Triggered Star Formation in OB Associations

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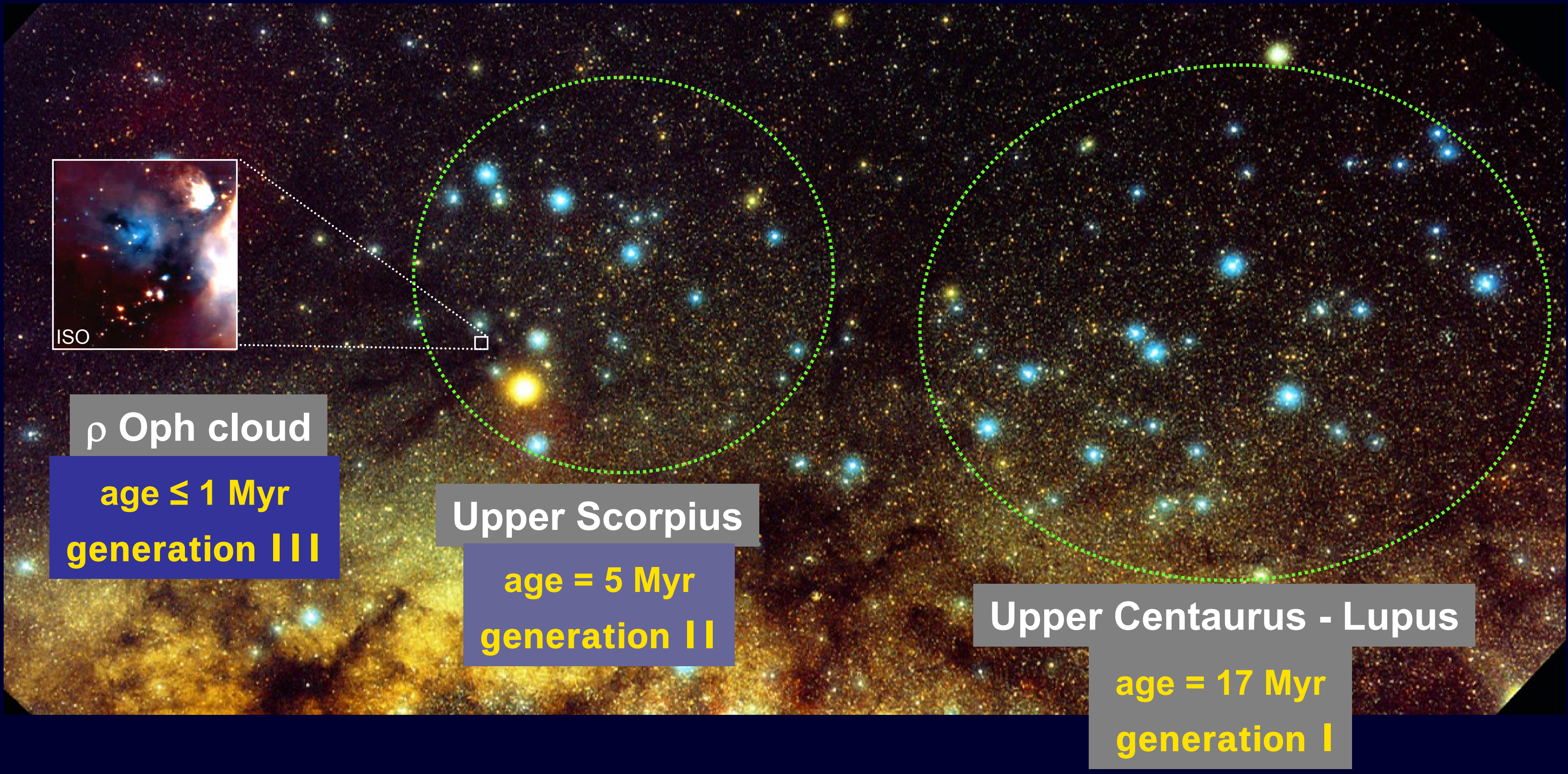


(Ambartsumian 1947; Protostars and Planets V chapter by Briceno et al. (2006; astro-ph/0602446)

OB Association:

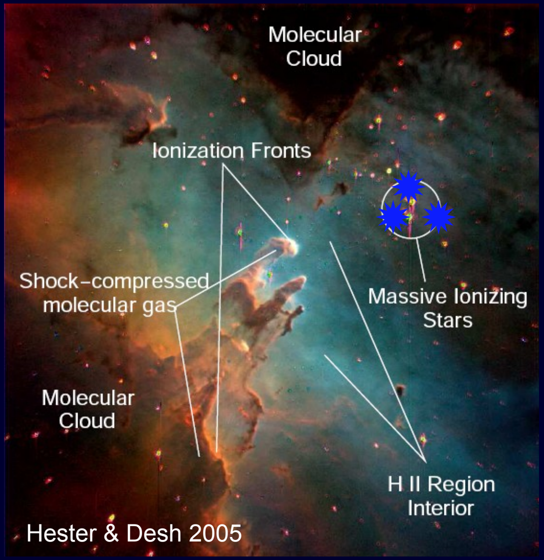
- **Unbound** stellar group containing O – B2 stars, Ø ~ 20 ... 50 pc
- Density < 0.1 $M_\odot$ pc^{-3} → unstable against galactic tidal forces → **<** 30 Myr old

Blaauw (1964, 1991):

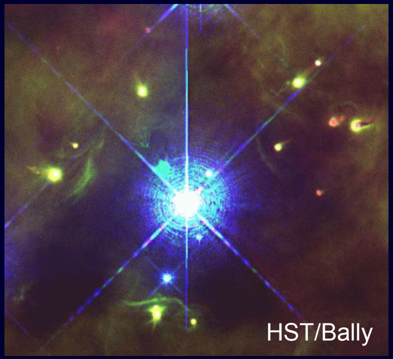
Many OB associations consist of distinct sub-groups

with different ages → *sequential (triggered ?) formation*

Massive stars profoundly affect their environment via

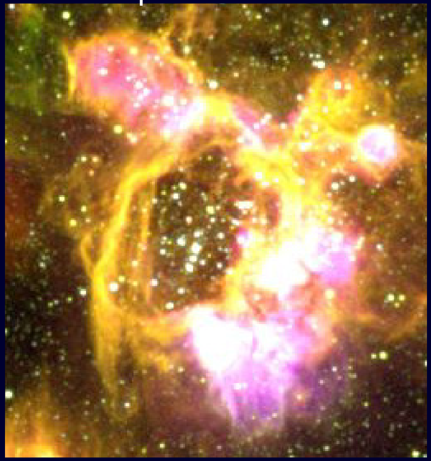


- UV radiation
- stellar winds



- Supernova explosions

Superbubble LMC N44



Effects:

- **Winds & radiation <u>disperse</u> surrounding clouds & disks:**

  → star (& planet) formation terminated

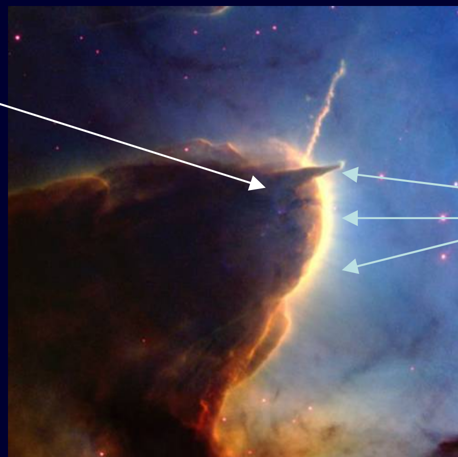
- **UV Radiation <u>compresses</u> surrounding clouds:**

  → radiation-driven implosion of irradiated globules
  may trigger further star formation

- **Winds & Supernovae drive large-scale shock waves:**

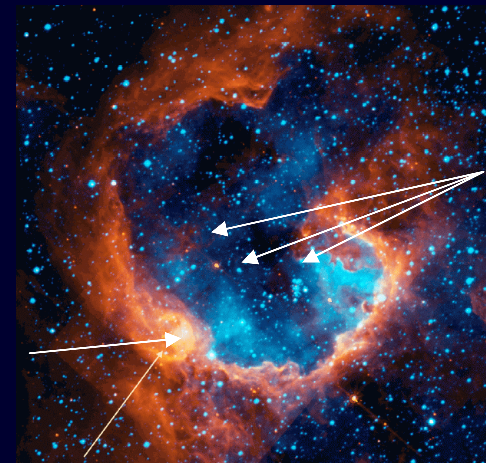
  → triggered star formation in other clouds

<u>Triggered</u> or <u>revealed</u> star formation ?



Trifid Nebula
HST, Hester
et al. (1999)

YSOs in irradiated globules



RCW 79
blue: Hα, red: 8 μm
Zavagno et al.
(2006, A&A 446,171)

YSOs in swept-up shells

Problem: **<u>Proof of causality</u>**

Was the formation of the YSOs really <u>triggered</u> by the shock,

or did YSOs form independently and are just <u>revealed</u> by the shock ?

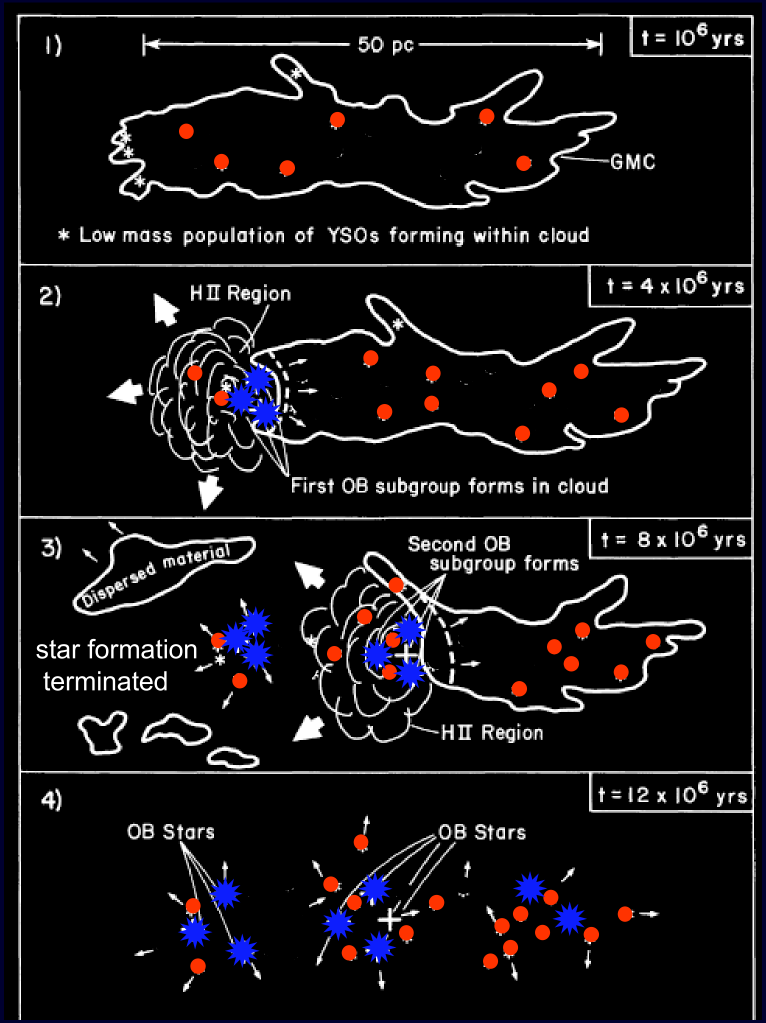
More insight: ***Determine <u>ages of the YSOs</u> and compare to shock arrival time***

OB associations show the ***result of a recently completed star formation process, reconstructed star formation history and initial mass function*** allow a ***quantitative comparison to models***

Theoretical models for triggering mechanisms in OB associations:

1. Sequentially triggered formation of OB subgroups

(Elmegreen & Lada 1977, Lada 1987)



Predictions:

- **Bimodal star formation**:
  low-mass stars form independently
  → are on average older, show large age spread

- **IMF variations**:
  younger OB subgroups should have larger fractions of low-mass stars

Age spread among low-mass stars: [8....12] Myr [4....12] Myr [0....12] Myr

IMF variations: deficit excess of low-mass stars

Theoretical models for triggering mechanisms in OB associations:

2. Radiation-driven implosion of globules near OB stars

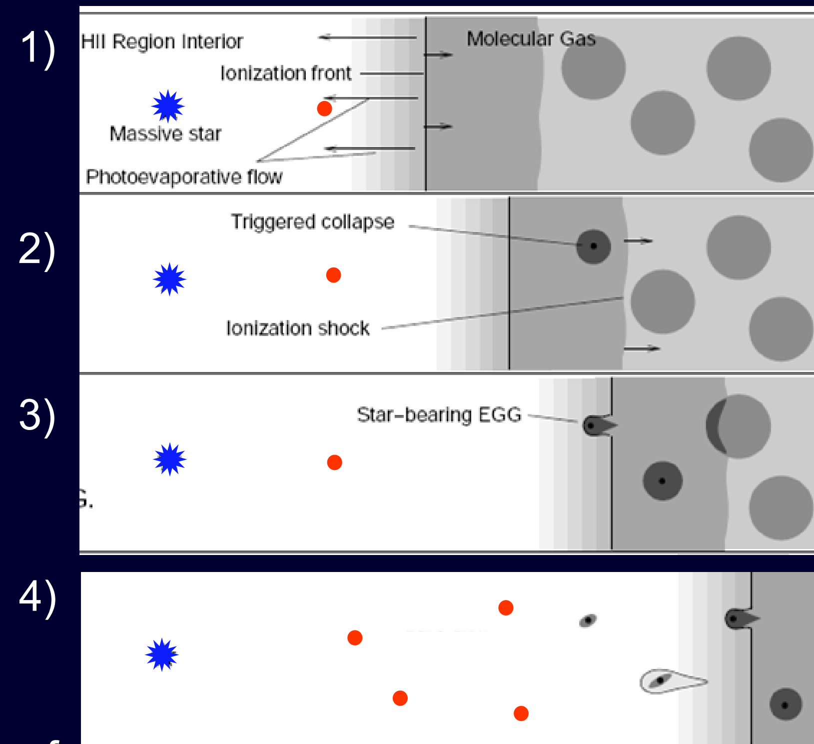
(Bertoldi 1989; Lefloch & Lazareff 1994; Kessel-Deynet & Burkert 2003)

Predictions:

- **OB stars form first,**
  are older than low mass stars

- **Age gradients:**
  stars close to the O star are older than those further away

Hester & Desh (2005)



Ages of the low-mass stars: 7 , 5 , 3 , 1 Myr

Theoretical models for triggering mechanisms in OB associations:

3. Supernova shock wave compression of clouds

(e.g. Foster & Boss 1996, ApJ 468, 784;
Vanhalla & Cameron 1998, ApJ 508, 291)

At suitable distances of ~ 20 ... 100 pc,

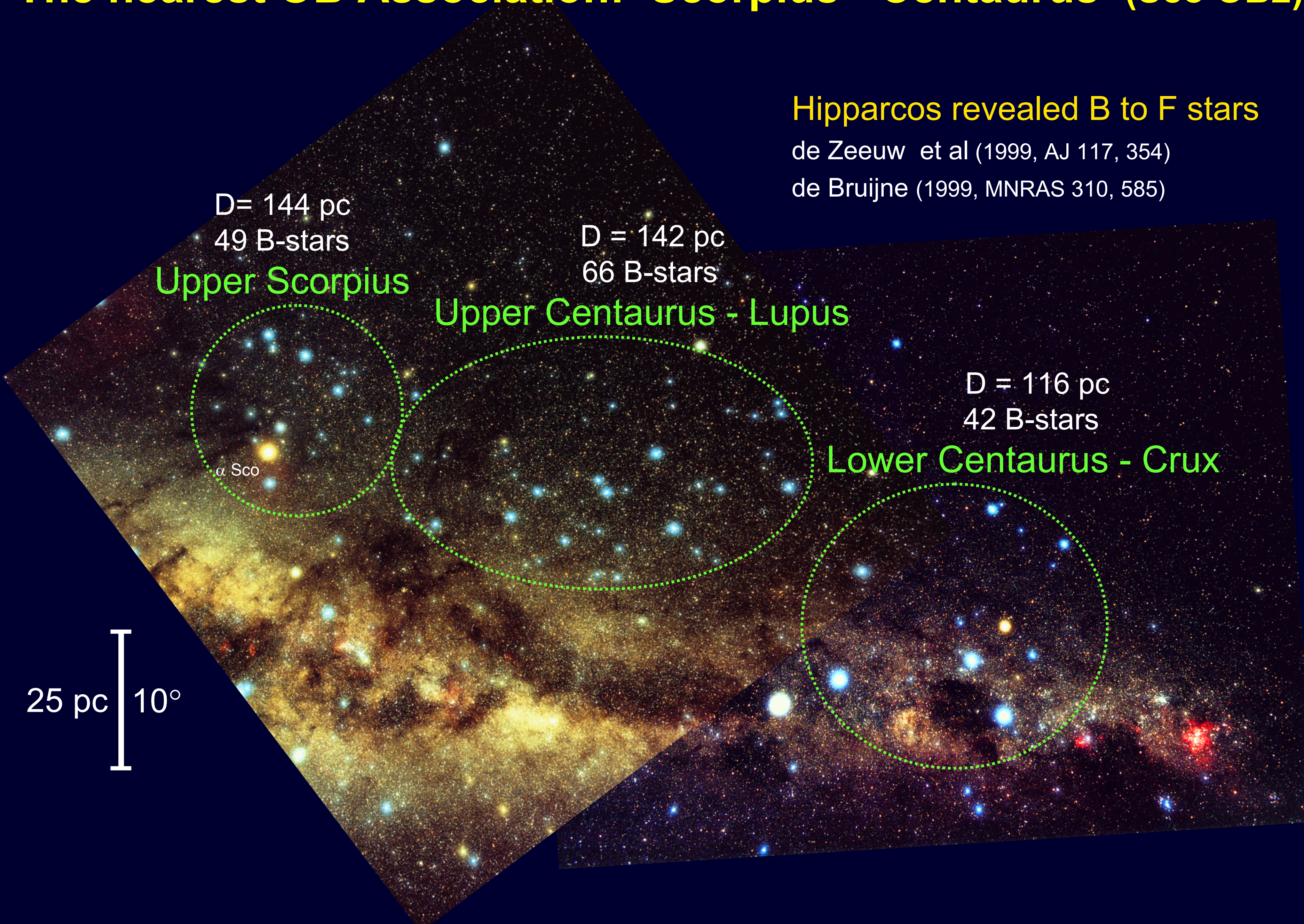
where v_{shock} = 20 ... 50 km/sec,

cloud collapse can be triggered

Predictions:

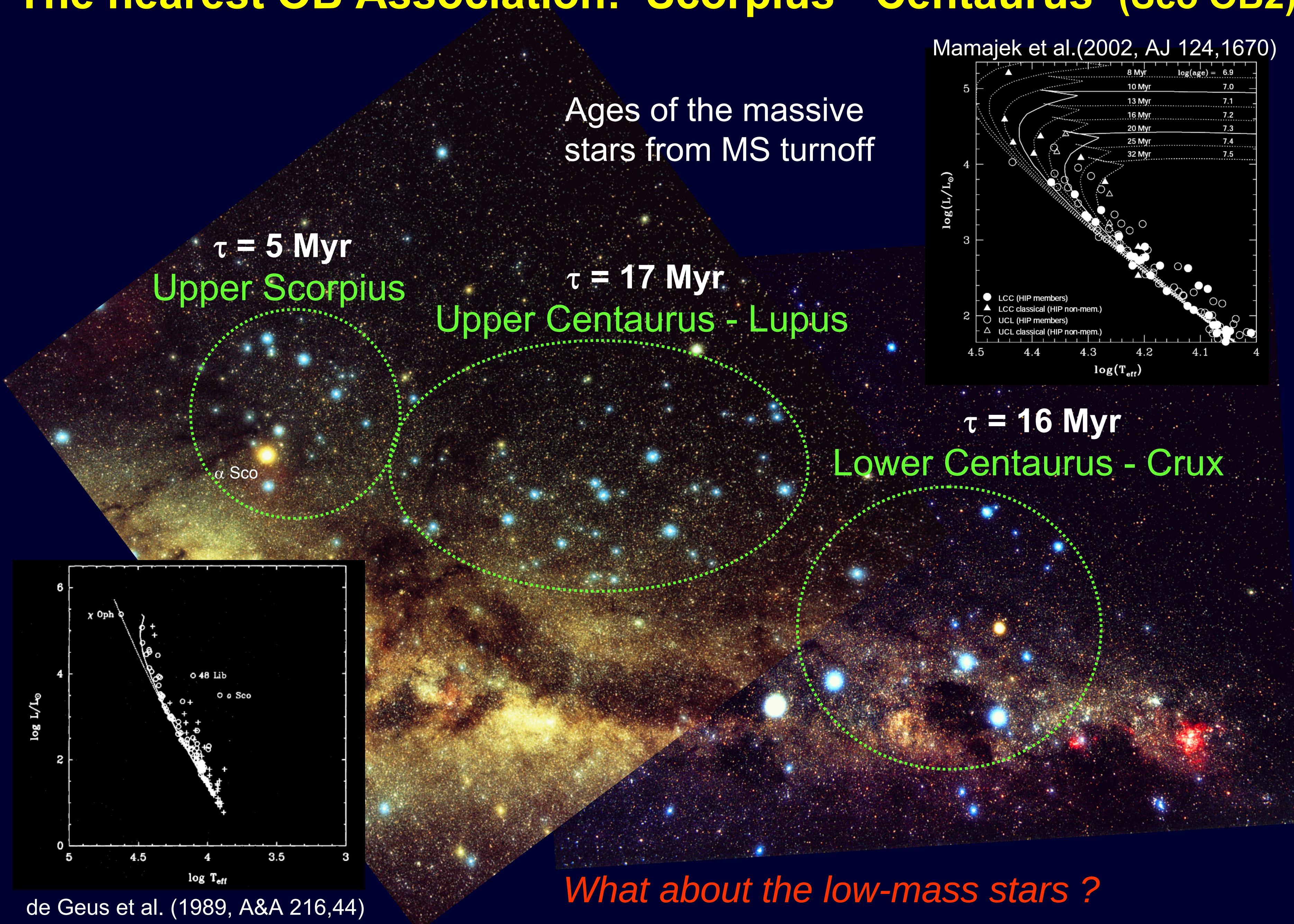
- **High- and low-mass stars have same age**
- **Small age spread** (since v_{shock} > 20 km/sec)
- **Age difference of ~ 5...10 Myr between subgroups**

The nearest OB Association: Scorpius - Centaurus (Sco OB2)



The nearest OB Association: Scorpius - Centaurus (Sco OB2)

Ages of the massive stars from MS turnoff



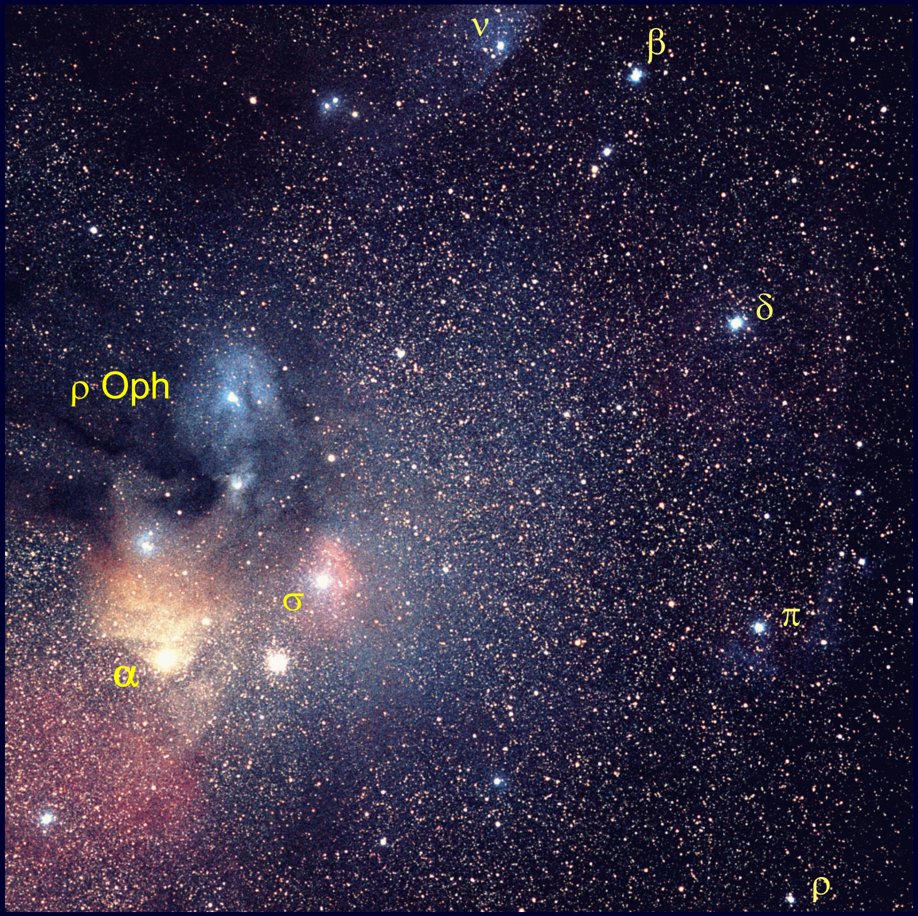
Mamajek et al.(2002, AJ 124,1670)

de Geus et al. (1989, A&A 216,44)

What about the low-mass stars ?

The low-mass stars in Upper Scorpius - needles in a haystack

Problem: **Huge field star confusion**

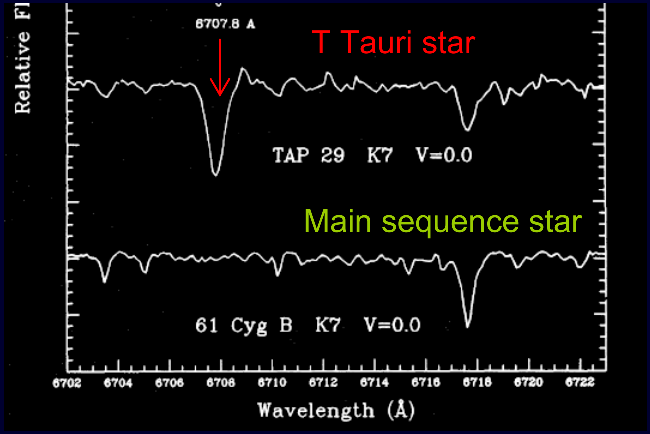


10° x 10° (25 x 25 pc)

The low-mass stars in Upper Scorpius - needles in a haystack

Problem: **Huge field star confusion**

Solution: **Look for Lithium**



Young members: Lithium preserved
Older field stars: Lithium depleted

10° x 10° (25 x 25 pc)

Task: **Obtain high-/medium-resolution spectra of *all* stars in the region**

feasible with modern multi-object spectrographs like 2dF

(400 objects in a 2° field-of-view)

The low-mass stars in Upper Scorpius - needles in a haystack

10° x 10° (25 x 25 pc)

Lithium surveys in Upper Sco:

- X-ray selected candidates:
  Walter et al (1994, AJ 107,692)
  Preibisch et al (1998, A&A 333,619)
- Survey with multi-object spectrograph 2dF
  (1045 candidate stars observed)
  Preibisch et al (2002 AJ 124, 404)

→ 250 low-mass members

including higher-mass stars
identified with Hipparcos:

→ 364 known members

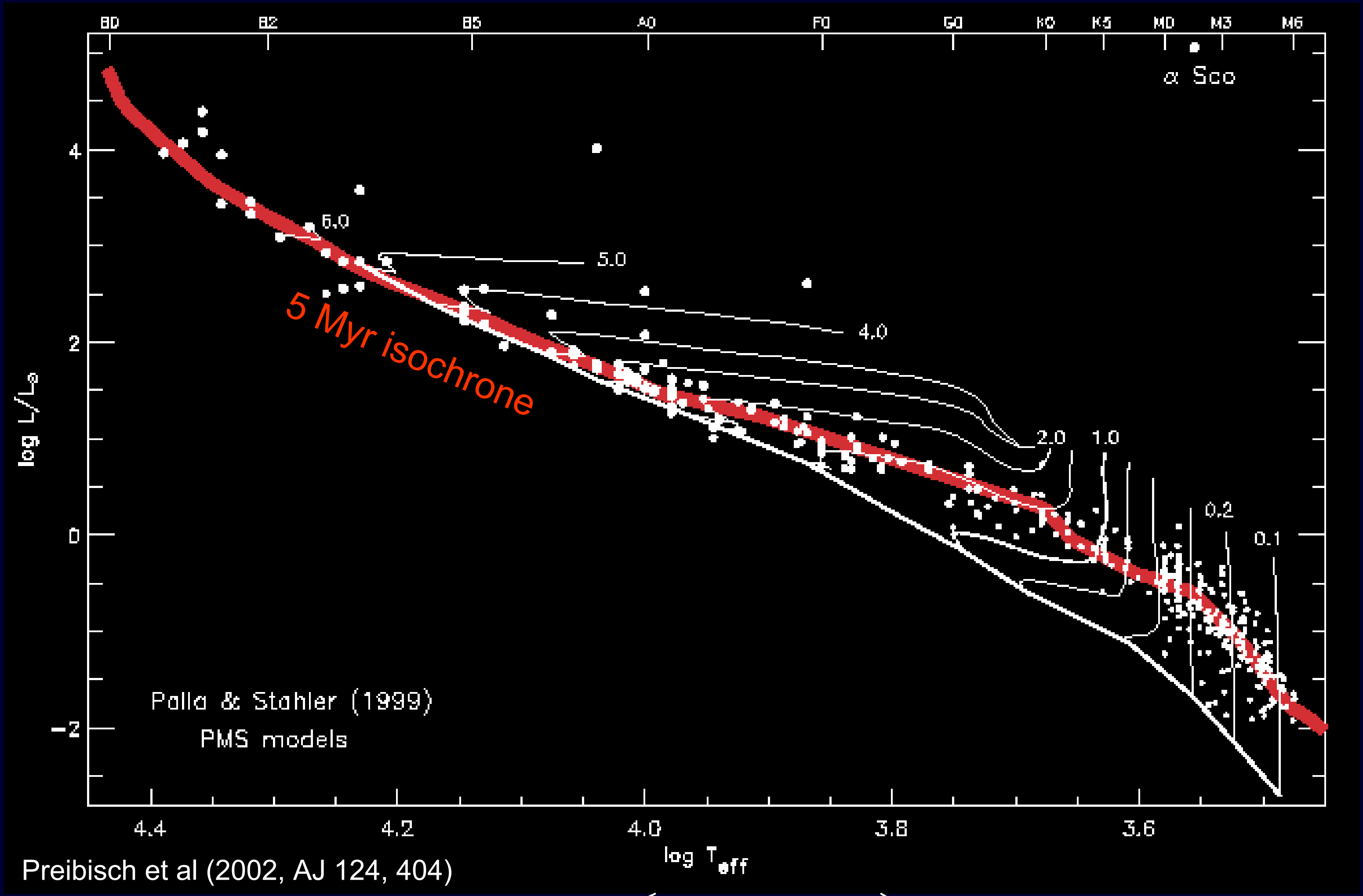
SpT = B0.5 – M6
M = 20 $M_\odot$ – 0.1 $M_\odot$

Statistically robust sample

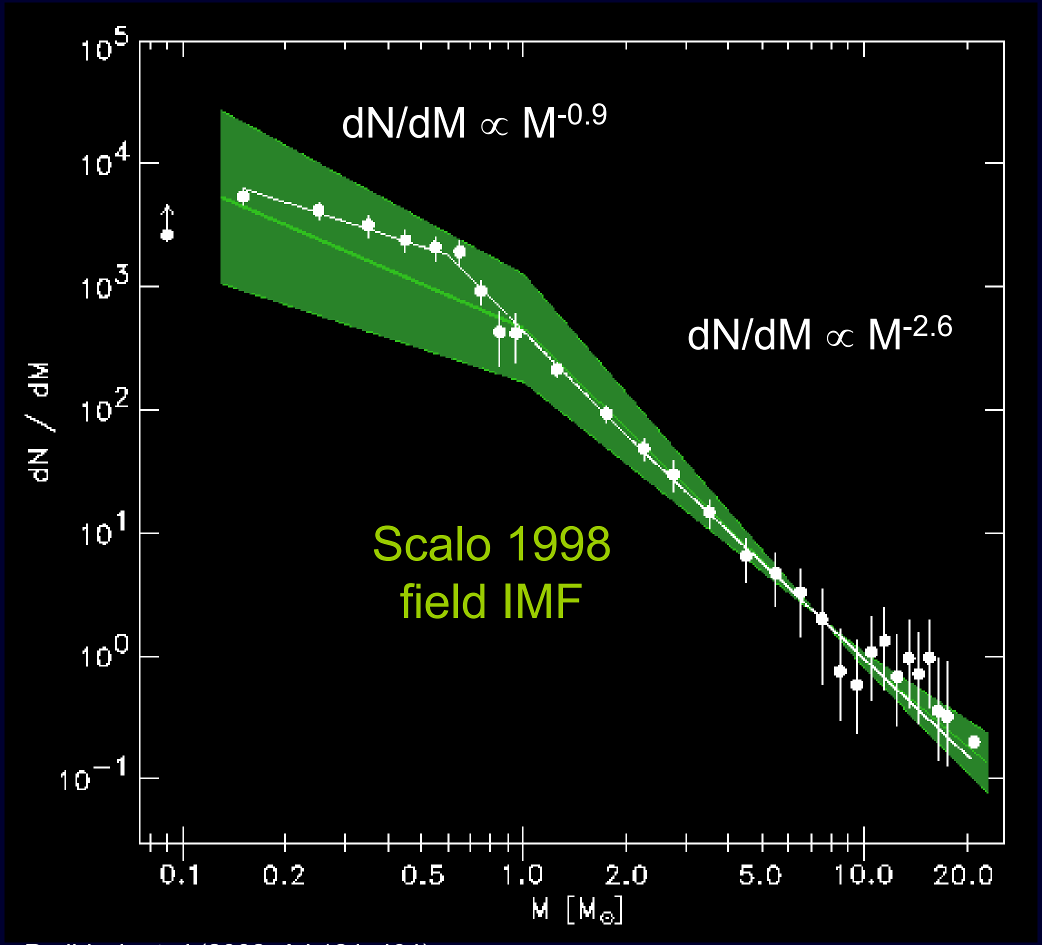
Individual spectral types and extinctions known:

can derive IMF and star formation history

The HR Diagram for Upper Scorpius



The Initial Mass Function of Upper Sco

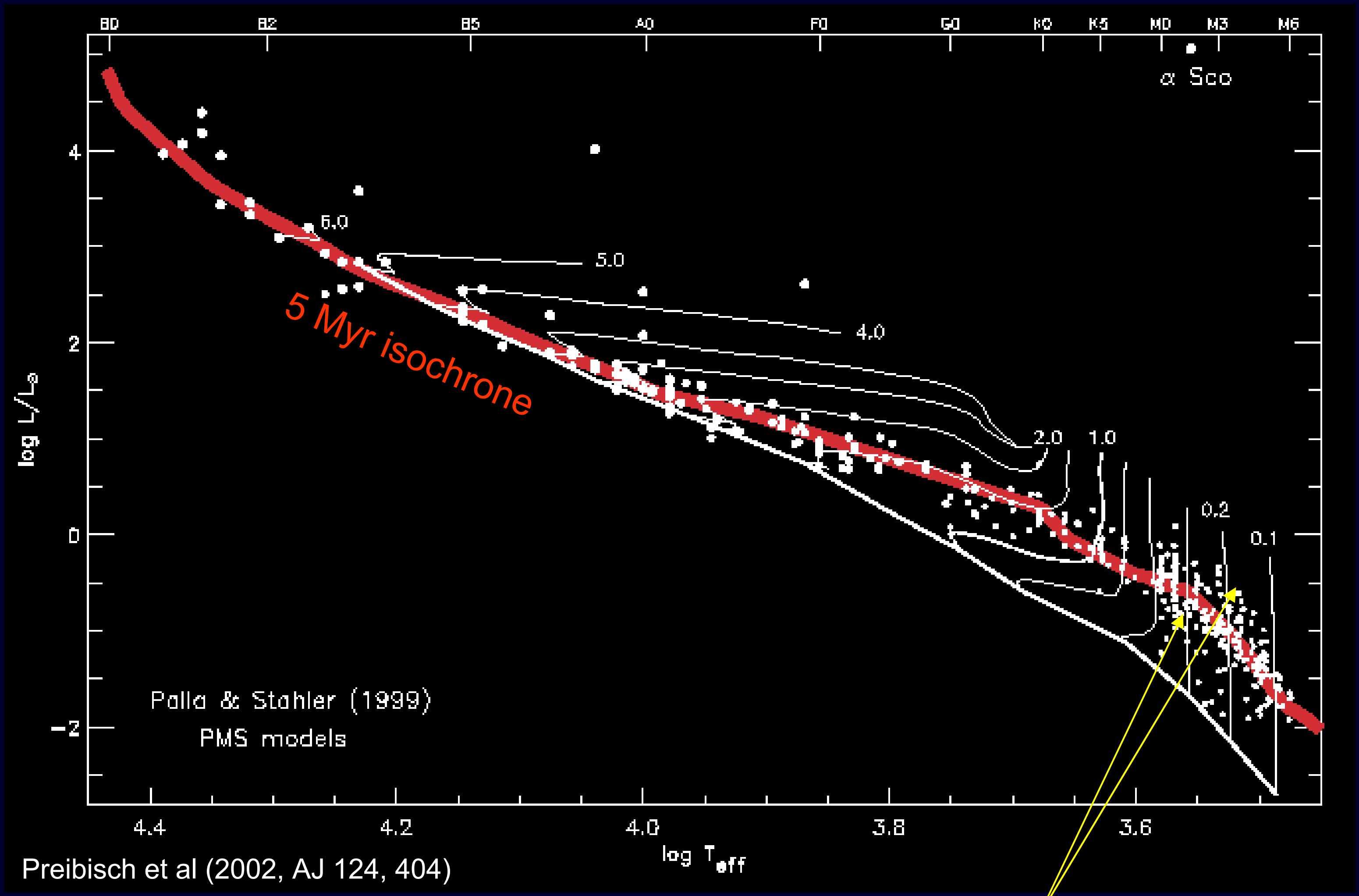


Preibisch et al (2002, AJ 124, 404)

- IMF is ***not*** truncated, ***no deficit*** of low-mass stars
- Observed IMF consistent with field IMF
- Total stellar mass: ~ 2200 $M_\odot$

Salpeter:
$dN/dM \propto M^{-2.35}$

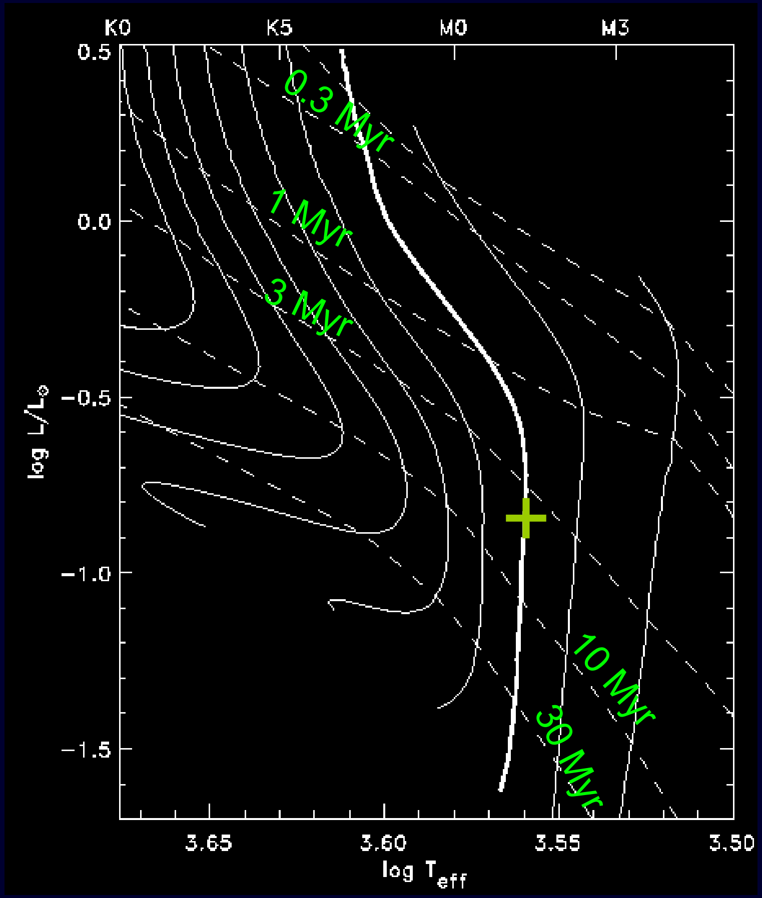
The HR Diagram for Upper Scorpius



→ **High- and low-mass stars are <u>coeval</u>**

Does this scatter imply ~10 Myr age spread ??

Problem with ages derived from HRD: $L_{obs} \neq L_{true}$ due to:



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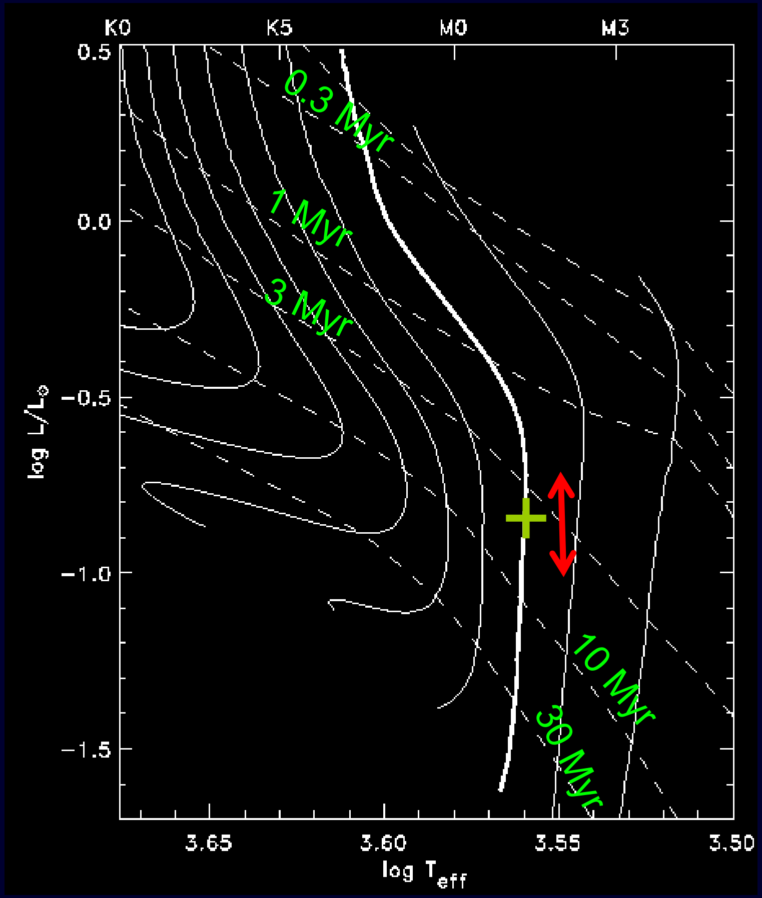
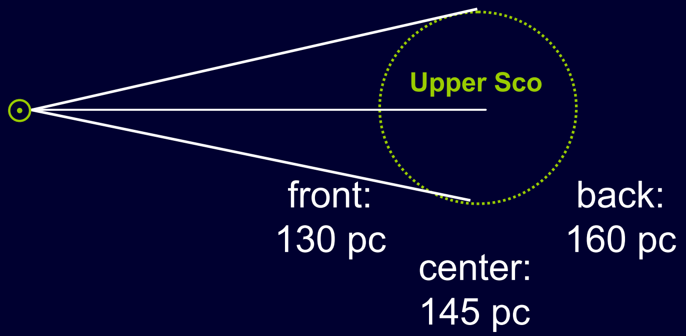


- spread of individual stellar distances:

$$\Delta \log L = [\ -0.15 \ \ldots \ +0.15\ ]$$



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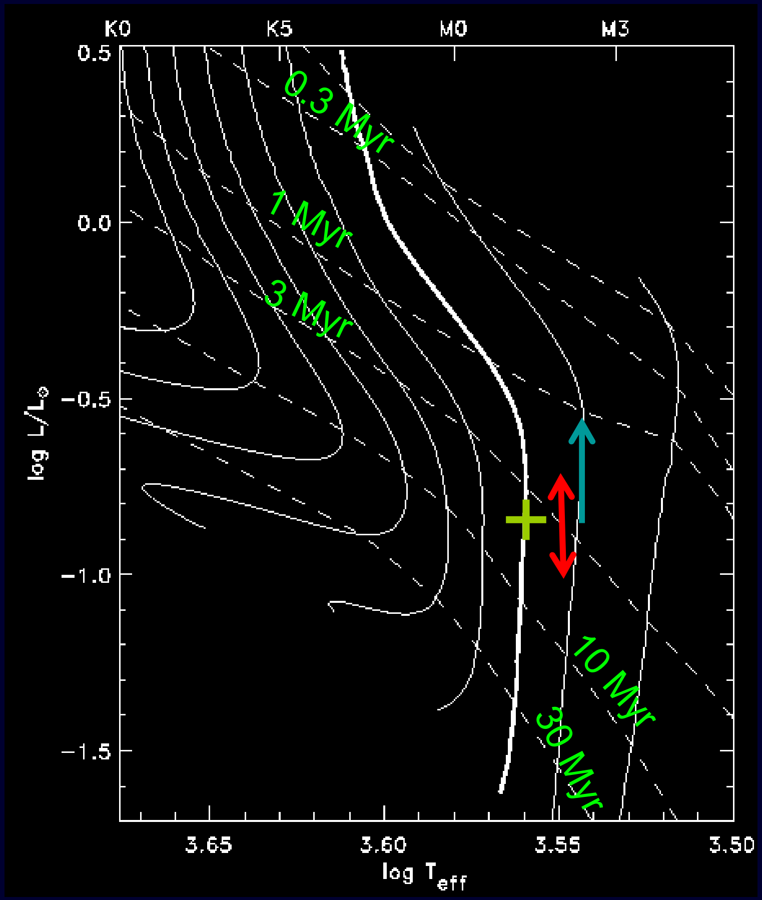

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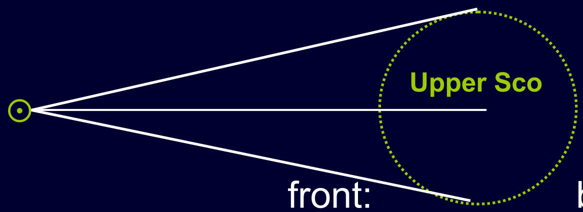

- unresolved binaries:

$$\Delta \log L = [\; 0 \;\ldots\; +0.3 \,]$$

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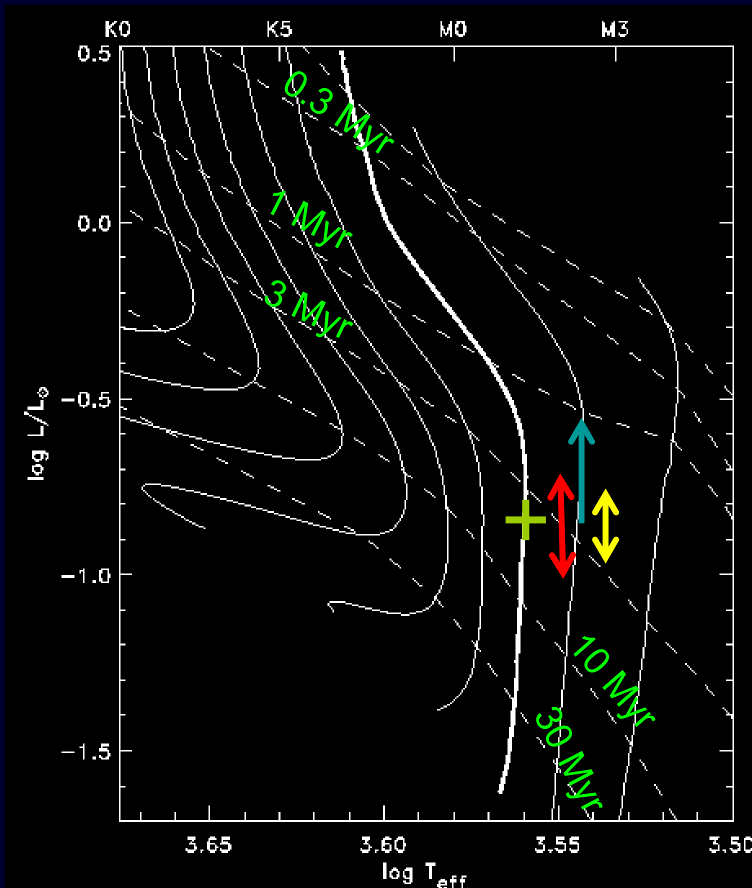

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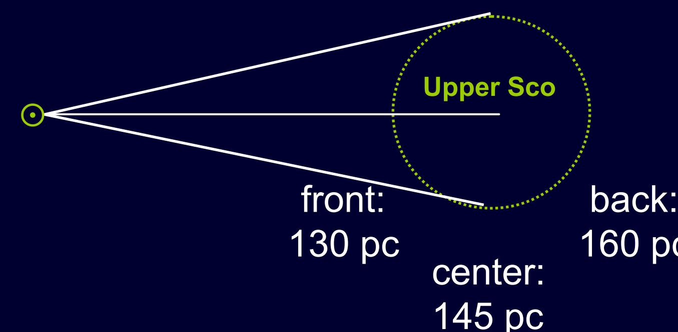

- unresolved binaries:

$$\Delta \log L = [\;0 \;\dots\; +0.3\,]$$

- photometric variability:

$$\Delta \log L = [\,-0.1 \;\dots\; +0.1\,]$$

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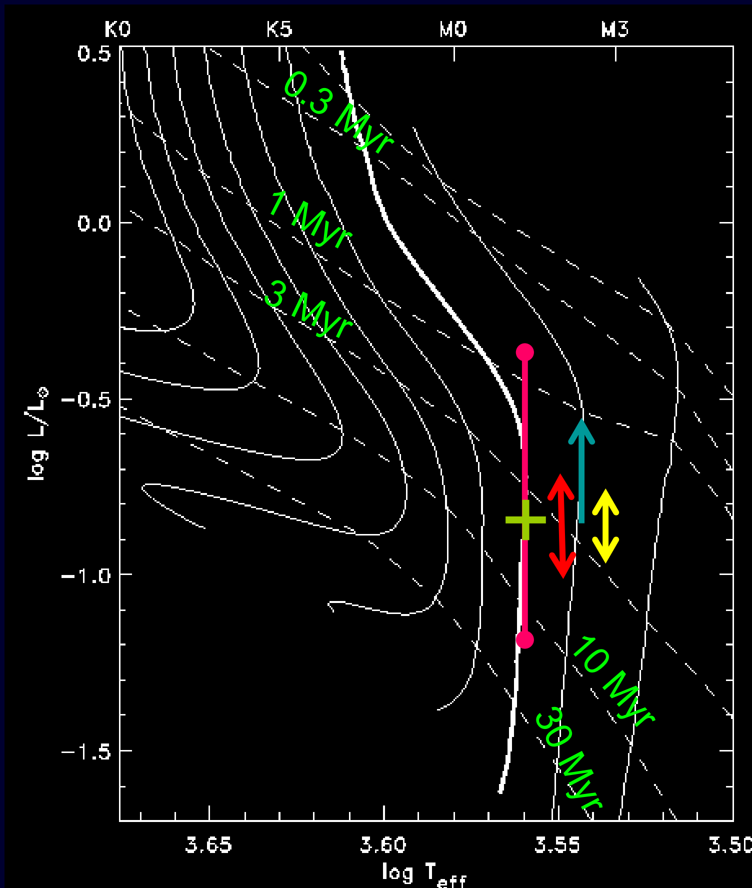
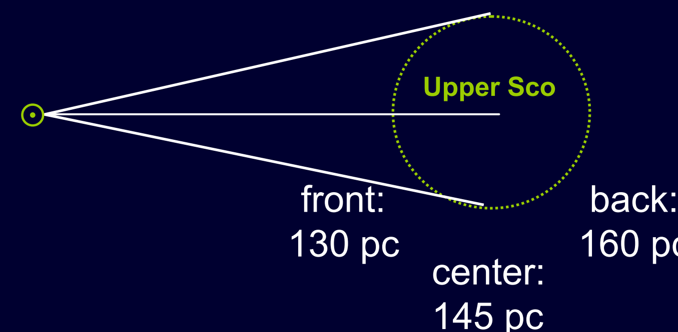


- spread of individual stellar distances:

Δ log L = [-0.15 … +0.15]



- unresolved binaries:

Δ log L = [0 … +0.3]

- photometric variability:

Δ log L = [-0.1 … +0.1]

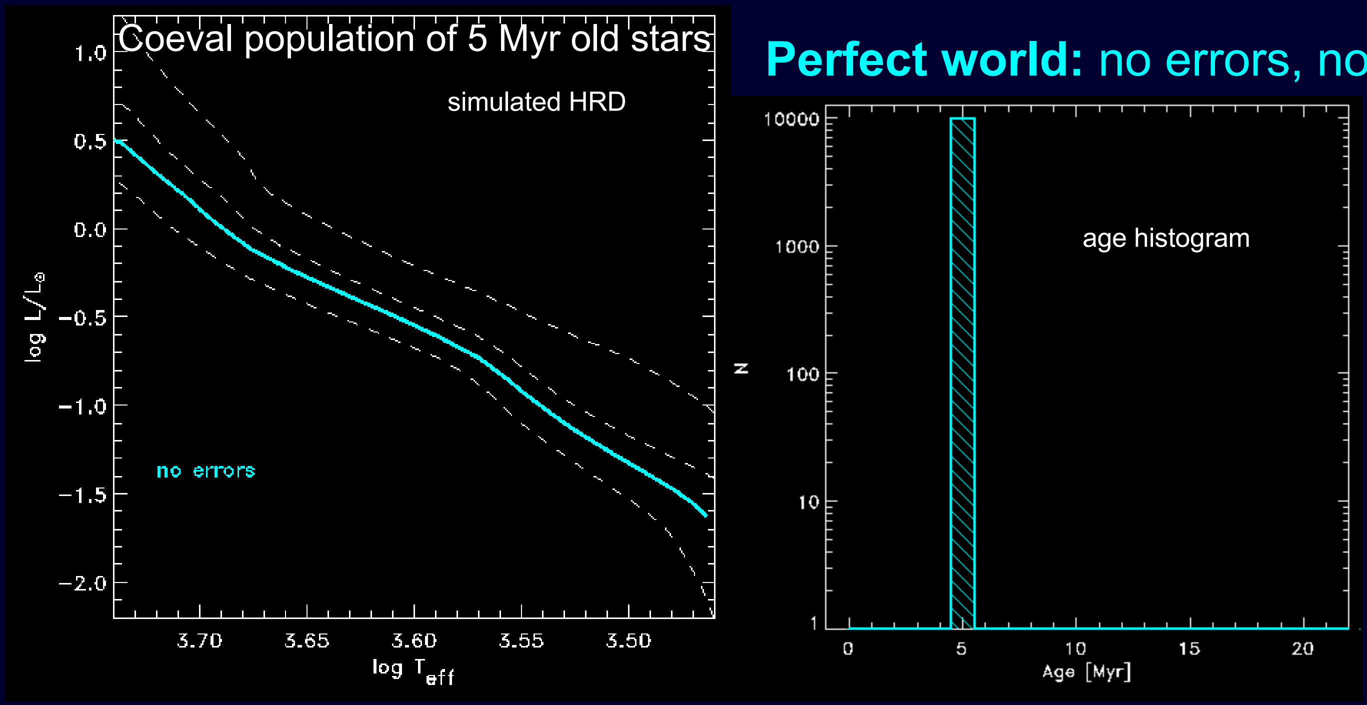
true age: 5 Myr

range of isochronal ages:

0.5 Myr .... 20 Myr

Monte-Carlo Simulation

Perfect world: no errors, no uncertainties



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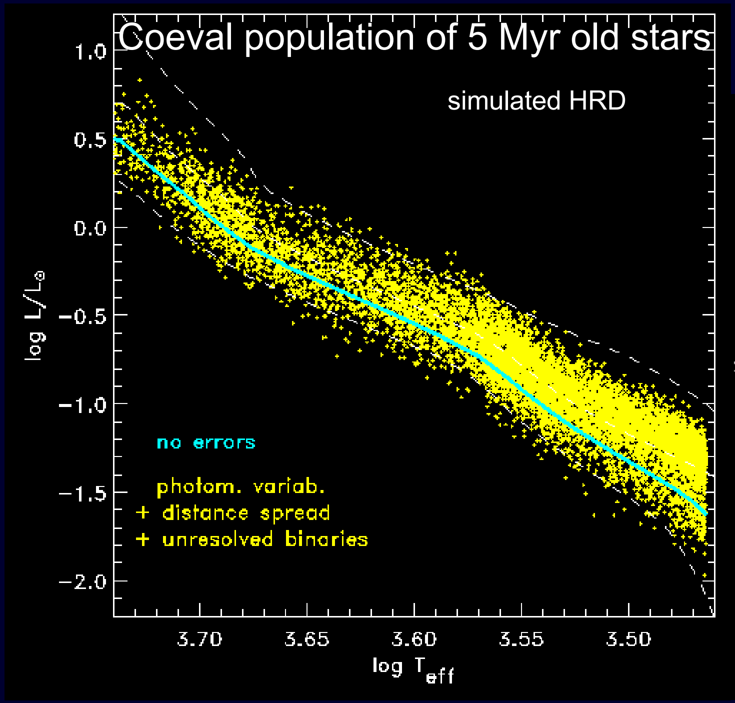
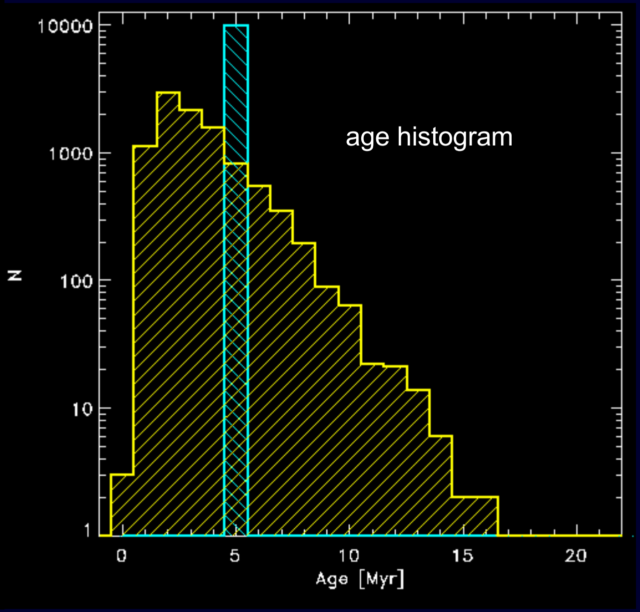


Perfect world: no errors, no uncertainties



Reality:

- photom. variability
- unres. binaries
- distance spread

→ **false impression** of **large age spread** & **accelerating star formation rate in an actually perfectly coeval population !**

HRD for Upper Sco consistent with

zero age spread

$\Delta\tau$ < 1 - 2 Myr

Implications on the star formation process

age of the high-mass stars: 5 Myr

age of the low-mass stars: 5 Myr

age spread < 1-2 Myr

diameter: ~ 30 pc

stellar velocity dispersion: 1.3 km/sec

→ *lateral crossing time ~ 25 Myr*

→ **age spread << crossing time**

→ **external agent coordinated onset of star formation over the full spatial extent**

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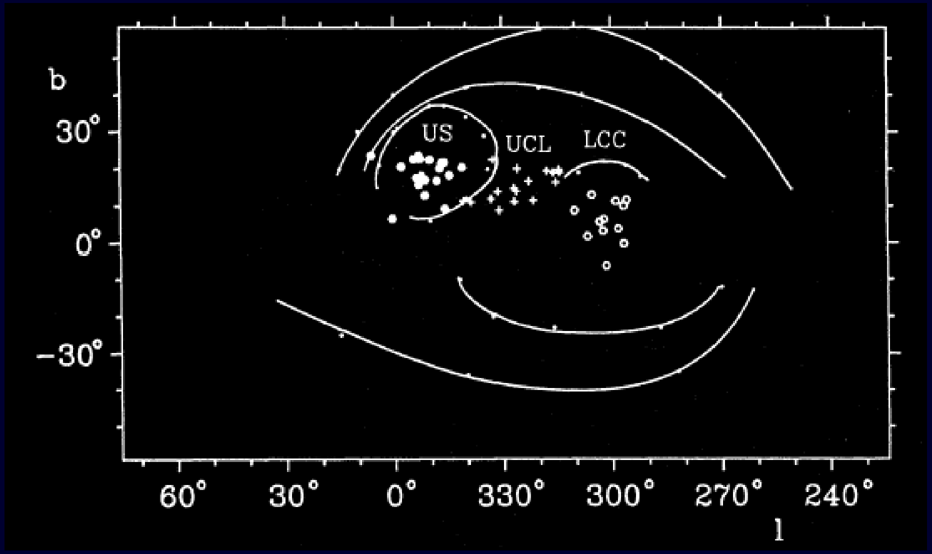
De Geus (1992, A&A 262, 258):

ScoCen is surrounded by several H I shells

Wind- & supernova-driven expanding superbubble from UCL crossed Upper Sco ~ 5 Myr ago



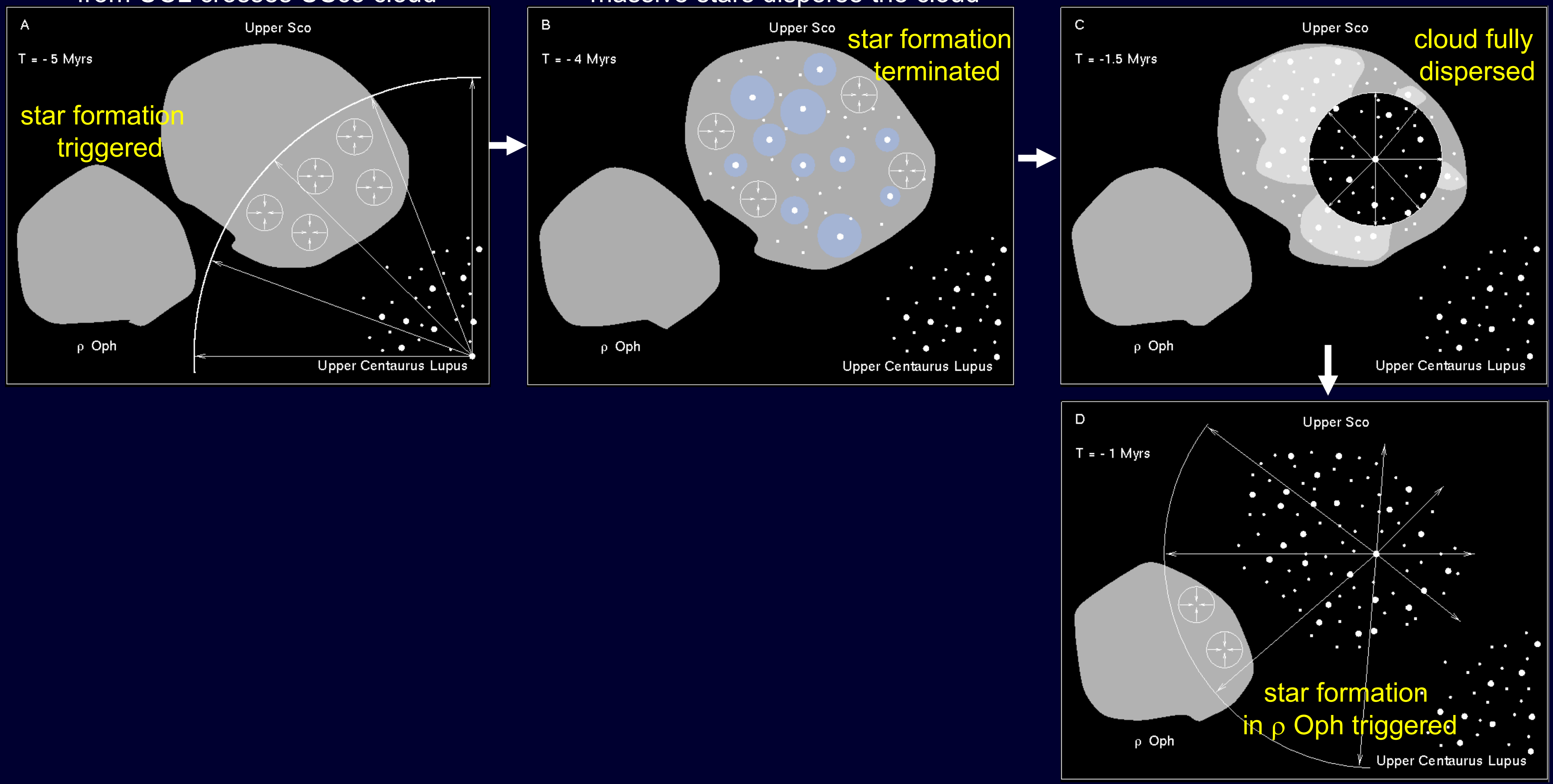
Scenario for the star formation history

de Geus (1992, A&A 262, 258); Preibisch & Zinnecker (1999, AJ 117, 2381)

Supernova & wind driven shock wave from UCL crosses USco cloud

Wind & ionizing radiation of the massive stars disperse the cloud

Supernova in USco



Supernova & wind driven shock wave from USco reaches ρ Oph cloud

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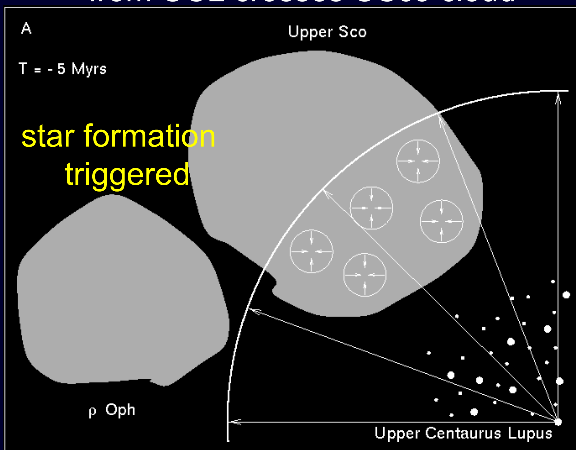

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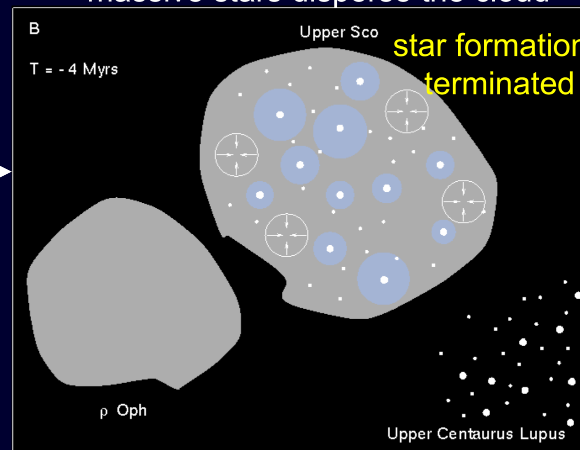
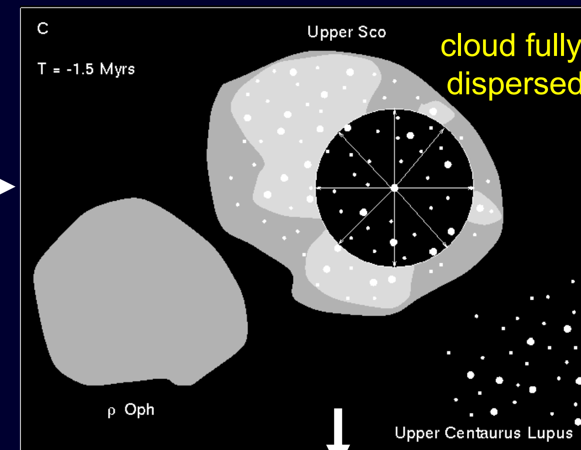
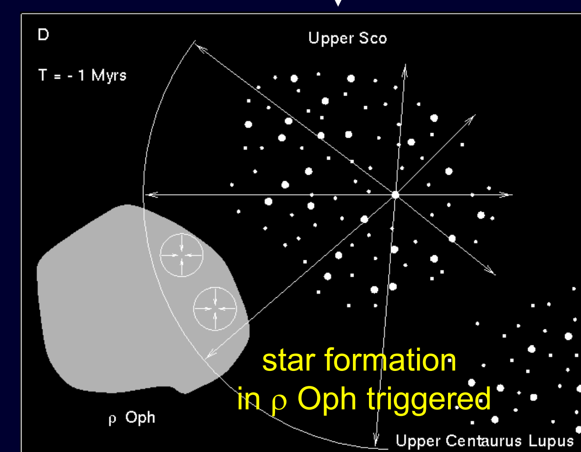


Supernova in USco





Supernova & wind driven shock wave from USco reaches ρ Oph cloud

"Any theory of star formation is incomplete without a corresponding theory of cloud formation"
(Elmegreen & Lada 1977)

Hartmann et al (2001, ApJ 562,852) and others:

Molecular clouds are short-lived structures,

i.e. do not exist for > 10 Myr without forming stars and "wait for a trigger"

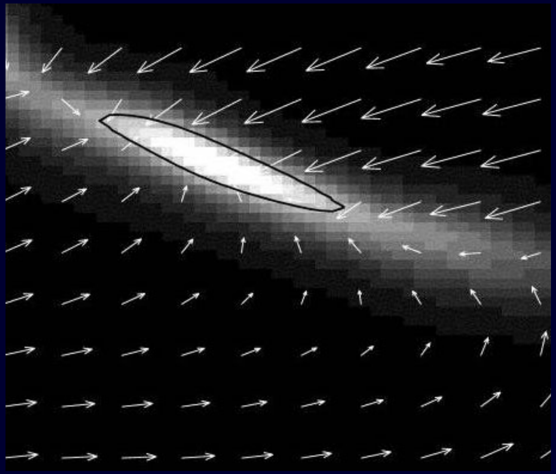
Rapid formation of molecular clouds and stars

Ballesteros-Paredes et al.(1999, ApJ 527,285); Hartmann et al.(2001 ApJ 562, 852); Clark et al.(2005, MNRAS 359,809)

Large-scale flows in the ISM

accumulate and compress gas

to form transient molecular clouds



Ballesteros-Paredes et al. (1999, ApJ 527,285)

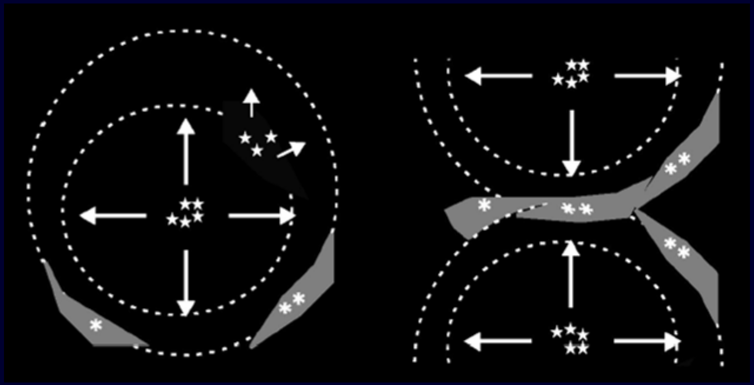
Wind & supernova shocks waves create

coherent large-scale velocity fields,

→ formation of large structures in which

star formation can be triggered nearly

simultaneously



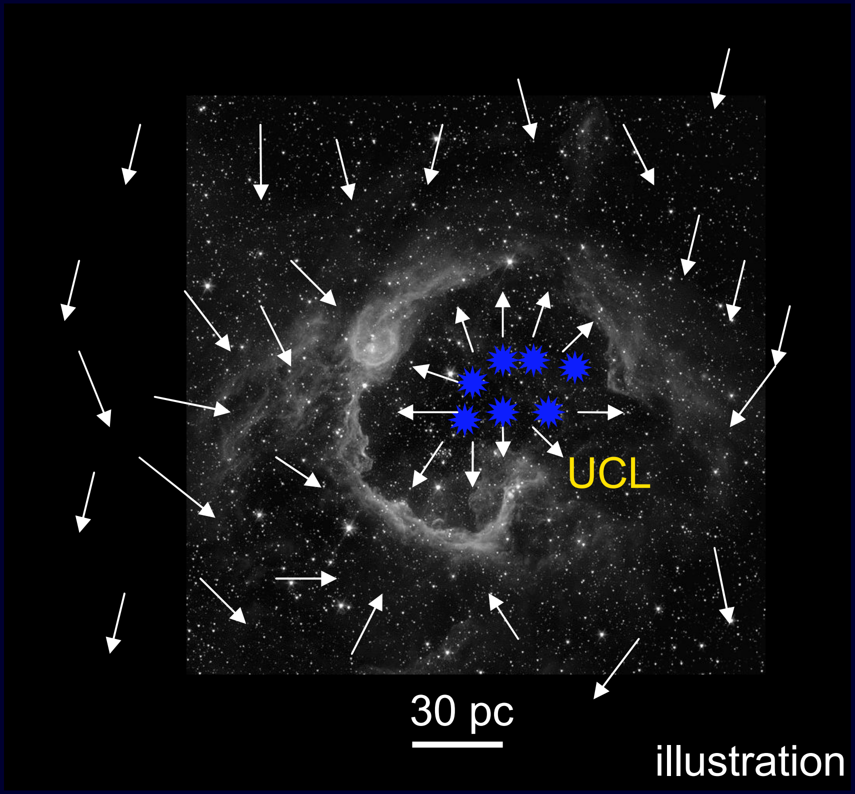
Hartmann et al. (2001 ApJ 562, 852)

Triggered cloud & star formation in ScoCen

T = - 14 Myr

OB star winds in UCL create expanding superbubble (v ~ 5 km/sec)

Interaction with ISM flows starts to sweep up clouds



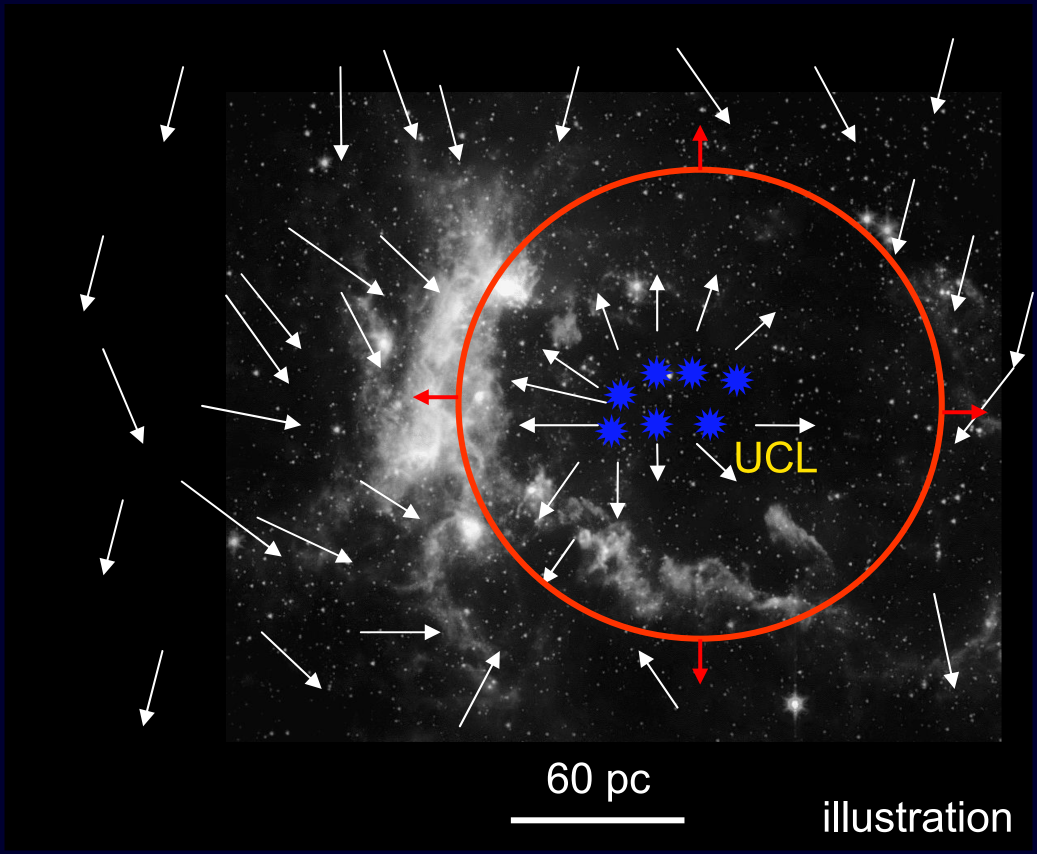
Triggered cloud & star formation in ScoCen

T = - 5 Myr

Supernovae in UCL add energy & momentum to expanding superbubble

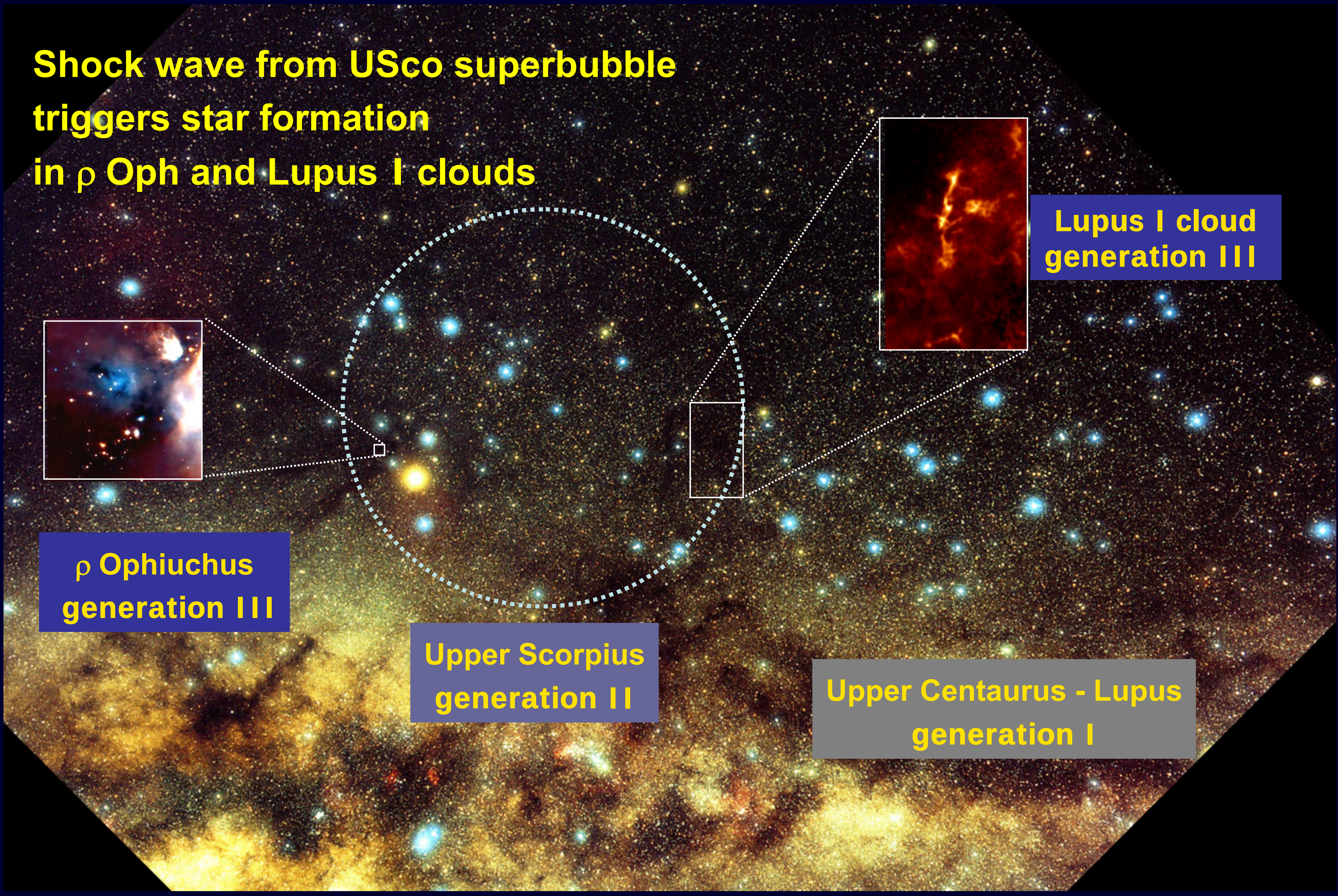
Shock wave (~ 30 km/sec) crosses cloud in Upper Sco

Increased pressure triggers star formation in this cloud

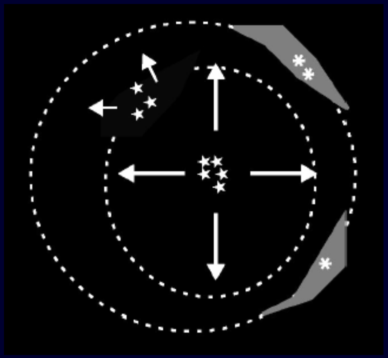


Triggered cloud & star formation in ScoCen

T = - 1 Myr



Model versus observations



Model Predictions I:

Stellar groups triggered in swept-up clouds move away from the trigger source

Observation:

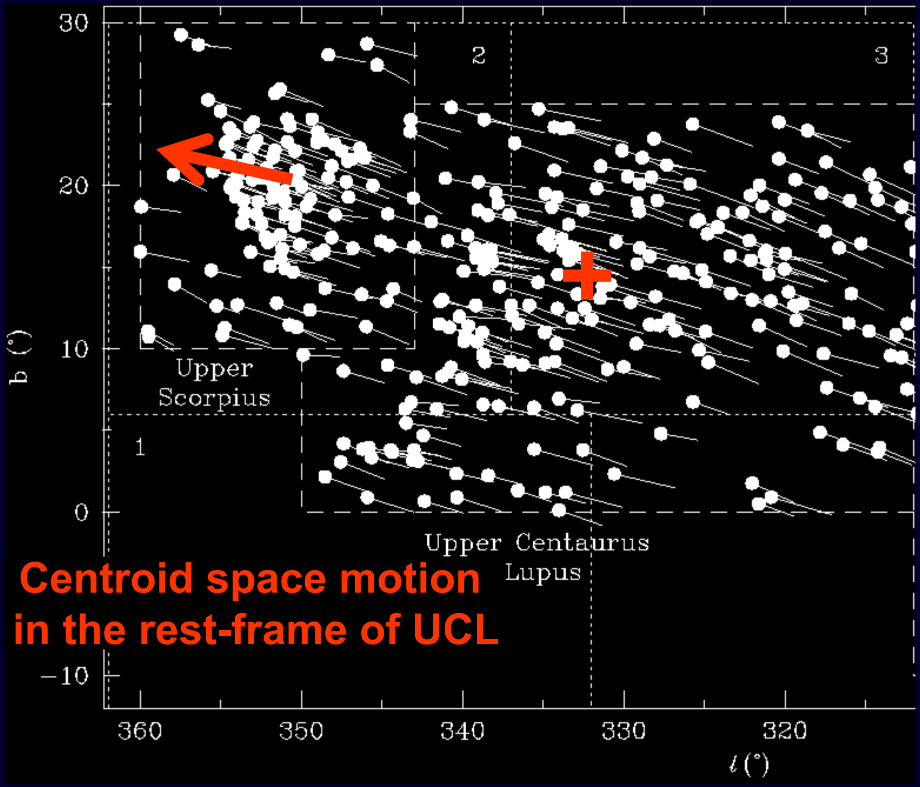
Centroid space motions of Upper Sco and UCL

de Bruijne (1999, MNRAS 310, 585)

show that

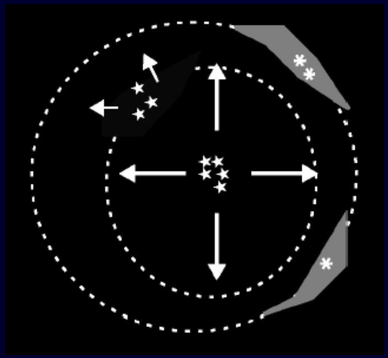
Upper Sco moves away from UCL with v ~ 5 (±3) km/sec

Hipparcos proper motions of USco and UCL members



de Zeeuw et al (1999, AJ 117, 354)

Model versus observations



Model Predictions Ib:

Stellar groups triggered in swept-up clouds move away from the trigger source

Observation:

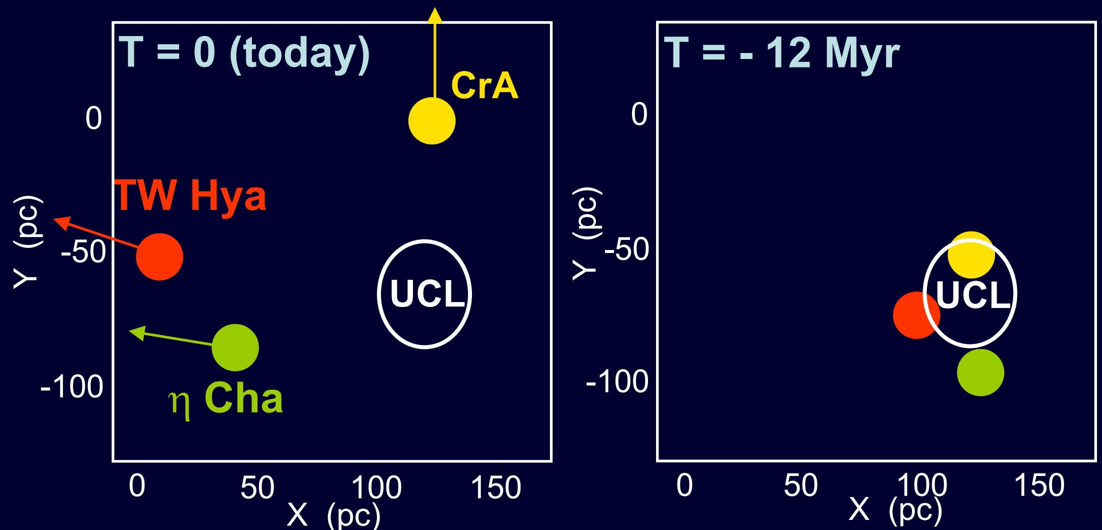
Mamajek & Feigelson (2001)

Several young stellar groups:

- η Cha cluster
- TW Hydra Association
- CrA cloud

move away from UCL with v ~ 10 km/sec

were located near the edge of UCL ~ 12 Myr ago (when SN exploded)

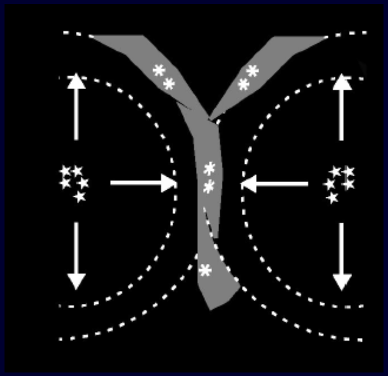


adapted from:
Mamajek & Feigelson (2001,in: Young Stars Near Earth, ASP 244, p. 104; astro-ph/0105290)

Model versus observations

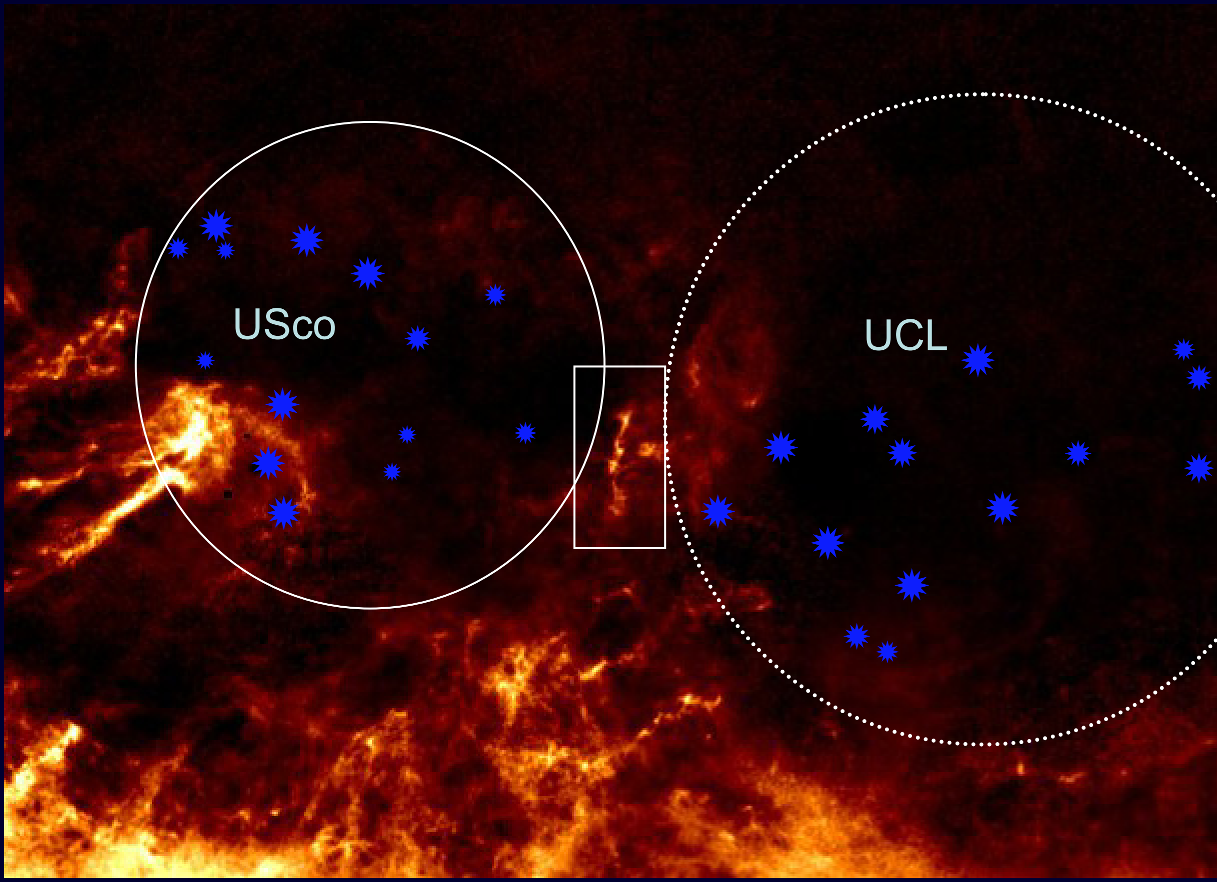
Model Predictions II:

Elongated star forming clouds form at the intersection of two expanding flows



Observation:

Lupus I cloud is located just between USco and UCL



Dust extinction map from Dobashi et al. 2005, PASJ 57,S1

Observations ⟷ Models

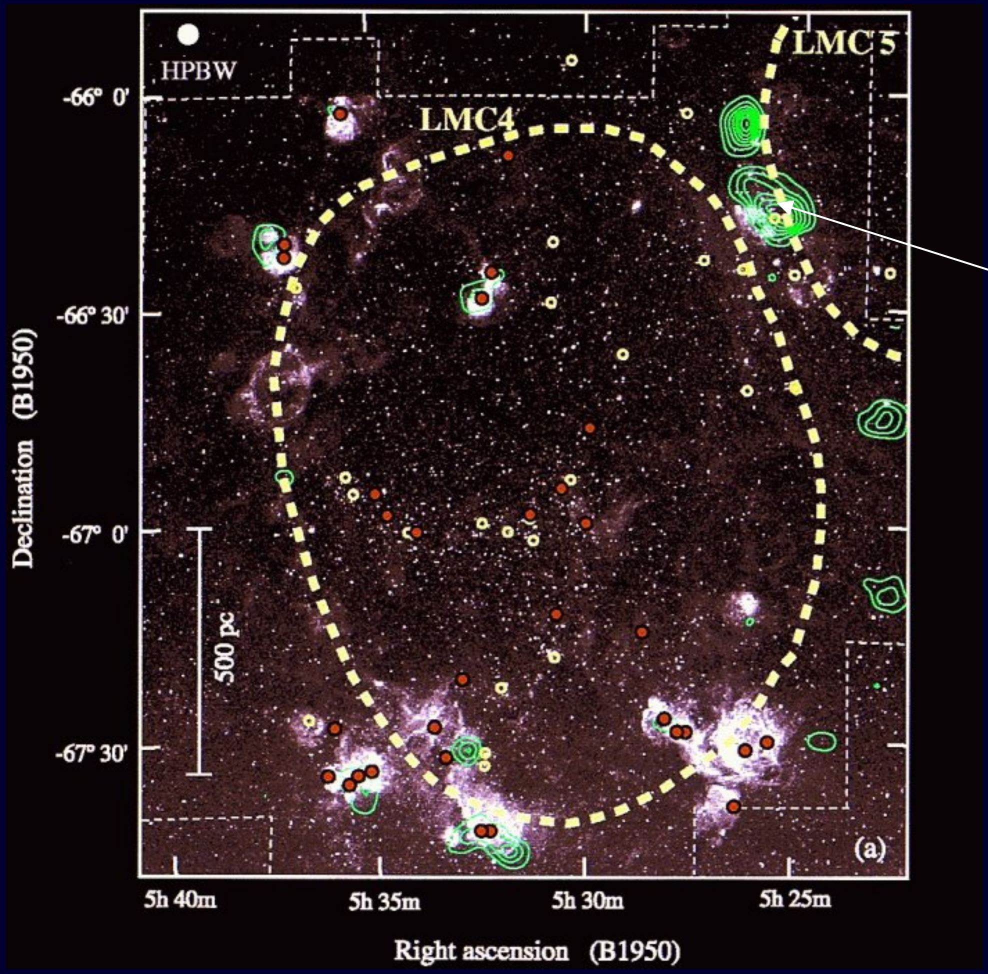
Key properties of ScoCen & other well investigated OB associations:

Briceno et al. (2006; Protostars & Planets V chapter; astro-ph/0602446)

	Bimodal SF	Radiative driven implosion	Large-scale shock waves
- **IMF is consistent with field IMF** no evidence for IMF variations	🔴	–	🟢
- **Low- and high-mass stars are coeval** formed simultaneously, not one first, the other later	🔴	🔴	🟢
- **Age spreads are often (much) smaller than the stellar crossing time** rapid star formation	🔴	?	🟢

Triggered cloud formation in action:

The Superbubble LMC4   Yamaguchi et al. (2001, ApJ 553, L185)



Note:
most massive clouds
are at bubble intersection

shell diameter 1.9 kpc
v(exp) = 10 – 40 km/sec

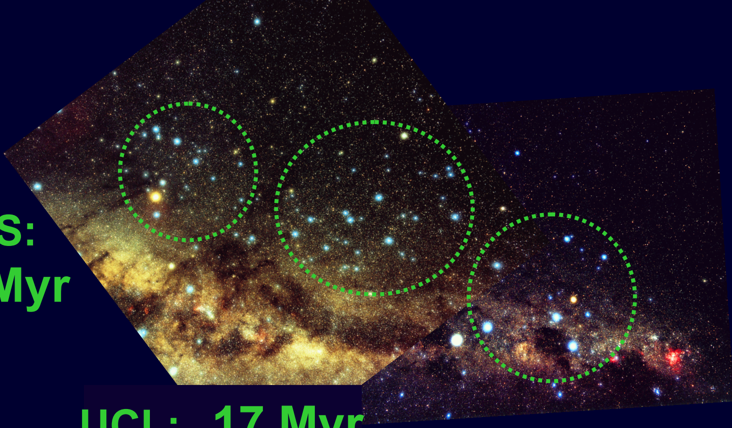
center: 400 OB stars
  ages 9-16 Myr

stars at the rim are < 6 Myr

Hα image, green contours: CO
open circles: > 10 Myr clusters, filled circles: < 10 Myr old clusters

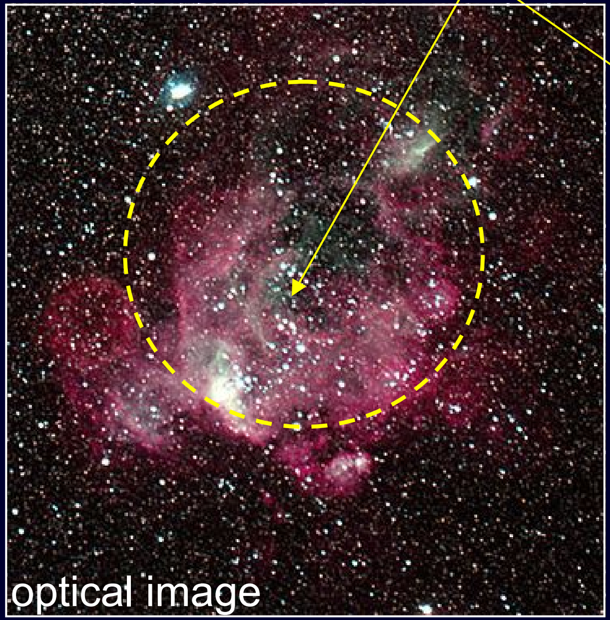
Possible problem:

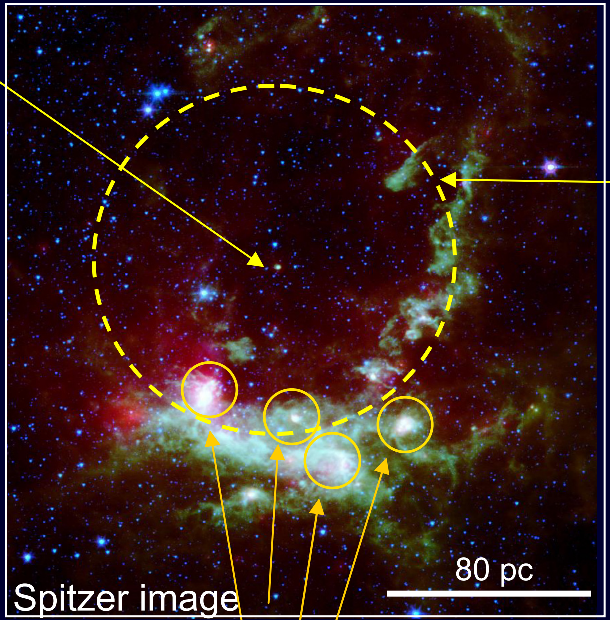
Subgroups with the same age



Hen 206 (LMC)

OB association NGC 2018: **age ~ 10 Myr**





blue: 3.6+4.5 μm, cyan: 5.8 μm, green: 8.0 μm, red: 24 μm

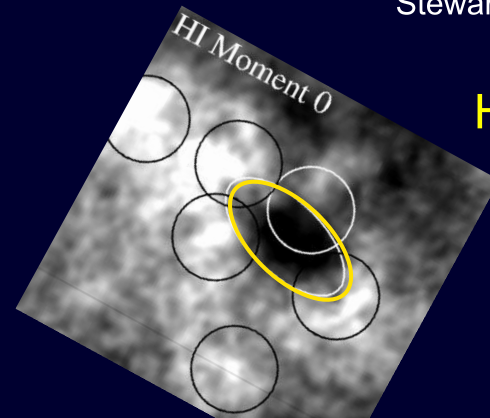
Supernova-driven expanding H I shell
v = 22 km/sec

Simultaneous triggered formation of several new OB subgroups

Gorjian et al. (2004,ApJS 154, 275)

The Supergiant Shell Region in IC 2574

Cannon et al. (2005, ApJ 630, L37)
Stewart & Walter (2000, AJ 120,1794)

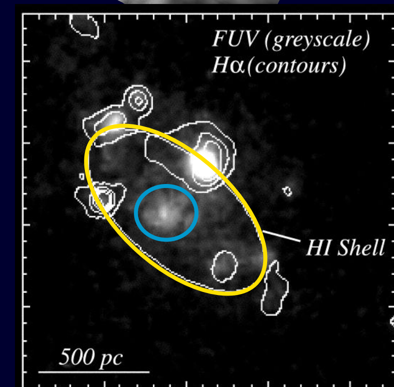


H I

cavity surrounded by expanding shell

Ø ~ 800 pc, M ~ 10^6 $M_\odot$

v ~ 25 km/sec

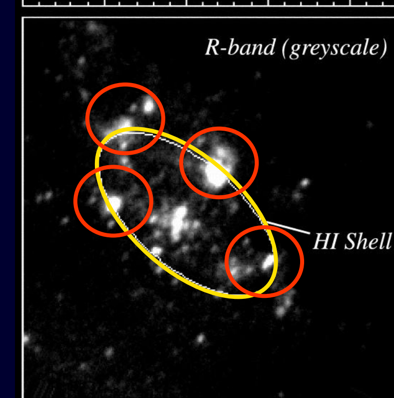


UV

central OB Association

total mass ~150 000 $M_\odot$

age ~ 11 Myr



Hα

young OB Associations

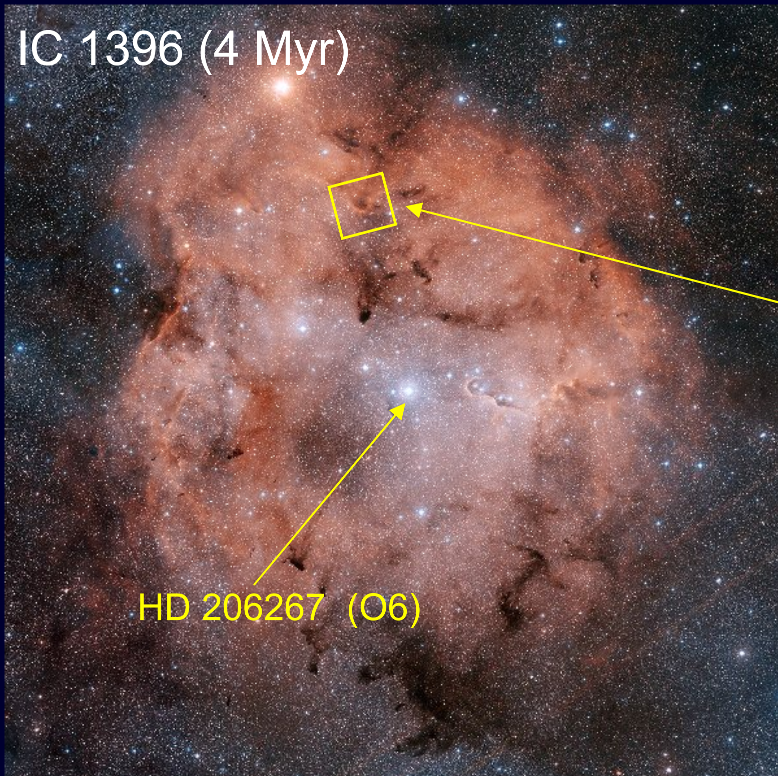
M ~ 5000 ... 300000 $M_\odot$

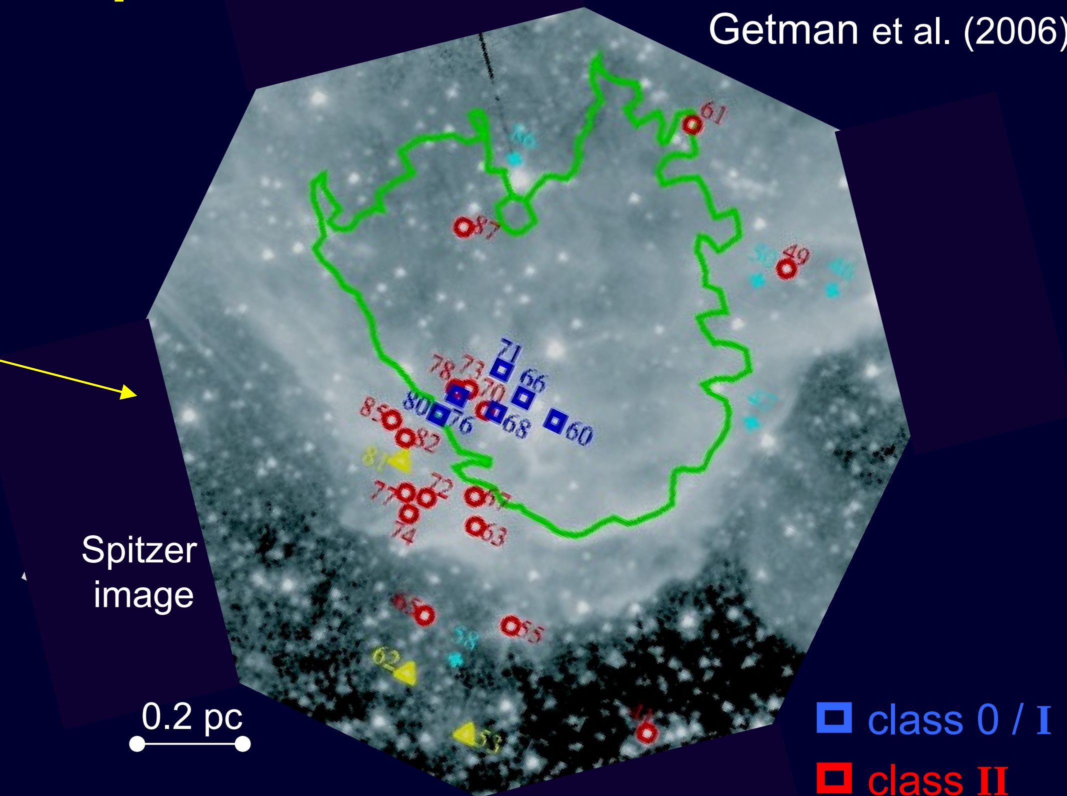
ages ~ 1 ... 4 Myr

Expanding shell triggers a second generation of OB Associations on its rim

HII region IC 1396 in the Cep OB 2 Association

Getman et al. (2006)





class 0 / I
class II
class III

X-ray detected YSOs show clear <u>age gradient</u>

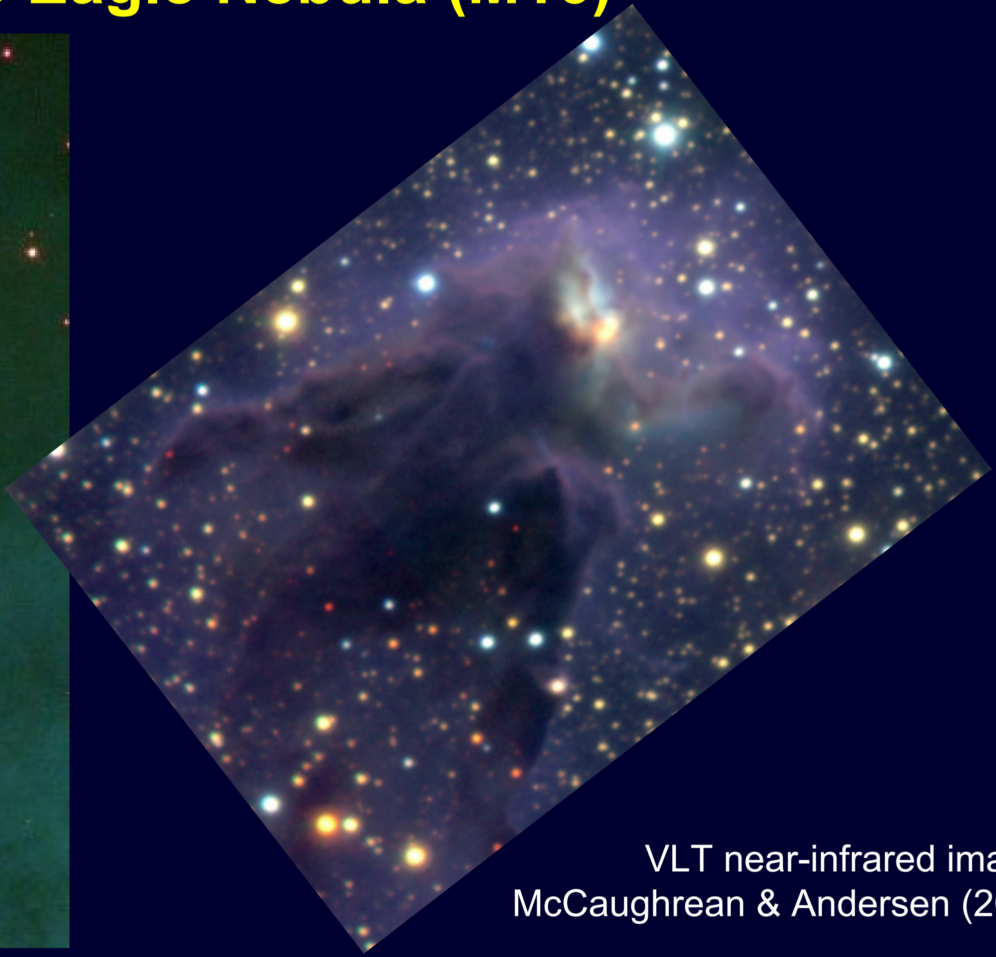
<u>Radiation-driven implosion</u> of globule triggers star formation

BUT:

This globule will only form a ***small* stellar group**, <u>no</u> OB subgroup!

"Pillars of Creation" in the Eagle Nebula (M16)

HST optical image; Hester et al. (1996)



VLT near-infrared image; McCaughrean & Andersen (2002)

Detection of evaporating gaseous globules "EGGs"; sites of triggered star formation ?

Only 11 of 73 EGGs have YSOs

< 100 stars will eventually form in the pillars, much less than the stellar population of the exciting OB cluster NGC 6611

Conclusions

OB subgroups with **well defined age sequences** and **small internal age spreads** suggest **large-scale triggered formation scenarios.**

(Supernova/wind driven shock waves)

Expanding bubbles → coherent large-scale ISM flows → **new clouds**

Supernova shock waves → cloud compression

→ **triggered formation of whole OB subgroups** (several 1000 stars).

Other triggering mechanisms (e.g. radiation-driven implosion of globules) may operate simultaneously, but seem to form only small groups of stars (i.e. are secondary processes).

Note: Our Sun formed in an OB association !

Supernova shock wave injected short-lived radionucleids (e.g. ^{26}Al, ^{60}Fe).

(Cameron & Truran 1977; Hester & Desh 2005)

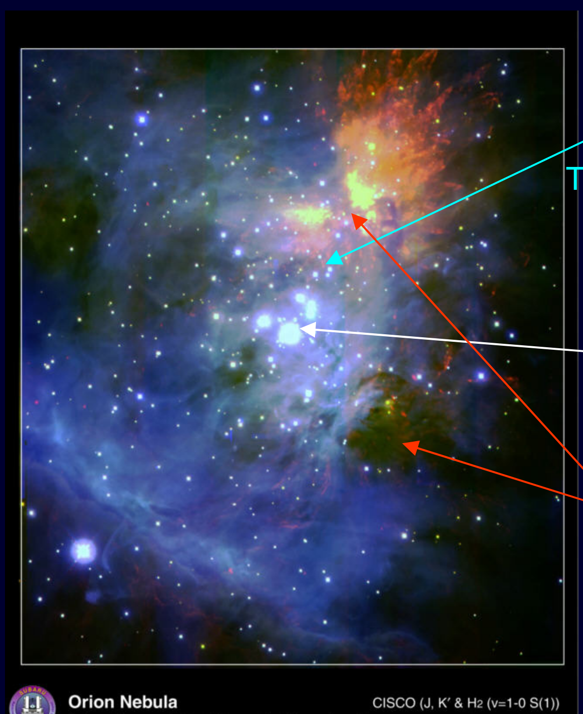
THE END

Age sequences / spreads and projection effects

no observed age sequence

false impression of
a large age spread
1 ... 15 Myr

e.g. Orion Nebula Cluster:

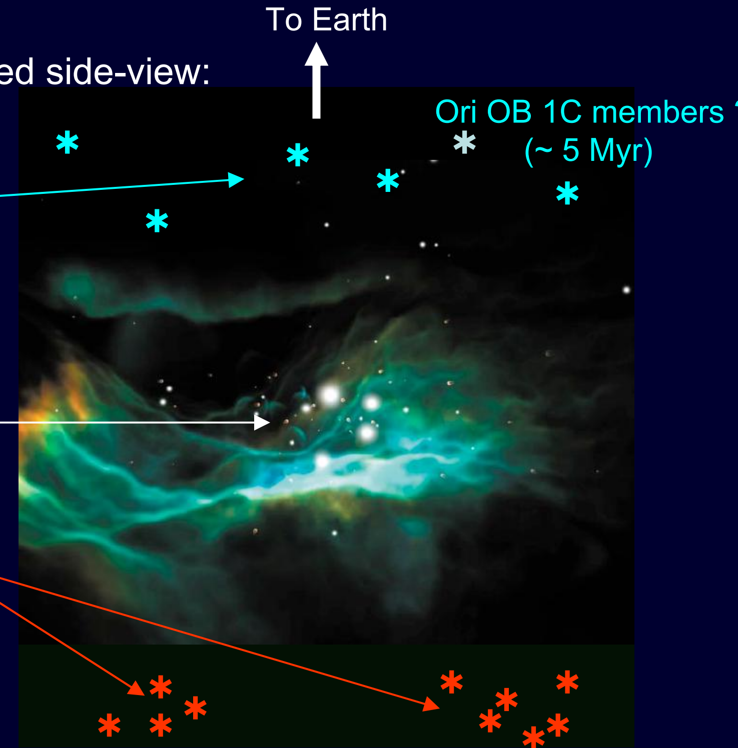


Distributed
T Tauri stars: ~ 2 -10 Myr

Trapezium cluster
stars: ~ 1 Myr

BN complex, OMC-S
protostars: <~ 0.1 Myr

simulated side-view:

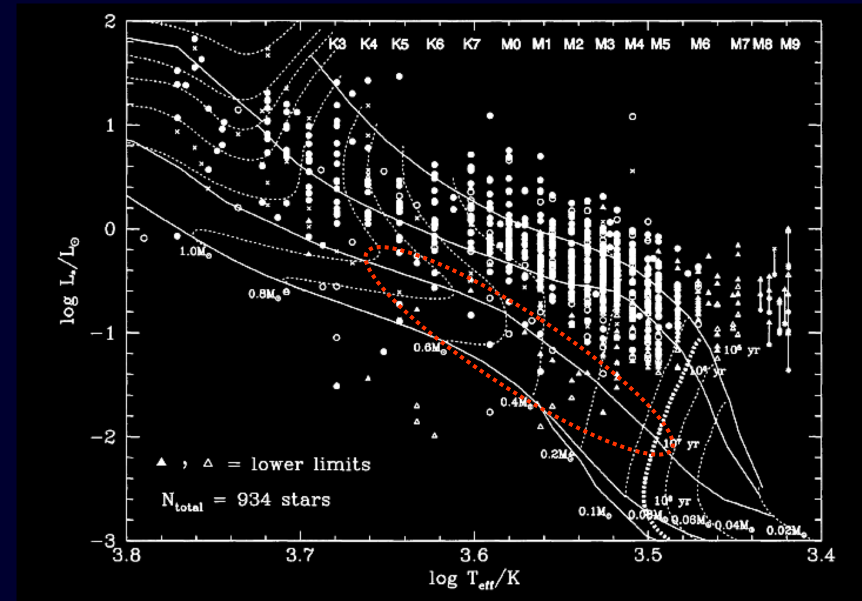


O'Dell 2001 ARAA 39, 99

HR Diagram of the Orion Nebula Cluster:

- most stars have ages <~ 1 Myr
- a few much older stars with ~ 10 – 20 Myr

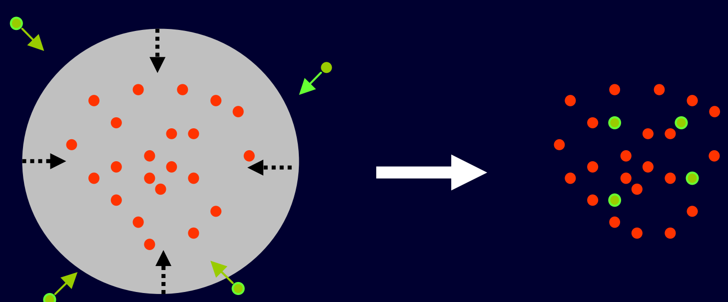
Is this evidence for extended periods of star formation activity ?



Hillenbrand 1997 (AJ 113, 1733)

Pflamm-Altenburg & Kroupa, (MNRAS, in press; astro-ph/0611517):

A collapsing cloud can capture stars from surrounding (i.e. older) populations

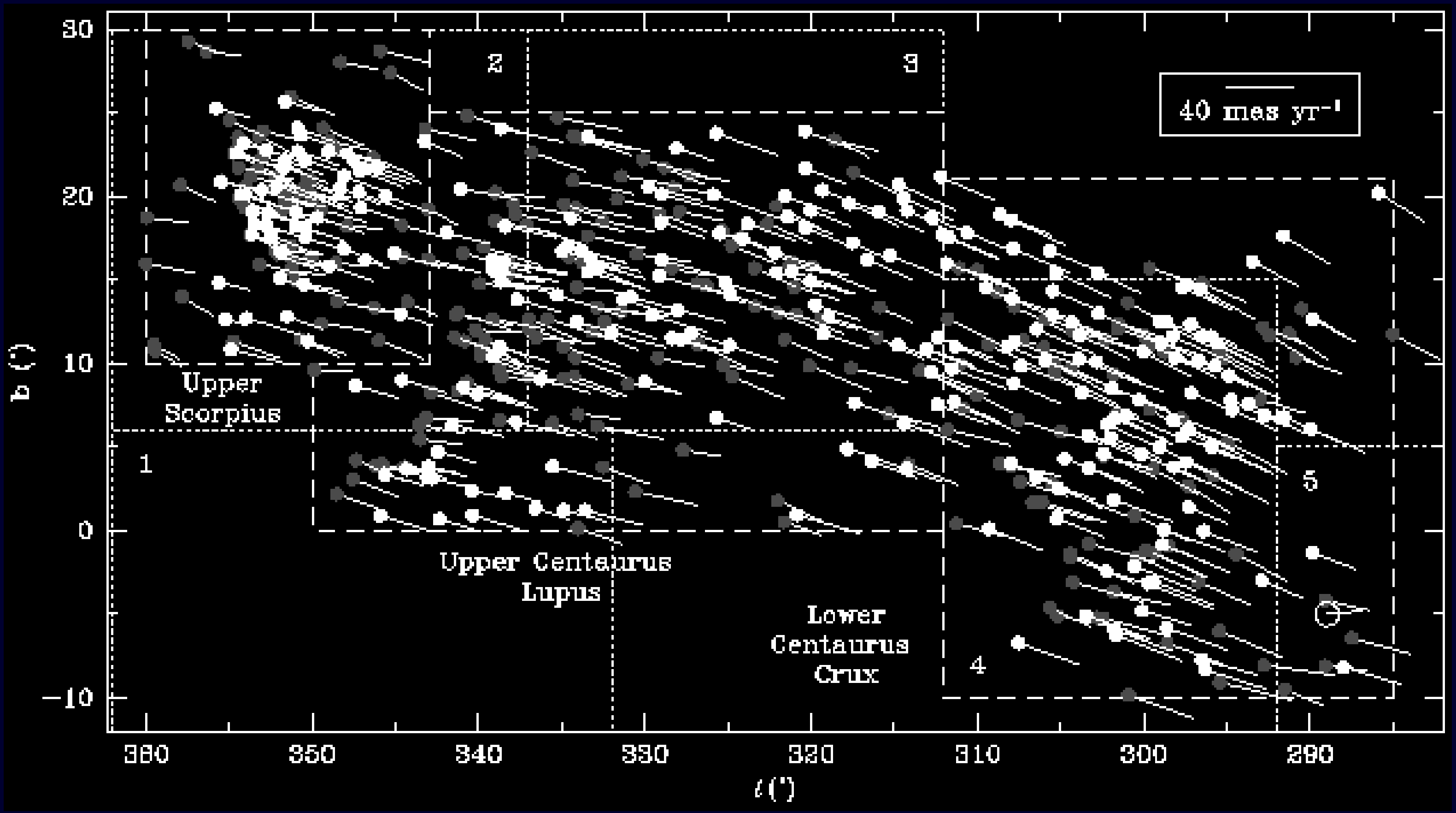


The captured stars will become *kinematic members* of the cluster/association

This model explains the number of apparently older ONC members:

→ no evidence for extended periods of star formation

Hipparcos results for Scorpius-Centaurus:

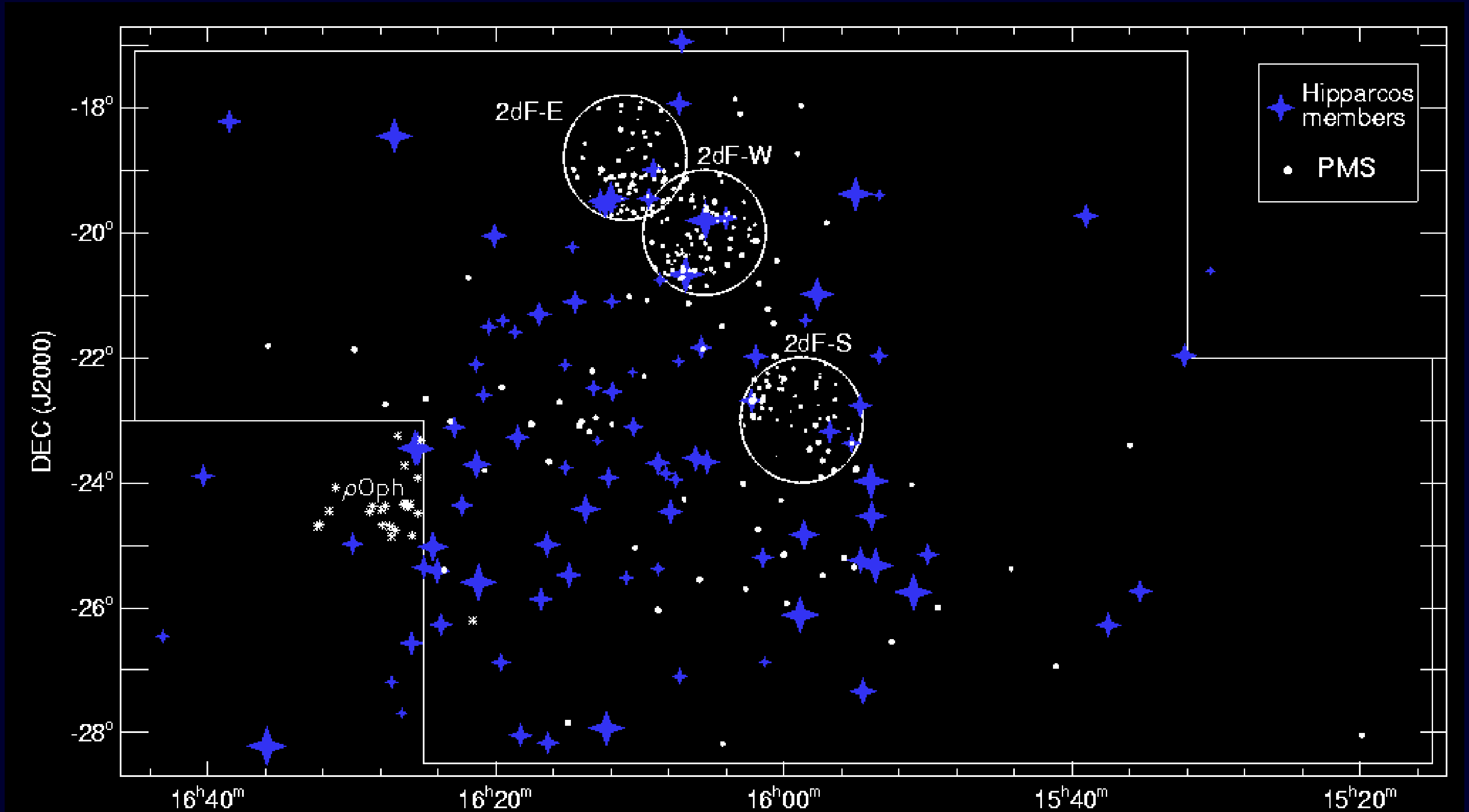


Upper Scorpius: 144 pc, 49 B-stars, 34 A-stars, 22 F-stars, 9 G-stars

Upper Centaurus Lupus: 142 pc, 66 B-stars, 68 A-stars, 55 F-stars, 25 G-stars

Lower Centaurus Crux: 116 pc, 42 B-stars, 55 A-stars, 61 F-stars, 15 G-stars

The stellar population of Upper Sco over the full stellar mass range 0.1 – 20 $M_{\odot}$



Preibisch et al (2002, AJ 124, 404)

114 Hipparcos members in 150 sqdeg, SpT = B0.5 to F

84 X-ray selected members in 150 sqdeg, SpT = G0 to M4

166 members revealed by 2dF survey (9 sqdeg), SpT = K5 to M6