Star formation from (local) molecular clouds to spiral arms

Lee Hartmann
University of Michigan

Michigan Star and Planet Formation

Structure of molecular clouds

Efficiency of star formation

Feedback

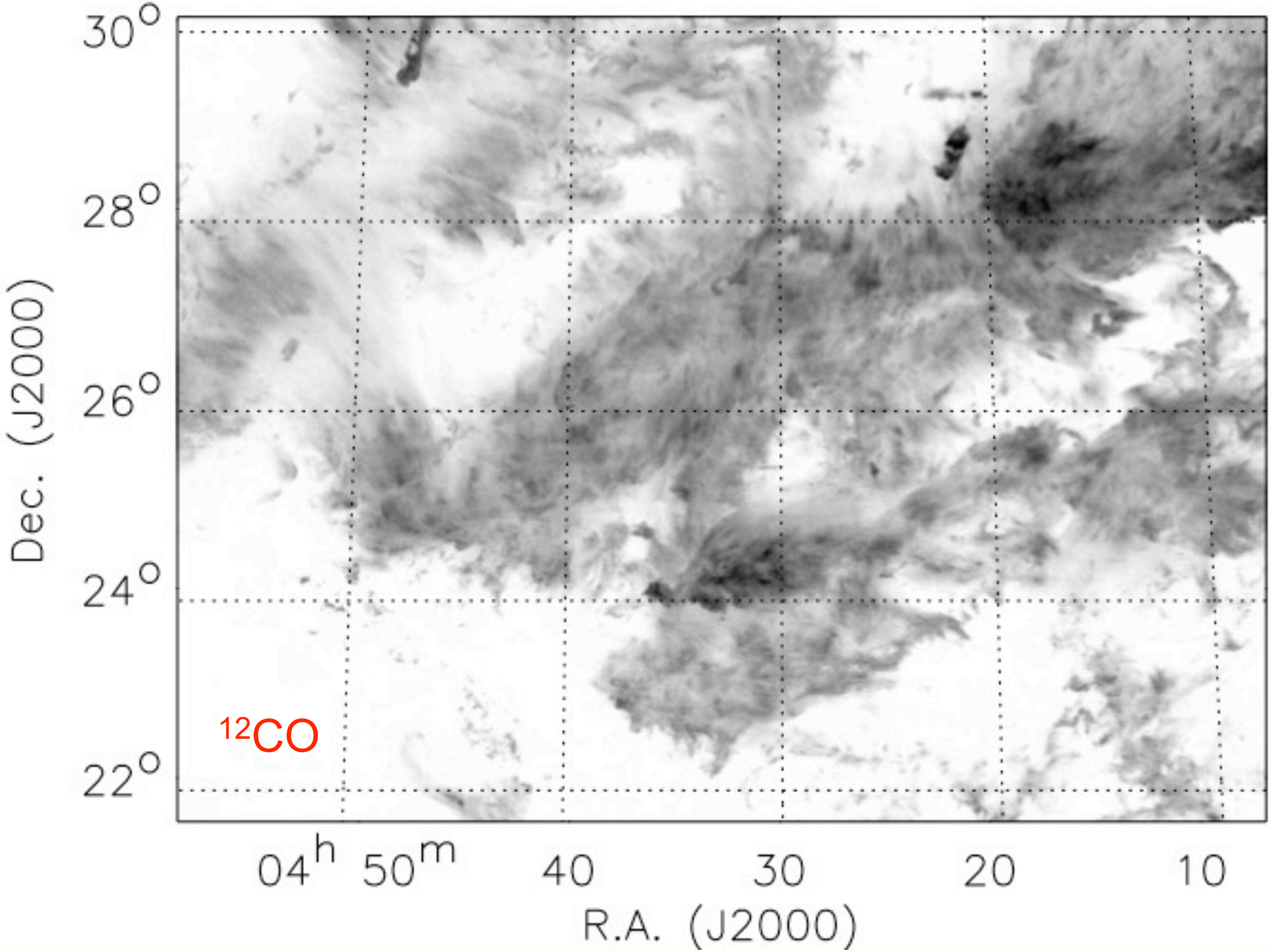
Mechanisms for forming molecular clouds

<u>Implications for:</u>

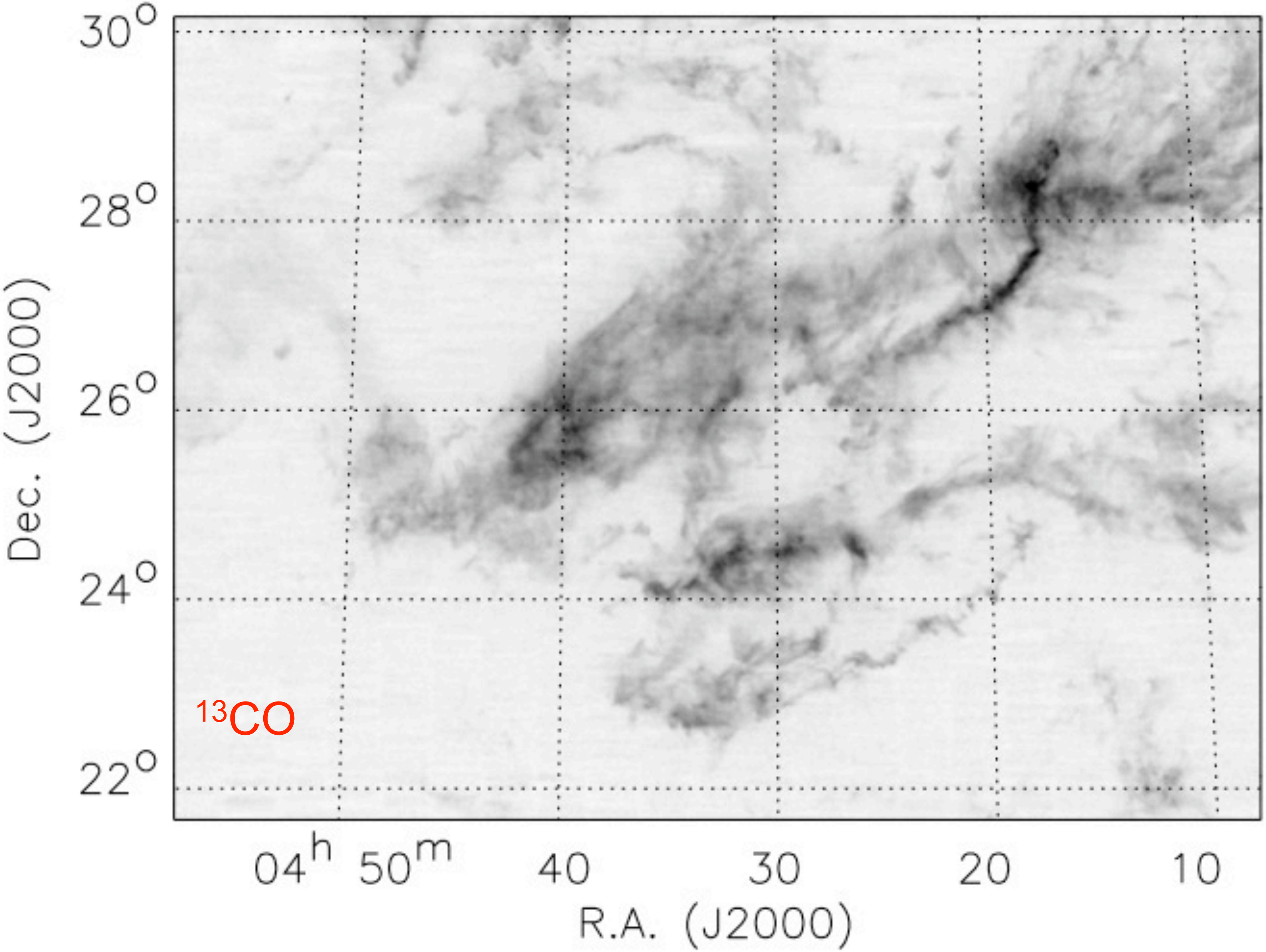
- observations of distant objects
- star formation rates
- IMFs


LOOK INSIDE!

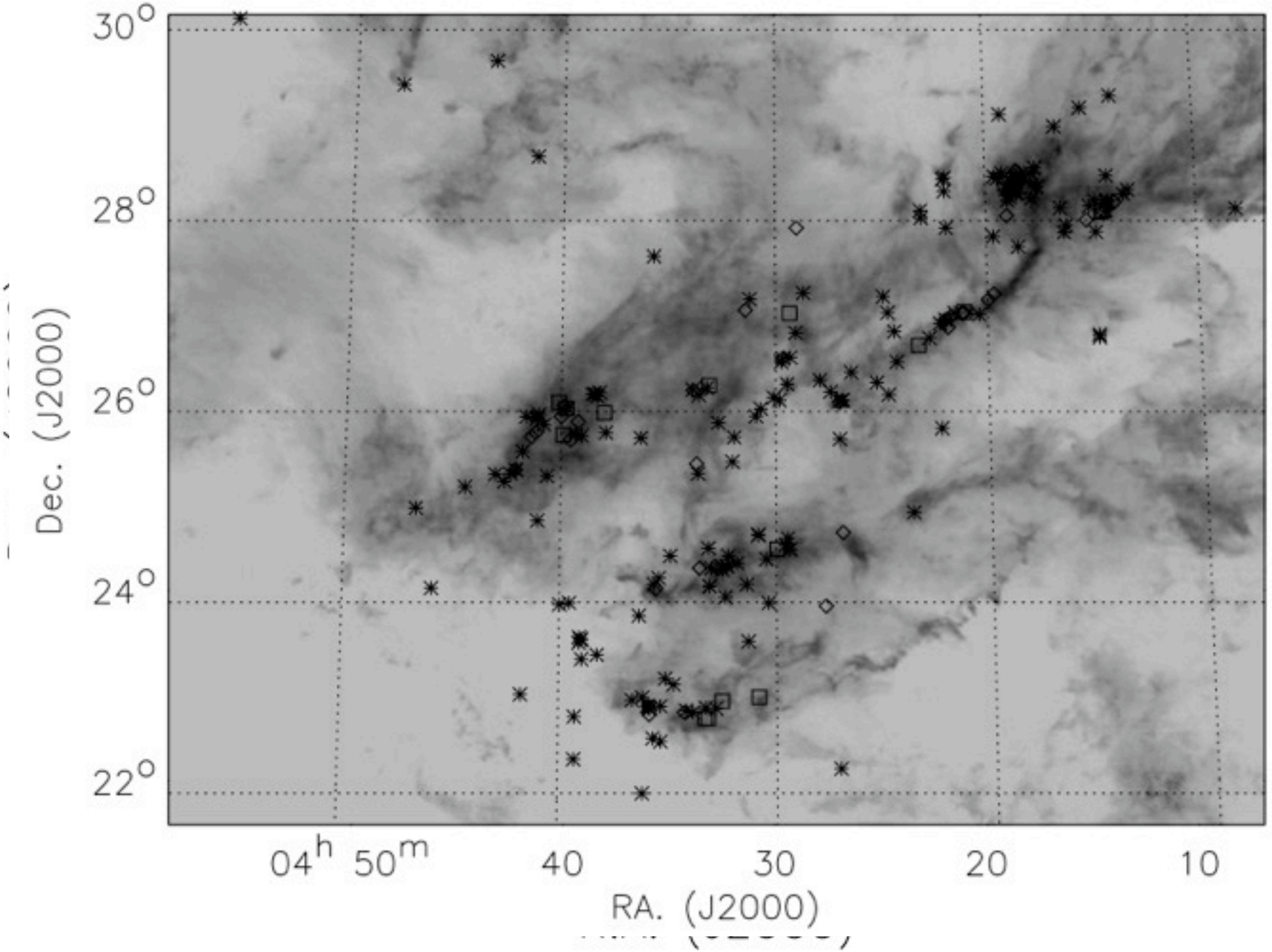
Taurus: Goldsmith et al. 2009



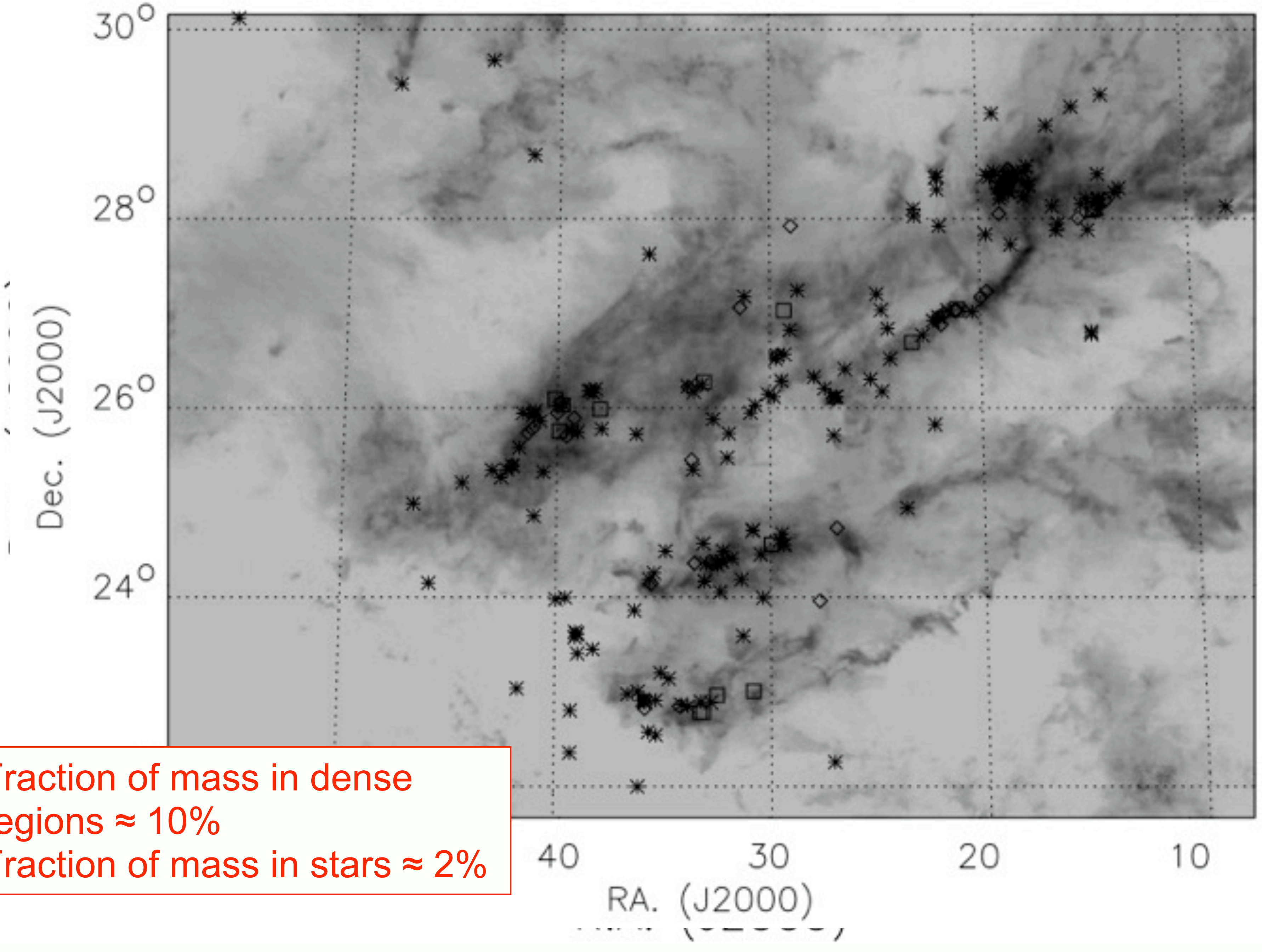
Taurus: Goldsmith et al. 2009



Taurus: Goldsmith et al. 2009



Taurus: Goldsmith et al. 2009



Fraction of mass in dense regions ≈ 10%
Fraction of mass in stars ≈ 2%

Efficiency of star formation:

Efficiency of star formation:

OBSERVATIONAL STUDIES OF STAR FORMATION: CONCLUSIONS

MARTIN COHEN AND LEONARD V. KUHI
Astronomy Department, University of California, Berkeley
Received 1978 June 21; accepted 1978 October 4

Efficiency of star formation:

OBSERVATIONAL STUDIES OF STAR FORMATION: CONCLUSIONS

MARTIN COHEN AND LEONARD V. KUHI
Astronomy Department, University of California, Berkeley
Received 1978 June 21; accepted 1978 October 4

7. The overall efficiency of star formation is a few percent, expressed as the ratio of mass observed in stars to total gas mass (in hydrogen, inferred from CO radio maps) for either entire aggregates or smaller entities.

Efficiency of star formation:

OBSERVATIONAL STUDIES OF STAR FORMATION: CONCLUSIONS

MARTIN COHEN AND LEONARD V. KUHI
Astronomy Department, University of California, Berkeley
Received 1978 June 21; accepted 1978 October 4

7. The overall efficiency of star formation is a few percent, expressed as the ratio of mass observed in stars to total gas mass (in hydrogen, inferred from CO radio maps) for either entire aggregates or smaller entities.

THE *SPITZER* c2d LEGACY RESULTS: STAR-FORMATION RATES AND EFFICIENCIES; EVOLUTION AND LIFETIMES

NEAL J. EVANS II[1], MICHAEL M. DUNHAM[1], JES K. JØRGENSEN[2], MELISSA L. ENOCH[3, 4], BRUNO MERÍN[5, 6], EWINE F. VAN DISHOECK[5, 7], JUAN M. ALCALÁ[8], PHILIP C. MYERS[9], KARL R. STAPELFELDT[10], TRACY L. HUARD[9, 11], LORI E. ALLEN[9], PAUL M. HARVEY[1], TIM VAN KEMPEN[5], GEOFFREY A. BLAKE[12], DAVID W. KOERNER[13], LEE G. MUNDY[11], DEBORAH L. PADGETT[14], AND ANNEILA I. SARGENT[3]

Efficiency of star formation:

OBSERVATIONAL STUDIES OF STAR FORMATION: CONCLUSIONS

MARTIN COHEN AND LEONARD V. KUHI
Astronomy Department, University of California, Berkeley
Received 1978 June 21; accepted 1978 October 4

7. The overall efficiency of star formation is a few percent, expressed as the ratio of mass observed in stars to total gas mass (in hydrogen, inferred from CO radio maps) for either entire aggregates or smaller entities.

THE *SPITZER* c2d LEGACY RESULTS: STAR-FORMATION RATES AND EFFICIENCIES; EVOLUTION AND LIFETIMES

NEAL J. EVANS II[1], MICHAEL M. DUNHAM[1], JES K. JØRGENSEN[2], MELISSA L. ENOCH[3, 4], BRUNO MERÍN[5, 6], EWINE F. VAN DISHOECK[5, 7], JUAN M. ALCALÁ[8], PHILIP C. MYERS[9], KARL R. STAPELFELDT[10], TRACY L. HUARD[9, 11], LORI E. ALLEN[9], PAUL M. HARVEY[1], TIM VAN KEMPEN[5], GEOFFREY A. BLAKE[12], DAVID W. KOERNER[13], LEE G. MUNDY[11], DEBORAH L. PADGETT[14], AND ANNEILA I. SARGENT[3]

Current star-formation efficiencies range from 3% to 6%;

Structure of molecular clouds $\Rightarrow$ most of the mass is at low density

Structure of molecular clouds ⇒ most of the mass is at low density

Structure of molecular clouds ⇒ most of the mass is at low density

Efficiency of star formation: low, because only high-density regions form stars... and because of

Structure of molecular clouds ⇒ most of the mass is at low density

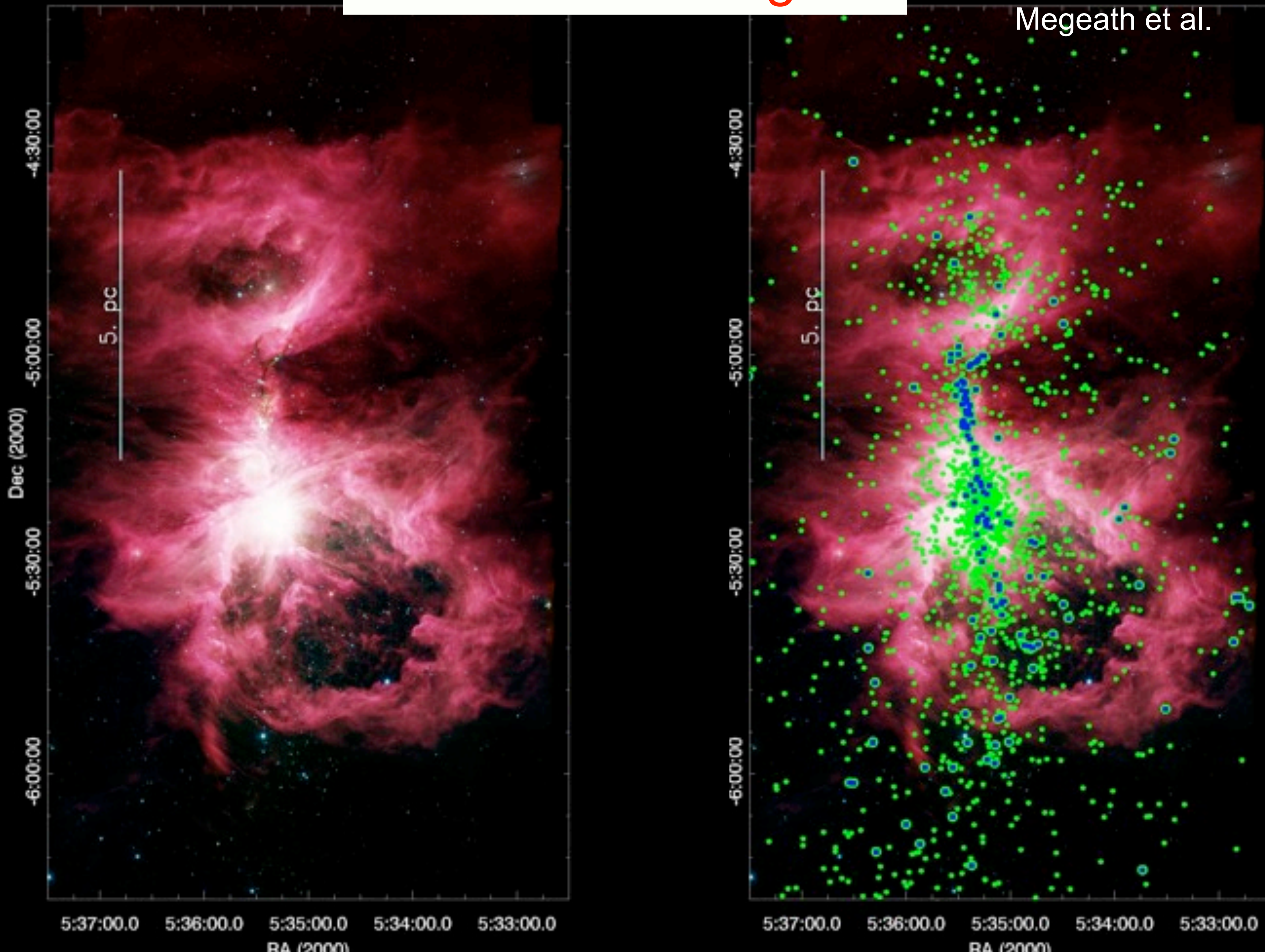
Efficiency of star formation: low, because only high-density regions form stars... and because of

Structure of molecular clouds $\Rightarrow$ most of the mass is at low density

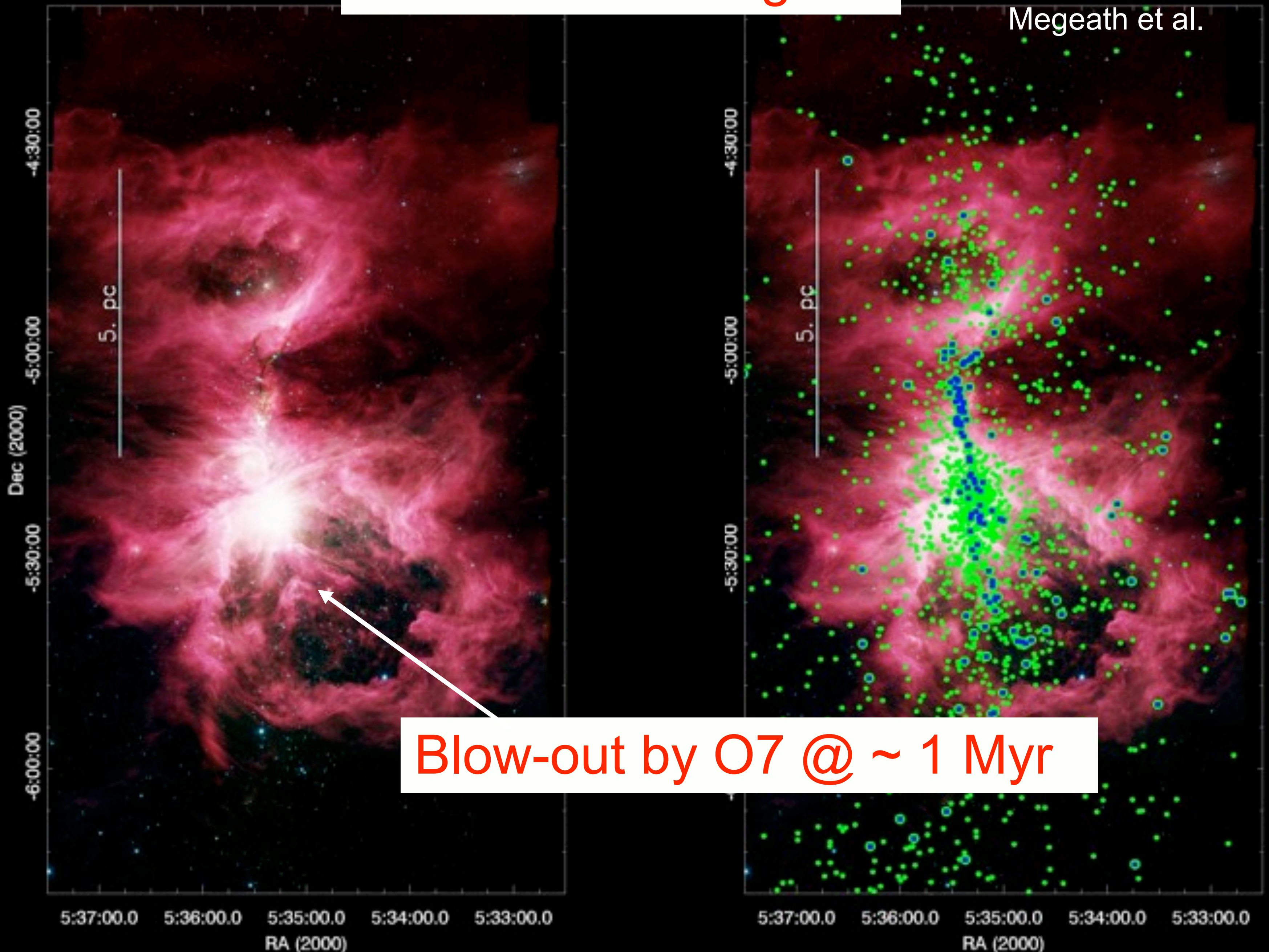
Efficiency of star formation: low, because only high-density regions form stars... and because of

Feedback! (strongly limits cloud lifetimes)

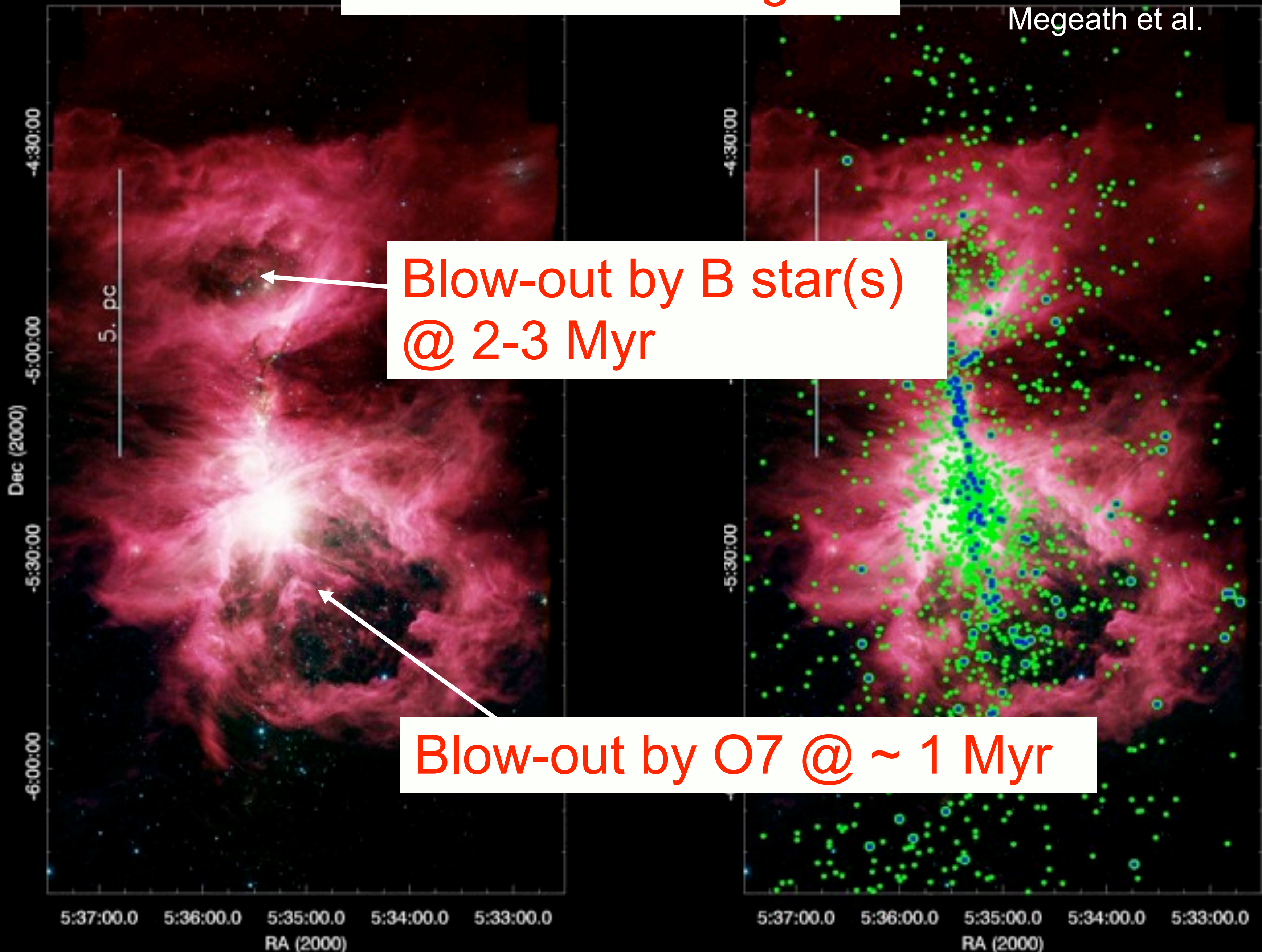
Orion Nebula region



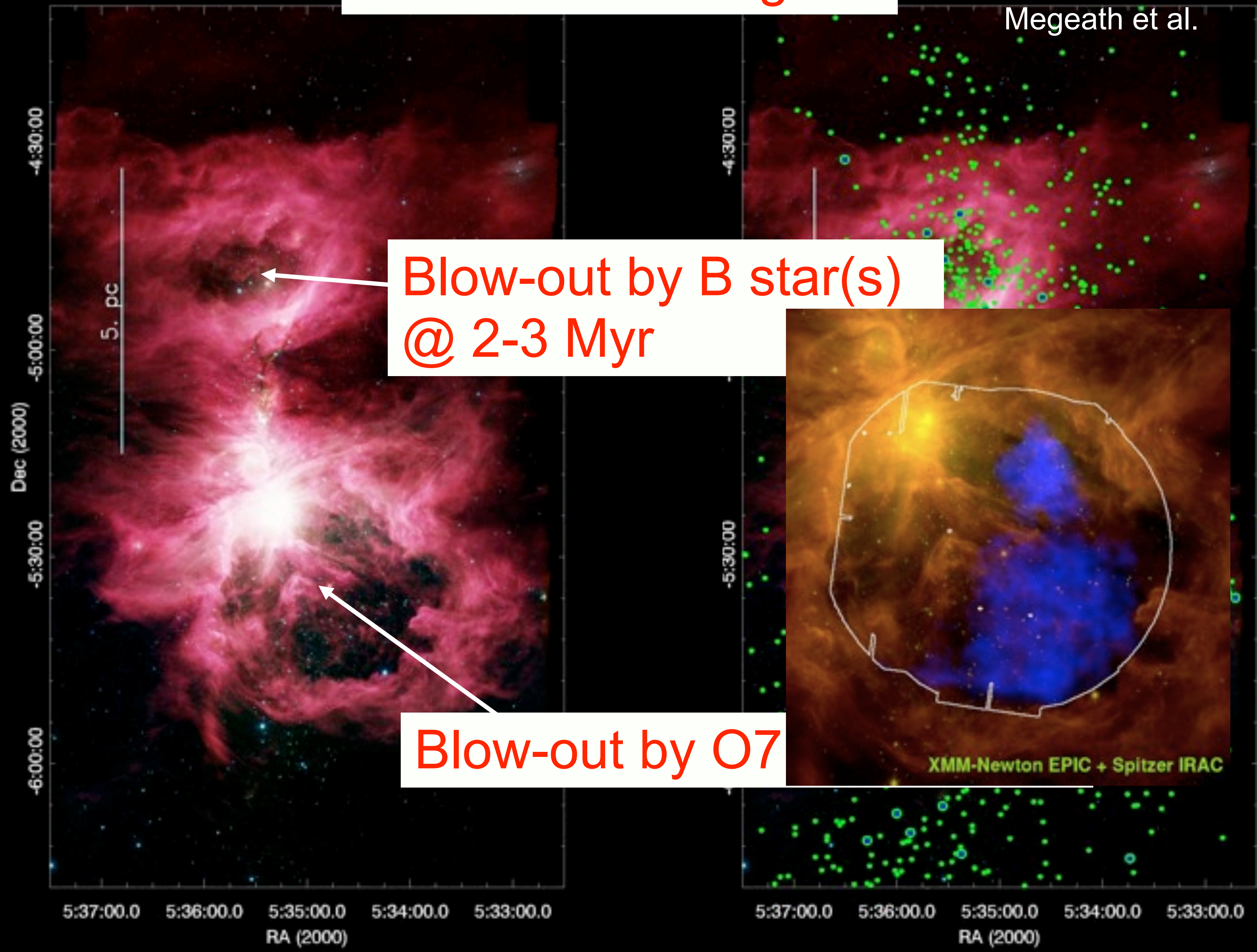
Orion Nebula region



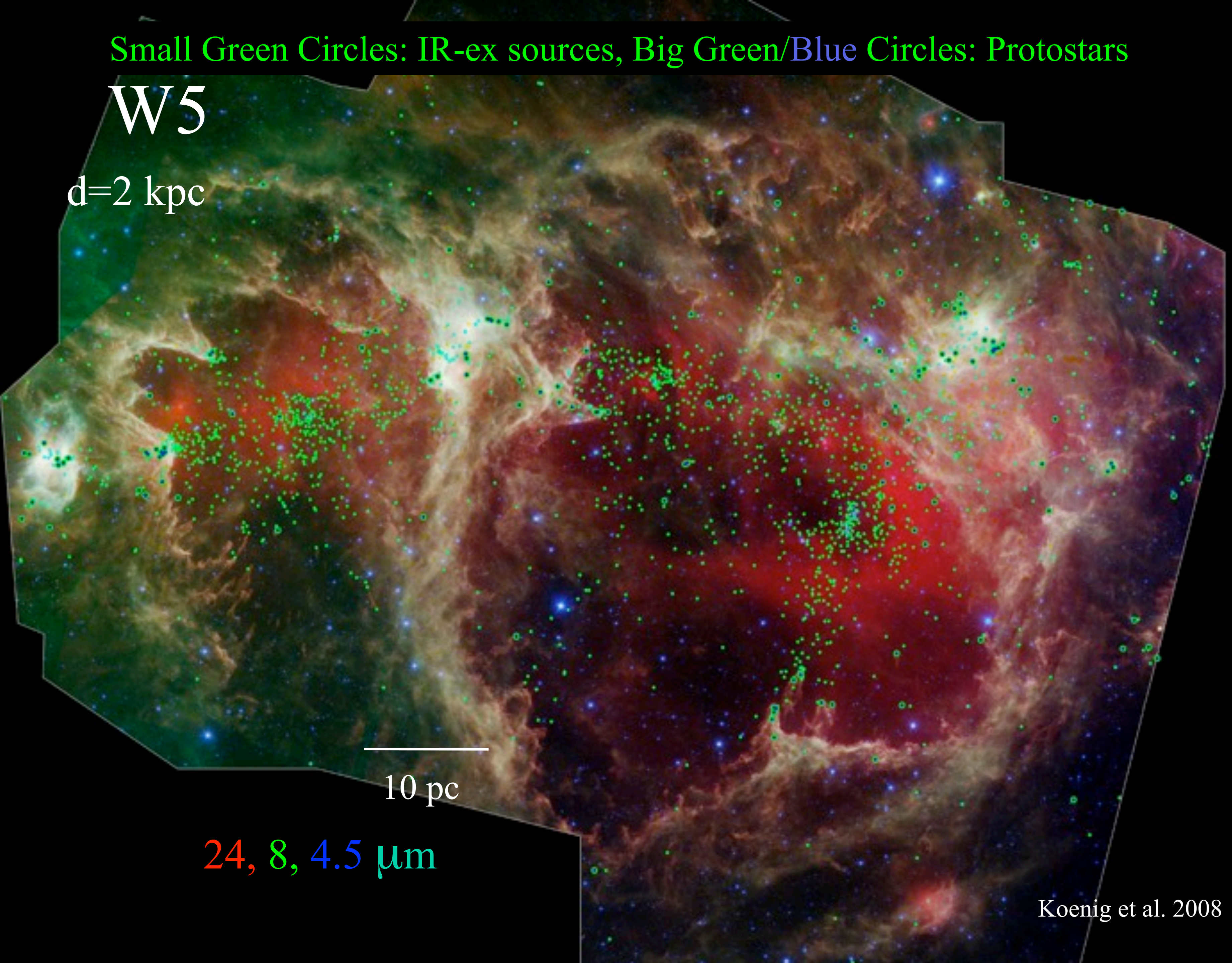
Orion Nebula region



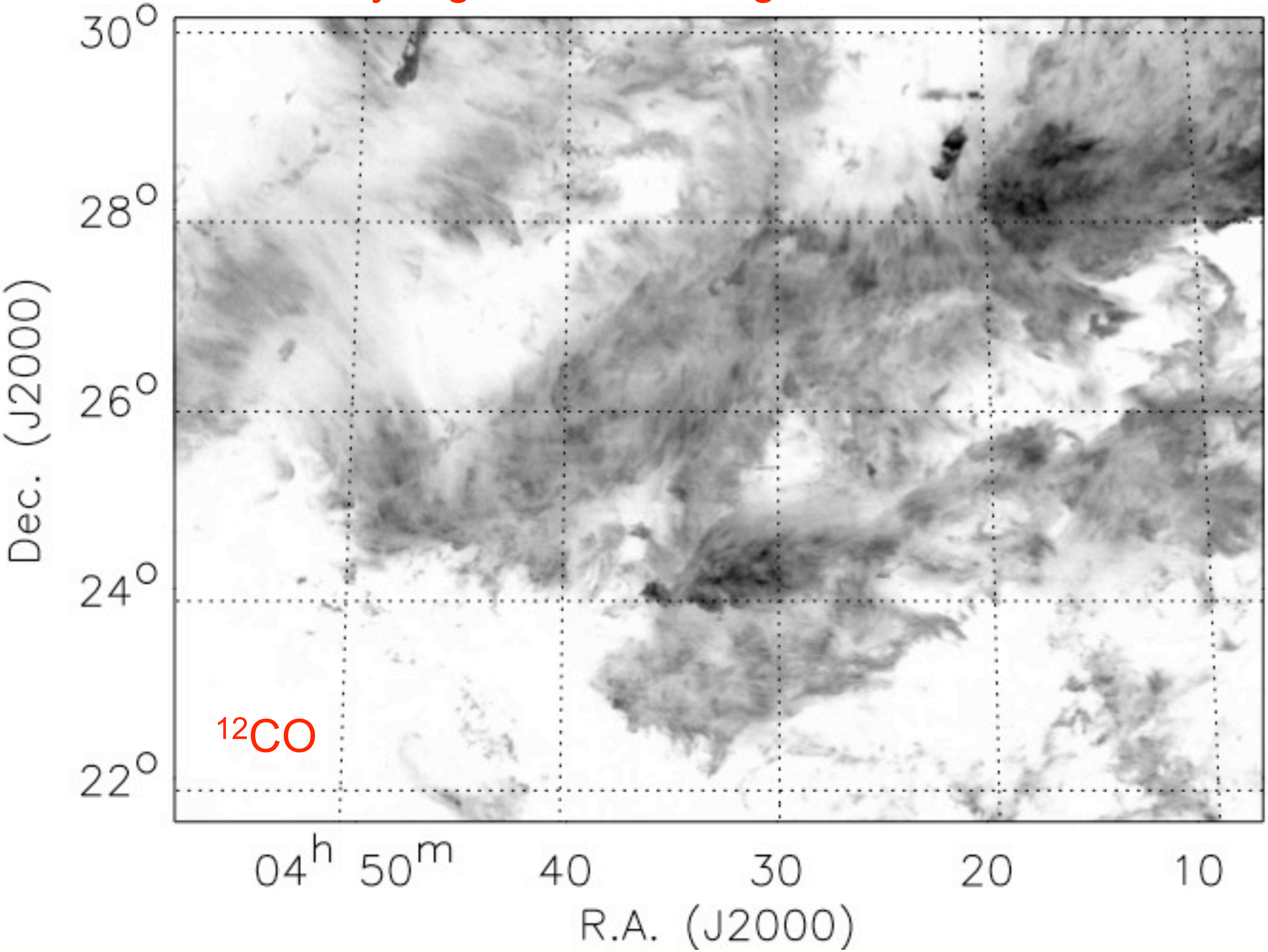
Orion Nebula region



Small Green Circles: IR-ex sources, Big Green/Blue Circles: Protostars



Taurus: low-density regions show magnetic "striations"



Low efficiency:

Low efficiency:

not due to ambipolar diffusion of magnetic fields

Low efficiency:

not due to ambipolar diffusion of magnetic fields

• feedback: energy input from massive stars limits cloud lifetimes

Low efficiency:

not due to ambipolar diffusion of magnetic fields

• feedback: energy input from massive stars limits cloud lifetimes

• structured clouds: high density regions small mass/volume filling factors due to

Low efficiency:

not due to ambipolar diffusion of magnetic fields

• feedback: energy input from massive stars limits cloud lifetimes

• structured clouds: high density regions small mass/volume filling factors due to

  • magnetic support of low-density regions (e.g., Price & Bate 2009)

Low efficiency:

not due to ambipolar diffusion of magnetic fields

• feedback: energy input from massive stars limits cloud lifetimes

• structured clouds: high density regions small mass/volume filling factors due to

  • magnetic support of low-density regions (e.g., Price & Bate 2009)
  • gravitational focusing

Structure of molecular clouds ⇒ most of the mass is at low density

Efficiency of star formation: low, because of feedback and

Structure of molecular clouds ⇒ most of the mass is at low density

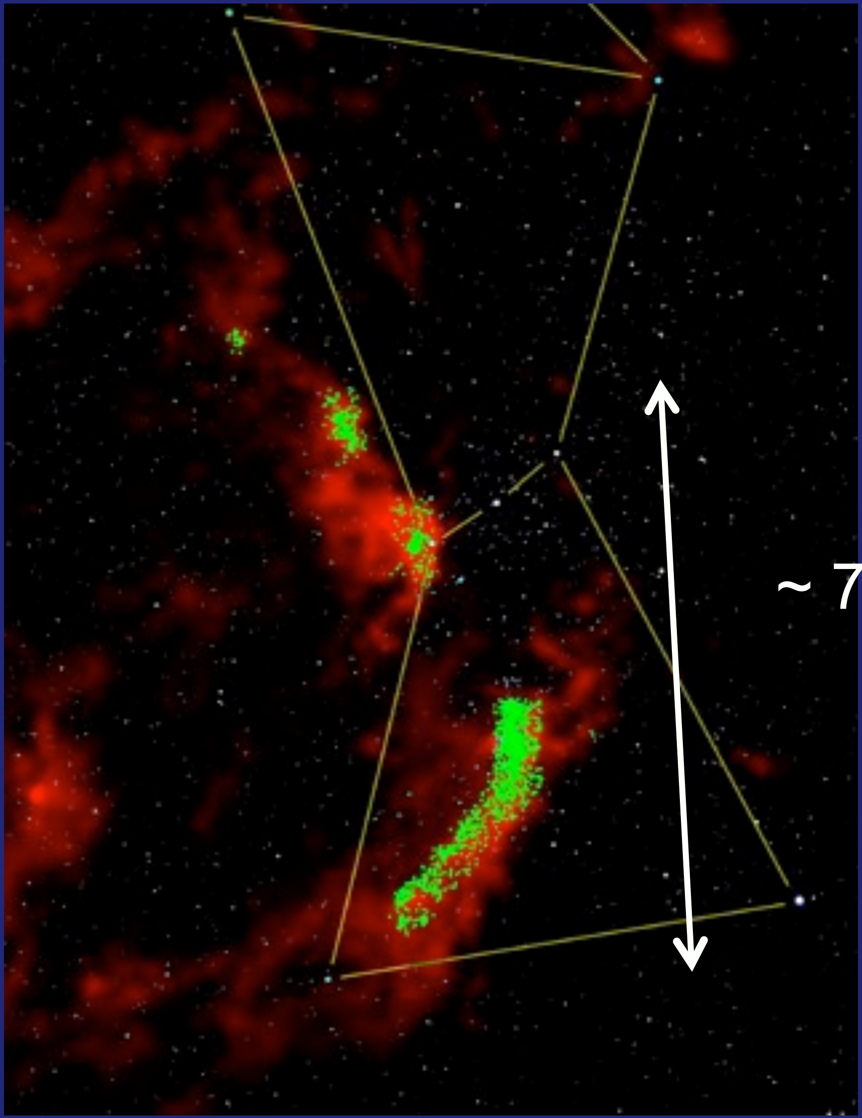
Efficiency of star formation: low, because of feedback and

Structure of molecular clouds ⇒ most of the mass is at low density

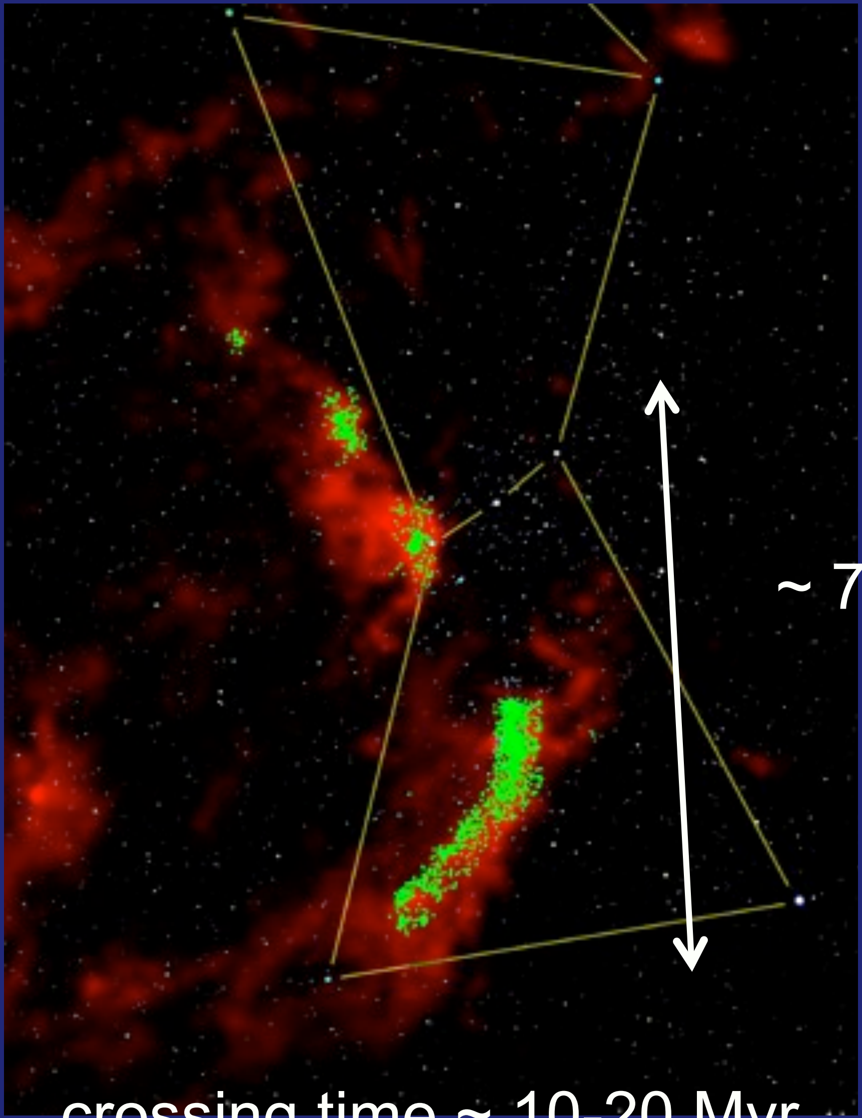
Efficiency of star formation: low, because of feedback and

Gravitational focusing- a natural byproduct of the formation mechanisms for molecular clouds

Young stars in Orion: most have ages ~ 1-2 Myr

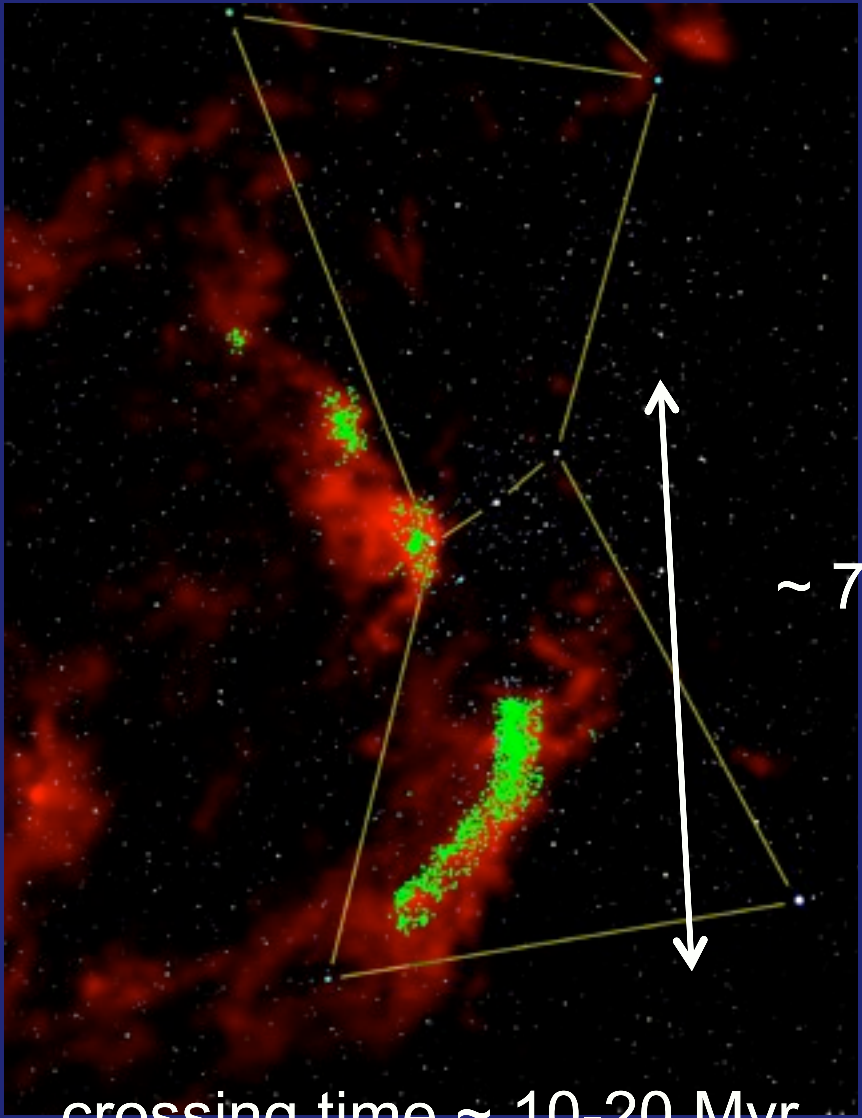


Young stars in Orion: most have ages ~ 1-2 Myr



crossing time ~ 10-20 Myr

Young stars in Orion: most have ages ~ 1-2 Myr



~ 70 pc

crossing time ~ 10-20 Myr

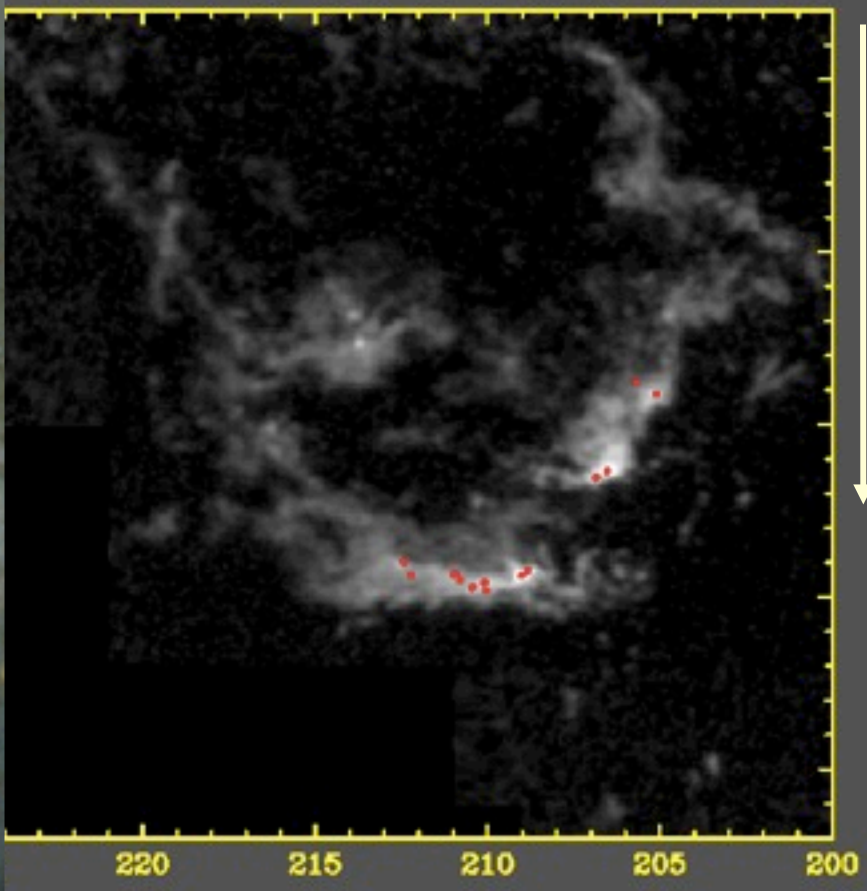
⇒ information not propagated laterally; swept up!

Star -forming clouds produced by shocked flows

Star -forming clouds produced by shocked flows

Star -forming clouds produced by shocked flows

Orion: supernova bubble?

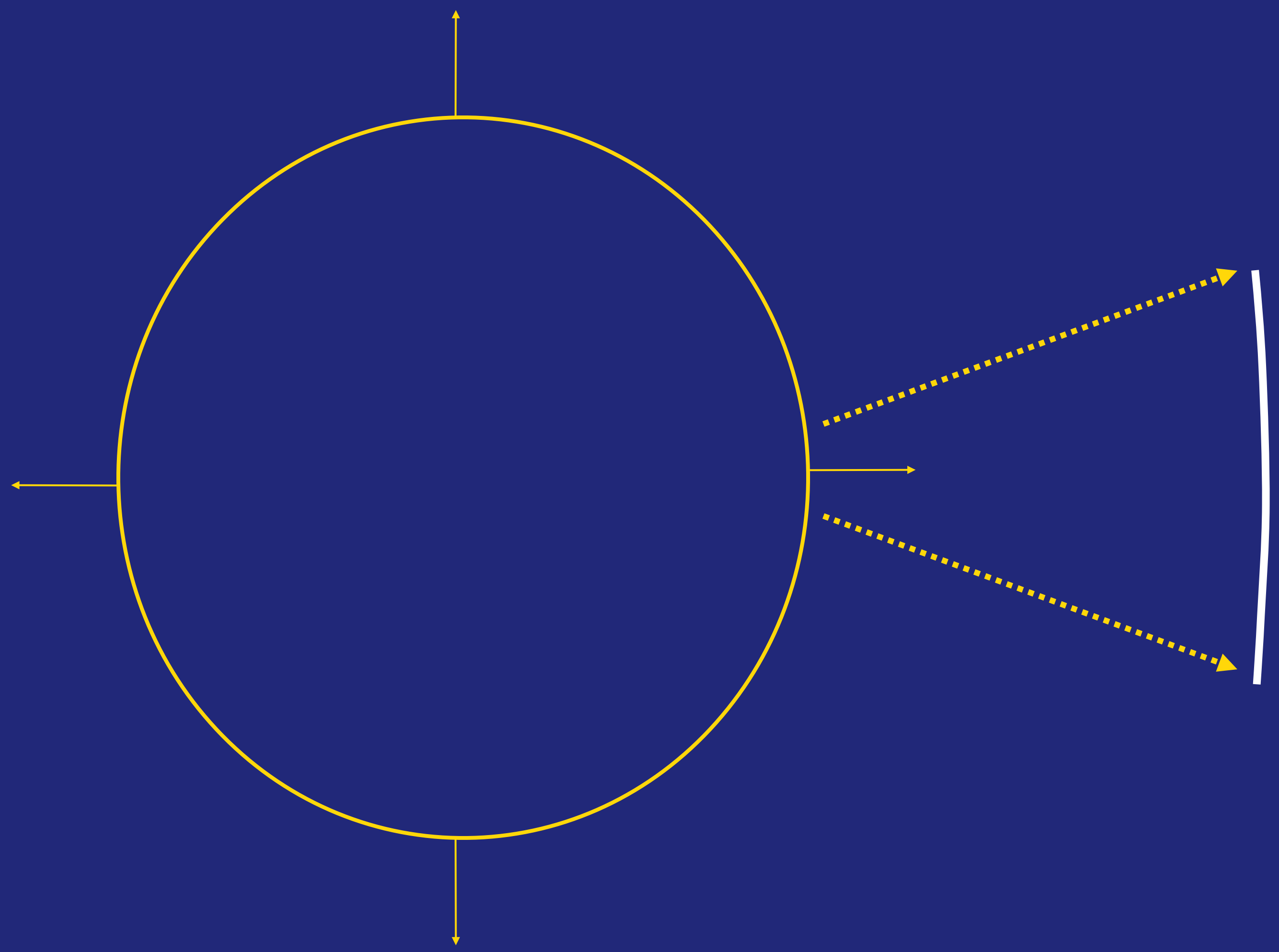


140 pc below galactic plane

^{12}CO

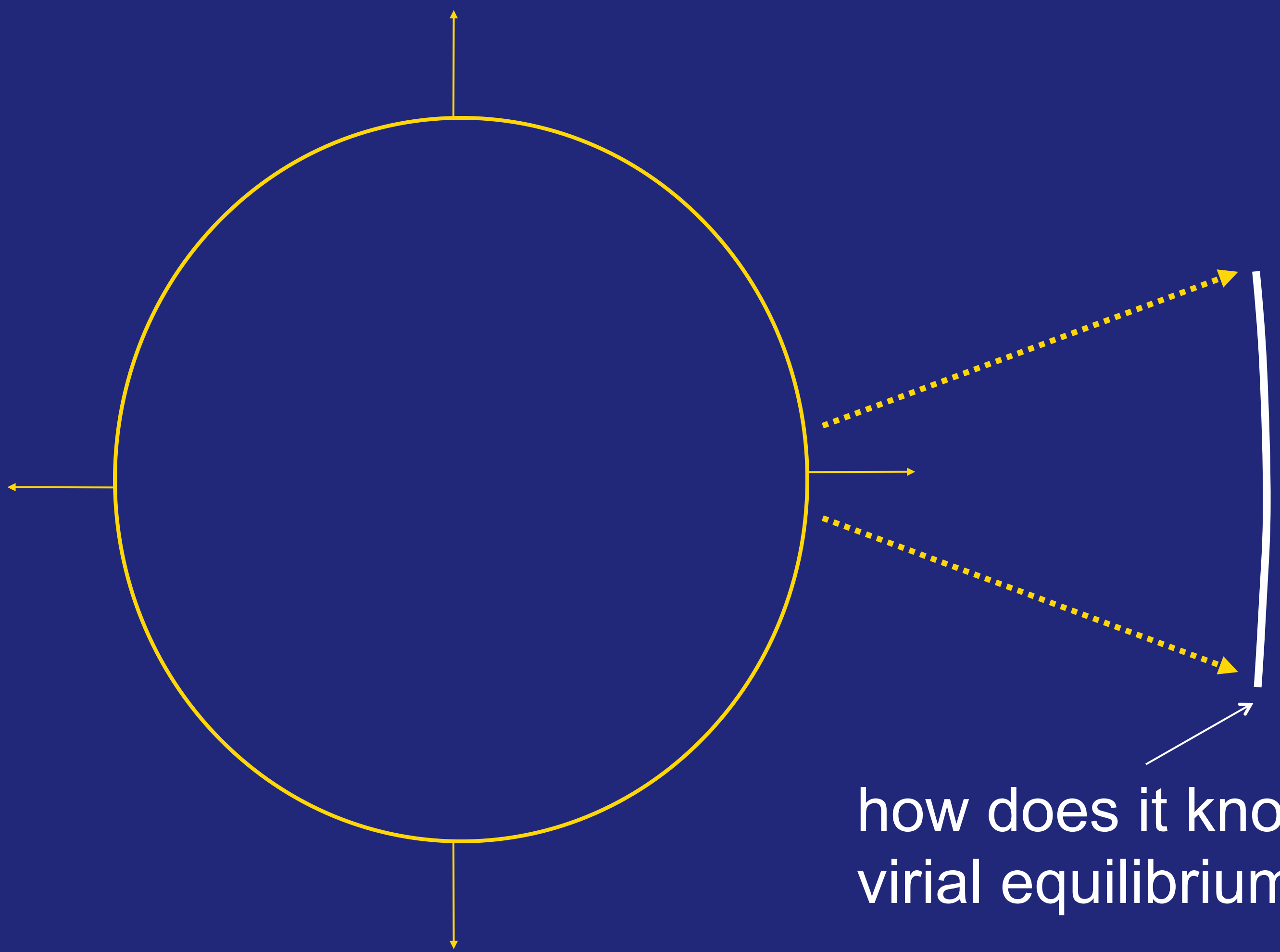
Finite sheet evolution with gravity

Burkert & Hartmann 04; piece of bubble wall ≈ sheet



Finite sheet evolution with gravity

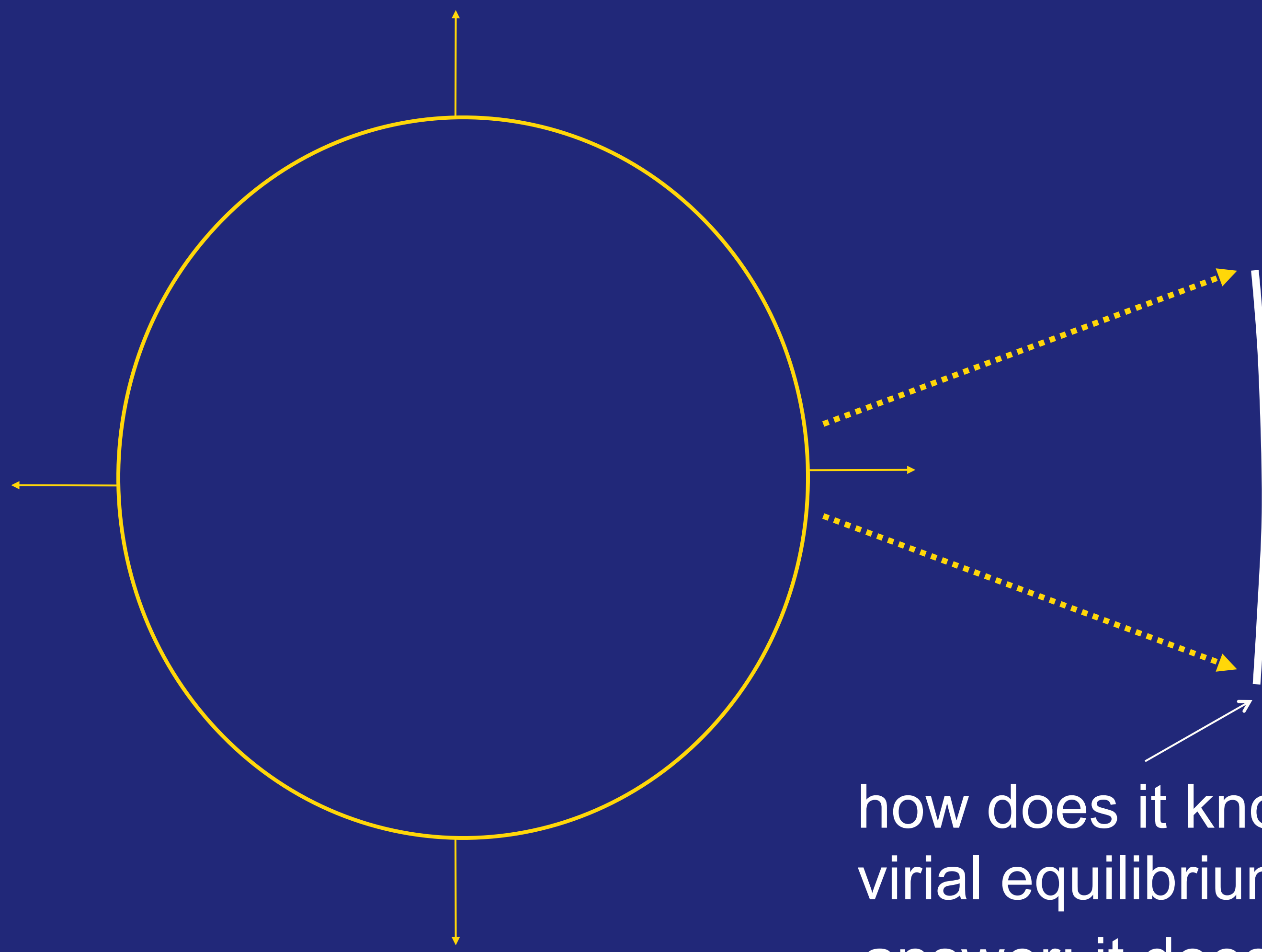
Burkert & Hartmann 04; piece of bubble wall ≈ sheet



how does it know to be in virial equilibrium?

Finite sheet evolution with gravity

Burkert & Hartmann 04; piece of bubble wall ≈ sheet

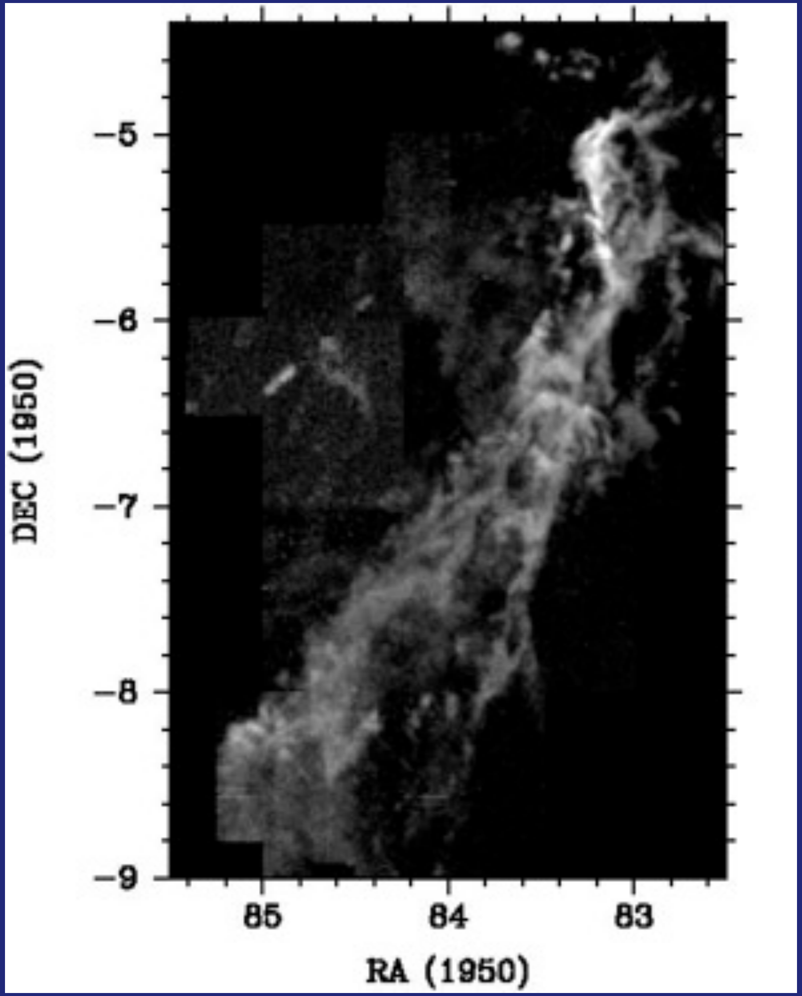


how does it know to be in virial equilibrium?

answer: it doesn't

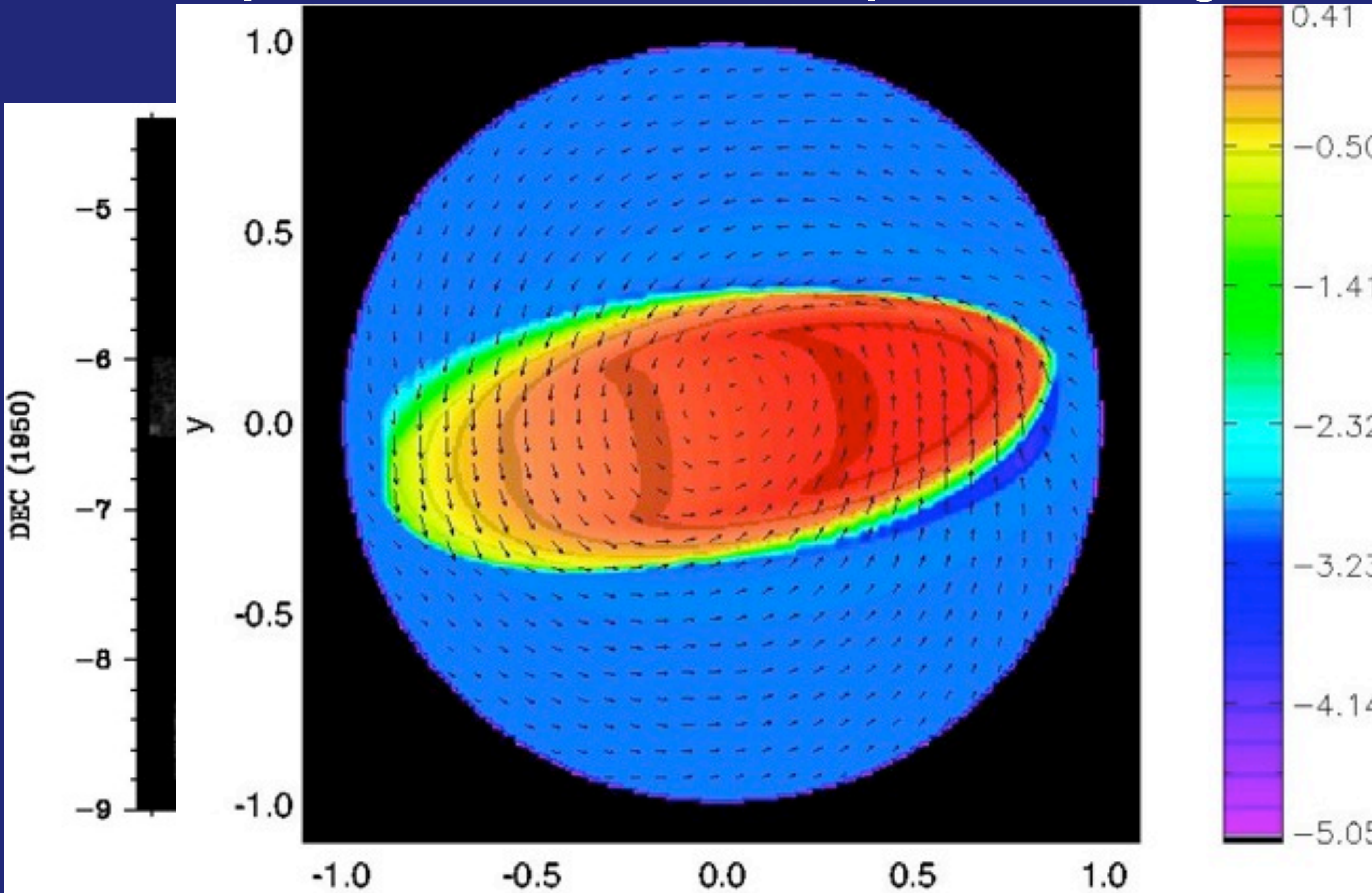
“Orion A” model (Hartmann & Burkert 2007);

collapse of finite, massive, elliptical, rotating sheet



^{13}CO, Bally et al.

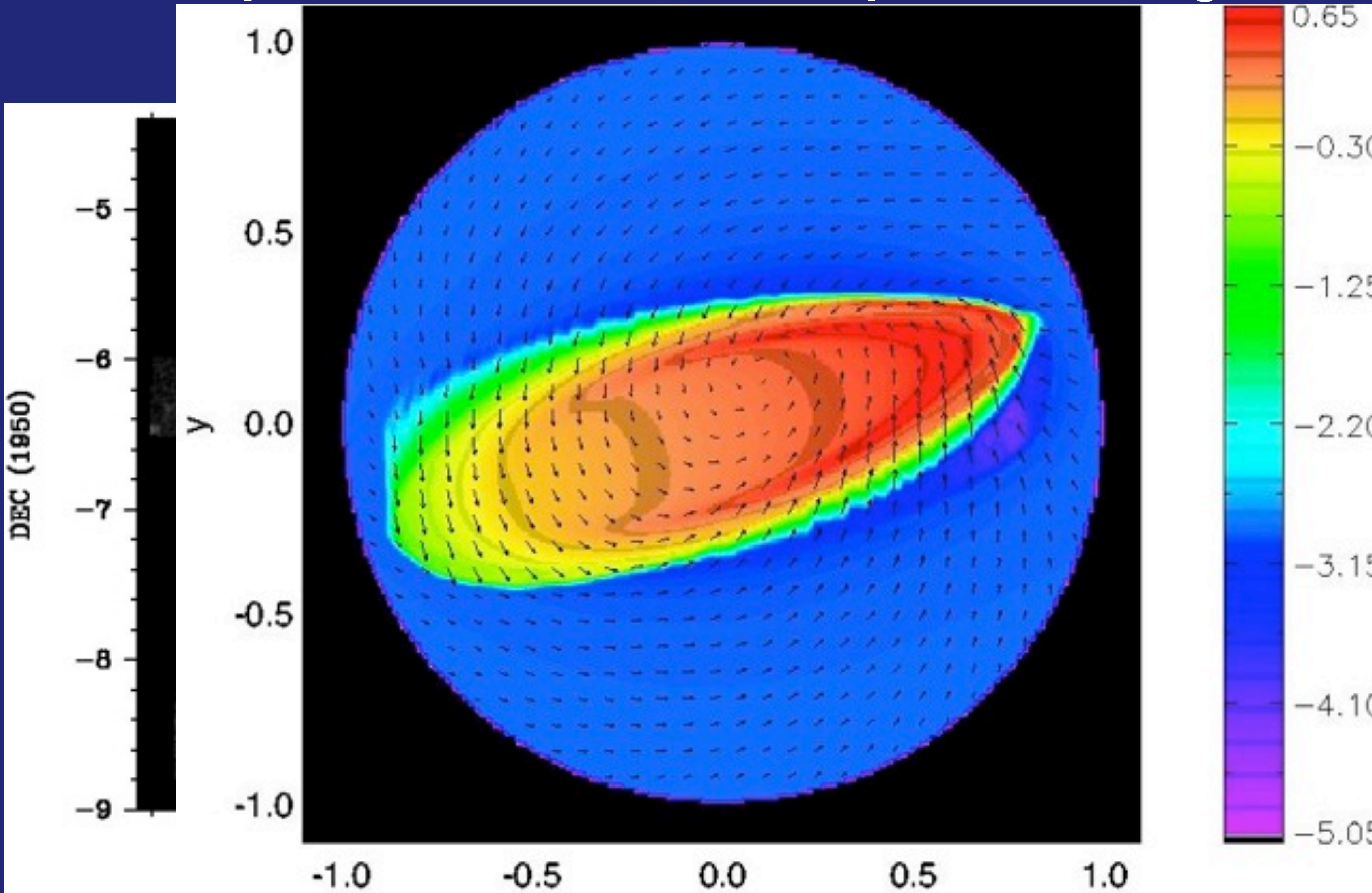
“Orion A” model (Hartmann & Burkert 2007); collapse of finite, massive, elliptical, rotating sheet



^{13}CO, Bally et al.

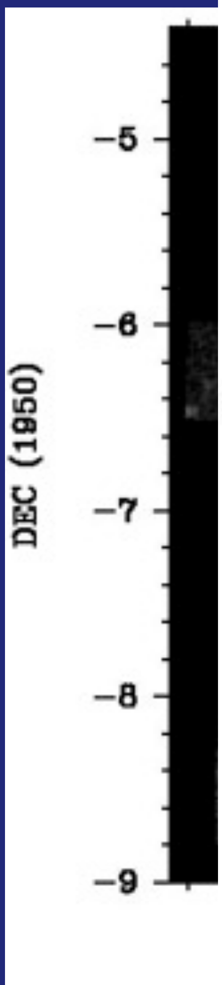
“Orion A” model (Hartmann & Burkert 2007);

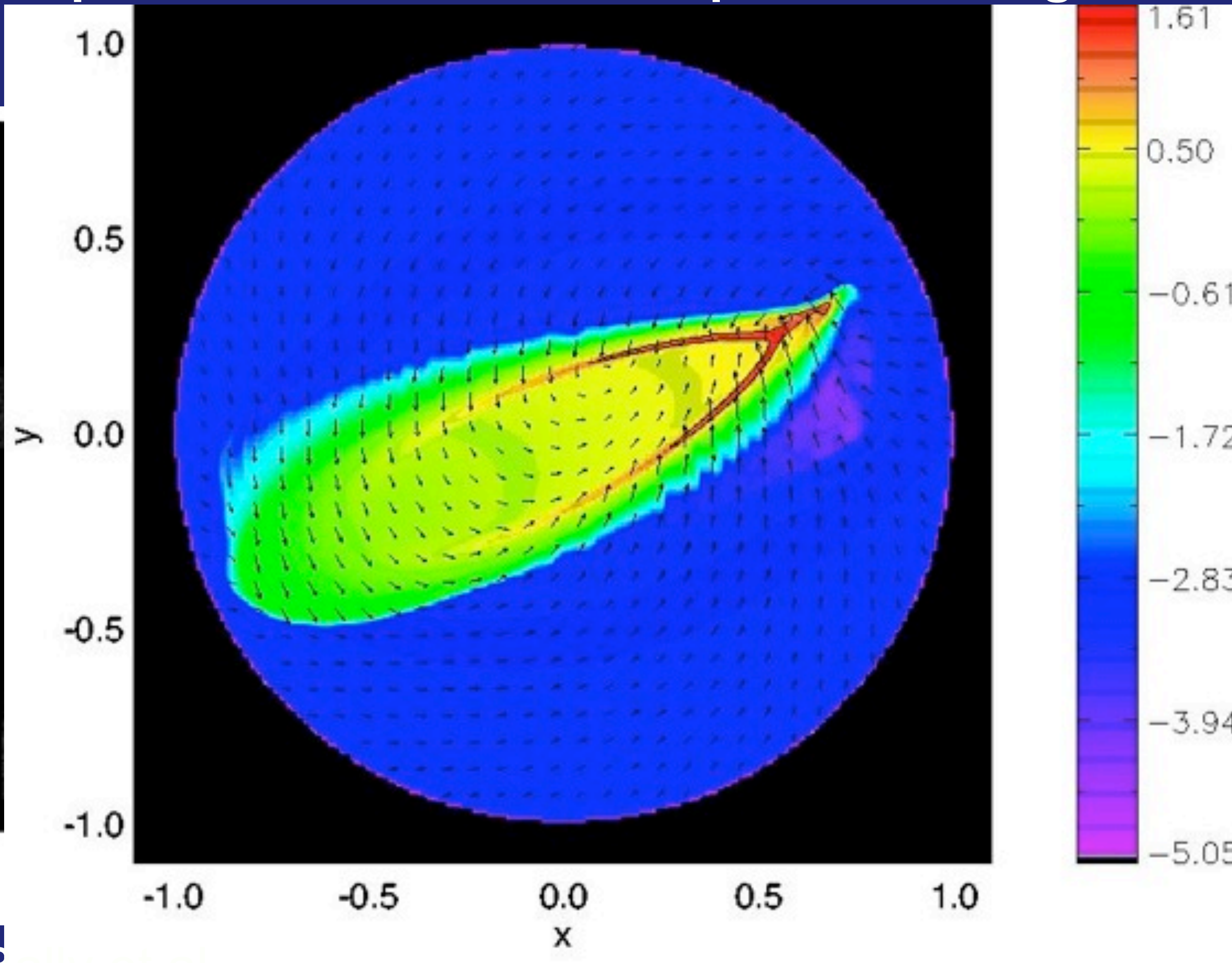
collapse of finite, massive, elliptical, rotating sheet



^{13}CO, Bally et al.

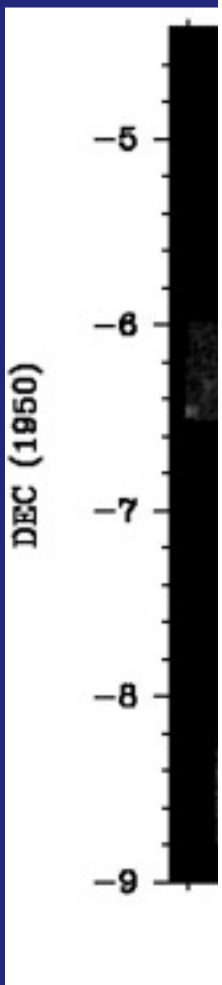
"Orion A" model (Hartmann & Burkert 2007); collapse of finite, massive, elliptical, rotating sheet

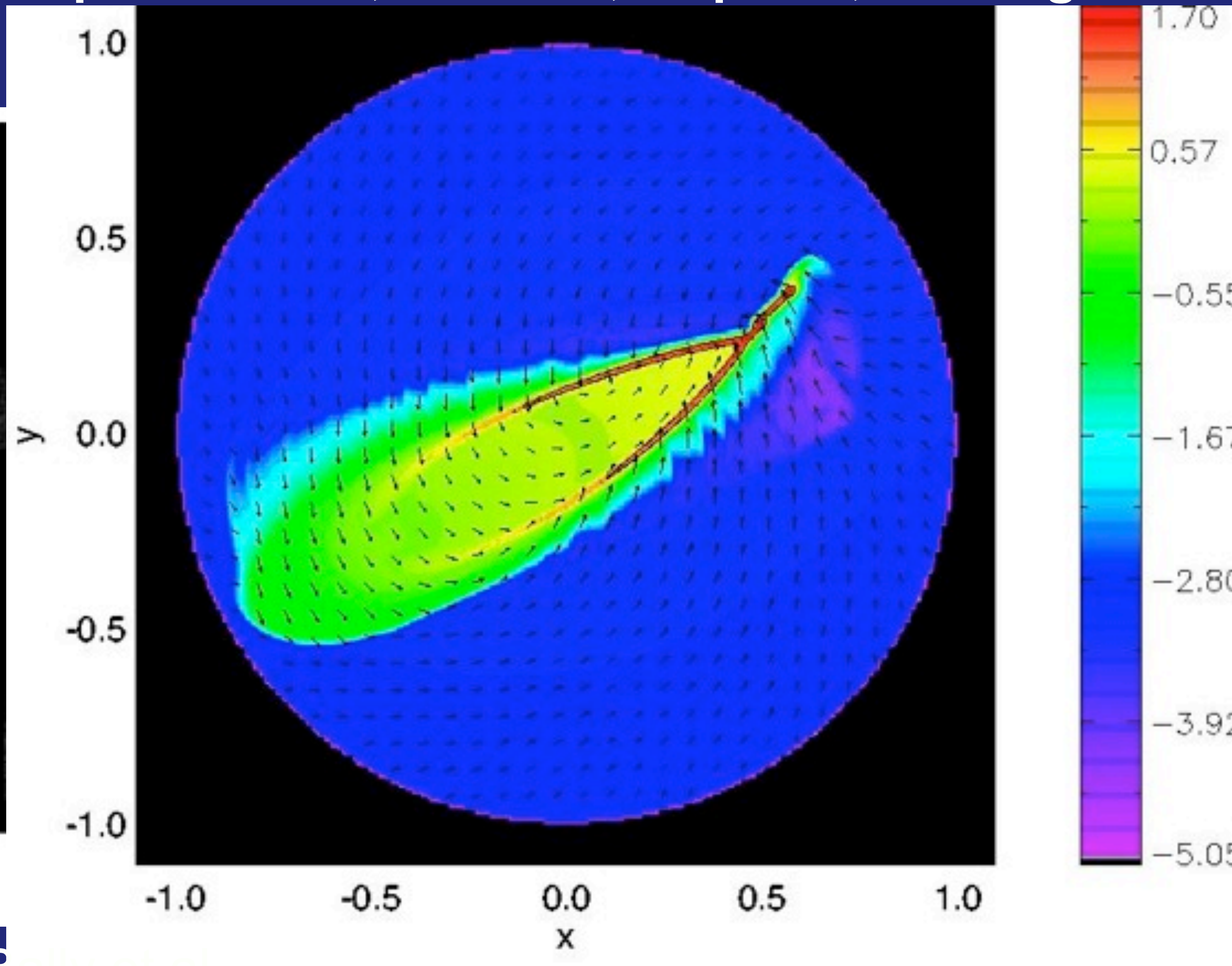




^{13}CO, Bally et al.

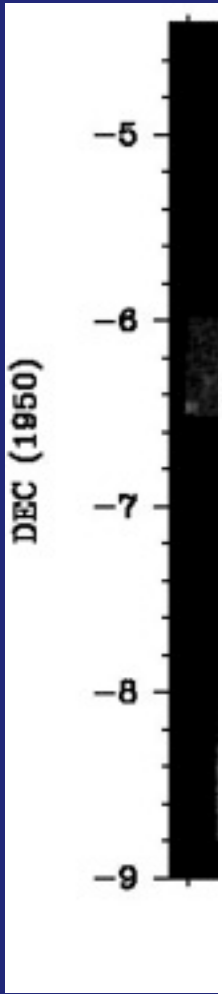
“Orion A” model (Hartmann & Burkert 2007); collapse of finite, massive, elliptical, rotating sheet

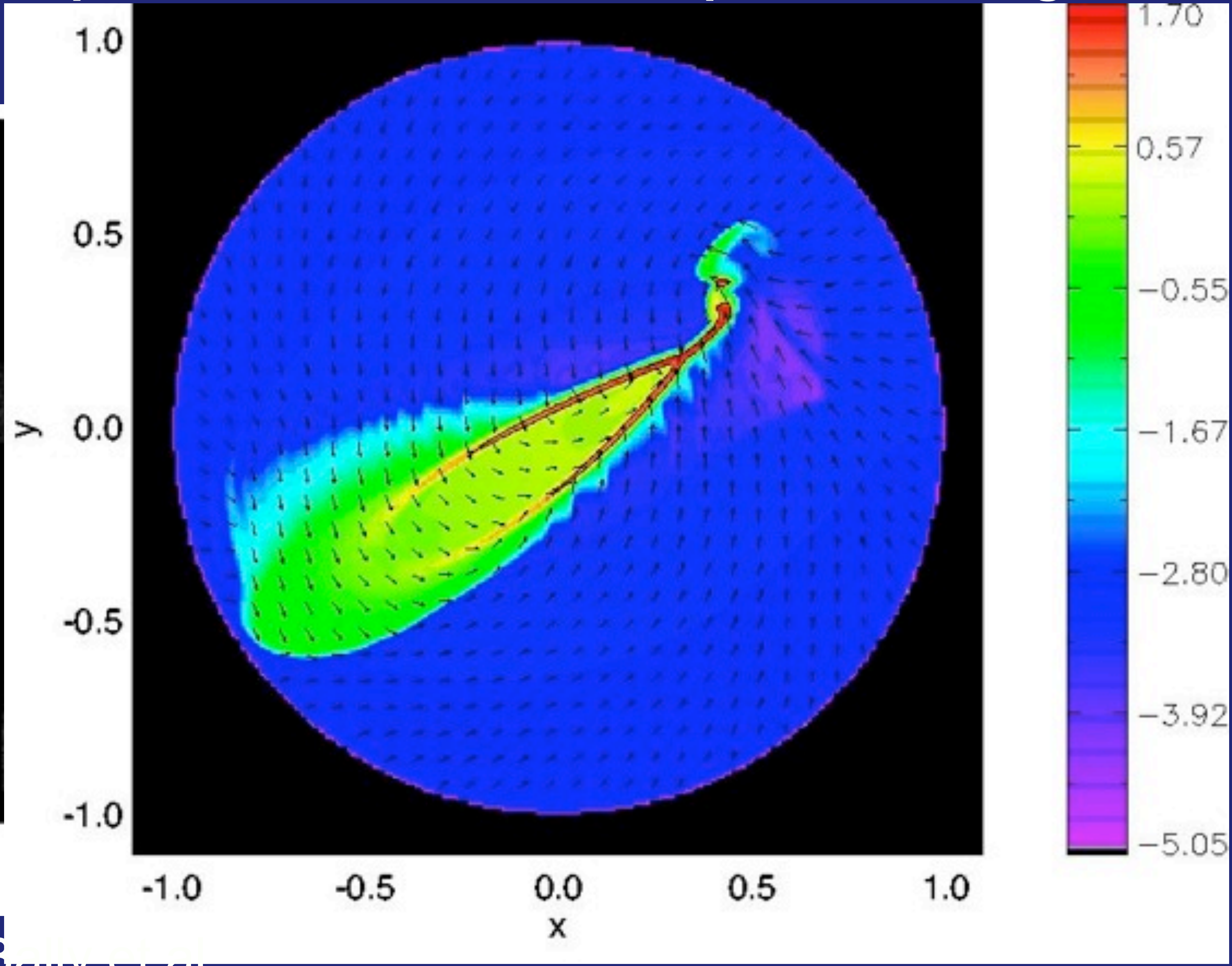




^{13}CO, Bally et al.

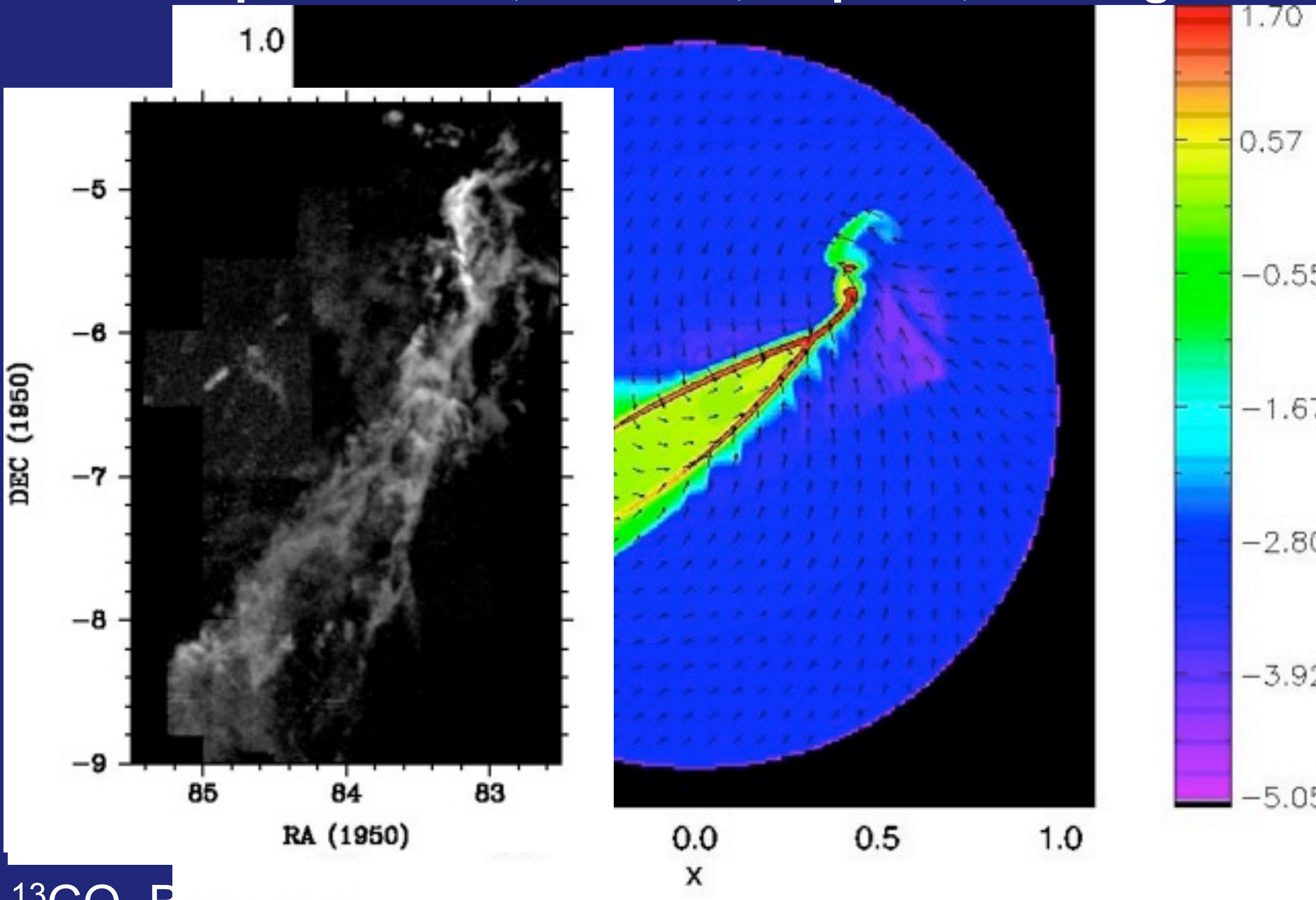
“Orion A” model (Hartmann & Burkert 2007); collapse of finite, massive, elliptical, rotating sheet





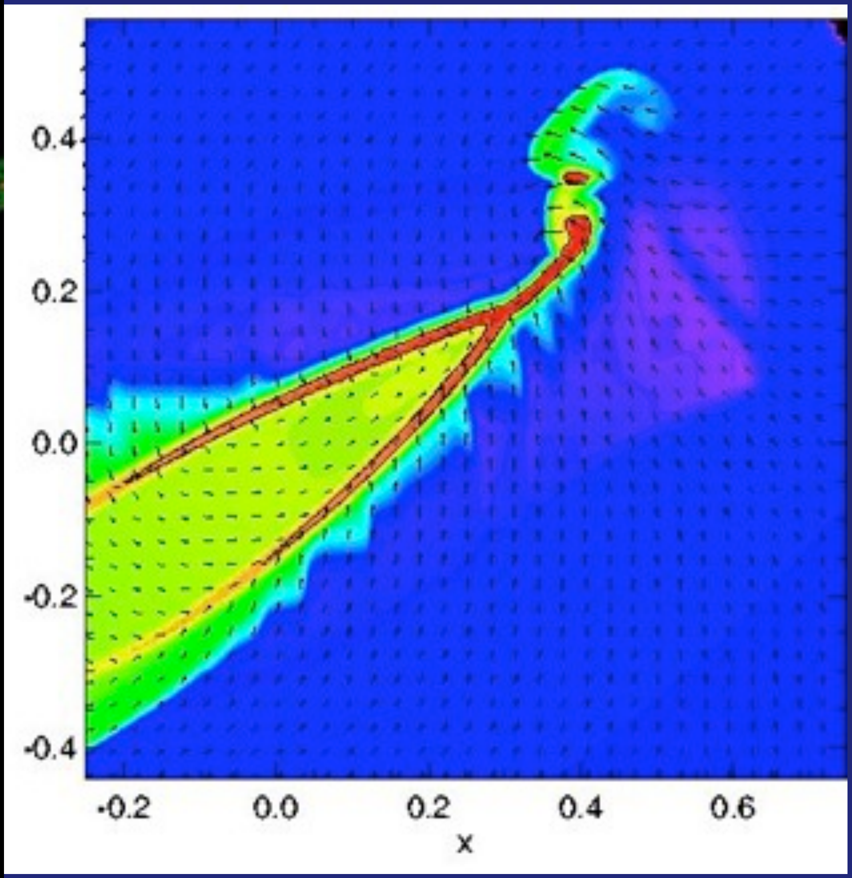
^{13}CO, Bally et al.

"Orion A" model (Hartmann & Burkert 2007); collapse of finite, massive, elliptical, rotating sheet

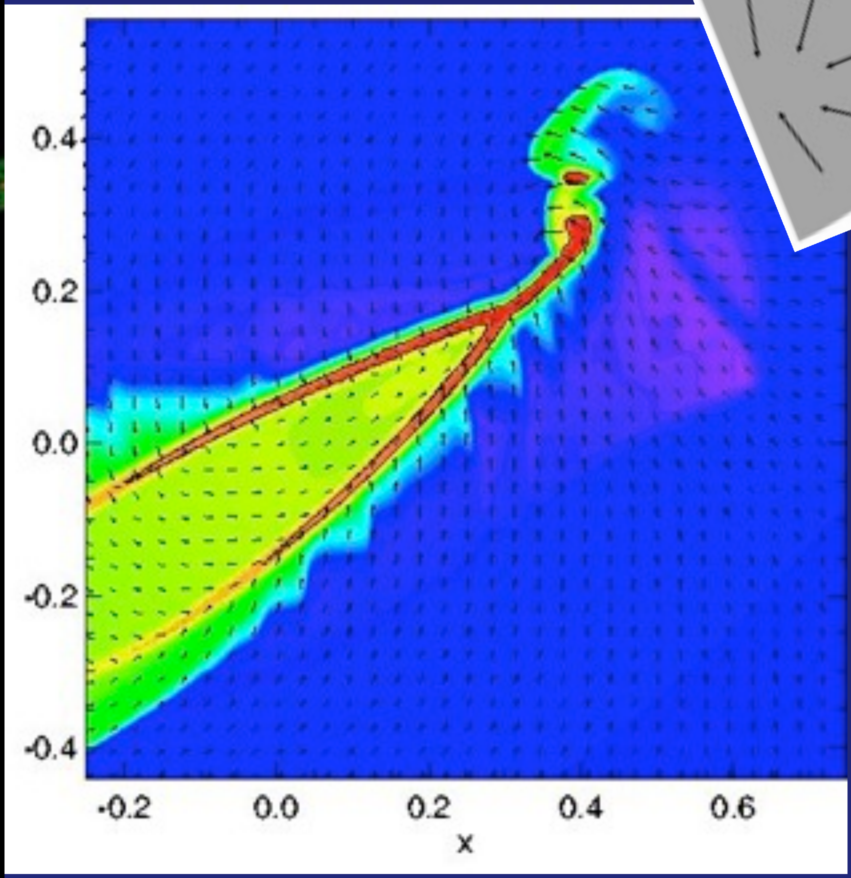


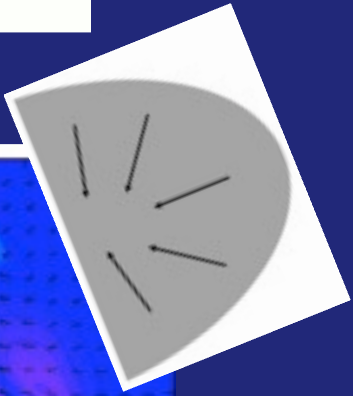
^{13}CO, Bally et al.

Global collapse (over ~ 2 Myr) - makes filamentary ridge, Orion Nebula cluster

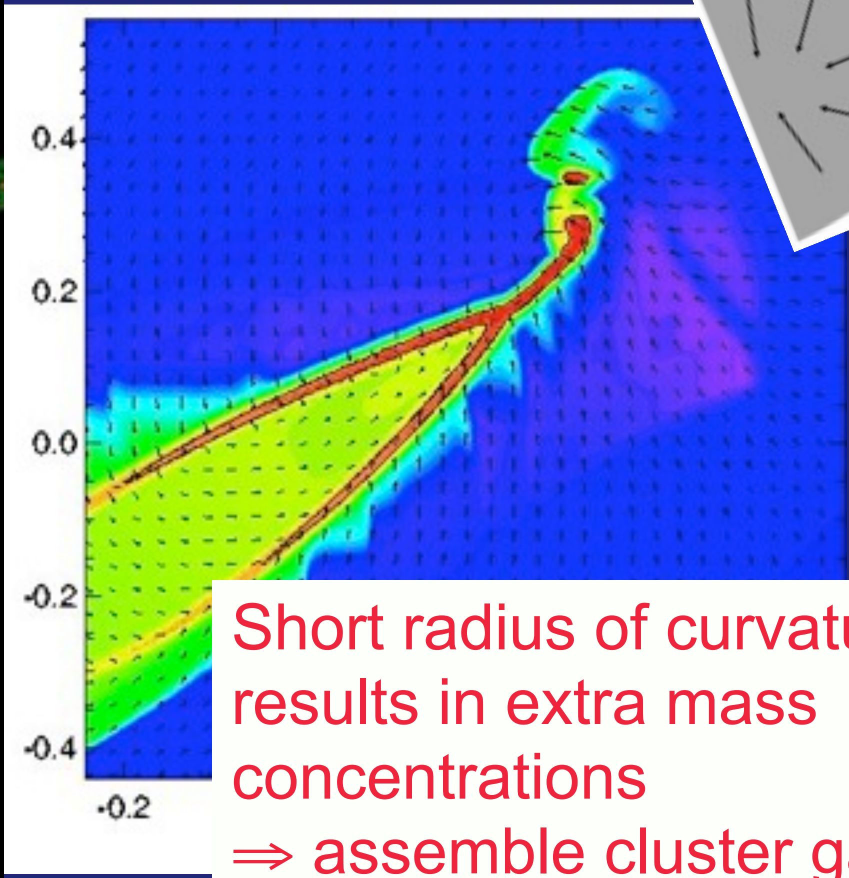


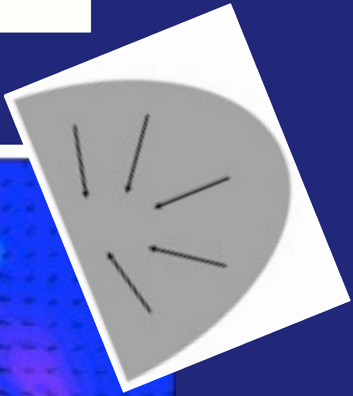
Global collapse (over ~ 2 Myr) - makes filamentary ridge, Orion Nebula cluster





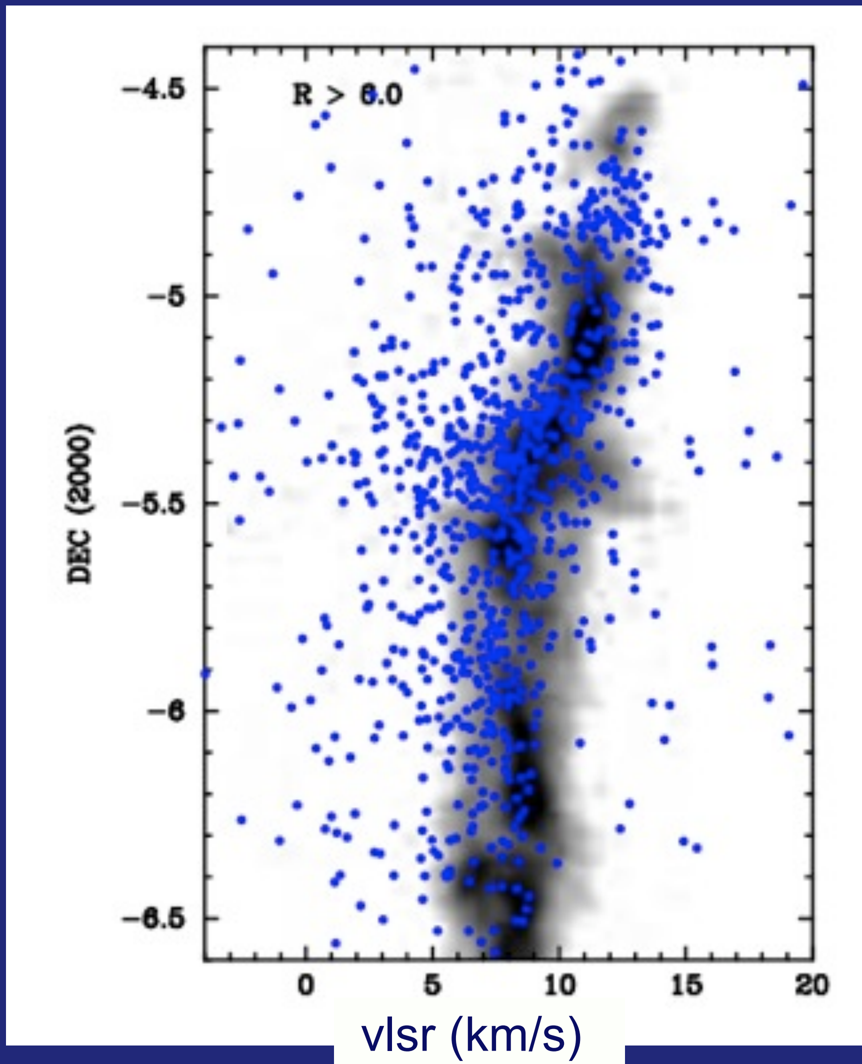
Global collapse (over ~ 2 Myr) - makes filamentary ridge, Orion Nebula cluster



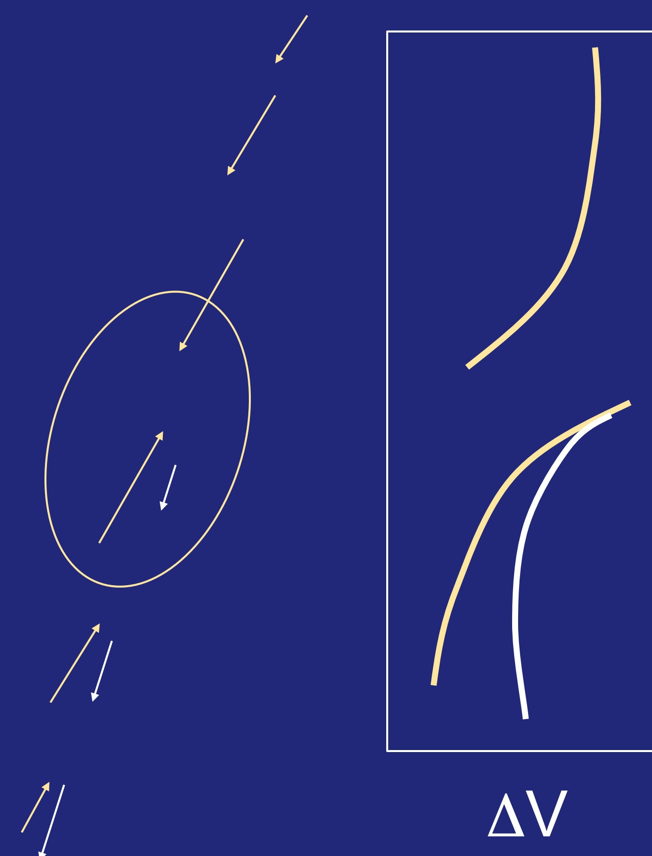


Short radius of curvature results in extra mass concentrations
⇒ assemble cluster gas/ stars

Orion Nebula cluster- (optical) kinematics of stars and gas: evidence for infall?

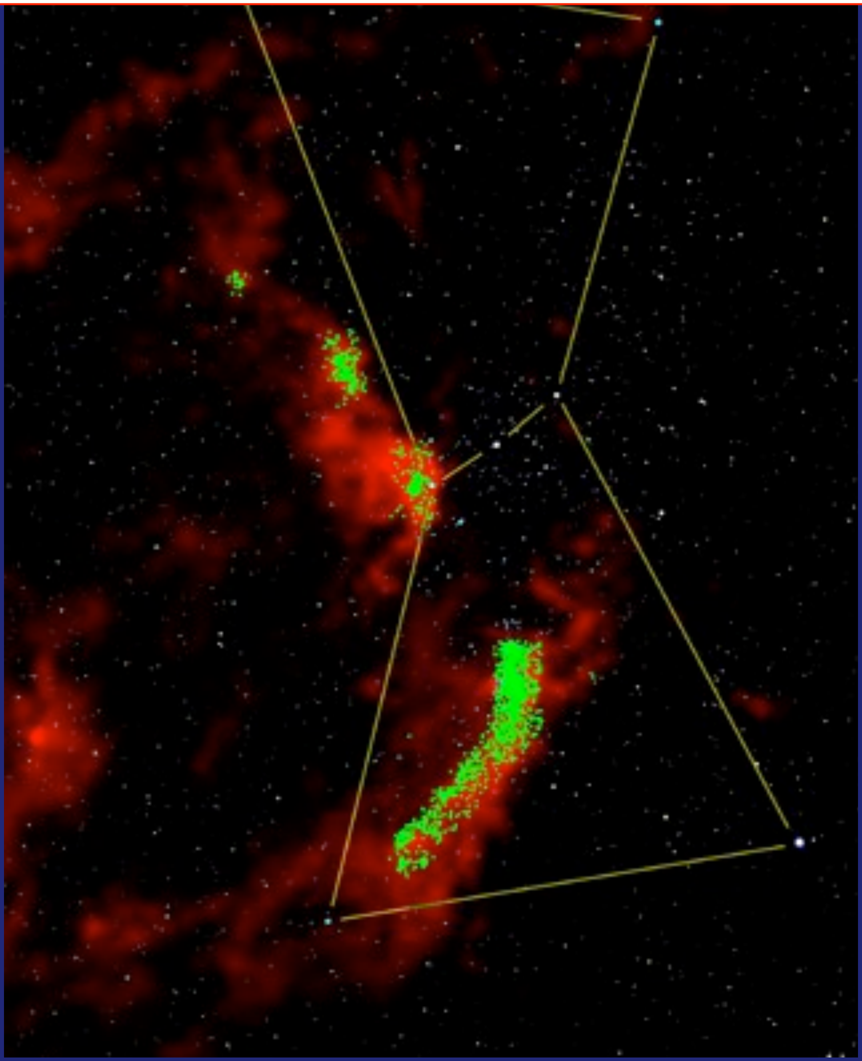


J. Tobin, et al. 2009

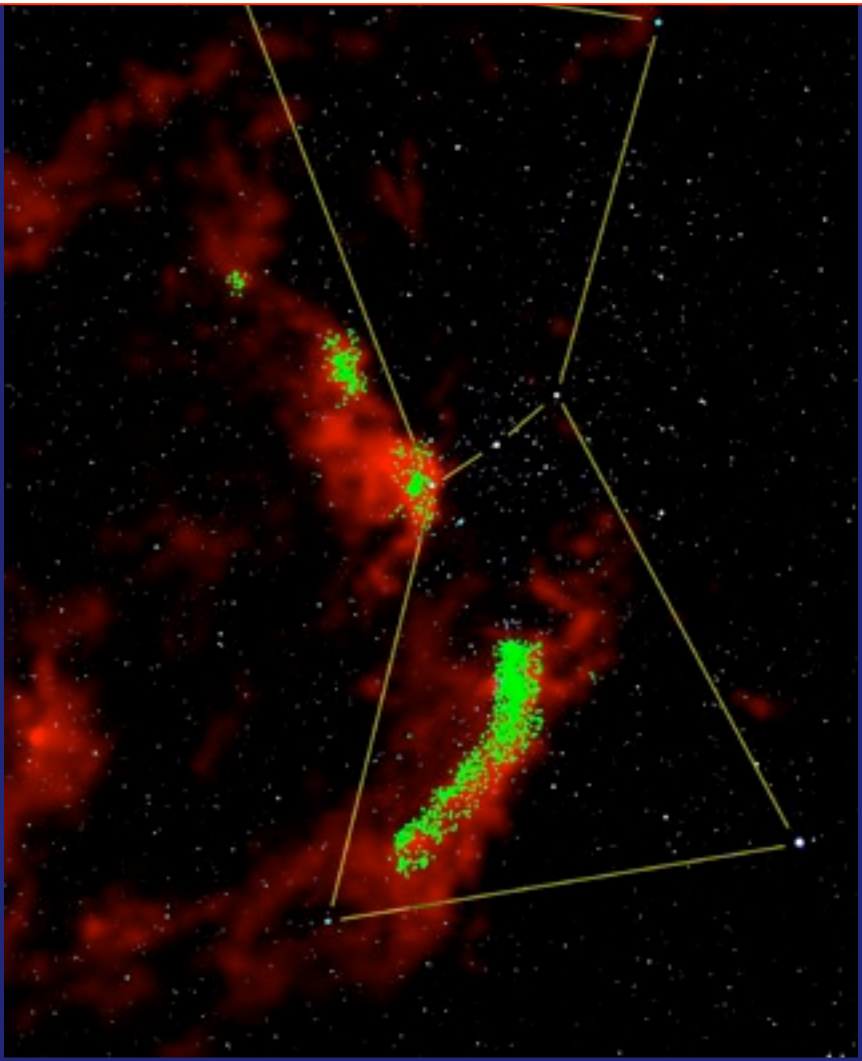


E. Proszkow, F. Adams

gravitational focusing: clusters form preferentially at ends of filaments

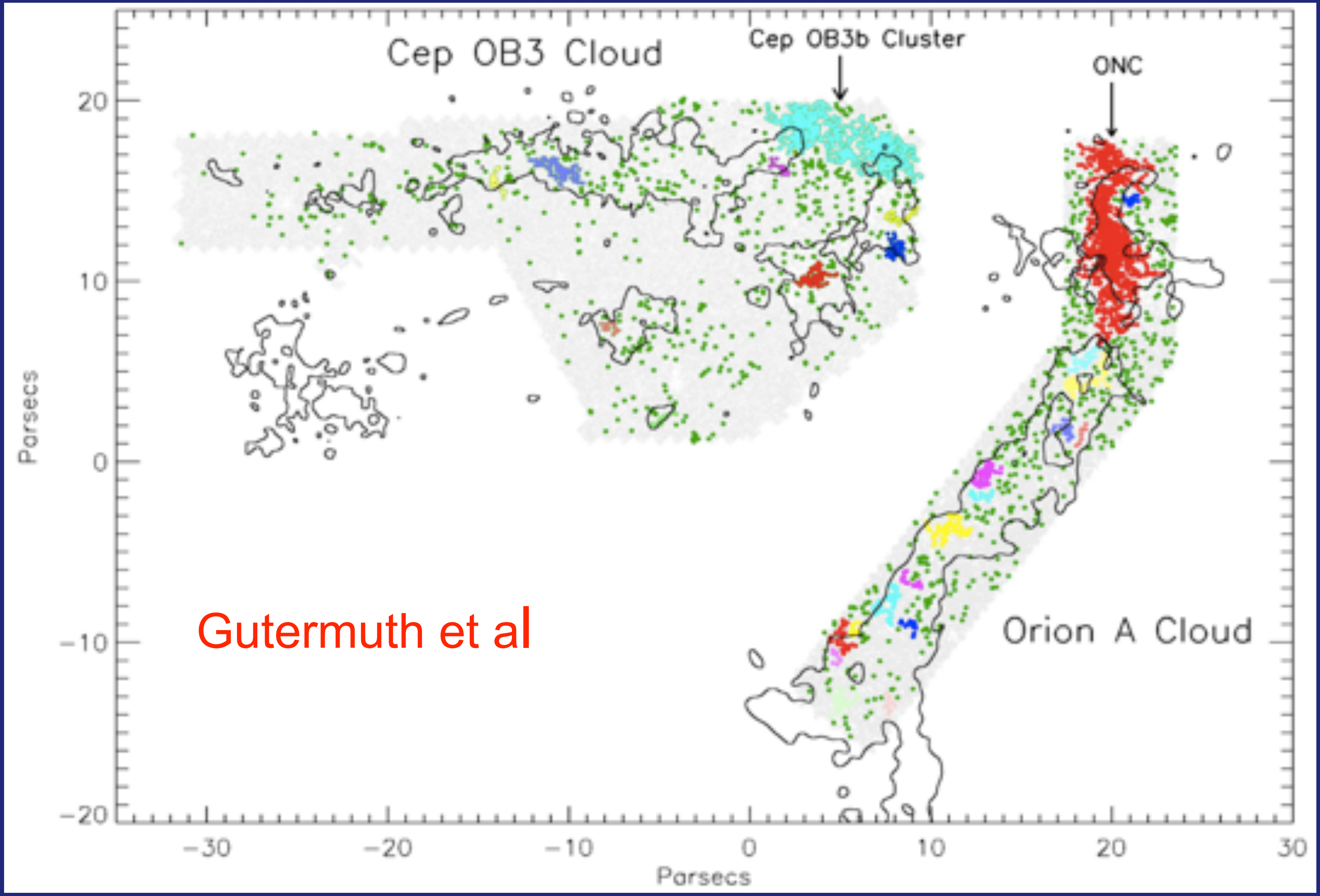


gravitational focusing: clusters form preferentially at ends of filaments



can't escape large-scale focusing by gravity

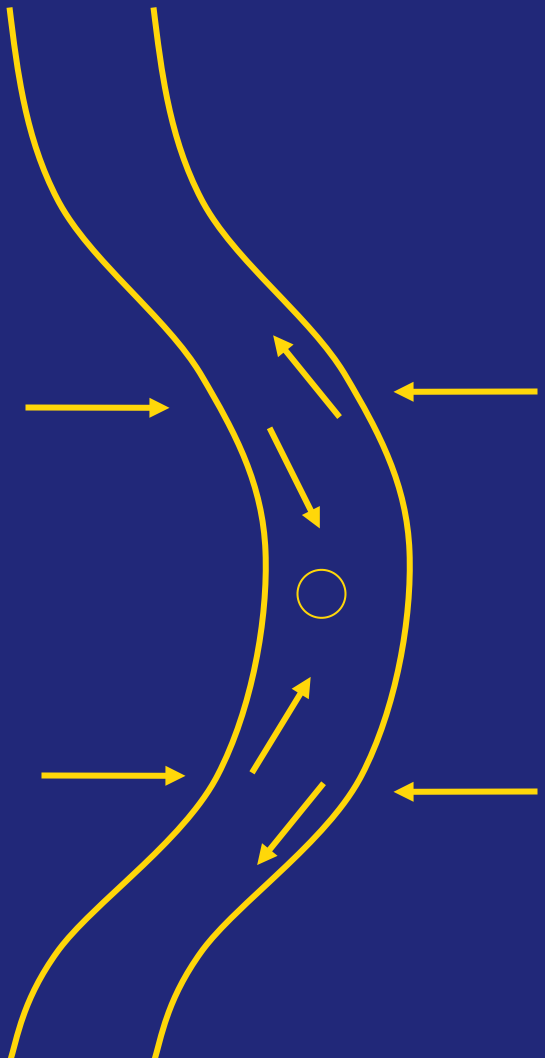
Cluster gravitational focusing- any short radius of curvature will do



NEED turbulence to generate density fluctuations during cloud formation- must be rapid to compete with global collapse

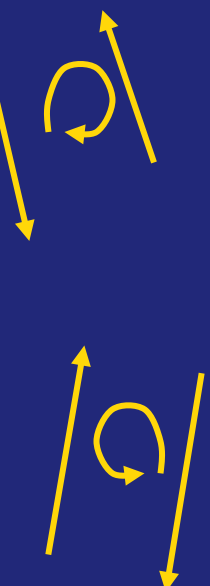
NEED turbulence to generate density fluctuations during cloud formation- must be rapid to compete with global collapse

Thin shell



Kelvin-

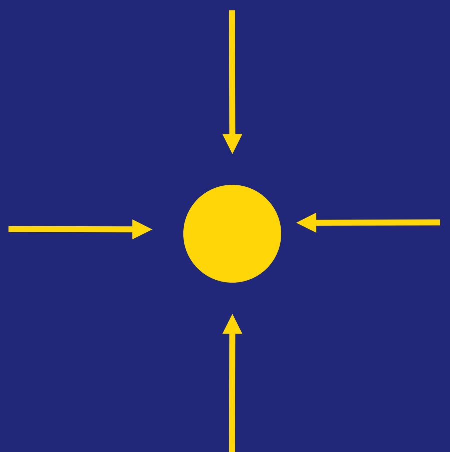
Helmholtz



cooling

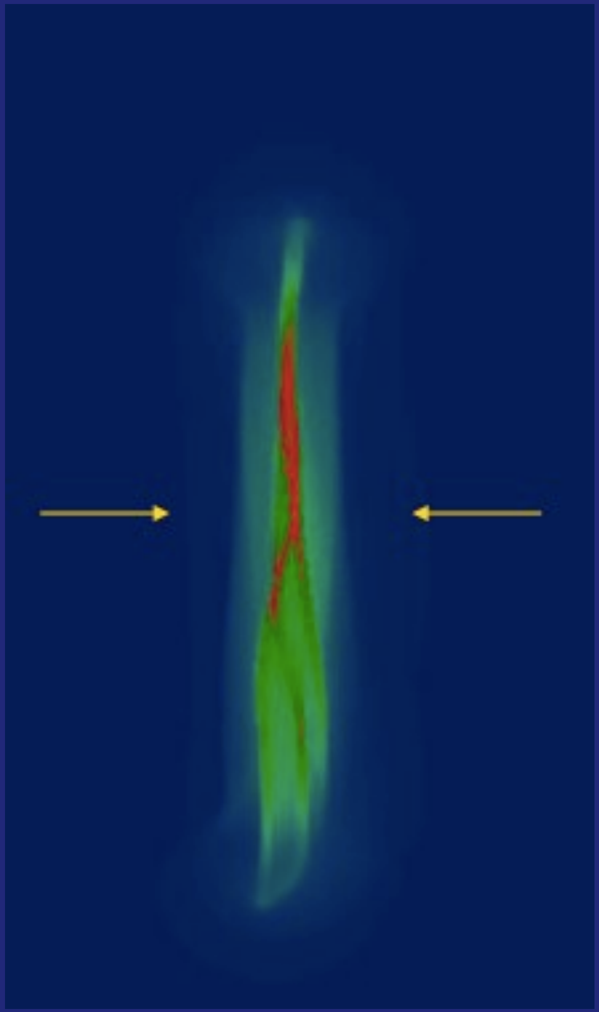
(thermal

instability)

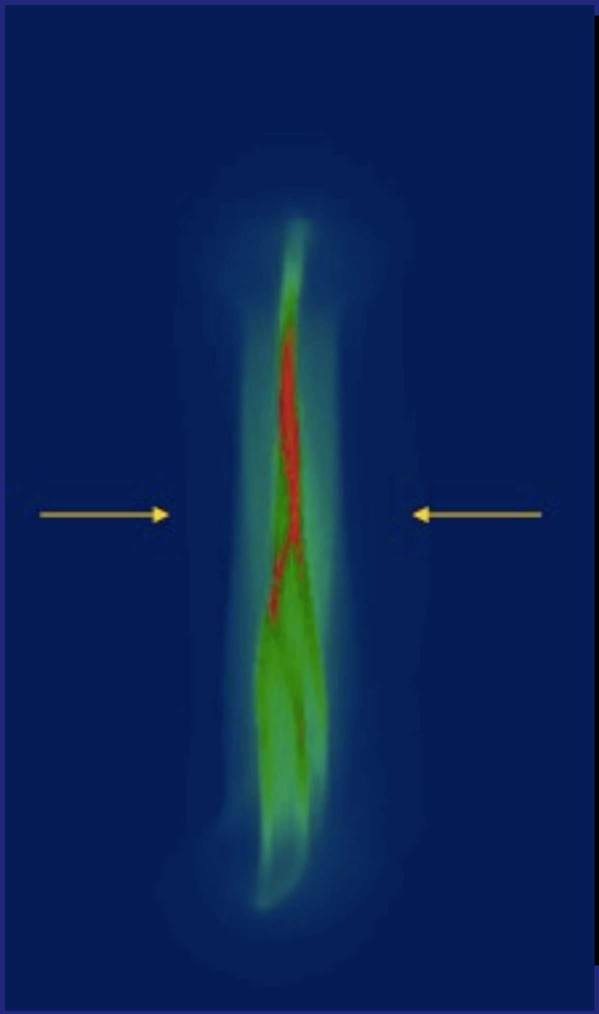


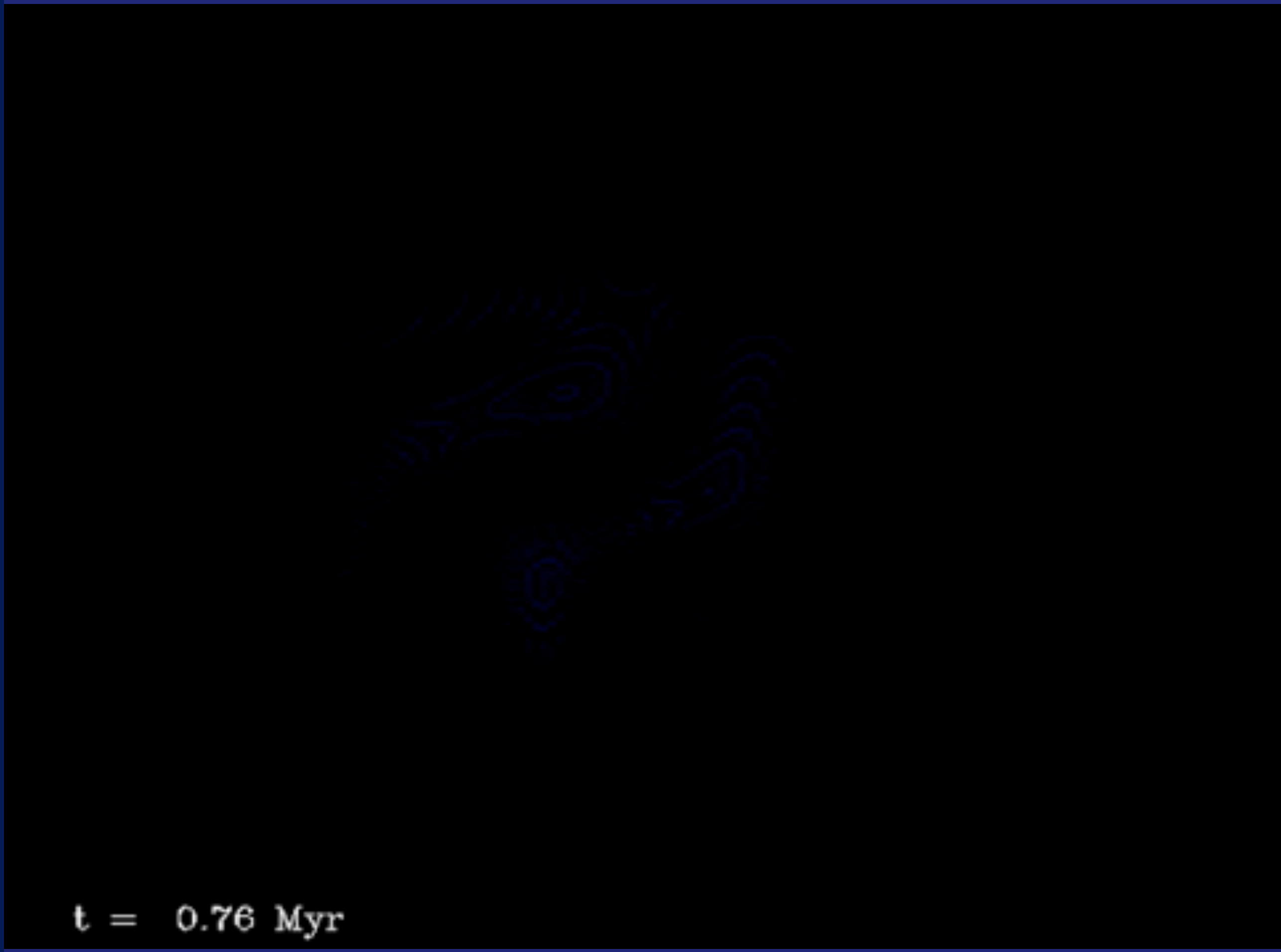
and gravity...

F. Heitsch et al. 2007; sheet made by inflows with cooling, gravity

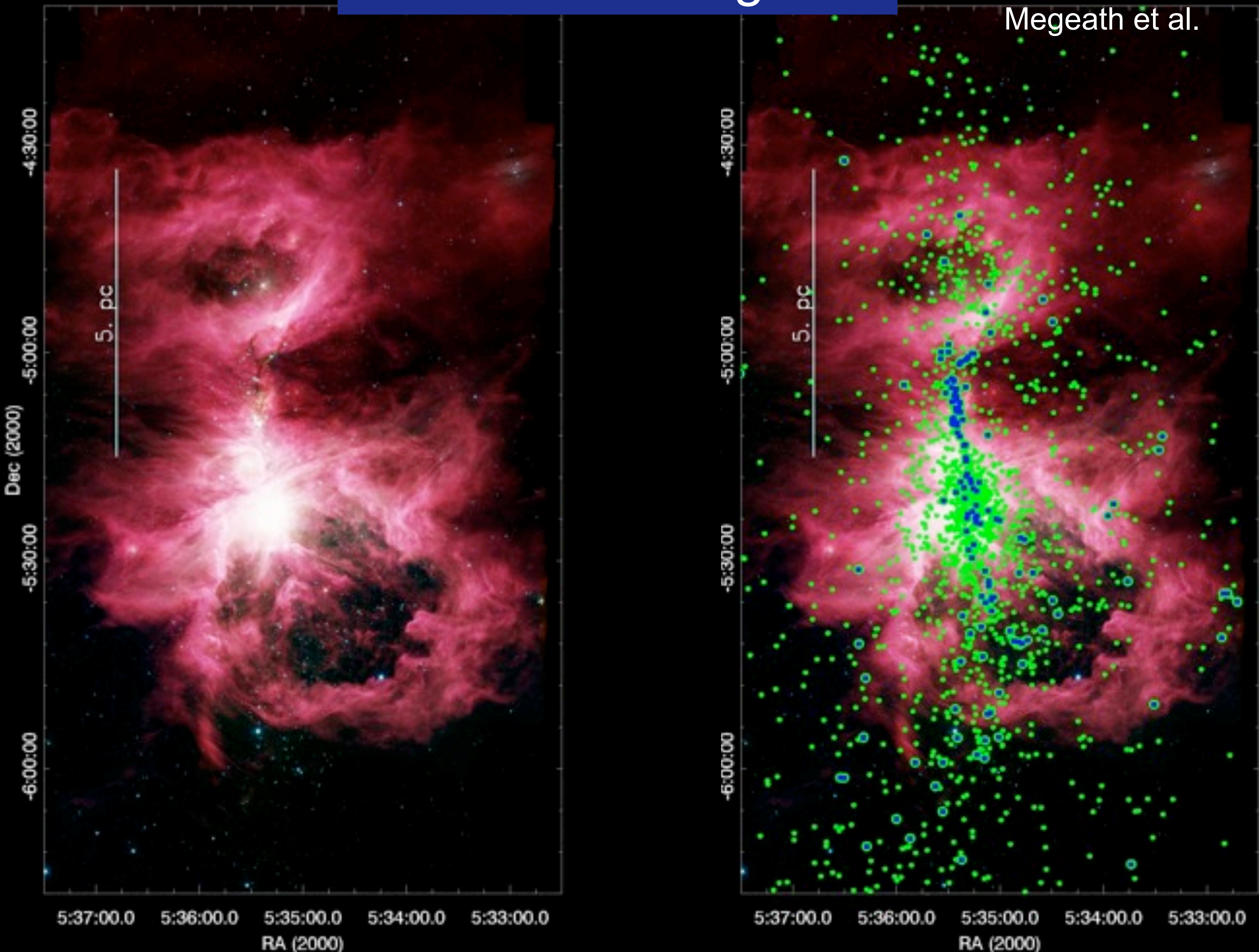


F. Heitsch et al. 2007; sheet made by inflows with cooling, gravity





Orion Nebula region



Structure of molecular clouds $\Rightarrow$ most of the mass is at low density

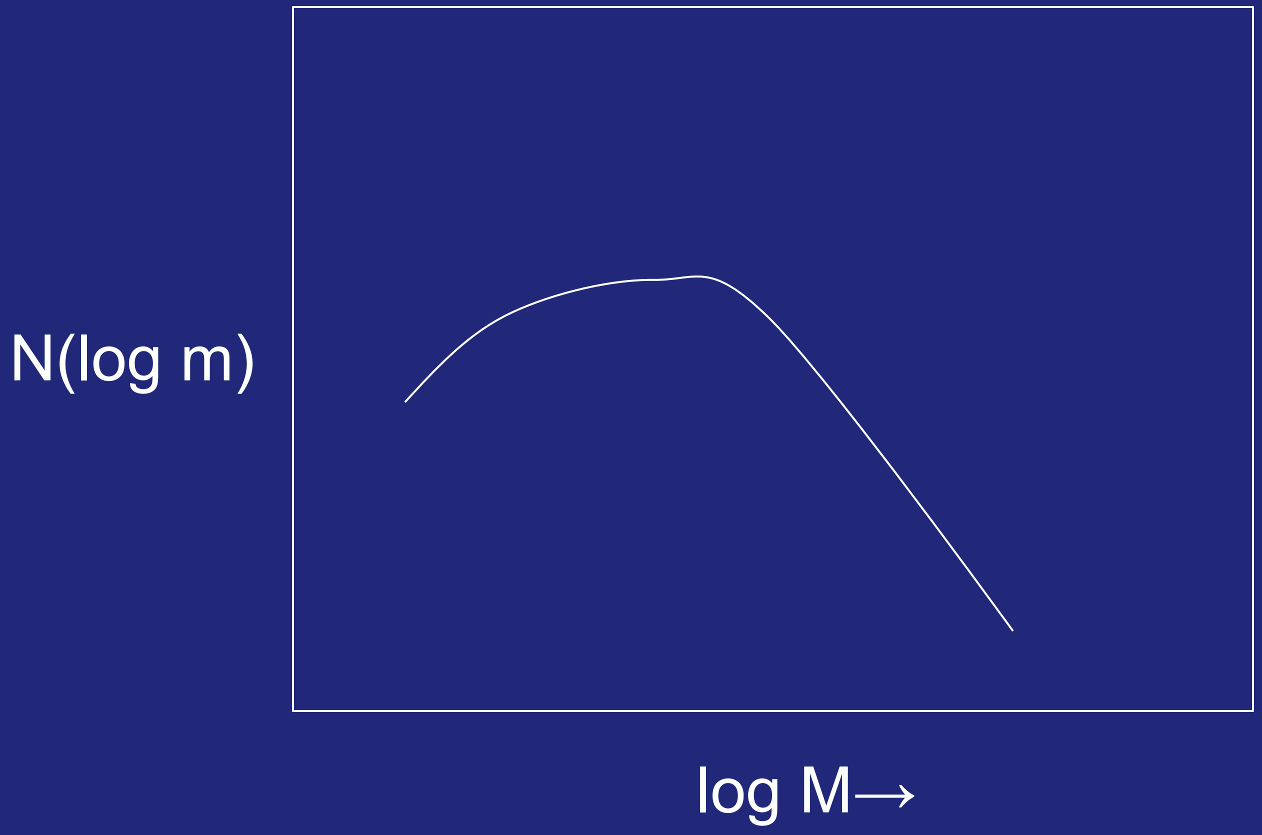
Efficiency of star formation: low, because of feedback and

Gravitational focusing- a natural byproduct of the formation mechanisms for molecular clouds: make

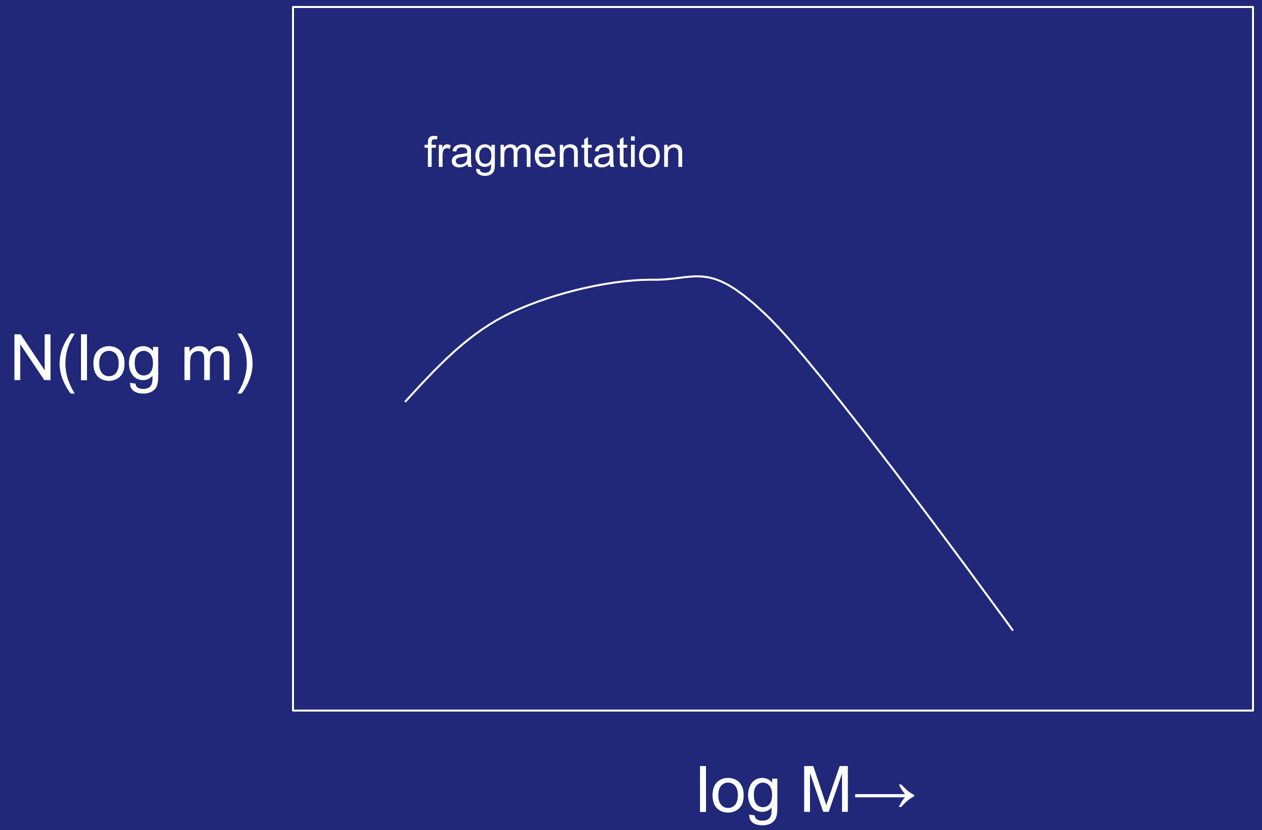
clusters

stars...

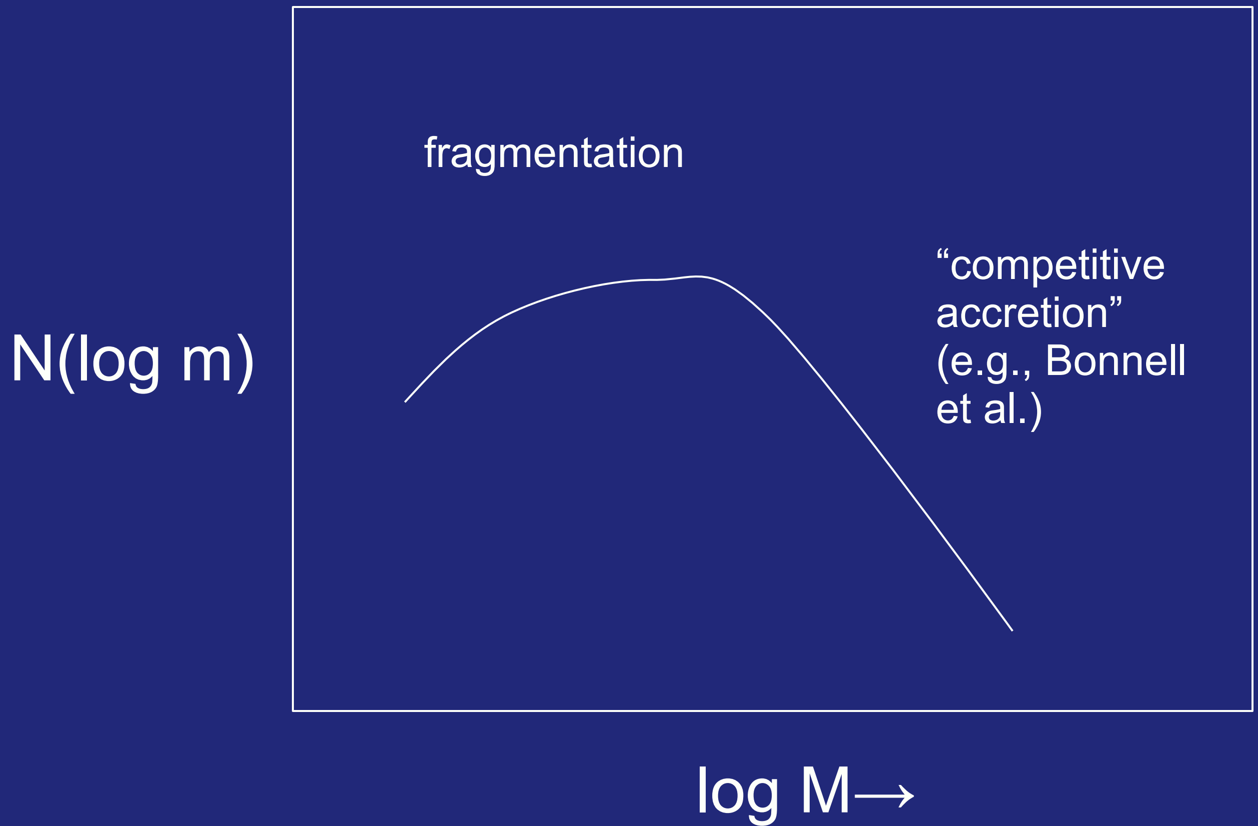
What about the stellar IMF?



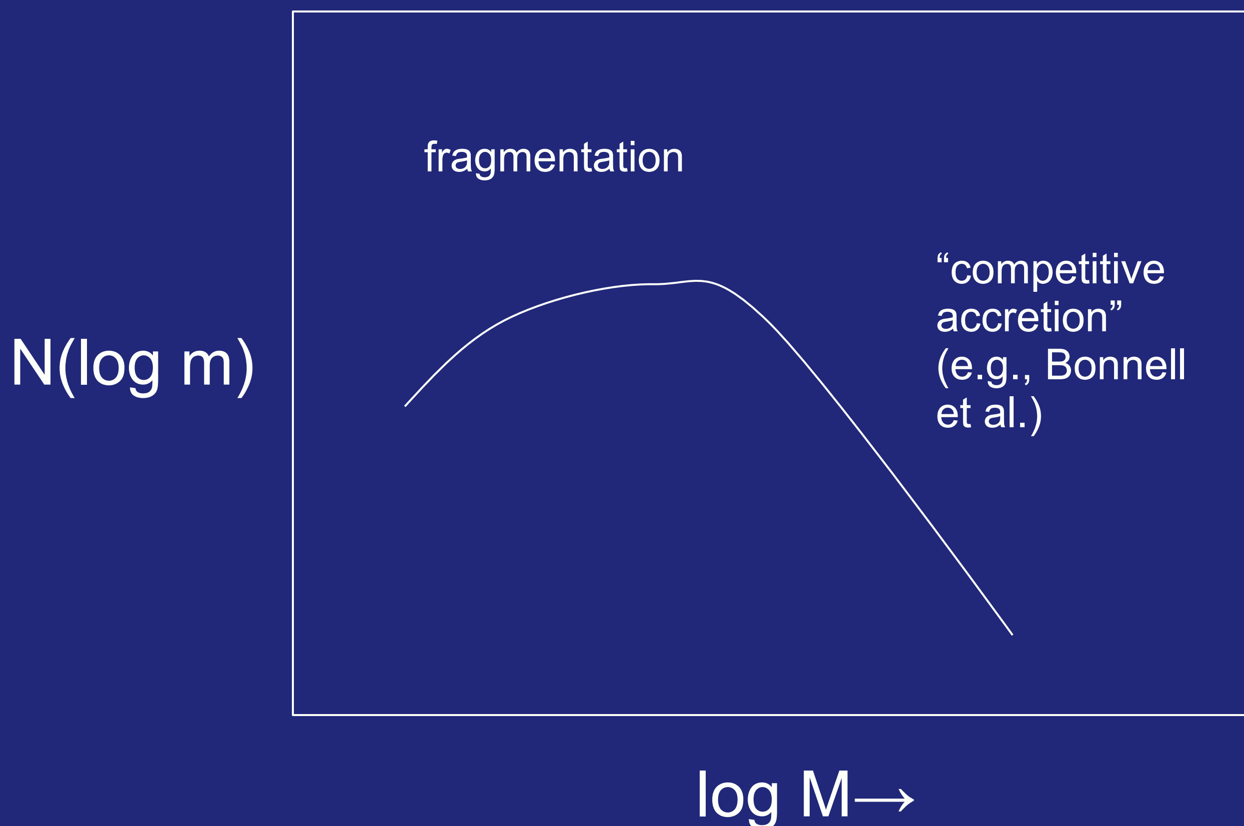
What about the stellar IMF?



What about the stellar IMF?



What about the stellar IMF?

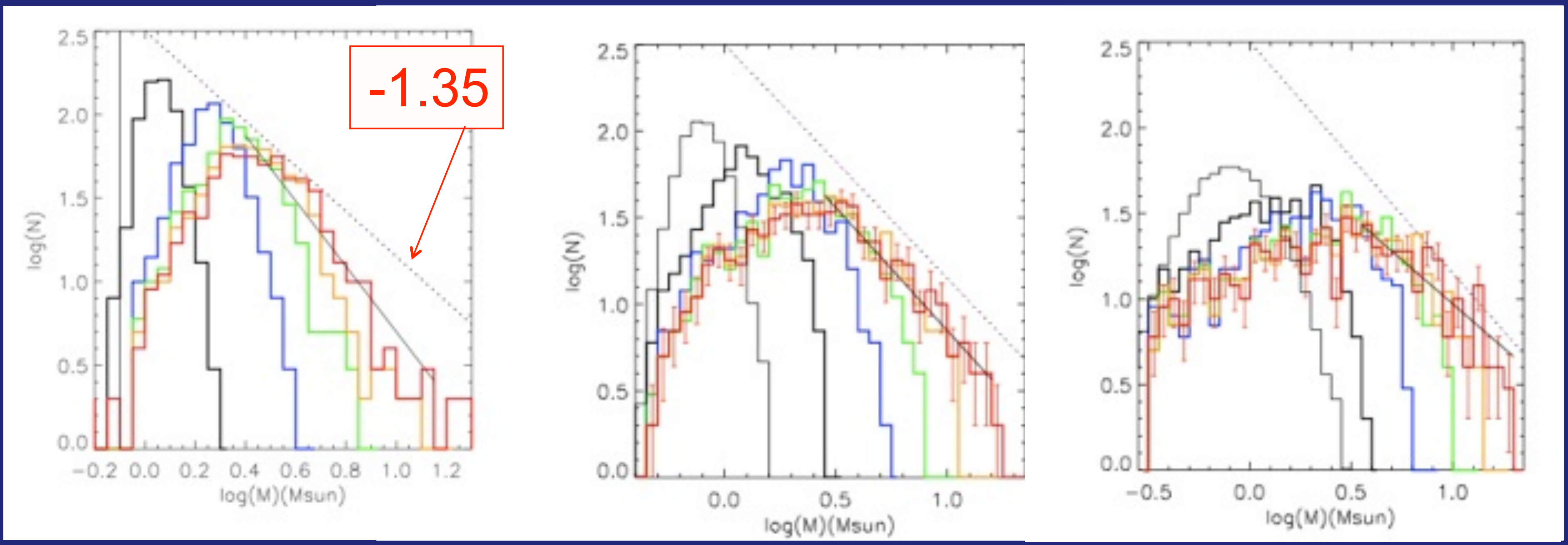


not clear evidence of variation, though massive clusters near GC suggest slightly flatter upper IMF (Stolte, Figer, etc.)

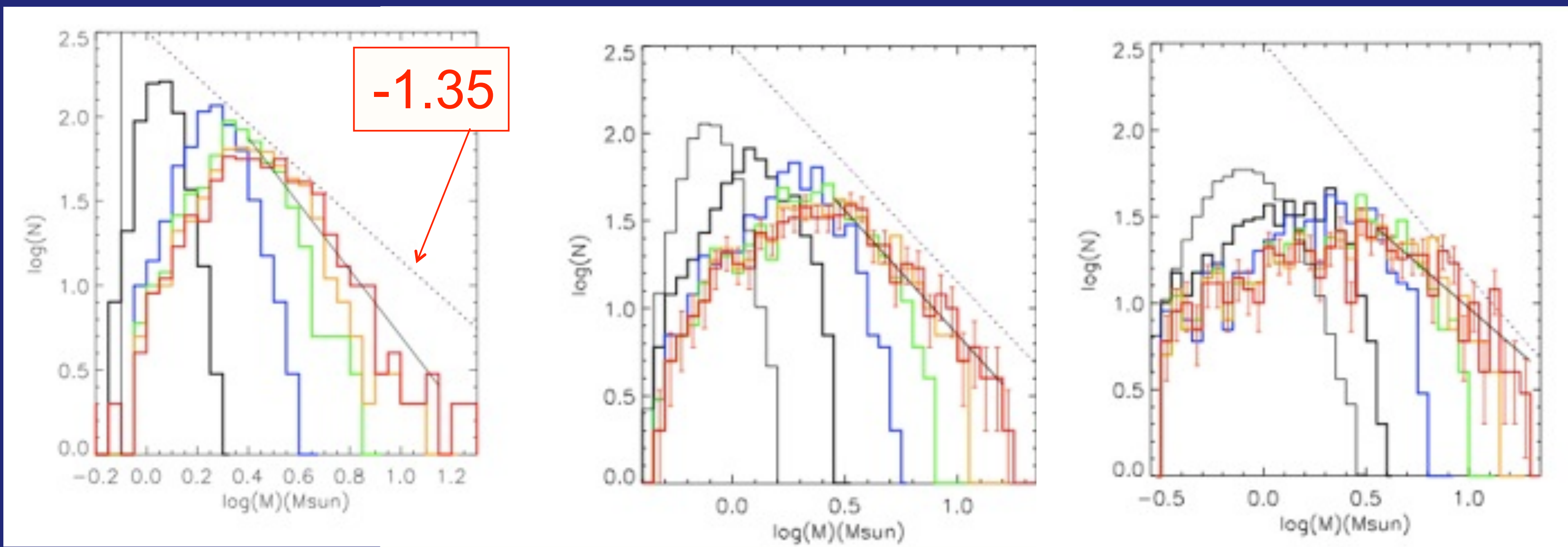
Numerical simulations of competitive accretion in sheets

(Hsu et al. 2010);

high-mass IMF depends upon amount of accretion, evolution toward Salpeter slope (or beyond?)



Numerical simulations of competitive accretion in sheets
(Hsu et al. 2010);
high-mass IMF depends upon amount of accretion,
evolution toward Salpeter slope (or beyond?)

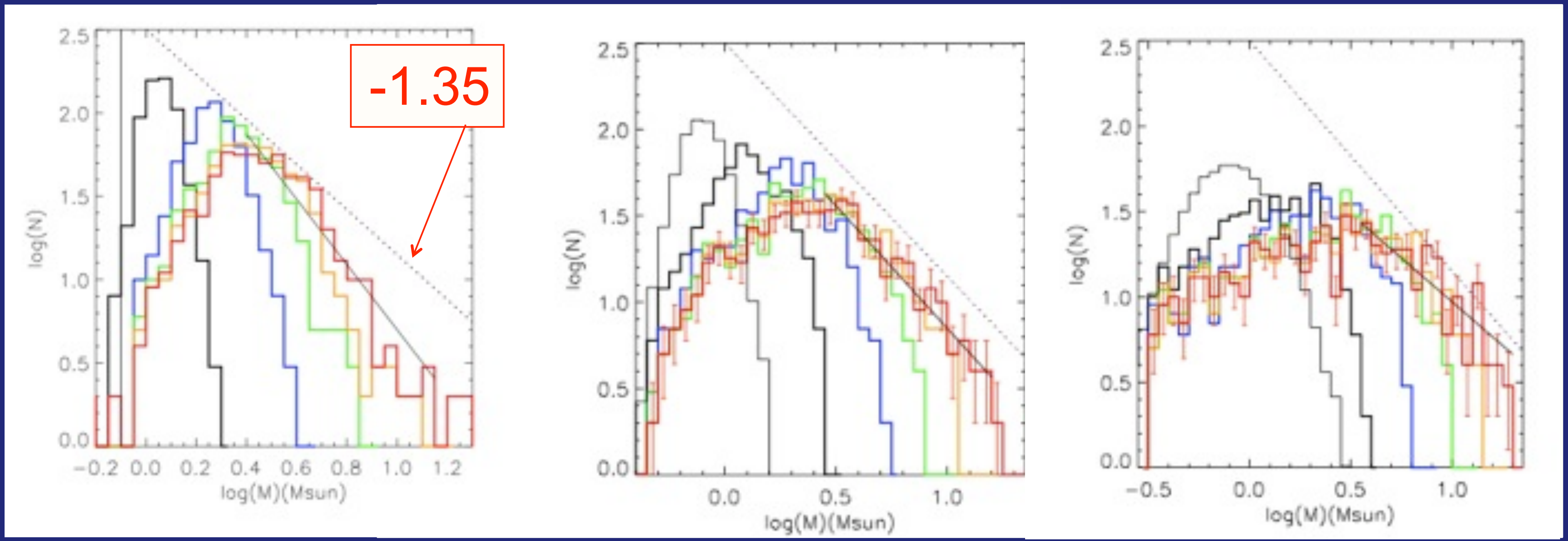


$\Gamma \Rightarrow -1$ as limiting slope

Numerical simulations of competitive accretion in sheets

(Hsu et al. 2010);

high-mass IMF depends upon amount of accretion, evolution toward Salpeter slope (or beyond?)



$\Gamma \Rightarrow -1$ as limiting slope

Similar to star cluster IMF (Fall, Chandar) ; gravitational focussing

The local story:

Compression

The local story:

Compression dM(tot)/dt

The local story:

Compression dM(tot)/dt

gravitational focusing

feedback (dispersal)

The local story:

Compression dM(tot)/dt

gravitational focusing

efficiency

feedback (dispersal)

The local story:

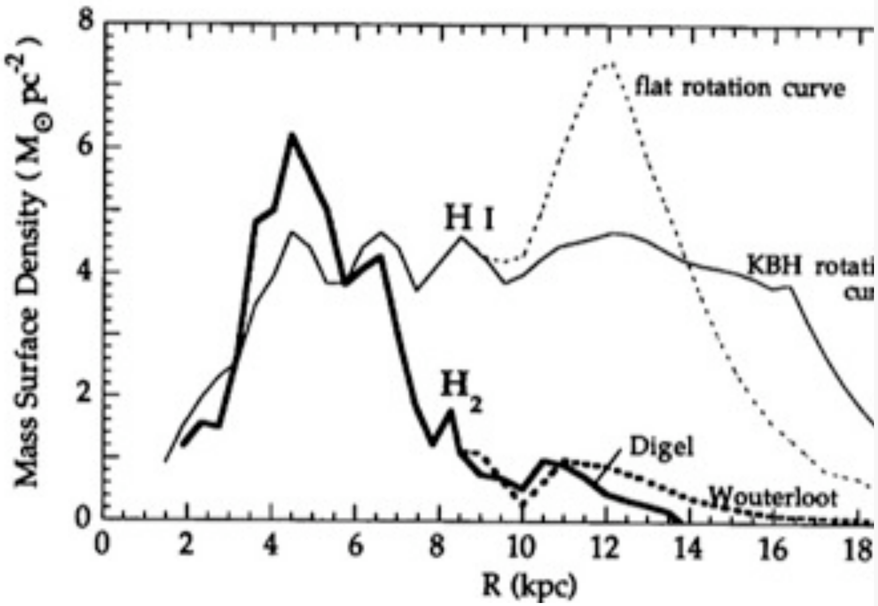
Compression dM(tot)/dt

gravitational focusing

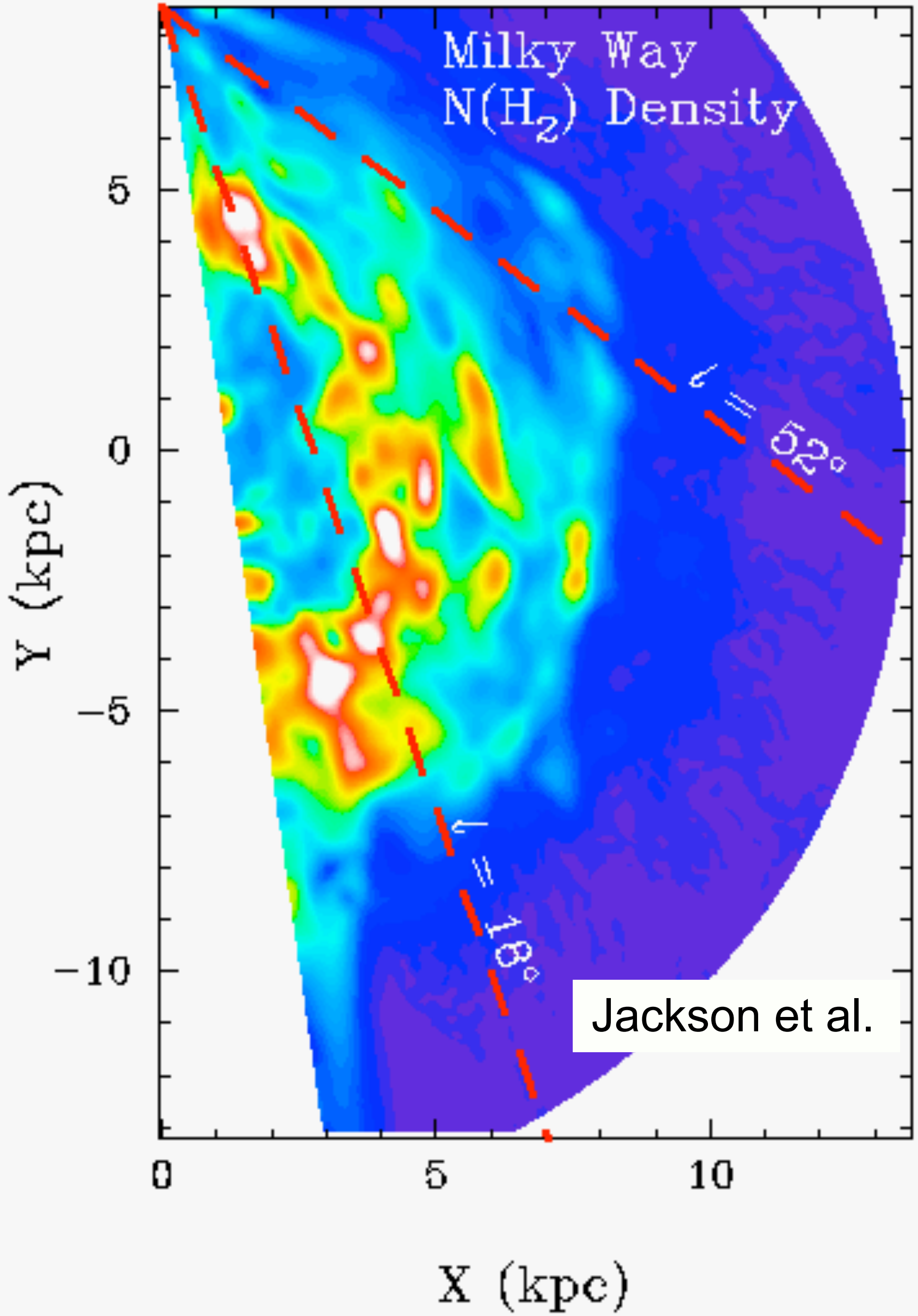
efficiency

feedback (dispersal)

How does this work for the molecular "ring"?



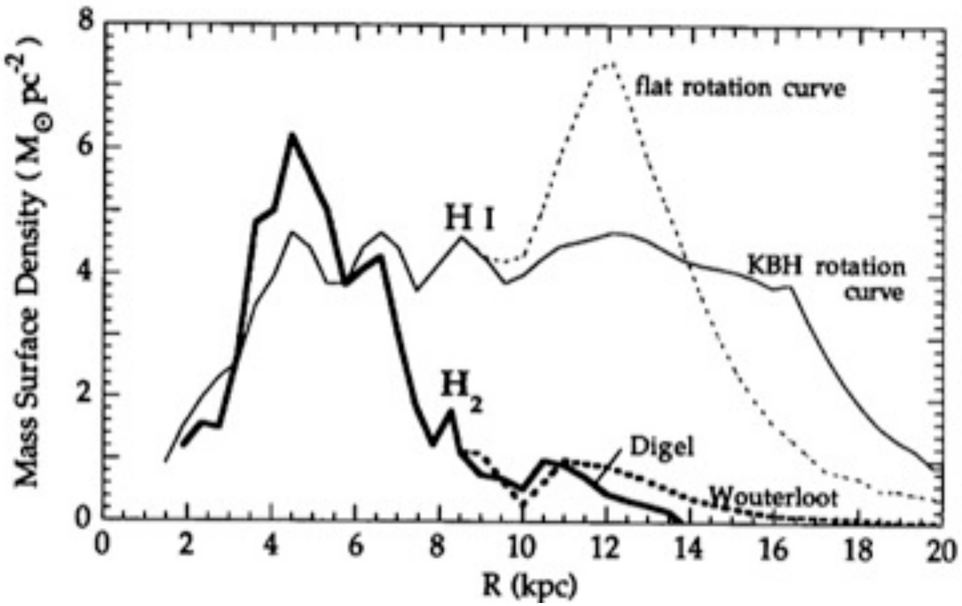
Dame 1993, AIPC 278, 267

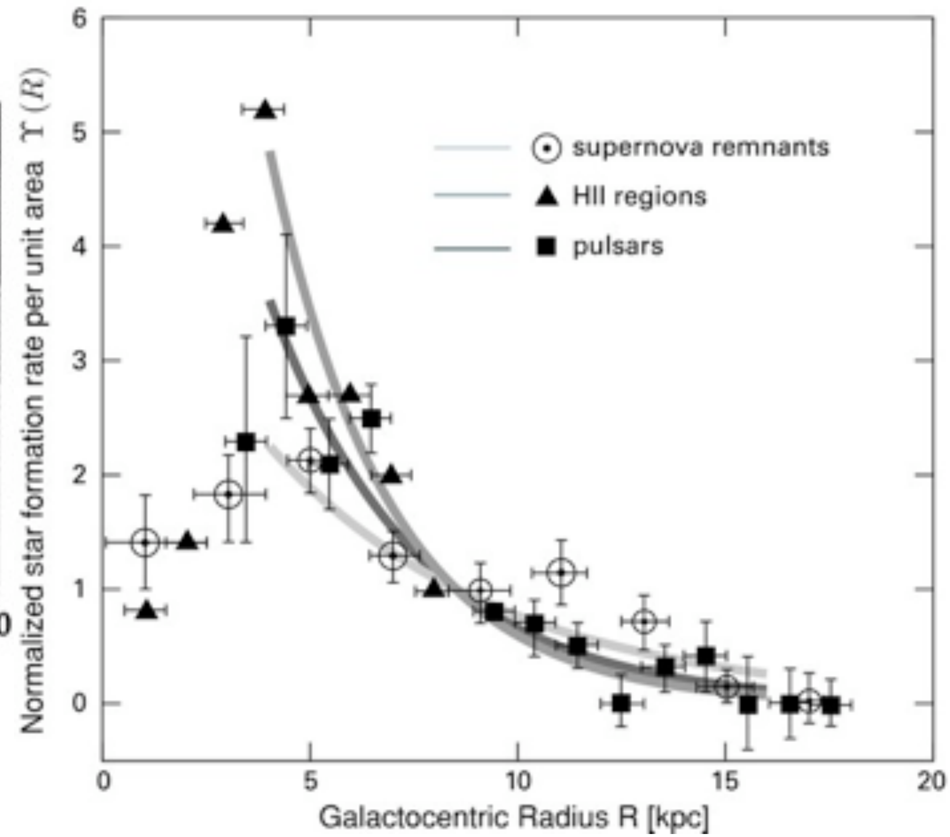


Does star formation follow the H_2 content?

Is the SFR low in the molecular "ring"?

Or just more diffuse "shielded" gas?



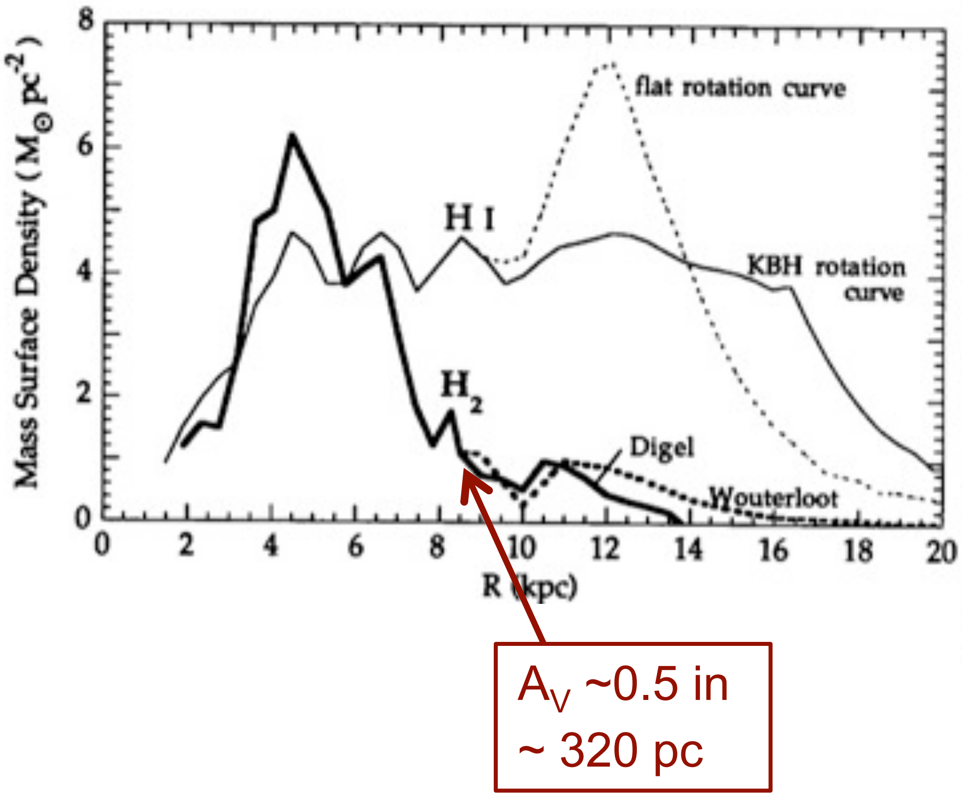


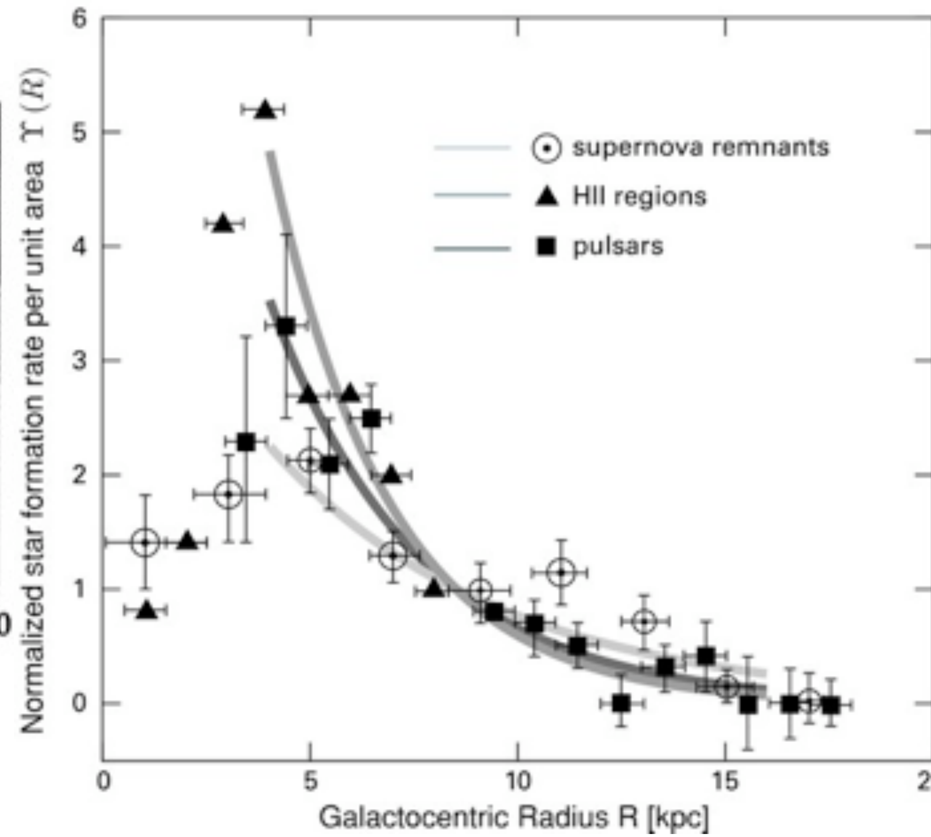
Peek 2009, ApJ 698, 1429,
from Stahler & Palla 2005

Does star formation follow the H_2 content?

Is the SFR low in the molecular "ring"?

Or just more diffuse "shielded" gas?



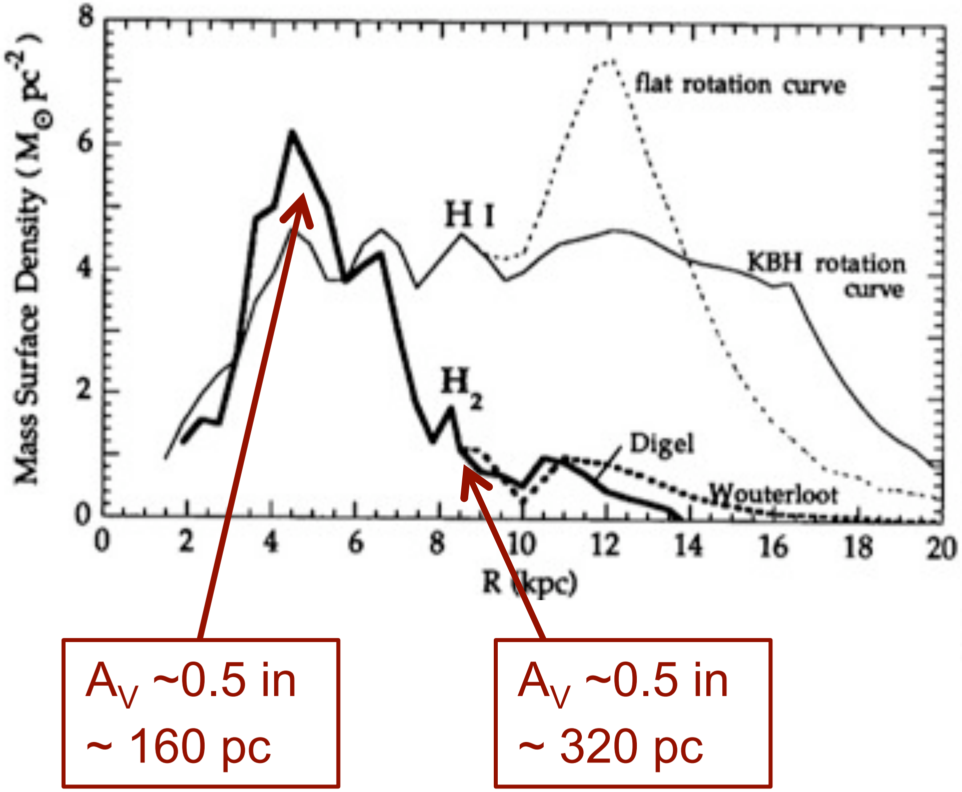


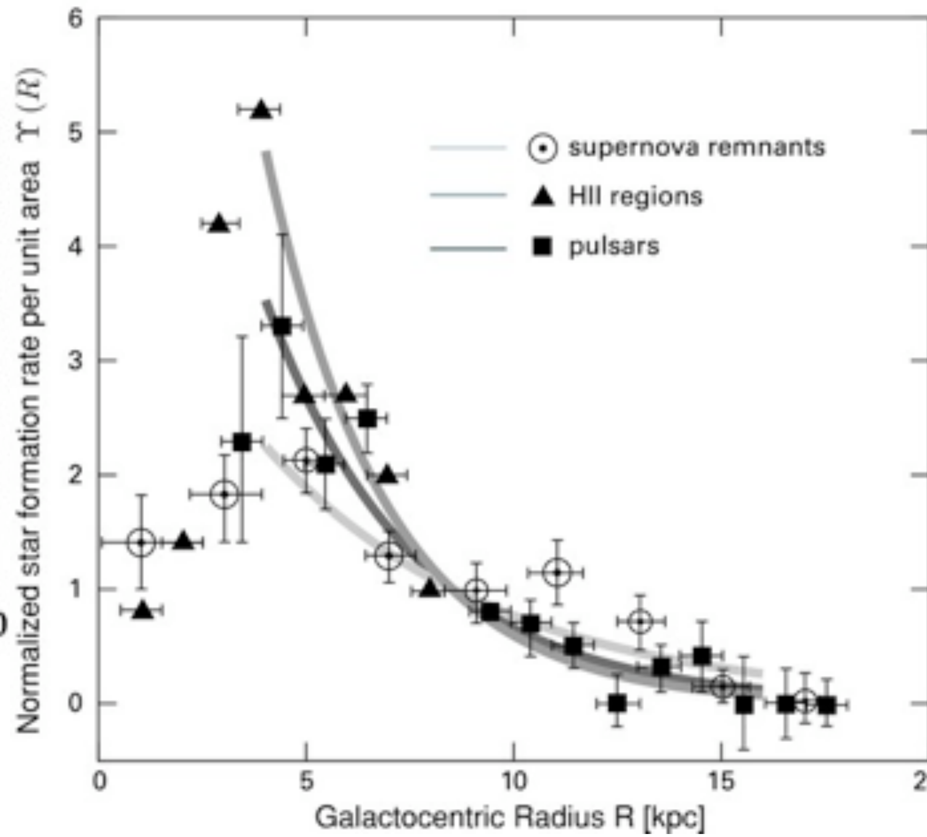
Peek 2009, ApJ 698, 1429,
from Stahler & Palla 2005

Does star formation follow the H_2 content?

Is the SFR low in the molecular "ring"?

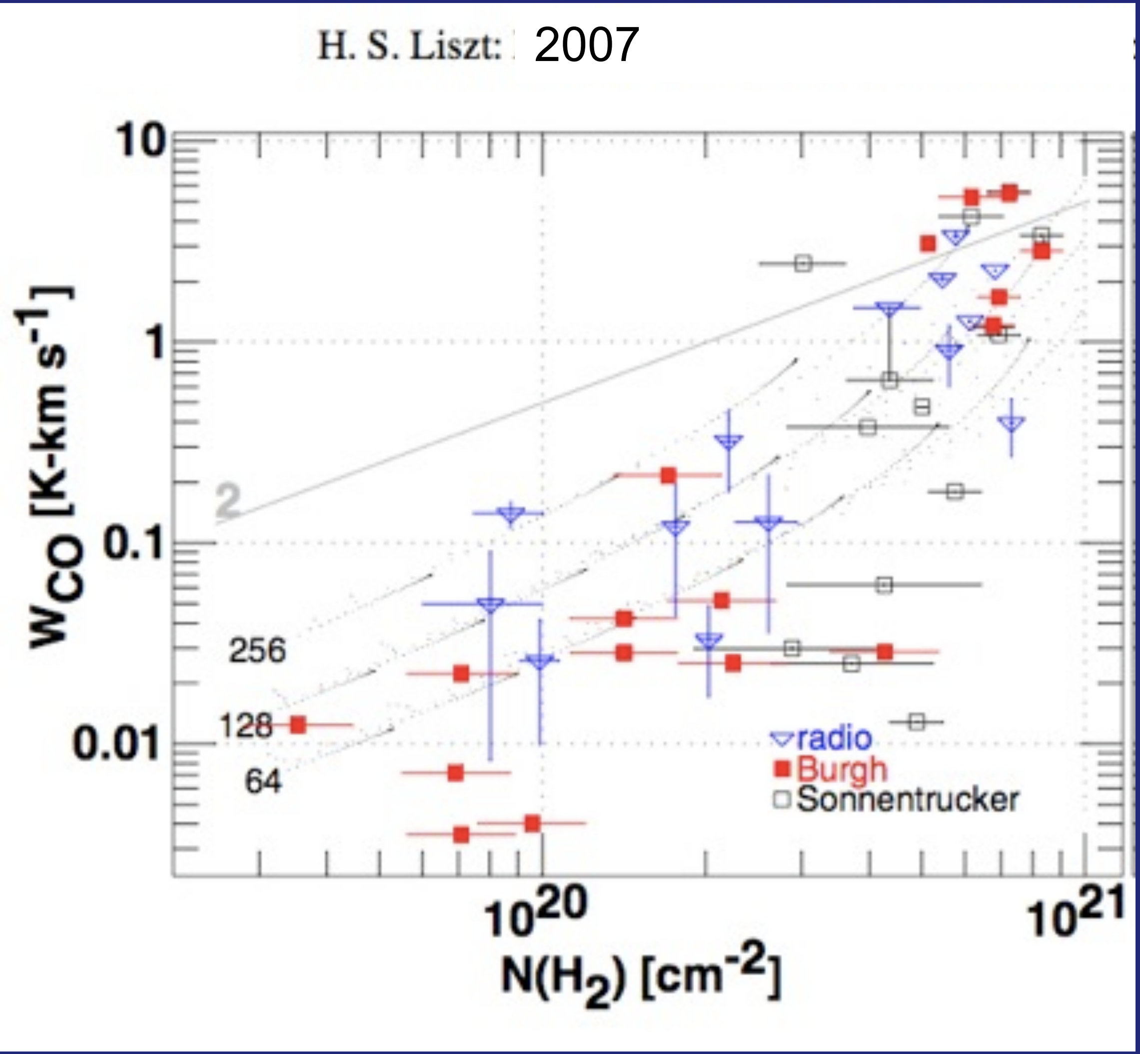
Or just more diffuse "shielded" gas?



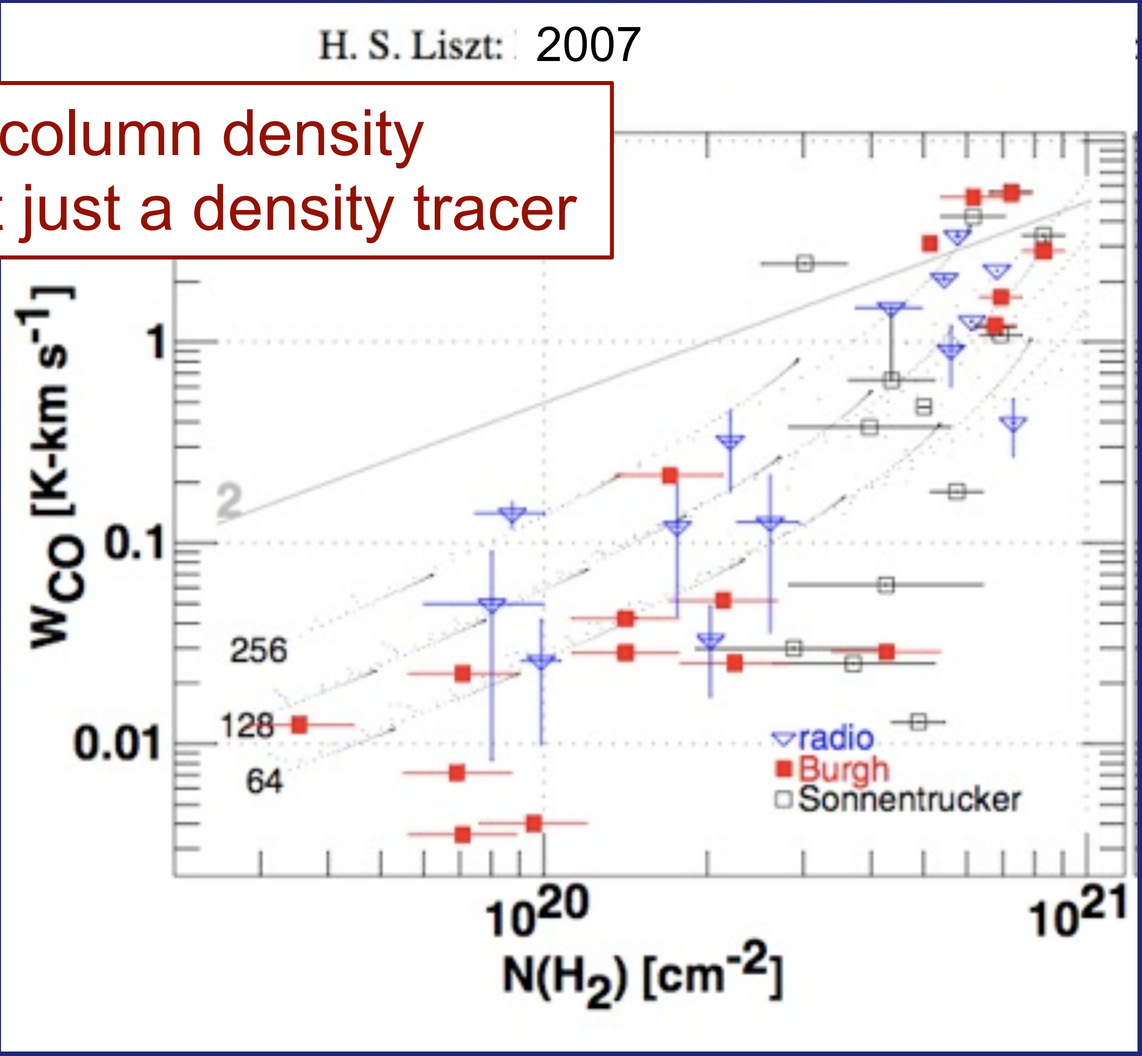


Peek 2009, ApJ 698, 1429,
from Stahler & Palla 2005

^{12}CO can be seen at low A_V ; if more shielding because higher average gas density, a solar neighborhood "molecular cloud" may differ from a molecular ring "cloud"



^{12}CO can be seen at low A_V ; if more shielding because higher average gas density, a solar neighborhood "molecular cloud" may differ from a molecular ring "cloud"



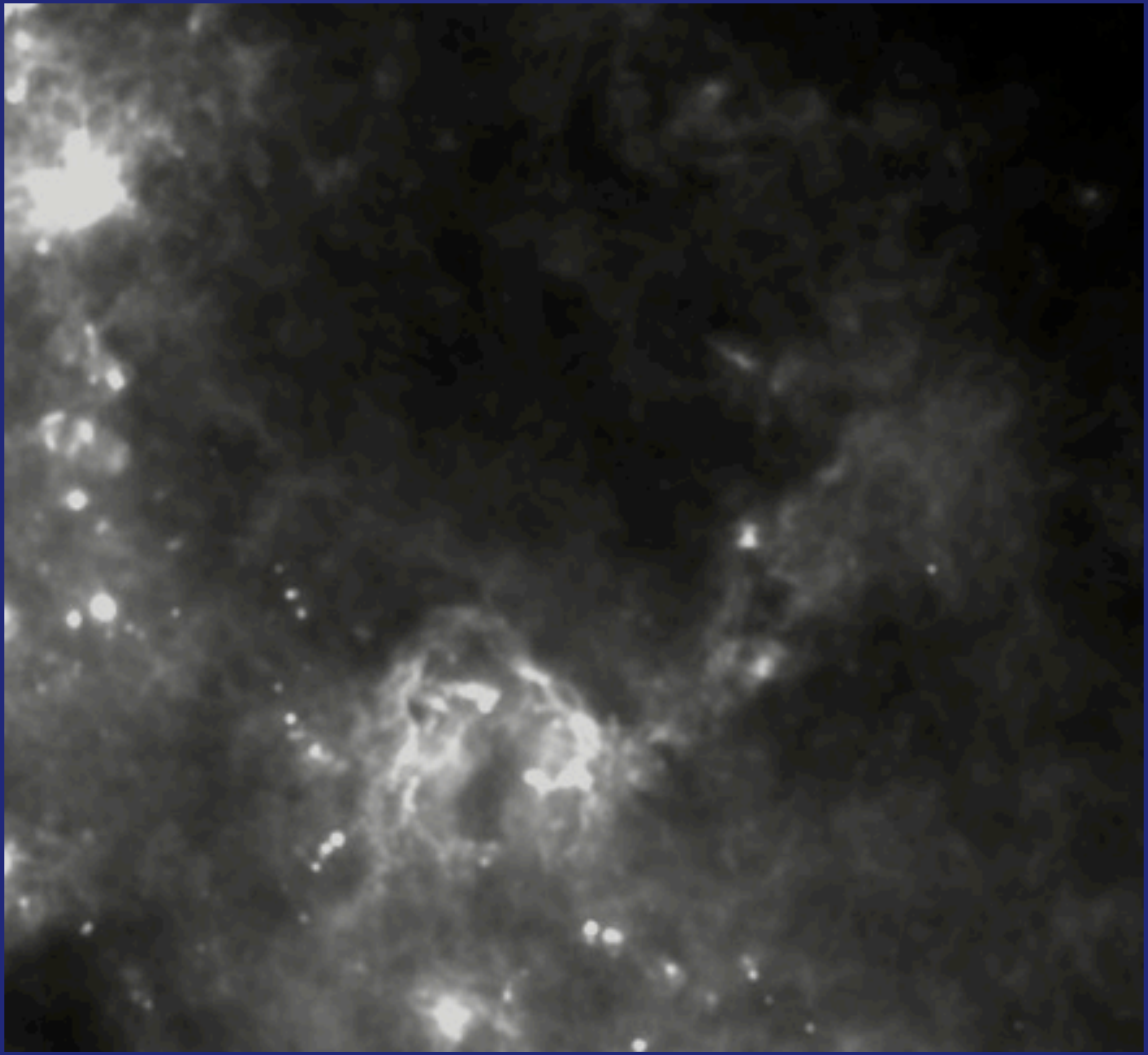
^{12}CO is a column density tracer, not just a density tracer

Implications for distant objects:

Age "spreads" and "cloud lifetimes"

Cep OB2

50 pc

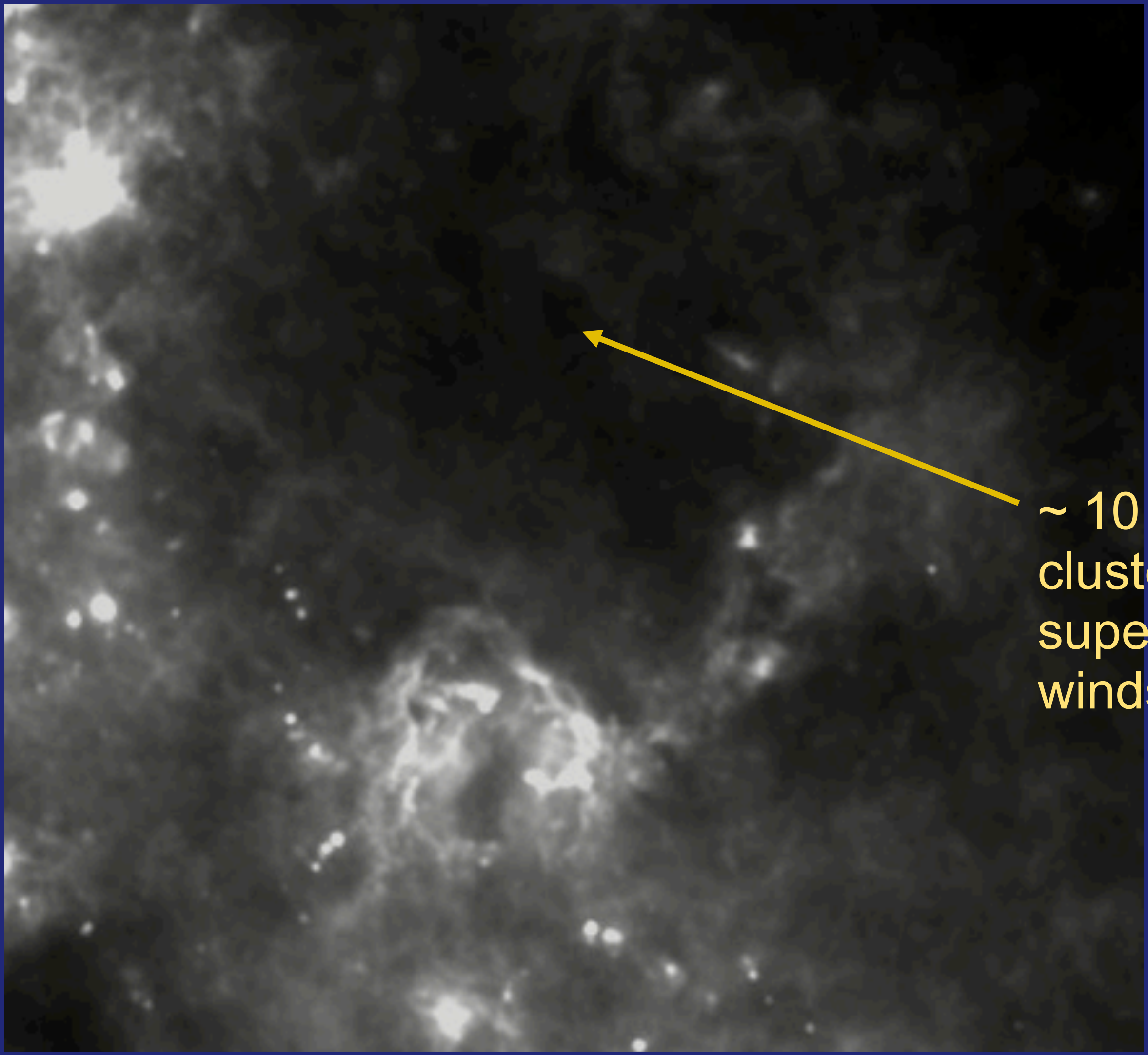


100 μm IRAS
dust emission

Age "spreads" and "cloud lifetimes"

Cep OB2

50 pc

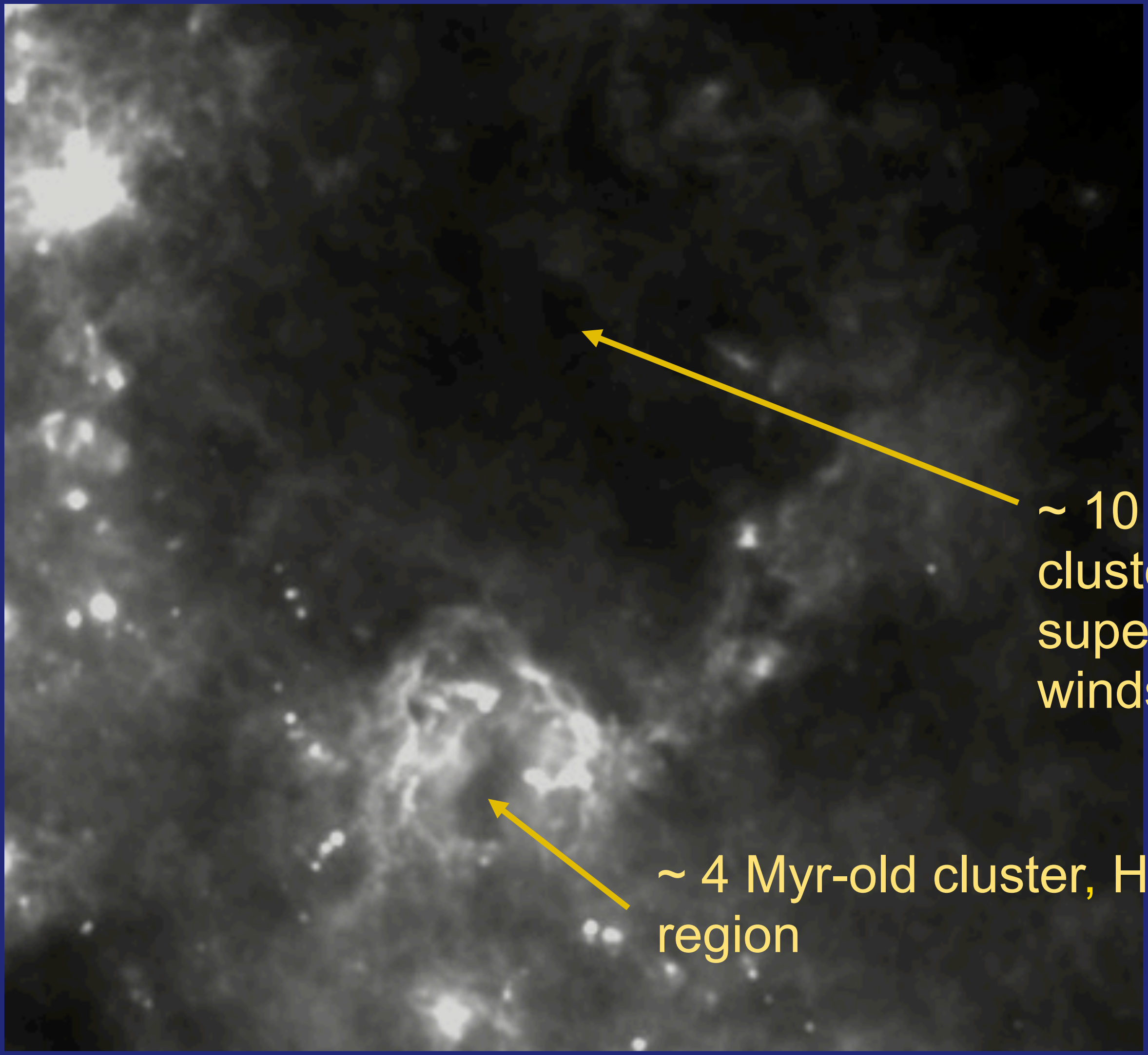


100 μm IRAS
dust emission

Age "spreads" and "cloud lifetimes"

Cep OB2

50 pc



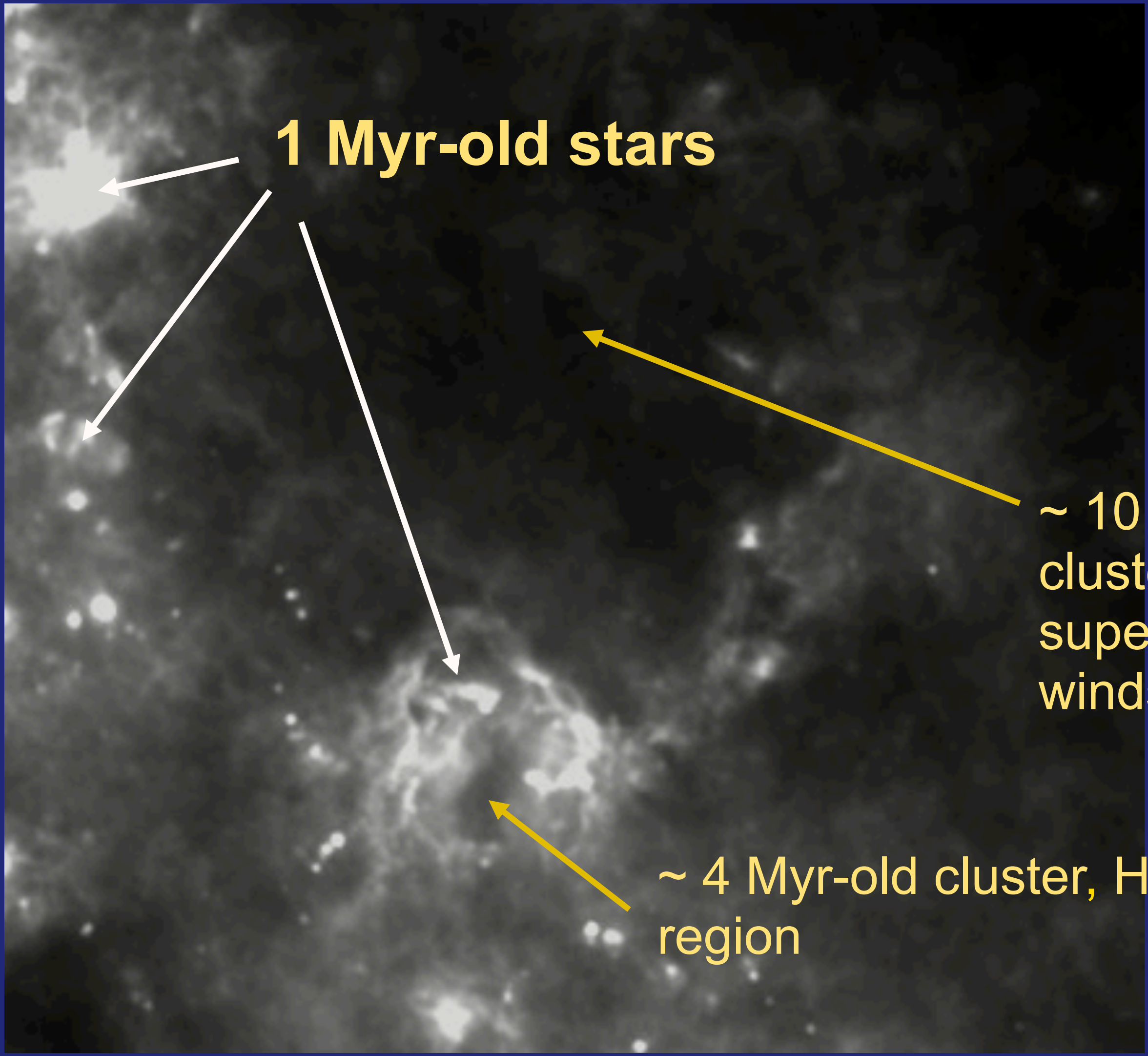
100 μm IRAS dust emission

Age "spreads" and "cloud lifetimes"

Cep OB2

50 pc

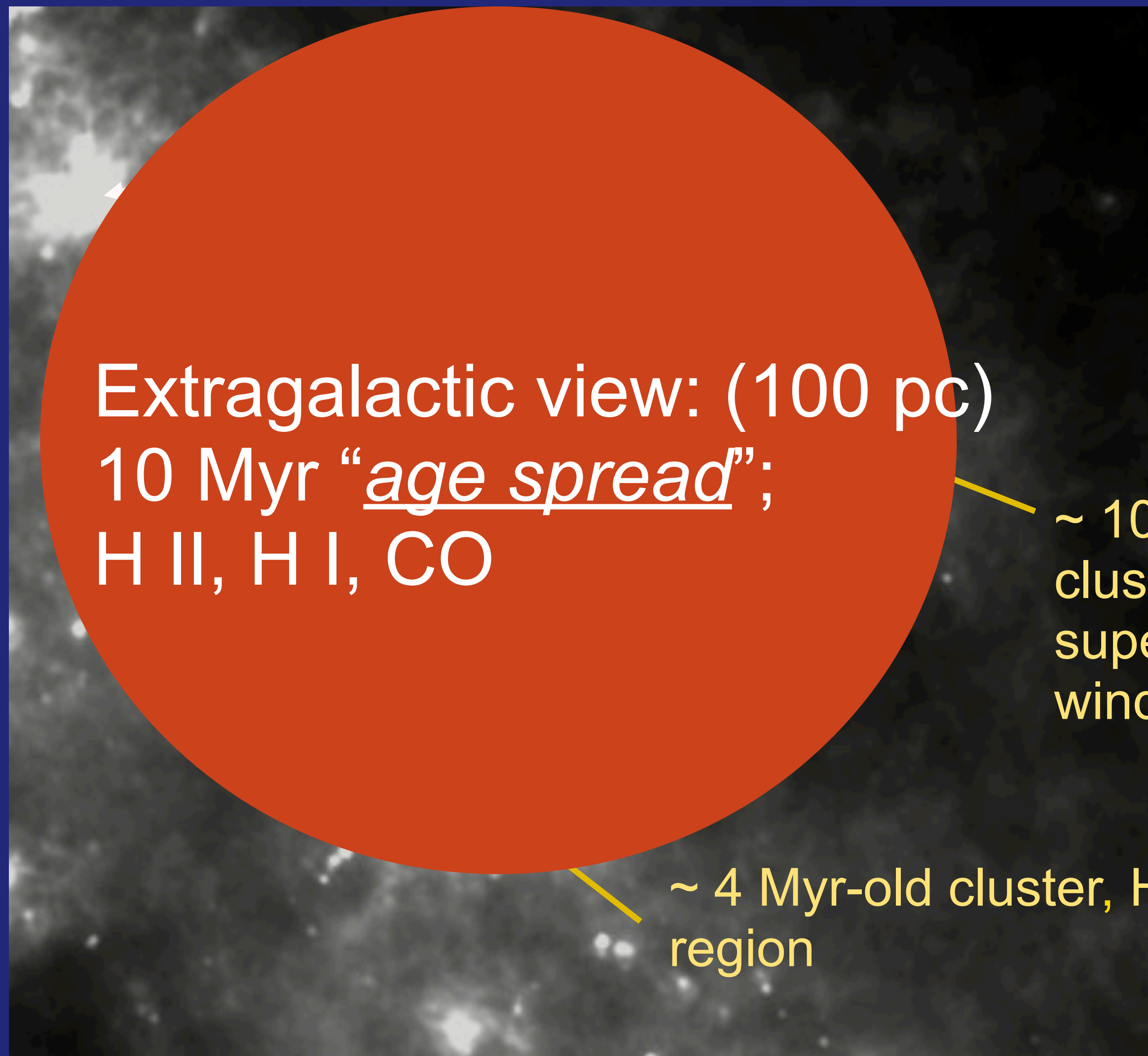
100 μm IRAS
dust emission



Age "spreads" and "cloud lifetimes"

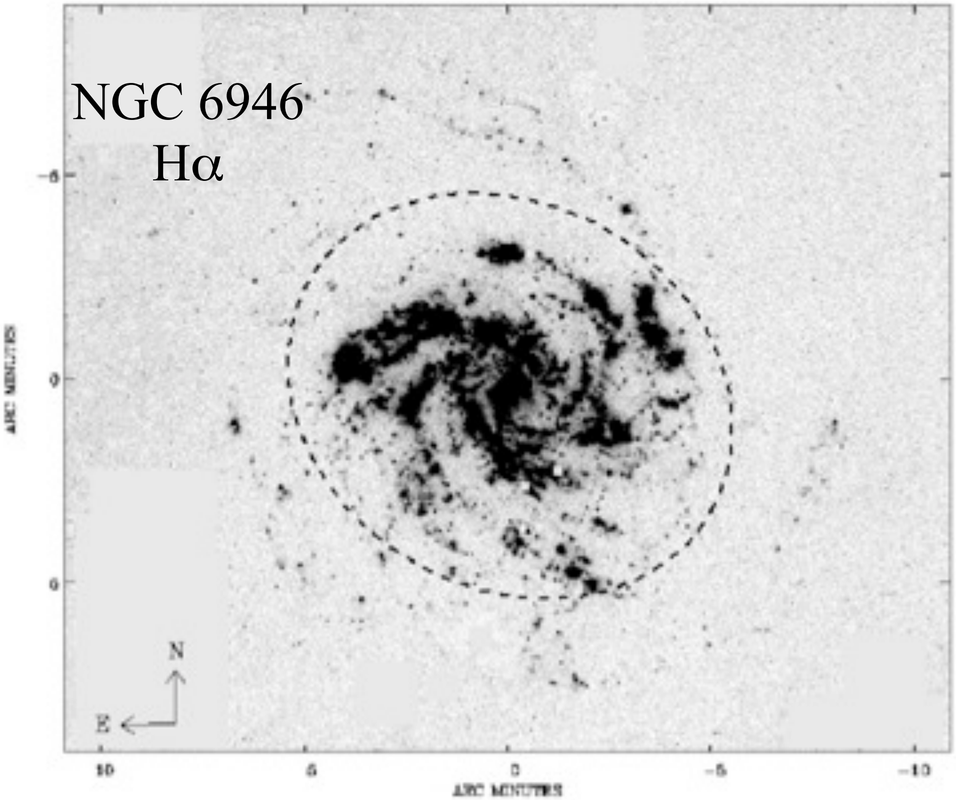
Cep OB2

50 pc



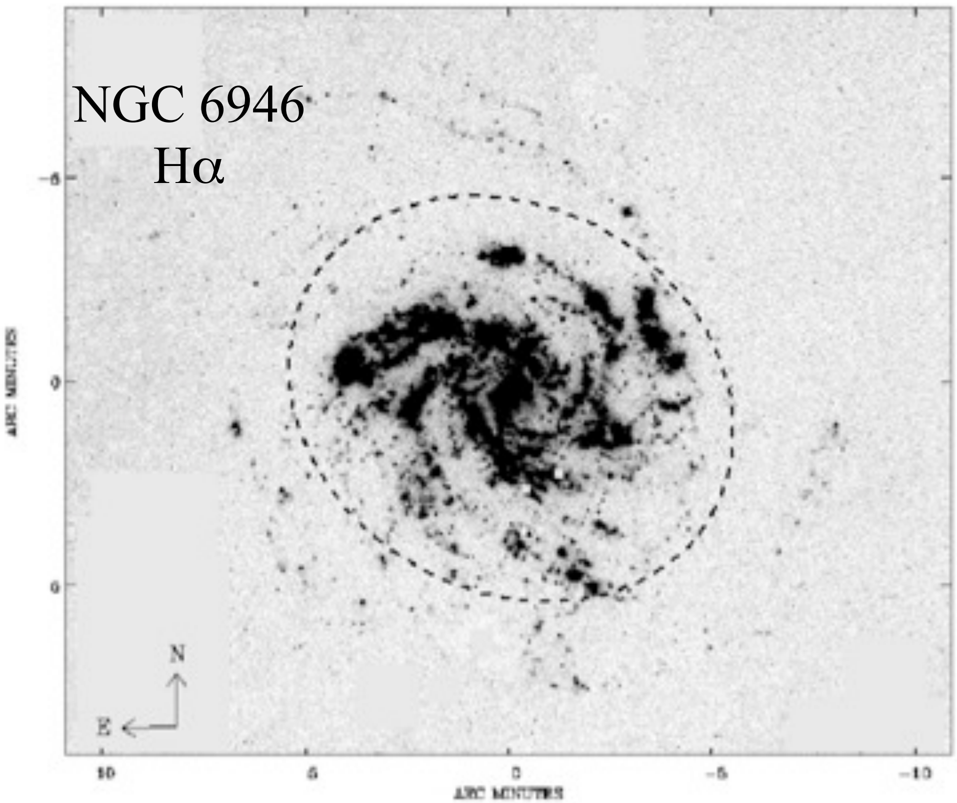
100 μm IRAS dust emission

Star formation where gas is ***compressed by shocks***



Ferguson et al. 1998

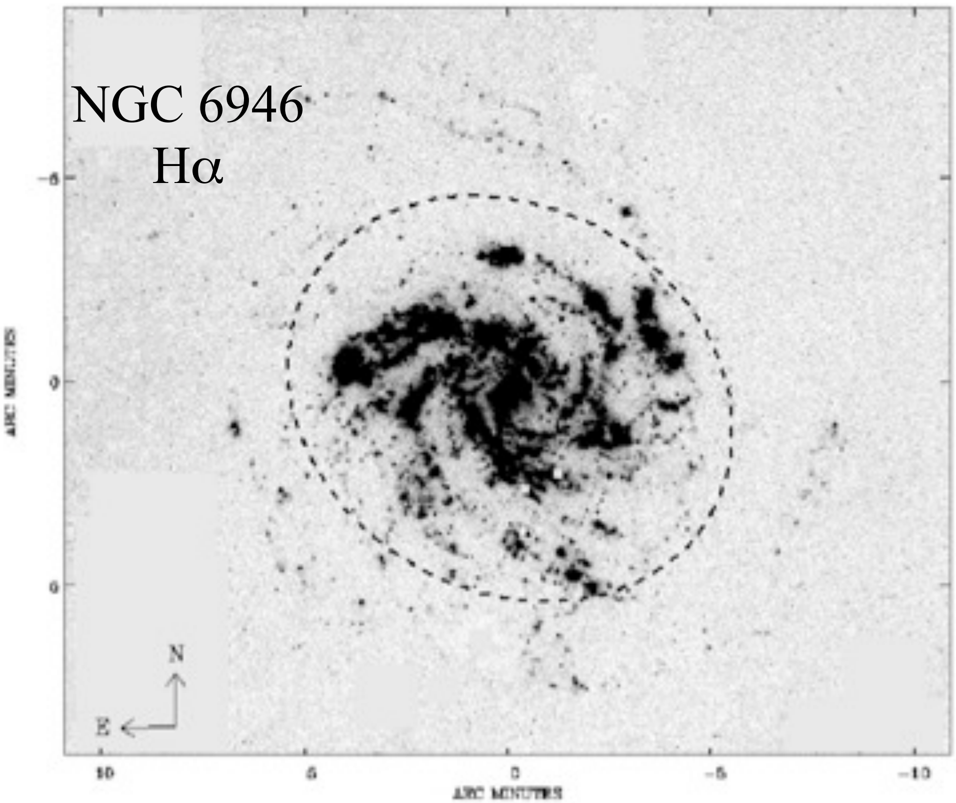
Star formation where gas is ***compressed by shocks***



Ferguson et al. 1998

• outer disk spiral shock; not enough material to continue propagating SF

Star formation where gas is ***compressed by shocks***

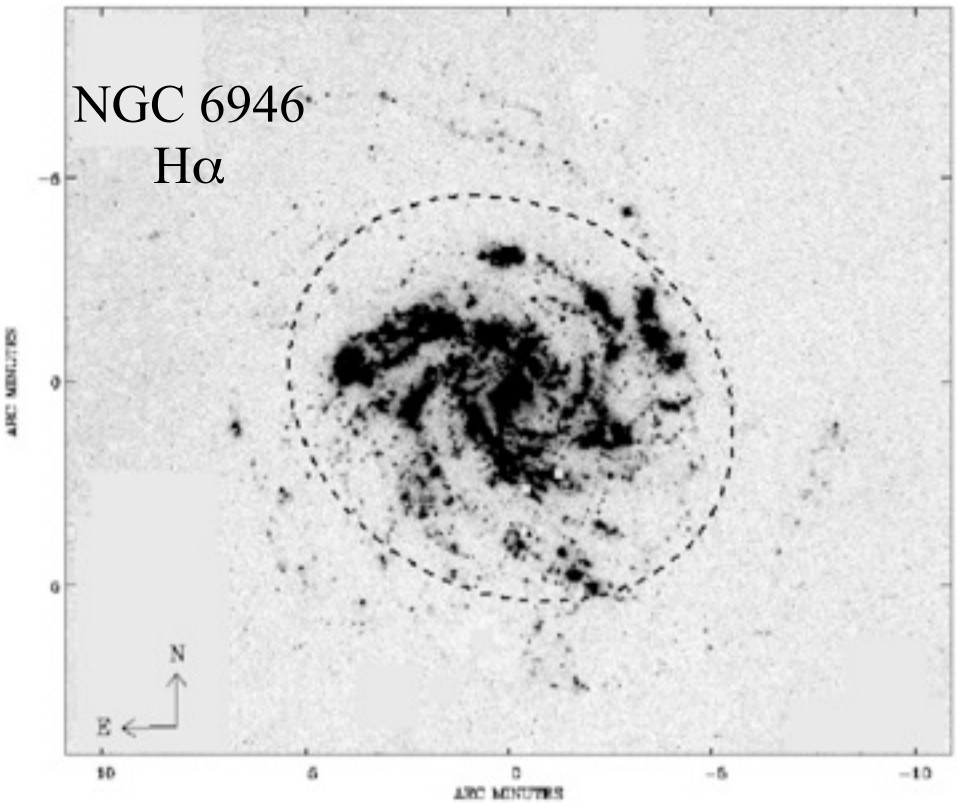


Ferguson et al. 1998

- outer disk spiral shock; not enough material to continue propagating SF

- inner disk; potential well, (Q <~ 1), more gas ⇒ more continuing SF (local feedback)

Star formation where gas is ***compressed by shocks***



Ferguson et al. 1998

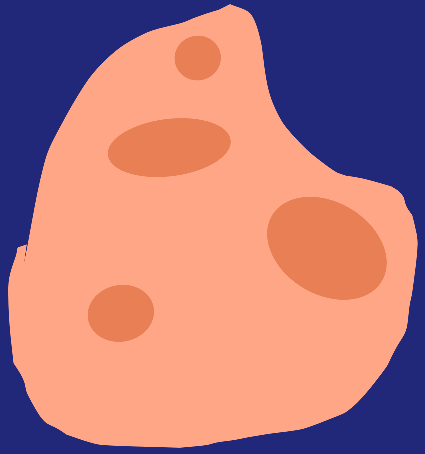
- outer disk spiral shock; not enough material to continue propagating SF
- inner disk; potential well, (Q <~ 1), more gas ⇒ more continuing SF (local feedback)

$$d\Sigma/dt \approx \Sigma \times \mathrm{eff} \times [v_{orb} - v(\mathrm{pattern})] \approx \Sigma/t_{dyn}$$

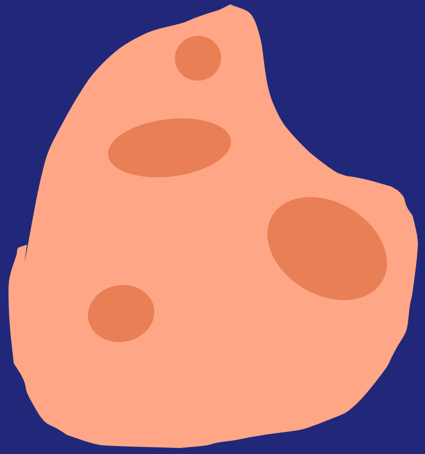
efficiency ~ 2% per cloud, × few triggered ⇒ 10%/orbit

⇒ one version of the Kennicutt-Schmidt law

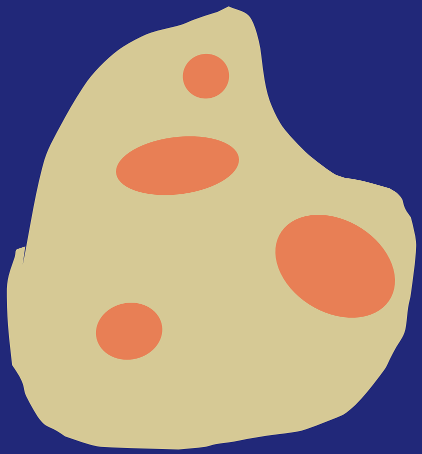
Gas content and SFR?



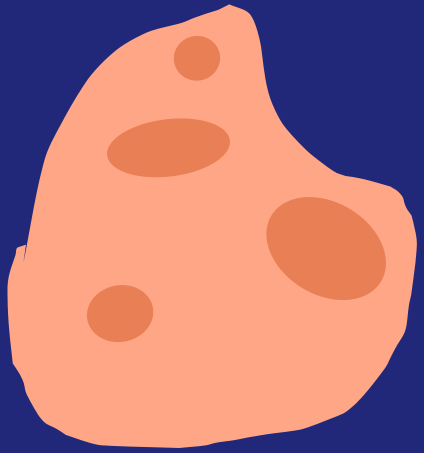
Gas content and SFR?



- molecular gas should trace SFR more closely, as it generally traces the densest gas

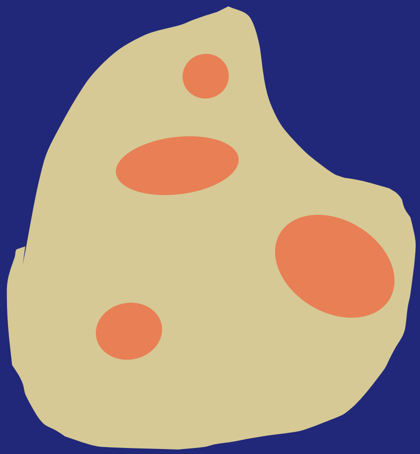


Gas content and SFR?

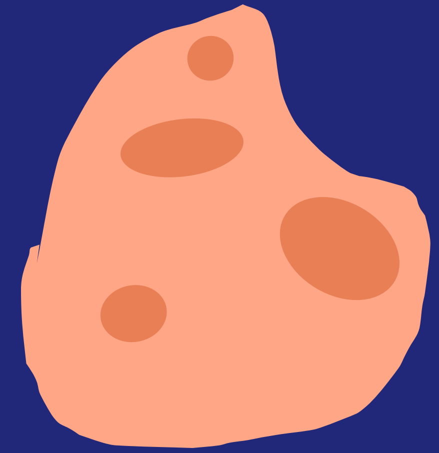


• molecular gas should trace SFR more closely, as it generally traces the densest gas

• high-density molecular tracers should follow the SFR very closely; but this does not address the question of the RATE of formation of dense molecular gas



Gas content and SFR?



• molecular gas should trace SFR more closely, as it generally traces the densest gas

• high-density molecular tracers should follow the SFR very closely; but this does not address the question of the RATE of formation of dense molecular gas

• CO is sensitive to column density as well as density; likely to trace different phases in differing regions (and most CO emission comes from non-star forming gas in the solar neighborhood)

Structure of molecular clouds: most mass at low ρ

Efficiency of star formation ~ few %

Feedback + gravitational focusing limit efficiency

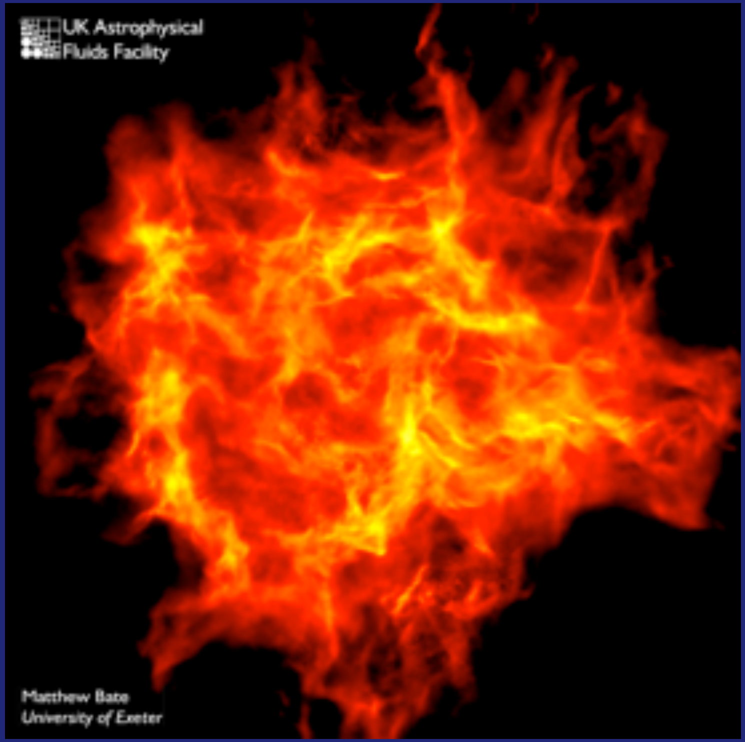
Molecular clouds formed by large-scale flows; creates turbulent structure necessary for fragmentation into stars

distant objects: averaging over cycling of gas

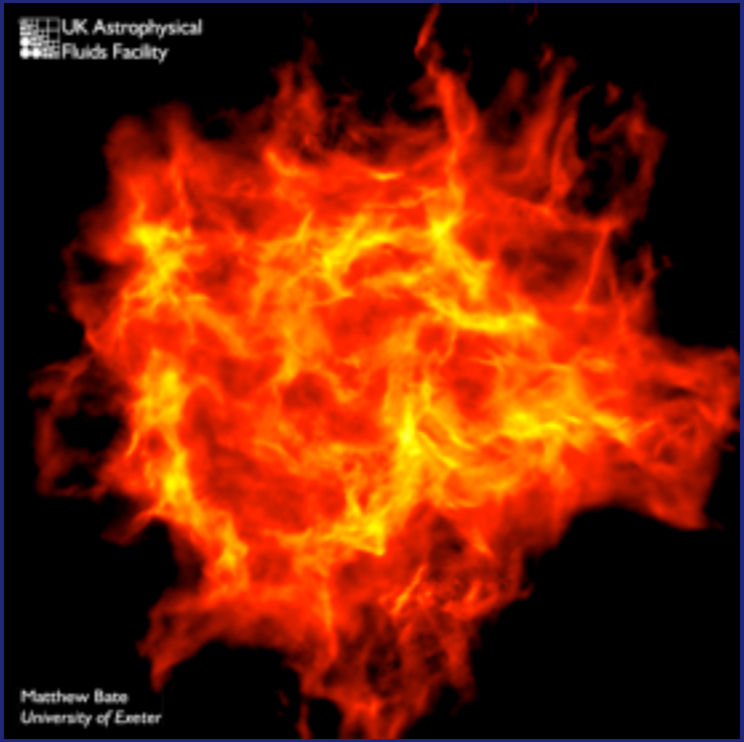
star formation rates set by gas content (not just molecular gas) plus rate of compressions

gravitational focusing may lead to similar massive star and cluster IMFs, but physics of peak unclear

Typical numerical simulations:
start with imposed turbulent velocity ≈ virial
⇒ prevents immediate collapse

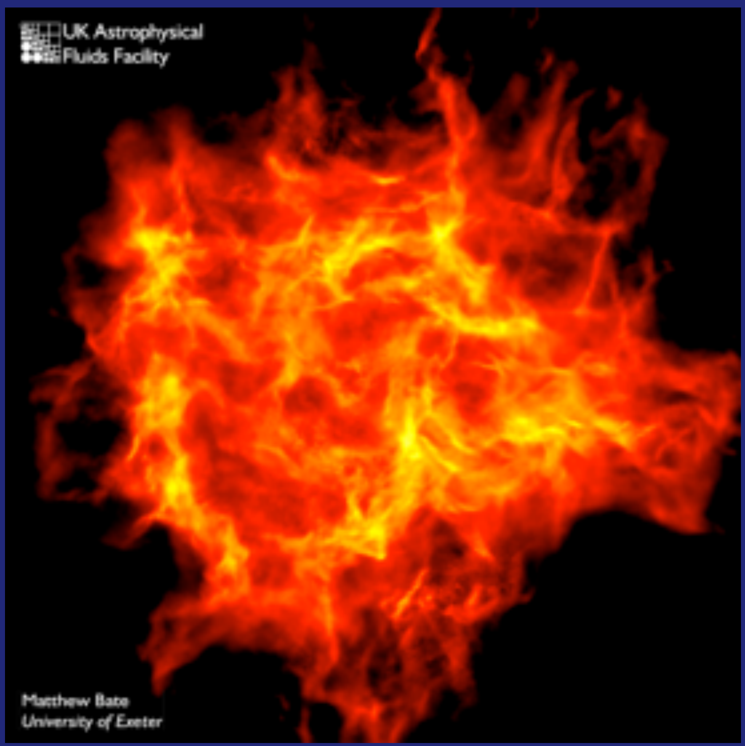


Typical numerical simulations: start with imposed turbulent velocity ≈ virial ⇒ prevents immediate collapse



How do clouds "know" to have this level of turbulence, given how the clouds form?

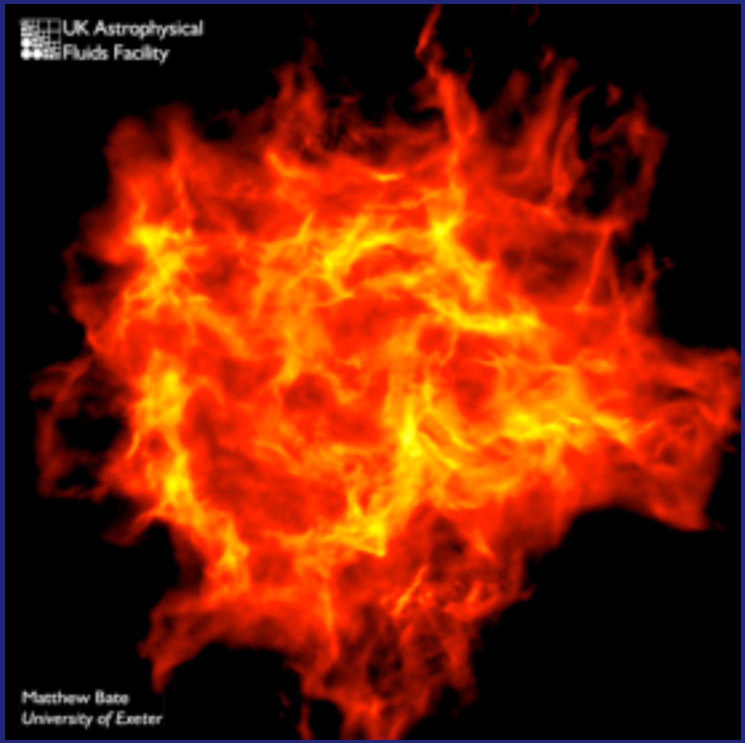
Typical numerical simulations: start with imposed turbulent velocity ≈ virial ⇒ prevents immediate collapse



How do clouds "know" to have this level of turbulence, given how the clouds form?

Too much: doesn't collapse, expands; too little, collapse; how to hit the sweet spot?

Typical numerical simulations: start with imposed turbulent velocity ≈ virial ⇒ prevents immediate collapse

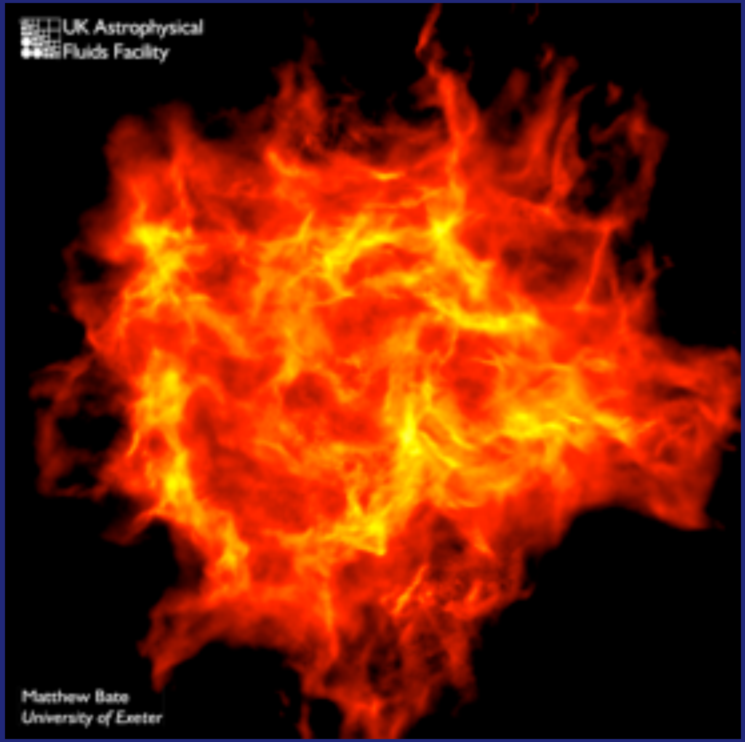


How do clouds "know" to have this level of turbulence, given how the clouds form?

Too much: doesn't collapse, expands; too little, collapse; how to hit the sweet spot?

can't in general.

Typical numerical simulations: start with imposed turbulent velocity ≈ virial ⇒ prevents immediate collapse



How do clouds "know" to have this level of turbulence, given how the clouds form?

Too much: doesn't collapse, expands; too little, collapse; how to hit the sweet spot?

can't in general.

However, turbulence IS needed to make stellar fragments...

Ages of young associations/clusters

Region	$< t >$ (Myr)	Molecular gas?	t(cross) (Myr)
Coalsack	–	yes	–
Cha III	–	yes	–
Pipe Nebula	–	yes	–
Orion Nebula	1	yes	1
Taurus	2	yes	10
Oph	1	yes	–
Cha I,II	2	yes	–
Lupus	2	yes	–
MBM 12A	2	yes	–
IC 348	2-3	yes	–
NGC 2264	2-3	yes	2-3
Upper Sco	5	no	5
Lower Cen-Crux	10-15	no	~ 50
Upper Cen-Lup	10-15	no	~ 50
TW HyA	~ 10	no	–
η Cha	~ 10	no	–

Ages of young associations/clusters

Region	$< t >$ (Myr)	Molecular gas?	t(cross) (Myr)
Coalsack	–	yes	–
Cha III	–	yes	–
Pipe Nebula	–	yes	–
Orion Nebula	1	yes	1
Taurus	2	yes	10
Oph	1	yes	–
Cha I,II	2	yes	–
Lupus	2	yes	–
MBM 12A	2	yes	–
IC 348	2-3	yes	–
NGC 2264	2-3	yes	2-3
Upper Sco	5	no	5
Lower Cen-Crux	10-15	no	$\sim$ 50
Upper Cen-Lup	10-15	no	$\sim$ 50
TW HyA	$\sim$ 10	no	–
η Cha	$\sim$ 10	no	–

Fast onset after MC formation!

Ages of young associations/clusters

Region	$<t>$ (Myr)	Molecular gas?	t(cross) (Myr)
Coalsack	–	yes	–
Cha III	–	yes	–
Pipe Nebula	–	yes	–
Orion Nebula	1	yes	1
Taurus	2	yes	10
Oph	1	yes	–
Cha I,II	2	yes	–
Lupus	2	yes	–
MBM 12A	2	yes	–
IC 348	2-3	yes	–
NGC 2264	2-3	yes	2-3
Upper Sco	5	no	5
Lower Cen-Crux	10-15	no	$\sim$ 50
Upper Cen-Lup	10-15	no	$\sim$ 50
TW HyA	$\sim$ 10	no	–
η Cha	$\sim$ 10	no	–

Fast onset after MC formation!

star formation lasts for ~ 3-4 Myr; then gas dispersed!

Ages of young associations/clusters

Region	$< t >$ (Myr)	Molecular gas?	t(cross) (Myr)
Coalsack	–	yes	–
Cha III	–	yes	–
Pipe Nebula	–	yes	–
Orion Nebula	1	yes	1
Taurus	2	yes	10
Oph	1	yes	–
Cha I,II	2	yes	–
Lupus	2	yes	–
MBM 12A	2	yes	–
IC 348	2-3	yes	–
NGC 2264	2-3	yes	2-3
Upper Sco	5	no	5
Lower Cen-Crux	10-15	no	$\sim$ 50

Fast onset after MC formation!

<t> << t(cross); clouds swept-up by large scale flows

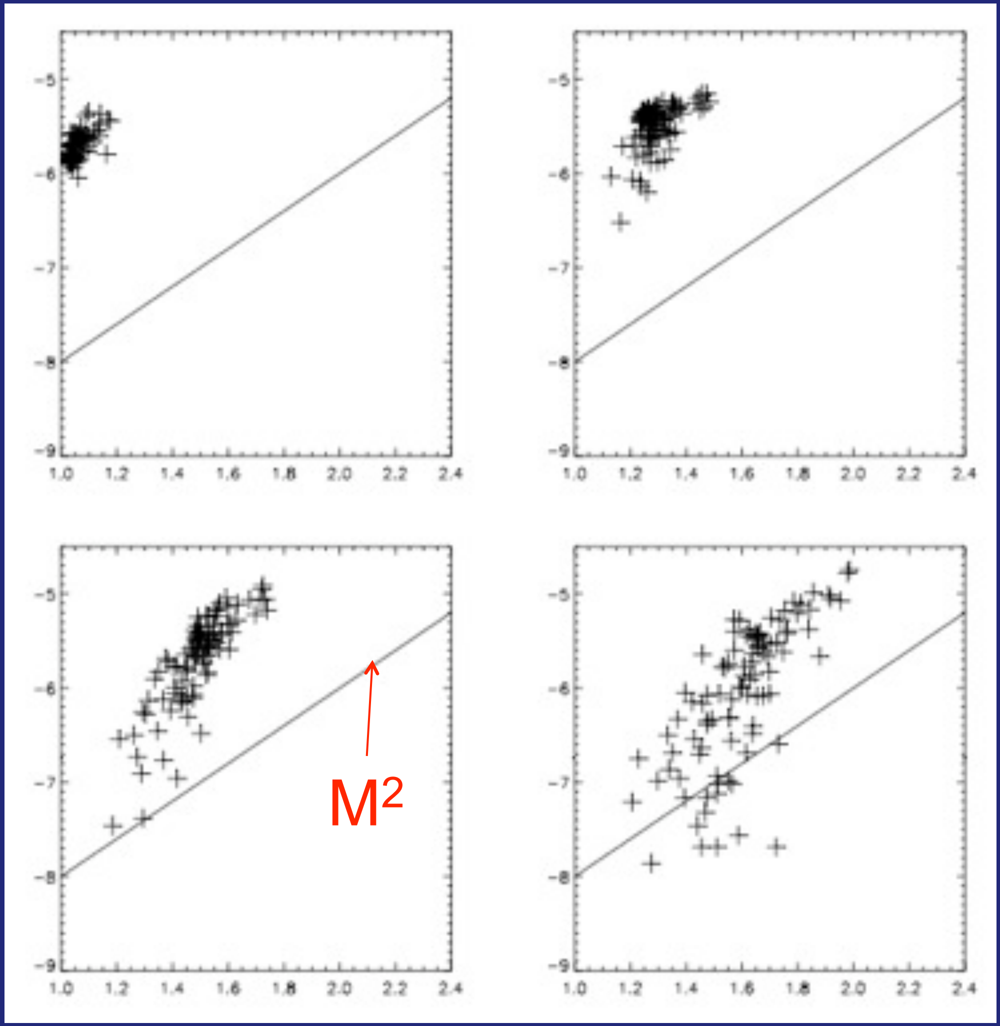
Growth of high-mass power-law tail:

- doesn't require initial cluster environment
- $dM/dt \propto M^2$

dM/dt

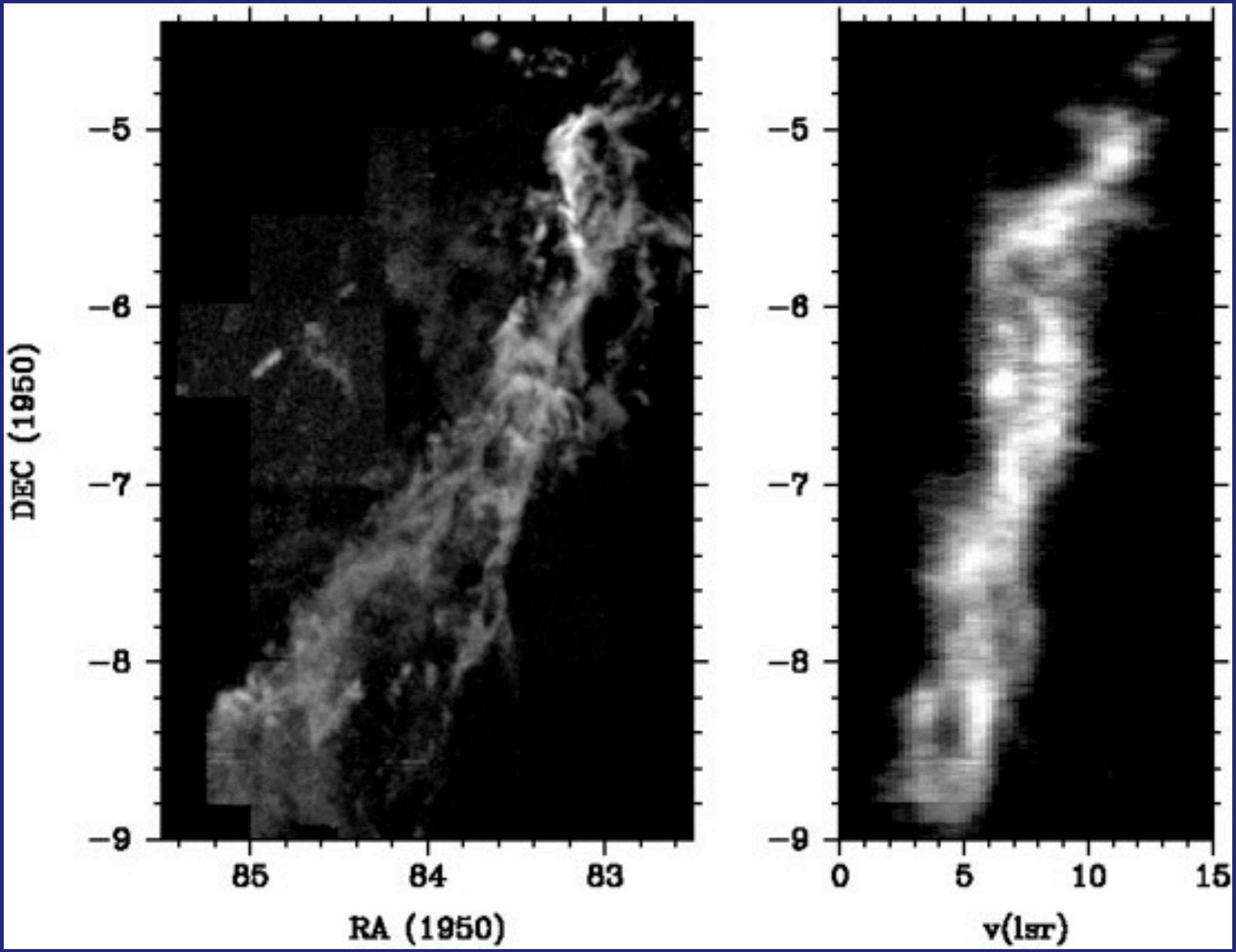
Bondi-Hoyle:

$dM/dt \propto M^2 \rho v^{-3}$



log M

Orion A: ^{13}CO (Bally et al.)



Ages of young associations/clusters

Region	$< t >$ (Myr)	Molecular gas?	t(cross) (Myr)
Coalsack	–	yes	–
Cha III	–	yes	–
Pipe Nebula	–	yes	–
Orion Nebula	1	yes	1
Taurus	2	yes	10
Oph	1	yes	–
Cha I,II	2	yes	–
Lupus	2	yes	–
MBM 12A	2	yes	–
IC 348	2-3	yes	–
NGC 2264	2-3	yes	2-3
Upper Sco	5	no	5
Lower Cen-Crux	10-15	no	$\sim$ 50
Upper Cen-Lup	10-15	no	$\sim$ 50
TW HyA	$\sim$ 10	no	–
η Cha	$\sim$ 10	no	–

Ages of young associations/clusters

Region	$< t >$ (Myr)	Molecular gas?	t(cross) (Myr)
Coalsack	–	yes	–
Cha III	–	yes	–
Pipe Nebula	–	yes	–
Orion Nebula	1	yes	1
Taurus	2	yes	10
Oph	1	yes	–
Cha I,II	2	yes	–
Lupus	2	yes	–
MBM 12A	2	yes	–
IC 348	2-3	yes	–
NGC 2264	2-3	yes	2-3
Upper Sco	5	no	5
Lower Cen-Crux	10-15	no	$\sim$ 50
Upper Cen-Lup	10-15	no	$\sim$ 50
TW HyA	$\sim$ 10	no	–
η Cha	$\sim$ 10	no	–

Fast onset after MC formation! (because cloud is already collapsing globally)

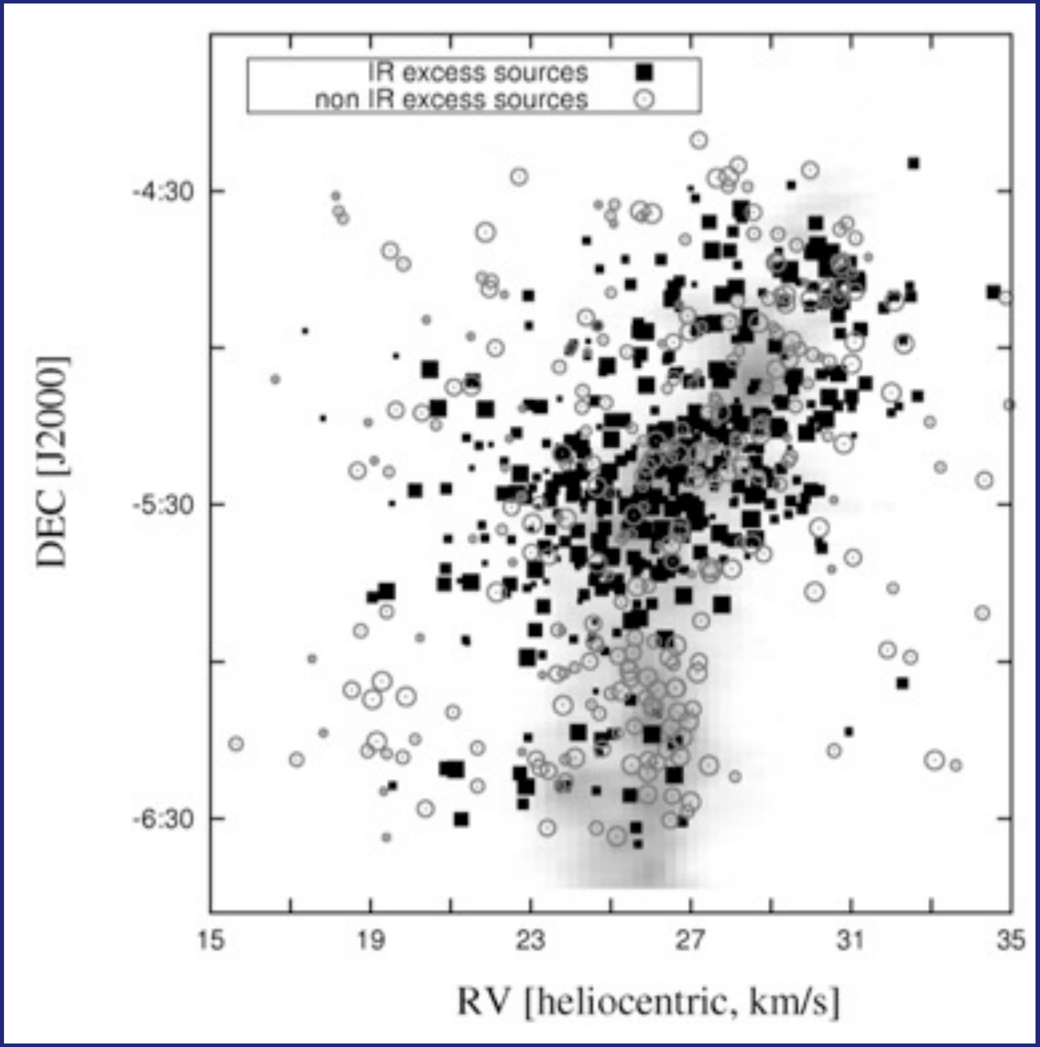
Ages of young associations/clusters

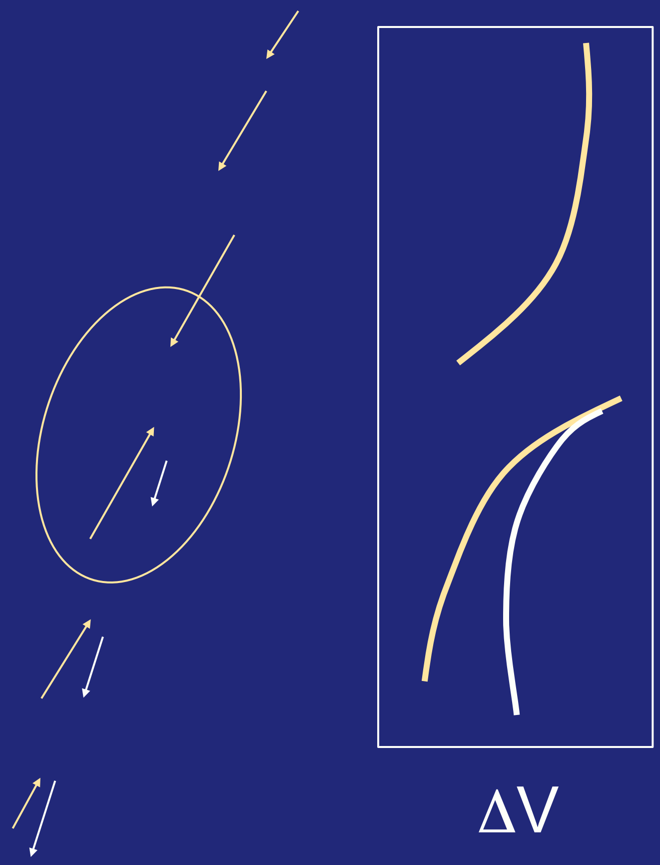
Region	$< t >$ (Myr)	Molecular gas?	t(cross) (Myr)
Coalsack	–	yes	–
Cha III	–	yes	–
Pipe Nebula	–	yes	–
Orion Nebula	1	yes	1
Taurus	2	yes	10
Oph	1	yes	–
Cha I,II	2	yes	–
Lupus	2	yes	–
MBM 12A	2	yes	–
IC 348	2-3	yes	–
NGC 2264	2-3	yes	2-3
Upper Sco	5	no	5
Lower Cen-Crux	10-15	no	$\sim$ 50
Upper Cen-Lup	10-15	no	$\sim$ 50
TW HyA	$\sim$ 10	no	–
η Cha	$\sim$ 10	no	–

Fast onset after MC formation! (because cloud is already collapsing globally)

star formation lasts for ~ 3-4 Myr; then gas dispersed!

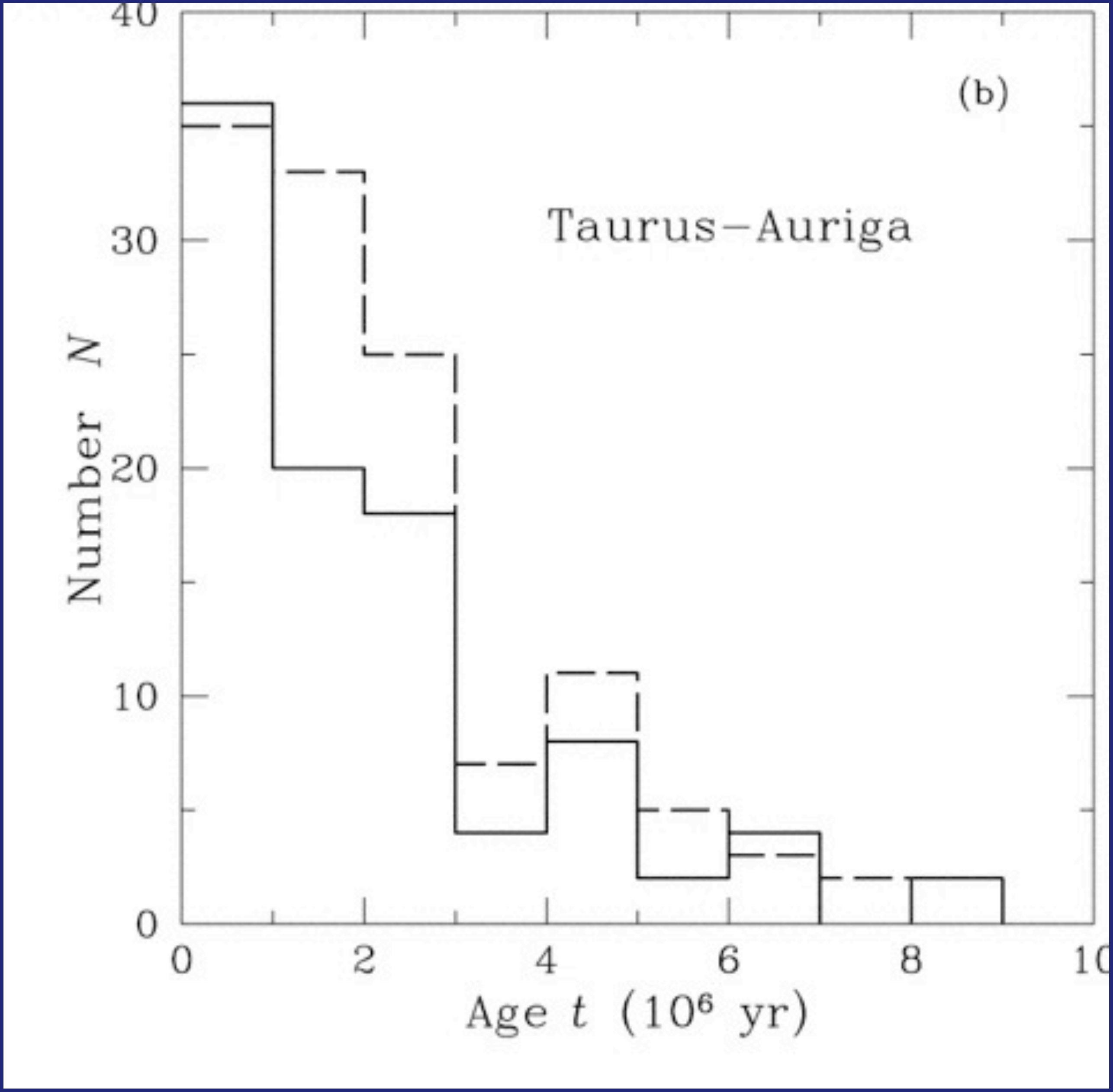
Orion Nebula cluster- kinematics of stars and gas: evidence for infall?



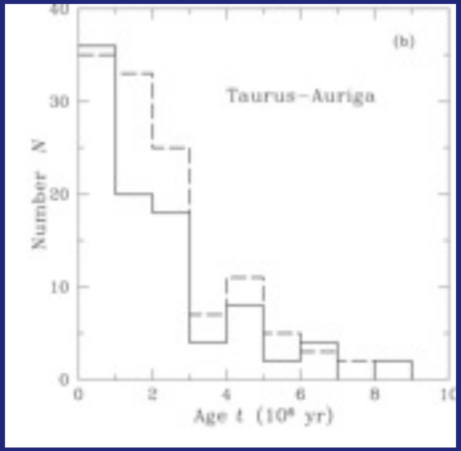


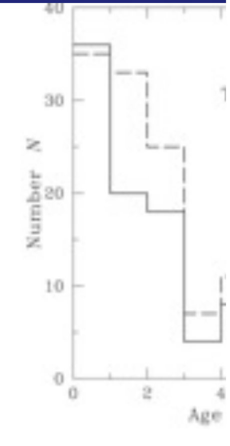
J. Tobin, et al. 2009

E. Proszkow, F. Adams

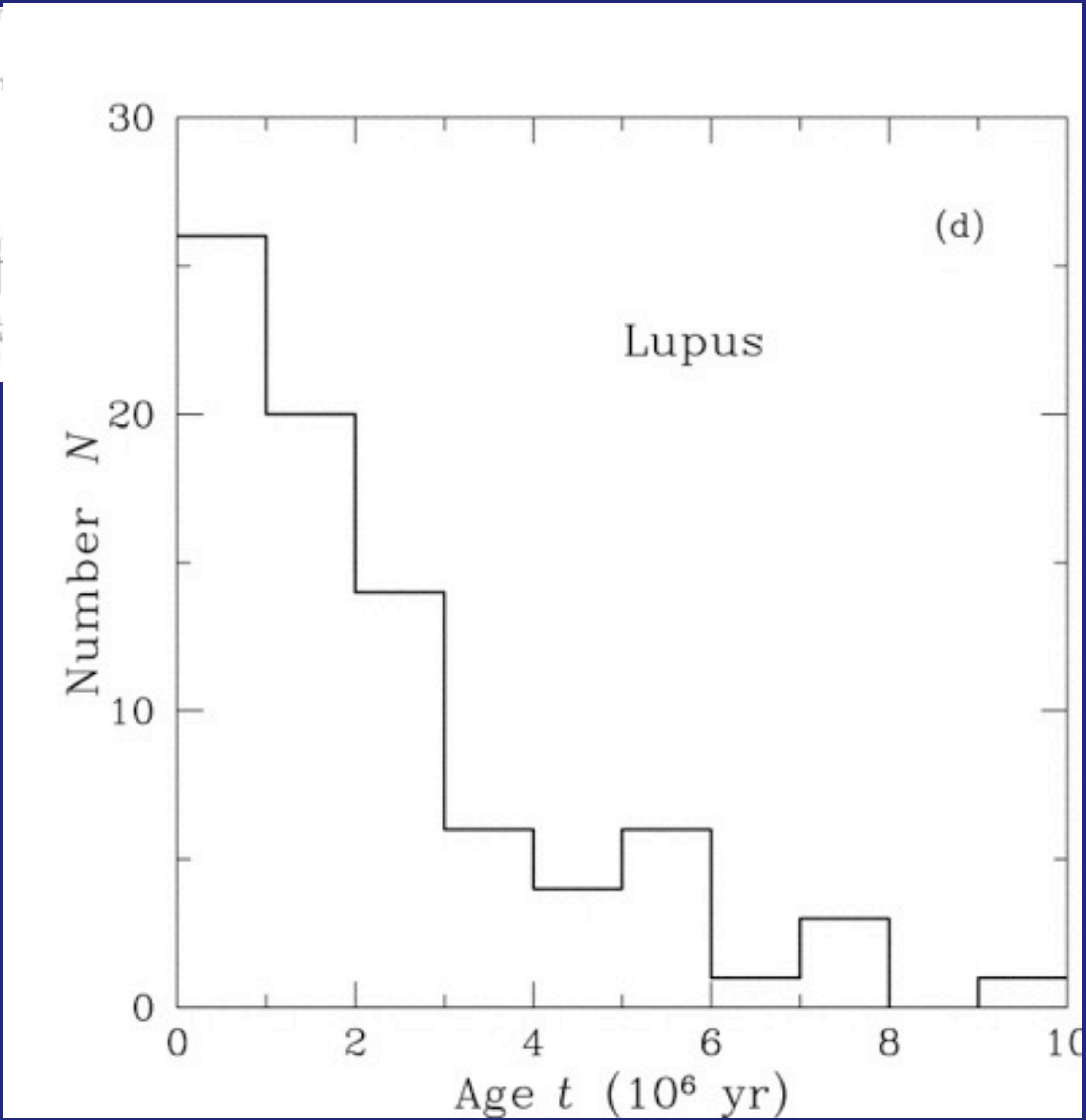


(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)
0
10
20
30
40
0
2
4
6
8
10

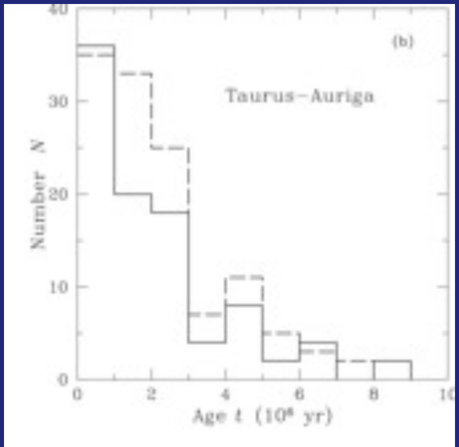

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)



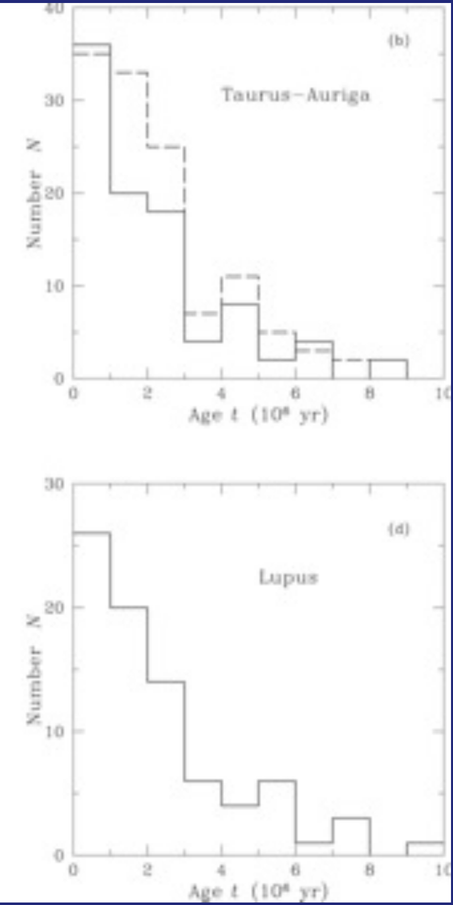
40
30
20
10
0
0
2
4
Number N
Age

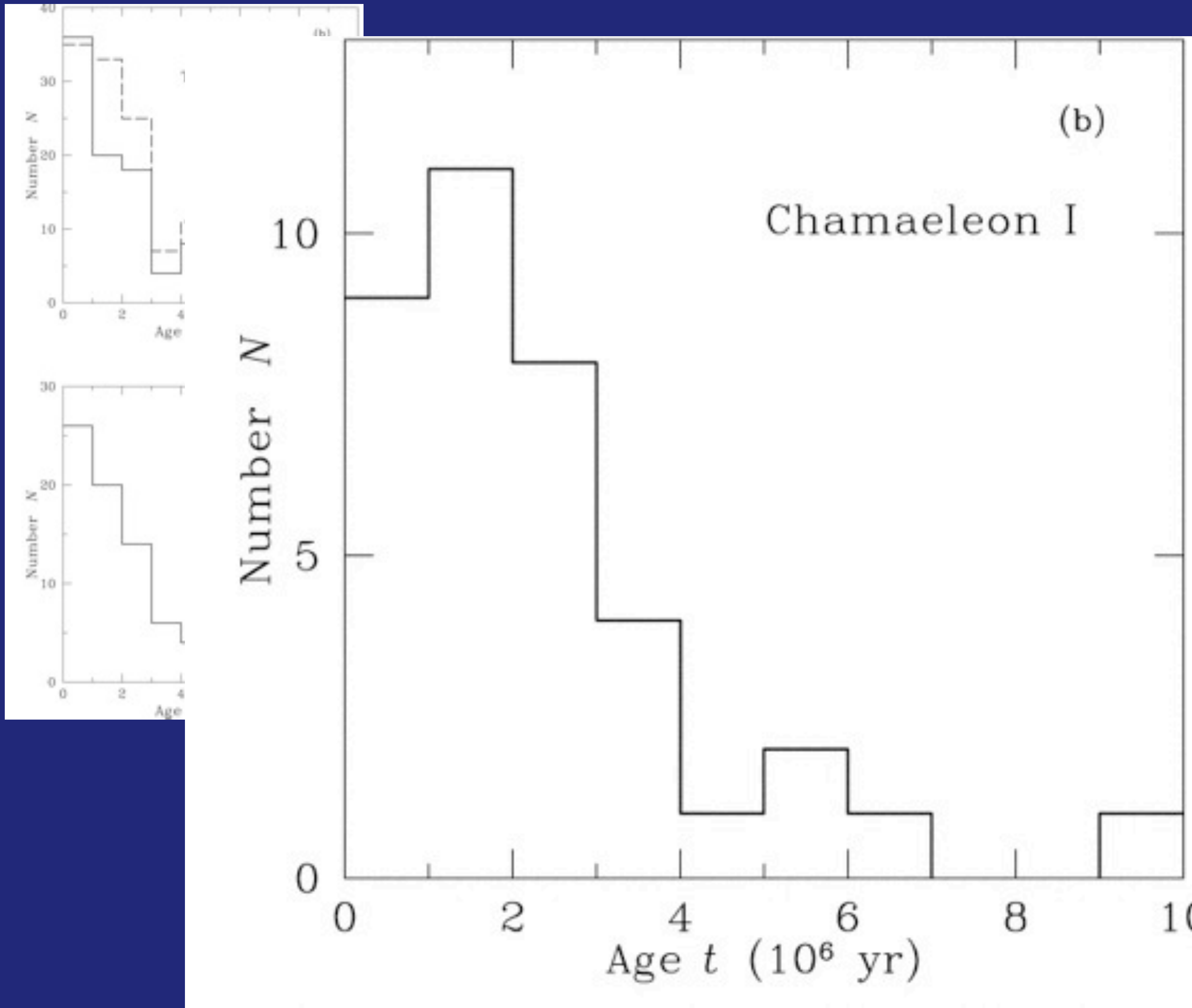


30
20
10
0
0
2
4
6
8
10
(d)
Lupus
Number N
Age t (10⁶ yr)

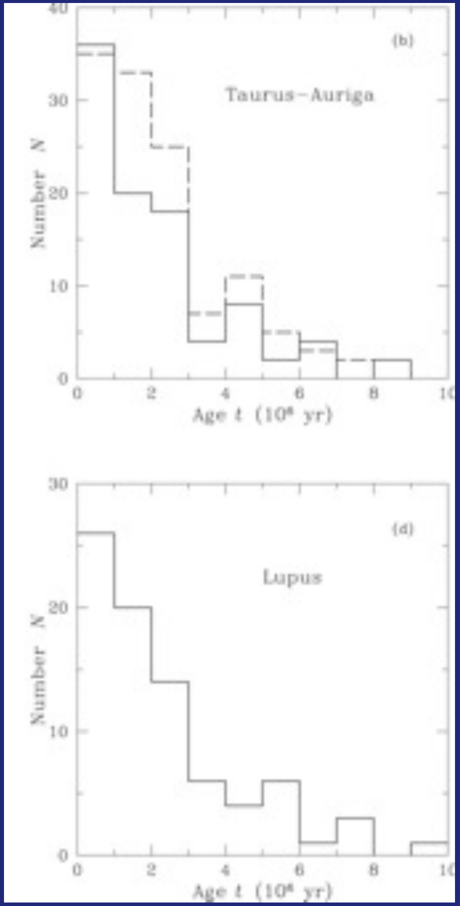


(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)

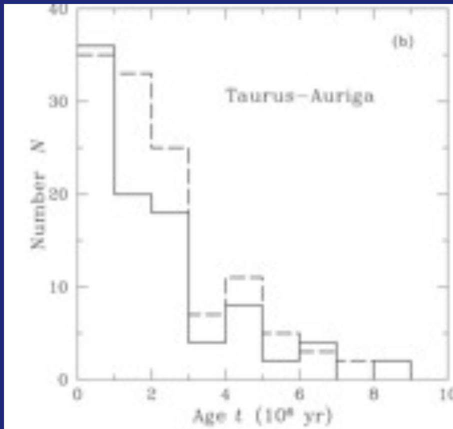

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)
(d)
Lupus
Number N
Age t (10^6 yr)

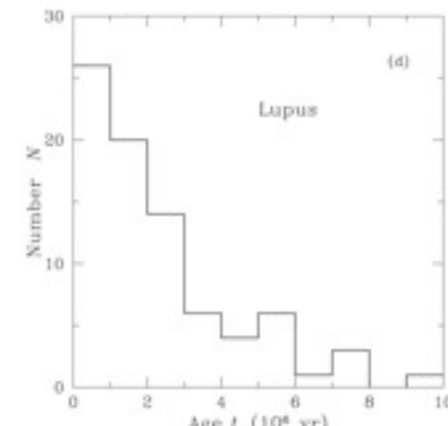


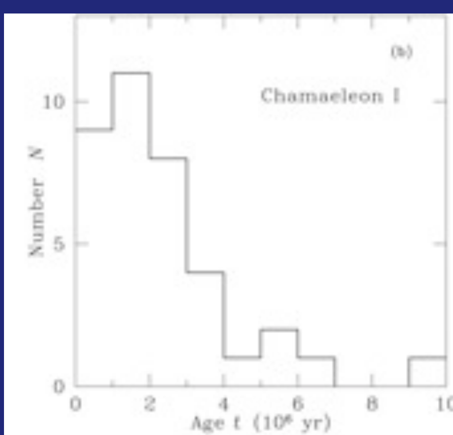
(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

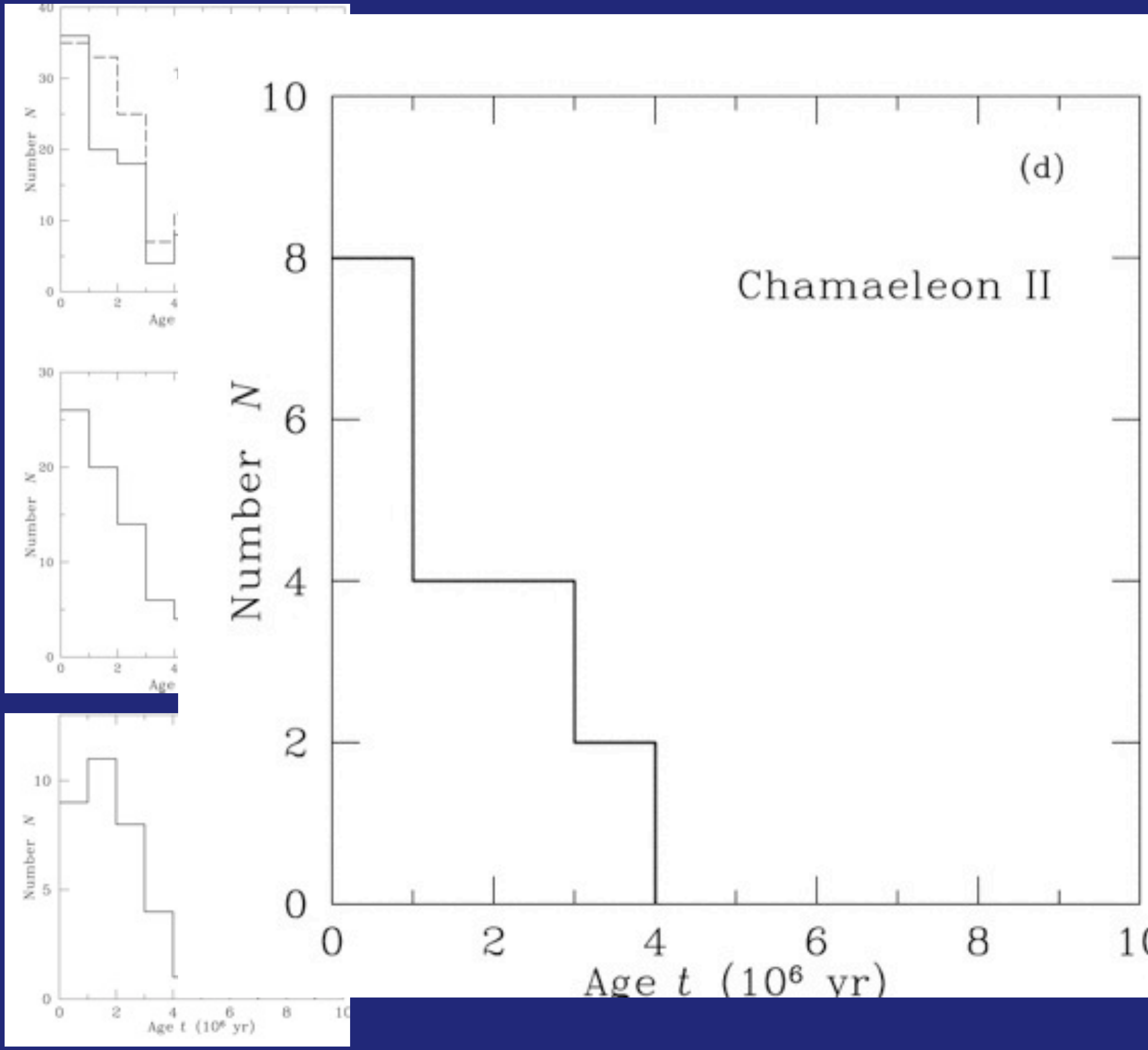


(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)
(d)
Lupus
Number N
Age t (10⁶ yr)

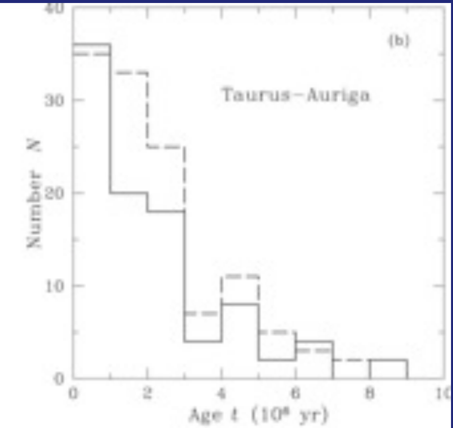

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)
0 10 20 30 40
0 2 4 6 8 10

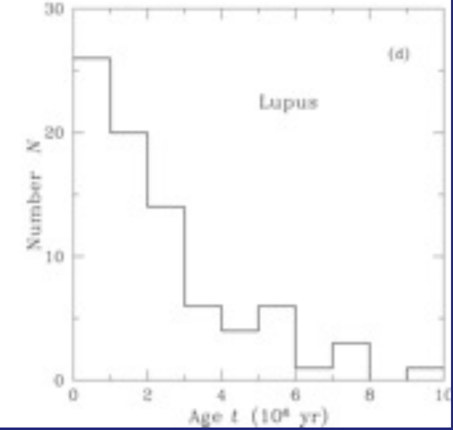

(d)
Lupus
Number N
Age t (10^6 yr)
0 10 20 30
0 2 4 6 8 10

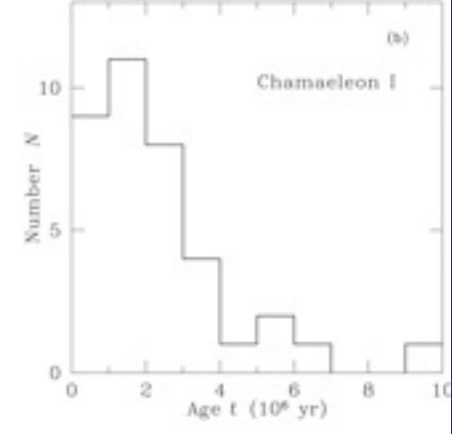

(b)
Chamaeleon I
Number N
Age t (10^6 yr)
0 5 10
0 2 4 6 8 10

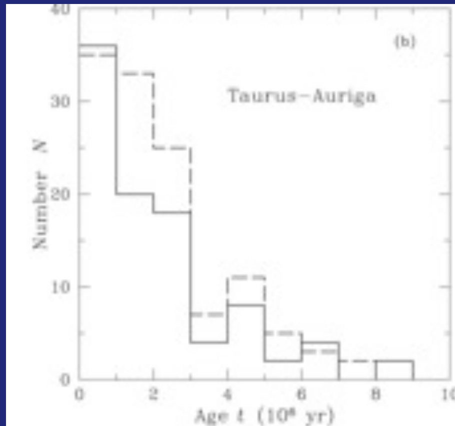


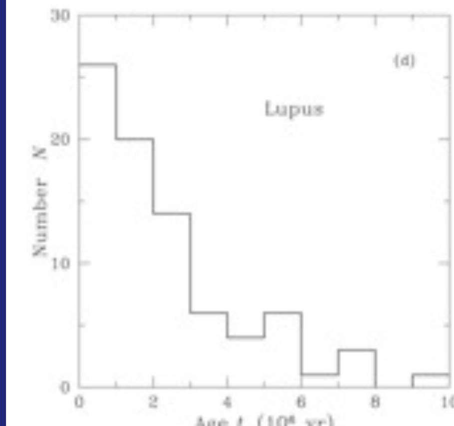
Chamaeleon II
(d)
Number N
Age t (10^6 yr)

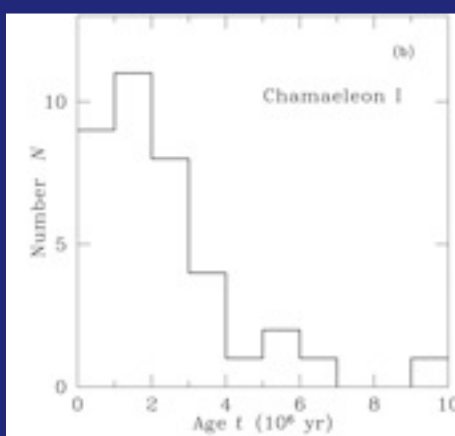

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)

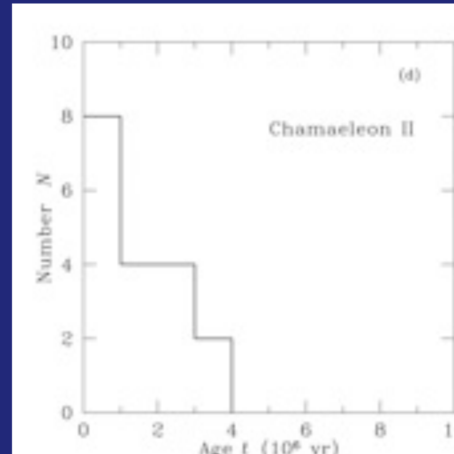

(d)
Lupus
Number N
Age t (10^6 yr)

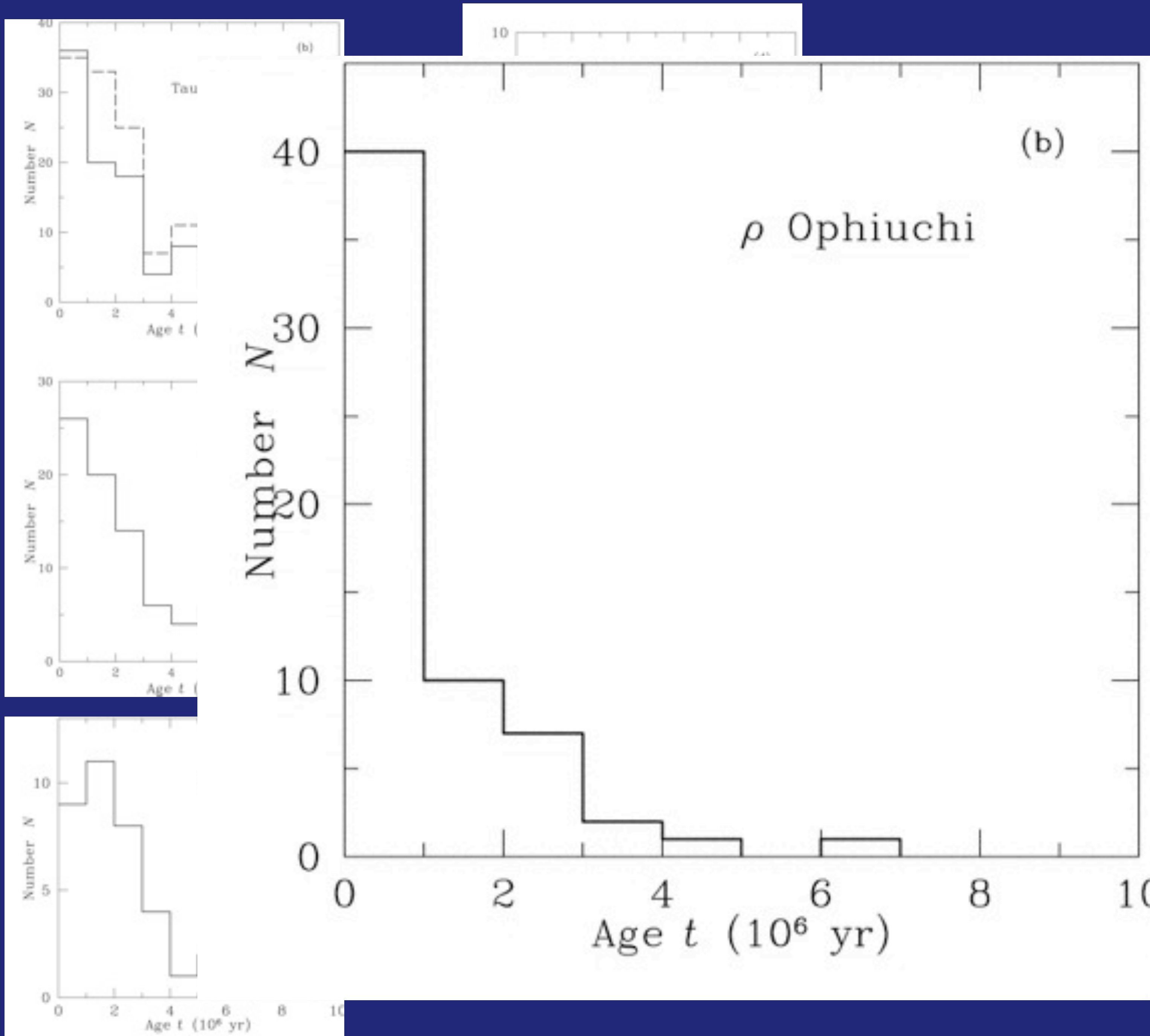

(b)
Chamaeleon I
Number N
Age t (10^6 yr)

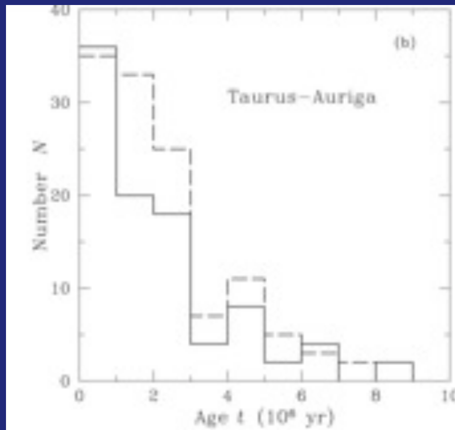

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)

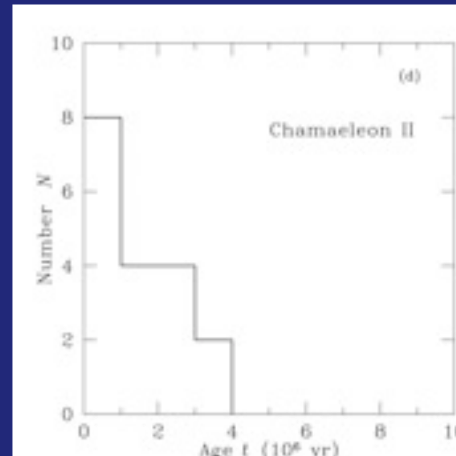

(d)
Lupus
Number N
Age t (10^6 yr)

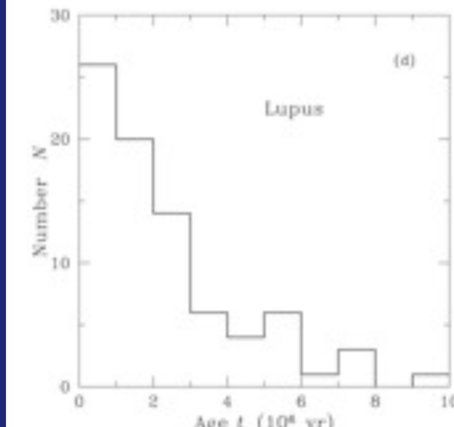

(b)
Chamaeleon I
Number N
Age t (10^6 yr)

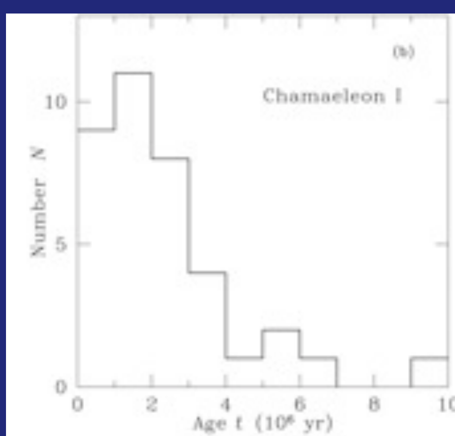

(d)
Chamaeleon II
Number N
Age t (10^6 yr)

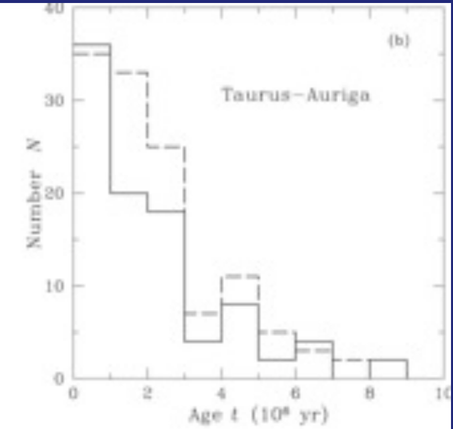

(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)
0
10
20
30
40
2
4
6
8
10

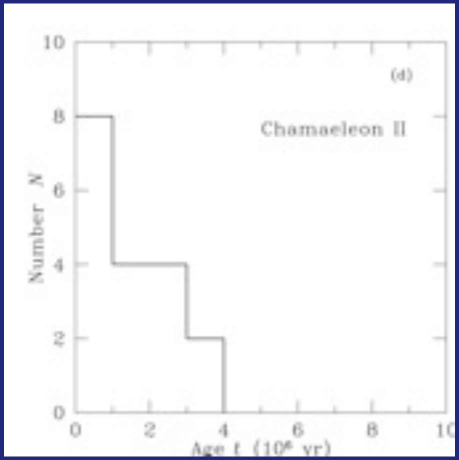

(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)

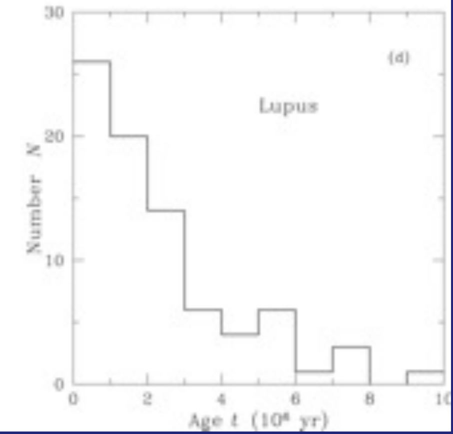

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)

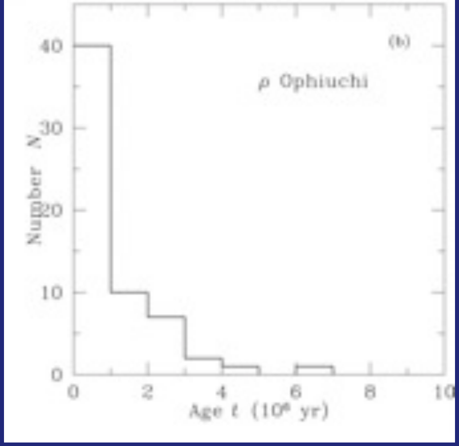

(d)
Lupus
Number N
Age t (10⁶ yr)

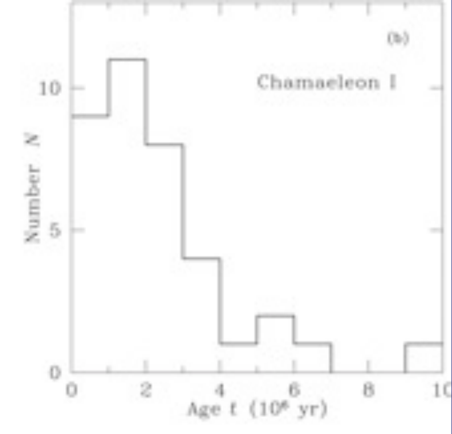

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

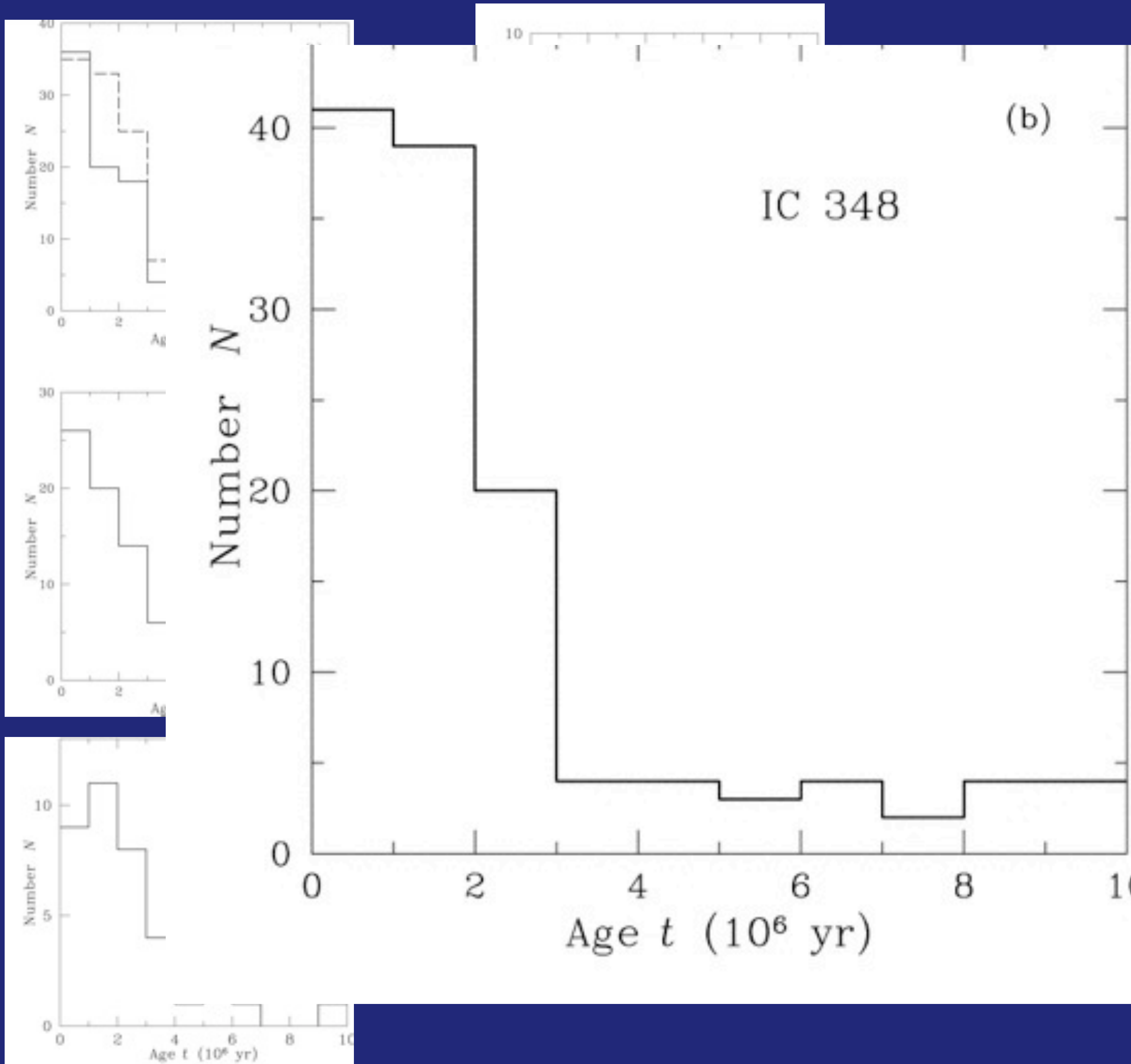

(b)
Taurus−Auriga
Number N
Age t (10⁶ yr)


(d)
Chamaeleon II
Number N
Age t (10⁶ yr)

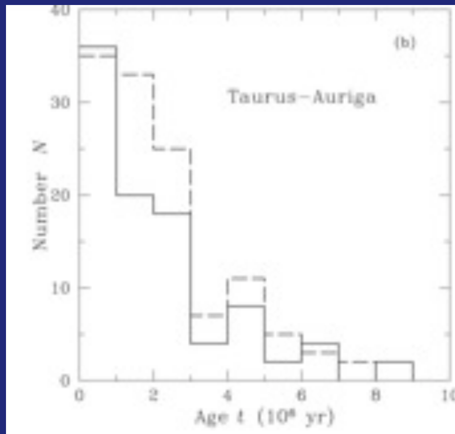

(d)
Lupus
Number N
Age t (10⁶ yr)

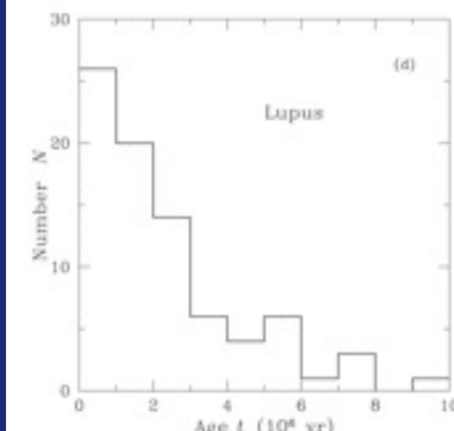

(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)

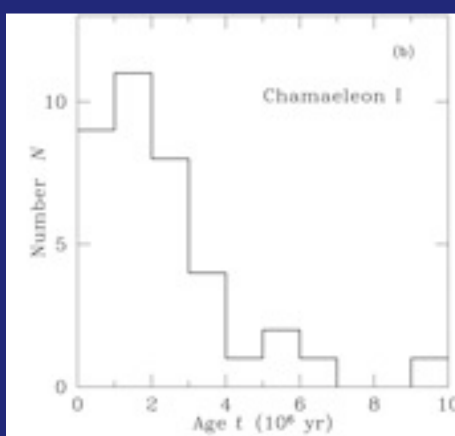

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

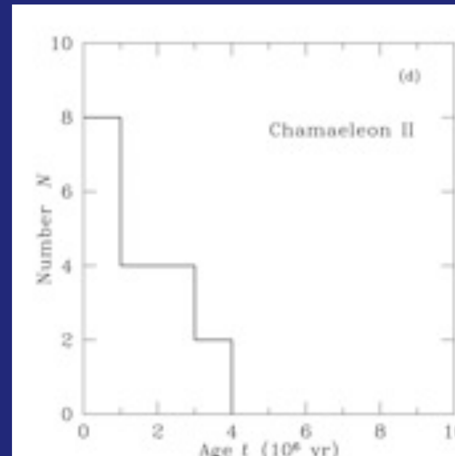


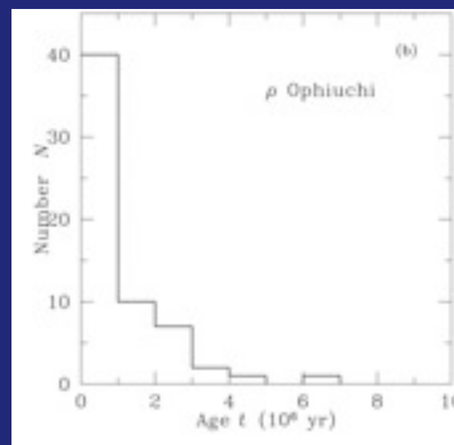
(b)
IC 348
Number N
Age t (10⁶ yr)

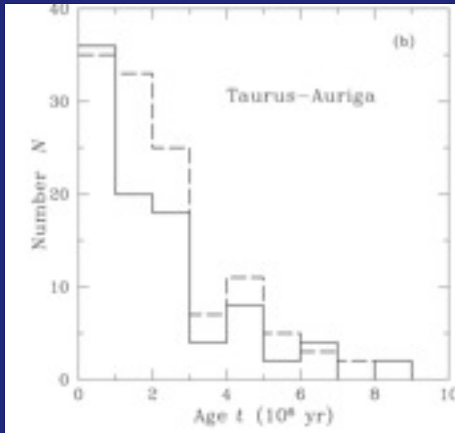

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)

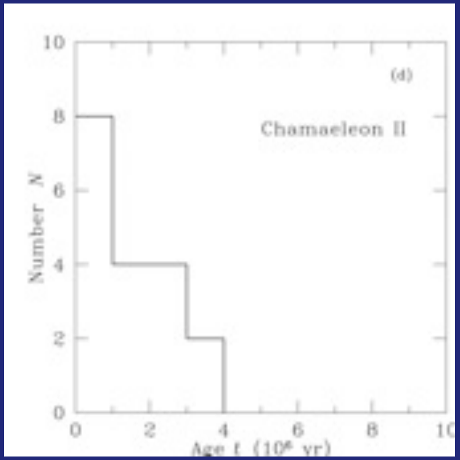

(d)
Lupus
Number N
Age t (10^6 yr)

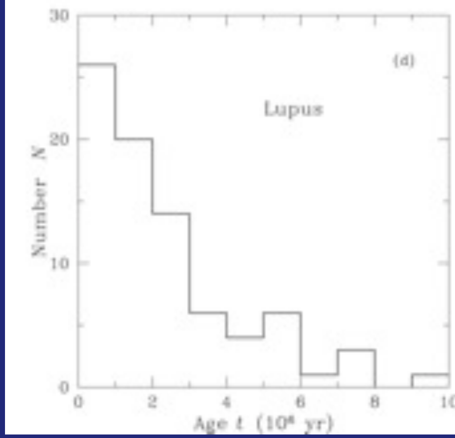

(b)
Chamaeleon I
Number N
Age t (10^6 yr)

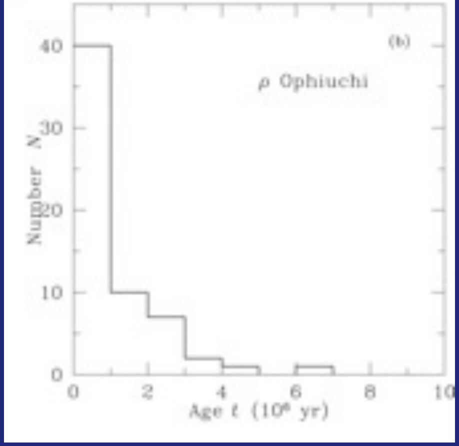

(d)
Chamaeleon II
Number N
Age t (10^6 yr)

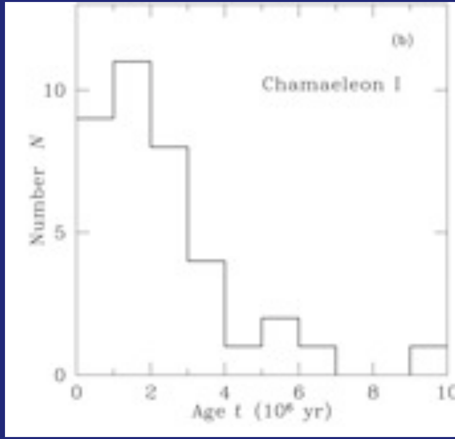

(b)
ρ Ophiuchi
Number N
Age t (10^6 yr)

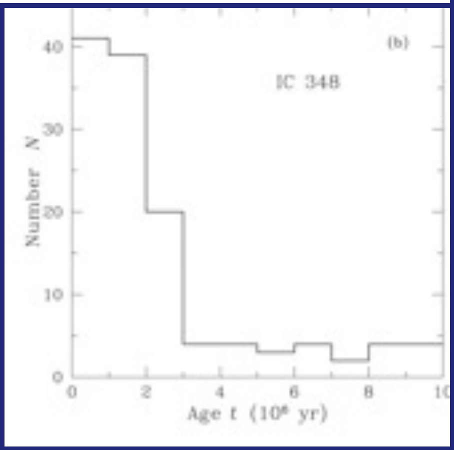

(b)
Taurus-Auriga
Number N
Age t (10⁶ yr)
0
10
20
30
40
0
2
4
6
8
10

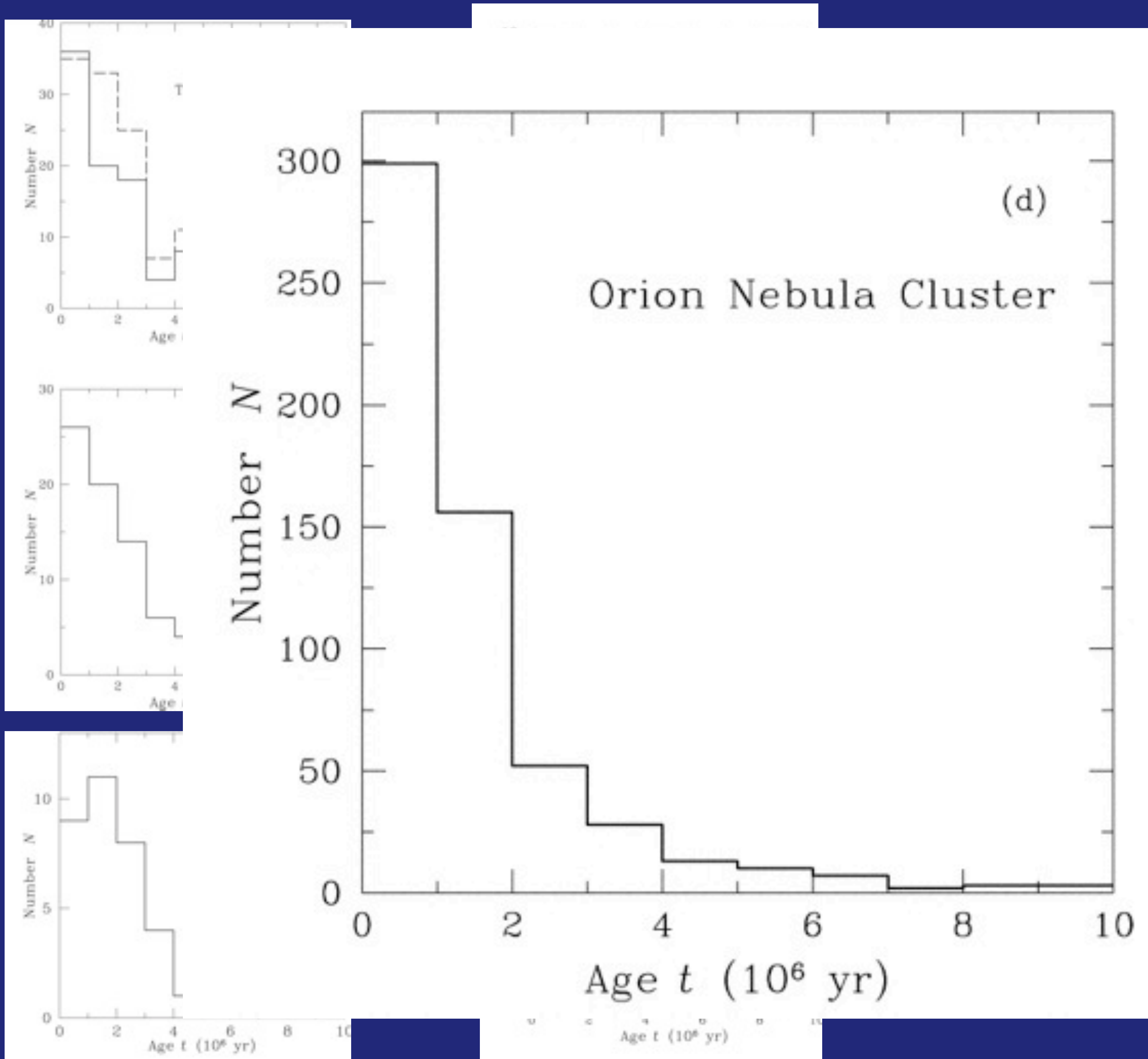

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)
0
2
4
6
8
10
0
2
4
6
8
10


(d)
Lupus
Number N
Age t (10⁶ yr)
0
10
20
30
0
2
4
6
8
10

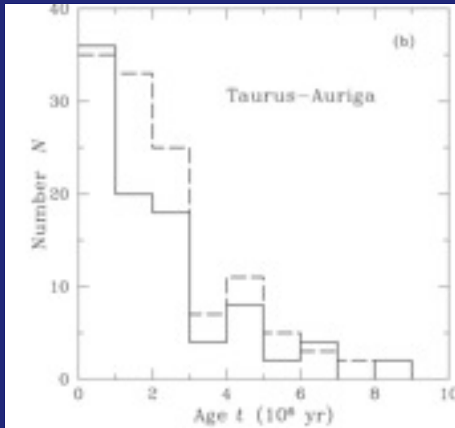

(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)
0
10
20
30
40
0
2
4
6
8
10

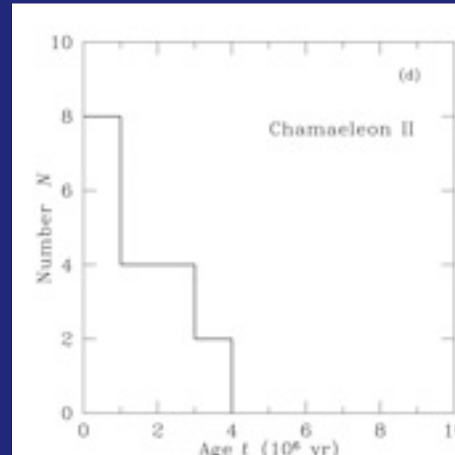

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)
0
5
10
0
2
4
6
8
10

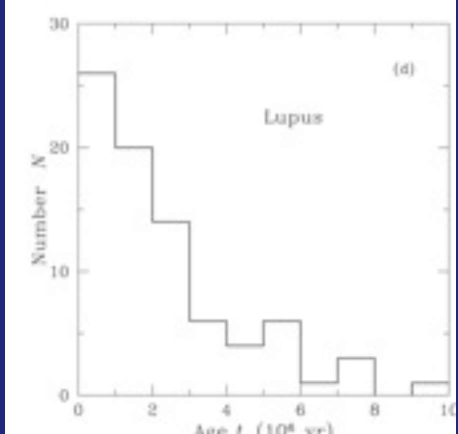

(b)
IC 348
Number N
Age t (10⁶ yr)
0
10
20
30
40
0
2
4
6
8
10

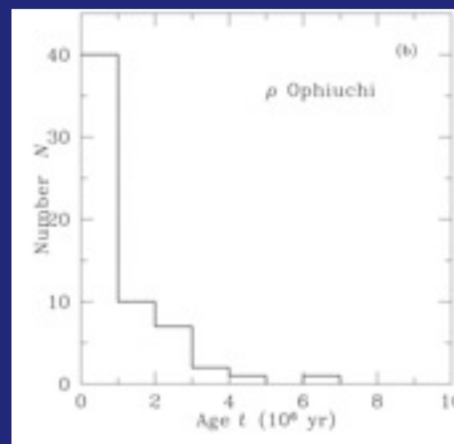


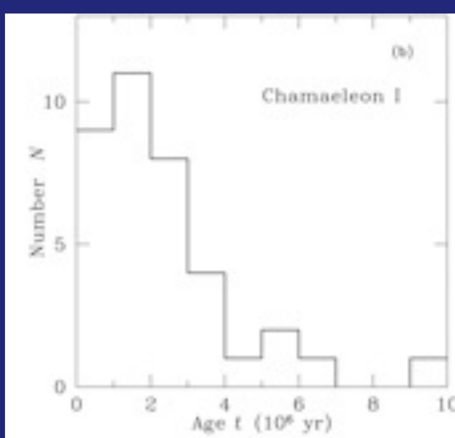
(d)
Orion Nebula Cluster
Number N
Age t (10^6 yr)
0
50
100
150
200
250
300
0
2
4
6
8
10

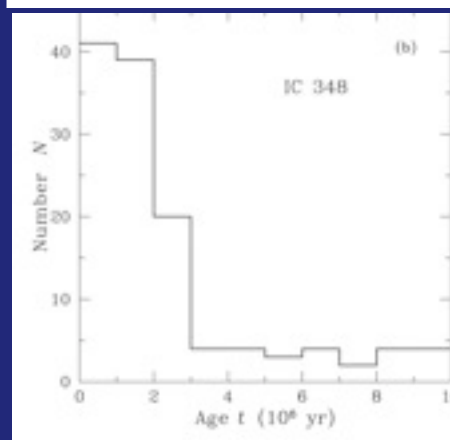

(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)

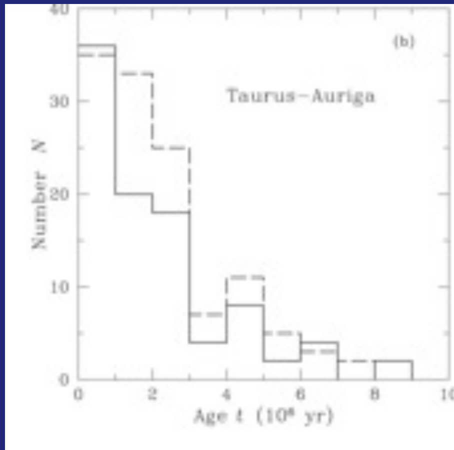

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)

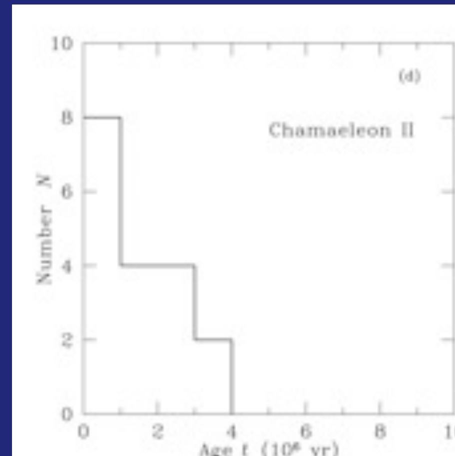

(d)
Lupus
Number N
Age t (10⁶ yr)

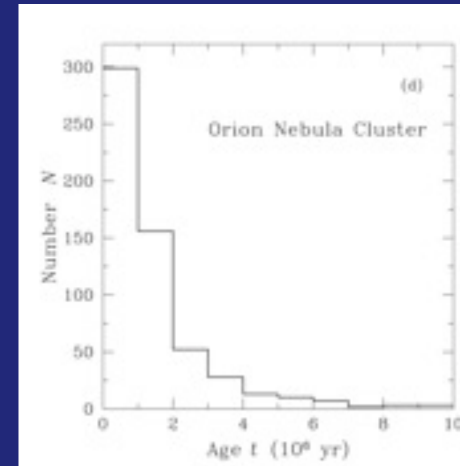

(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)

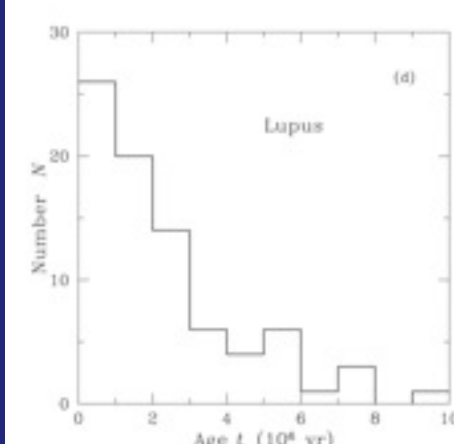

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

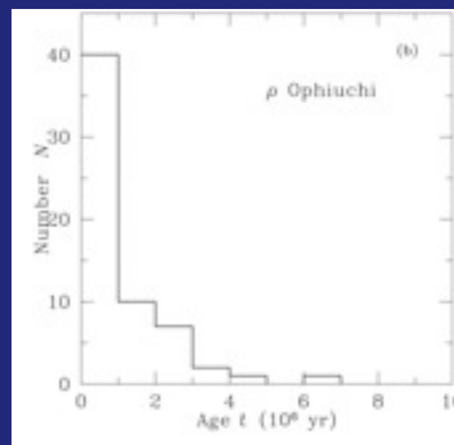

(b)
IC 348
Number N
Age t (10⁶ yr)

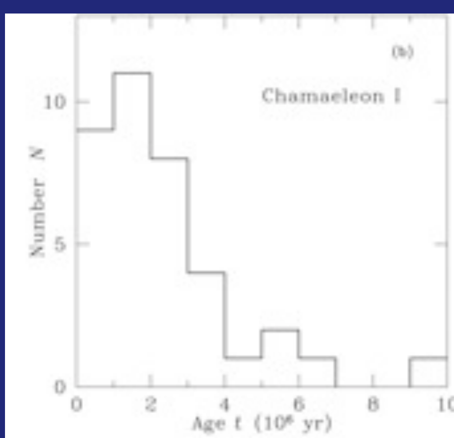

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)

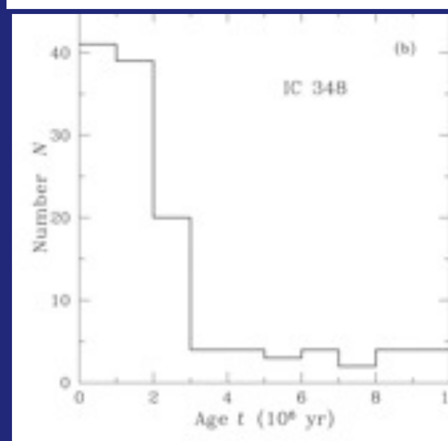

(d)
Chamaeleon II
Number N
Age t (10^6 yr)

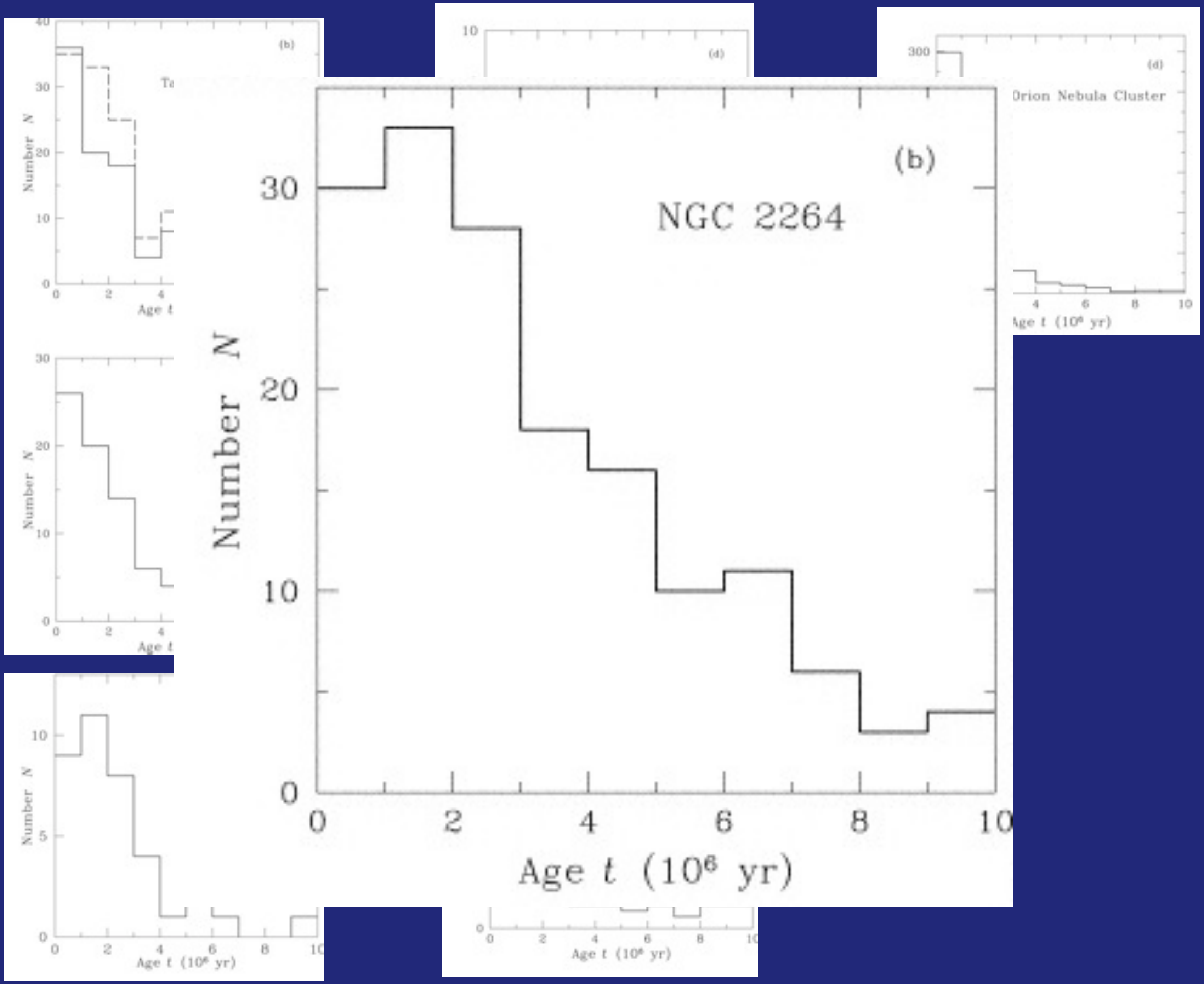

(d)
Orion Nebula Cluster
Number N
Age t (10^6 yr)


(d)
Lupus
Number N
Age t (10^6 yr)

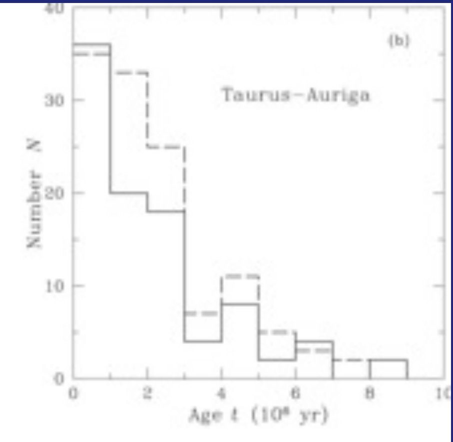

(b)
ρ Ophiuchi
Number N
Age t (10^6 yr)

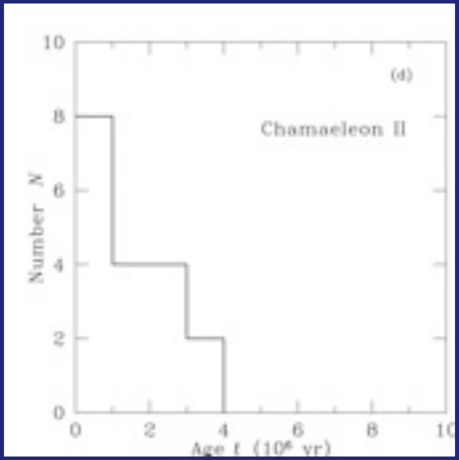

(b)
Chamaeleon I
Number N
Age t (10^6 yr)

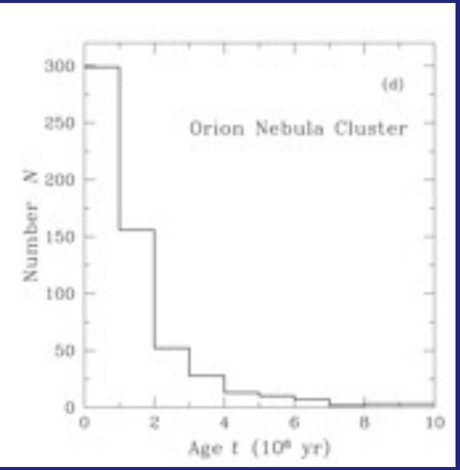

(b)
IC 348
Number N
Age t (10^6 yr)

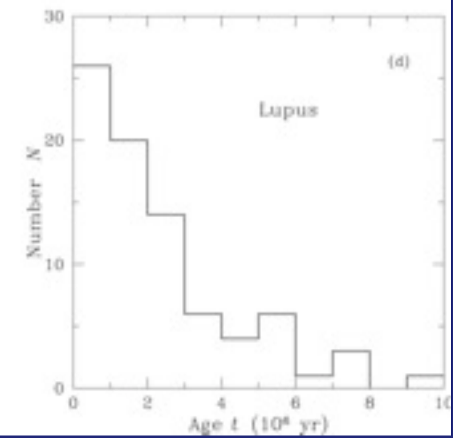


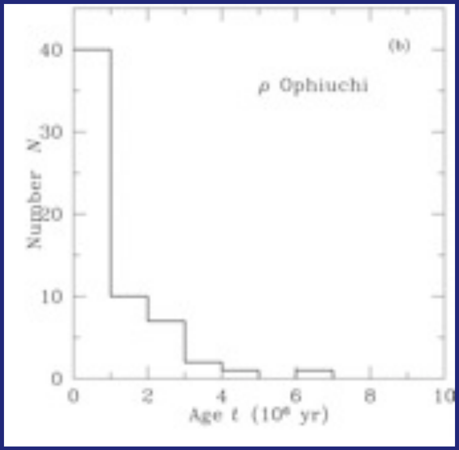
NGC 2264
(b)
Number N
Age t (10⁶ yr)
Orion Nebula Cluster

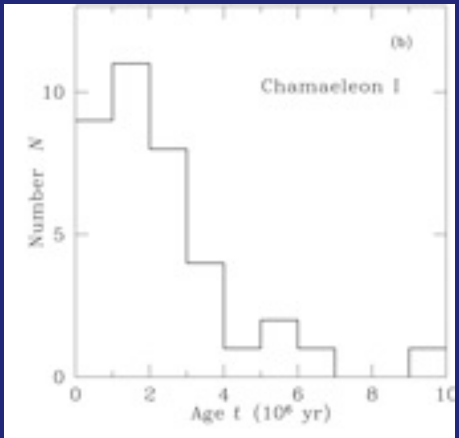

(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)

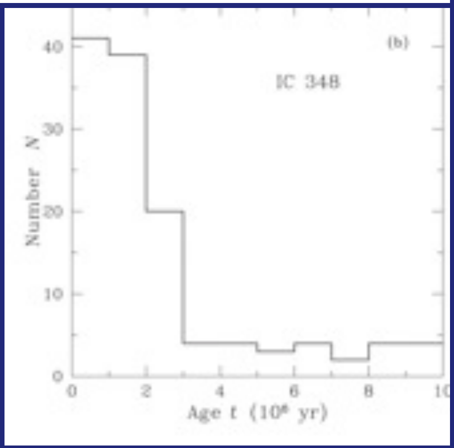

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)

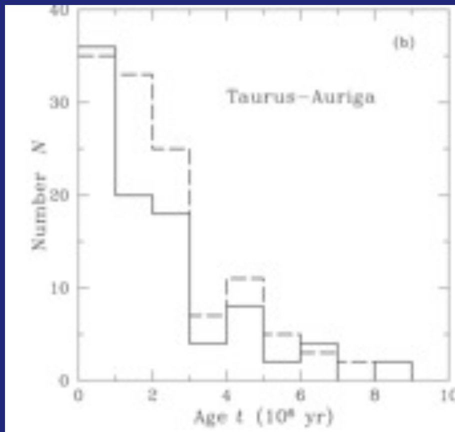

(d)
Orion Nebula Cluster
Number N
Age t (10⁶ yr)

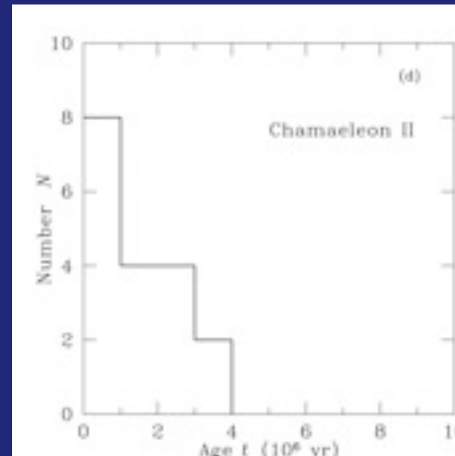

(d)
Lupus
Number N
Age t (10⁶ yr)

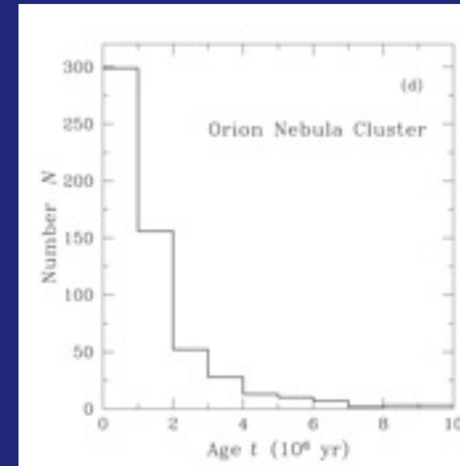

(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)

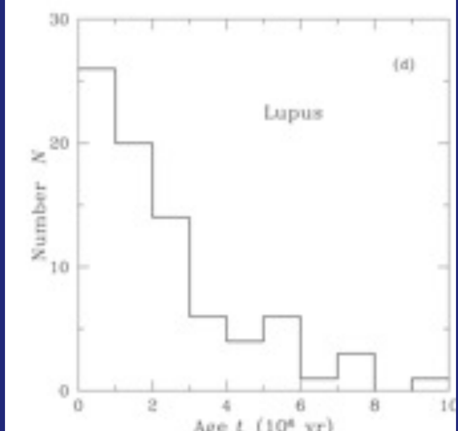

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

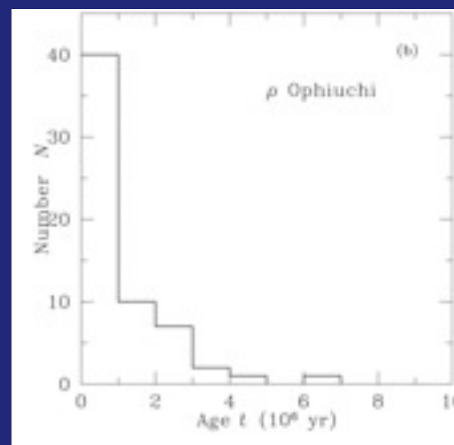

(b)
IC 348
Number N
Age t (10⁶ yr)

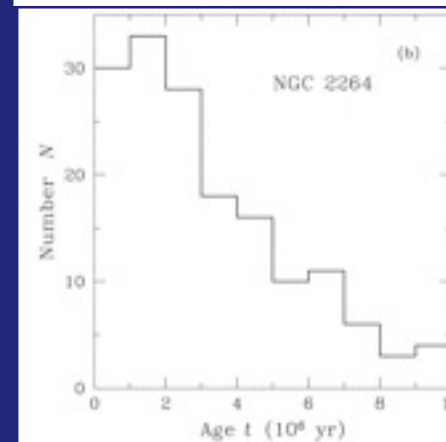

(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)

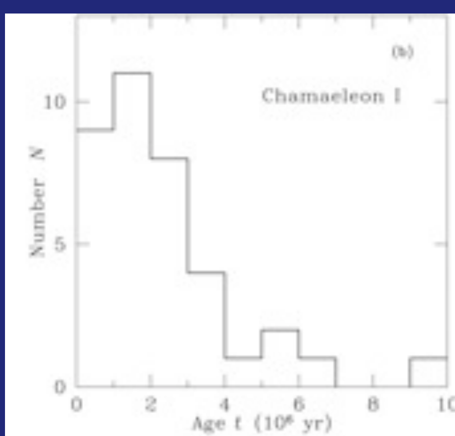

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)

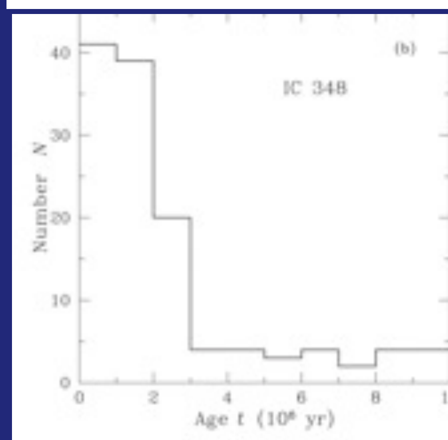

(d)
Orion Nebula Cluster
Number N
Age t (10⁶ yr)

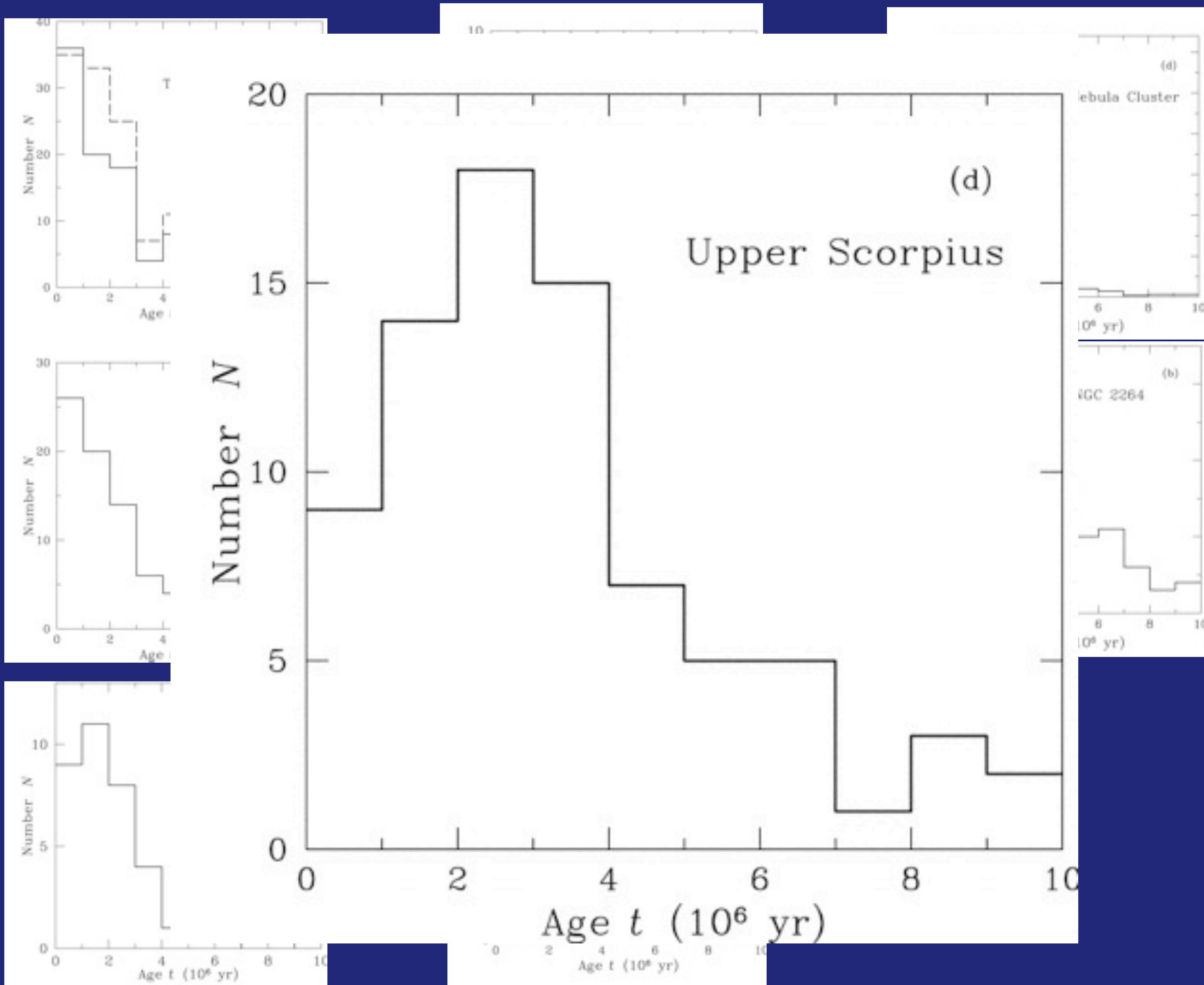

(d)
Lupus
Number N
Age t (10⁶ yr)


(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)

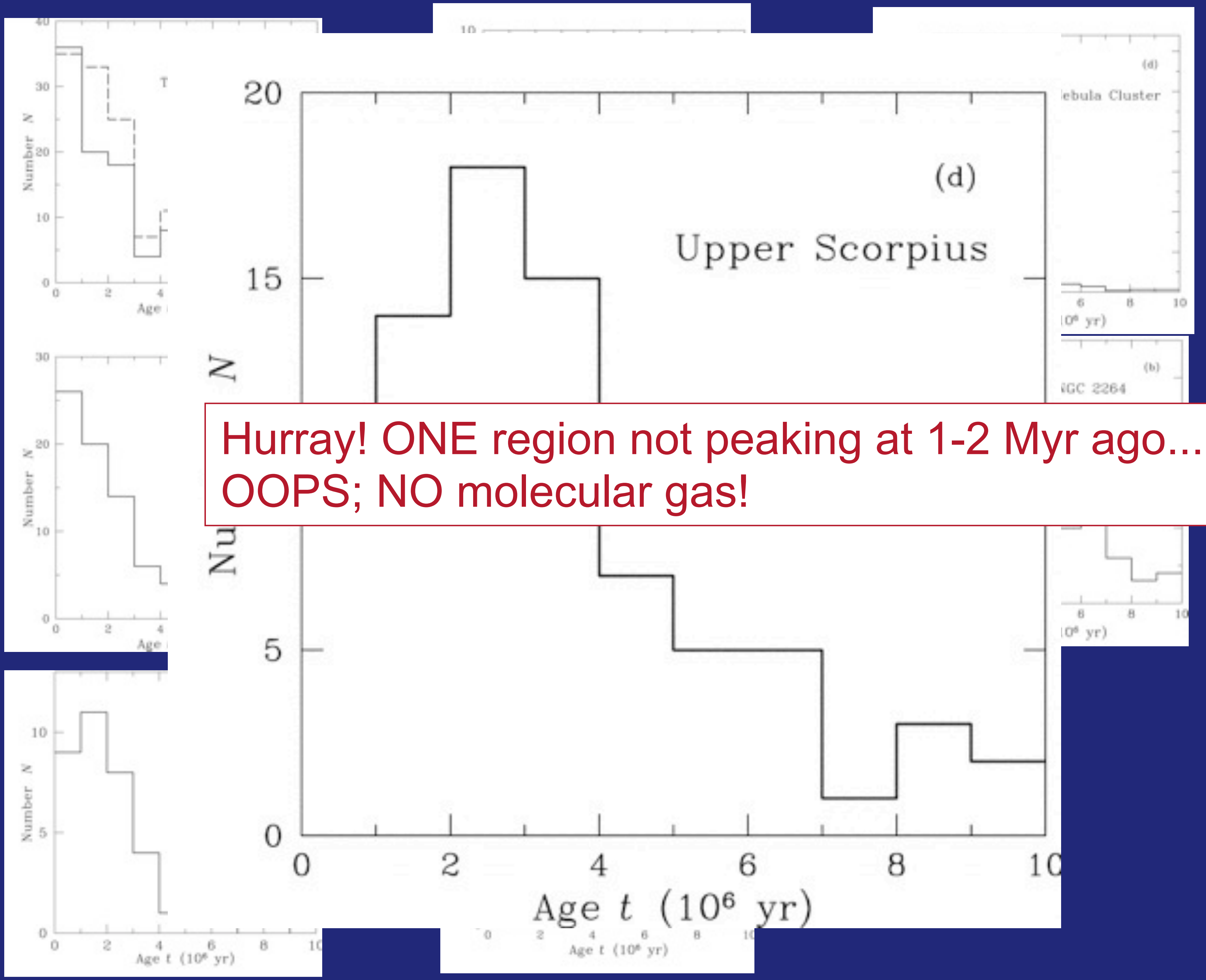

(b)
NGC 2264
Number N
Age t (10⁶ yr)


(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

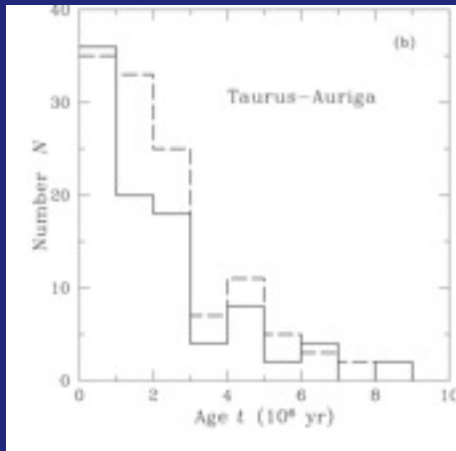

(b)
IC 348
Number N
Age t (10⁶ yr)

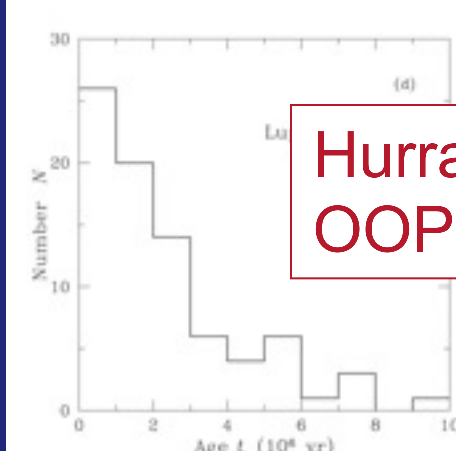


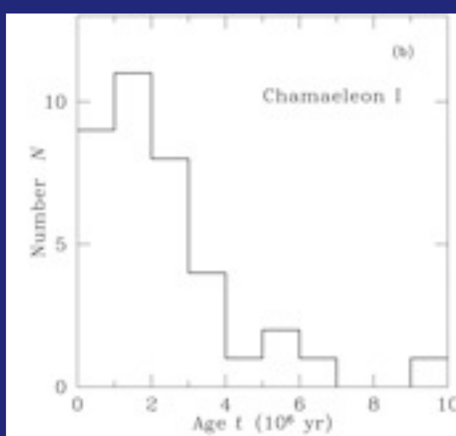
(d)
Upper Scorpius
Number N
0
5
10
15
20
0
2
4
6
8
10
Age t (10⁶ yr)
ebula Cluster
GC 2264
Age t (10⁶ yr)

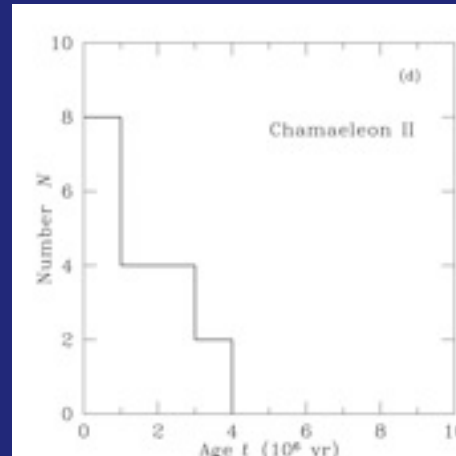


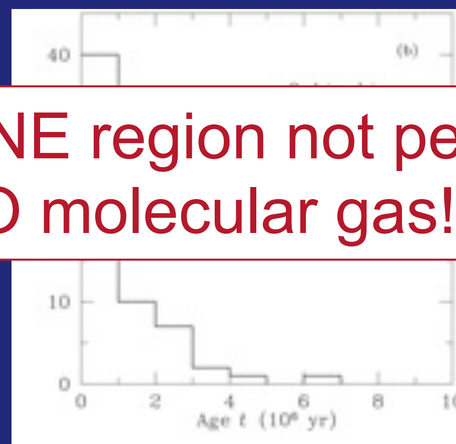
Upper Scorpius
(d)
Number N
Age t (10^6 yr)
Hurray! ONE region not peaking at 1-2 Myr ago...
OOPS; NO molecular gas!

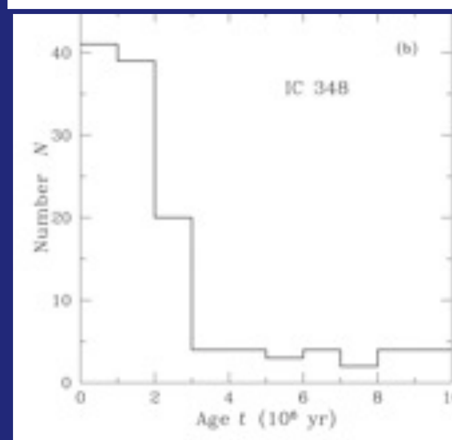


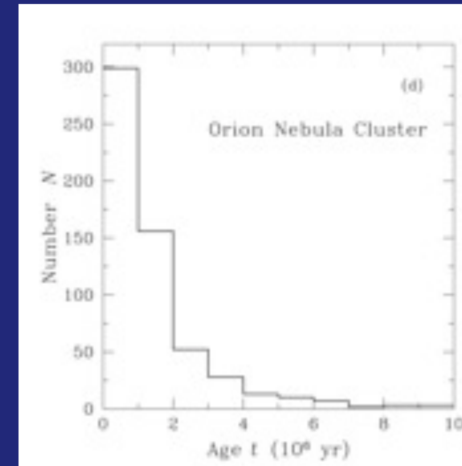


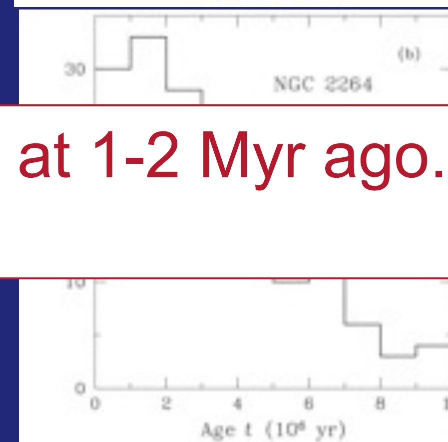




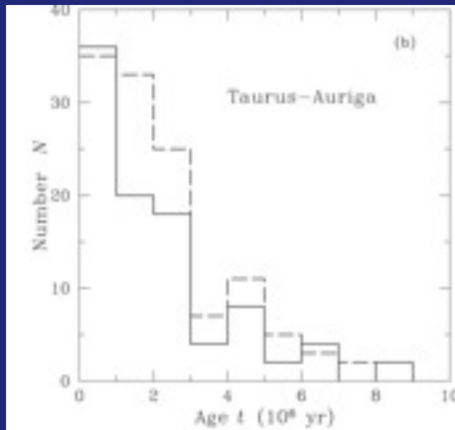


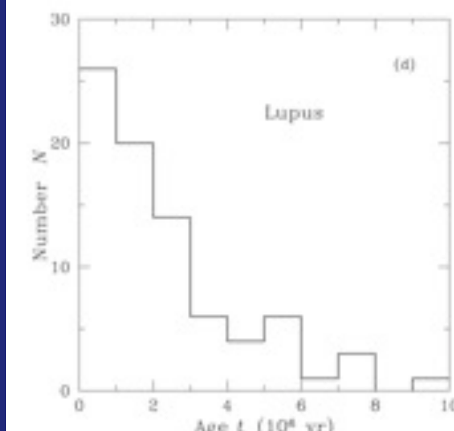


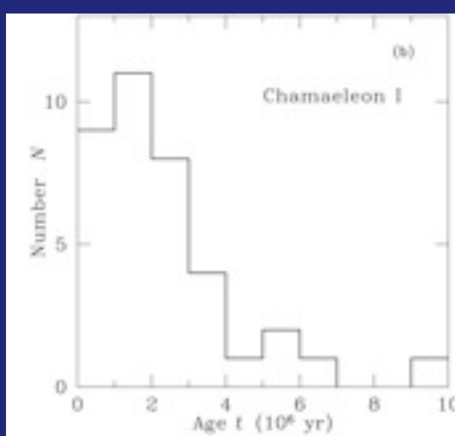


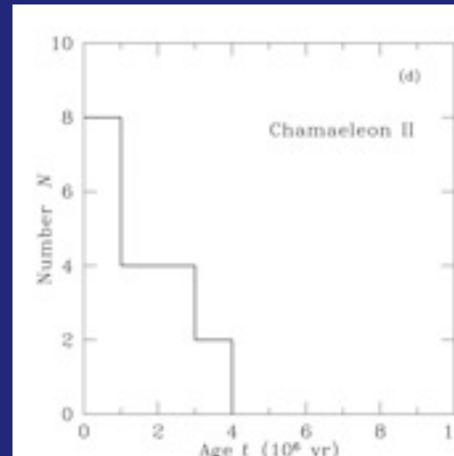


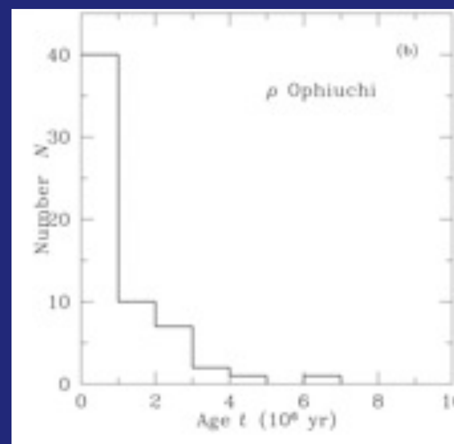
Hurray! ONE region not peaking at 1-2 Myr ago...
OOPS; NO molecular gas!

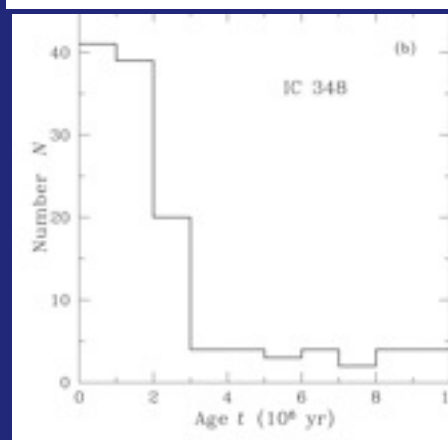

(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)

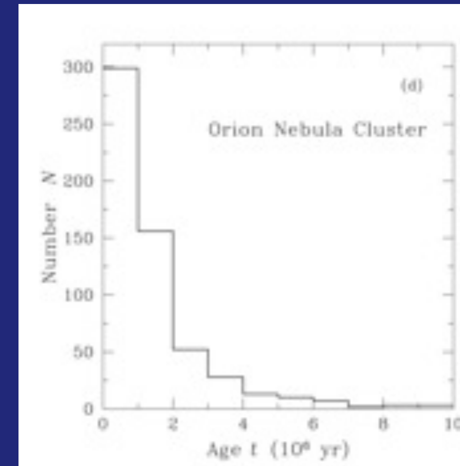

(d)
Lupus
Number N
Age t (10⁶ yr)

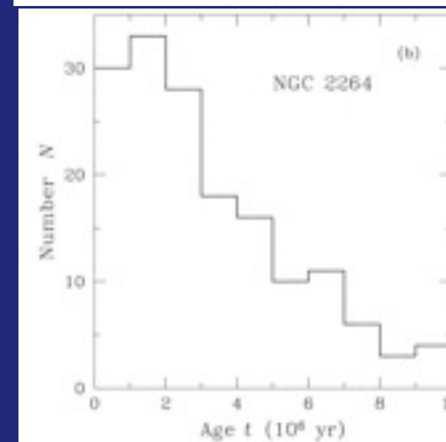

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

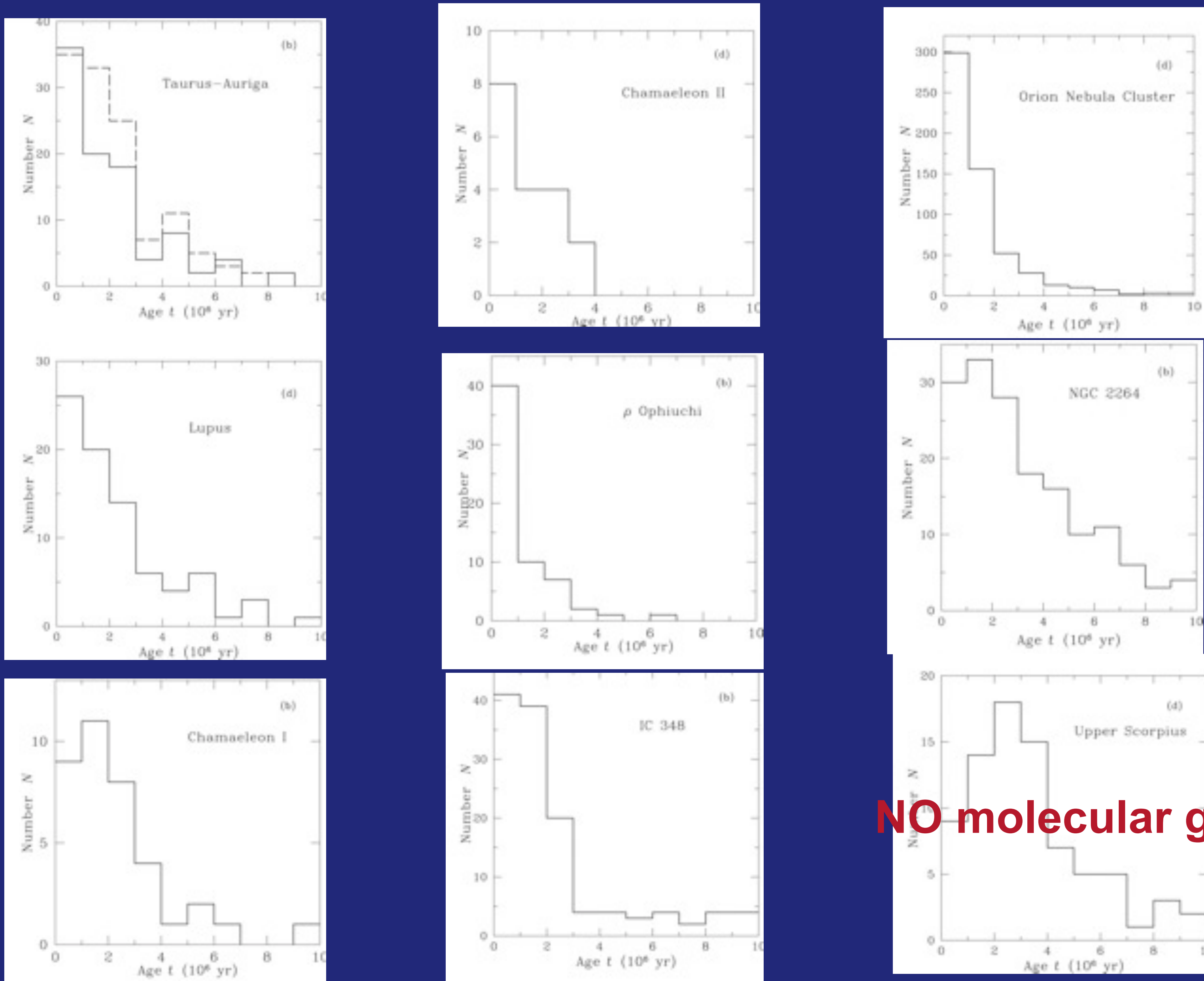

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)


(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)

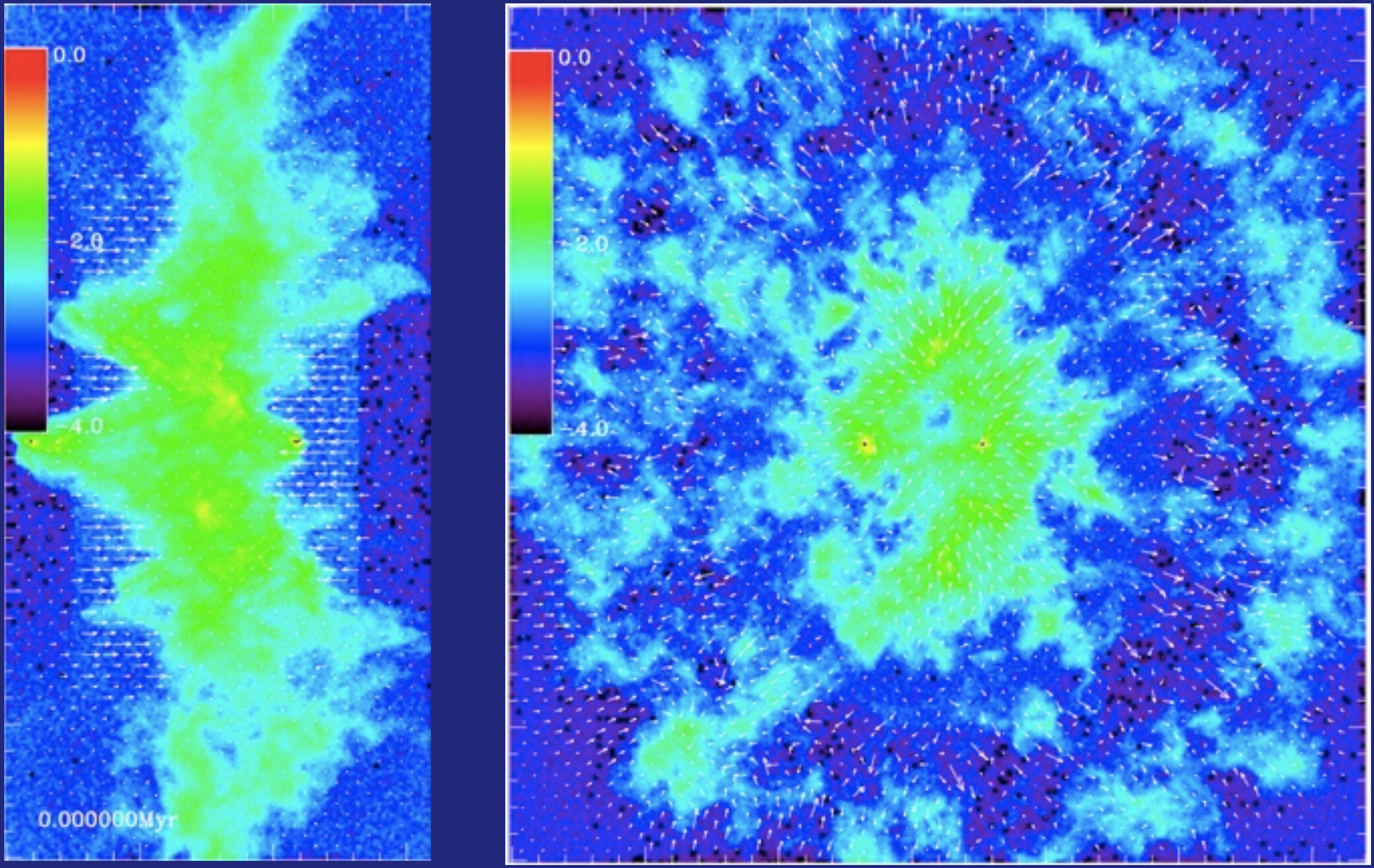

(b)
IC 348
Number N
Age t (10⁶ yr)


(d)
Orion Nebula Cluster
Number N
Age t (10⁶ yr)


(b)
NGC 2264
Number N
Age t (10⁶ yr)



(b)
Taurus–Auriga
(d)
Chamaeleon II
(d)
Orion Nebula Cluster
(d)
Lupus
(b)
ρ Ophiuchi
(b)
NGC 2264
(b)
Chamaeleon I
(b)
IC 348
(d)
Upper Scorpius
NO molecular gas!
Number N
Age t (10⁶ yr)



Hsu, Heitsch et al.

Compression

Compression

dM(tot)/dt

Compression dM(tot)/dt

gravitational focusing

feedback (dispersal)

Compression

gravitational focusing

feedback (dispersal)

dM(tot)/dt

efficiency

Compression

dM(tot)/dt

gravitational focusing

efficiency

feedback (dispersal)

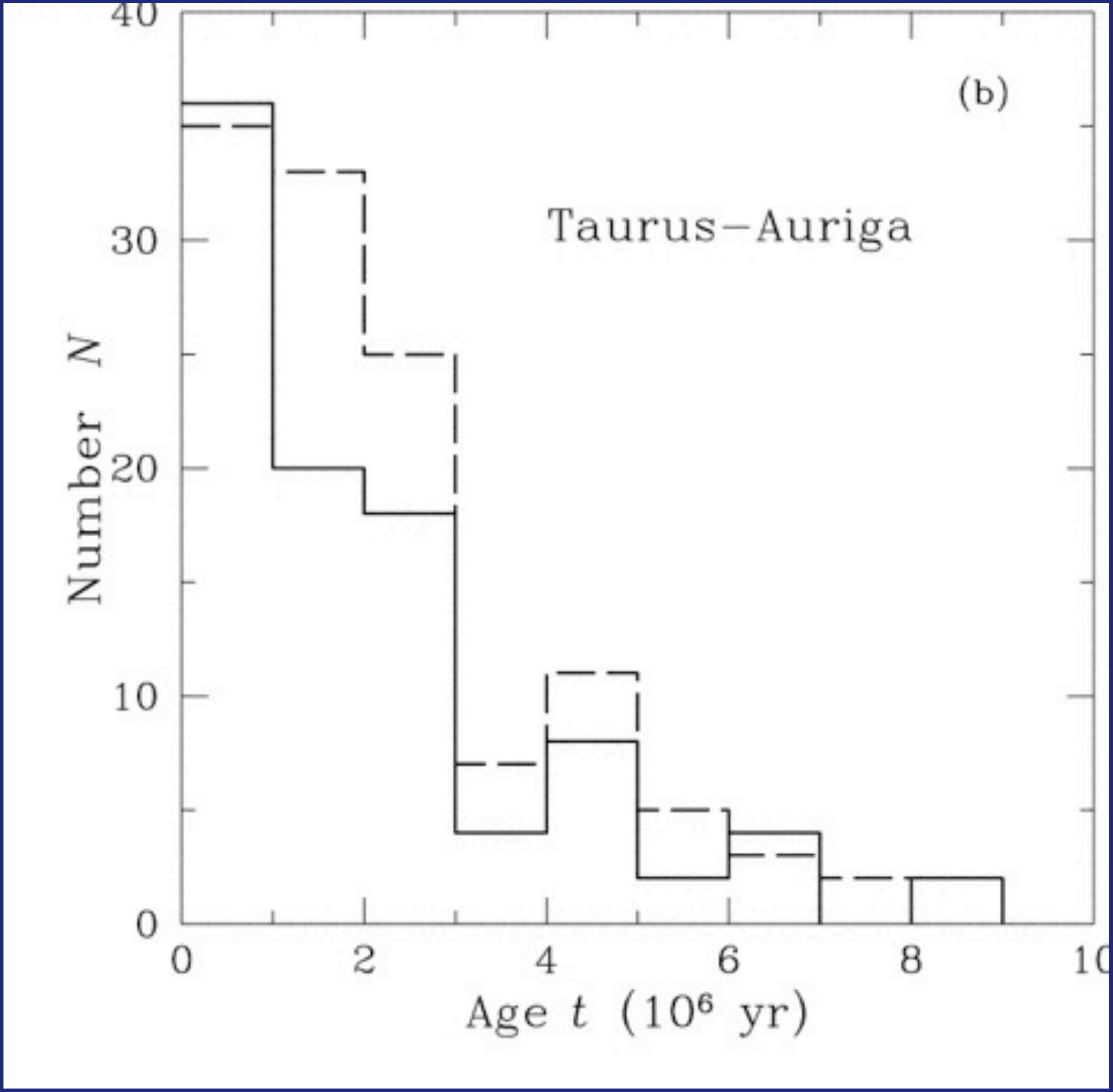
Summary: SFR set by

dM(tot)/dt × efficiency;

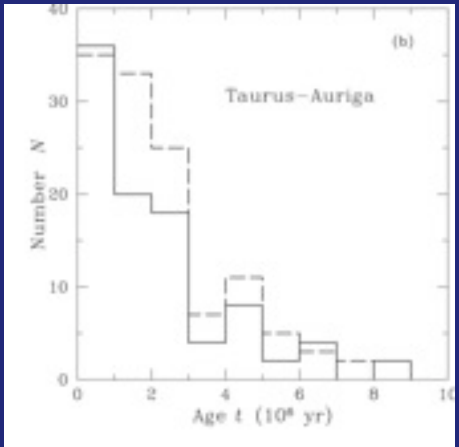
Compression (rate of)

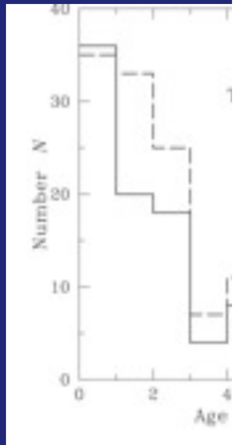
gravitational focusing (makes low efficiency by feedback possible)

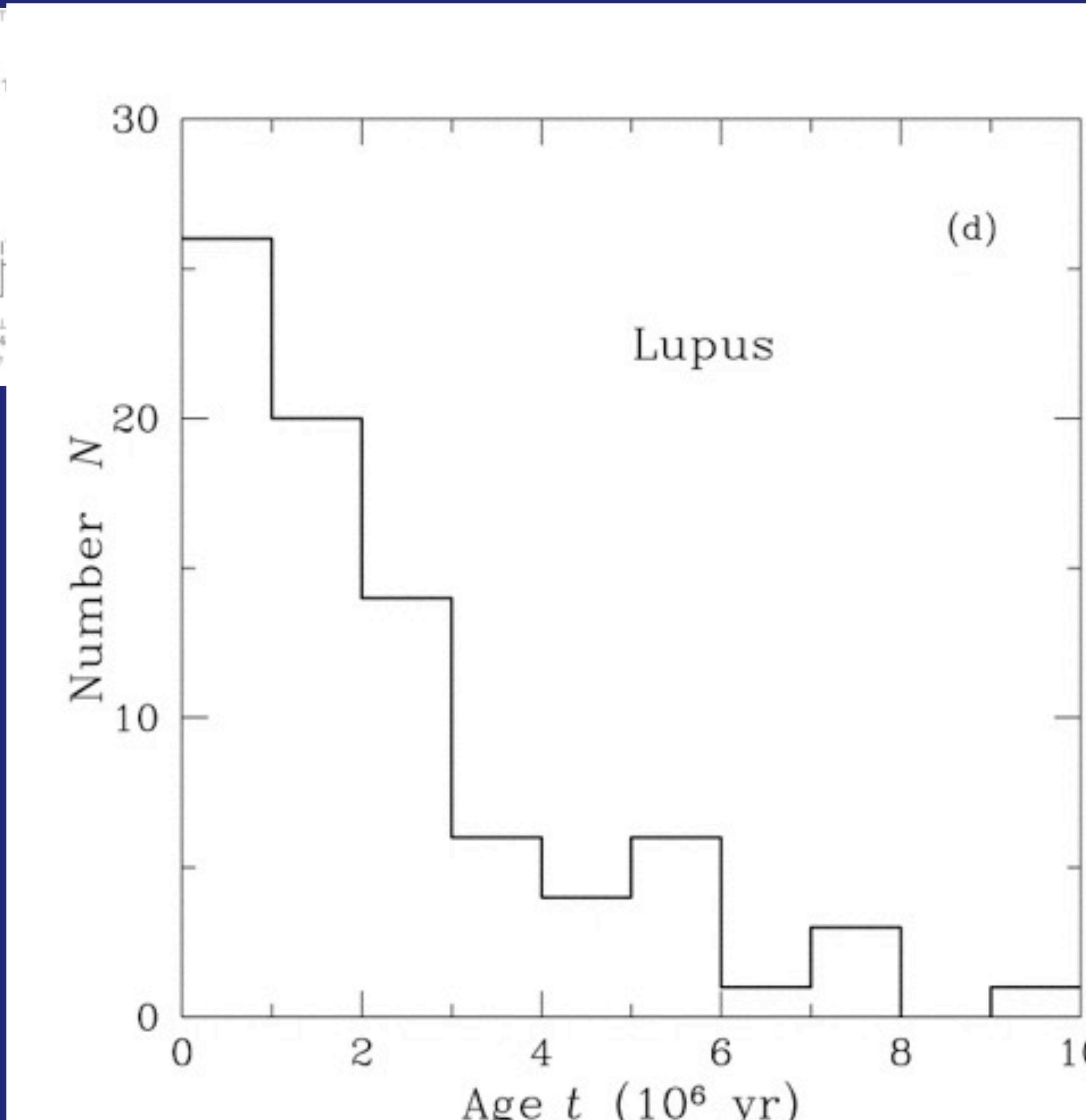
feedback (dispersal)

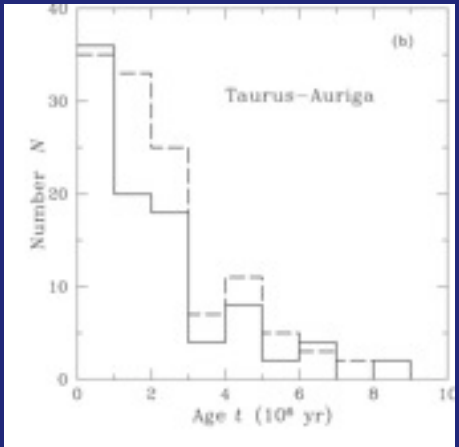


(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)
0
10
20
30
40
0
2
4
6
8
10

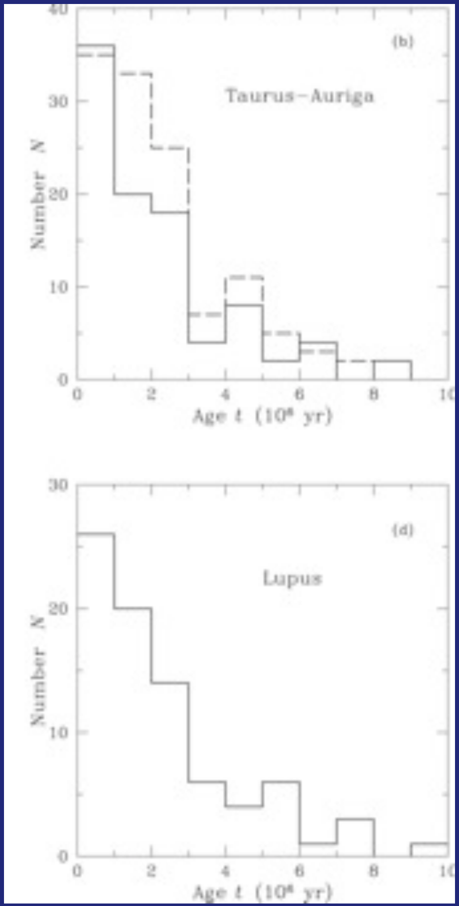

(b)
Taurus−Auriga
Number N
Age t (10⁶ yr)
0
10
20
30
40
0
2
4
6
8
10


Number N
Age

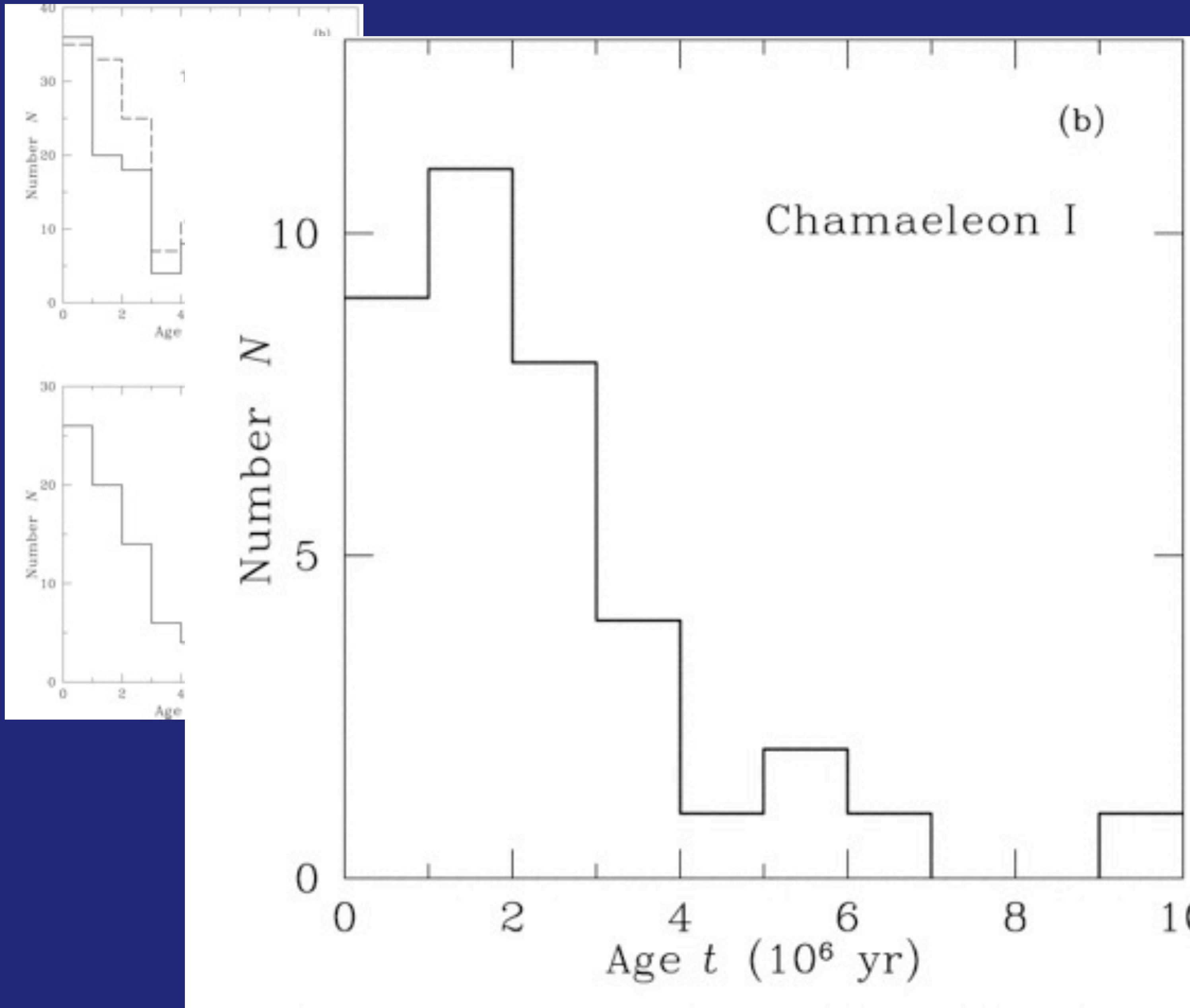

(d)
Lupus
Number N
Age t (10⁶ yr)
0
10
20
30
0
2
4
6
8



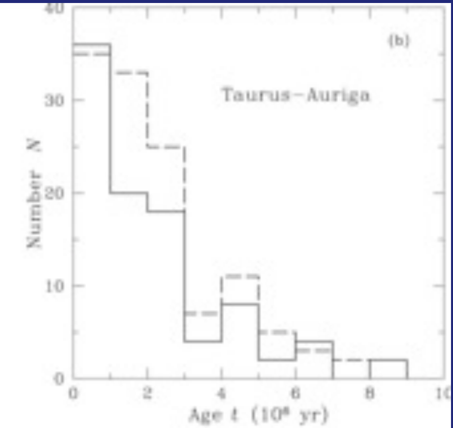
(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)



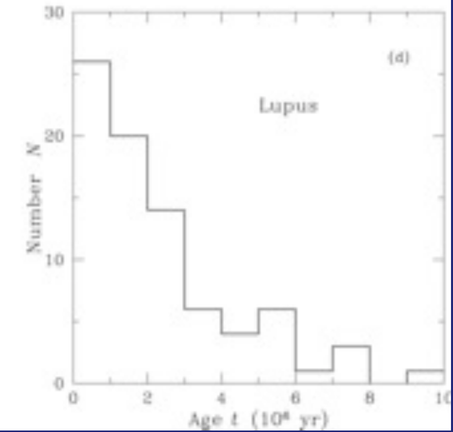
(b)
Taurus–Auriga
Number N
Age t (10^6 yr)
(d)
Lupus
Number N
Age t (10^6 yr)



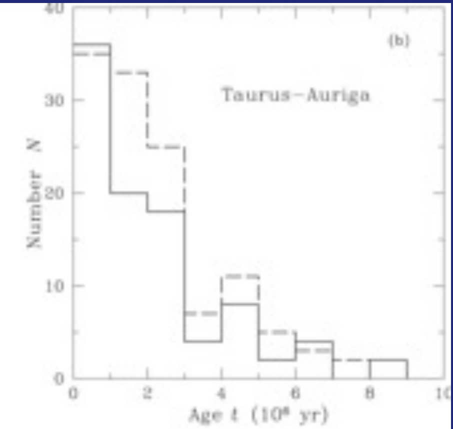
(b)
Chamaeleon I
Number N
Age t (10⁶ yr)
0
5
10
0
2
4
6
8



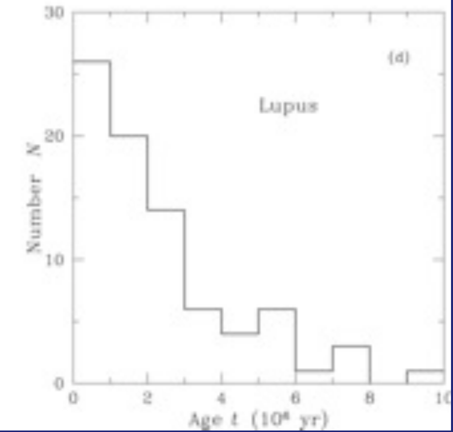
(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)



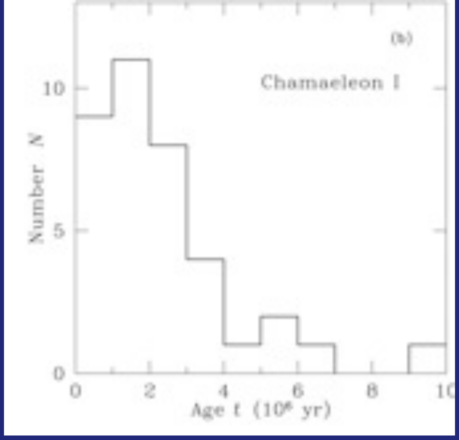
(d)
Lupus
Number N
Age t (10⁶ yr)



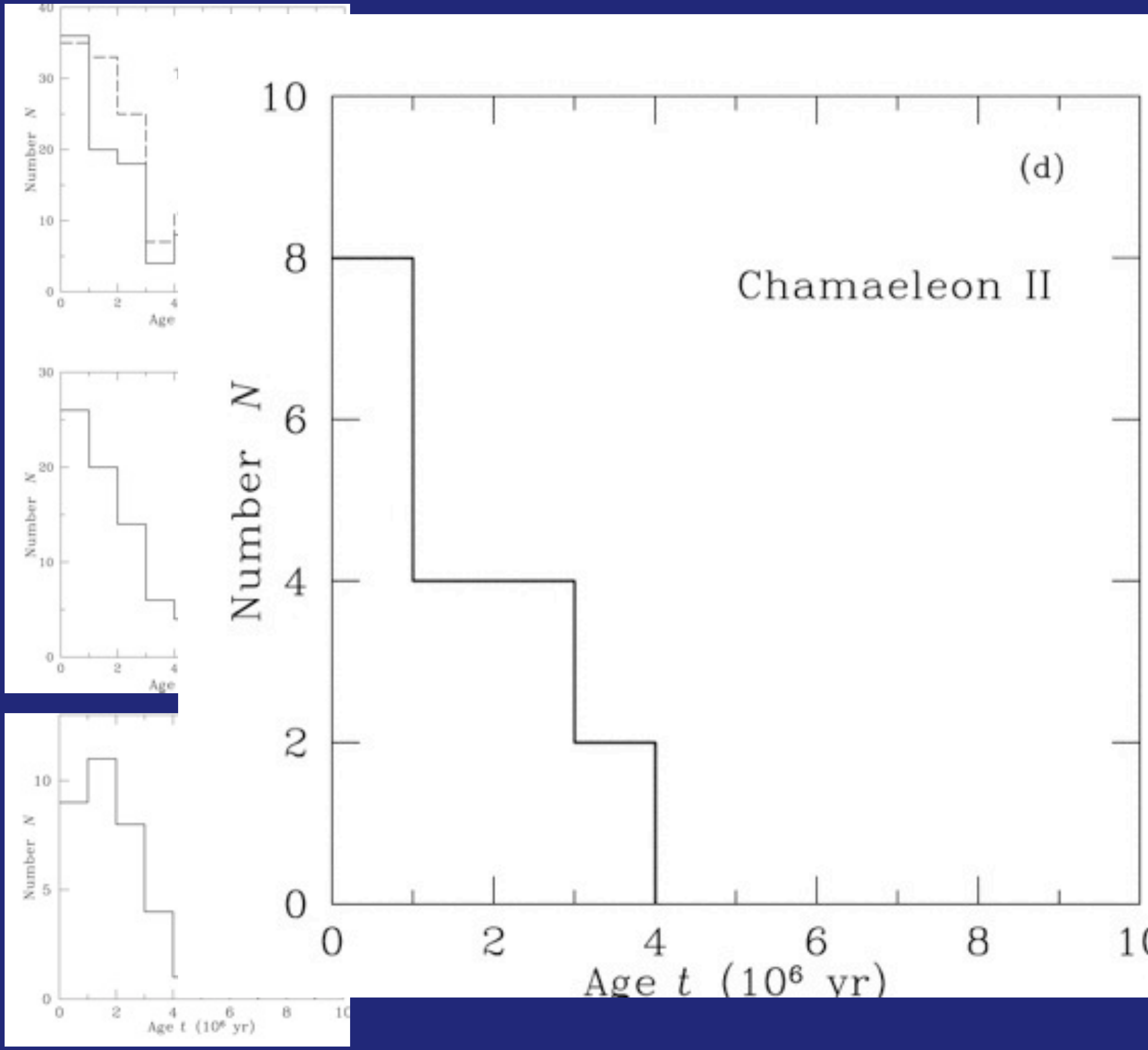
(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)



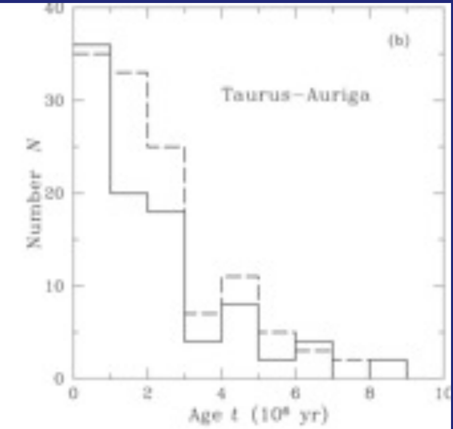
(d)
Lupus
Number N
Age t (10⁶ yr)



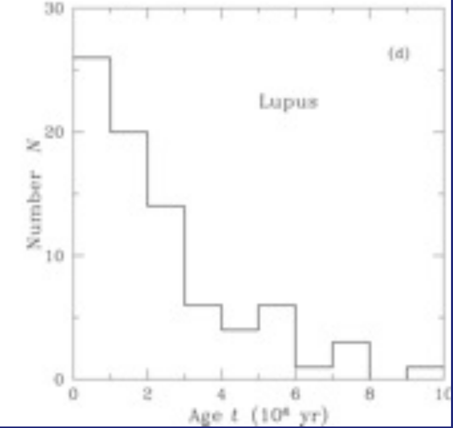
(b)
Chamaeleon I
Number N
Age t (10⁶ yr)



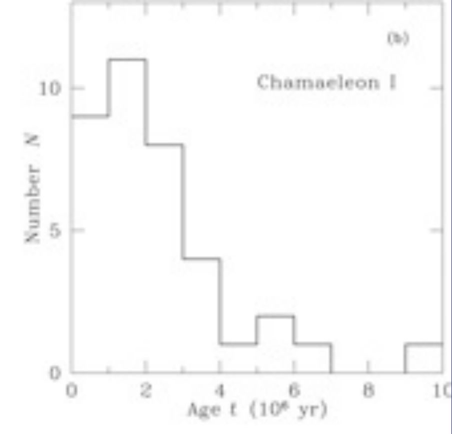
(d)
Chamaeleon II
Number N
Age t (10⁶ yr)



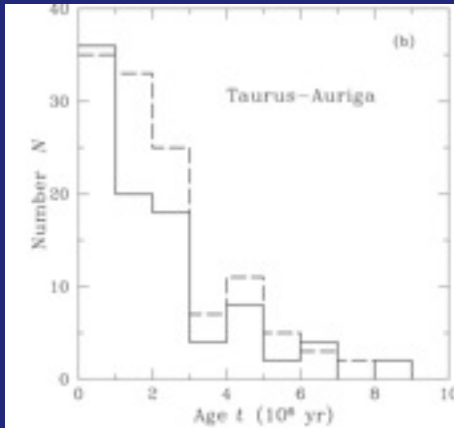
(b)
Taurus−Auriga
Number N
Age t (10^6 yr)

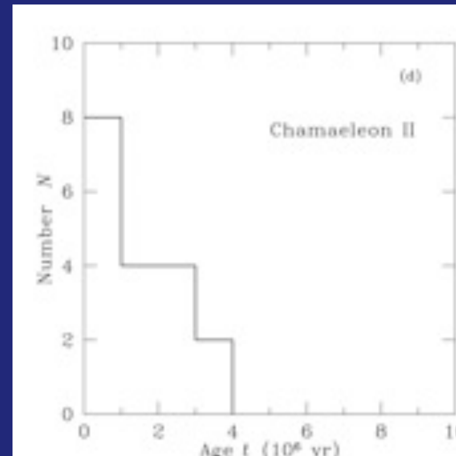


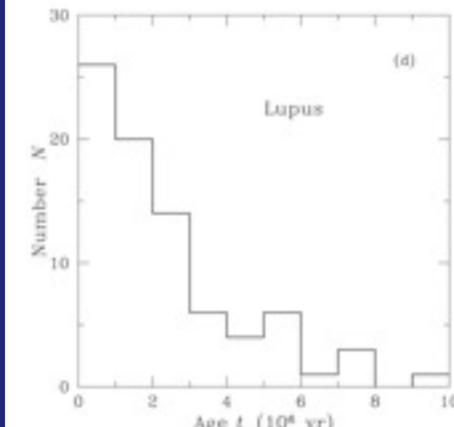
(d)
Lupus
Number N
Age t (10^6 yr)

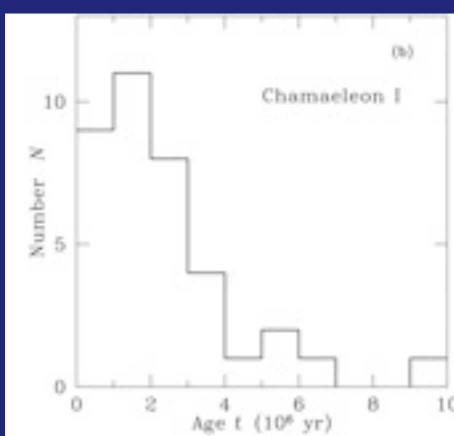


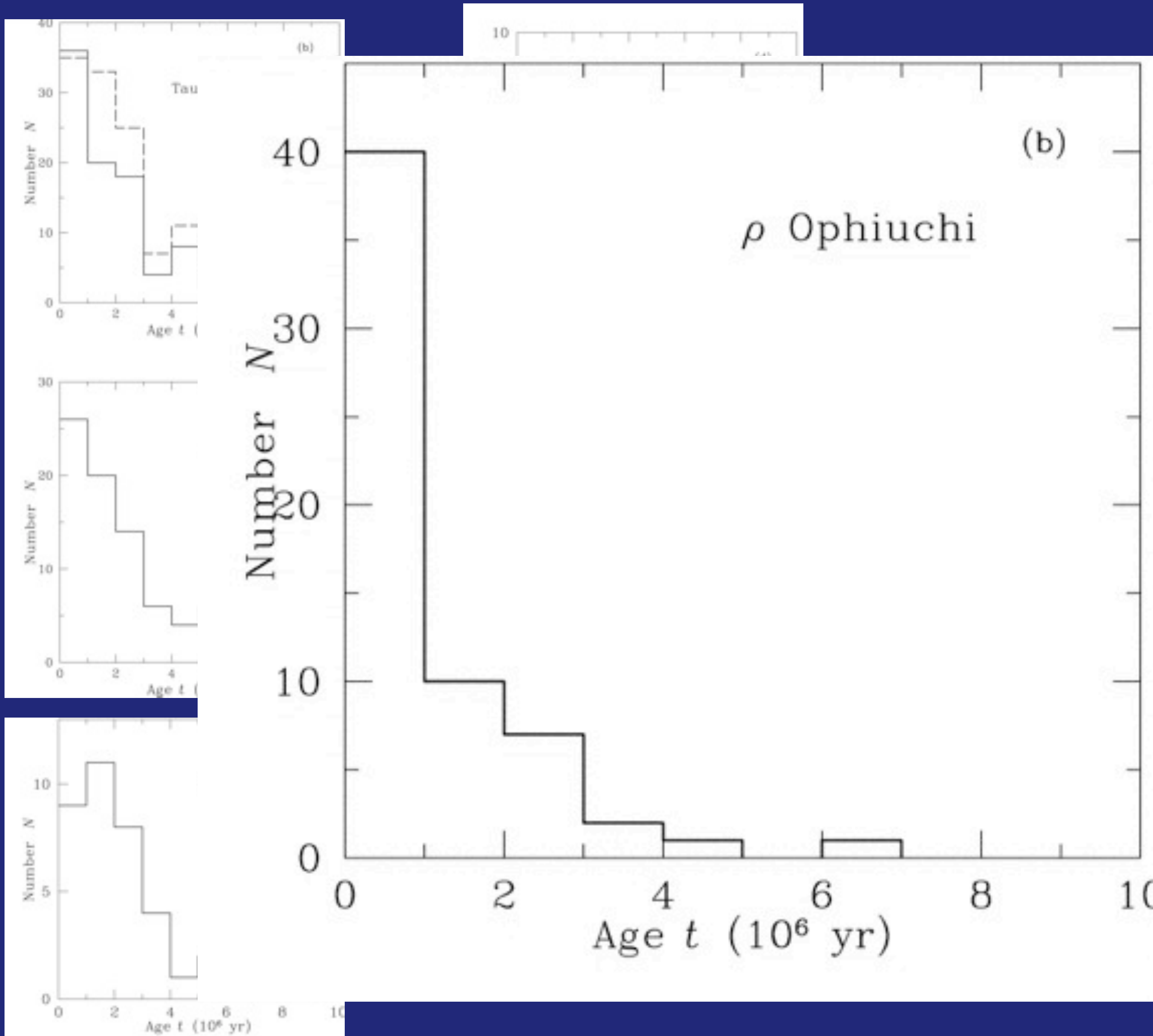
(b)
Chamaeleon I
Number N
Age t (10^6 yr)


(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)
0
2
4
6
8
10
20
30
40

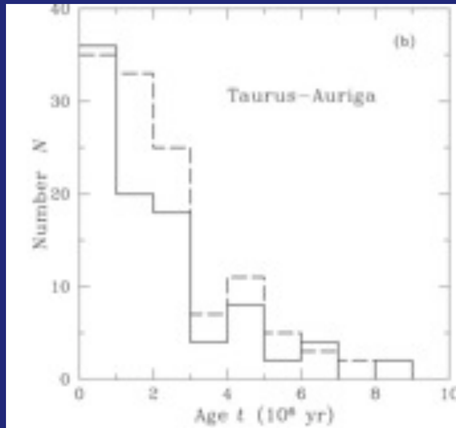

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)
0
2
4
6
8
10

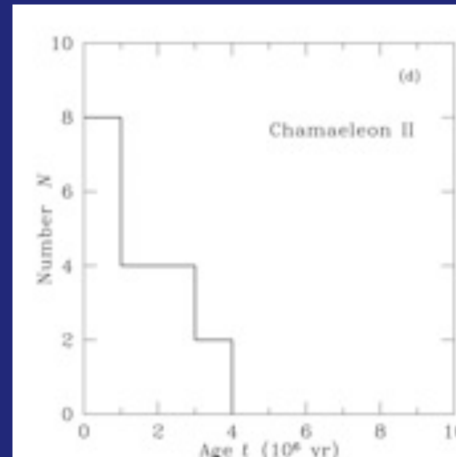

(d)
Lupus
Number N
Age t (10⁶ yr)
0
2
4
6
8
10
20
30

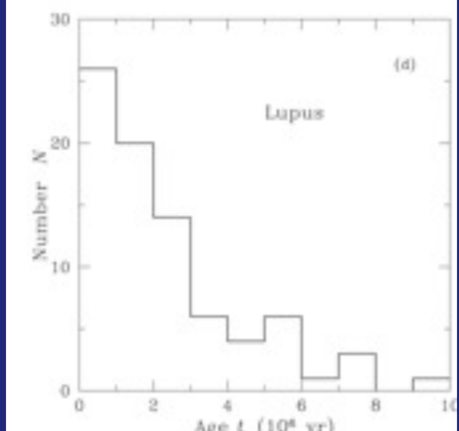

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)
0
2
4
6
8
5
10

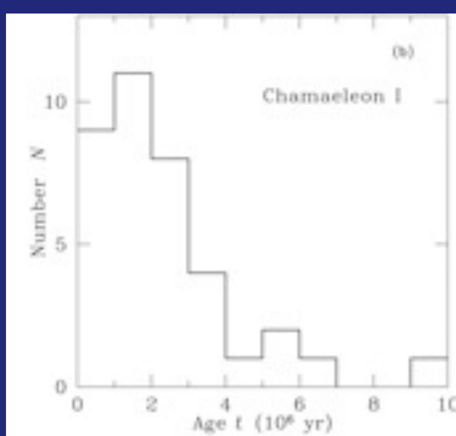


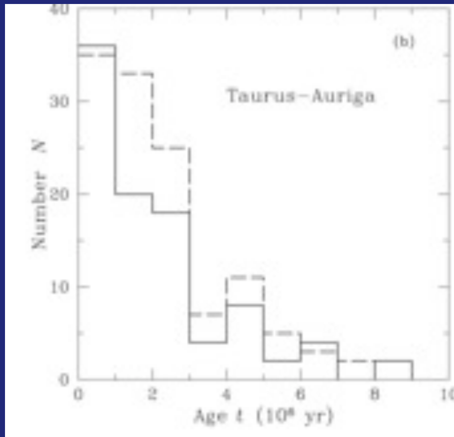
(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)
0
10
20
30
40
0
2
4
6
8
10
Tau

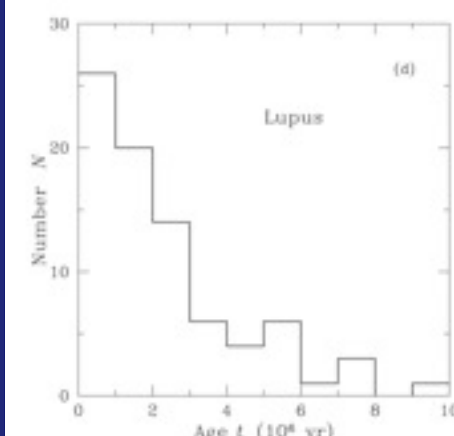

(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)

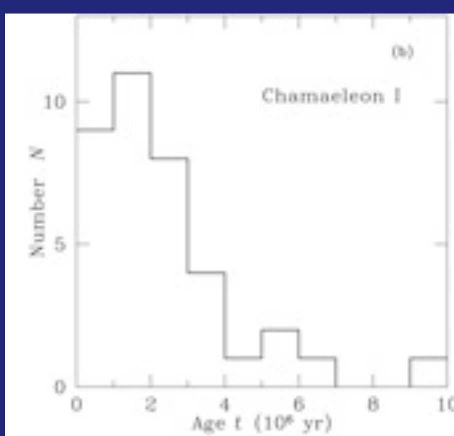

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)

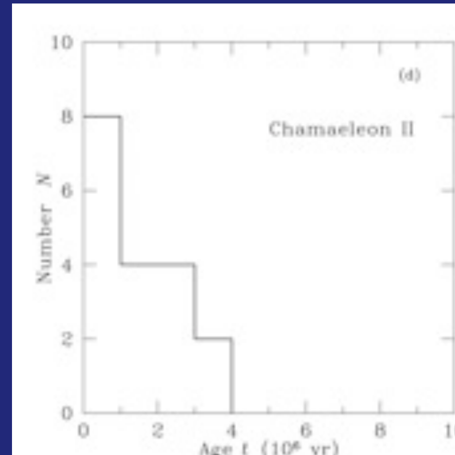

(d)
Lupus
Number N
Age t (10⁶ yr)

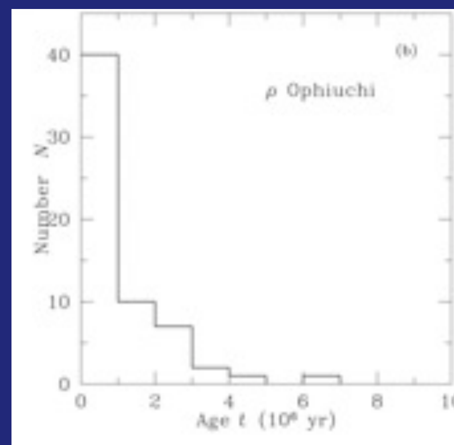

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

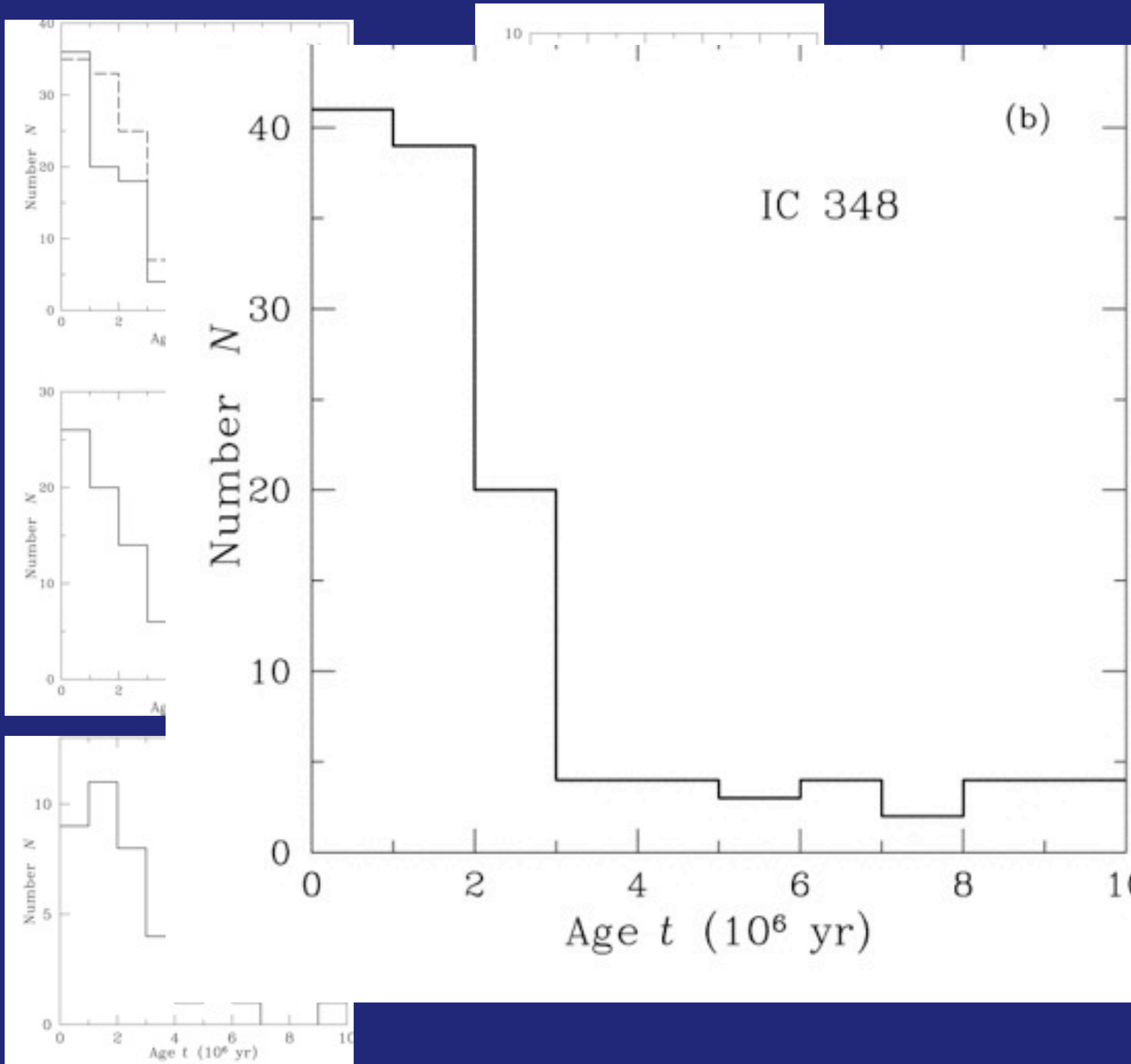

(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)


(d)
Lupus
Number N
Age t (10⁶ yr)

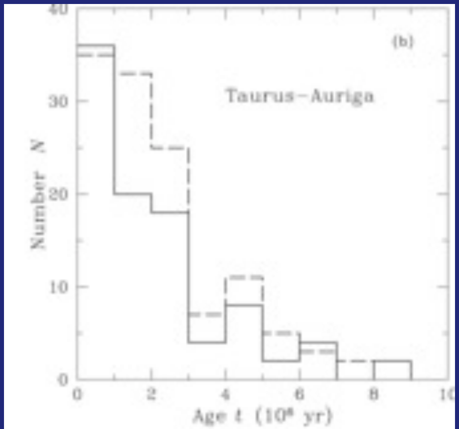

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

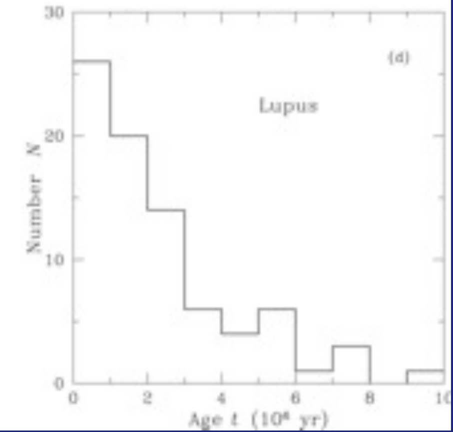

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)

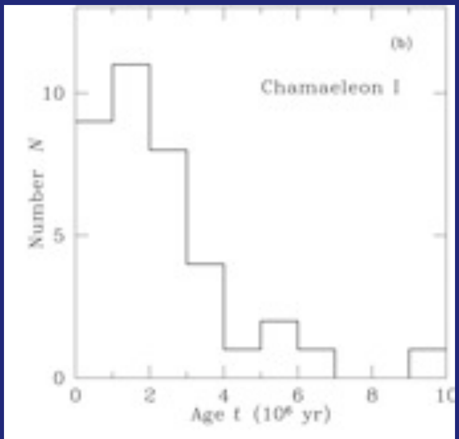

(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)

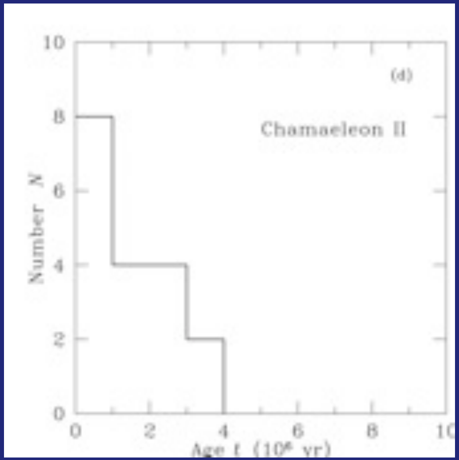


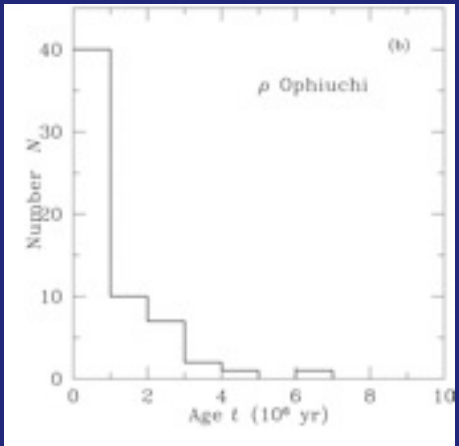
(b)
IC 348
Number N
Age t (10⁶ yr)

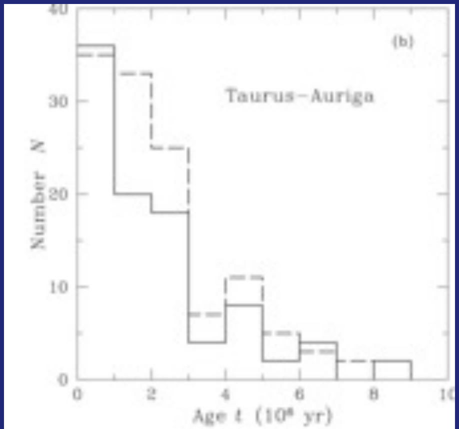

(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)

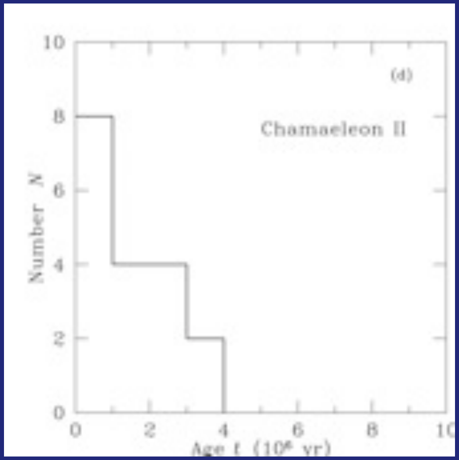

(d)
Lupus
Number N
Age t (10⁶ yr)

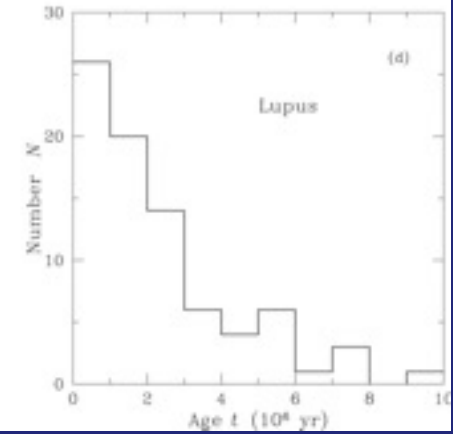

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

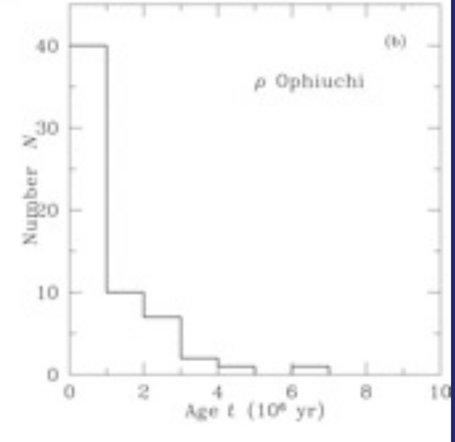

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)

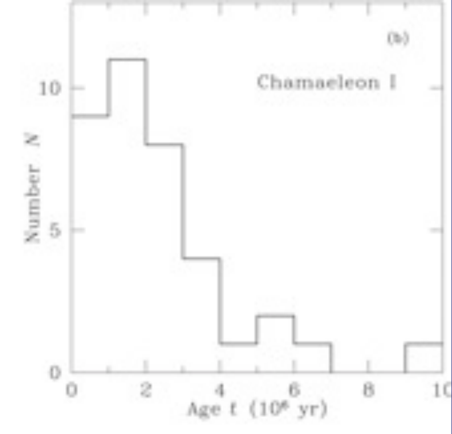

(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)

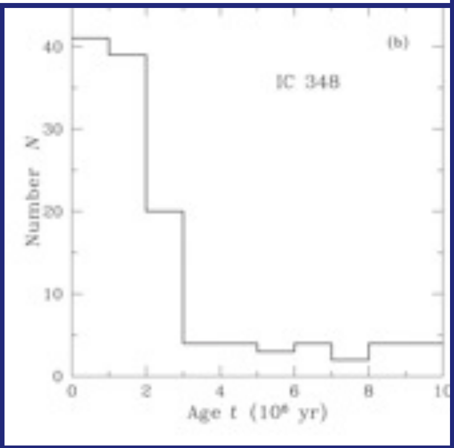

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)

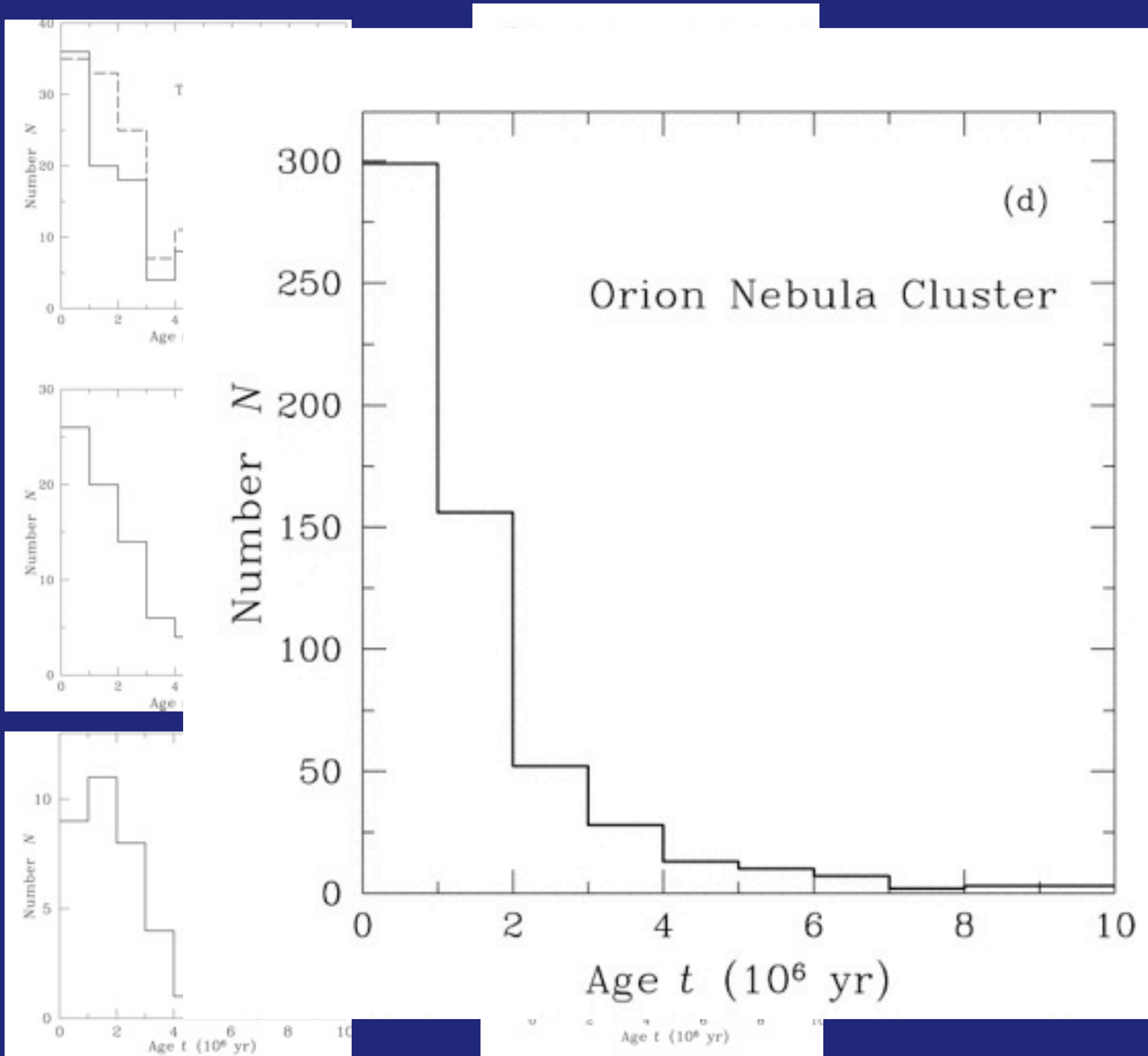

(d)
Chamaeleon II
Number N
Age t (10^6 yr)


(d)
Lupus
Number N
Age t (10^6 yr)

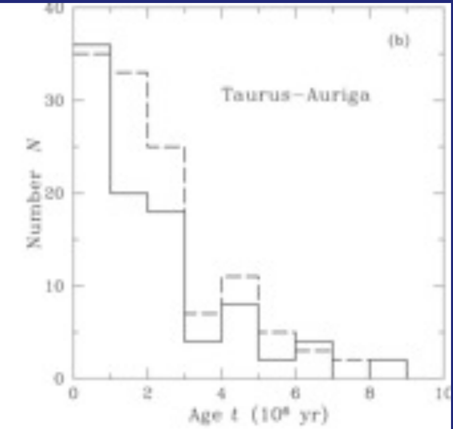

(b)
ρ Ophiuchi
Number N
Age t (10^6 yr)

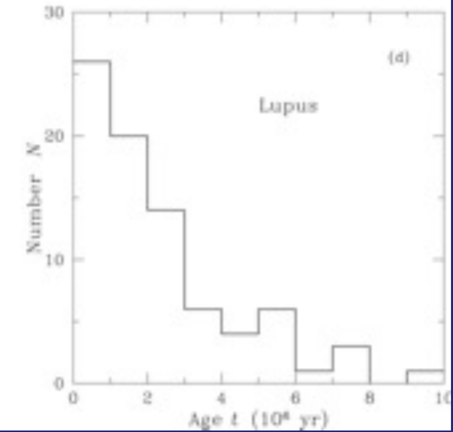

(b)
Chamaeleon I
Number N
Age t (10^6 yr)

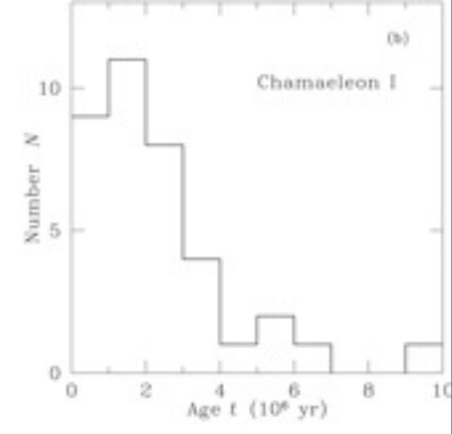

(b)
IC 348
Number N
Age t (10^6 yr)

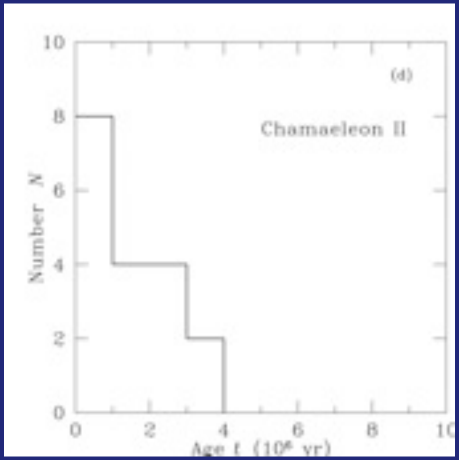


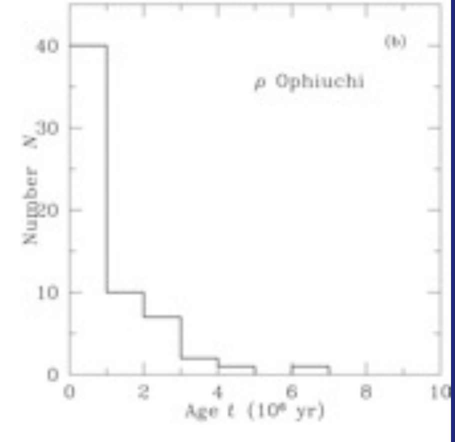
Orion Nebula Cluster
(d)
Number N
Age t (10^6 yr)
0
50
100
150
200
250
300
0
2
4
6
8
10

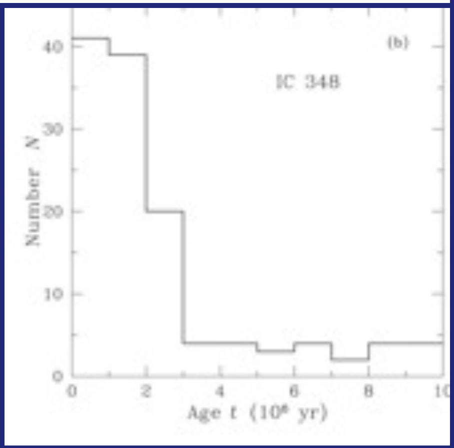

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)

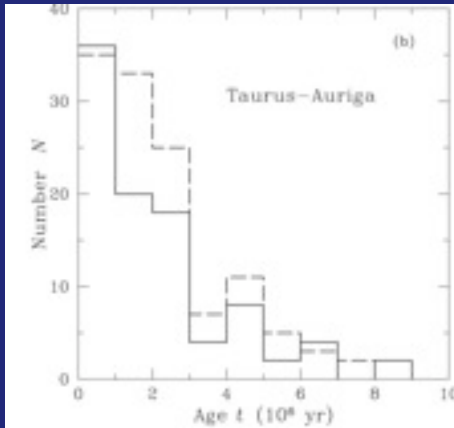

(d)
Lupus
Number N
Age t (10^6 yr)

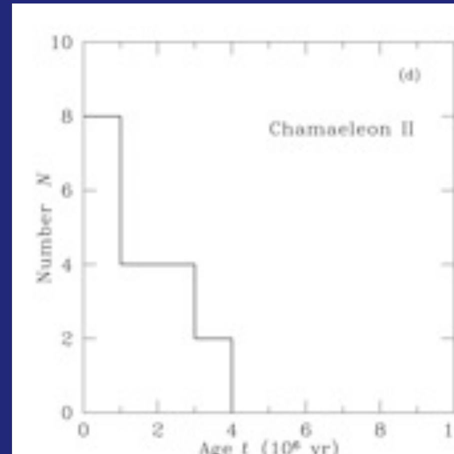

(b)
Chamaeleon I
Number N
Age t (10^6 yr)

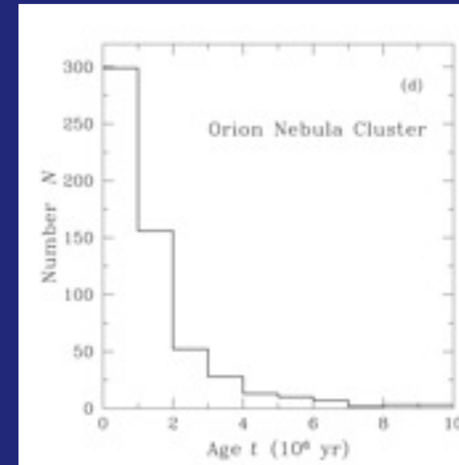

(d)
Chamaeleon II
Number N
Age t (10^6 yr)

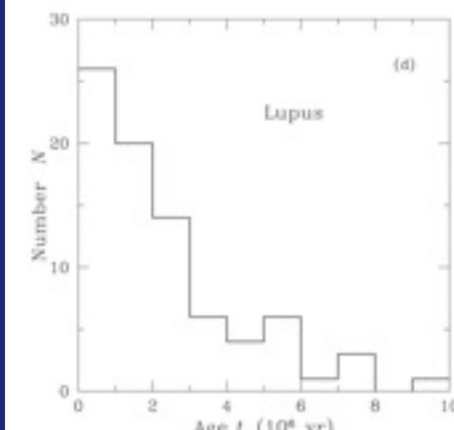

(b)
ρ Ophiuchi
Number N
Age t (10^6 yr)

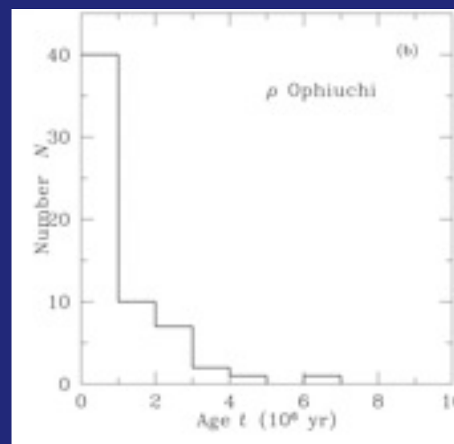

(b)
IC 348
Number N
Age t (10^6 yr)

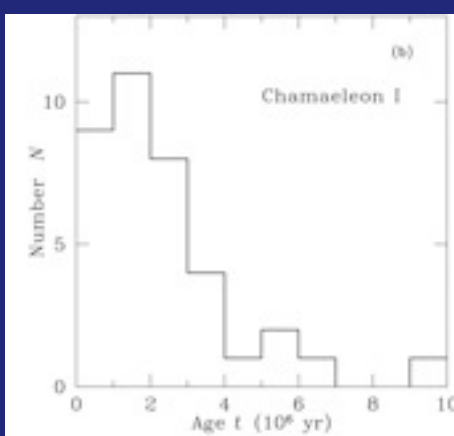

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)

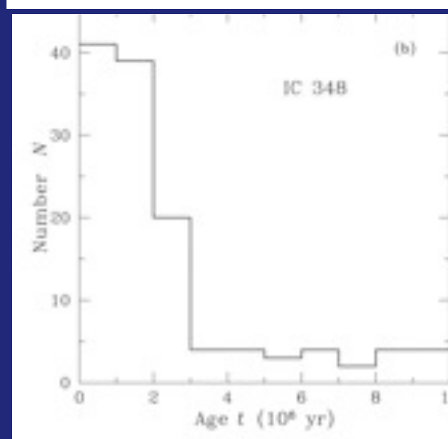

(d)
Chamaeleon II
Number N
Age t (10^6 yr)

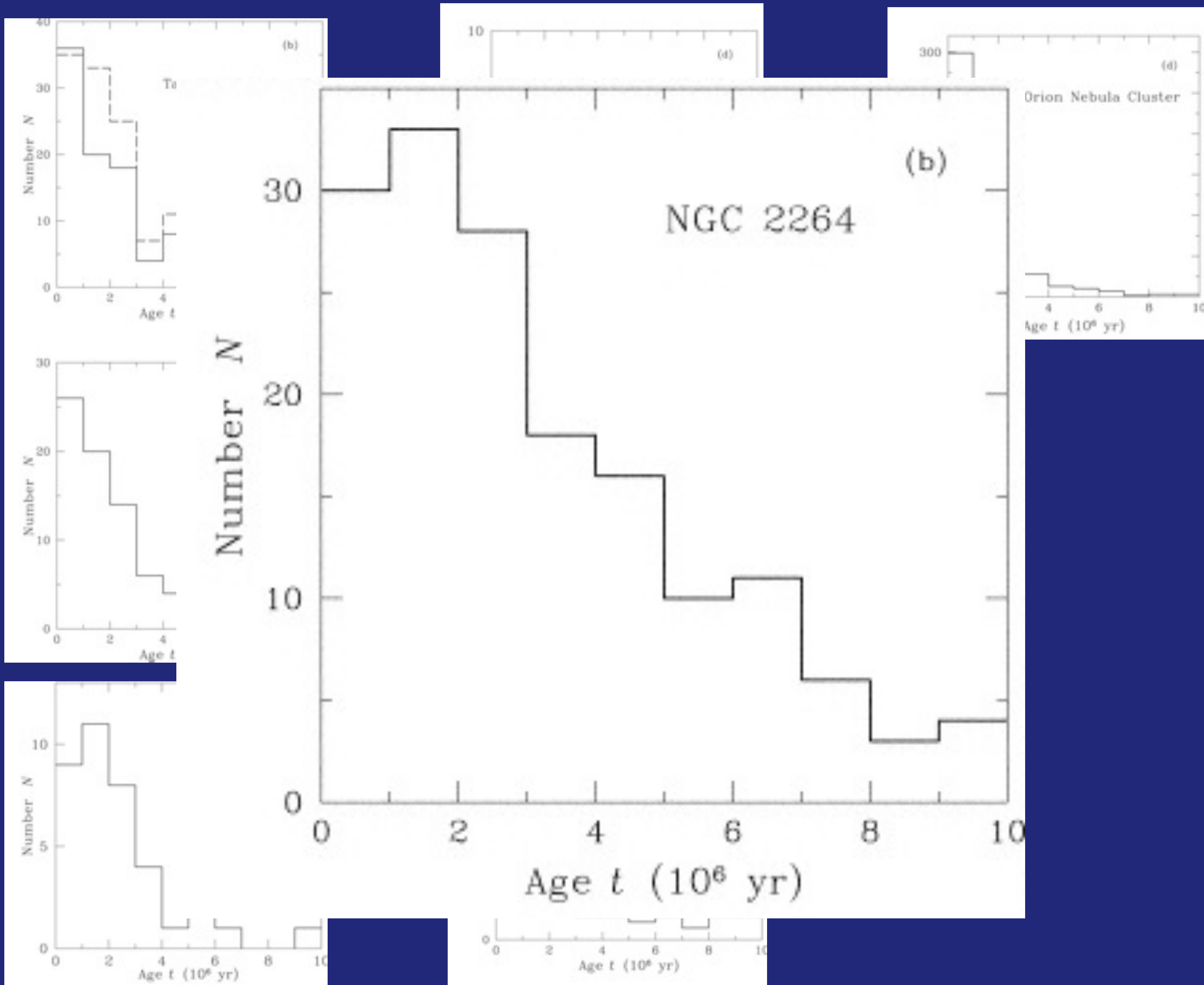

(d)
Orion Nebula Cluster
Number N
Age t (10^6 yr)


(d)
Lupus
Number N
Age t (10^6 yr)

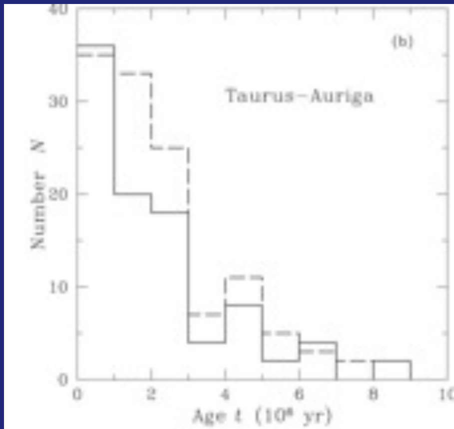

(b)
ρ Ophiuchi
Number N
Age t (10^6 yr)

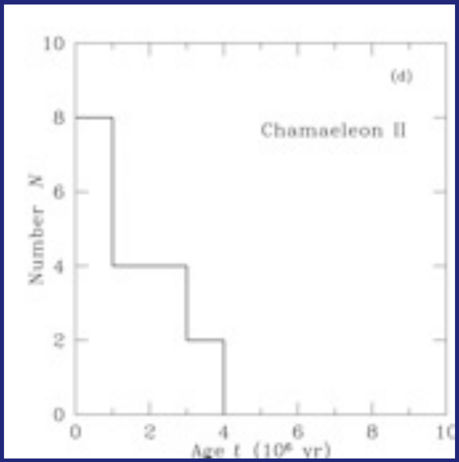

(b)
Chamaeleon I
Number N
Age t (10^6 yr)

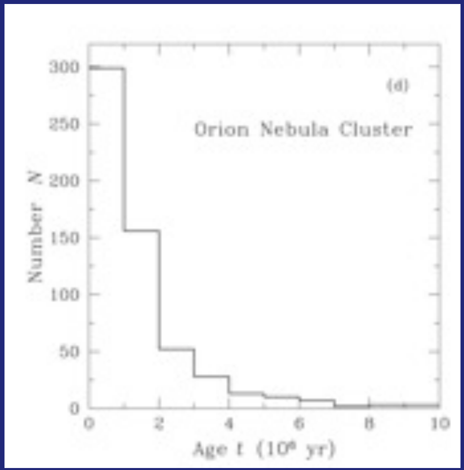

(b)
IC 348
Number N
Age t (10^6 yr)

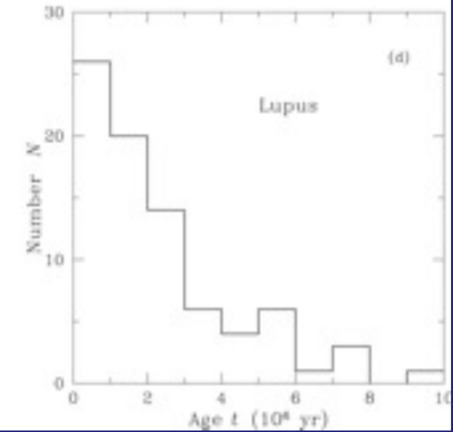


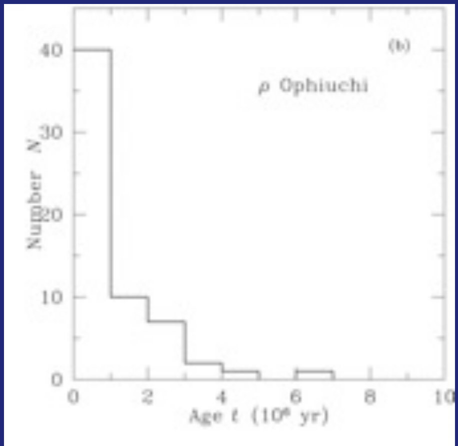
(b)
NGC 2264
Number N
Age t (10⁶ yr)
Orion Nebula Cluster
(d)

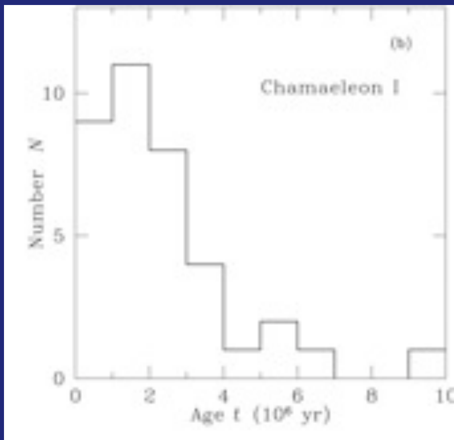

(b)
Taurus−Auriga
Number N
Age t (10⁶ yr)

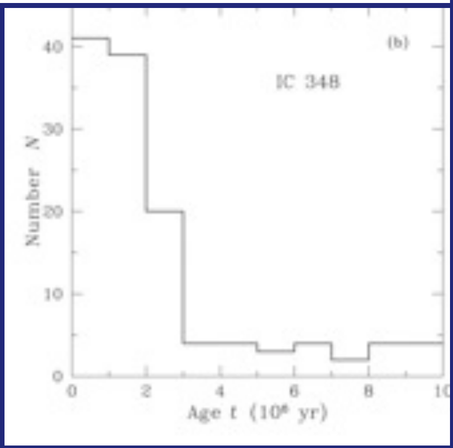

(d)
Chamaeleon II
Number N
Age t (10⁶ yr)

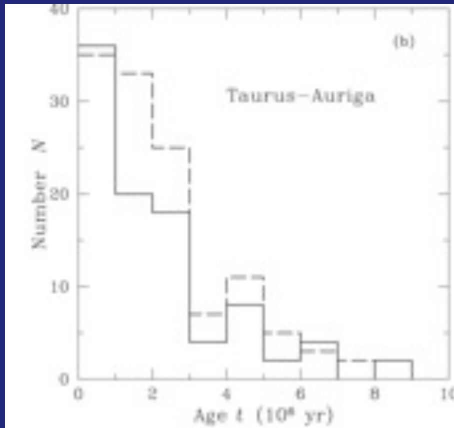

(d)
Orion Nebula Cluster
Number N
Age t (10⁶ yr)

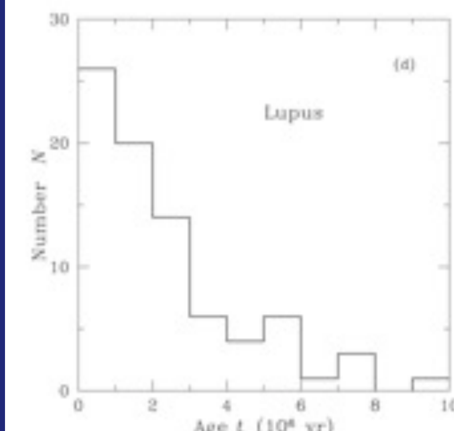

(d)
Lupus
Number N
Age t (10⁶ yr)

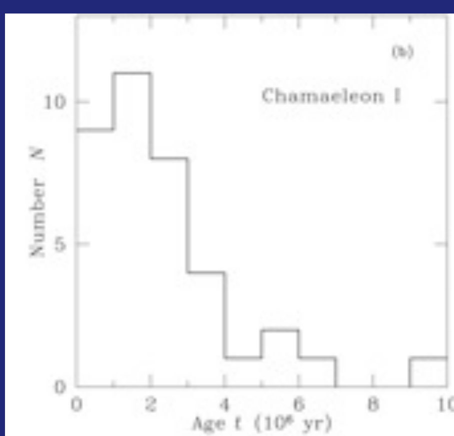

(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)

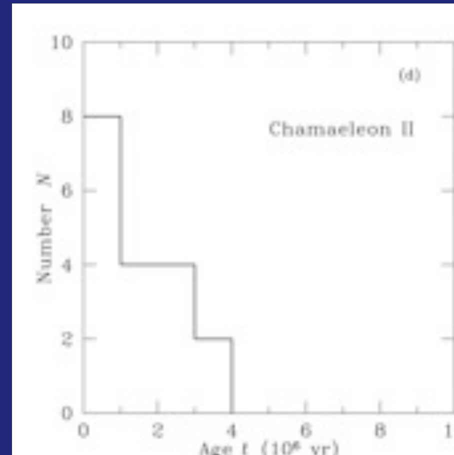

(b)
Chamaeleon I
Number N
Age t (10⁶ yr)

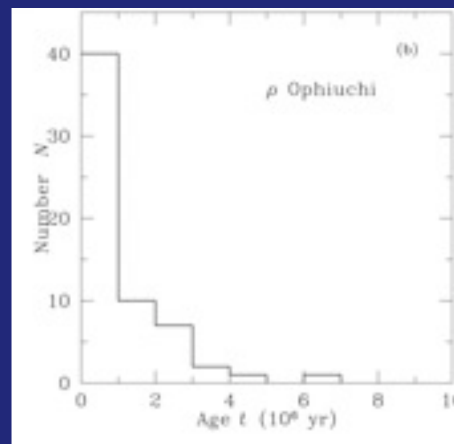

(b)
IC 348
Number N
Age t (10⁶ yr)

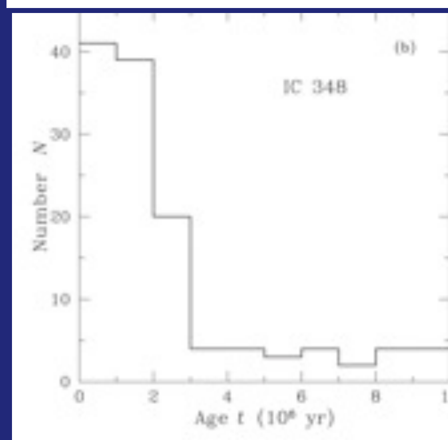

(b)
Taurus–Auriga
Number N
Age t (10^6 yr)

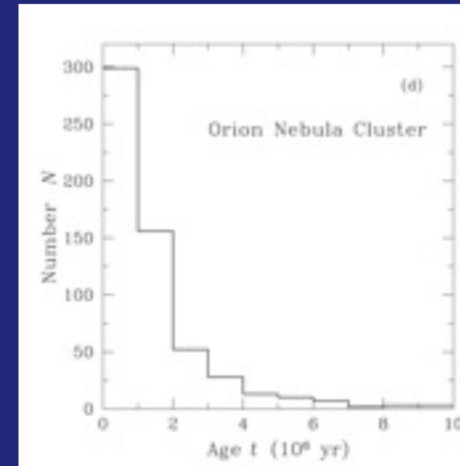

(d)
Lupus
Number N
Age t (10^6 yr)

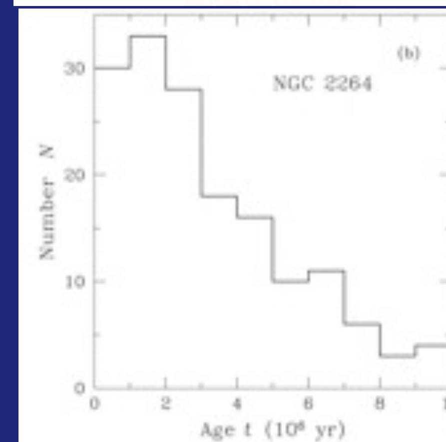

(b)
Chamaeleon I
Number N
Age t (10^6 yr)

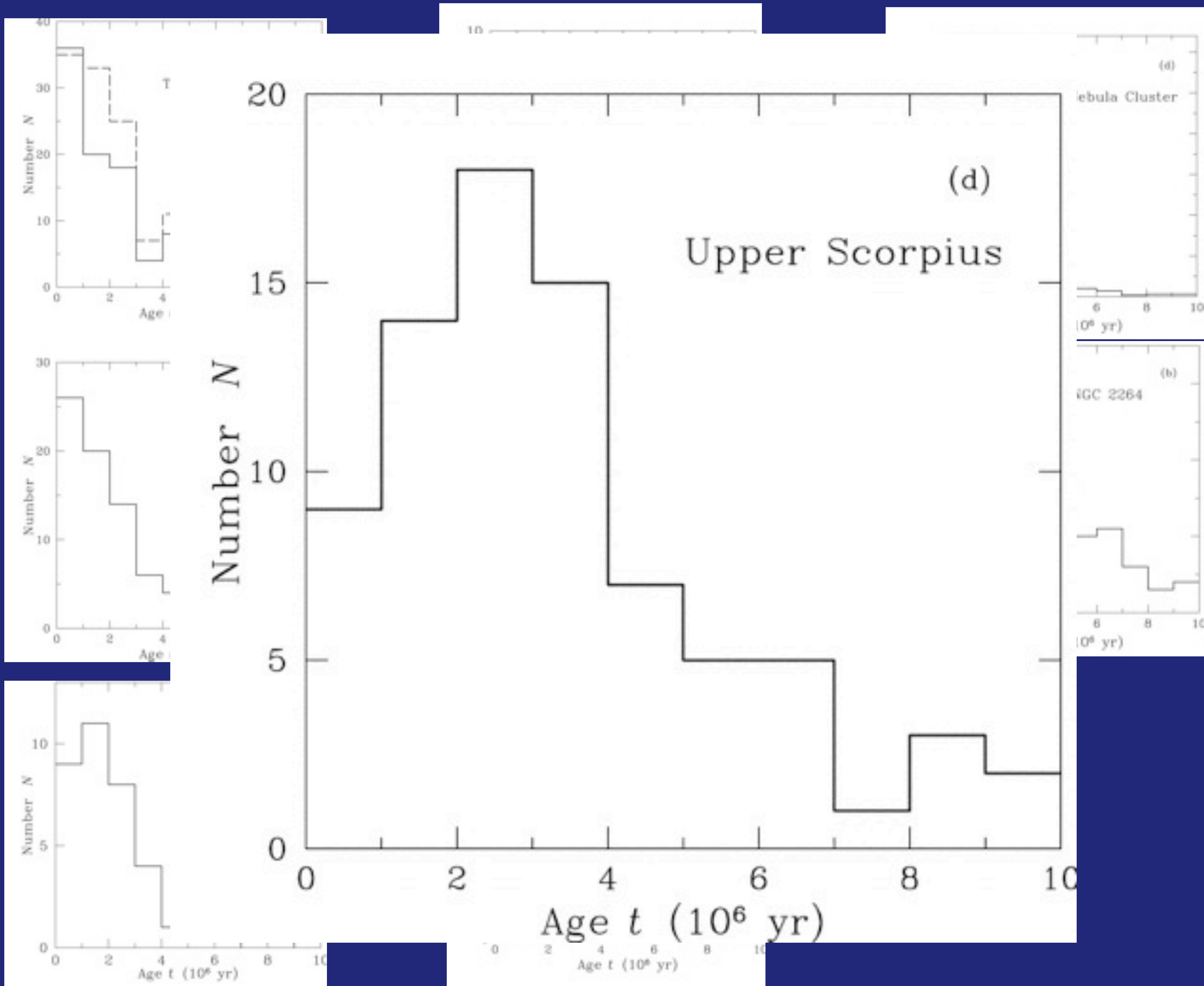

(d)
Chamaeleon II
Number N
Age t (10^6 yr)


(b)
ρ Ophiuchi
Number N
Age t (10^6 yr)

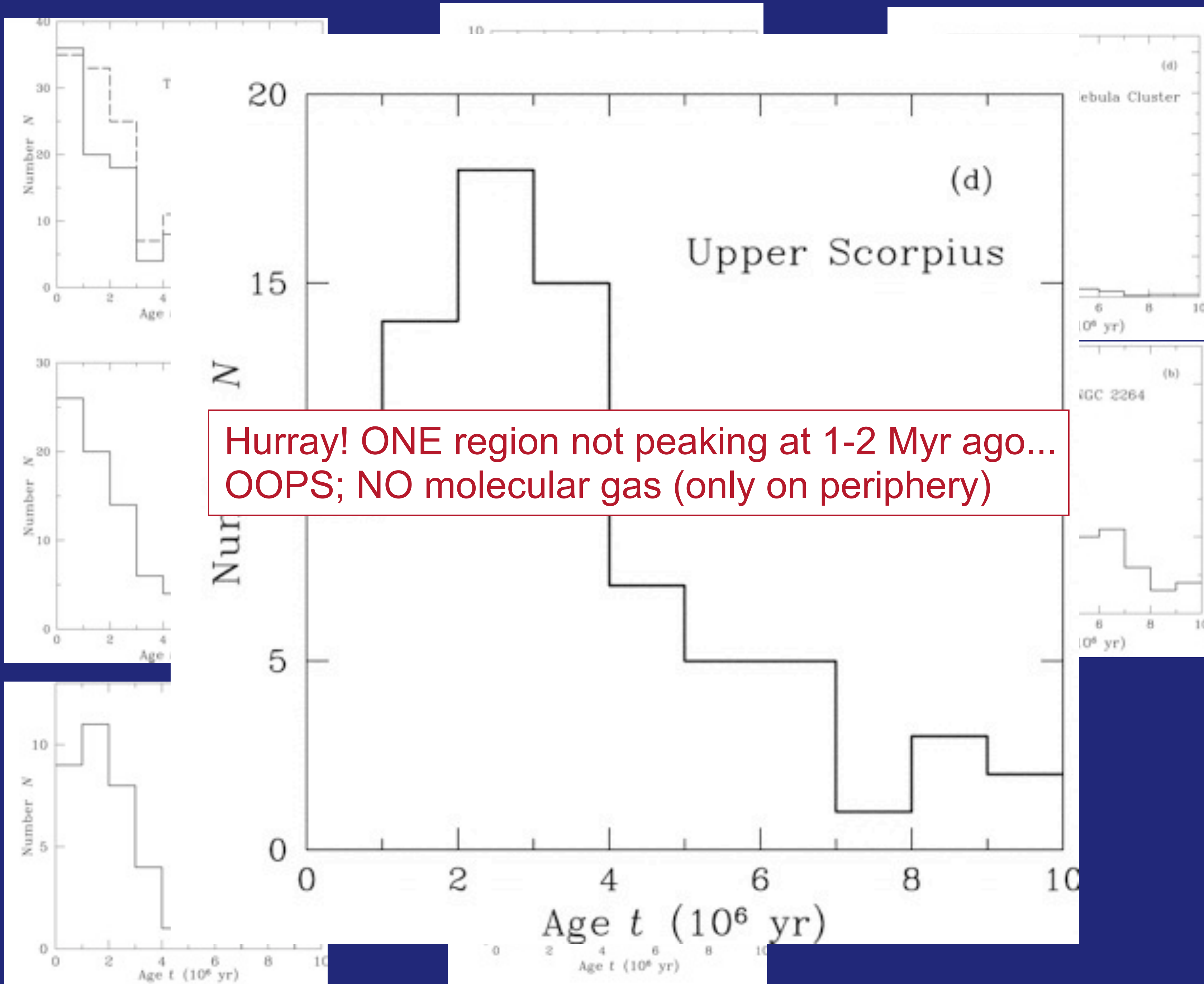

(b)
IC 348
Number N
Age t (10^6 yr)


(d)
Orion Nebula Cluster
Number N
Age t (10^6 yr)

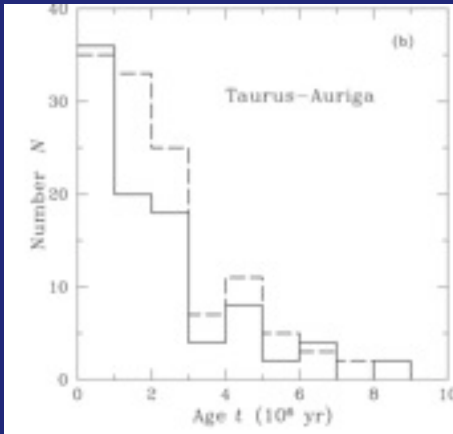

(b)
NGC 2264
Number N
Age t (10^6 yr)

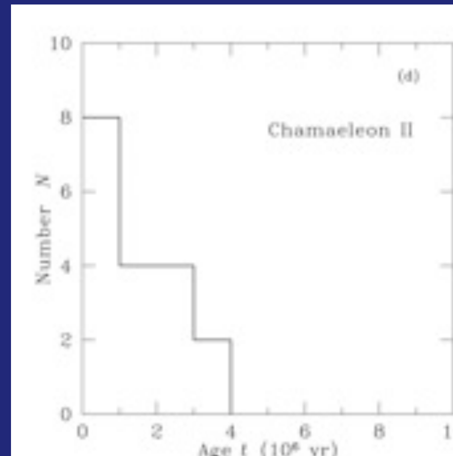


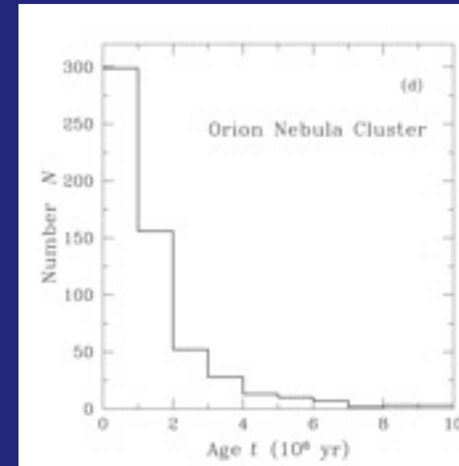
(d)
Upper Scorpius
Number N
Age t (10⁶ yr)

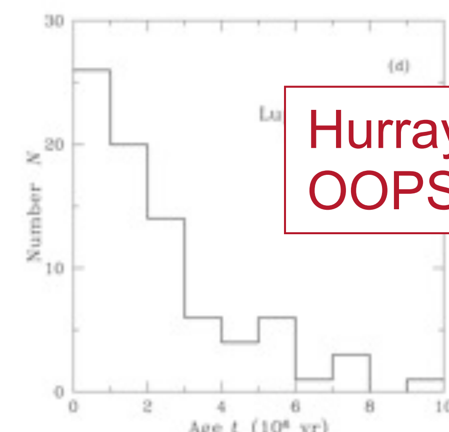


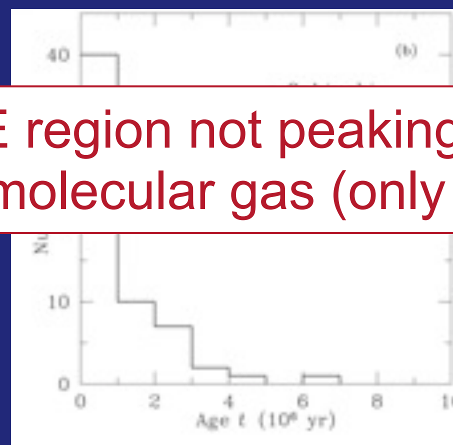
Hurray! ONE region not peaking at 1-2 Myr ago...
OOPS; NO molecular gas (only on periphery)

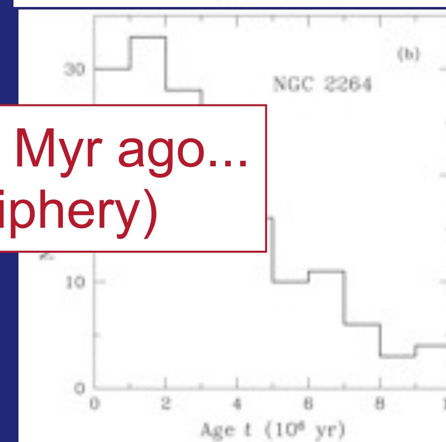




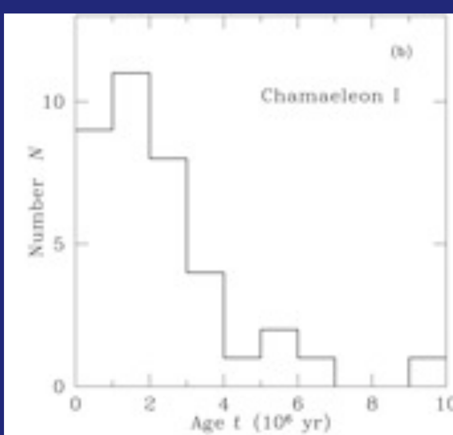


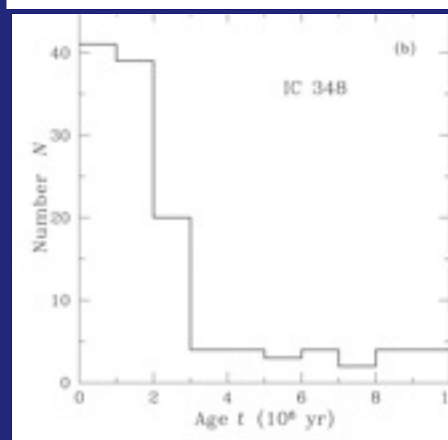


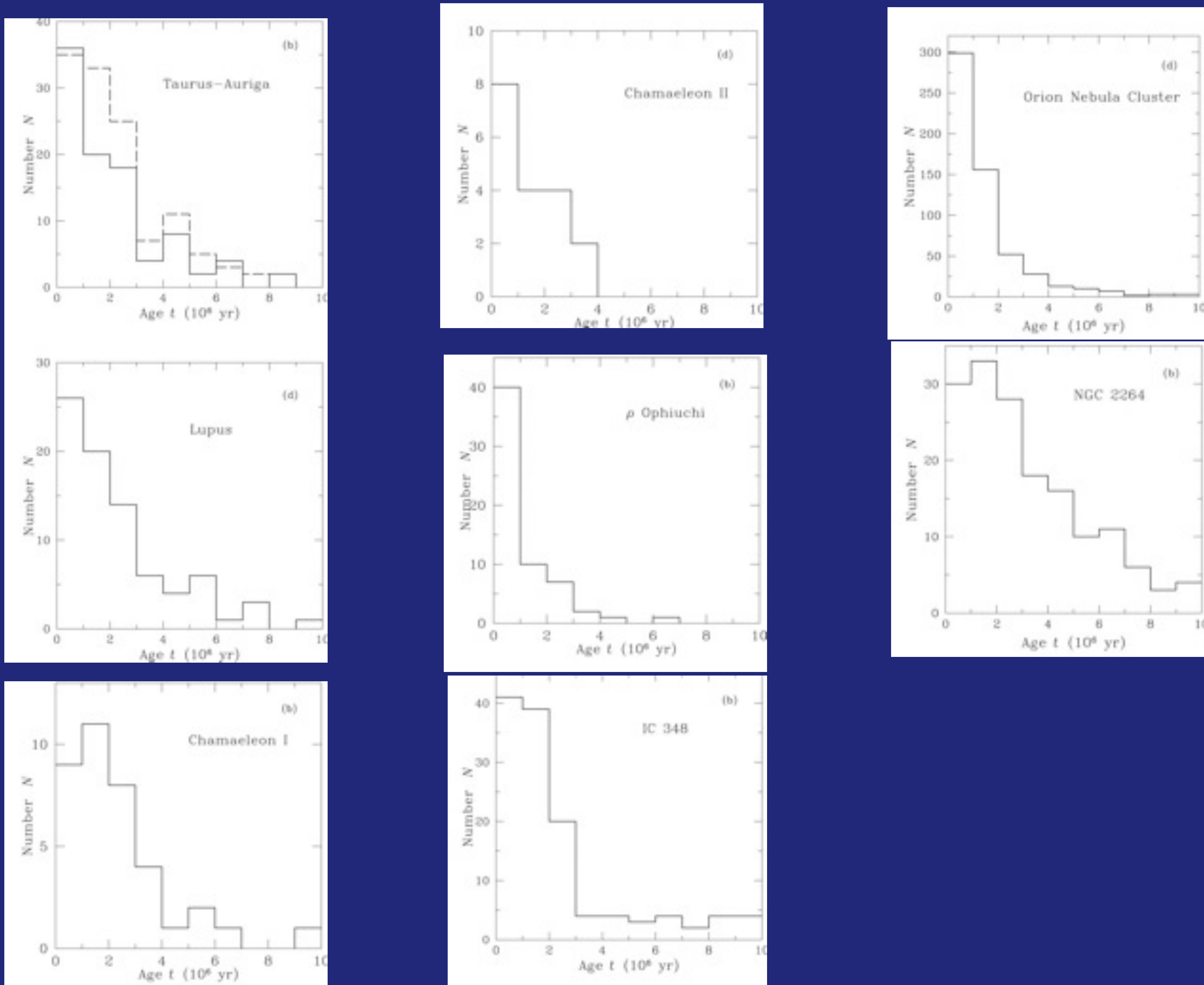


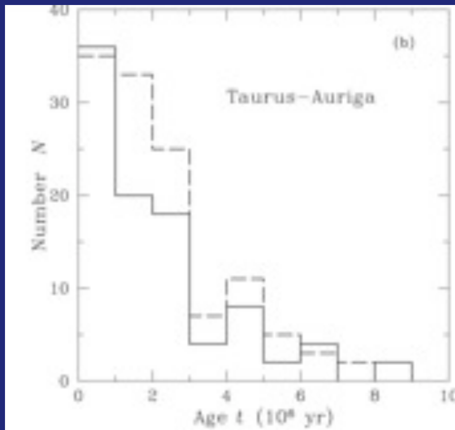


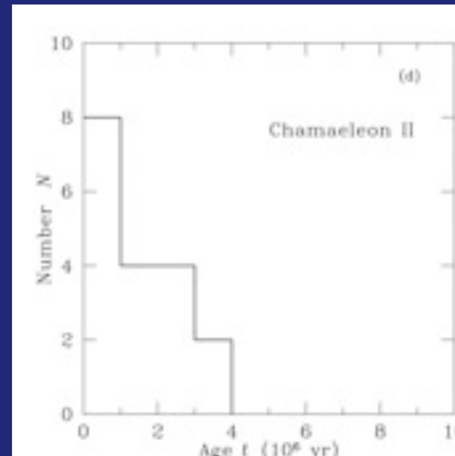
Hurray! ONE region not peaking at 1-2 Myr ago...
OOPS; NO molecular gas (only on periphery)

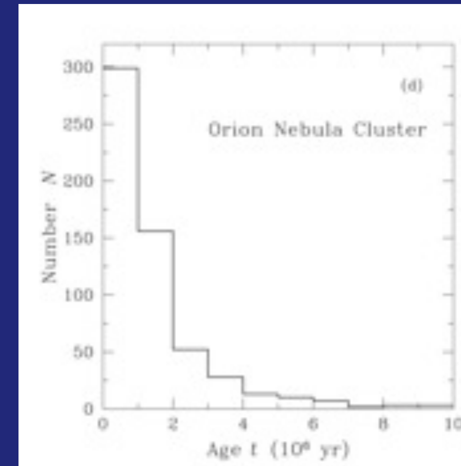


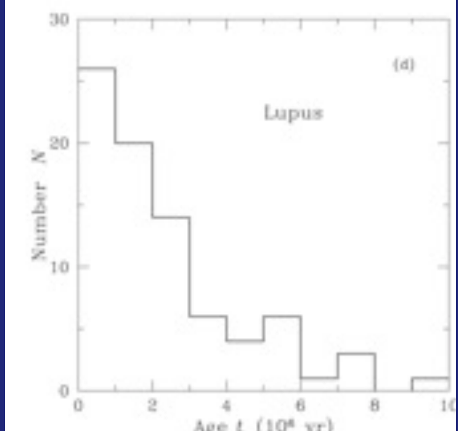


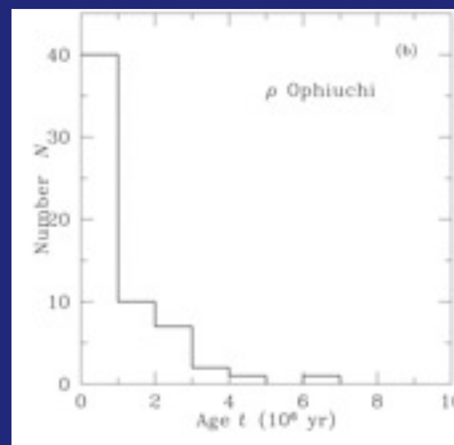

(b)
Taurus–Auriga
Number N
Age t (10⁶ yr)
(d)
Chamaeleon II
Number N
Age t (10⁶ yr)
(d)
Orion Nebula Cluster
Number N
Age t (10⁶ yr)
(d)
Lupus
Number N
Age t (10⁶ yr)
(b)
ρ Ophiuchi
Number N
Age t (10⁶ yr)
(b)
NGC 2264
Number N
Age t (10⁶ yr)
(b)
Chamaeleon I
Number N
Age t (10⁶ yr)
(b)
IC 348
Number N
Age t (10⁶ yr)

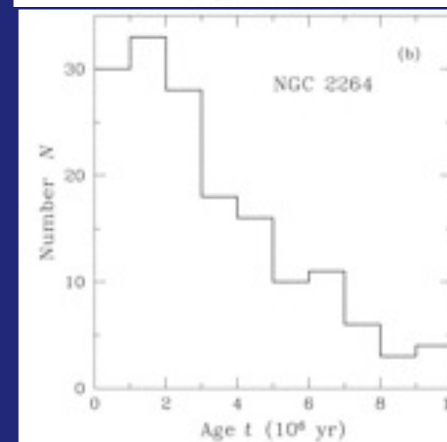


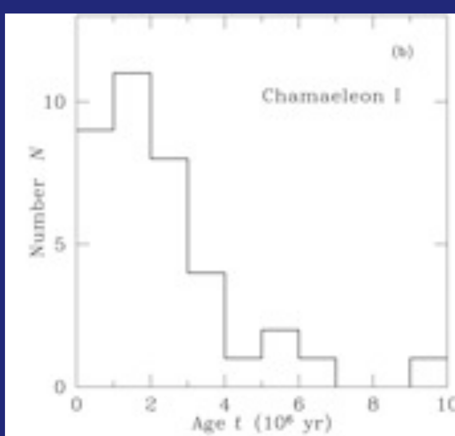


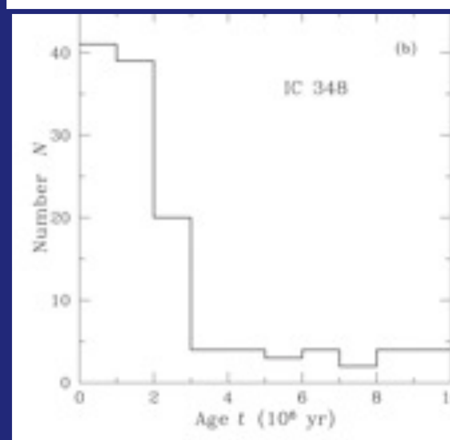


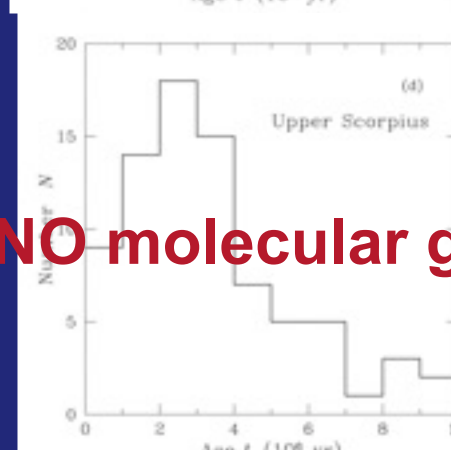








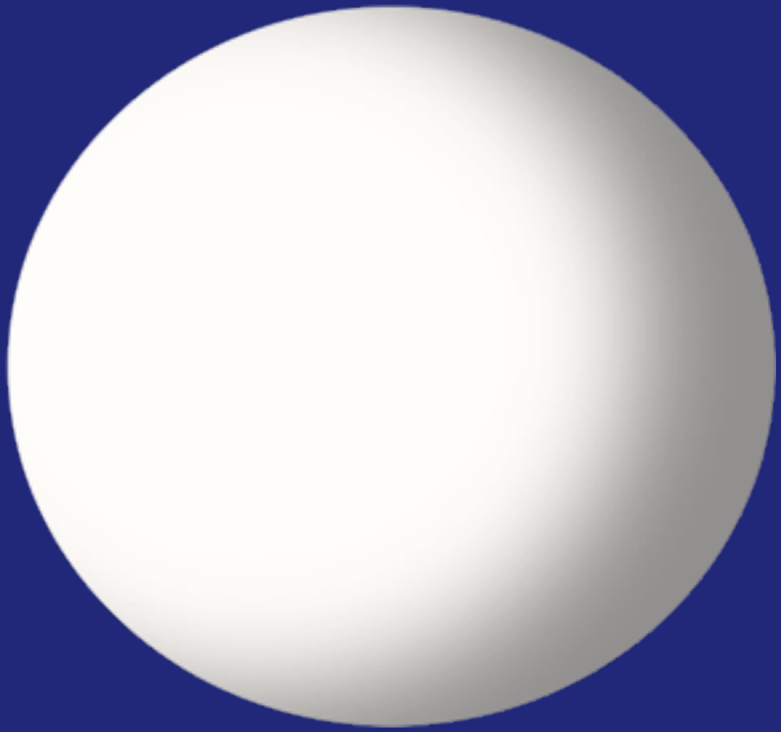




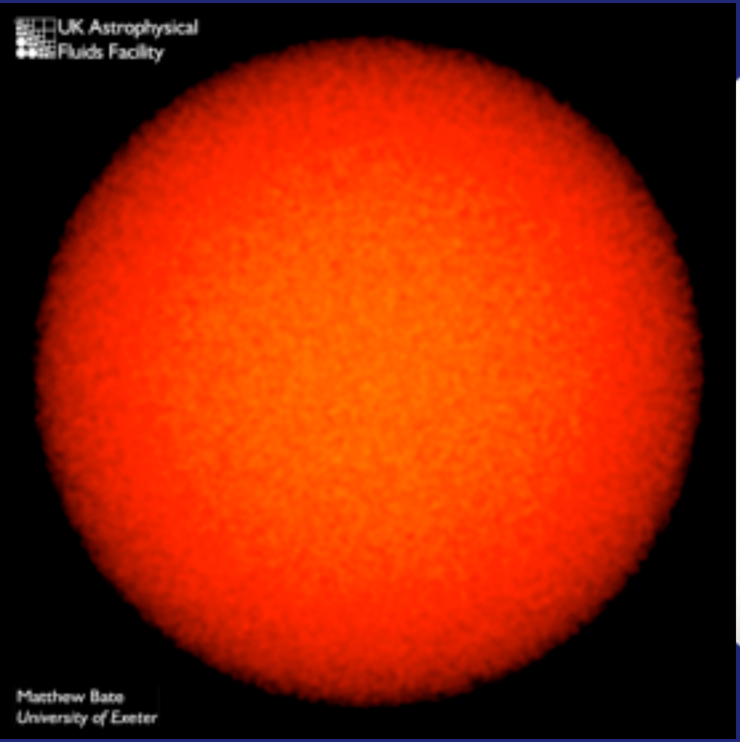
NO molecular gas!

A popular cloud model:

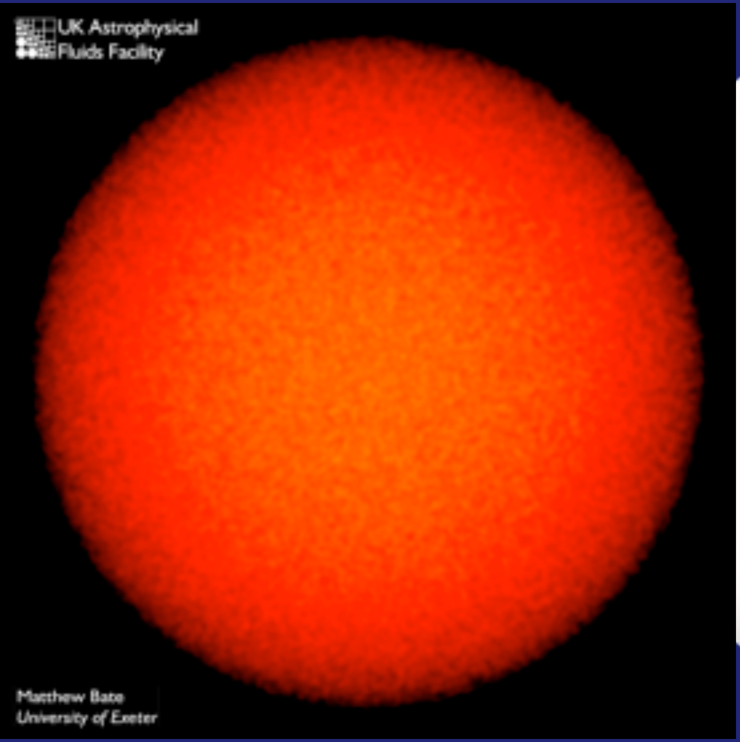
A popular cloud model:

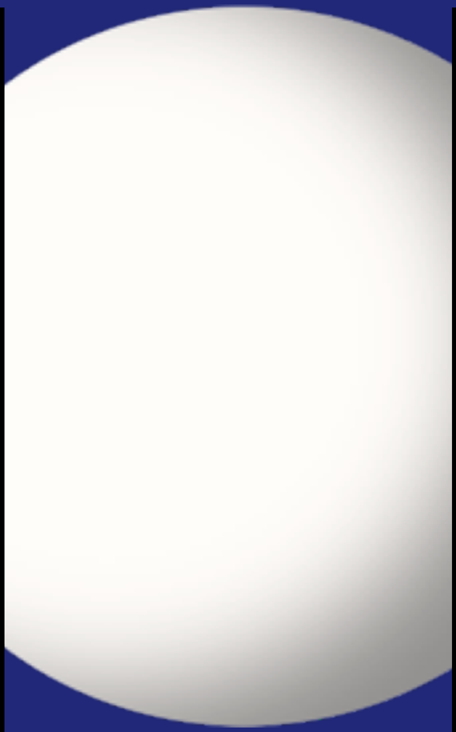
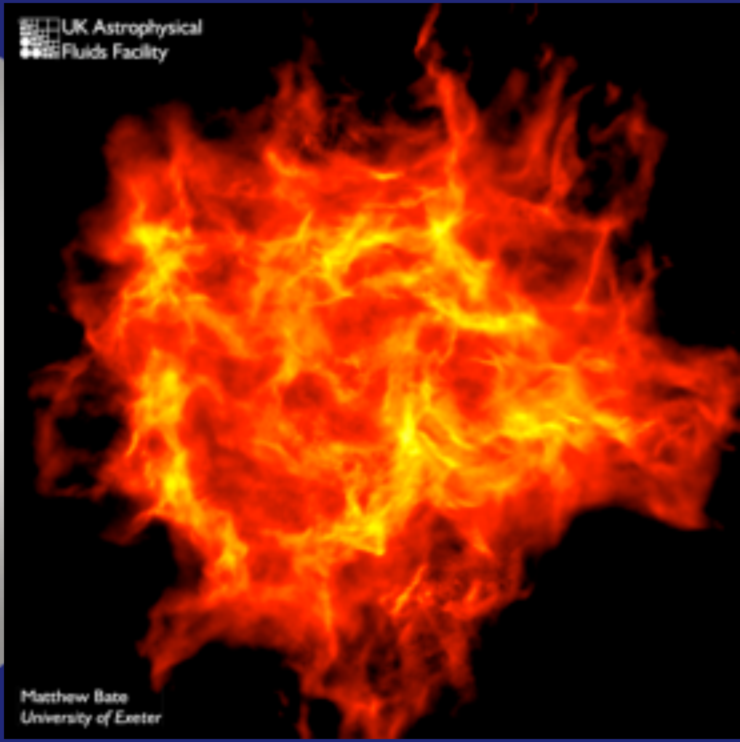


A popular cloud model:

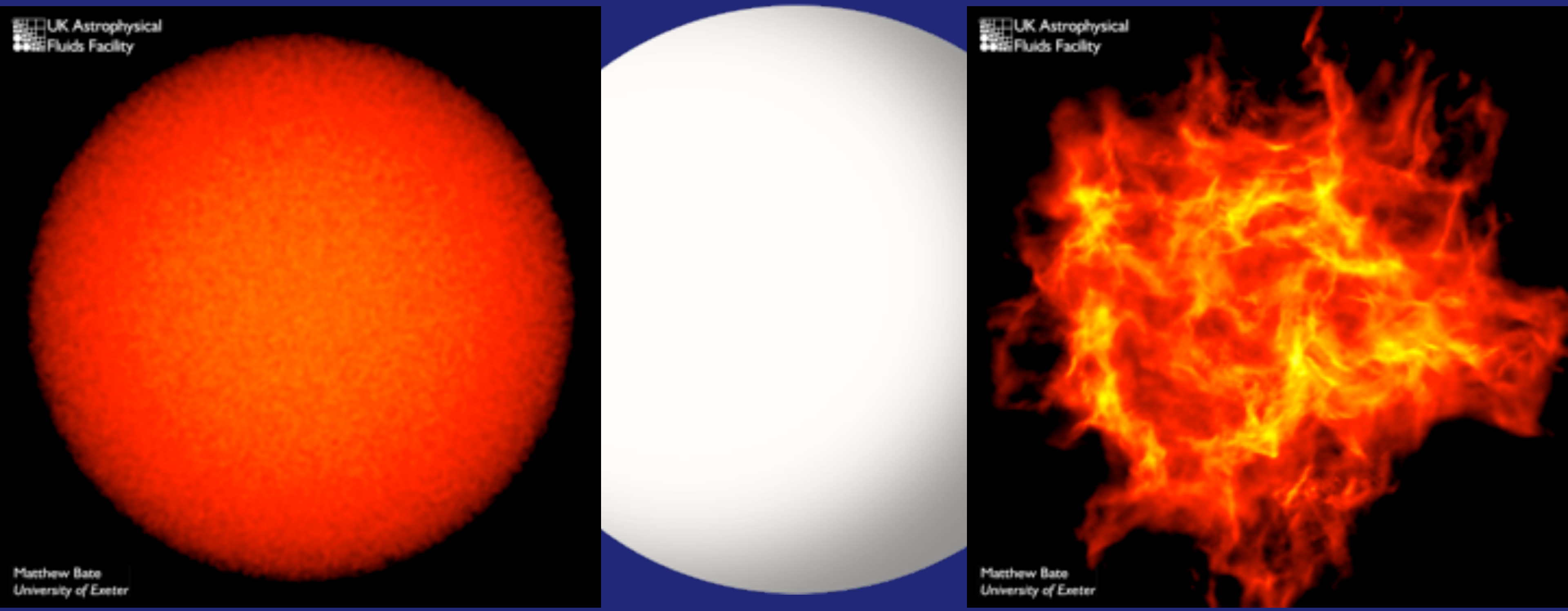


A popular cloud model:



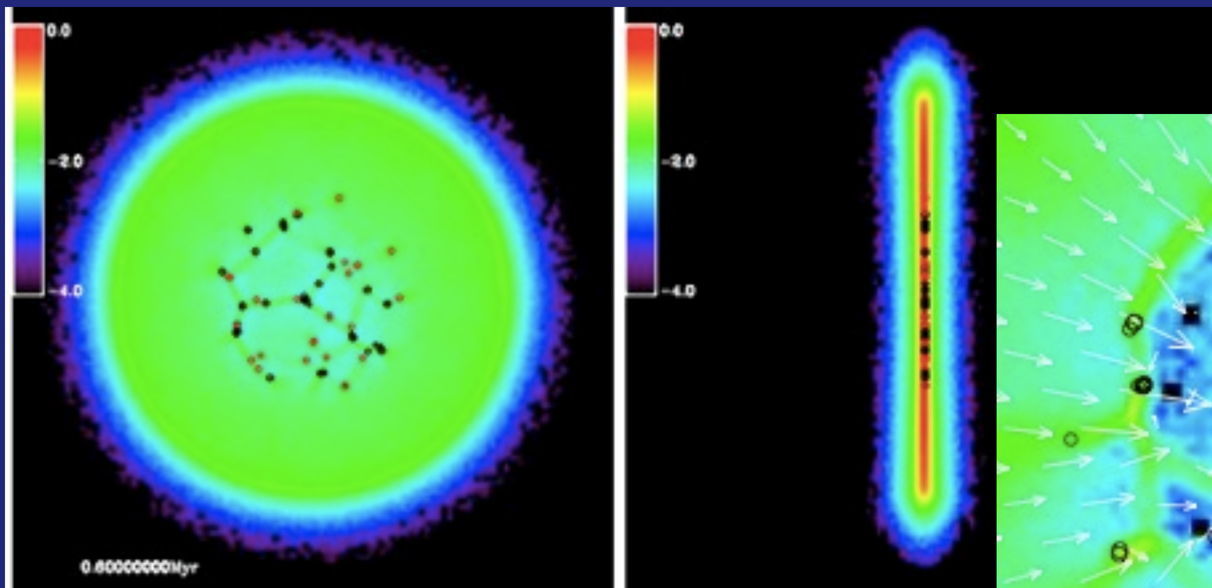



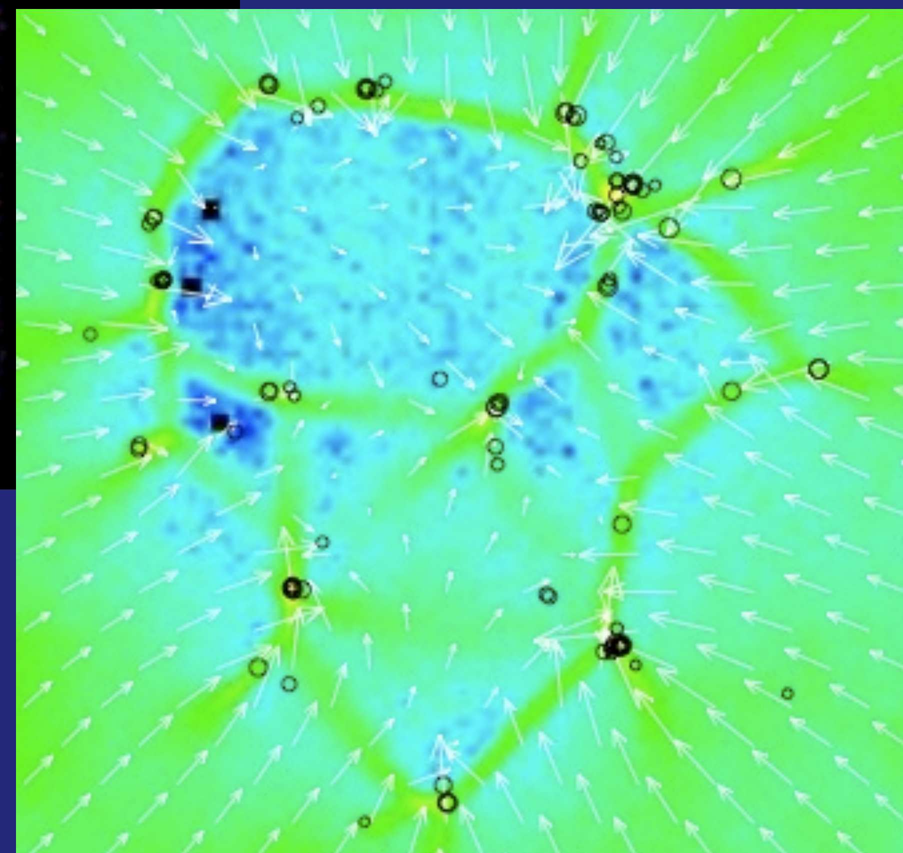
A popular cloud model:



Must put in (arbitrary) velocity field with some "large scale" component to make it look like a real cloud

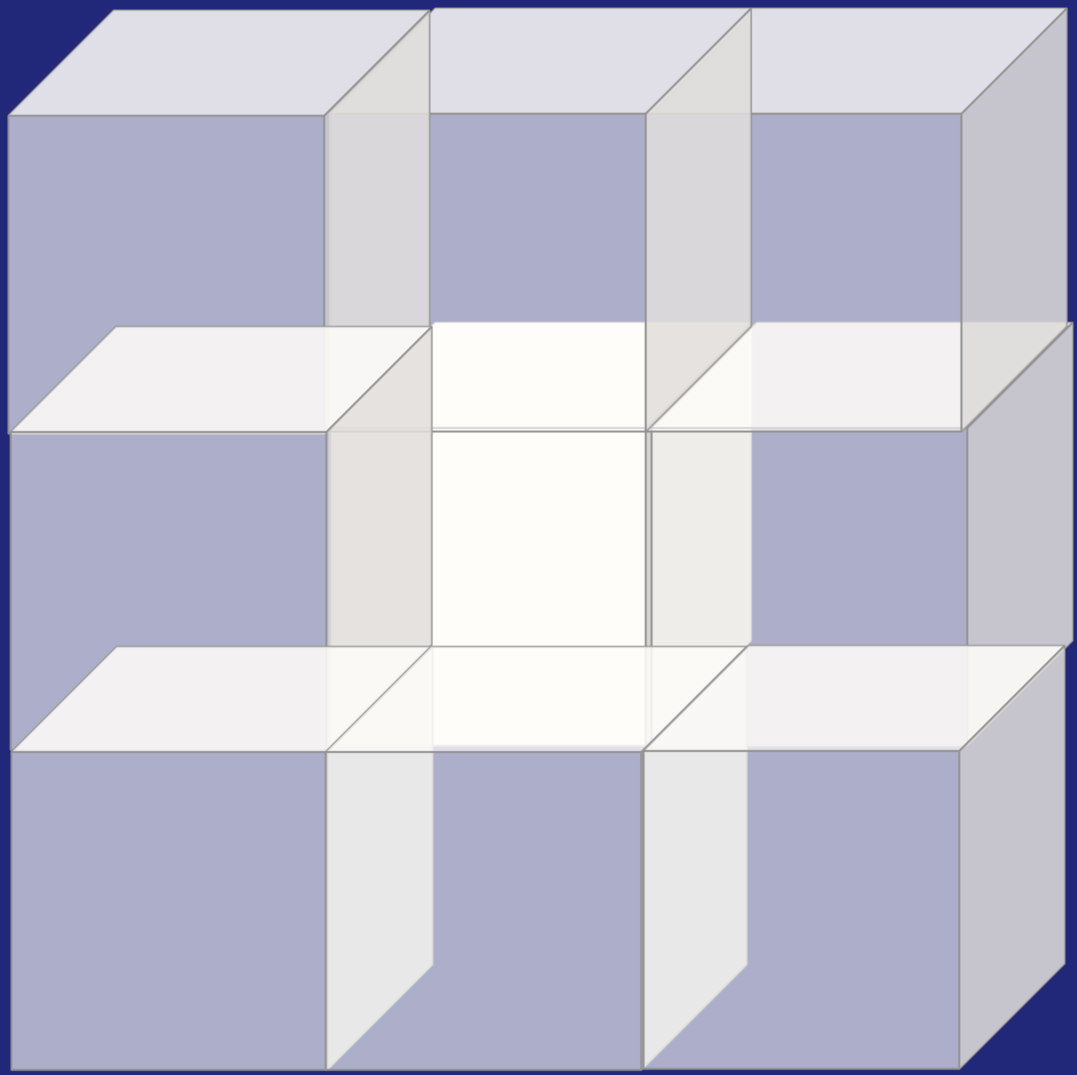
Accretion of randomly-placed sink particles in a sheet; does competitive accretion still work?





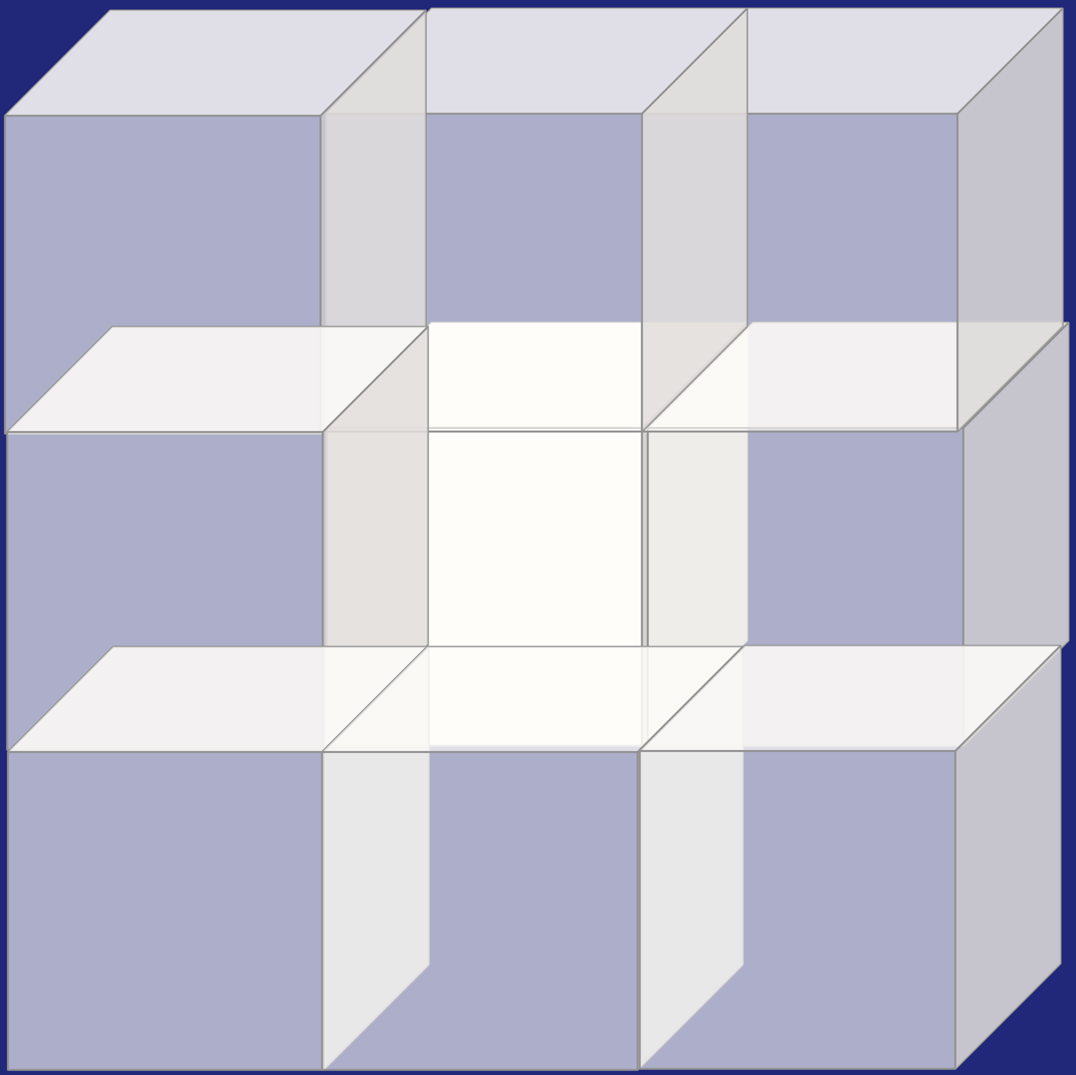
Tina Hsu, LH, Gilberto Gomez, Fabian Heitsch

Another popular cloud model: periodic box



Another popular cloud model: periodic box

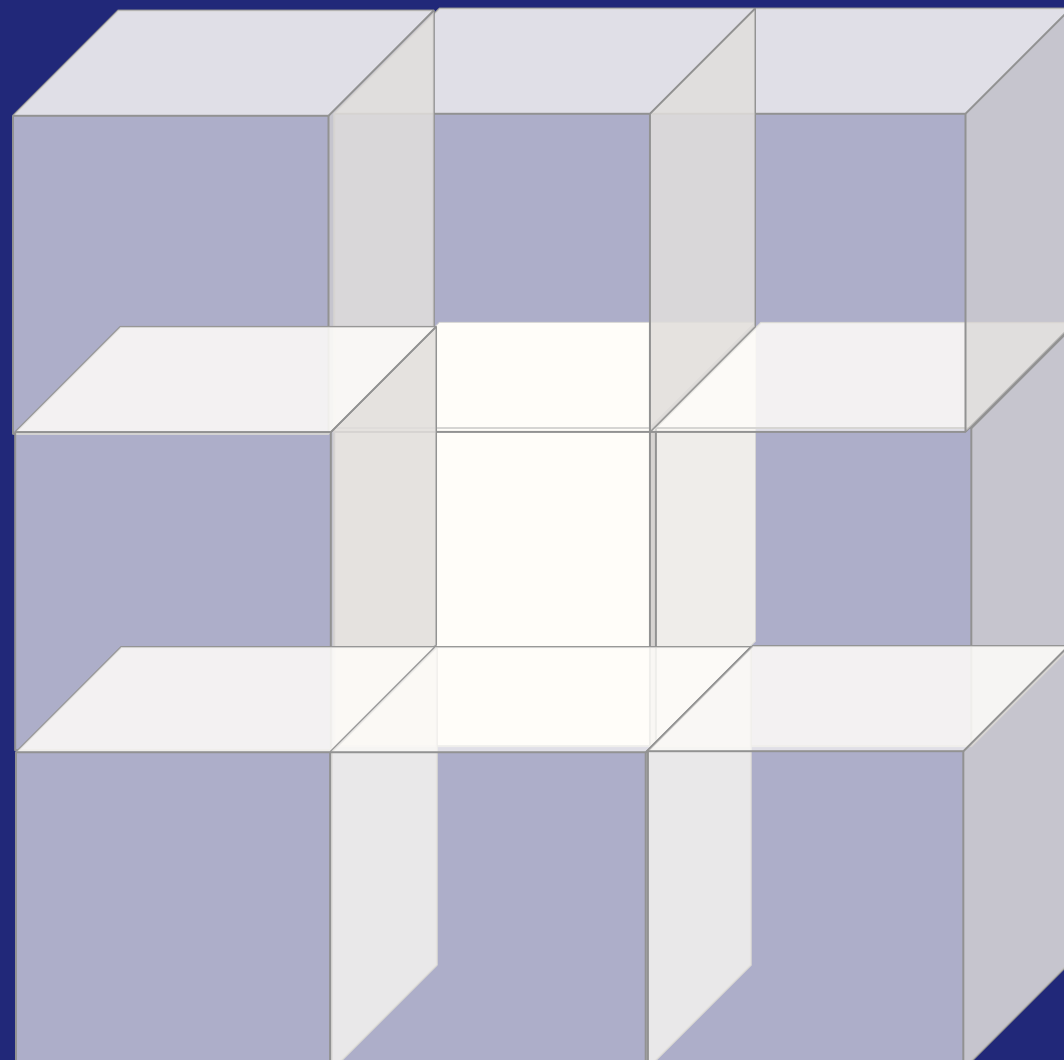
This model also needs imposed turbulence to make reasonable-looking structure;



Another popular cloud model: periodic box

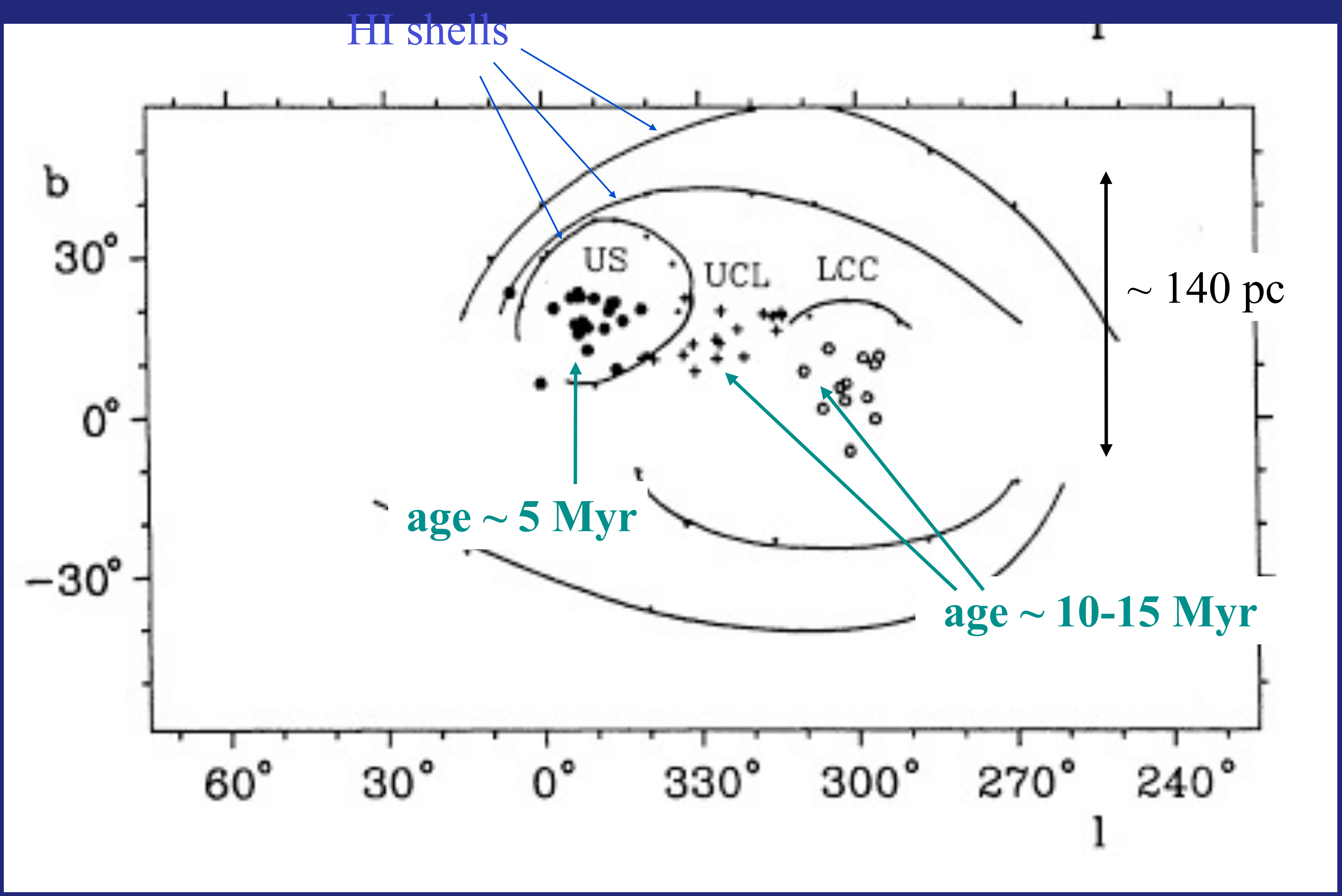
This model also needs imposed turbulence to make reasonable-looking structure;

also: eliminates large-scale gravity



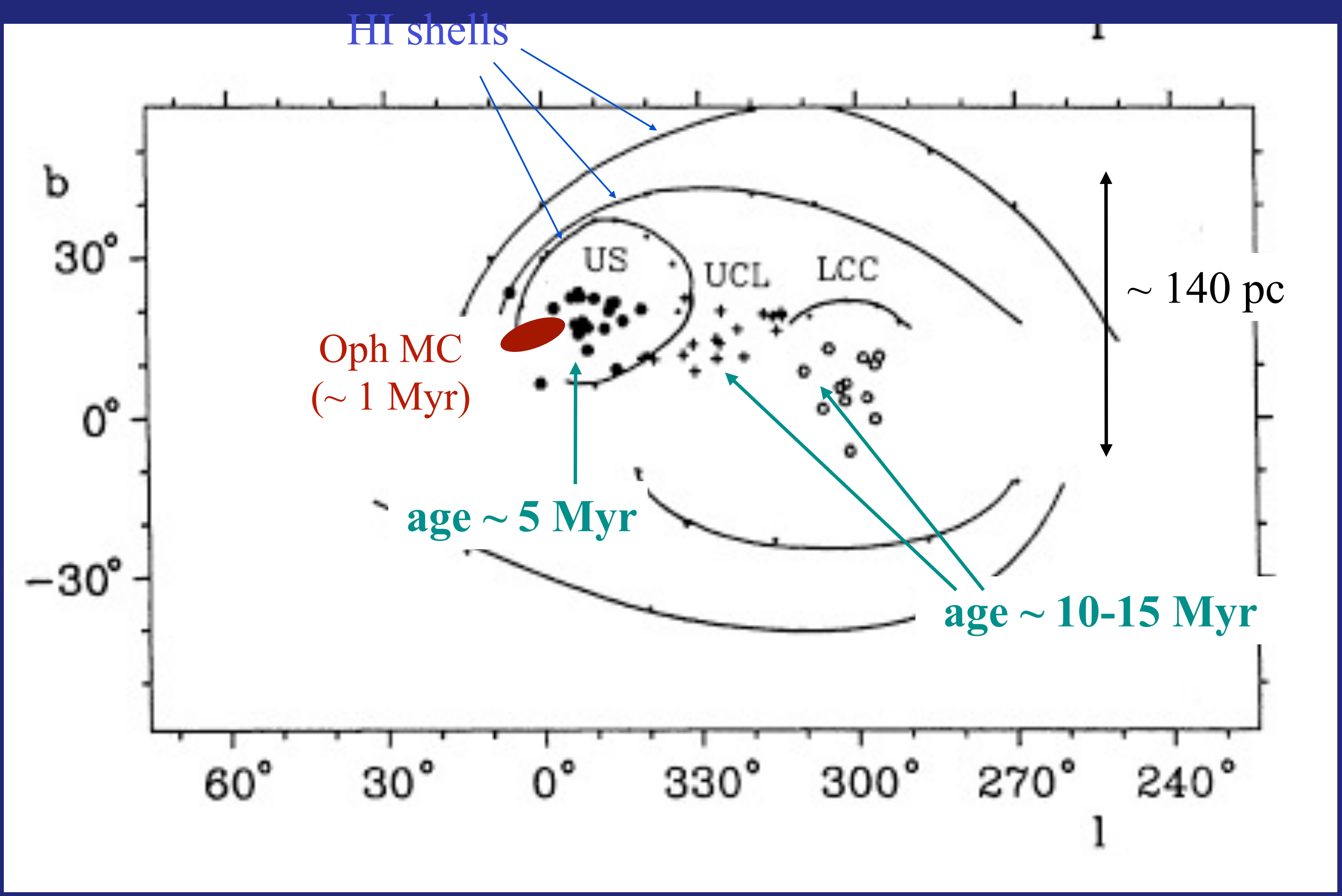
Sco OB2: quickly emptied by winds, SN

de Geus 1992; Preibisch & Zinnecker 99, 02



Sco OB2: quickly emptied by winds, SN

de Geus 1992; Preibisch & Zinnecker 99, 02



Sco OB2: quickly emptied by winds, SN

de Geus 1992; Preibisch & Zinnecker 99, 02