Star Formation Rates in Molecular Gas and the Nature of the Extragalactic Scaling Relations

Marco Lombardi, University of Milan

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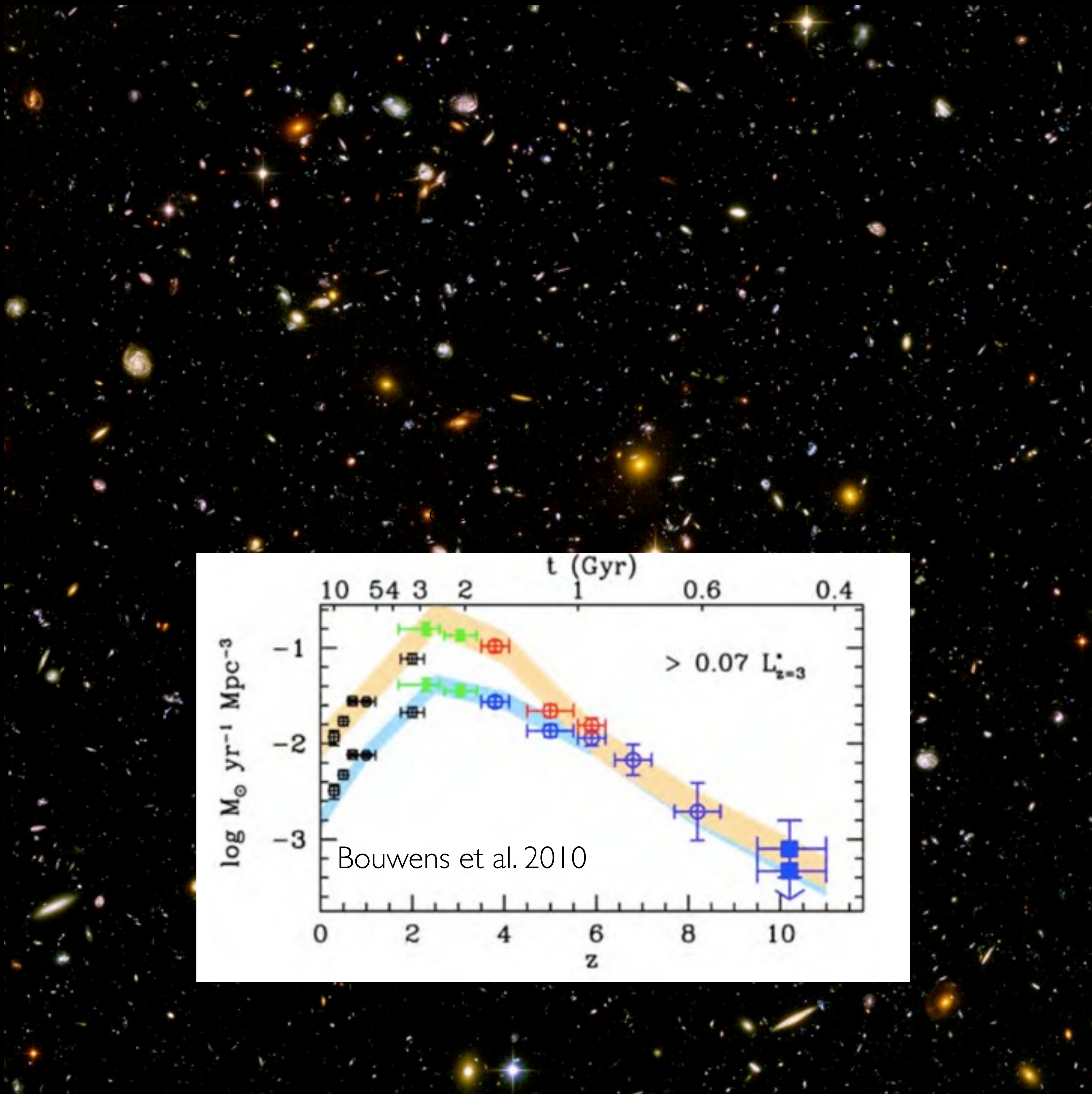
Marco Lombardi, University of Milan

with:
Charles Lada, CfA
Joao Alves et al., University of Vienna

$z = 0.1 - 10$

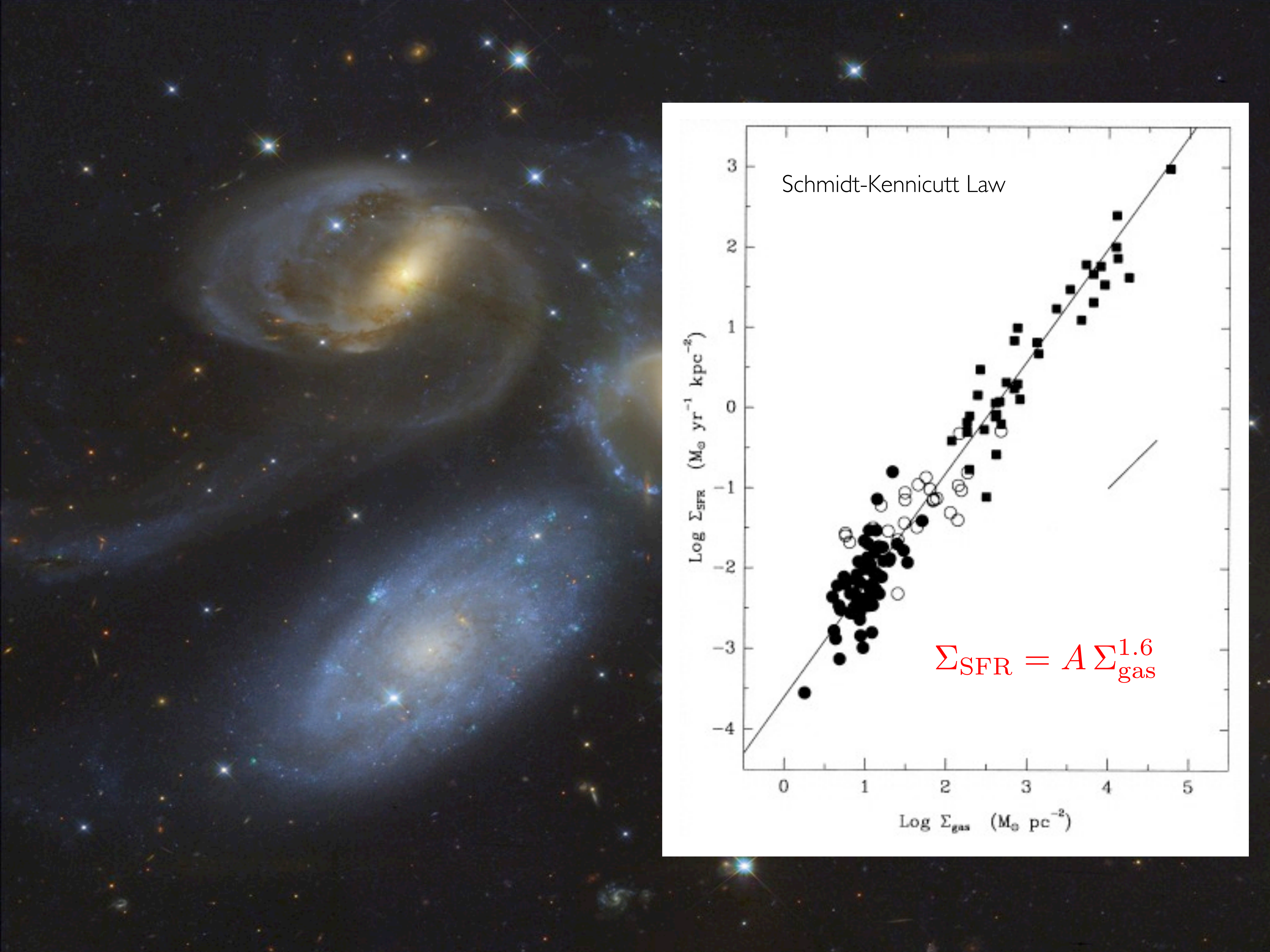


t (Gyr)
10 54 3 2 1 0.6 0.4
log M⊙ yr⁻¹ Mpc⁻³
−1
−2
−3
> 0.07 L*z=3
0 2 4 6 8 10
z
Bouwens et al. 2010

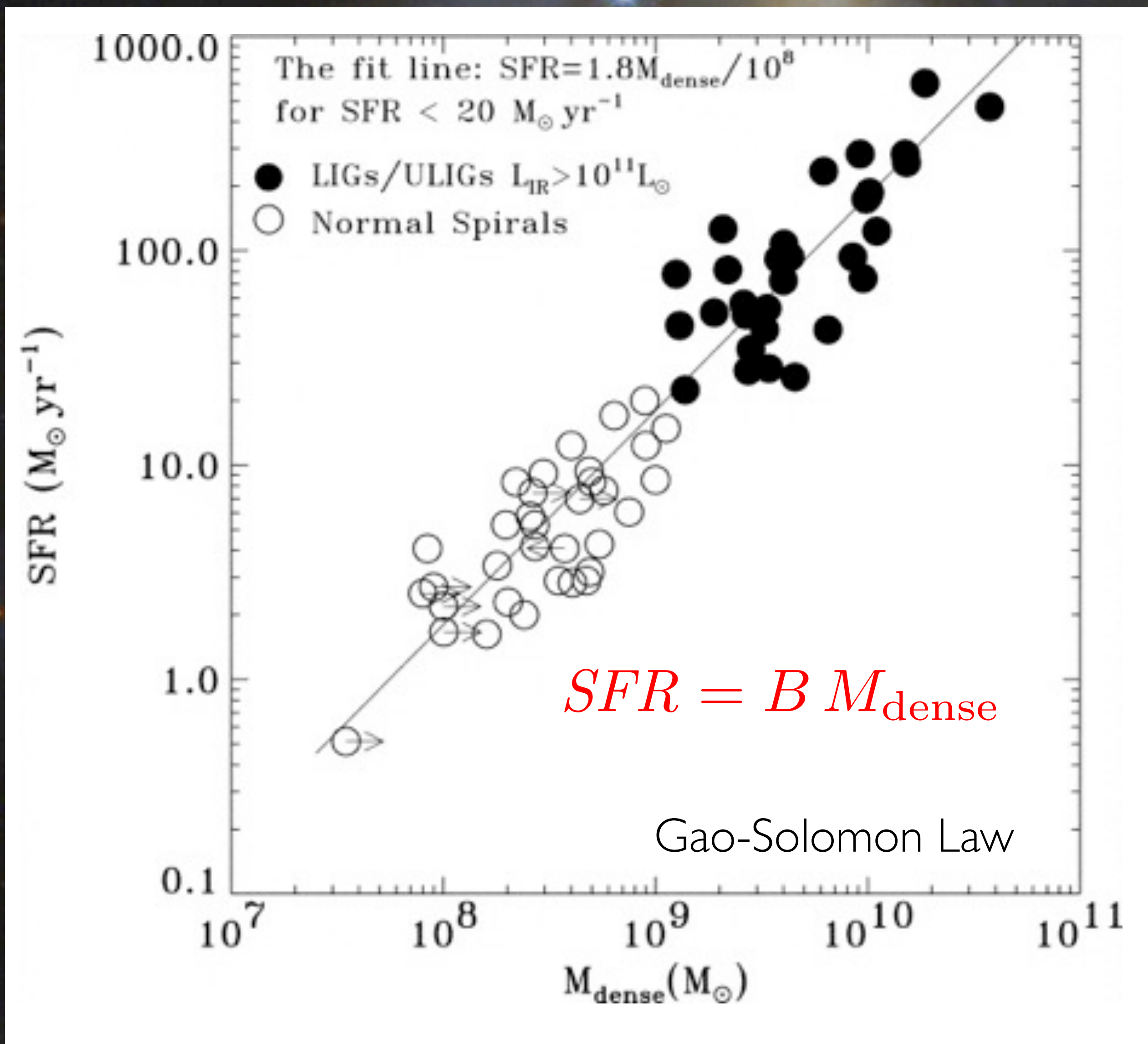
Local Universe

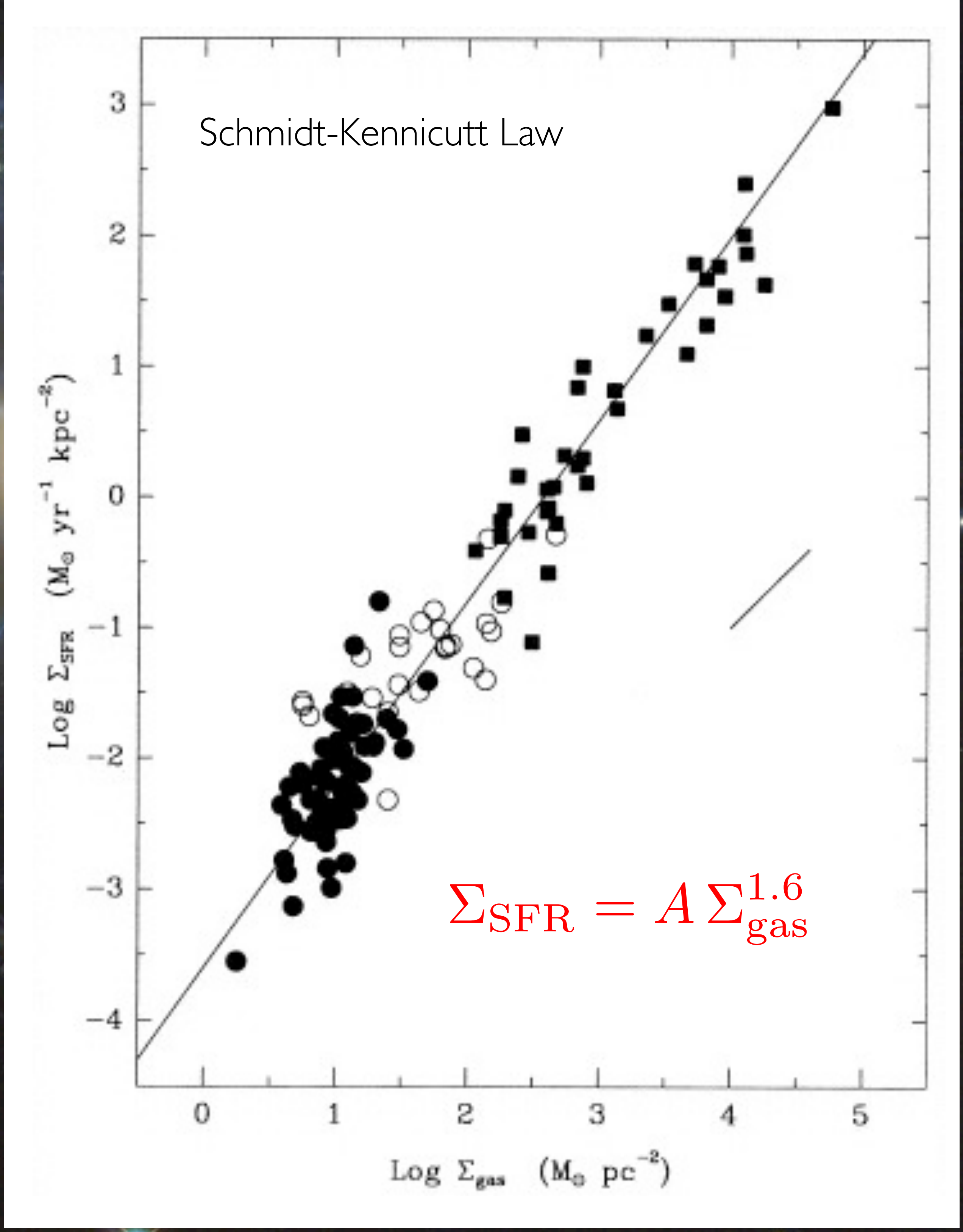
"It would seem most probable that the rate of star formation depends on the gas density and we shall assume that the number formed per unit interval of time varies with a power of the gas density ..."

(Schmidt 1959)



Schmidt-Kennicutt Law
Log Σ_{SFR} ($M_\odot$ yr^{-1} kpc^{-2})
Log Σ_{gas} ($M_\odot$ pc^{-2})
$\Sigma_{\rm SFR} = A\,\Sigma_{\rm gas}^{1.6}$


The fit line: SFR=1.8M_dense/10^8
for SFR < 20 M_⊙ yr^-1
LIGs/ULIGs L_IR>10^11 L_⊙
Normal Spirals
SFR (M_⊙ yr^-1)
M_dense(M_⊙)
$SFR = B\, M_{\rm dense}$
Gao-Solomon Law


Schmidt-Kennicutt Law
Log Σ_SFR (M_⊙ yr^-1 kpc^-2)
Log Σ_gas (M_⊙ pc^-2)
$\Sigma_{\rm SFR} = A\, \Sigma_{\rm gas}^{1.6}$

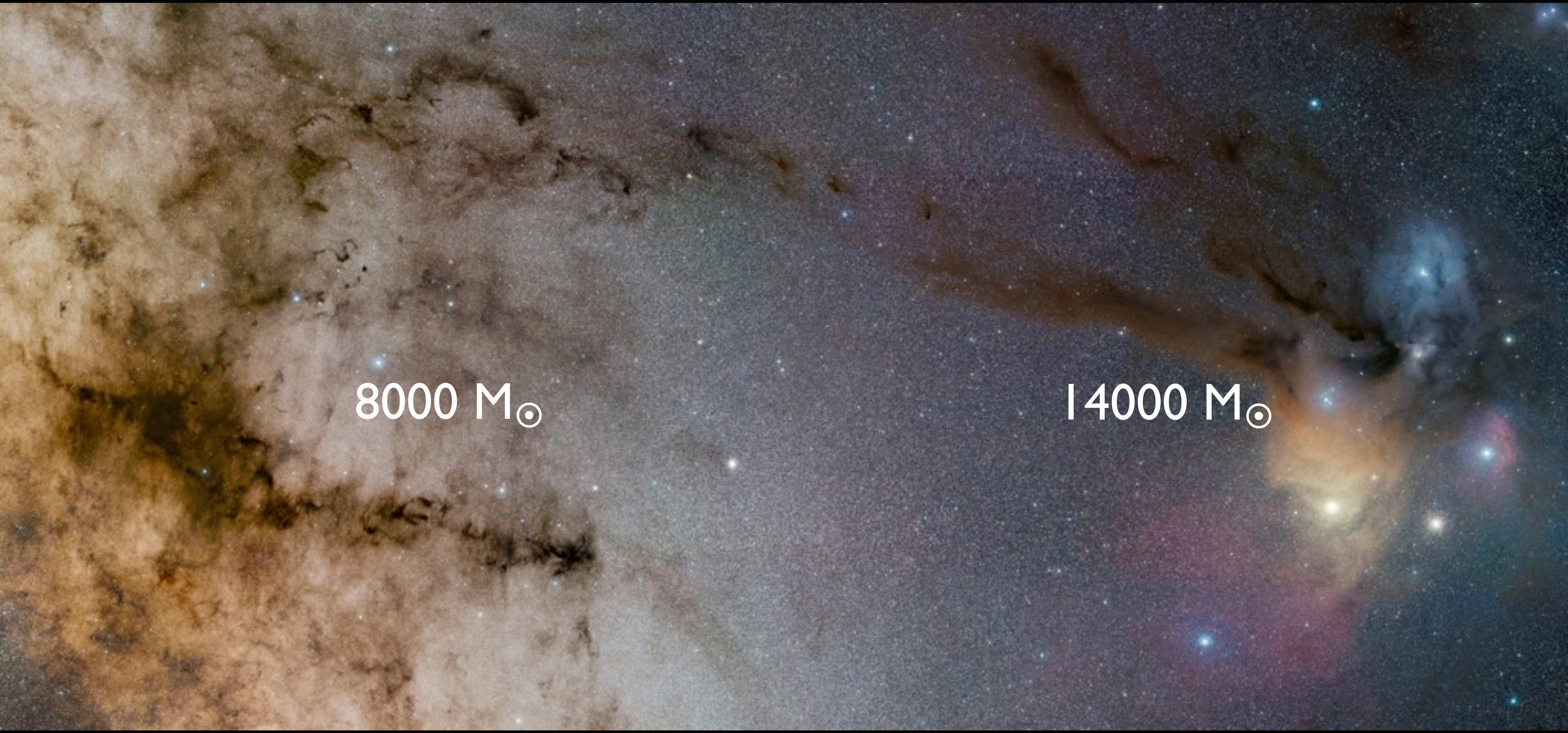
The Milky Way

Pipe Nebula

ρ Ophiuchi Cloud

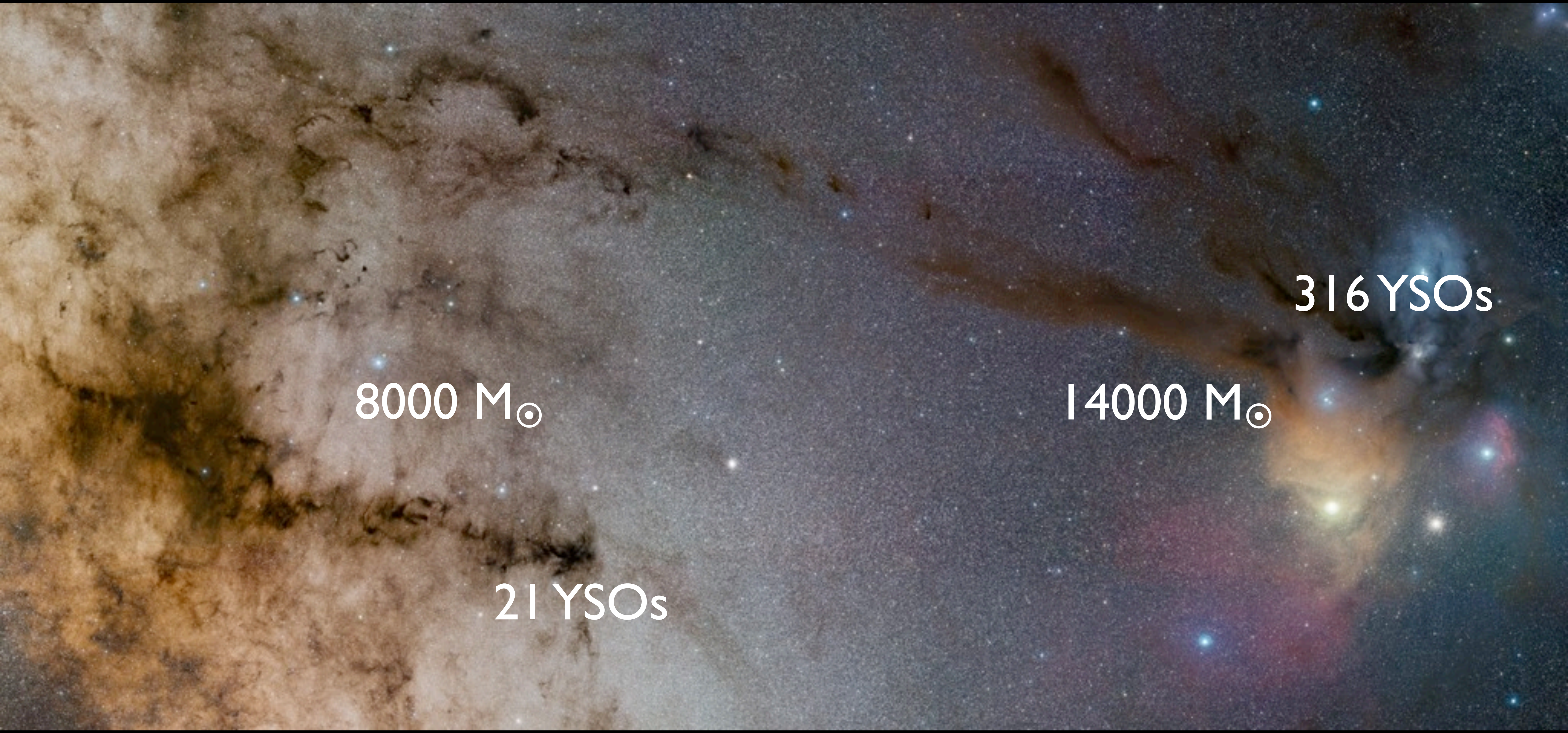
$\Sigma_{Pipe} = 50\ M_{\odot}\ pc^{-2}$

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



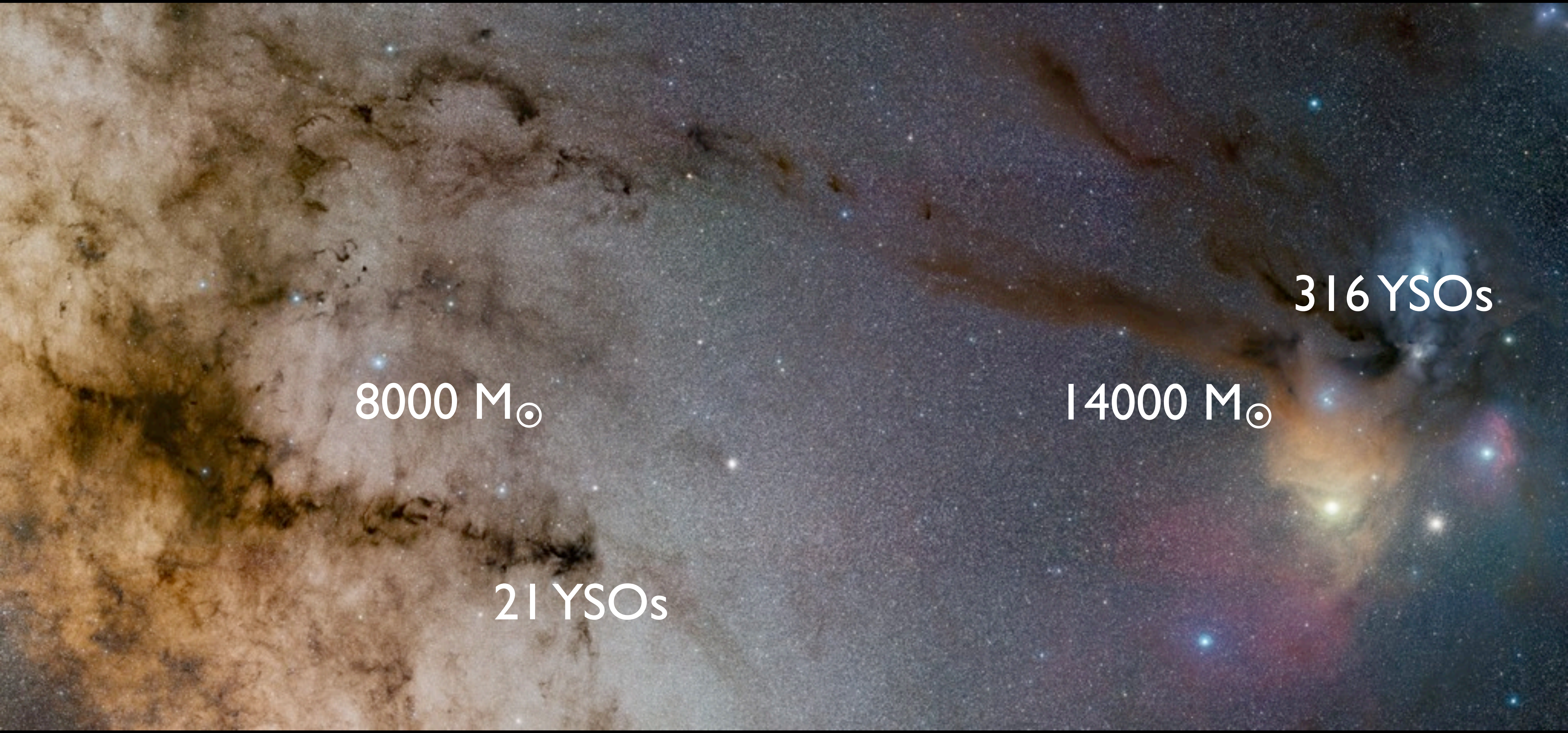
Σ_{Pipe} = 50 M$_\odot$ pc^{-2}

Σ_{Oph} = 40 M$_\odot$ pc^{-2}



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

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



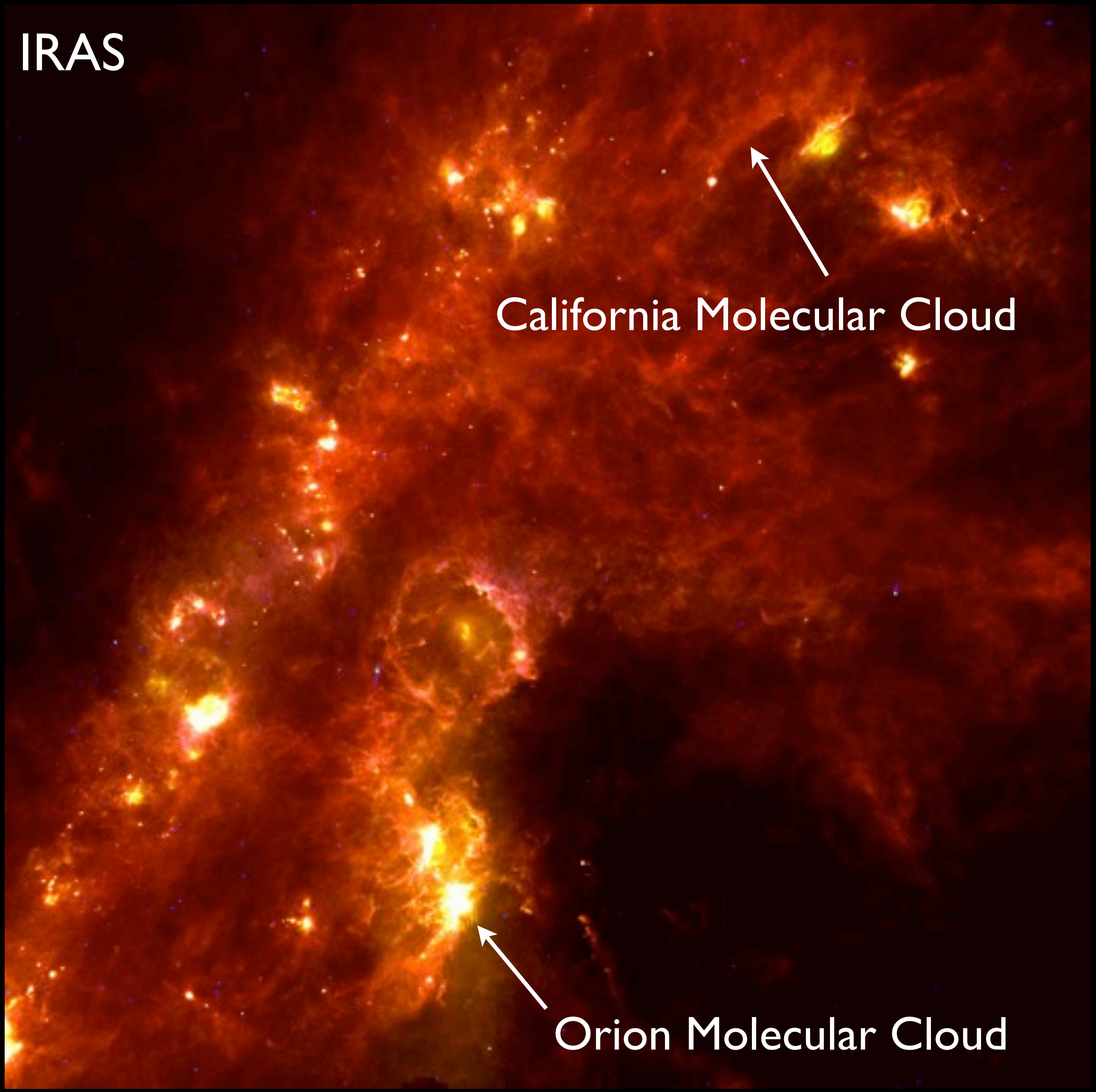
$$SFR_{Oph} = 15 \times SFR_{Pipe}$$

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

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

Not just an exception…

Not just an exception…



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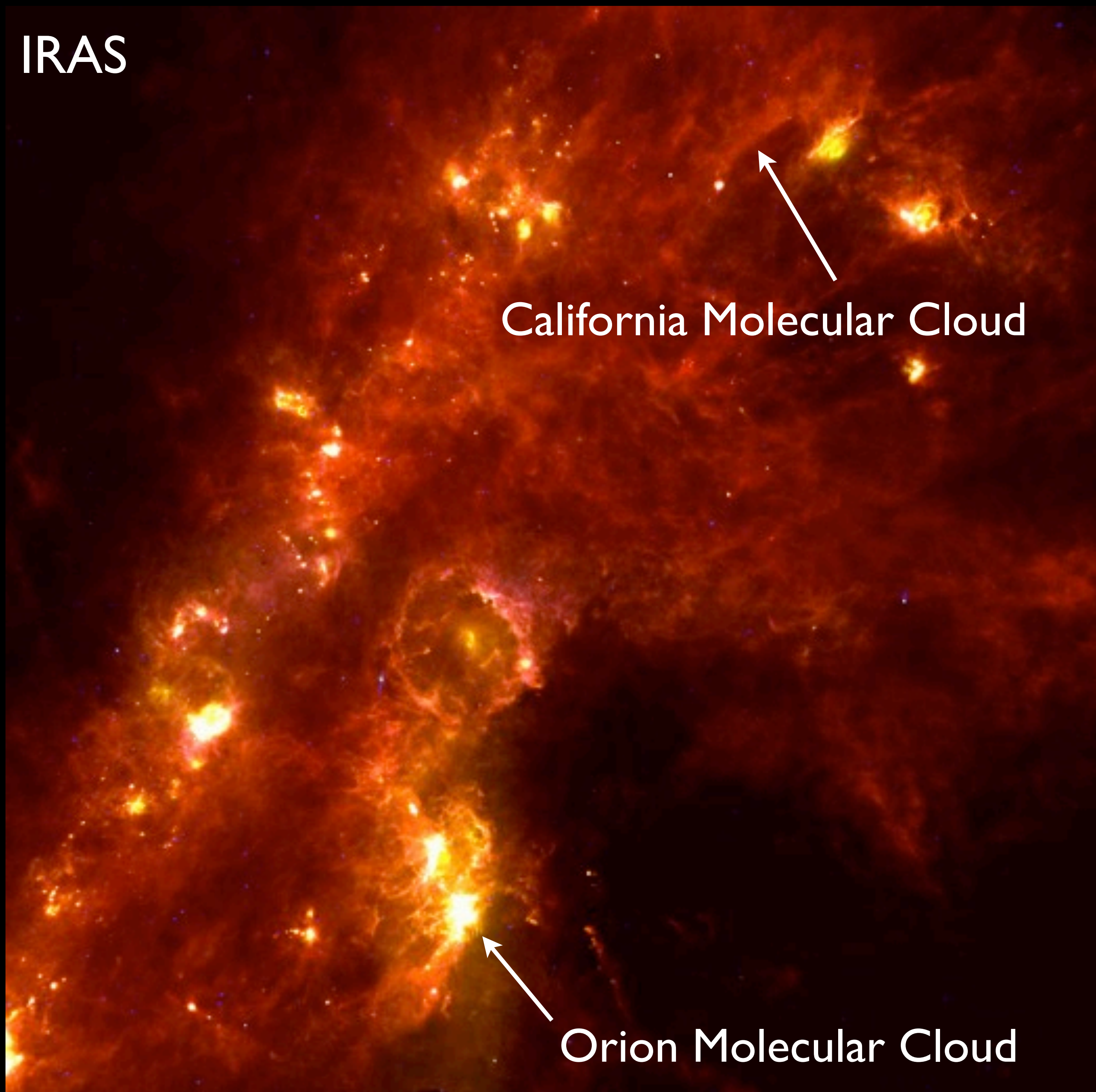

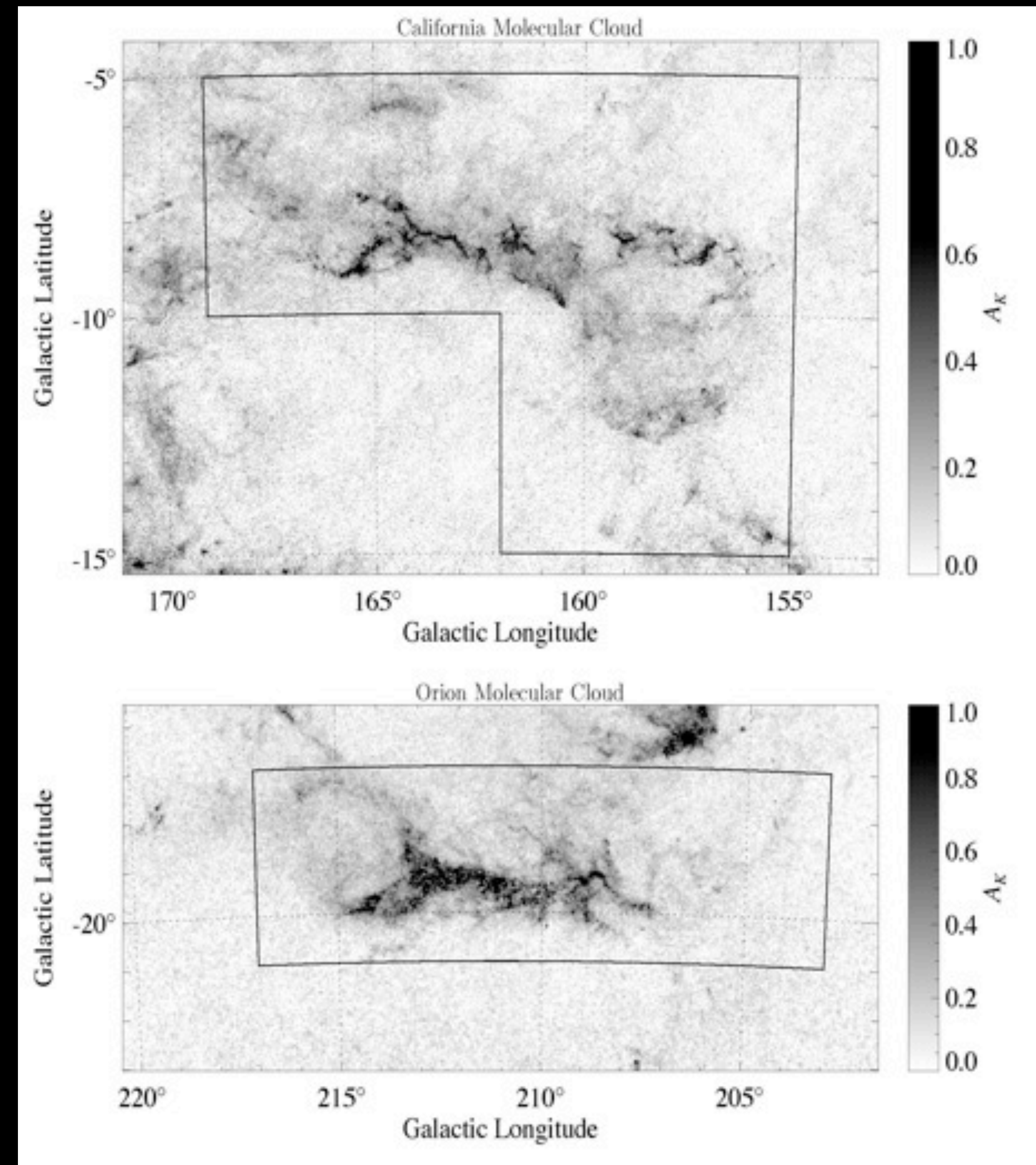

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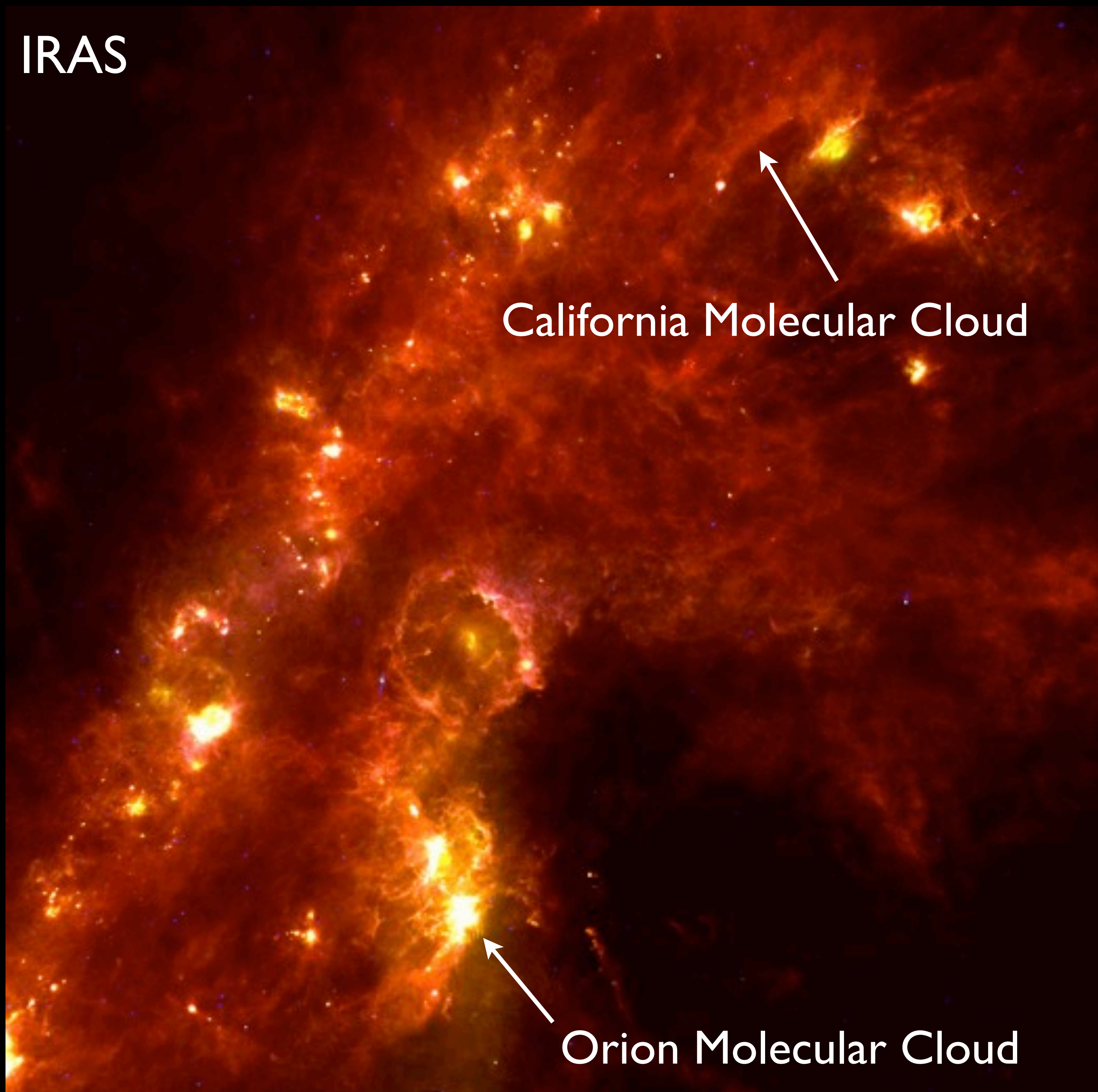
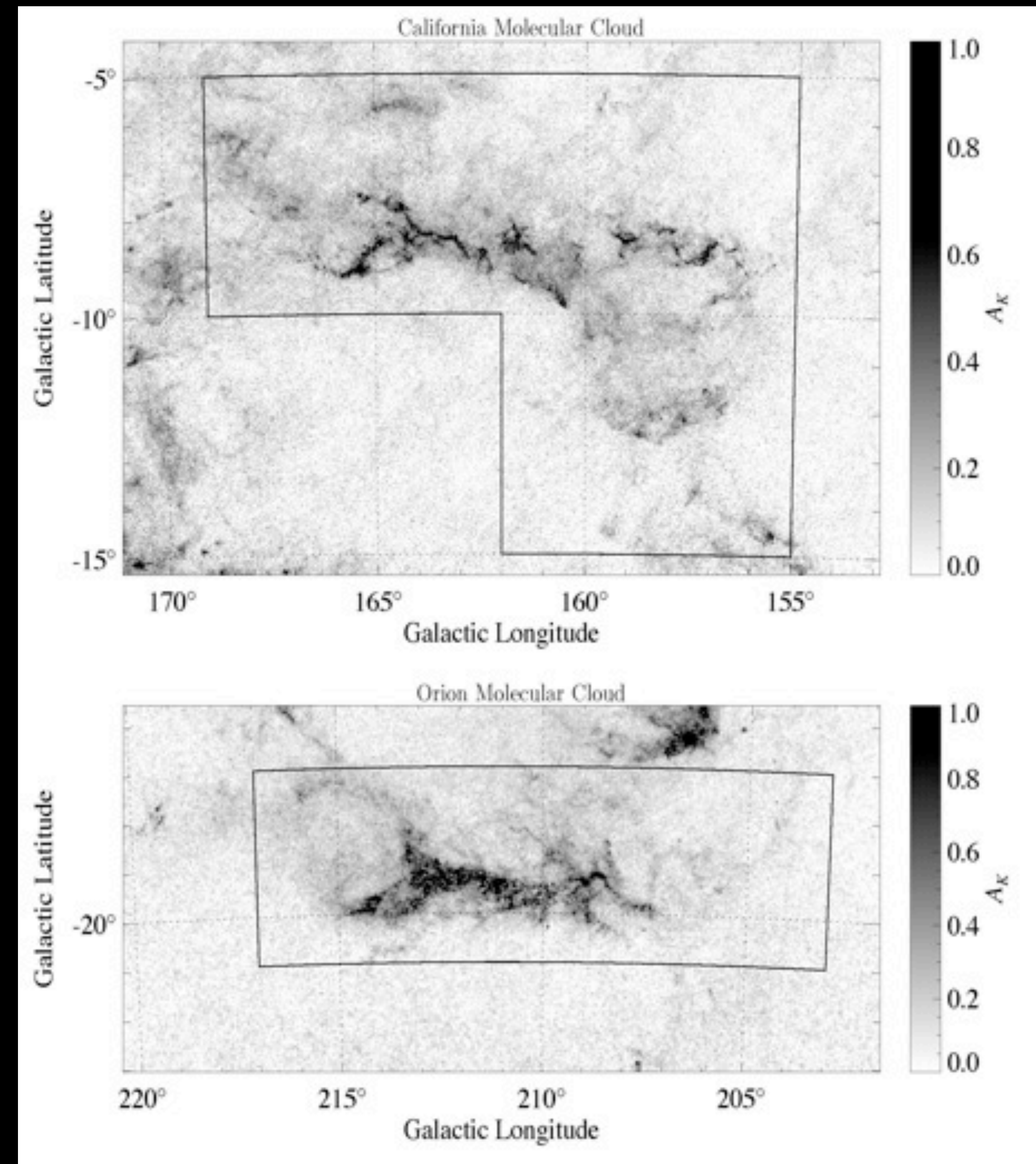
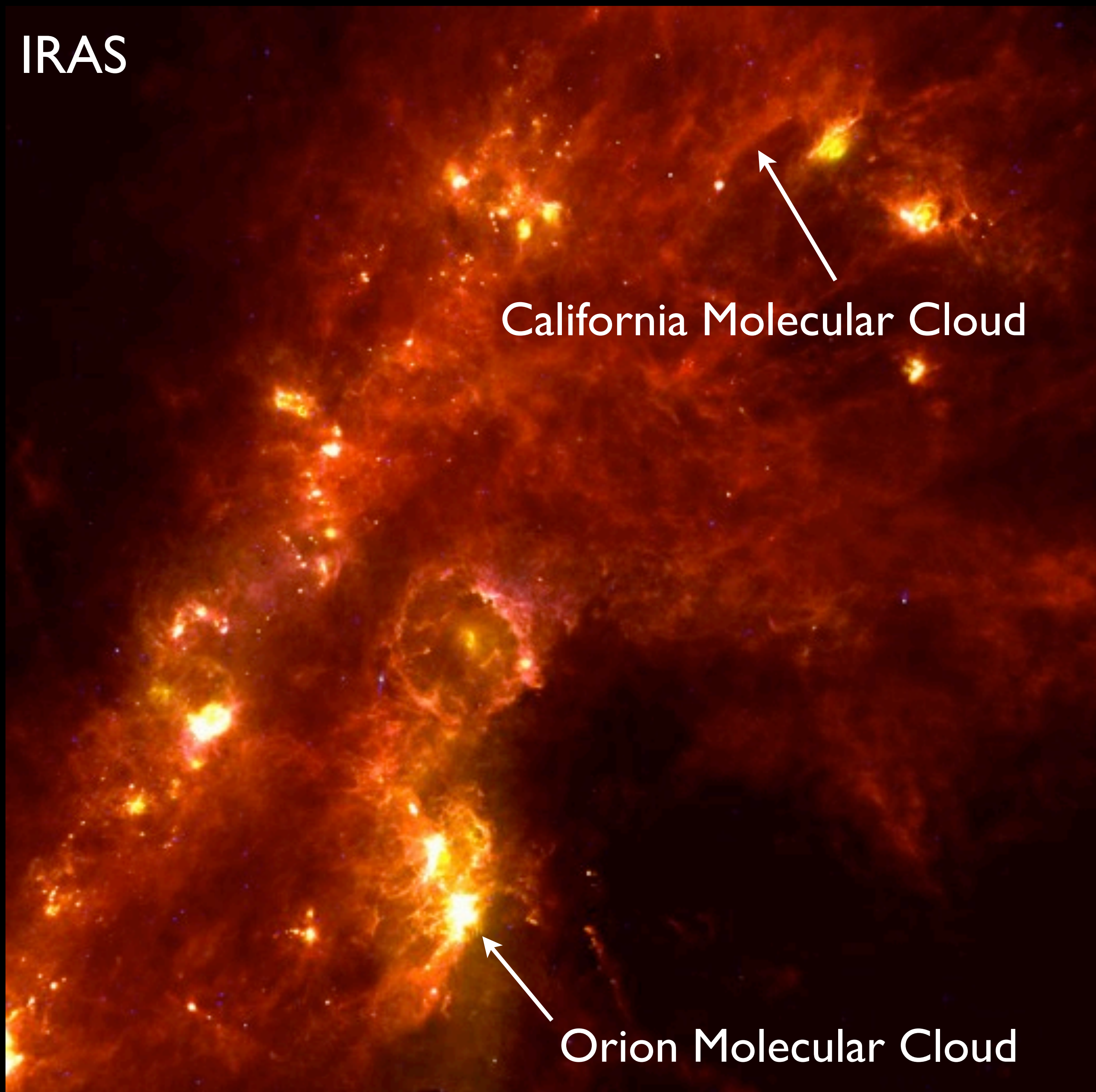
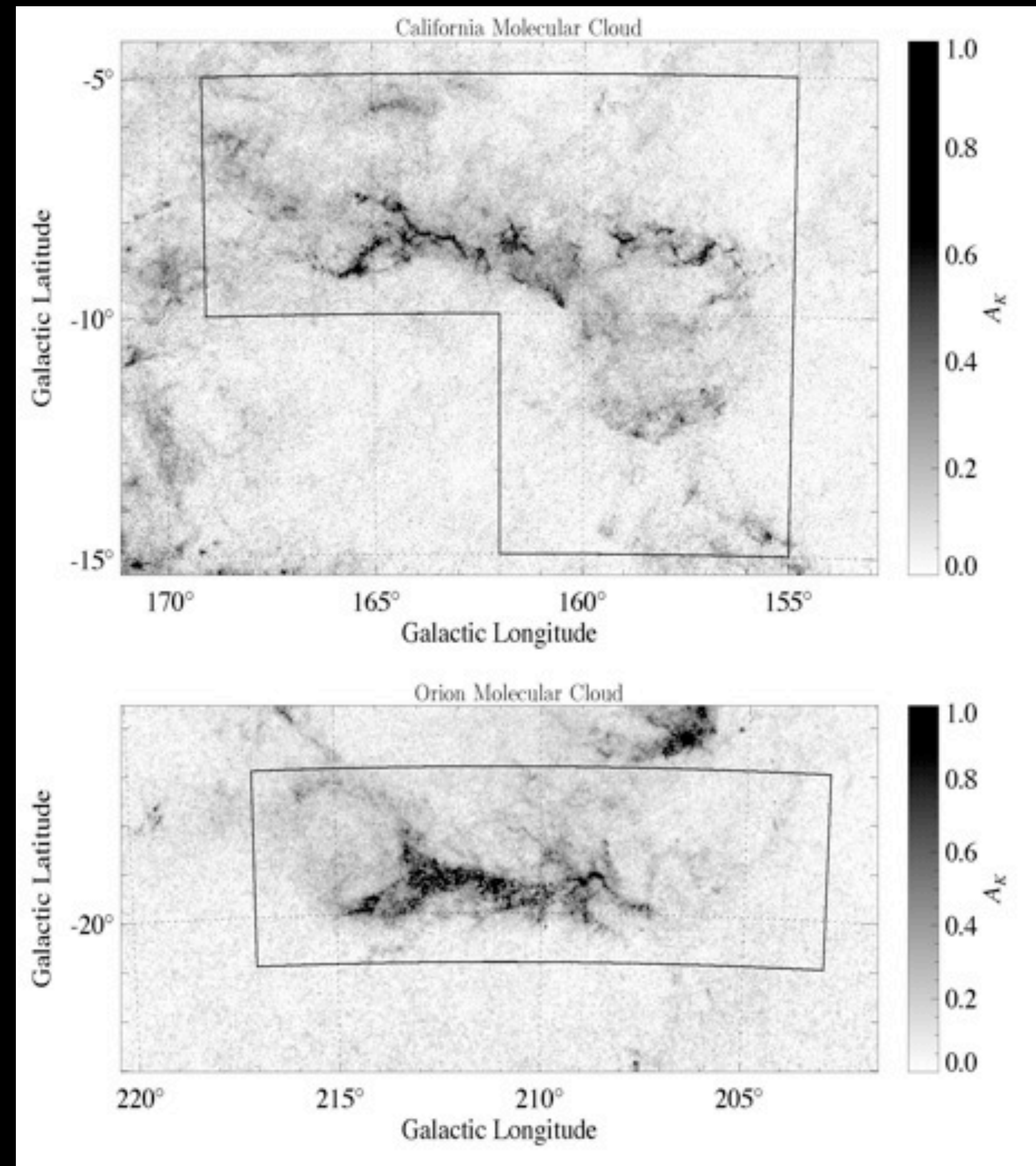




$SFR_{Orion} = 10 \times SFR_{California}$

Not just an exception…





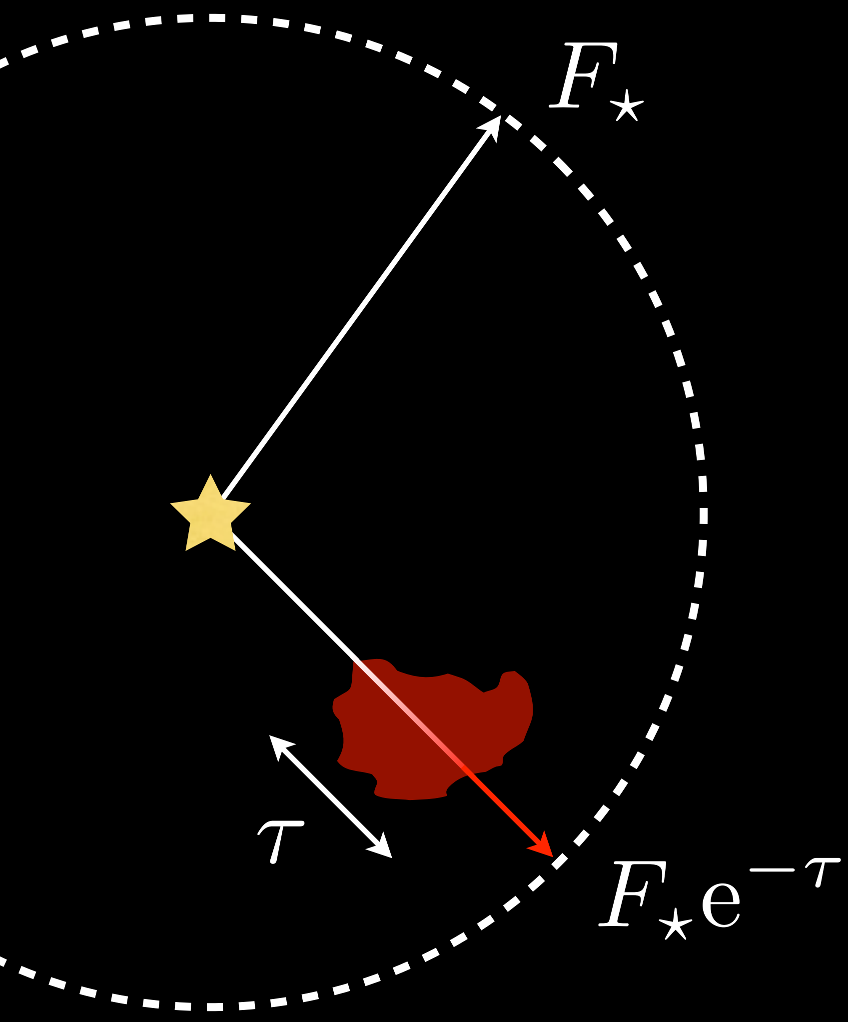
SFR_{Orion} = 10 x $SFR_{California}$

Clouds identical in mass & size

Inventory of Local Star Formation Activity

Infrared extinction and cloud masses

Extinction Primer



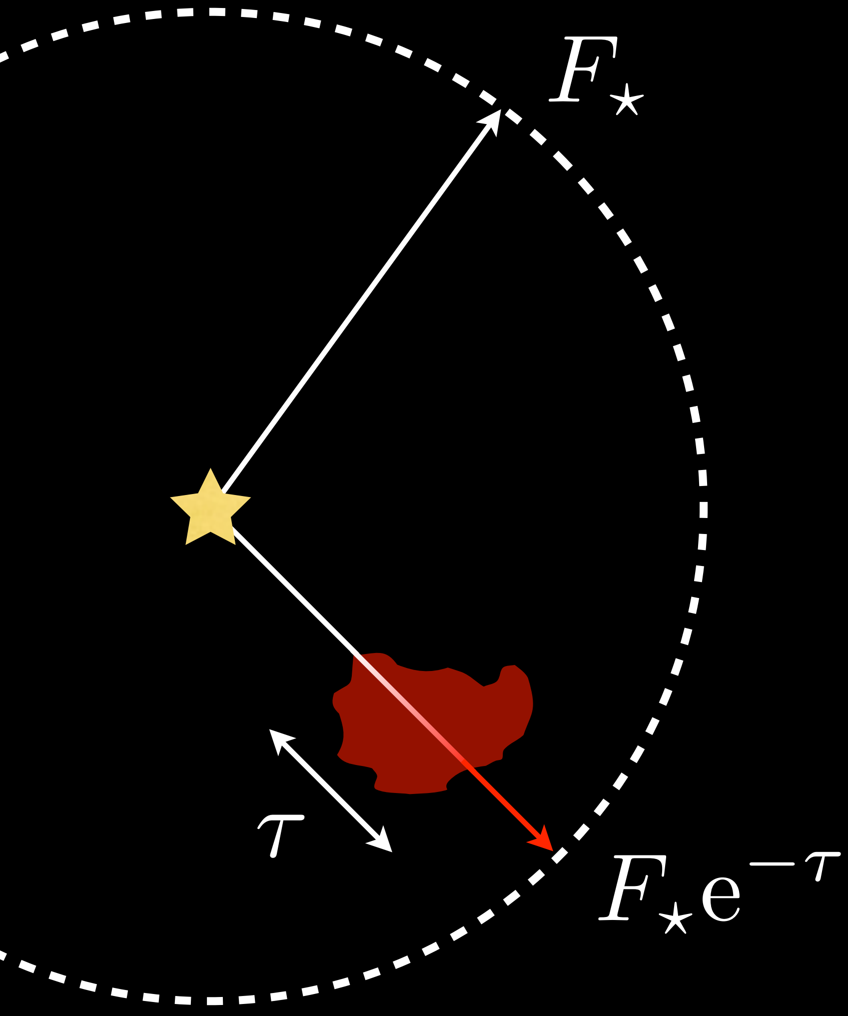
Brightness

$$m_{\rm obs} = -2.5\log\left(F_\star e^{-\tau}\right)$$
$$= -\underbrace{2.5\log F_\star}_{m_\star} + \underbrace{2.5\,\tau\log e}_{A_{\rm V}}$$

Extinction

$$m_{\rm obs} - m_\star = A_{\rm V} = 1.086\,\tau$$

Extinction Primer



Color

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

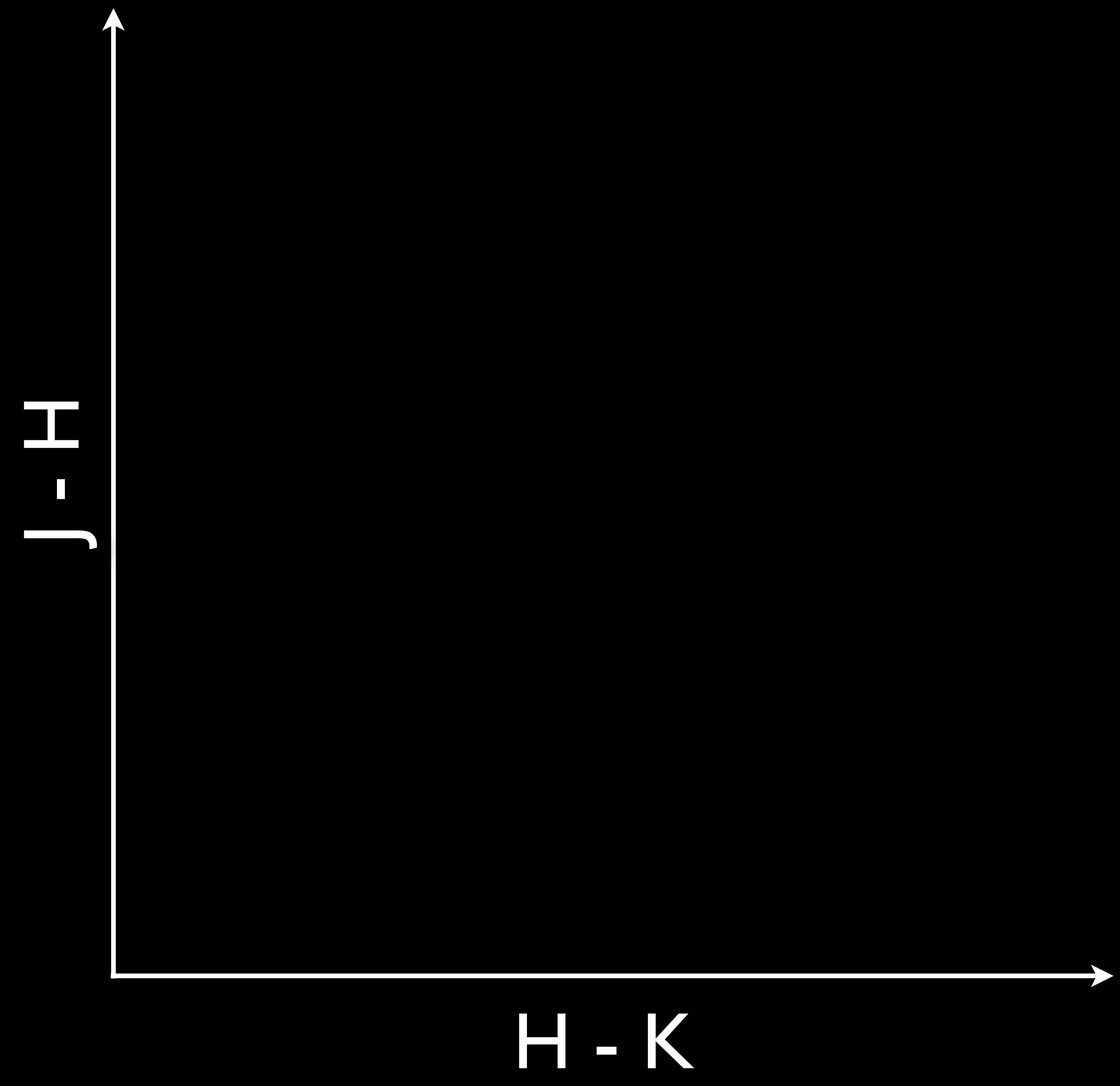
Color Excess

$$E(\lambda_1 - \lambda_2) = \Delta m_{\mathrm{obs}} - \Delta m_\star$$

$$= A_{\lambda_1} - A_{\lambda_2} = R_{1,2}^{-1} A_{\lambda_1}$$

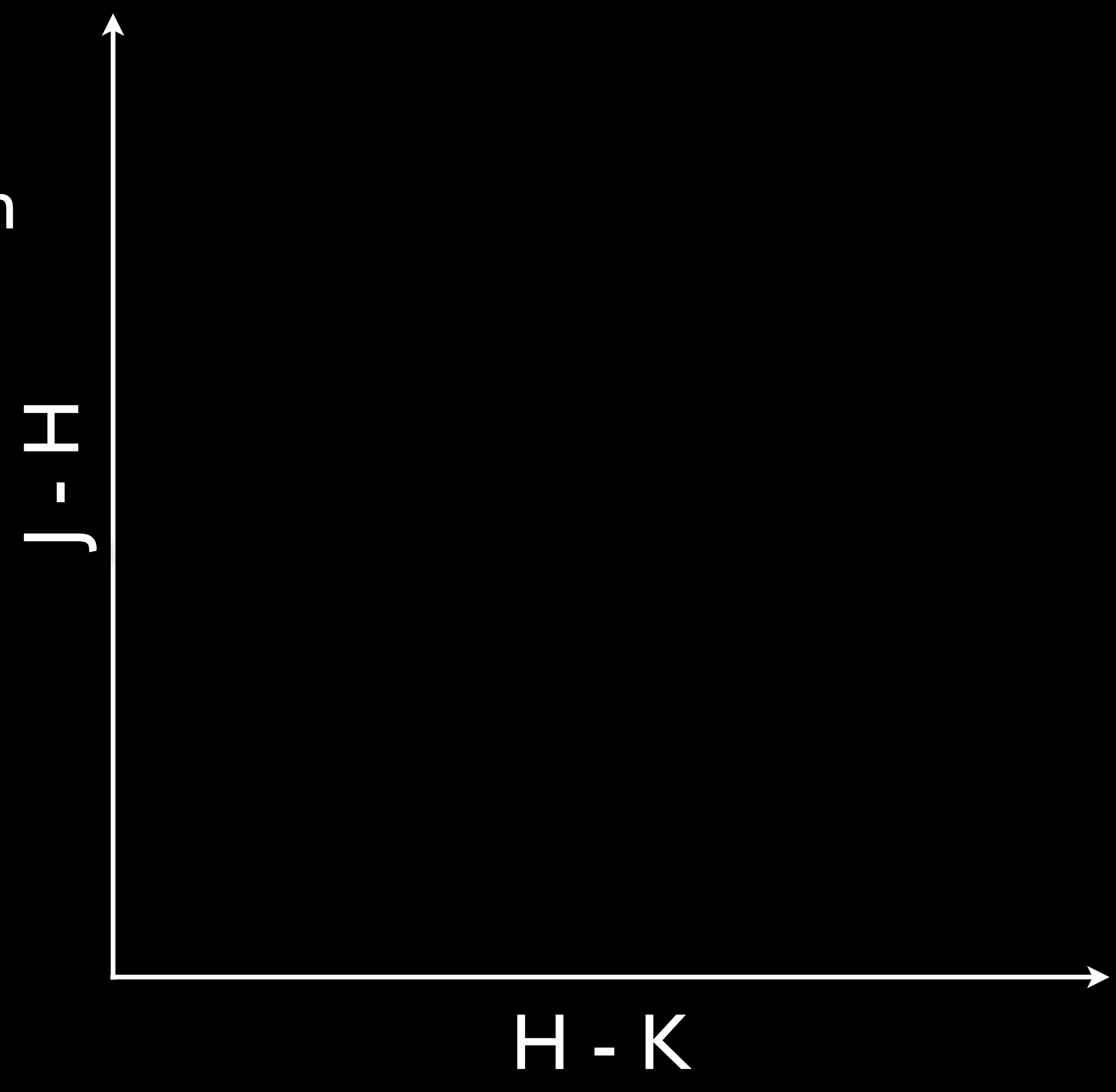
$R_{1,2}$ parametrizes our knowledge (or ignorance) on the dust properties at the two frequencies λ_1 and λ_2

The NICER technique



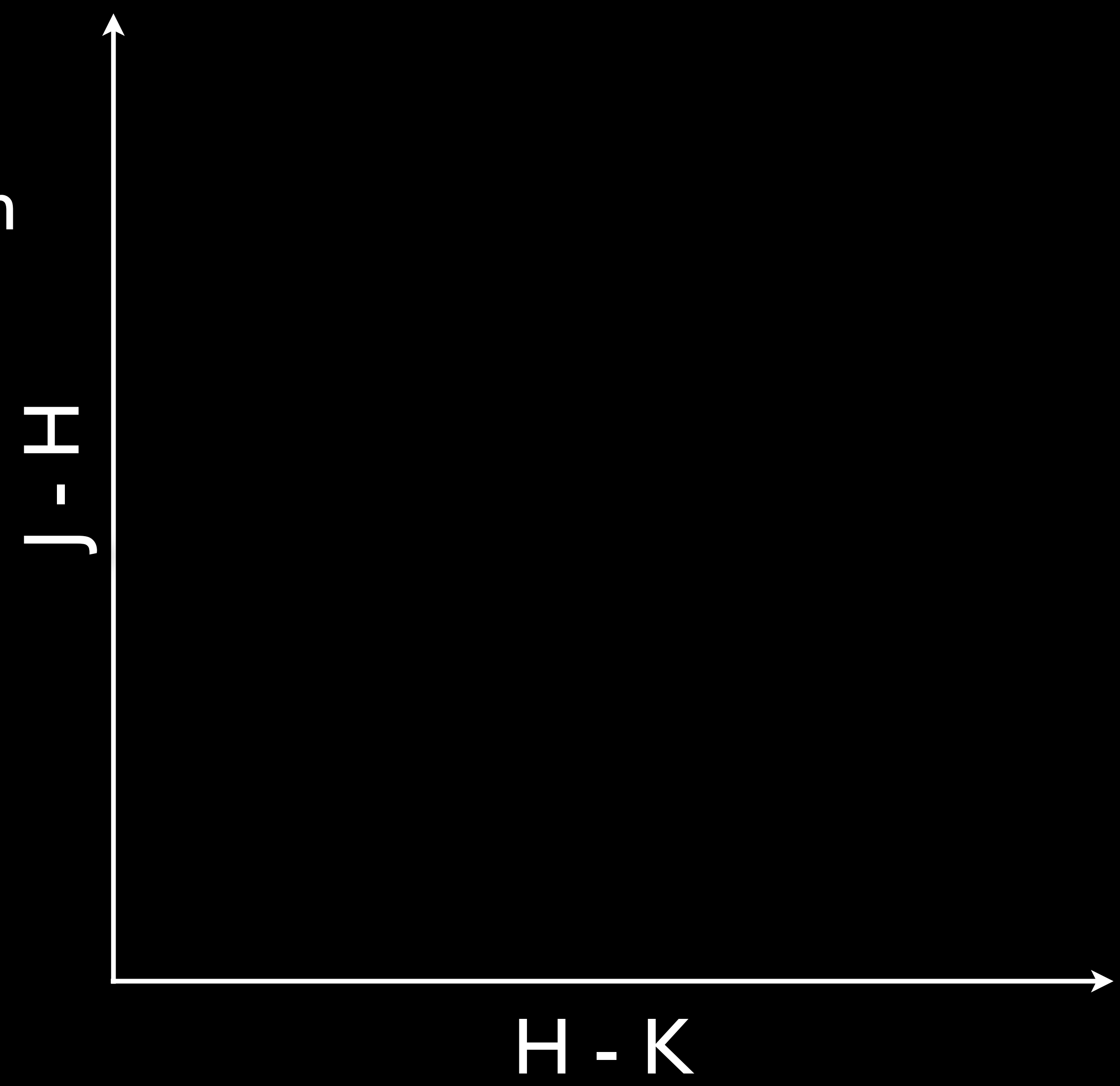
The NICER technique

- Un-reddened stars occupy a small region in the color-color plane



The NICER technique

- Un-reddened stars occupy a small region in the color-color plane
- Reddened stars are shifted in this plane



The NICER technique

- Un-reddened stars occupy a small region in the color-color plane
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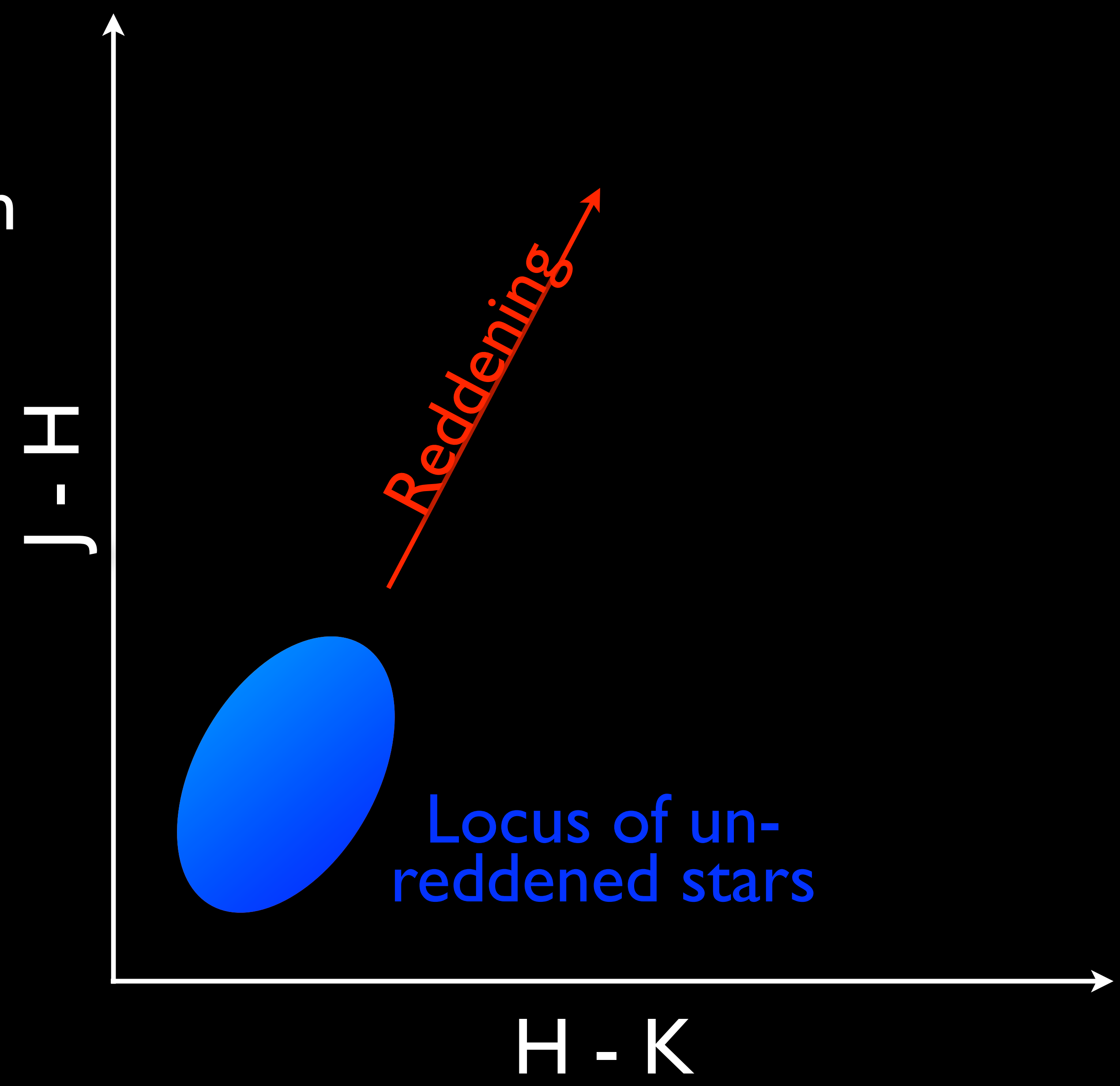
- Optimal extinction obtained from colors and errors of each star



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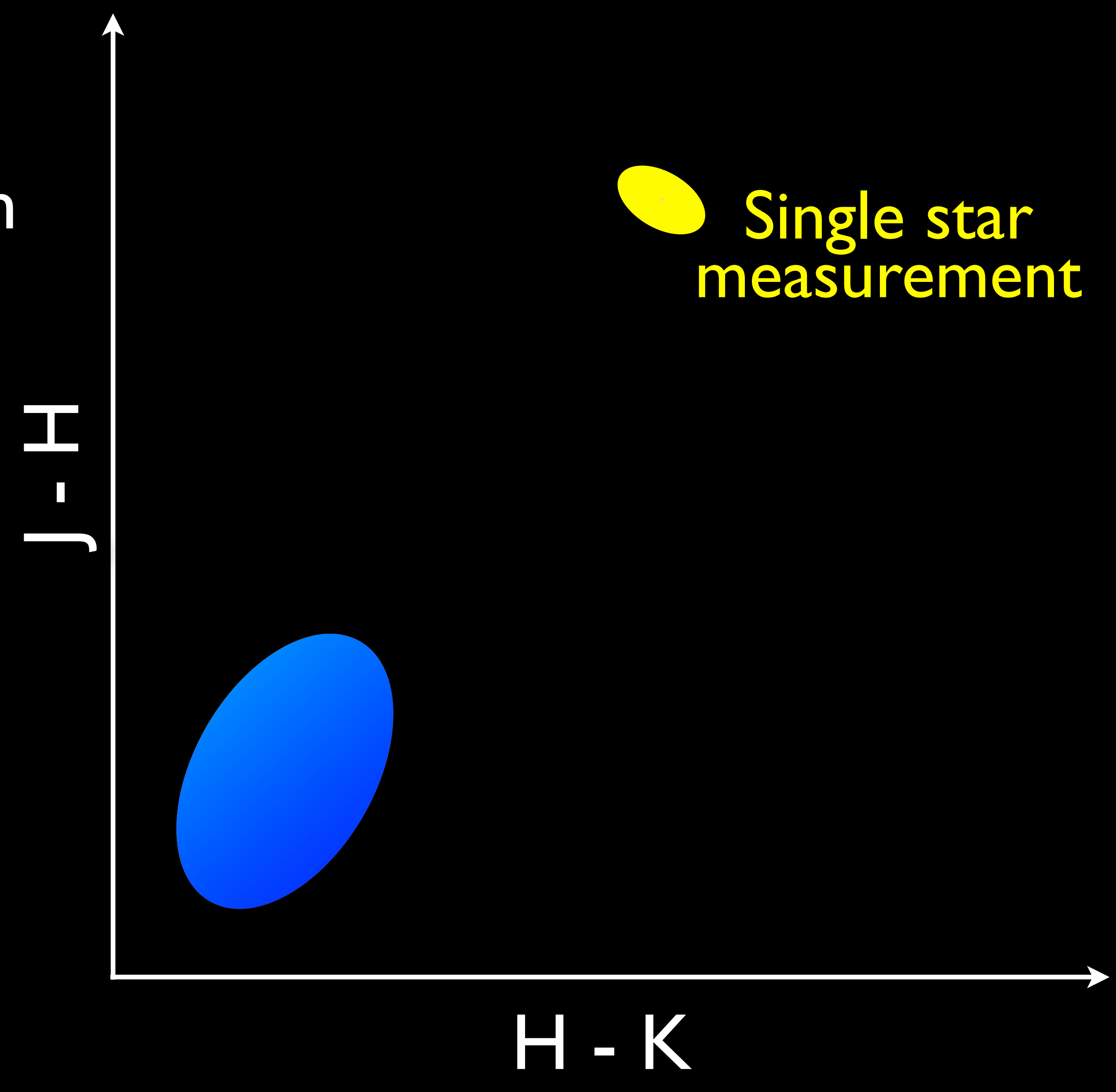

The NICER technique

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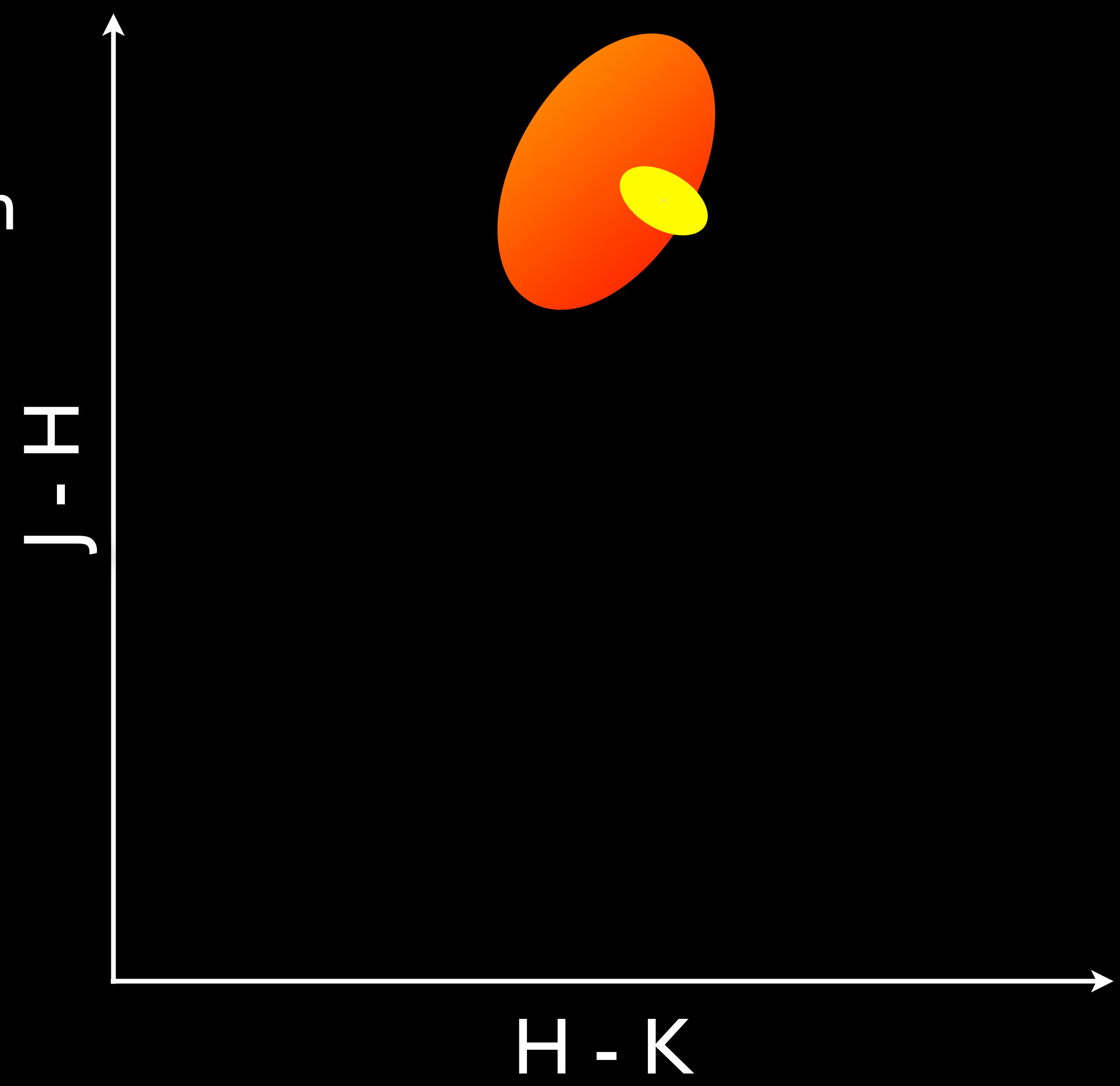

The NICER technique

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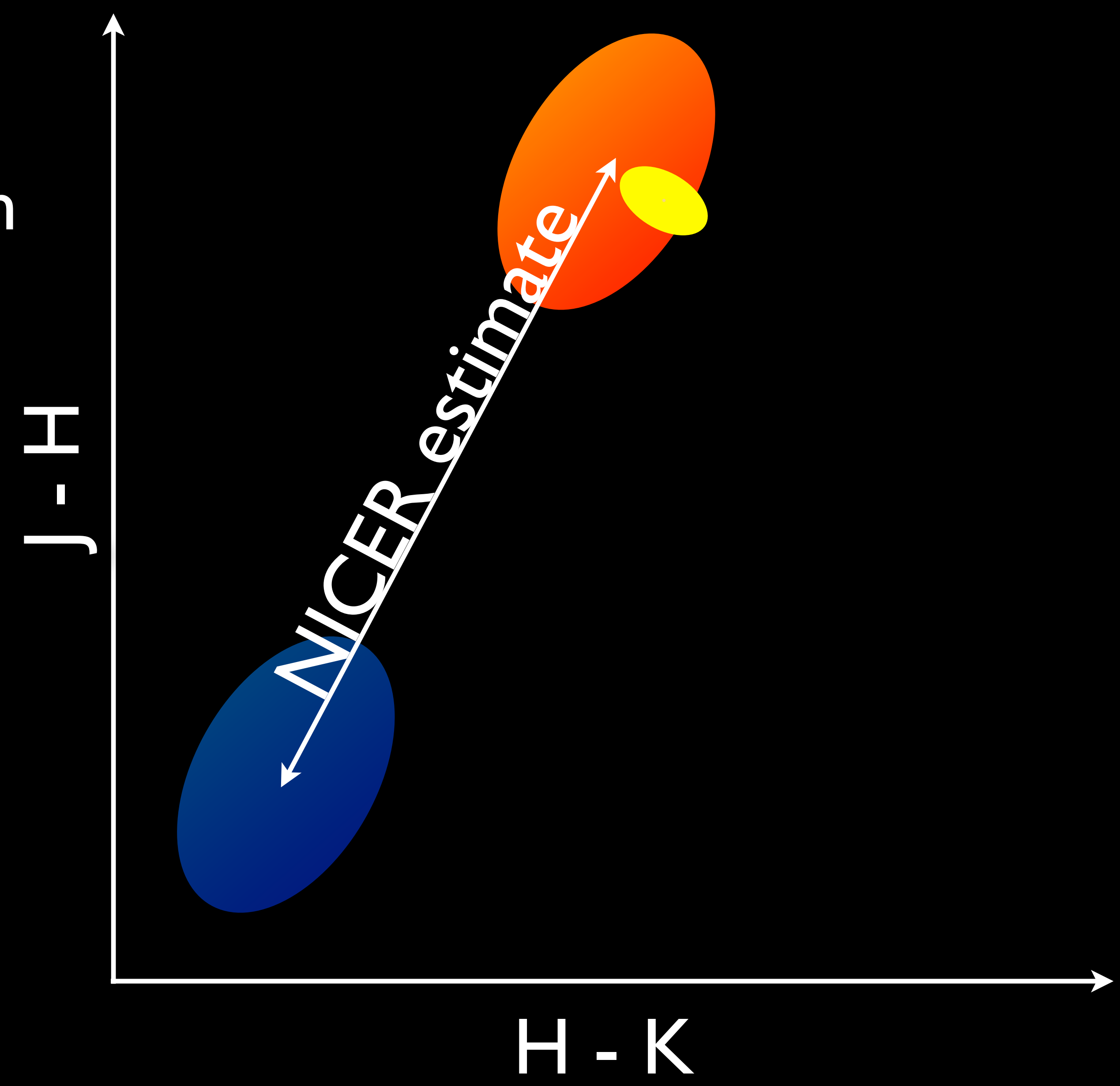
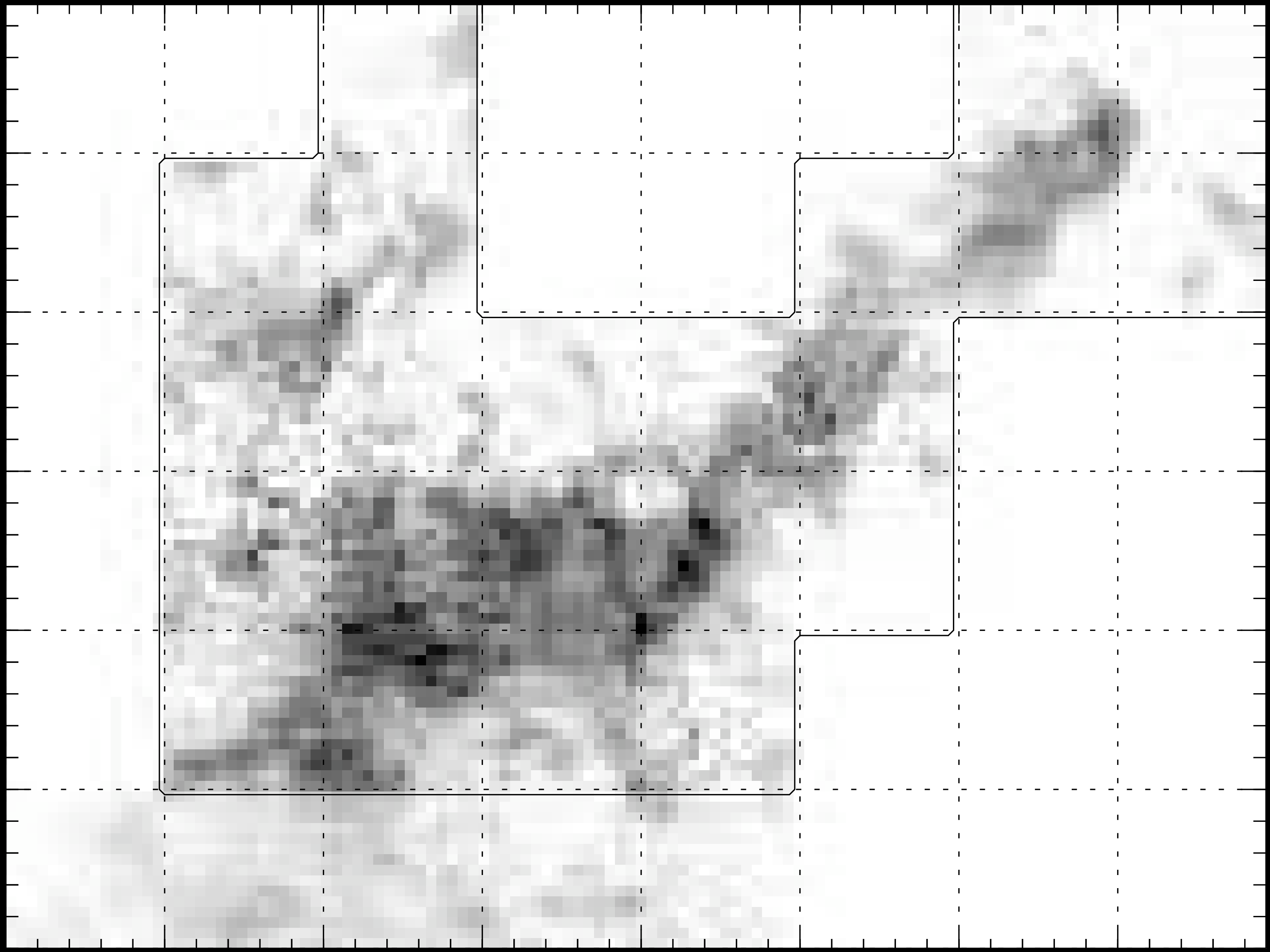
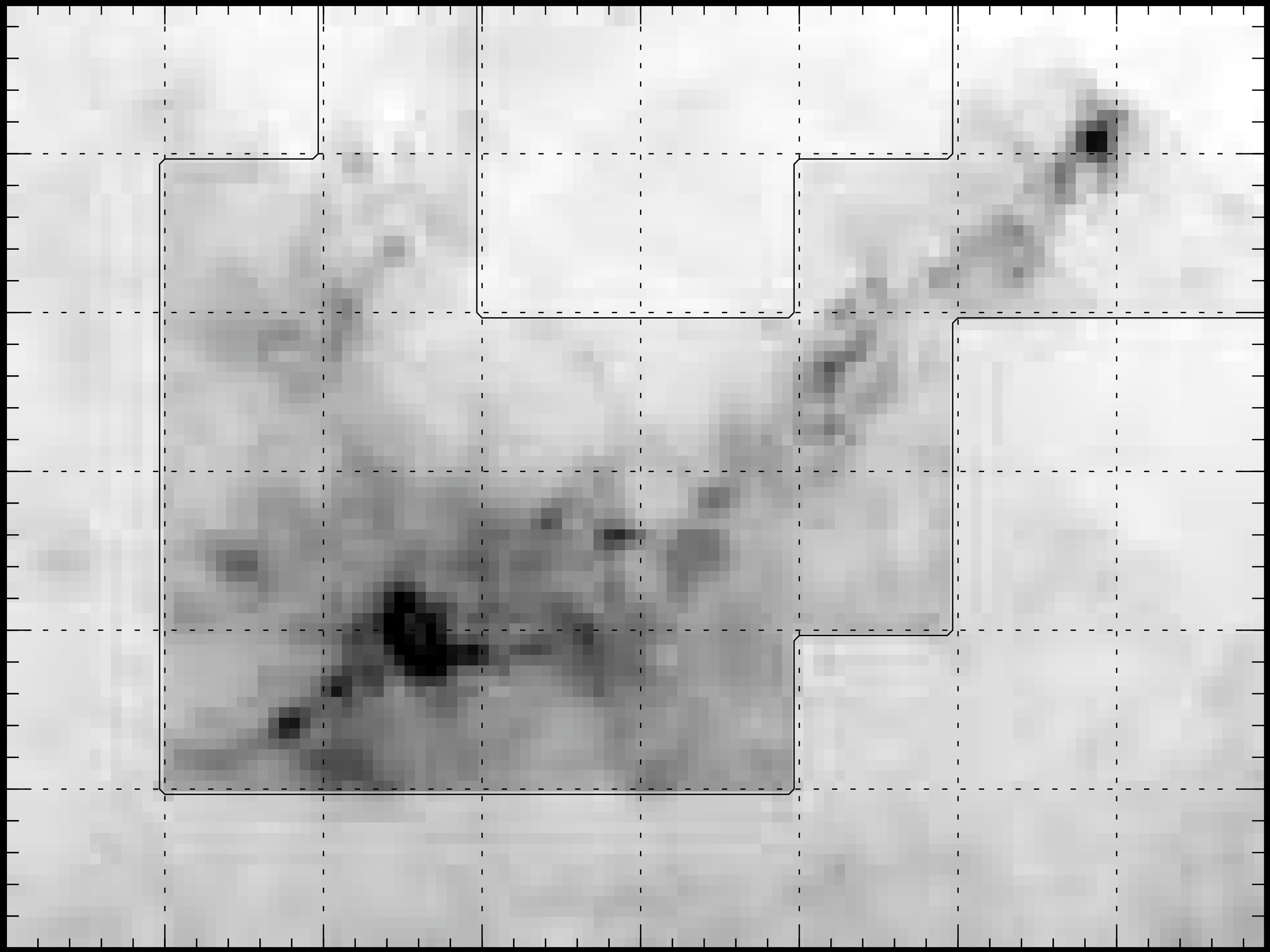


CO vs. dust



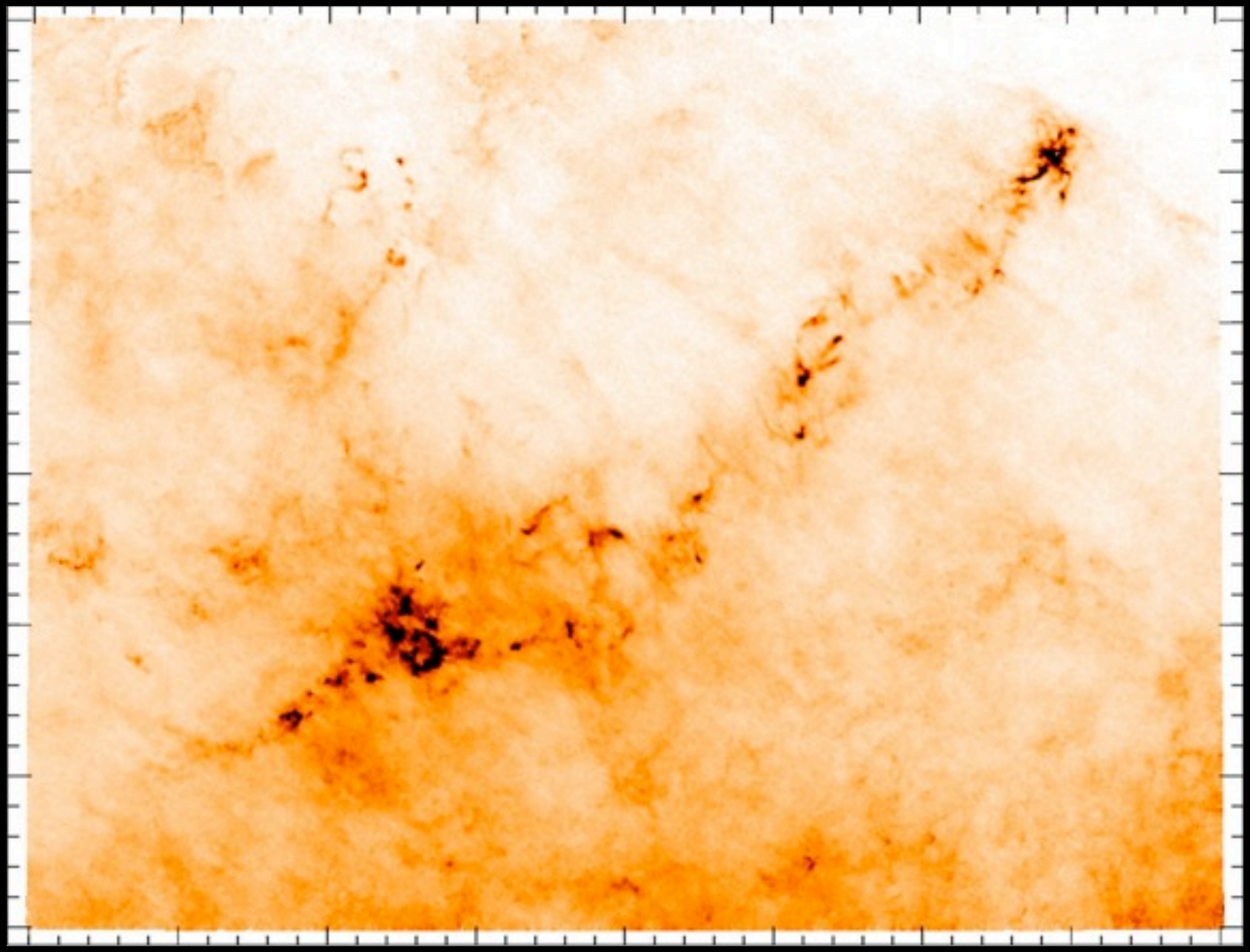
^{12}CO: Onishi et al. (1999), M=6500

CO vs. dust



NICER: Lombardi et al. (2006), M=11000

CO vs. dust



NICER: full resolution (1 arcmin)

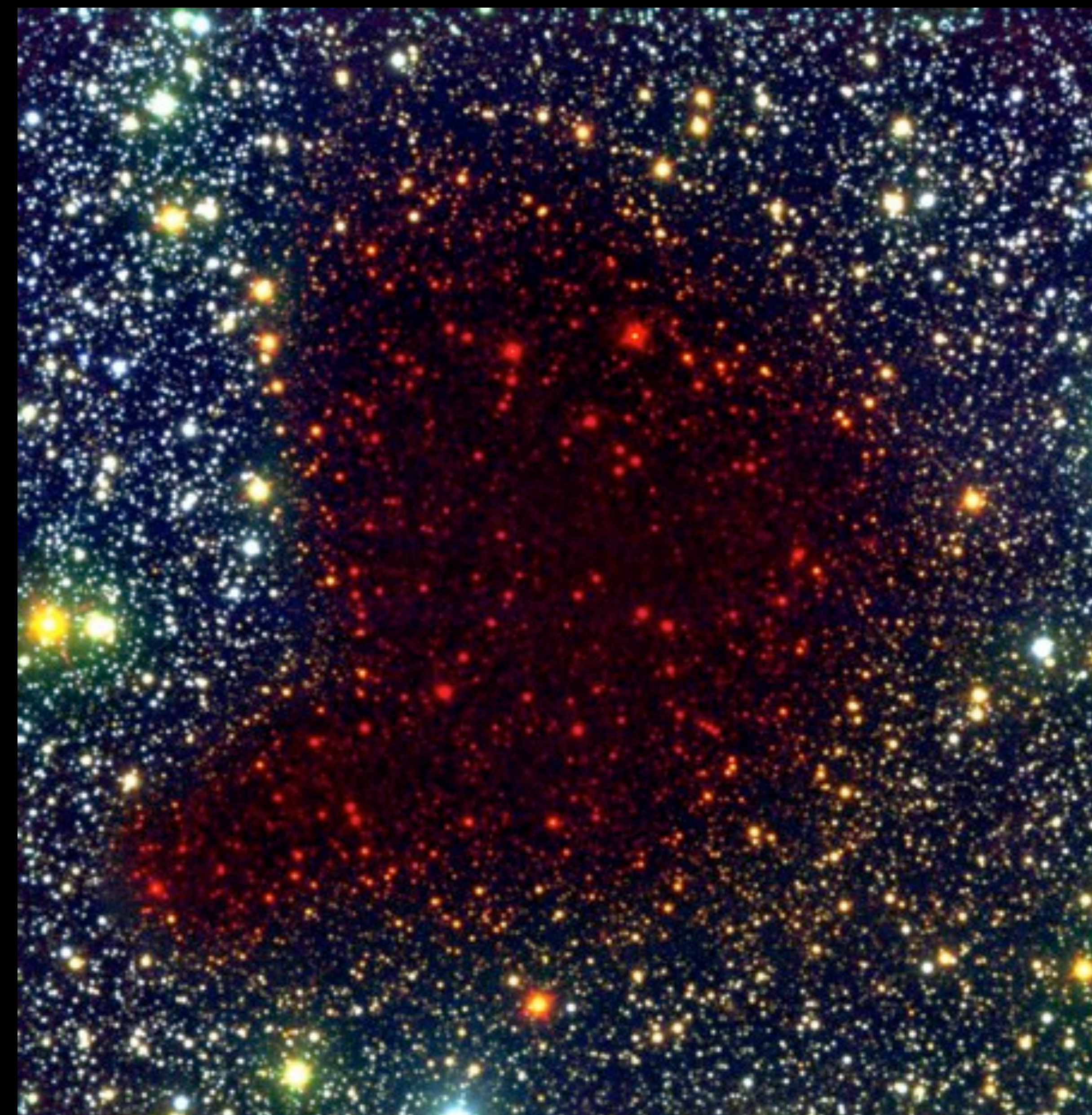
Extinction

VLT (BVI)

Alves et al. (2000)

Extinction

VLT (BVI)

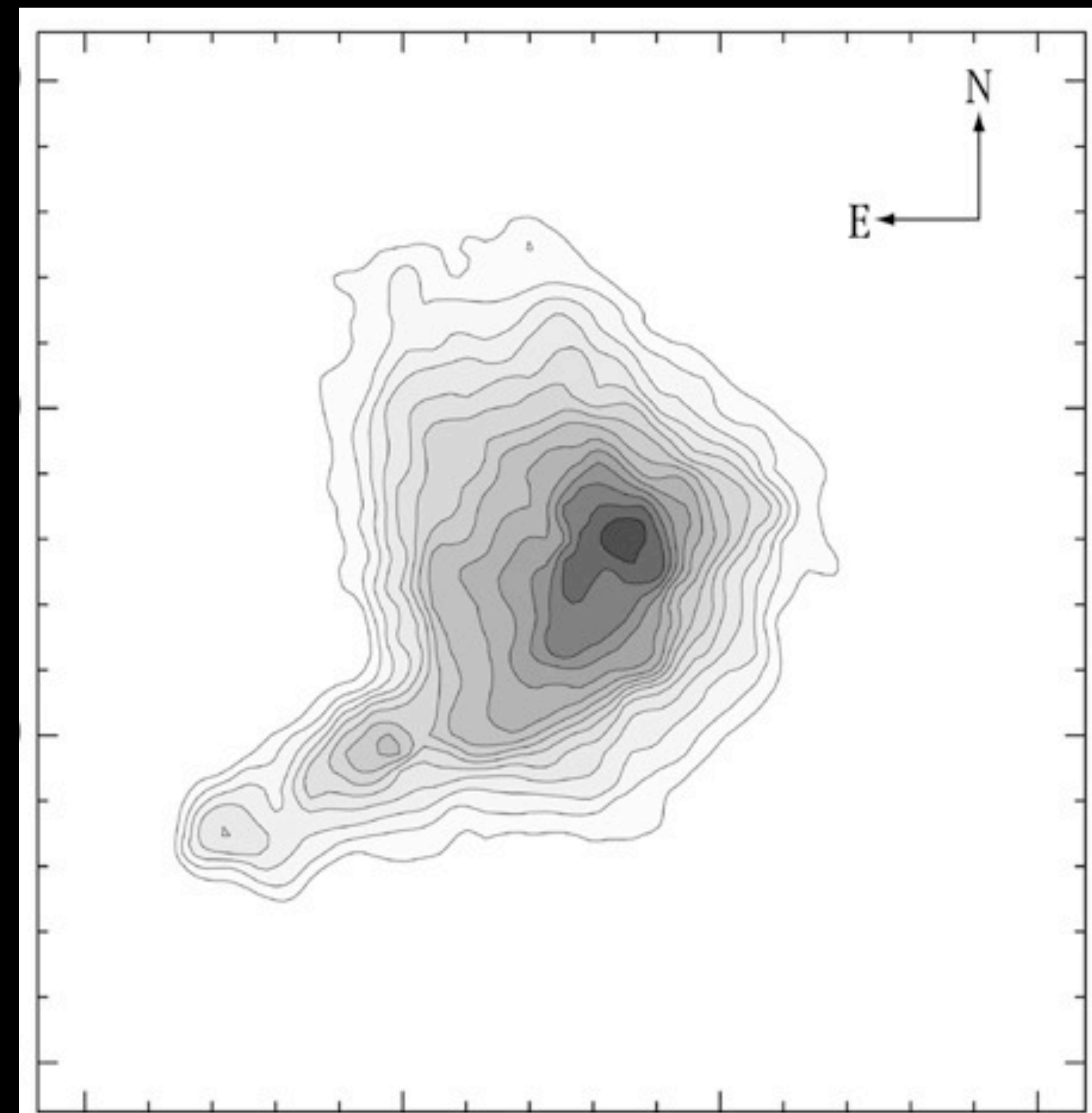


VLT + NTT (BIK)

Alves et al. (2000)

Extinction

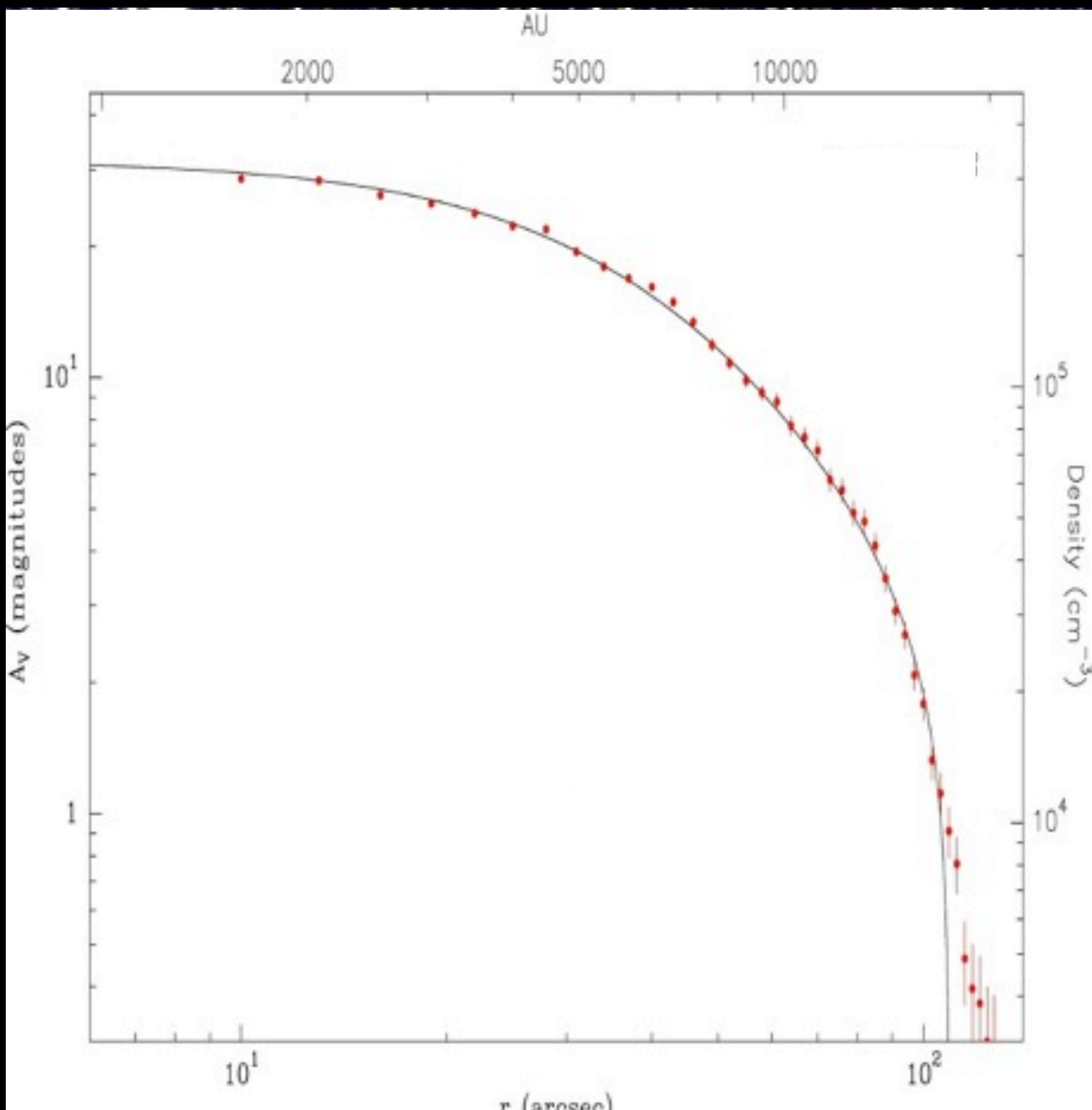
VLT (BVI)



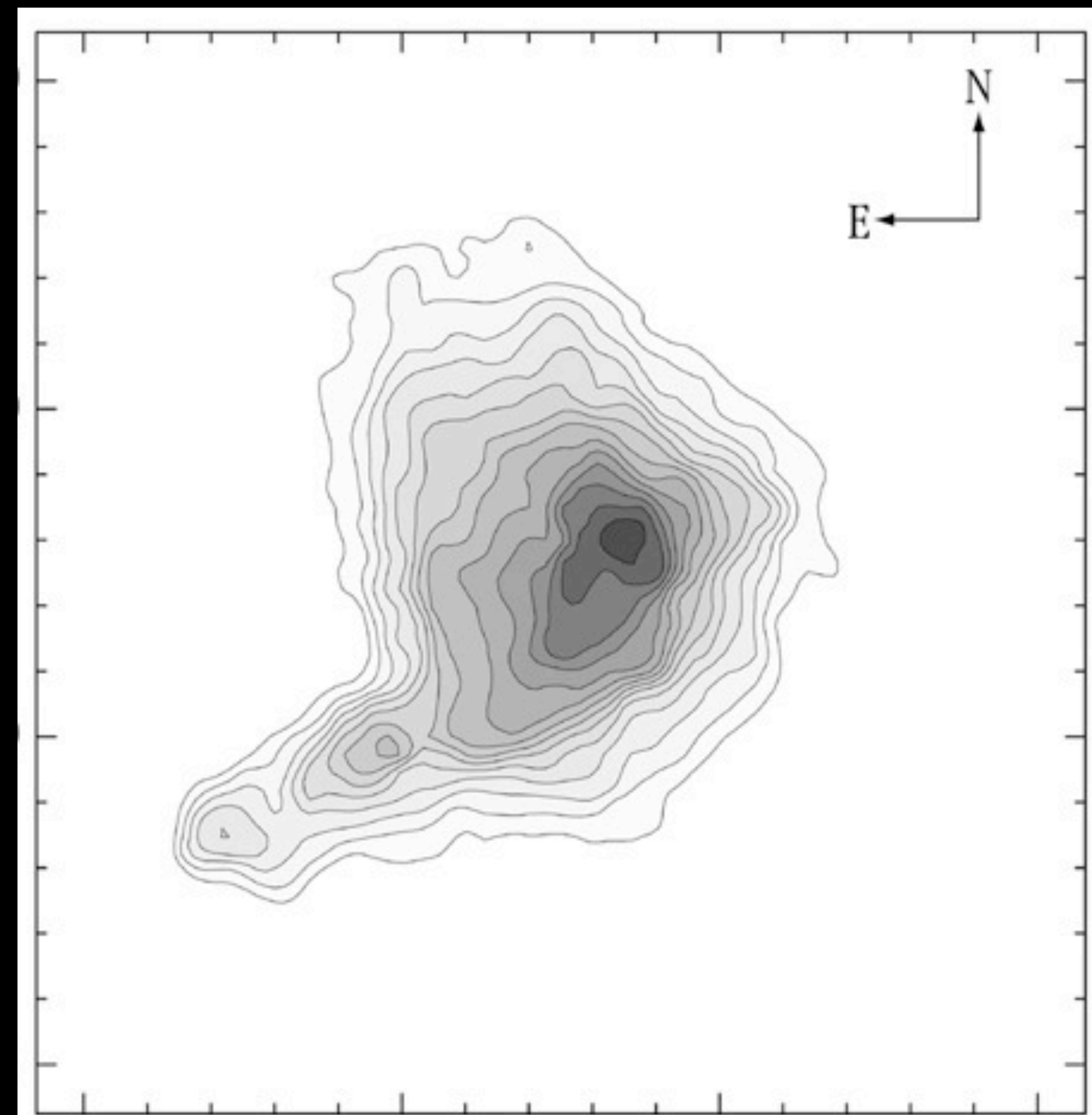
VLT + NTT (BIK)

Alves et al. (2000)

Extinction



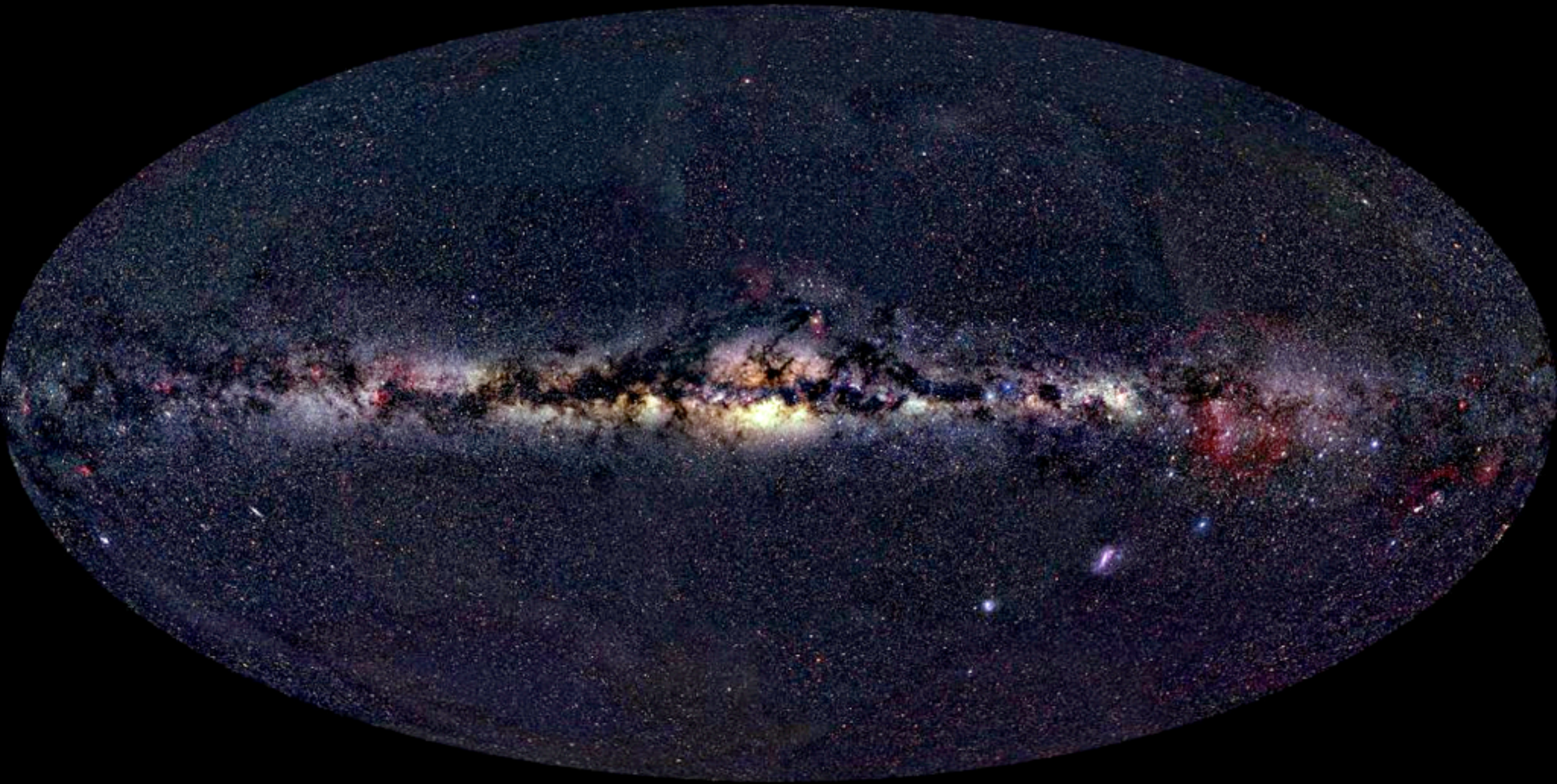
VLT (BVI)



VLT + NTT (BIK)

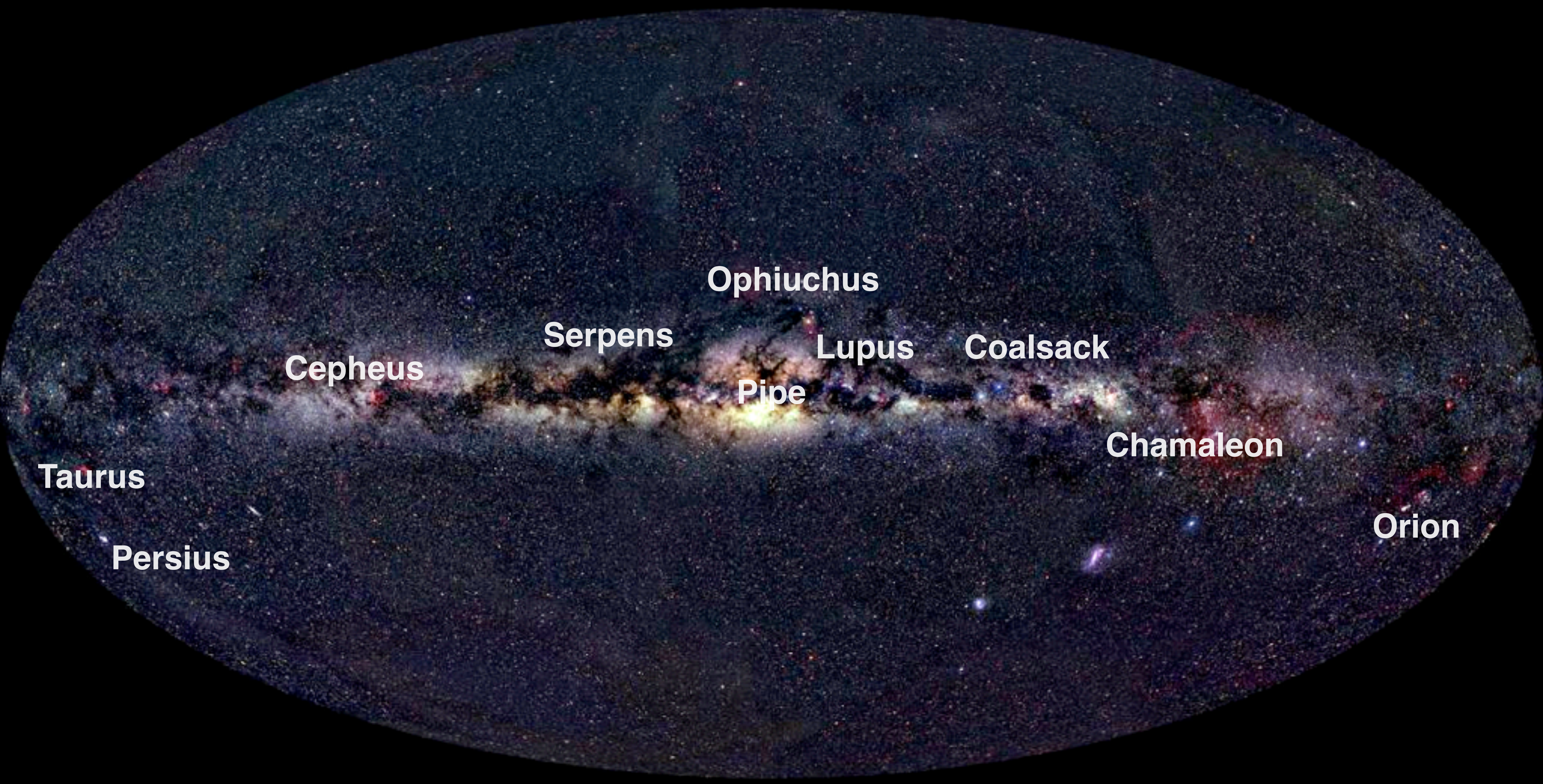
Alves et al. (2000)

Milky Way & Gould belt (optical)



A. Mellinger

Milky Way & Gould belt (optical)



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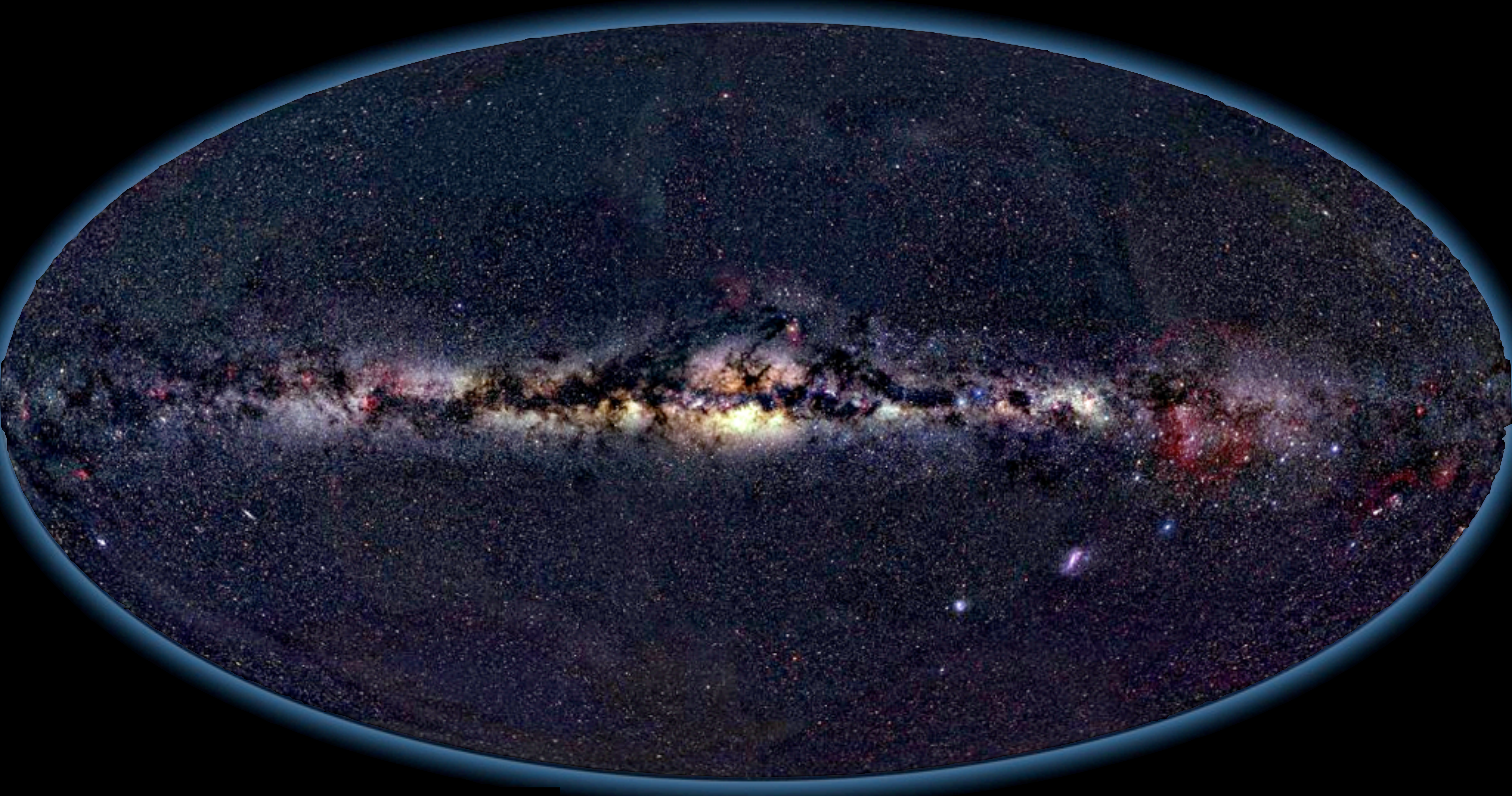
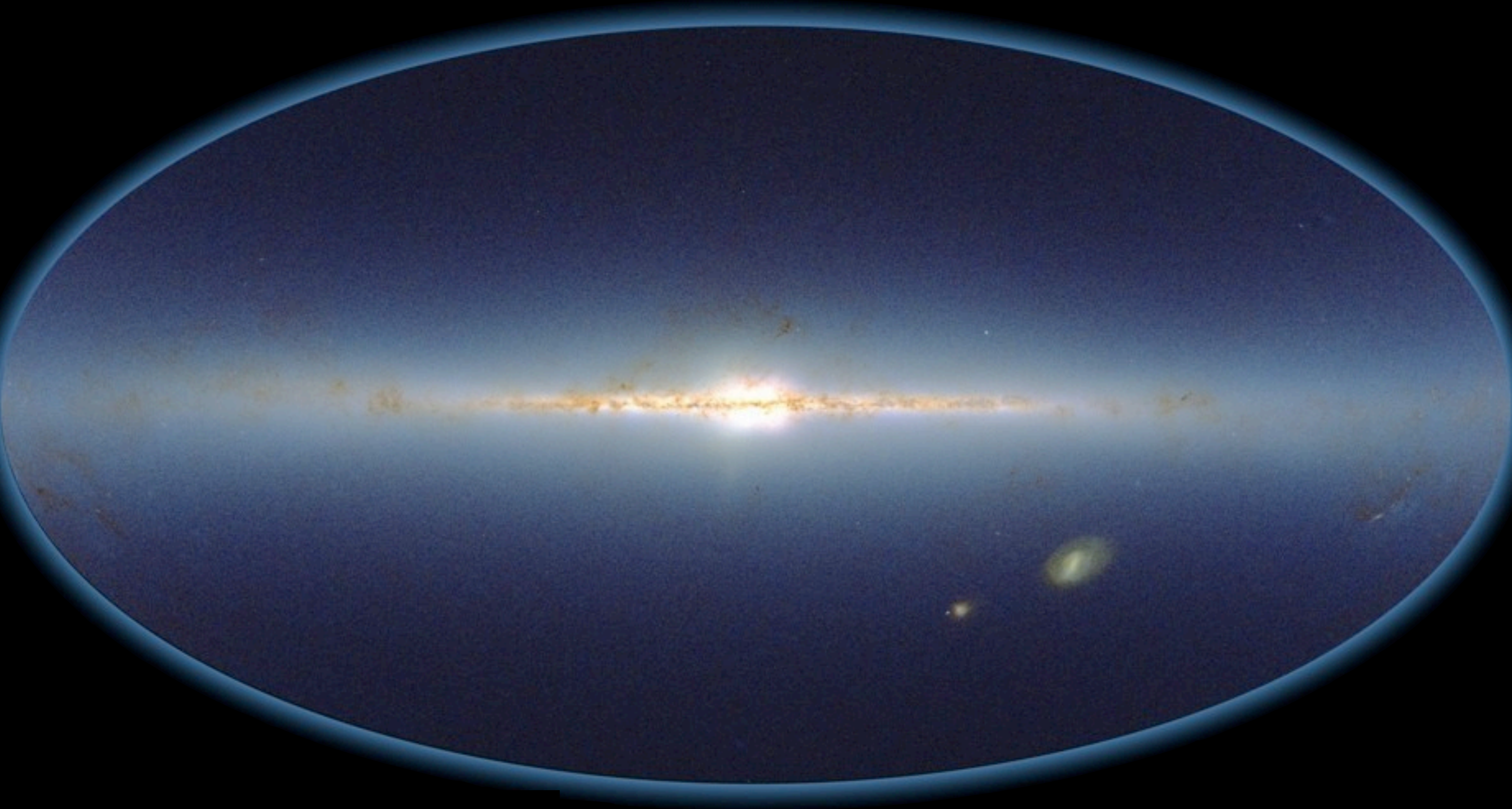
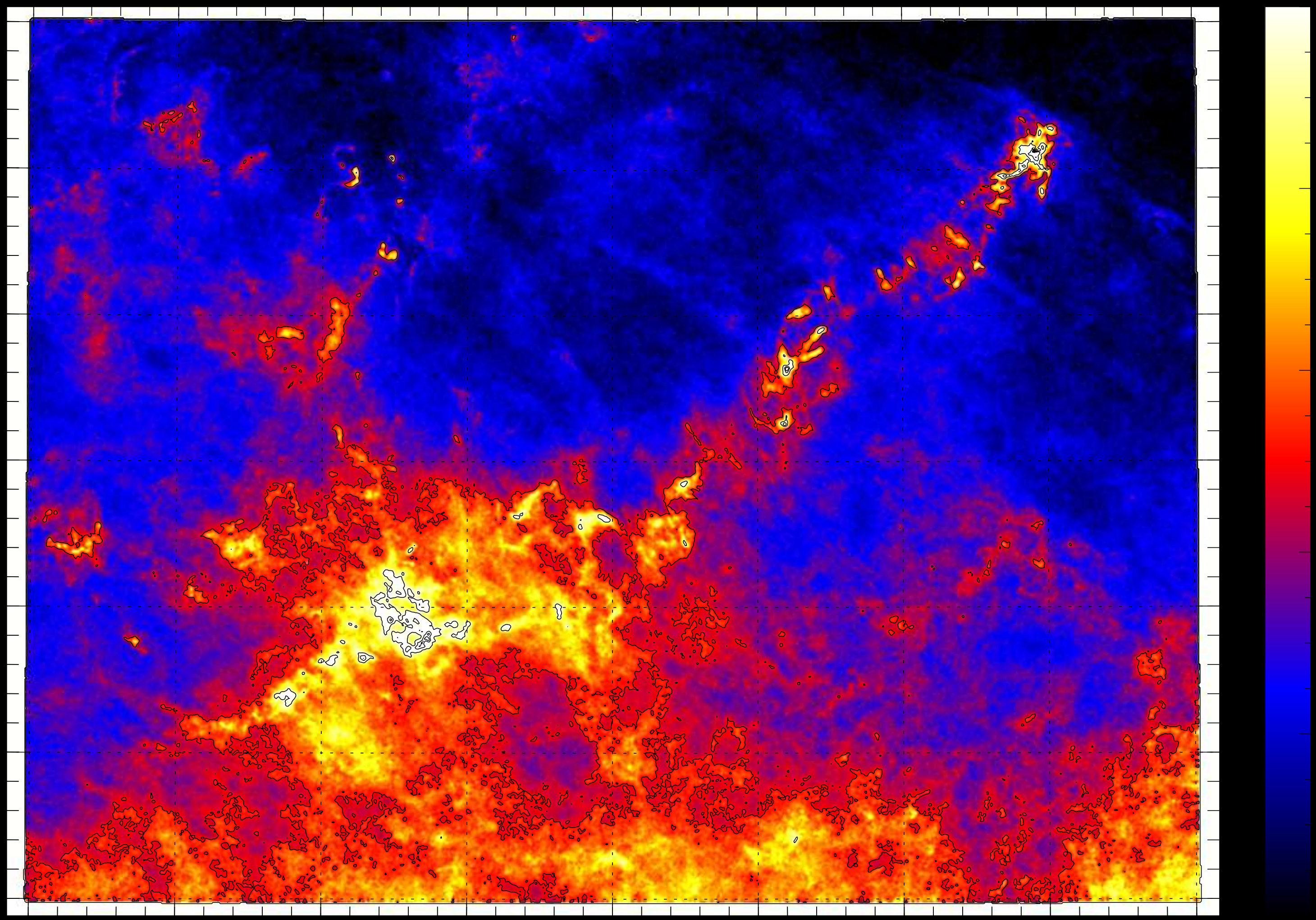


A. Mellinger

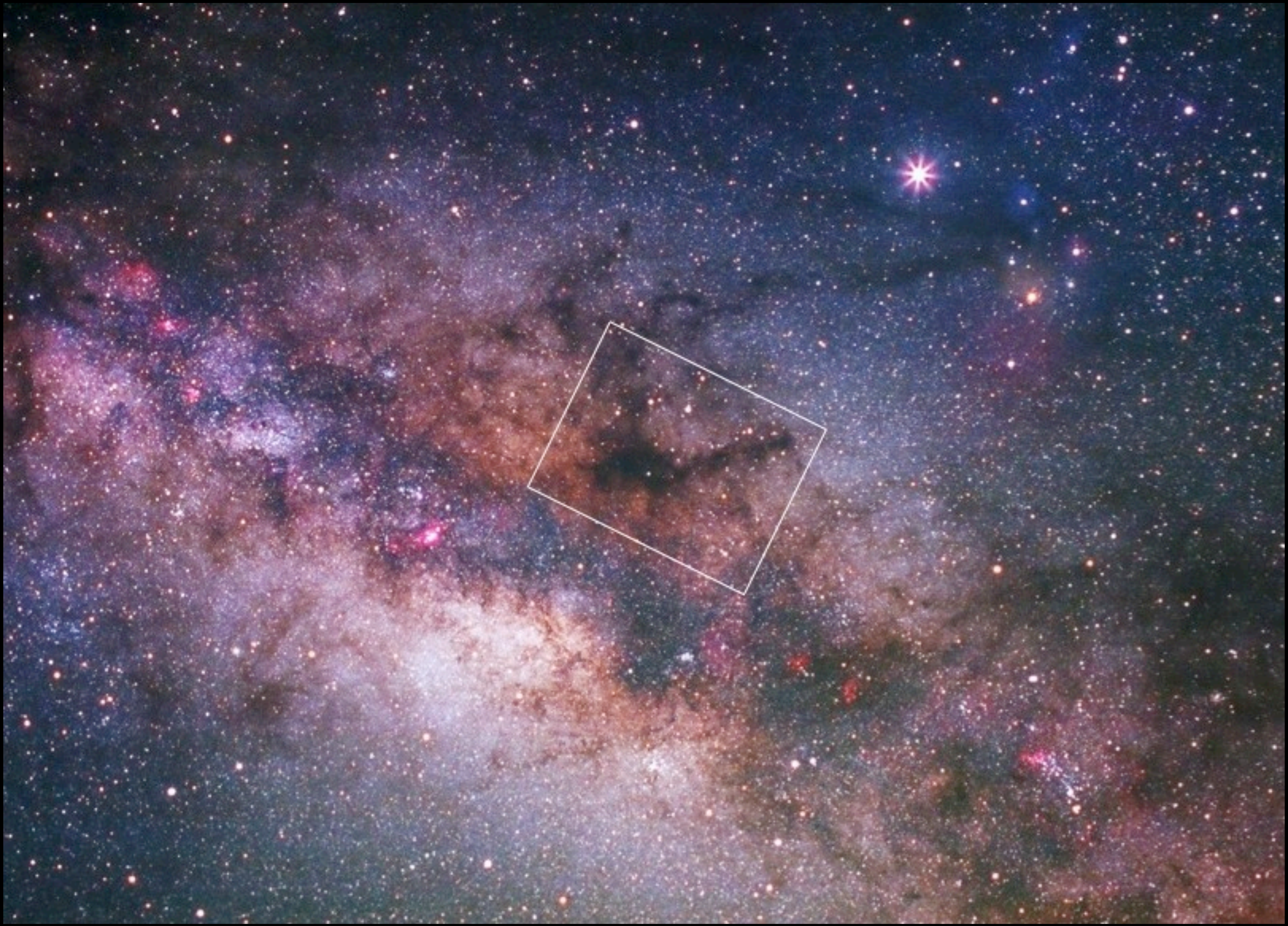
Milky Way & Gould belt (NIR)



2MASS

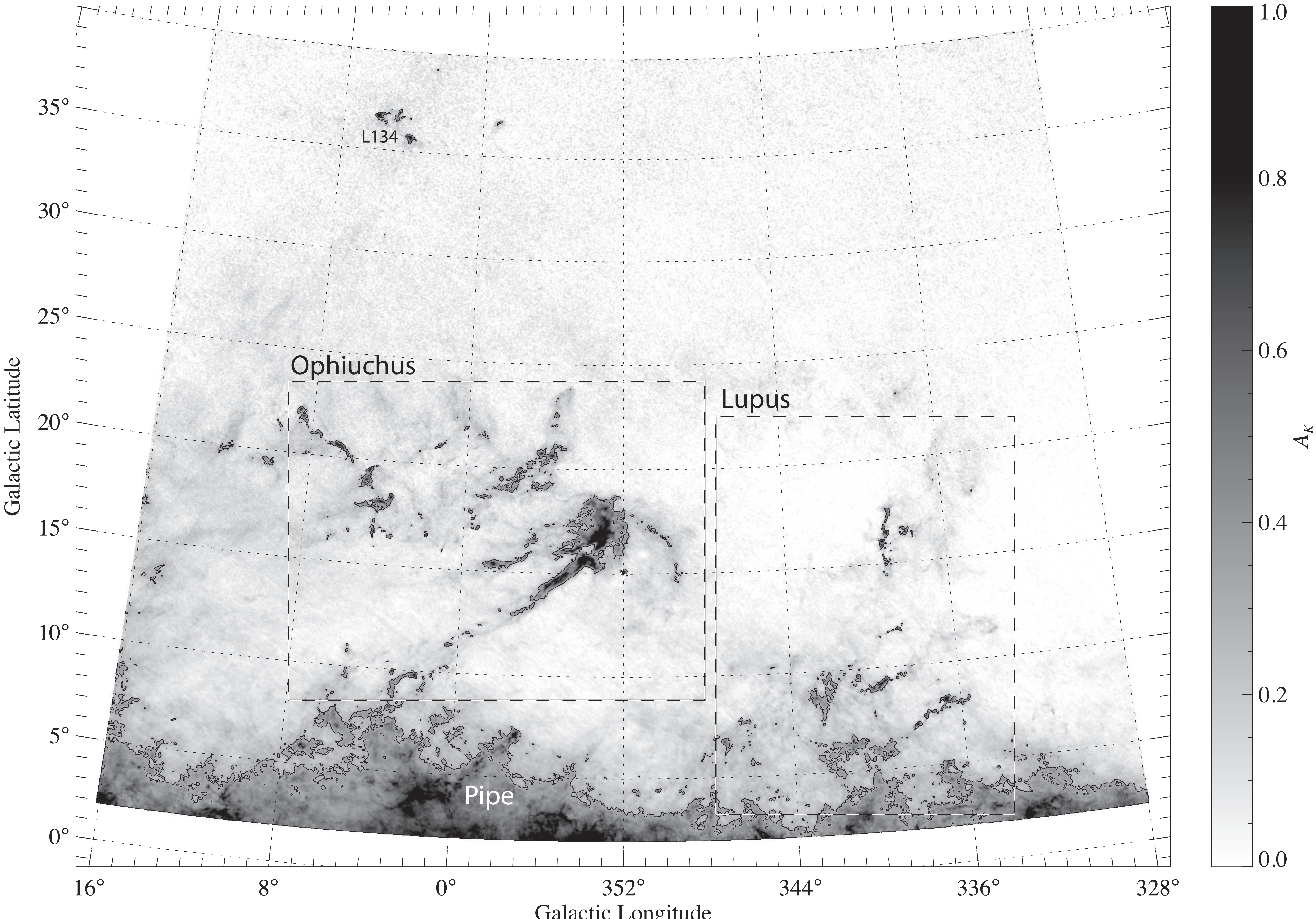


The Pipe Nebula (Lombardi et al. 2006)

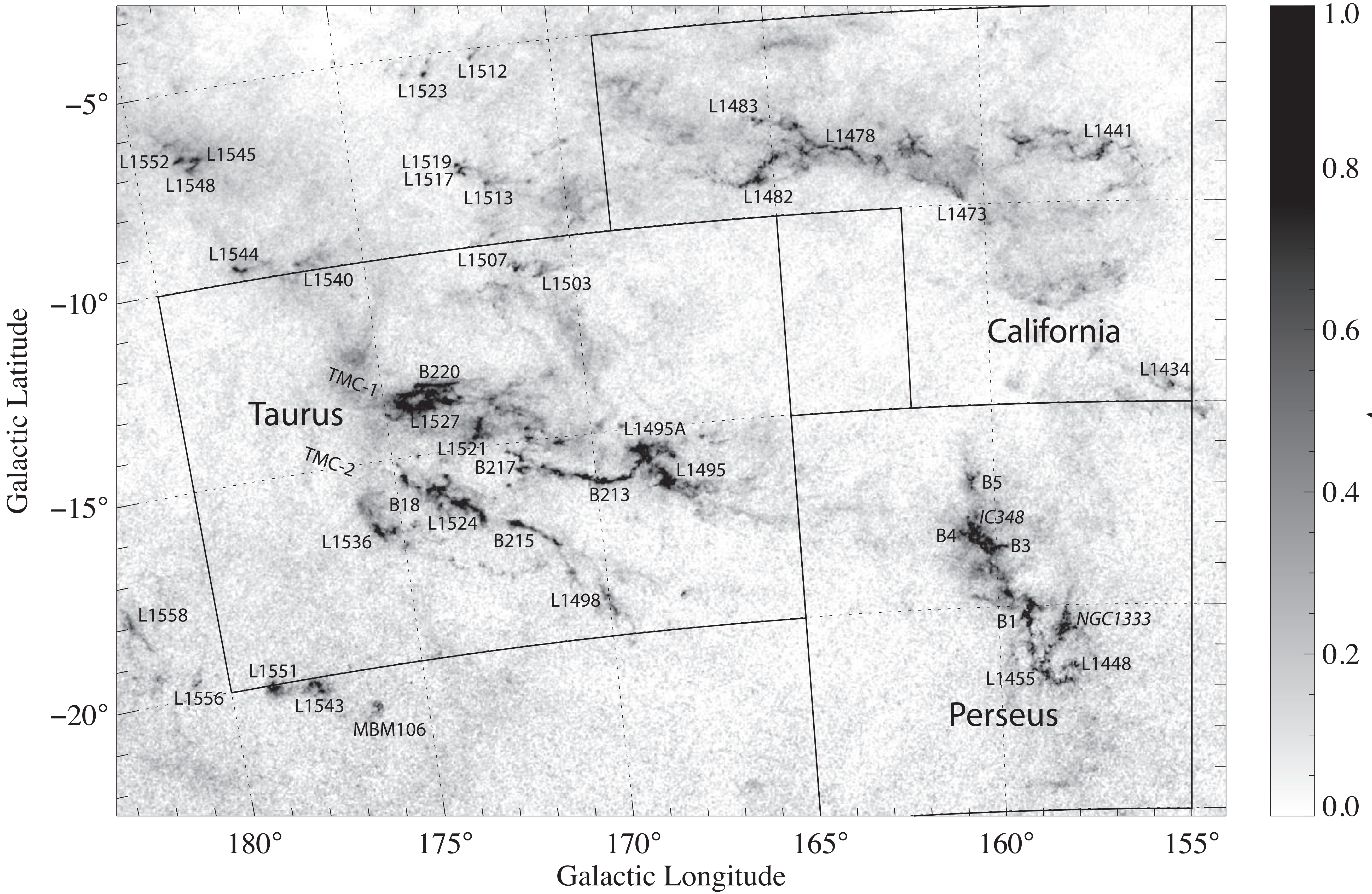


The Pipe Nebula (Lombardi et al. 2006)

Lombardi et al. (2009)



Lombardi et al. (2009)



Lombardi et al. (2010)

Lombardi et al. (2011)

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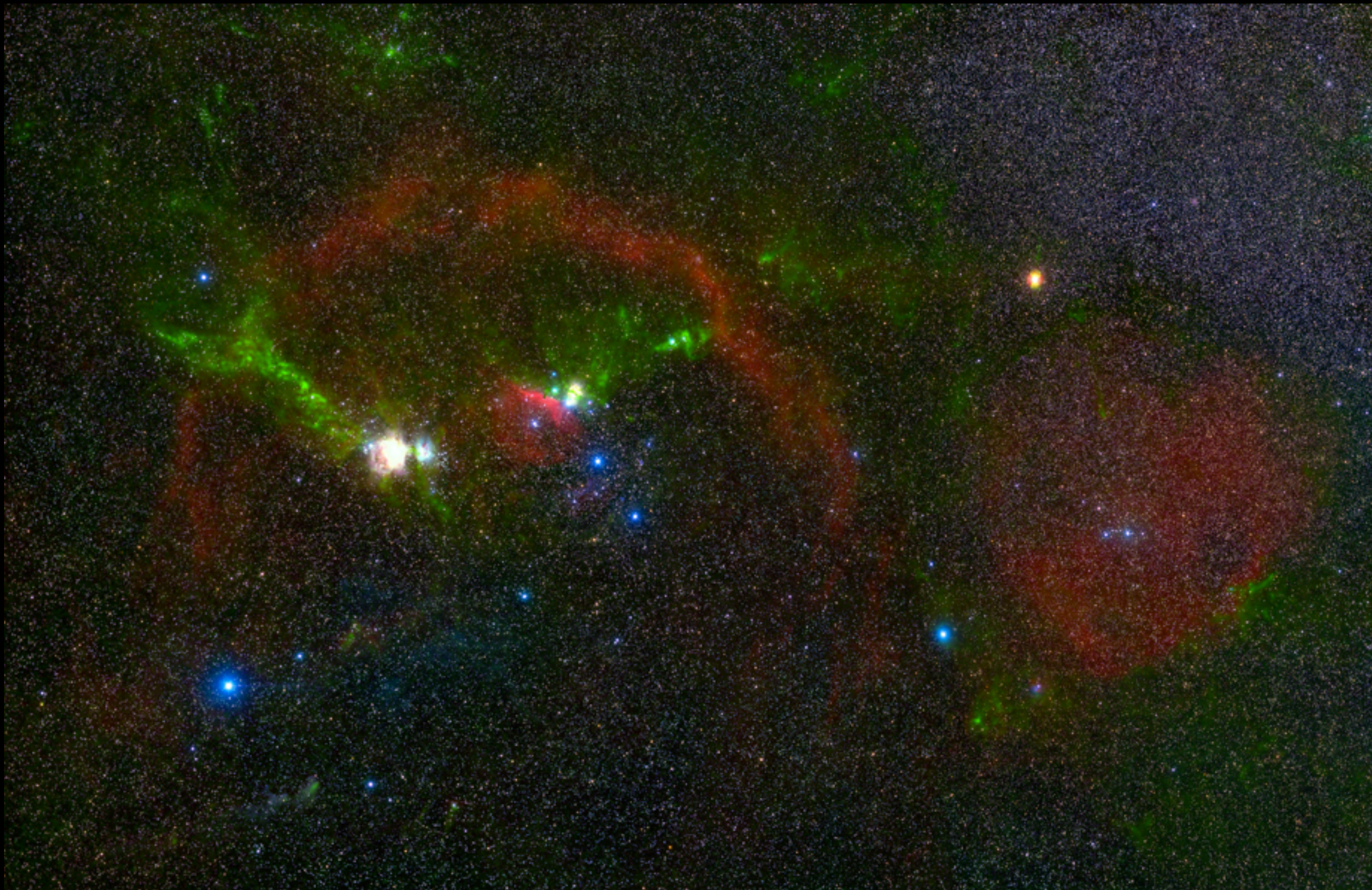
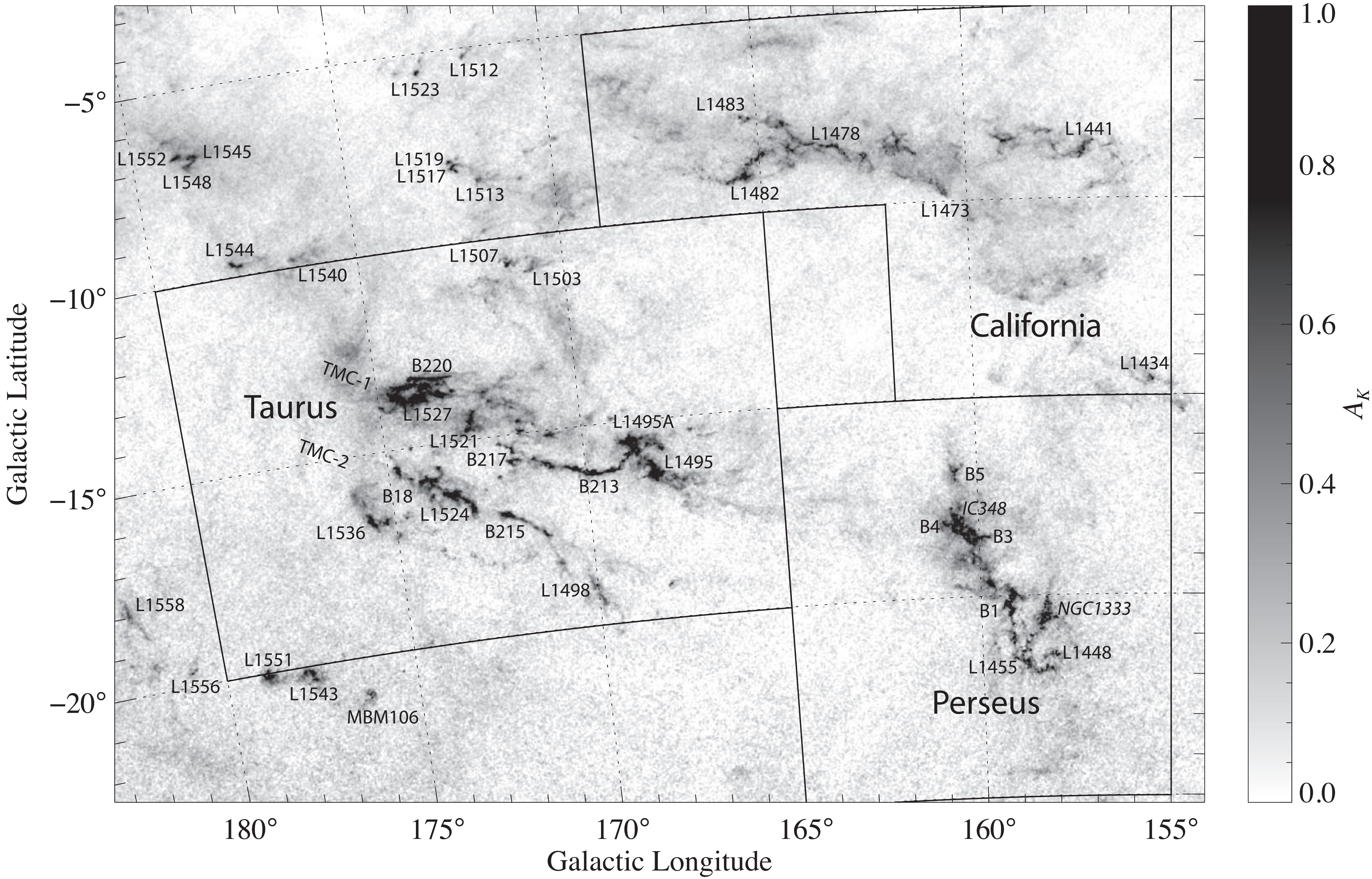


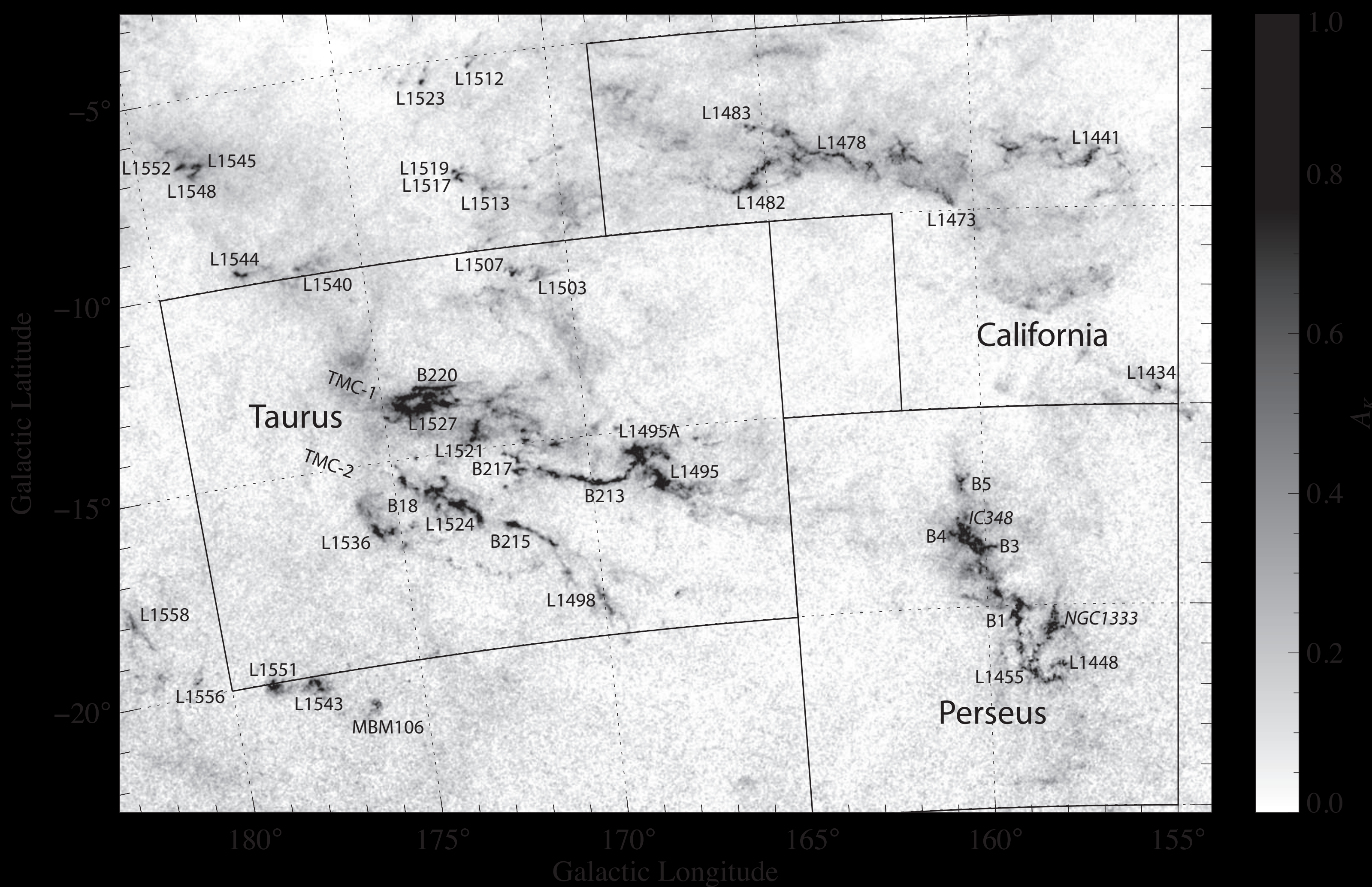
Lombardi et al. (2011)



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

Inventory of Star Formation Activity: Molecular Clouds

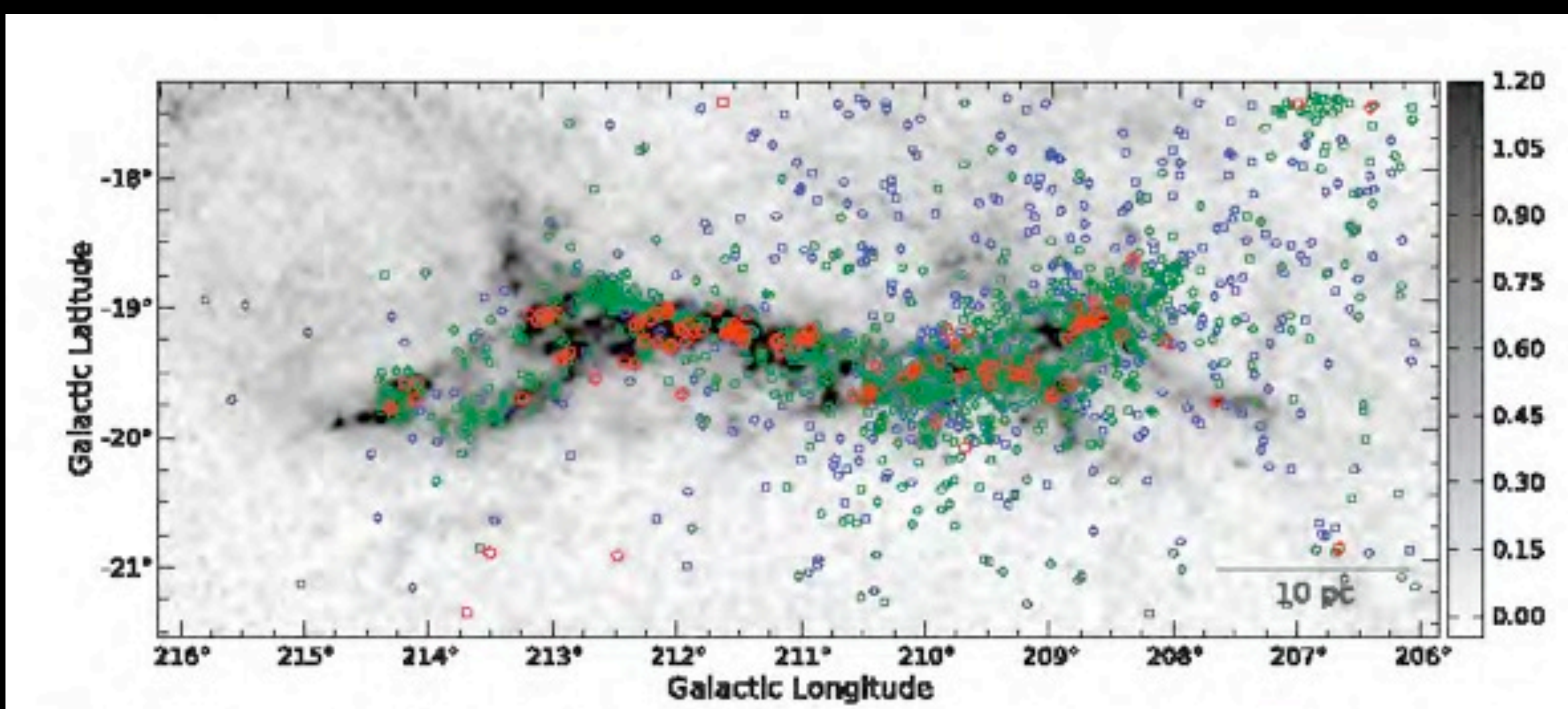
Cloud sample: wide field 2MASS/NICER extinction survey of 21 local modelcular clouds



Cloud	Mass (10^4 $M_\odot$)
Orion A	6.77
Orion B	7.18
California	9.99
Perseus	1.84
Taurus	1.49
Ophiuchus	1.41
RCrA	0.11
Pipe	0.79
Lupus 1	0.22
Lupus 3	0.14
Lupus 4	0.08

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

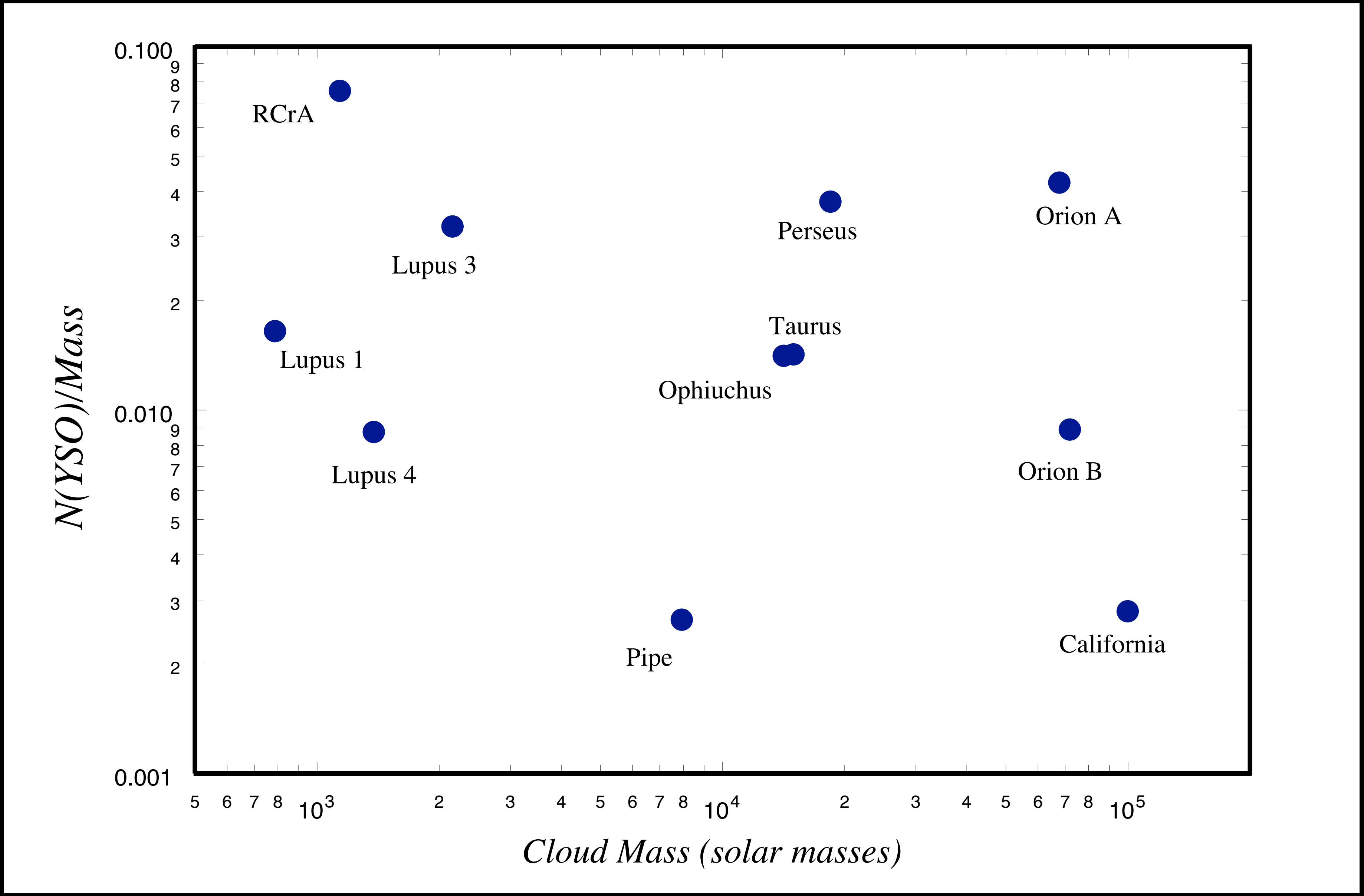
Mining the literature: mostly IR data (SPITZER)



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

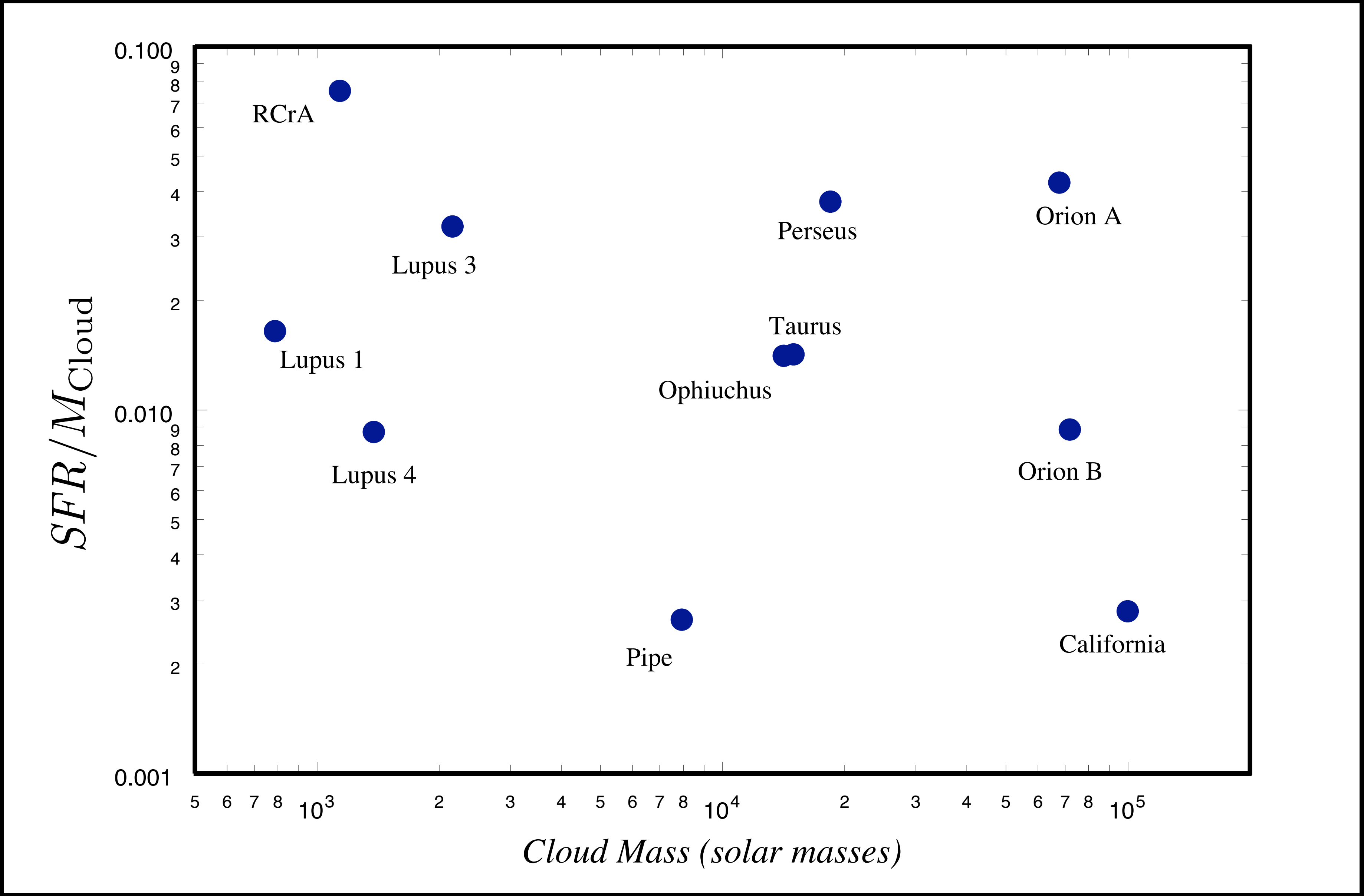
Variation of specific star formation rate

Variations of efficiencies and star formation rates in local molecular clouds



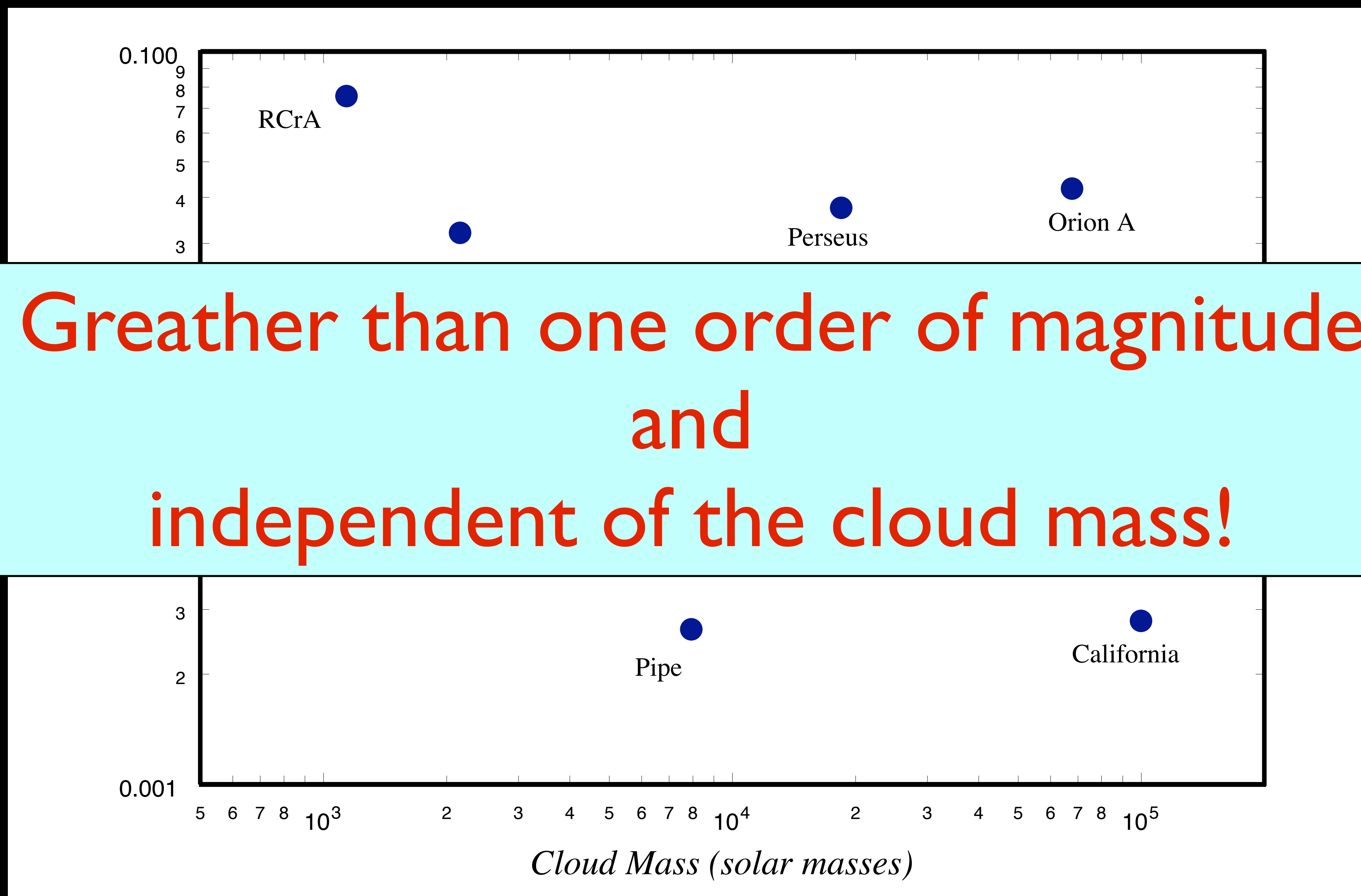
$$SFR = \langle m_\star \rangle N_{\rm YSOs}/t_{\rm sf} \simeq 0.25 \times 10^{-6} N_{\rm YSOs}\ {\rm M_\odot\ yr^{-1}}$$

Variations of efficiencies and star formation rates in local molecular clouds



$$SFR = \langle m_\star \rangle N_{\rm YSOs}/t_{\rm sf} \simeq 0.25 \times 10^{-6} N_{\rm YSOs}\ {\rm M_\odot\ yr^{-1}}$$

Variations of efficiencies and star formation rates in local molecular clouds

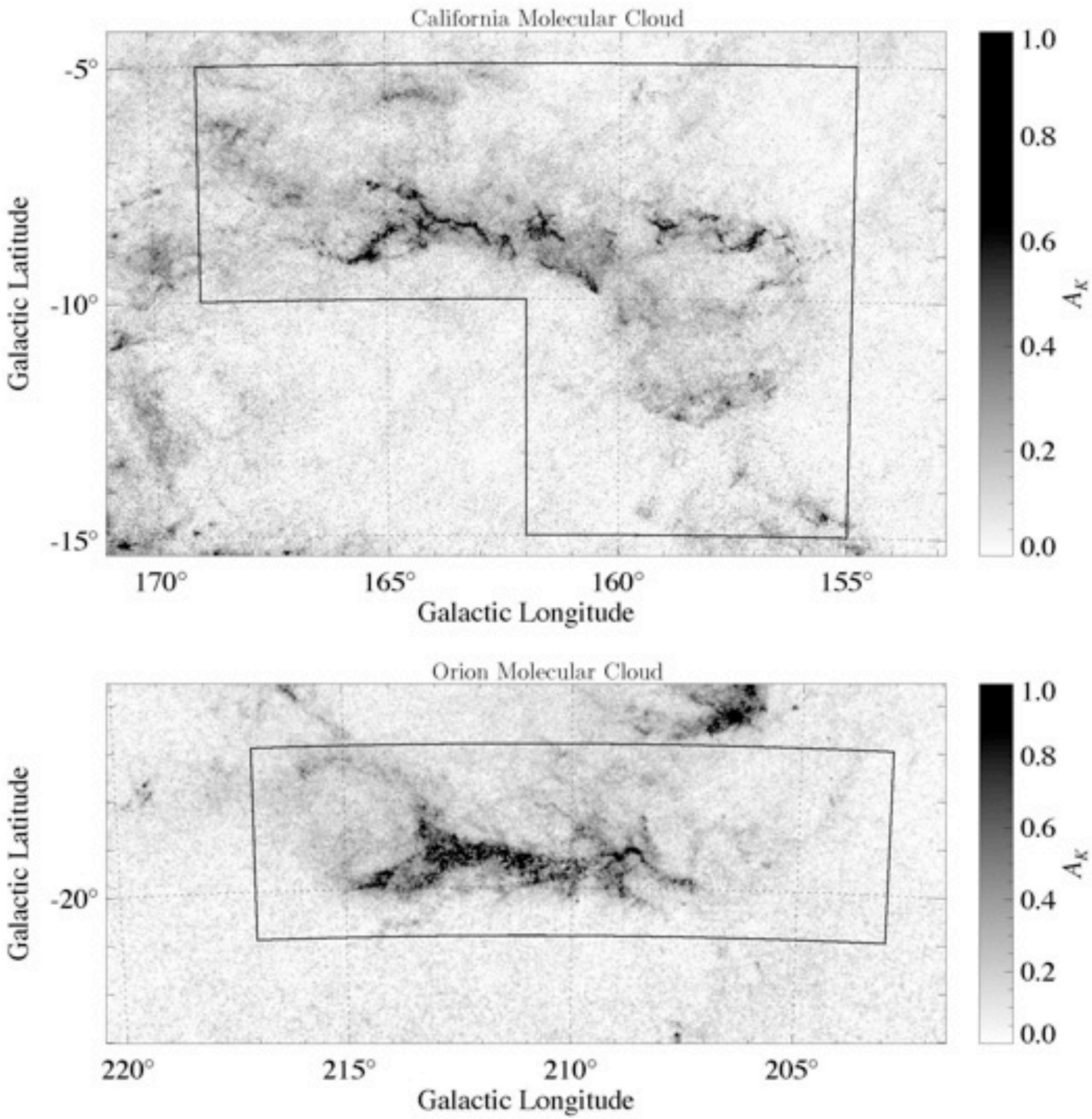


Greather than one order of magnitude
and
independent of the cloud mass!

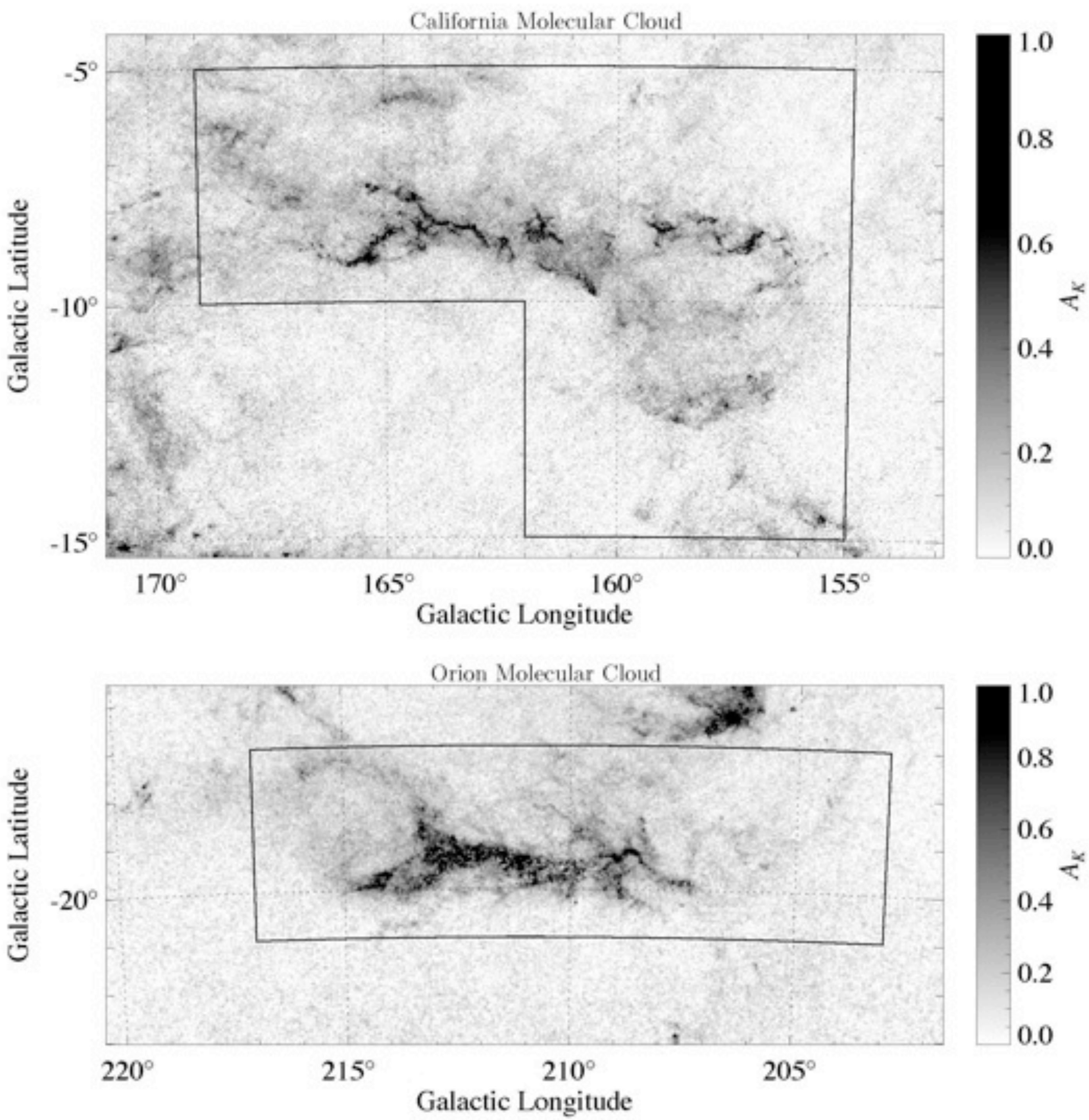
$$SFR = \langle m_\star \rangle N_{\rm YSOs}/t_{\rm sf} \simeq 0.25 \times 10^{-6} N_{\rm YSOs}\ {\rm M_\odot\ yr^{-1}}$$

What determines the star formation rate?

Comparing the California and Orion molecular clouds



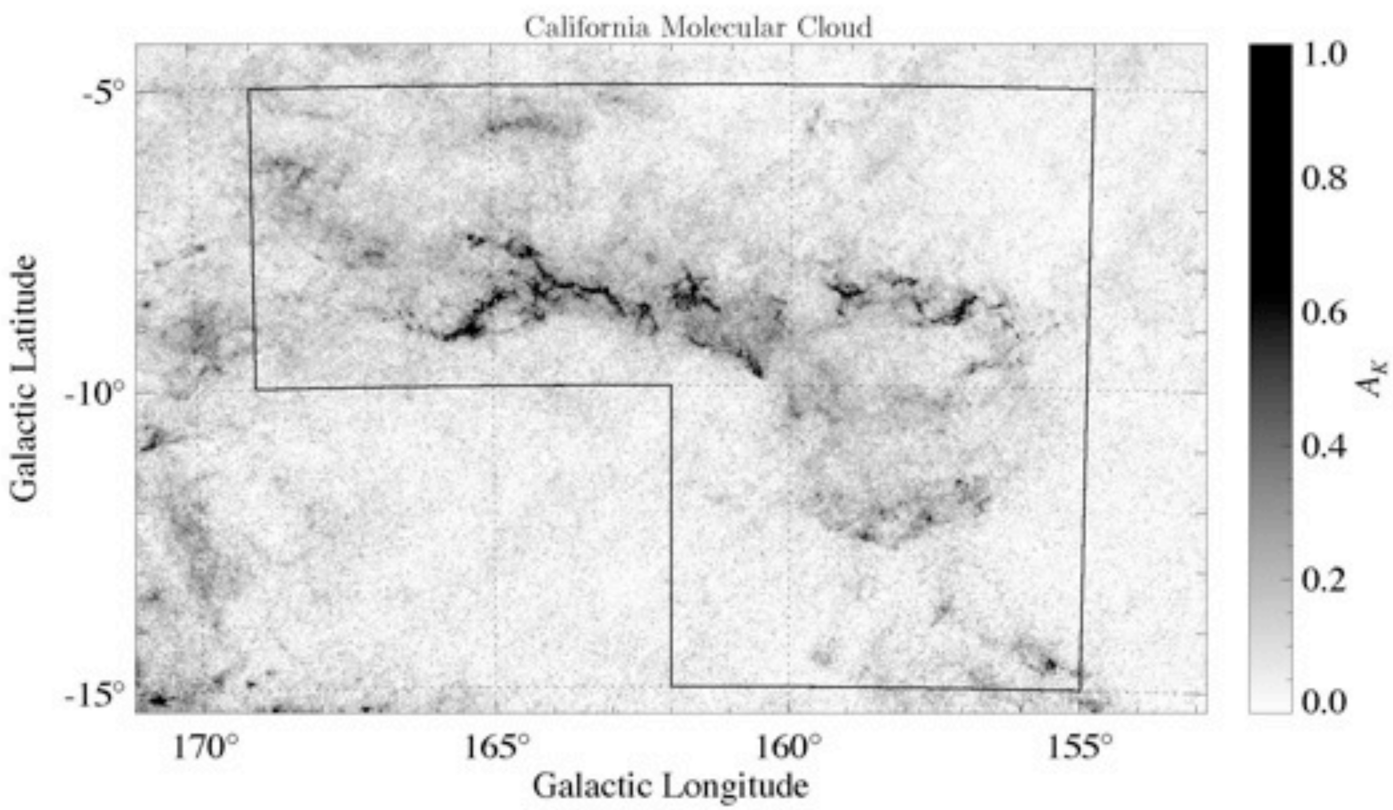
Comparing the California and Orion molecular clouds

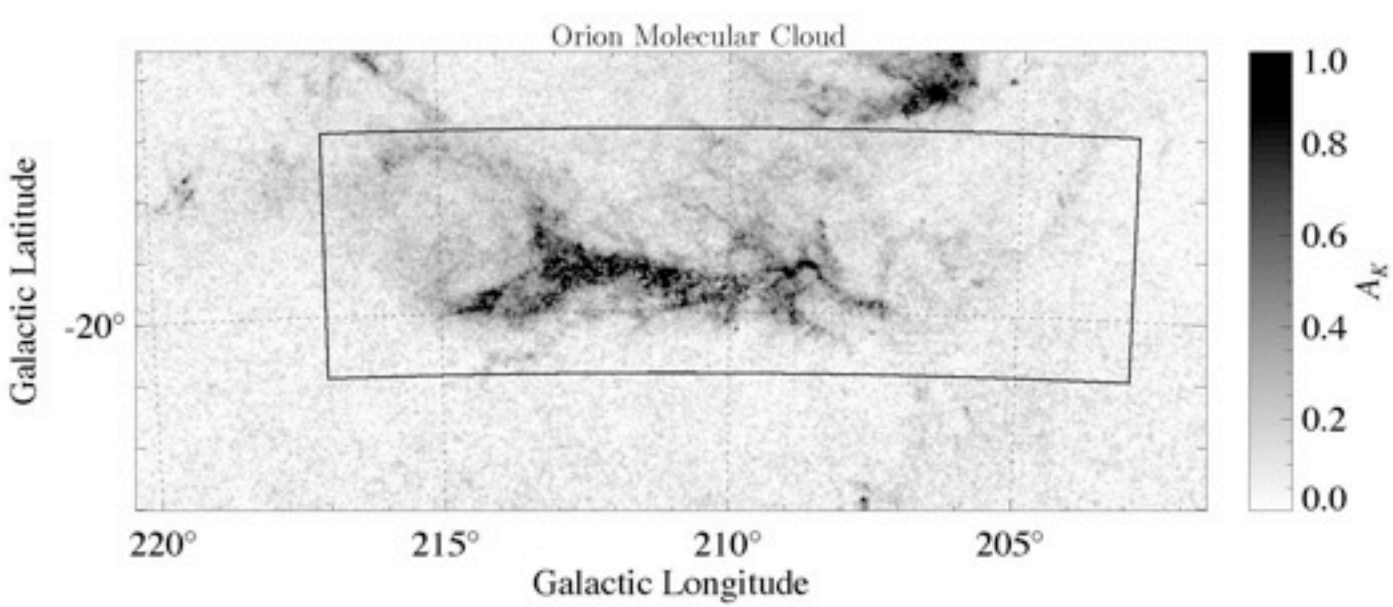


Nearly identical shapes & sizes, but

YSOs(Orion) > 10 x YSOs(California)

Comparing the California and Orion molecular clouds





Nearly identical shapes & sizes, but

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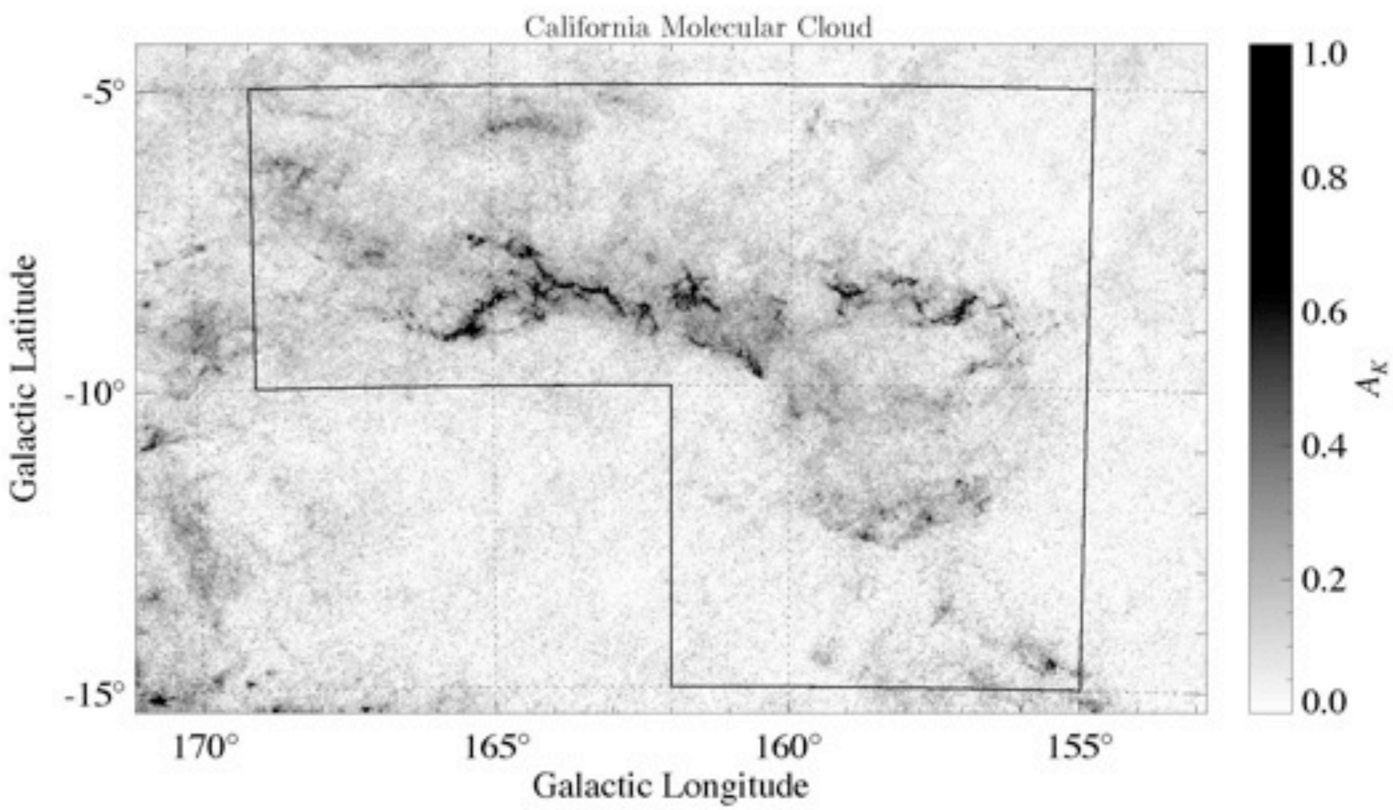
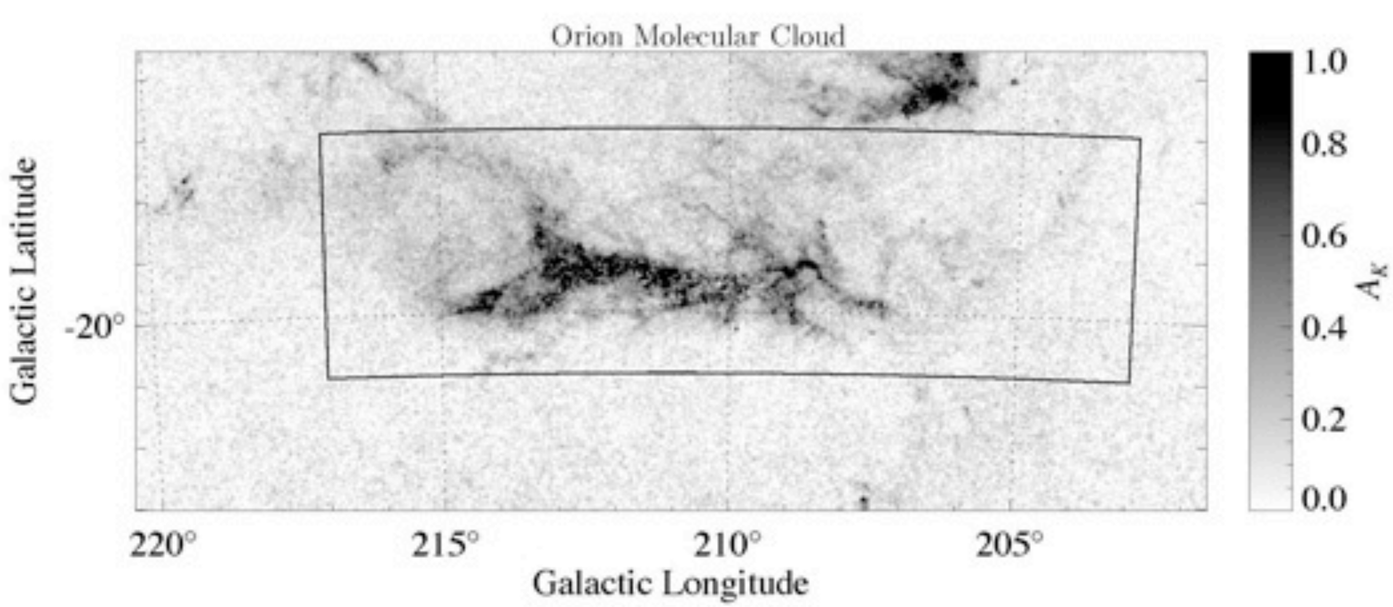
SFR(Orion) > 10 x SFR(California)

Comparing the California and Orion molecular clouds





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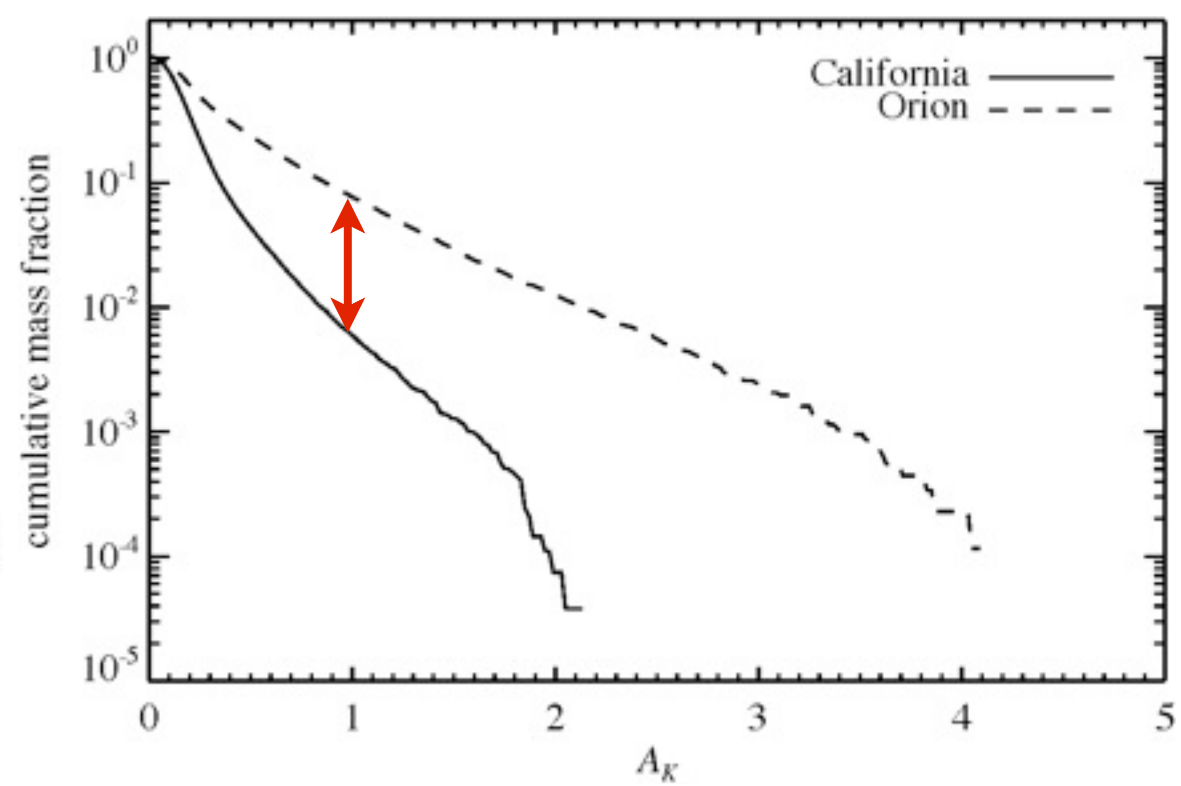


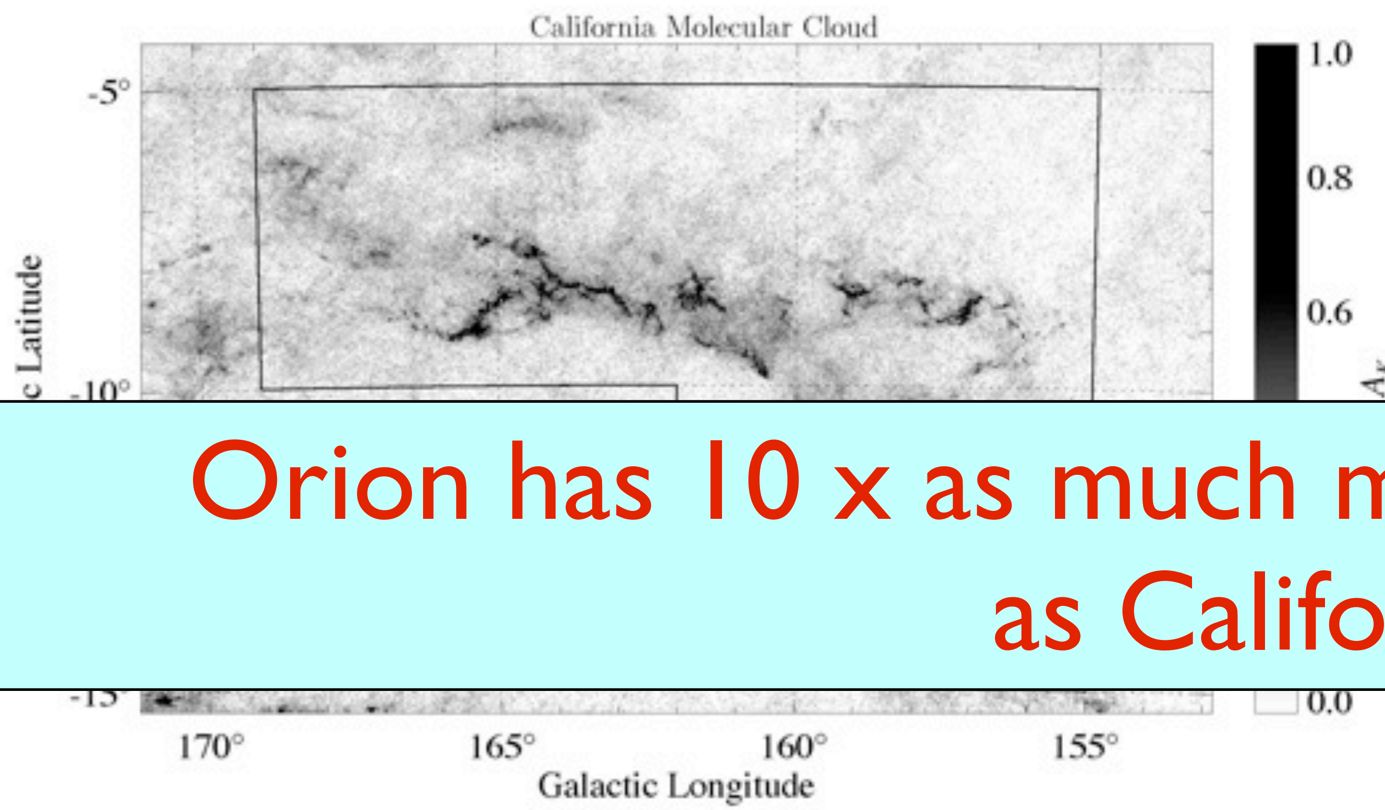
Comparing the California and Orion molecular clouds

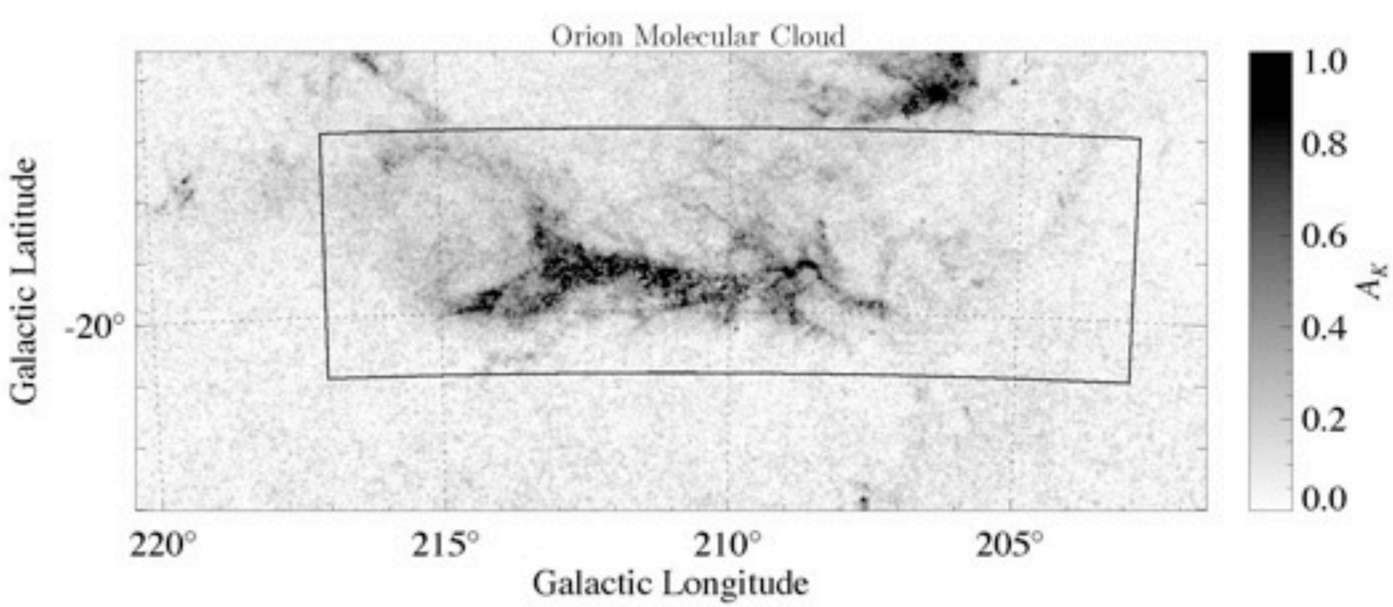
Nearly identical shapes & sizes, but

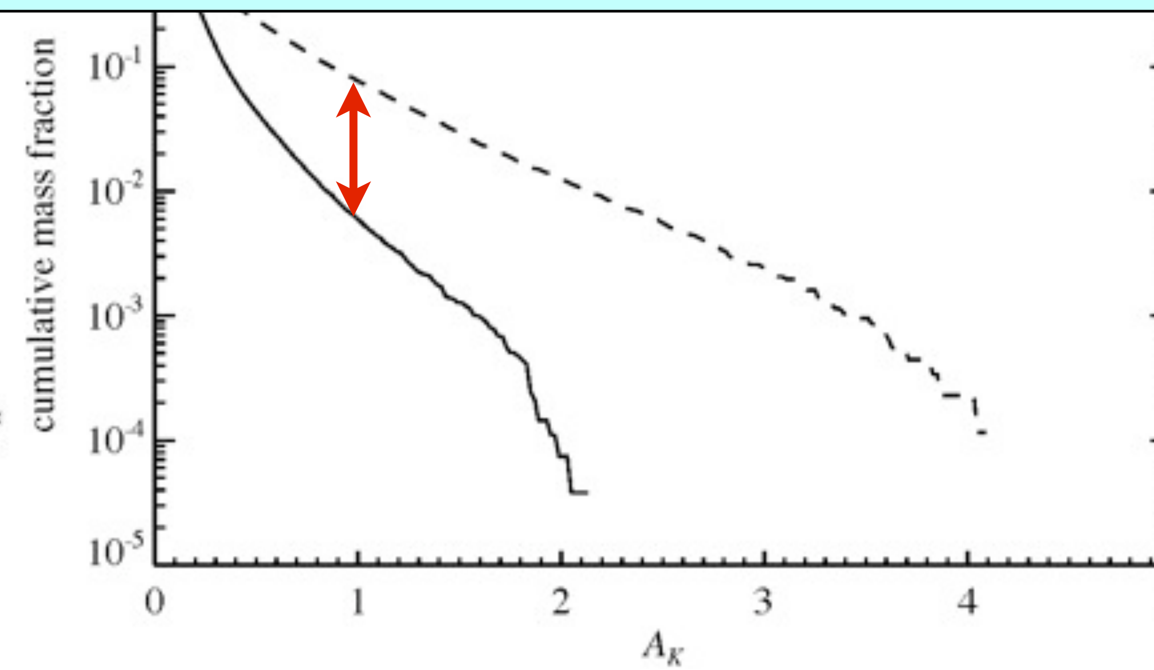
YSOs(Orion) > 10 x YSOs(California)

SFR(Orion) > 10 x SFR(California)

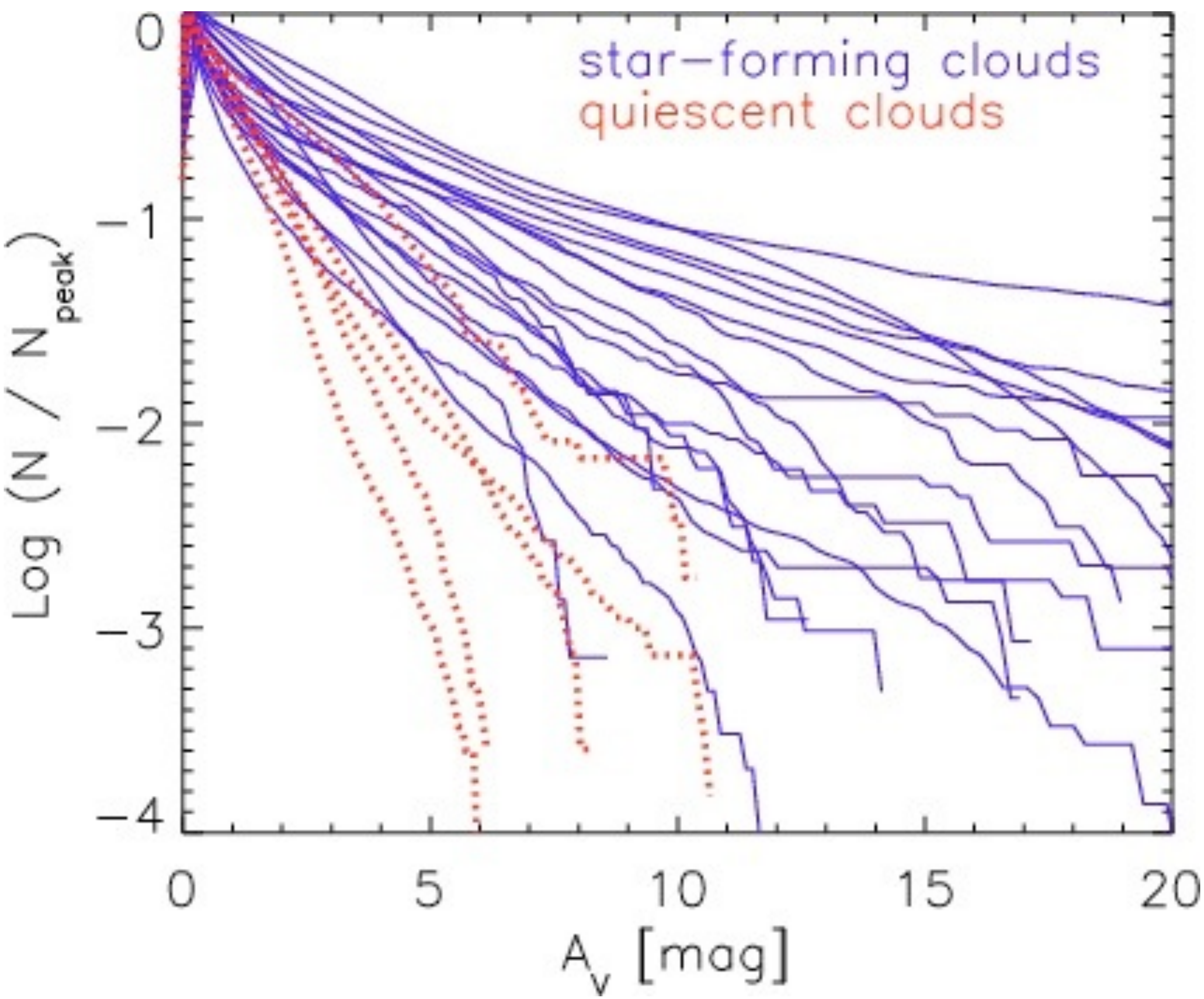
Orion has 10 x as much material at A_K > 1 mag as California





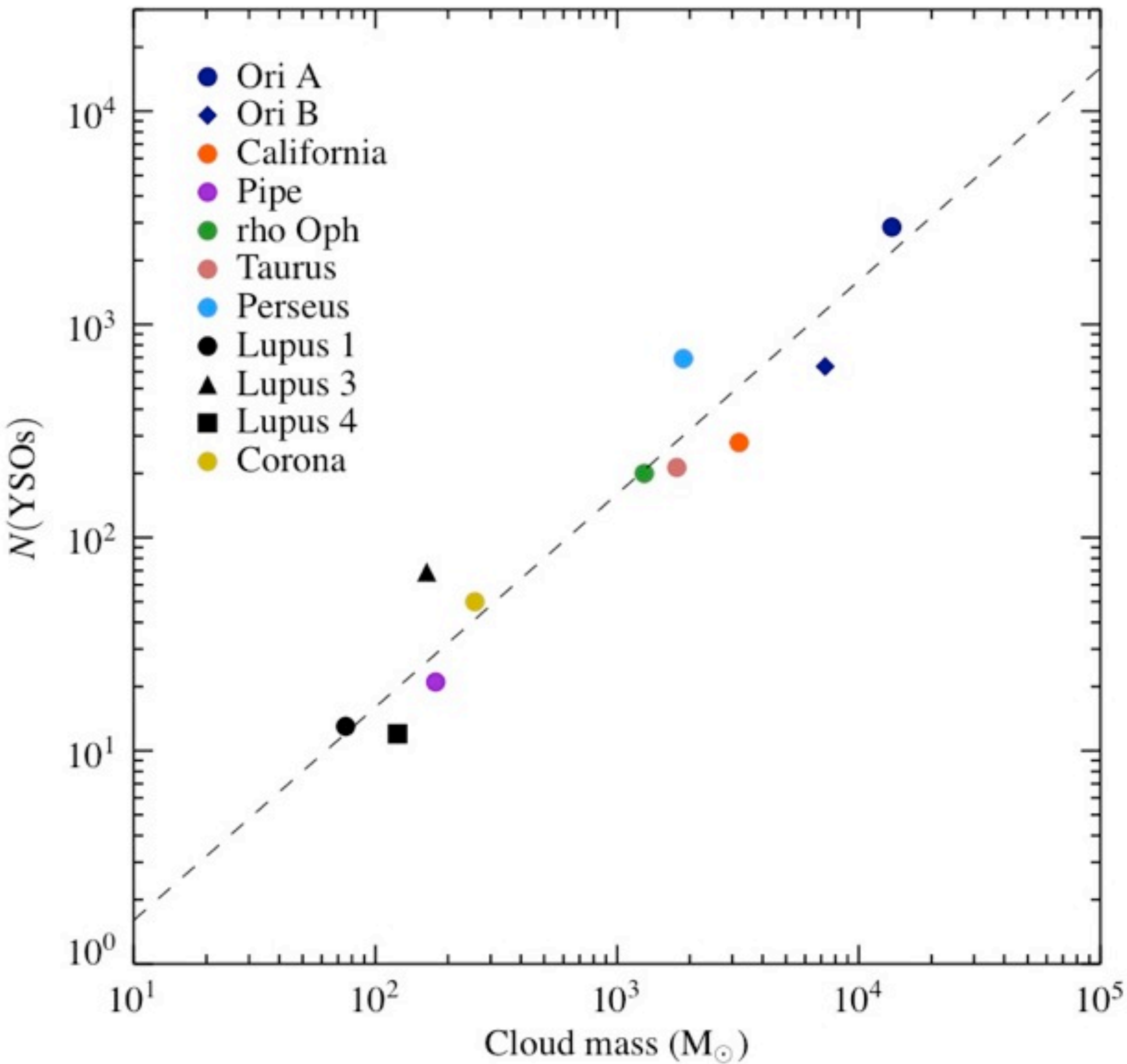


Normalized cloud mass profiles



Kainulainen et al. (2009)

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



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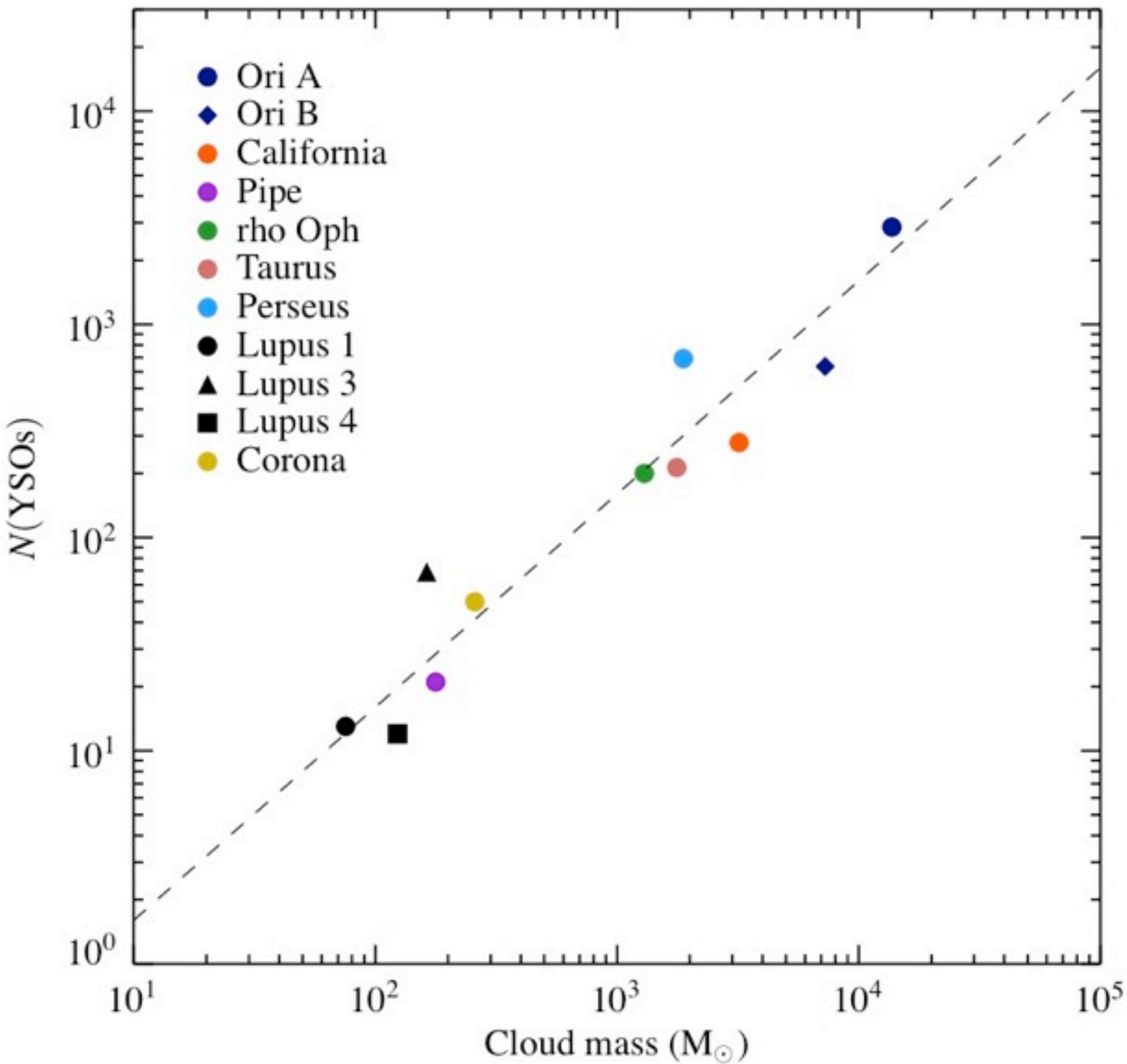

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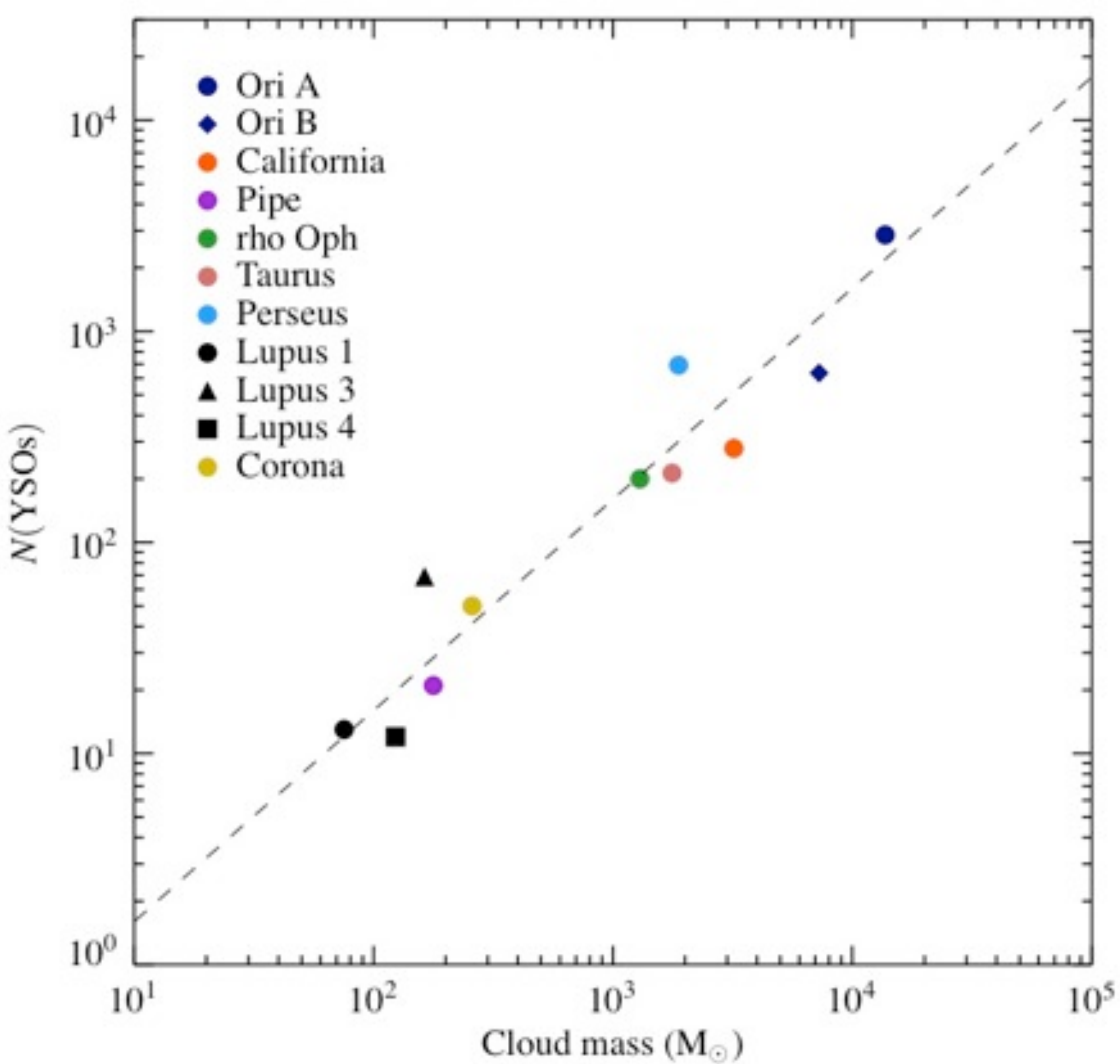

SFR directly proportional to mass above $A_K > 0.8$ mag ($\Sigma > 116\ M_\odot\ pc^{-2}$)

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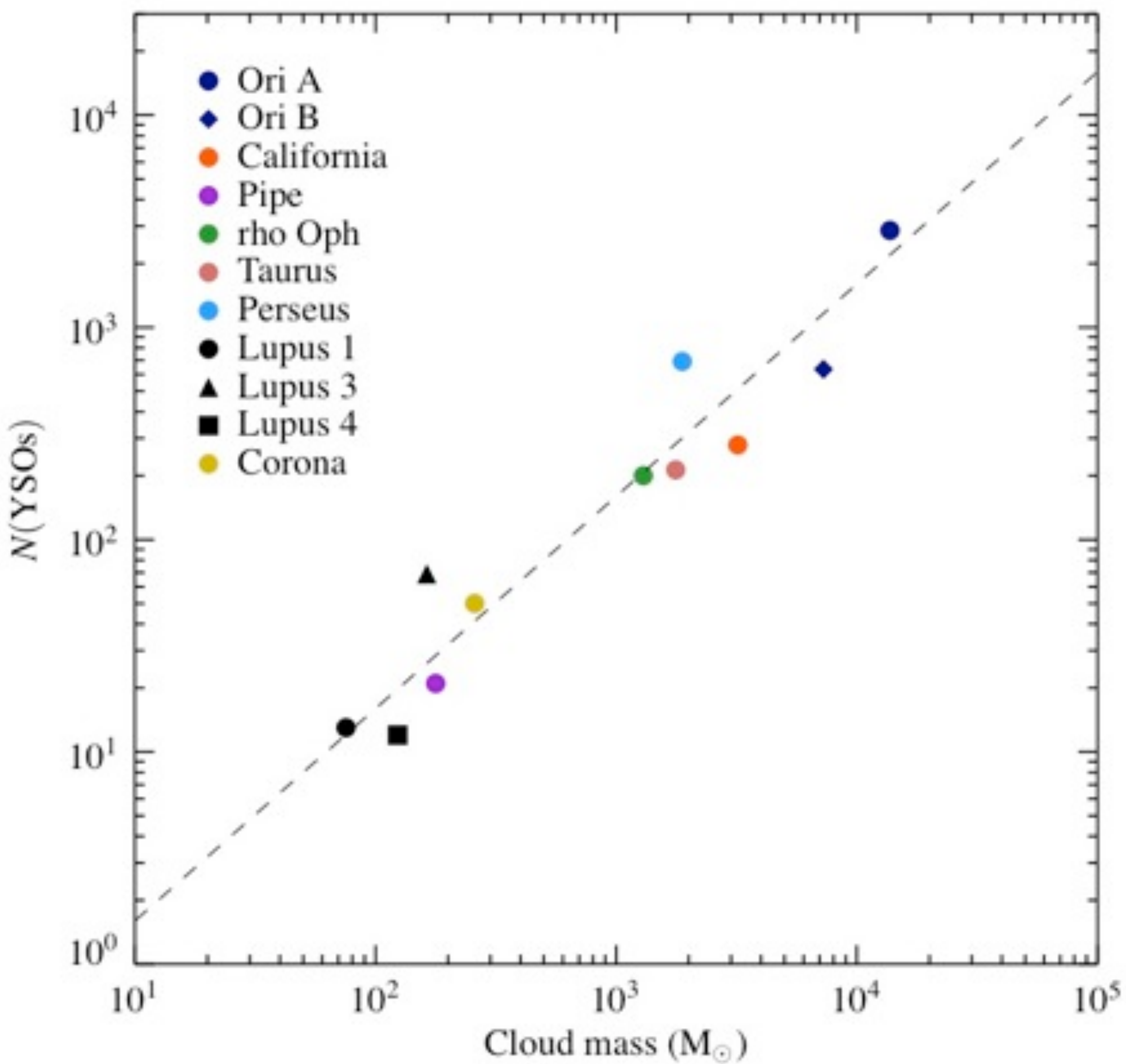

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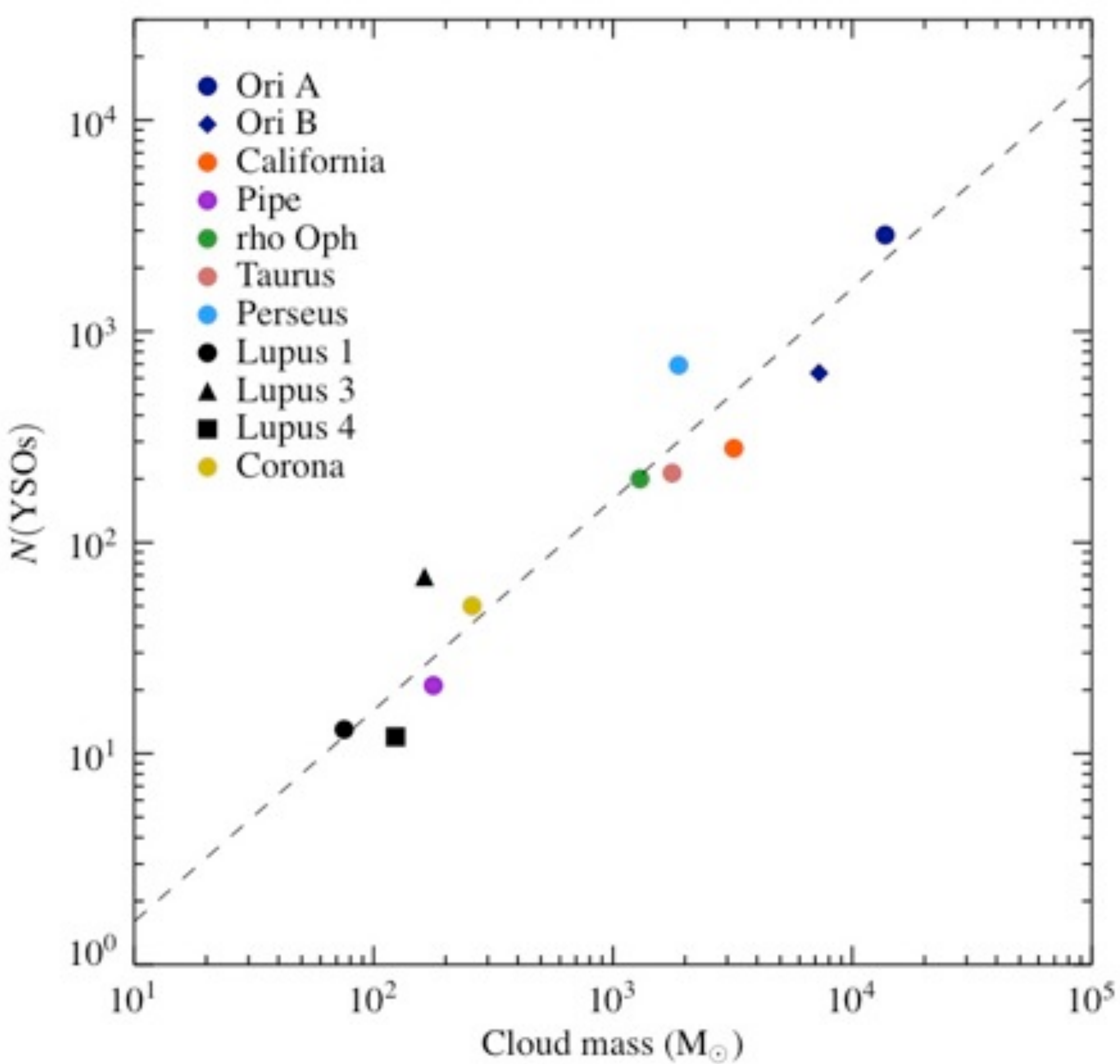

What is the meaning of the slope of this relation?

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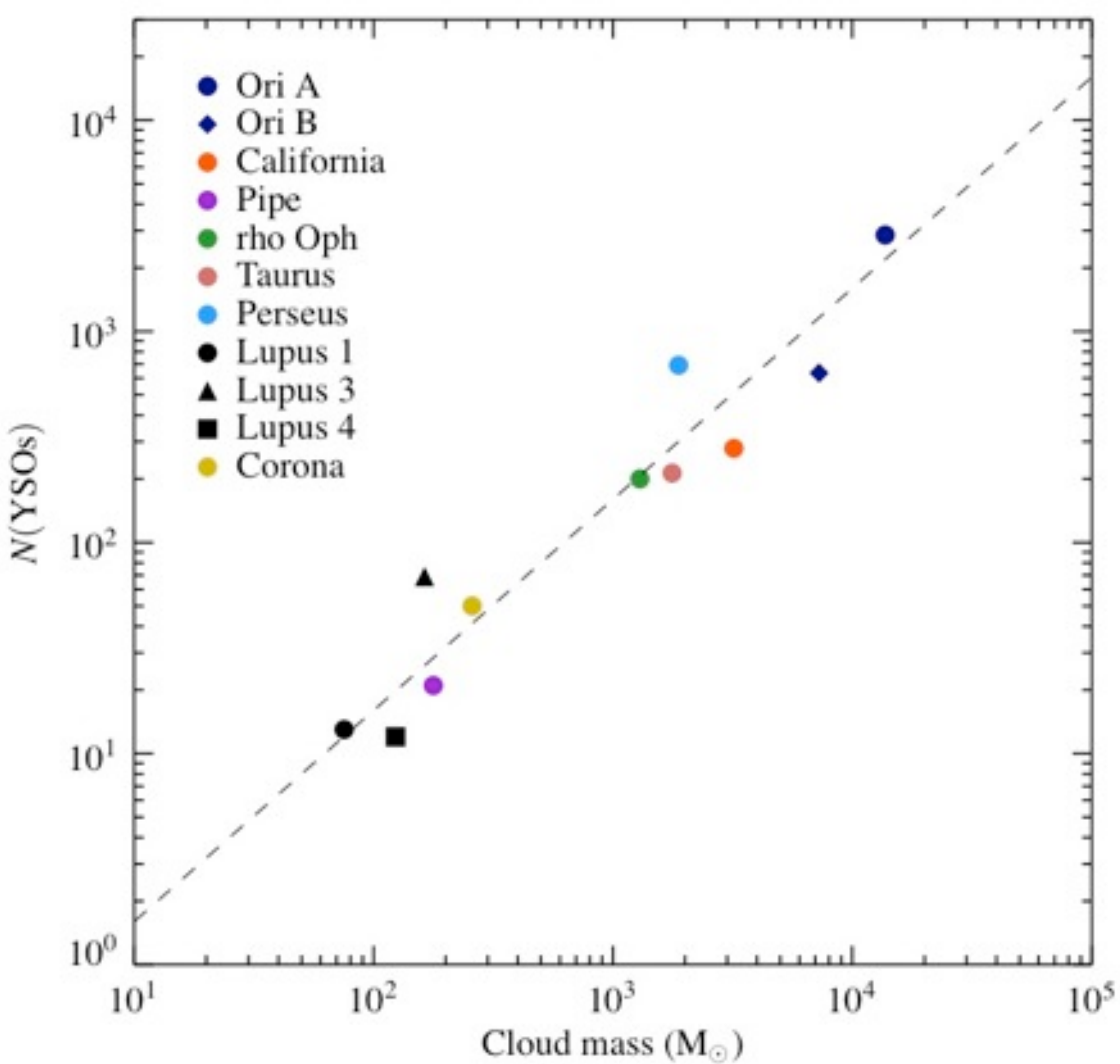


What is the meaning of the slope of this relation?

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

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

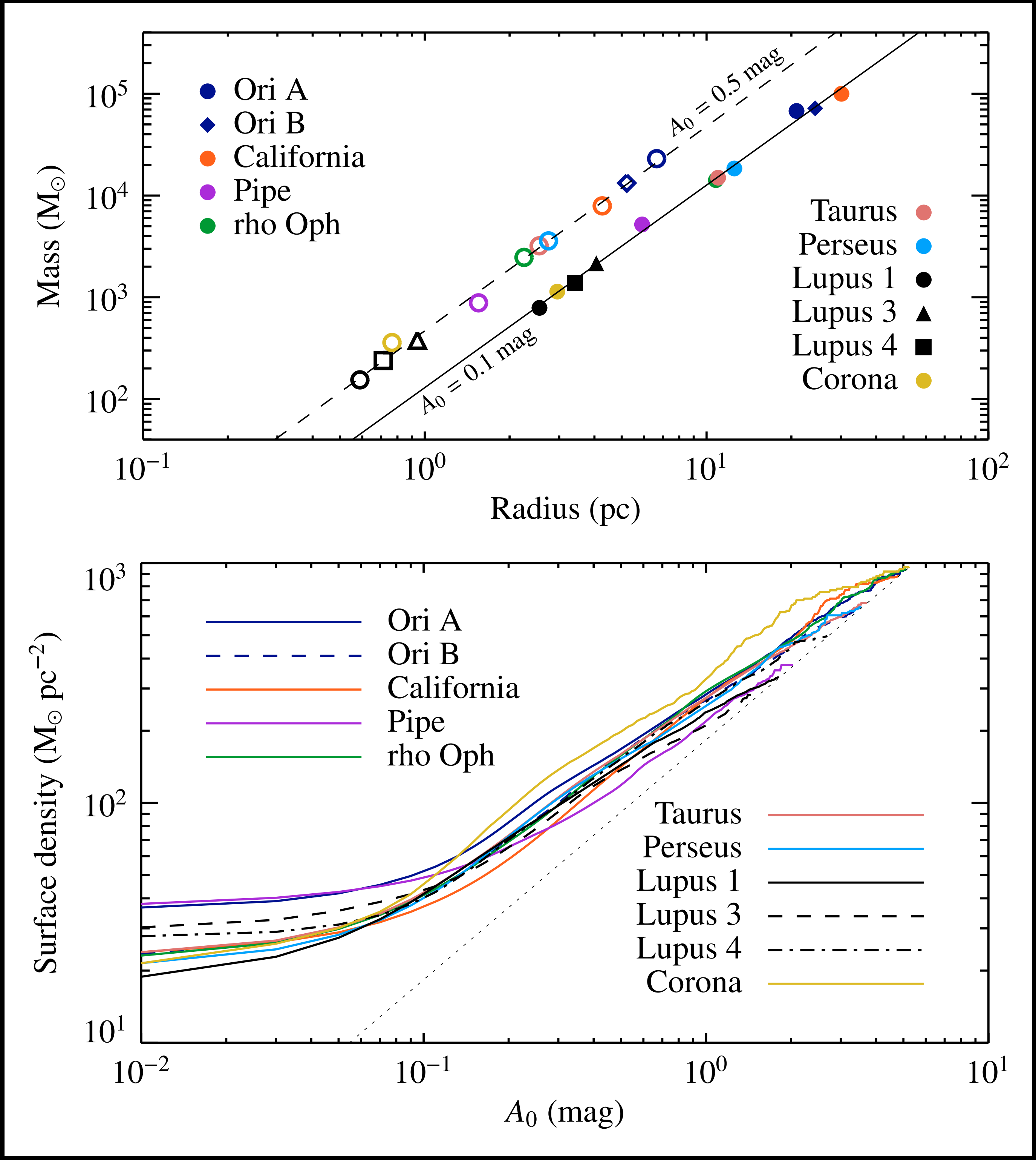
$$\varepsilon = SFE \simeq 0.10$$

The physical process

- Stars form in dense regions of molecular clouds
  - “proctected” environment: cold gas, no UV radiation, Jeans/Bonnor-Ebert instability
- We find that the SFR correlates with the amount of mass above a projected density threshold
- The projected mass density is unphysical (depends on the line of sight); we should have instead a volume density threshold!

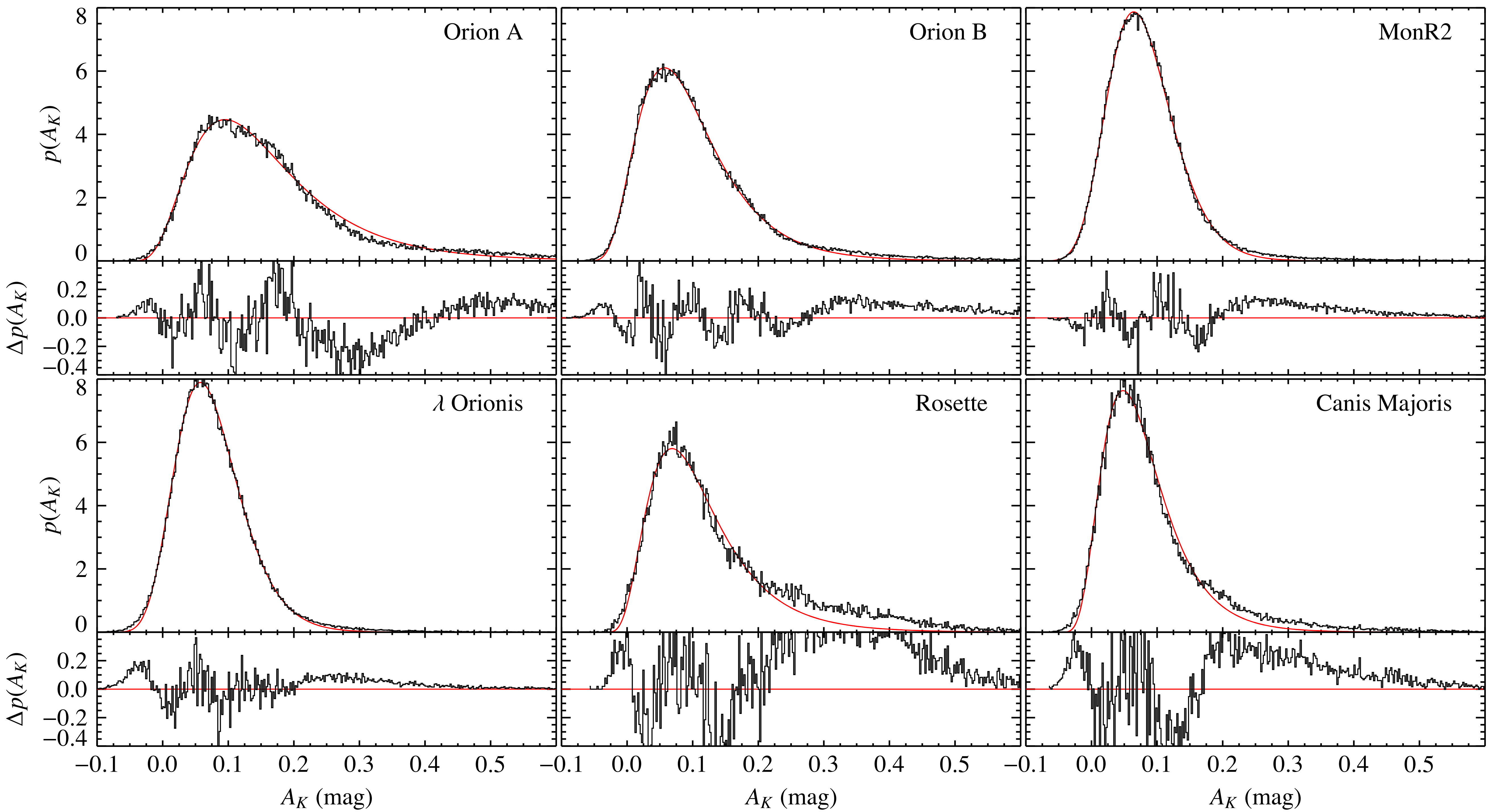
A Σ-ρ relation for molecular clouds

- Different Molecular clouds show consistent structure
  - Same average density a above threshold value (as predicted by WDM)
  - Same probability distribution for Σ (log-normal)
  - Similar stratification of surface density contours



Lombardi et al. (2010)

Log-normal fits to cloud projected density distributions



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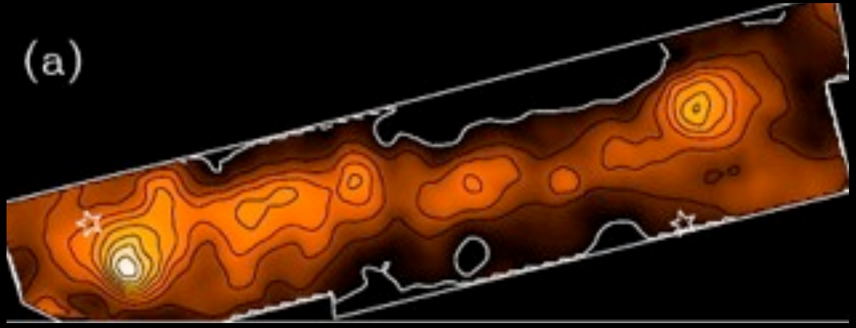

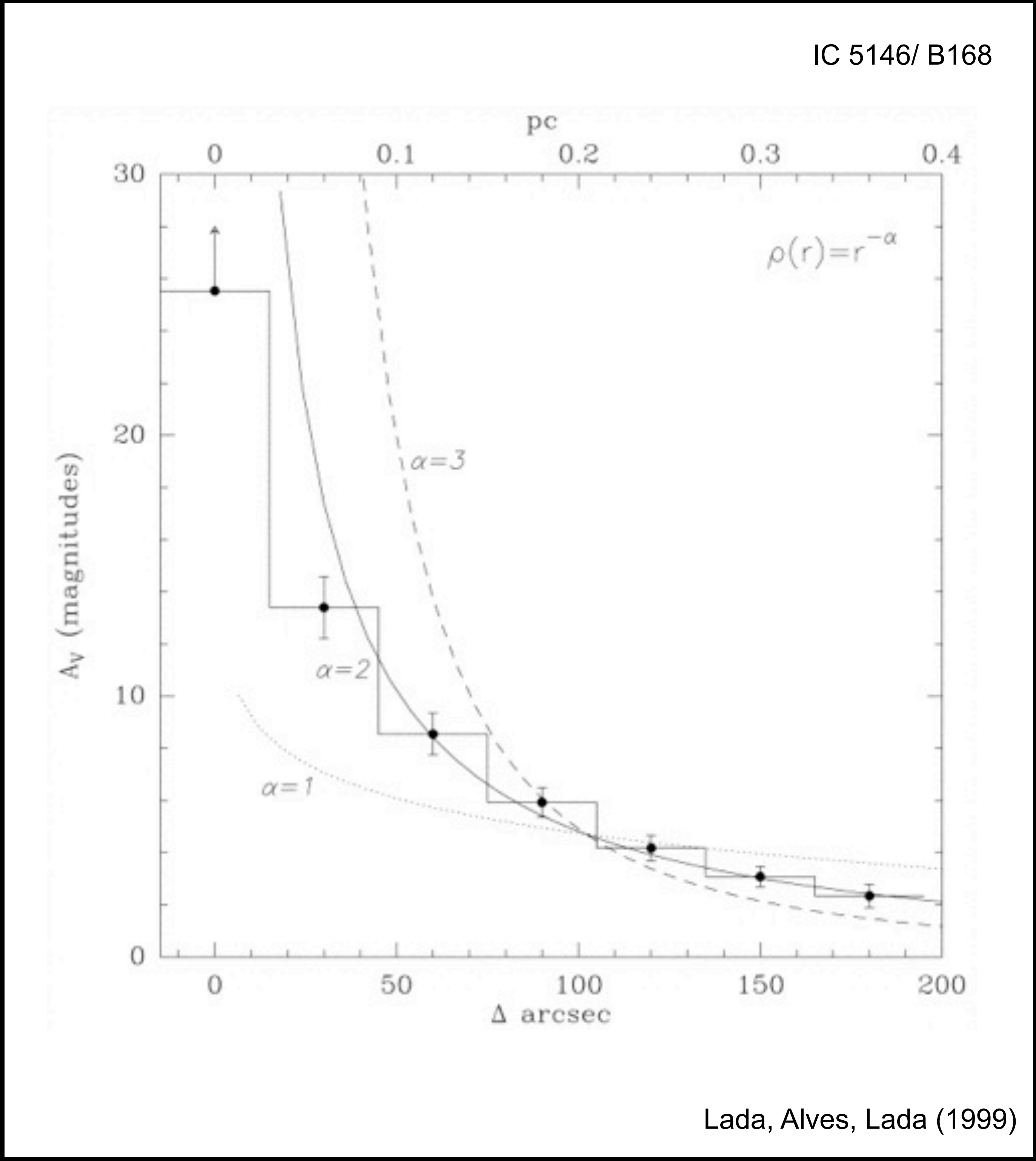

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SFR directly proportional to mass above $n > 10^4$ cm^{-3} (ρ > 700 $M_\odot$ pc^{-3})

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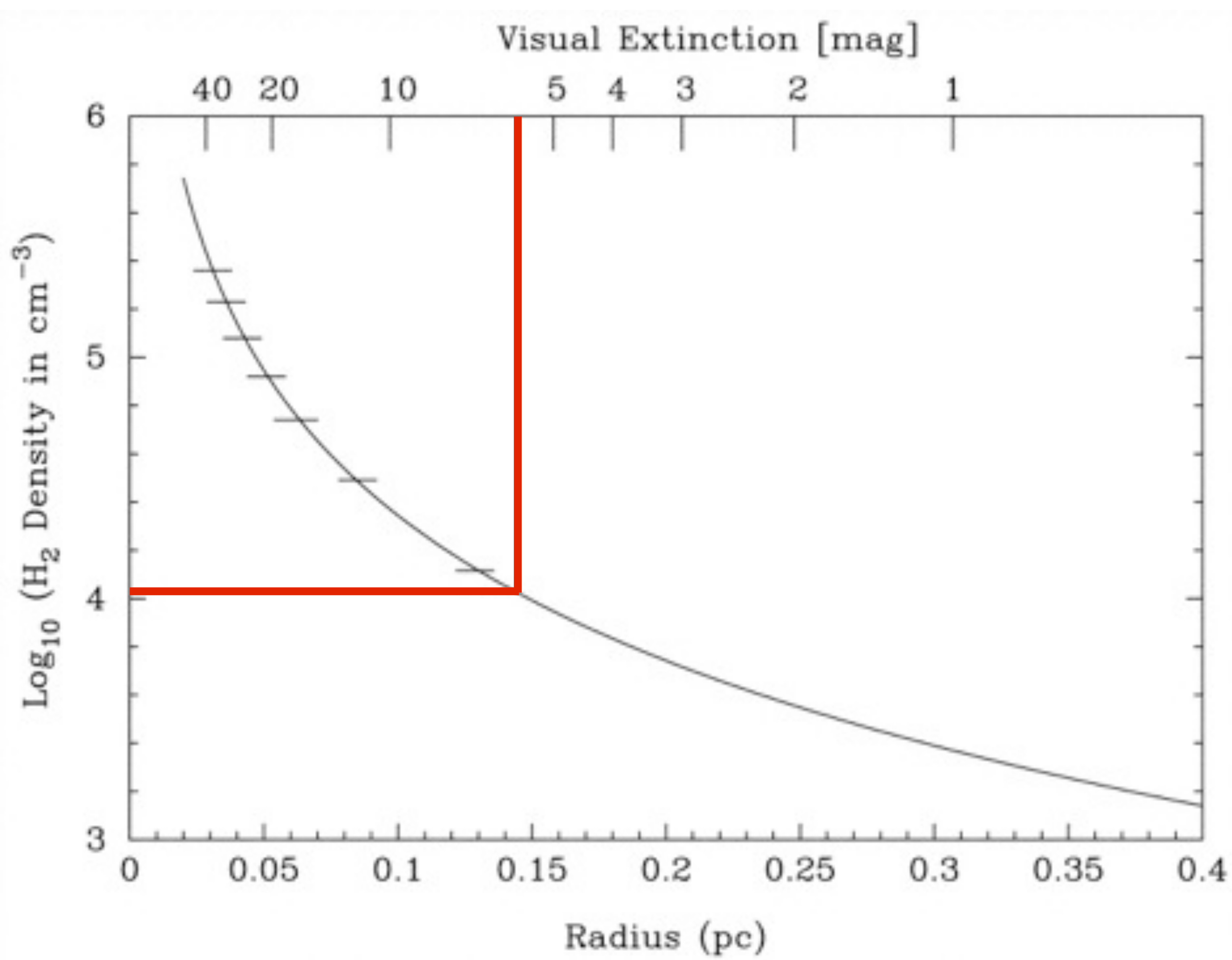

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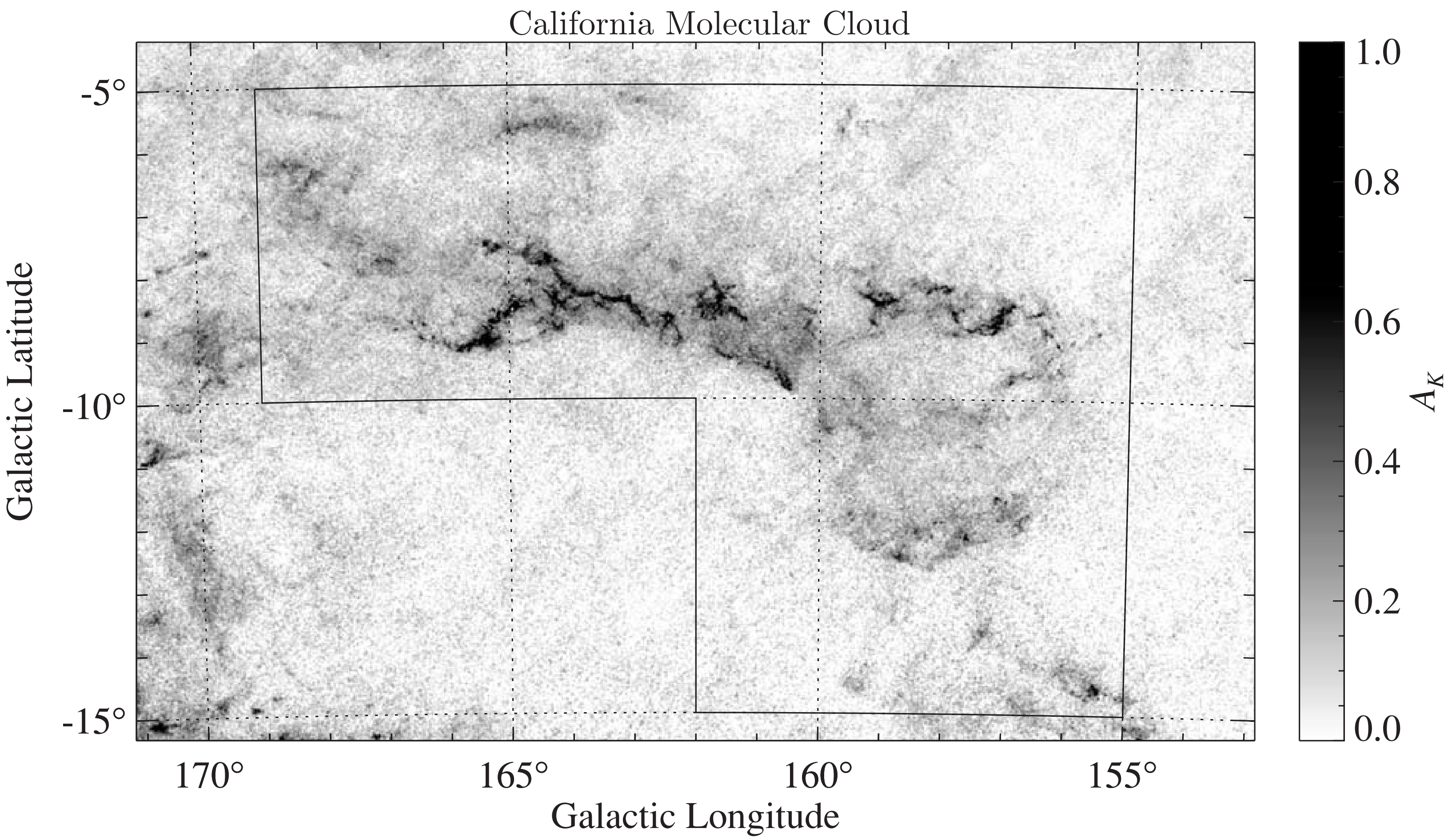
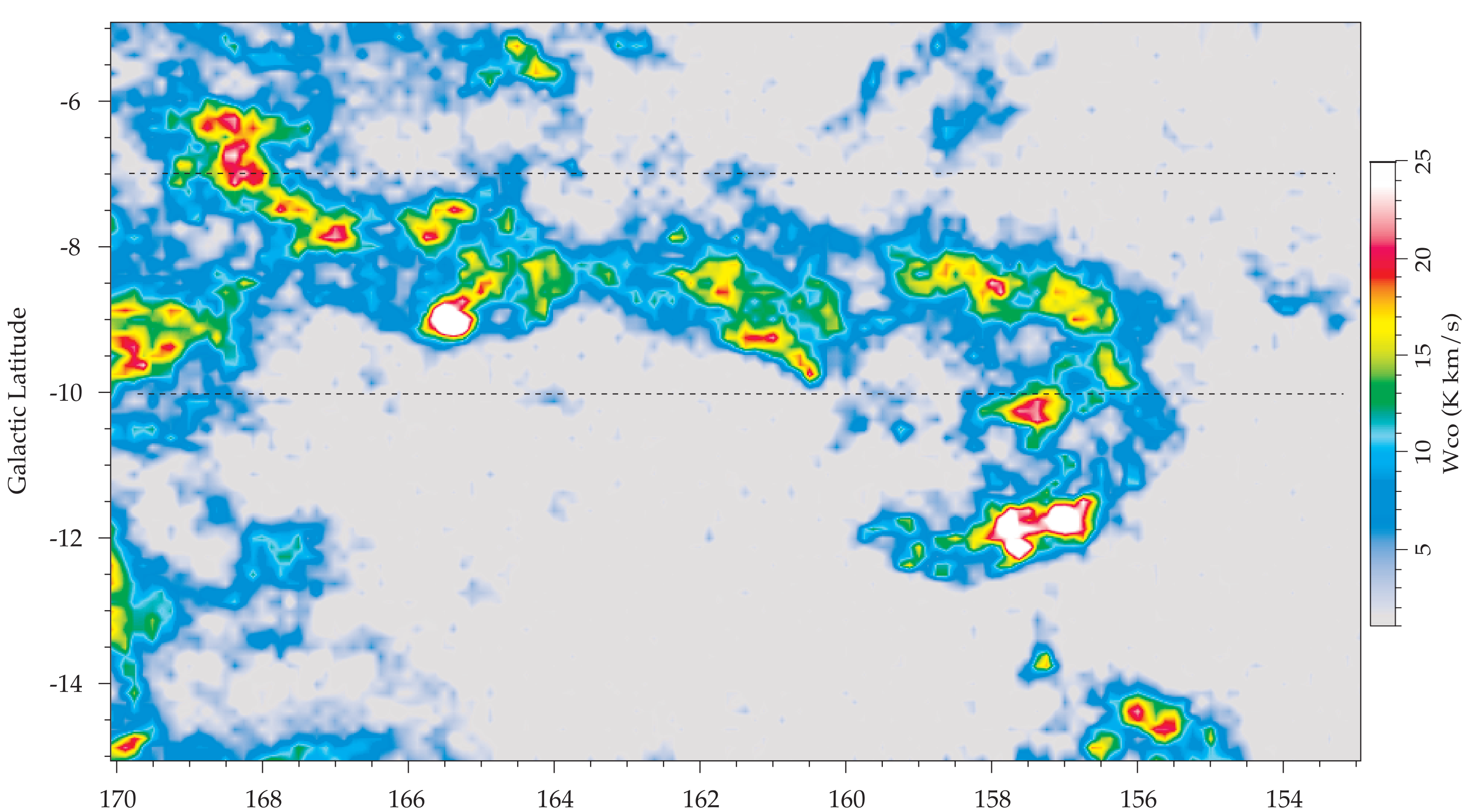
Star formation scaling laws for low density gas

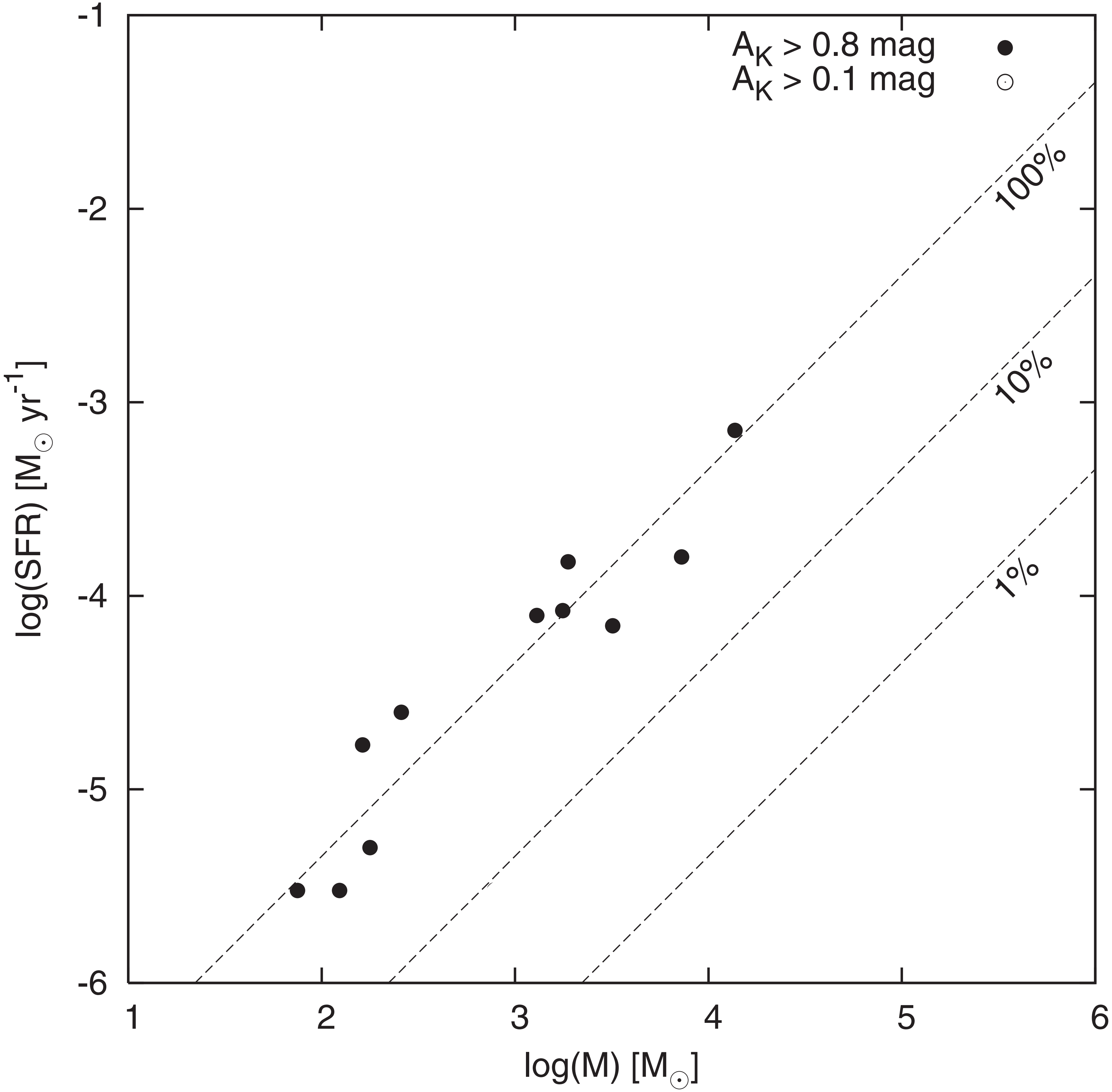


Extinction map (Lada et al. 2009)

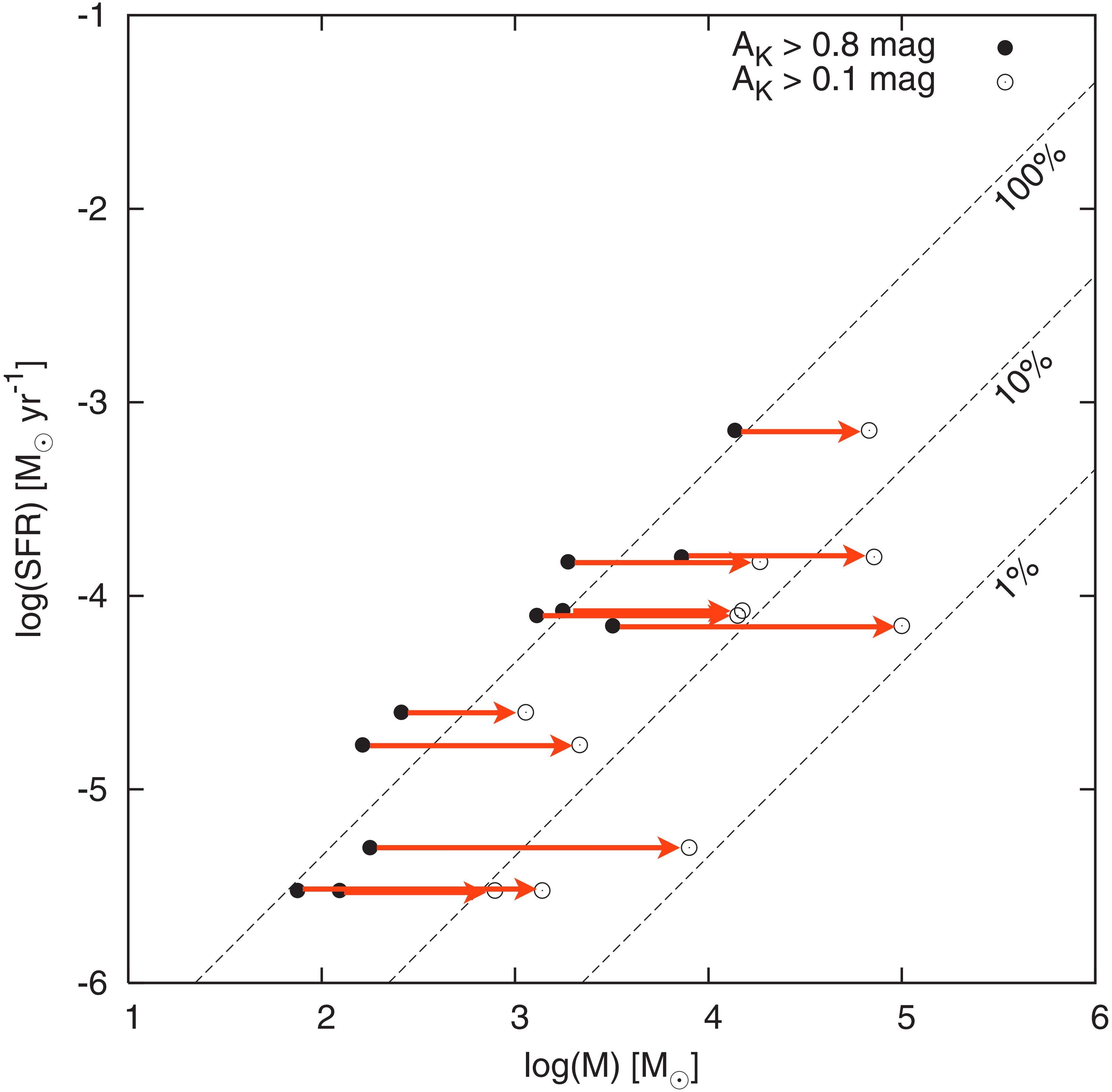


^{12}CO observations (Dame et al 2001)

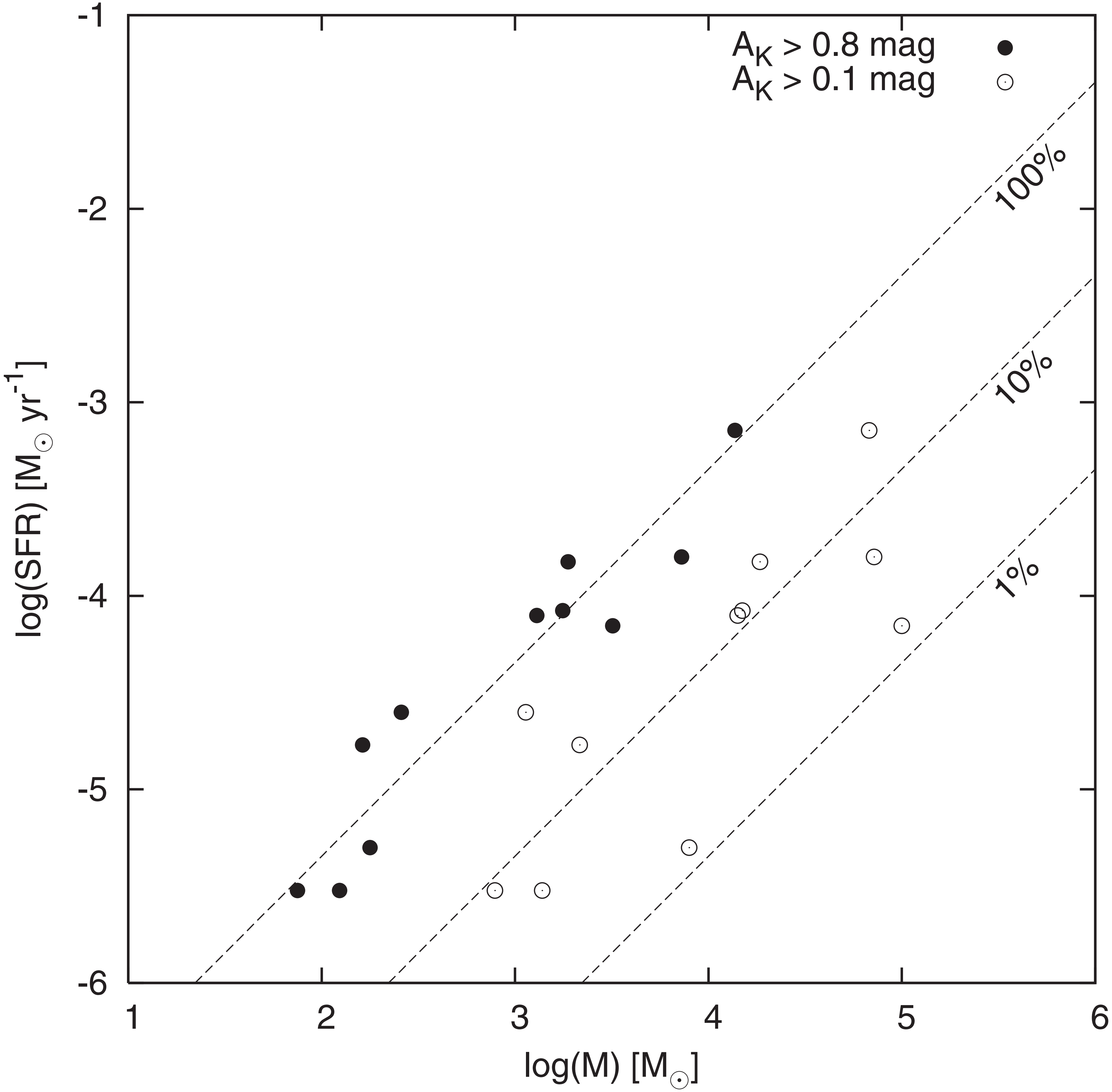
$M(\mathrm{CO}) \sim M(A_K > 0.1\ \mathrm{mag})$



A_K > 0.8 mag
A_K > 0.1 mag
100%
10%
1%
log(SFR) [M⊙ yr⁻¹]
log(M) [M⊙]
-1
-2
-3
-4
-5
-6
1
2
3
4
5
6



A_K > 0.8 mag
A_K > 0.1 mag
100%
10%
1%
-1
-2
-3
-4
-5
-6
1
2
3
4
5
6
log(SFR) [$M_\odot$ yr^{-1}]
log(M) [$M_\odot$]



$A_K > 0.8$ mag
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100%
10%
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log(SFR) [$M_\odot$ yr^{-1}]
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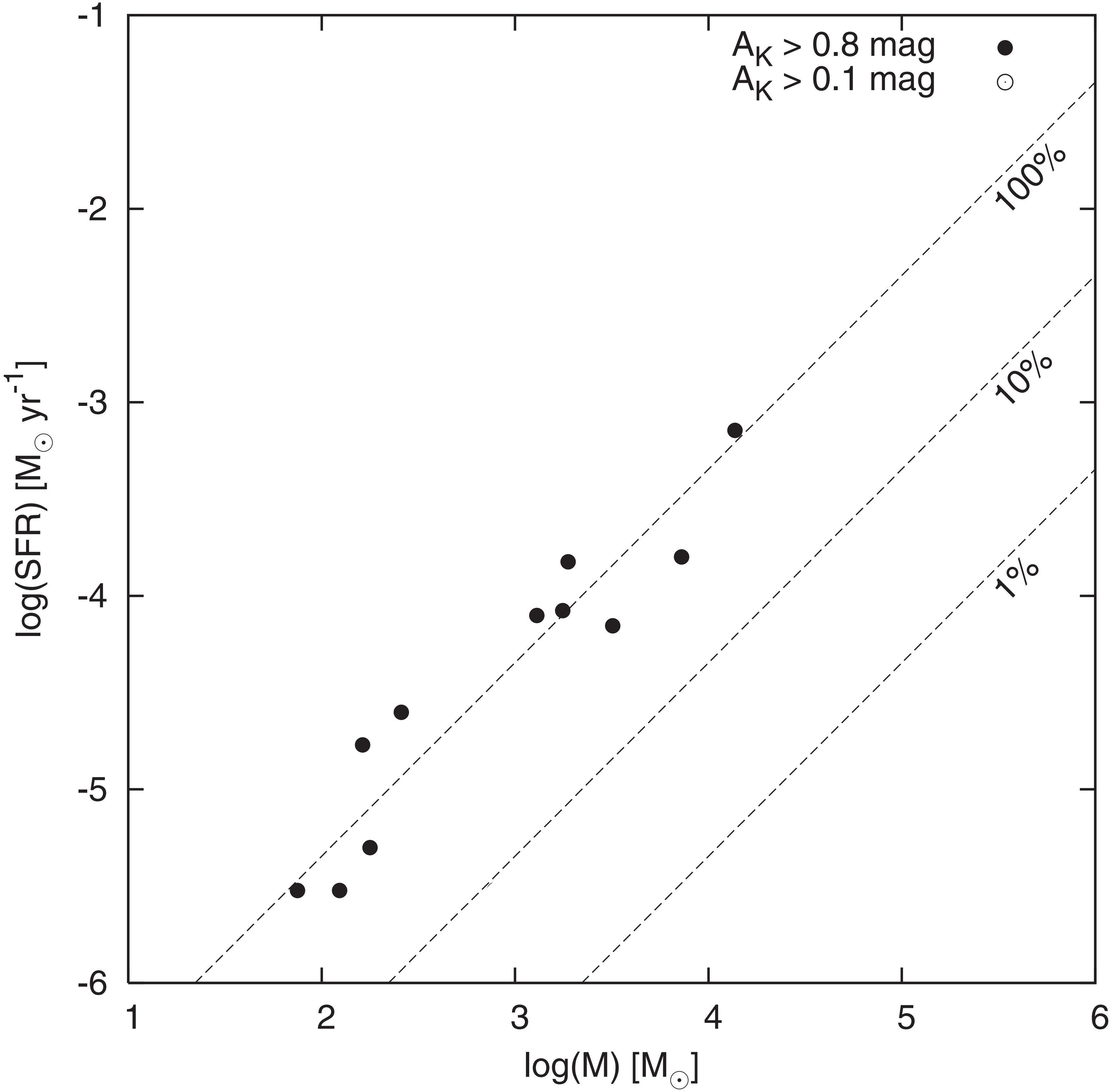
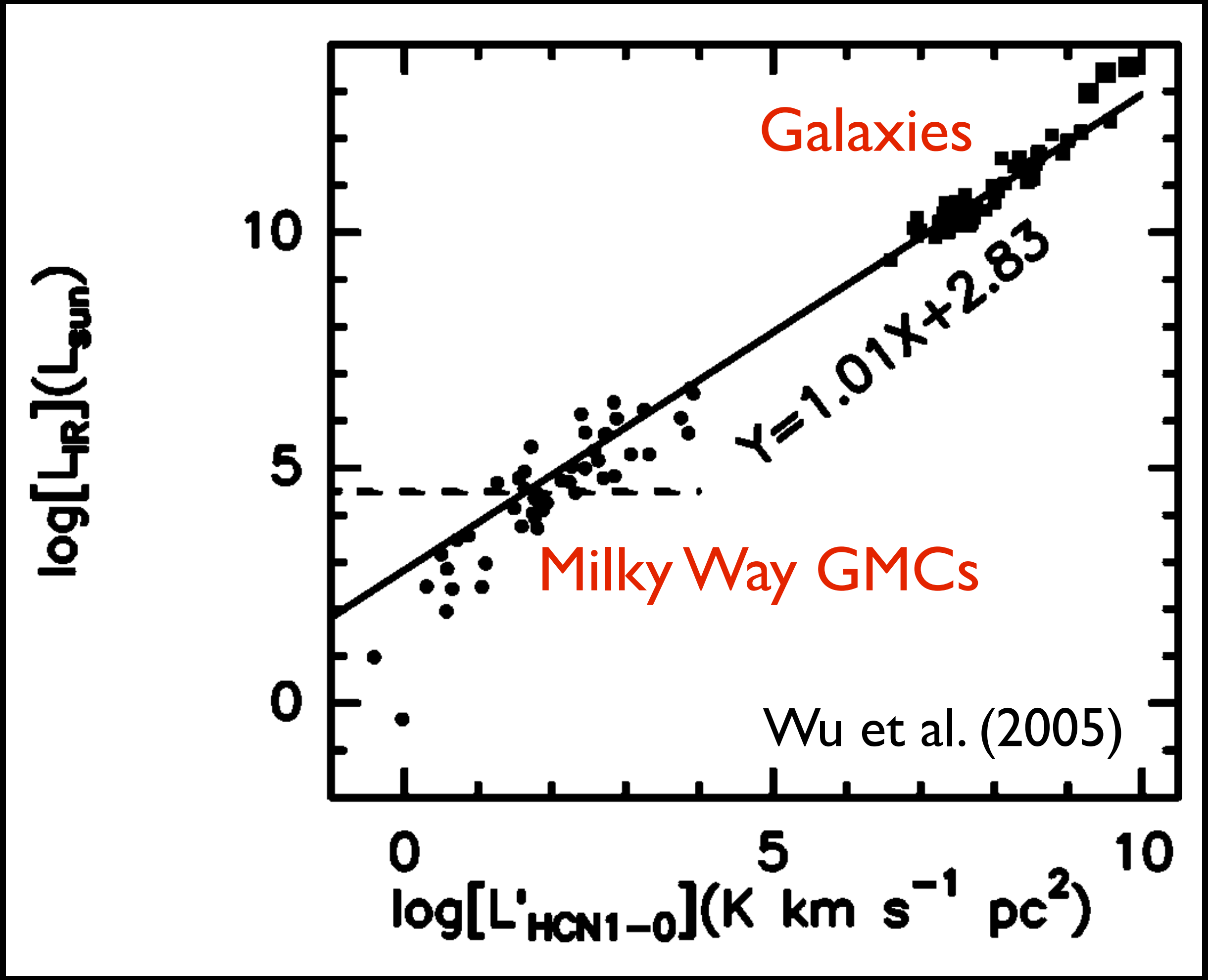
-1
-2
-3
-4
-5
-6
1
2
3
4
5
6

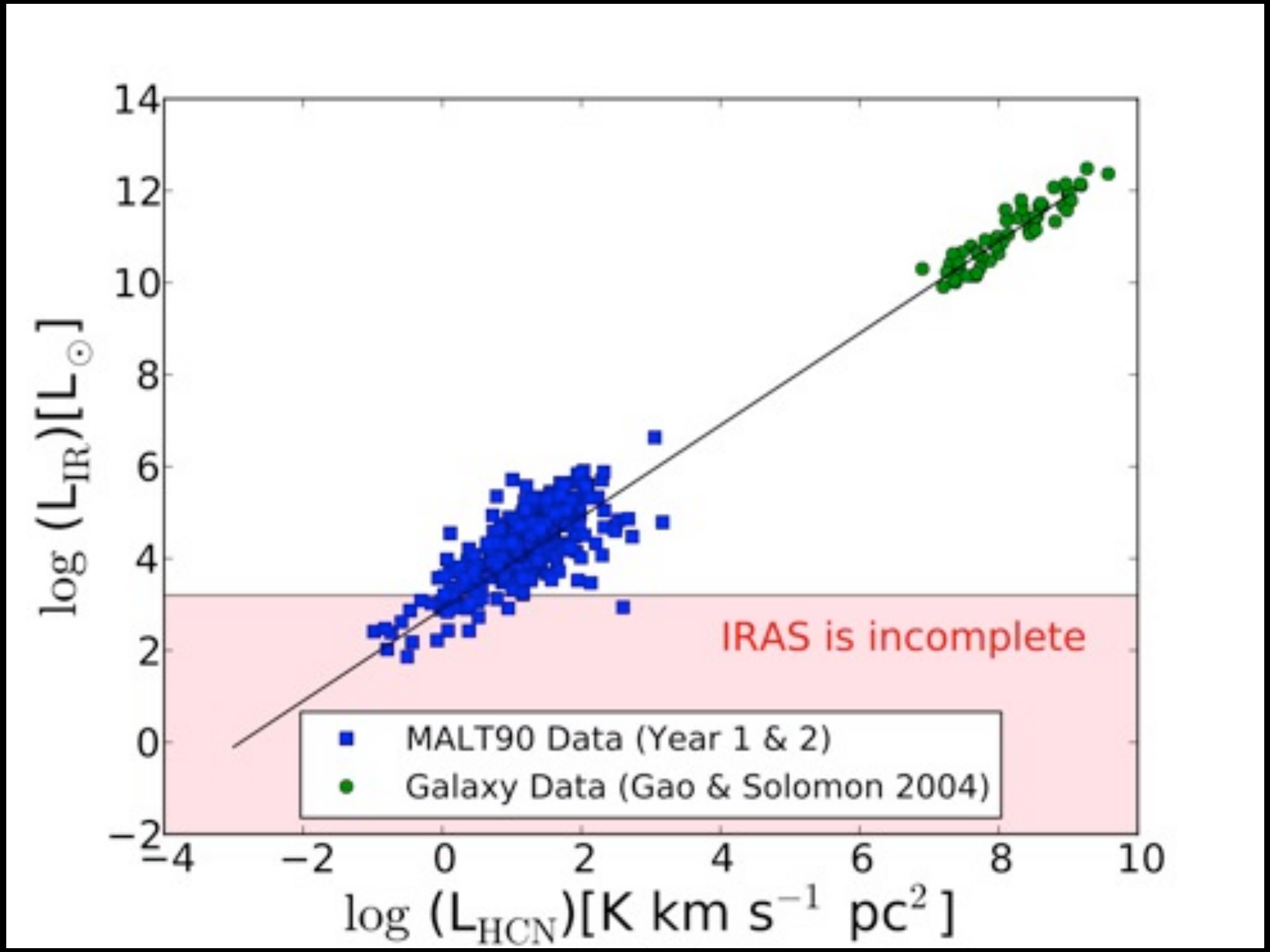


$$SFR = 4.6 \times 10^{-8} M_{dense} = 4.6 \times 10^{-8} f_{dense} M_{tot}$$

From local clouds to galaxies

Extragalactic scaling law



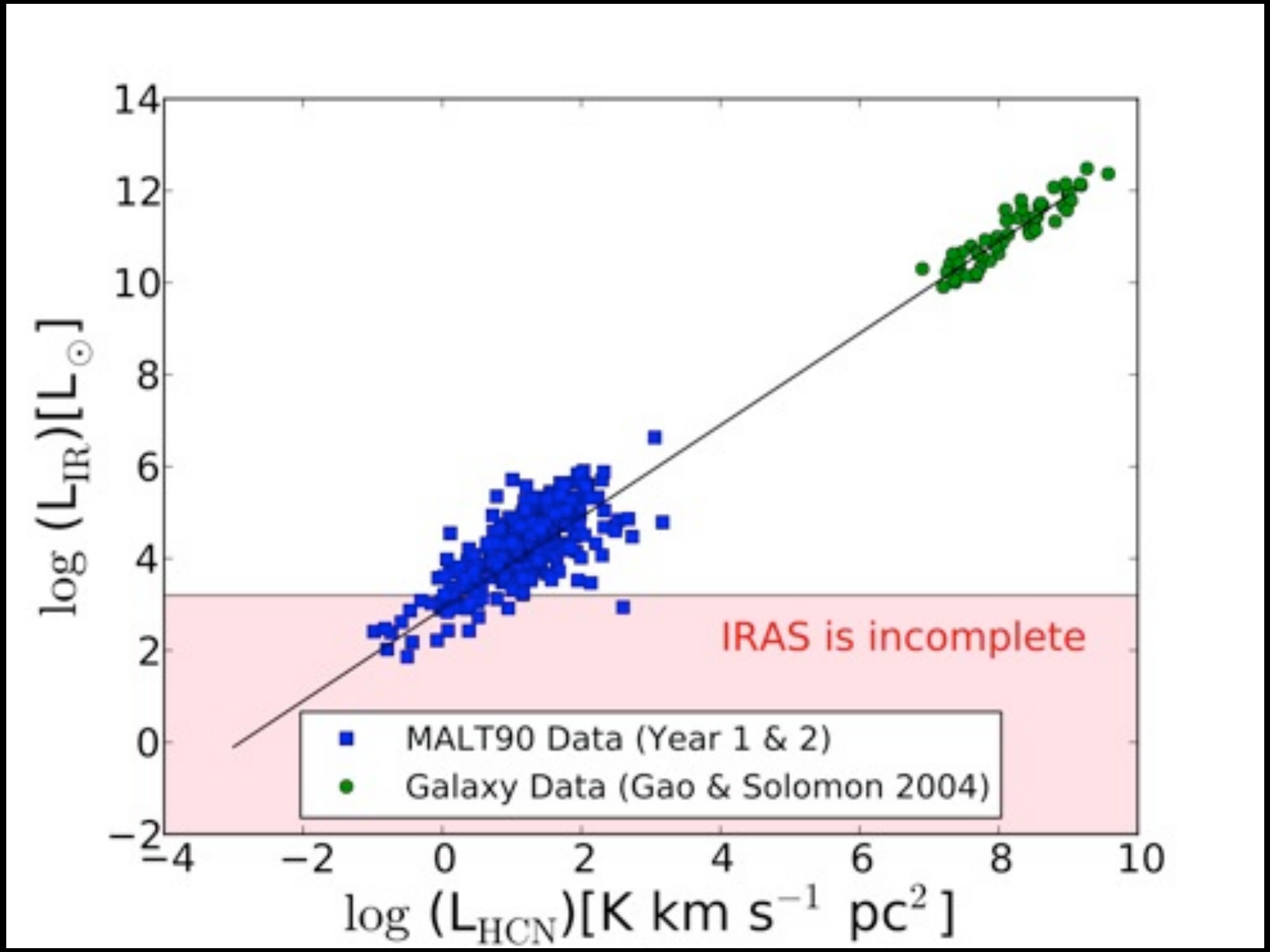


Local clouds SF law: $SFR_{MC} = 4.6 \times 10^{-8} M_{0.8}$

Extragalactic SF law: $SFR_{XGAL} = 1.8 \times 10^{-8} M_{HCN}$

Extragalactic scaling law

- Does $M_{0.8} \sim M_{HCN}$?
  - $M_{HCN} = X_{HCN} I_{HCN}$
  - $\rho_{HCN} > 2–3 \times 10^4 \text{ cm}^{-3}$
  - $\rho_{0.8} > 1–2 \times 10^4 \text{ cm}^{-3}$
- Probably!



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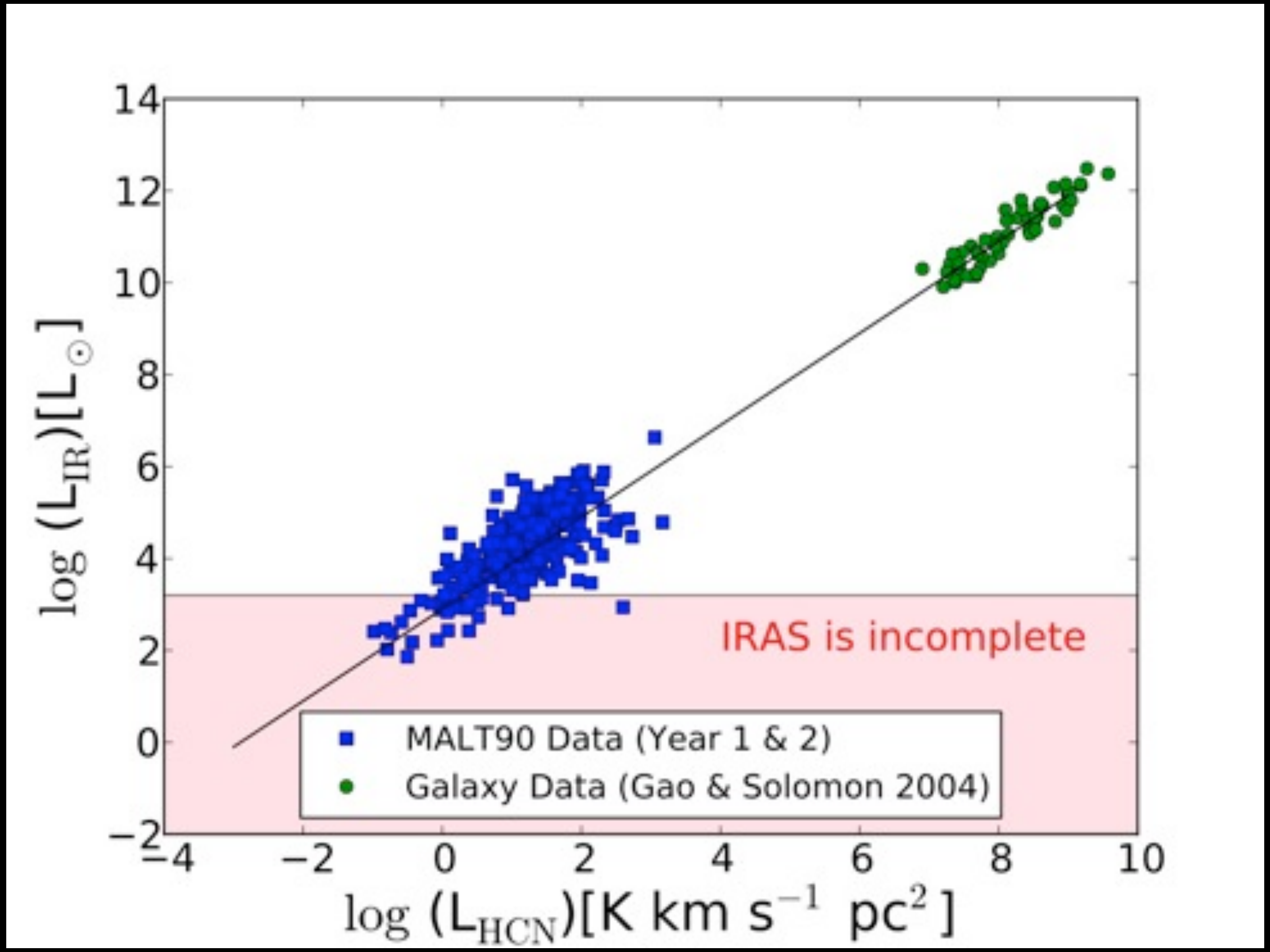
Extragalactic scaling law

- Does SFR_{MC} ~ SFR_{XGAL} ?
  - SFR_{XGAL} derived from SB99 code
  - $SFR_{MC} = N_* \langle M_* \rangle / t_{sf}$
  - SB99 code often used as a "black box" with default parameters



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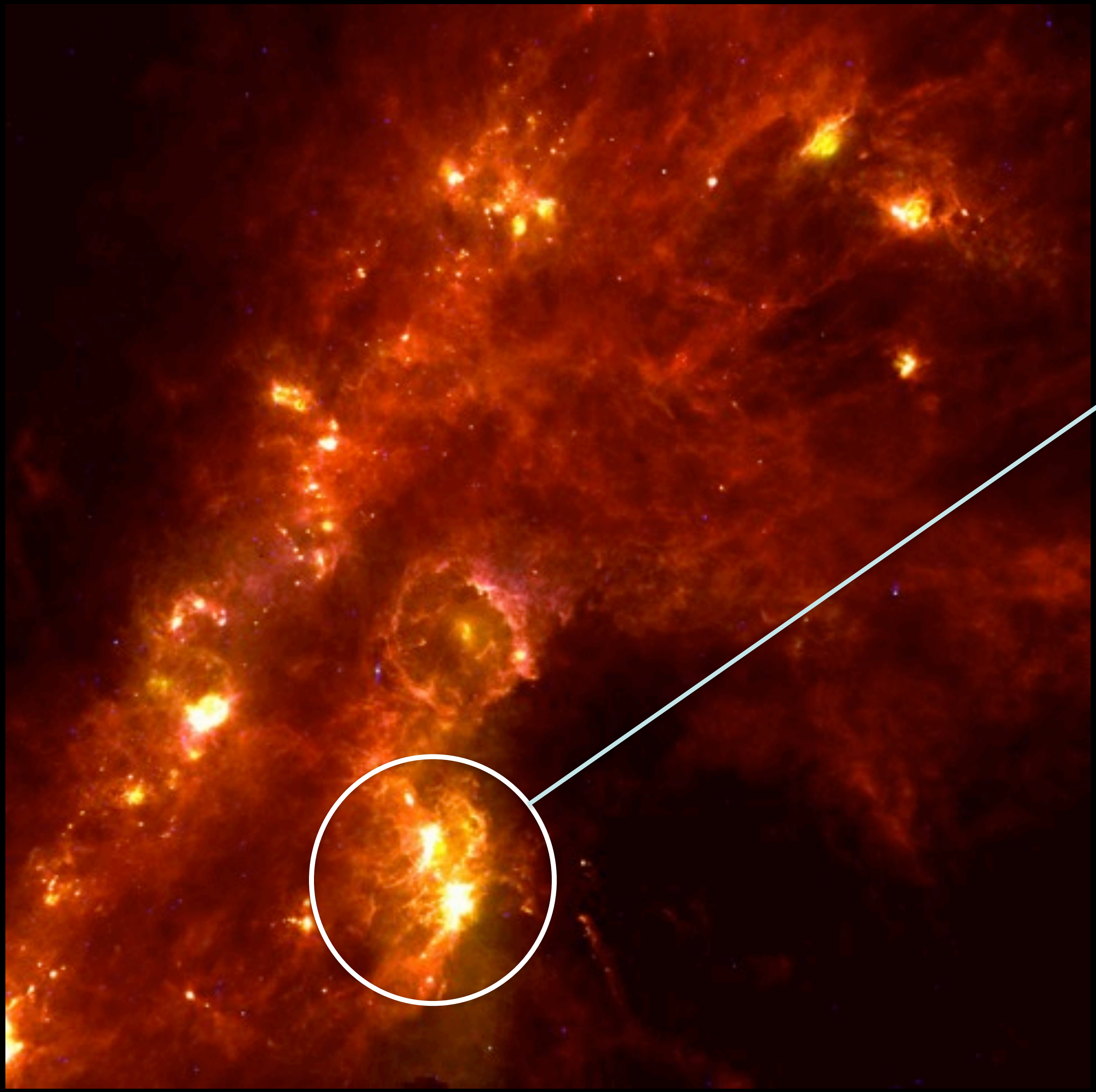
On determining the SFRs with Starburst 99

Standard parameters:

$SFR_{99} = 2.0 \times 10^{-10}\, L_{IR}/L_{\odot}\; M_{\odot}\; yr^{-1}$

$SFR_{obs} = 8.7 \times 10^{-4}\; M_{\odot}\; yr^{-1}$

On determining the SFRs with Starburst 99



Standard parameters:

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$L_{IR}(obs) = 5.4 \times 10^5\ L_\odot$

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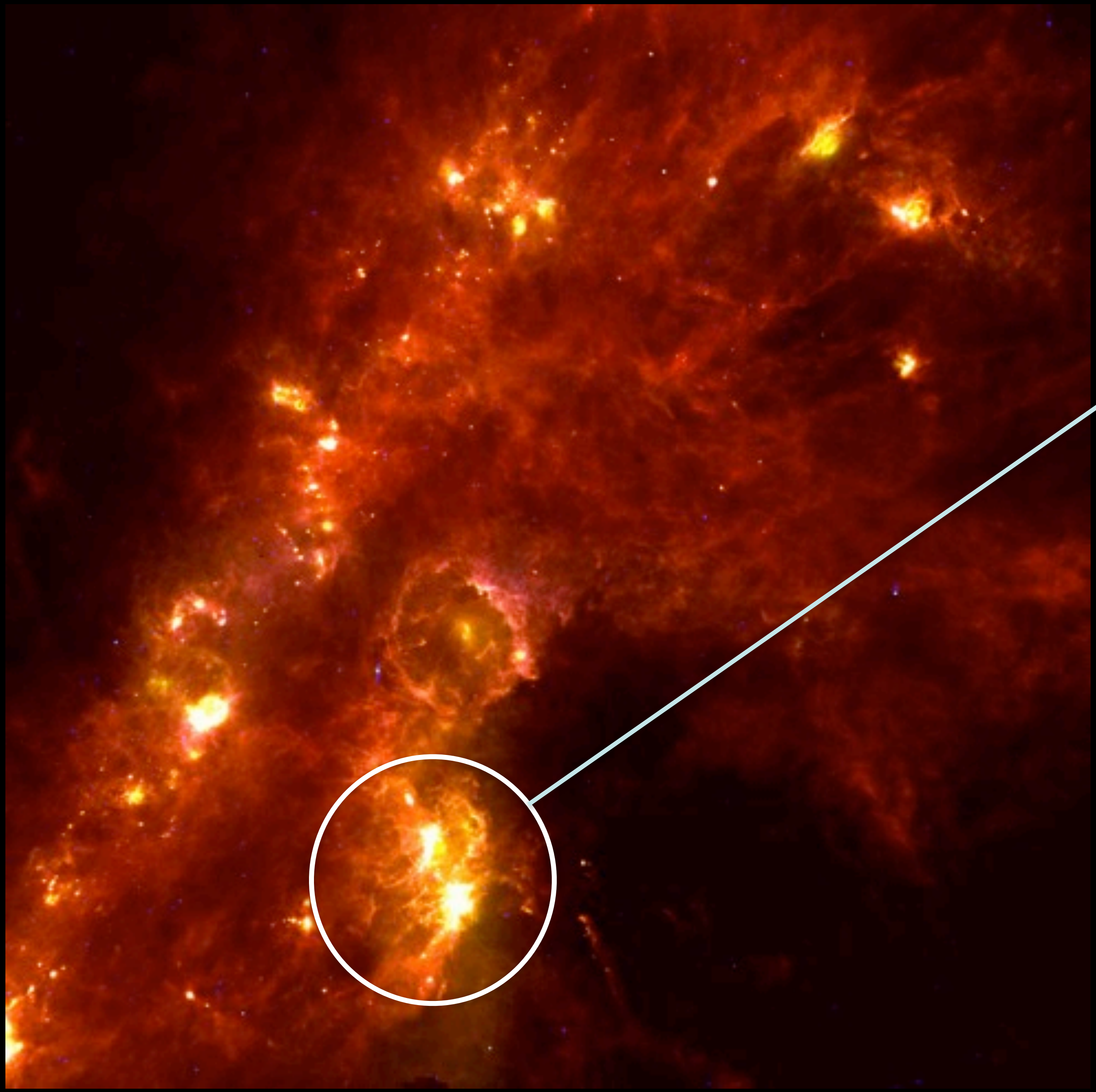

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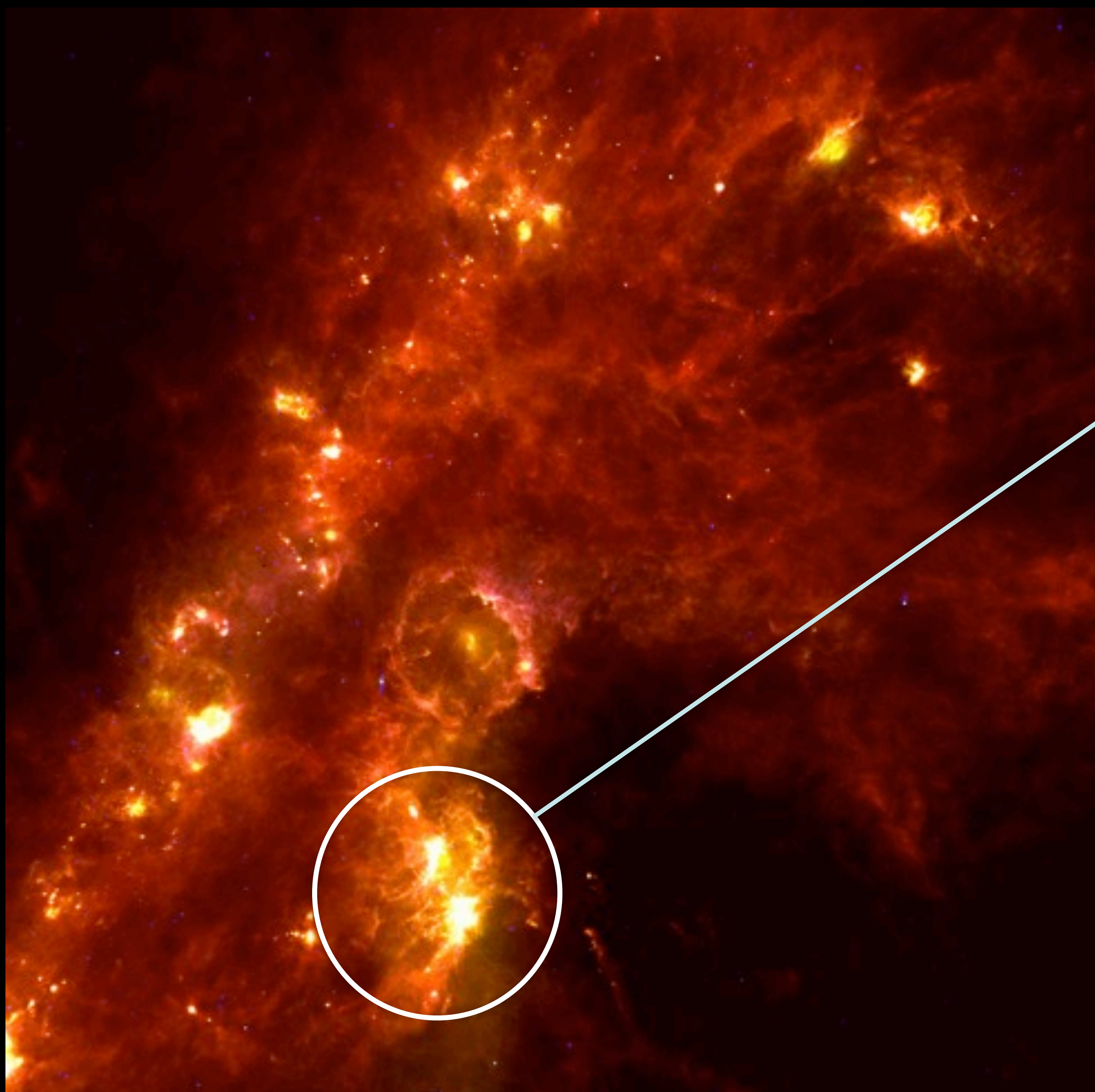
On determining the SFRs with Starburst 99



For t_{sf} = 2 Myr:

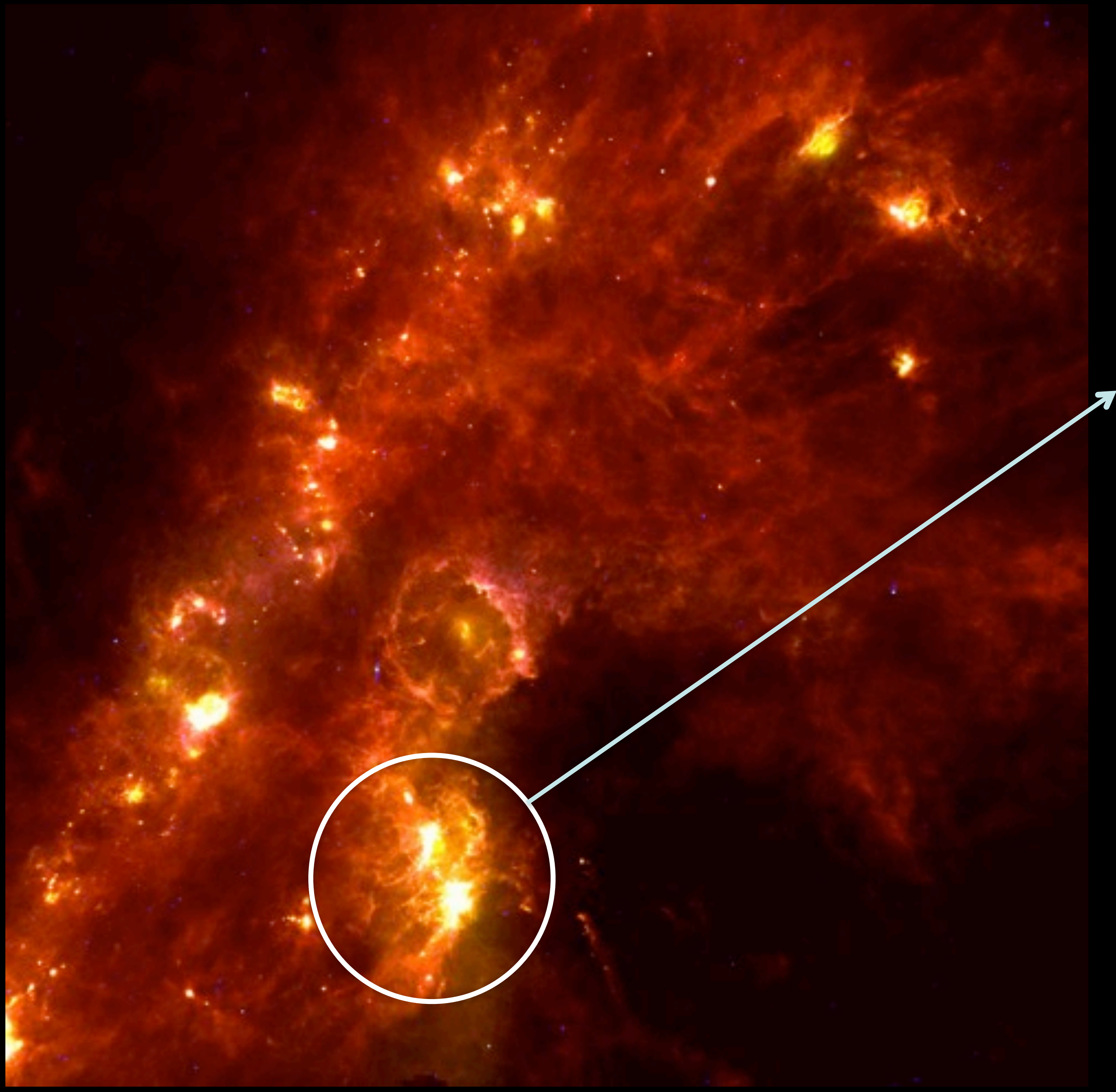
SFR_{99} = 3.2 x 10^{-10} $L_{IR}/L_{\odot}$ $M_{\odot}$ yr^{-1}

L_{IR}(obs) = 5.4 x 10^{5} $L_{\odot}$

SFR_{99} = 1.6 x 10^{-4} $M_{\odot}$ yr^{-1}

SFR_{obs} = 8.7 x 10^{-4} $M_{\odot}$ yr^{-1}

On determining the SFRs with Starburst 99



For t_{sf} = 2 Myr & M_{max} = 30 $M_\odot$

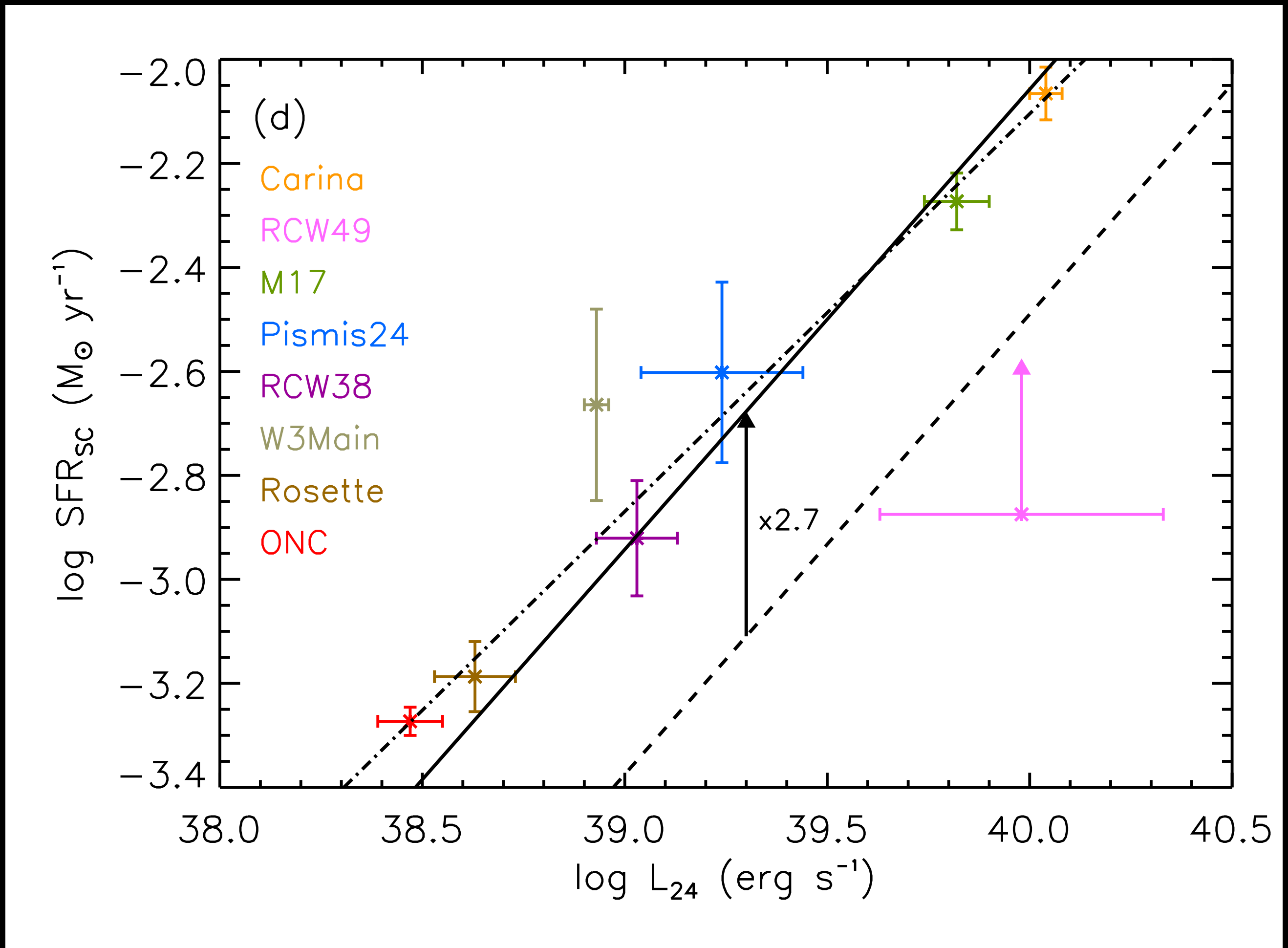
SFR_{99} = $10 \times 10^{-10}\ L_{IR}/L_\odot\ M_\odot\ yr^{-1}$

$L_{IR}(obs) = 5.4 \times 10^5\ L_\odot$

SFR_{99} = $5.6 \times 10^{-4}\ M_\odot\ yr^{-1}$

SFR_{obs} = $8.7 \times 10^{-4}\ M_\odot\ yr^{-1}$

On determining the SFRs with Starburst 99



For t_{sf} = 2 Myr & M_{max} = 30 $M_\odot$

SFR_{99} = 10×10^{-10} $L_{IR}/L_\odot$ $M_\odot$ yr^{-1}

L_{IR}(obs) = 5.4×10^5 $L_\odot$

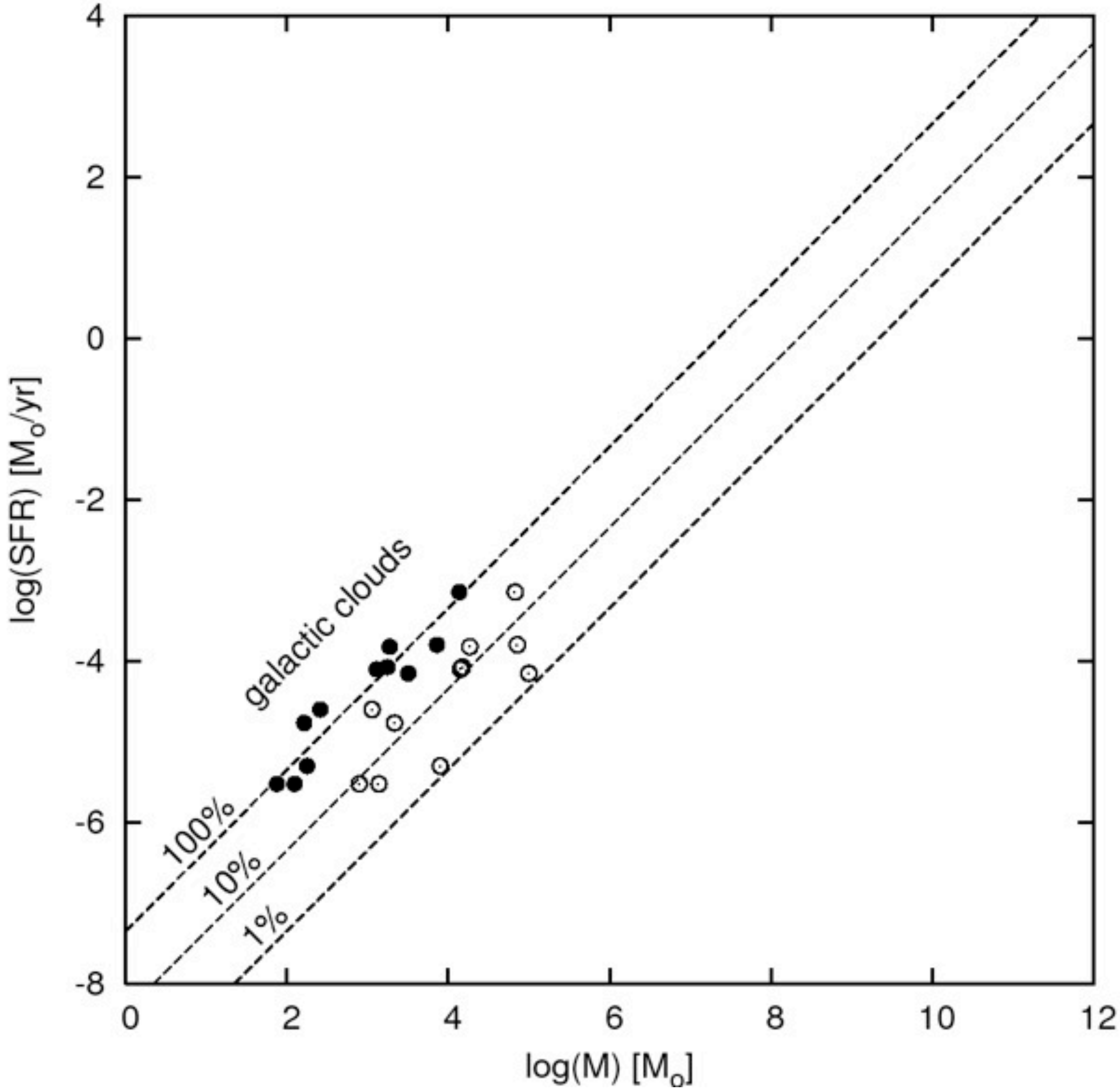
SFR_{99} = 5.6×10^{-4} $M_\odot$ yr^{-1}

SFR_{obs} = 8.7×10^{-4} $M_\odot$ yr^{-1}

Similar results obtained by Chomiuk & Povich (2011):

SFR_{GMCs} = 2.7 SFR_{SB99}

Star Formation Scaling Laws from Local Clouds to Galaxies



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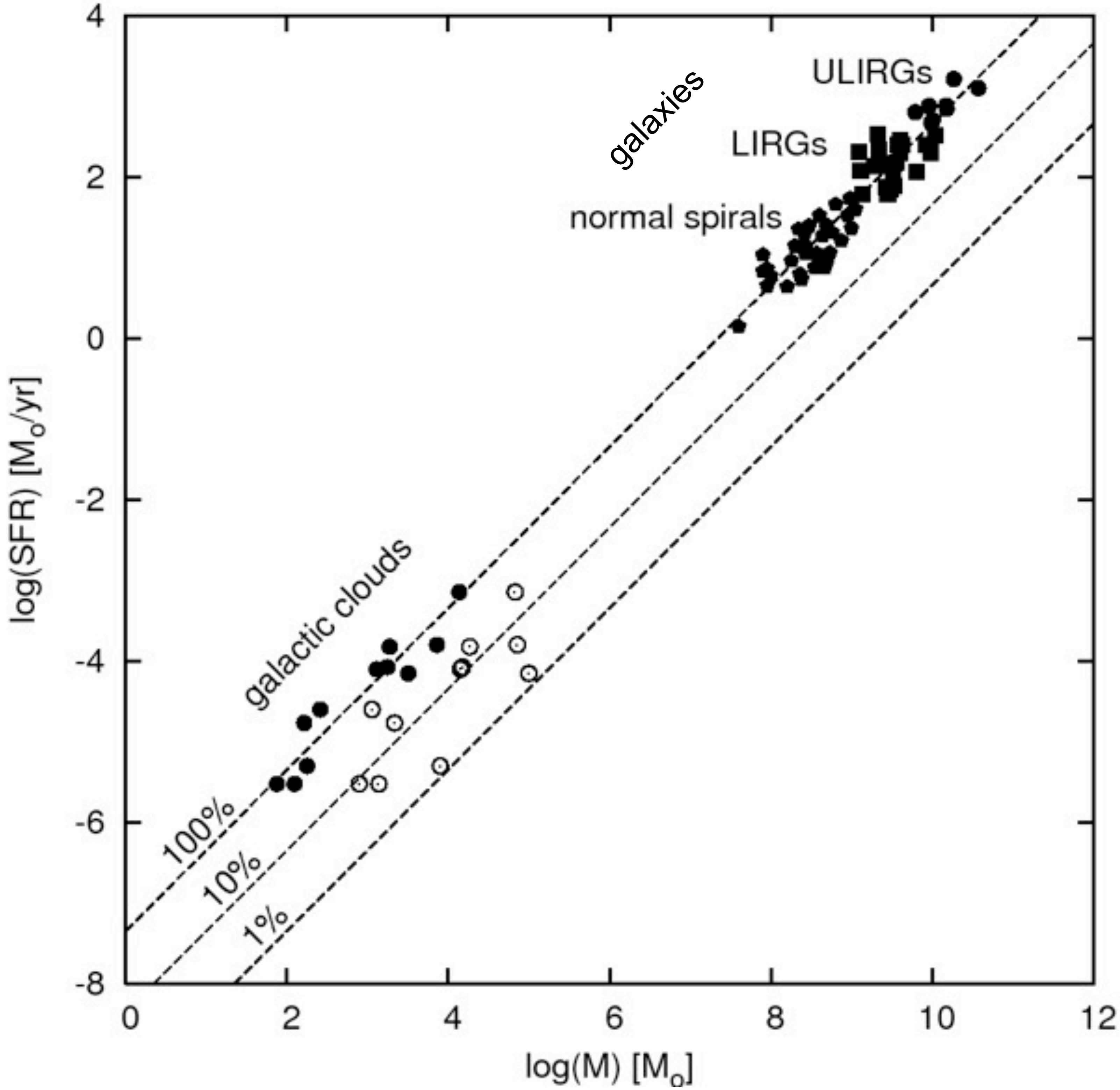

■ HCN Gao & Solomon 2004

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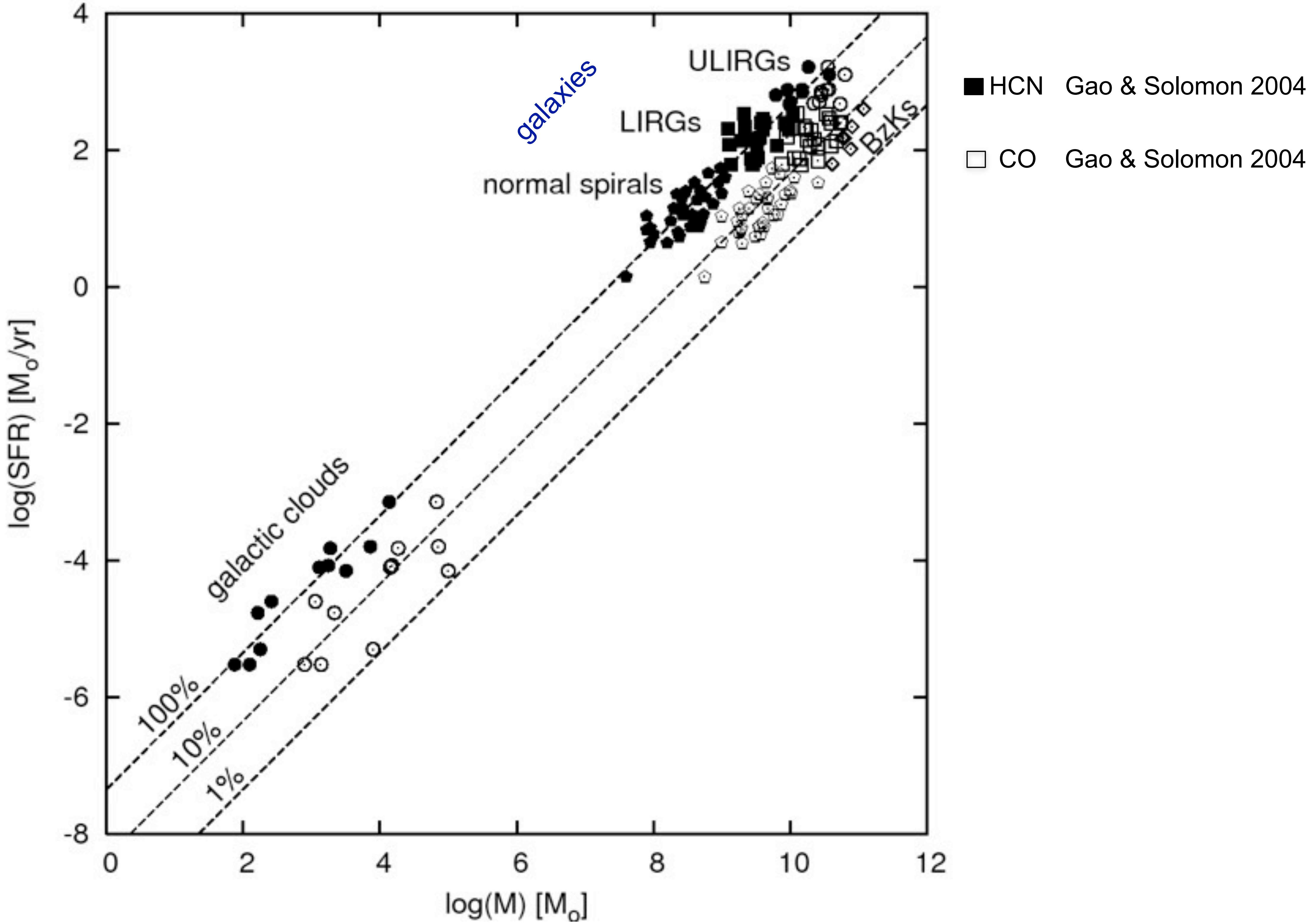
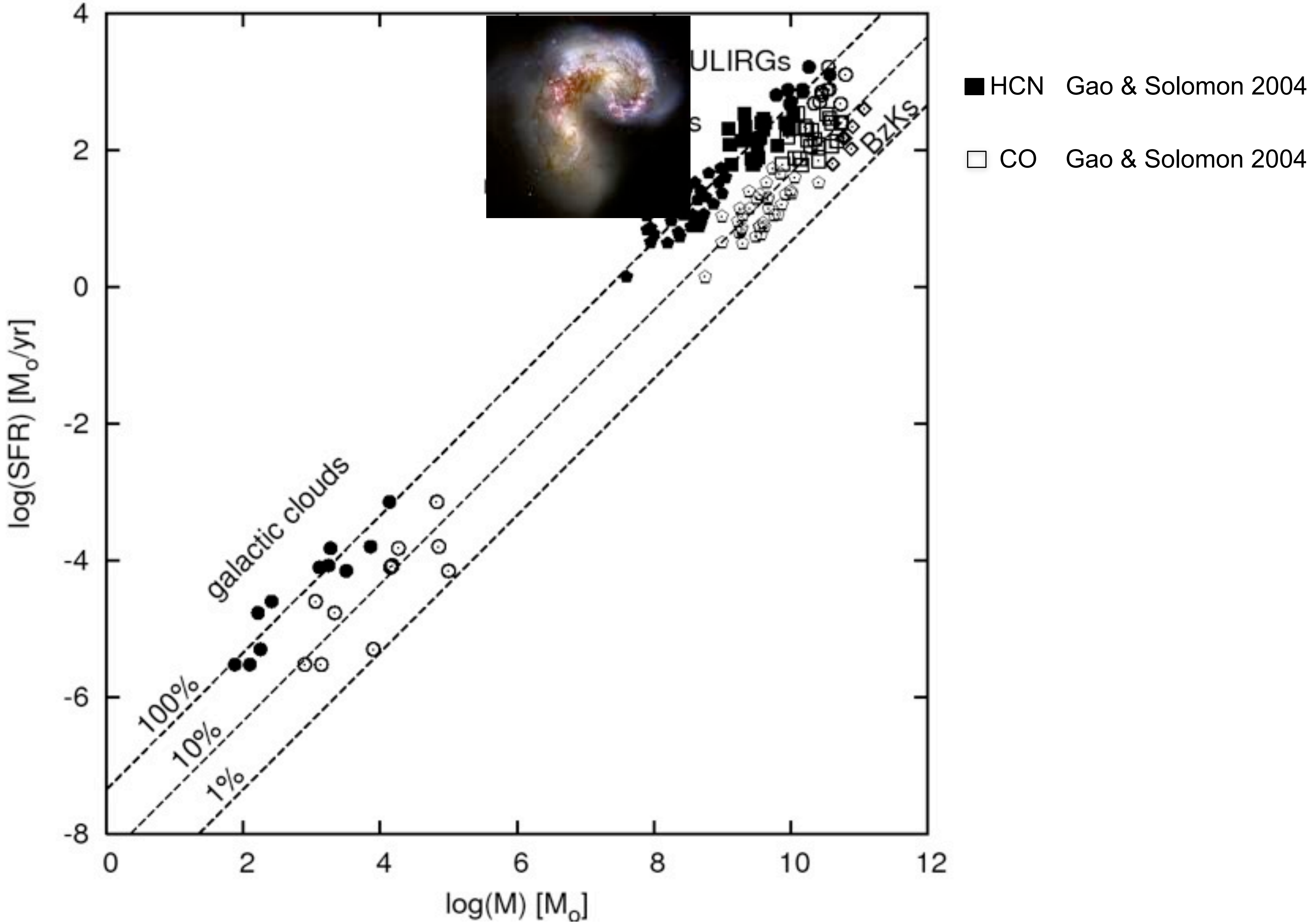


SFR = 4.6 x 10^{-8} M_{dense}

Star Formation Scaling Laws from Local Clouds to Galaxies



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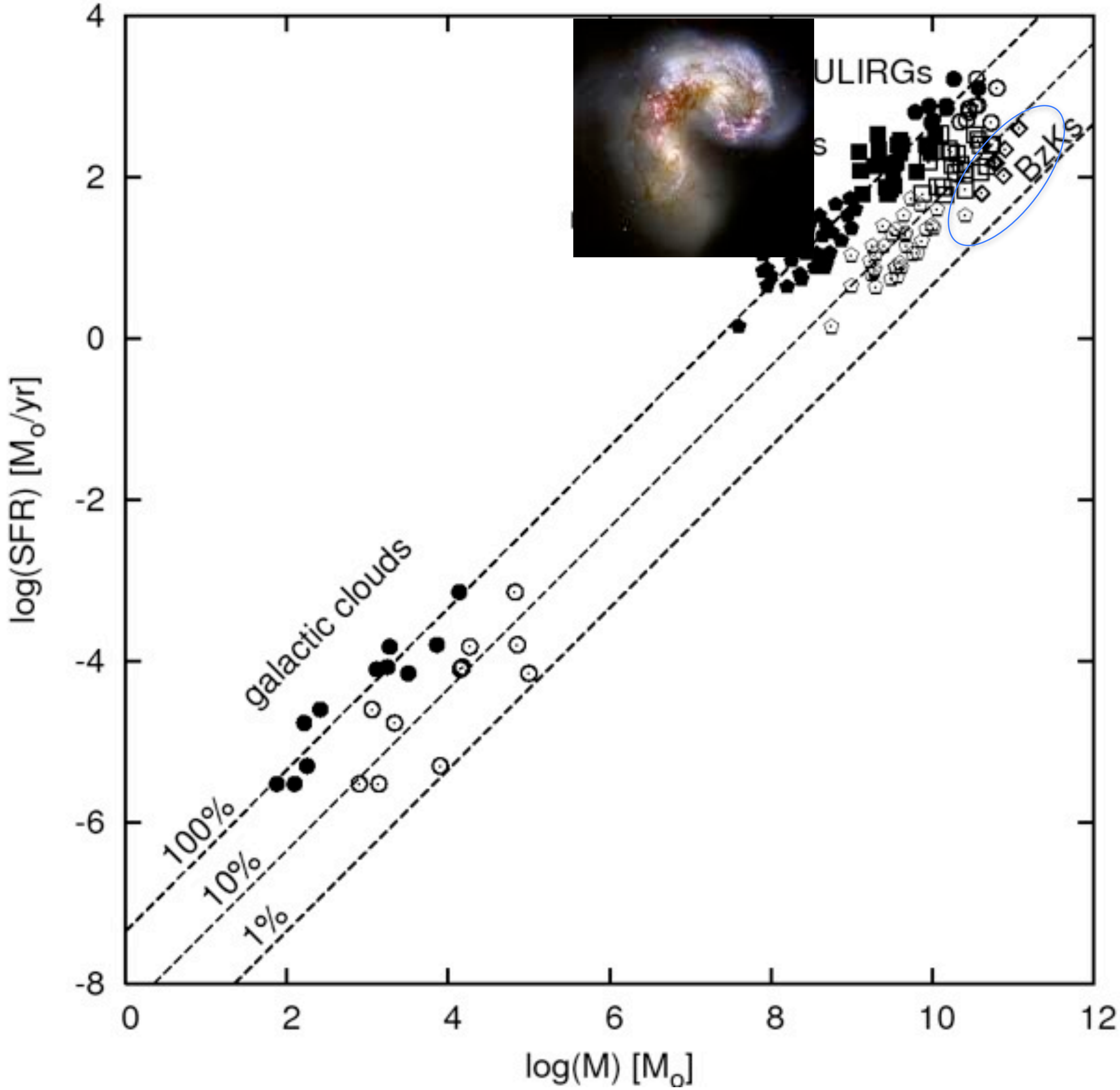

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Daddi et al. (2010)

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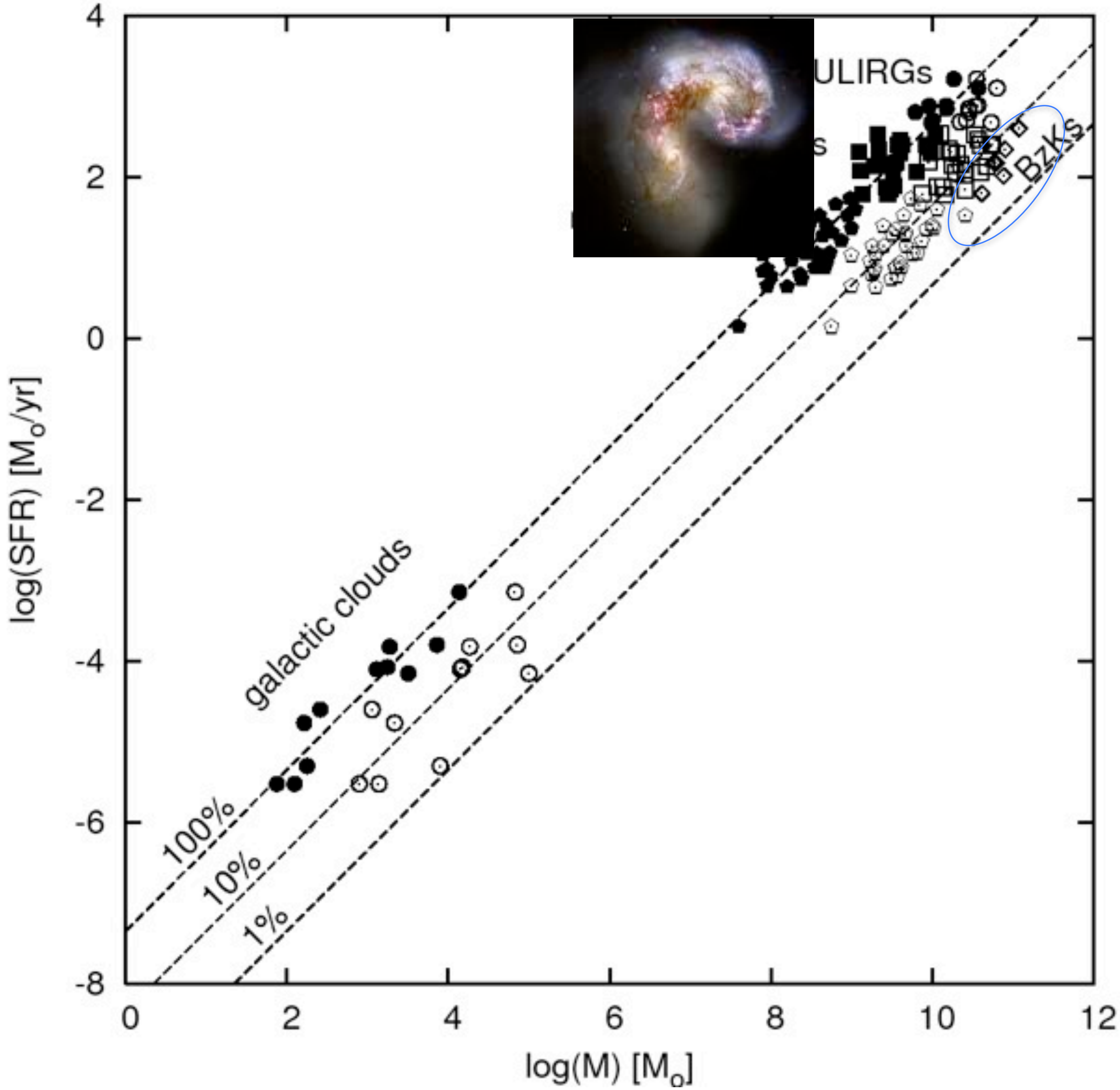

mon 2004

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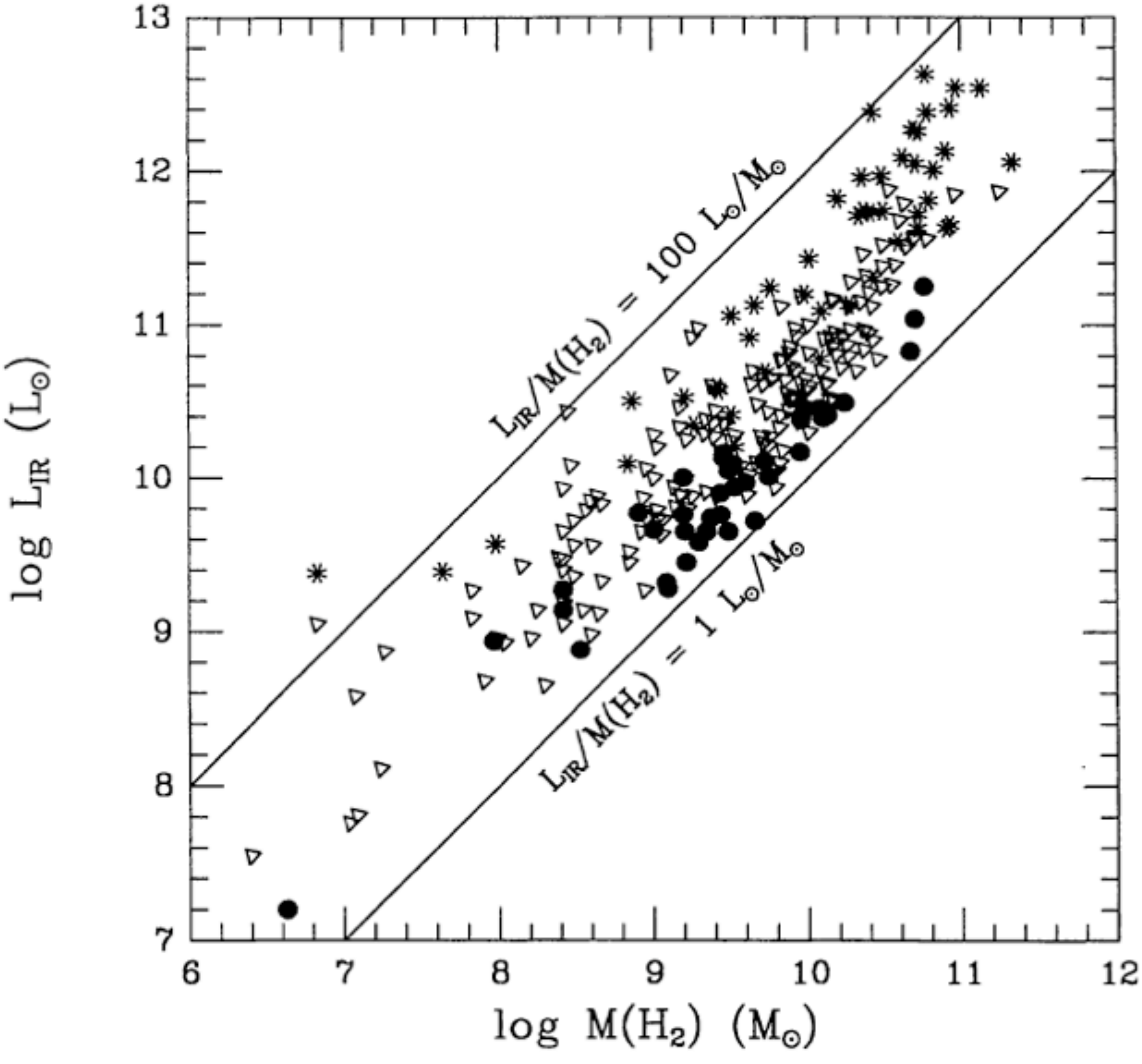
A Linear Scaling Law for Galaxies

Young & Scoville 1991, ARAA 32, 581



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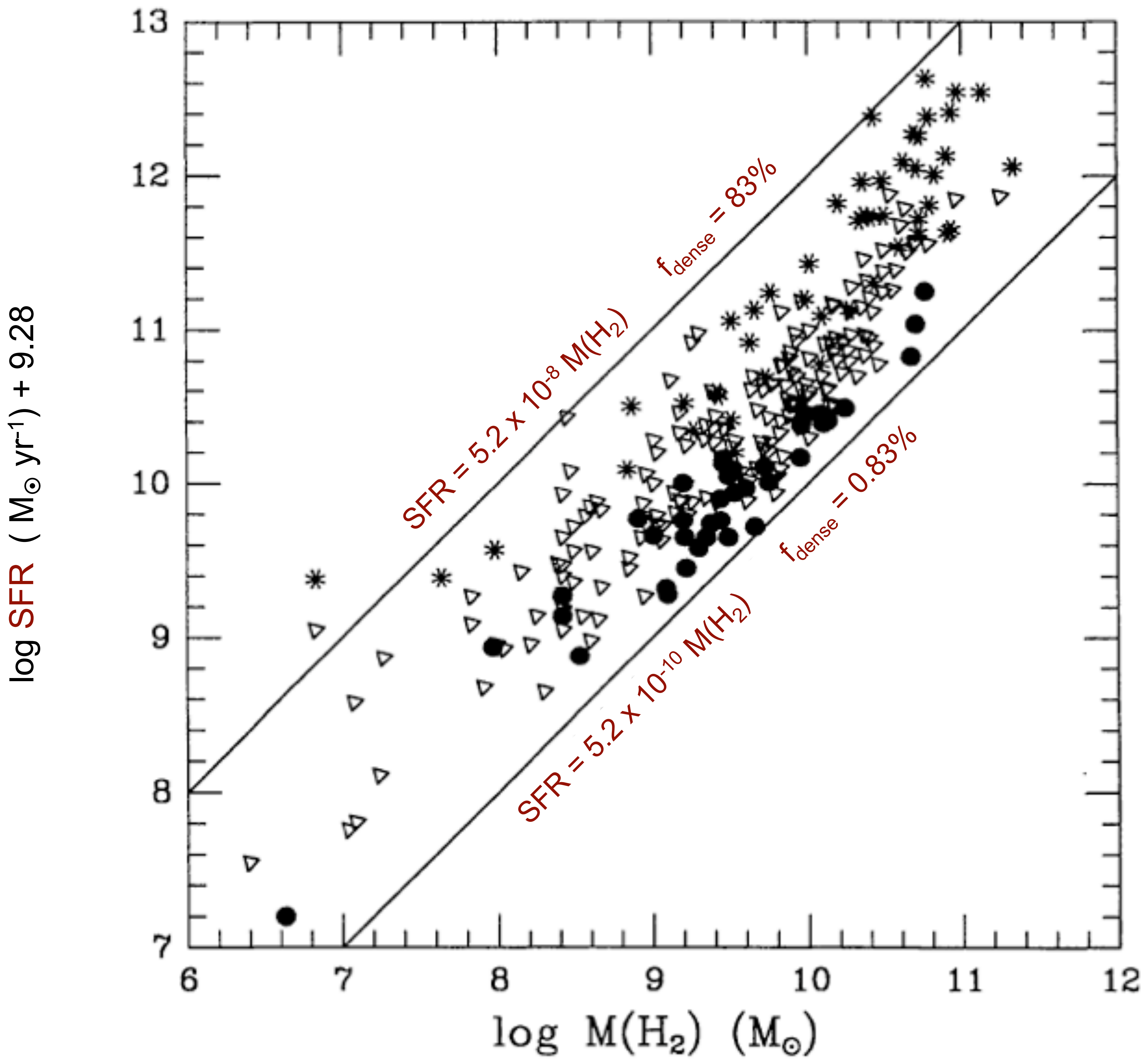

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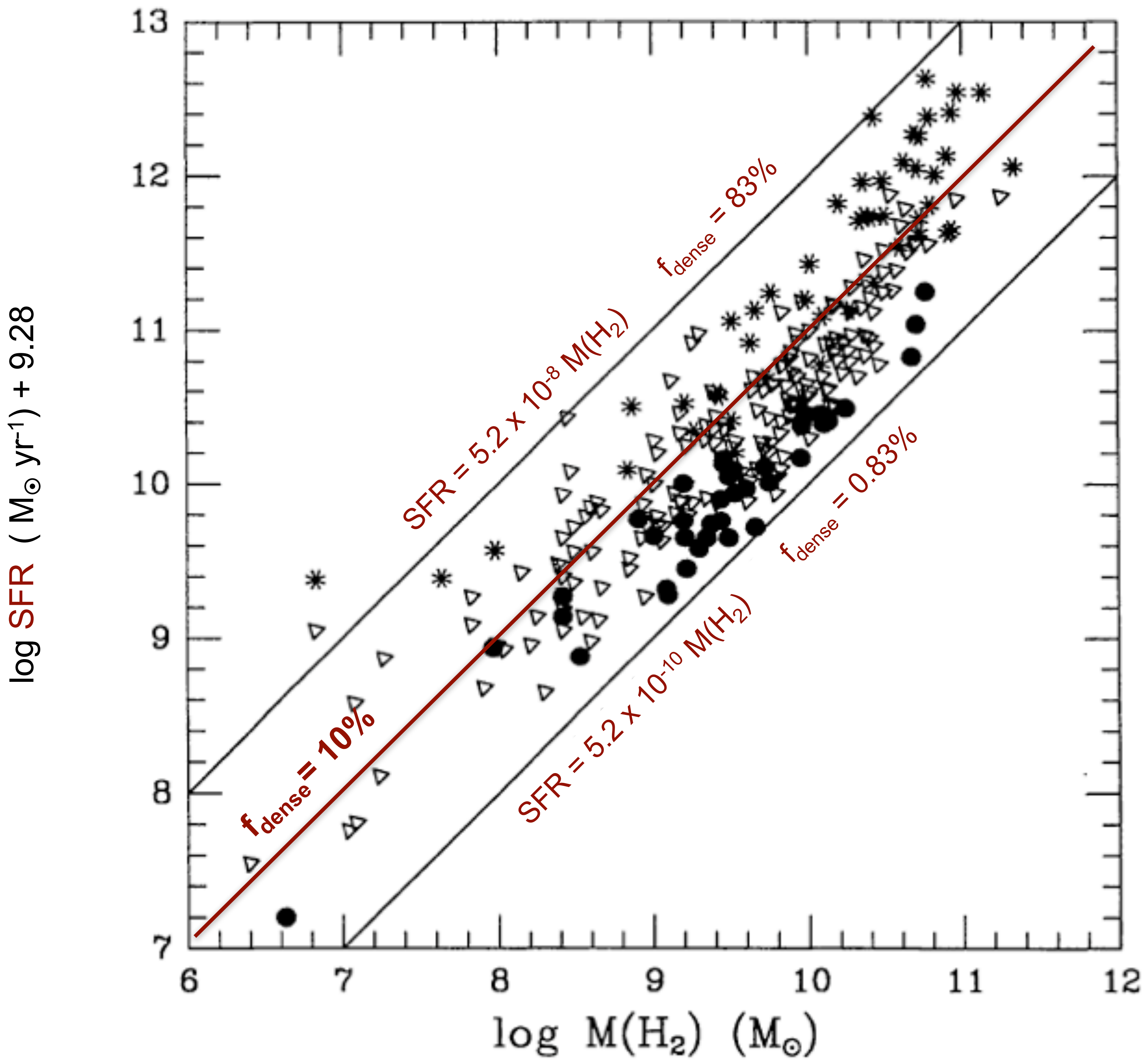

The nature of the Schmidt-Kennicutt scaling relation

Physical interpretation

- Standard interpretation:
  $$\rho_{\rm SF} \propto \frac{\rho_{\rm gas}}{\tau_{\rm ff}} \propto \sqrt{G}\rho^{1.5}$$
  - We do not observe collapsing gas forming stars
  - A CO beam (~kpc) includes several clouds: higher CO intensity implies more clouds, not densier gas
  - A shallower relation should hold

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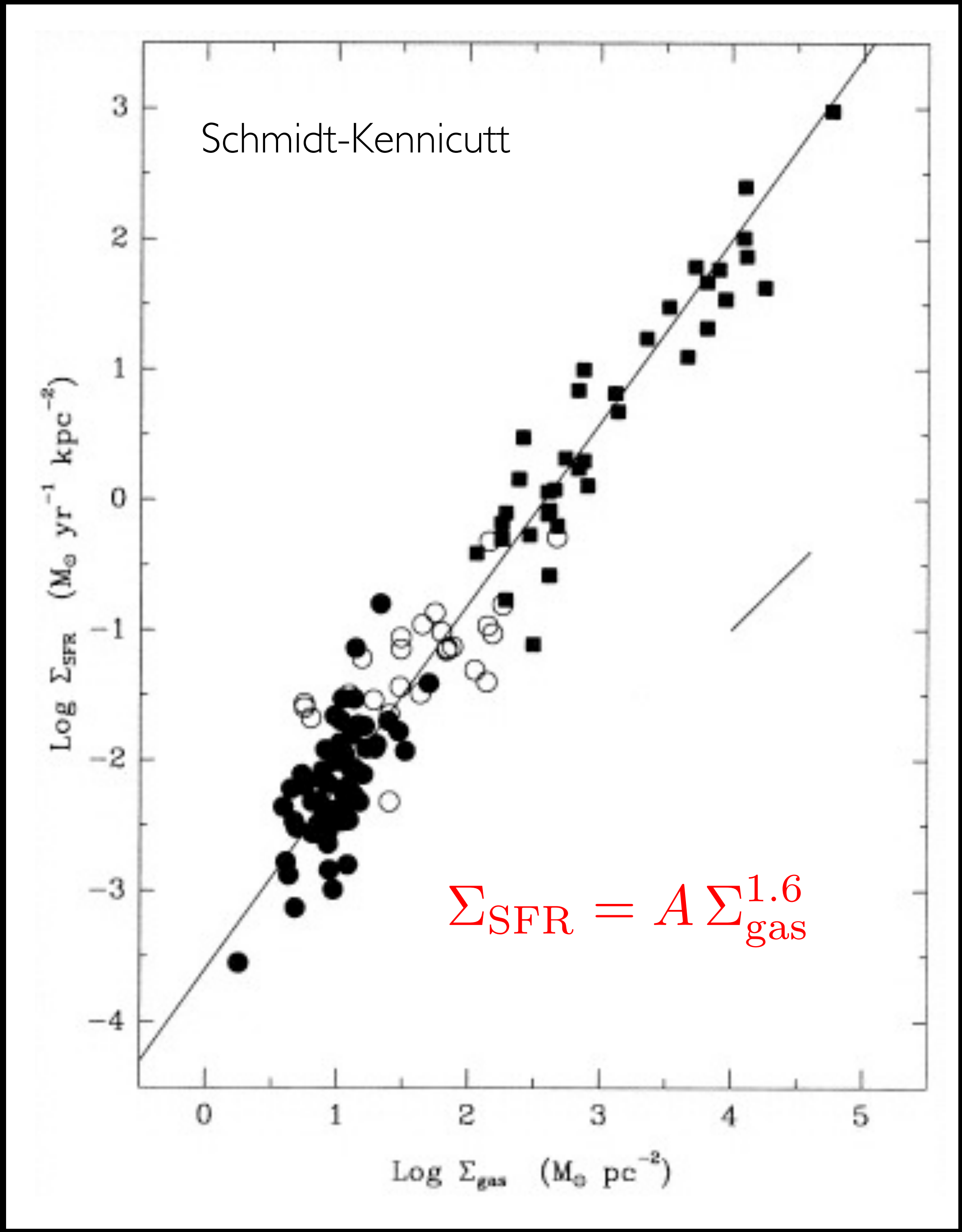
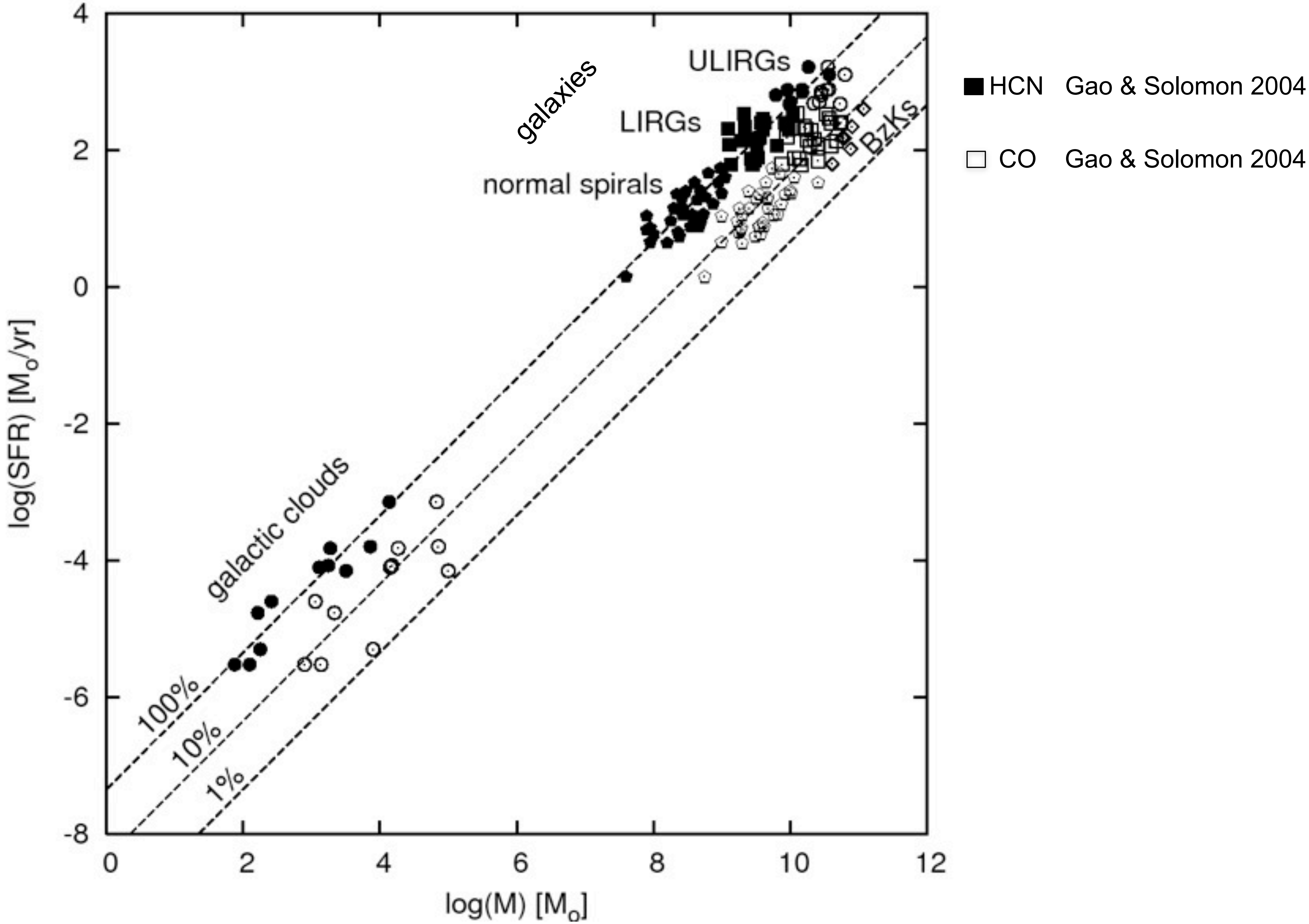


Star Formation Scaling Laws from Local Clouds to Galaxies



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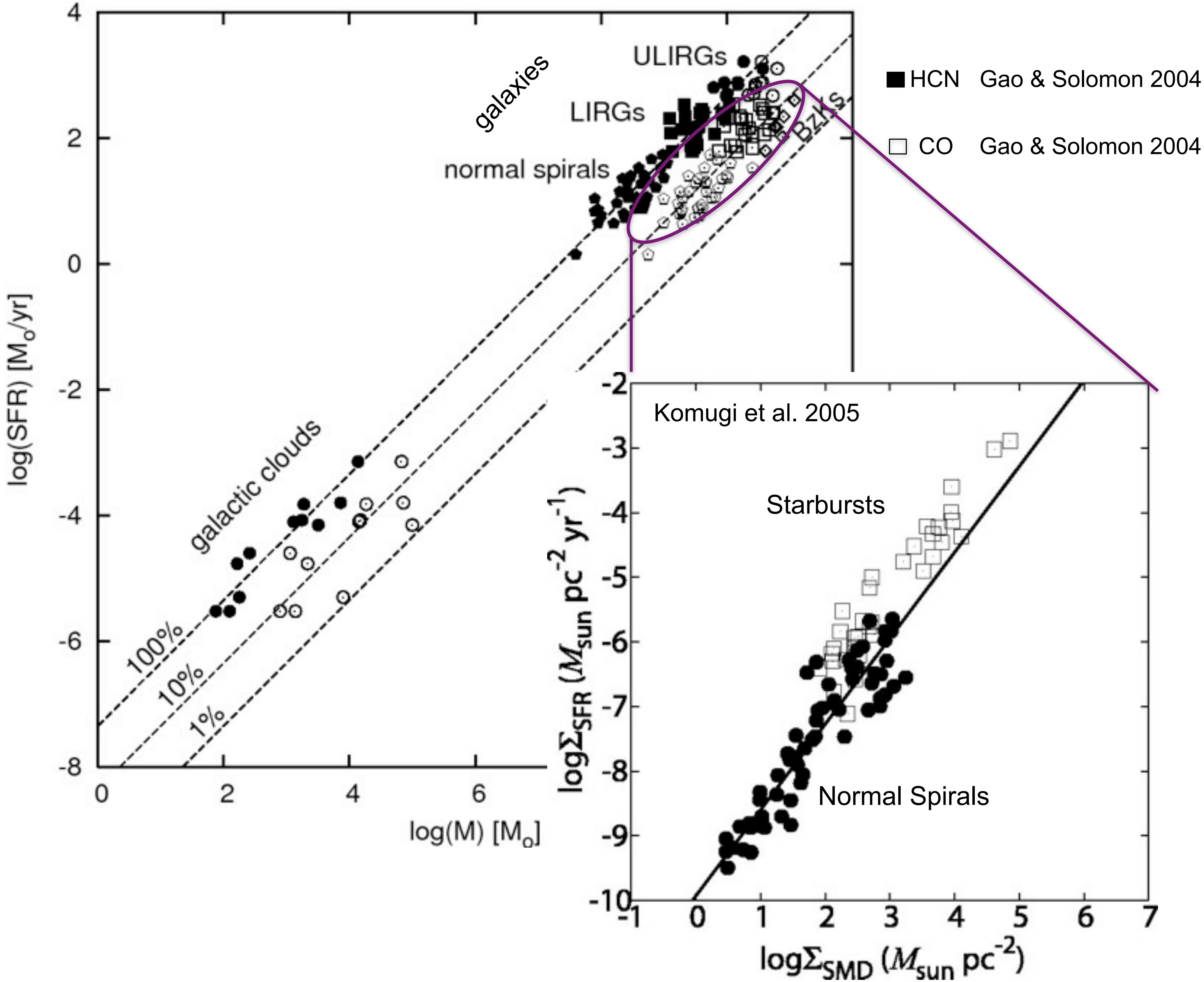
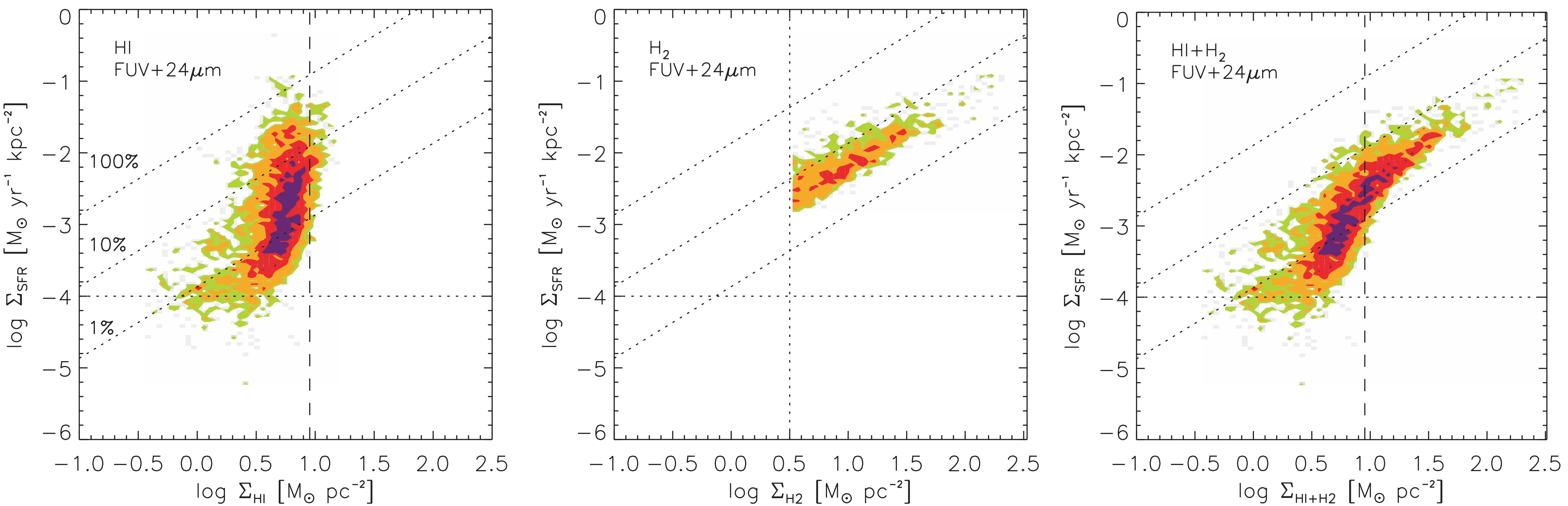


Sample of 17 nearby galaxies

Biegel et al. 2008



- HI does not correlate at all with the SFR
- H_2 correlates with slope 1 (Gao-Solomon law)
- HI + H_2 correlates with slope ~1.5 (Schmidt-Kennicutt law)

Smidth-Kennicutt law seems to be just the result of gas dilution!

Star Formaiton Scaling Laws: A Comparison

Observational Implications and Test:

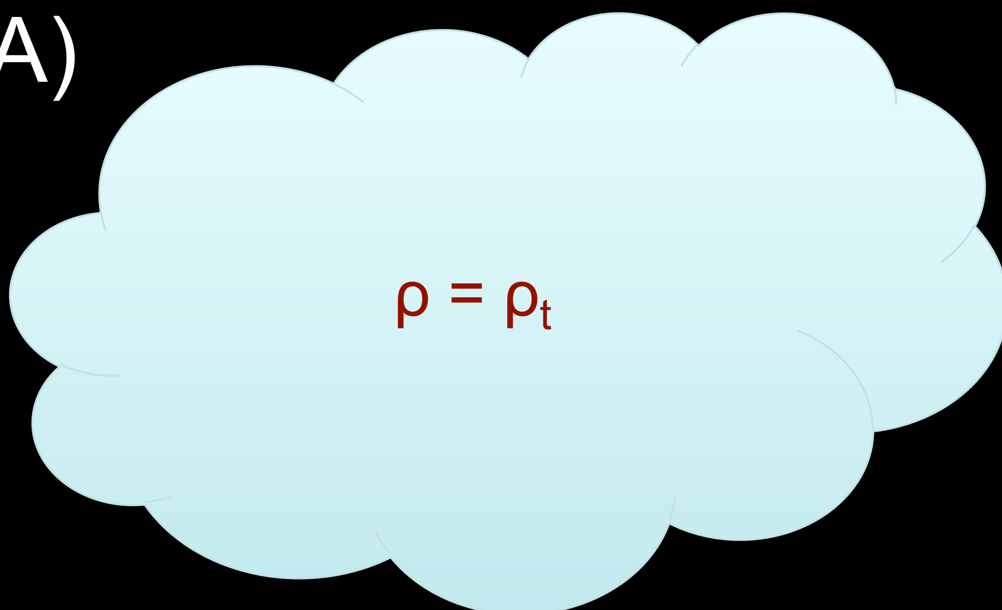
A)

B)

Star Formaiton Scaling Laws: A Comparison

Observational Implications and Test:

A)



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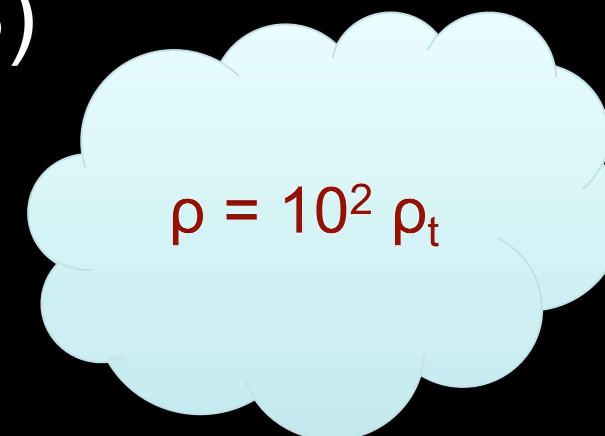
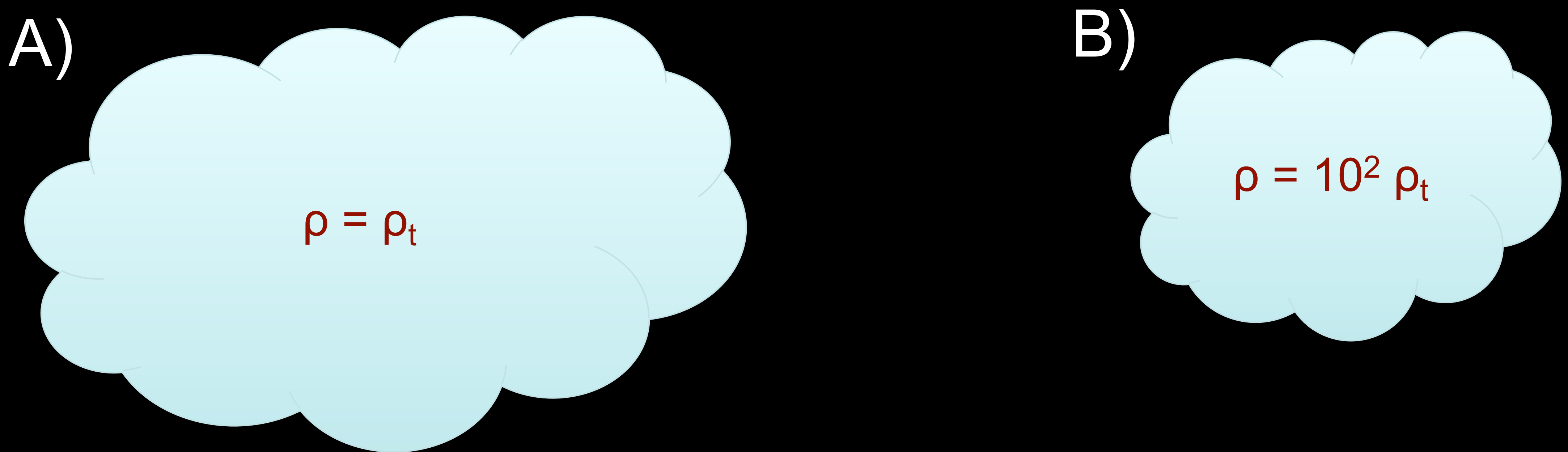


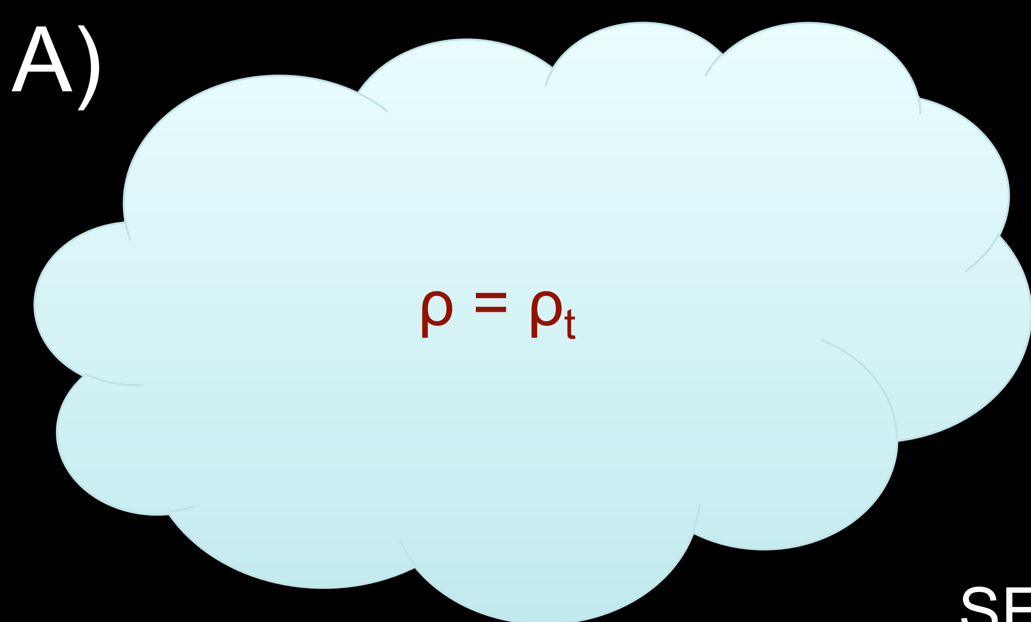
Star Formaiton Scaling Laws: A Comparison

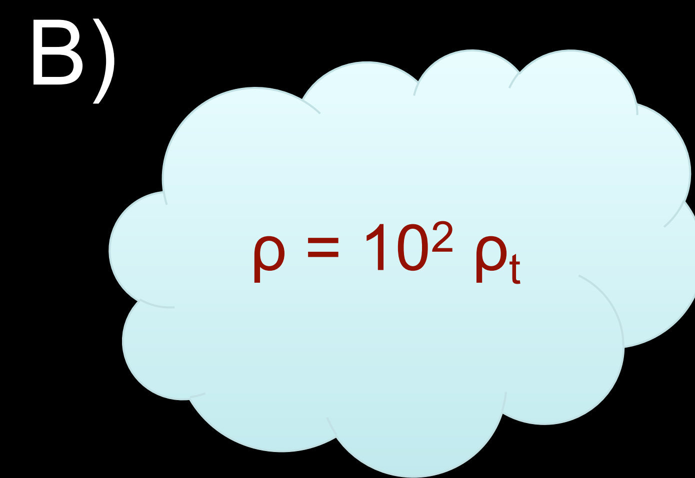
Observational Implications and Test: Mass(A) = Mass(B)



Star Formaiton Scaling Laws: A Comparison

Mass(A) = Mass(B)





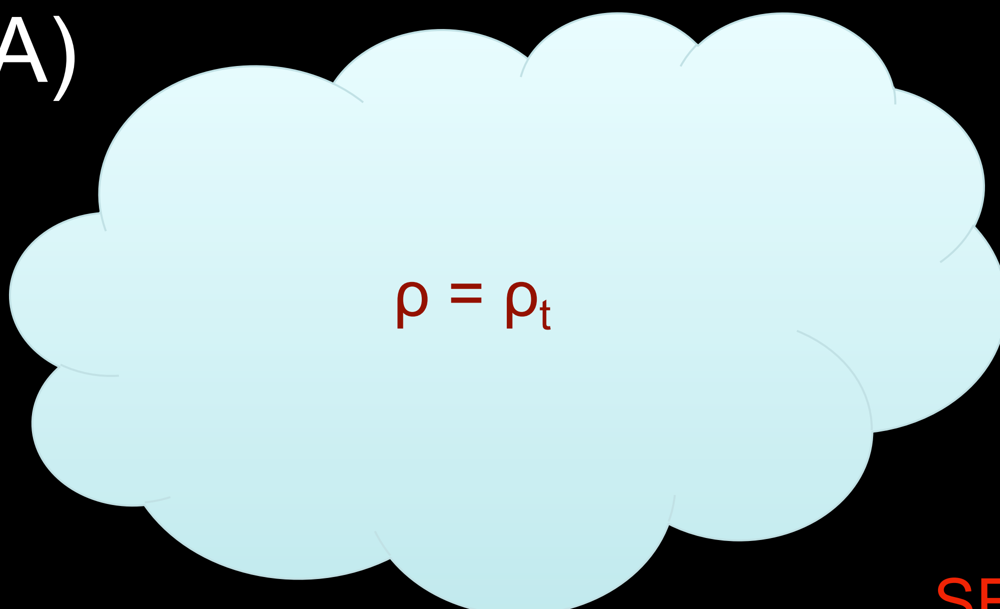
SFR(B) = SFR(A)

Density Scaling Law

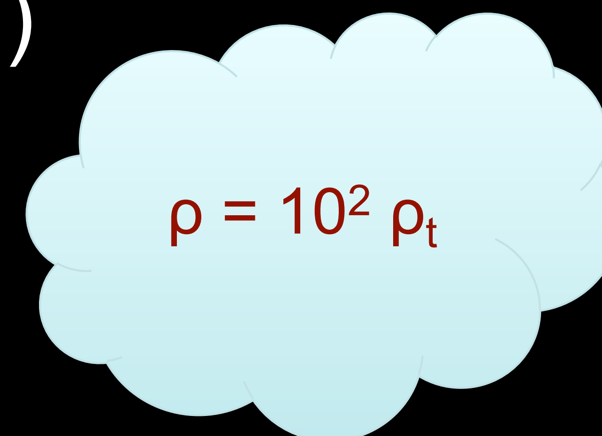
Star Formaiton Scaling Laws: A Comparison

Mass(A) = Mass(B)

A)



B)



SFR(B) = SFR(A)

Density Scaling Law

Schmidt Scaling Laws

n= 1.5

SFR ~ ρ^n

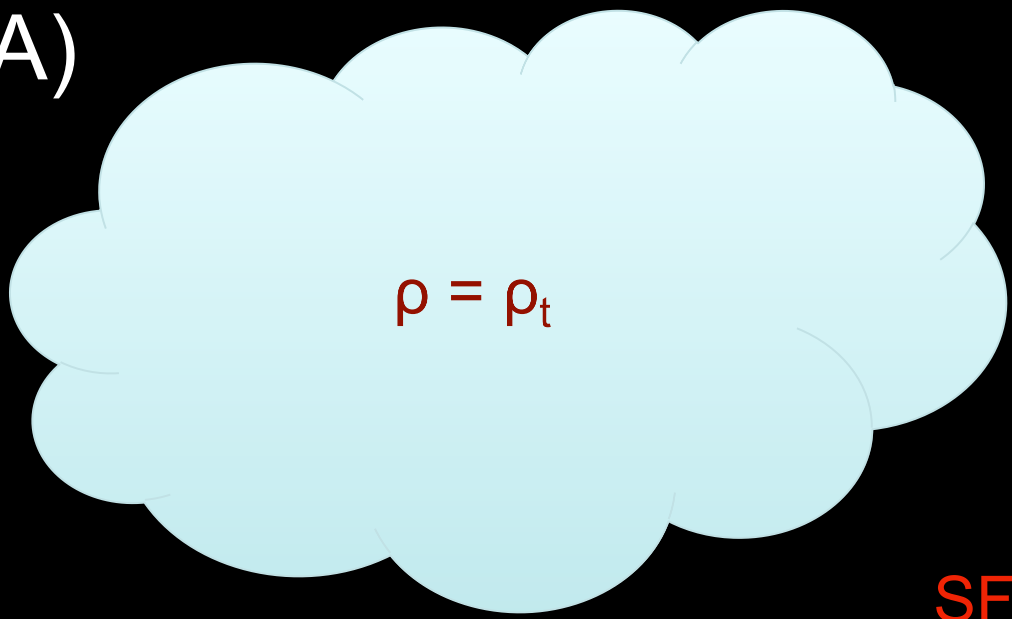
$\rho_{SFR} \sim (\rho_g)^n$

$\Sigma_{SFR} \sim (\Sigma_g)^n$

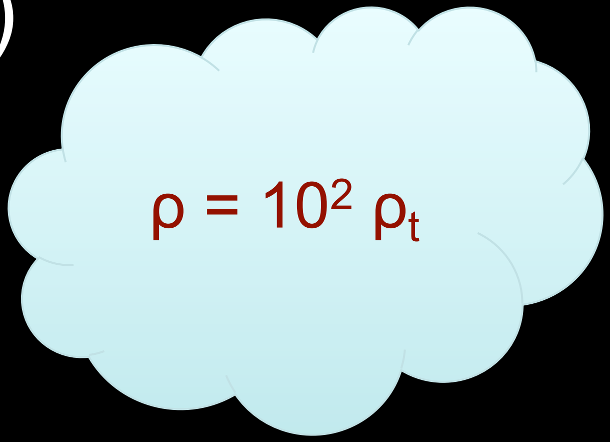
Star Formaiton Scaling Laws: A Comparison

Mass(A) = Mass(B)

A)



B)



SFR(B) = SFR(A) Density Scaling Law

Schmidt Scaling Laws n= 1.5

SFR ~ ρ^n SFR(B) = $(\rho_{g(B)}/\ \rho_{g(A)})^n$ SFR(A)

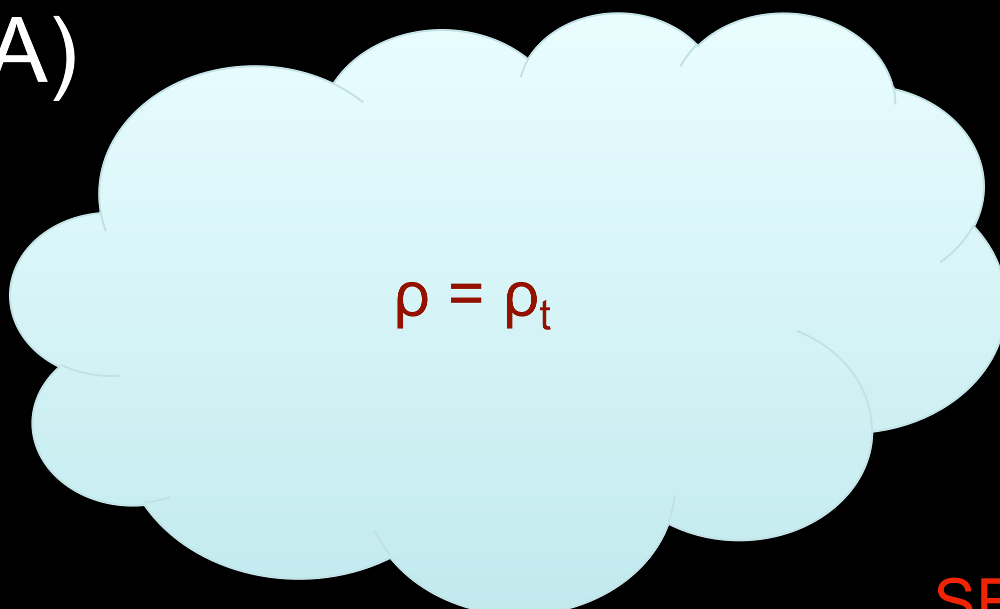
$\rho_{SFR} \sim (\rho_g)^n$

$\Sigma_{SFR} \sim (\Sigma_g)^n$

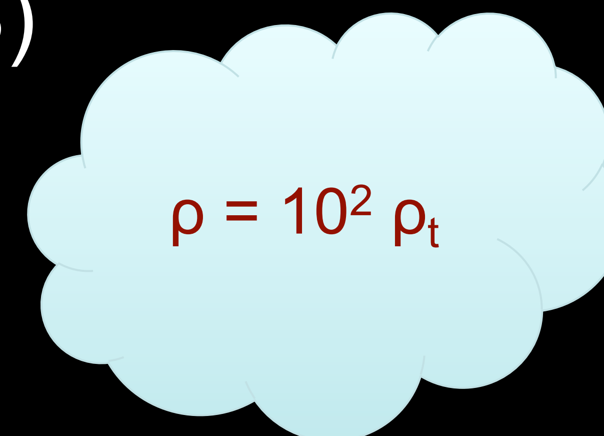
Star Formaiton Scaling Laws: A Comparison

Mass(A) = Mass(B)

A)



B)



SFR(B) = SFR(A)   Density Scaling Law

Schmidt Scaling Laws   n= 1.5

$SFR \sim \rho^n$ $SFR(B) = (\rho_{g(B)} / \rho_{g(A)})^n\ SFR(A)$ SFR(B) = 1600 SFR(A)

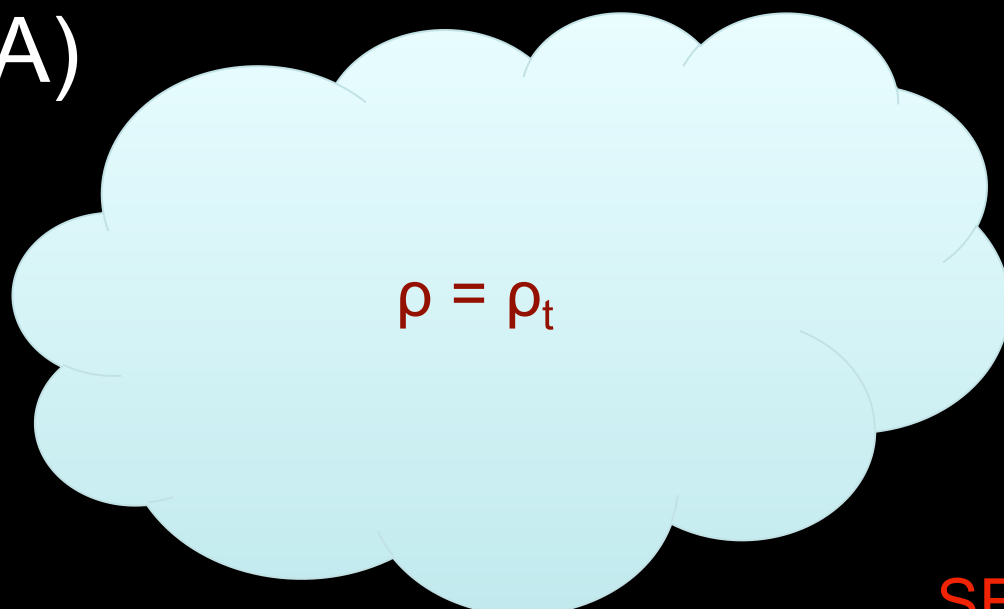
$\rho_{SFR} \sim (\rho_g)^n$

$\Sigma_{SFR} \sim (\Sigma_g)^n$

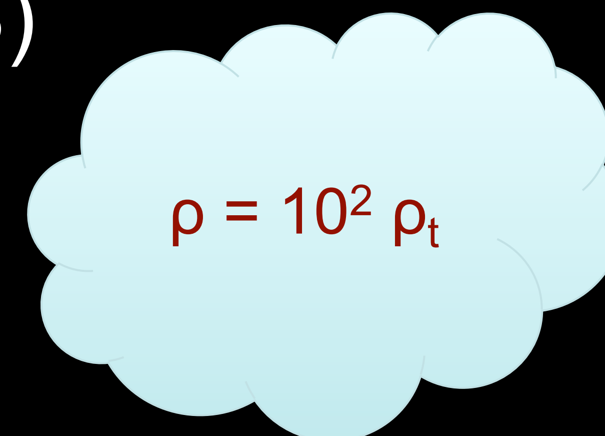
Star Formaiton Scaling Laws: A Comparison

Mass(A) = Mass(B)

A)



B)



SFR(B) = SFR(A) Density Scaling Law

Schmidt Scaling Laws n= 1.5

$SFR \sim \rho^n$ $SFR(B) = (\rho_{g(B)} / \rho_{g(A)})^n \, SFR(A)$ $SFR(B) = 1600 \, SFR(A)$

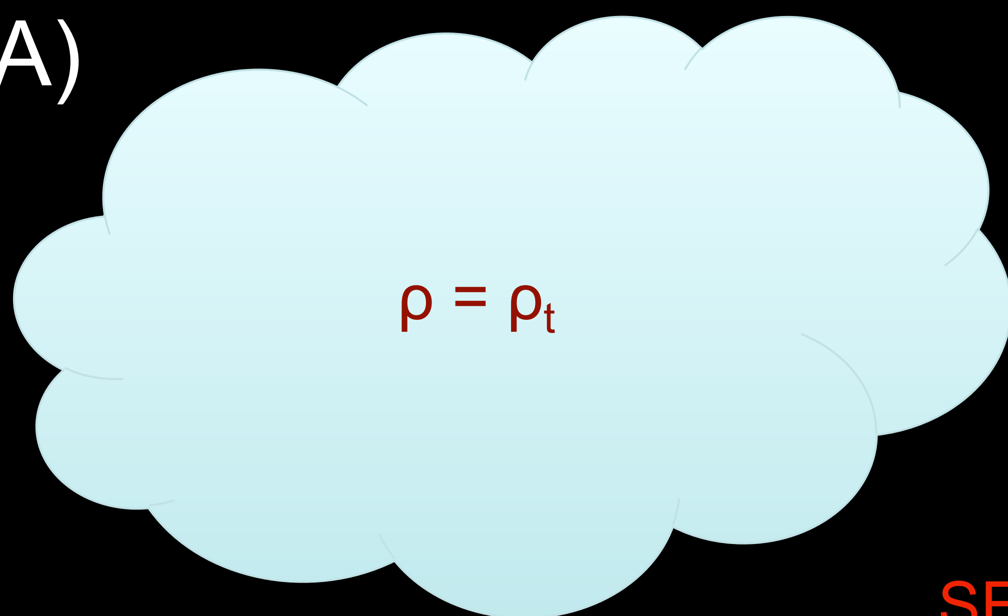
$\rho_{SFR} \sim (\rho_g)^n$ $SFR(B) = (\rho_{g(B)} / \rho_{g(A)})^{n-1} \, SFR(A)$

$\Sigma_{SFR} \sim (\Sigma_g)^n$

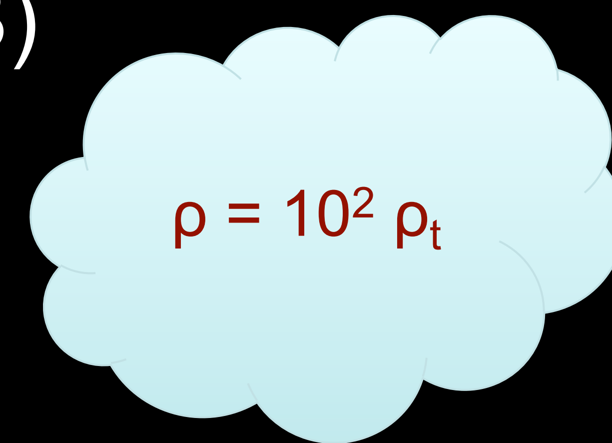
Star Formaiton Scaling Laws: A Comparison

Mass(A) = Mass(B)

A)



B)



SFR(B) = SFR(A)   Density Scaling Law

Schmidt Scaling Laws

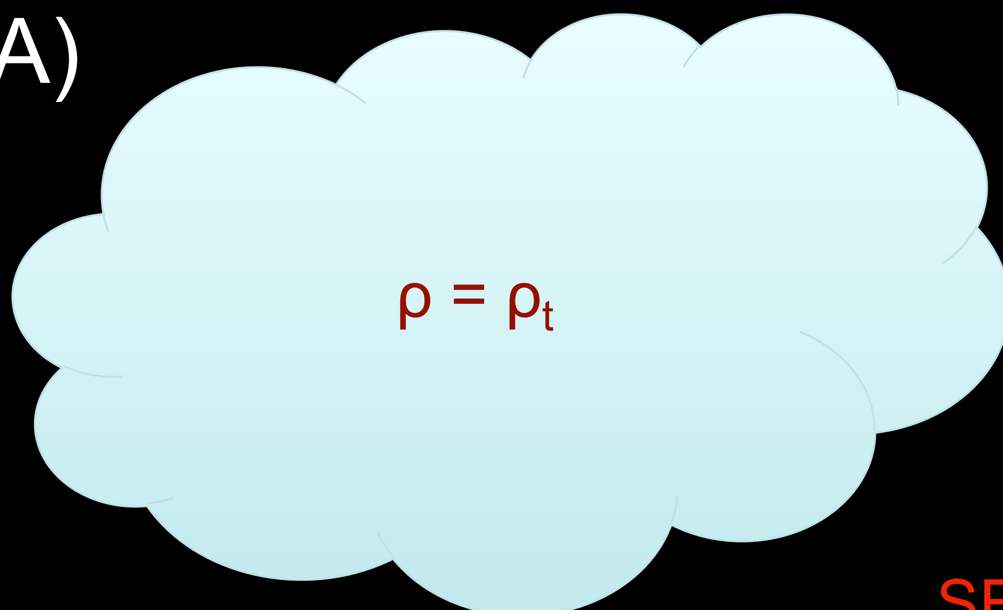
n= 1.5

SFR ~ ρ^n	SFR(B) = $(\rho_{g(B)}/ \rho_{g(A)})^n$ SFR(A)	SFR(B) = 1600 SFR(A)
$\rho_{SFR} \sim (\rho_g)^n$	SFR(B) = $(\rho_{g(B)}/ \rho_{g(A)})^{n-1}$ SFR(A)	SFR(B) = 10 SFR(A)
$\Sigma_{SFR} \sim (\Sigma_g)^n$		

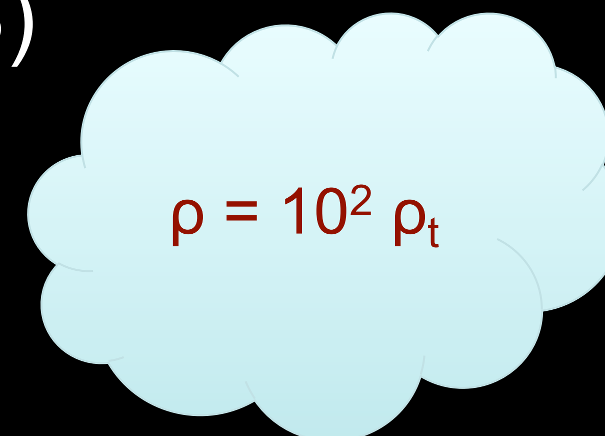
Star Formaiton Scaling Laws: A Comparison

Mass(A) = Mass(B)

A)



B)



SFR(B) = SFR(A)   Density Scaling Law

Schmidt Scaling Laws		n= 1.5
$SFR \sim \rho^n$	$SFR(B) = (\rho_{g(B)} / \rho_{g(A)})^n\ SFR(A)$	SFR(B) = 1600 SFR(A)
$\rho_{SFR} \sim (\rho_g)^n$	$SFR(B) = (\rho_{g(B)} / \rho_{g(A)})^{n-1}\ SFR(A)$	SFR(B) = 10 SFR(A)
$\Sigma_{SFR} \sim (\Sigma_g)^n$	$SFR(B) = (\Sigma_{g(B)} / \Sigma_{g(A)})^{n-1}\ SFR(A)$	

Star Formaiton Scaling Laws: A Comparison

Mass(A) = Mass(B)

A)

$\rho = \rho_t$

B)

$\rho = 10^2\ \rho_t$

SFR(B) = SFR(A)

Density Scaling Law

Schmidt Scaling Laws		n= 1.5
$SFR \sim \rho^n$	$SFR(B) = (\rho_{g(B)}/\ \rho_{g(A)})^n\ SFR(A)$	SFR(B) = 1600 SFR(A)
$\rho_{SFR} \sim (\rho_g)^n$	$SFR(B) = (\rho_{g(B)}/\ \rho_{g(A)})^{n-1}\ SFR(A)$	SFR(B) = 10 SFR(A)
$\Sigma_{SFR} \sim (\Sigma_g)^n$	$SFR(B) = (\Sigma_{g(B)}/\ \Sigma_{g(A)})^{n-1}\ SFR(A)$	SFR(B) = (1–5) SFR(A)

SUMMARY

1. Specific star formation rates in molecular clouds vary considerably

2. The SFR correlates most directly with total mass of dense gas above a threshold column density of $A_V \approx 7$ mag, corresponding to $n \approx 10^4$ cm^{-3}

3. A single, linear, star formation law connects galactic clouds to external galaxies: $SFR = 4.6 \pm 2.6 \times 10^{-8}\ M_{dense}\quad (M_\odot\ yr^{-1})$