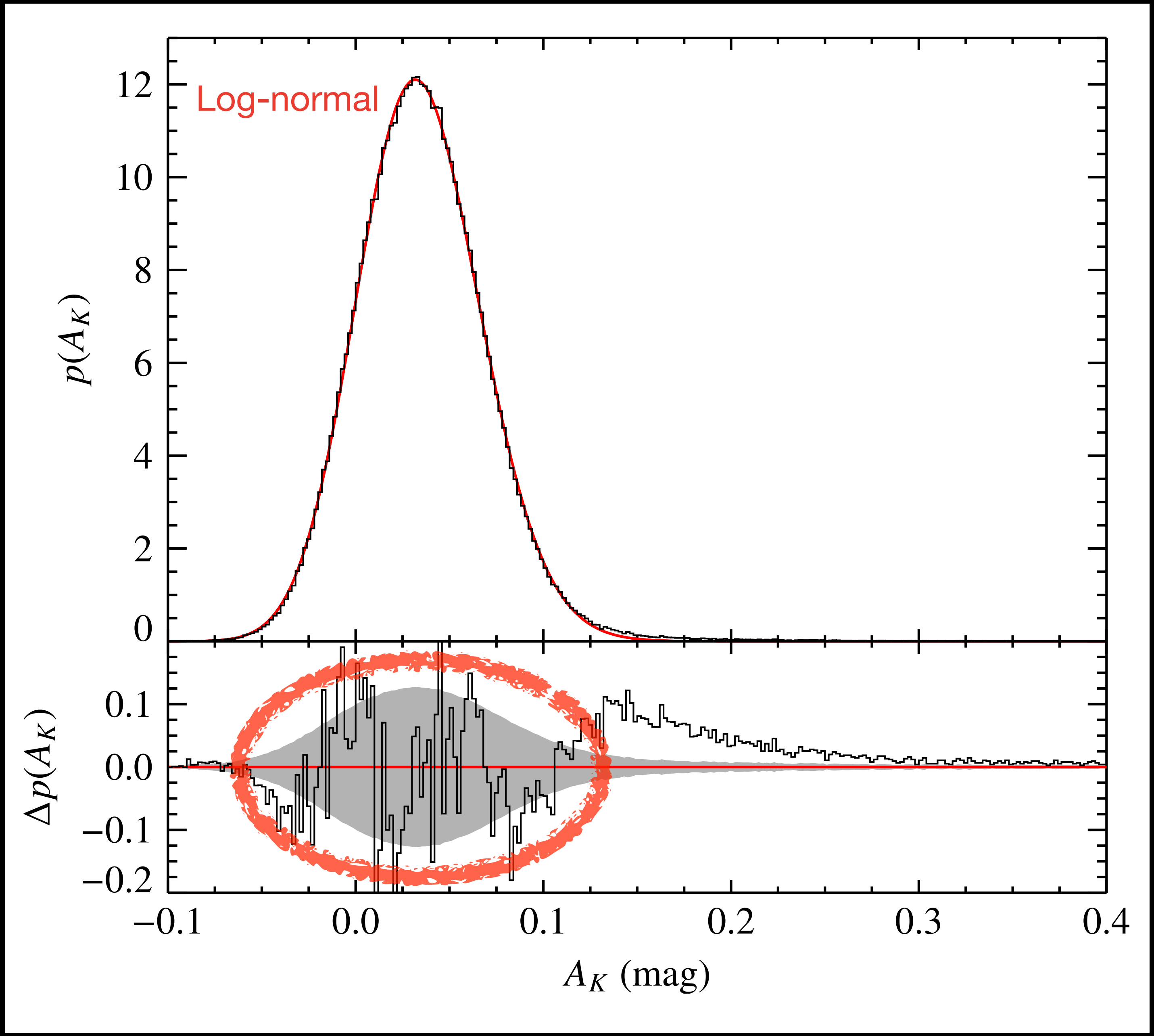


Systematic residuals in the entire fitting region!

Alves et al. (2014)

The end of a dream





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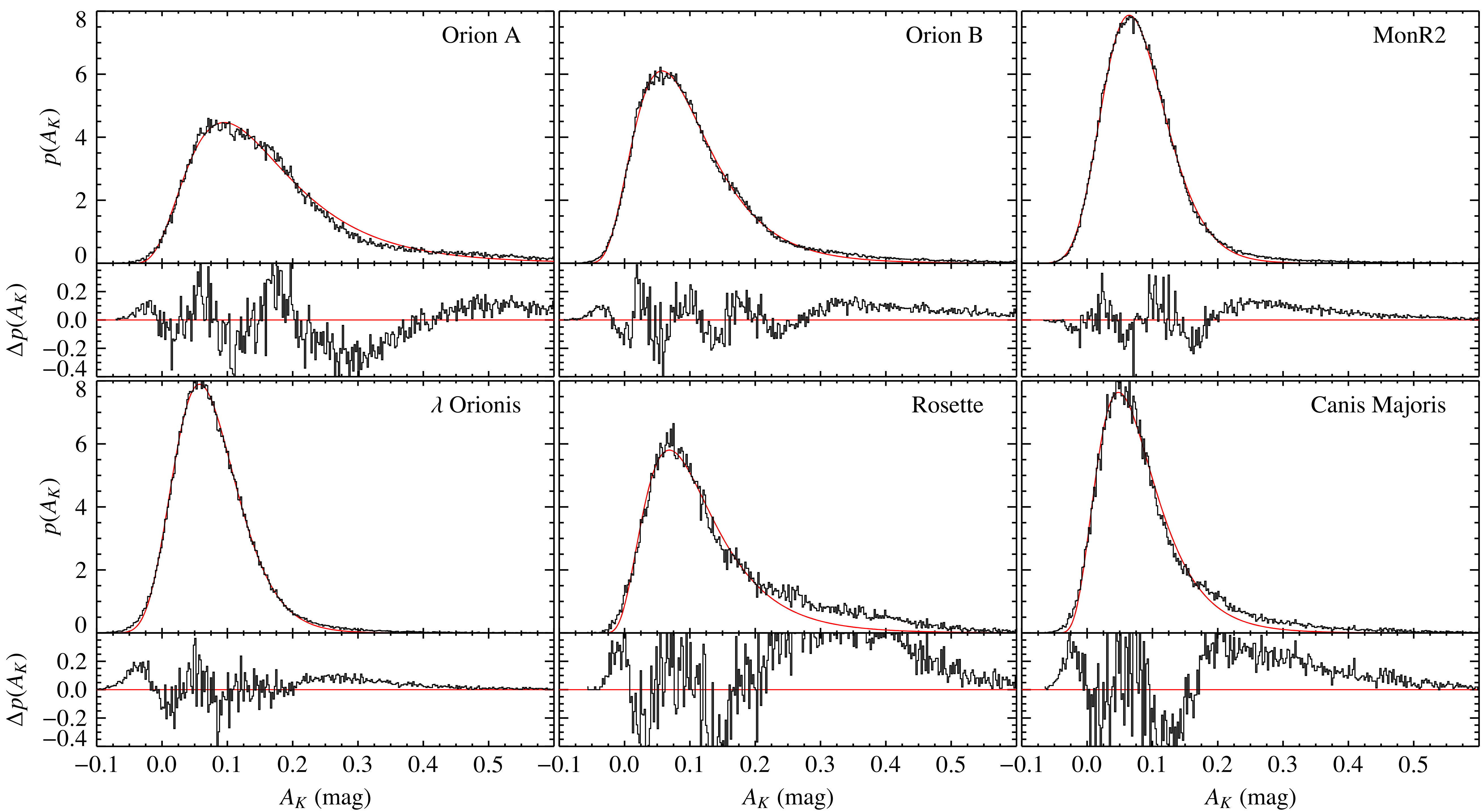
All log-normal fits show systematic residuals



Lombardi et al. (2011)

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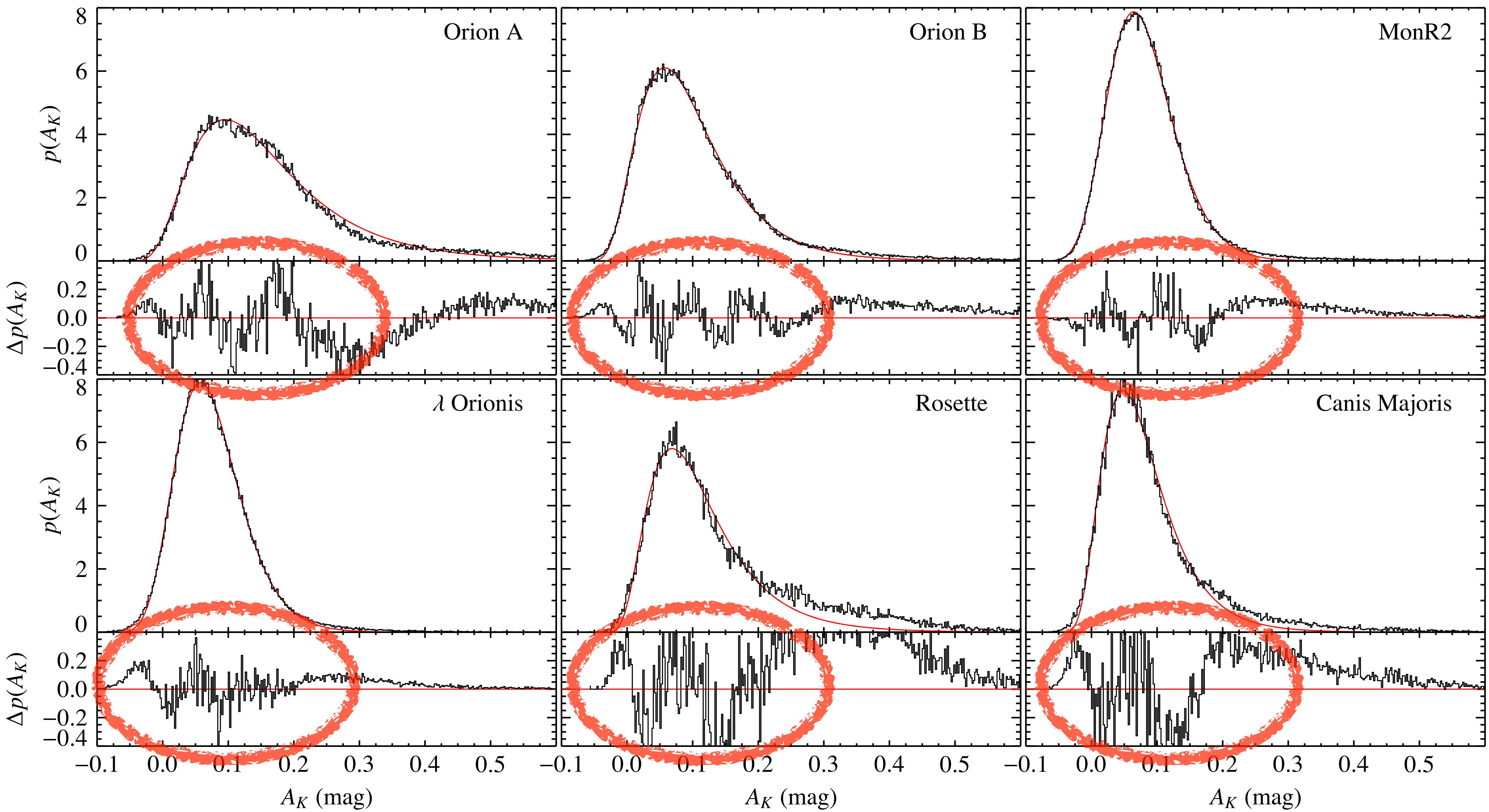
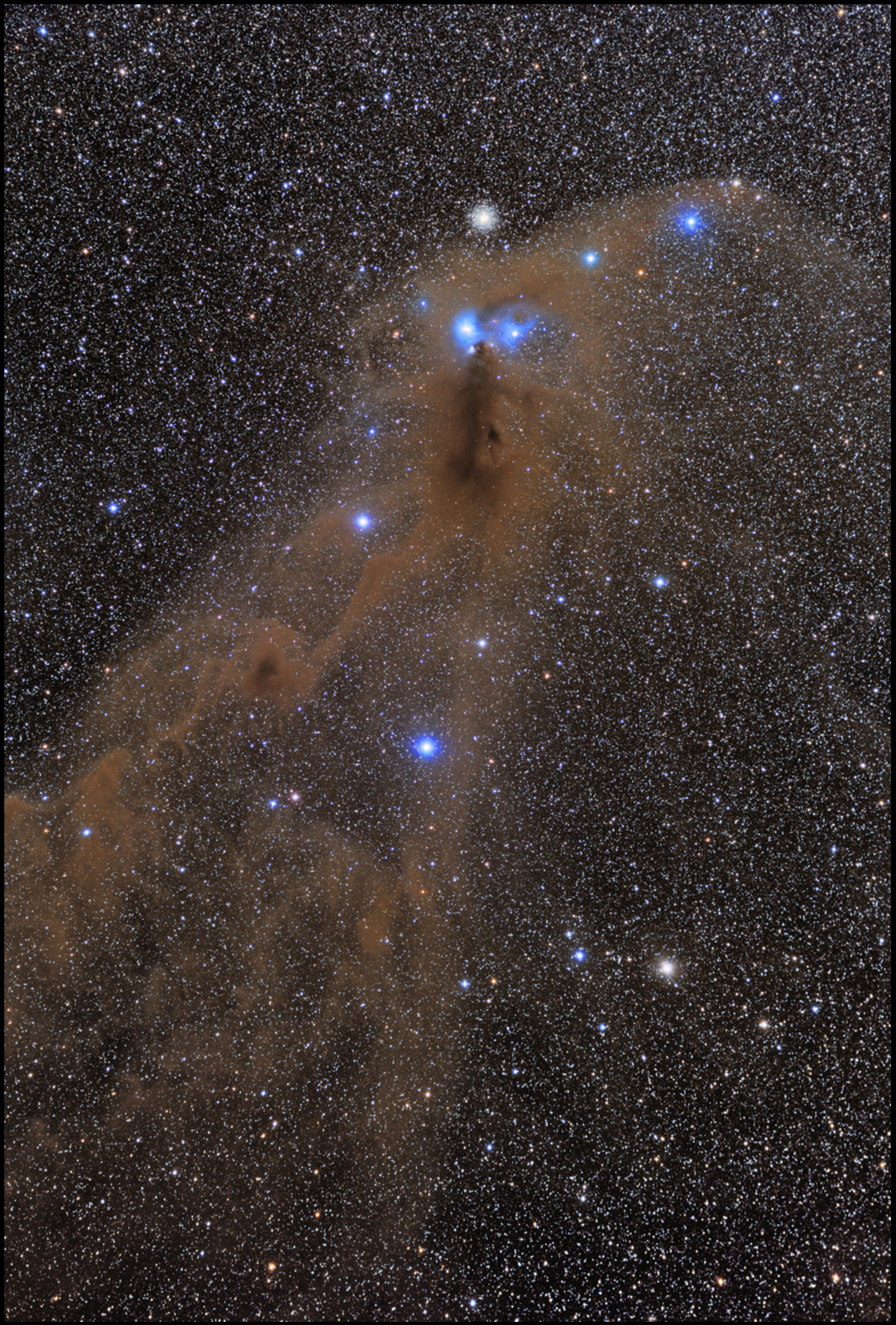
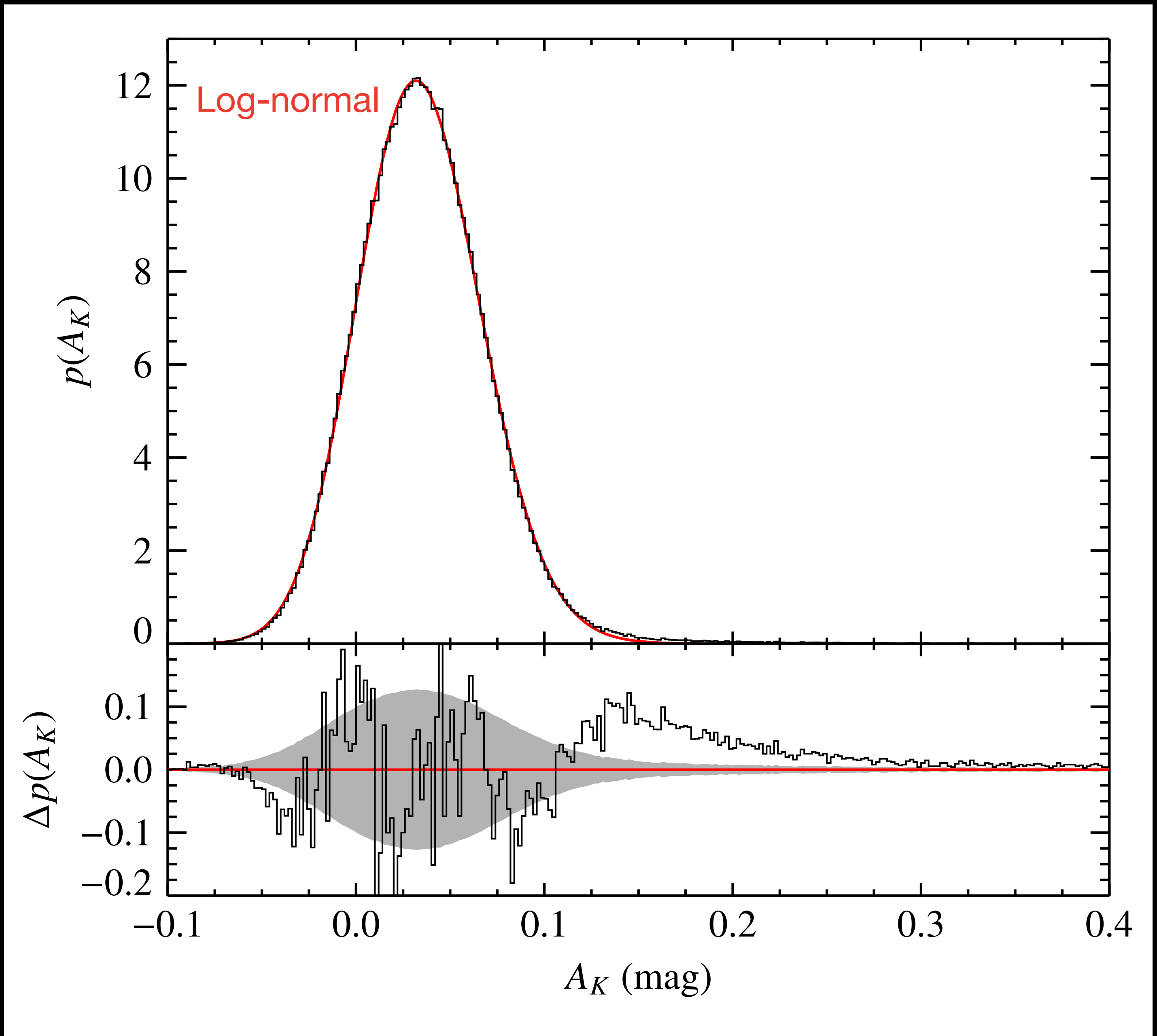


Lombardi et al. (2011)

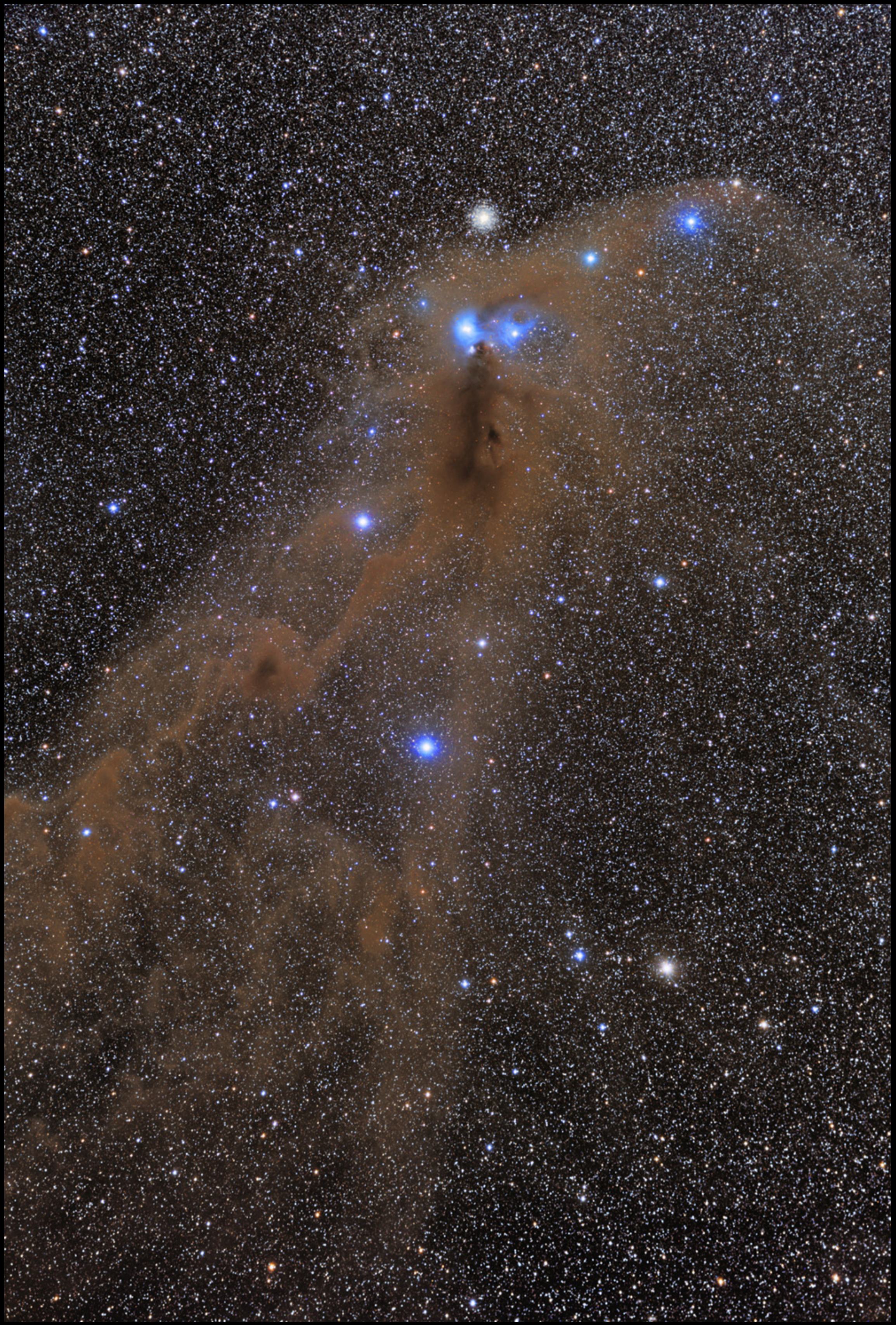
The end of a dream

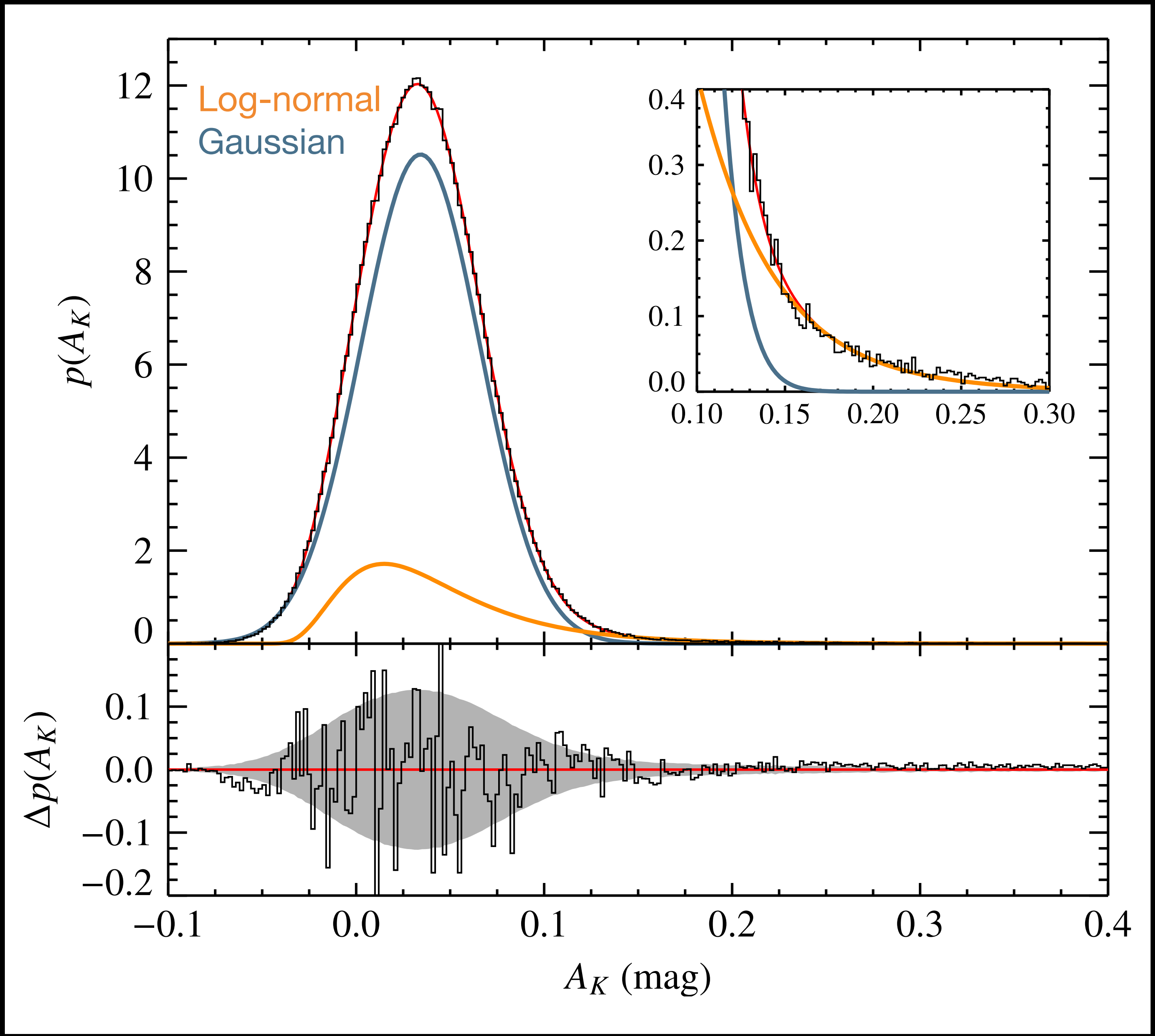




Alves et al. (2014)

The end of a dream

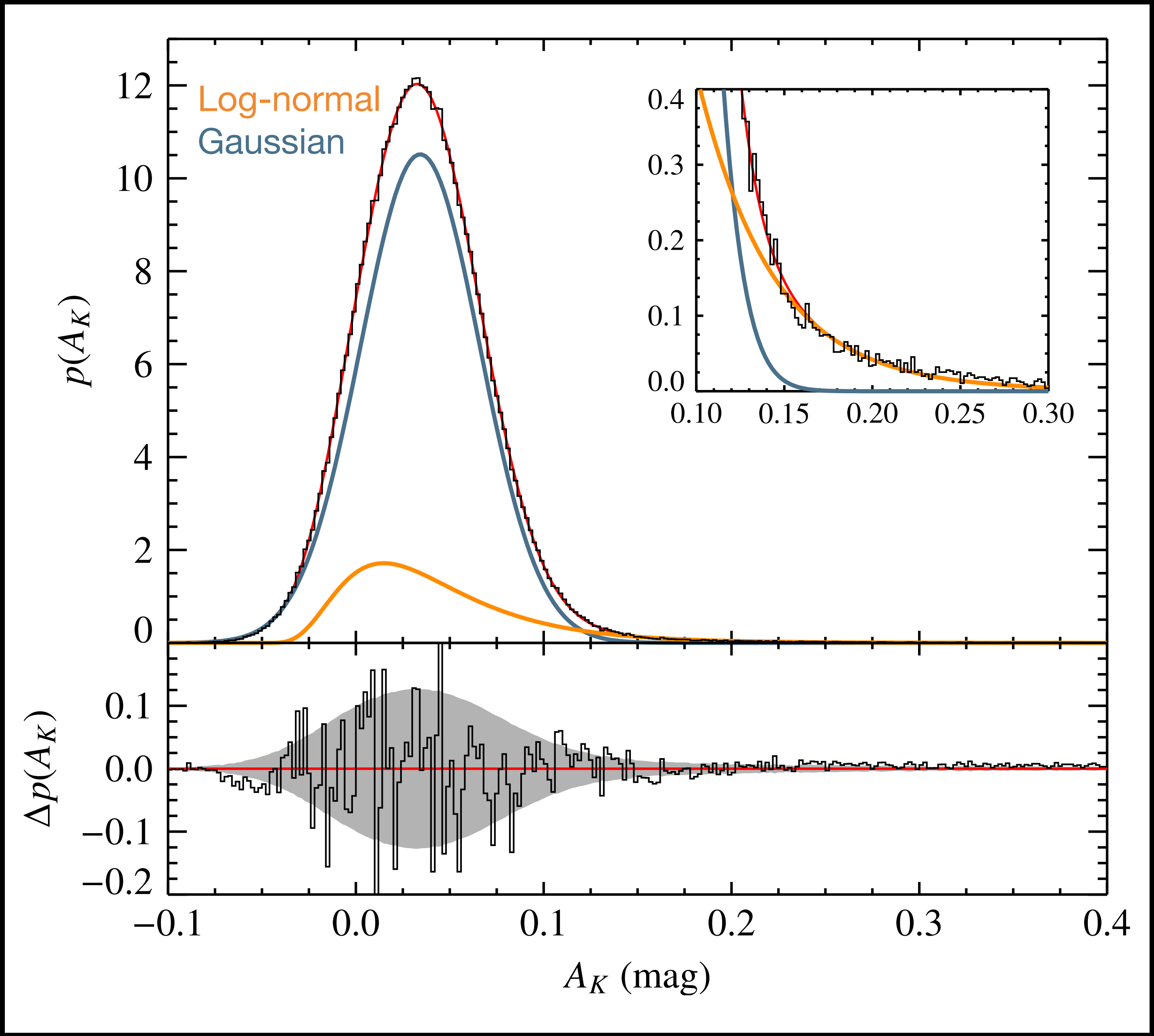




Residuals disappear when fitting a Gaussian + Log-normal.

Alves et al. (2014)

The end of a dream



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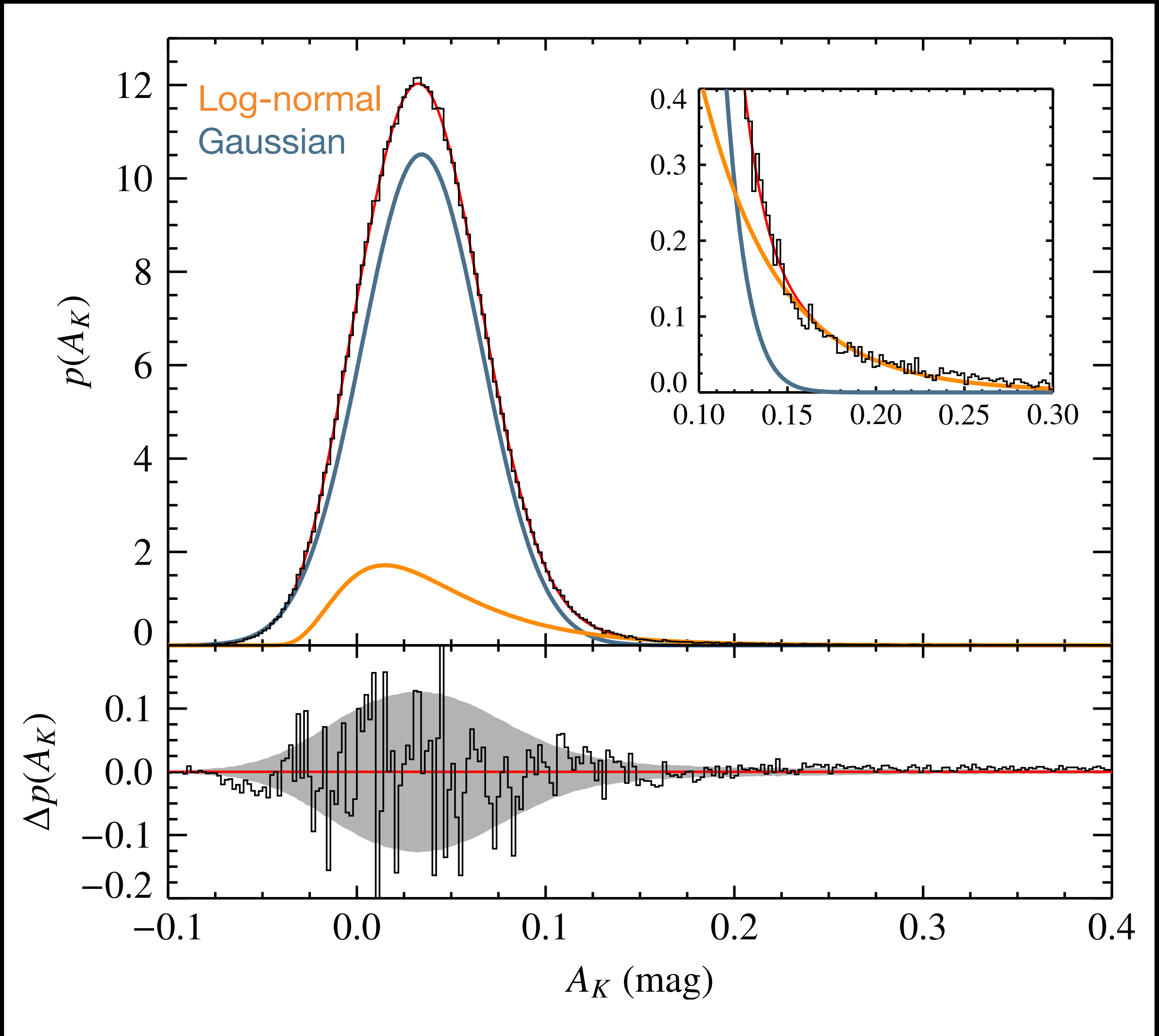
The end of a dream

- What is the physical meaning?



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The end of a dream

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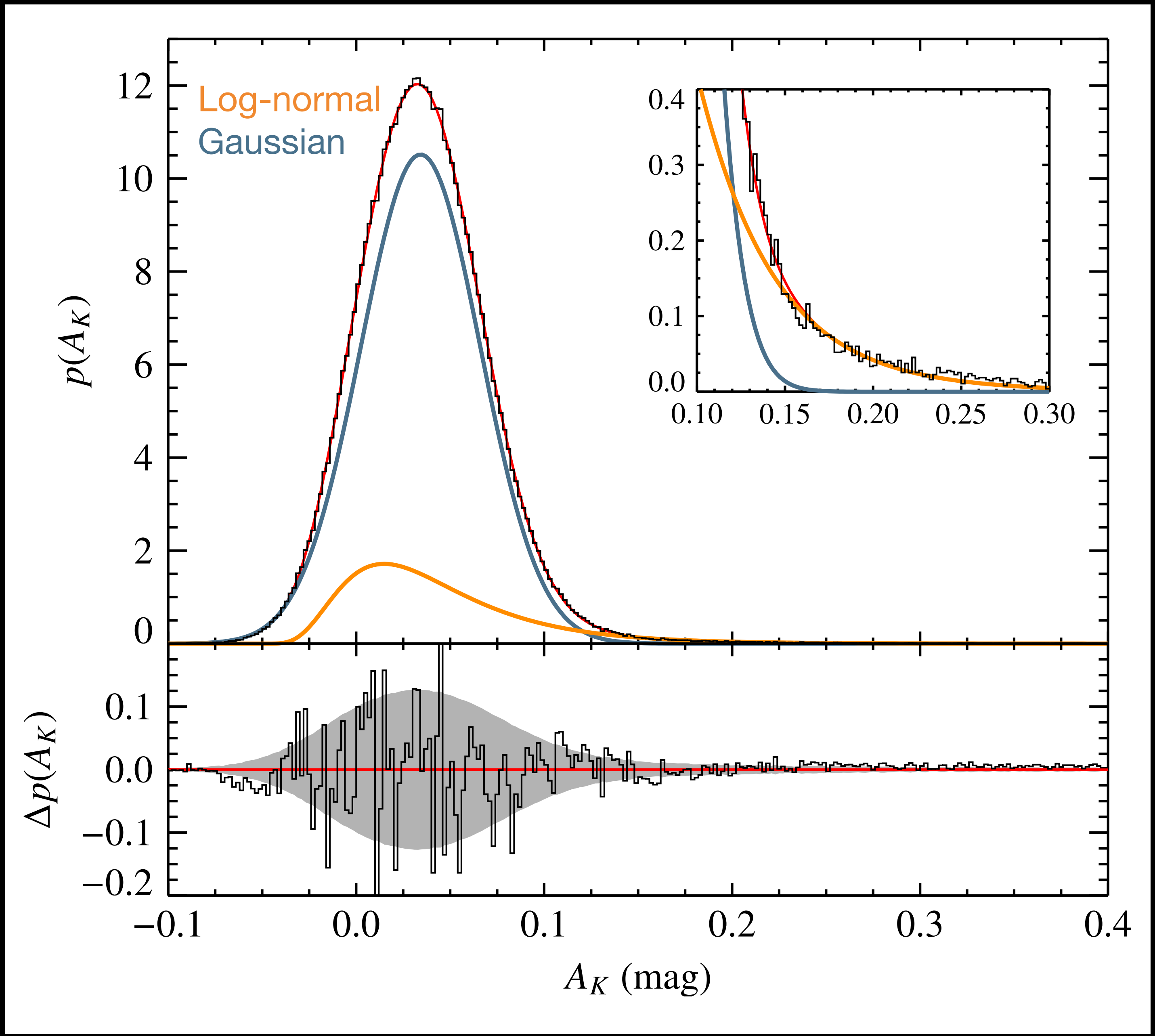

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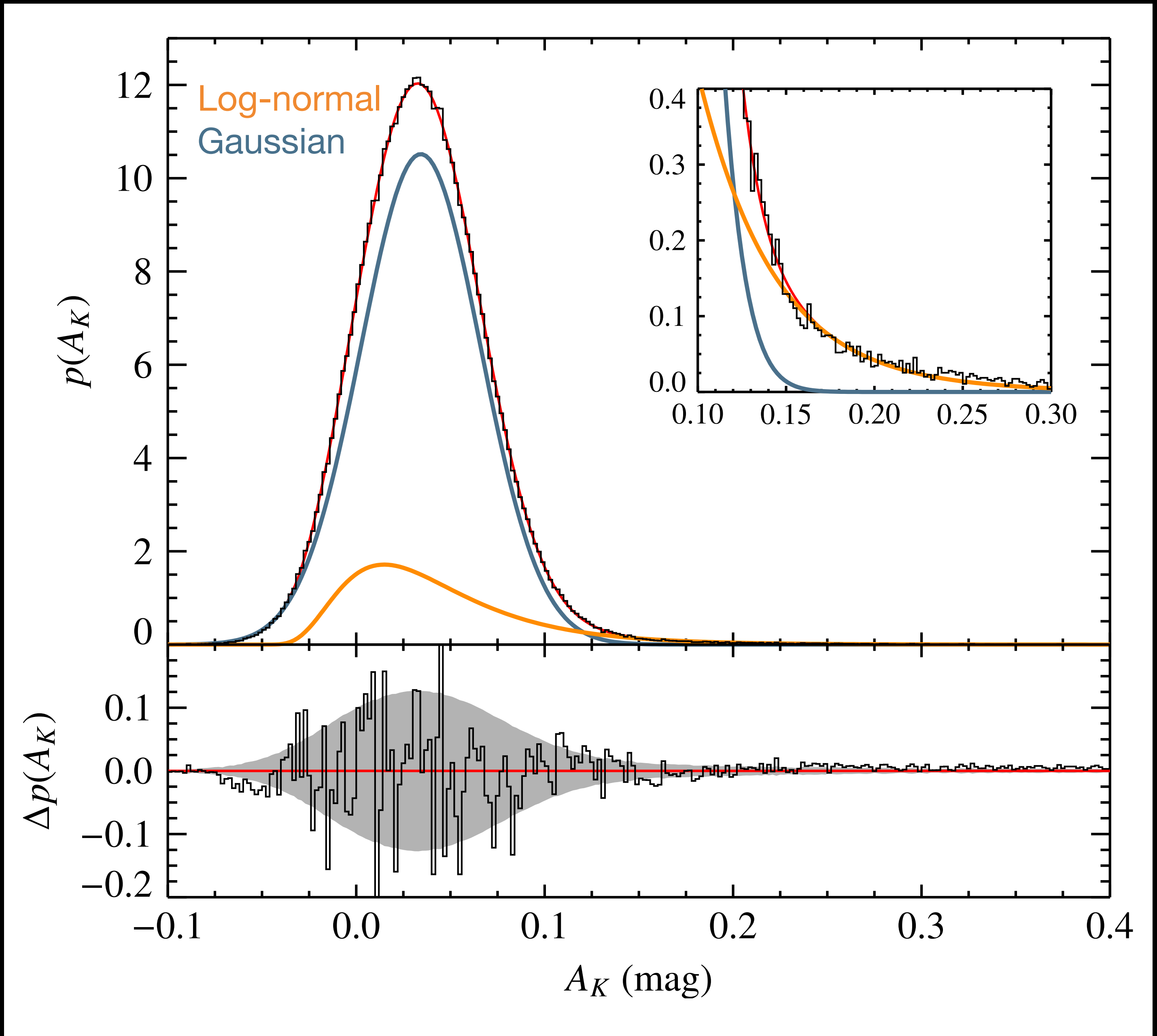

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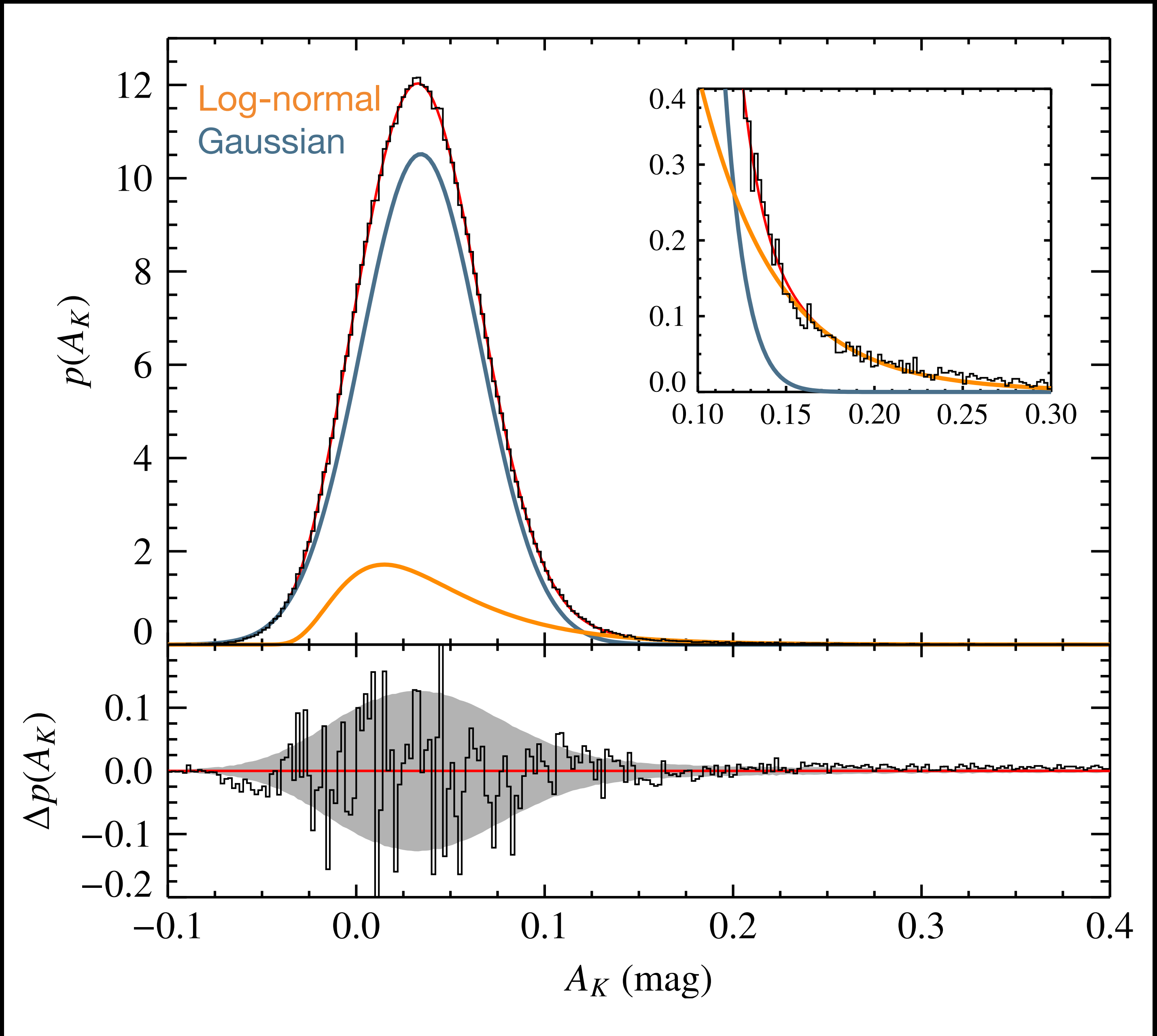

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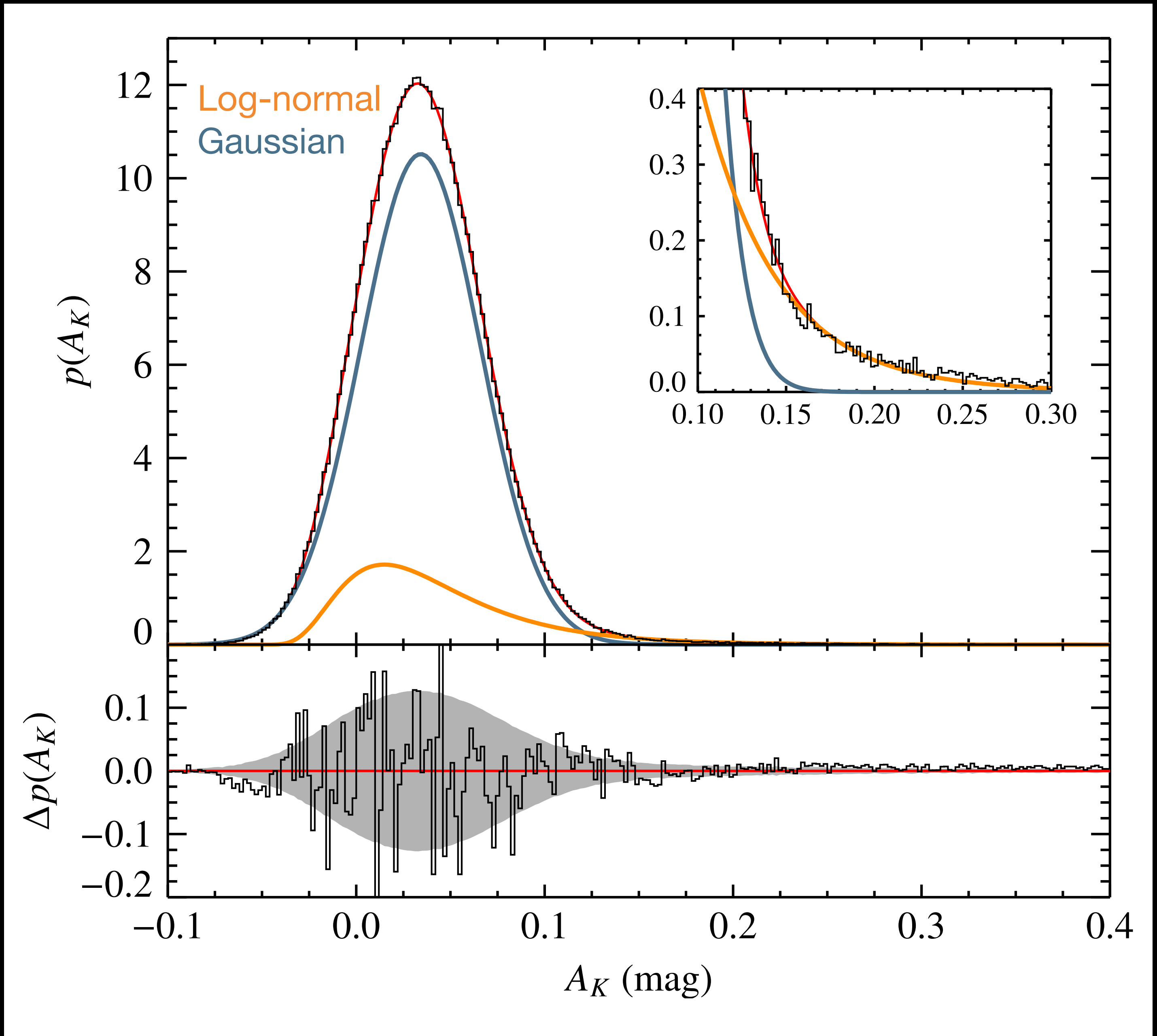

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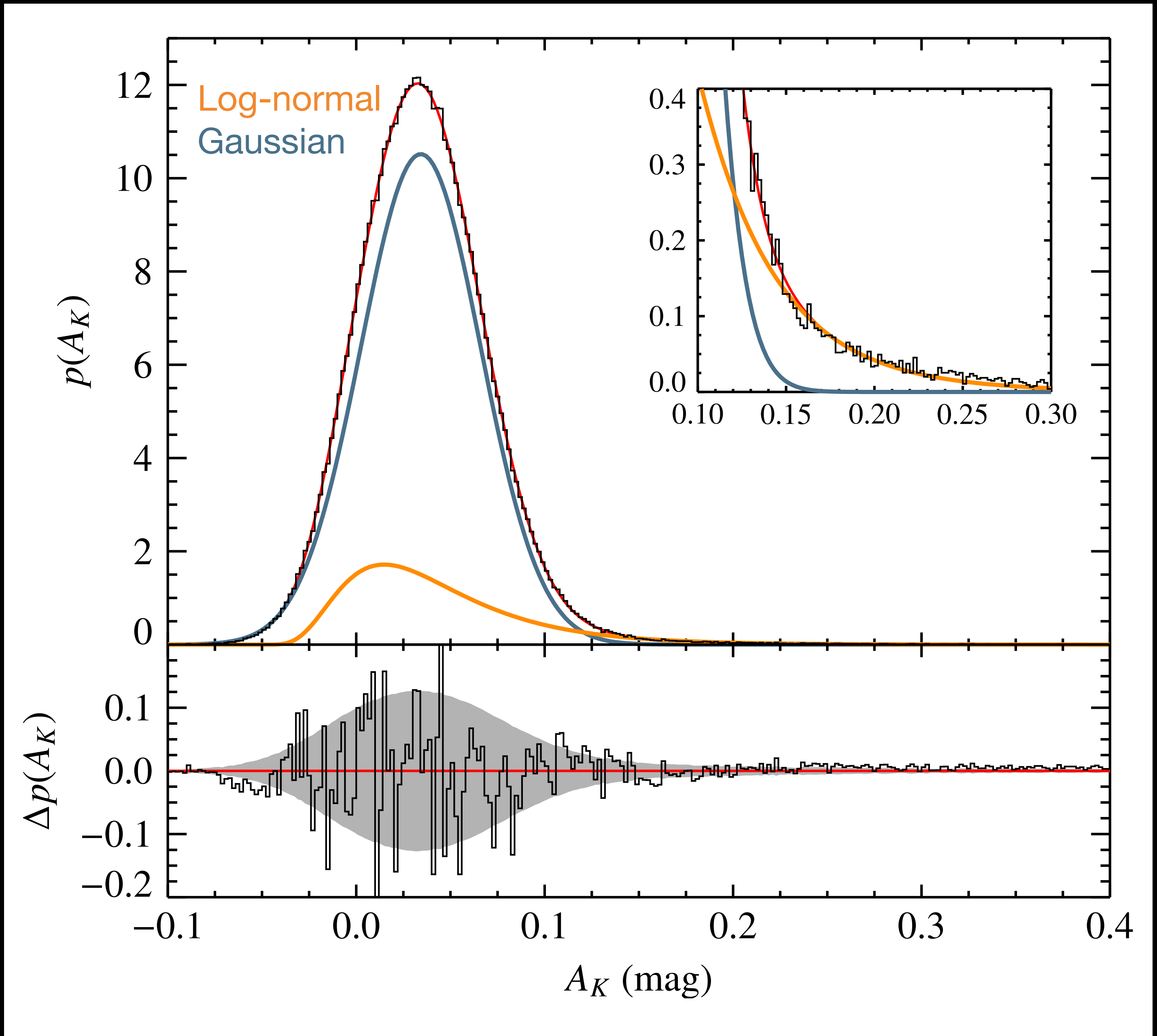

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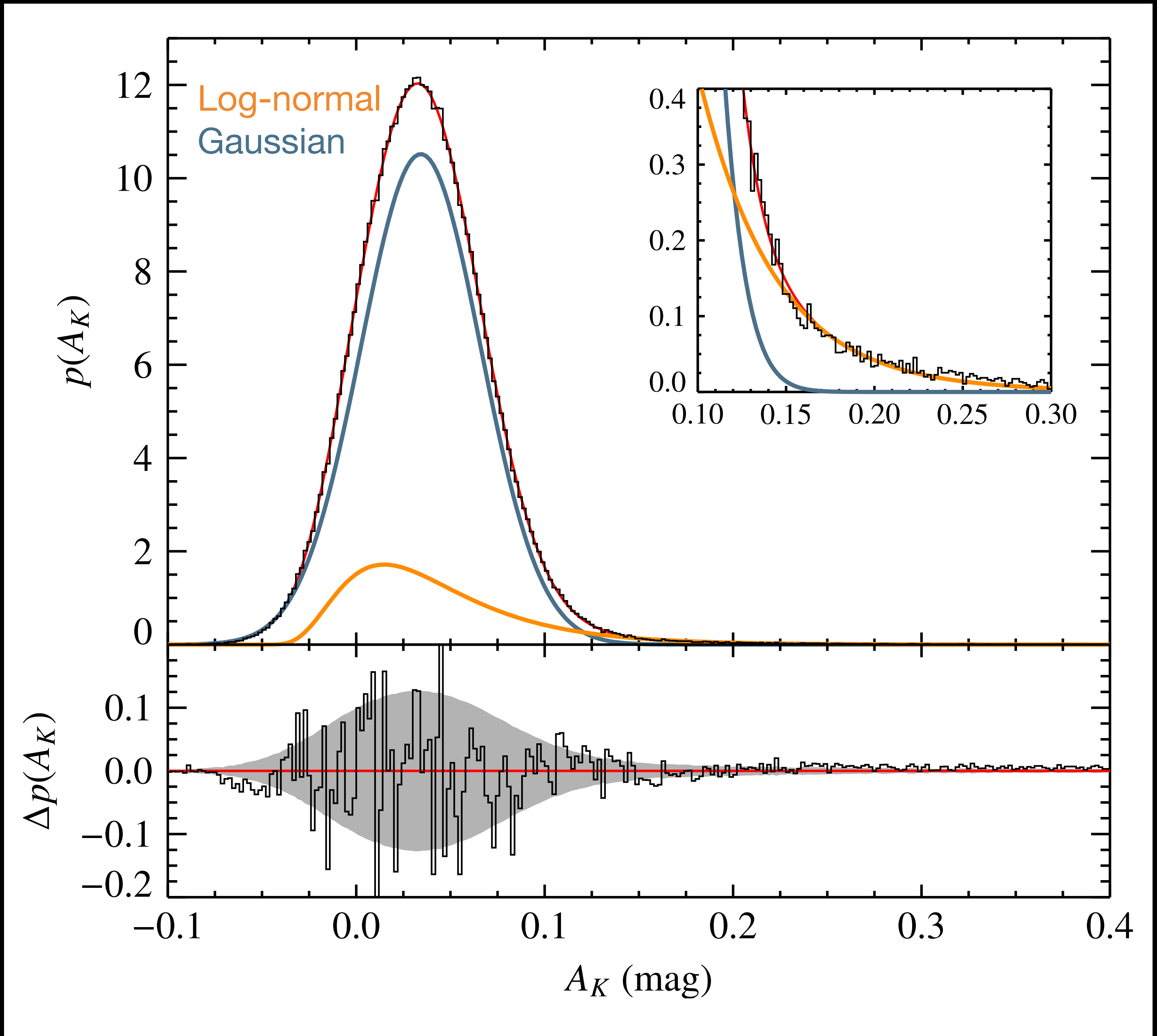

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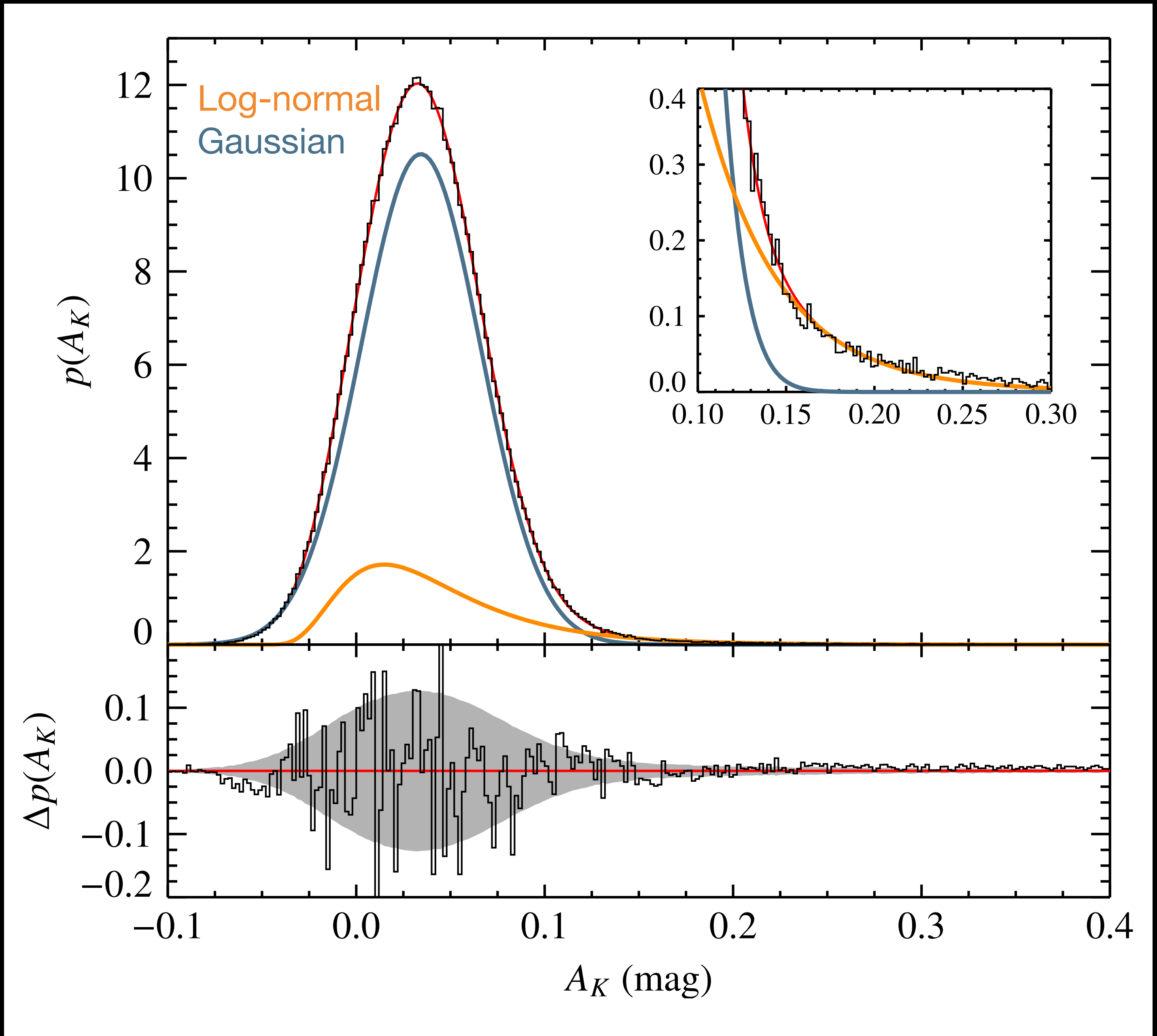
- Log-normals: are they real?



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Do yourself your log-normal!

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Recipe

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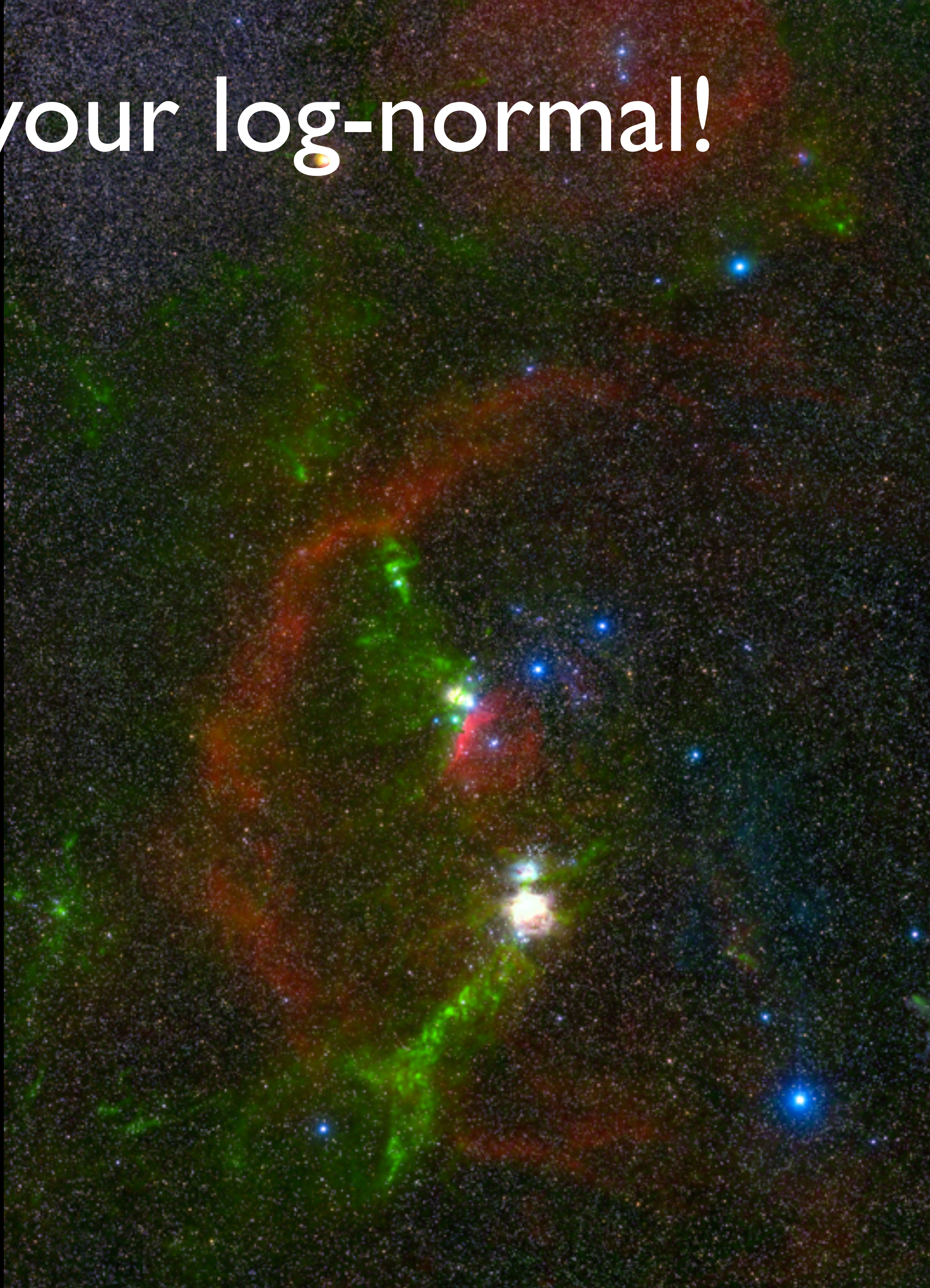


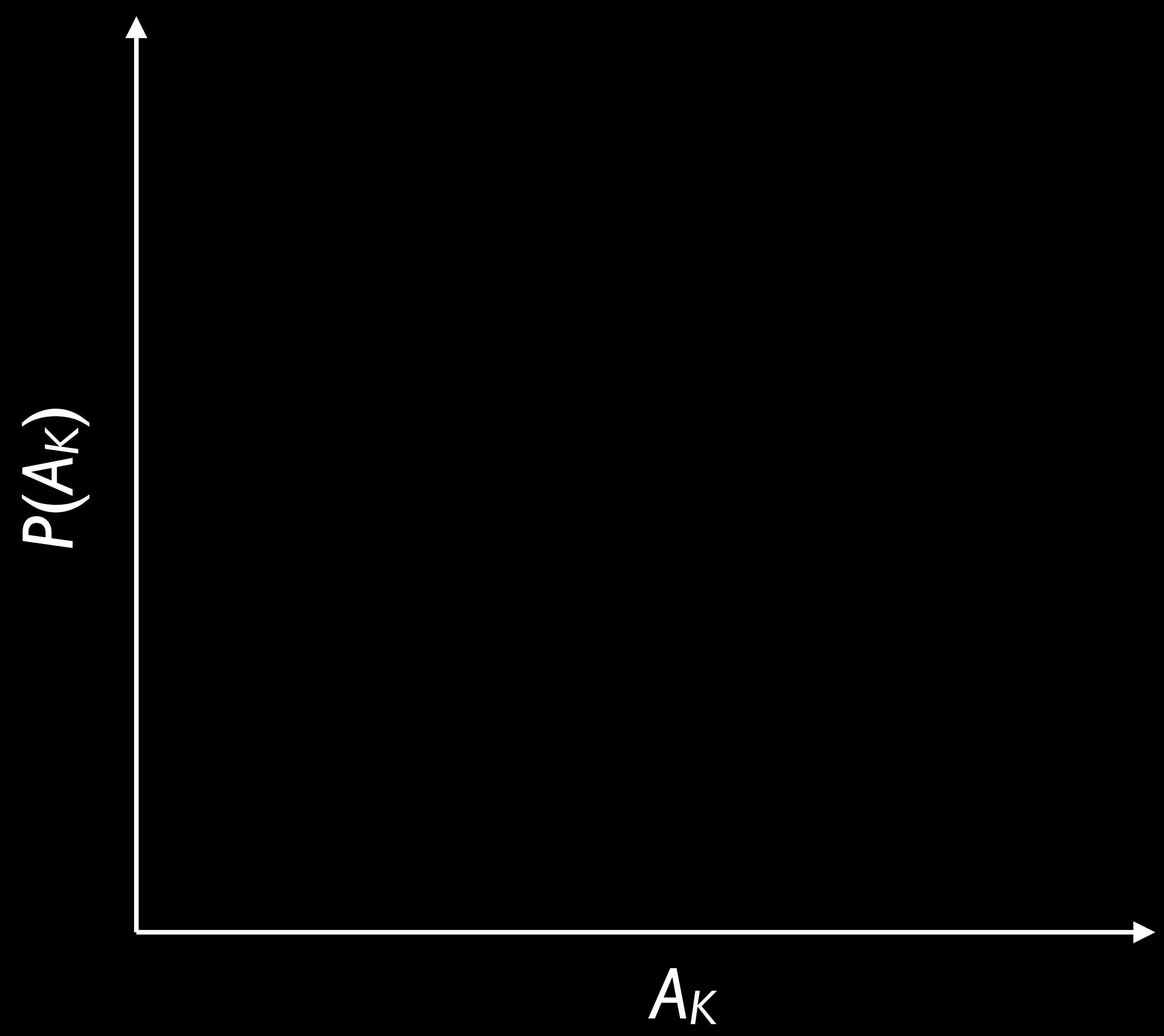
Recipe

- Take any nice cloud

Do yourself your log-normal!

Recipe

- Take any nice cloud
  - For optimal results, make sure the *true* PDF is decreasing



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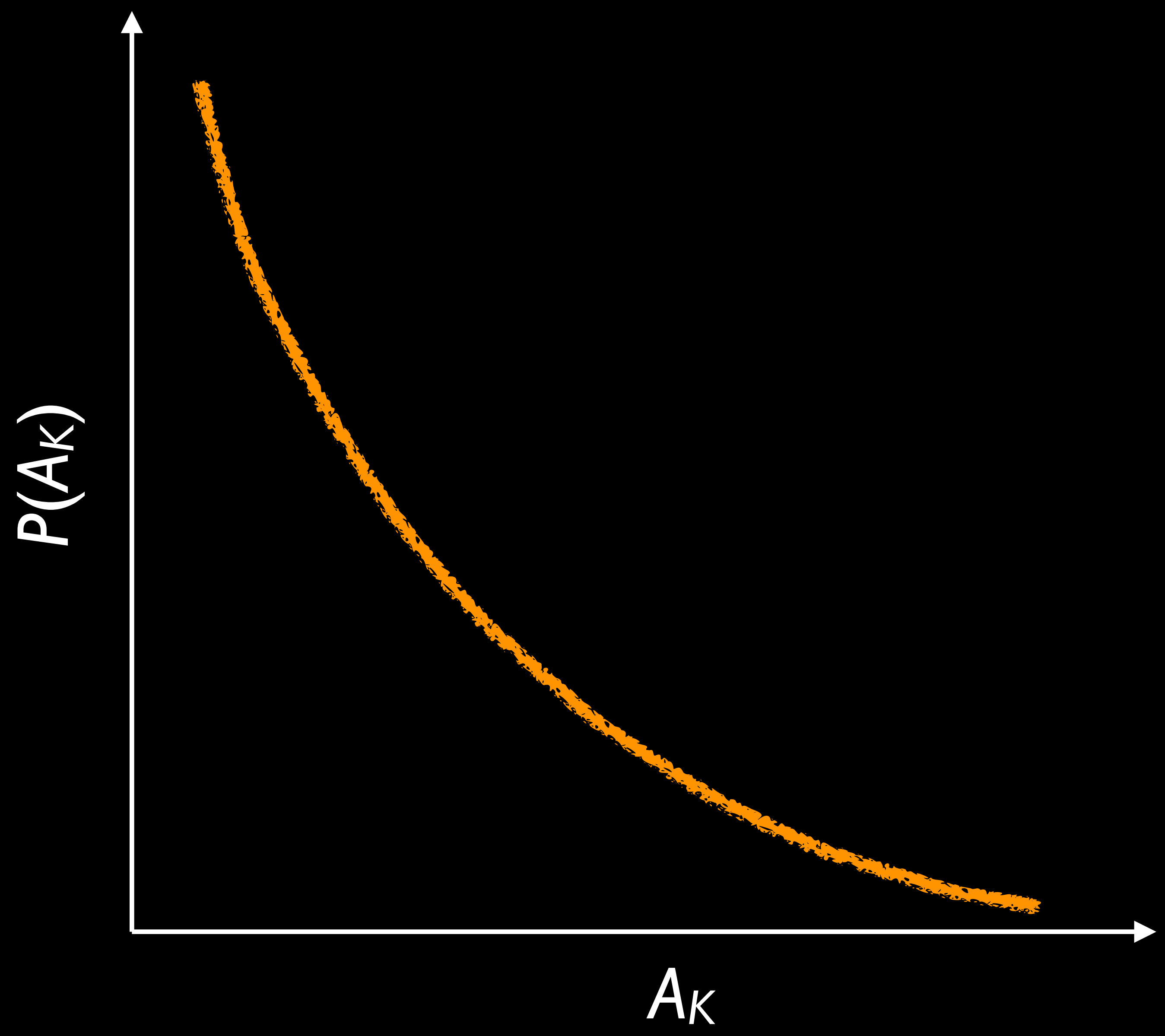

Do yourself your log-normal!

Recipe

- Take any nice cloud
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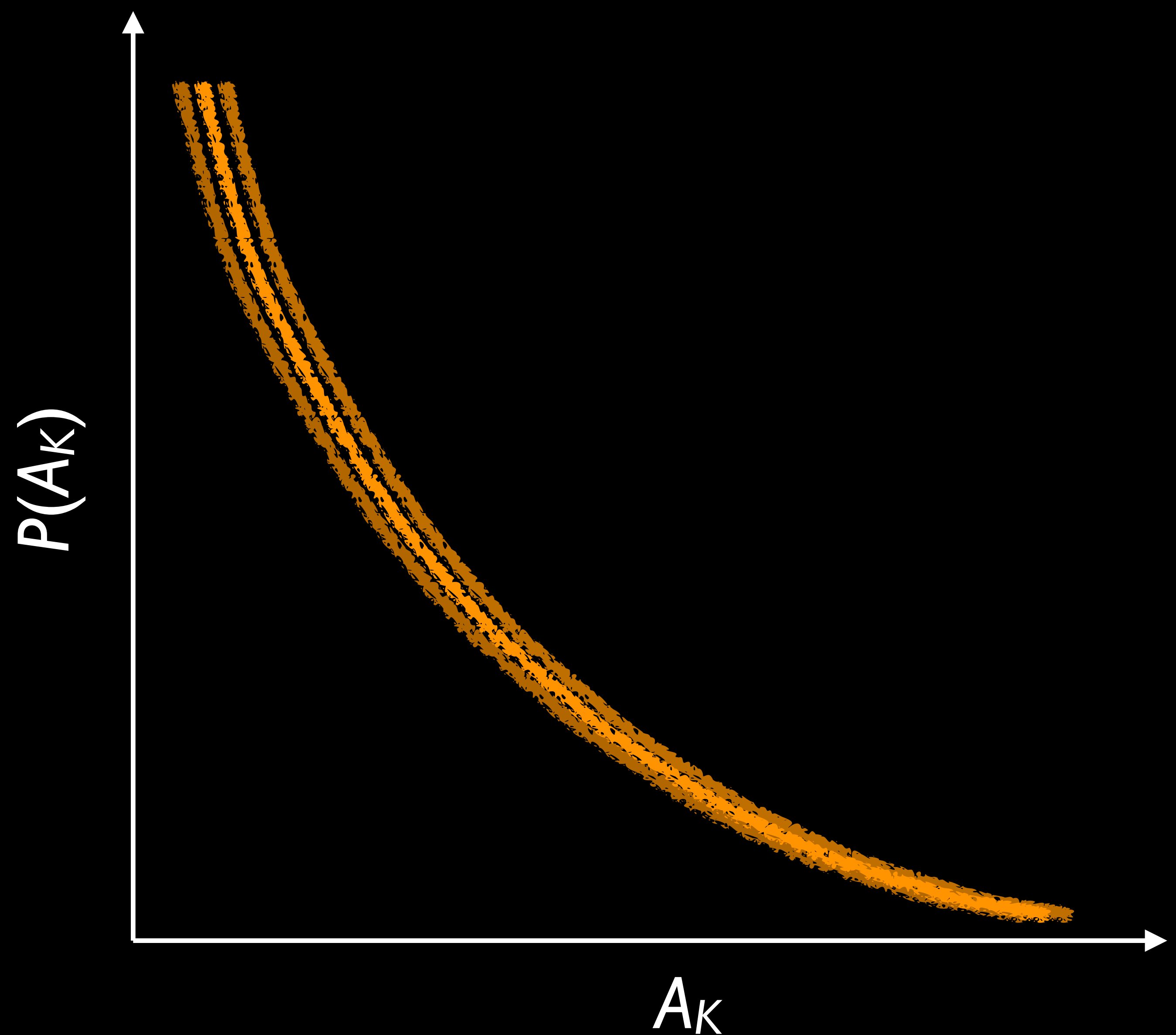
- Observe the cloud



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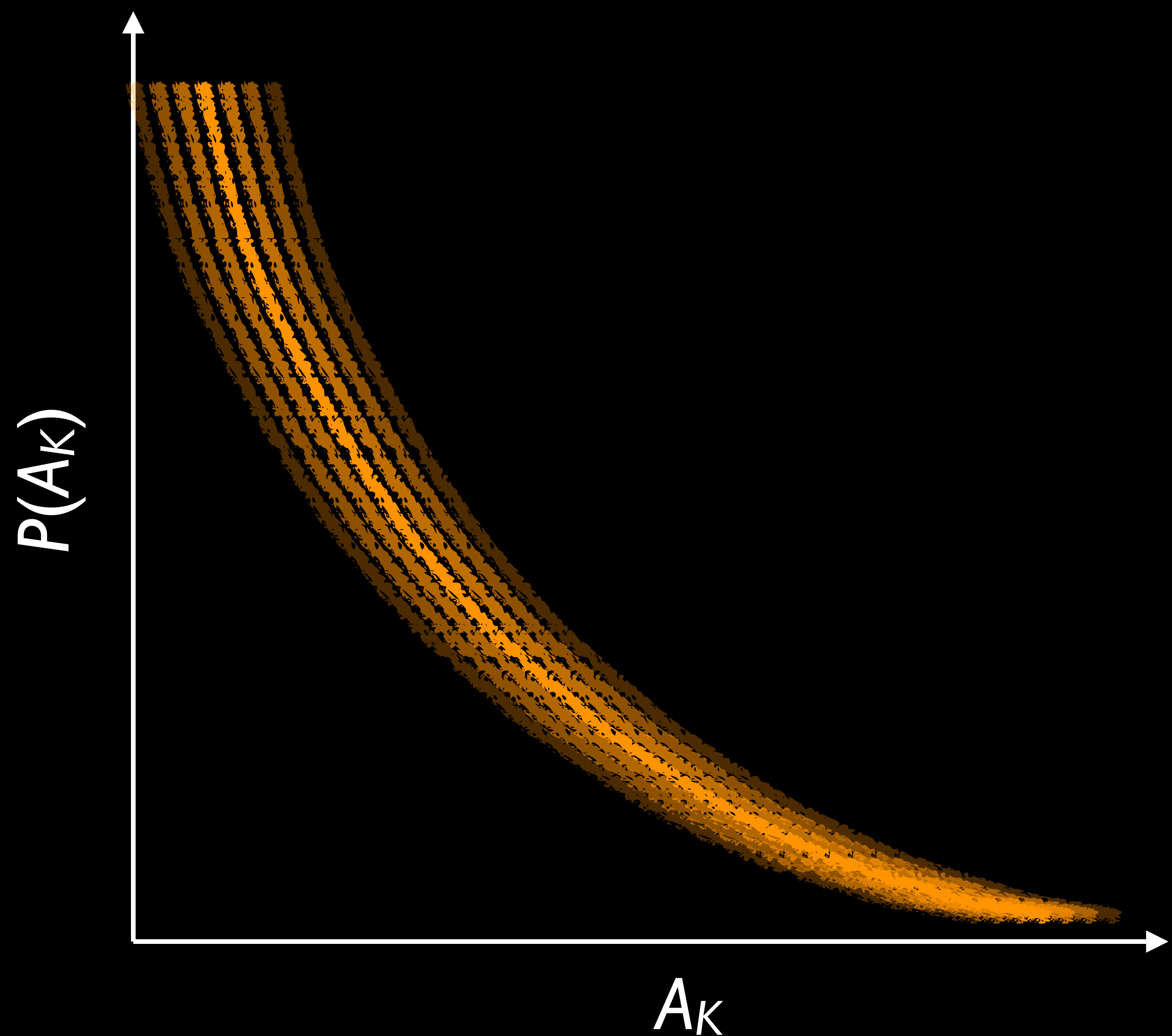

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- Take any nice cloud
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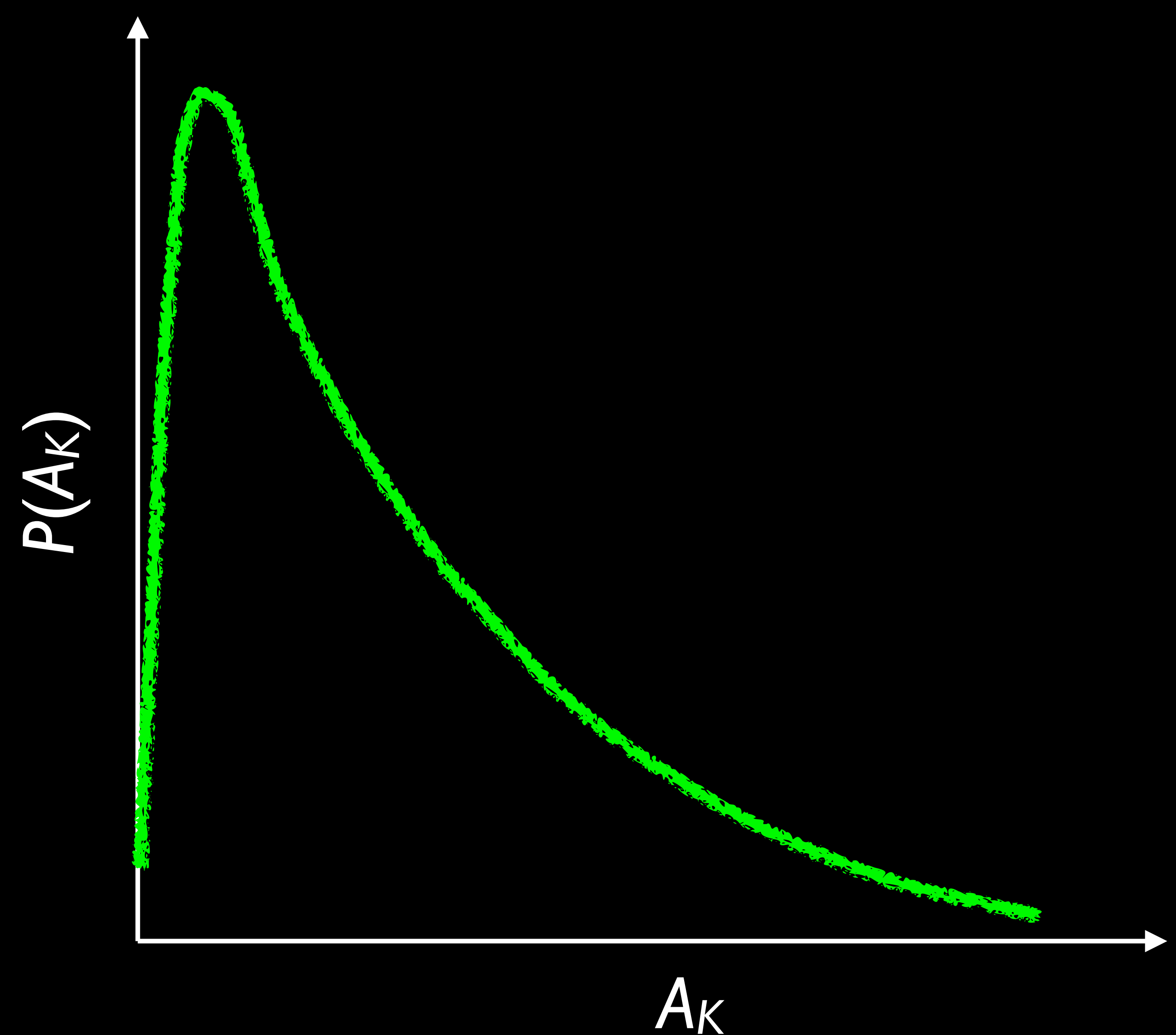
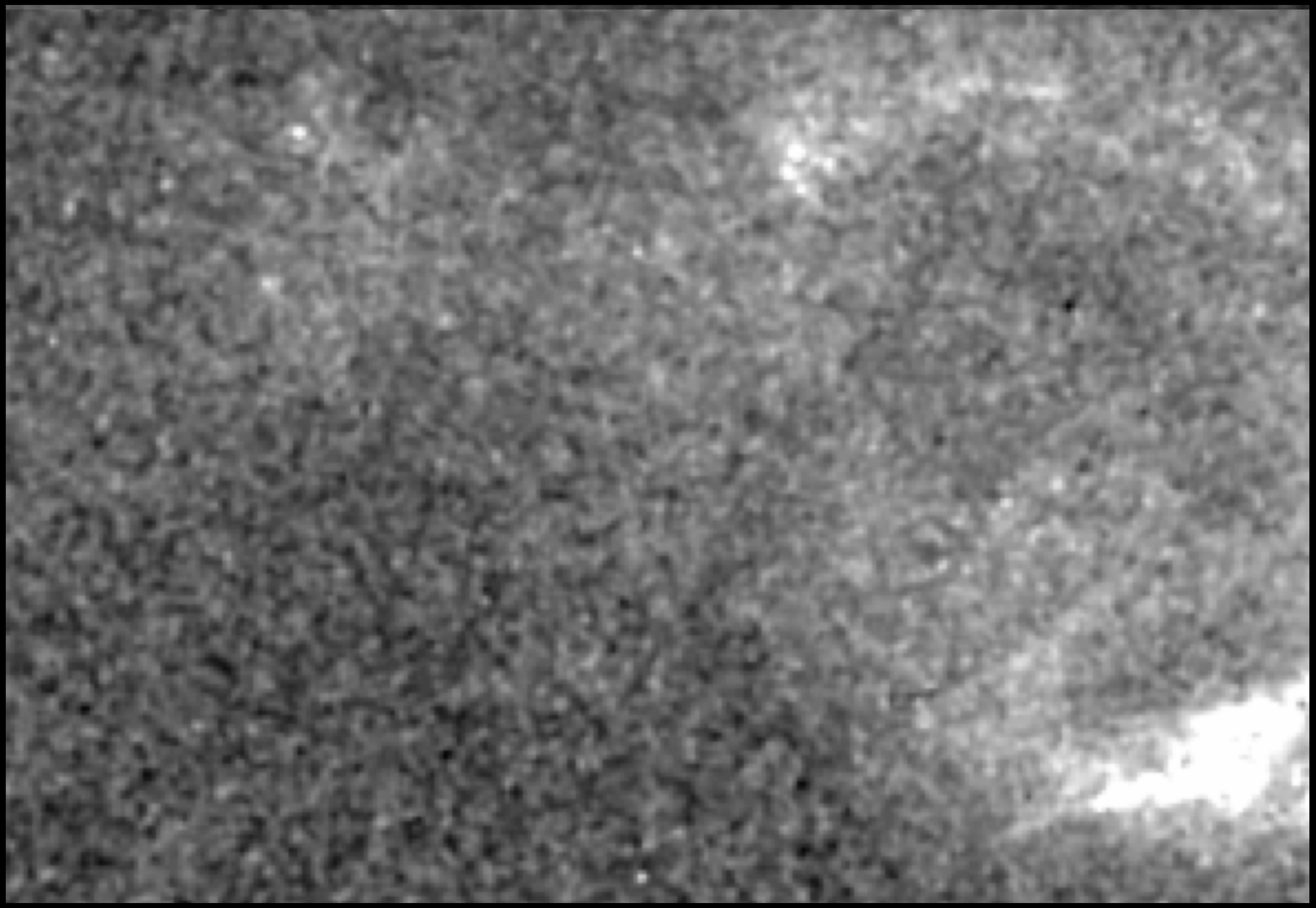
  - A nice $P(A_K) \sim A_K^{-n}$ will do
- Observe the cloud
  - Make sure you make significant statistical errors
- You are done! The *observed* PDF looks like a log-normal!

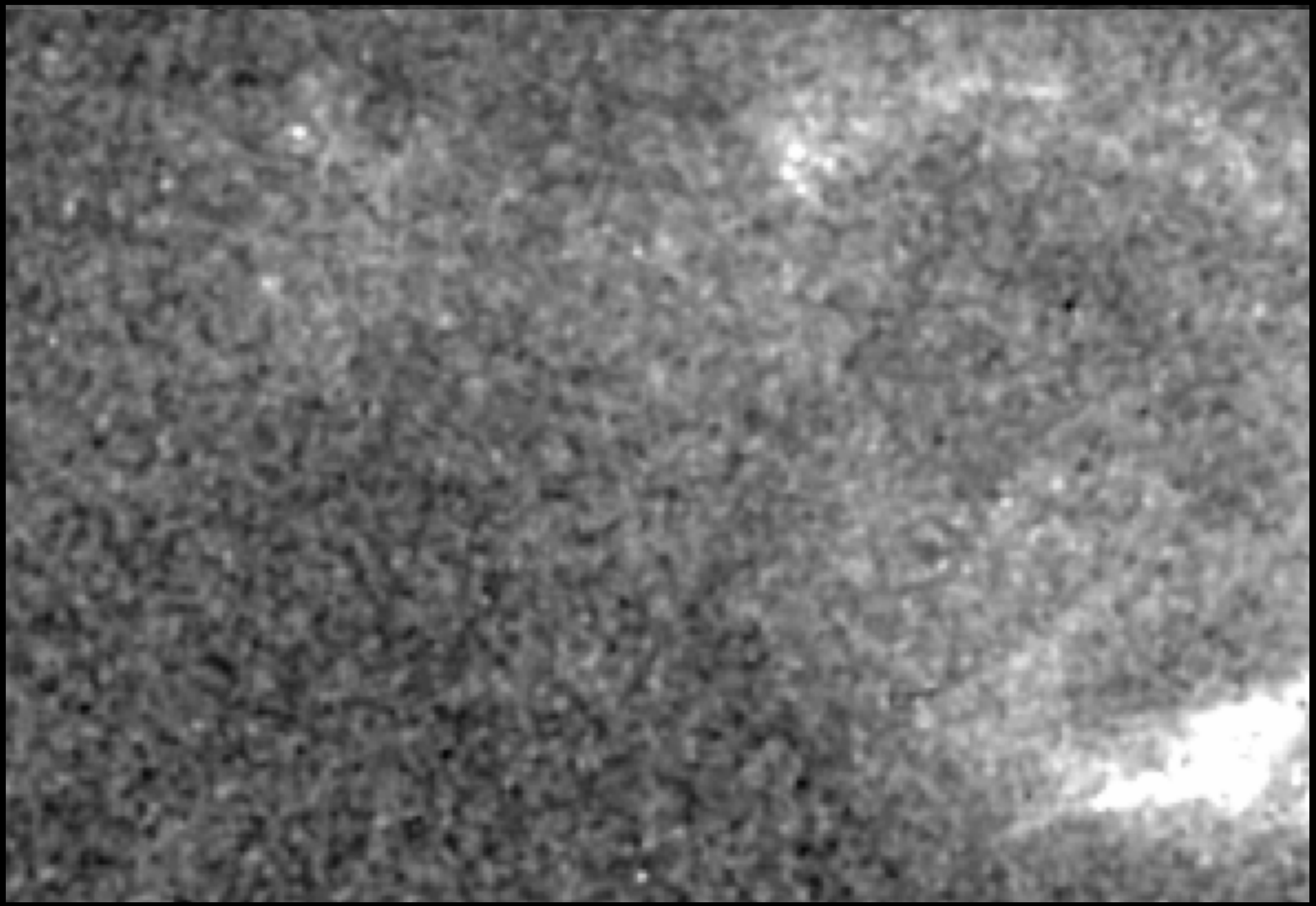


PDFs, noise, and resolution



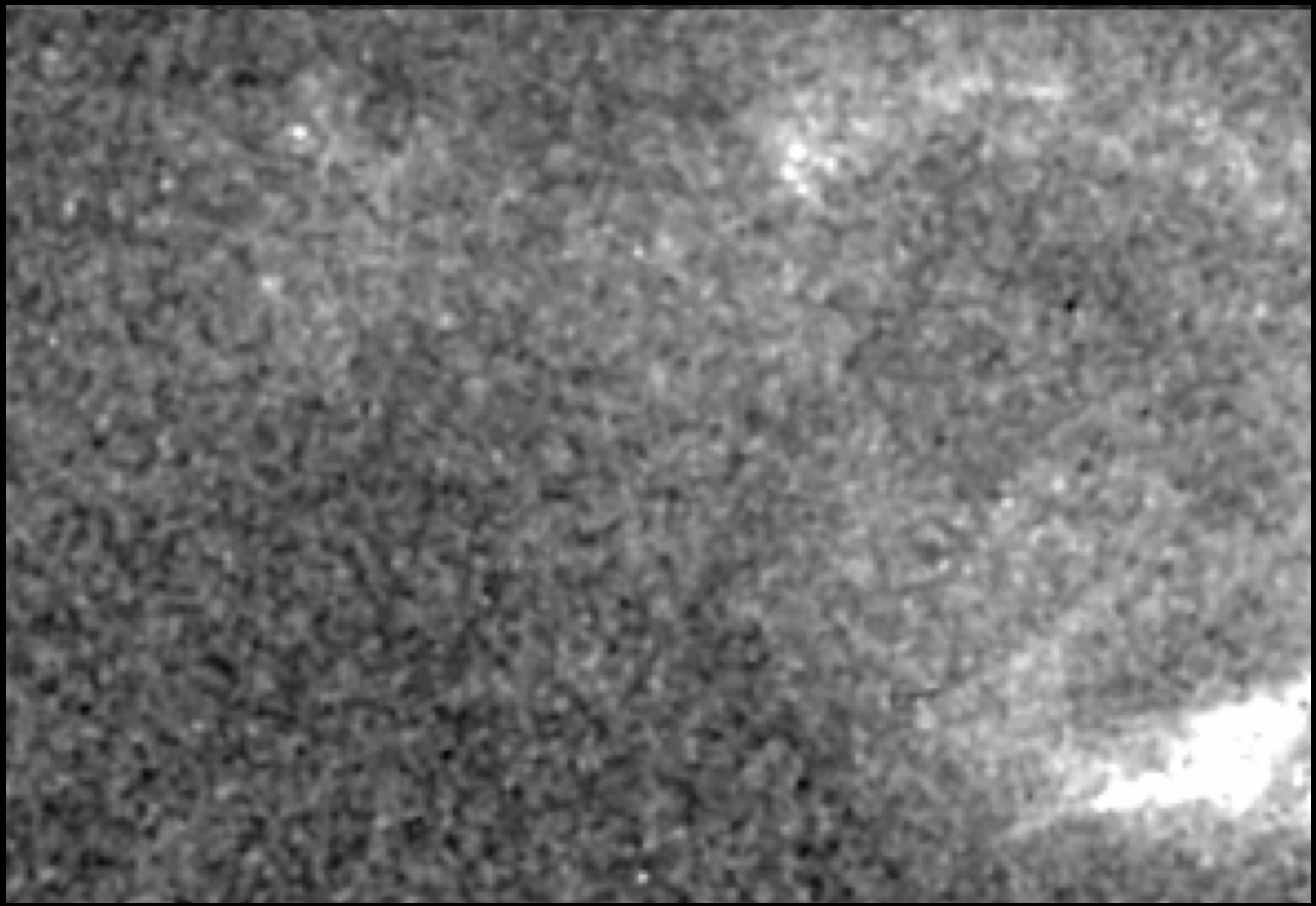
PDFs, noise, and resolution

- Noise can be significant at low column densities



PDFs, noise, and resolution

- Noise can be significant at low column densities
  - It affects mostly extinction maps of clouds at high *b*



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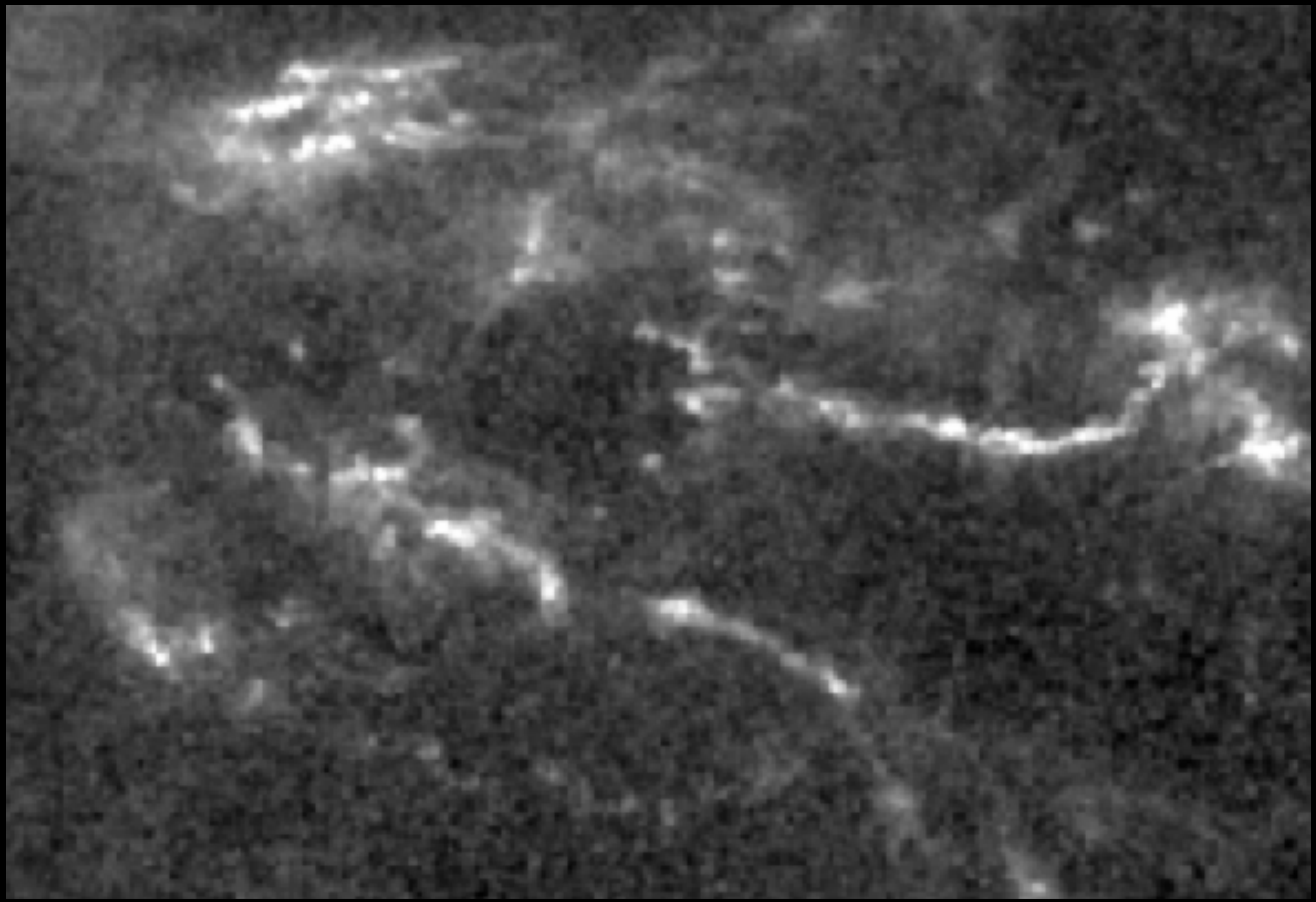

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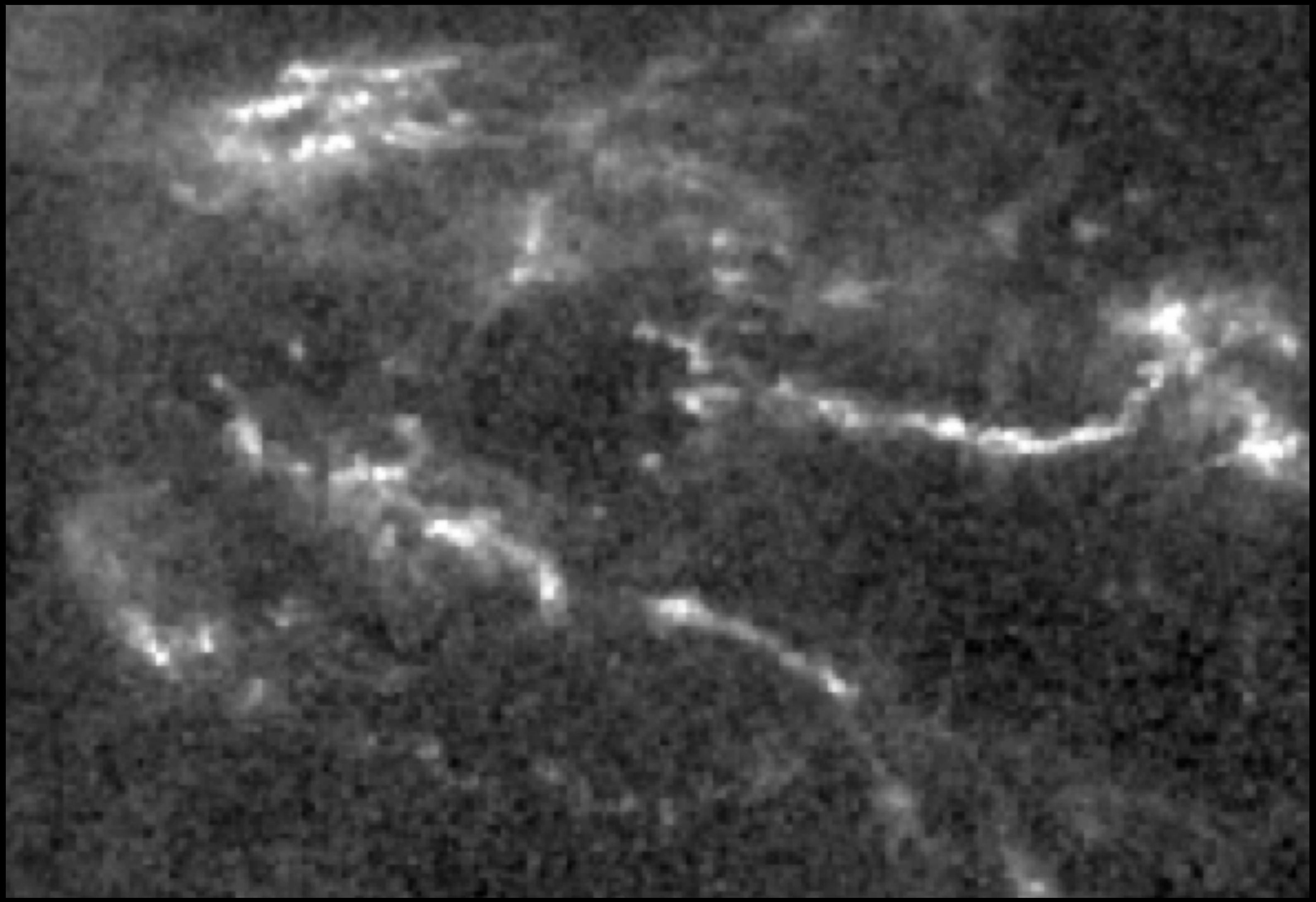

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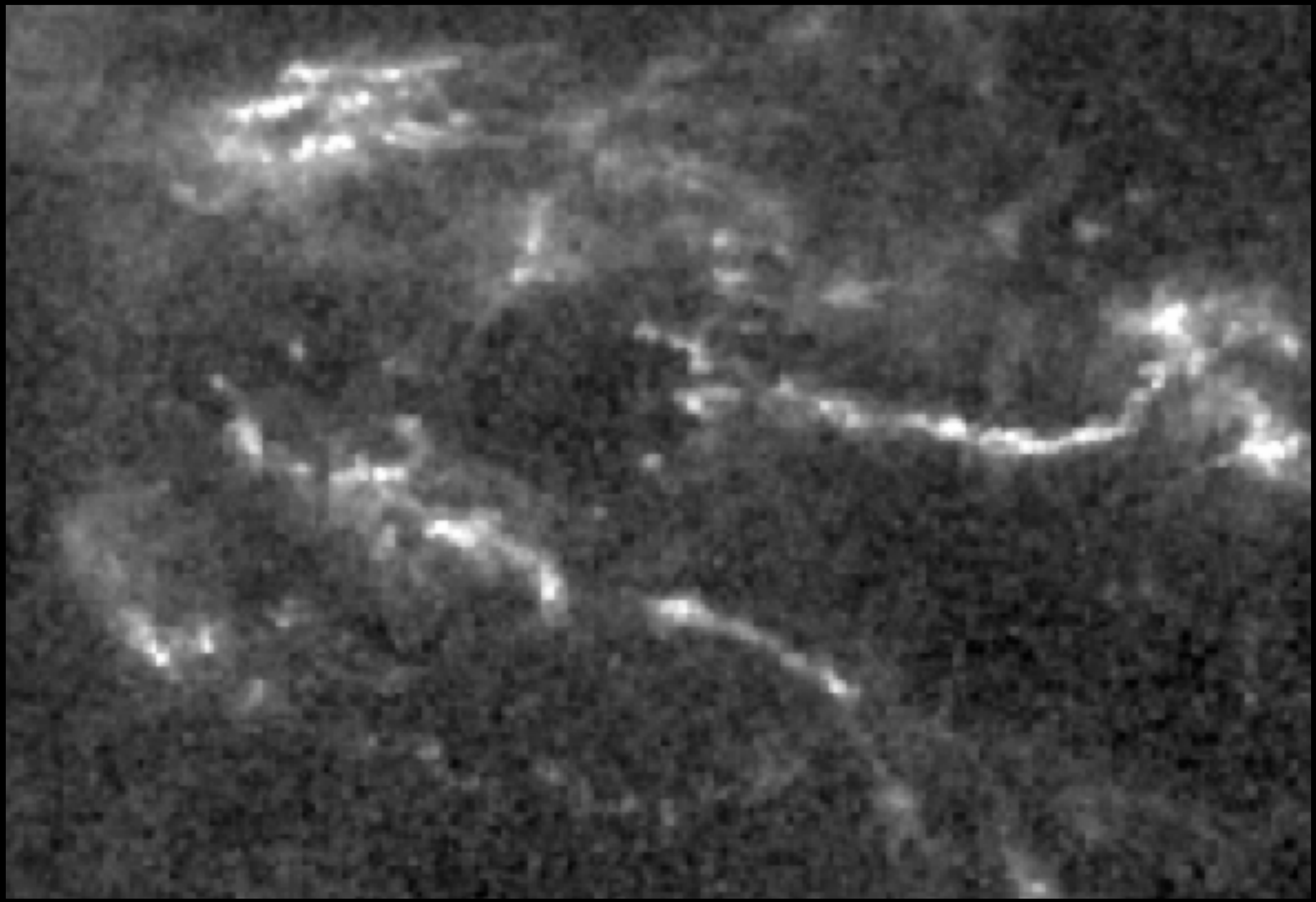
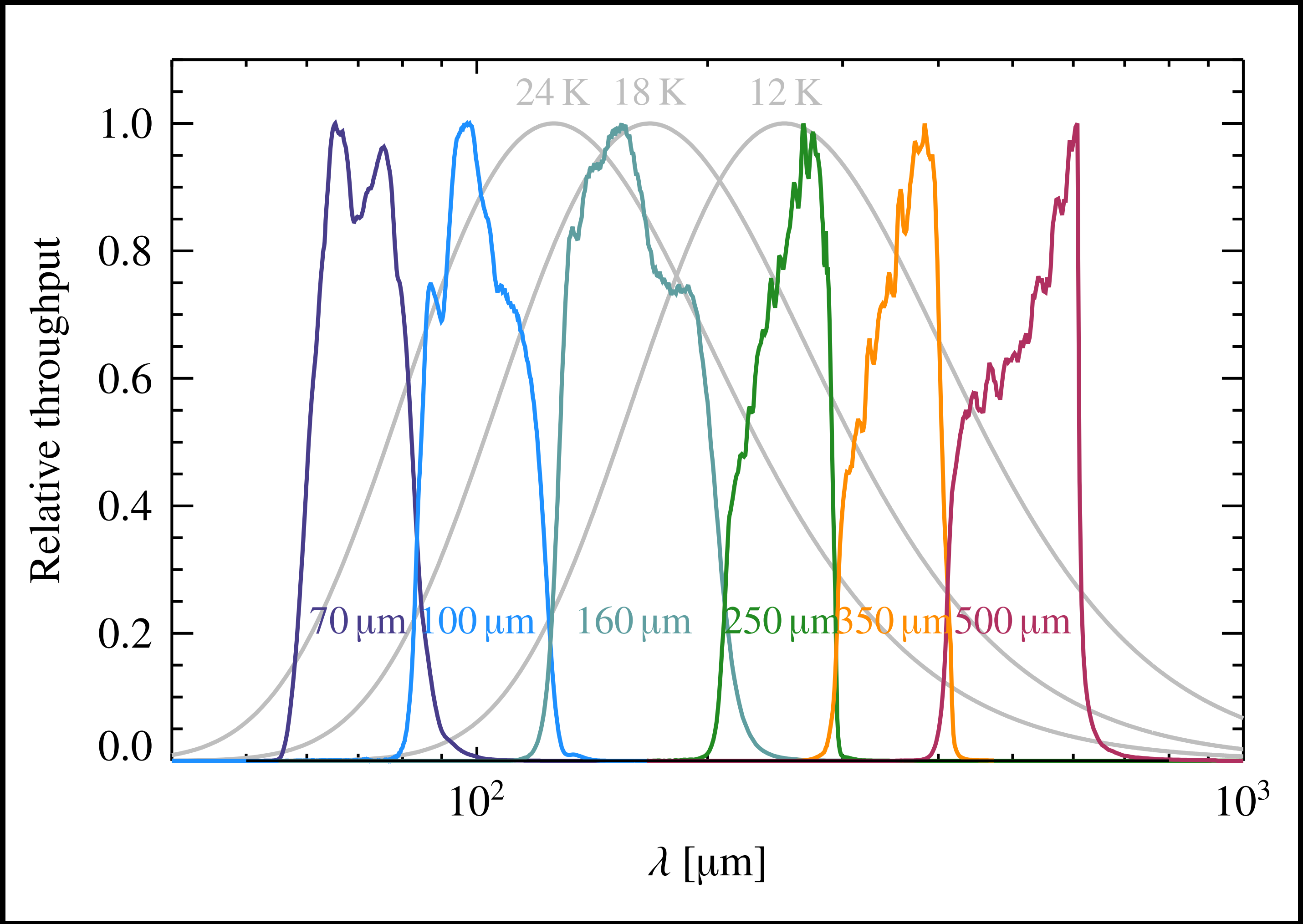


Ideally we would like to have high-res, low-noise density maps of clouds

Beat the noise: Herschel maps!

Dust emission data

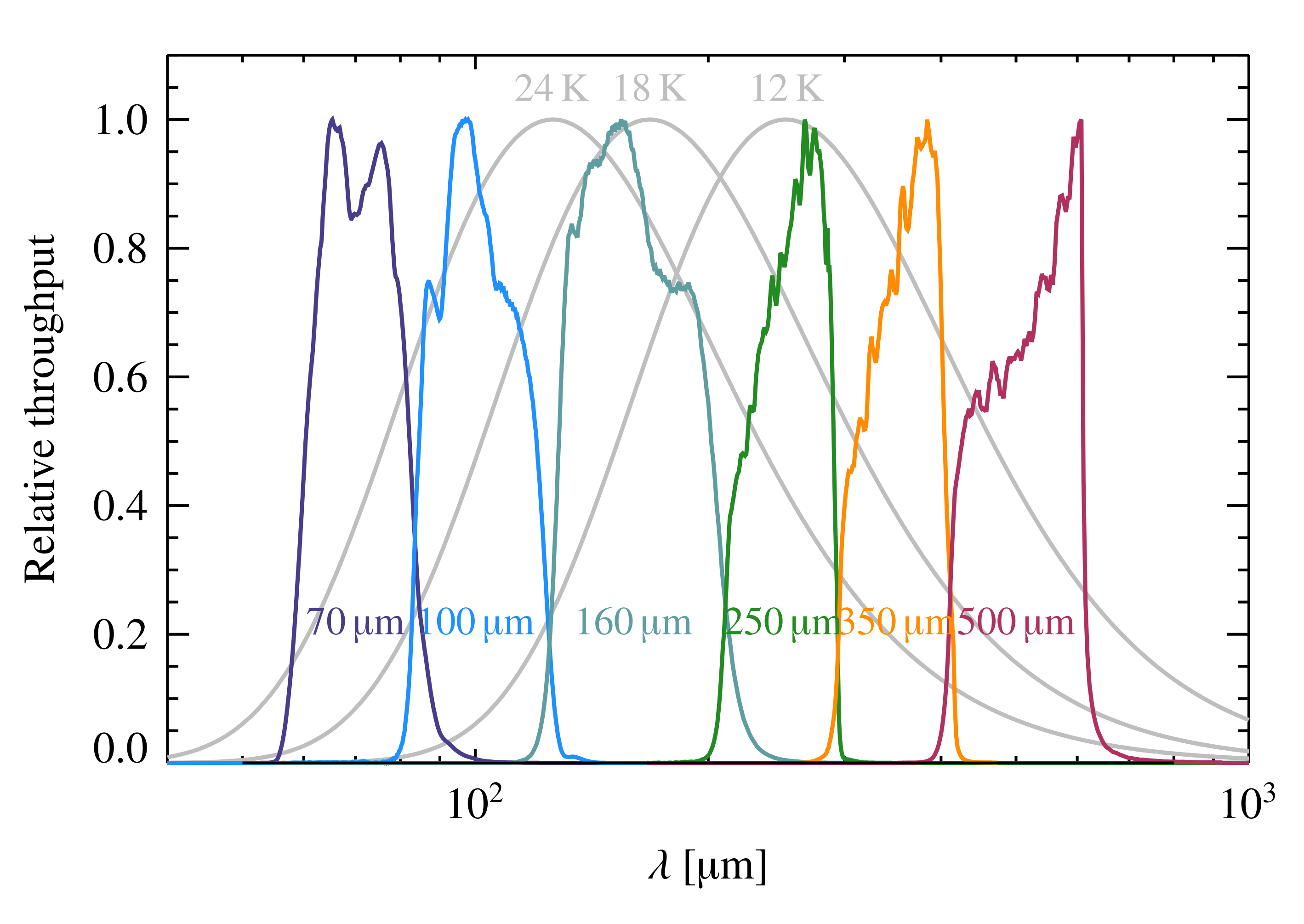


Dust emission data

- A cloud emits a (modified) black body spectrum

$$I_\nu = B_\nu(T)\left[1 - \mathrm{e}^{-\tau_\nu}\right] \simeq B_\nu(T)\tau_\nu$$

$$\tau_\nu = \kappa_\nu \Sigma_{\mathrm{dust}} \propto \nu^\beta$$



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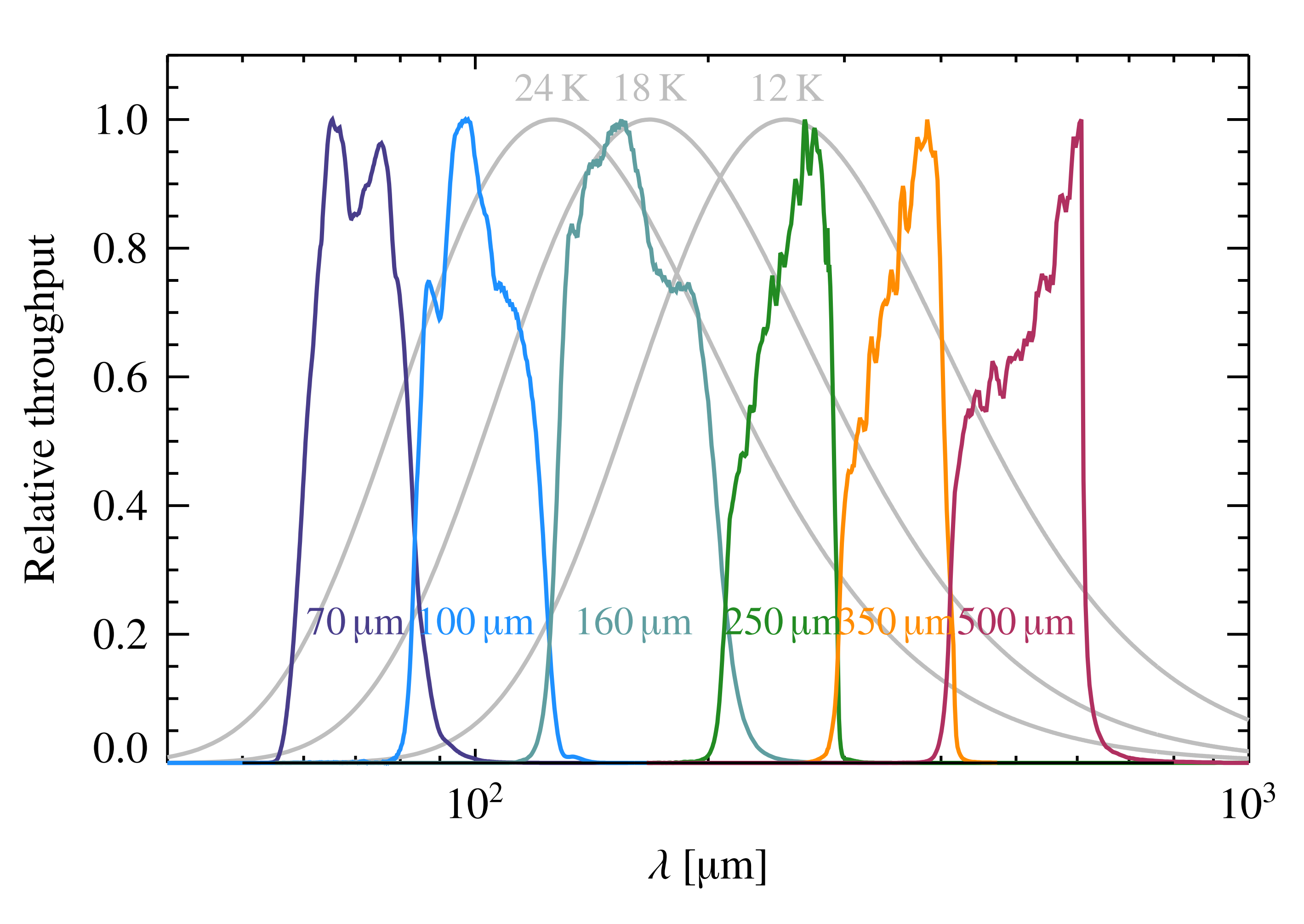

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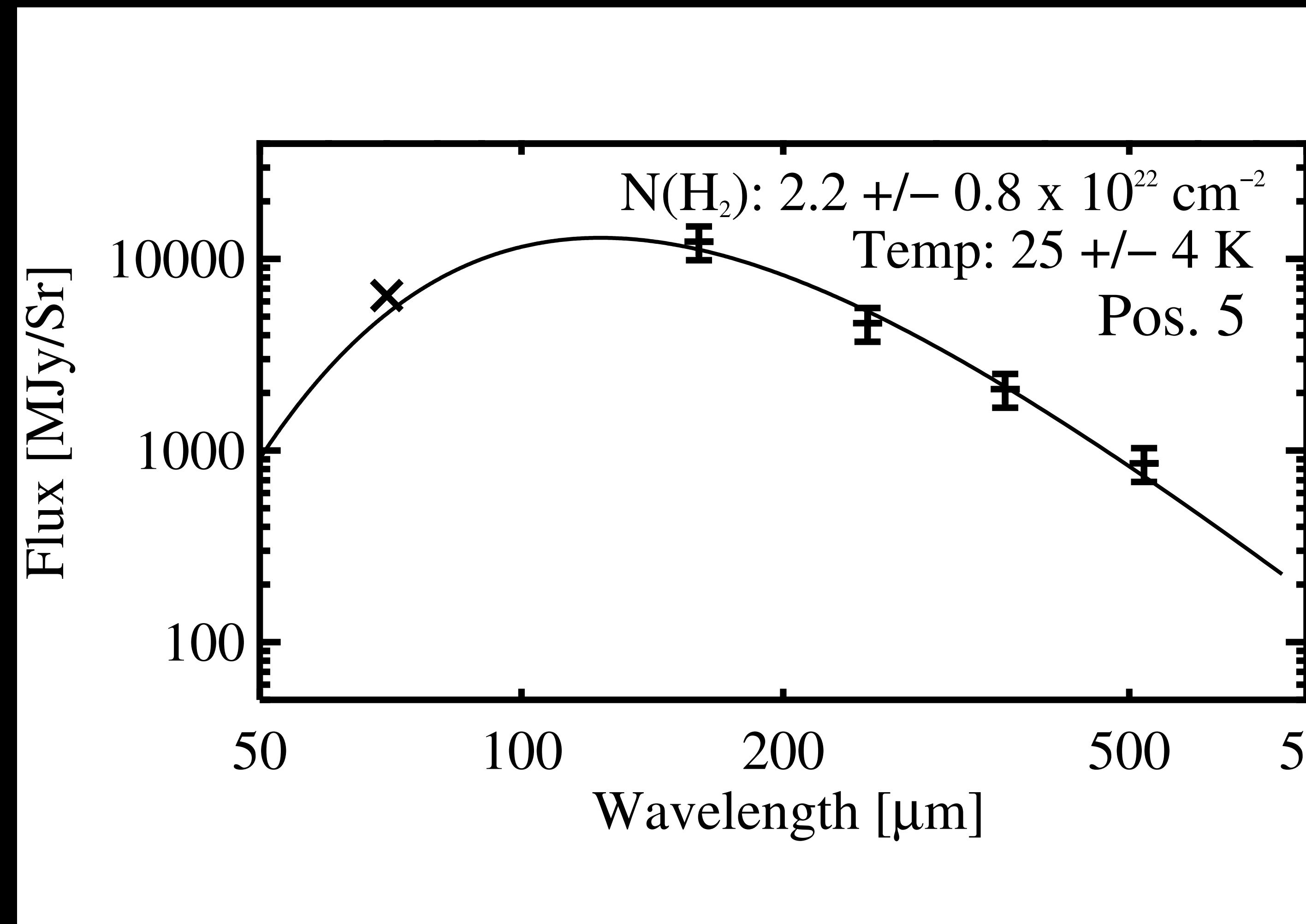

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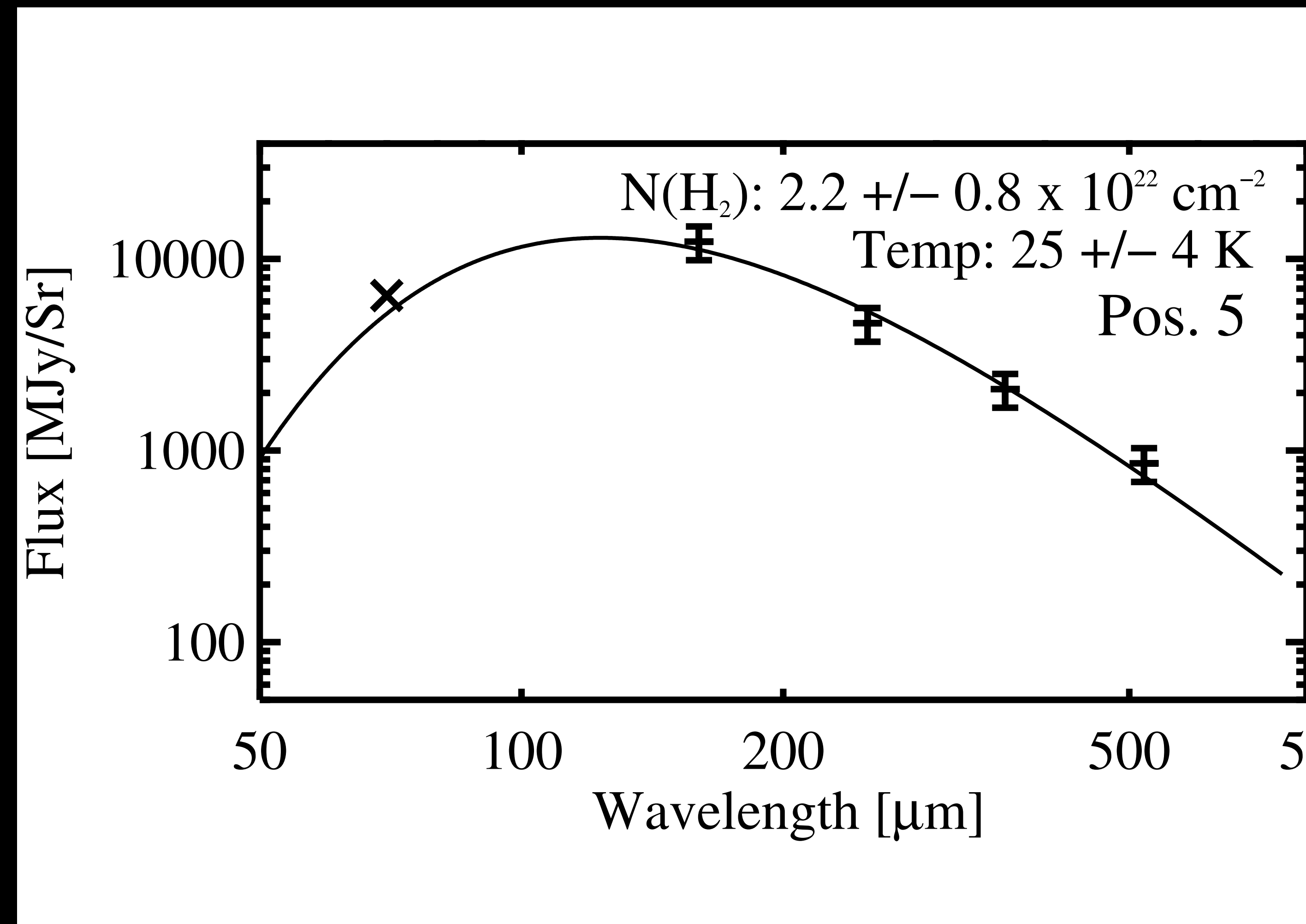

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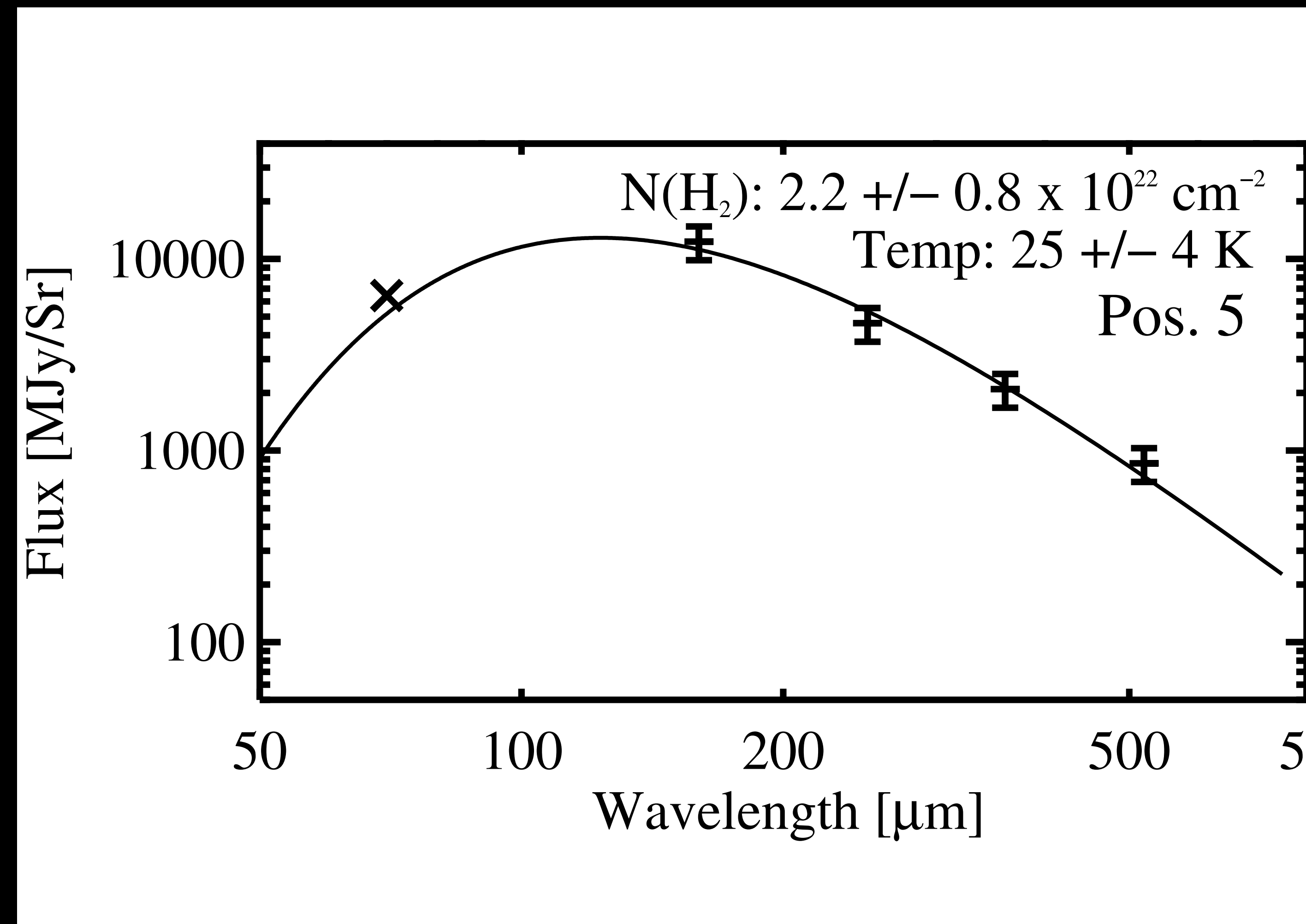

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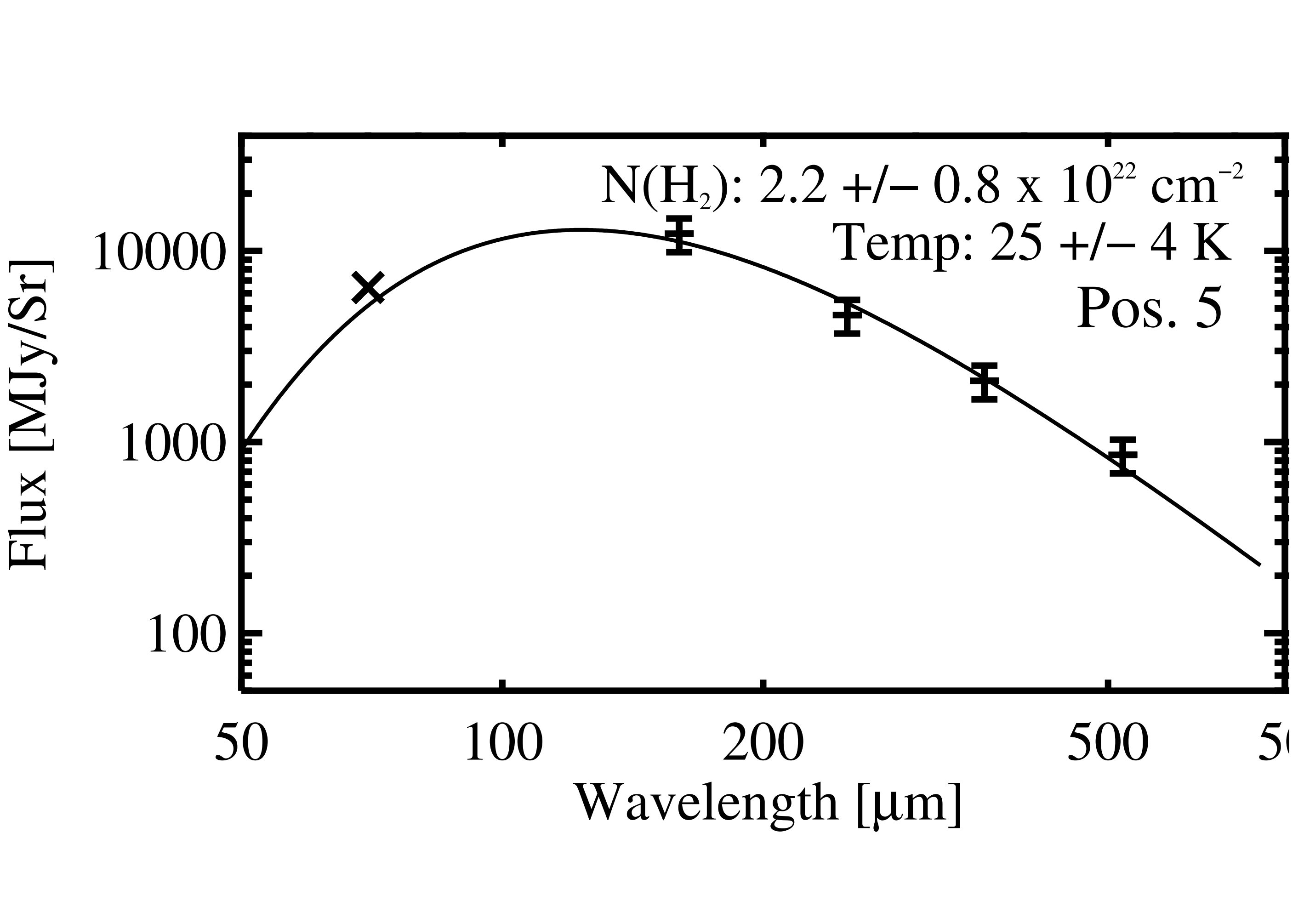
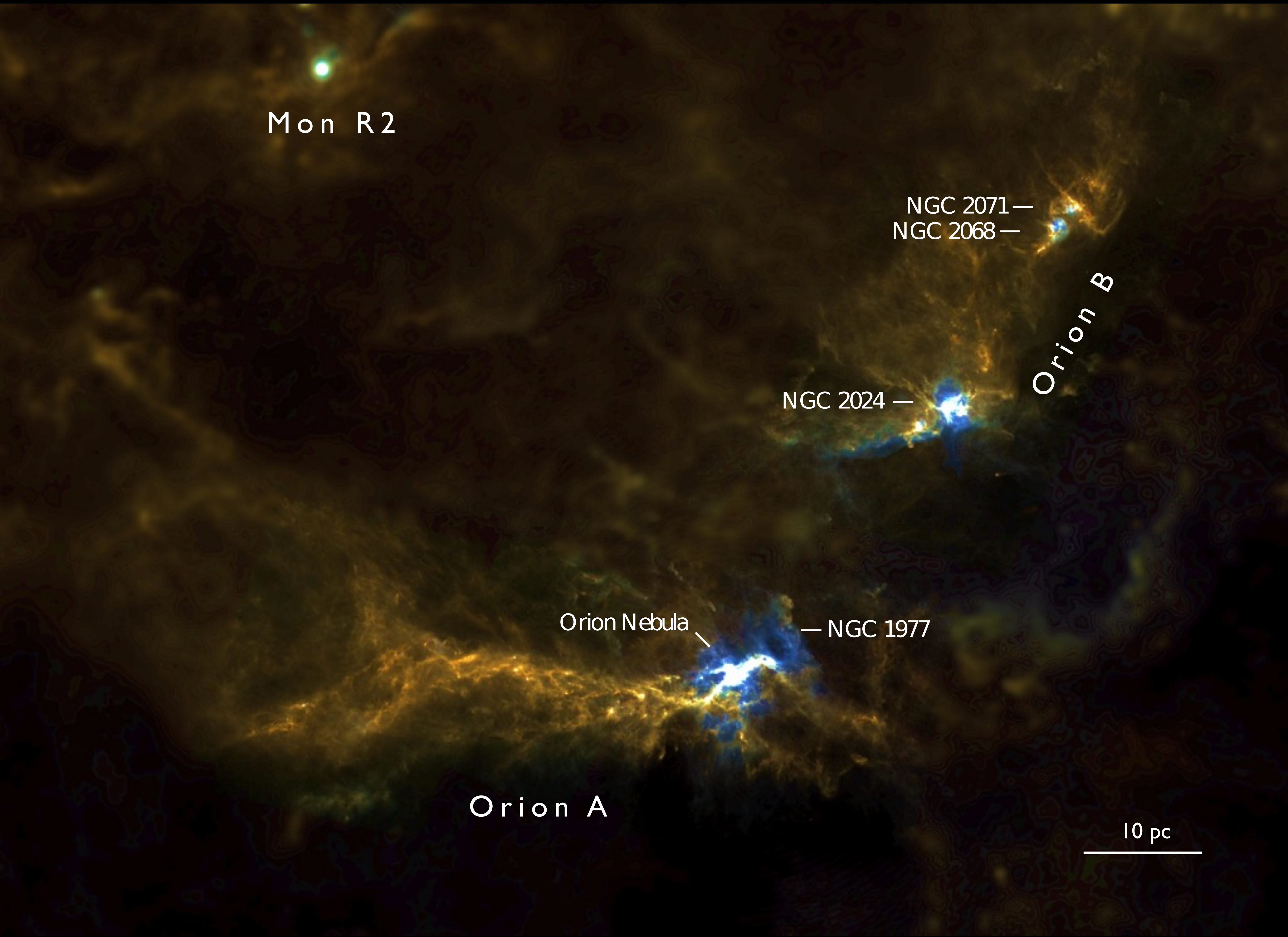


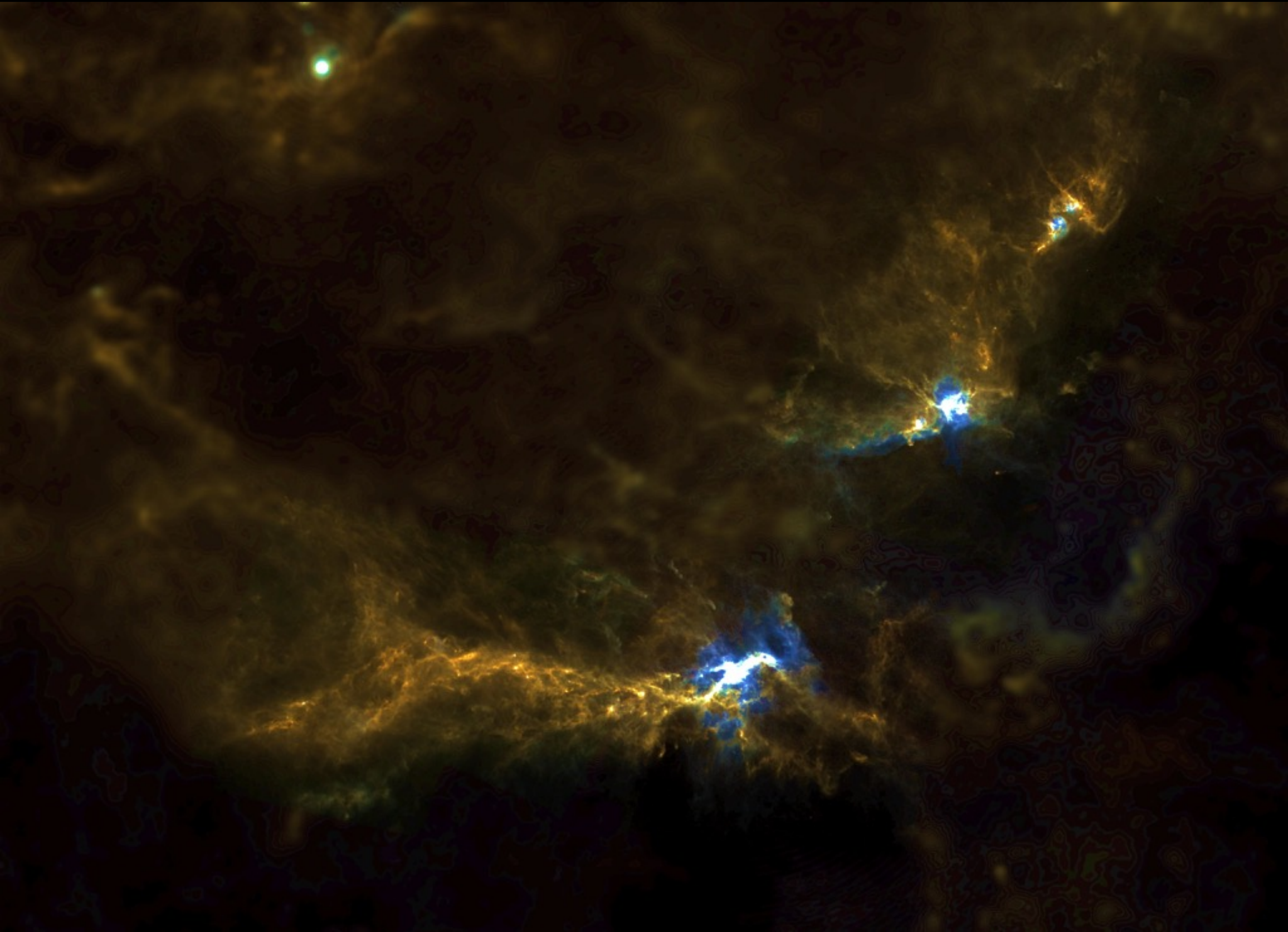
- Temperature gradients along the l.o.s. bias τ low

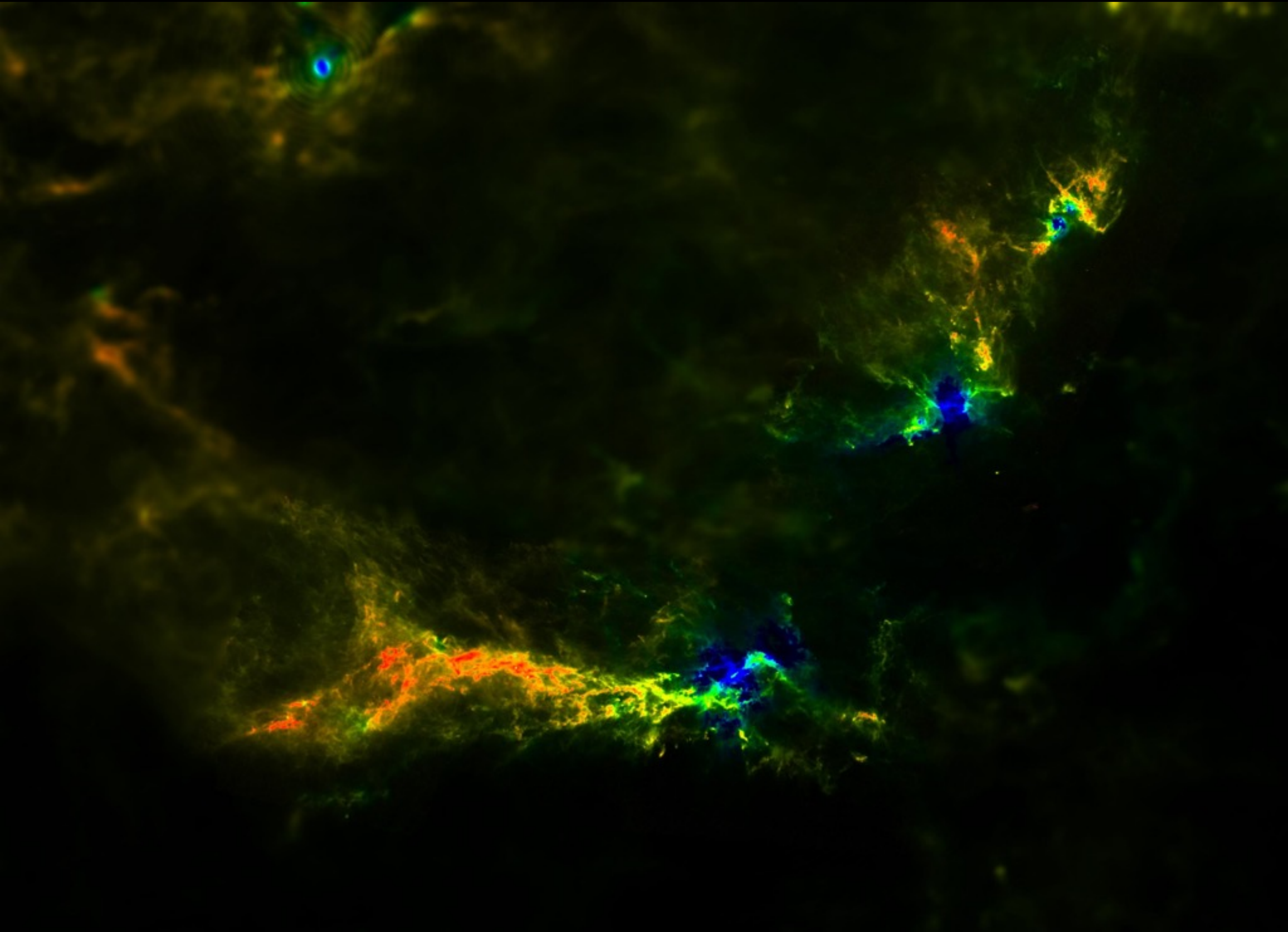
- Things almost certainly go wrong near OB associations y

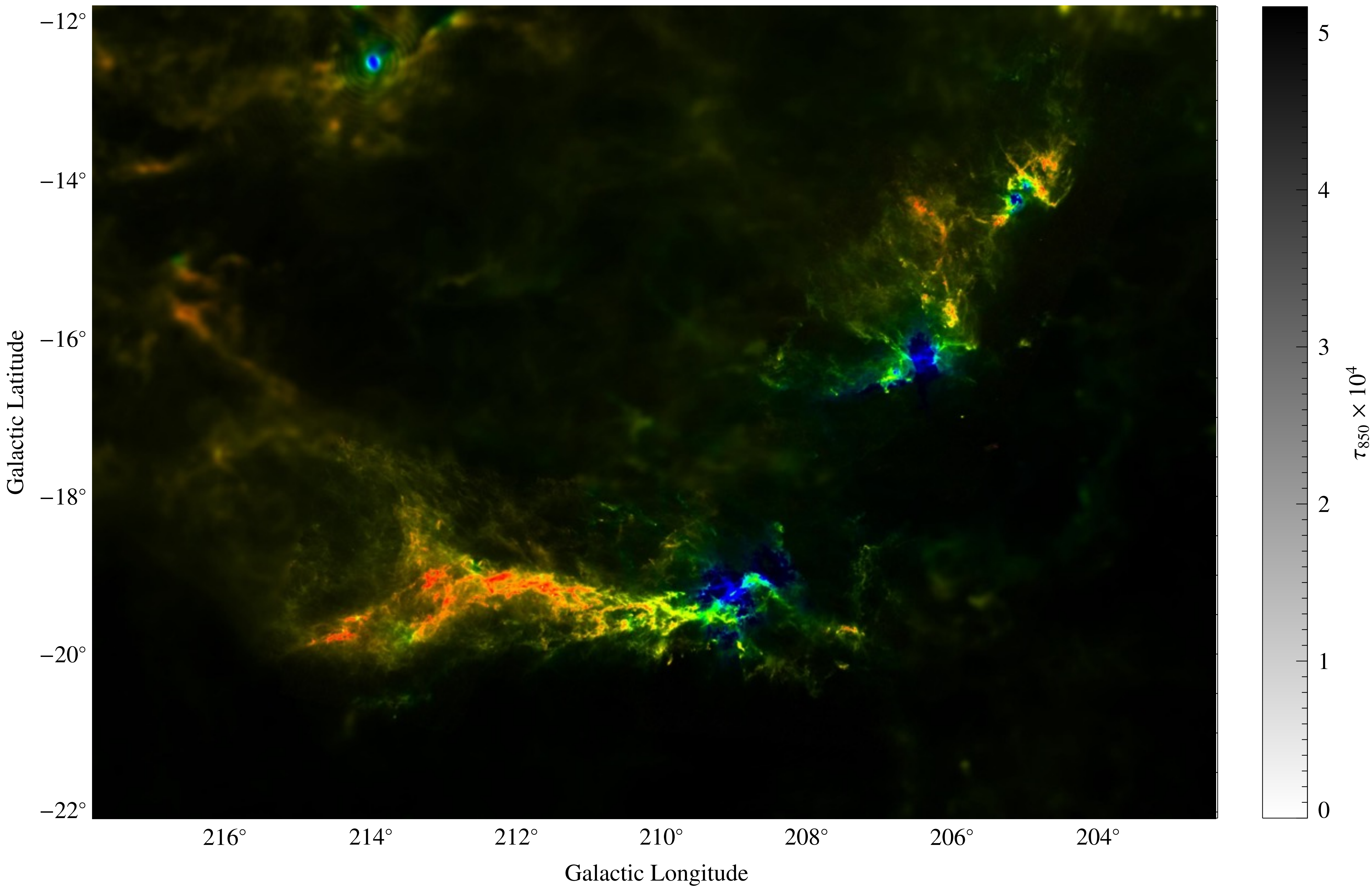
Orion A & B

(Lombardi et al. 2014)


Mon R2
NGC 2071
NGC 2068
Orion B
NGC 2024
Orion Nebula
NGC 1977
Orion A
10 pc







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Galactic Latitude
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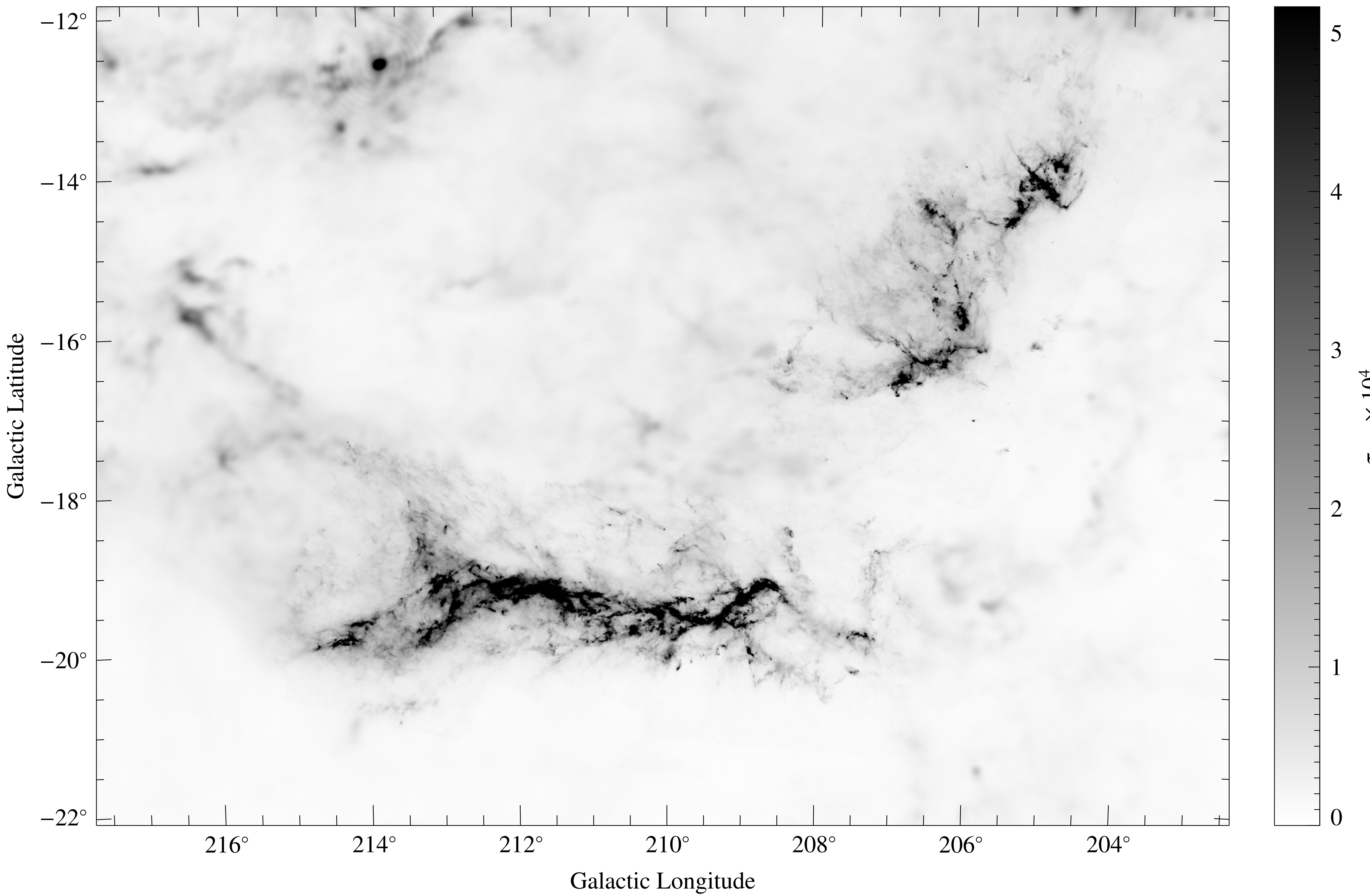
$\tau_{850} \times 10^4$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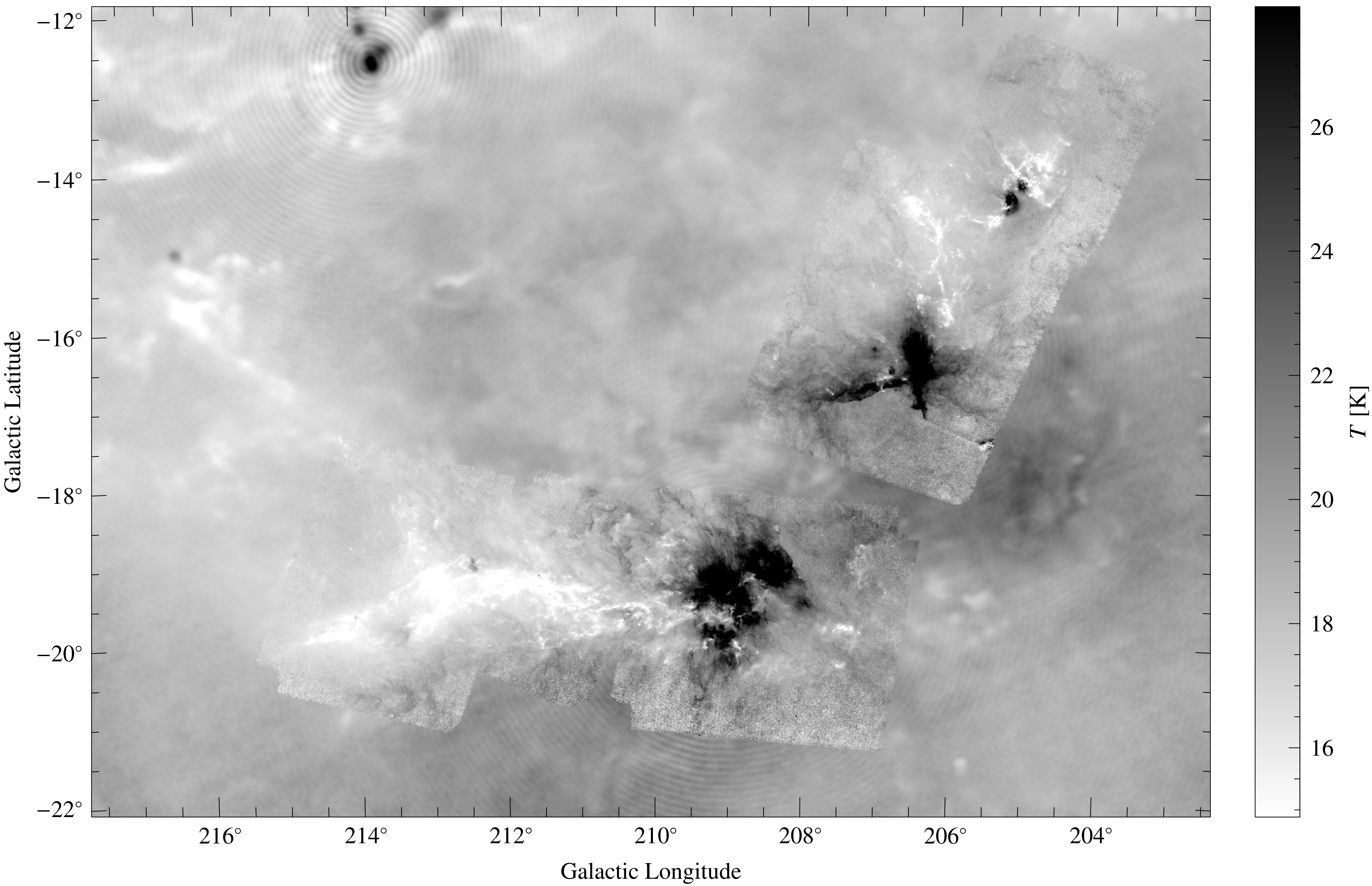

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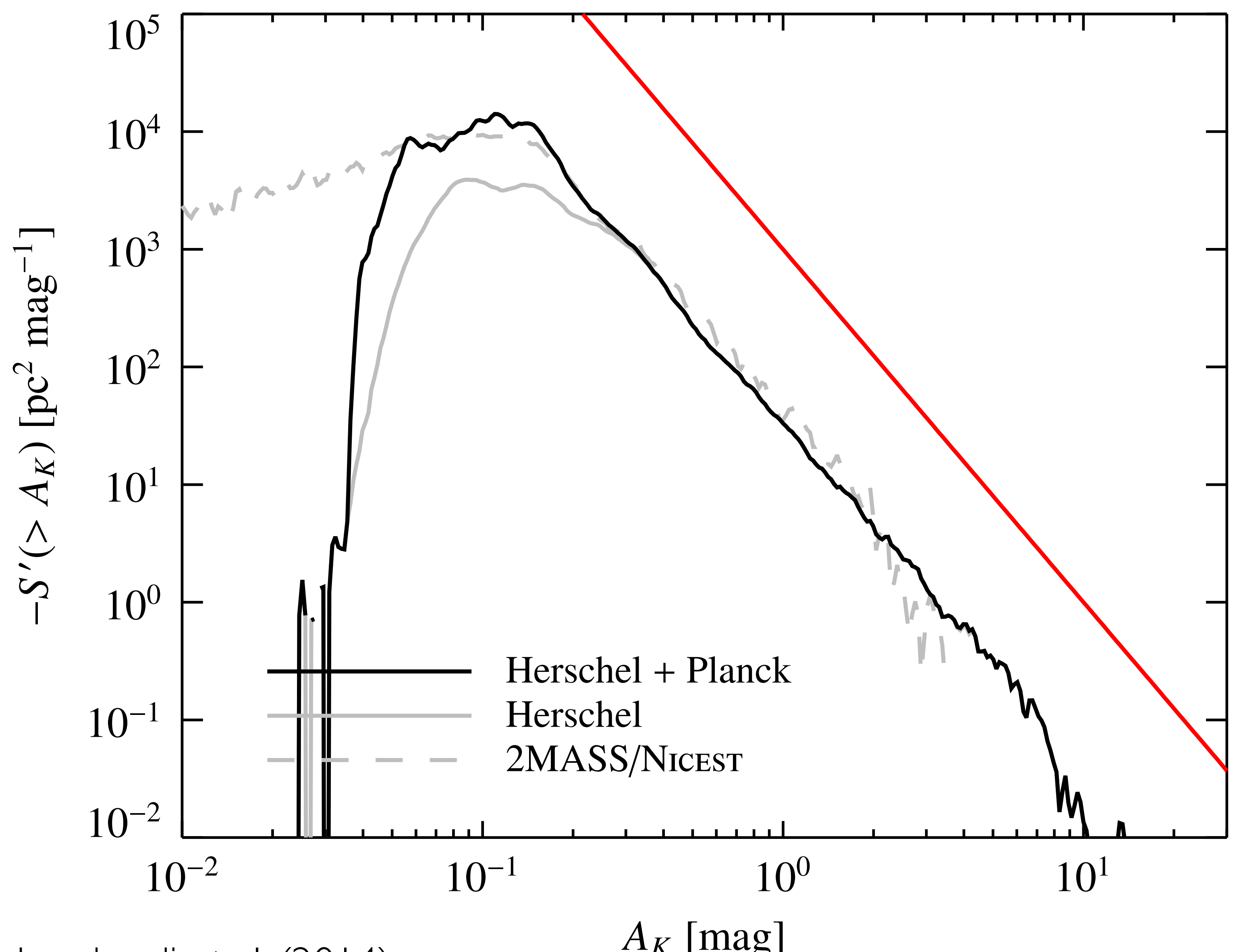
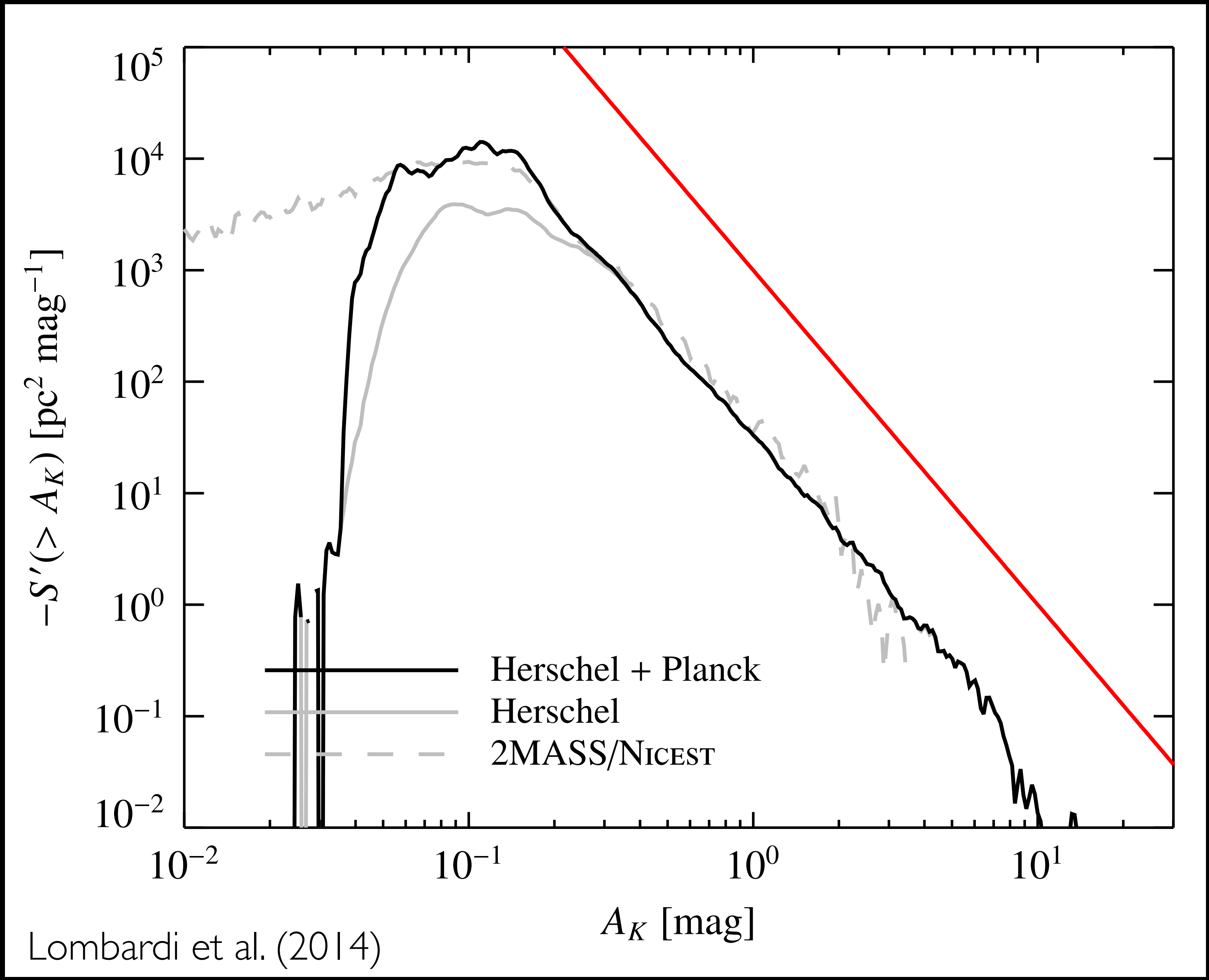
Herschel PDF for Orion B



Lombardi et al. (2014)

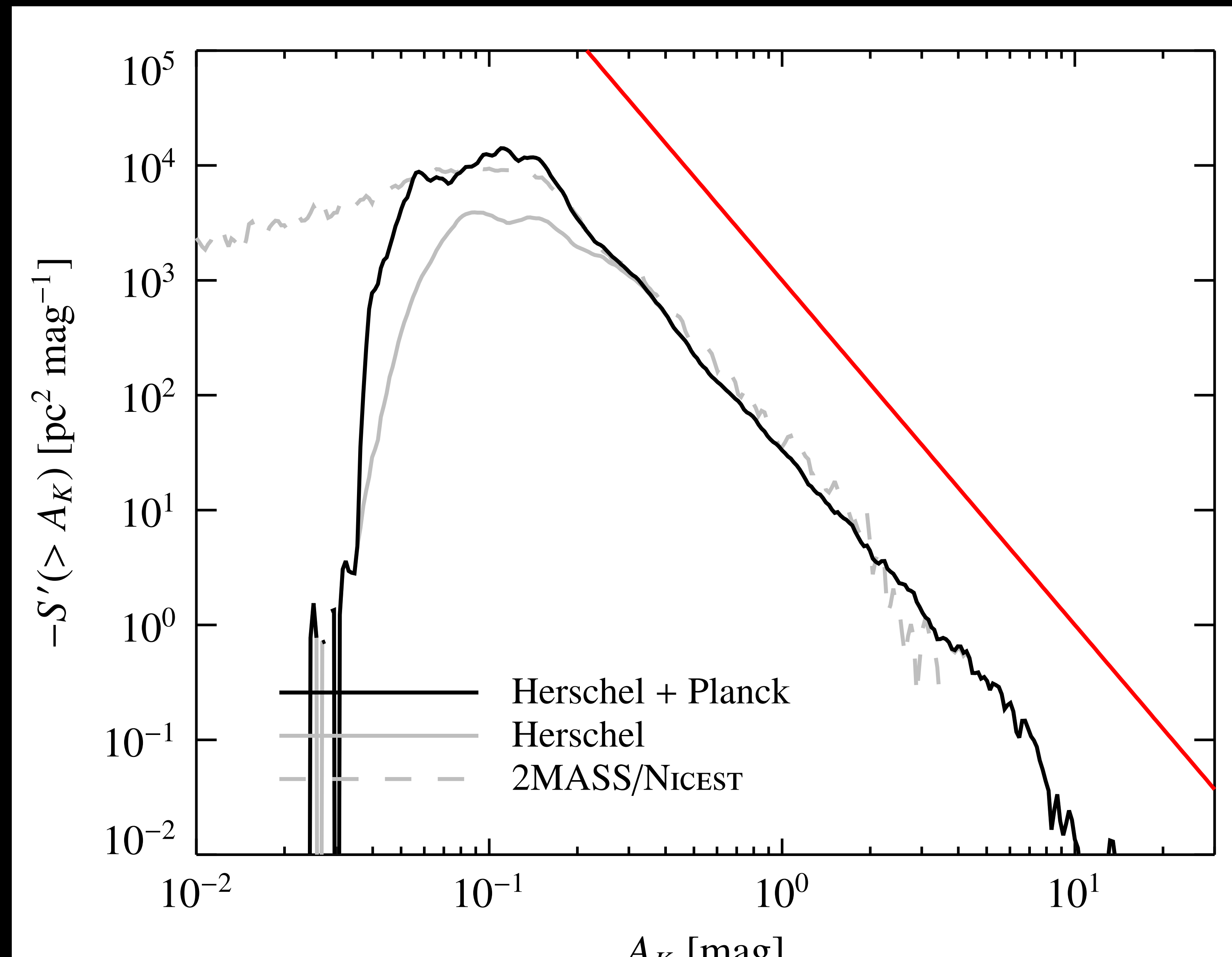
Herschel PDF for Orion B

- PDF is hardly symmetric in log-log



Herschel PDF for Orion B

- PDF is hardly symmetric in log-log
- Turn @ A_K ~ 0.15 mag



Lombardi et al. (2014)

Herschel PDF for Orion B

- PDF is hardly symmetric in log-log
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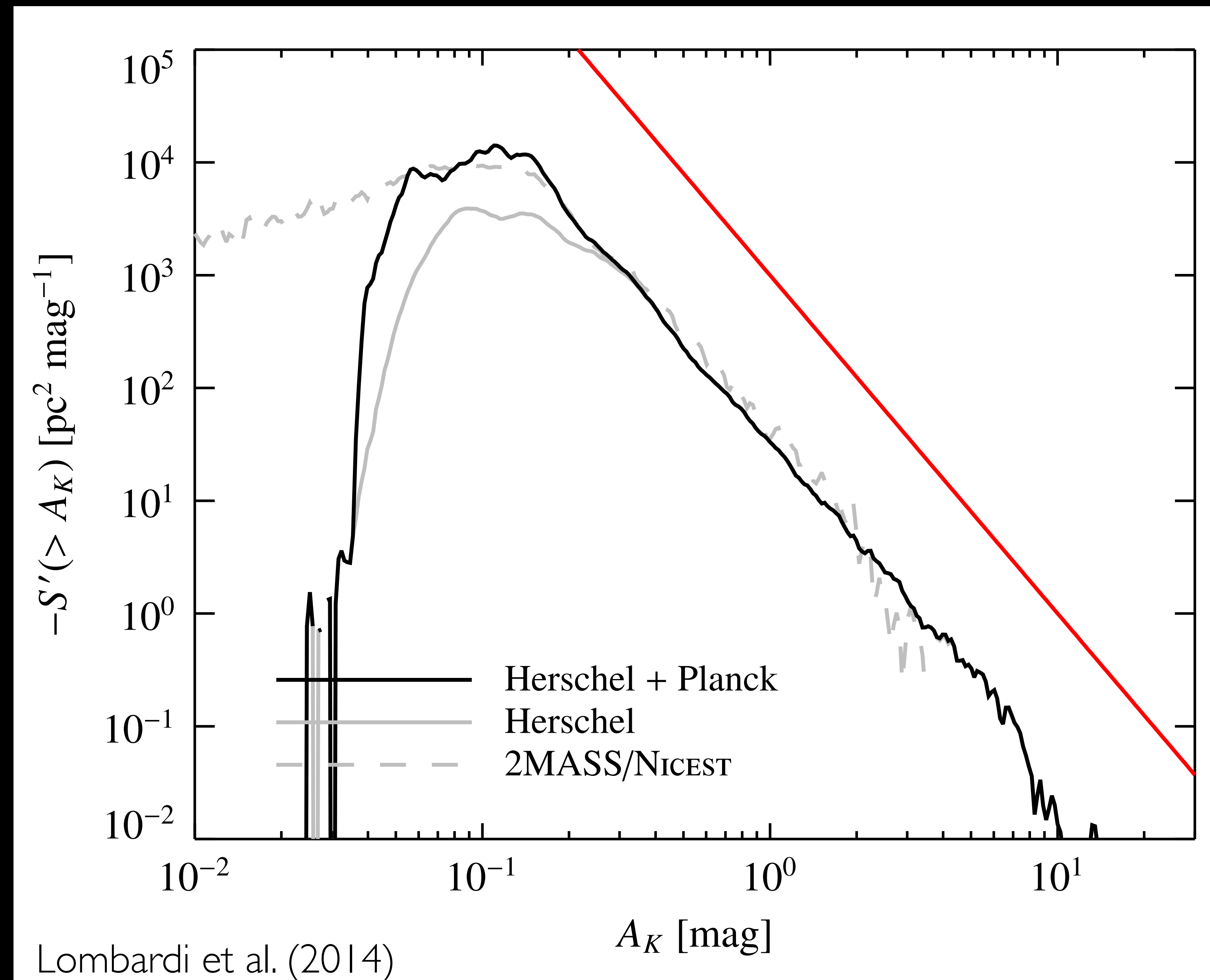
- Perfect power law at higher column densities



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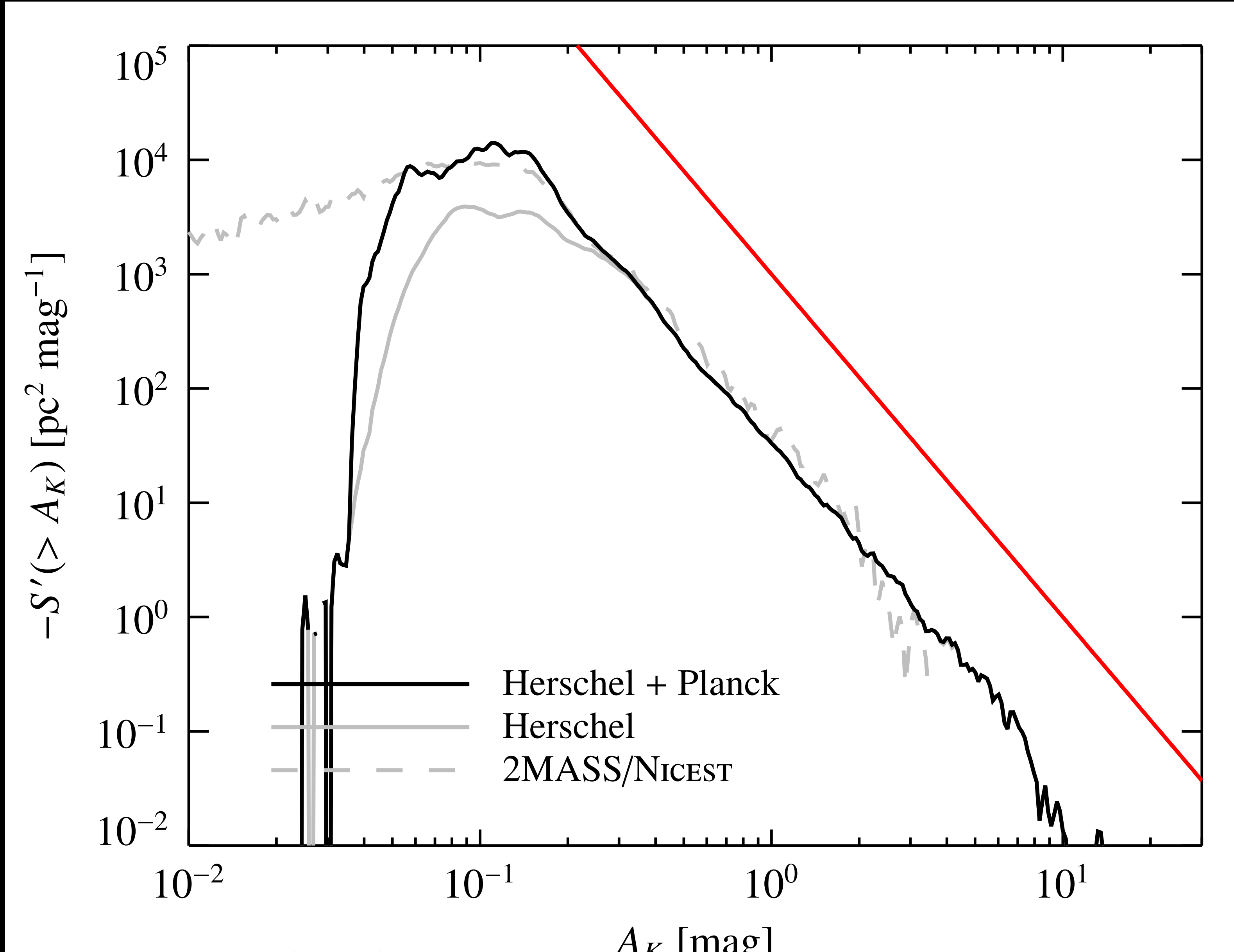

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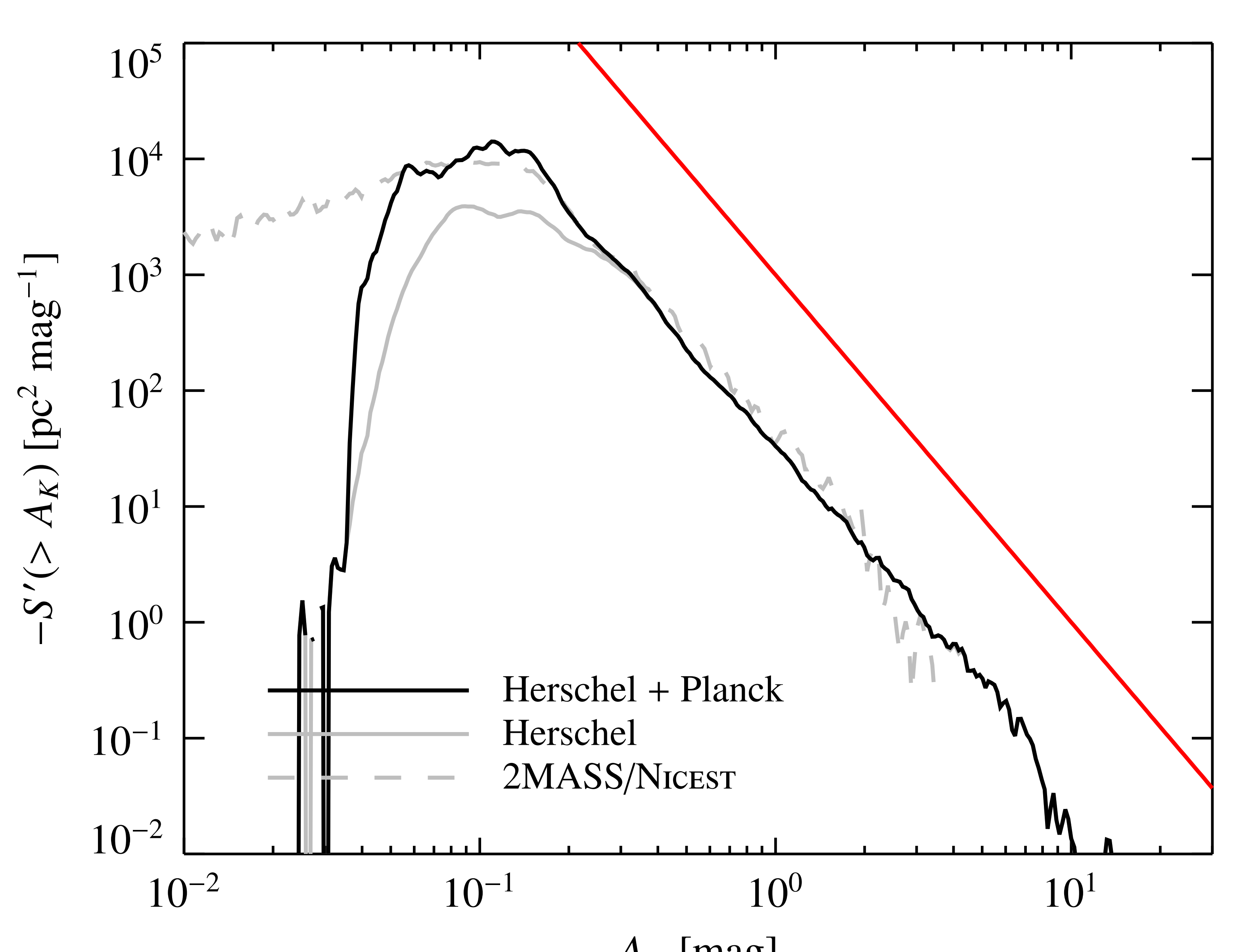

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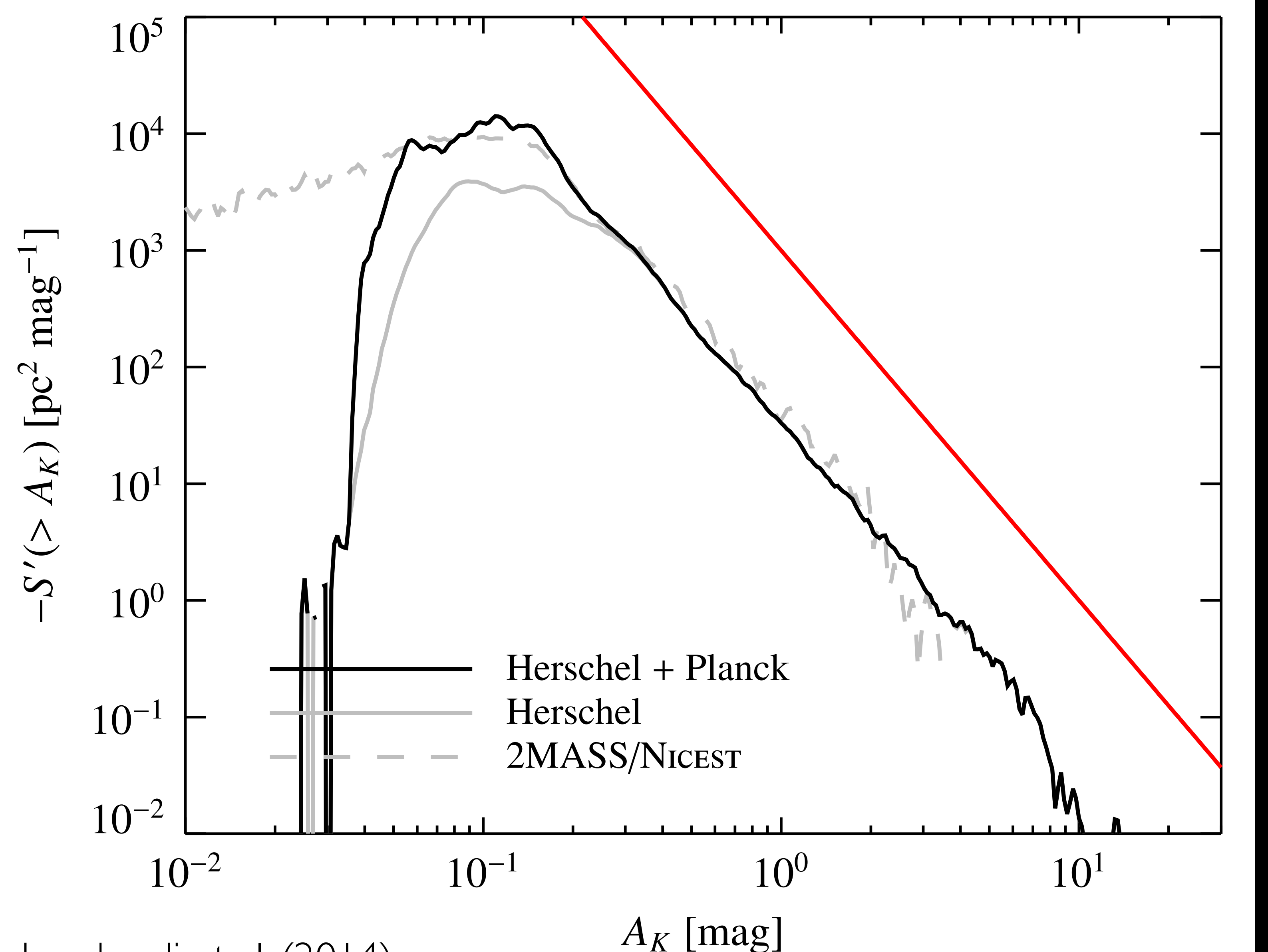


Lombardi et al. (2014)

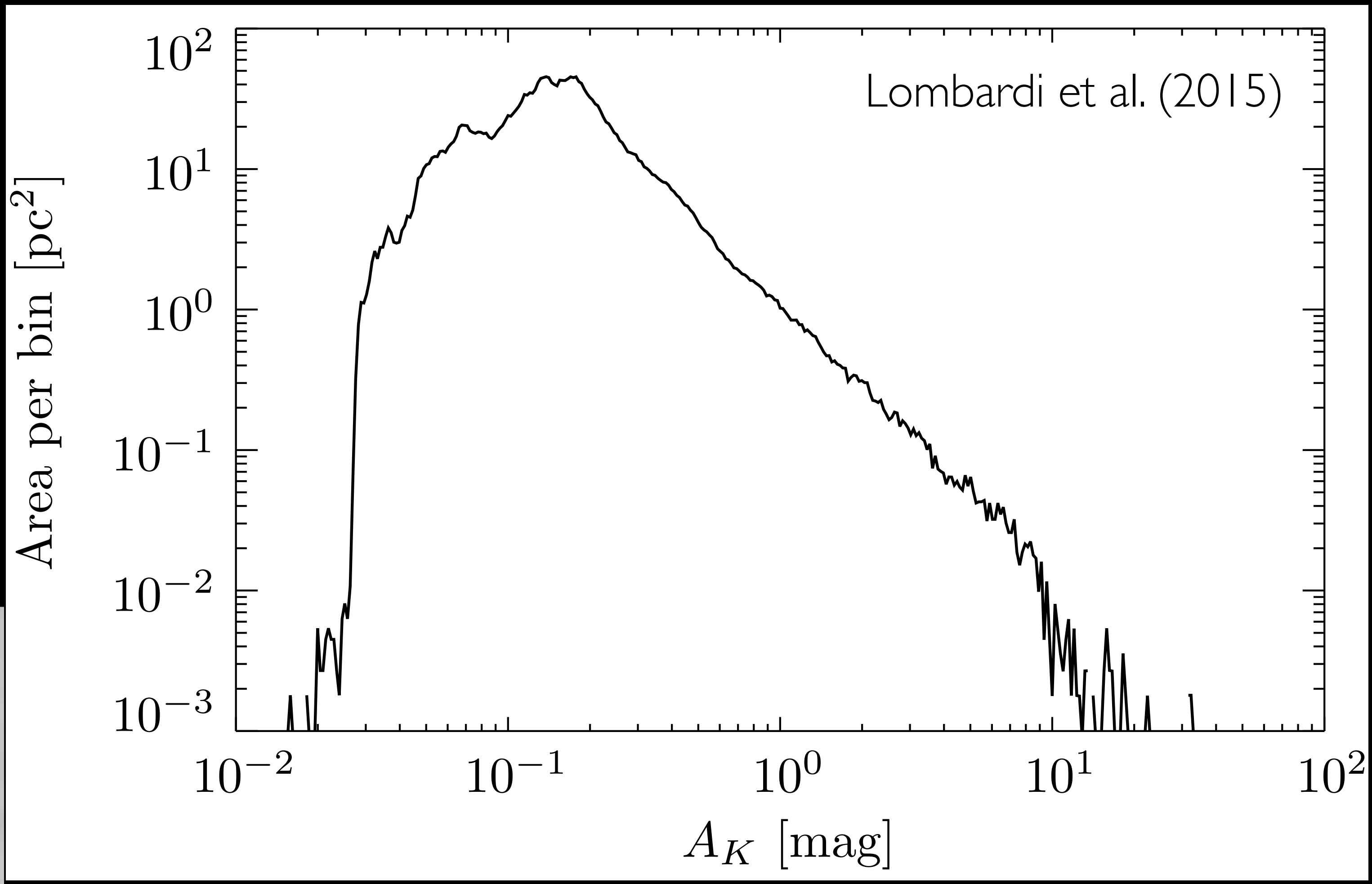
Log-normals, if present, confined to low A_K

Can we actually probe the low A_K?

Lombardi et al. (2015)

Can we actually probe the low A_K?

- Cloud boundaries are not well defined!



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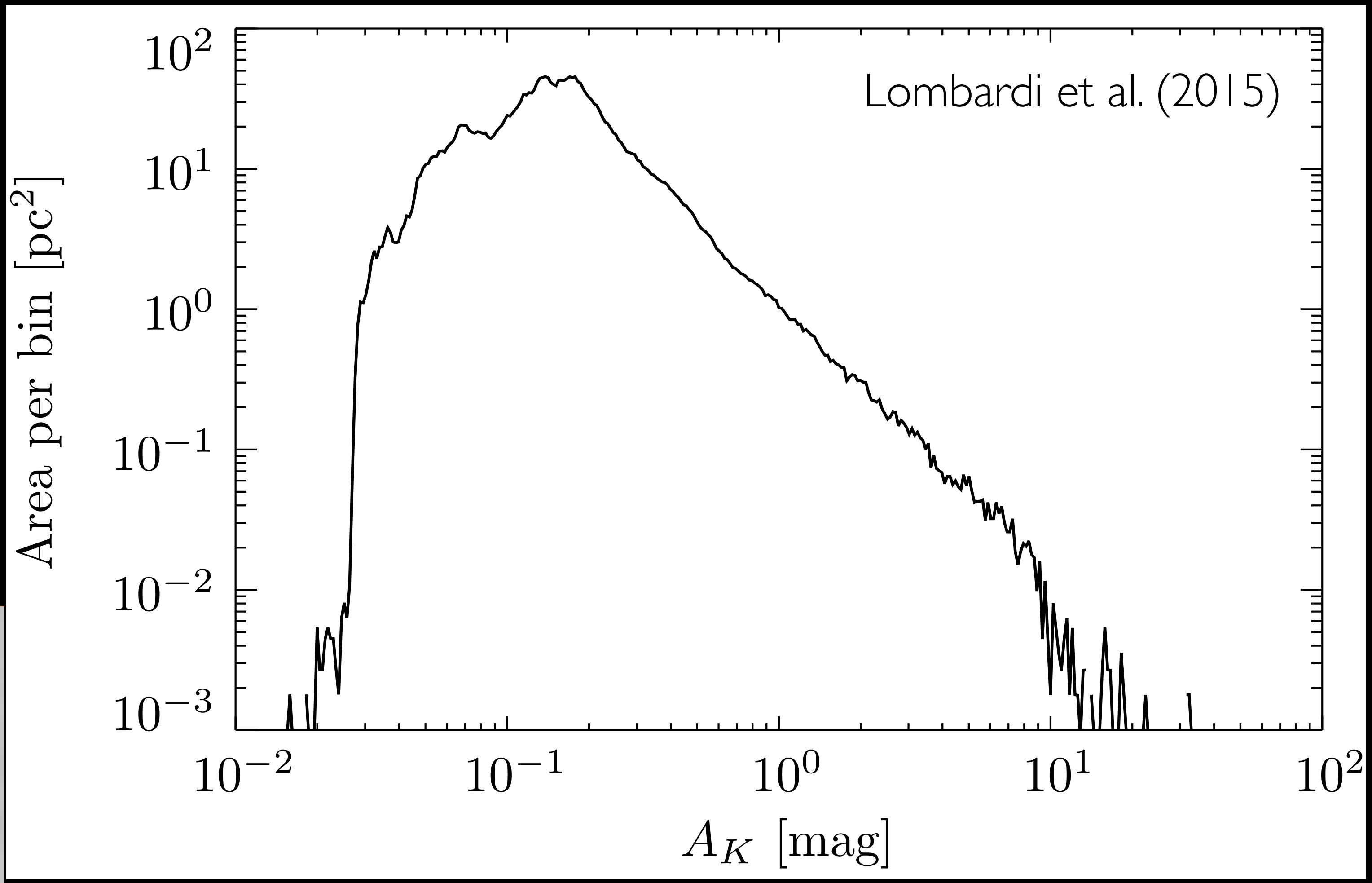

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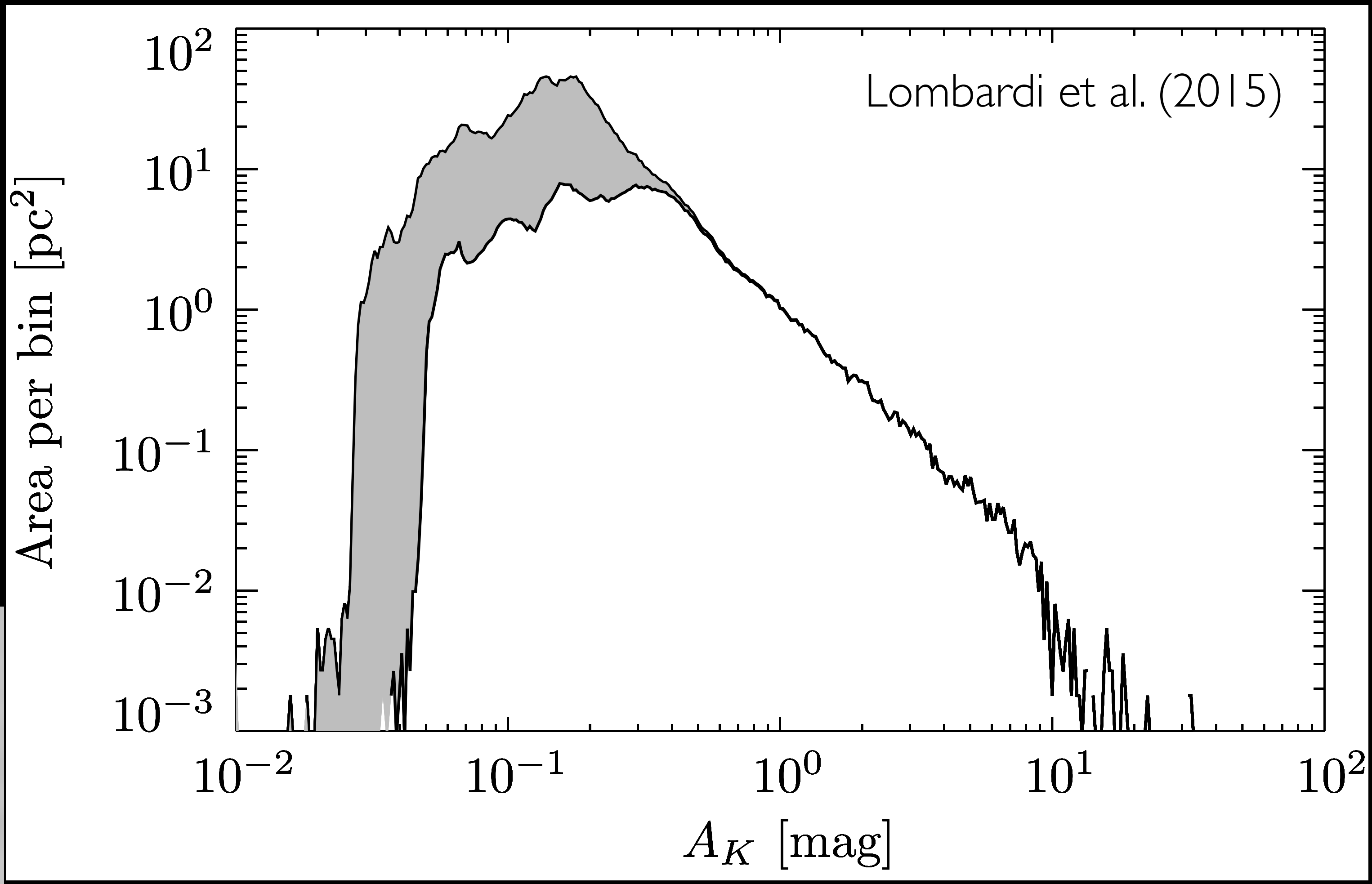

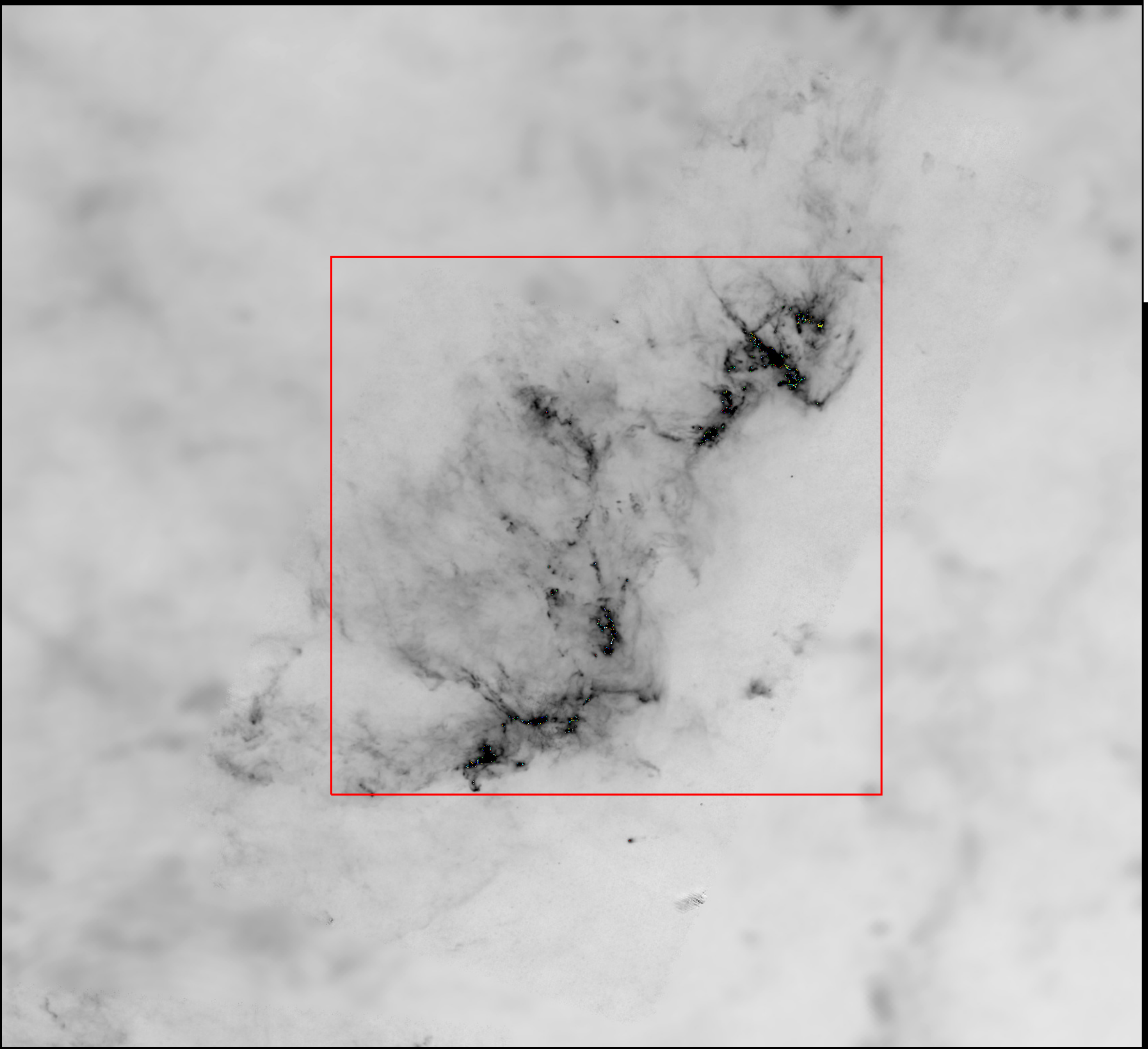

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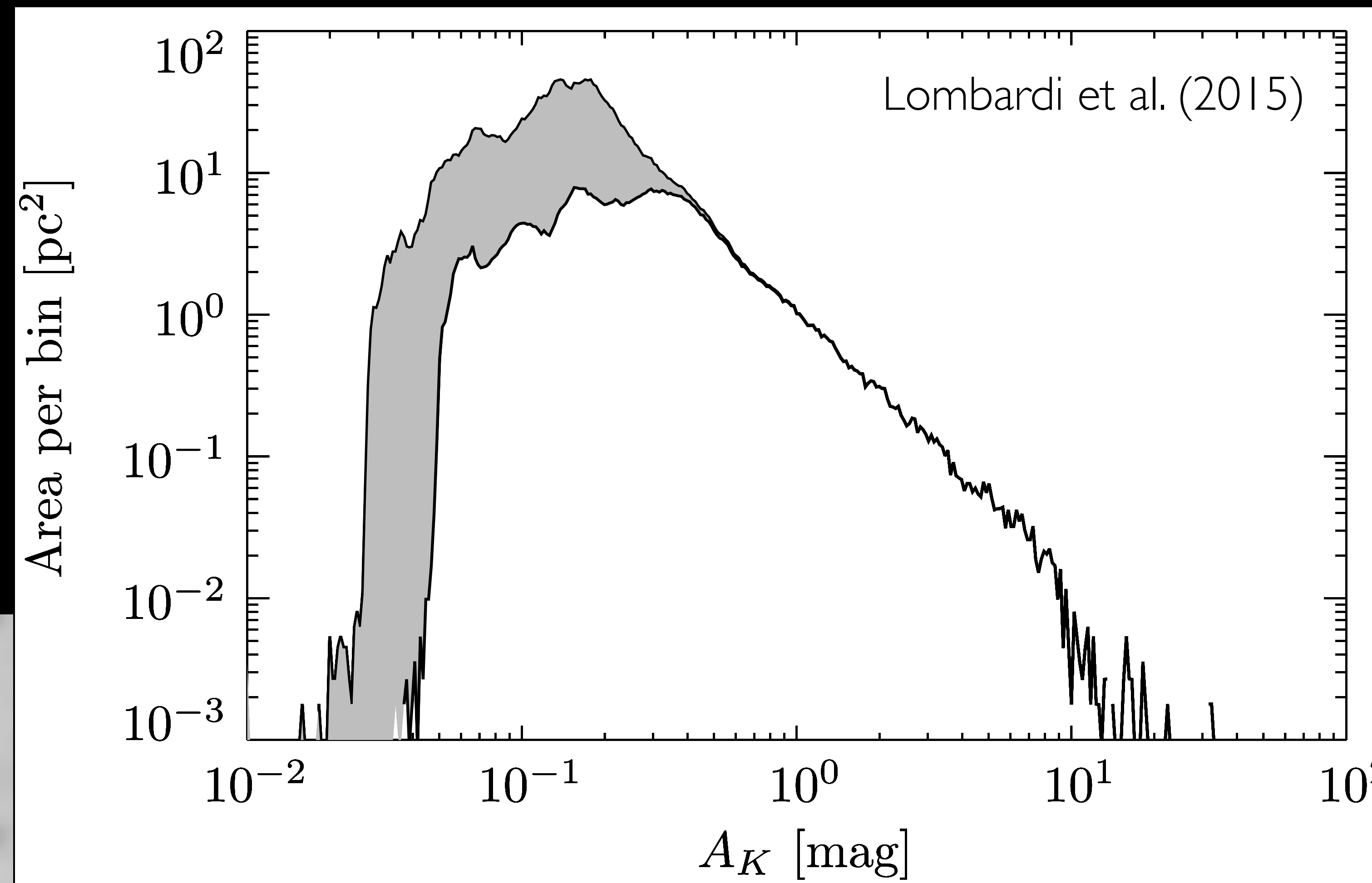

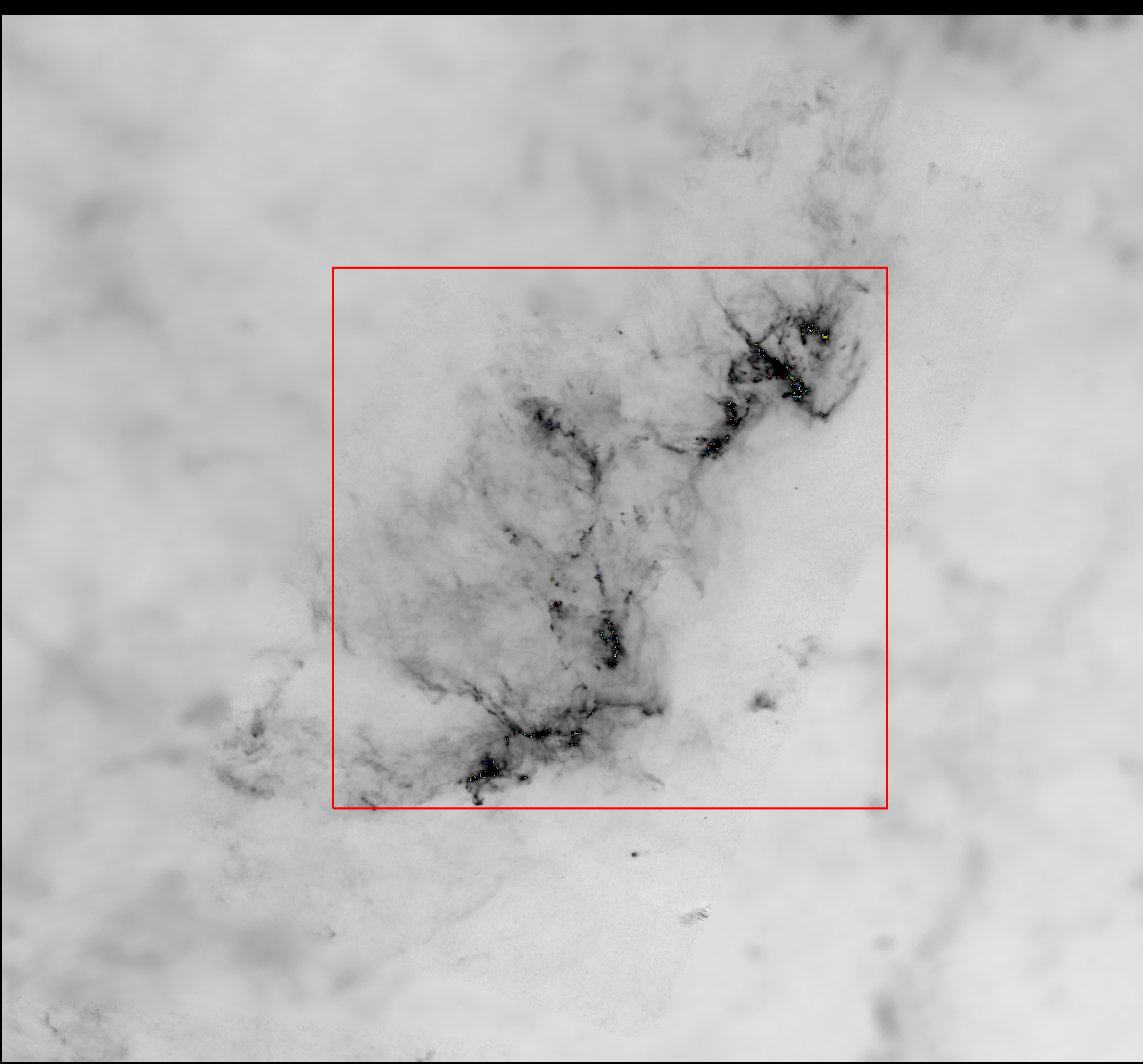

- The only sensible definition of a cloud boundary is using iso-density contours.

Can we actually probe the low A_K?

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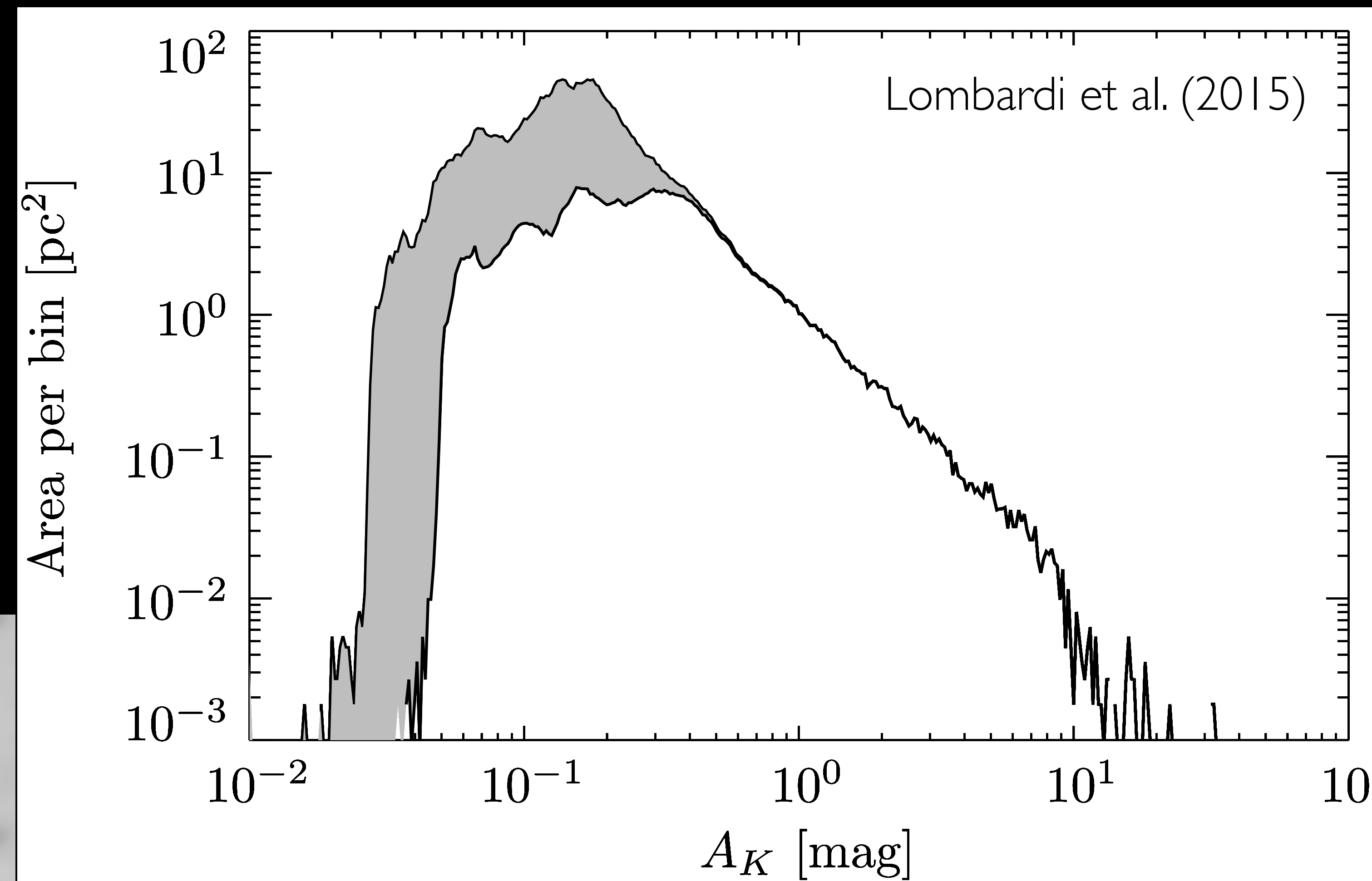
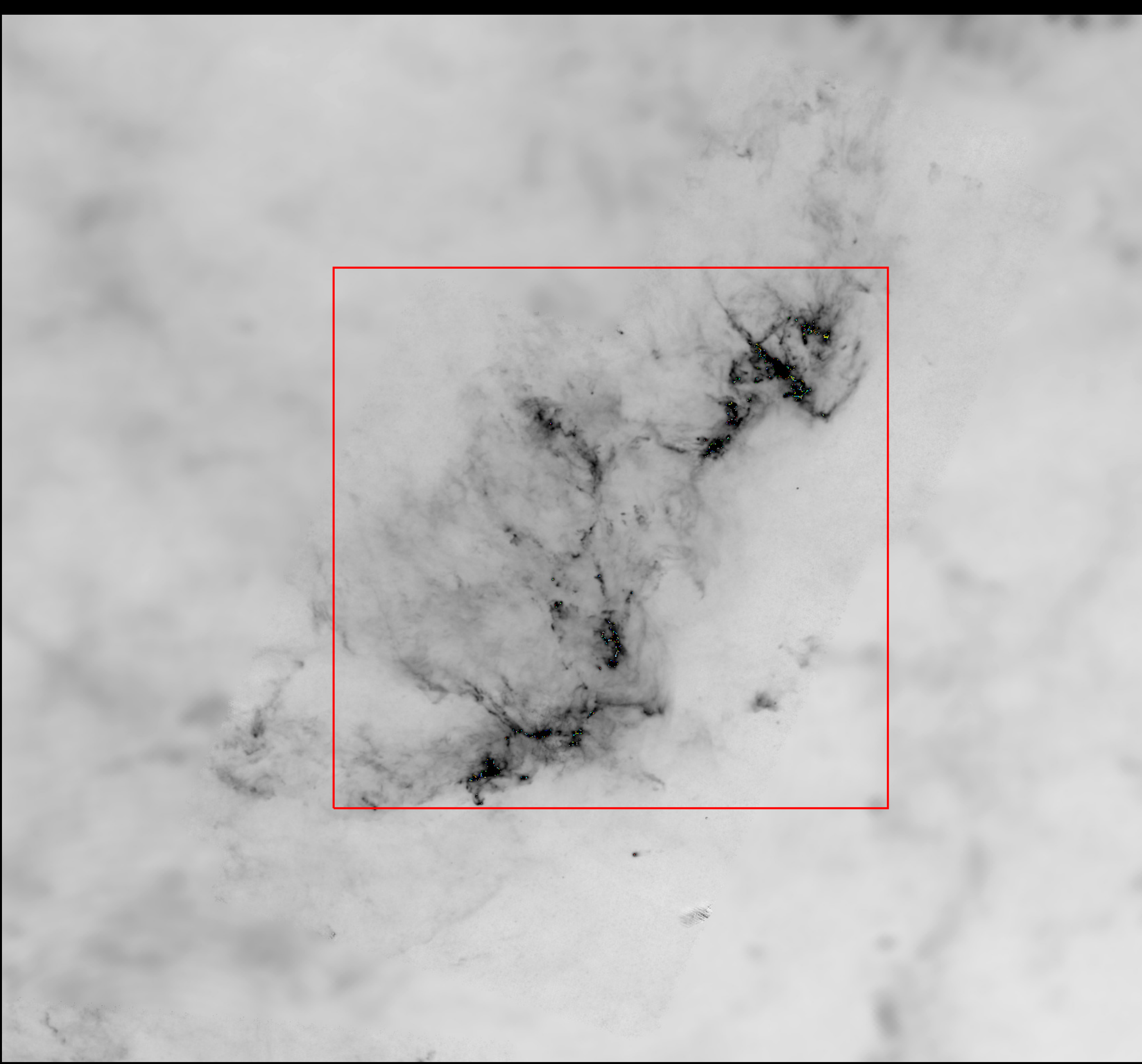
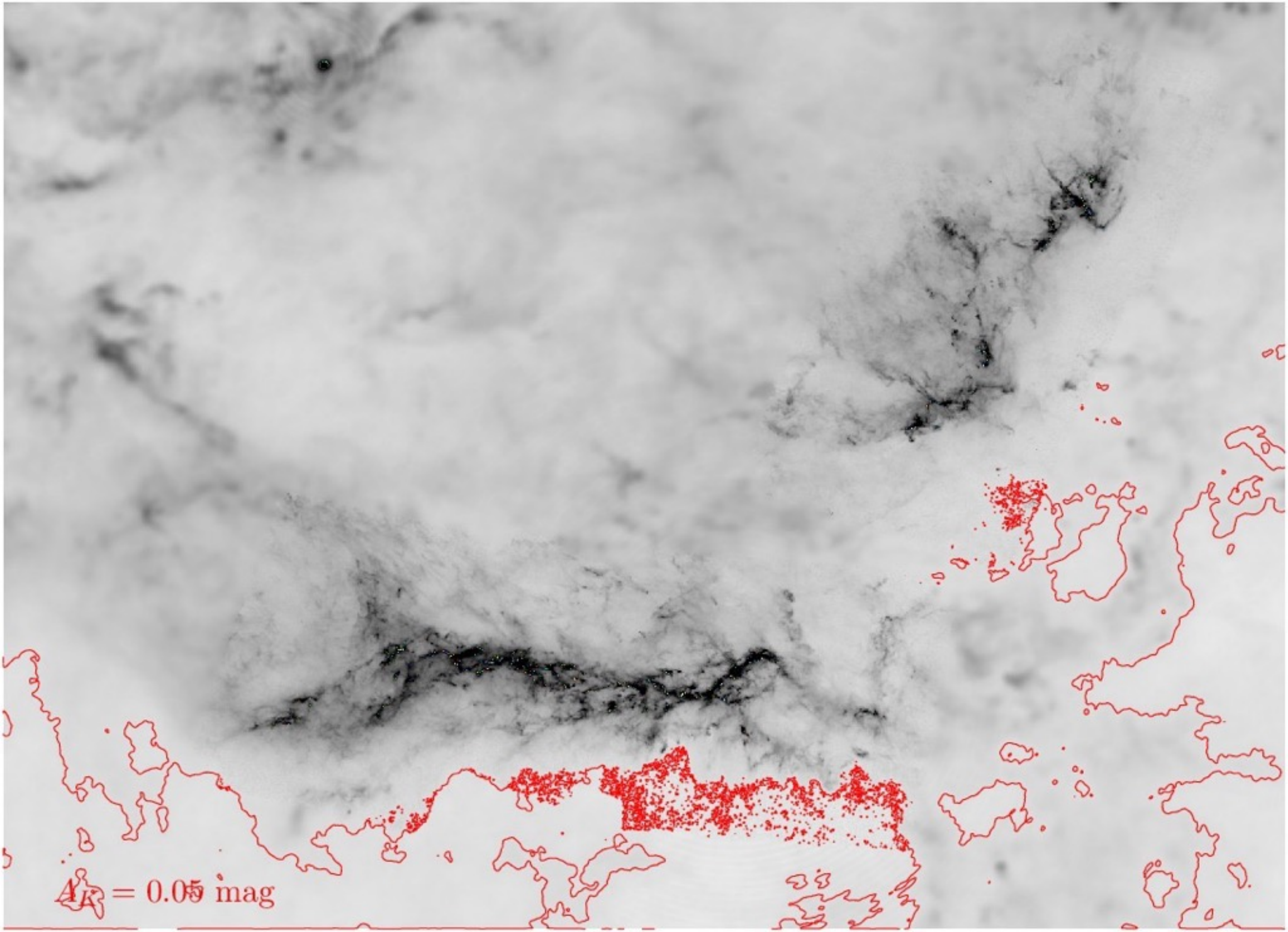
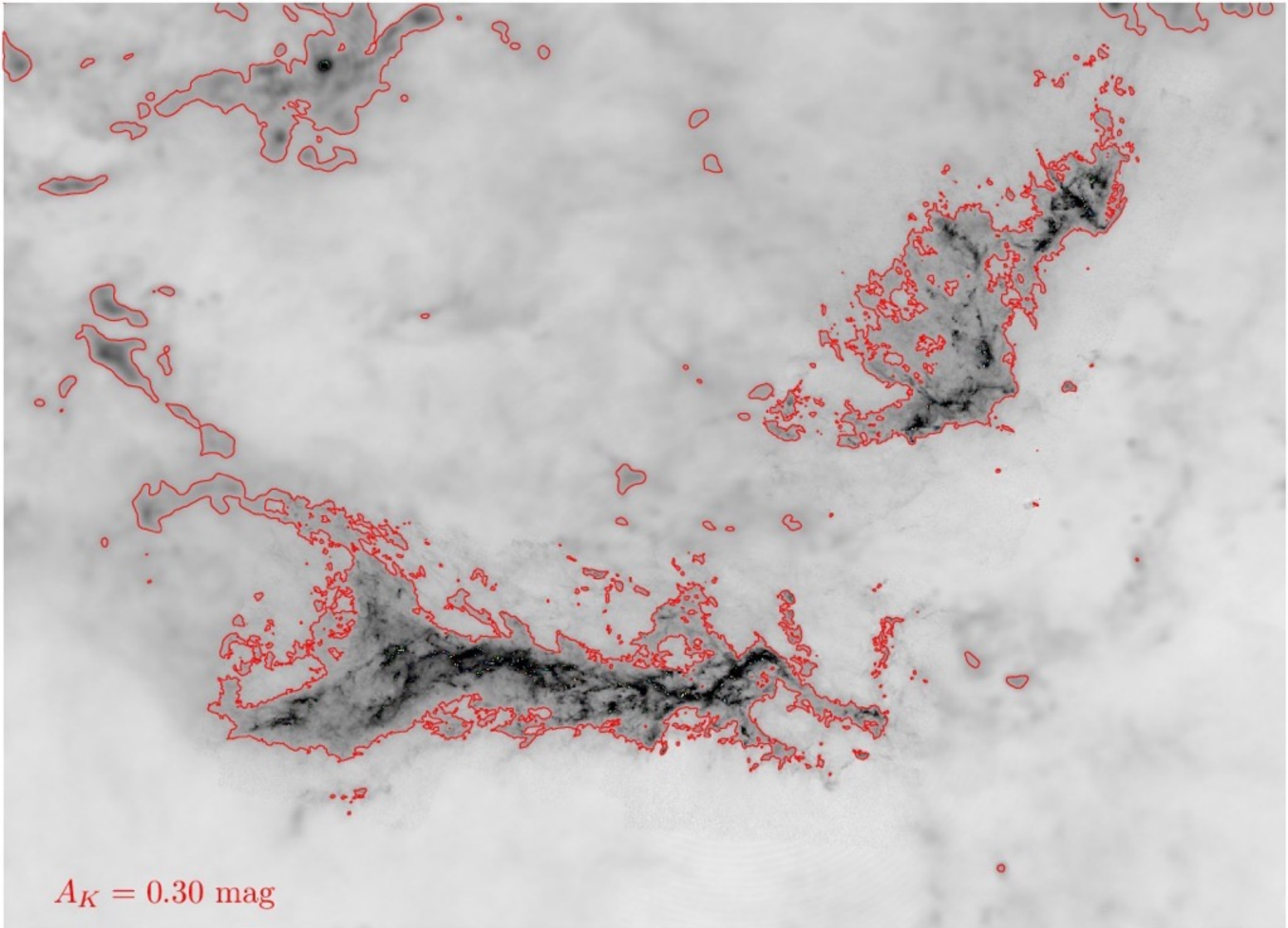




- The only sensible definition of a cloud boundary is using iso-density contours.
- Which contour levels are we able to use securely?


$A_K = 0.05$ mag

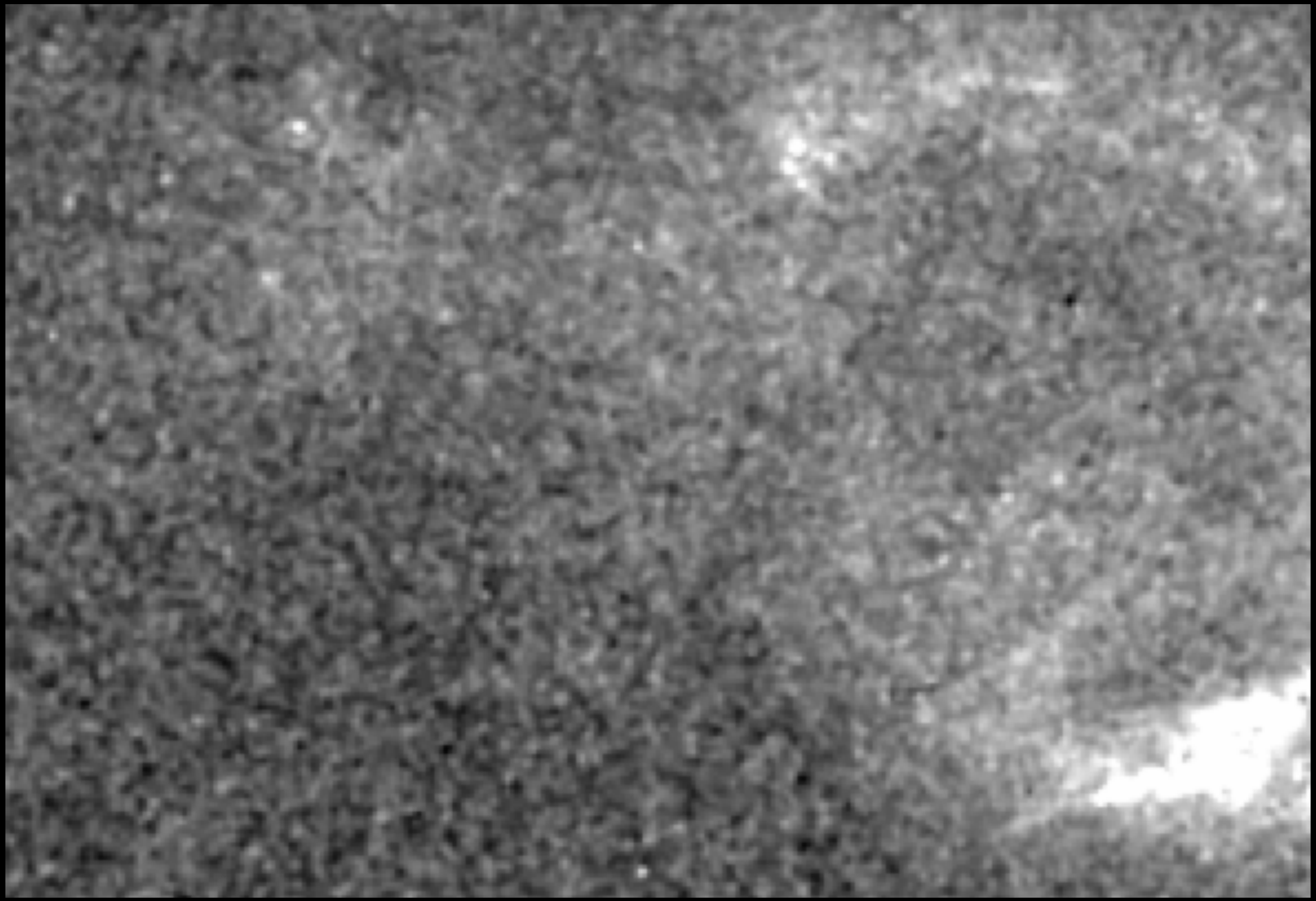

$A_K = 0.30$ mag

Things are actually worse than they appear


Things are actually worse than
they appear
If something can go wrong, it will.

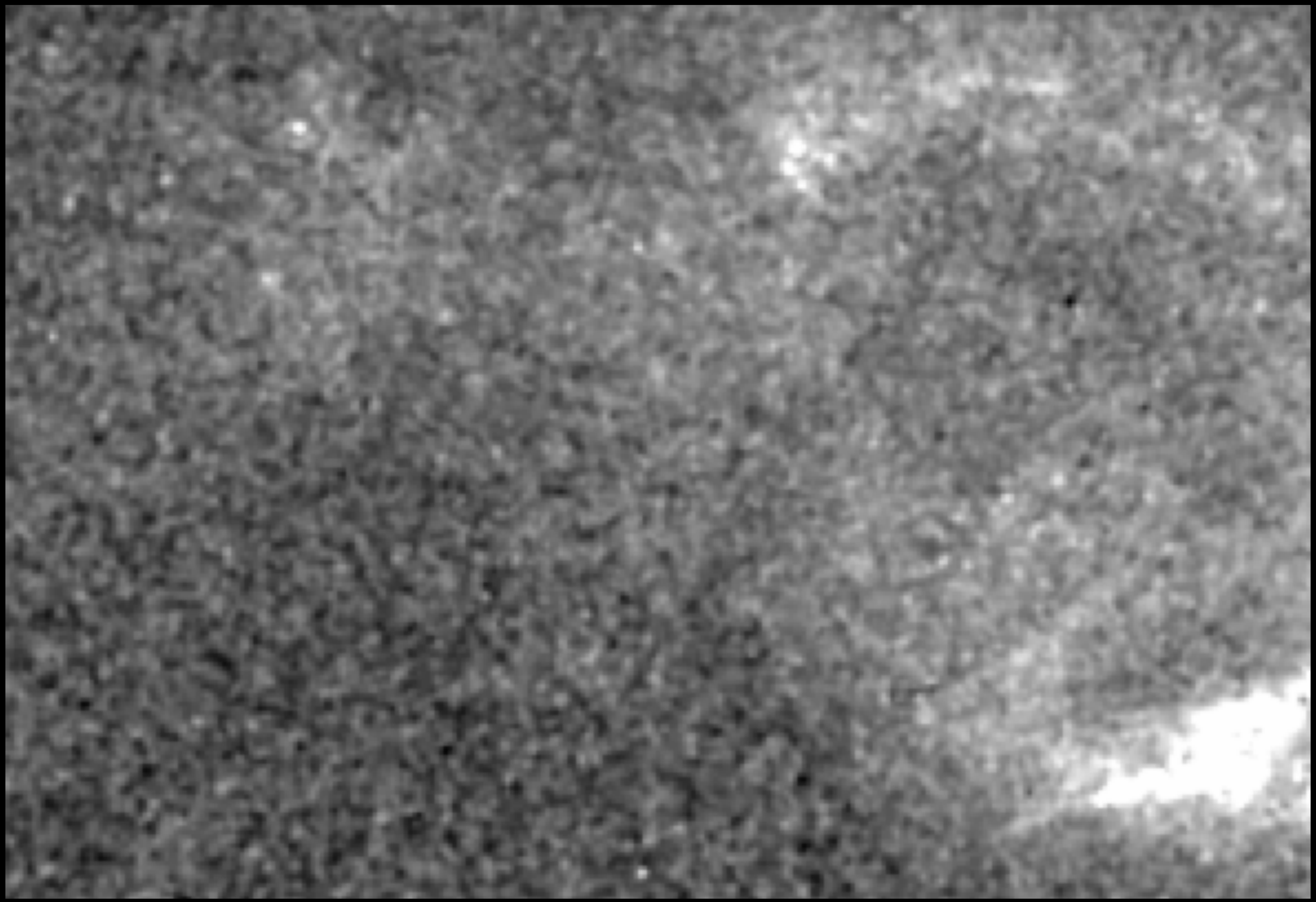

Things are actually worse than they appear
If something cannot go wrong, it will anyway.

Low-column density part of PDFs



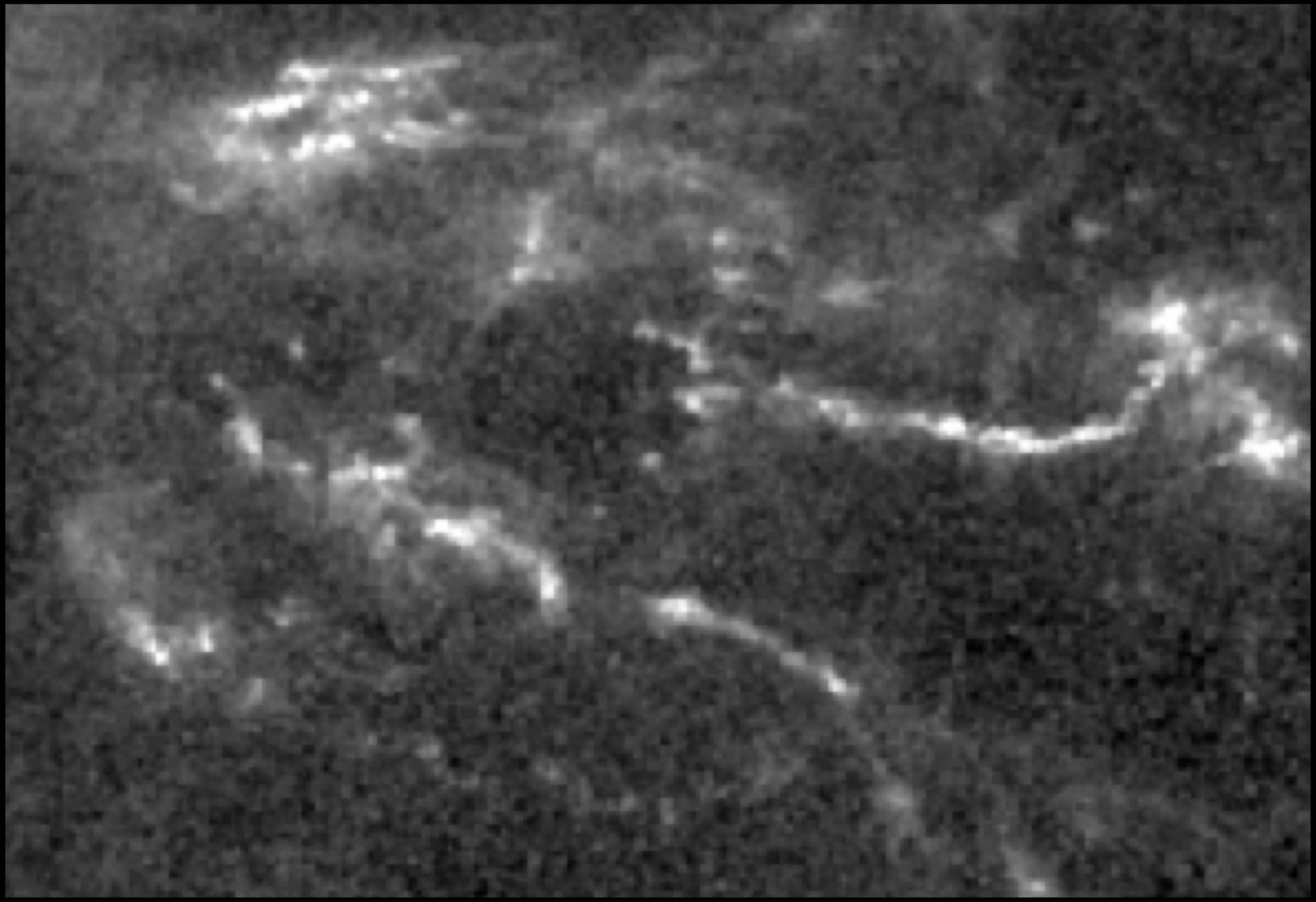
Low-column density part of PDFs

- Noise can be significant at low column densities



Low-column density part of PDFs

- Noise can be significant at low column densities
- Resolution effects (all bins): hard to model…



Low-column density part of PDFs

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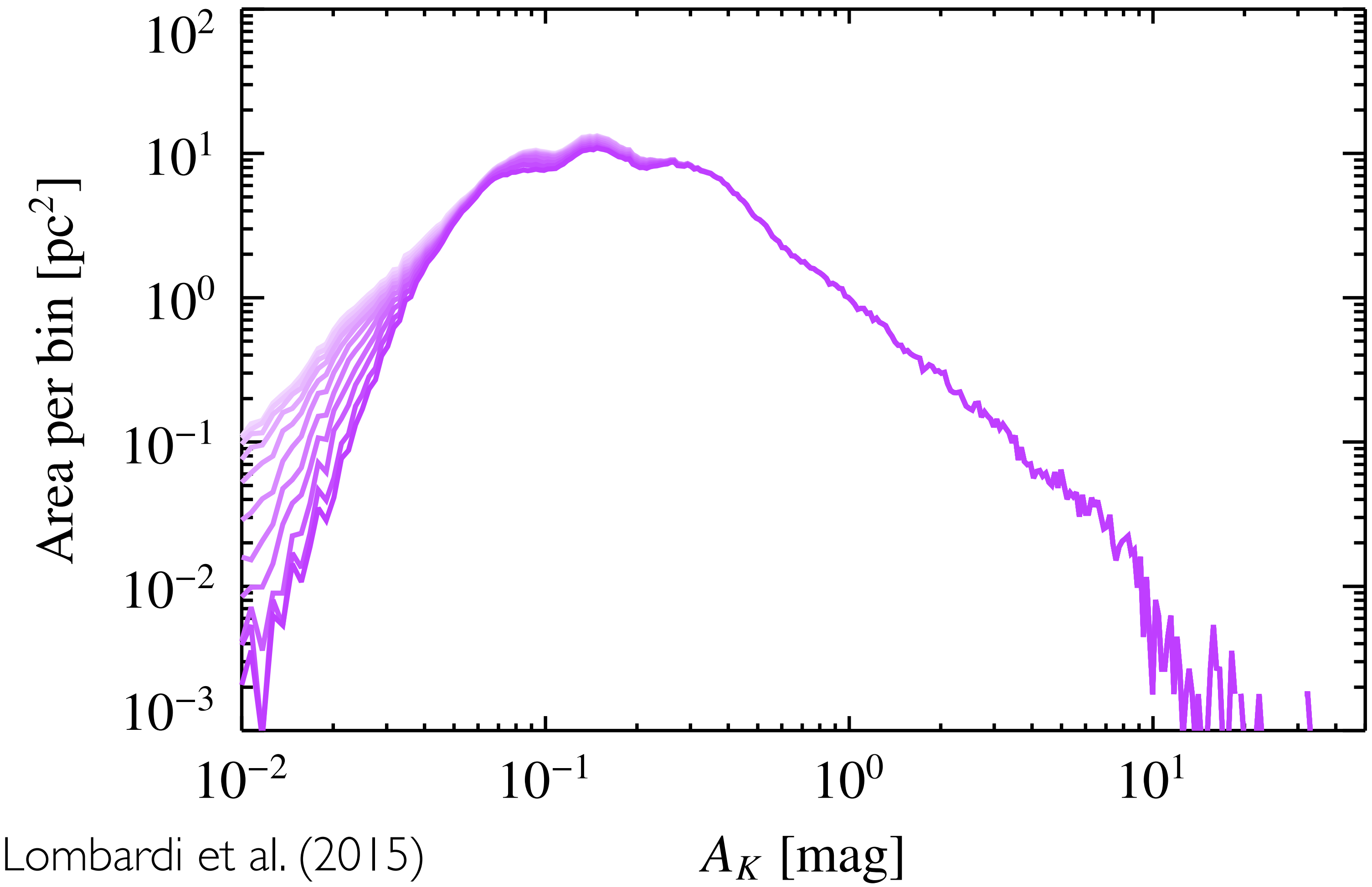

Lombardi et al. (2015)

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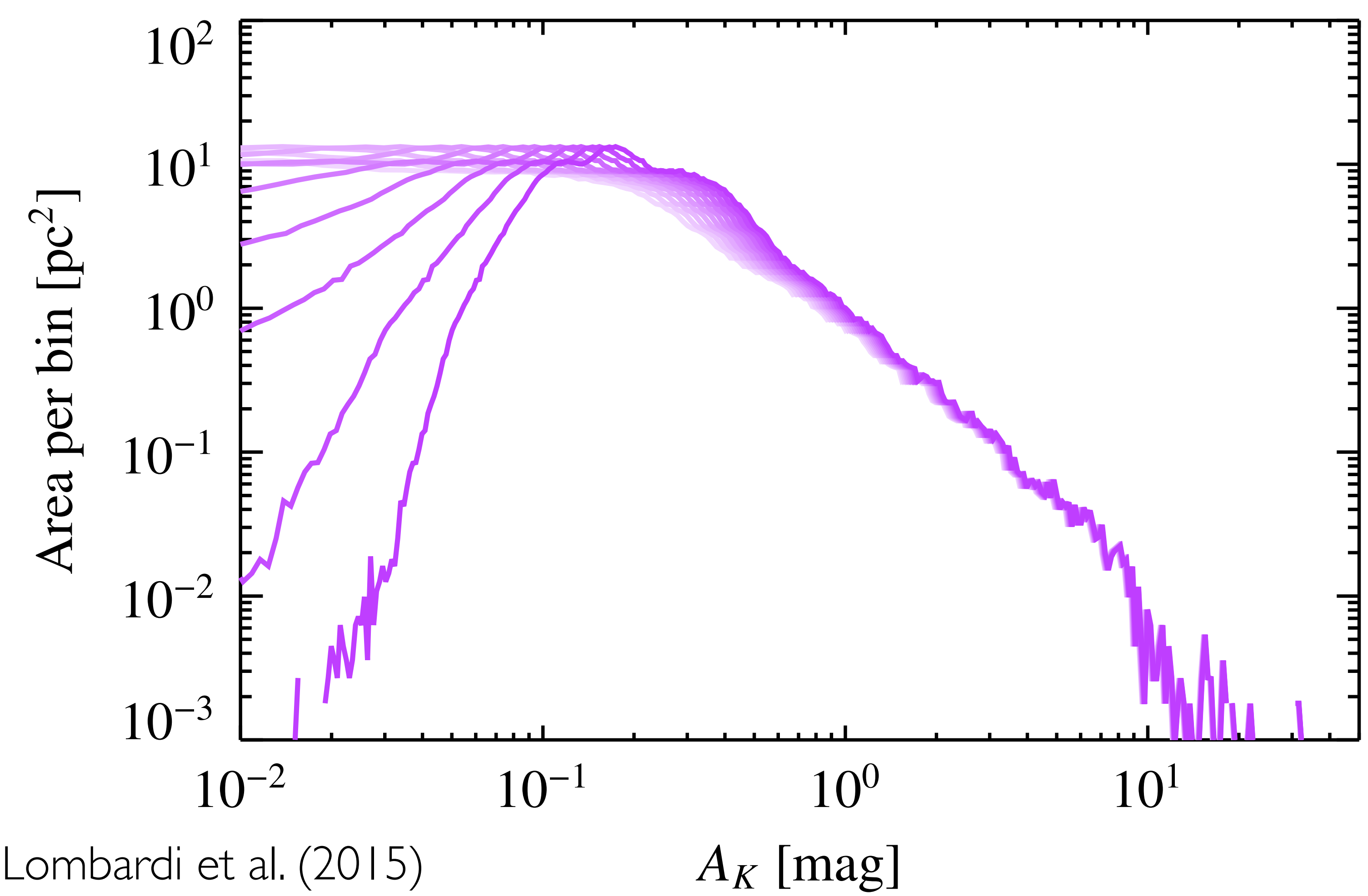

Lombardi et al. (2015)

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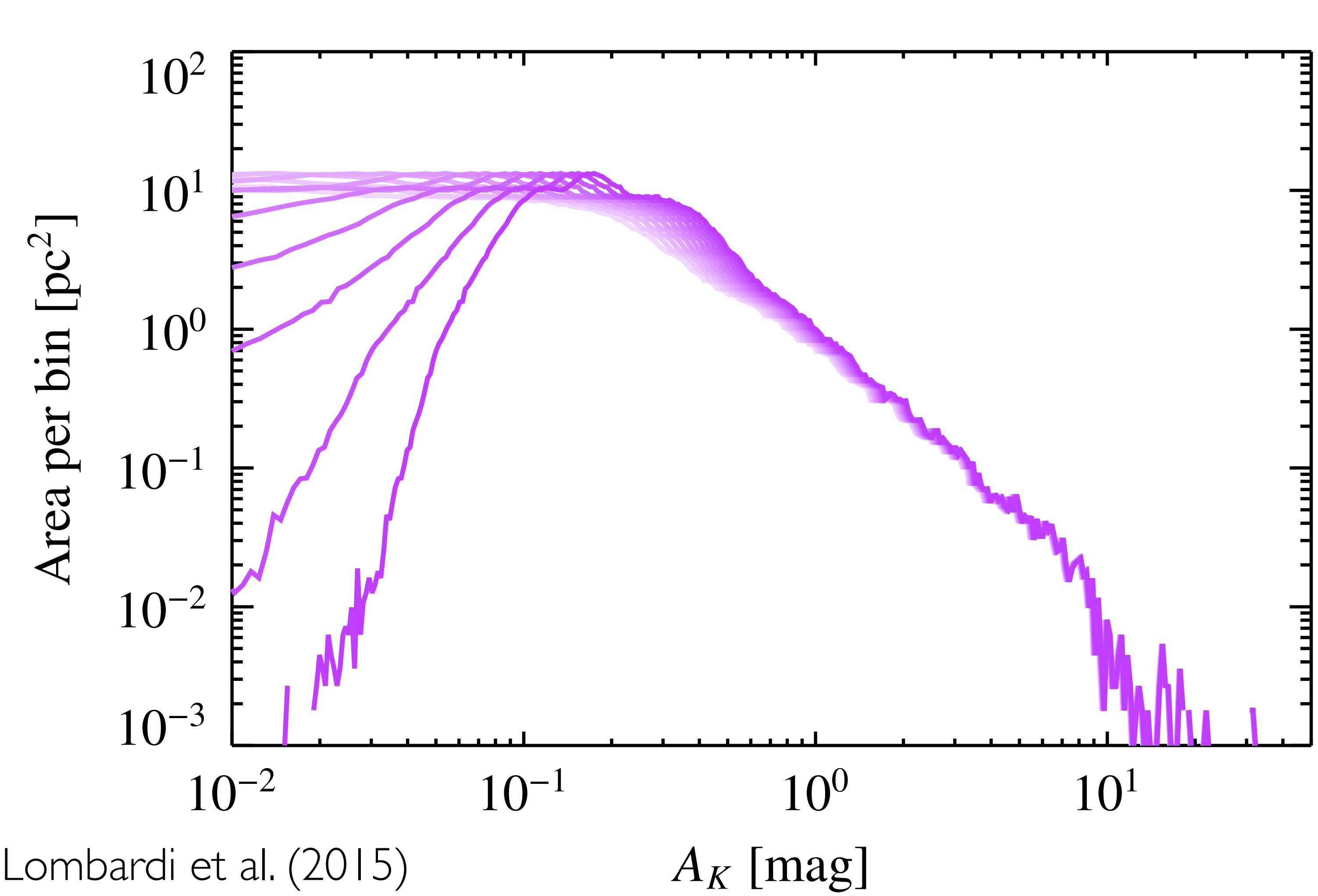
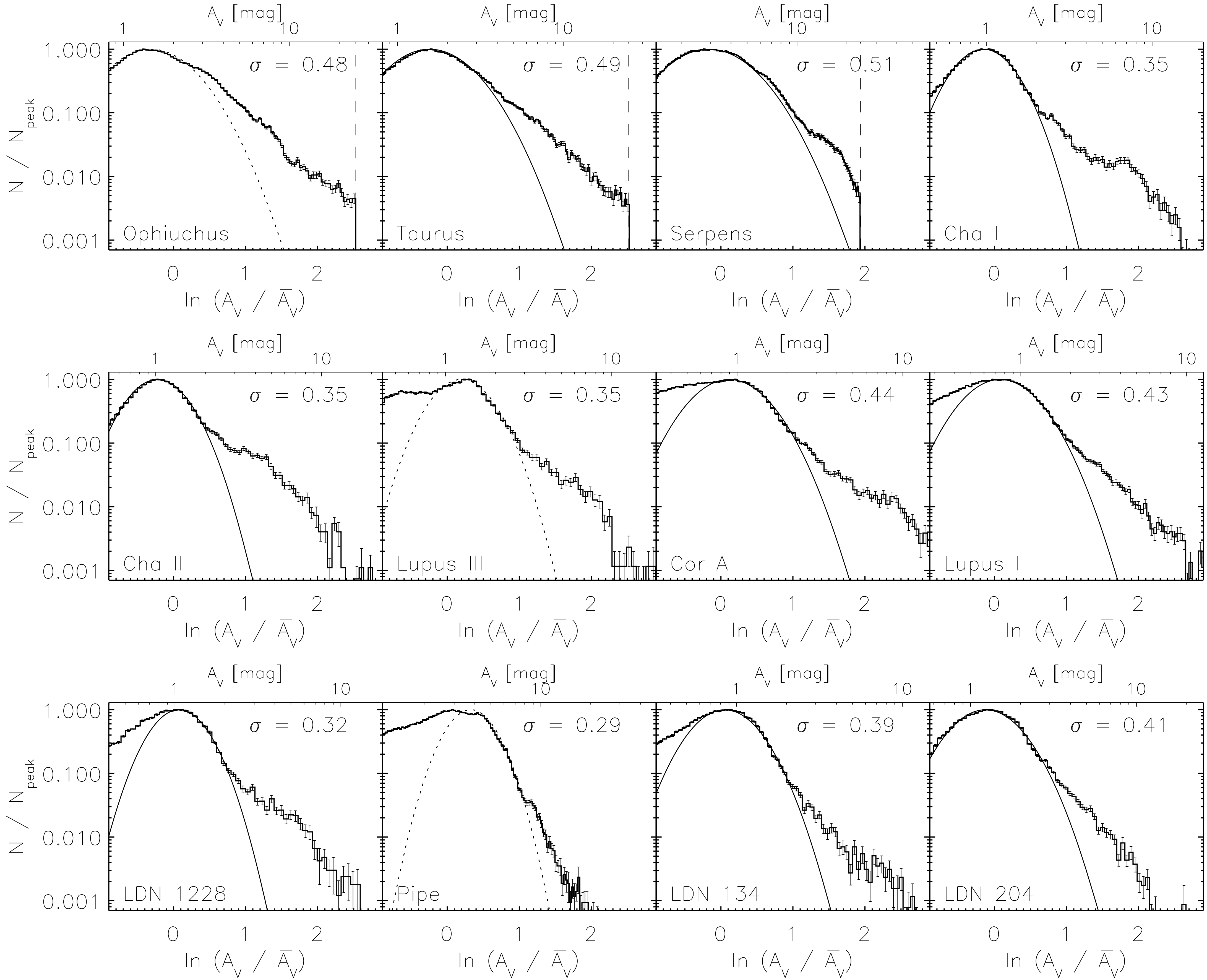


Lombardi et al. (2015)

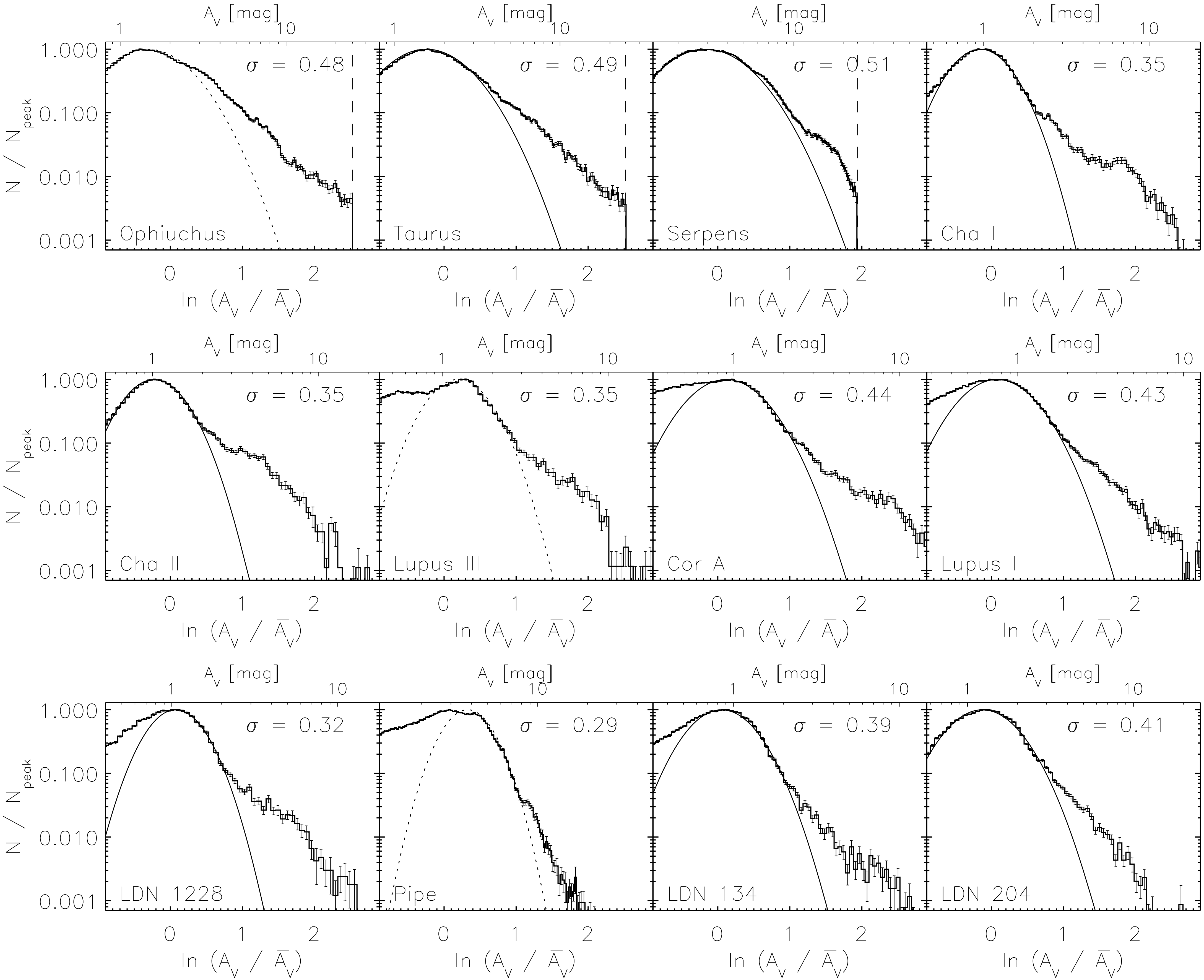
We are virtually unable to study the PDF below (at least) $A_K \sim 0.15$ mag

Log-normals everywhere!



Kainulainen et al. (2009)

Log-normals everywhere?



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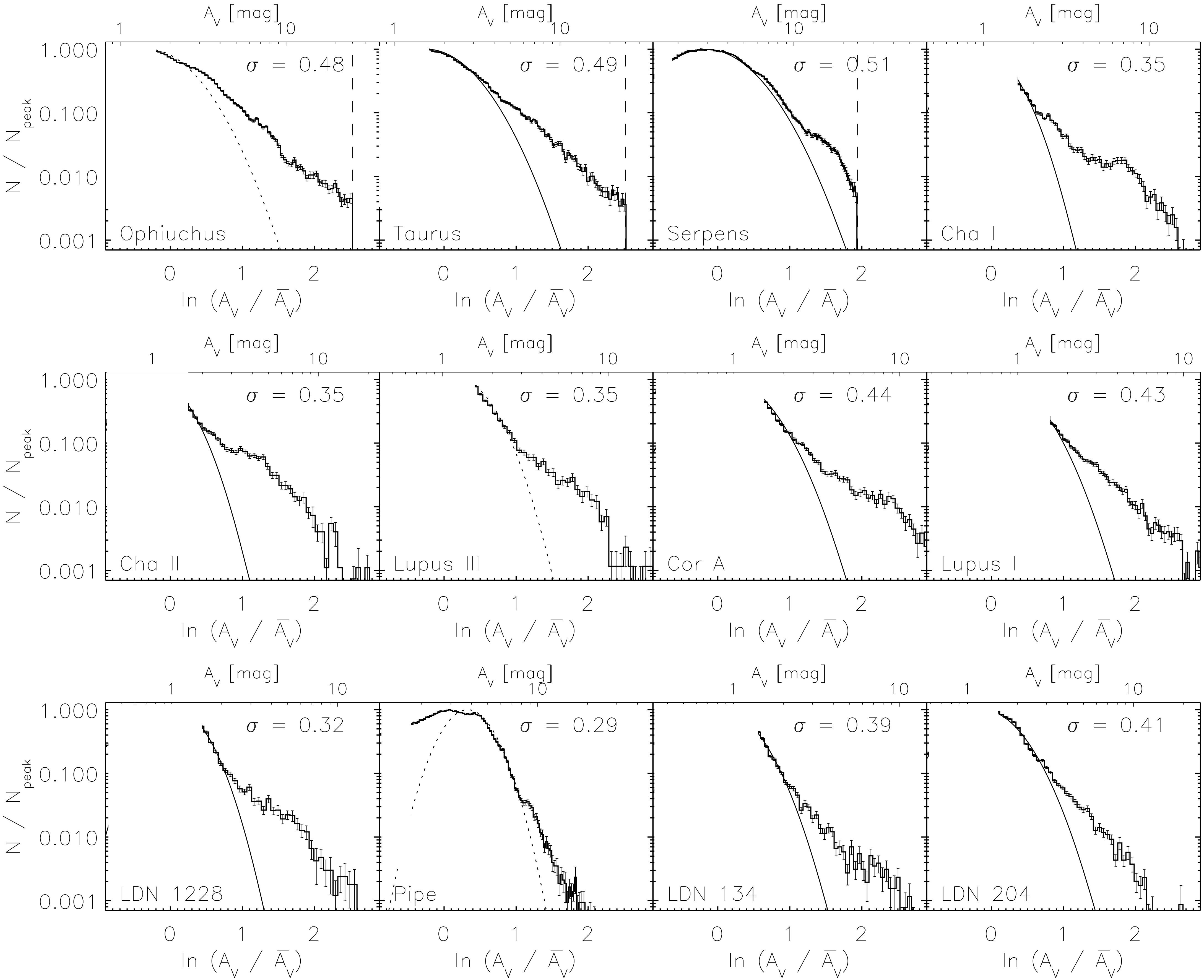
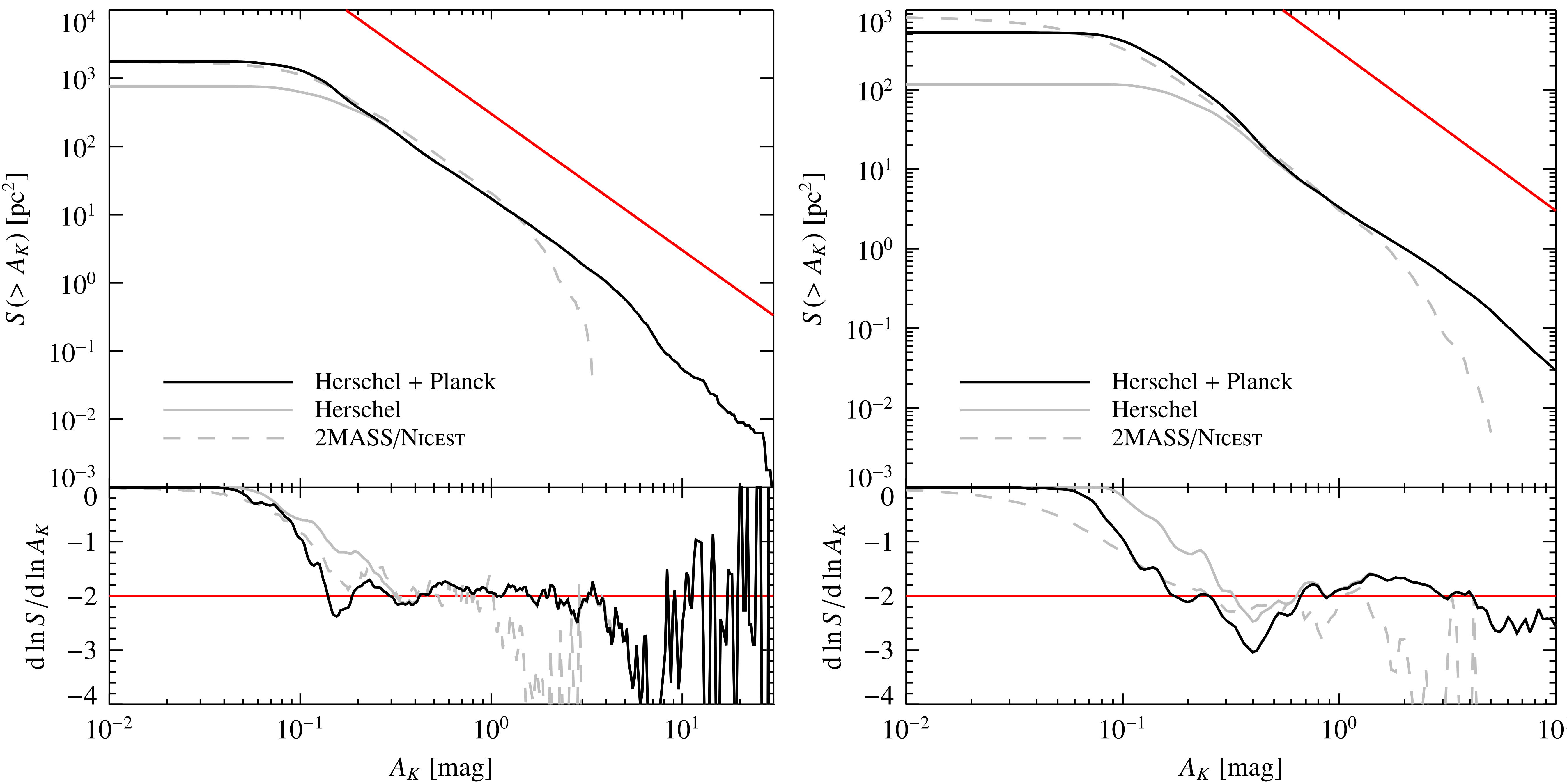


Kainulainen et al. (2009), censored

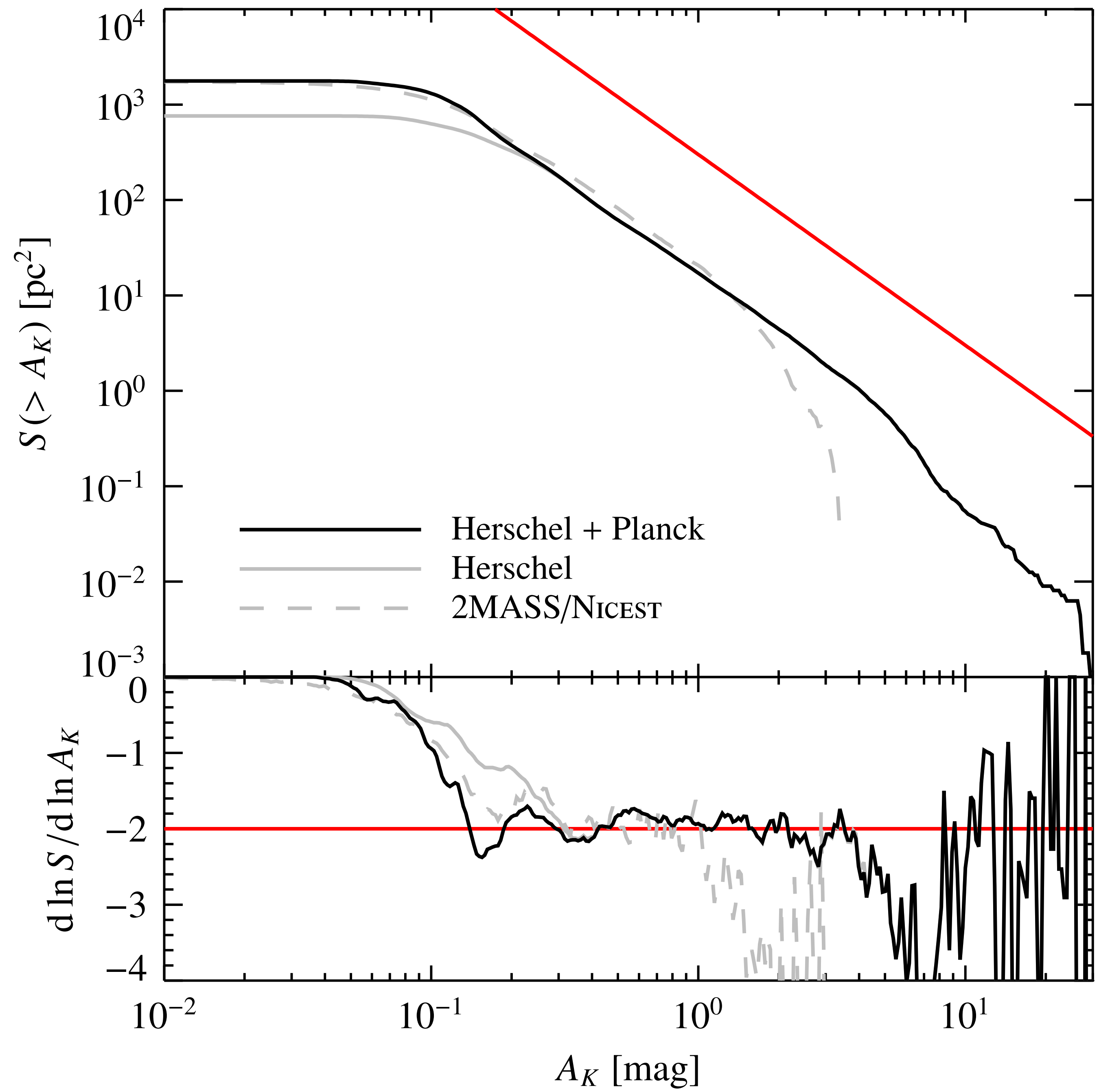
Area functions (integrals of PDFs)



Lombardi et al. (2014)

Alves et al. (2015)

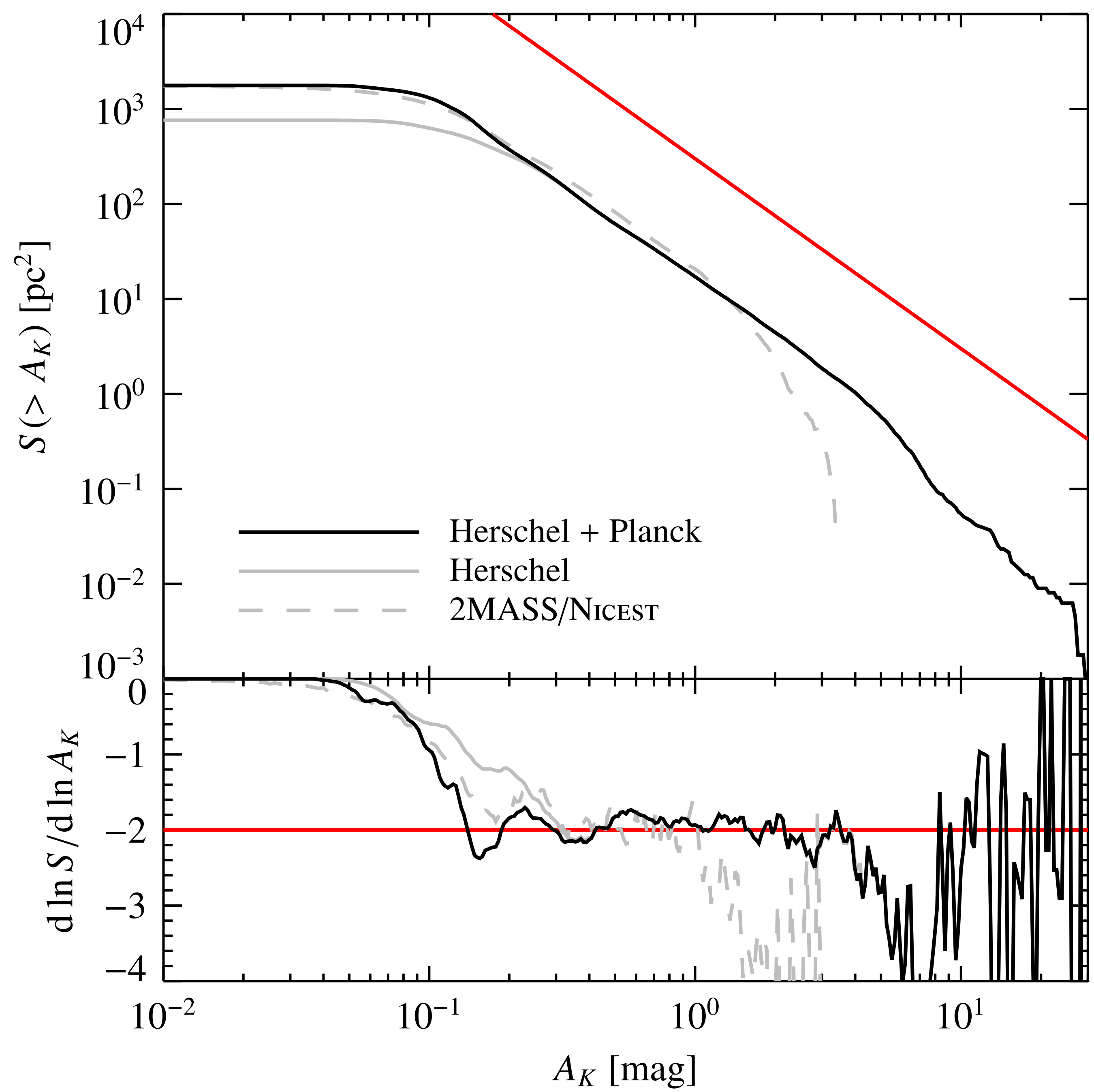
Toy model



Lombardi et al. (2014)

Toy model

Consider an isothermal sphere:

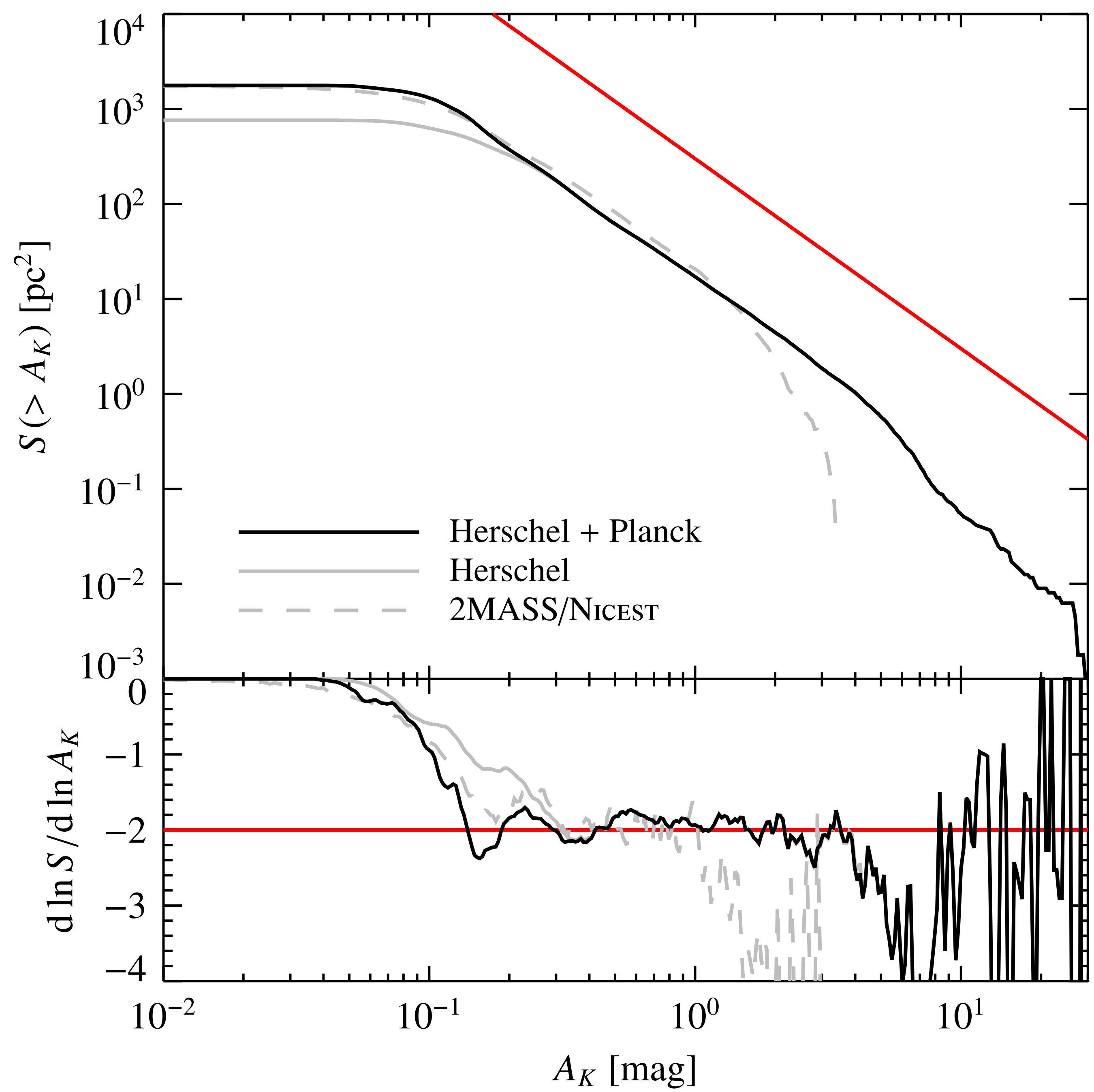


Lombardi et al. (2014)

Toy model

Consider an isothermal sphere:

$\rho \sim R^{-2}$



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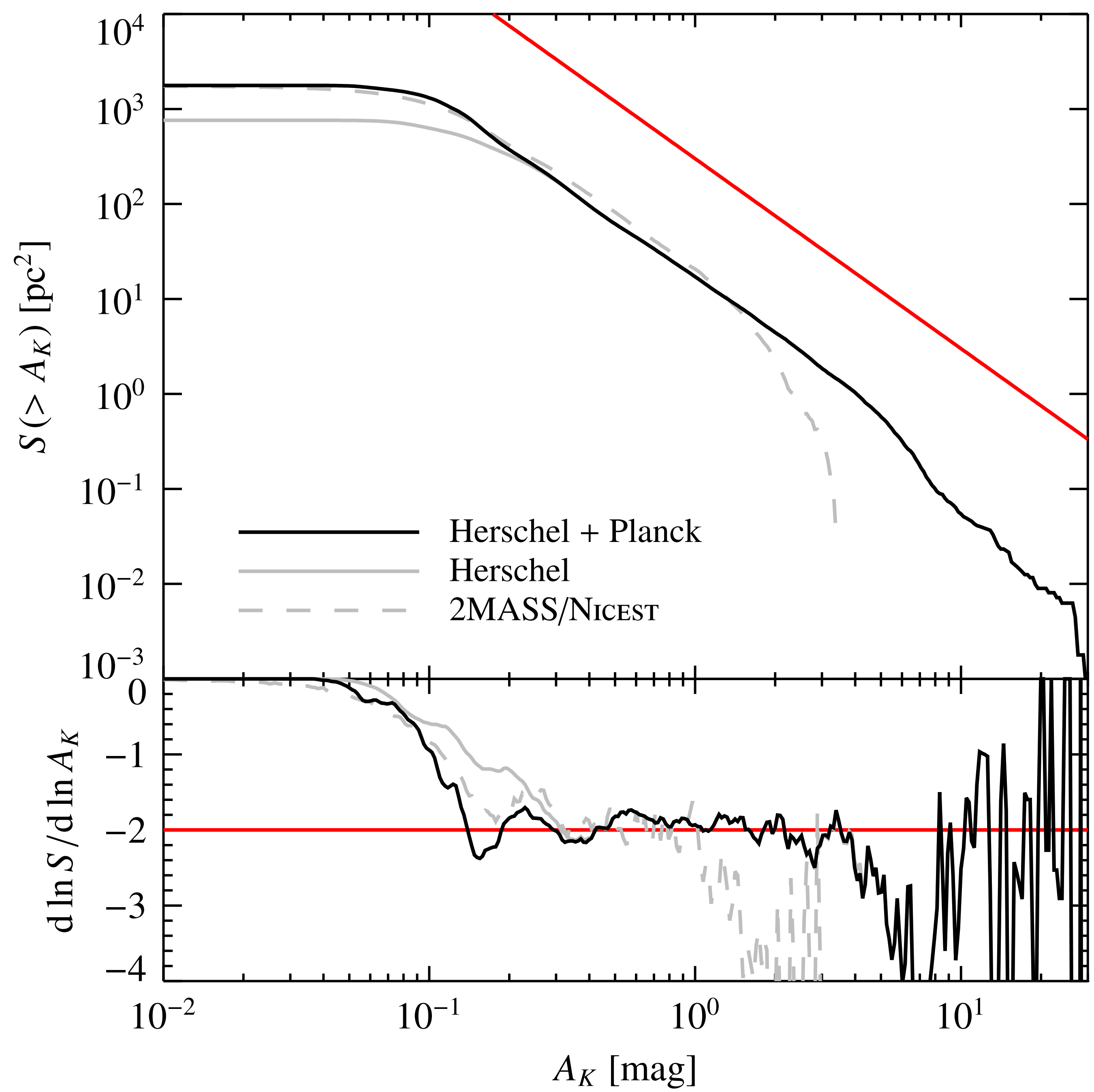

Lombardi et al. (2014)

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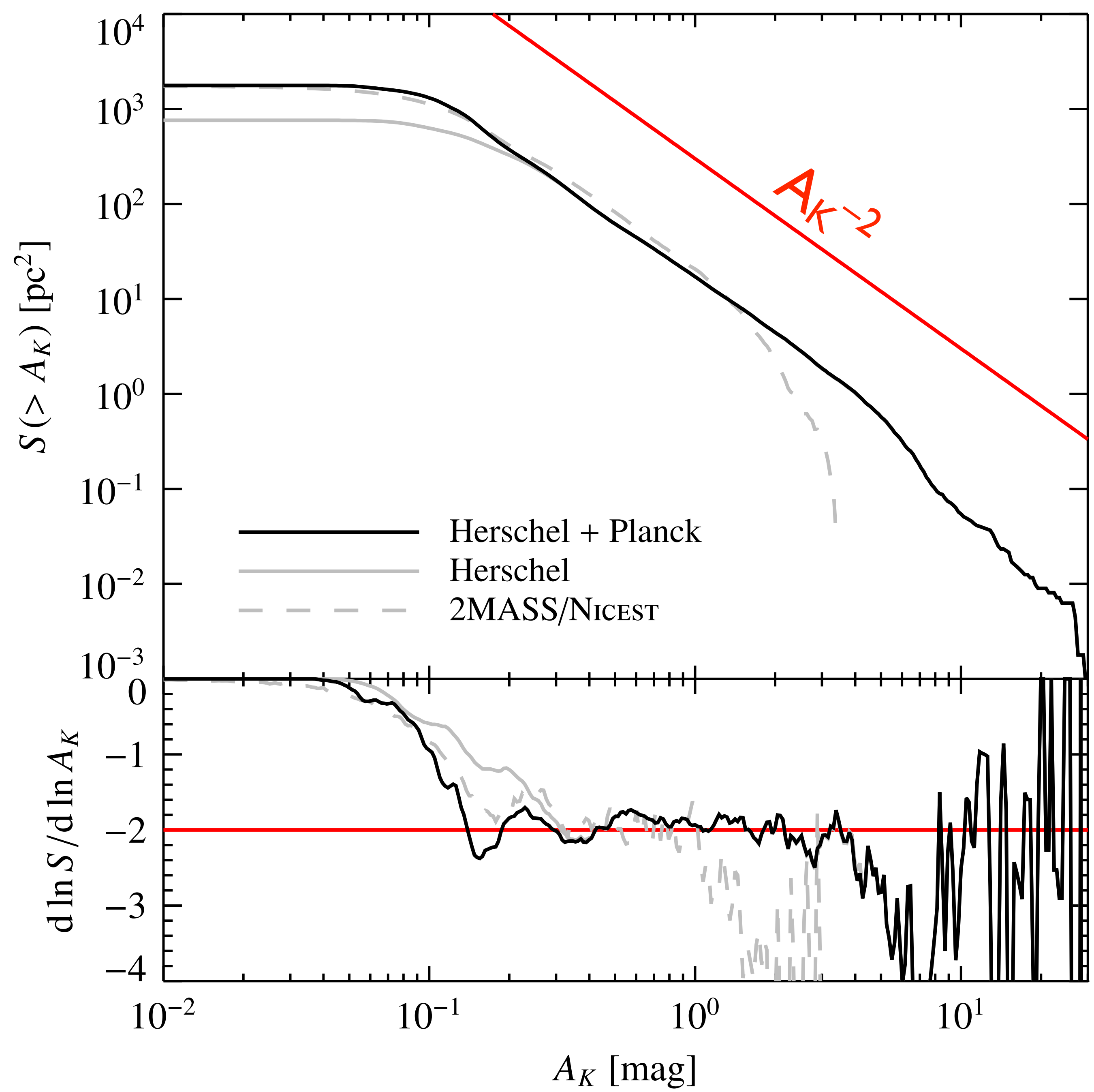
$S(> A_K) \sim R^2 \sim A_K^{-2}$



Lombardi et al. (2014)

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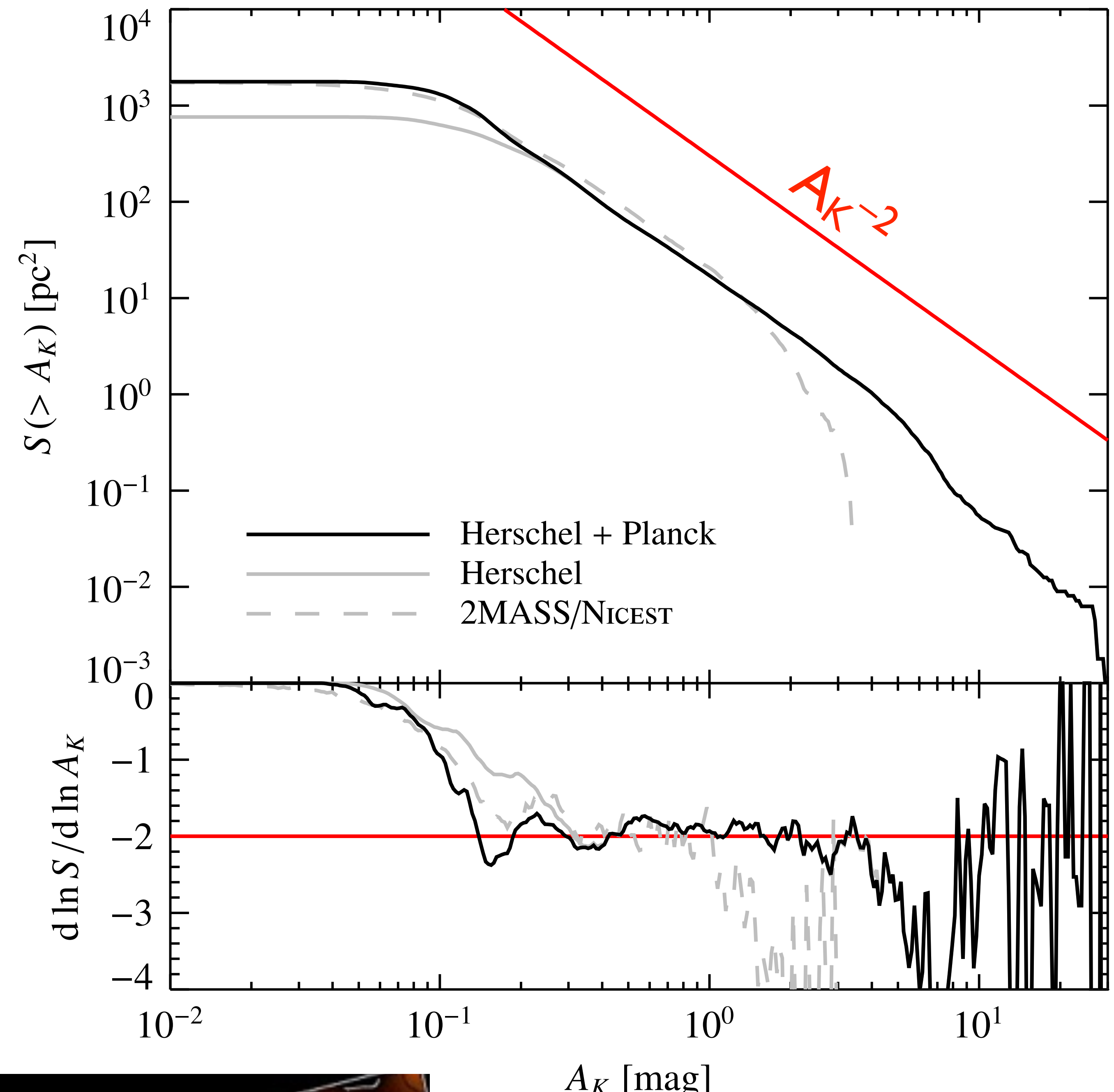
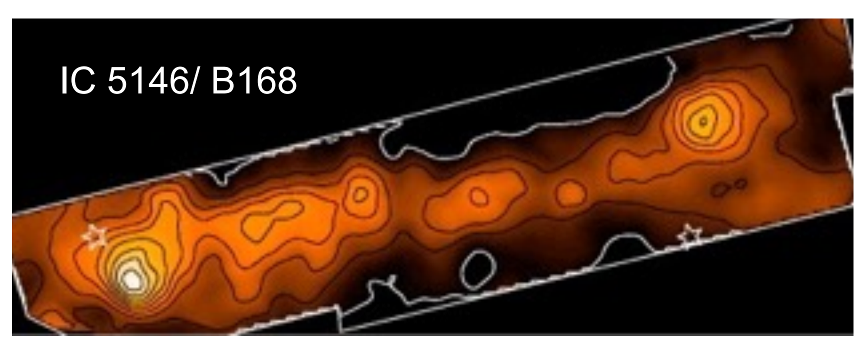
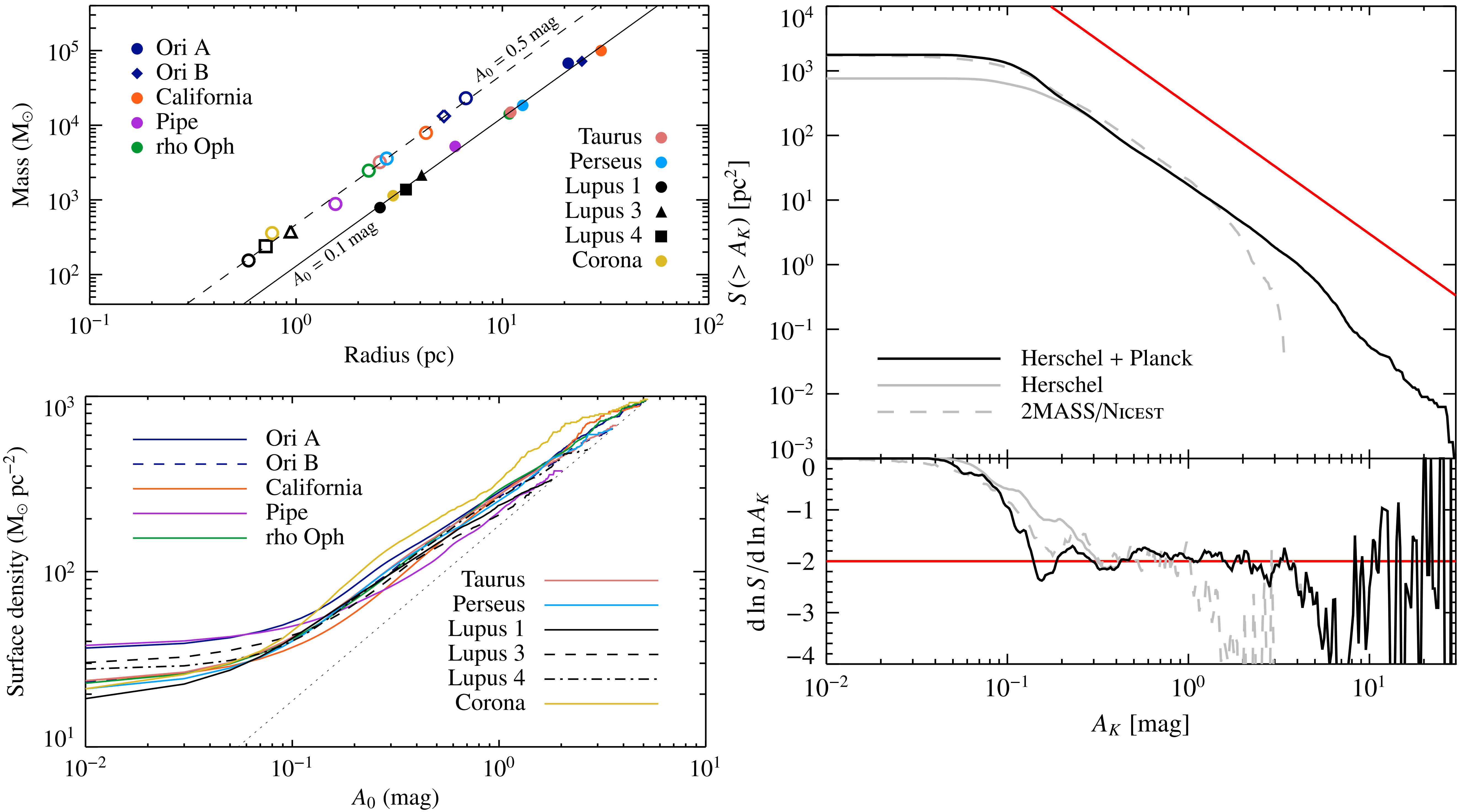




Lombardi et al. (2014)

3rd Larson's law



Lombardi et al. (2014)

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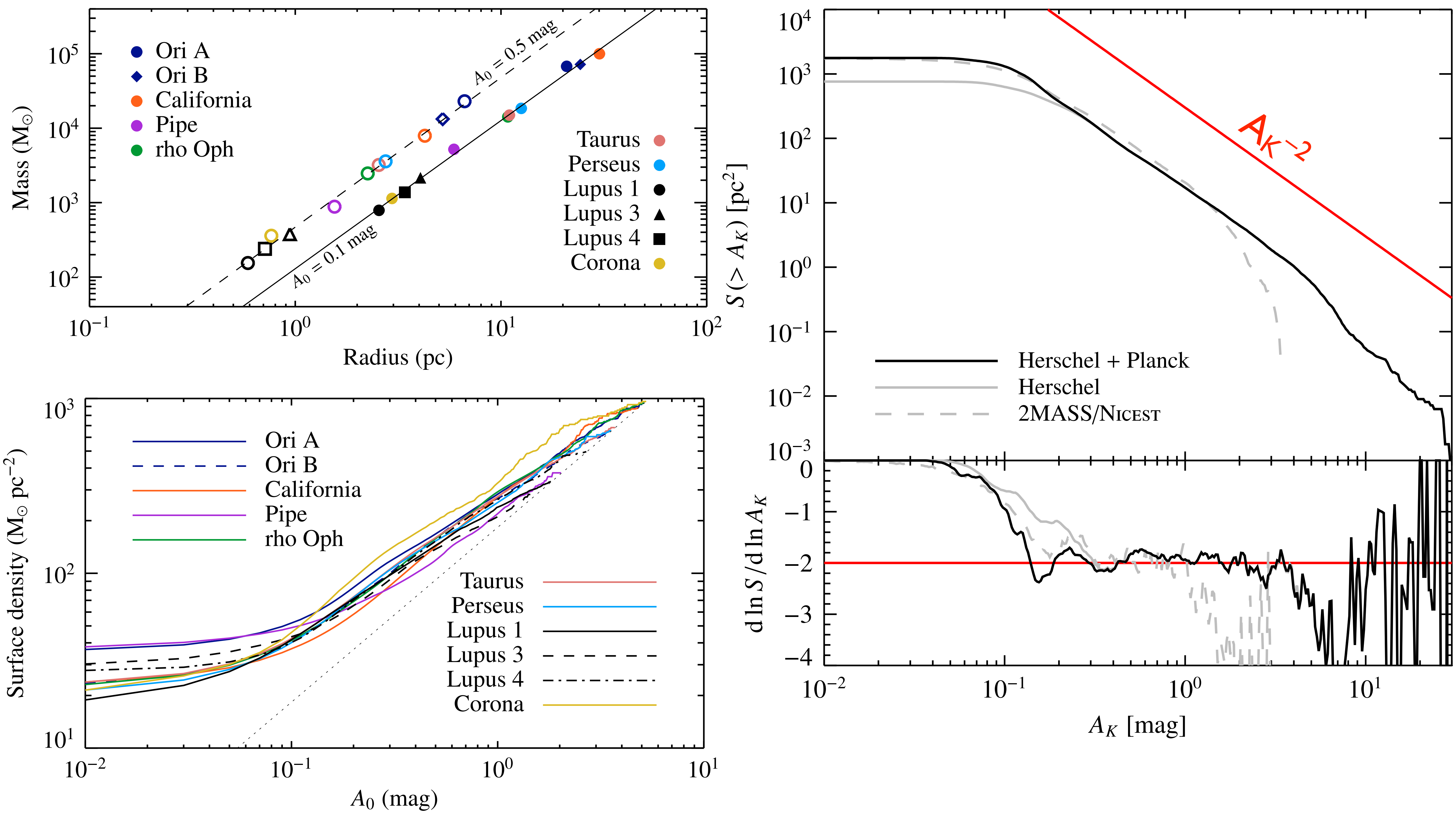
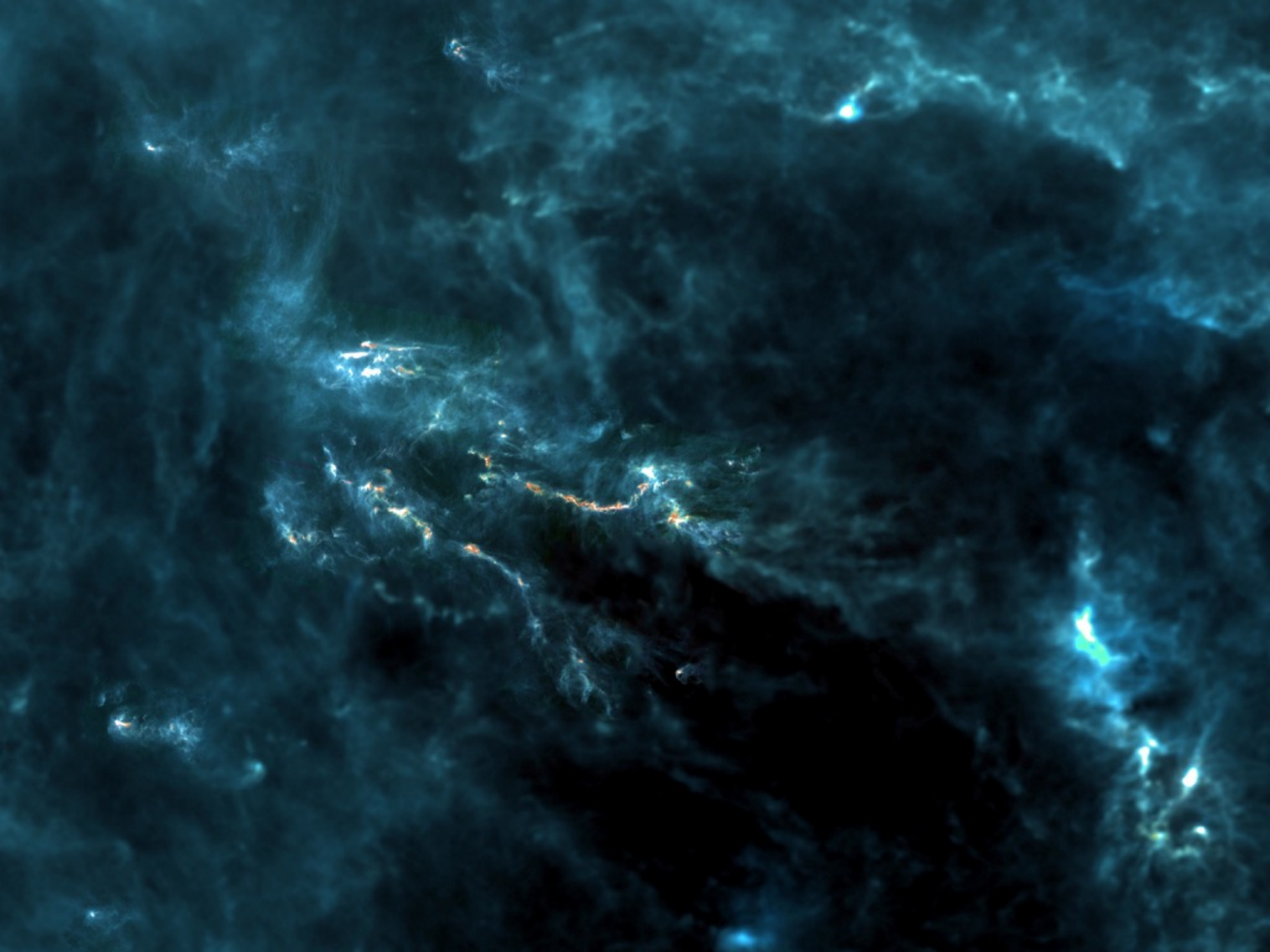
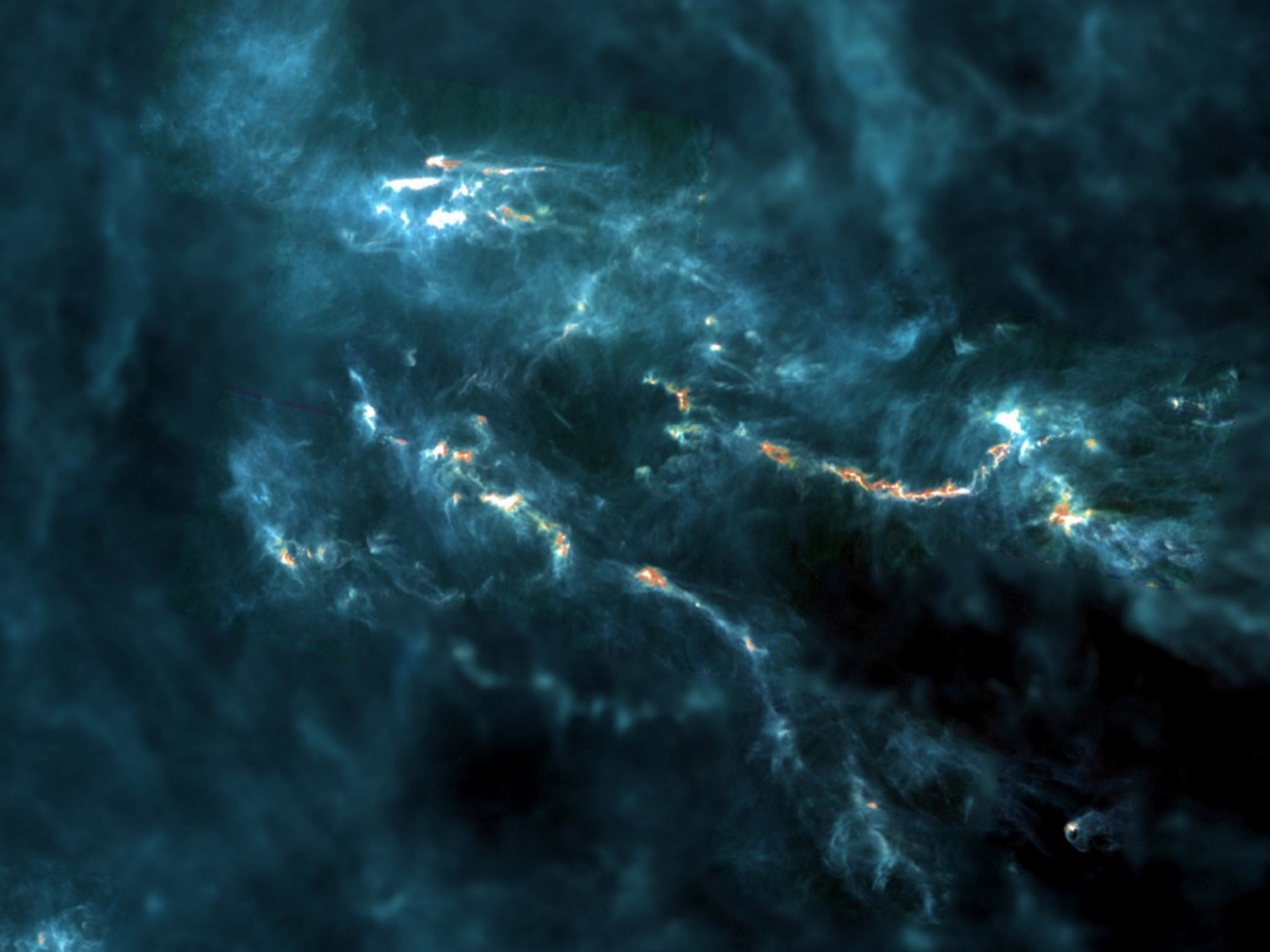


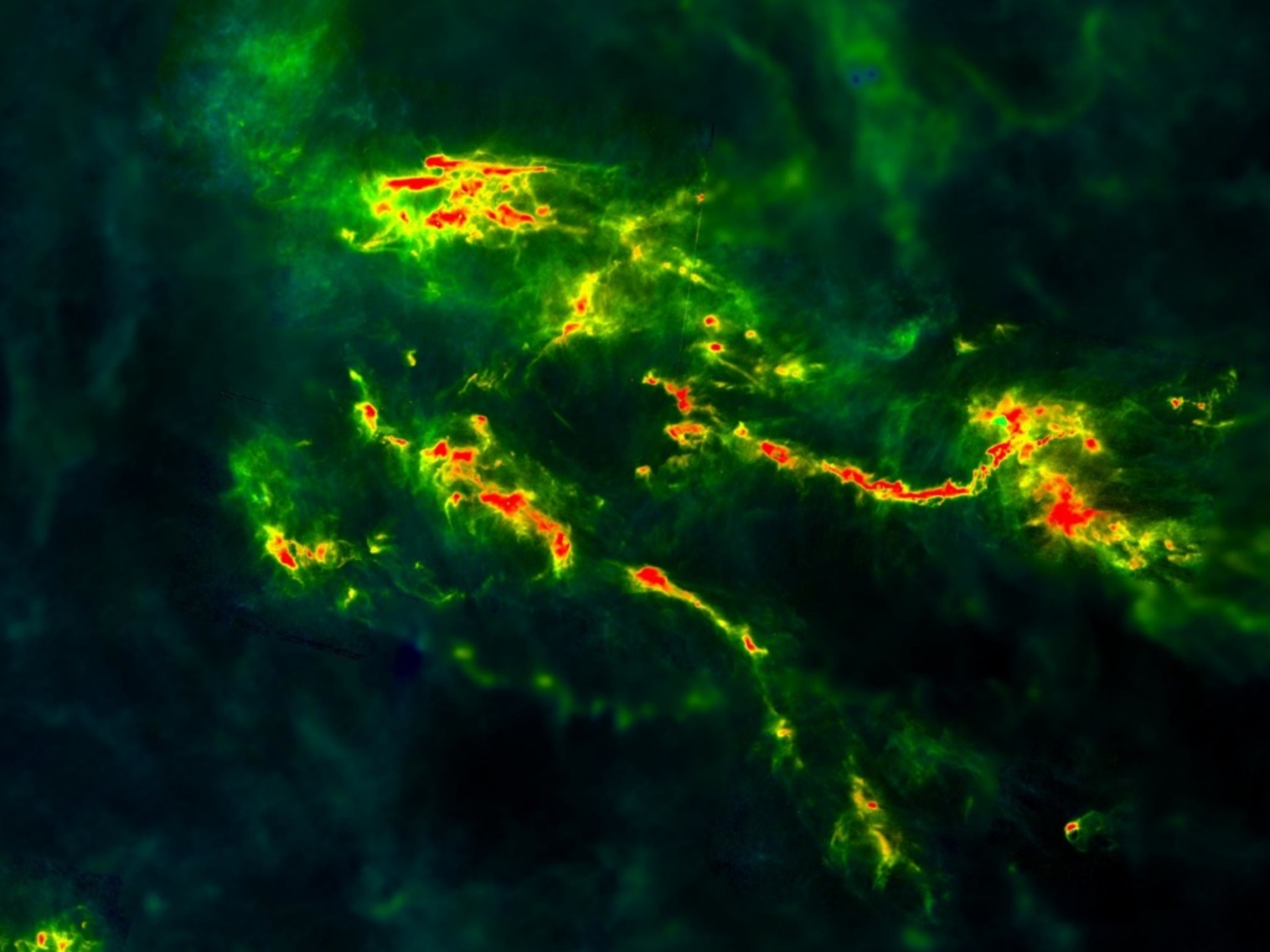
Lombardi et al. (2014)

Taurus

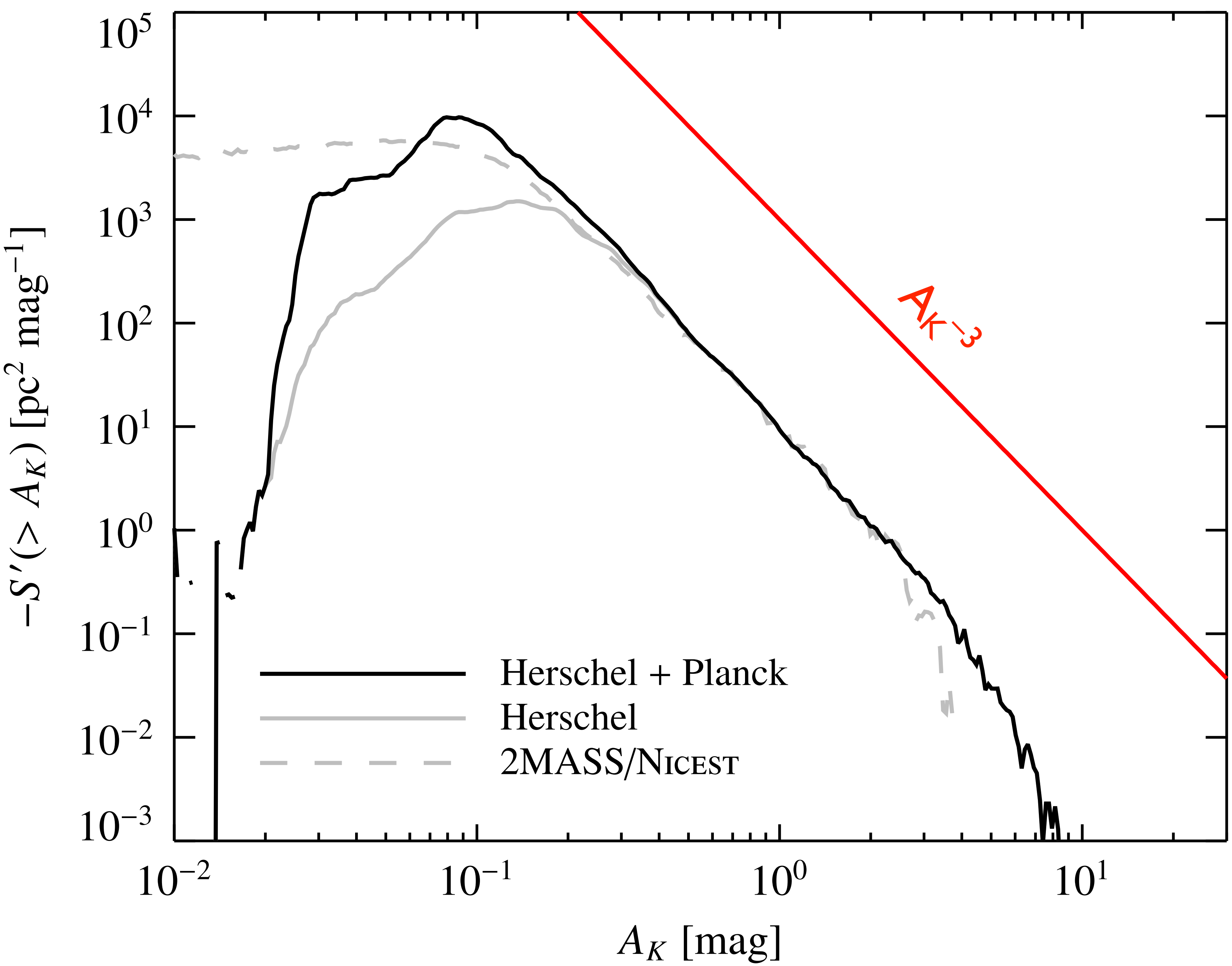
(Lombardi et al. 2015)







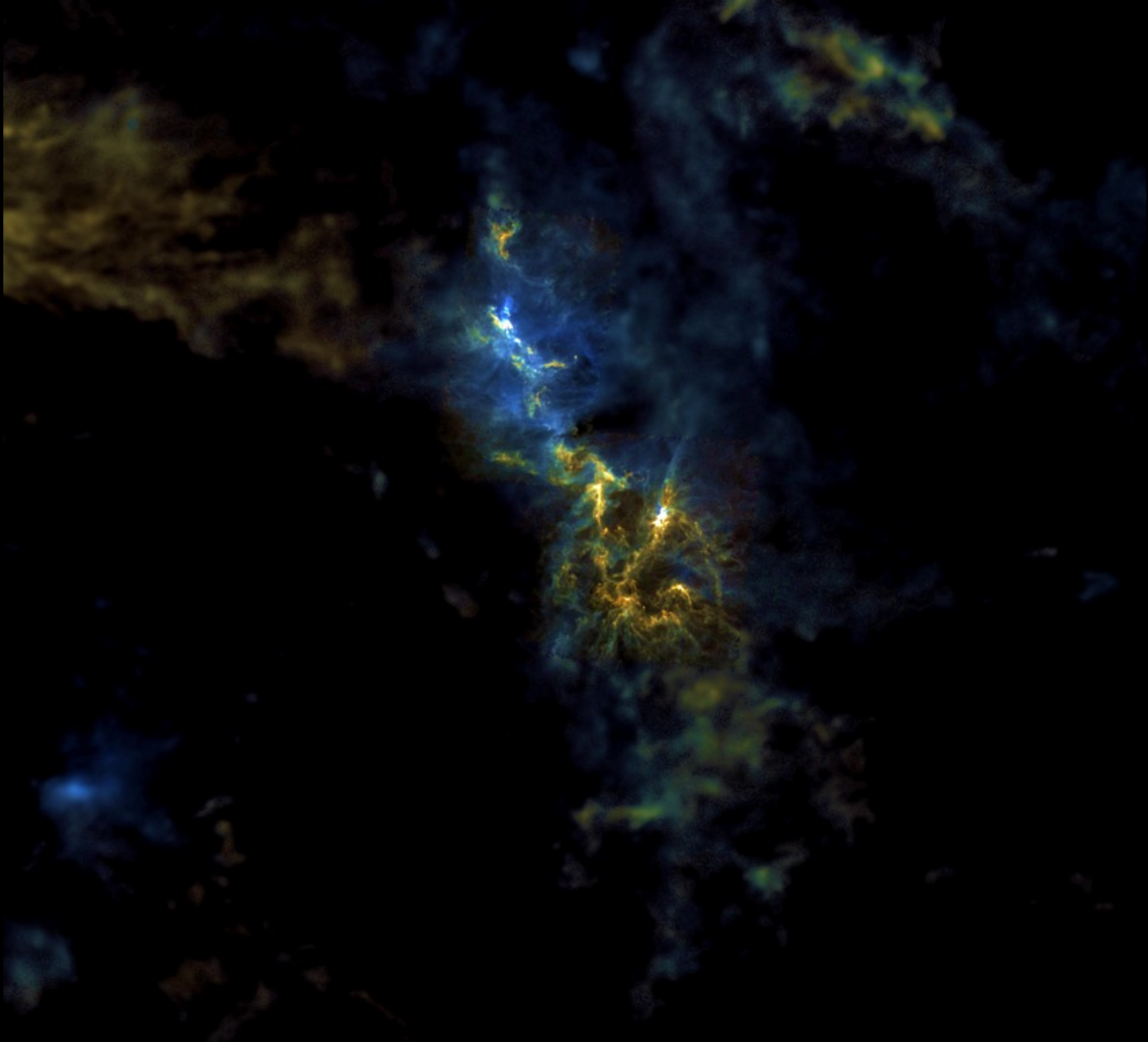
Herschel PDF for Taurus

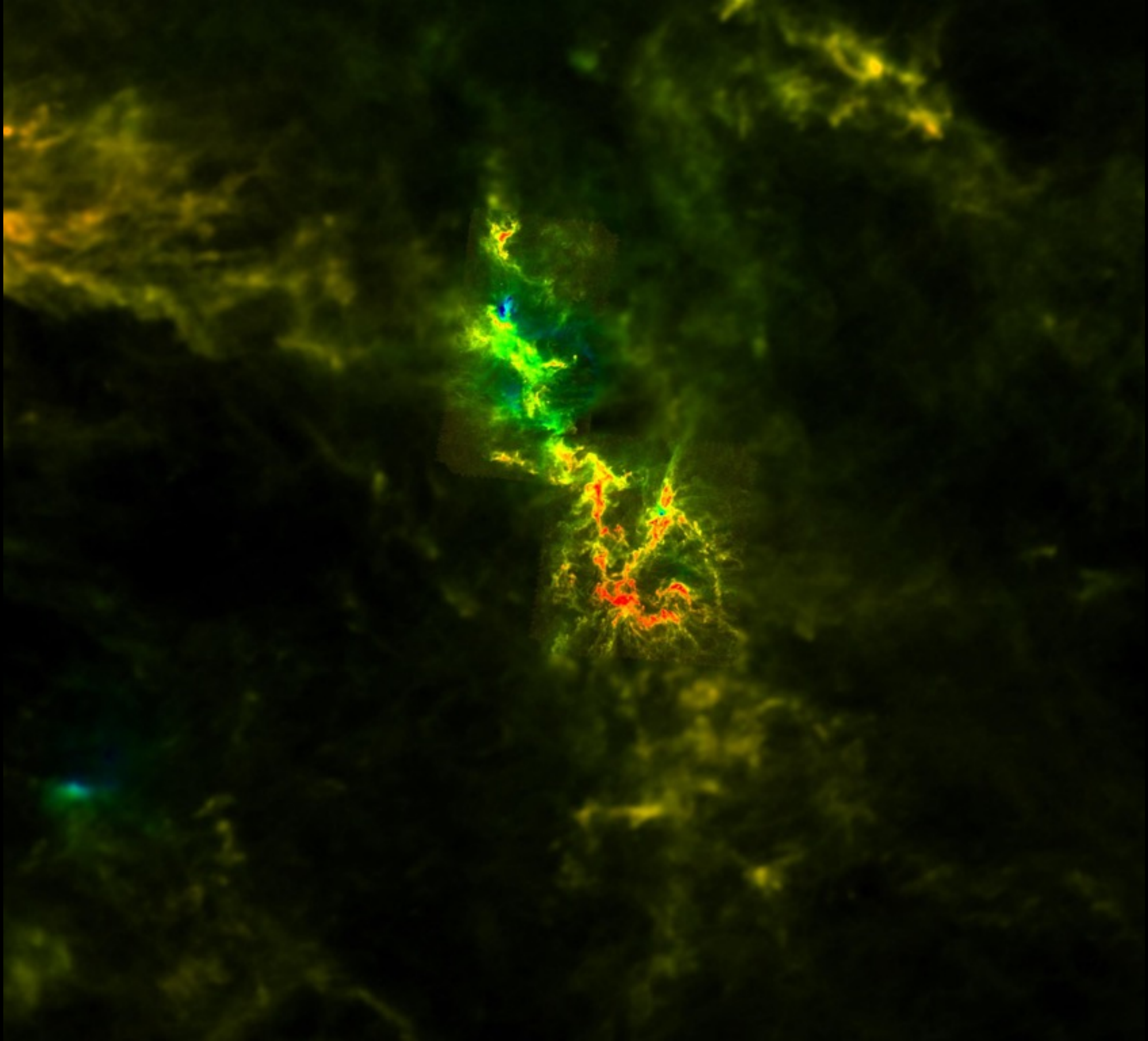


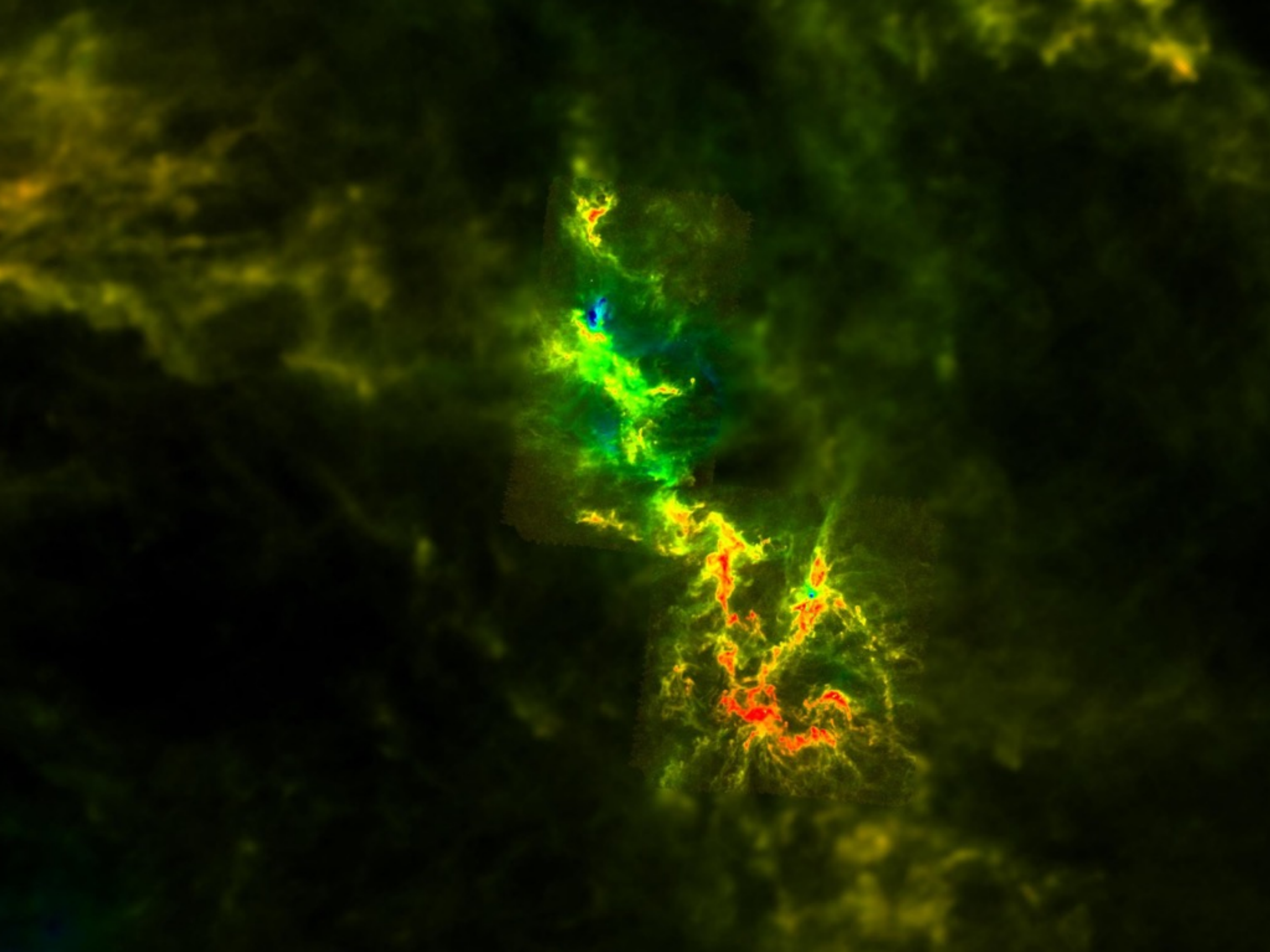
Lombardi et al. (2015)

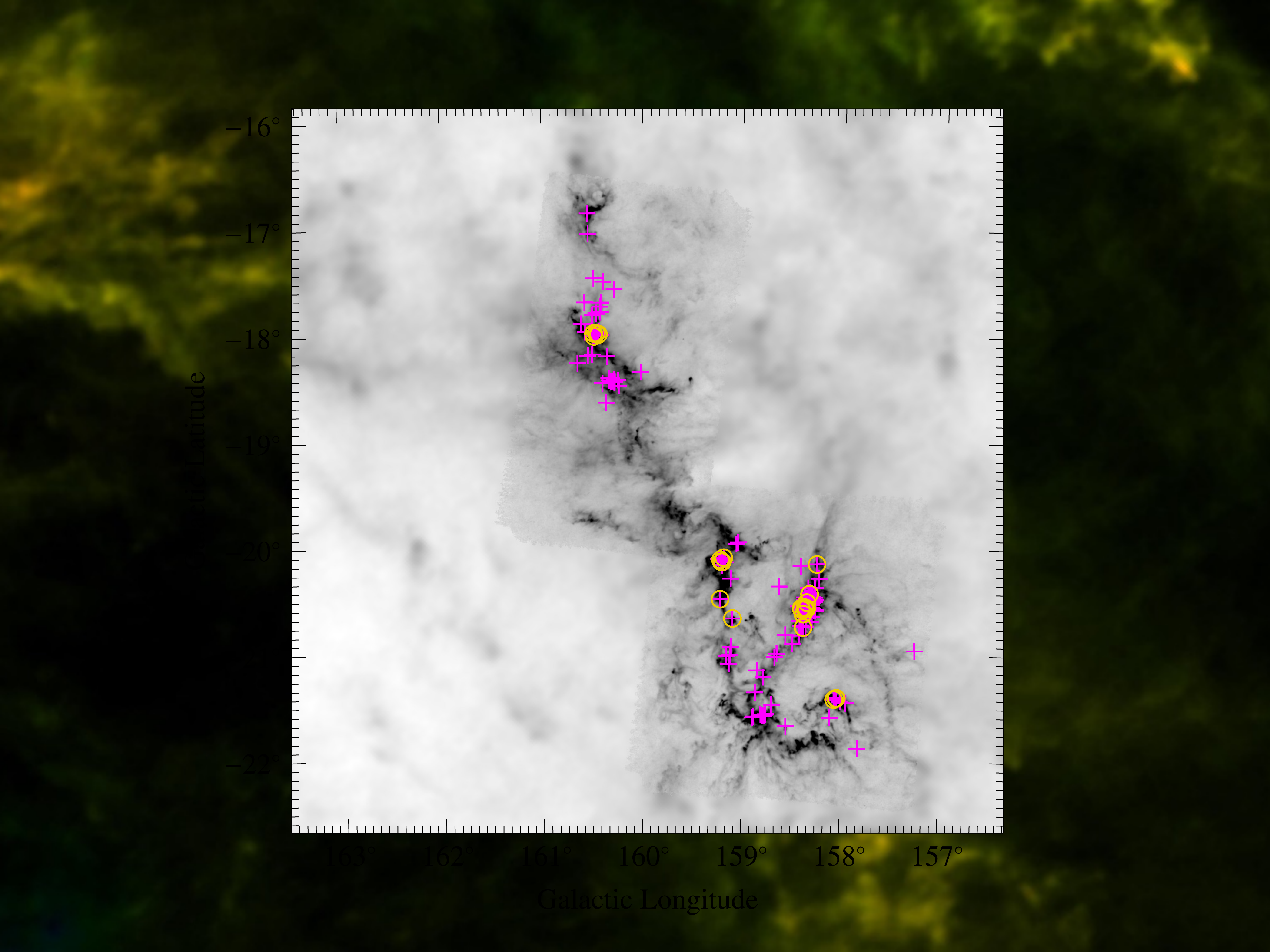
Perseus

(Zari et al. 2015)

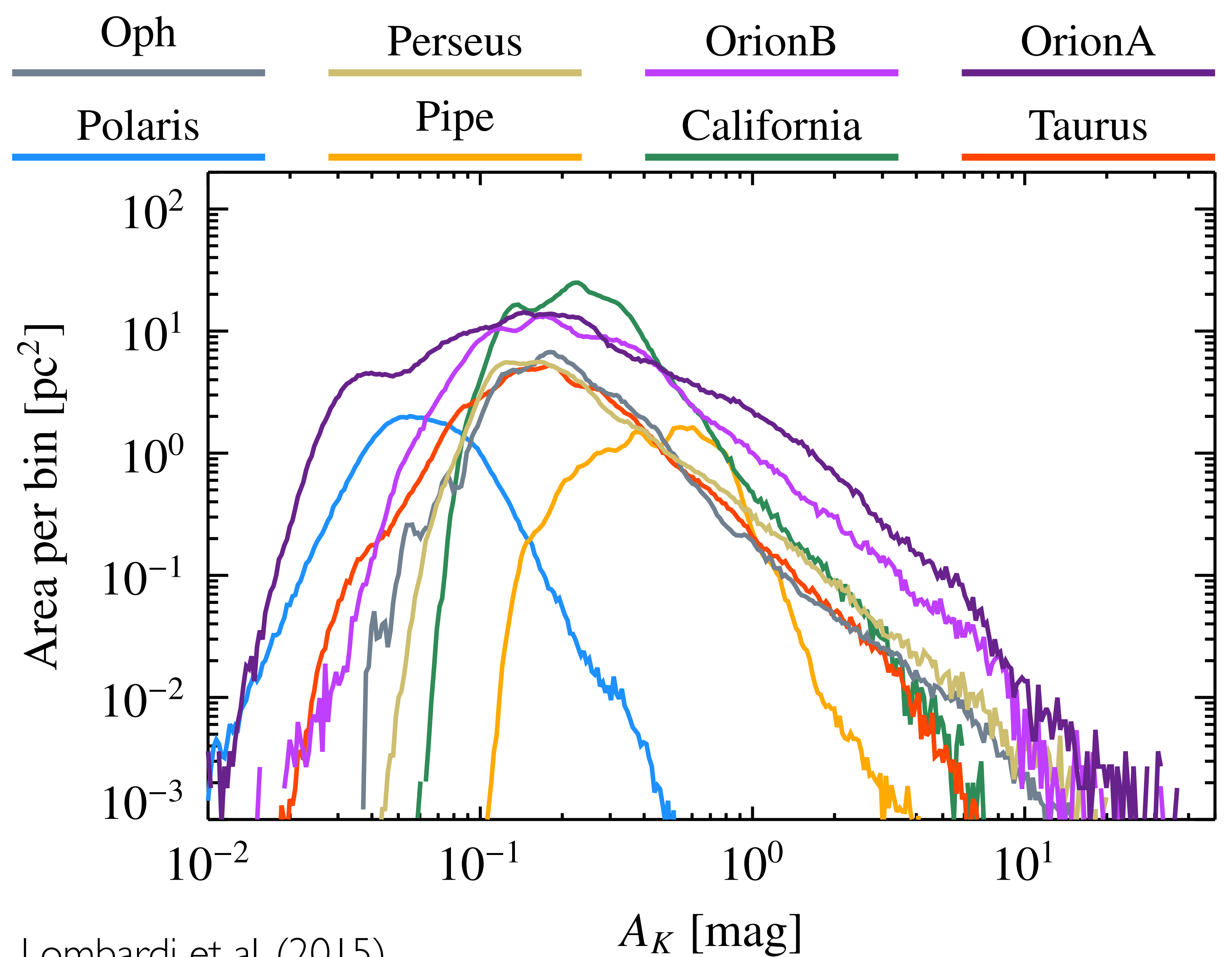







−16°
−17°
−18°
−19°
−20°
−22°
163°
162°
161°
160°
159°
158°
157°
Galactic Longitude

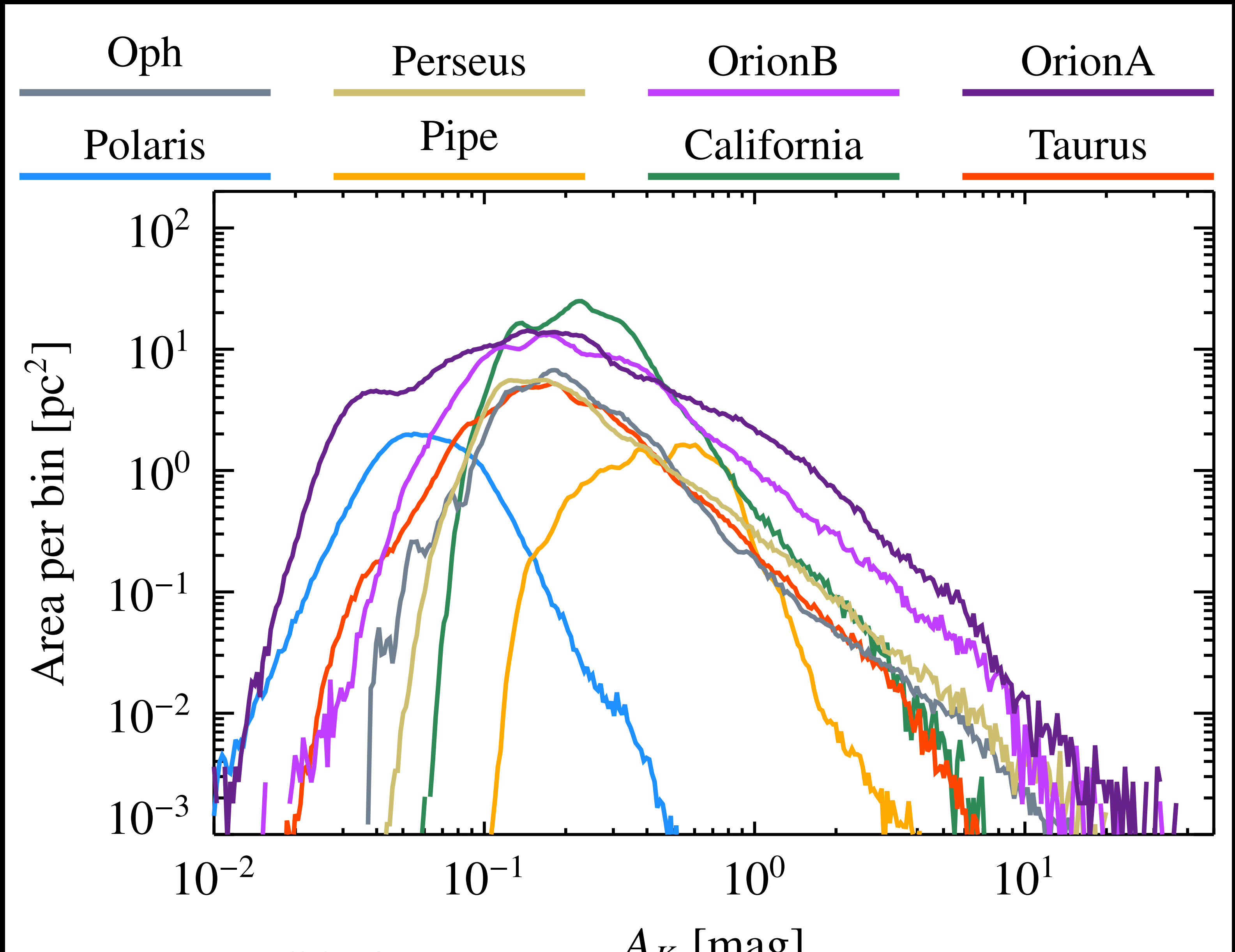
PDFs from Herschel



Lombardi et al. (2015)

PDFs from Herschel

- PDFs are hardly symmetric in log-log



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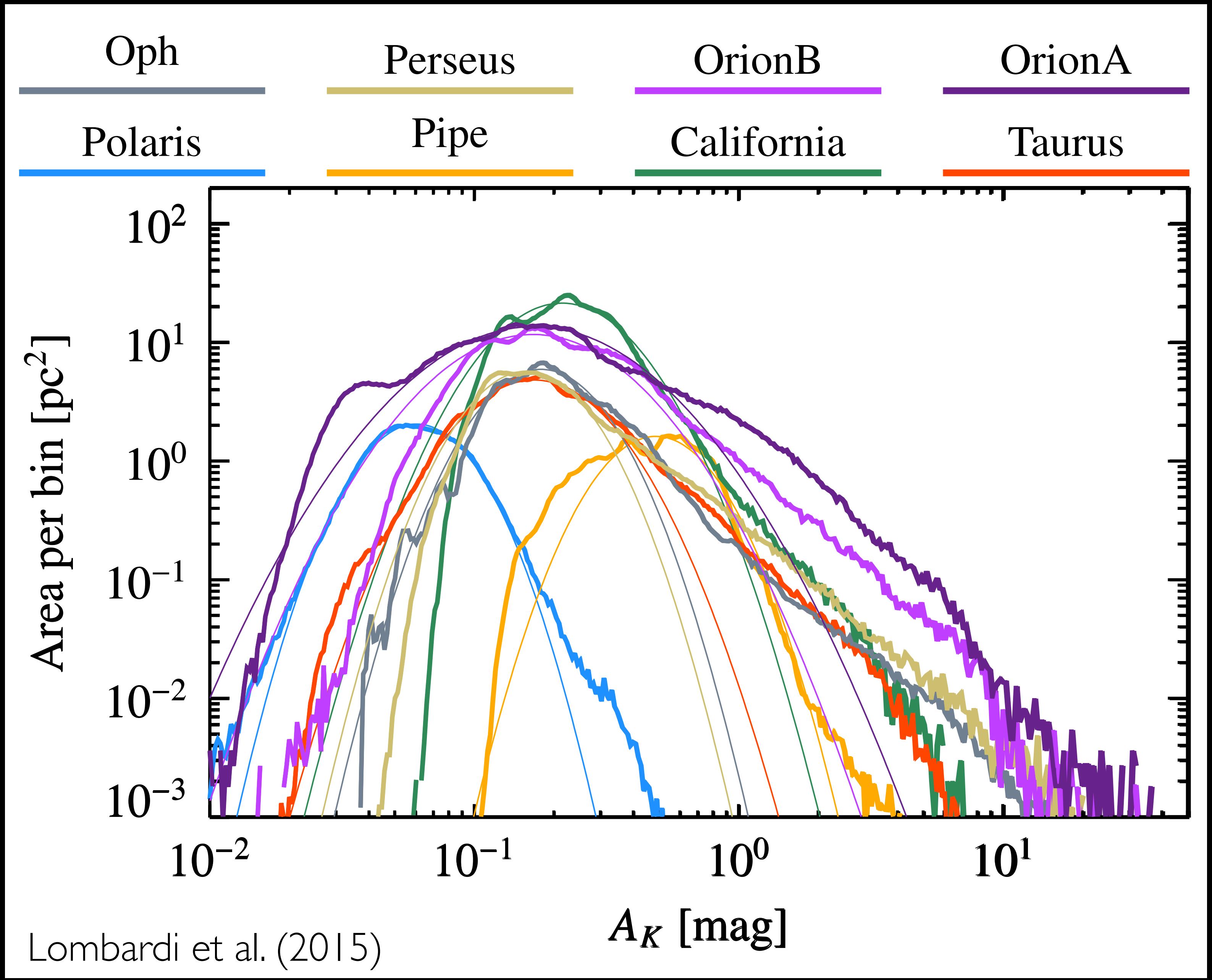

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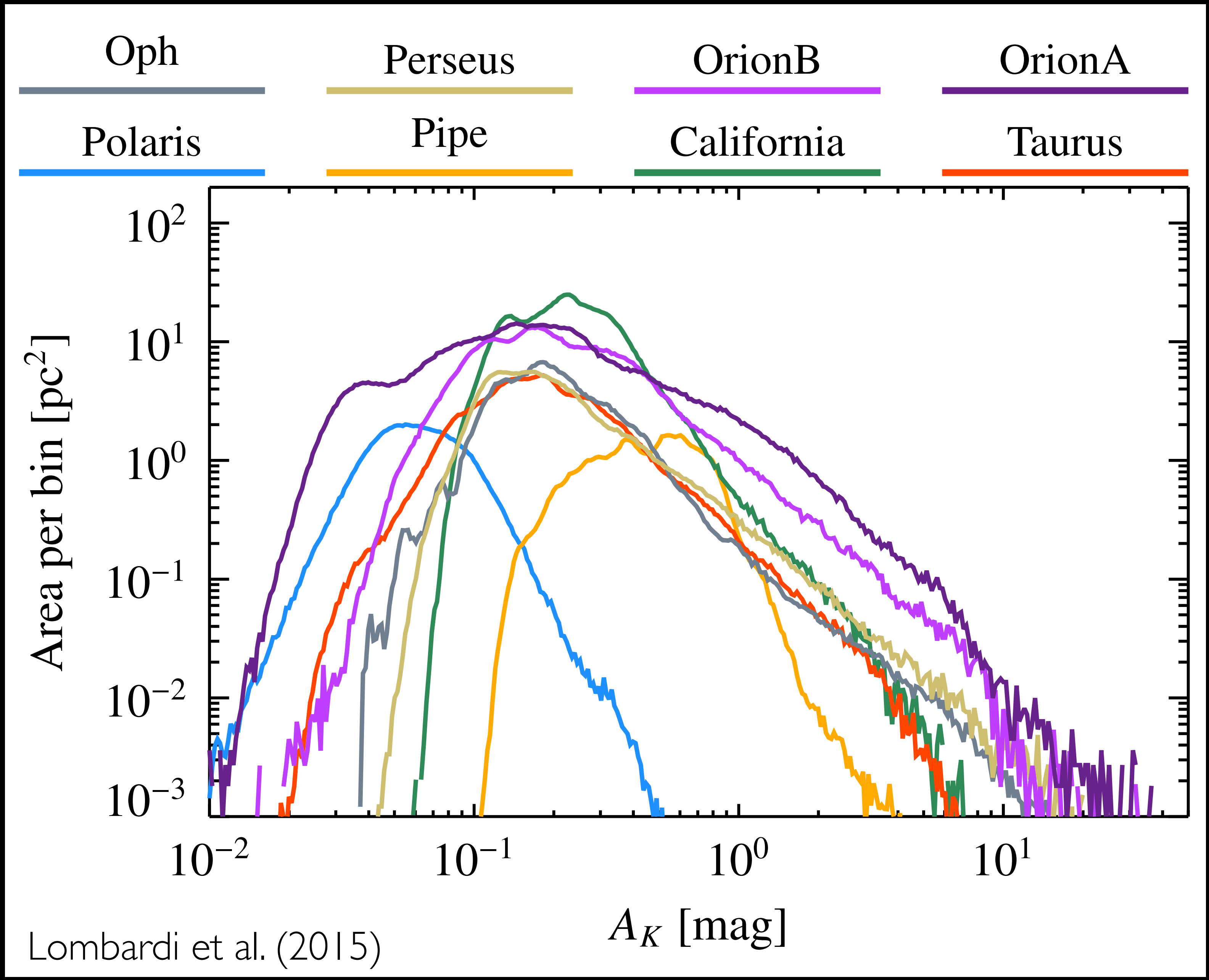

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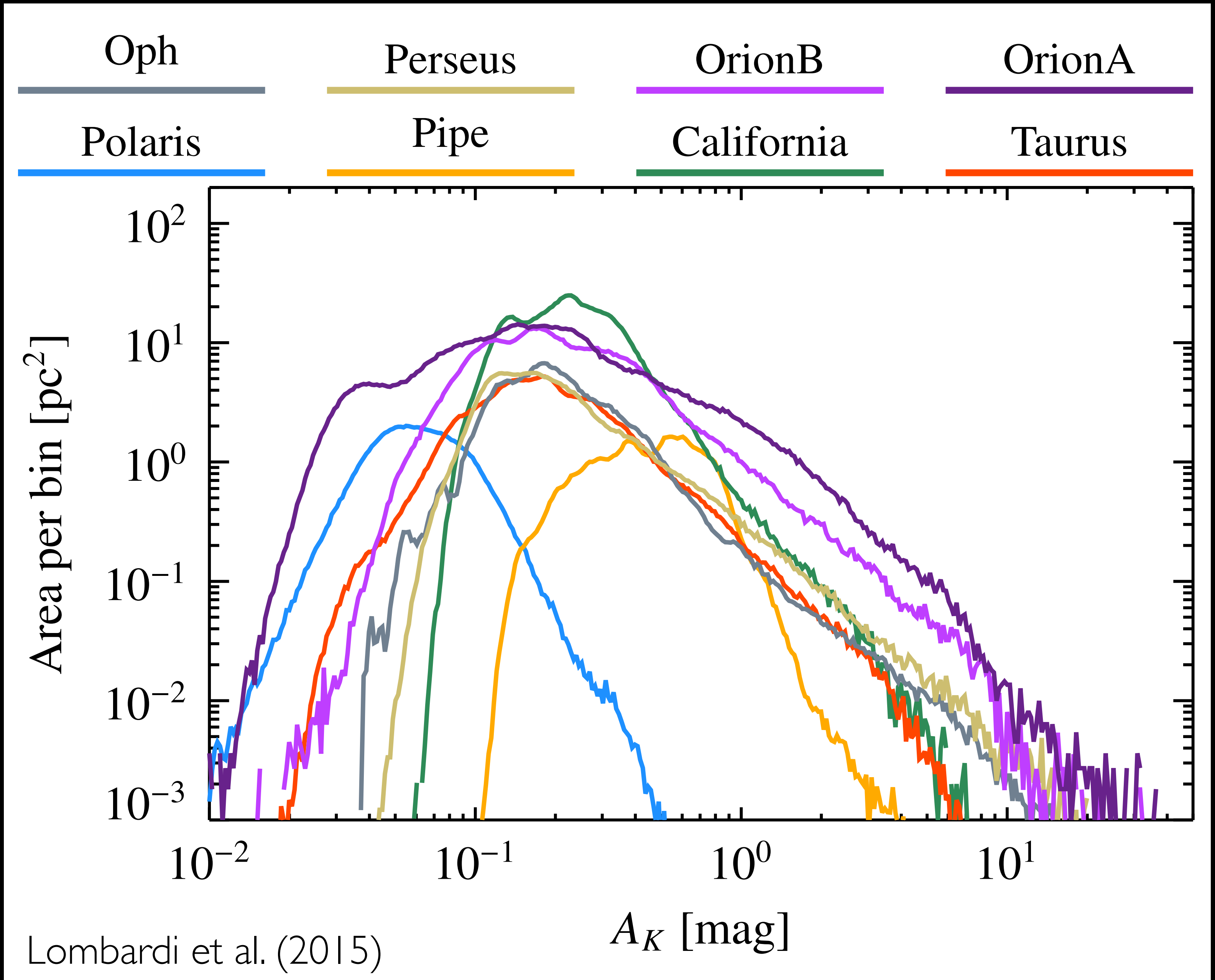

Lombardi et al. (2015)

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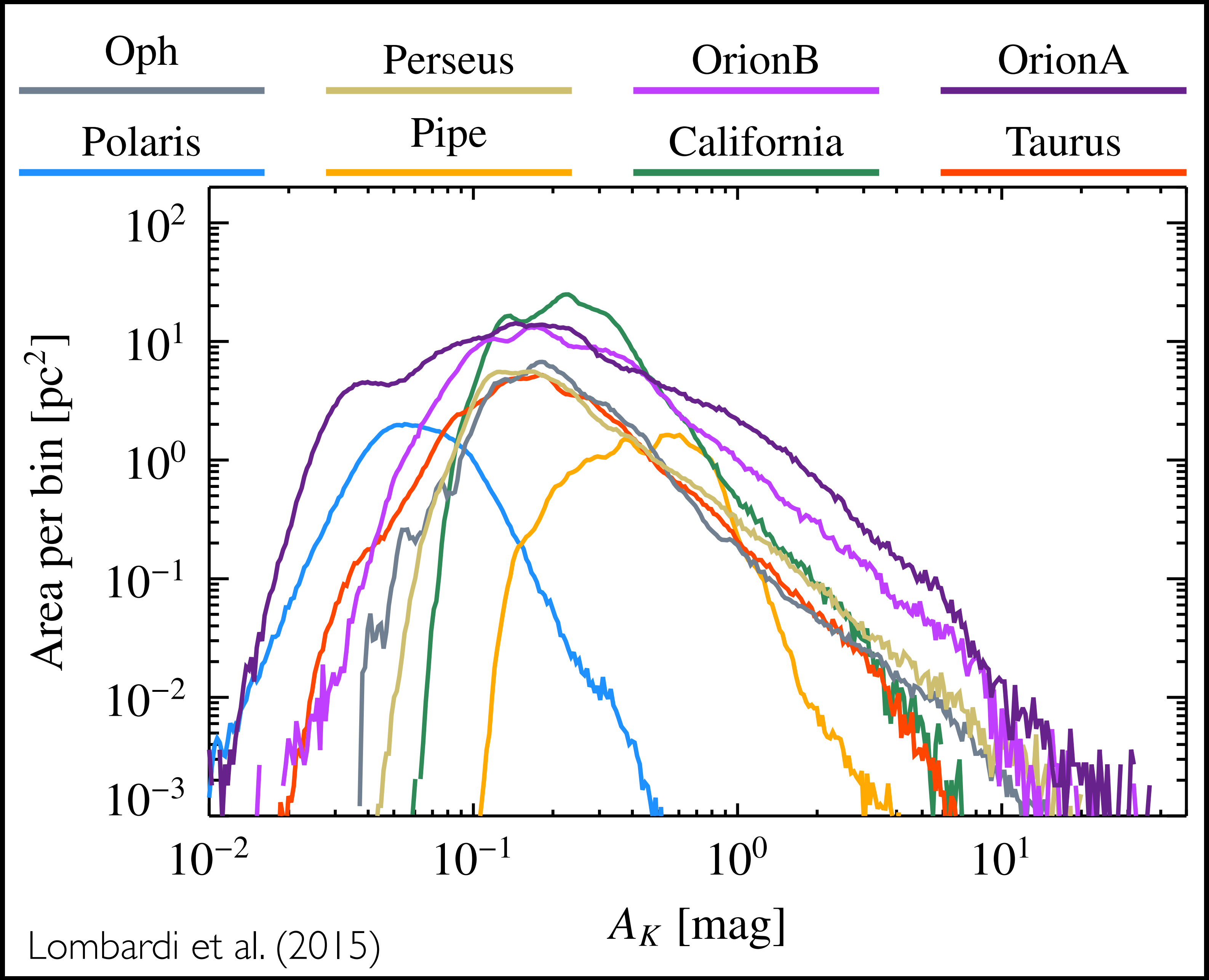
- Exponents in the range 3 to 5 (2 to 4 in log plot)



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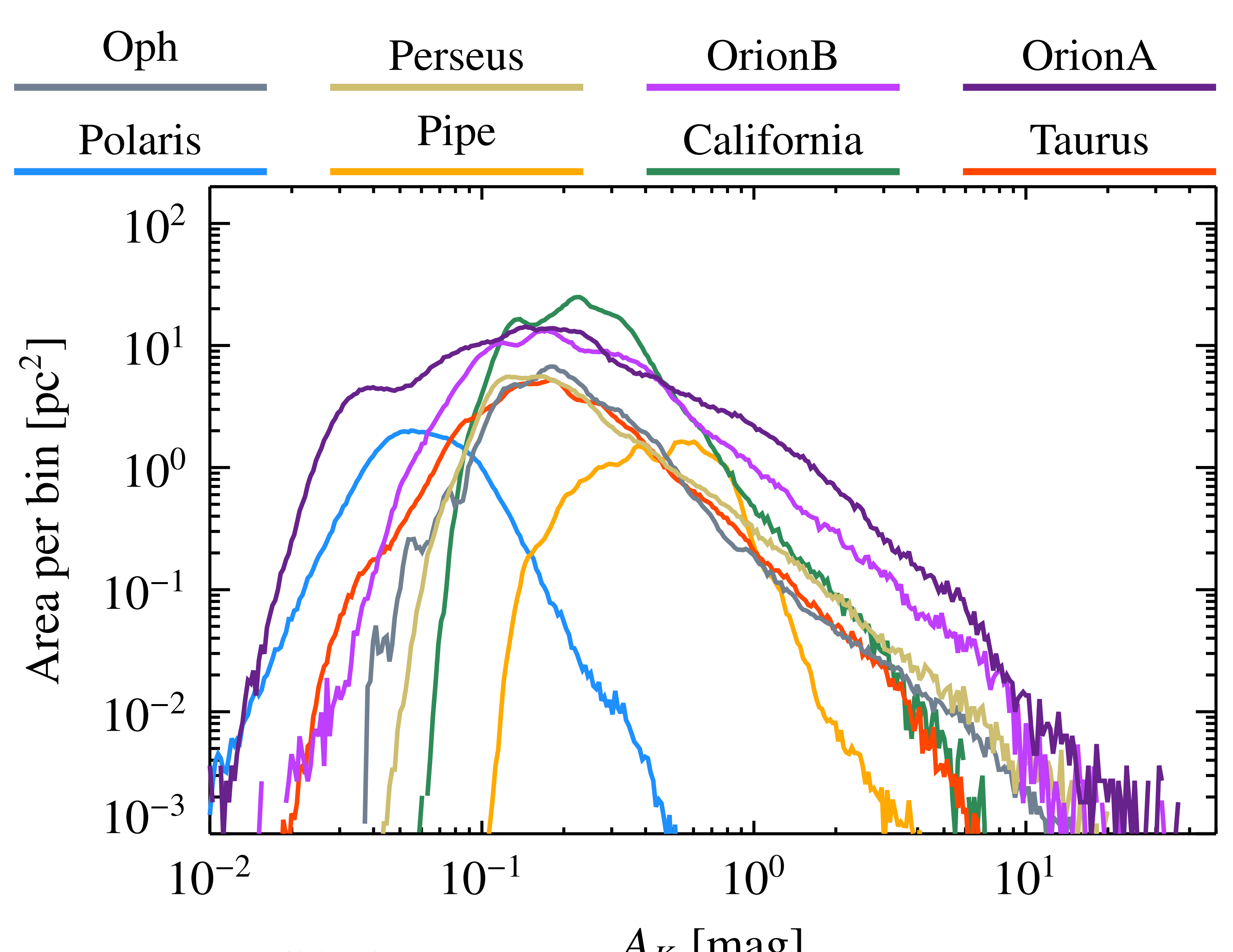

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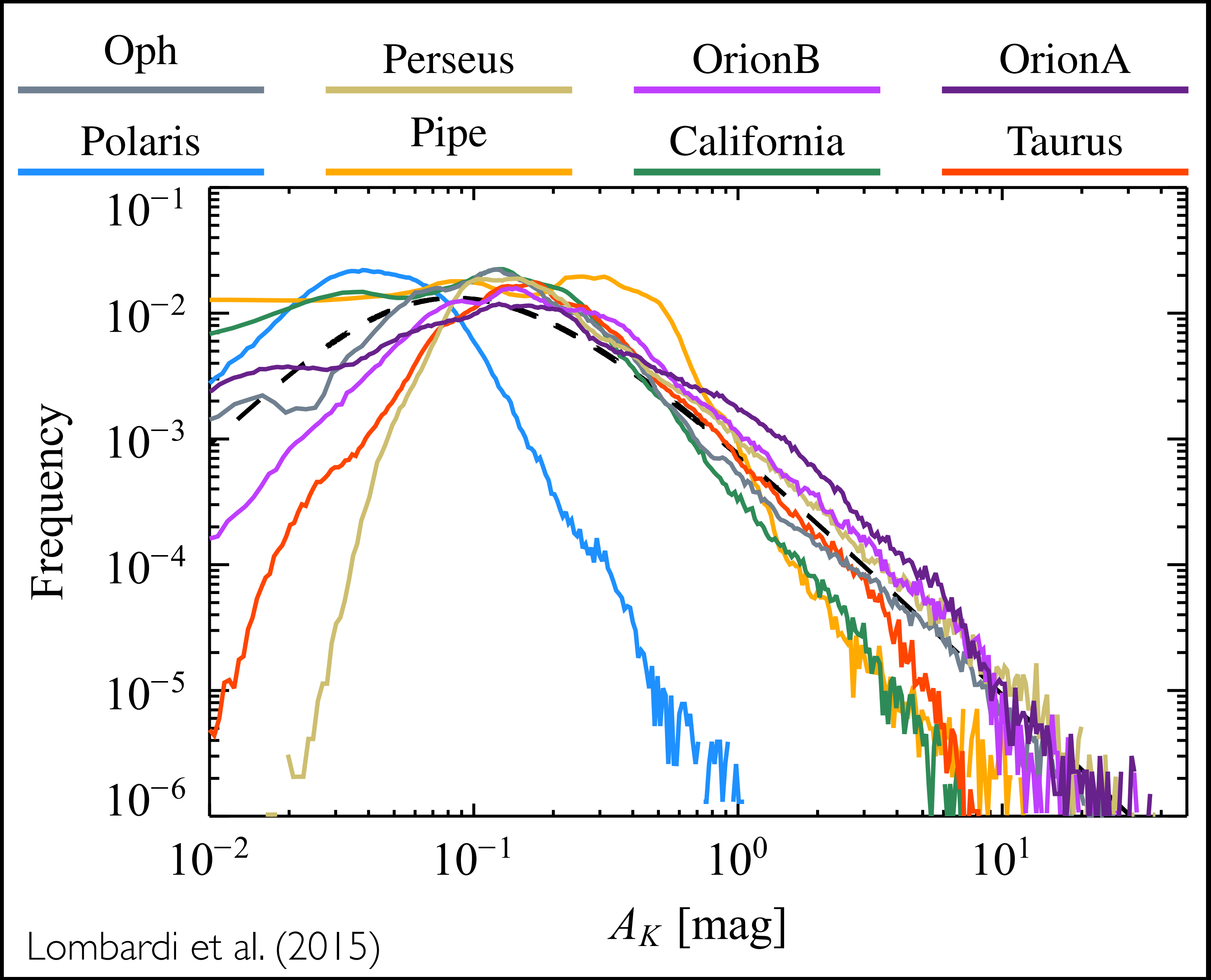

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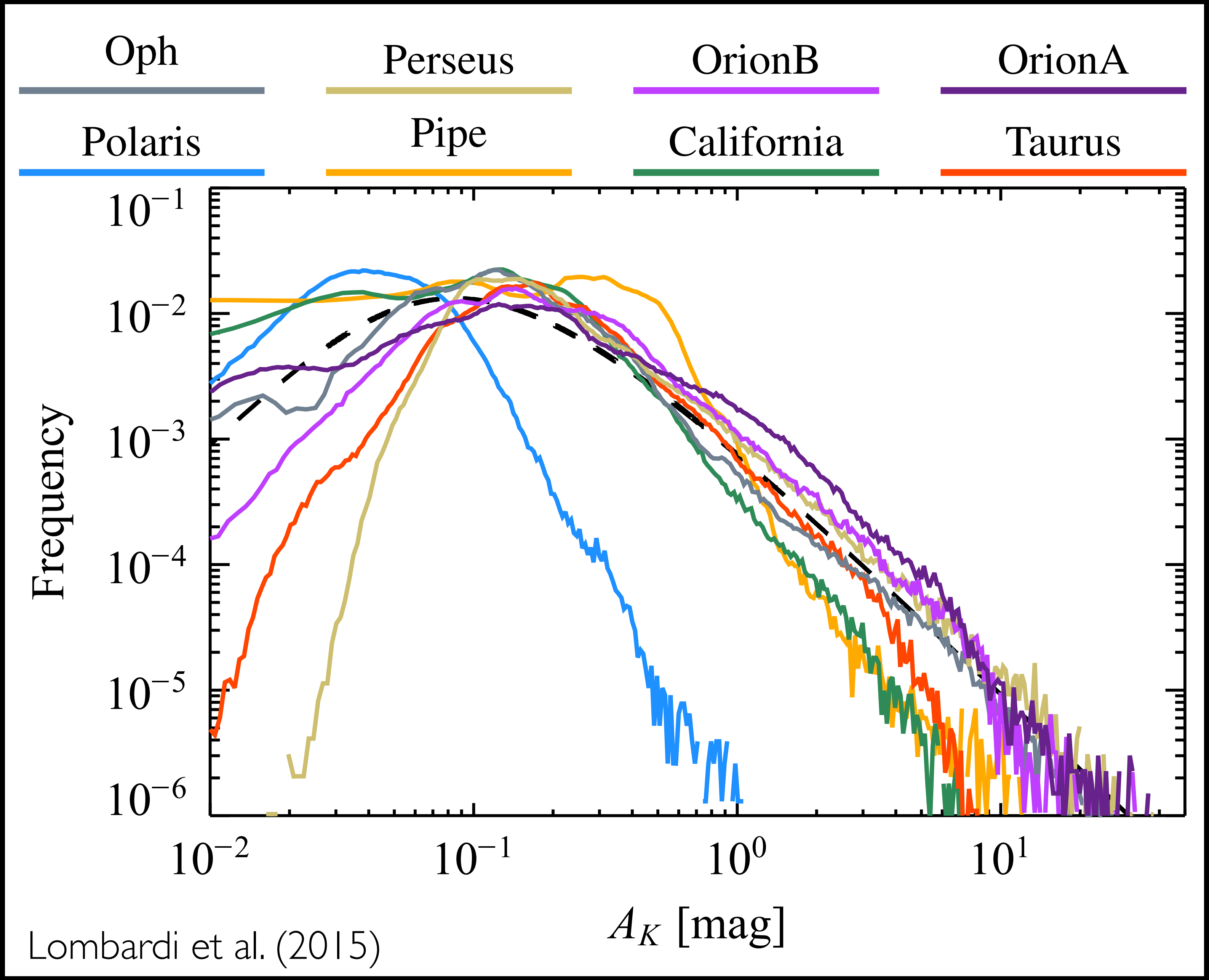
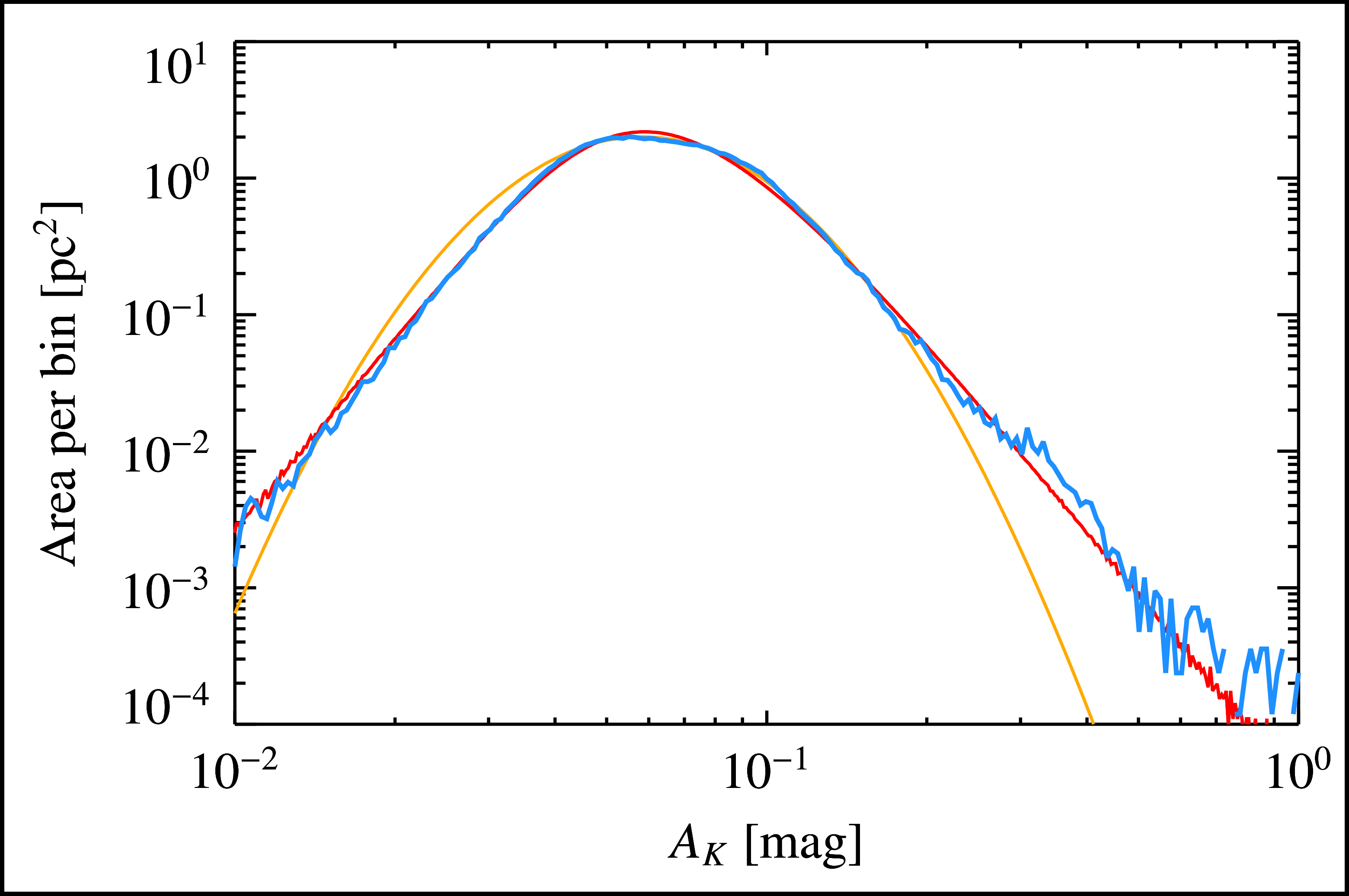


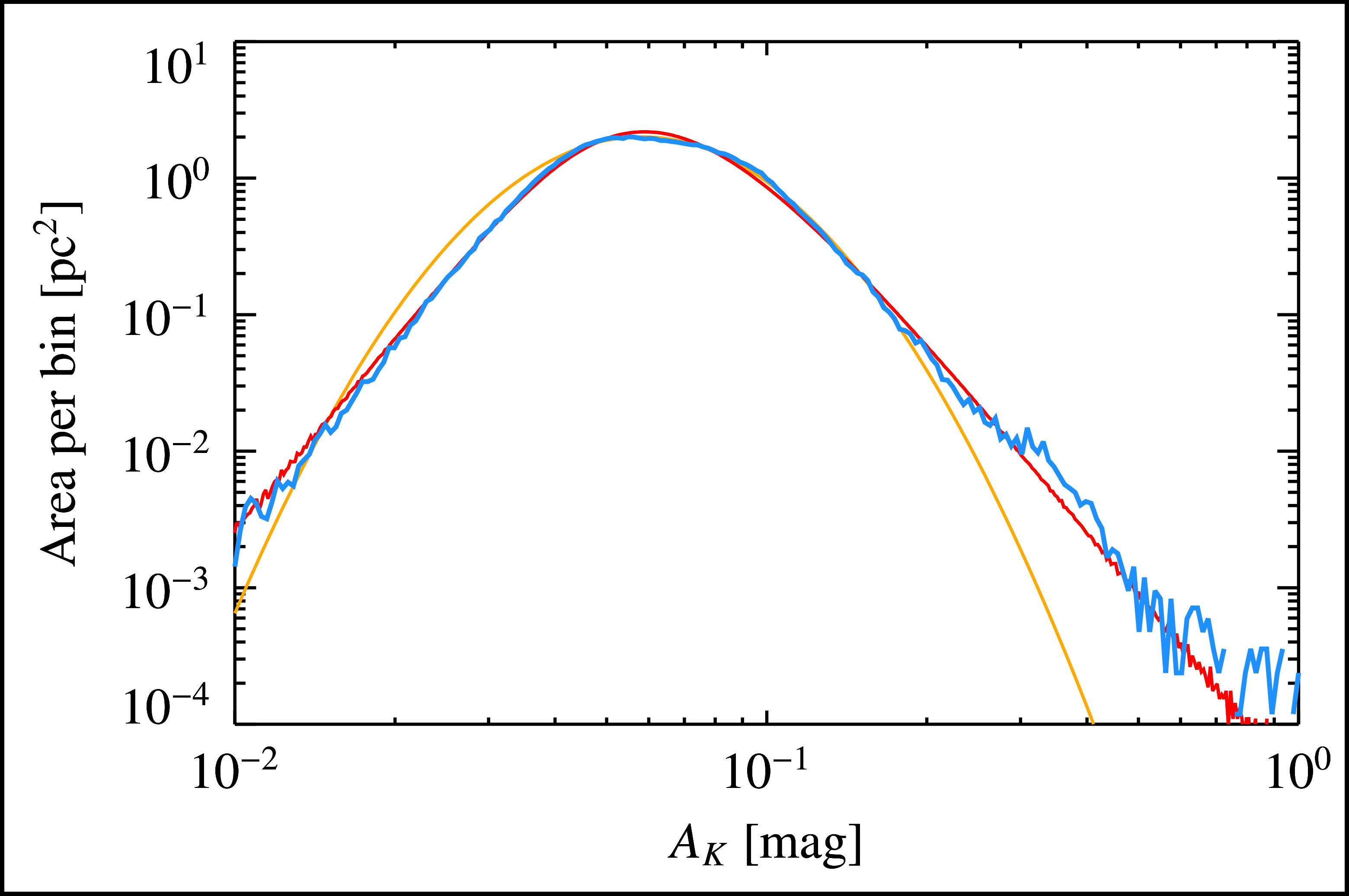
Can Polaris be described as log-normal?

Polaris log-normal fit



Polaris log-normal fit

- A log-normal fit of Polaris works in the range A_K 0.05 to 0.2 mag



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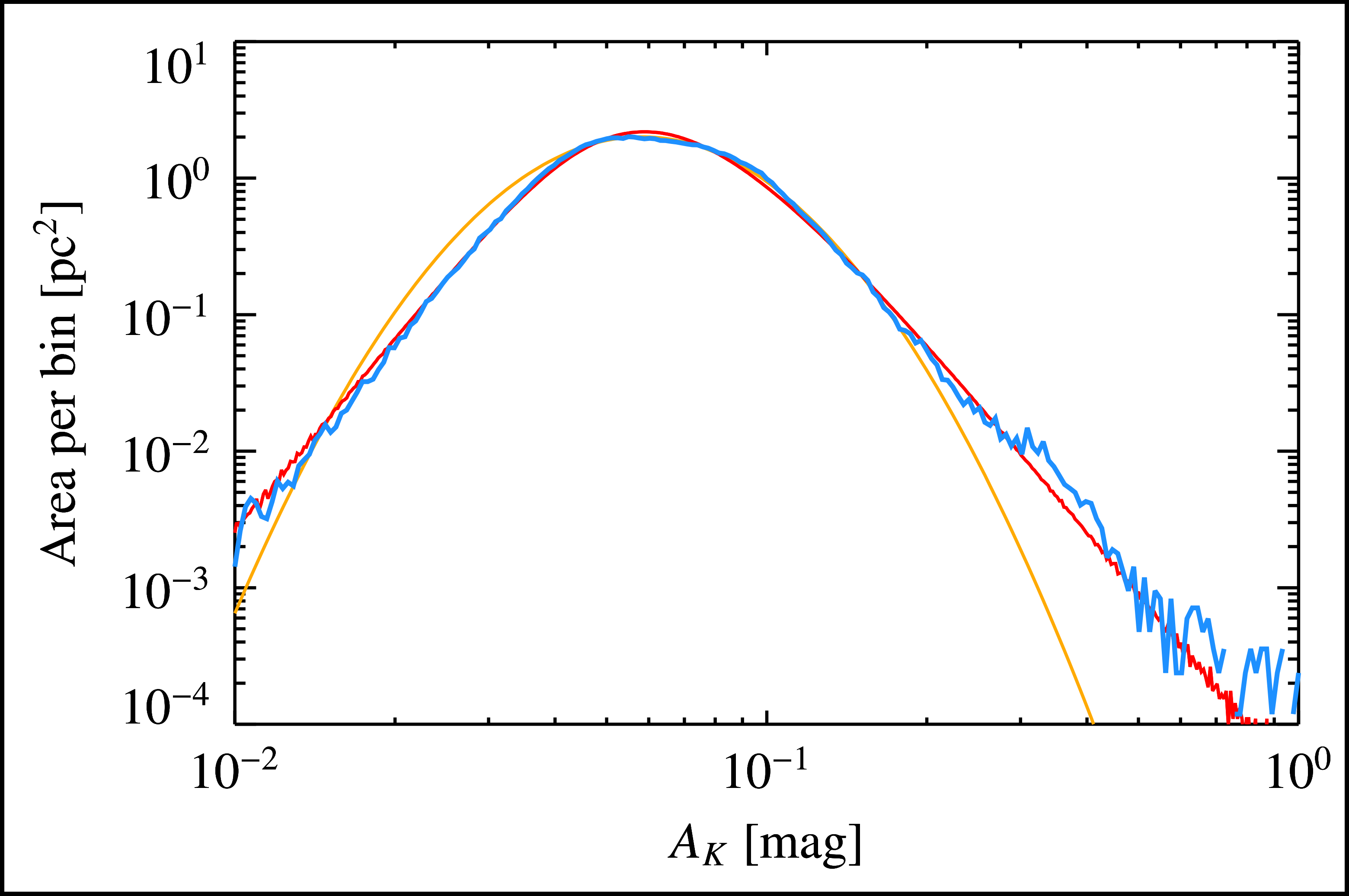

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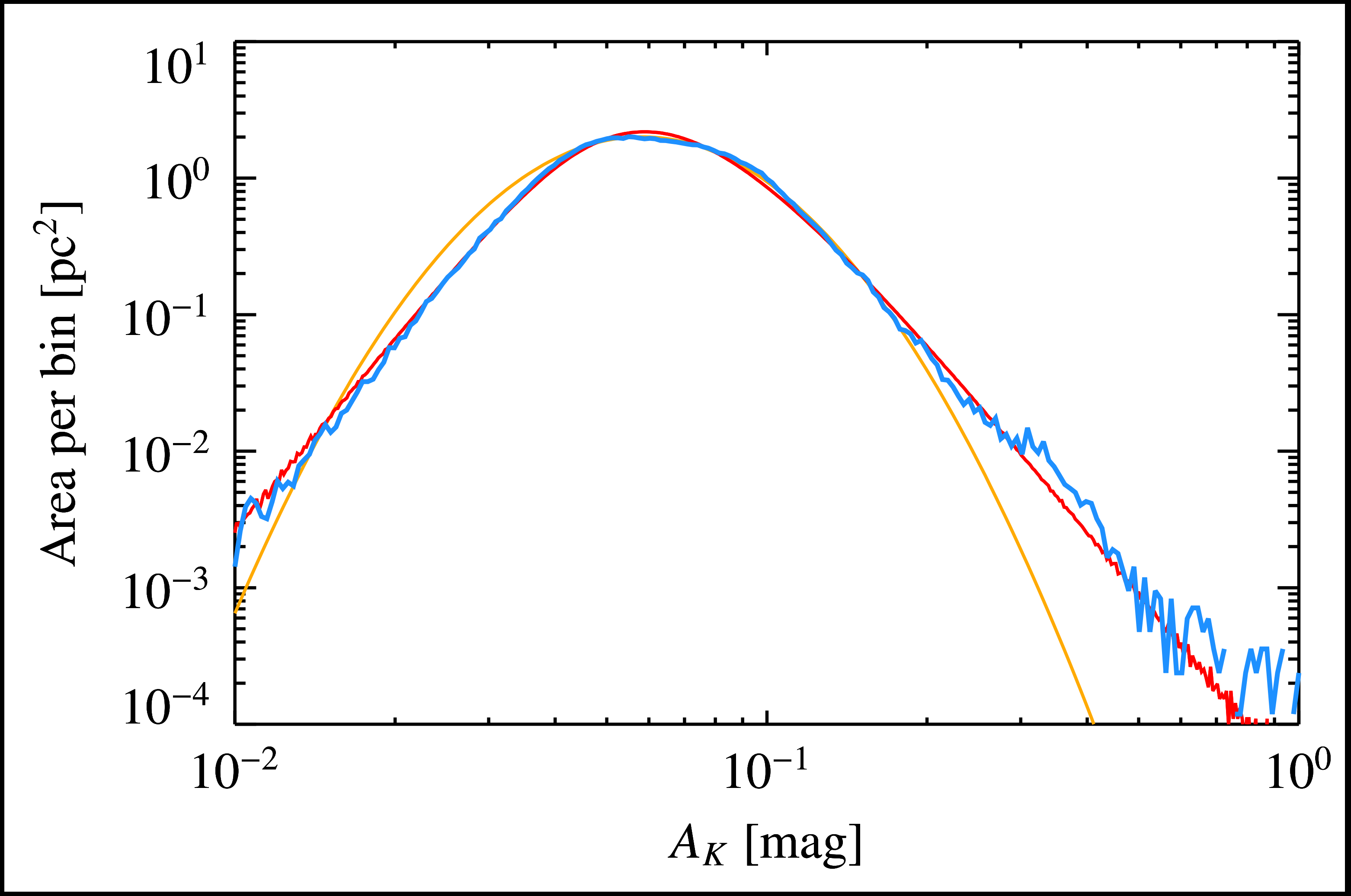

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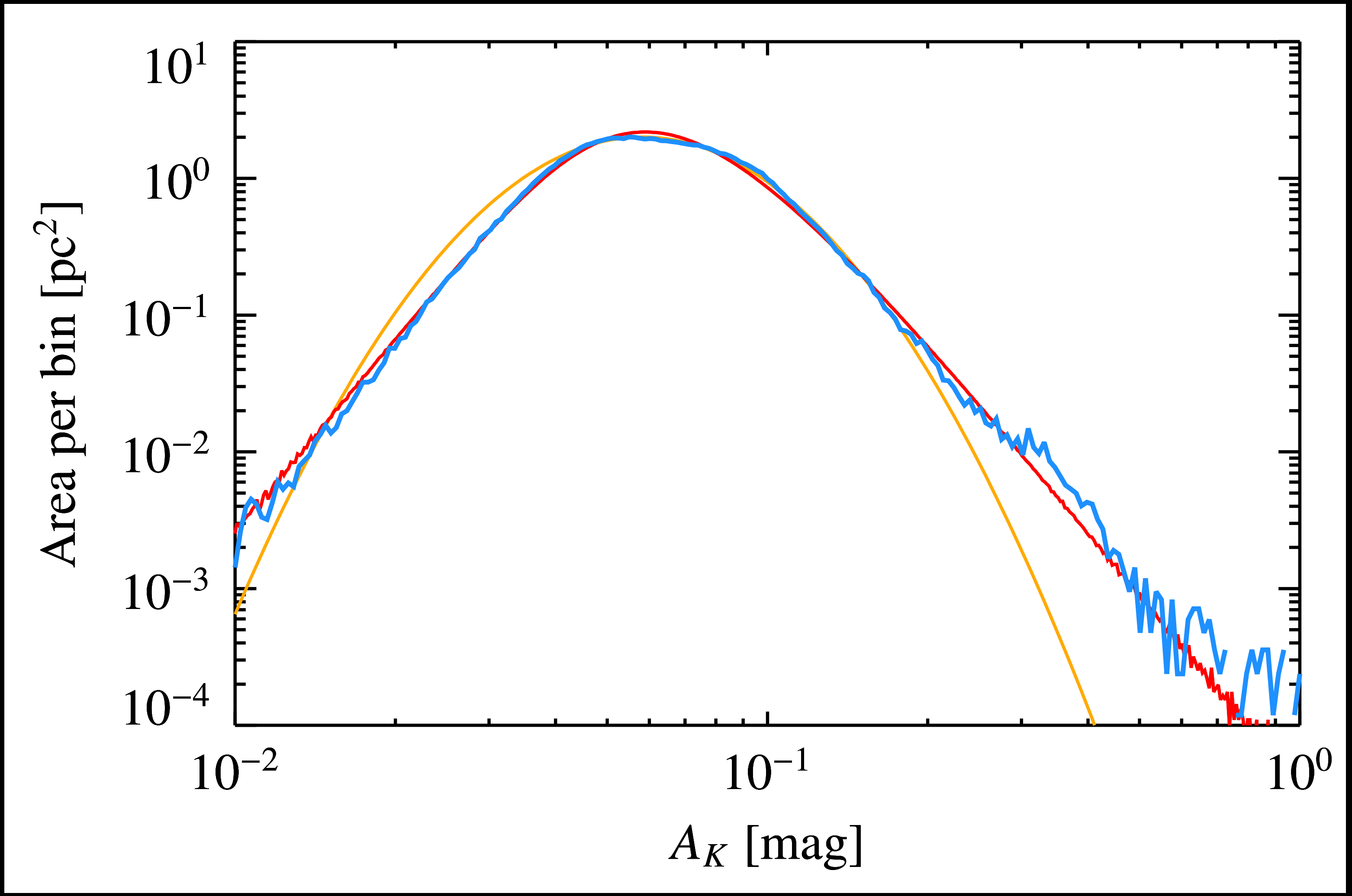
- Caveat: ad-hoc model, but shows that log-normal is not that good



The local Schmidt law

Lombardi et al. (2013), Lada et al. (2013)

The local Schmidt law

- In the cloud we studied, the density of protostars is well described by

$$\boxed{\Sigma_\star(x) = \kappa \big[A_K(x) \big]^\beta}$$

Lombardi et al. (2013), Lada et al. (2013)

The local Schmidt law

- In the cloud we studied, the density of protostars is well described by

$$\boxed{\Sigma_\star(x) = \kappa\big[A_K(x)\big]^\beta}$$

- Both coefficients seem to have a limited range of variation

Lombardi et al. (2013), Lada et al. (2013)

The local Schmidt law

- In the cloud we studied, the density of protostars is well described by

$$\boxed{\Sigma_\star(x) = \kappa\big[A_K(x)\big]^\beta}$$

- Both coefficients seem to have a limited range of variation
- The SFE of a cloud is ultimately linked to its internal structure and PDF (amount of dense gas)

Lombardi et al. (2013), Lada et al. (2013)

The local Schmidt law

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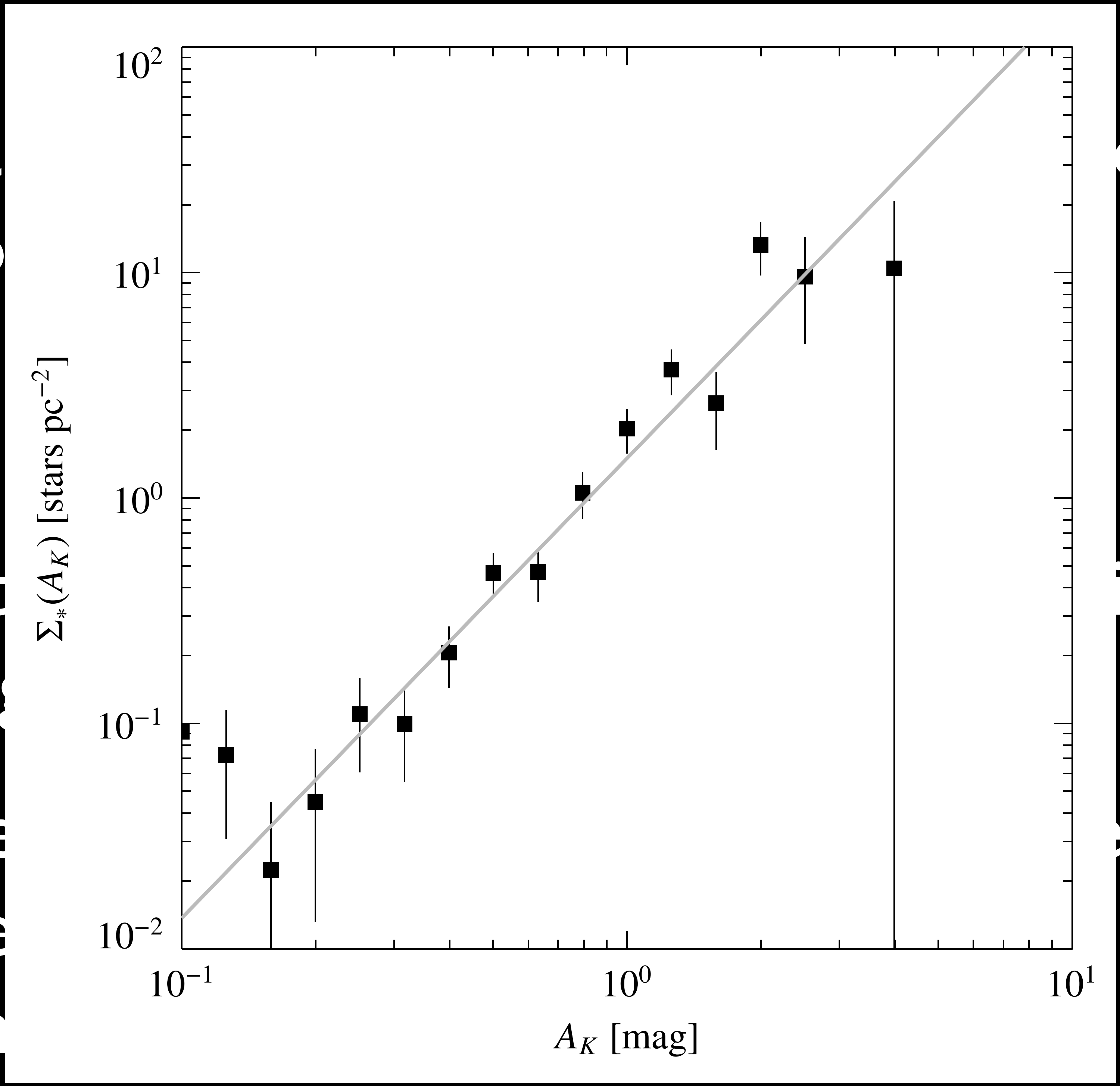
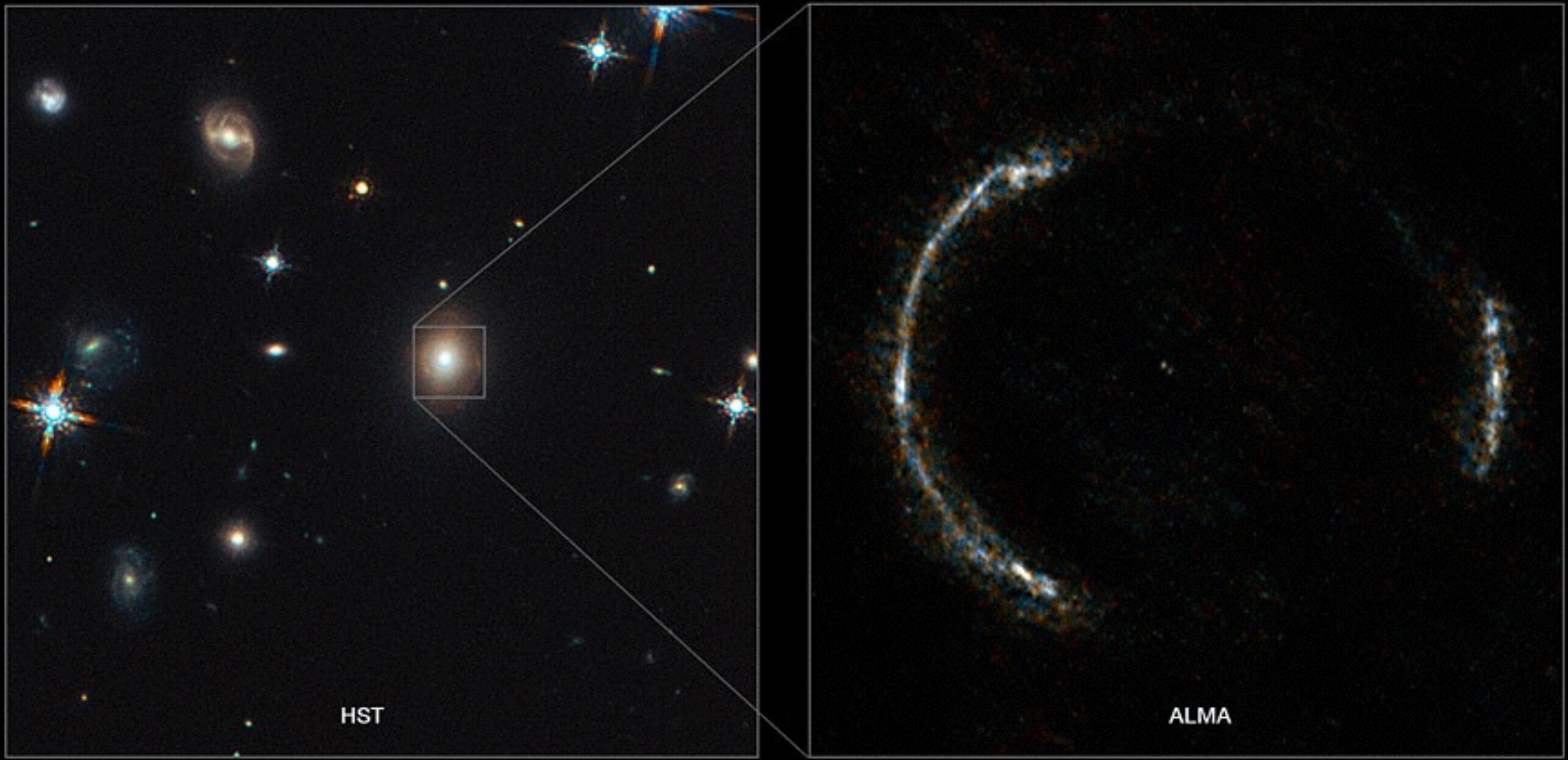


Lombardi et al. (2013), Lada et al. (2013)

SUMMARY

1. For 20 years we have screwed up the simplest characterization of cloud structure, the PDF… but we now know PDFs are power lows
2. Various other scaling laws hold (Larson’s 3rd law, the local Schmidt law)
3. Large differences in the SFRs of molecular clouds are to be linked to their internal structure (slope of the PDF)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