The structure of molecular clouds and their influence on star formation

Marco Lombardi, University of Milan

with
Joao Alves et al., University of Vienna
Charles Lada, CfA, Harvard
Hervé Bouy, ESAC

Fact 1

Stars forms within dense molecular clouds

Herschel / SPIRE

Spitzer / 24 μm

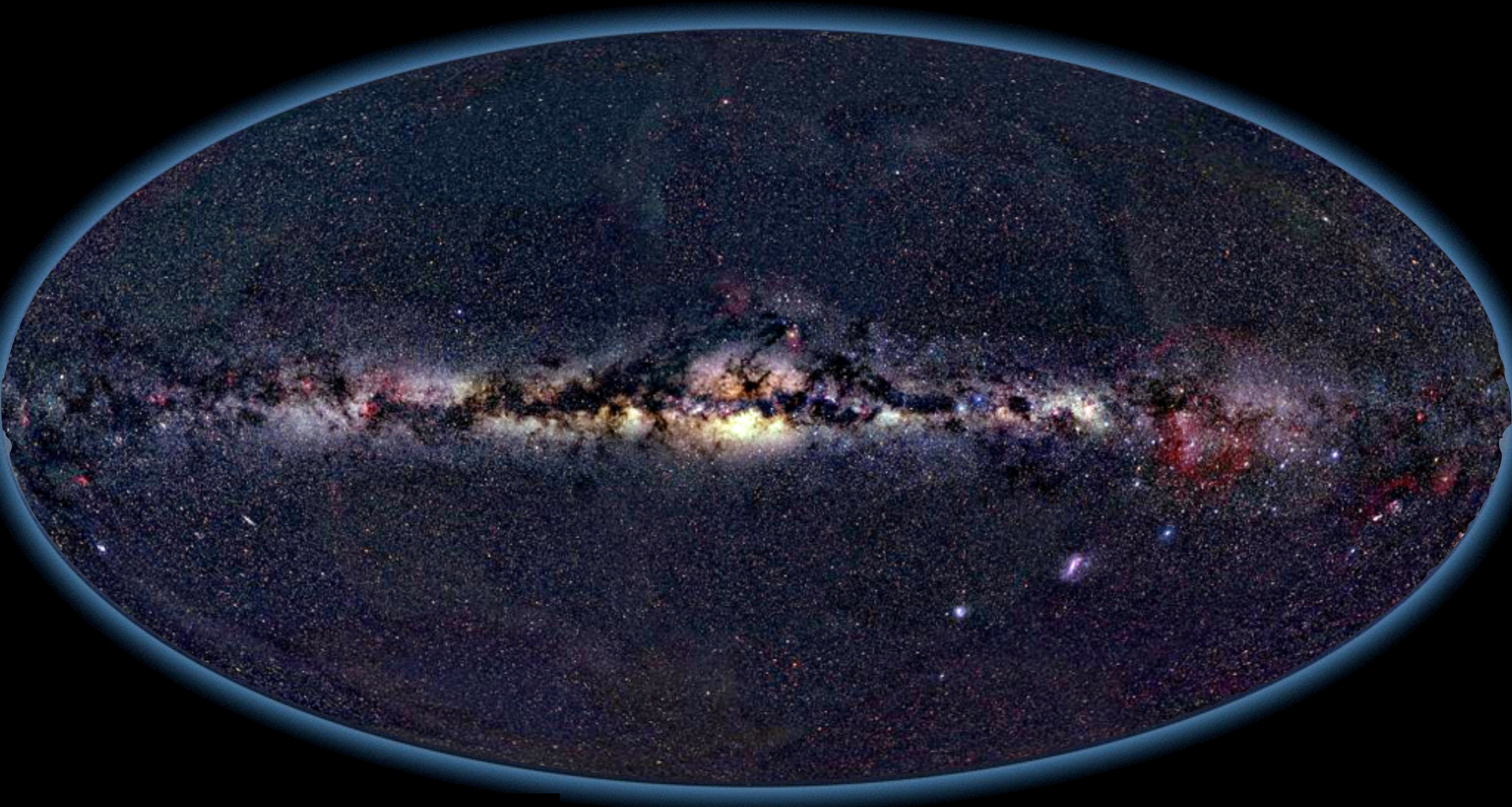
NASA – HST

Fact 2
Star formation is a complex process

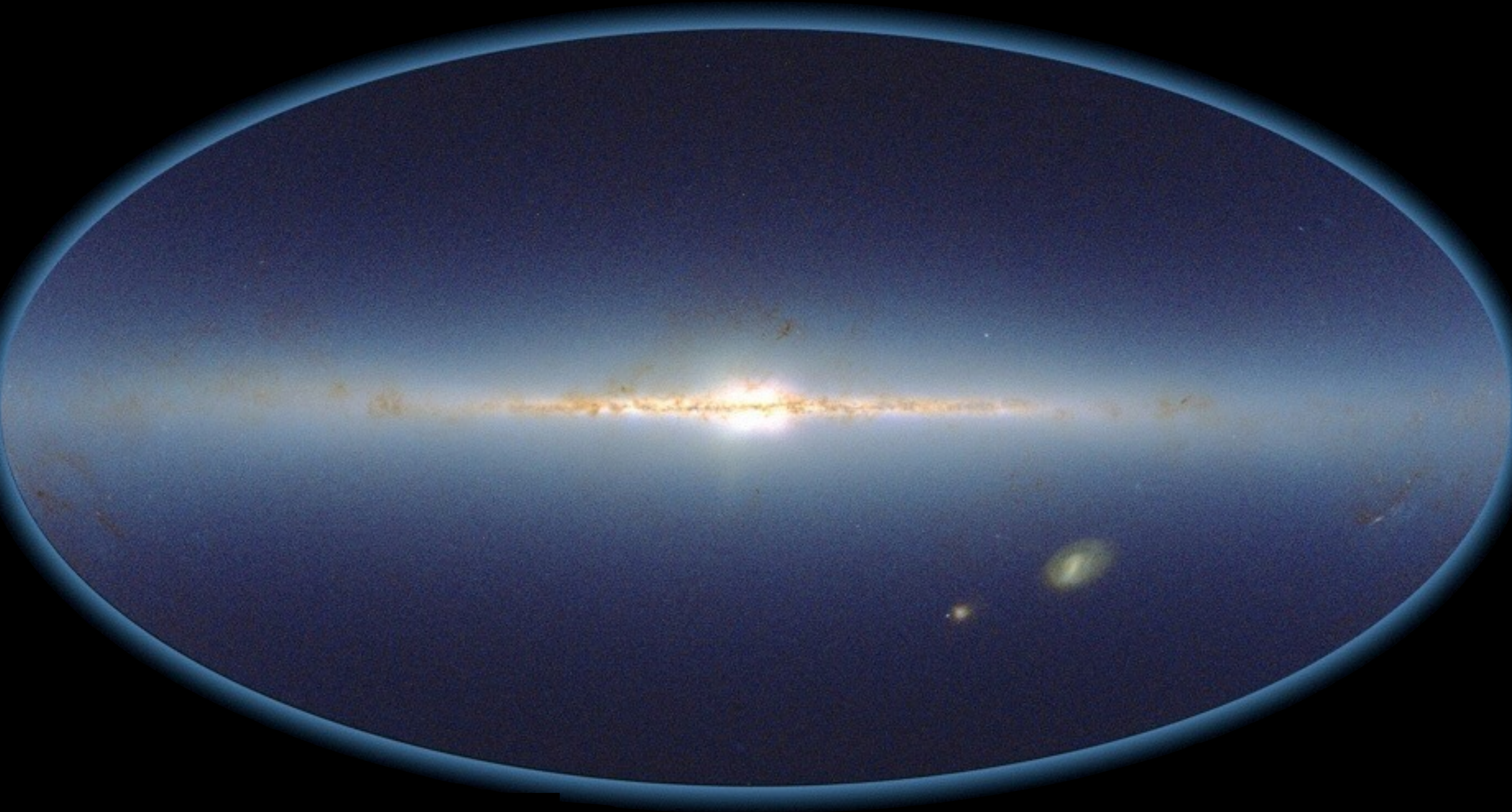
ESO / HAWK-I – Carina

NASA – HST

Molecular clouds in the Milky Way

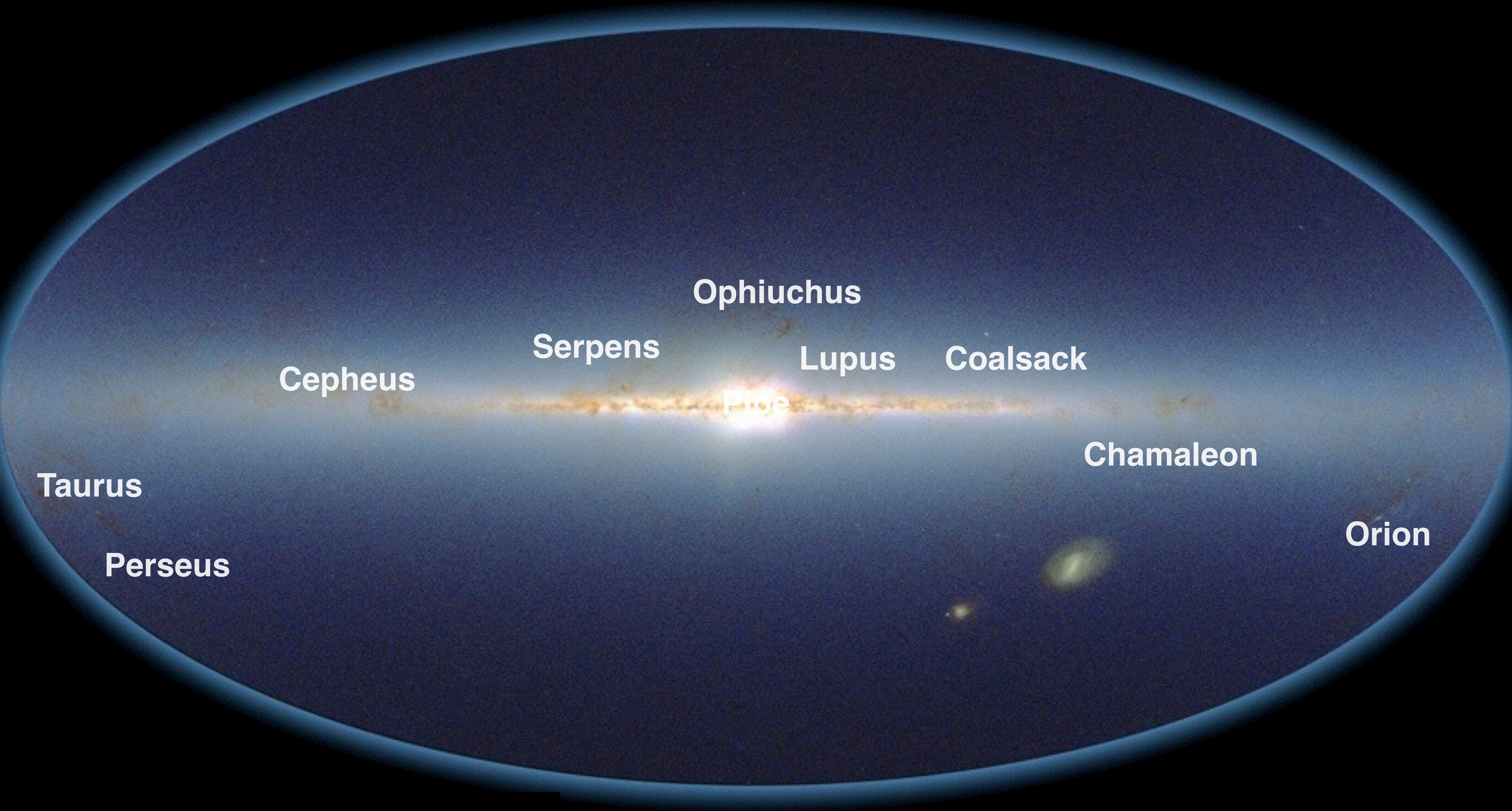


A. Mellinger



2MASS

Gould belt



2MASS

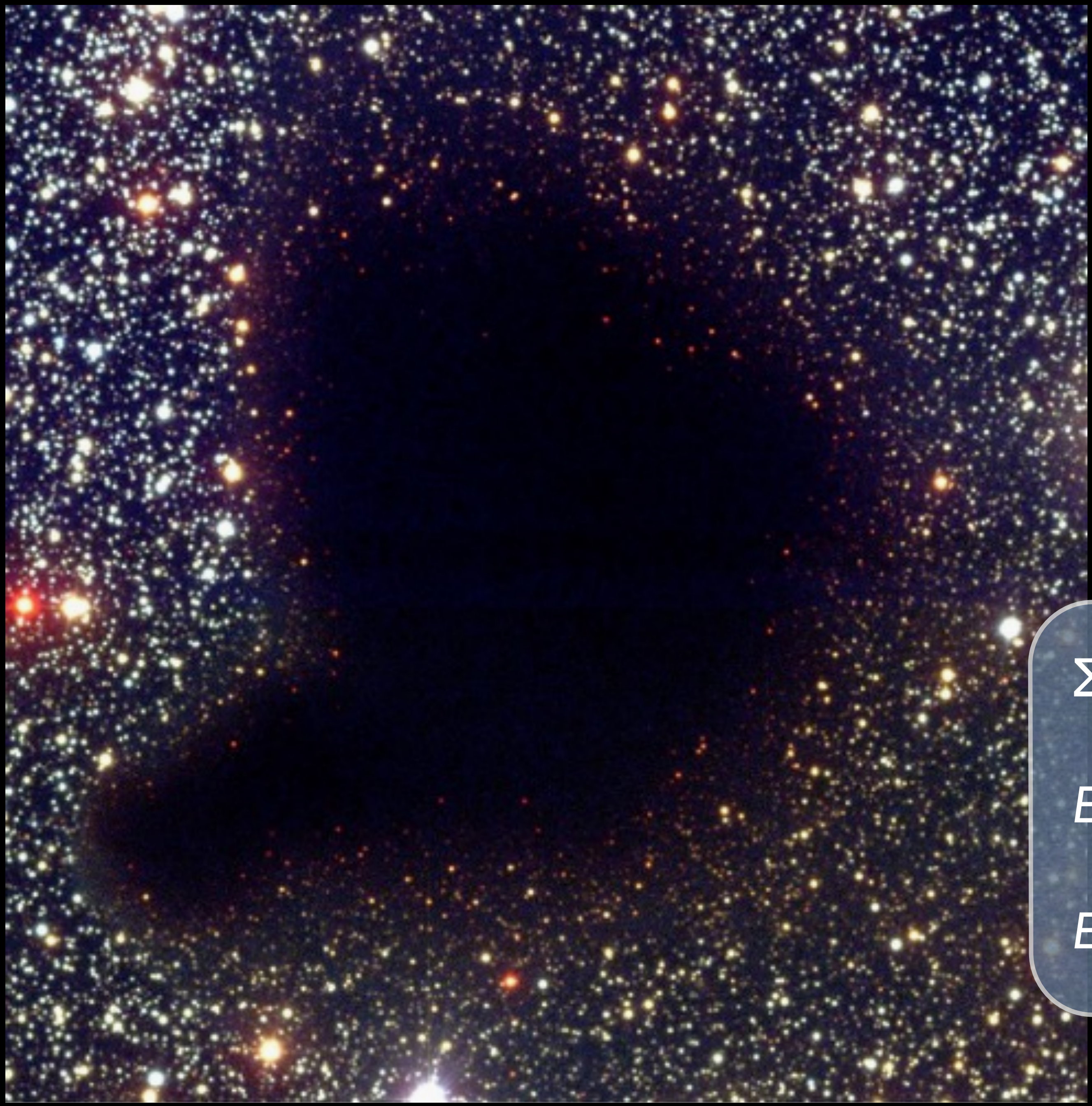
Extinction

VLT (BVI)

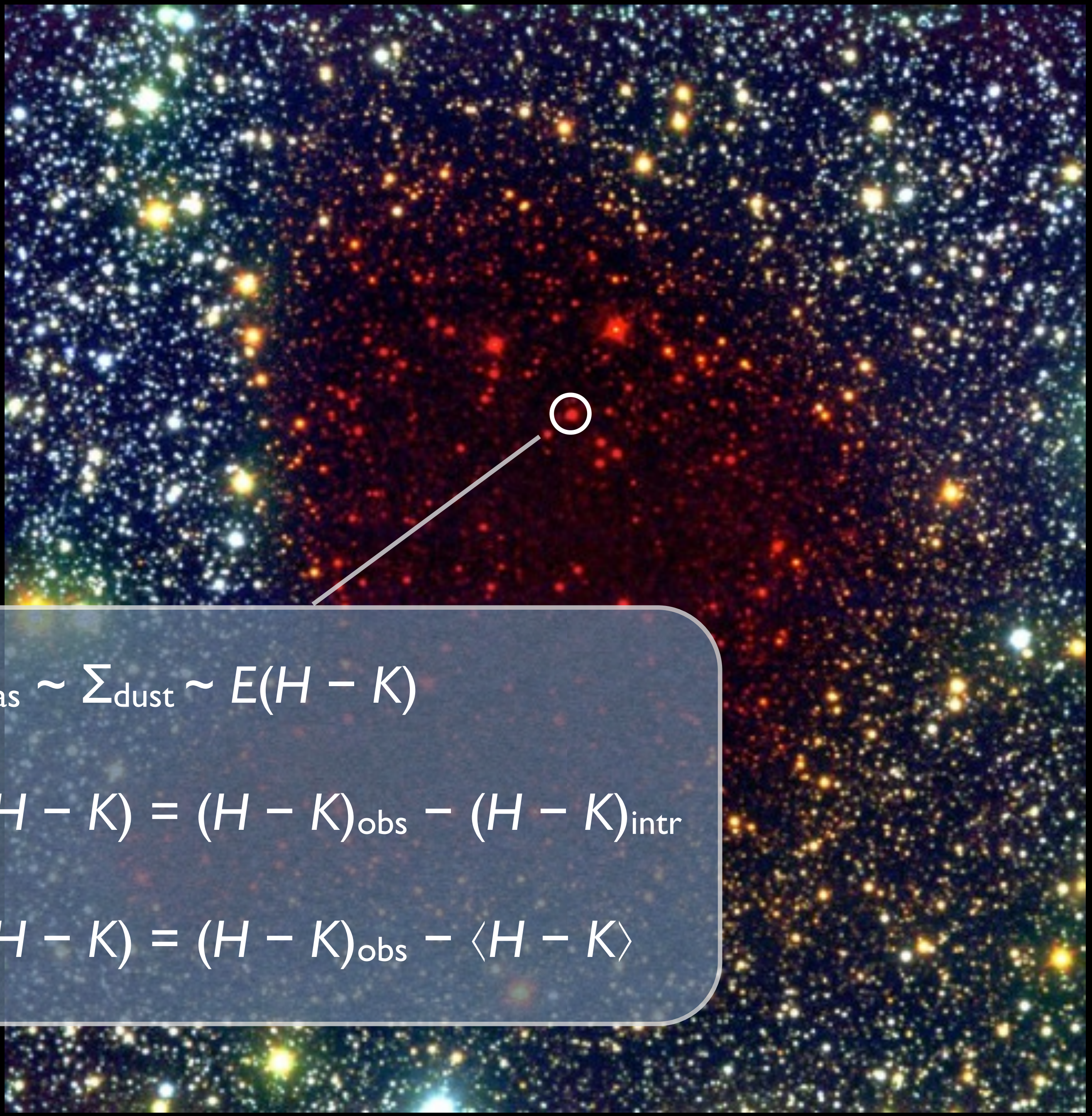
VLT + NTT (BIK)

Alves et al. (2000)

NICER



VLT (BVI)



$$\Sigma_{\mathrm{gas}} \sim \Sigma_{\mathrm{dust}} \sim E(H-K)$$

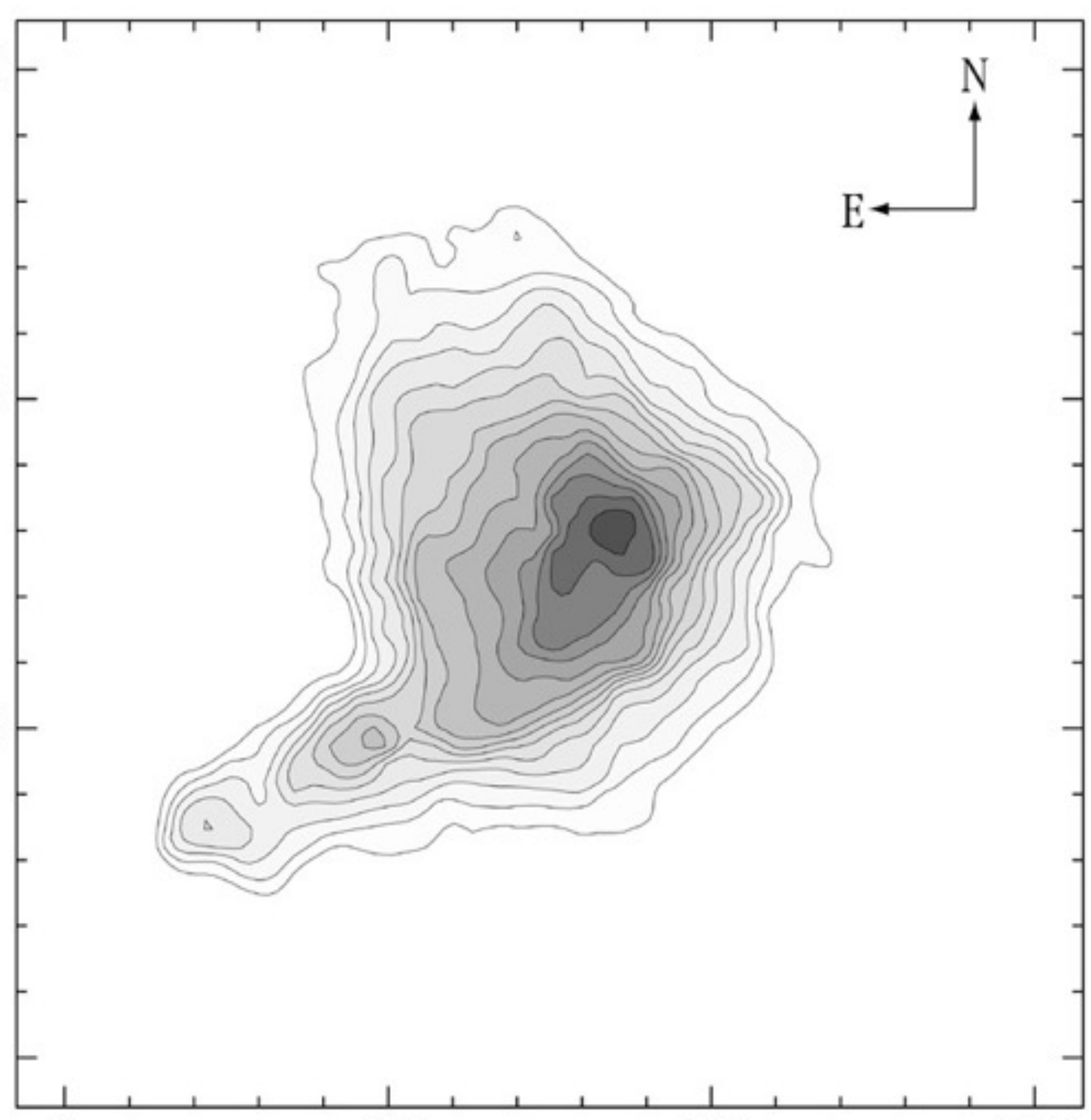
$$E(H-K) = (H-K)_{\mathrm{obs}} - (H-K)_{\mathrm{intr}}$$

$$E(H-K) = (H-K)_{\mathrm{obs}} - \langle H-K \rangle$$

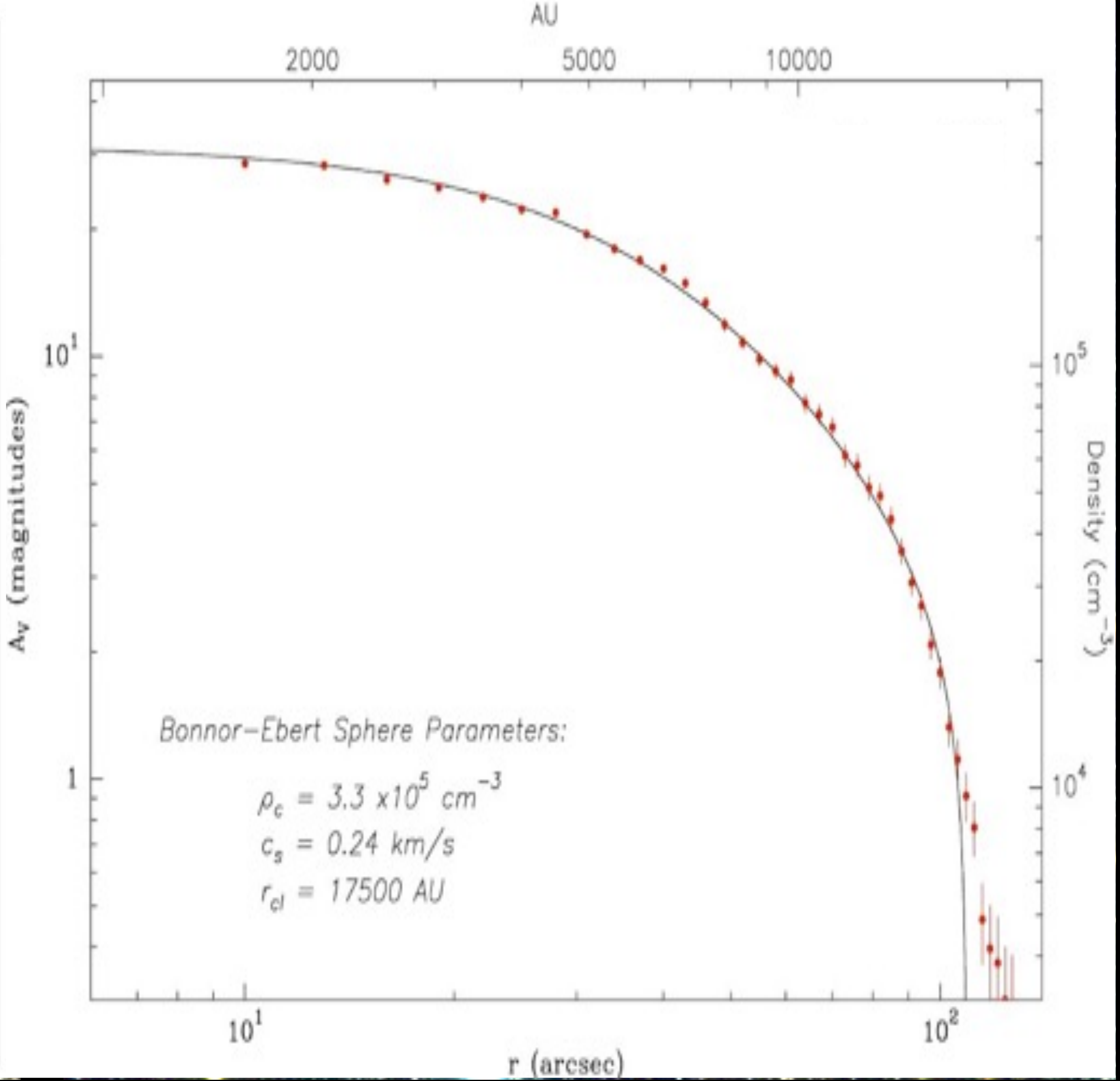
VLT + NTT (BIK)

Lombardi & Alves (2001)

Bonnor 68



VLT (BVI)



VLT + NTT (BIK)

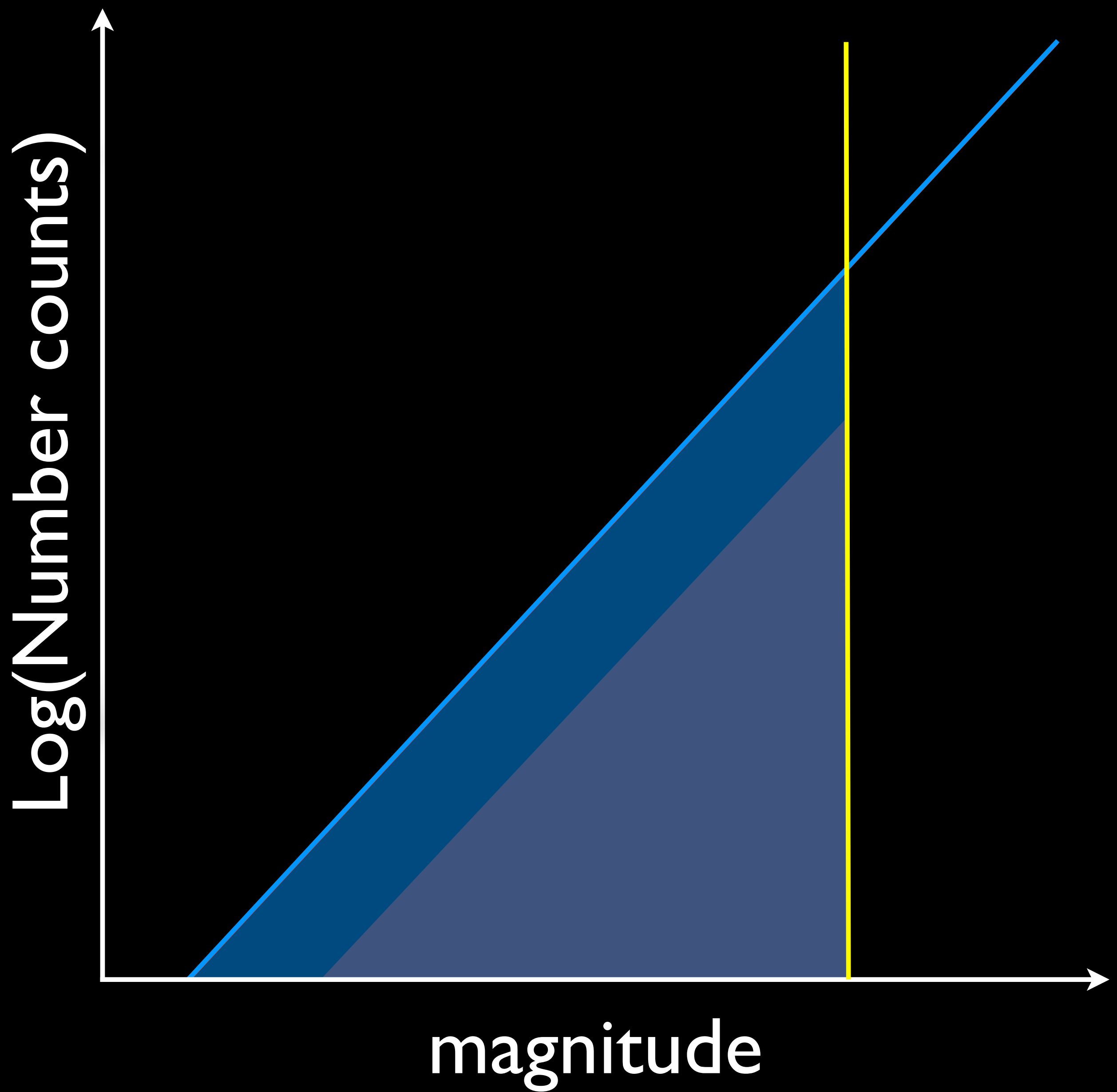
Alves et al. (2000)

Bonnor 68

Alves et al. (2000)

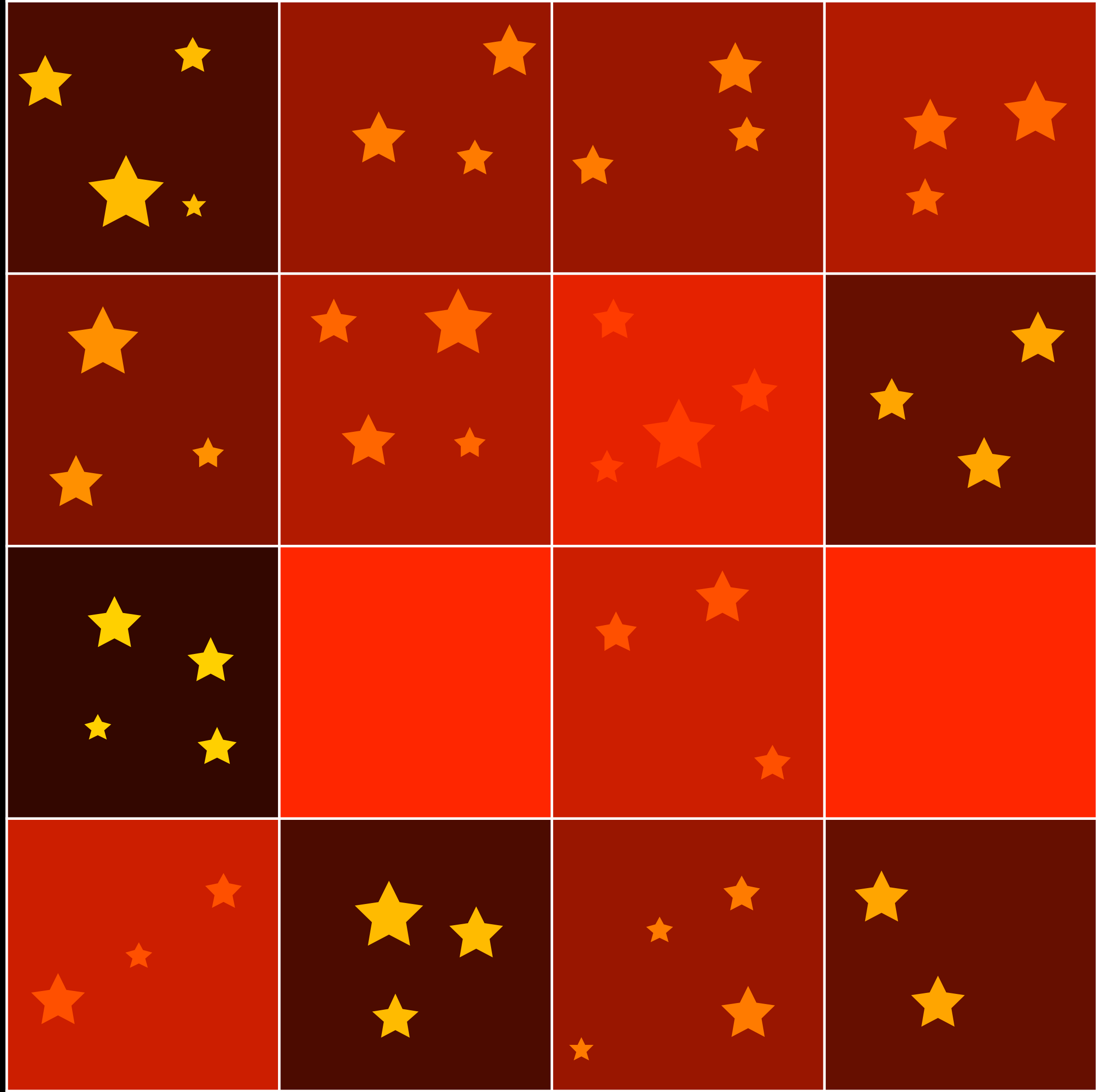
A bias and its solution

- Star number counts follow a power law
- Extinction shifts the number counts line: we observe less stars
- Unresolved structures bias the extinction low



A bias and its solution

- Star number counts follow a power law
- Extinction shifts the number counts line: we observe less stars
- Unresolved structures bias the extinction low

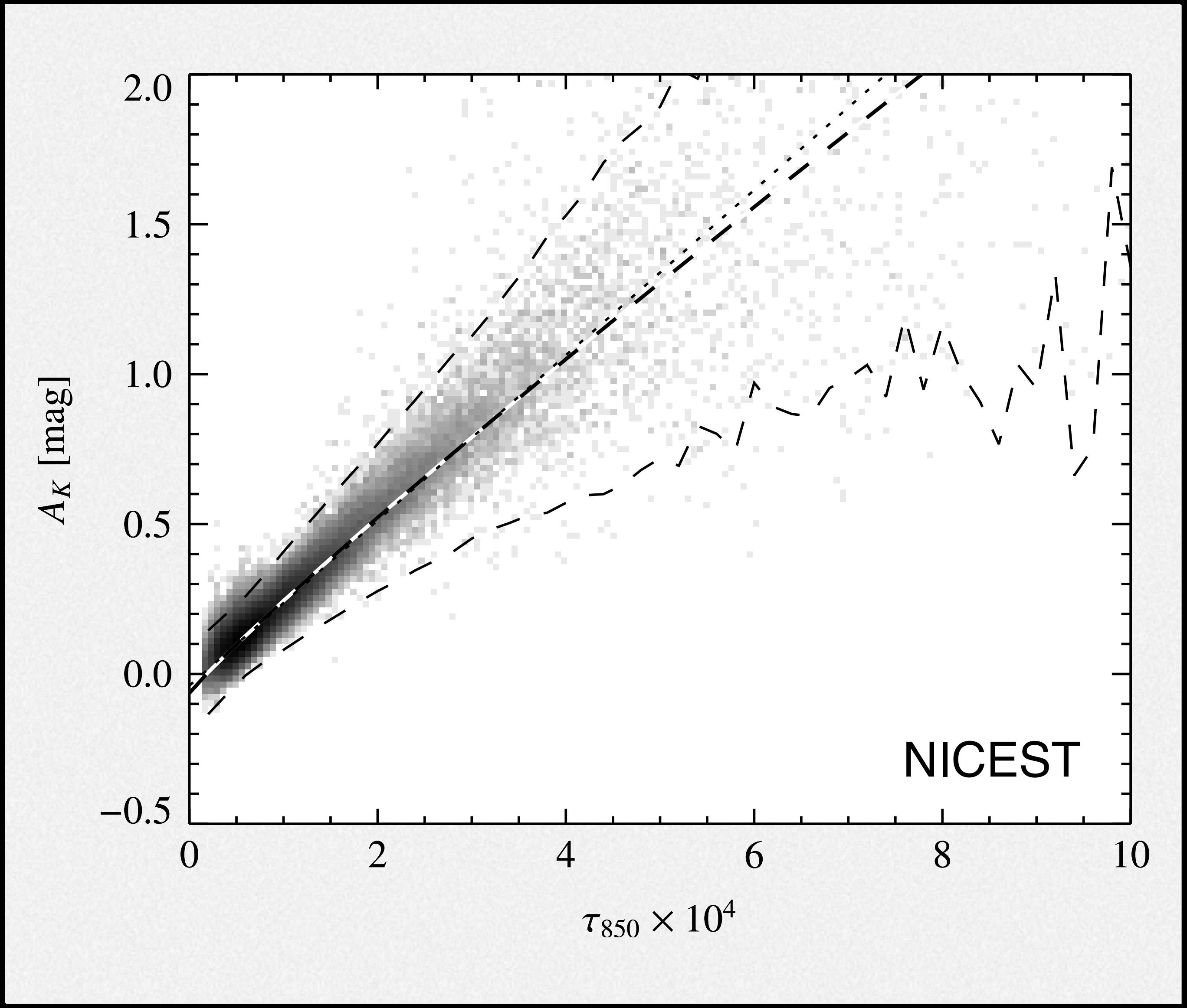


A bias and its solution

- Star number counts follow a power law
- Extinction shifts the number counts line: we observe less stars
- Unresolved structures bias the extinction low
- Solution: weight each star by its extinction (NICEST, Lombardi 2009)

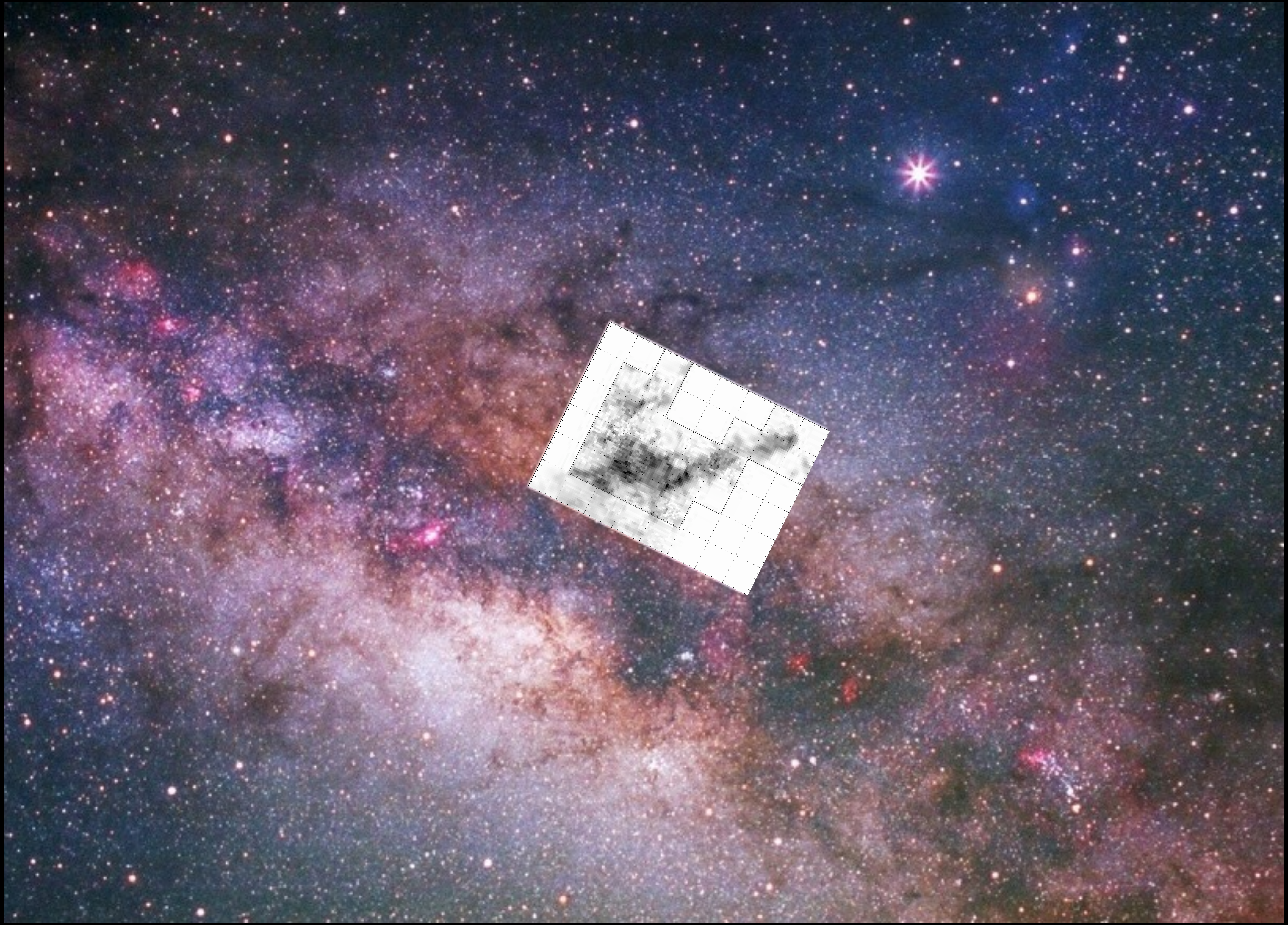
A bias and its solution

- Star number counts follow a power law
- Extinction shifts the number counts line: we observe less stars
- Unresolved structures bias the extinction low
- Solution: weight each star by its extinction (NICEST, Lombardi 2009)




Ceci n'est pas une pipe.
Magritte

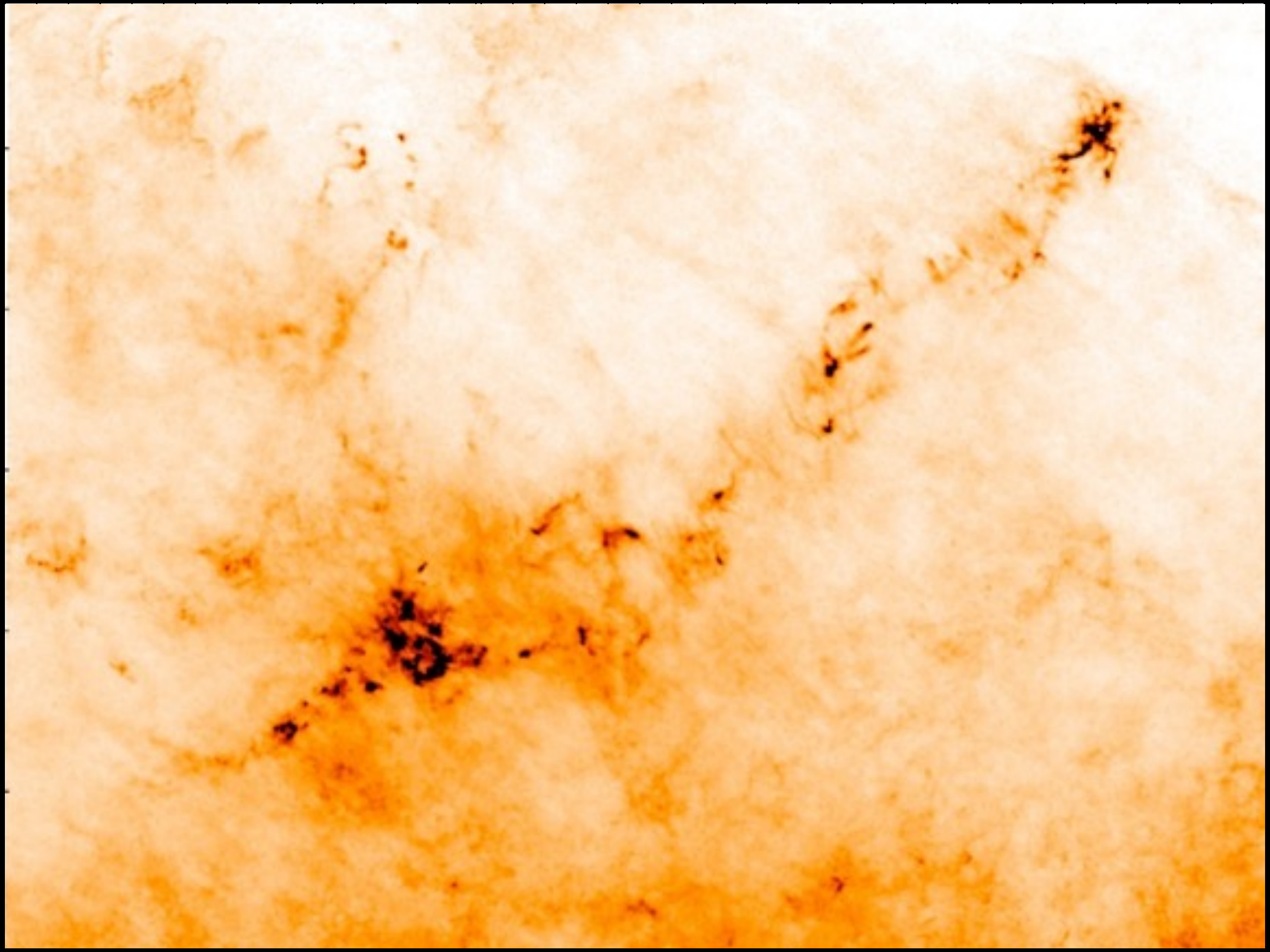

Ceci n'est pas une pipe.



The Pipe Nebula

Lombardi et al. (2006)

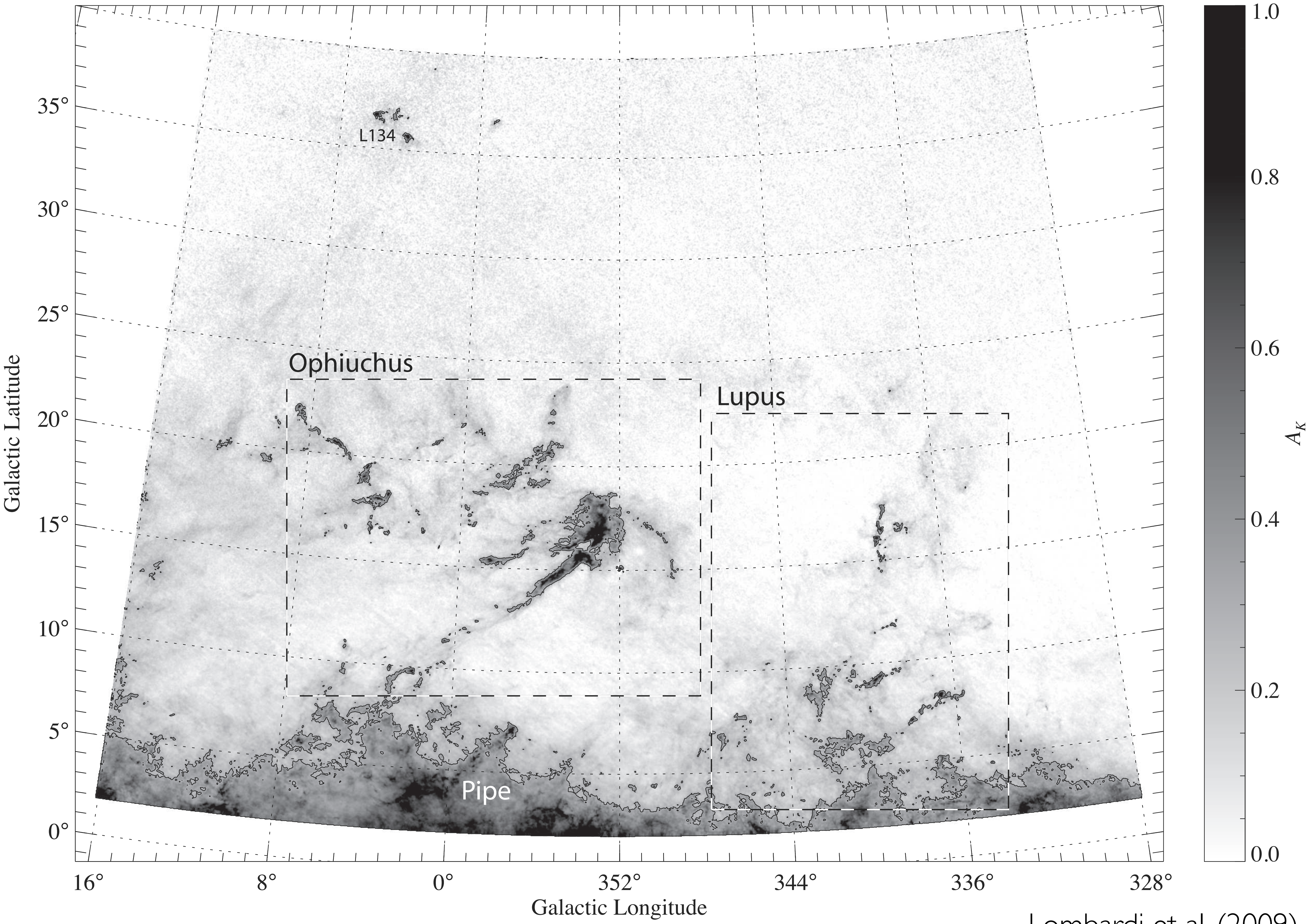
CO vs. dust



NICER: Lombardi et al. (2006), M = 10000 M$_\odot$

^{12}CO: Dame et al. (2001), M = 6500 M$_\odot$

Lombardi et al. (2006)



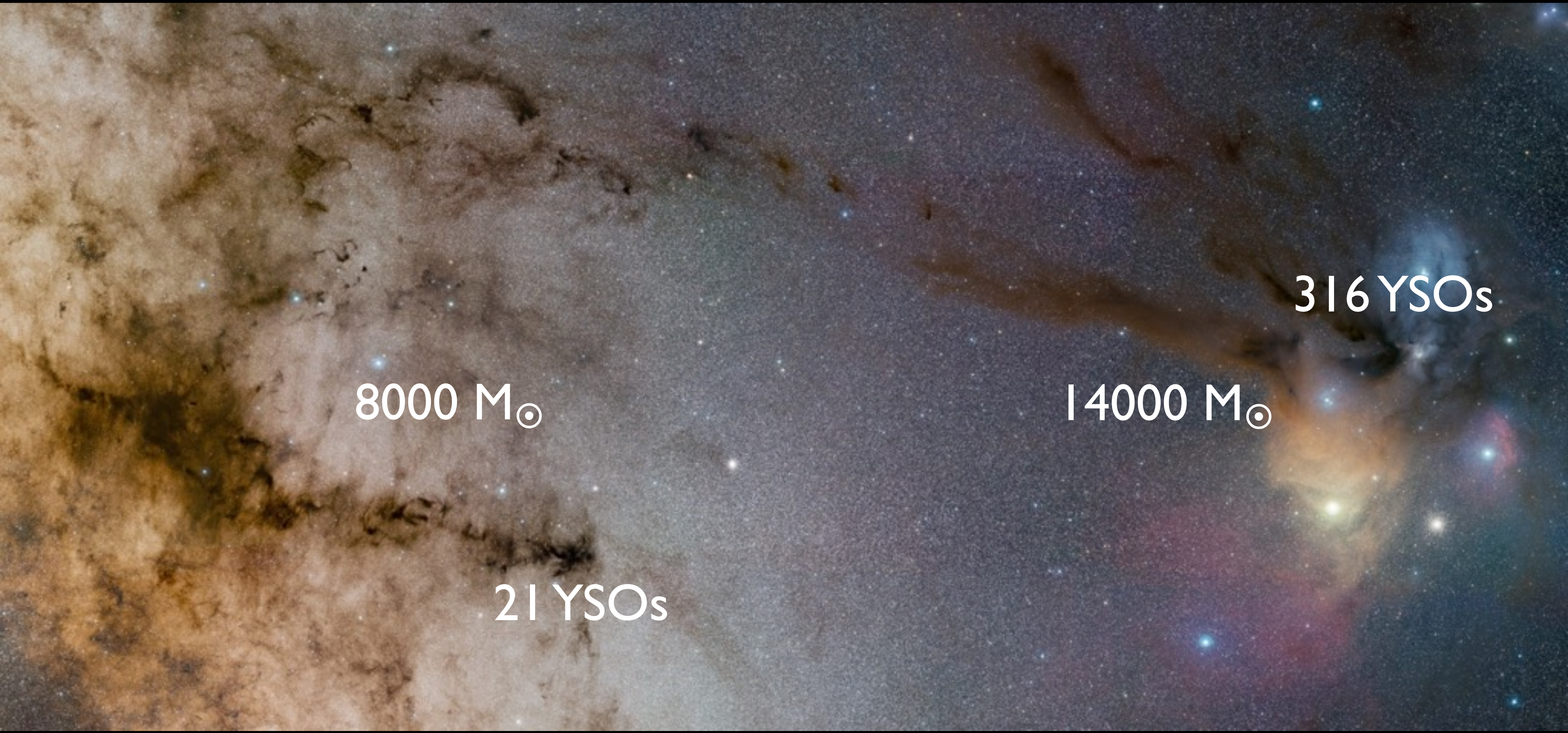
Lombardi et al. (2009)

Fact 3
Different molecular clouds have different SFRs


S. Guisard (ESO)

Pipe nebula

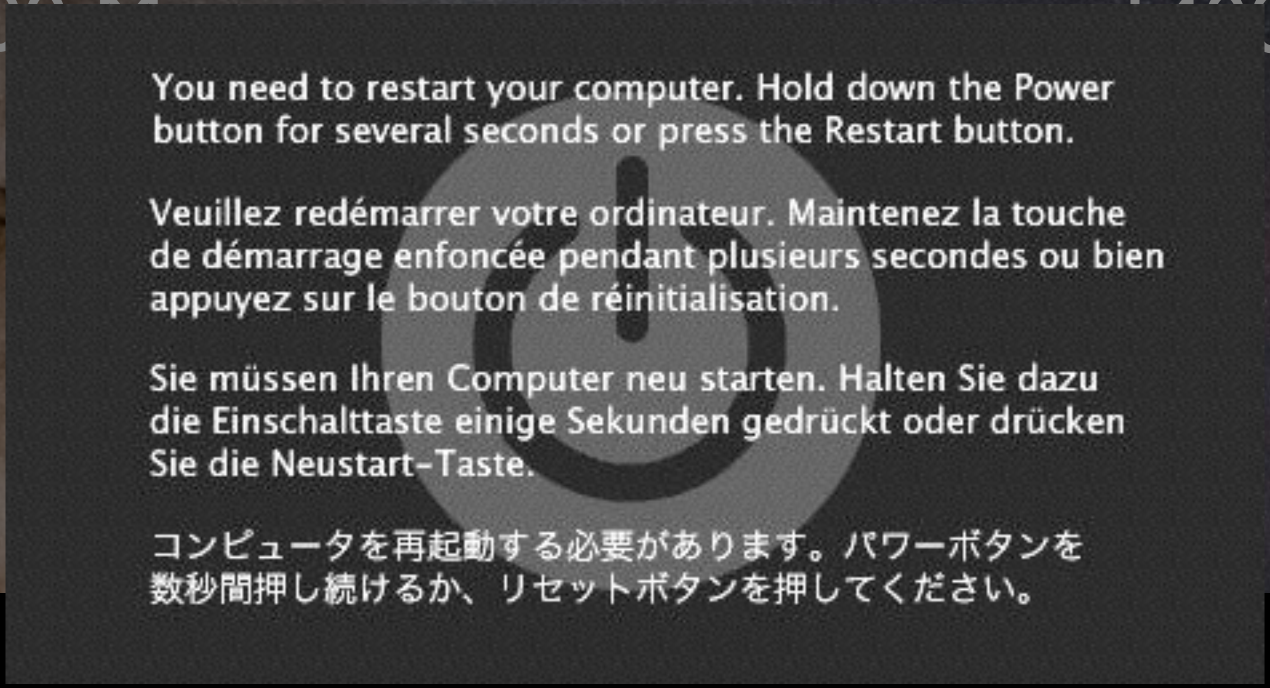
ρ Ophiuchi cloud



$$\mathrm{SFR}_{\mathrm{Oph}} = 15 \times \mathrm{SFR}_{\mathrm{Pipe}}$$

$\Sigma_{\mathrm{Pipe}} = 50\ M_\odot\ \mathrm{pc}^{-2}$

$\Sigma_{\mathrm{Oph}} = 40\ M_\odot\ \mathrm{pc}^{-2}$


You need to restart your computer. Hold down the Power button for several seconds or press the Restart button.

Veuillez redémarrer votre ordinateur. Maintenez la touche de démarrage enfoncée pendant plusieurs secondes ou bien appuyez sur le bouton de réinitialisation.

Sie müssen Ihren Computer neu starten. Halten Sie dazu die Einschalttaste einige Sekunden gedrückt oder drücken Sie die Neustart-Taste.

コンピュータを再起動する必要があります。パワーボタンを数秒間押し続けるか、リセットボタンを押してください。

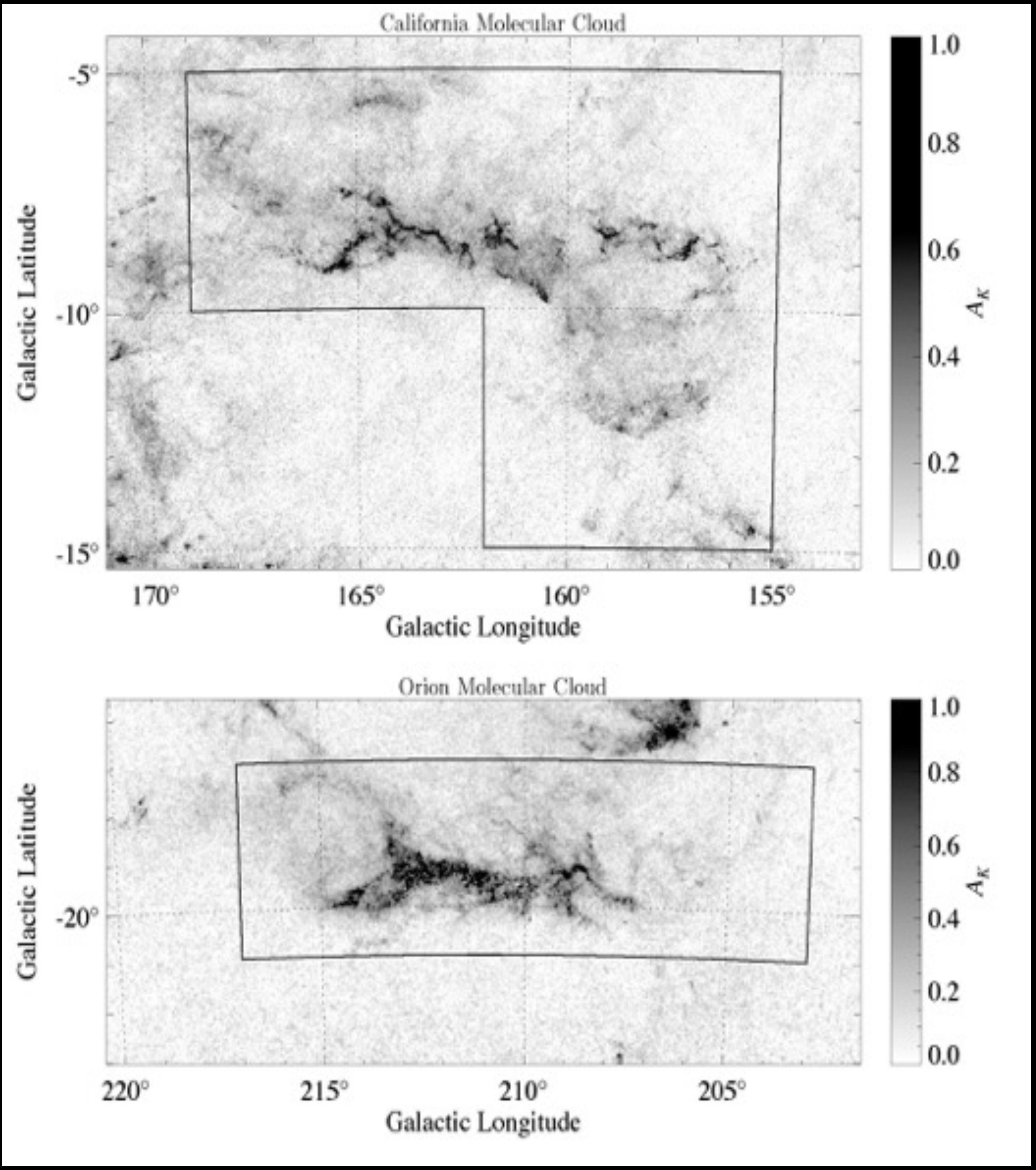
$$\mathrm{SFR_{Oph}} = 15 \times \mathrm{SFR_{Pipe}}$$

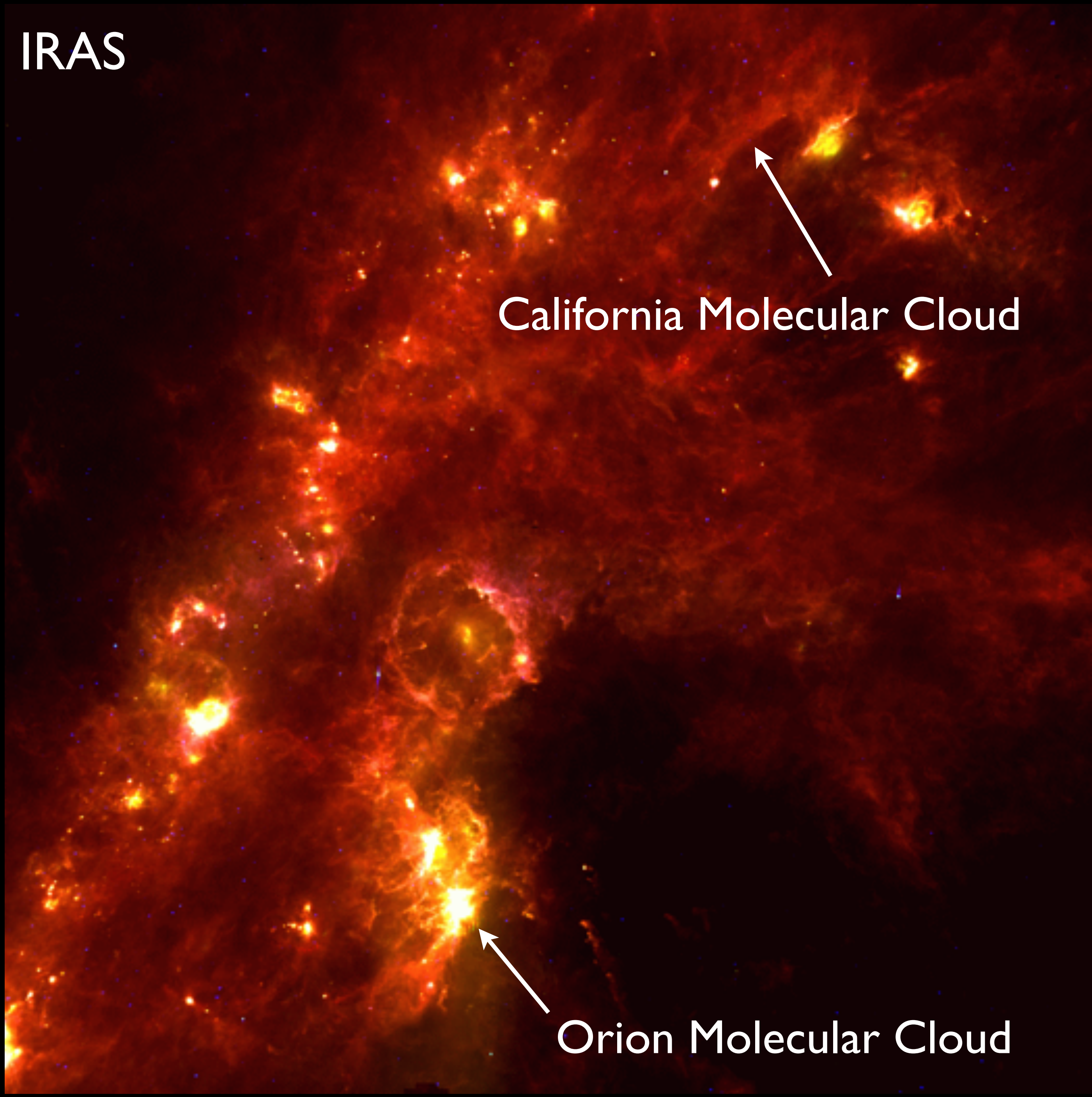
Ceci n’est pas une exception.

$\Sigma_{\mathrm{Pipe}} = 50\ M_\odot\ \mathrm{pc}^{-2}$

$\Sigma_{\mathrm{Oph}} = 40\ M_\odot\ \mathrm{pc}^{-2}$

Ceci n'est pas une exception.



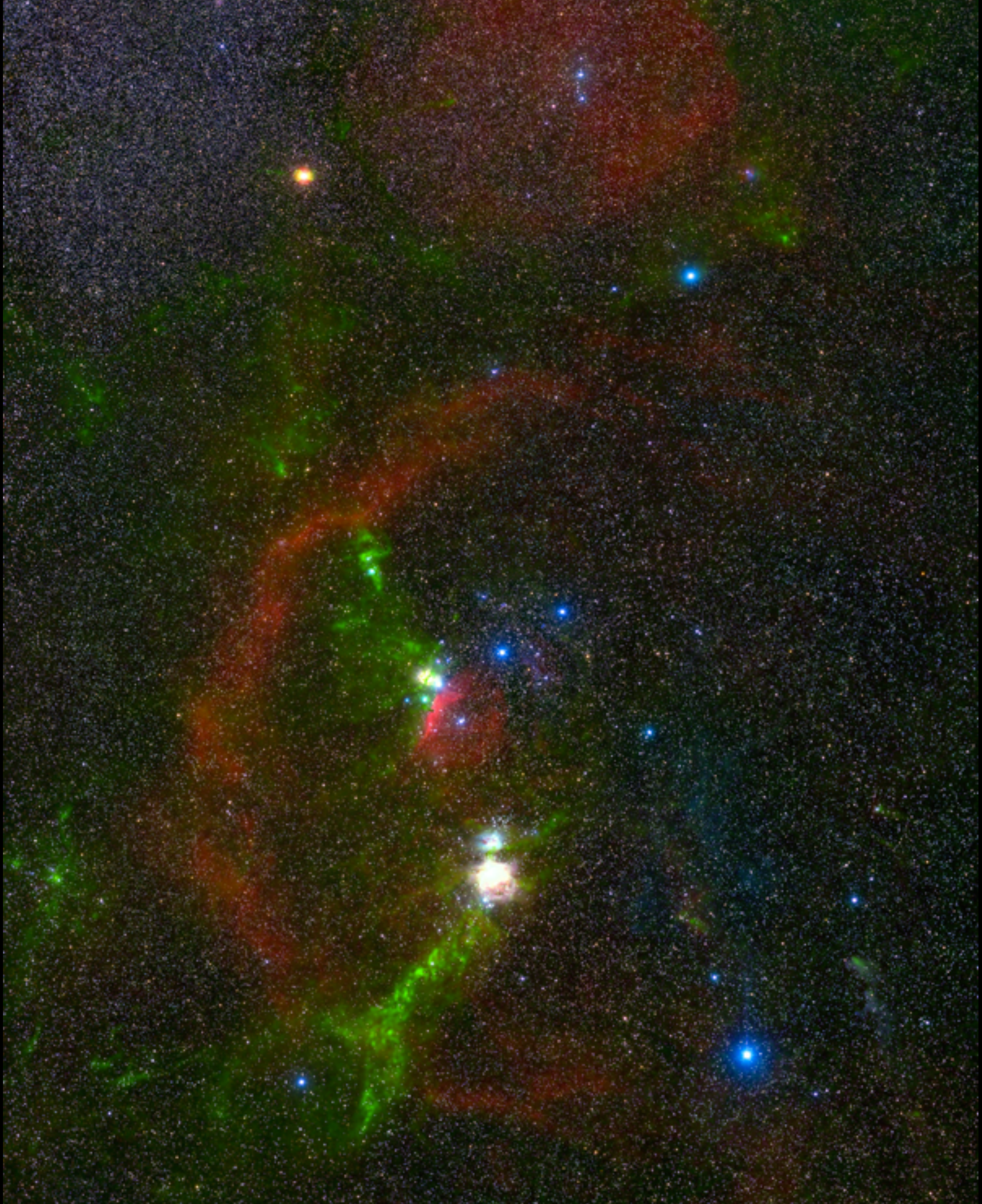


Identical in mass & size

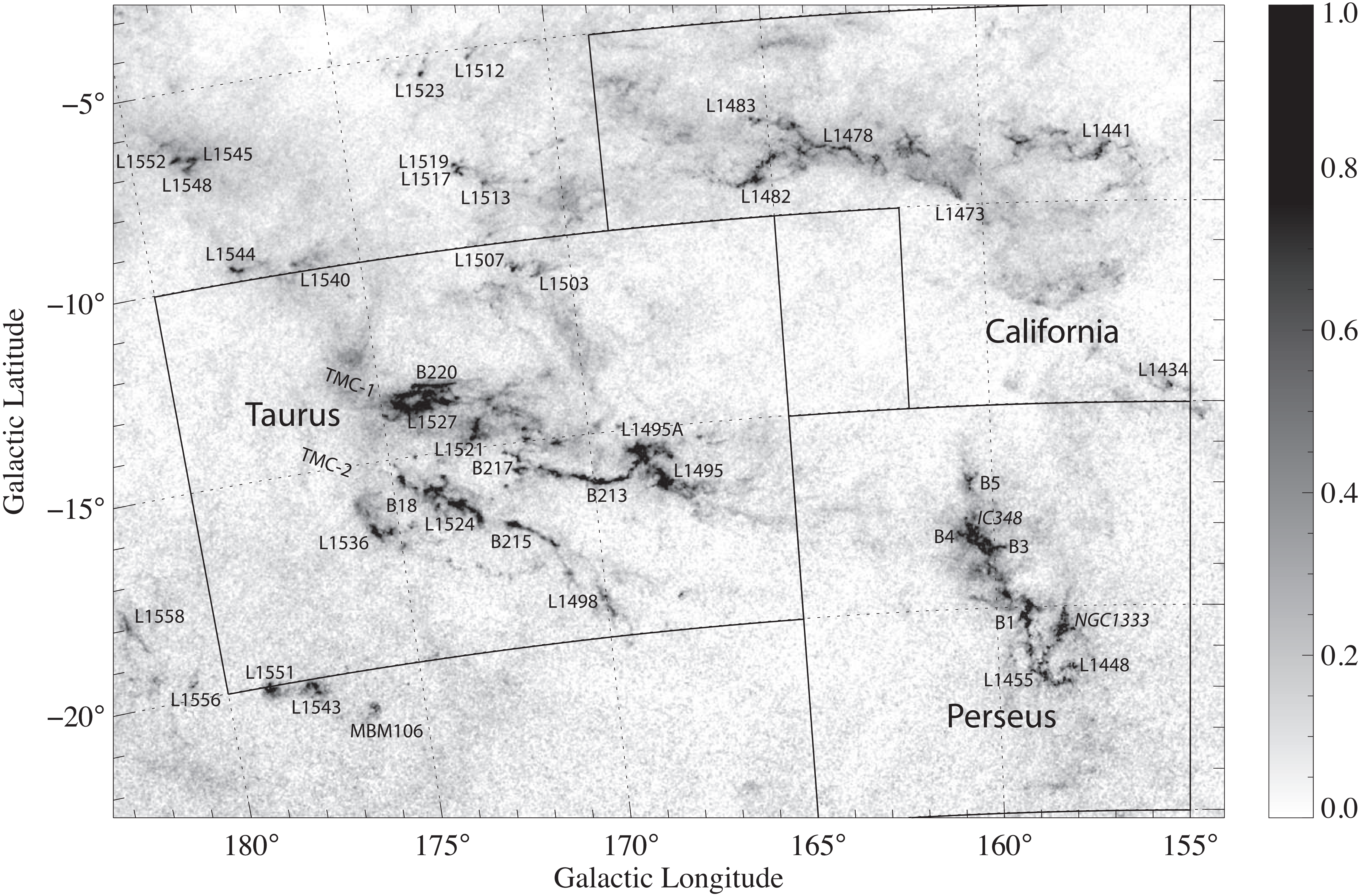
$\mathrm{SFR}_{\mathrm{Orion}} = 10 \times \mathrm{SFR}_{\mathrm{California}}$

Inventory of Local Star Formation Activity

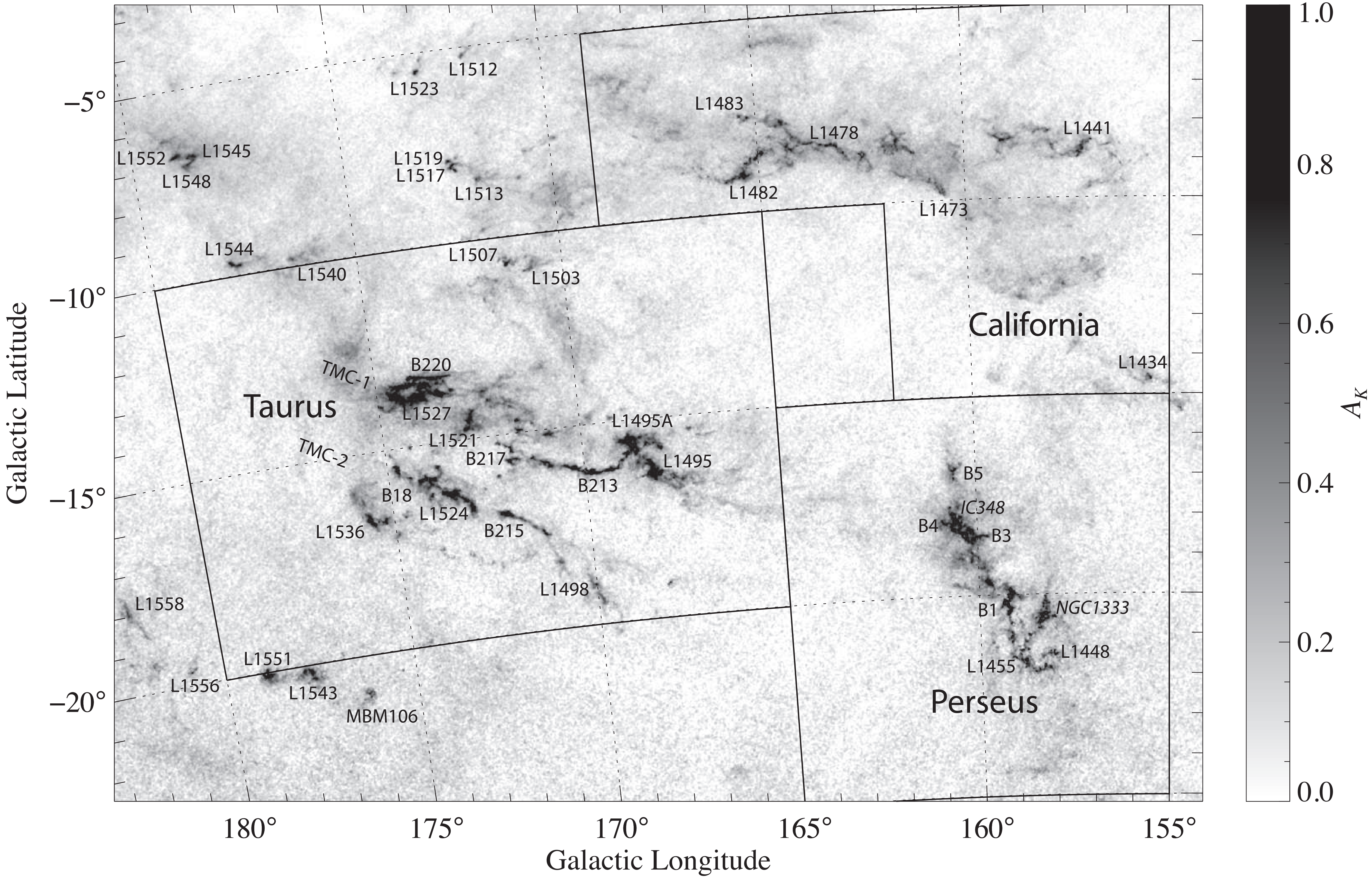
Infrared extinction and cloud masses



Lombardi et al. (2011)

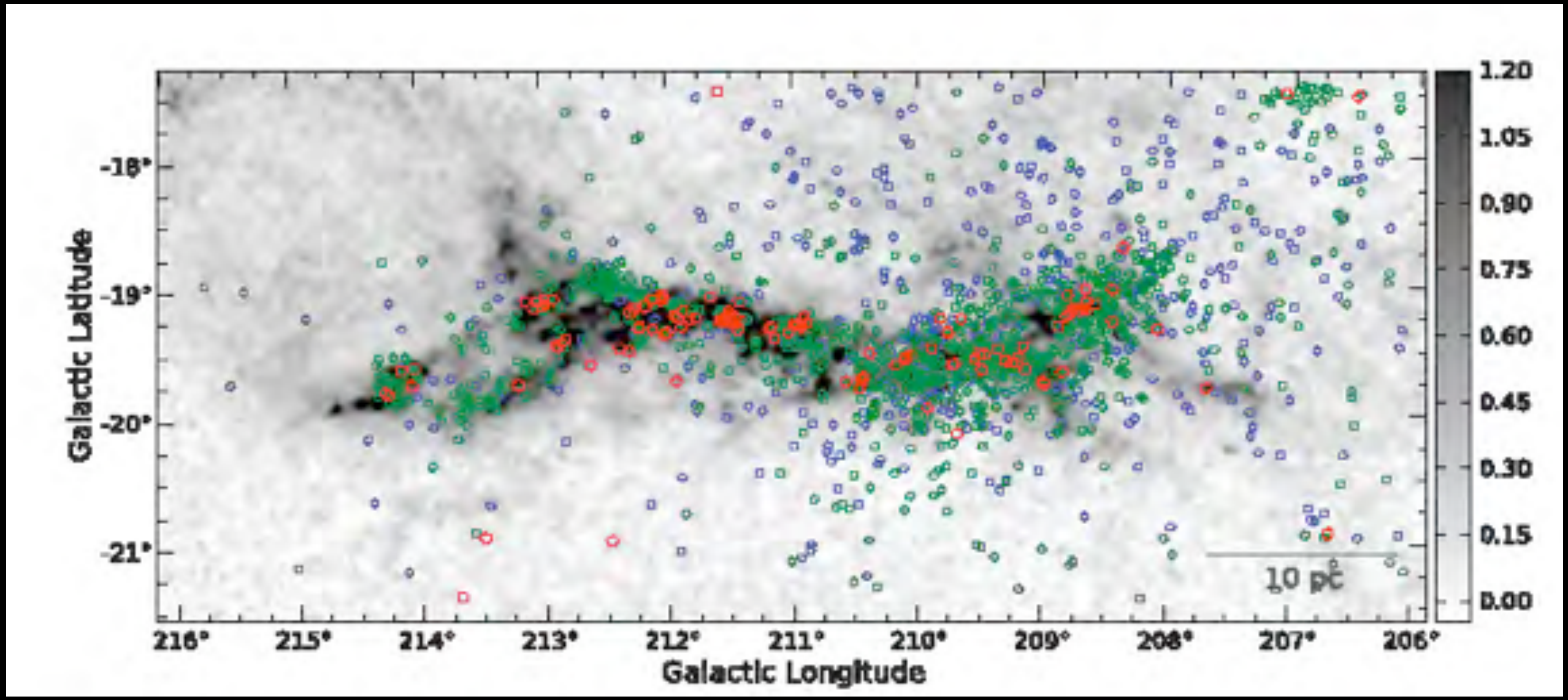


Lombardi et al. (2010)


L1512
L1523
L1483
L1478
L1441
L1552
L1545
L1548
L1519
L1517
L1513
L1482
L1473
L1544
L1540
L1507
L1503
California
L1434
B220
TMC-1
Taurus
L1527
L1495A
L1521
B217
L1495
TMC-2
B213
B5
IC348
B18
L1524
B4
B3
L1536
B215
L1498
L1558
B1
NGC1333
L1551
L1448
L1455
L1556
L1543
Perseus
MBM106
−5°
−10°
−15°
−20°
Galactic Latitude
180°
175°
170°
165°
160°
155°
Galactic Longitude
1.0
0.8
0.6
0.4
0.2
0.0
A_K

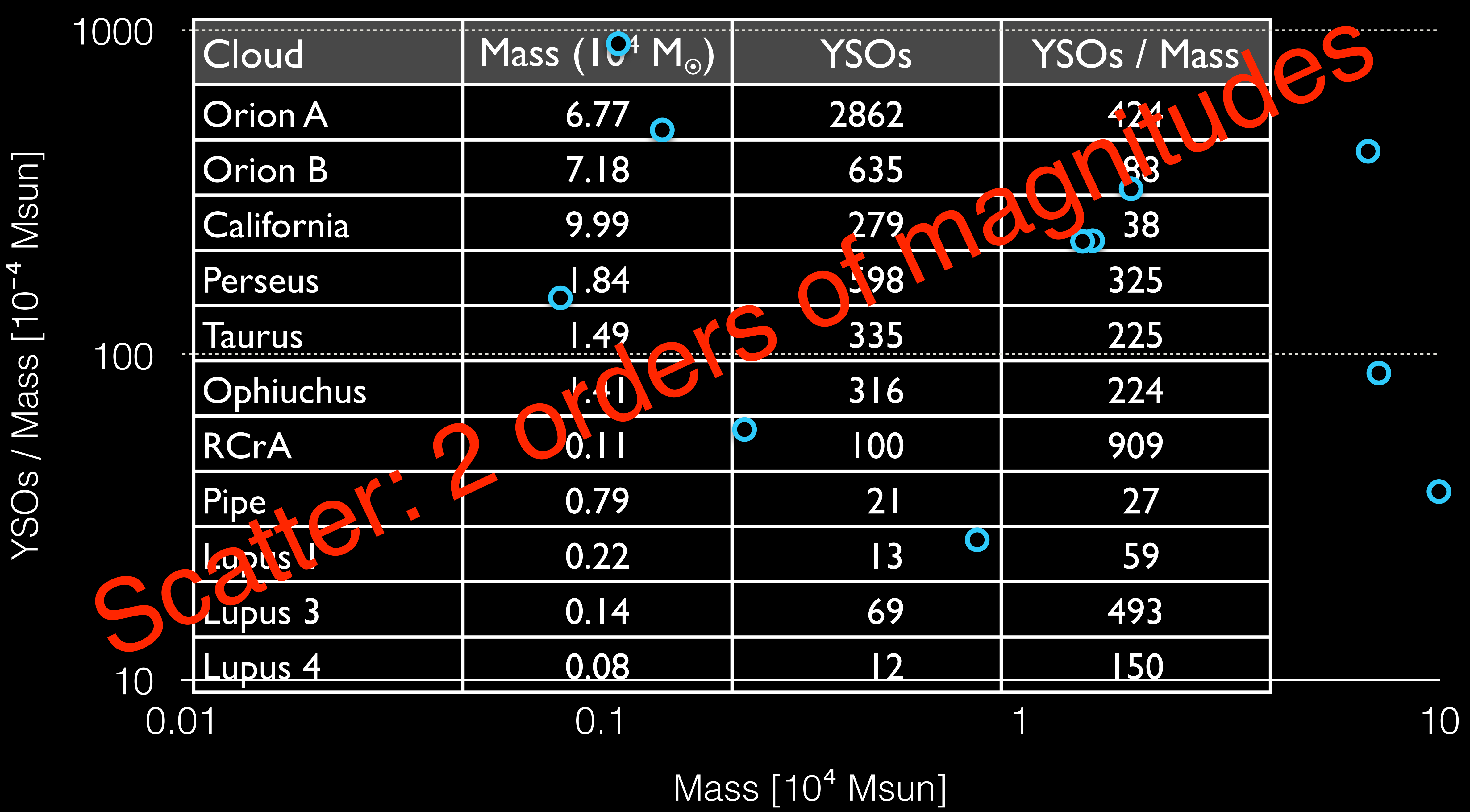
Inventory of Star Formation Activity: Young Stellar Objects (YSOs)

Mining the literature: mostly IR data (SPITZER)



Cloud	YSOs
Orion A	2862
Orion B	635
California	279
Perseus	598
Taurus	335
Ophiuchus	316
RCrA	100
Pipe	21
Lupus 1	13
Lupus 3	69
Lupus 4	12

Inventory of Star Formation Activity: Young Stellar Objects (YSOs)



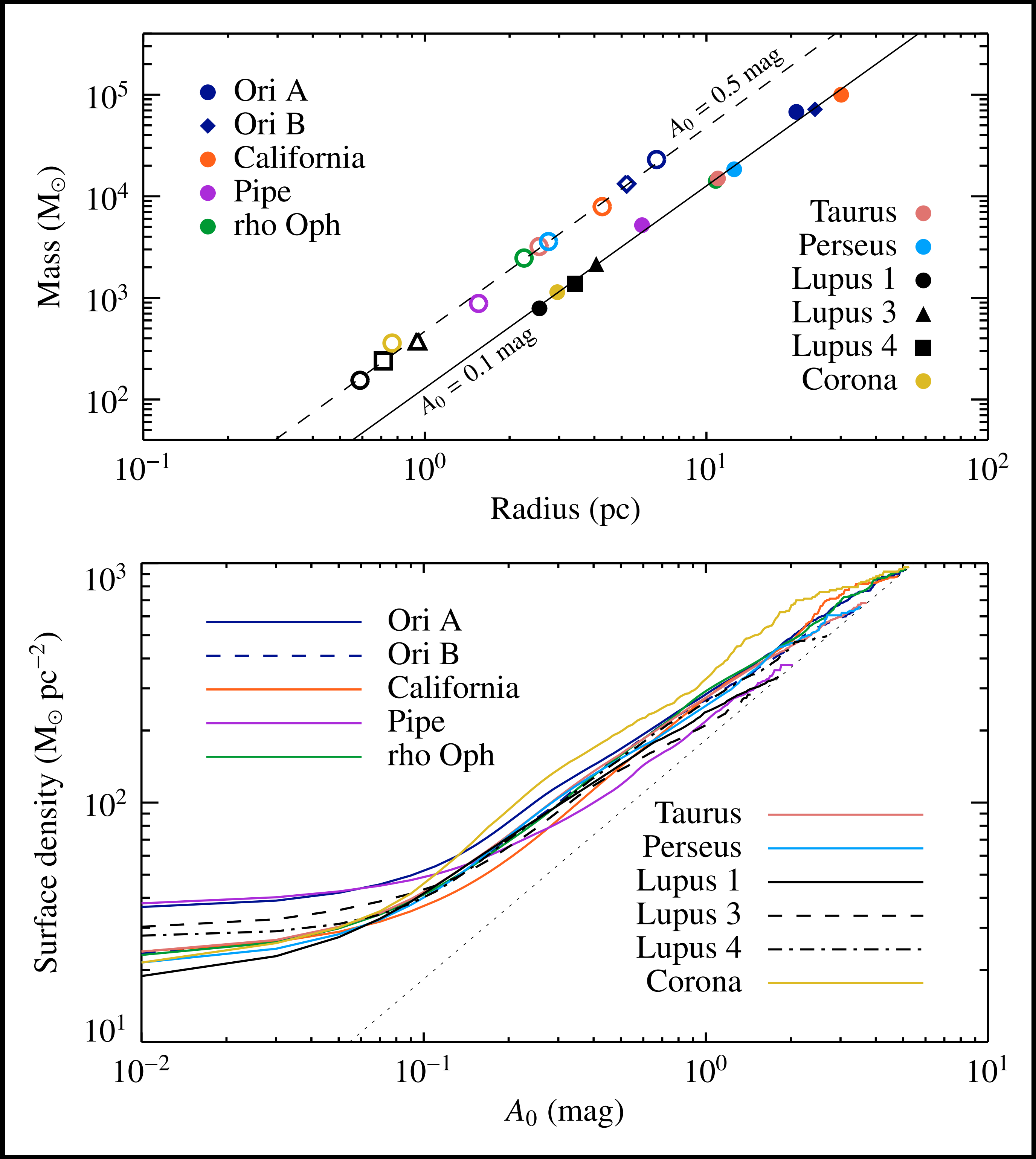
Cloud	Mass (10^4 $M_\odot$)	YSOs	YSOs / Mass
Orion A	6.77	2862	424
Orion B	7.18	635	88
California	9.99	279	38
Perseus	1.84	598	325
Taurus	1.49	335	225
Ophiuchus	1.41	316	224
RCrA	0.11	100	909
Pipe	0.79	21	27
Lupus 1	0.22	13	59
Lupus 3	0.14	69	493
Lupus 4	0.08	12	150

Scatter: 2 orders of magnitudes

Fact 4
Molecular clouds have a peculiar structure

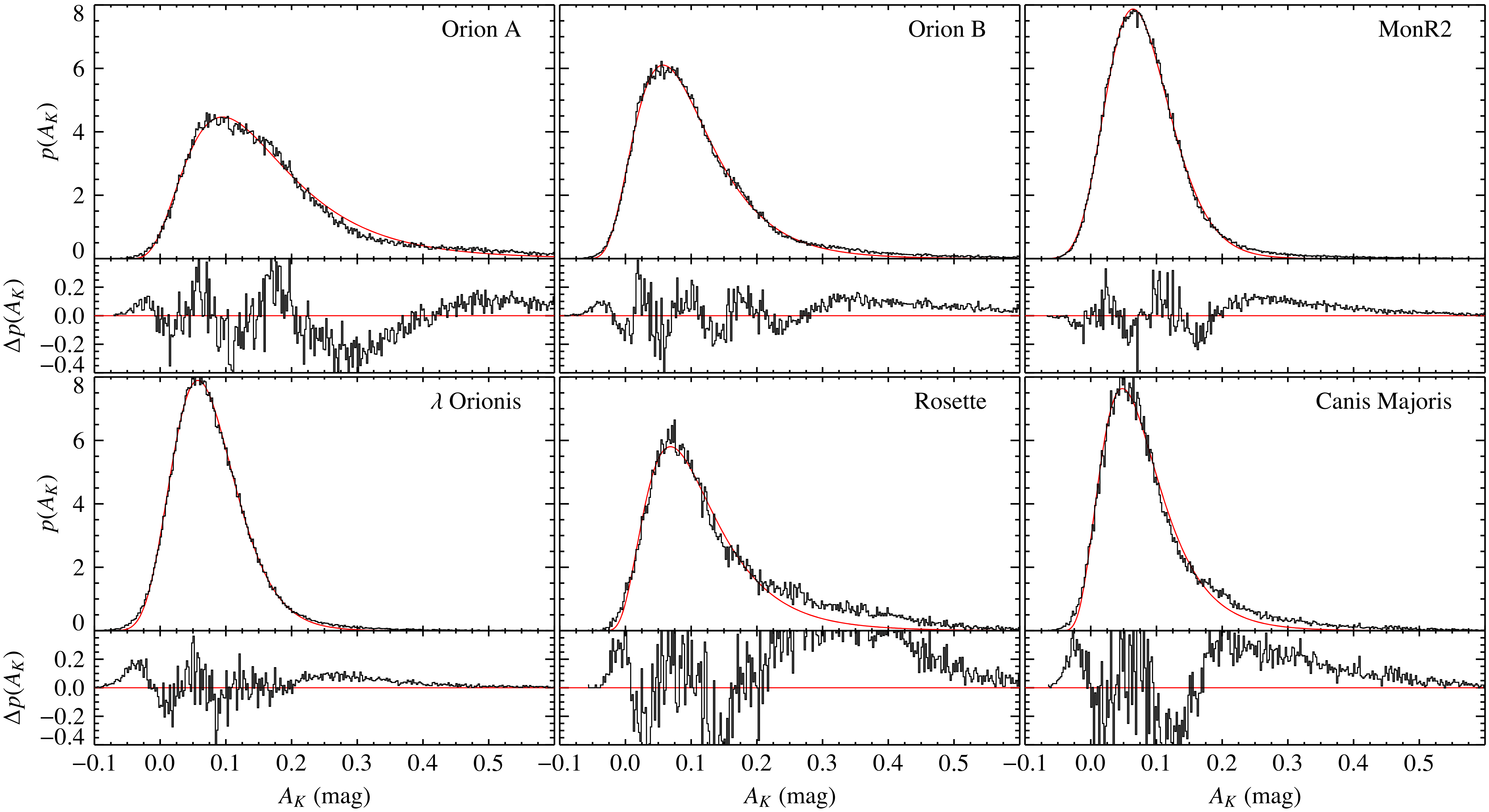
The structure of molecular clouds

- Different molecular clouds show consistent structure
  - Same average density a above threshold value (as predicted by WDM)
  - Same probability distribution for Σ (log-normal)



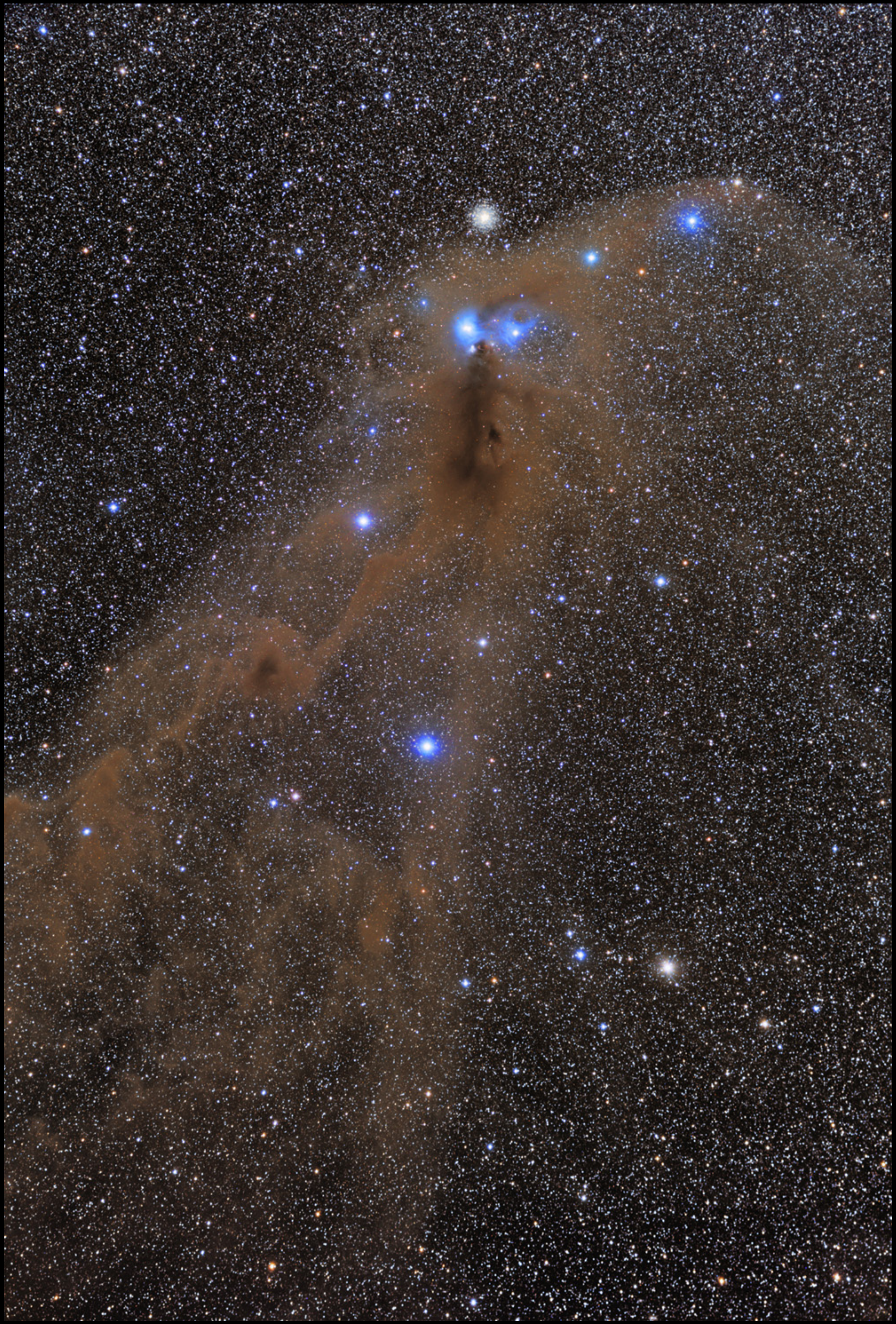
Lombardi et al. (2010)

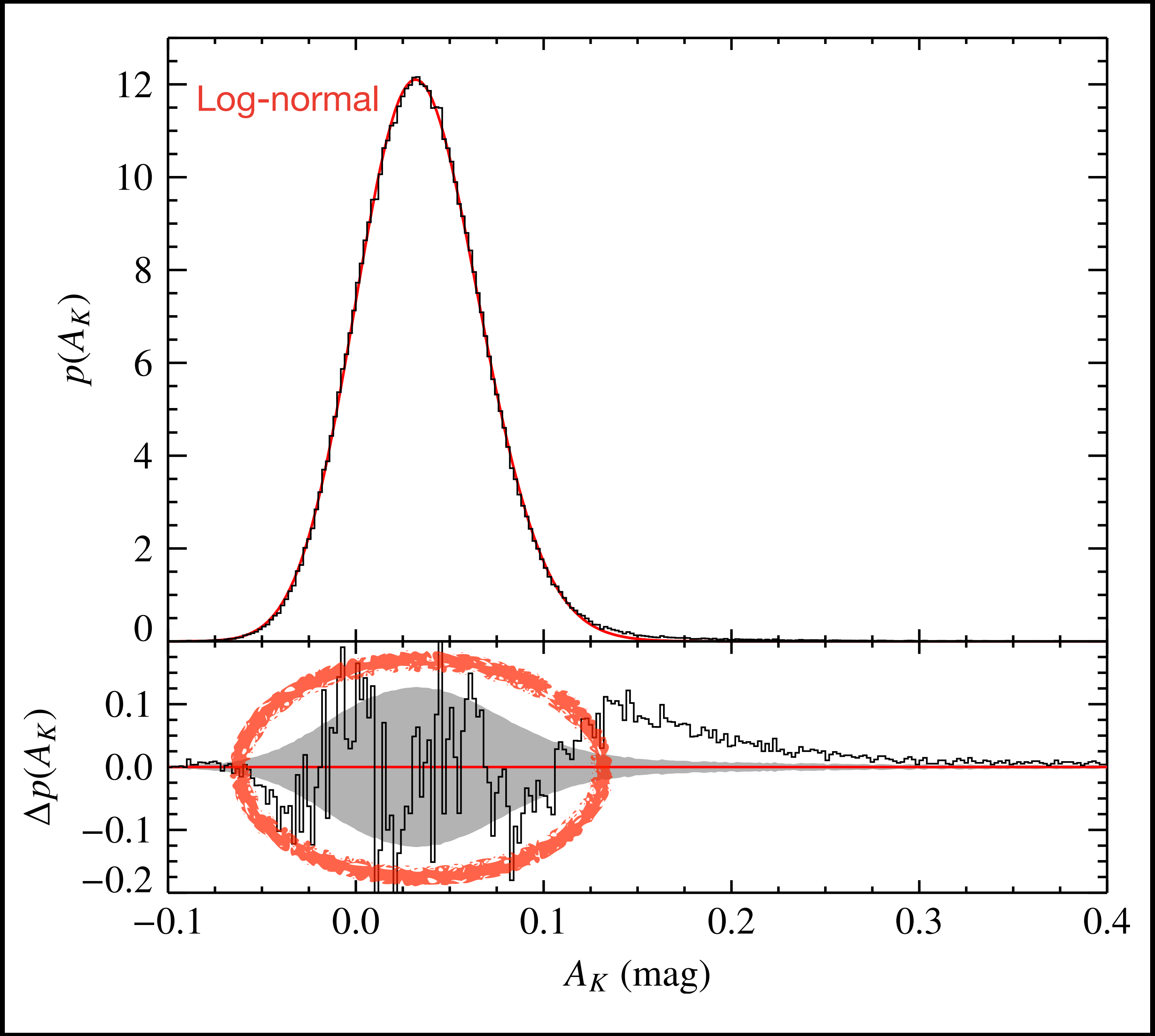
Log-normal fits to cloud projected density distributions



Lombardi et al. (2011)

Log-normals? Think it twice

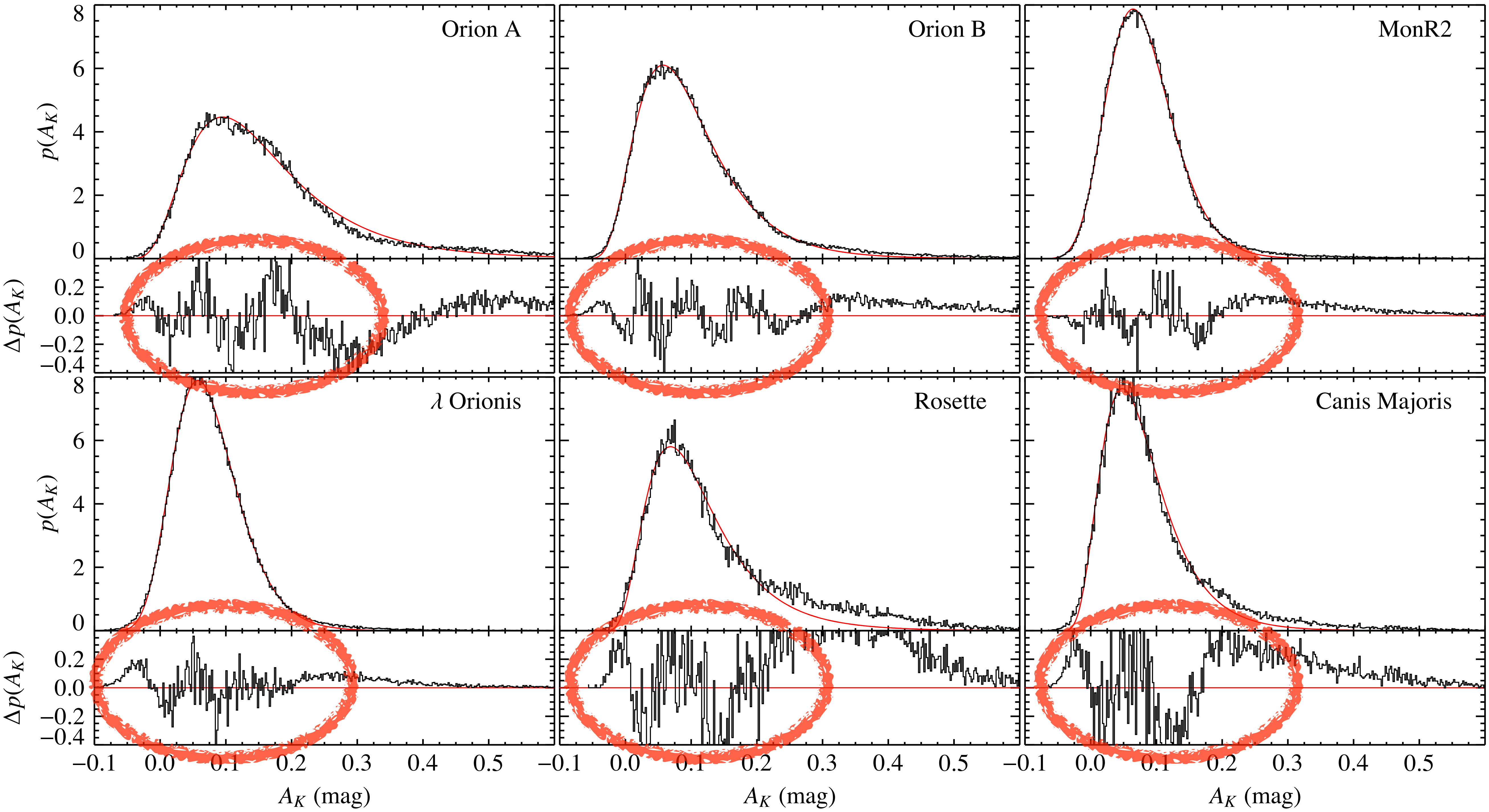




Systematic residuals in the entire fitting region!

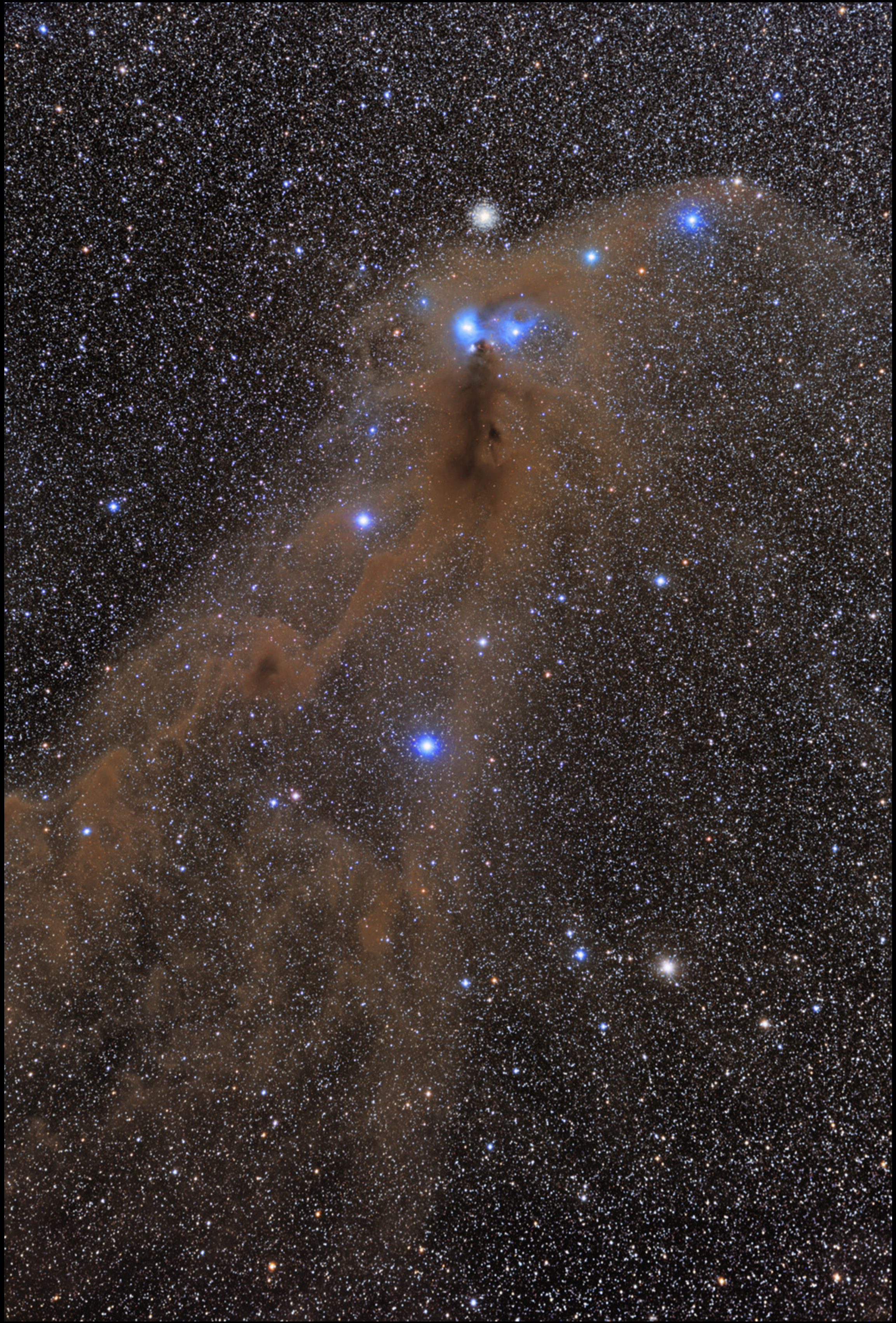
Alves et al. (2014)

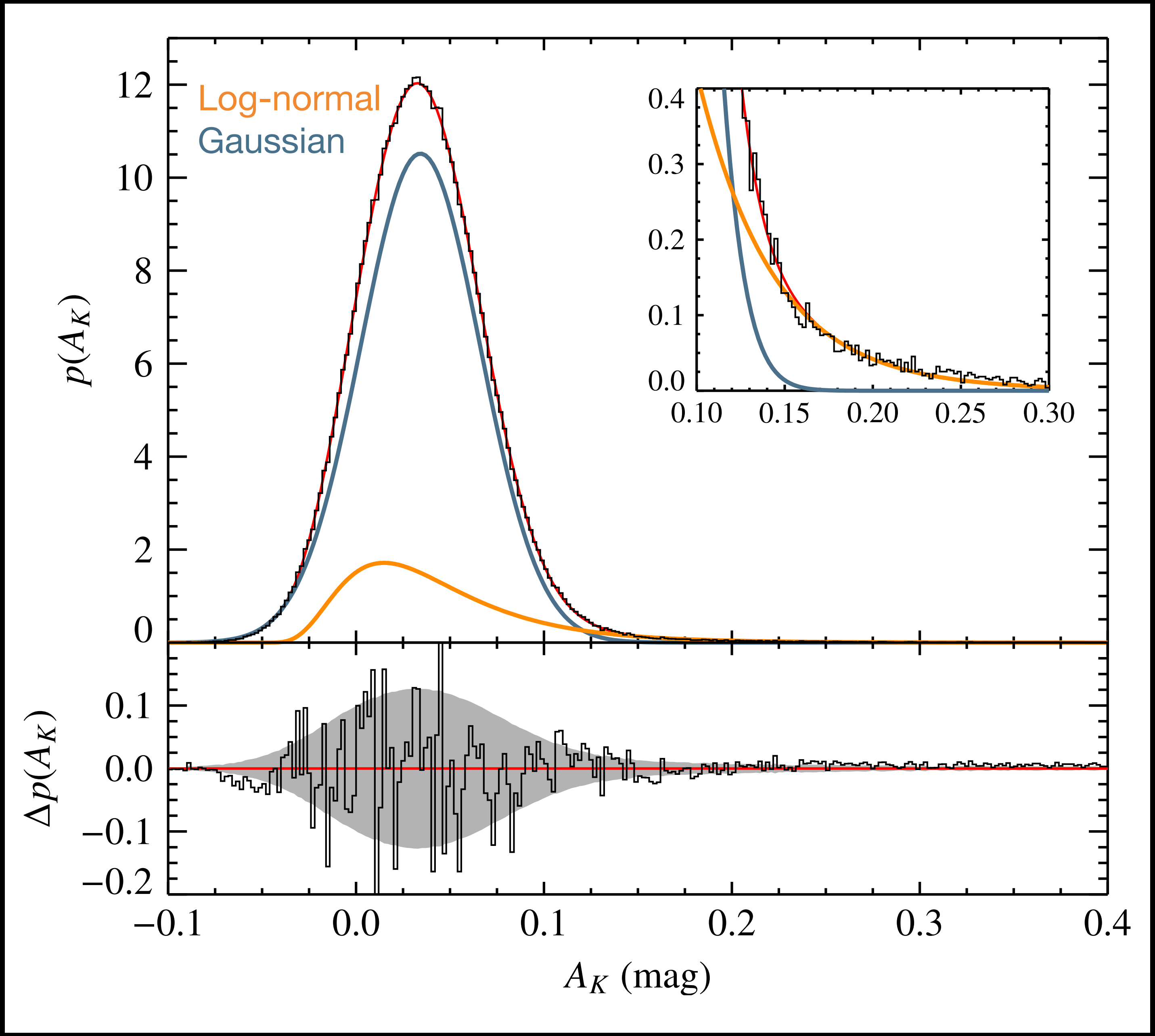
All log-normal fits show systematic residuals



Lombardi et al. (2011)

Log-normals? Think it twice



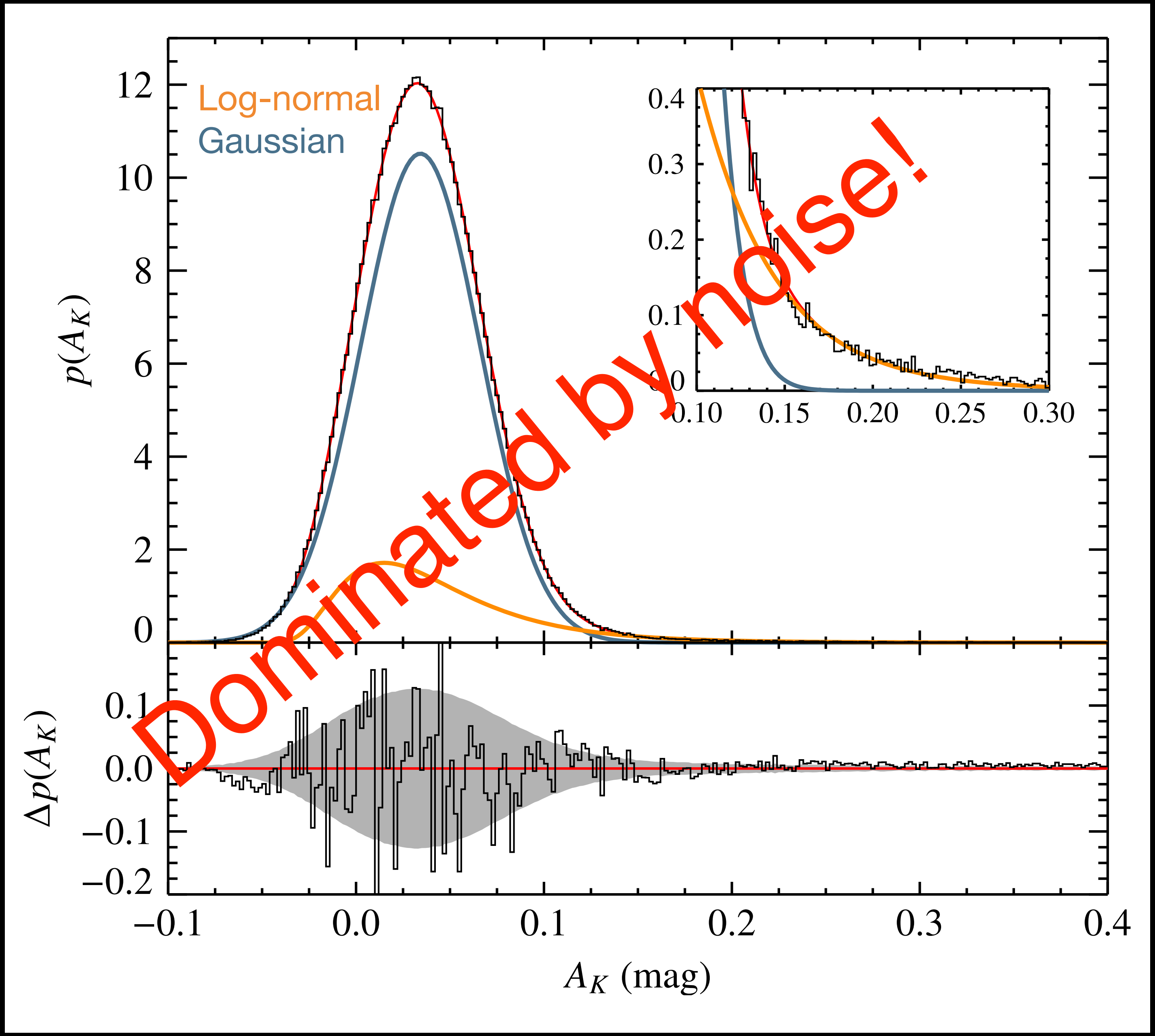


Residuals disappear when fitting a Gaussian + Log-normal.

Alves et al. (2014)

Log-normals? Think it twice

- What is the physical meaning?
    - Gaussian: diffuse extended region + noise
    - Log-normal: denser parts
- What is the role of noise?
    - Dominates at low A_K!
    - Is still present at large A_K
- PDFs not well defined: depend on the boundaries!
- Log-normals: are they real?



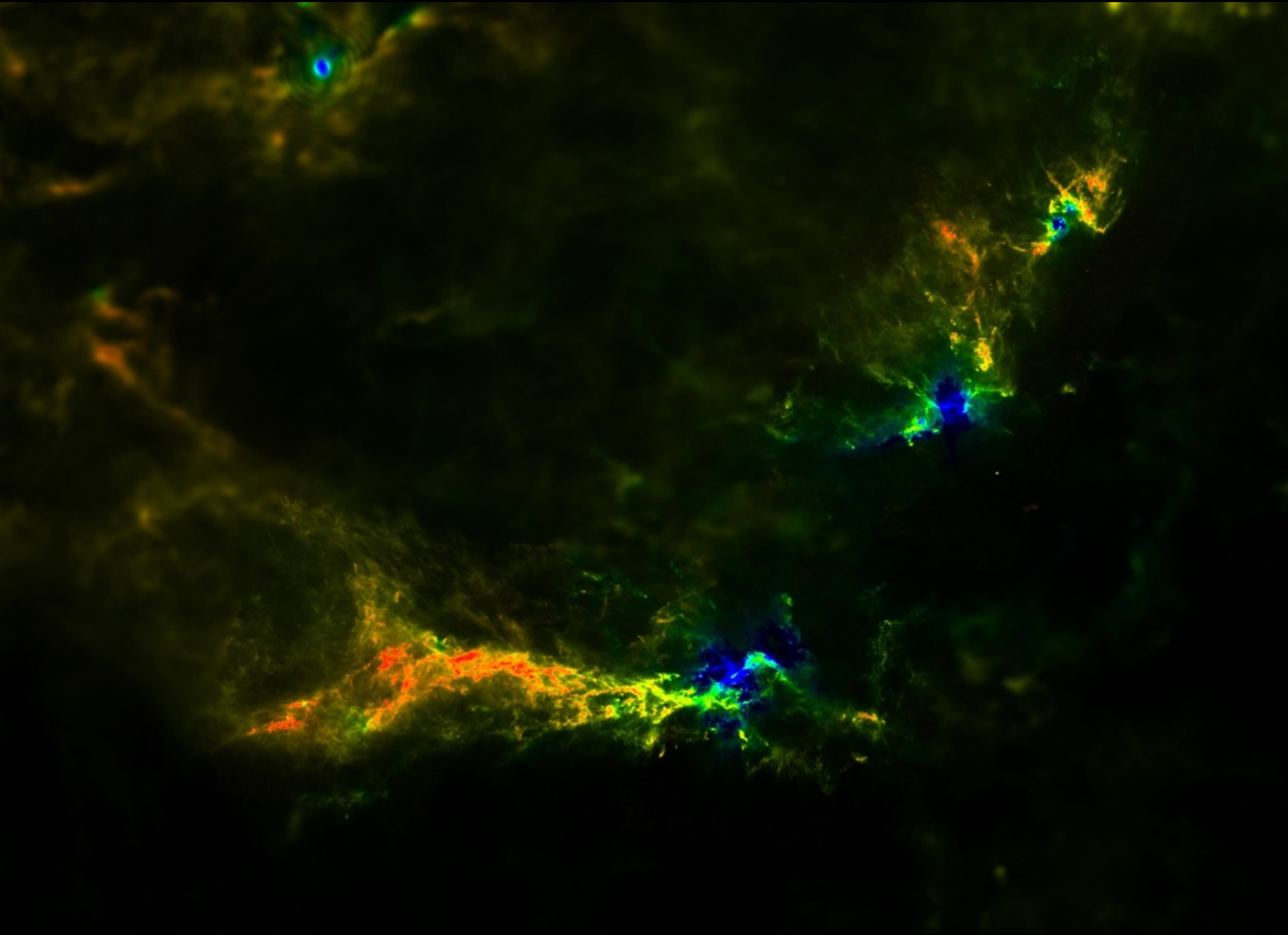
Dominated by noise!

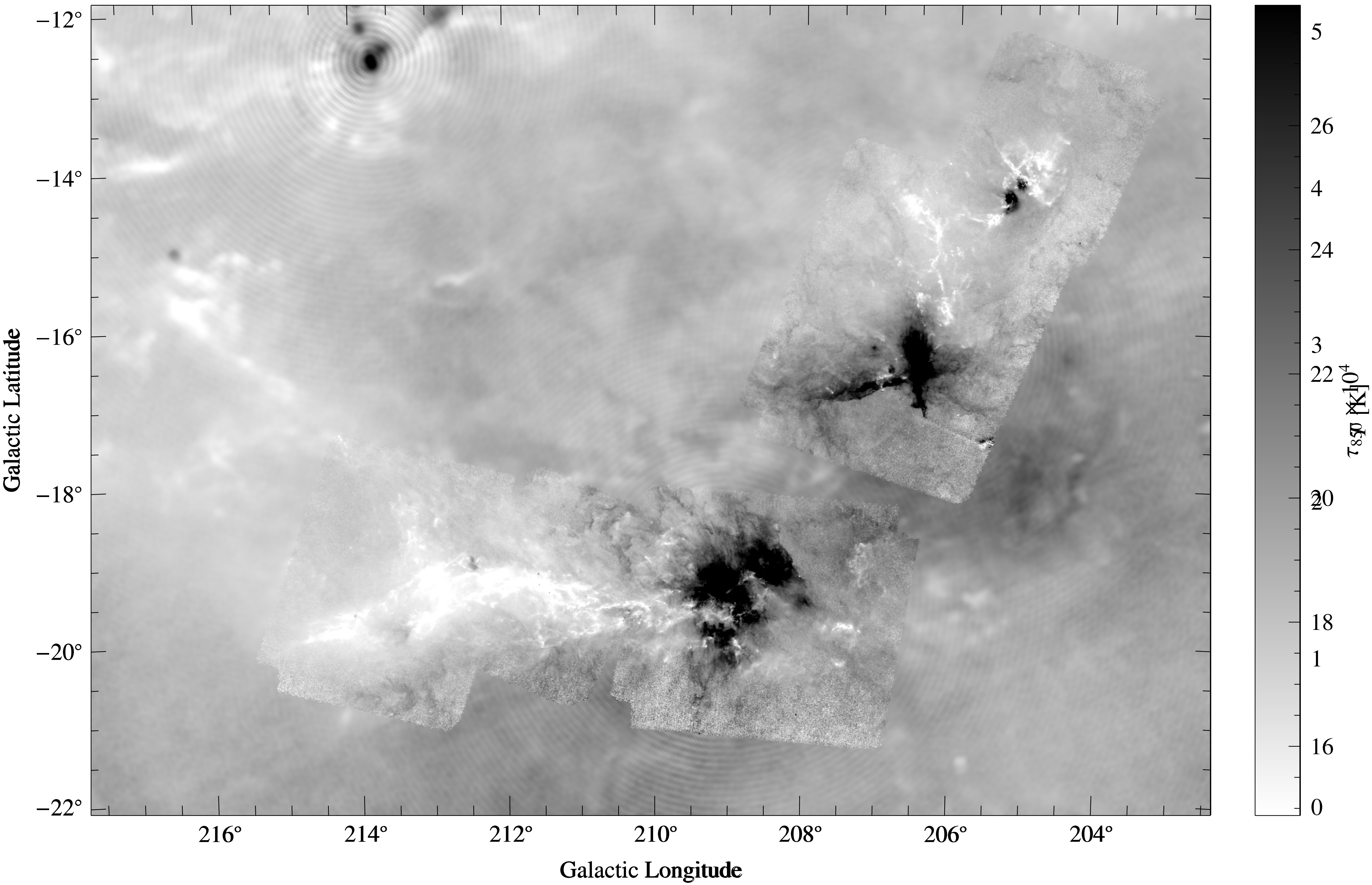
Residuals disappear when fitting a Gaussian + Log-normal.

Alves et al. (2014)

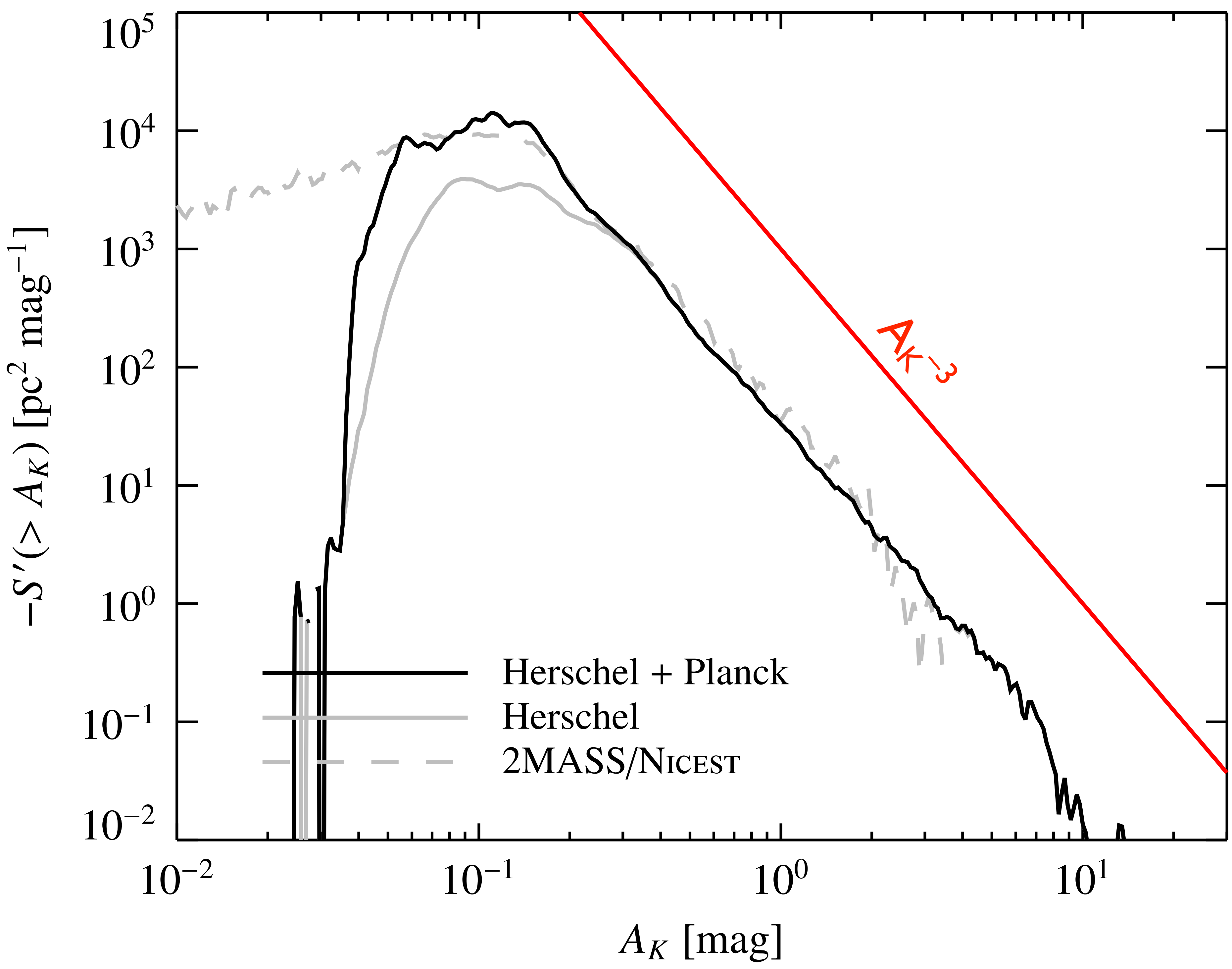
We need high-resolution, low-noise density maps of molecular clouds

i.e., Herschel data…




−12°
−14°
−16°
−18°
−20°
−22°
Galactic Latitude
216°
214°
212°
210°
208°
206°
204°
Galactic Longitude
5
26
4
24
3
22
20
2
18
1
16
0
$\tau_{850} \times 10^4$
T [K]

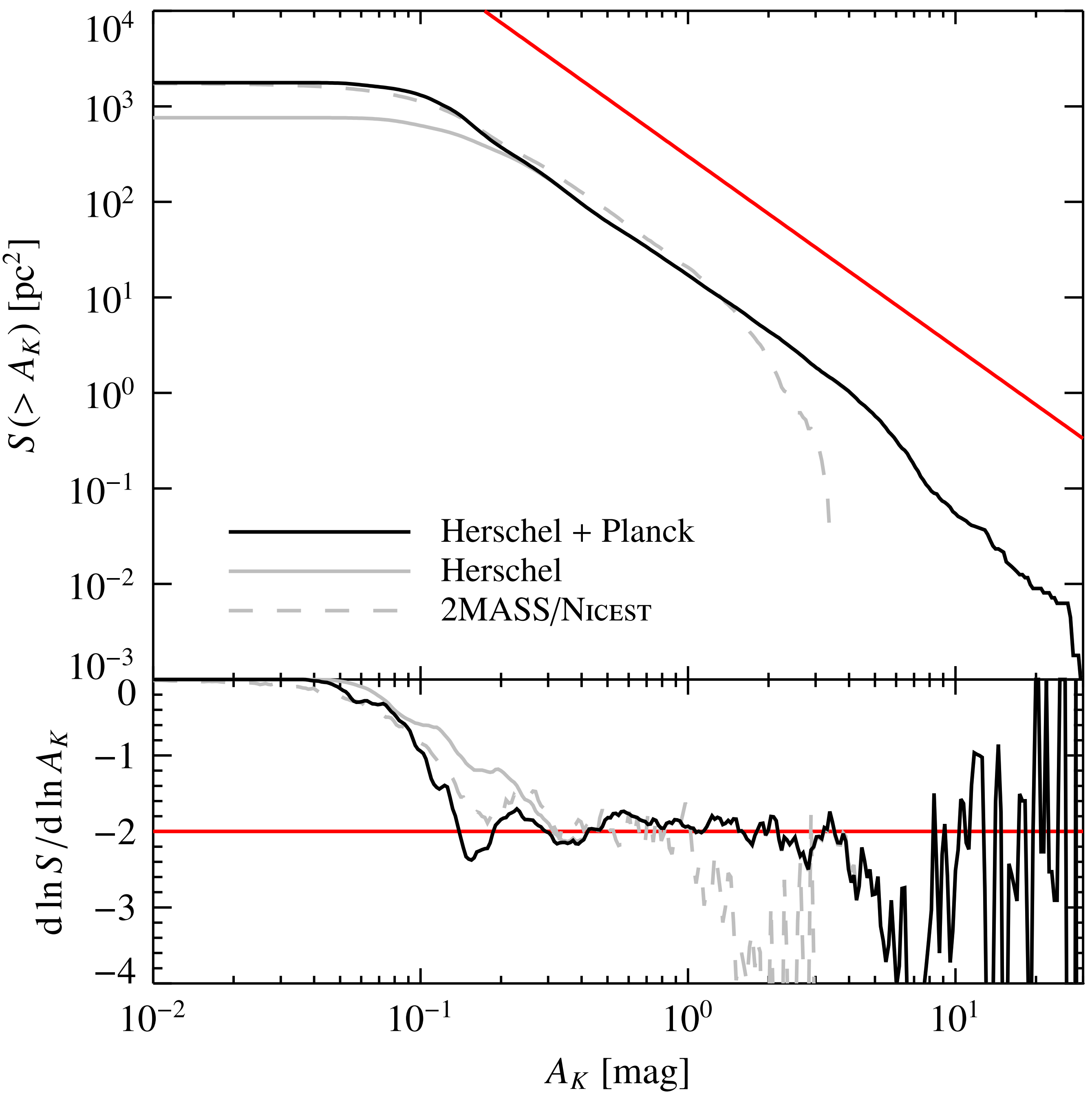
Herschel PDF for Orion B



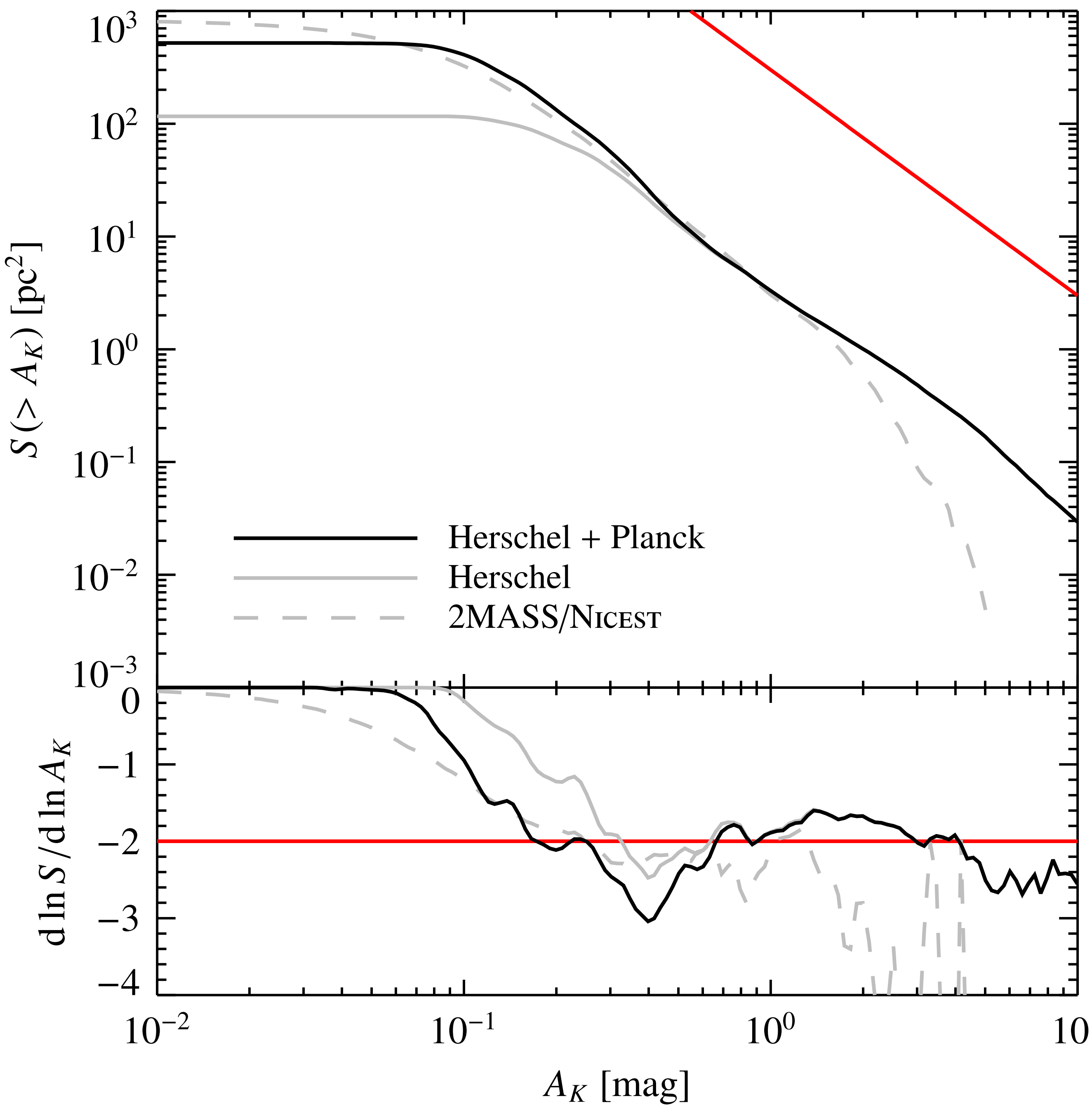
Lombardi et al. (2014)

Fact 5
Scaling laws play a fundamental role in SF

Area functions (integrals of PDFs)



Lombardi et al. (2014)



Alves et al. (2014)

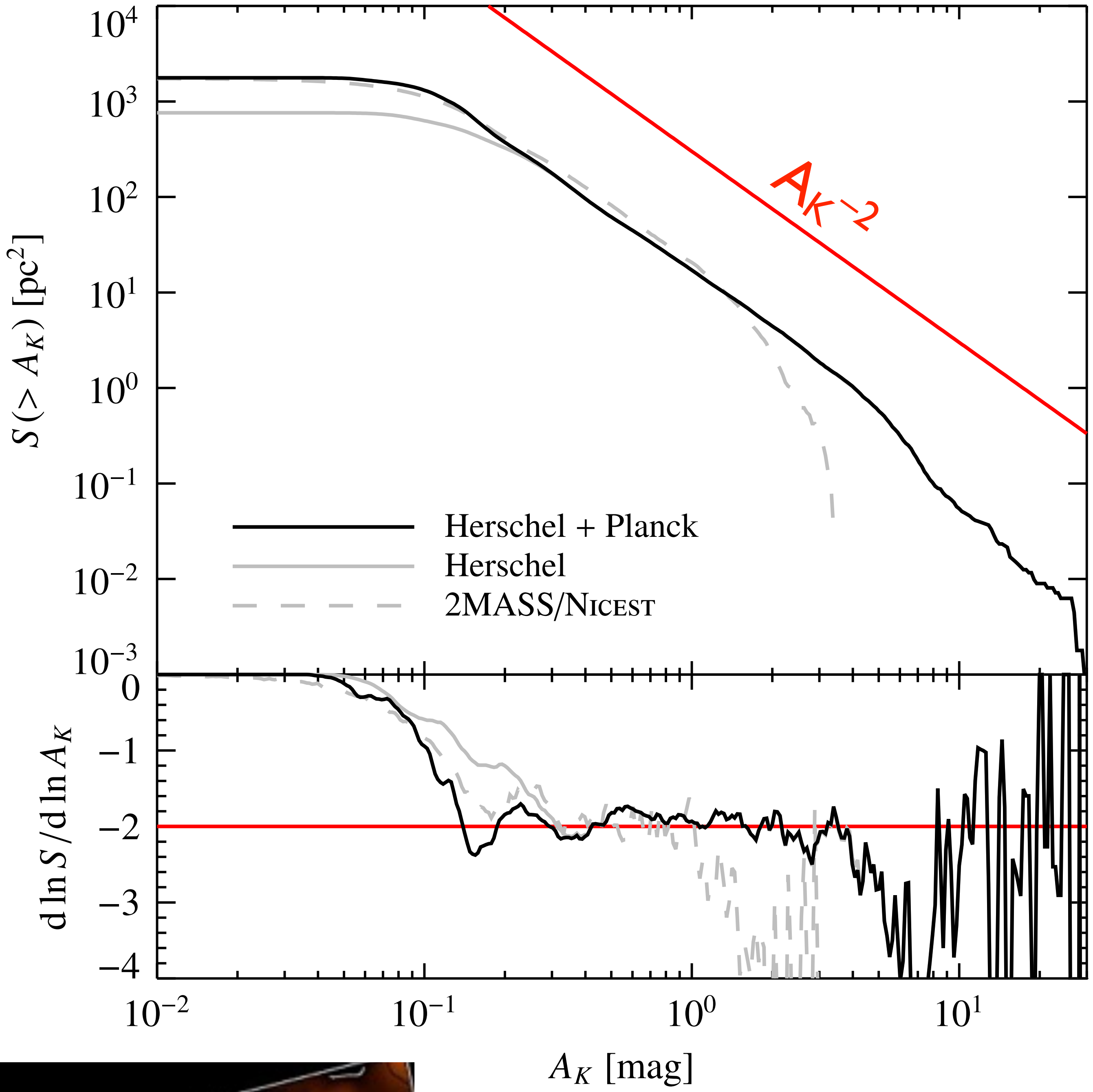
Toy model

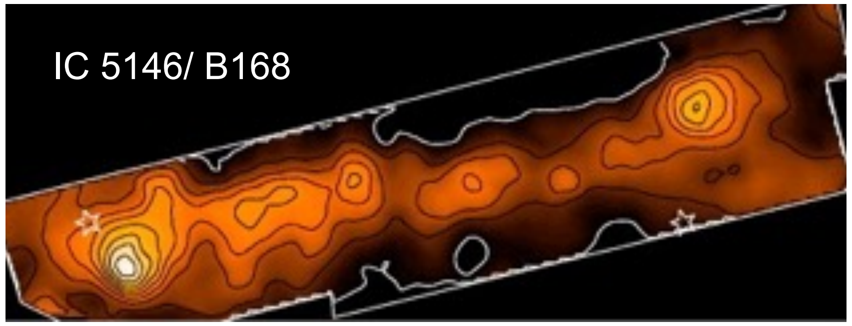
Consider a singular isothermal sphere:

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

$A_K \sim \Sigma \sim R^{-1}$

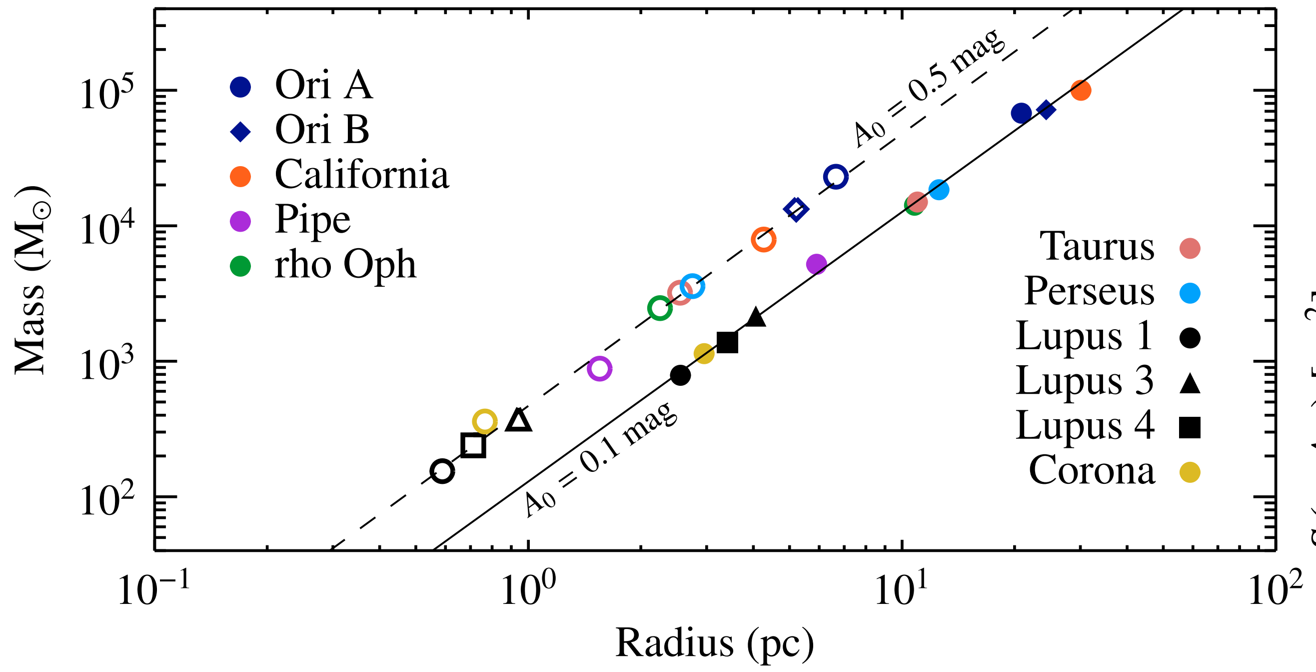
$S(> A_K) \sim R^2 \sim A_K^{-2}$

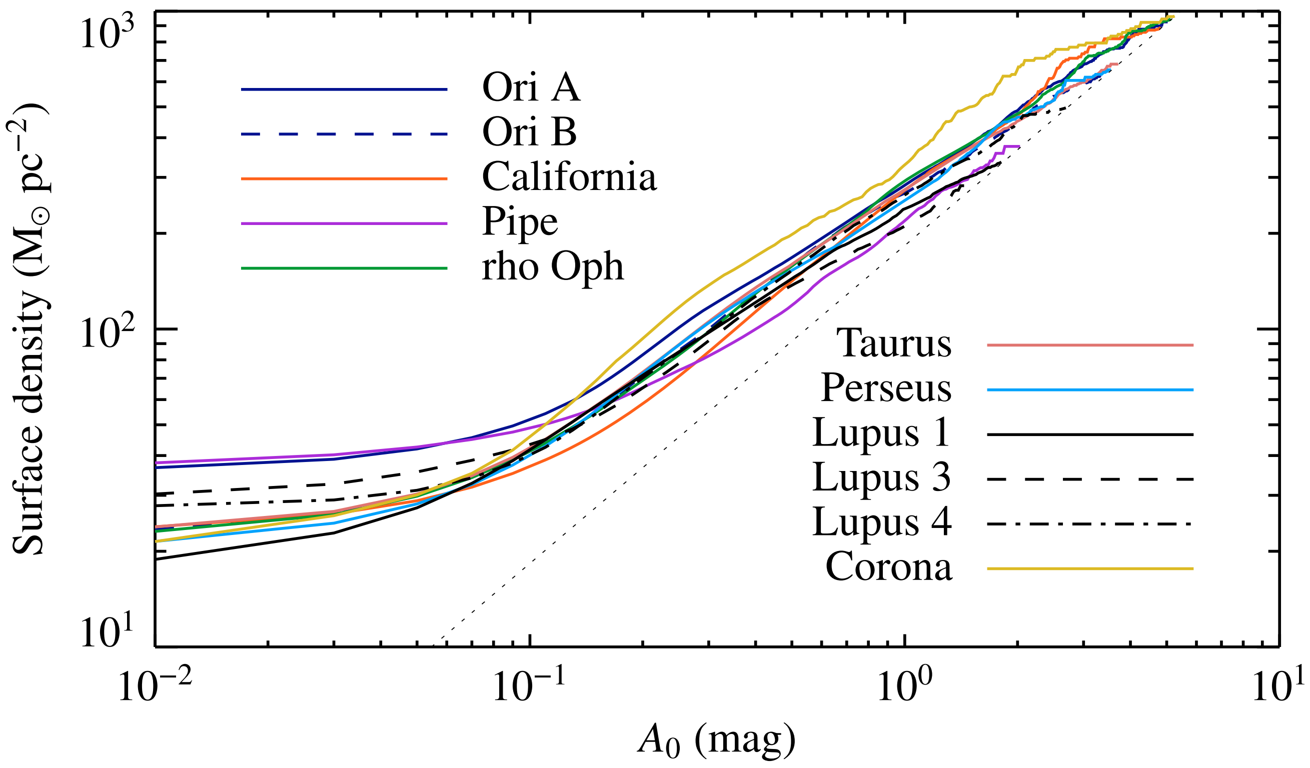


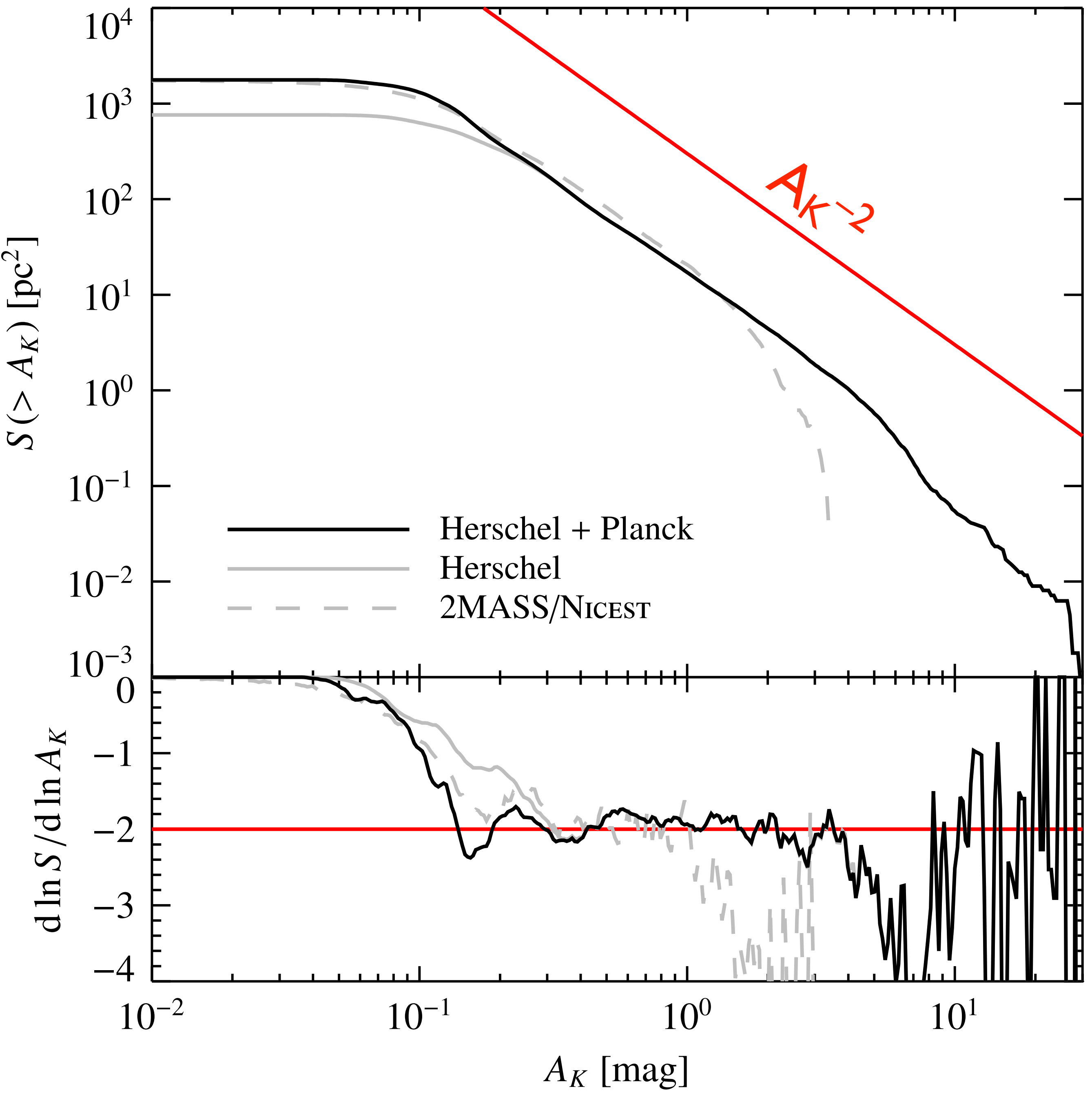


Lombardi et al. (2014)

Various scaling laws are related







Lombardi et al. (2014)

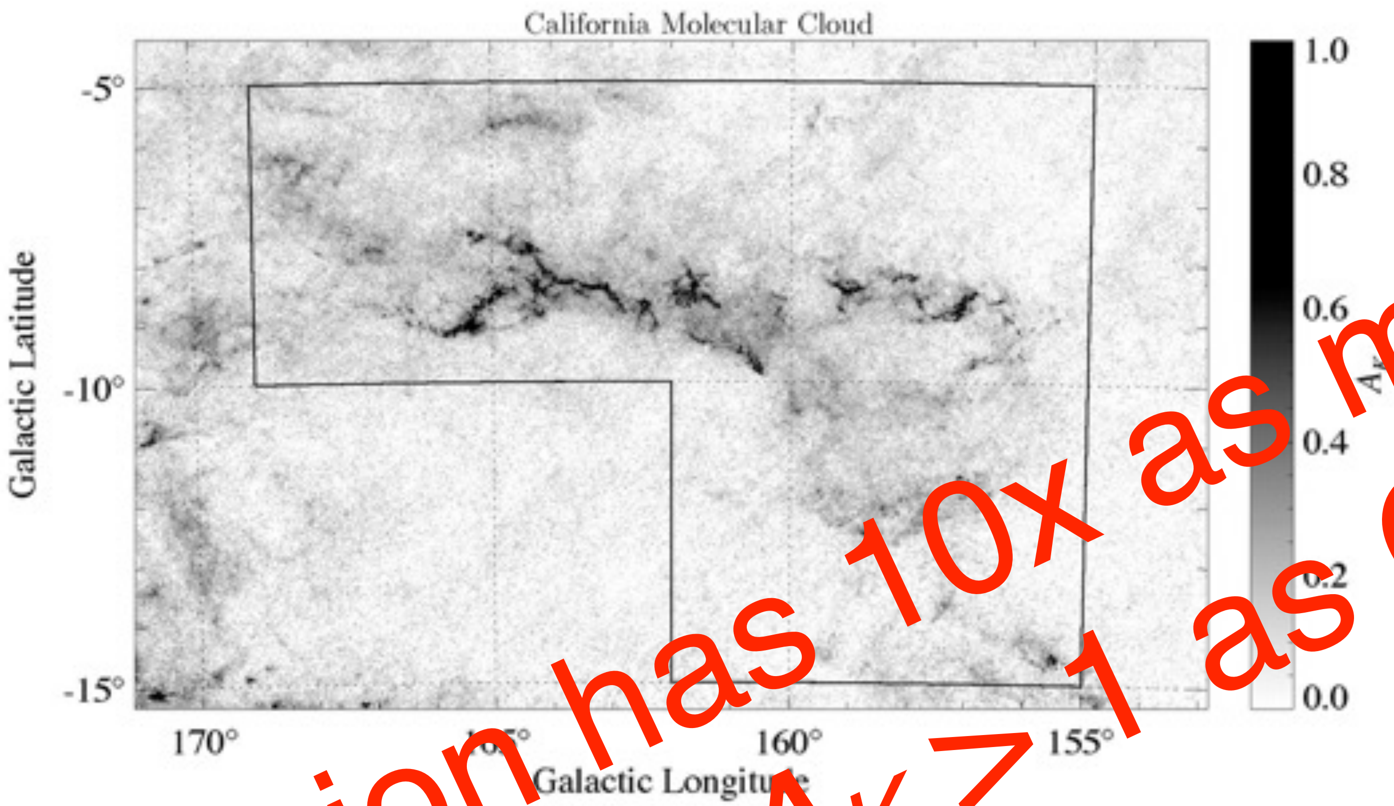
SFRs in the California and Orion molecular clouds

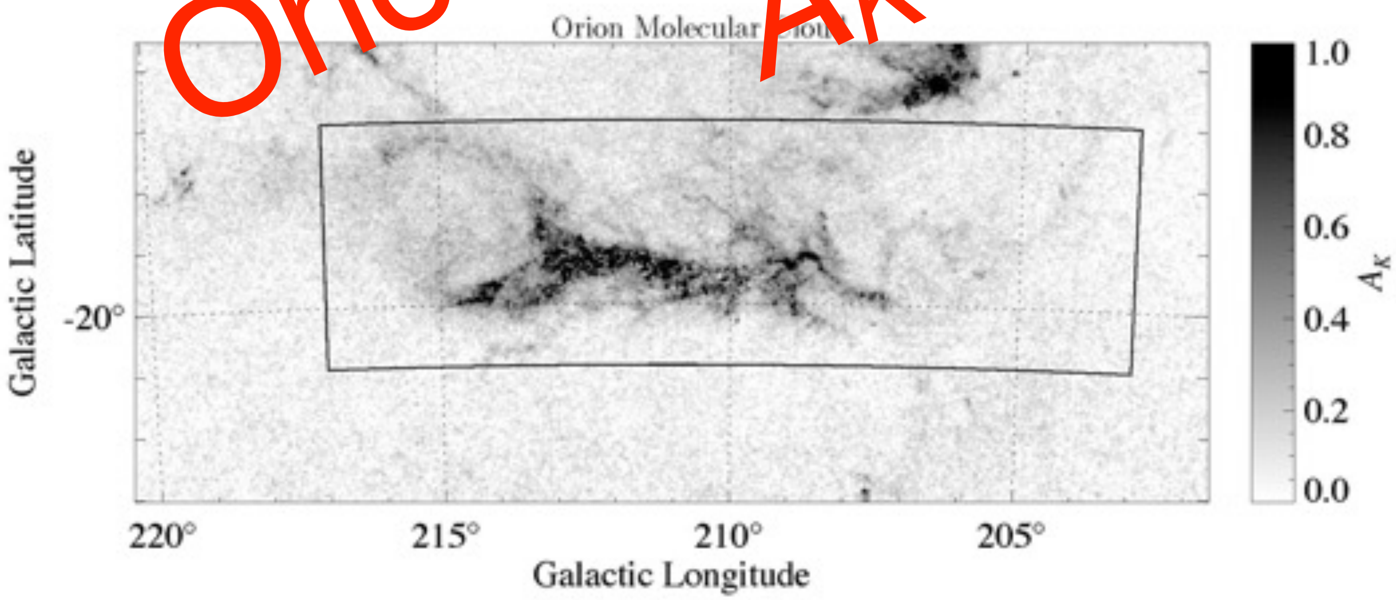
Nearly identical shapes & sizes, but

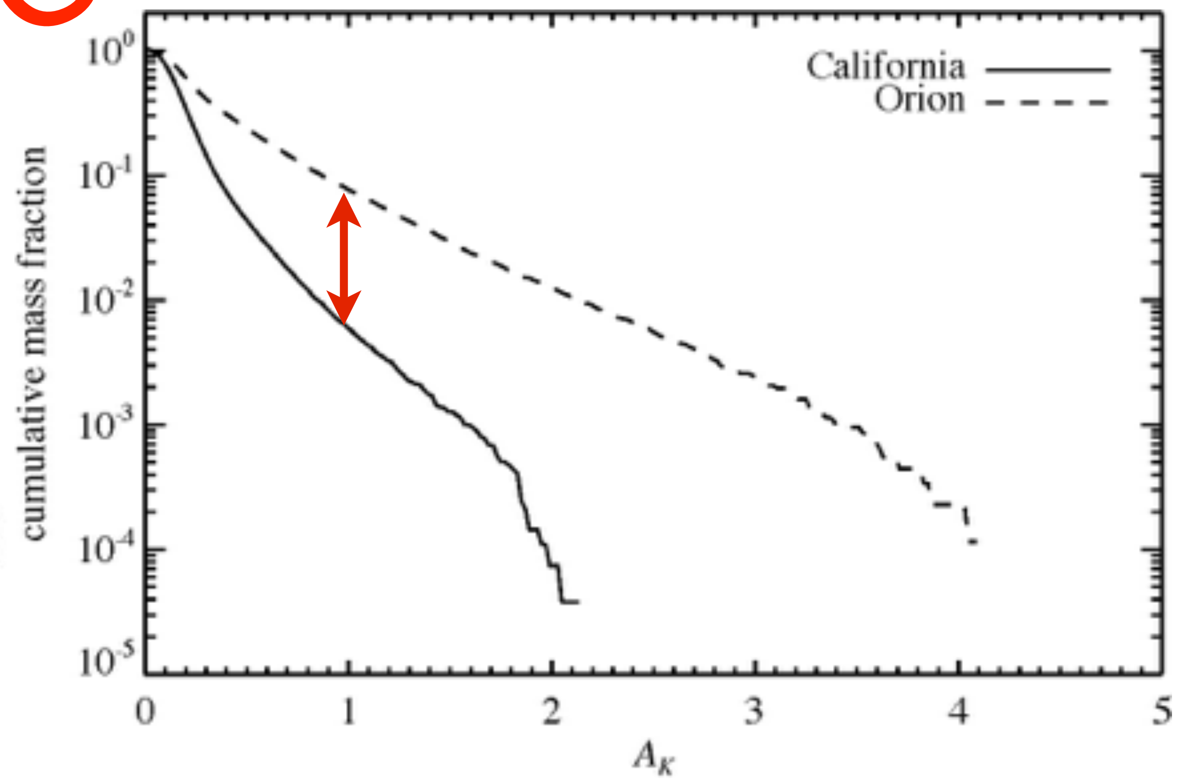
YSOs(Orion) > 10 x YSOs(California)

SFR(Orion) > 10 x SFR(California)

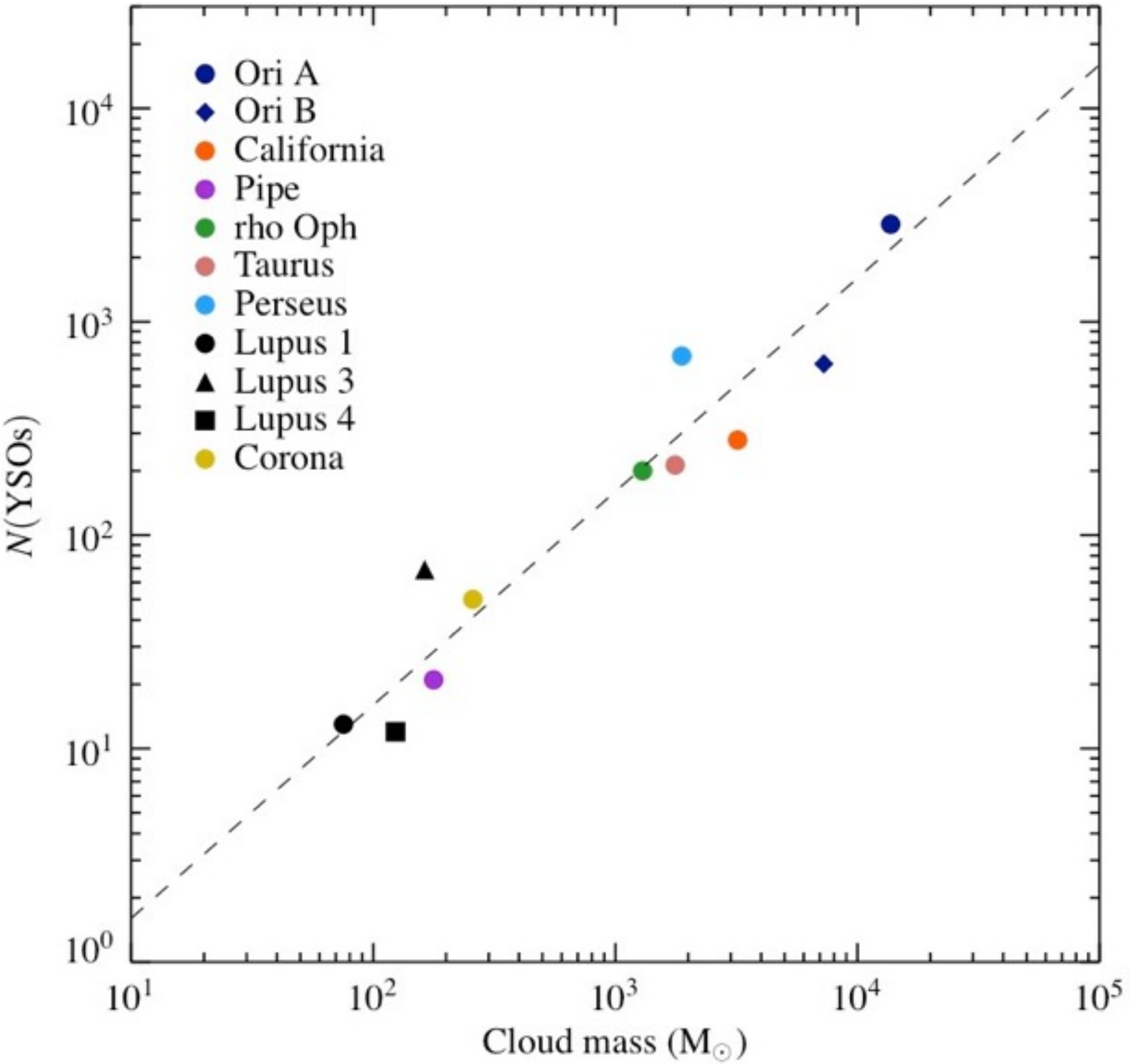
Orion has 10x as much material at $A_K > 1$ as California



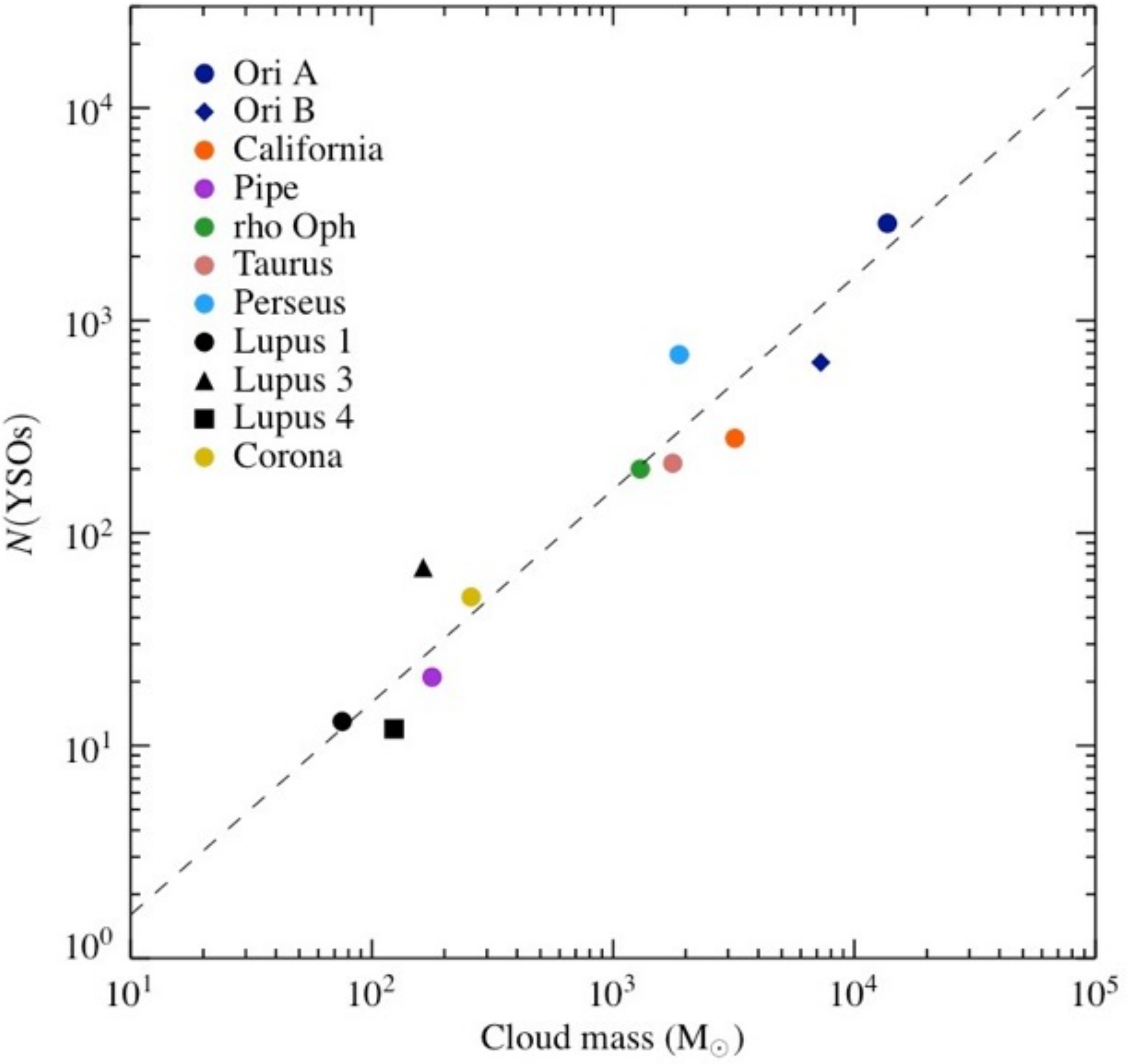




SFR directly proportional to mass above $A_K > 0.8$ mag ($\Sigma > 116\ M_\odot\ \mathrm{pc}^{-2}$)

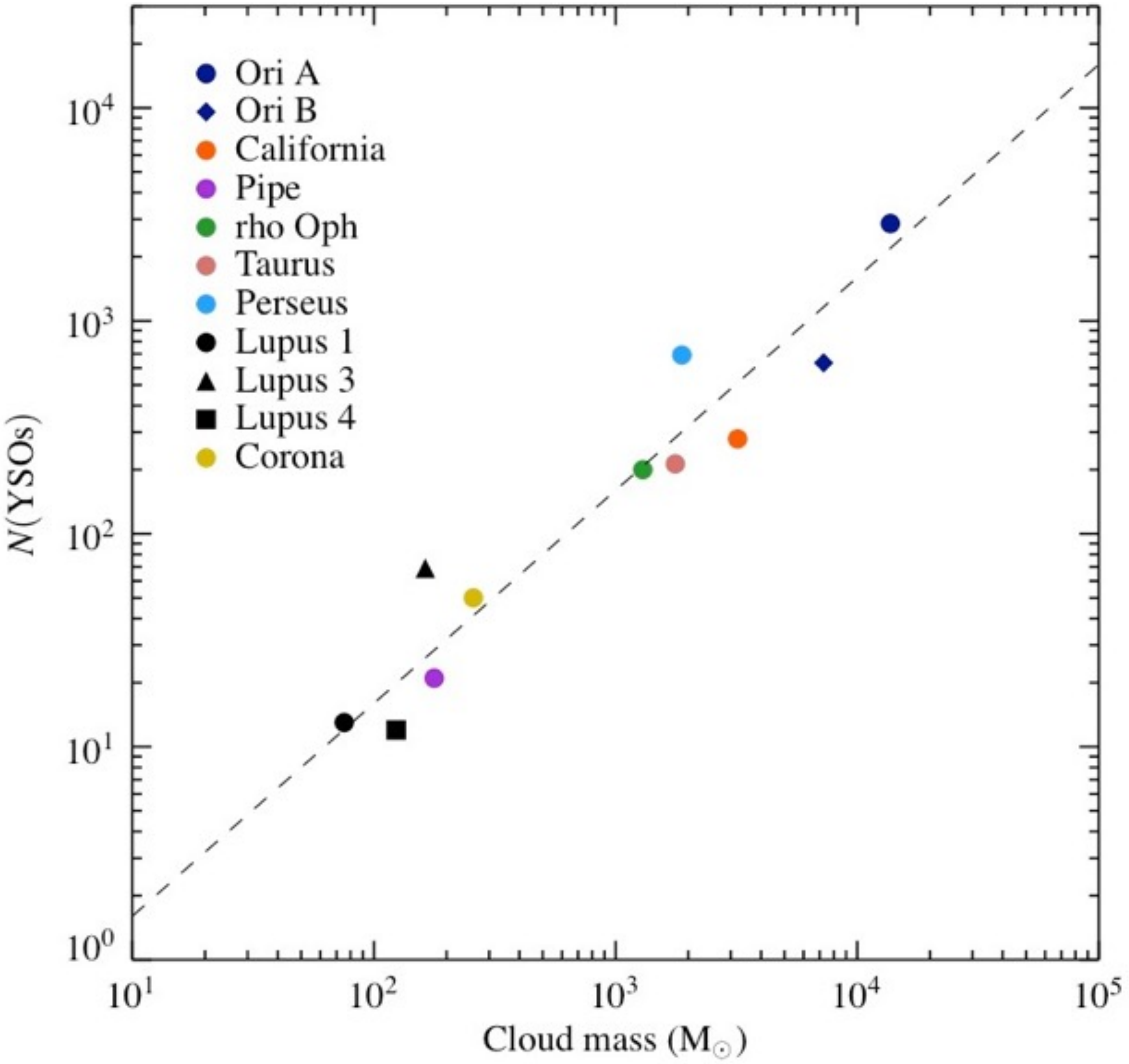


SFR directly proportional to mass above A_K > 0.8 mag (Σ >116 $M_\odot$ pc^{-2})



SFR directly proportional to mass above $A_K > 0.8$ mag ($\Sigma > 116\ M_\odot\ \mathrm{pc}^{-2}$)

$$\boxed{\left(\frac{SFR}{\mathrm{M}_\odot\ \mathrm{yr}^{-1}}\right) = 4.6 \times 10^{-8} \left(\frac{M_{0.8}}{\mathrm{M}_\odot}\right)}$$

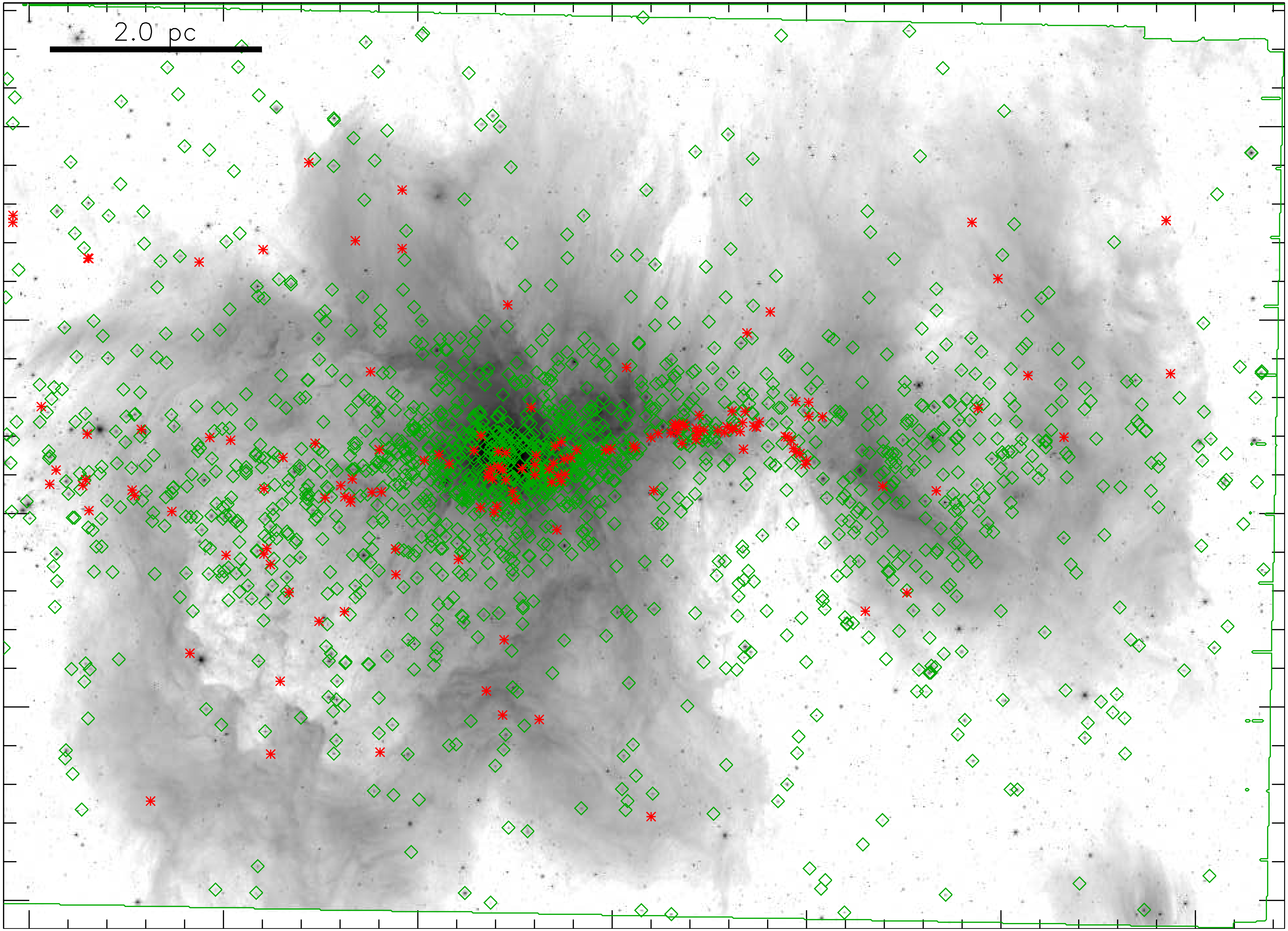


What is the meaning of the slope of this relation?

$$SFR = \varepsilon M_{0.8}/\tau_{\mathrm{sf}}$$

$$\tau_{\mathrm{sf}} \simeq 2 \times 10^6\ \mathrm{yr}$$

$$\varepsilon = SFE \simeq 0.10$$



Megeath et al. (2012)

Interlude
Fitting random spatial data

Fitting random spatial data

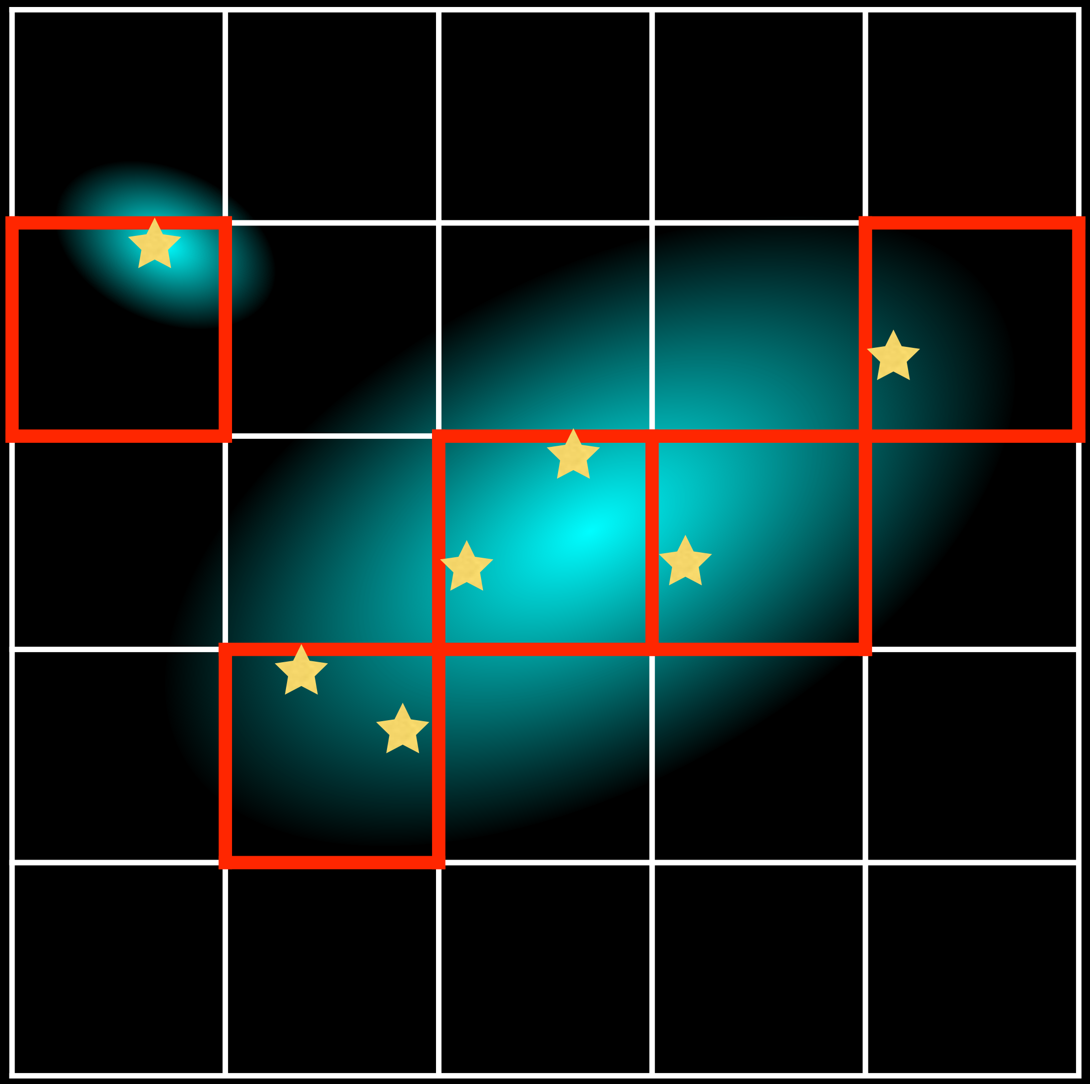
Problem 1: check if a set of points is a likely realization of a 2D density

Solution: bin the data and apply a Poisson statistics

$$P(N_i) = \mathrm{e}^{-\mu_i} \frac{\mu_i^{N_i}}{N_i!}$$

$$\mu_i = \int_{\square_i} \Sigma(x)\, \mathrm{d}^2 x$$

$$P_{\text{tot}} = \prod_i P(N_i)$$



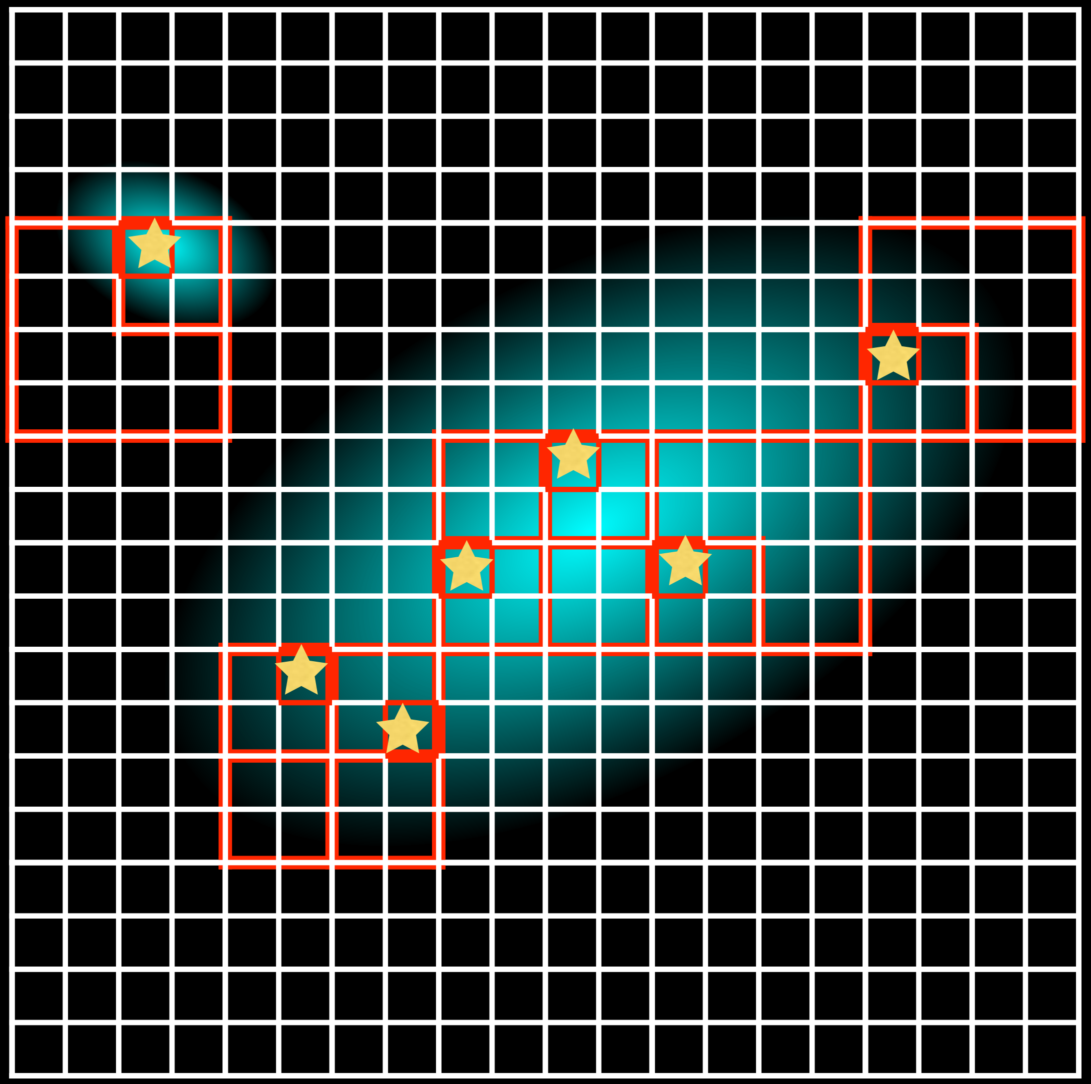
(Sarazin 1980, Lombardi et al. 2013)

Fitting random spatial data

Problem II: how should we bin the data?

Solution: use infinitesimal bins (easier math, optimal test)

$$P(N_i) = \begin{cases} 1 - a\Sigma(x_i) \\ a\Sigma(x_i) \end{cases}$$

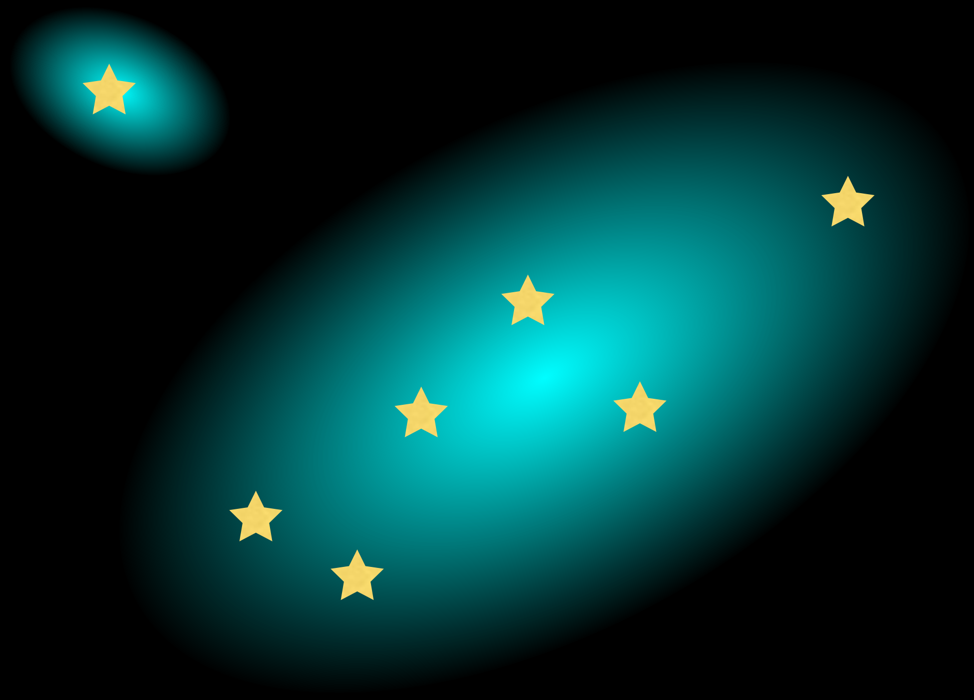


The final solution is best expressed using logarithms

$$\ln P_{\rm tot} \equiv L = \sum_i \ln \Sigma(x_i) - \int \Sigma(x)\, \mathrm{d}^2 x$$

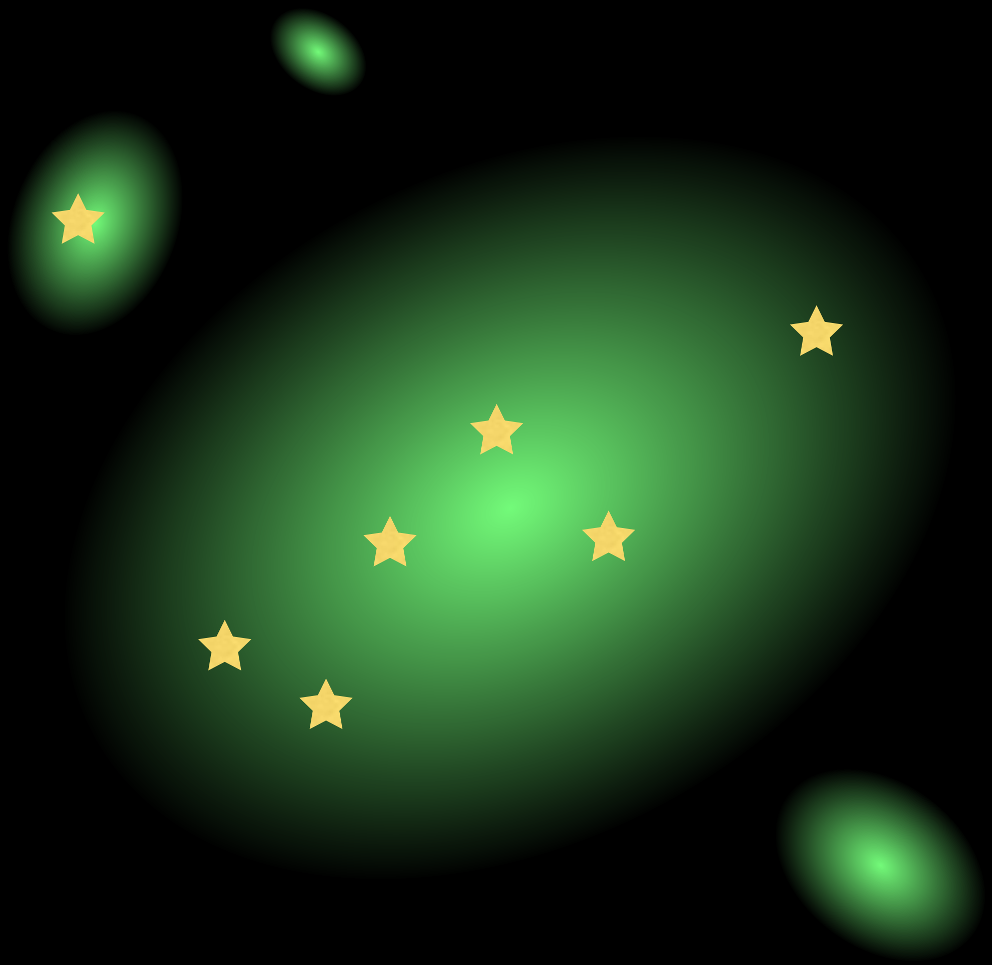
Fitting random spatial data

Problem III: which density fits best the data?



Fitting random spatial data

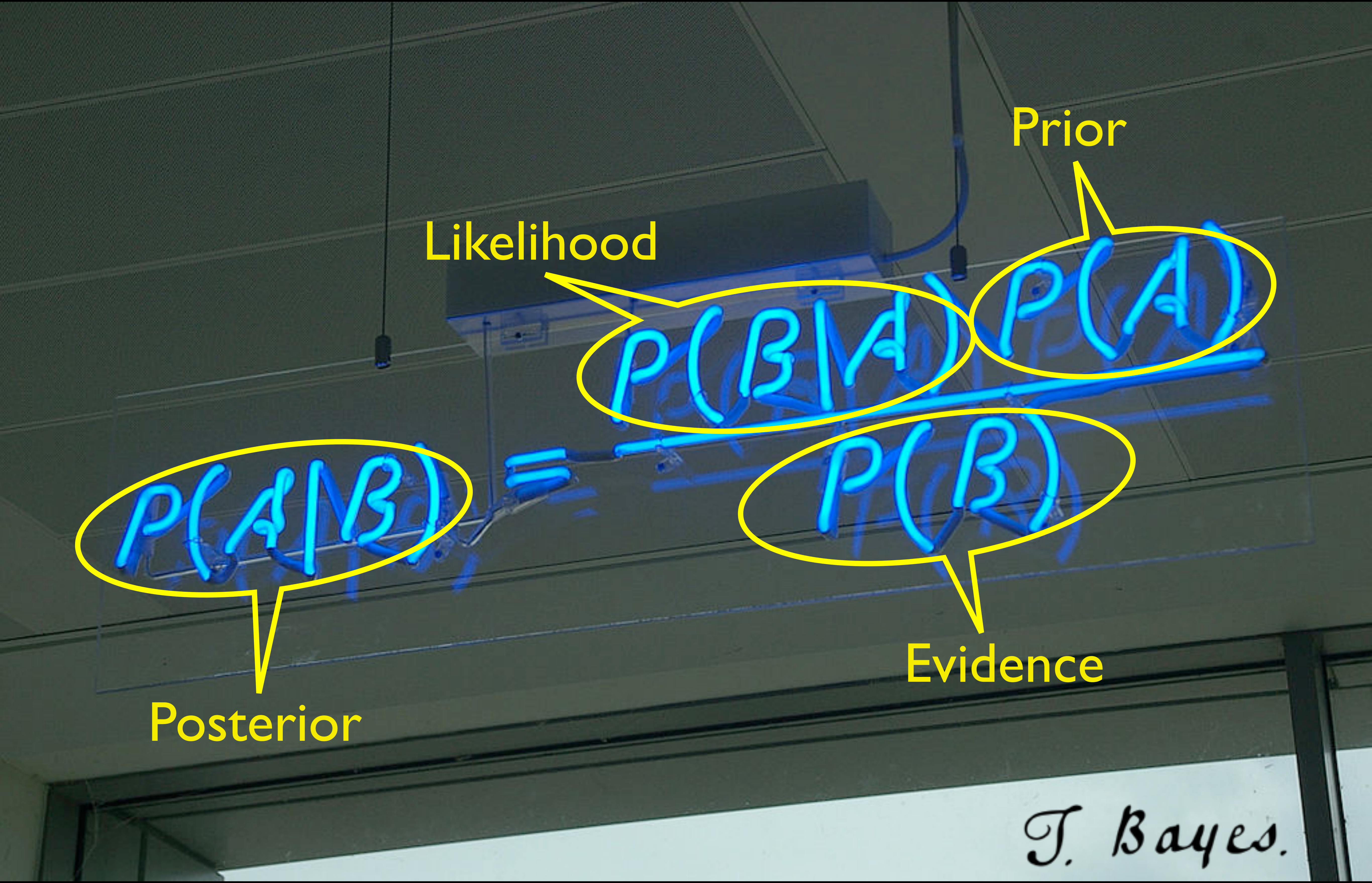
Problem III: which density fits best the data?



Fitting random spatial data

Problem III: which density fits best the data?

Solution: this is an inverse problem, and therefore we use...



Prior

Likelihood

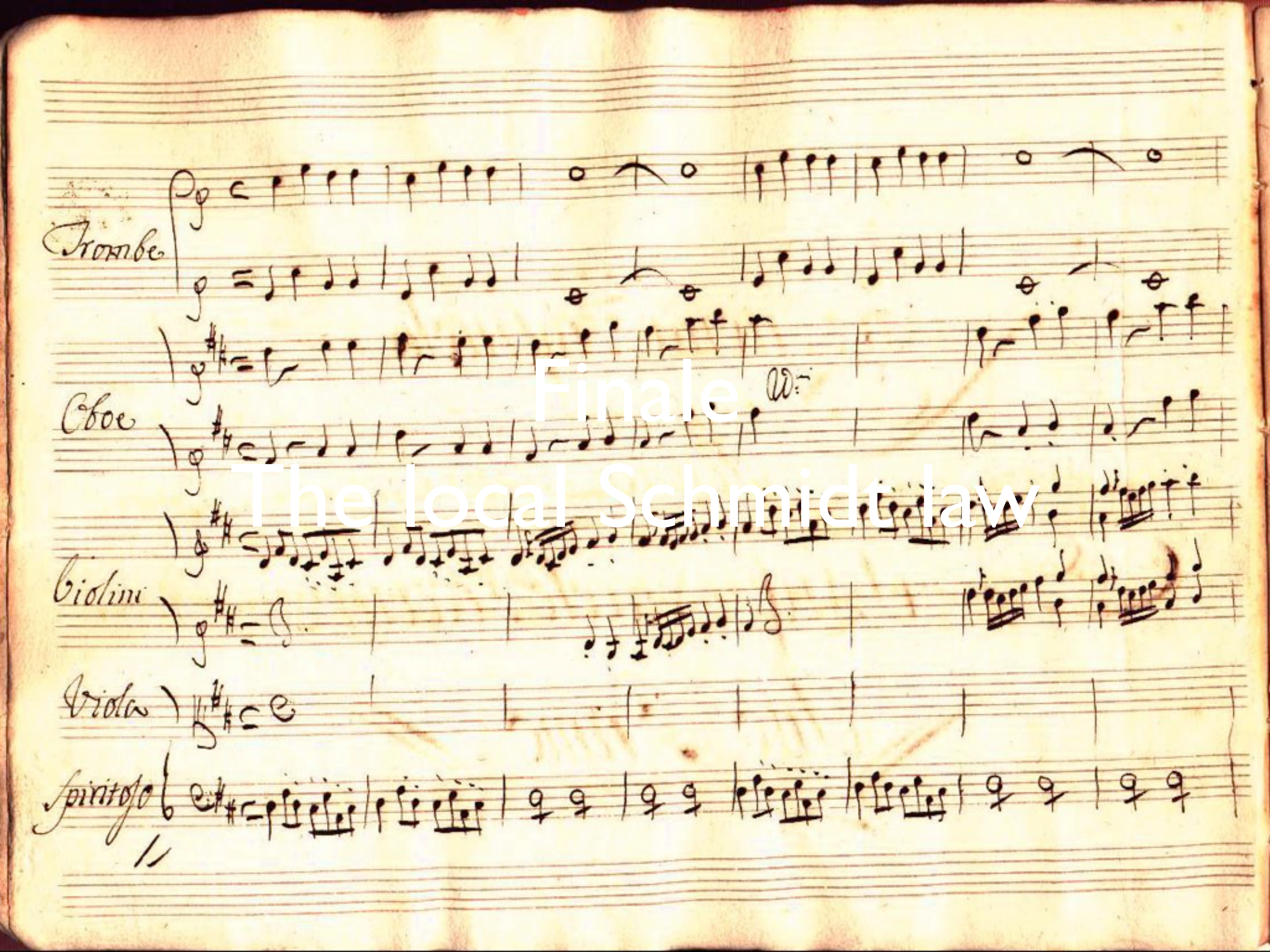
Evidence

Posterior

T. Bayes.

Finale

The local Schmidt law

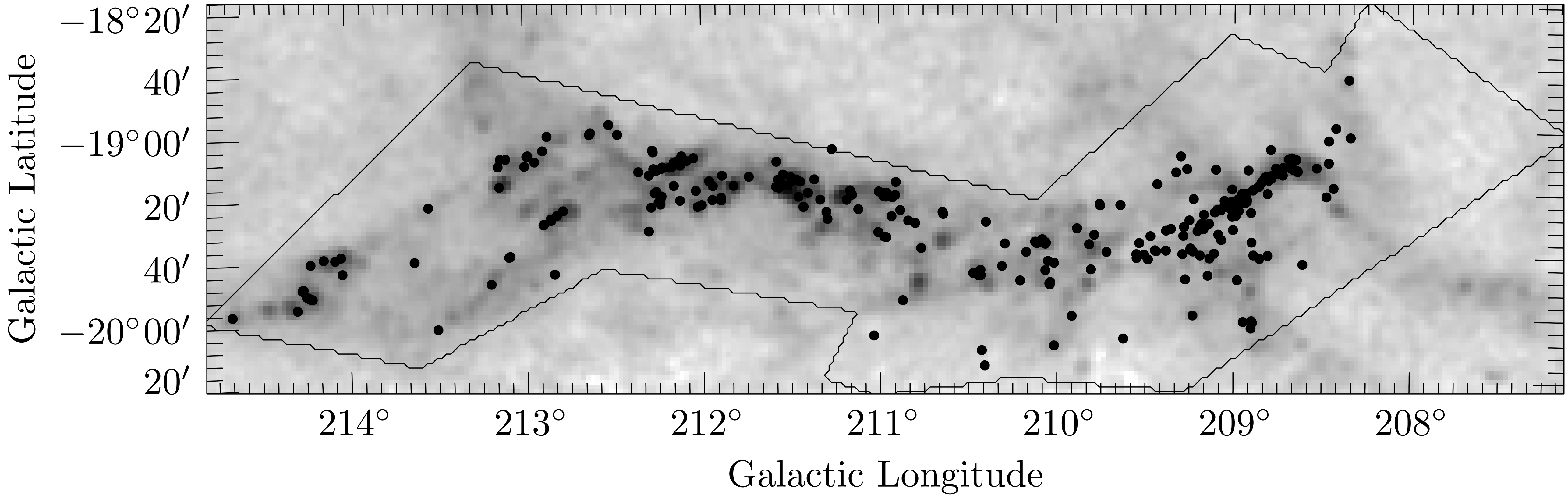


The local Schmidt law

- Density of protostars: $\boxed{\Sigma_\star(x) = \kappa\big[A_K(x)\big]^\beta}$
- Include other possible effects:
    - A threshold: $\Sigma_\star(x) = 0$ if $A_K(x) < A_0$
    - The diffusion of the stars from the cloud (σ)
    - [Contamination by spurious sources…]
- Data: 2MASS/Nicer extinction maps and Spitzer catalogues of YSOs

Orion A

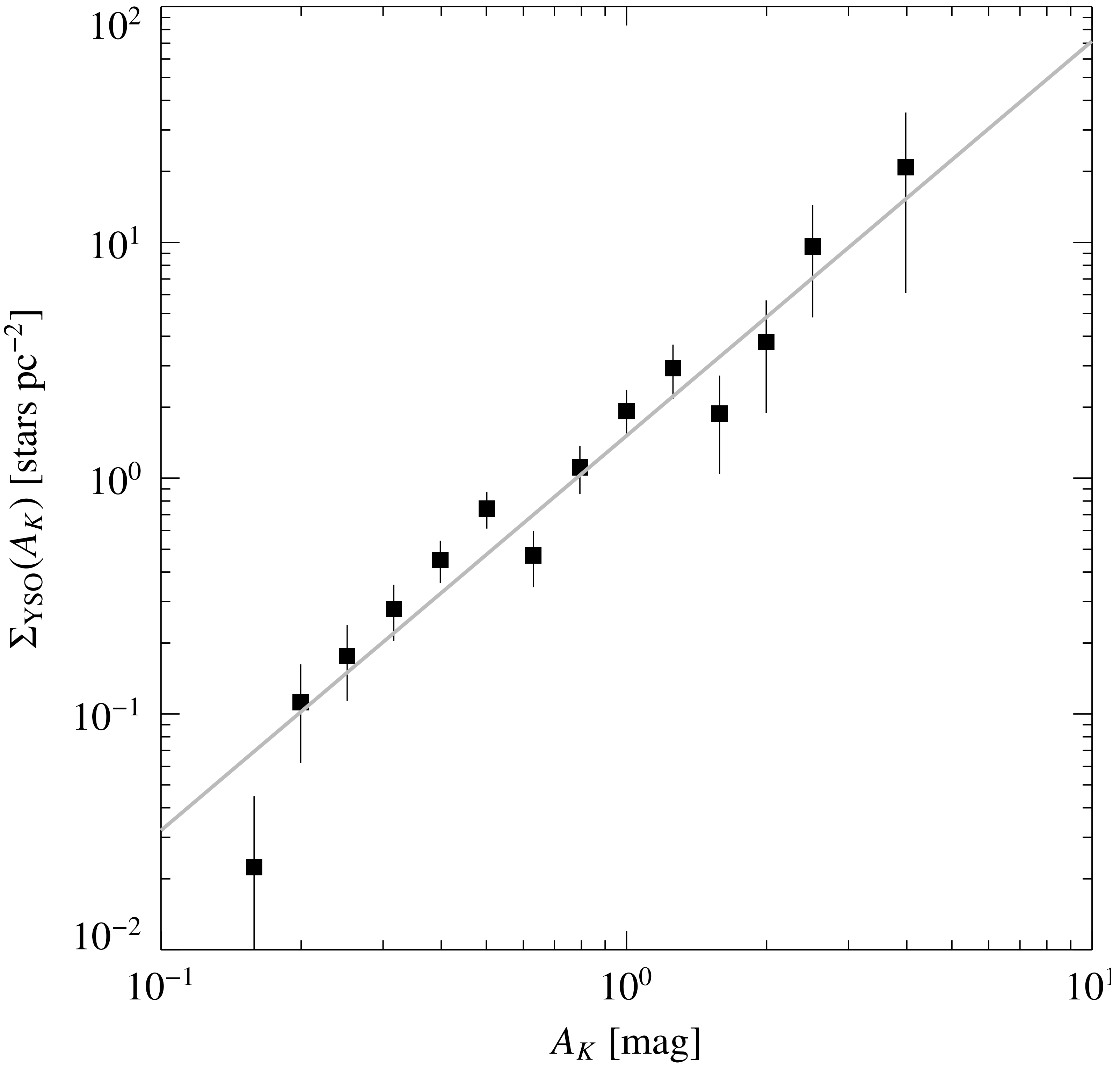
(Lombardi et al. 2011, 2013)

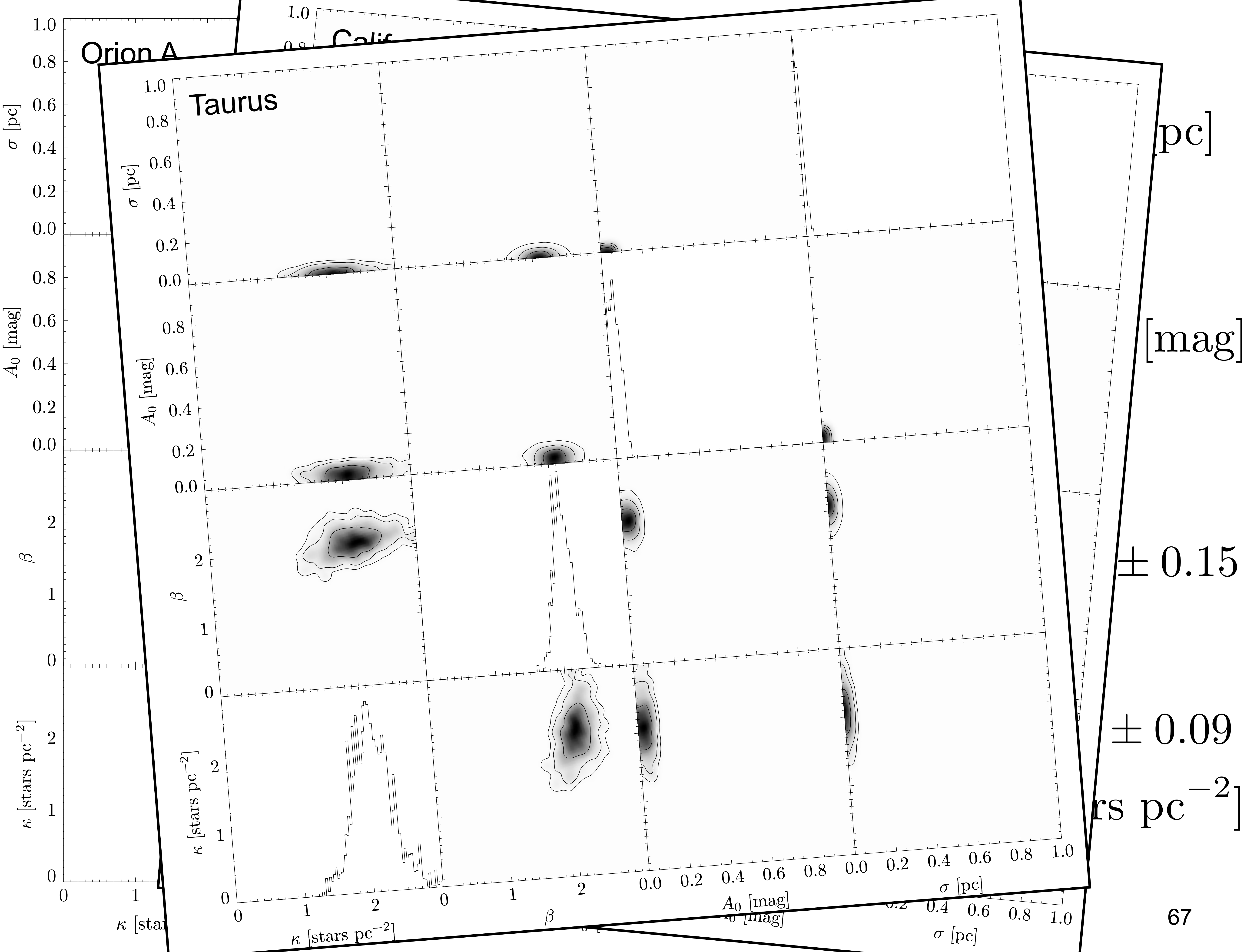


- 329 Class I protostars in Orion A
- Posterior distribution sampled with MCMC
- Inferred credible intervals over 4 parameters

Orion A

(Lombardi et al. 2011, 2013)




Taurus
Orion A
Calif
σ [pc]
A_0 [mag]
β
κ [stars pc^{-2}]
[pc]
[mag]
± 0.15
± 0.09
rs pc^{-2}]
0.0
0.2
0.4
0.6
0.8
1.0
0
1
2

A consistent picture

- The local Schmidt law holds: SFR ~ Σ^2
- Clouds are self-similar above a threshold, with isothermal profiles $S(>\Sigma) \sim \Sigma^{-2}$
  - 3rd Larson's law holds: identical Σ above threshold
- Stars form in dense regions of molecular clouds
  - "protected" environment: cold gas, no UV radiation, Jeans/Bonnor-Ebert instability
  - SFR proportional to the amount of mass above a (projected) density threshold, SFR ~ M_{dense}

SUMMARY

1. Scaling laws are ubiquitous in molecular cloud physics (local Schmidt law, Larson’s law, power-laws for PDFs)

2. Large differences in the properties of molecular clouds might be confined to the low-density, peripheral areas

3. Current observations show that clouds have self-similar structures