Star Formation: Current issues and future prospects

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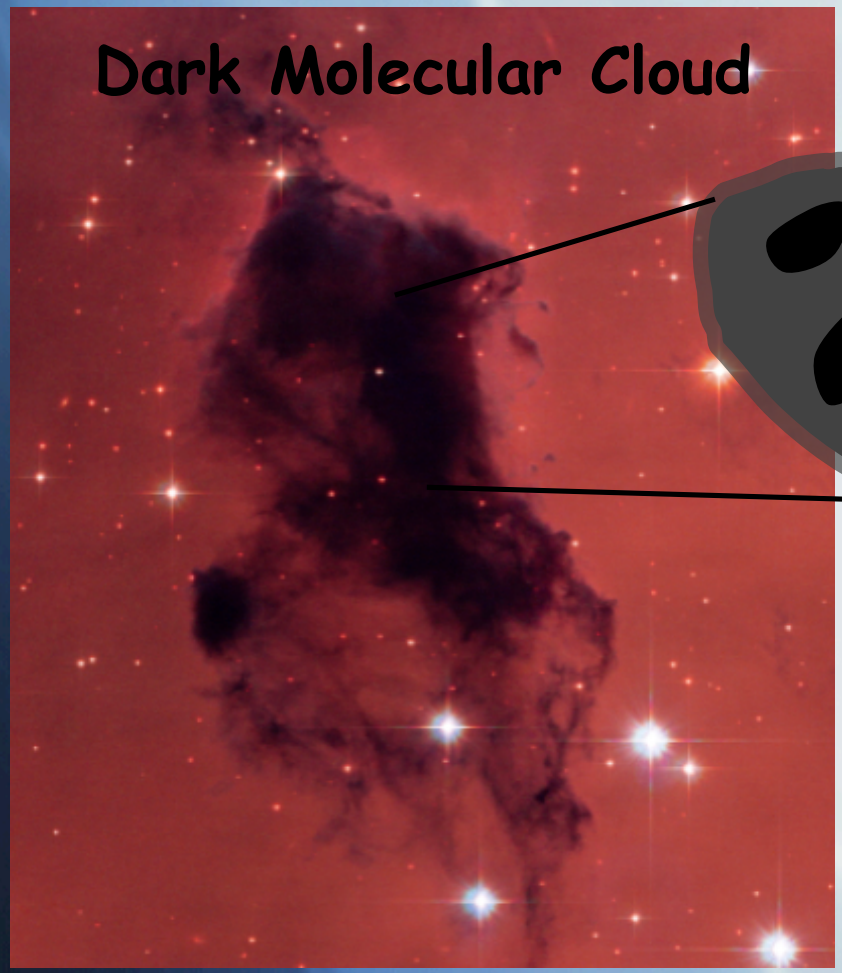
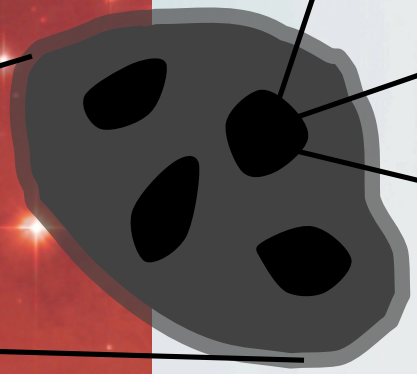
ESO-Garching

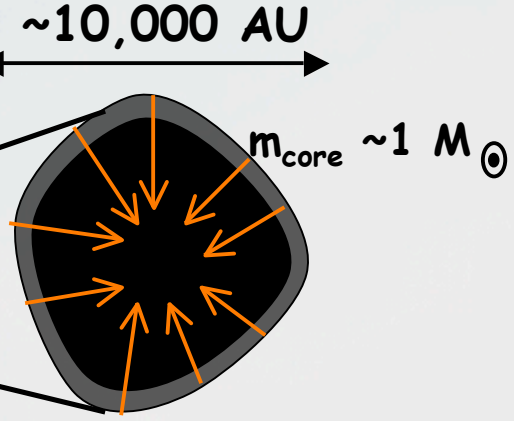
ESO Workshop: Beyond MAD, June 08-10, 2009

Star Formation in a nutshell

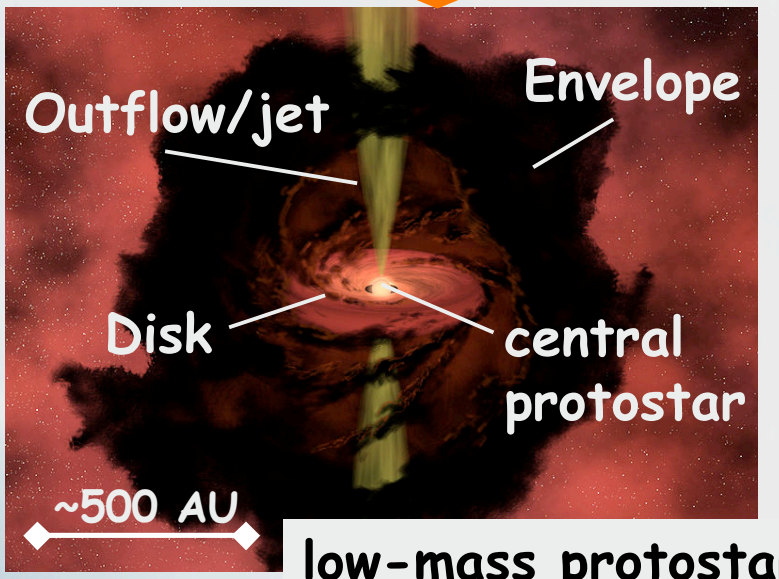


molecular cloud masses:
$\sim 10^3 - 10^6\ M_\odot$





gravitational collapse



low-mass protostar

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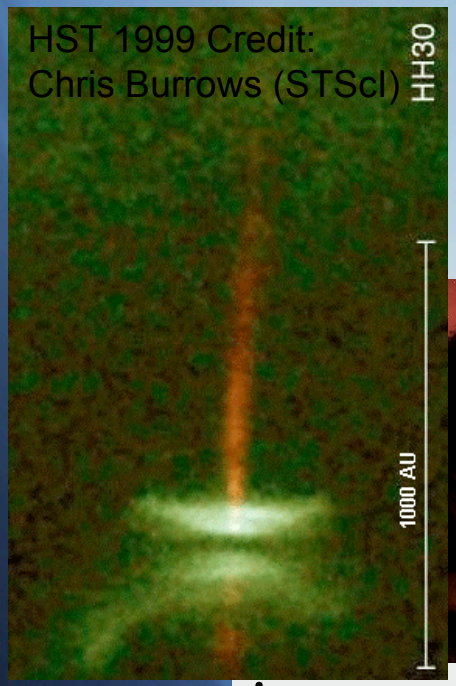


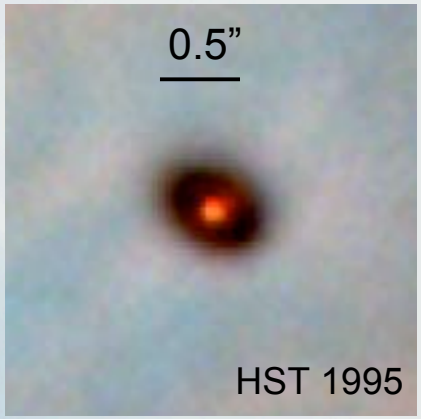
low-mass protostar

General picture of low-mass star formation is understood!

Open issues:

- How is material accreted from circumstellar disk to the star? Magnetospheric accretion?
- What's the launching mechanism for the jet+outflow?
- How do planets form from circumstellar protoplanetary disks?

→ Resolution + contrast !!!



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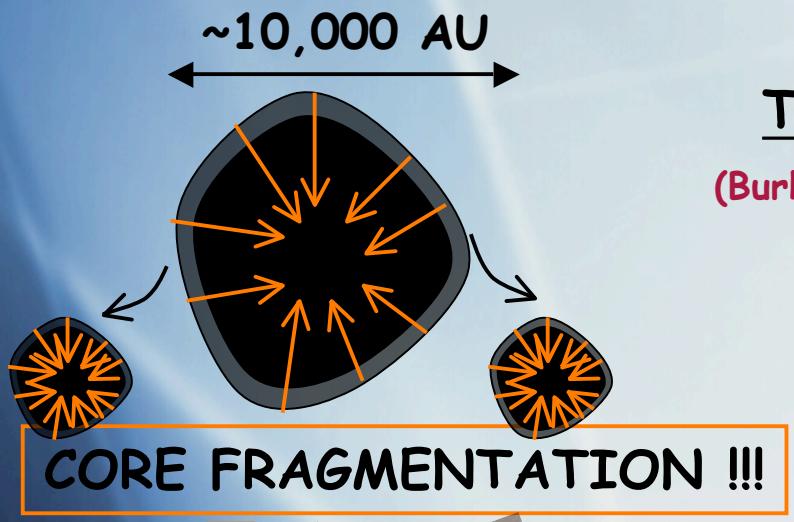
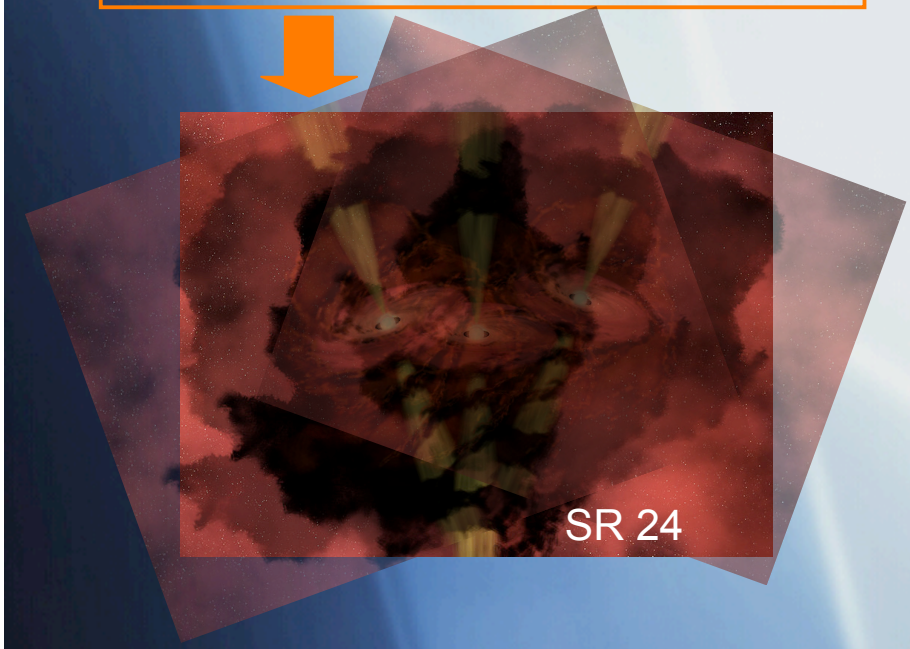


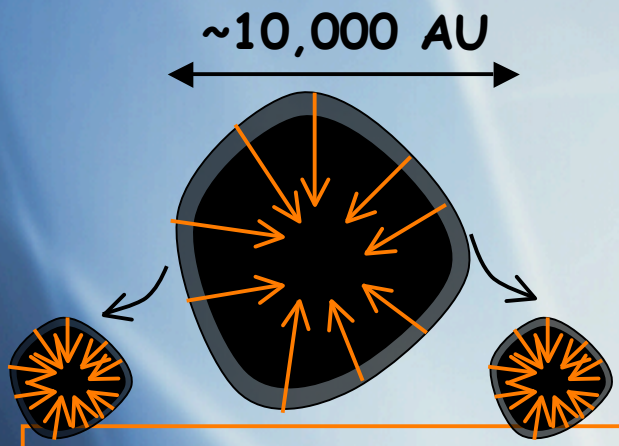


Theory of core fragmentation

(Burkert & Bodenheimer 93 MNRAS, Goodwin et al. 07 PPV)

predicts $N_{\text{pre-stellar obj.}} >> 3$

Star Formation in a nutshell



CORE FRAGMENTATION !!!

Theory of core fragmentation

(Burkert & Bodenheimer 93 MNRAS, Goodwin et al. 07 PPV)

predicts $N_{\text{pre-stellar obj.}} >> 3$

AO-observations of embedded protostars (class I sources):

(Duchene et al. A&A 07, Haisch et al. AJ 06, Connelley et al. AJ 08)

high fraction of binaries and triples, but few higher-order multiples

Current questions

Missing physics in simulations ?

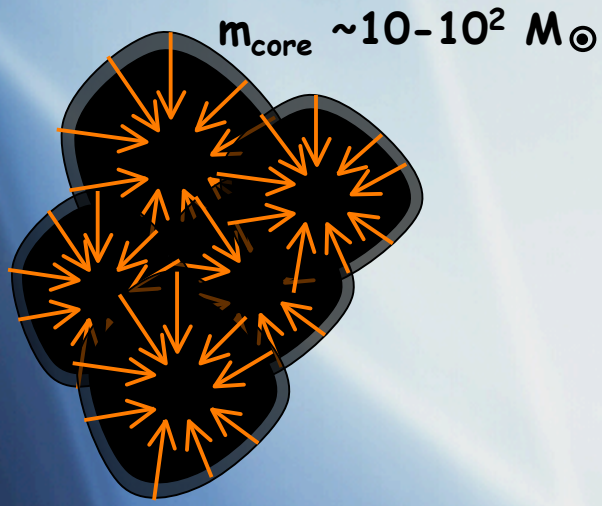
Dynamical decay of non-hierarchical class 0 multiples ?

WHAT ABOUT HIGH MASS STAR FORMATION ?

Zinnecker & Yorke 2007, Ann. Rev. A&A 45

Star Formation in a nutshell

Massive cores in giant molecular clouds form massive stars and star clusters



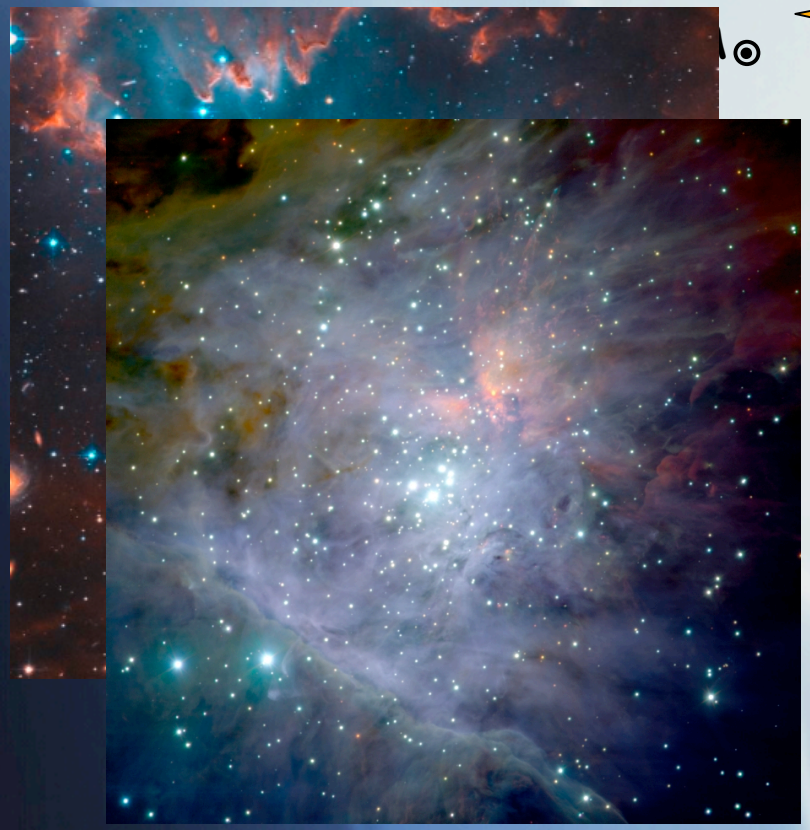
Star Formation in a nutshell

Massive cores in giant molecular clouds form massive stars and star clusters

- Most (if not all) massive stars form in massive stellar clusters
- Young stellar clusters are prime targets for studying the spectrum of stellar masses created during the star formation process

Star Formation in a nutshell

Massive cores in giant molecular clouds form massive stars and star clusters



Orion Trapezium cluster VLT/ISAAC

- Most (if not all) massive stars form in massive stellar clusters

- Young stellar clusters are prime targets for studying the spectrum of stellar masses created during the star formation process

For the youngest clusters, the observed distribution of stellar masses is often considered as the mass distribution at birth

➡ **IMF !**

The stellar Initial Mass Function

IMF ⟺ main acting physical process in star formation

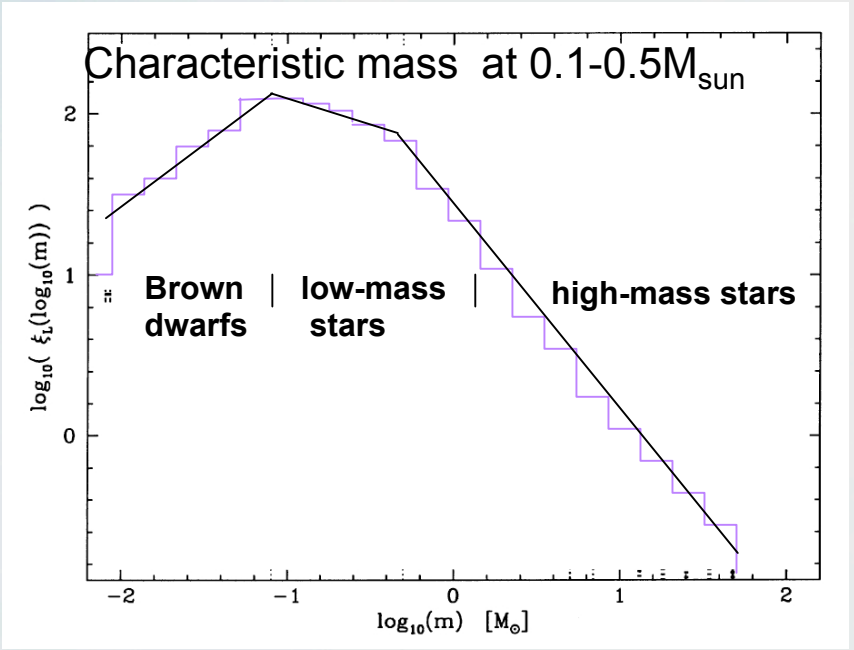
Original: Salpeter 1955

Kroupa IMF

(Kroupa 2001, MNRAS 322)

$$\xi(m) \propto m^{-\alpha_i}$$

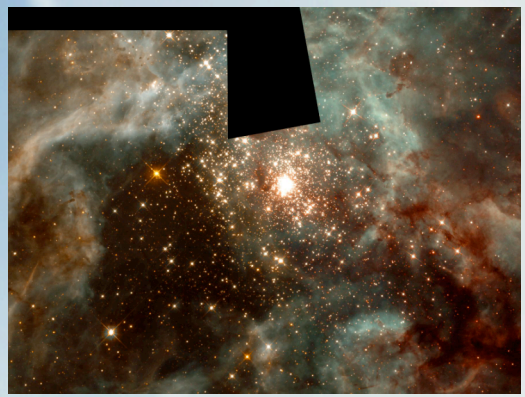
$$\alpha_0 = +0.3 \pm 0.7, \quad 0.01 \leq m/\mathrm{M}_\odot < 0.08,$$
$$\alpha_1 = +1.3 \pm 0.5, \quad 0.08 \leq m/\mathrm{M}_\odot < 0.50,$$
$$\alpha_2 = +2.3 \pm 0.3, \quad 0.50 \leq m/\mathrm{M}_\odot$$

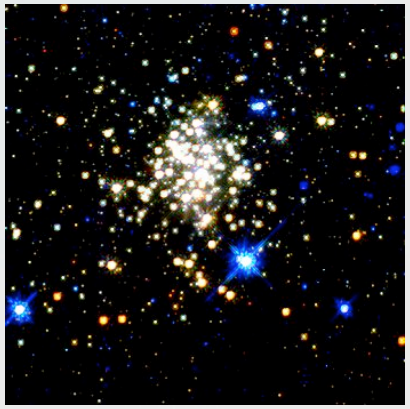


- Overall: the IMF is surprisingly similar (in particular for > 0.5M$_{sun}$) for young stellar clusters and nearby SFR, with a 'Salpeter' slope (alpha = 2.35) at high-mass end
- There is a turn-over in the mass function for all SFR that have been observed!

e.g. Andersen et al. 2008, ApJ 683

. . . at the high-mass end

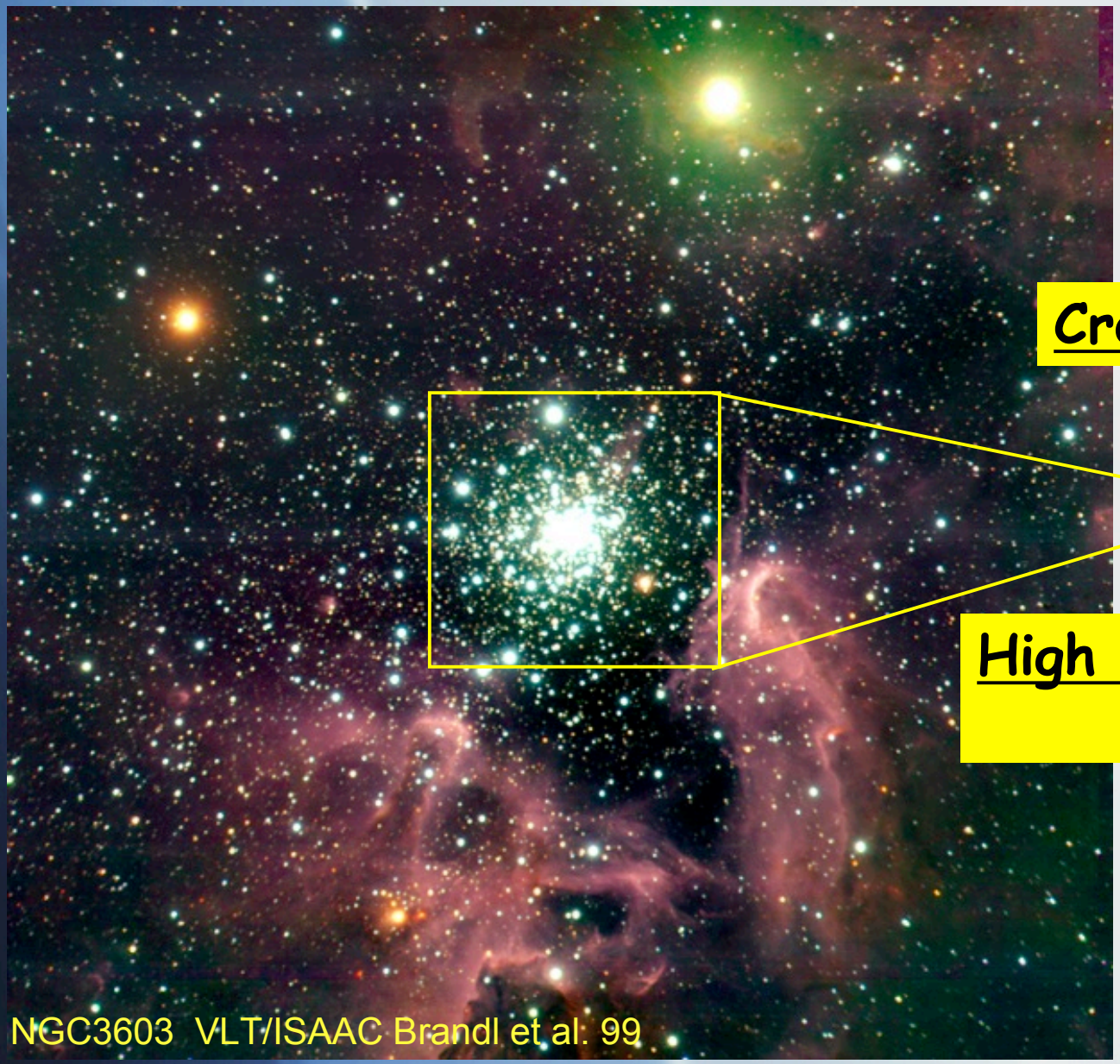





- Starburst clusters with several tens of O-type stars,
  Feedback from winds and shocks terminate SF?
  Lower mass cut-off?
- IMF in very massive star clusters (starburst clusters)
  is top-heavy ? Overall or only the core?

Controversial issue/observational results on flattened IMF:

yes	Brandl et al. 96, Figer et al. 99, Stolte 2005, Harayama et al. 08, …
no	Massey & Hunter 98, Nurnberger & Petr-Gotzens 02, Espinoza et al. 09, Ascenso et al. 09, …
maybe	Stolte et al. 2006



Crowding problem !

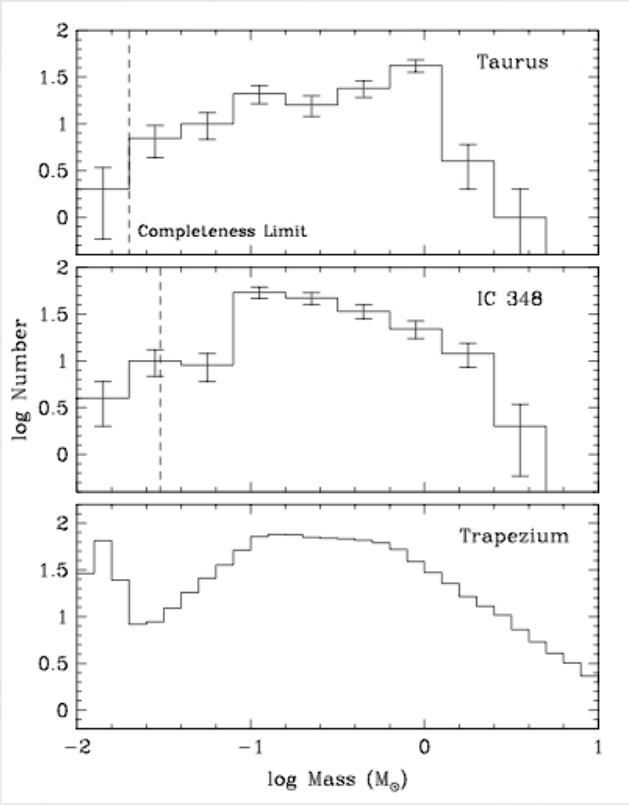
1x1arcmin

High spatial resolution is a must !!

IMF at the low-mass end

Lowest mass object formed?

- Low-mass star > 0.08 M_{sun}
  - ↓
  - Brown dwarf 0.08-0.013M_{sun}
  - ↓
  - Planetary mass object <0.013M_{sun}



(from Luhman 2004, ApJ 617)

- Theoretical "Opacity limit" at ~3M_{Jup} (object can't cool faster than it contracts)
  Low & Lynden-Bell 1976

Observations are currently limited by sensitivity; but also how to distinguish a real extremely low-mass object from a background source?

IMF at the low-mass end

Brown dwarf formation?

- Collapse of very low-mass cores; continuity of low-mass star formation
  → Brown dwarf disks and outflows ? Yes!
  (e.g. Natta et al. 2004 A&A 424, Luhman et al. 2005 ApJ 635)
- Premature ejection from small N-body systems
  (Reipurth & Clarke 2001, AJ 122)
  → No binaries (just some close ones) !
- Photo-erosion of pre-stellar cores in the vicinity of massive Stars (Whitworth & Zinnecker 2004, A&A 427)
  → Strong environmental dependence !

High contrast imaging at high spatial resolution is required, e.g. MAD

MAD targeting the Orion Trapezium Cluster

Young star cluster, ~1Myr

High- and low-mass star formation, r~440pc

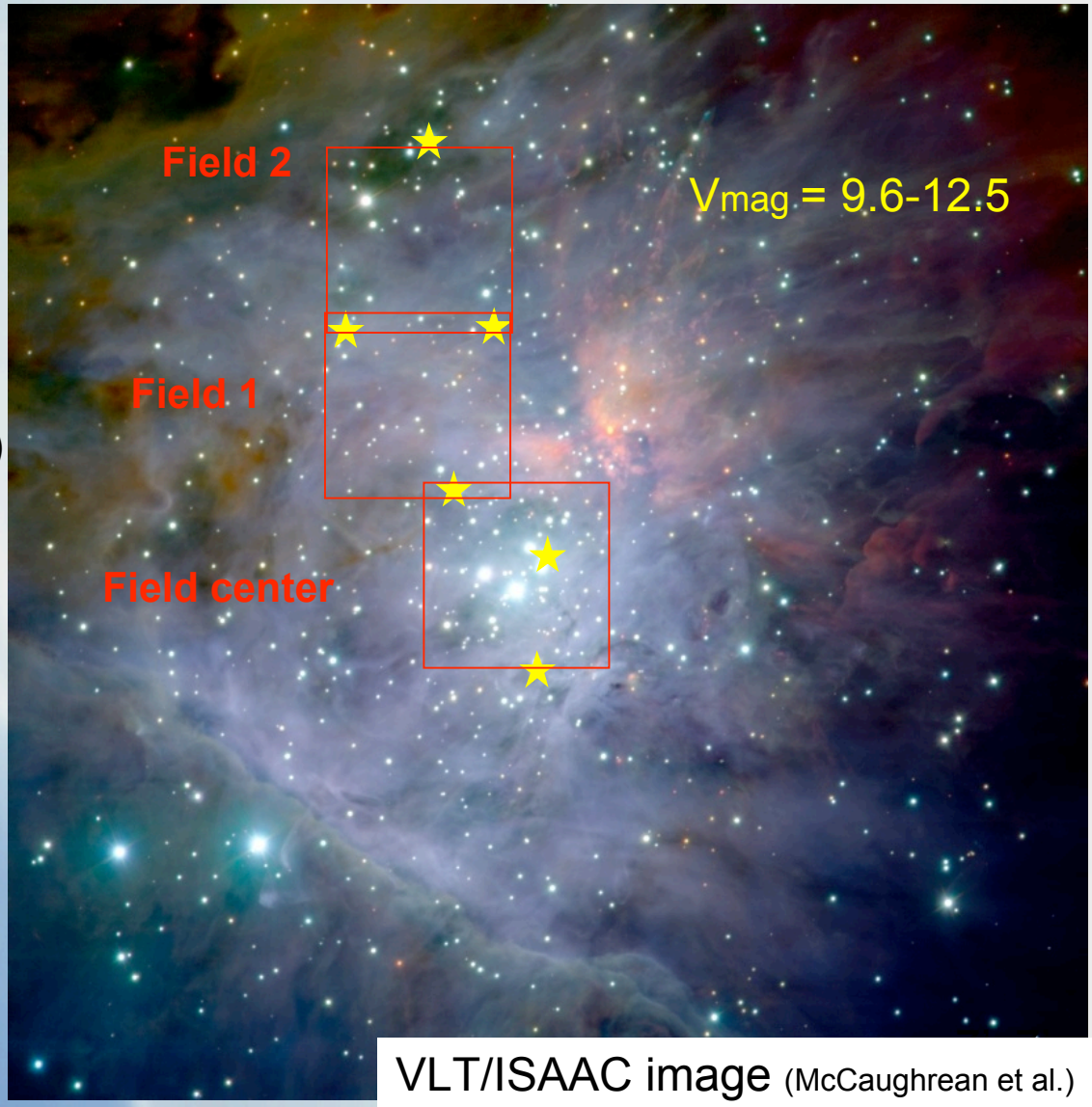
1 Sub-stellar IMF and planetary mass (3-13 M_{Jup}) objects in the Trapezium Cluster Center ??

Muench et al. 2002, ApJ 573
Slesnick et al. 2004,ApJ 610
Lucas et al. 2005, MNRAS 361
McCaughrean et al. 2002, Mess. 109

2 Binary brown dwarfs ??

Why MAD?

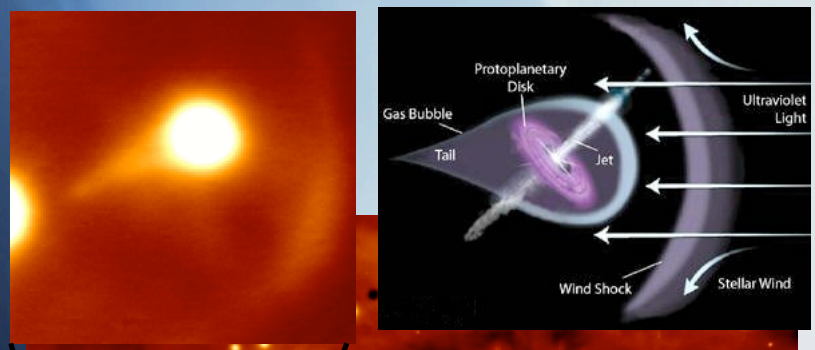
Sensitivity, spatial resolution, high dynamic range!

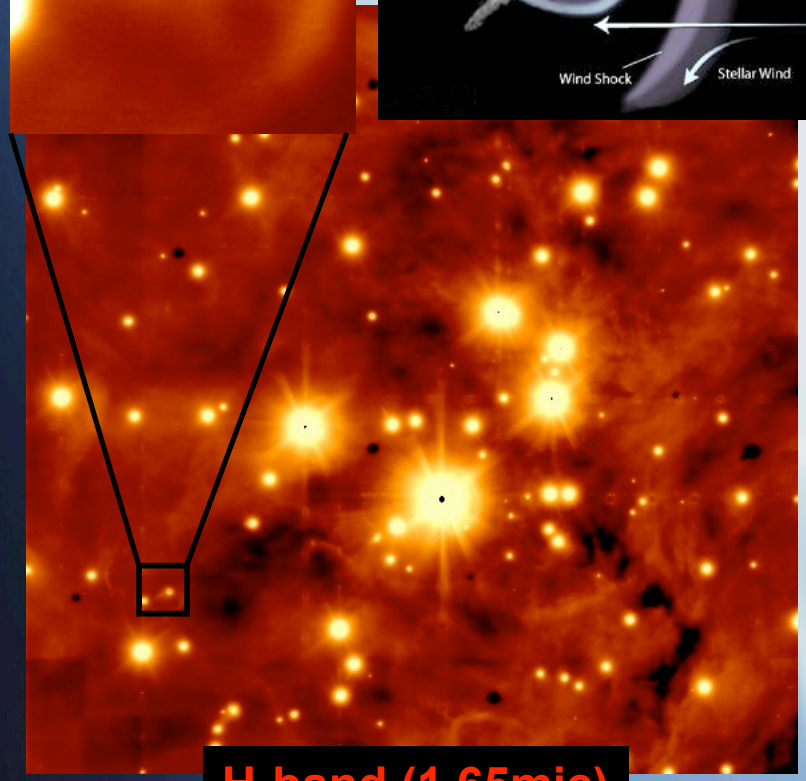


VLT/ISAAC image (McCaughrean et al.)

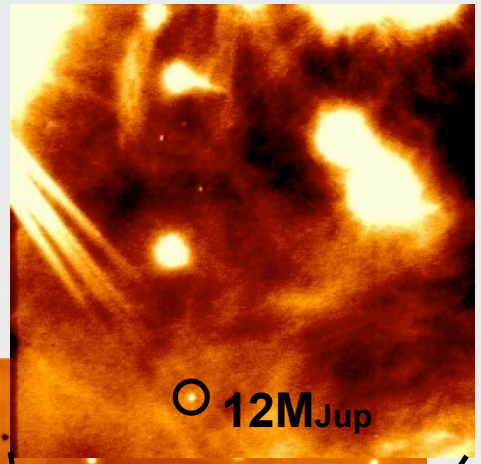
MAD targeting the Orion Trapezium Cluster

H-band det.limit: 21.0mag
K-band det.limit: 19.8mag (3M_{Jup} ~ 19mag)

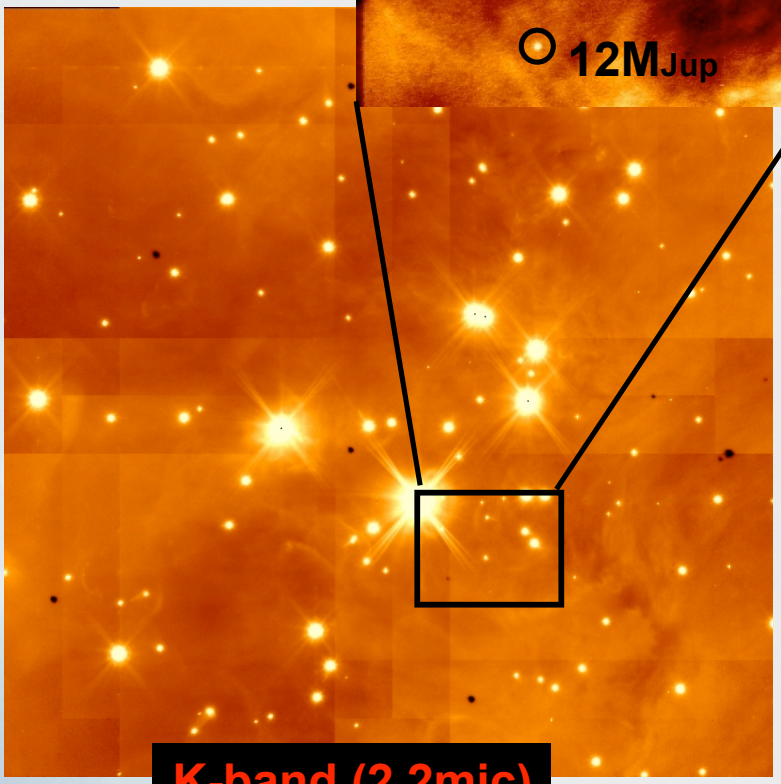




H-band (1.65mic)

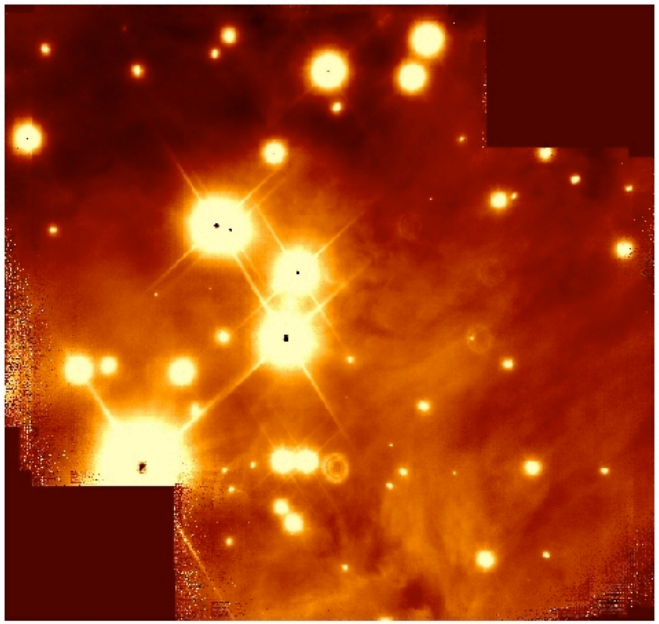


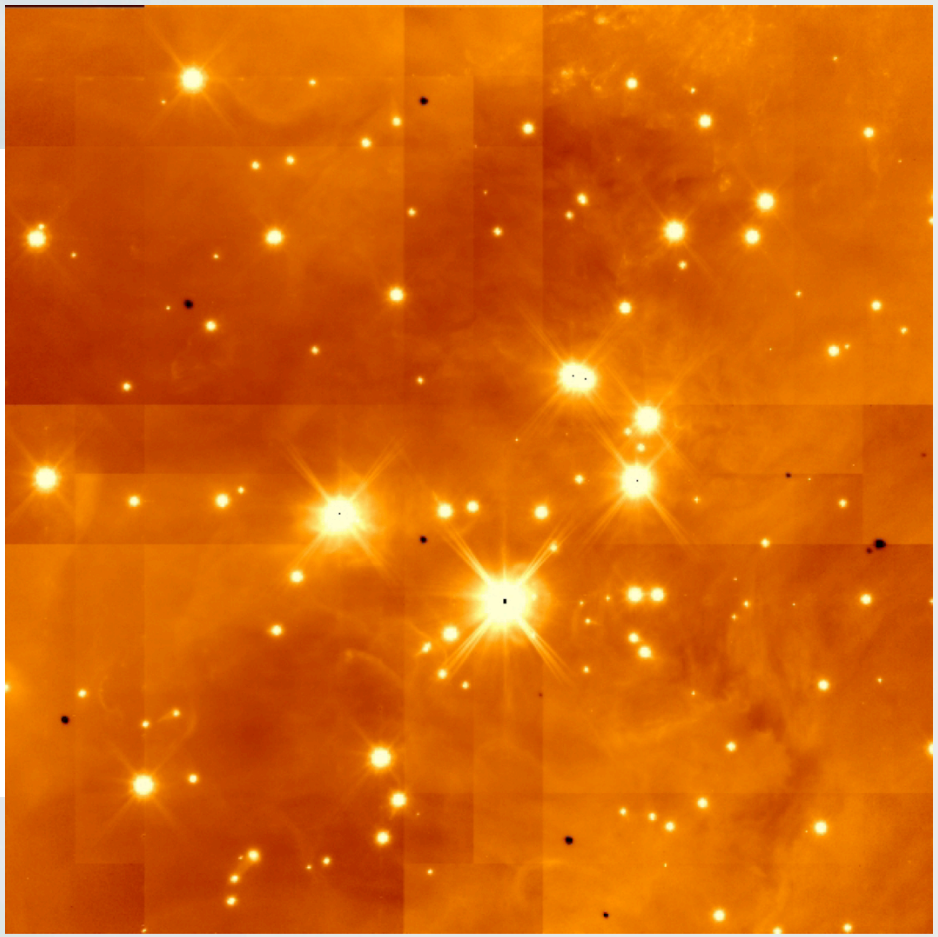
12M_{Jup}



K-band (2.2mic)

NACO
Exposure time ~13min.

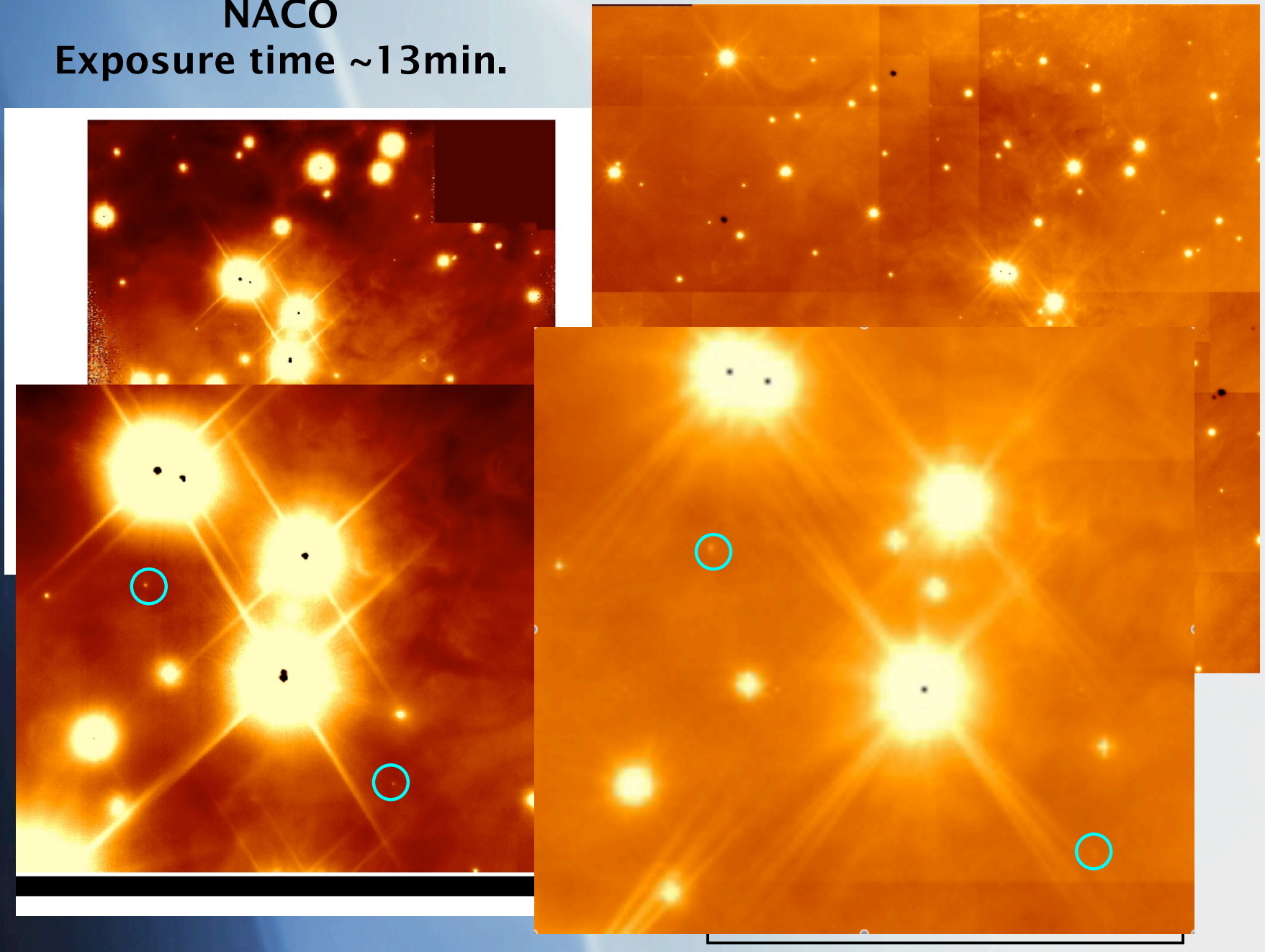




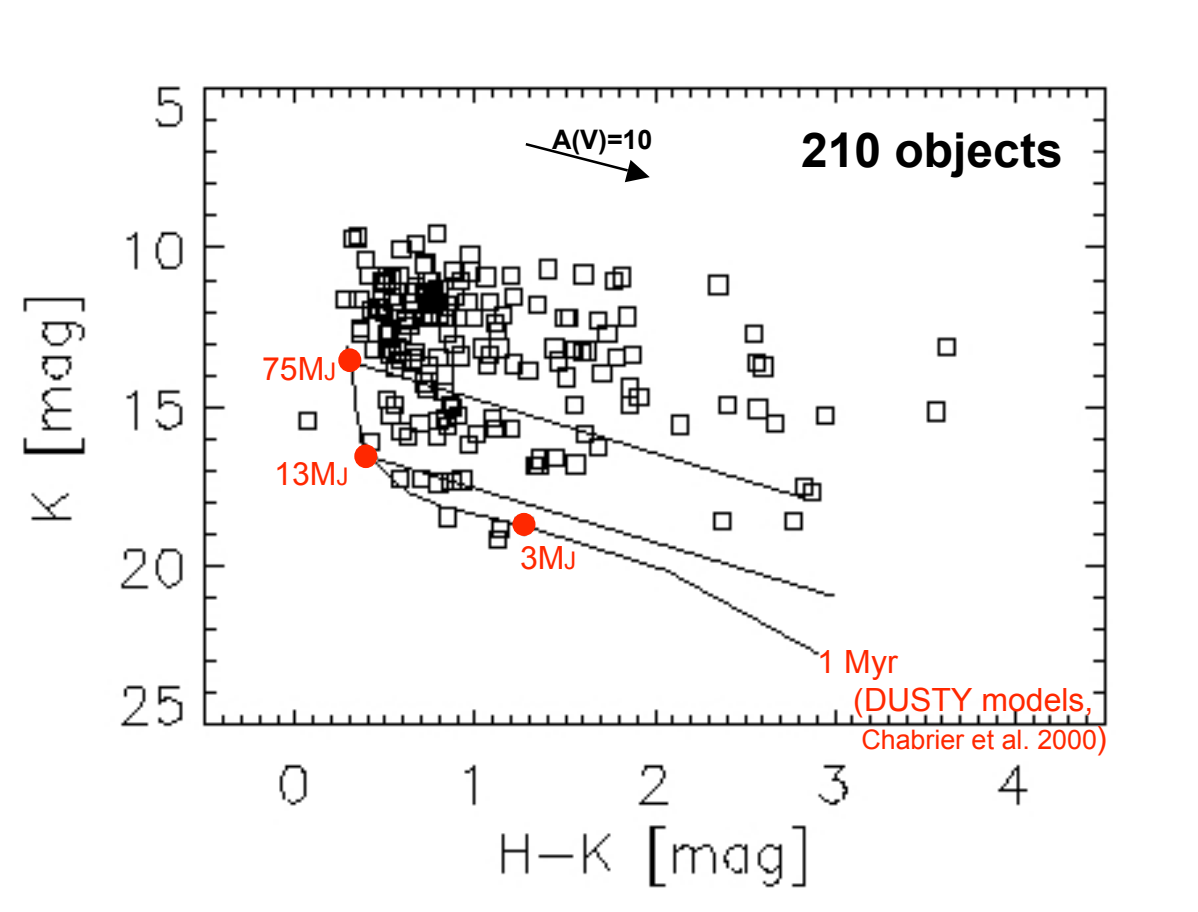
MAD
Exposure time ~12min

Faint objects detected by MAD are confirmed by NACO

NACO
Exposure time ~13min.



Brown dwarfs and planetary mass objects



All the PMO candidates are new detections Plus some of the BD candidates

Sub-stellar IMF in Trapezium Cluster Center:

N(BD)/N(PMO) = 3.0

in Trapezium Cluster periphery:
(Lucas et al. 2005, MNRAS 361)

N(BD)/N(PMO) = 3.2

Only 1 candidate binary brown-dwarf found

Summary

- High binary/triple fraction among the youngest low-mass protostars

  Further study of separation distribution and higher order multiplicity, outflows and protoplanetary disks

- Top-heavy IMF in starburst clusters?

  Resolve the cores and high-mass stars (!) into the individual stellar components

- Lower mass cut-off of the IMF? Brown dwarf formation?

  Study brown-dwarf multiples and the lowest mass objects (in cores of stellar clusters)