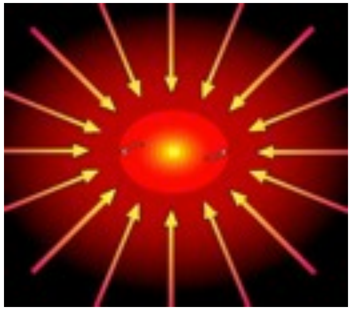
Star Formation & ALMA

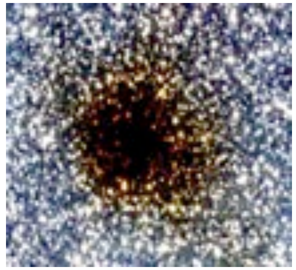
Leonardo Testi (ESO/Arcetri)

Thanks: **J. Ascenso** (ESO), **E. Bressert** (Exeter/ESO), **G. Costigan** (ESO/DIAS), **G. Fuller** (UManchester), **C. Goddi** (ESO), **S. Longmore** (ESO), **C. Manara** (ESO/LMU), **N. Peretto** (Saclay), **L. Ricci** (Caltech), **J. Tan** (UFlorida), ...

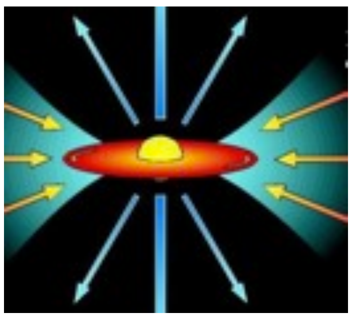
- Star Formation as a "local" process
- The extremes of SF as a testbed
- (Setting the stage for Planet Formation)

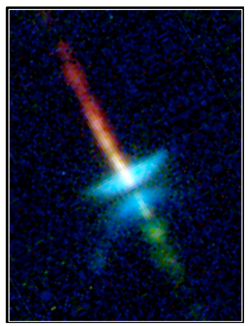
From Cores to Planetary Systems



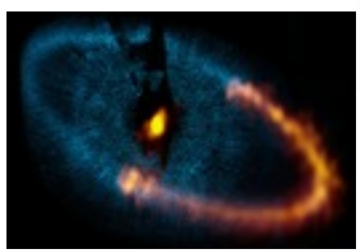


Core

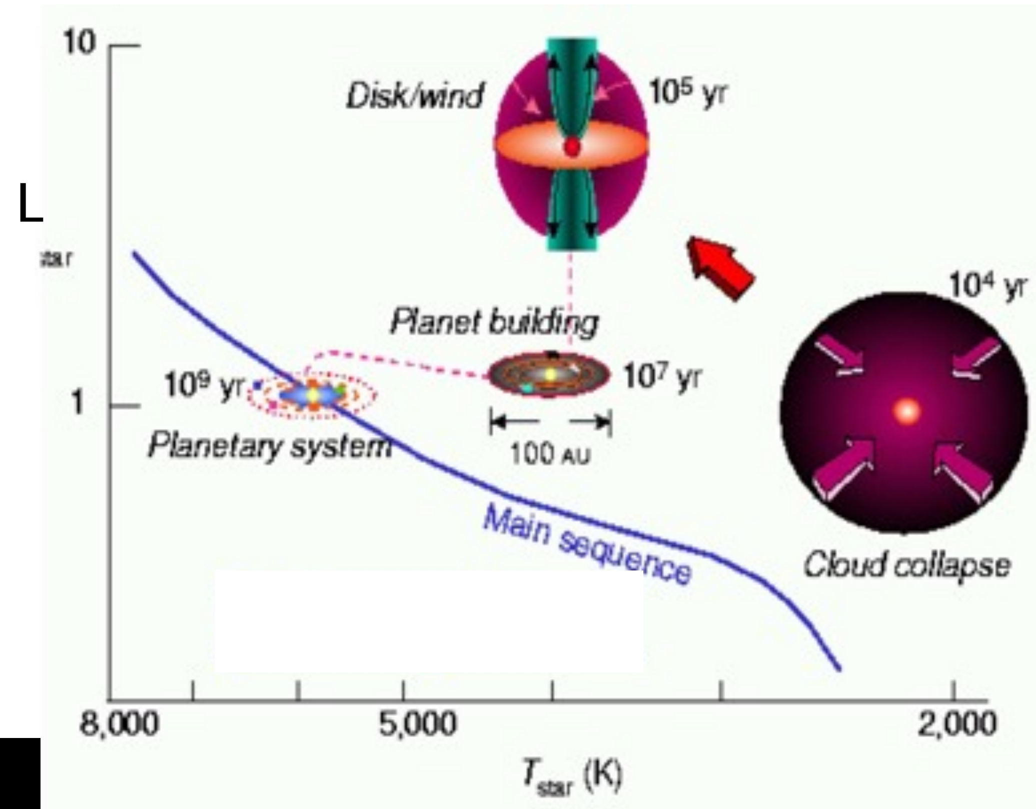




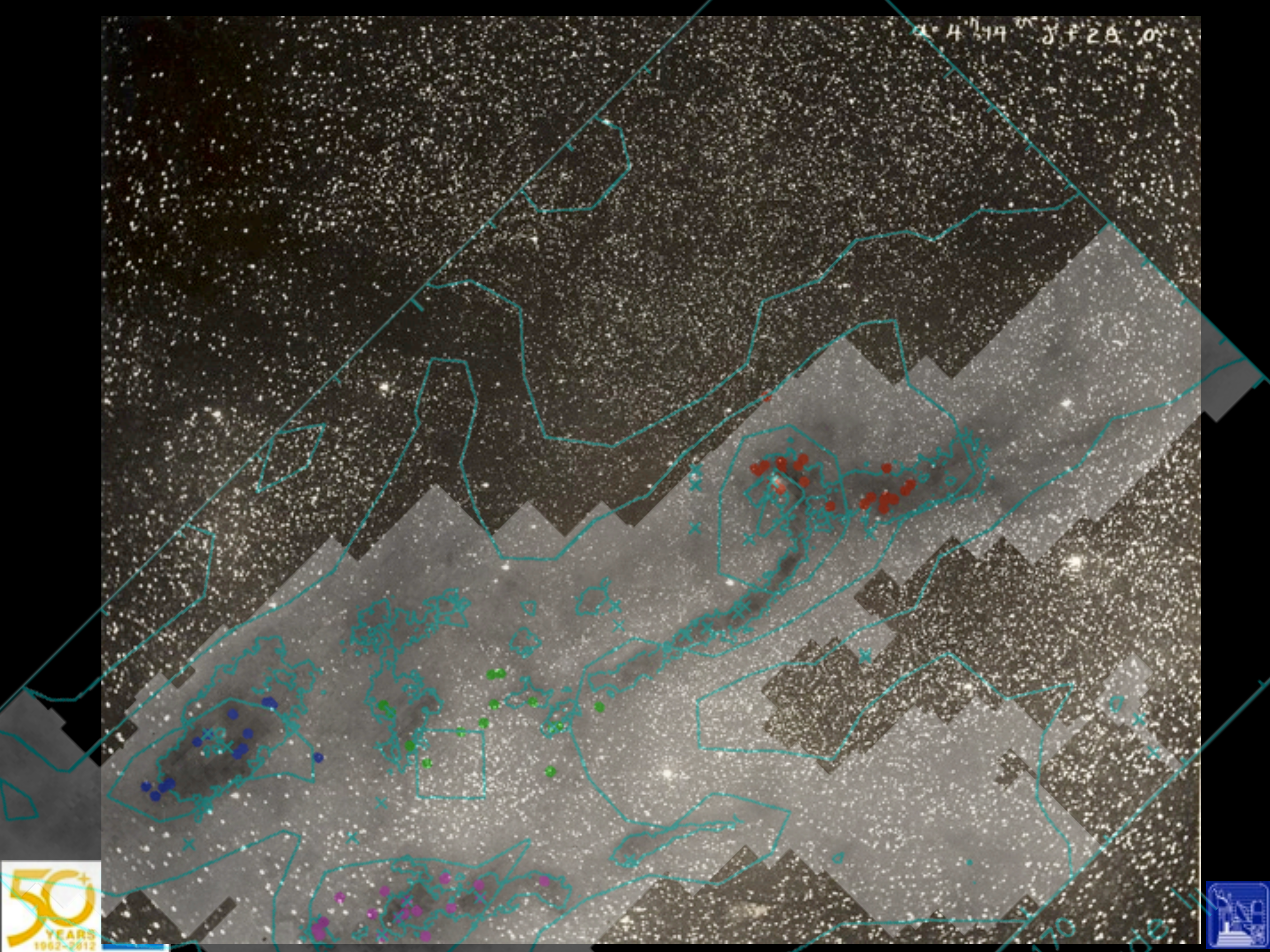
Disk



Debris Disk

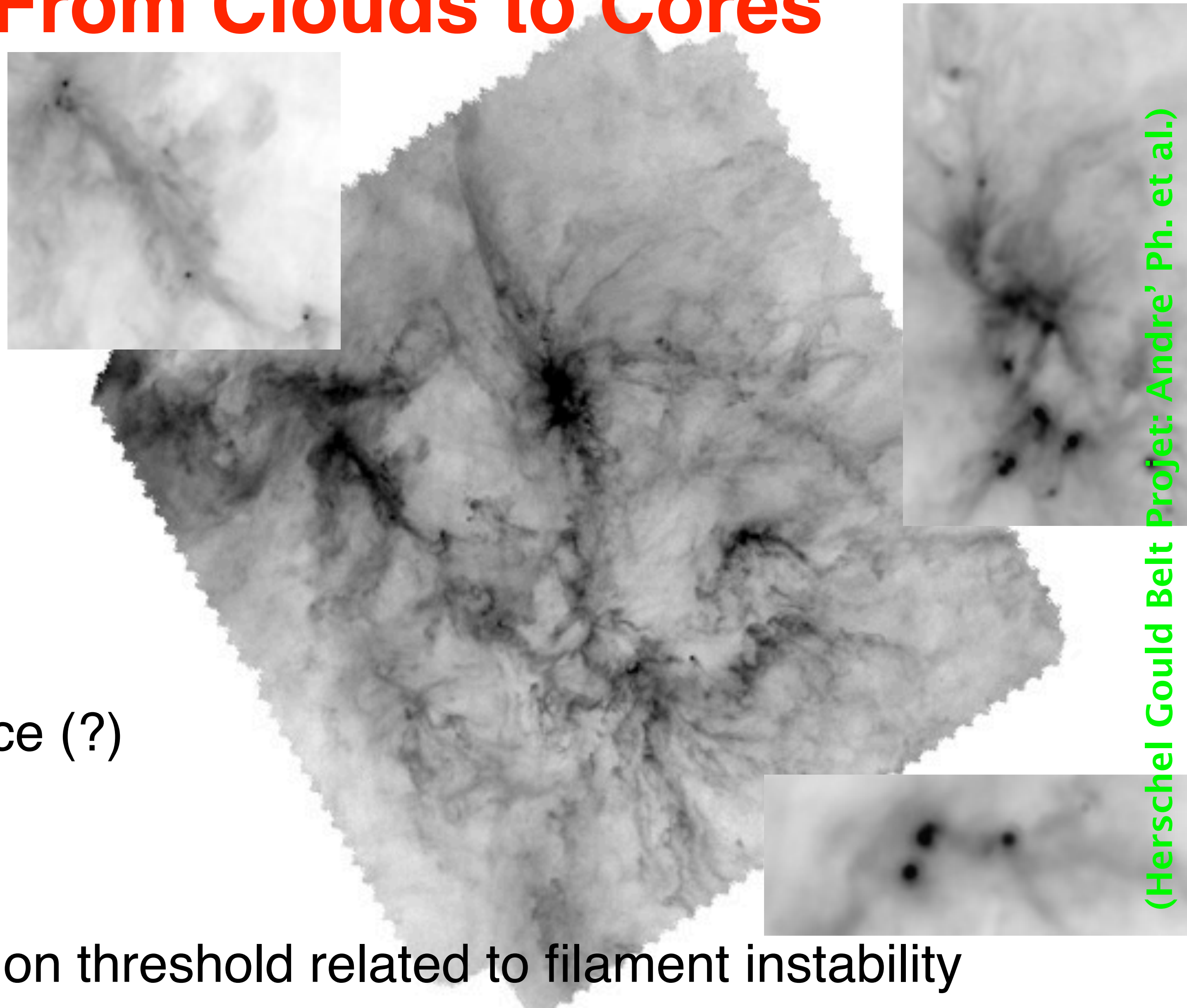



α = 4h 44m δ + 28.0°



α 4h 44m δ +28.0

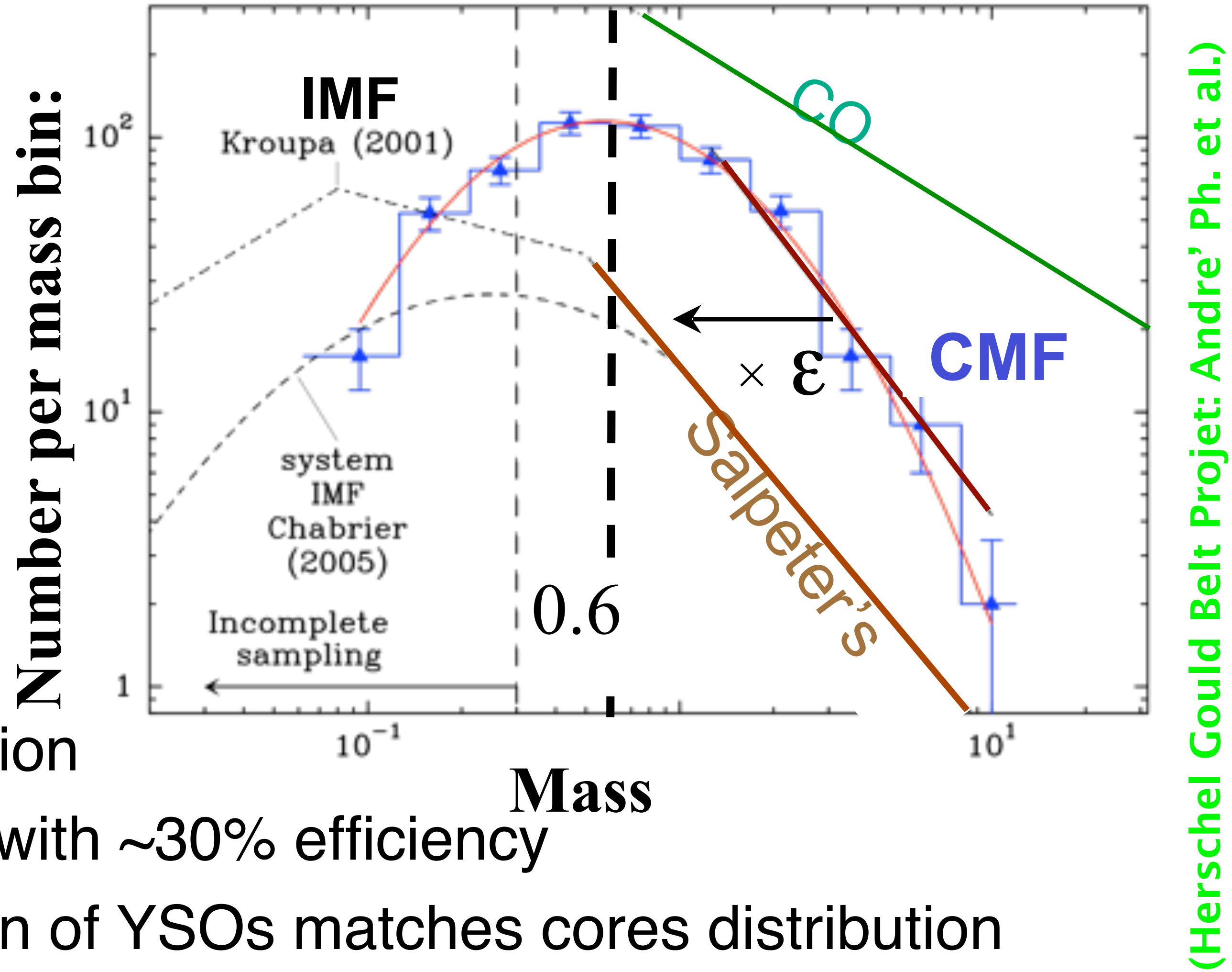
From Clouds to Cores



(Herschel Gould Belt Projet: André Ph. et al.)

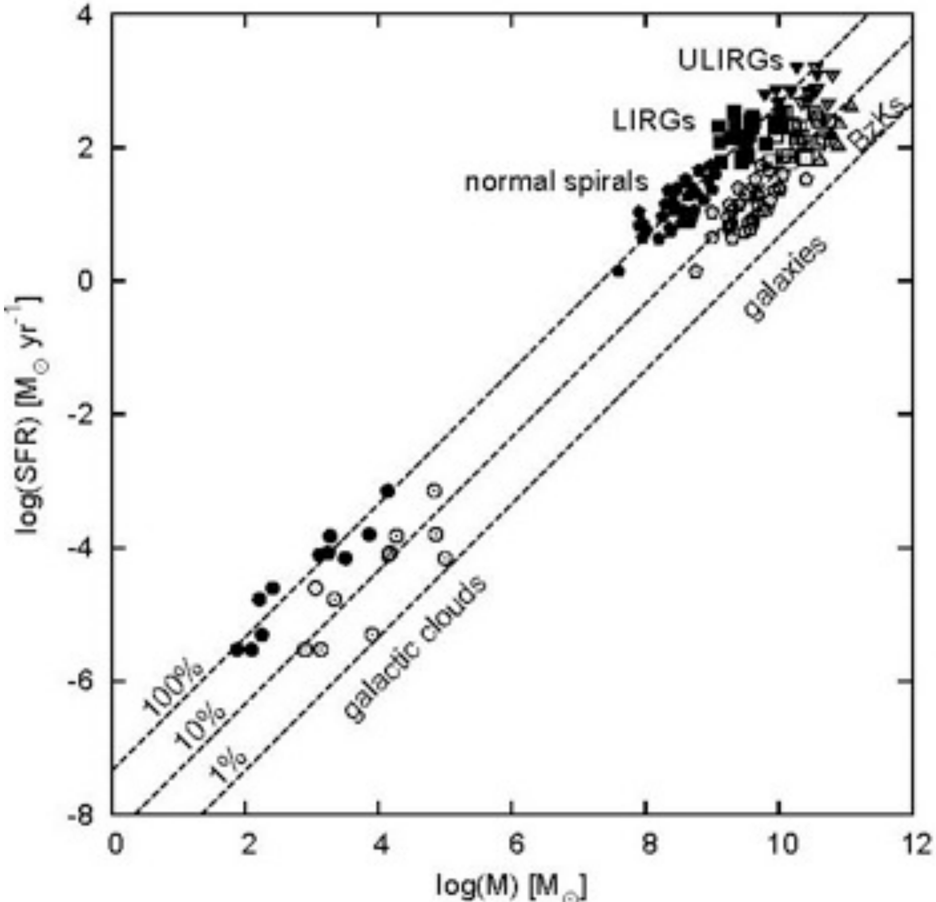
- Filaments
  - Turbulence (?)
- Cores
  - Gravity
- Core formation threshold related to filament instability

From Cores to Stars



- Core Mass Function
  - Matches IMF, with ~30% efficiency
- Spatial distribution of YSOs matches cores distribution
- Output of SF determined by cloud fragmentation

Is Star Formation a Local Process?



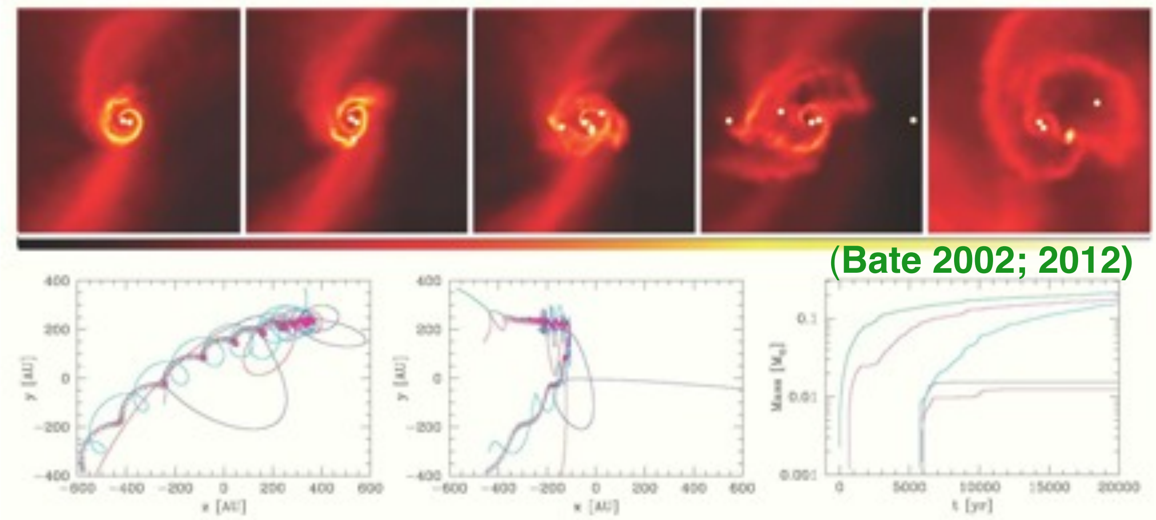
(Lada et al. 2012)

- Star Formation is consistent with high efficiency conversion of dense gas into stars
- Clouds -> Filaments -> Cores -> Stars

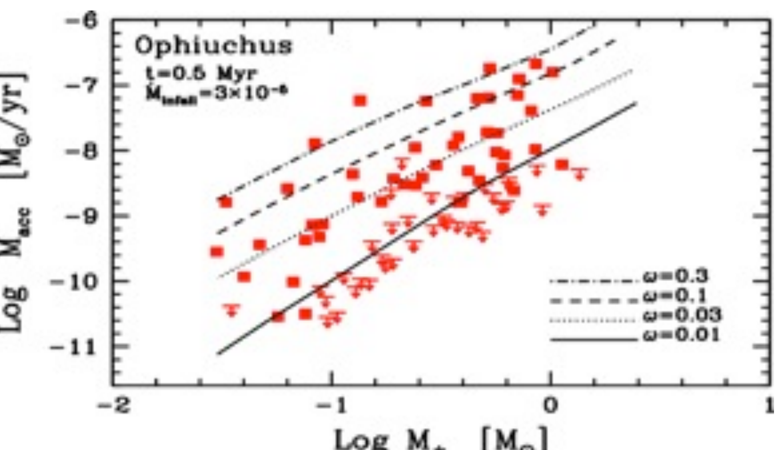
Check the Extremes

- Formation of Brown Dwarfs and Planetary mass objects
  - Can BDs for as stars from isolated cores?
- Formation of massive stars and groups/clusters
  - Are clusters “needed” to form massive stars?
  - Are filaments and dense cores the right basic recipe?
- Formation of Young Massive Clusters
  - Do the simple laws break down?
  - Do YMCs require “different” conditions to form?

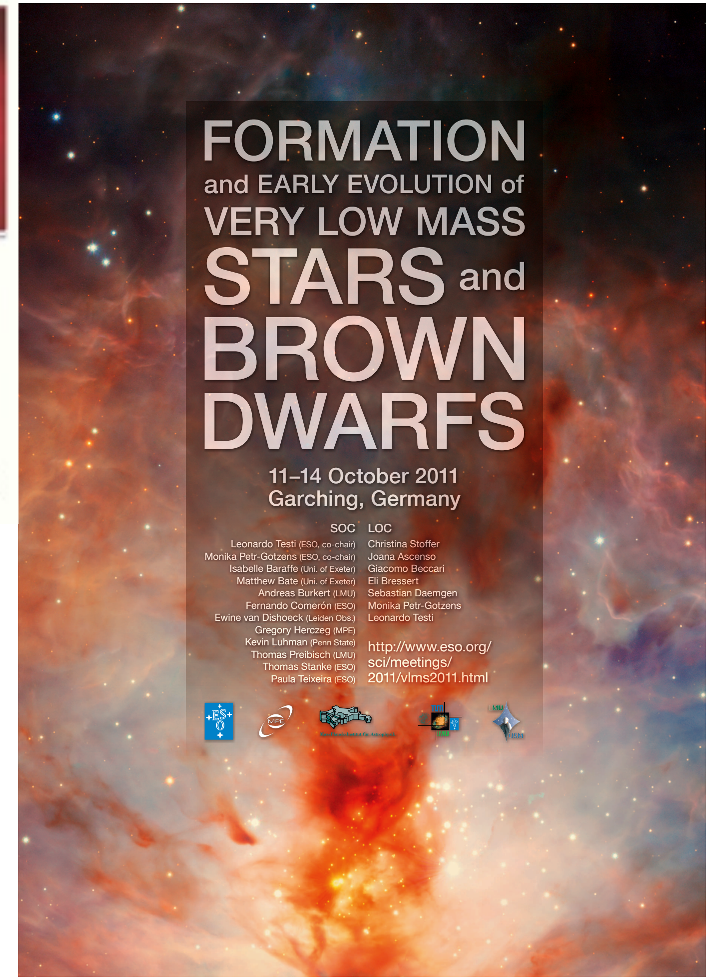
Formation of Brown Dwarfs



(Bate 2002; 2012)



(Dullemond, Natta & Testi 2006)

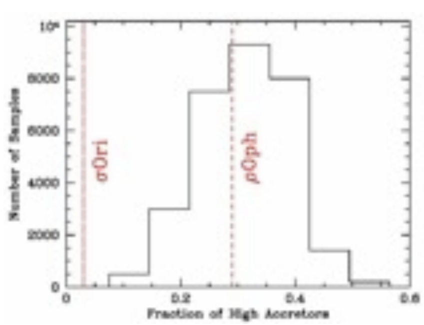


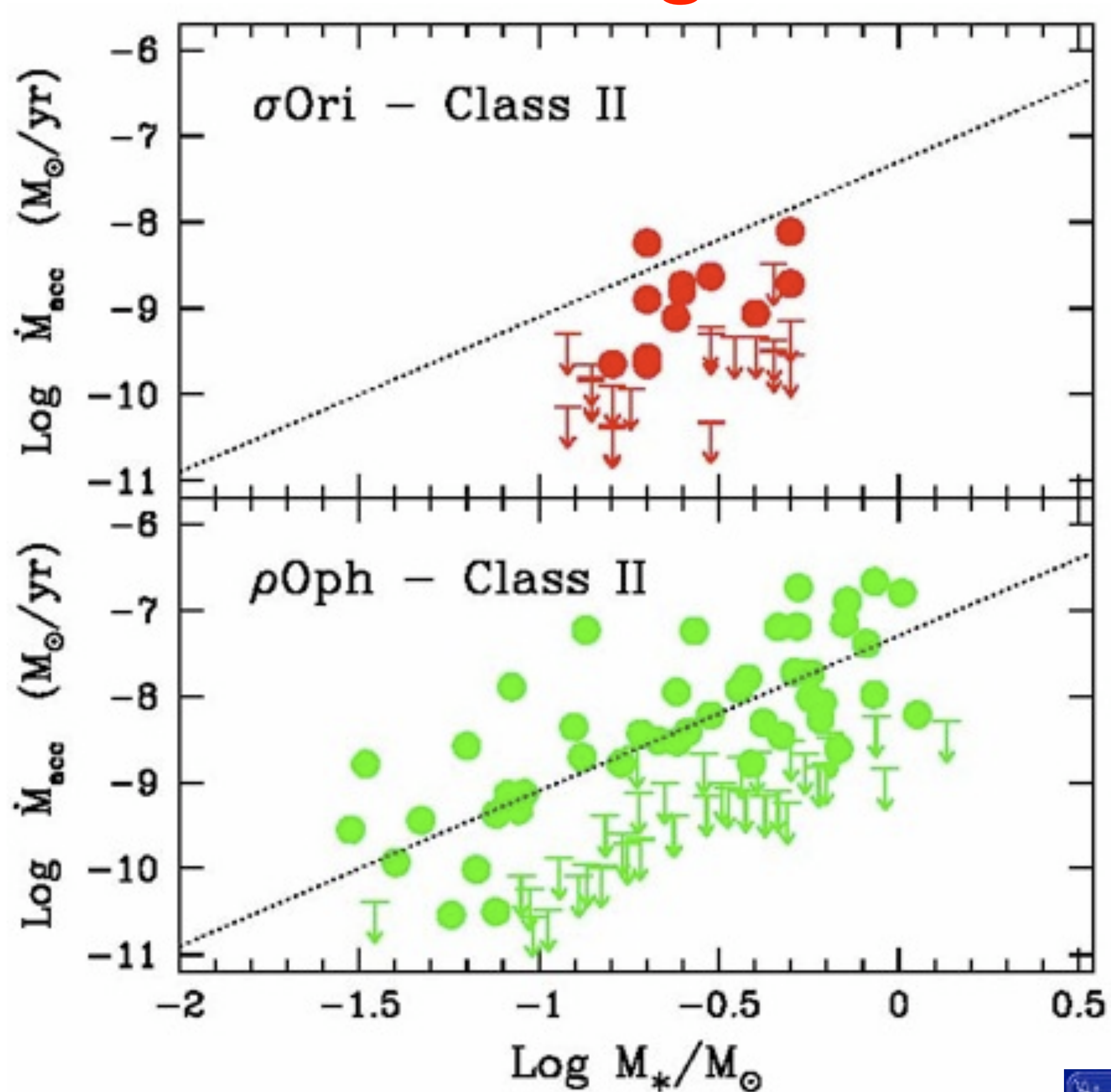
- Can Brown Dwarfs fit in the paradigm?
- Formation and Early Evolution of VLMS and BDs (http://www.eso.org/sci/meetings/2011/vlms2011.html)

Accretion vs mass/age

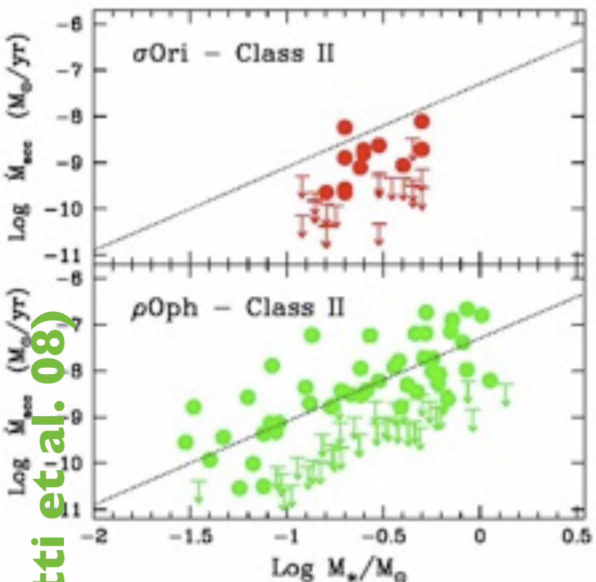
- NIR hydrogen recombination lines NTT/VLT survey
- ρ-Oph vs σ-Ori
- ~0.5-1Myr vs ~3-5Myr

(Natta et al. 06; Gatti et al. 08)

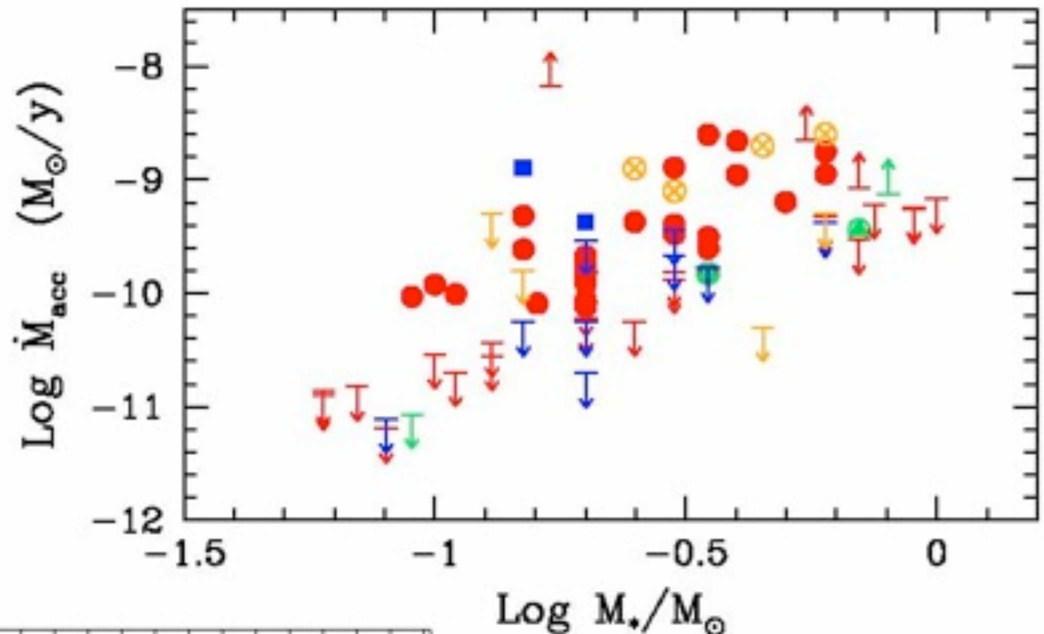




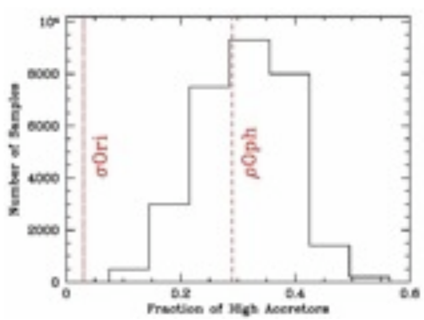
Accretion vs mass/age

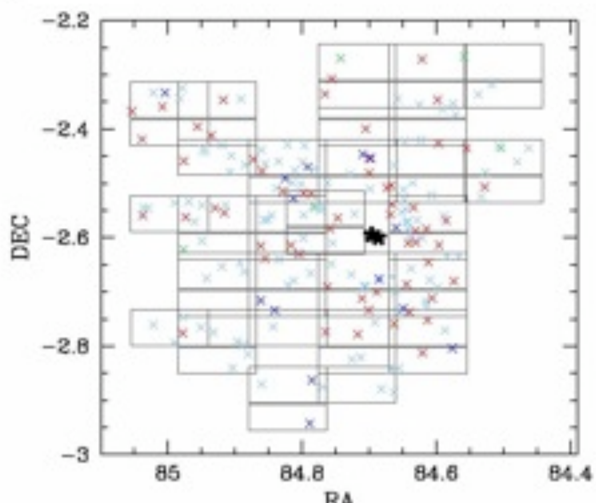


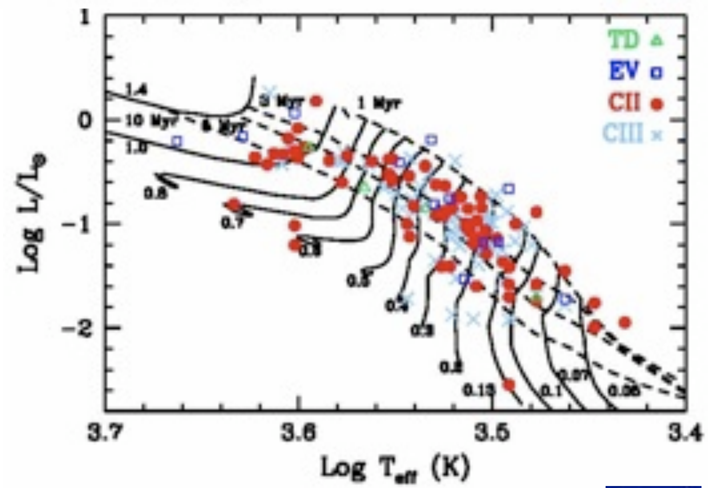
(Natta et al. 06; Gatti et al. 08)



(Rigliaco et al. 11)



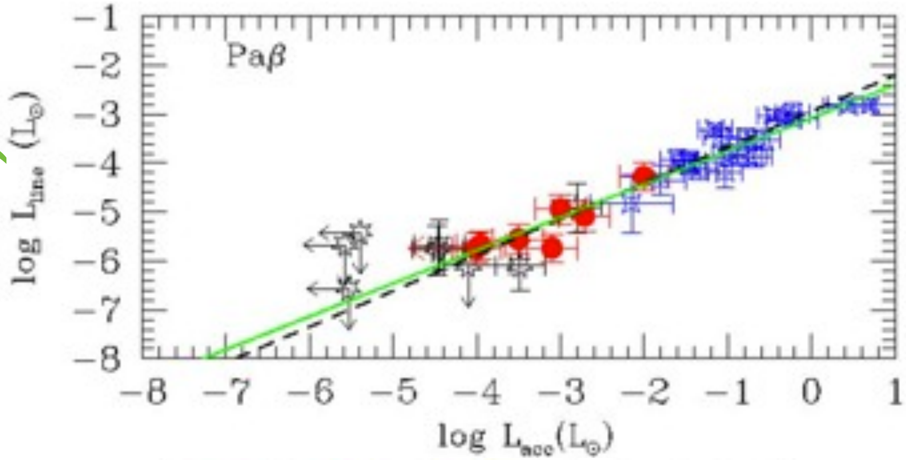


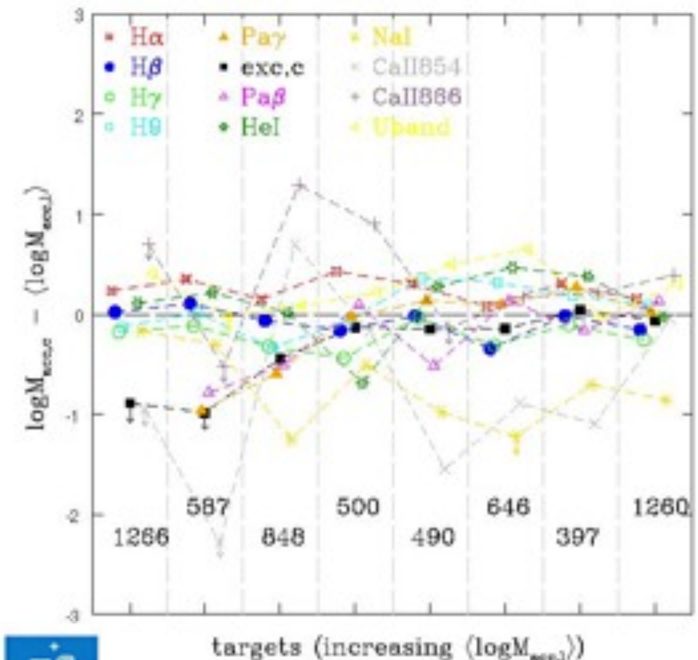


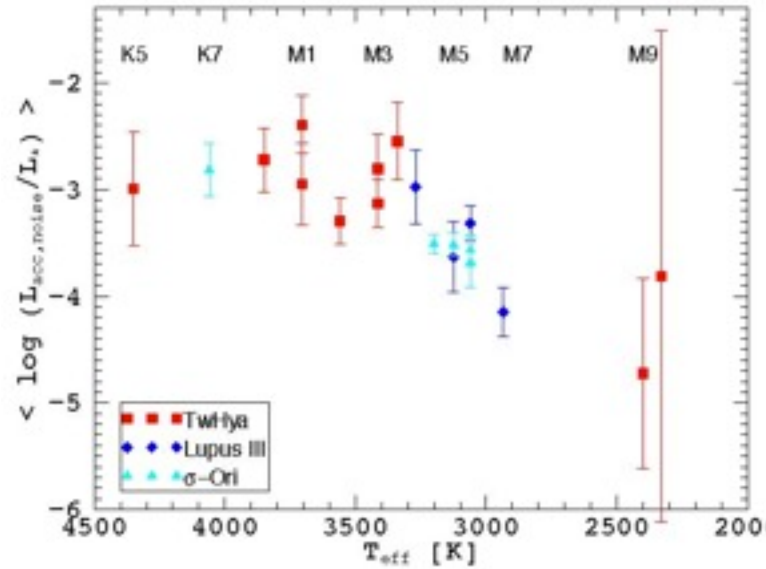
VLT U-Band survey

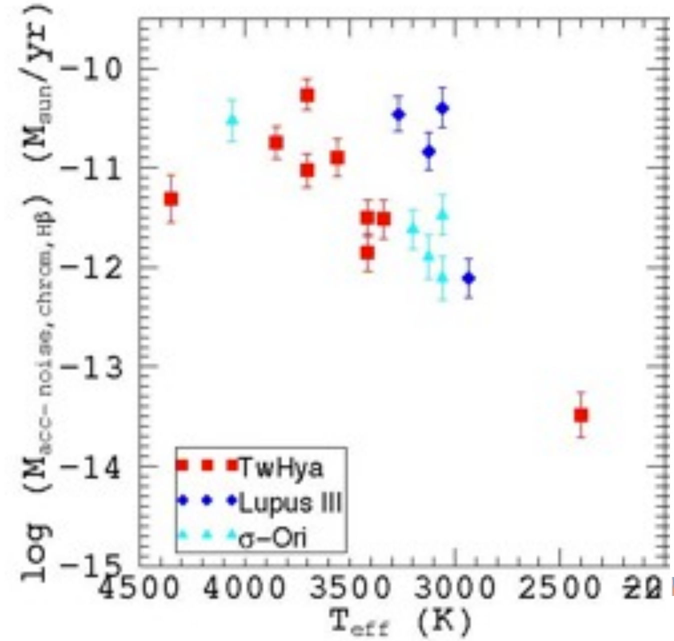
Accuracy matters in the BDs domain...

(Natta et al. 2004; Rigliaco et al. 2012)





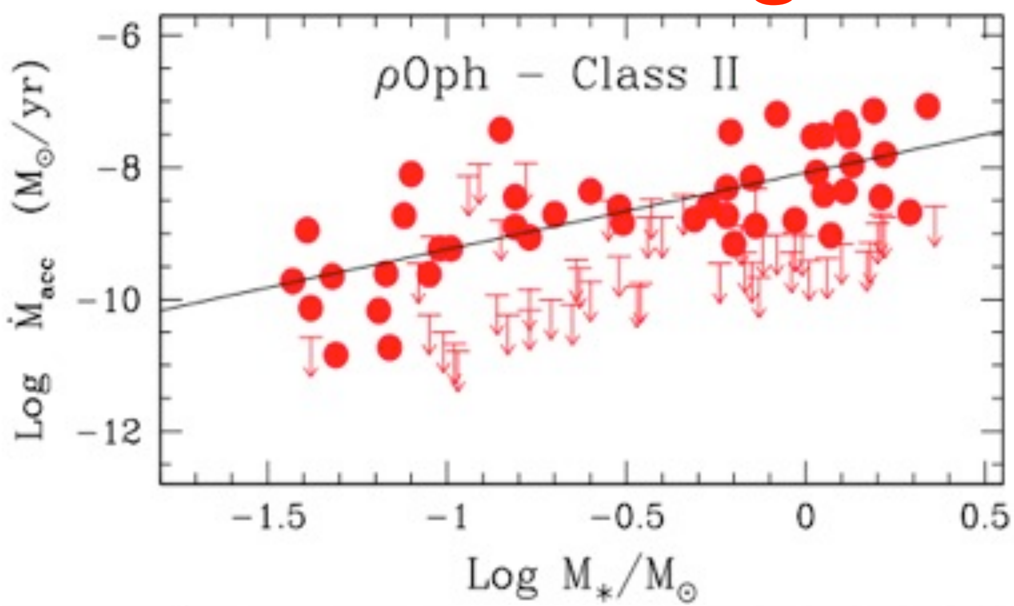


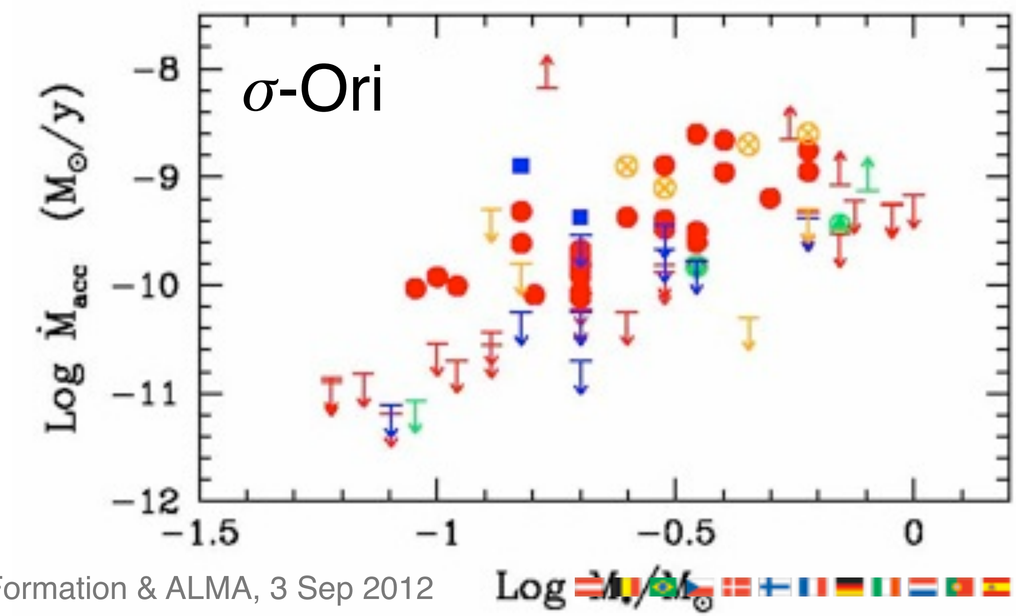


(Manara et al. 12)

Accretion vs mass/age

- ρ-Oph vs σ-Ori
- ~0.5-1Myr vs ~3-5Myr





(Rigliaco et al. 11)

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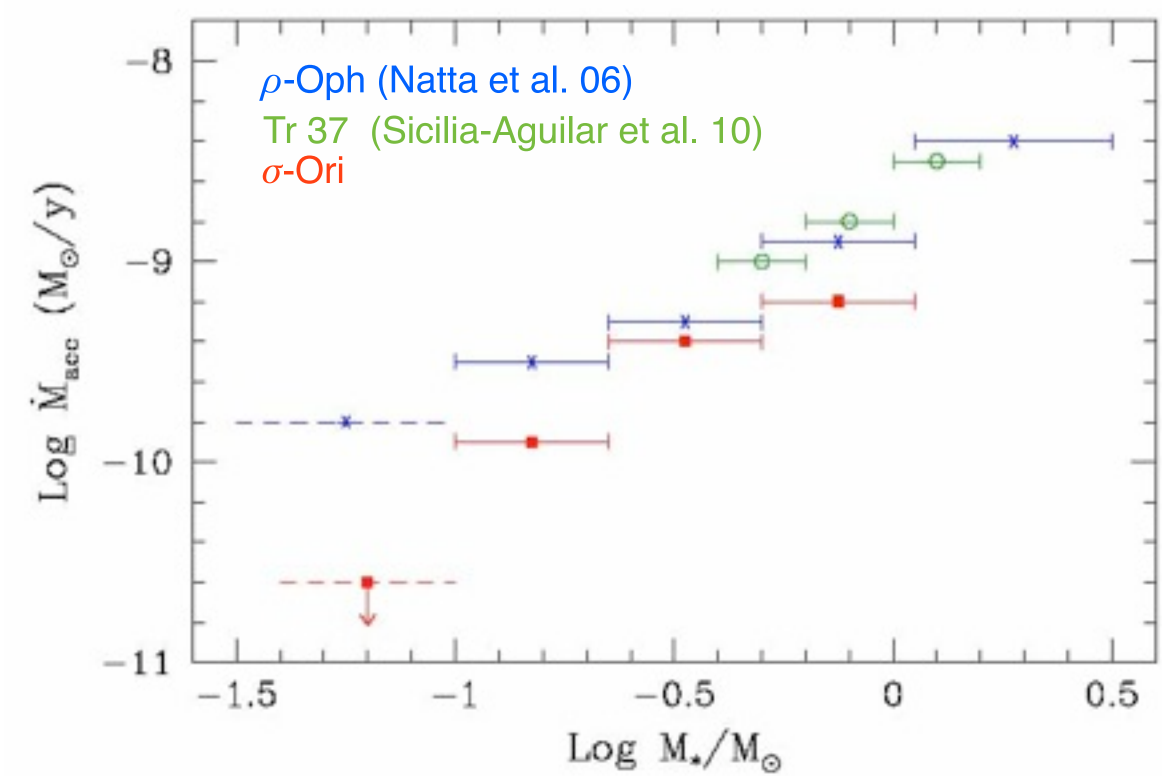
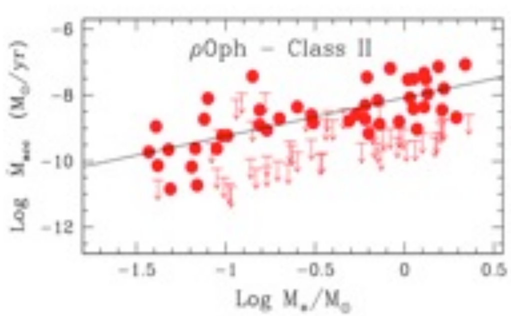
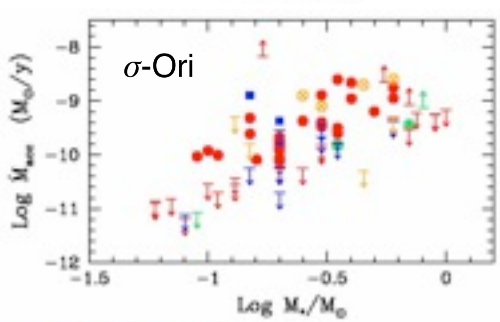


(Rigliaco et al. 11)

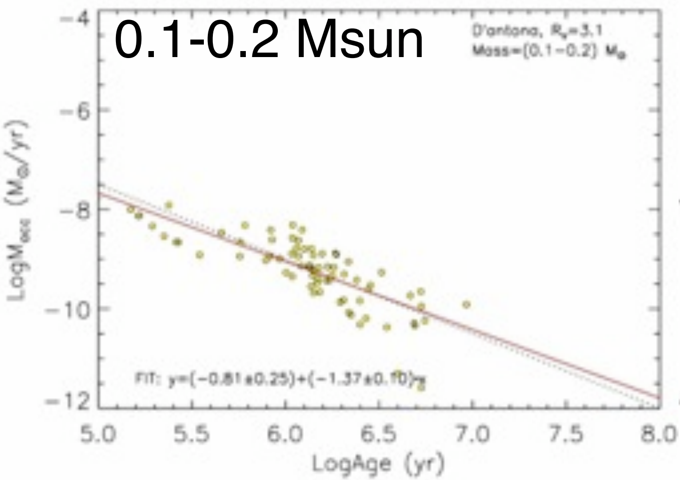


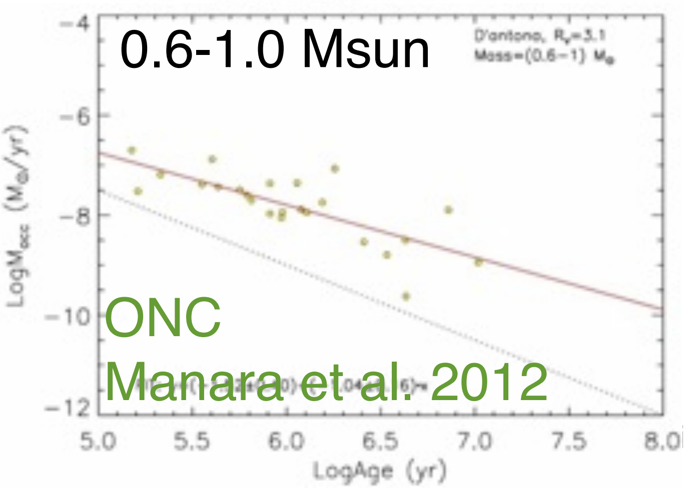


- Possible evidence for a change of slope with stellar mass
- possible evidence for a faster evolution at the low mass end

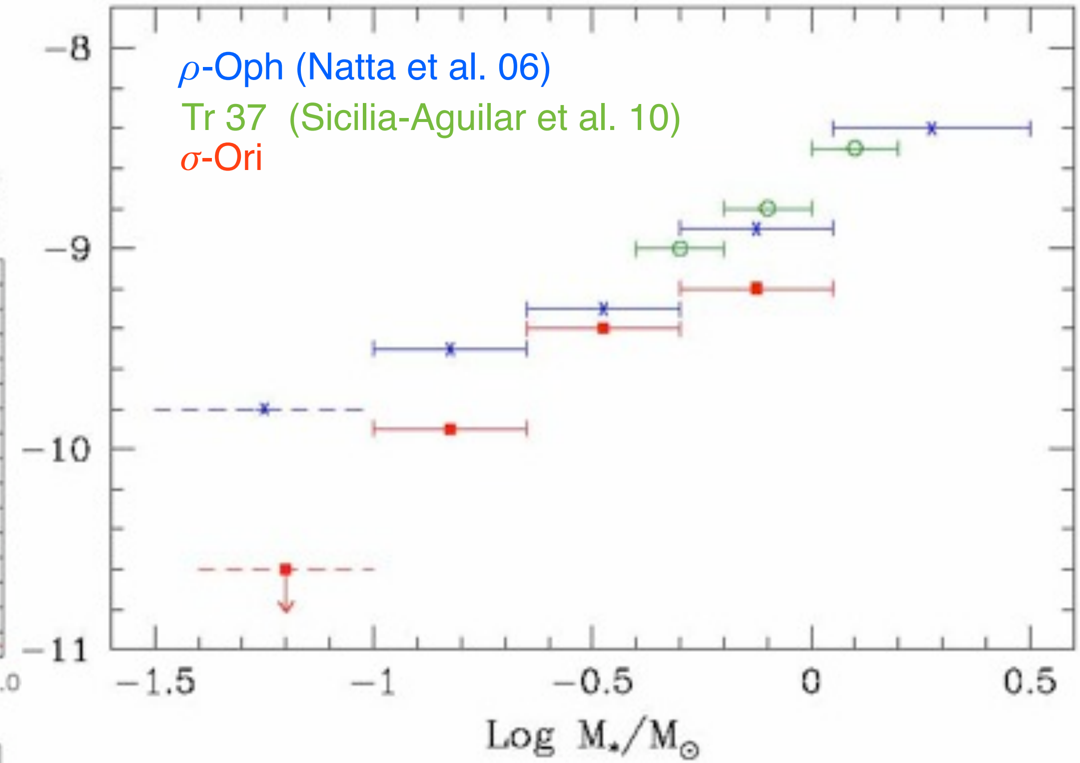
Accretion vs mass/age

- ρ-Oph vs σ-Ori
- ~0.5-1Myr vs ~3.5Myr





ONC
Manara et al. 2012

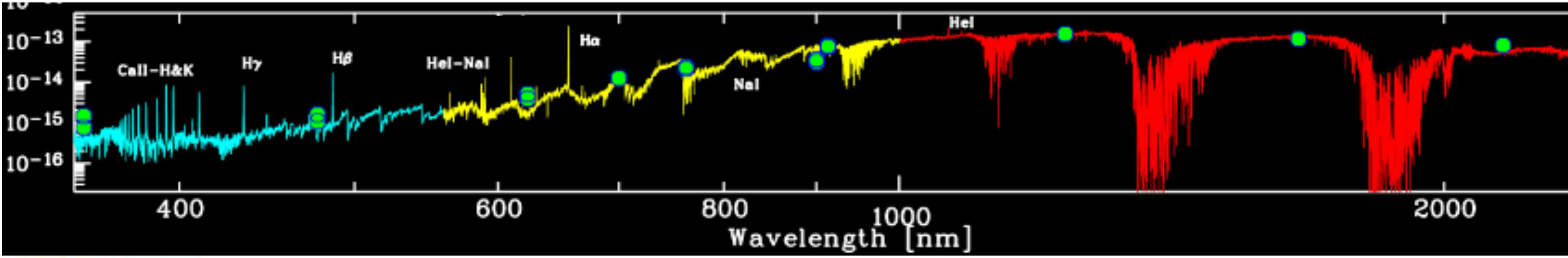


(Rigliaco et al. 11)

- Possible evidence for a change of slope with stellar mass
- possible evidence for a faster evolution at the low mass end

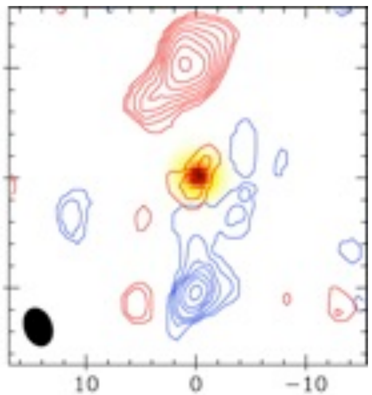
XShooter surveys

- Simultaneous observation of photosphere, accretion and wind indicators across a broad wavelength range
- Surveys:
  - Alcala' et al. GTO program: TW Hya, Lupus, σ-Ori, +
    - Alcala' et al. 2011, Rigliaco et al. 2012, Manara et al. 2012b
  - Testi et al.: ρ-Oph
  - Herczeg et al.: Chamaeleon +
  - Several smaller programs

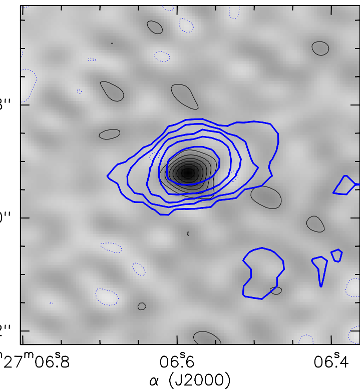


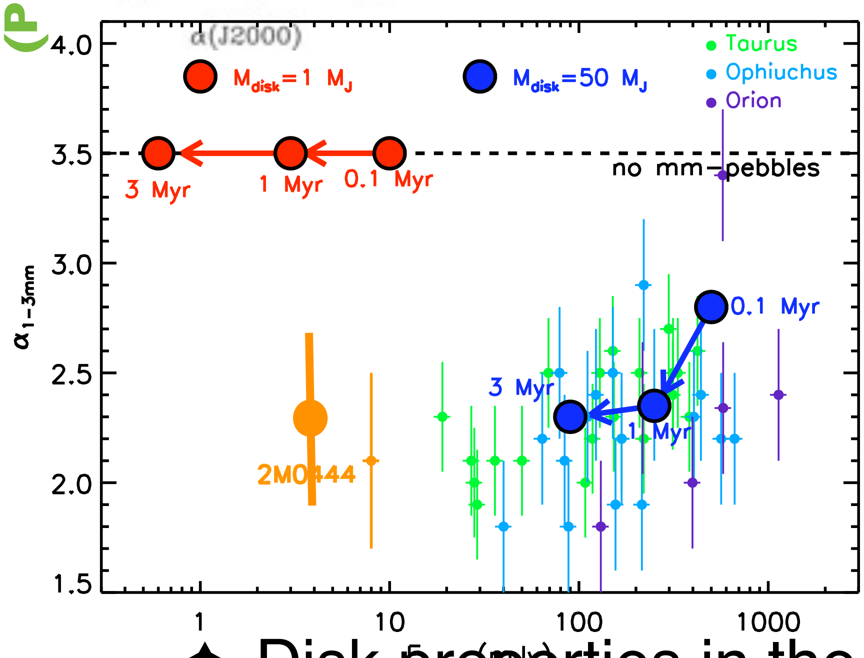
Disk properties

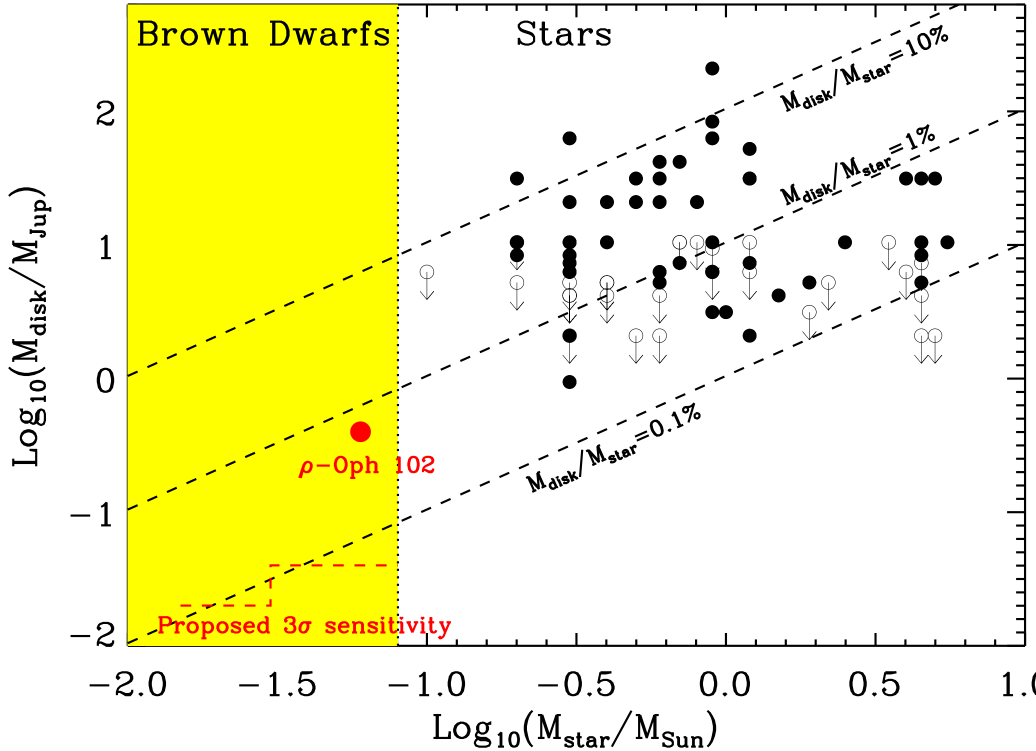
(Phan-Bao et al. 08)



(Ricci et al. 2012)







- ✦ Disk properties in the substellar domain: a major topic for ALMA (sensitivity and angular resolution)

Lessons and questions from BDs

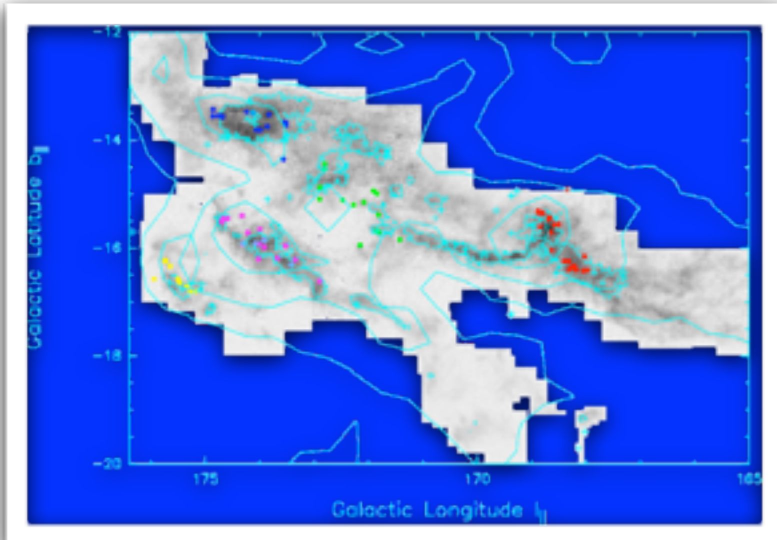
- Young BDs can have similar characteristics as low mass stars
  - Consistent with same formation and evolution mechanisms

- Ejection/interaction pathways have to become important for the lowest mass objects

- Open questions for ALMA
  - Identification of pre-BDs cores?
  - Disk properties around young BDs?
  - Planet formation in the BDs regime?

Memories from a few yrs ago

(The clustered vs dispersed population debate)

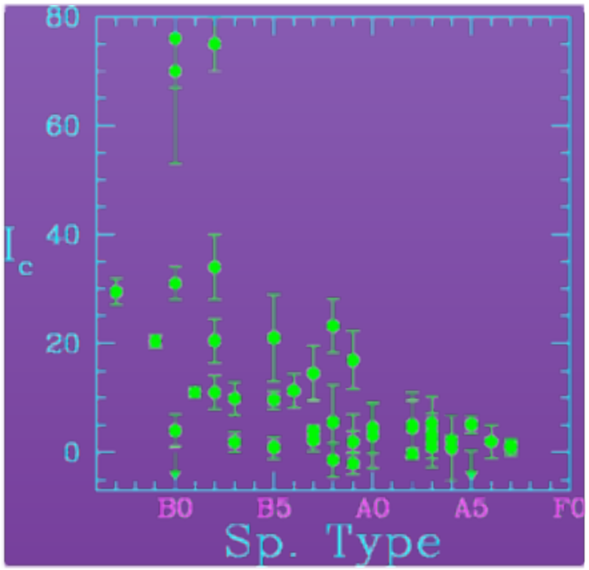


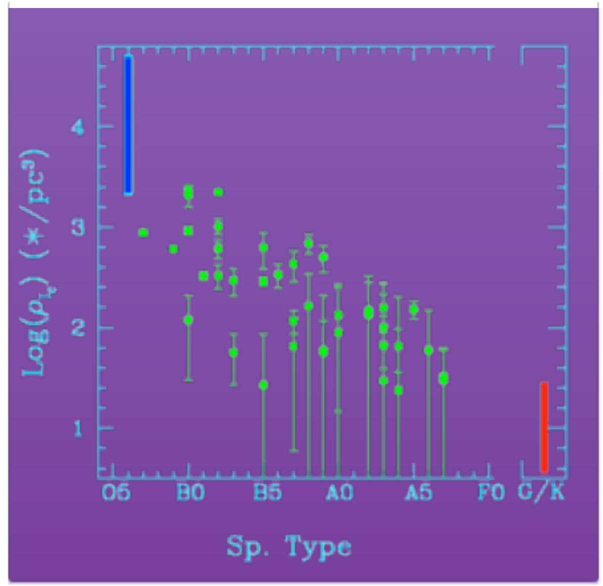
Intermediate-mass stars

- Low-mass stars in nearby associations are found in isolation or loose groups ($\rho_* \sim$ few $*/pc^3$)

- High-mass stars are found in dense and well populated stellar clusters ($\rho_* \sim 10^4$ $*/pc^3$)

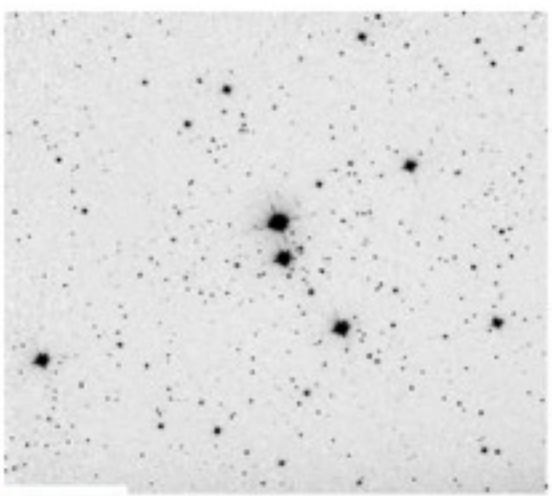
Clustering properties of HAeBe and O stars

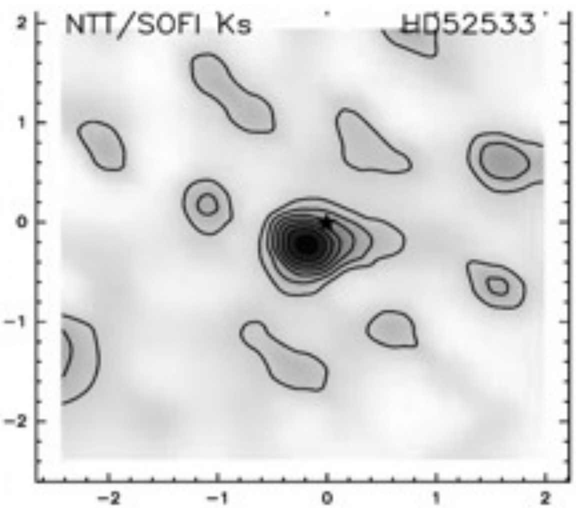


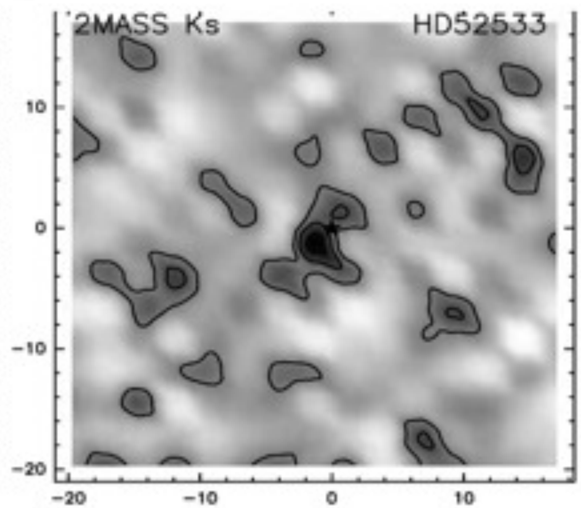


- ✦ Possible correlation between clusters and massive stars
- ✦ Random sampling not excluded

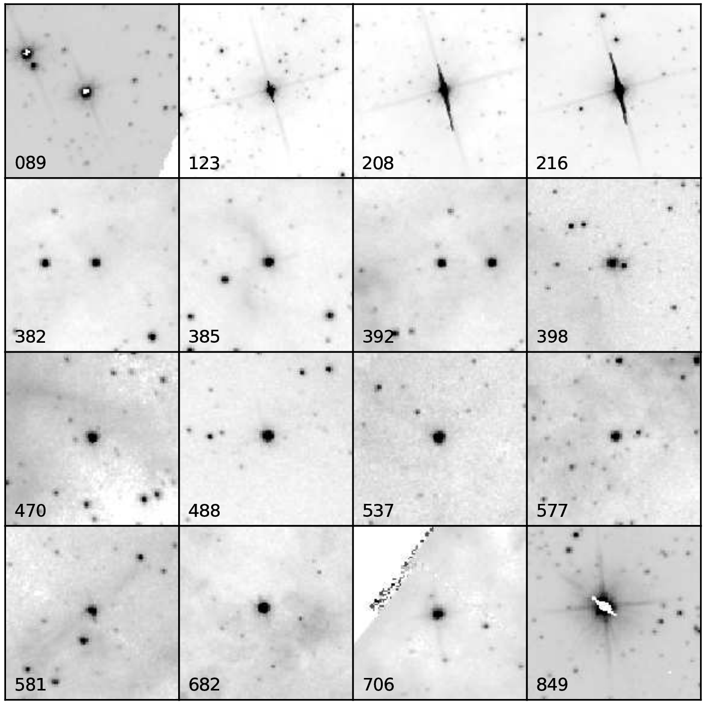
(Testi et al. 1997, 1998, 1999
de Witt et al. 2004, 2005)

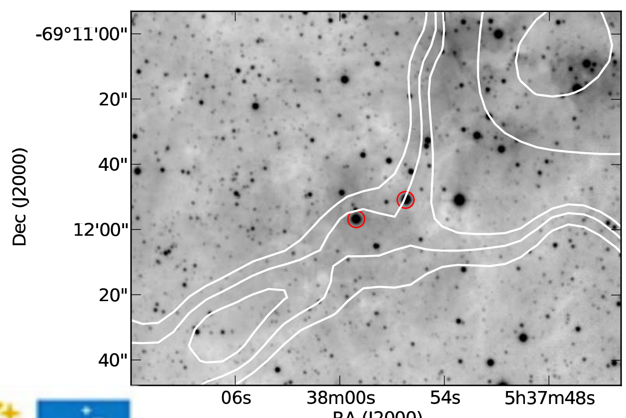


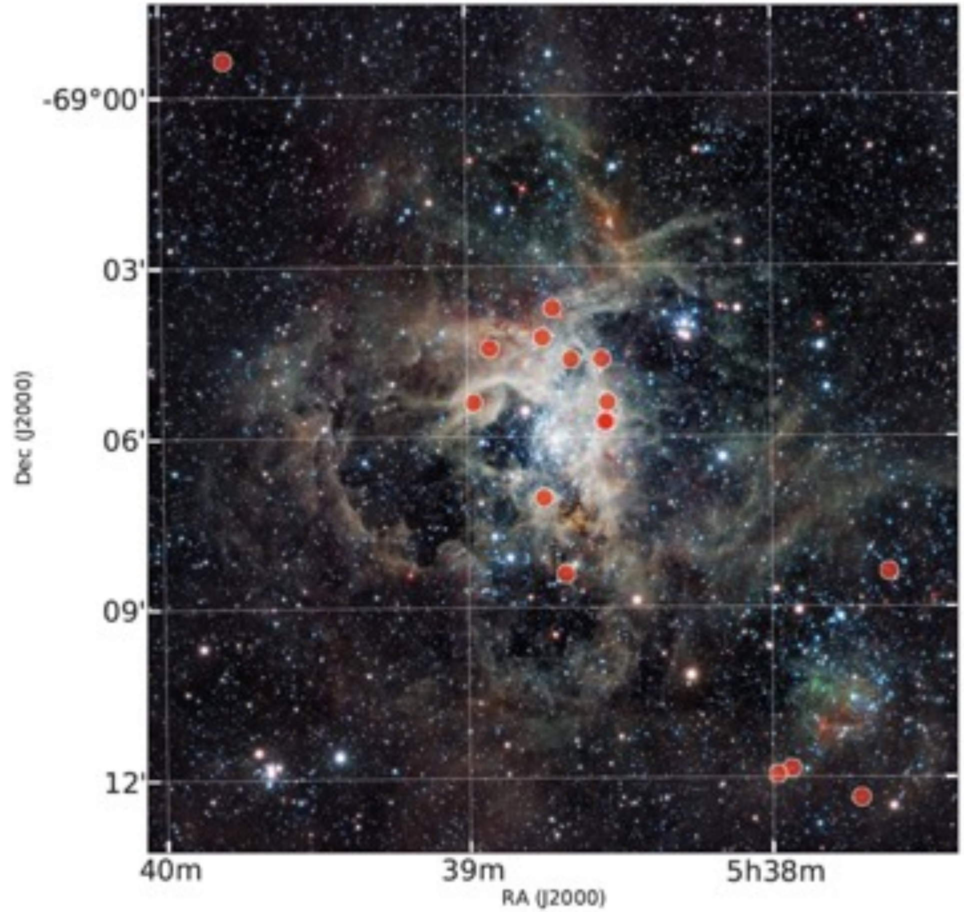




"Isolated" O-stars in 30Dor field



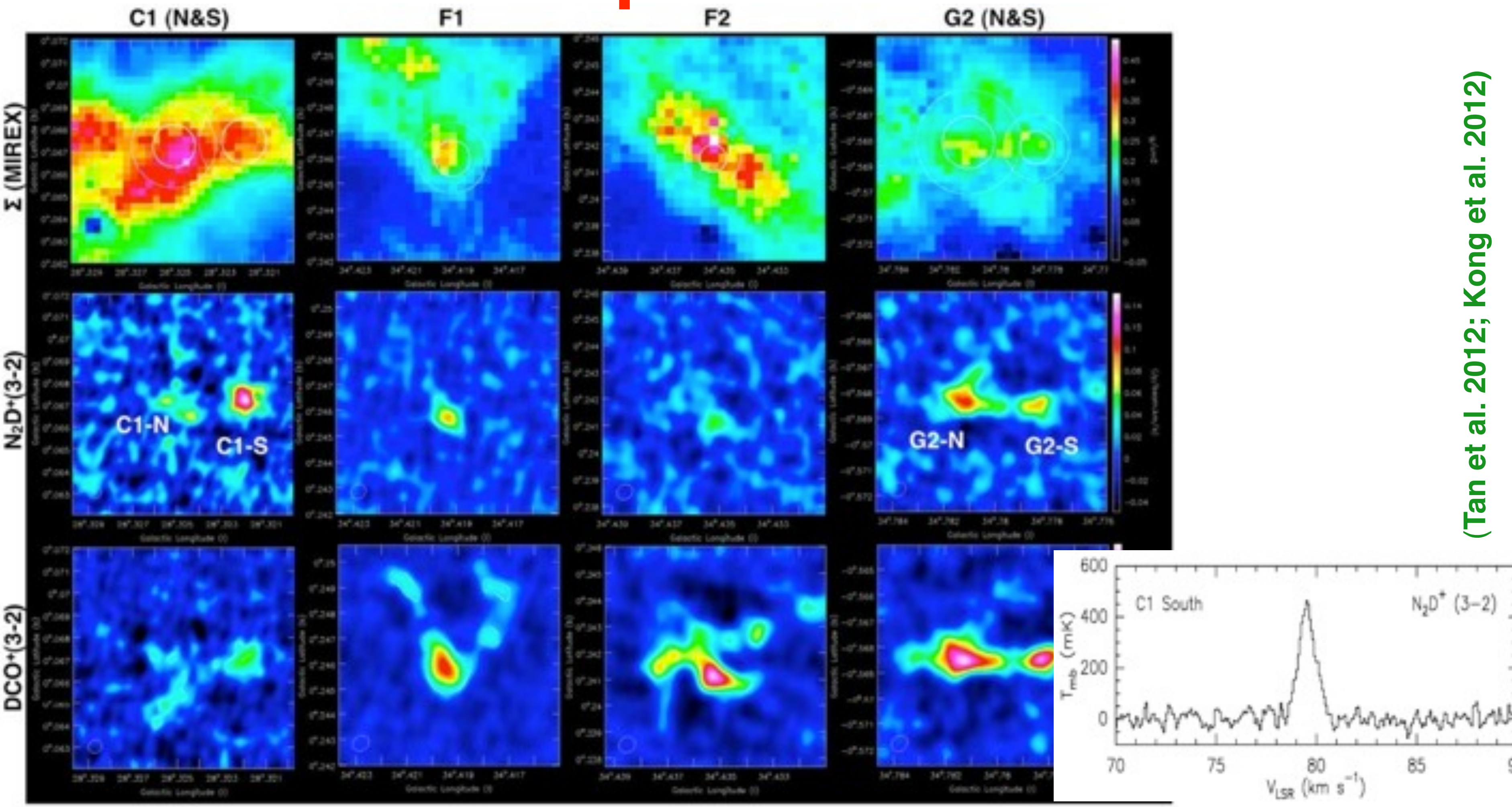




(Bressert et al. 2012)

- Candidate "isolated" O-stars from the VLT Tarantual Survey

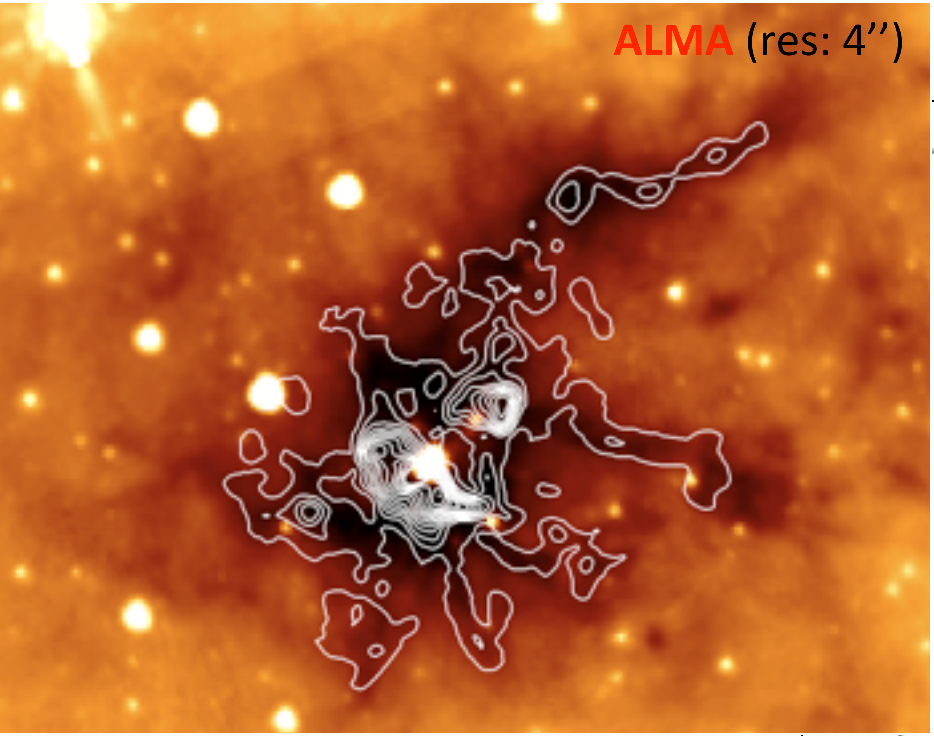
The birthplaces of O-stars

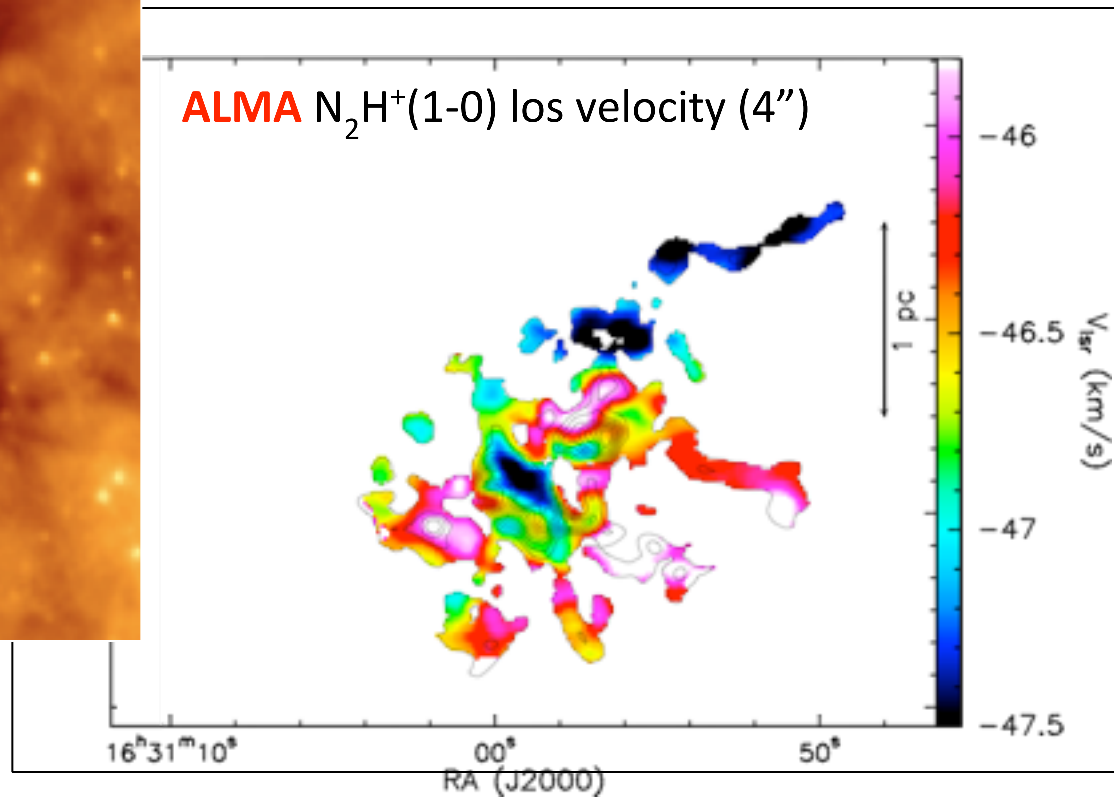


(Tan et al. 2012; Kong et al. 2012)

- ALMA Cycle 0 observations of deuterated species in IRDCs
- Dense massive cores in virial equilibrium

The filamentary structure of IRDCs

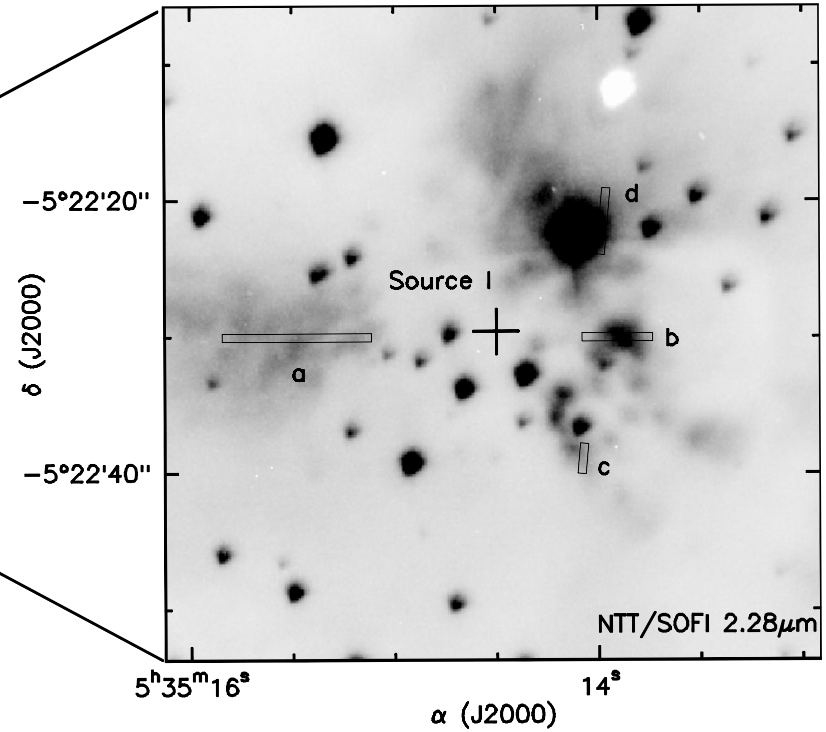


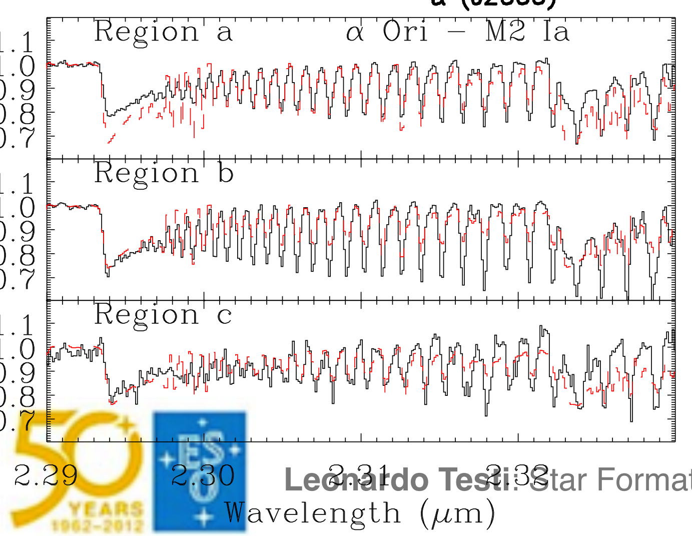


(Peretto et al. 2012)

- ALMA Cycle 0 observations of N_2H^+(1-0)
- Coherent kinematic structure of filaments

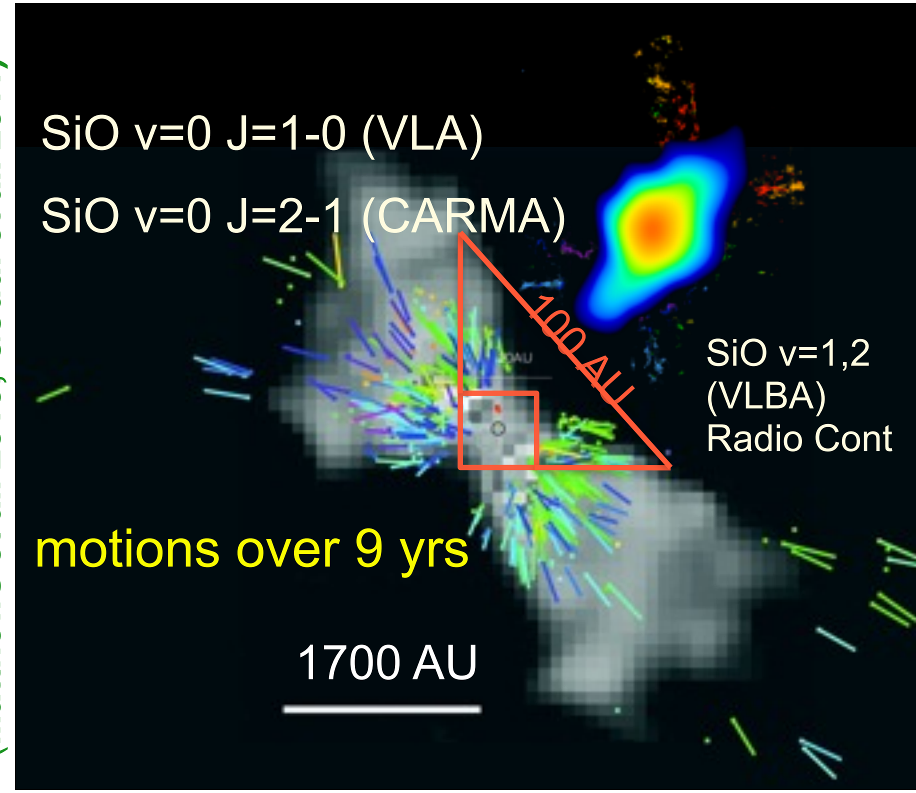
Disk-outflow systems in high-mass YSO





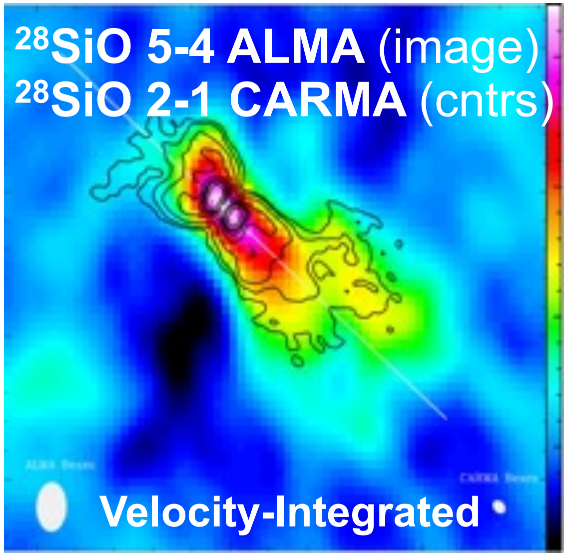
(Testi et al. 2010)

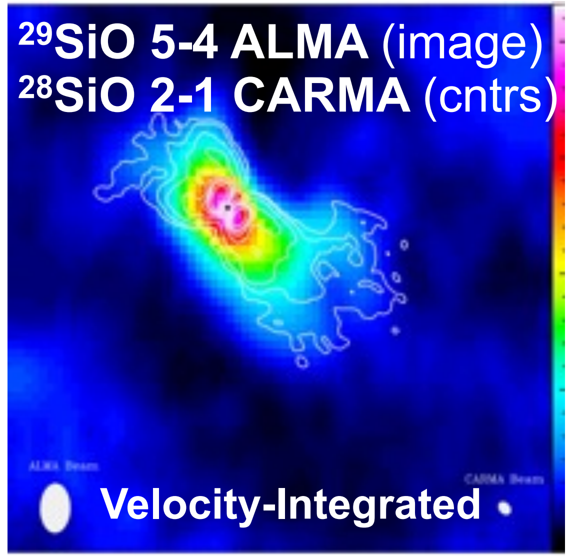
(Matthews et al. 2010; Goddi et al. 2011)

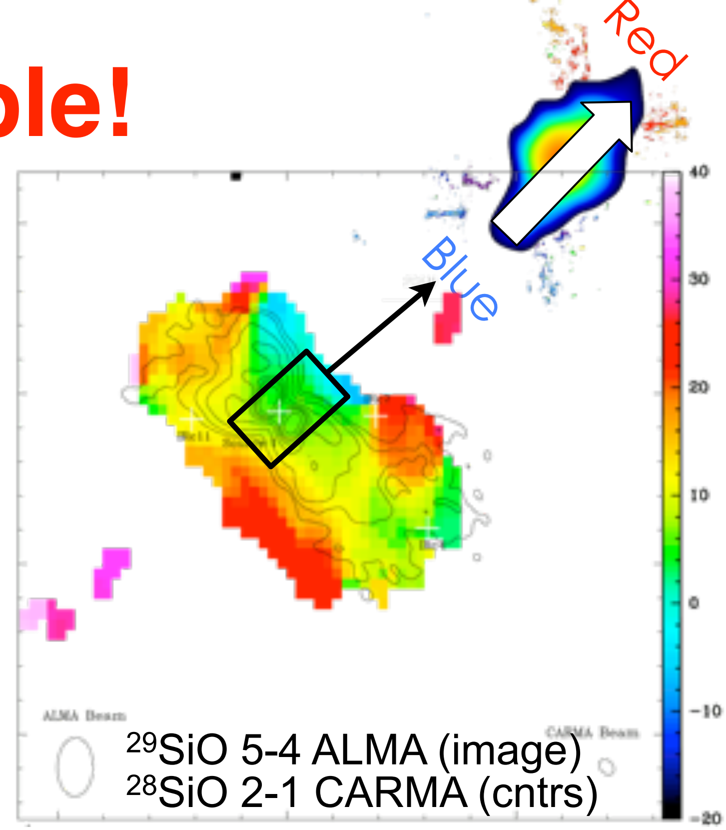


- Orion: the nearest high-mass YSOs
- Reflected IR VLT spectroscopy and mm/cm data consistent with disk-outflow system
- Scaled-up version of TTauri stars

...not so simple!





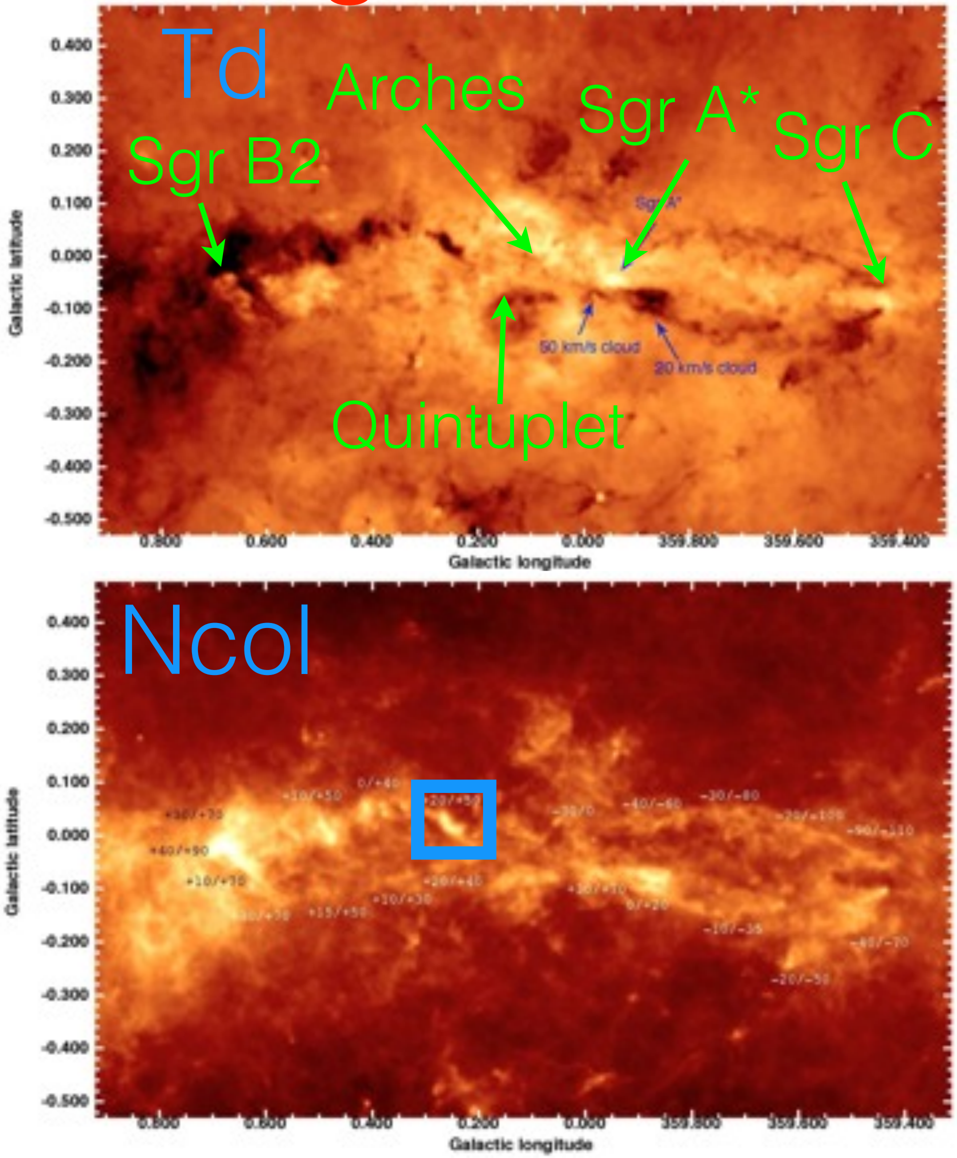


(Niederhofer et al. 2012)

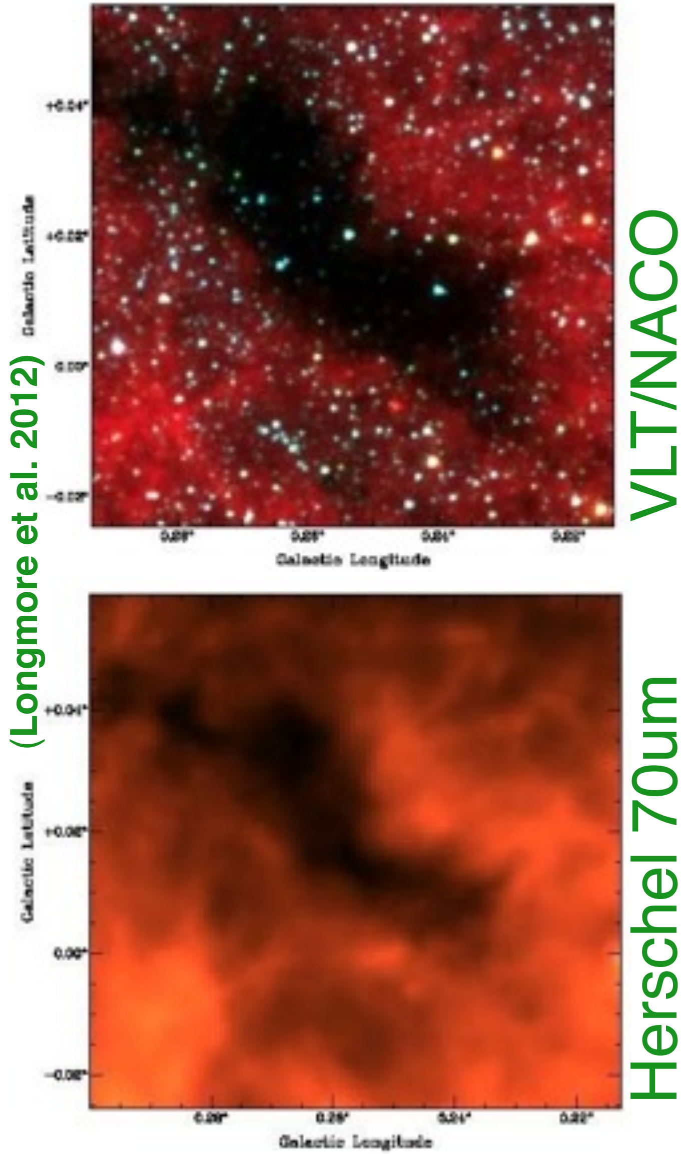
ALMA Science Verification Data

- Evidence for interaction with other massive YSOs
- Evidence for interaction with surrounding cloud cores
- Are environment and interactions more important than initial conditions?
- High resolution of ALMA essential to expand sample

Young Massive Clusters precursors



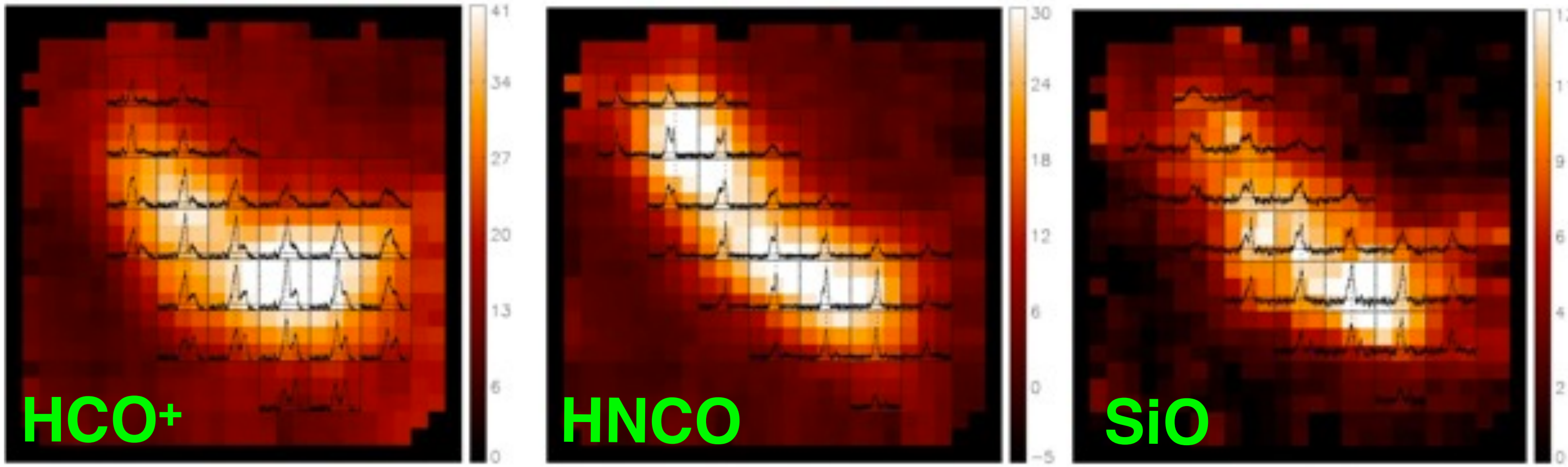
(Molinari et al. 2011)



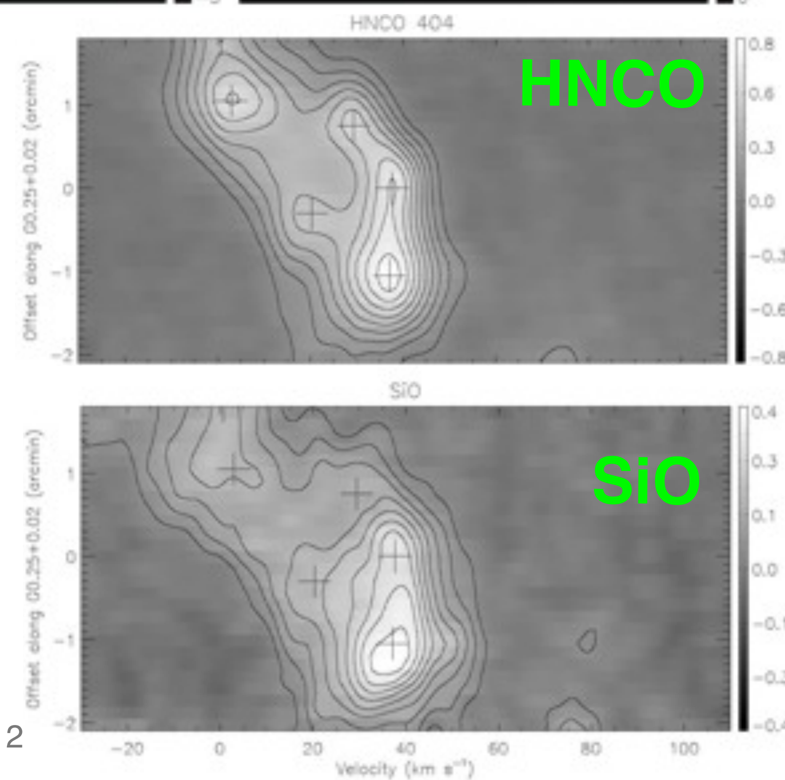
(Longmore et al. 2012)

Young Massive Clusters precursors

(Longmore et al. 2012; Rathborne et al al 2012)



- ✦ Very dense and compact molecular clump
- ✦ Widespread SiO, little evidence for ongoing star formation
- ✦ Internal structure/filaments?
- ✦ Rosetta Stone for origin of Young Massive Clusters



Lessons and questions from HM-YSOs

- Continuum distribution of stellar densities
  - No strong evidence (so far) of causal relationship between clusters and high-mass stars (!highly debated!)
  - HM-stars may form as low mass stars
- Formation of cores from filaments is observed
- Open questions for ALMA
  - Structure of HM cores and relation with filaments?
  - Disk/outflow properties around young HMYSOs?
  - Formation of YMCs and Super Star Clusters?

Summary

- We think we have a "simple" framework for understanding star formation

- The complexity of star formation seems to be captured in the process of converting gas into dense cores

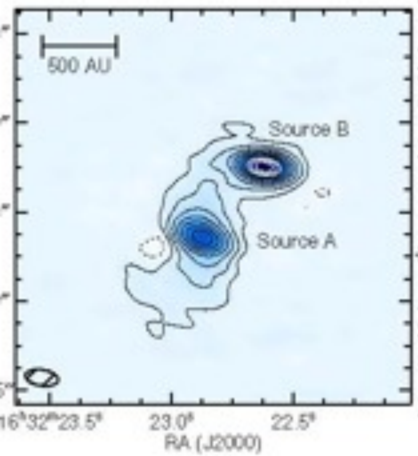
- Most of the "extremes" seem to fit in this overall framework
  - The path of more exotic formation mechanisms is open for a small minority of systems
  - These "minority systems" may be dominant SF modes in some peculiar environments

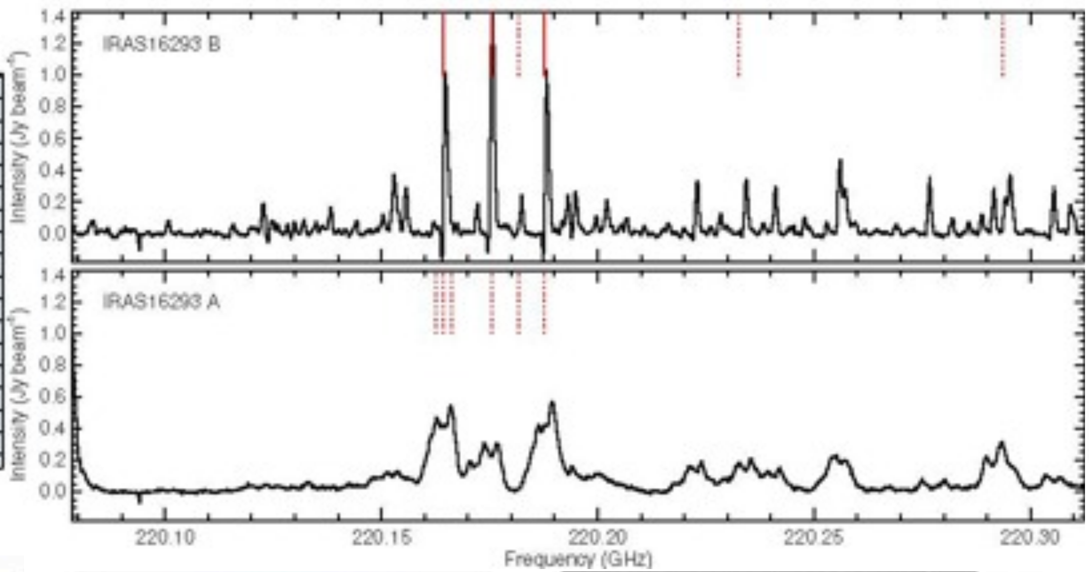
I have consciously avoided:

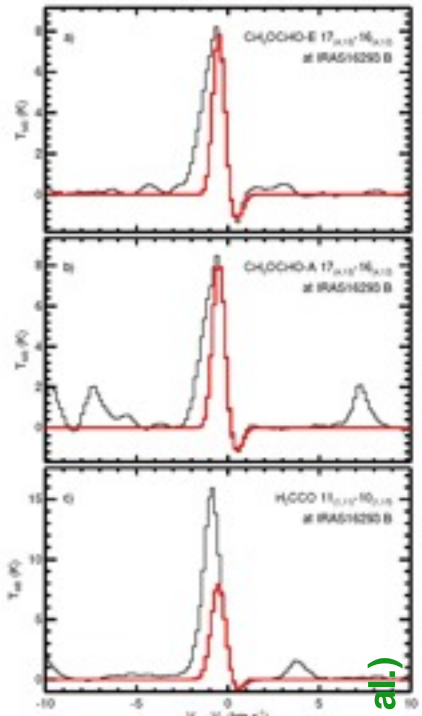
- The complex physics of the formation and evolution of a single object and multiple systems (and what this imply for the fate of disks and planetary systems)
- The effects that an object or a population has on other forming stars (and the fate of their disks)
- The processes within disks and of the disk-star interactions that set the stage for the formation of planetary systems
- How the formation of our own Solar System may fit into the overall picture

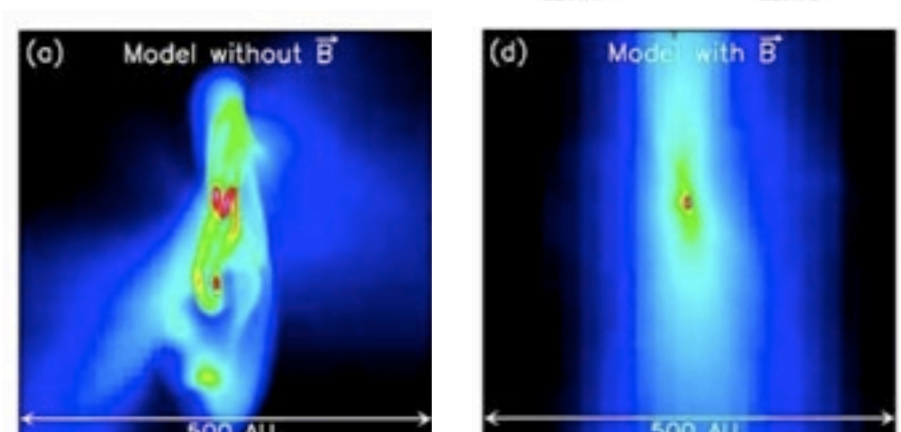
ALMA SV Science Results

- The multiple protostar IRAS16293
  - Jorgensen et al. 2012; Pineda et al. 2012; Dumas et al. 2012









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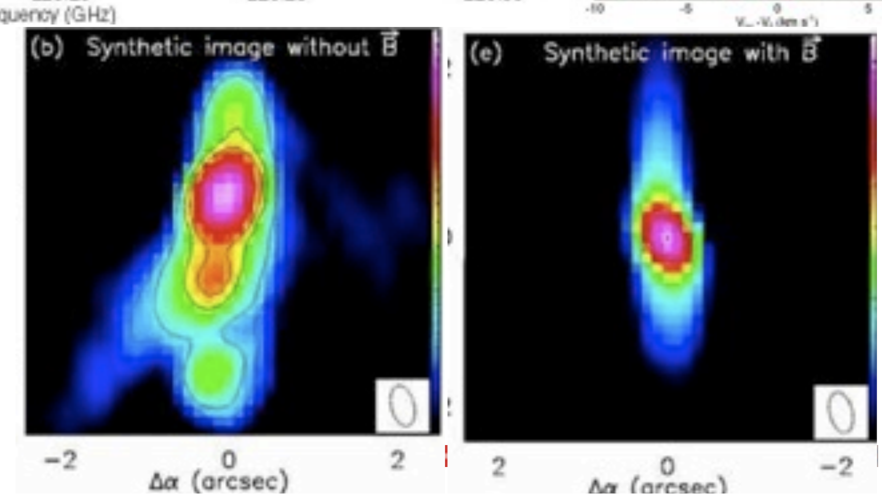
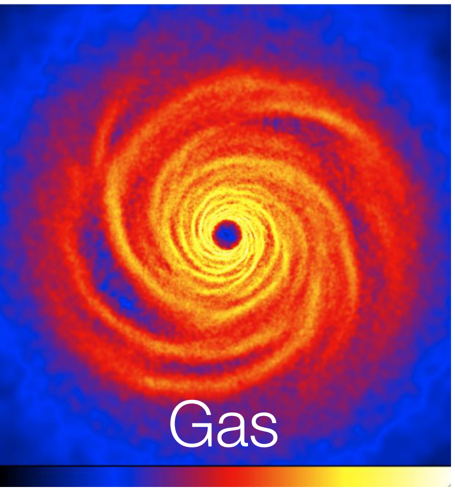
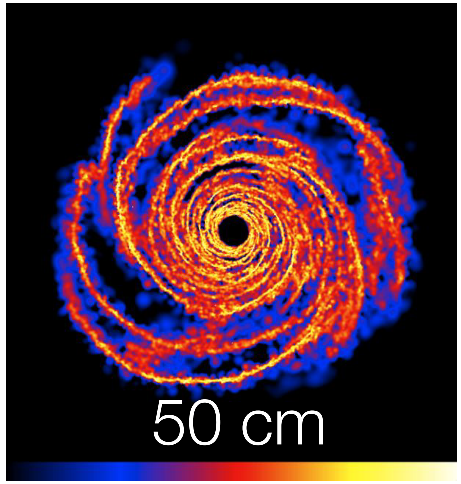
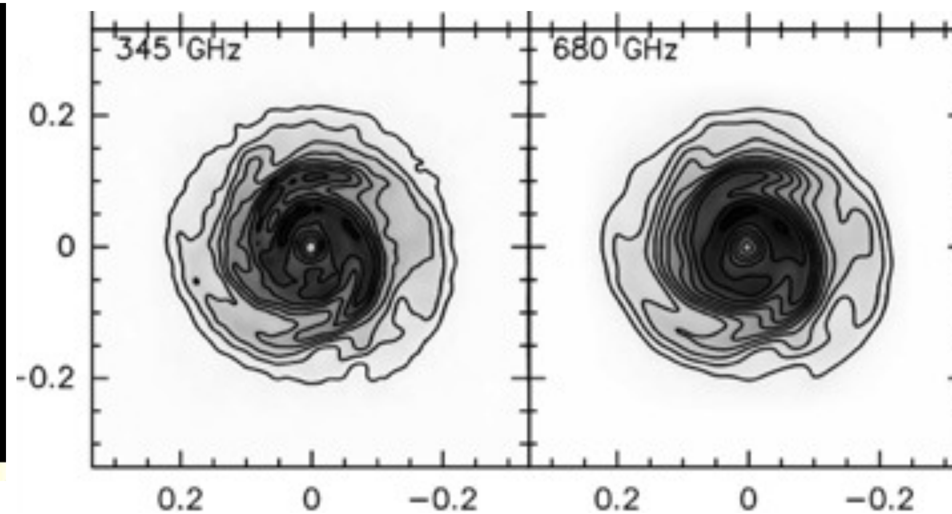


(Maury et al./Hennebelle et al.)

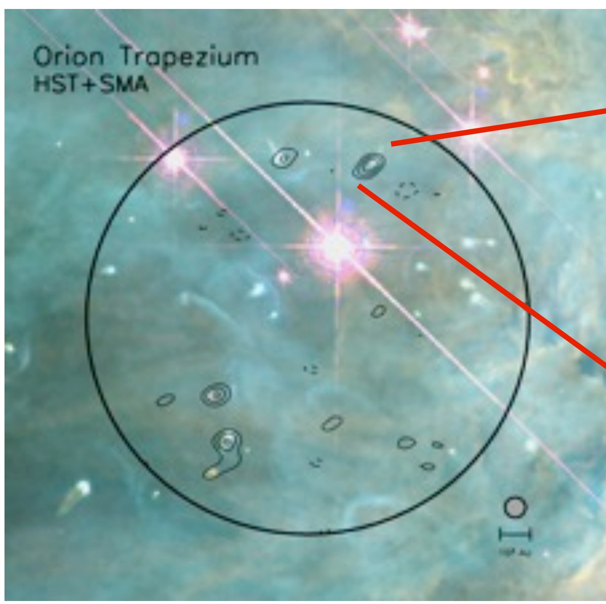
Slowing down radial drift: grain trapping

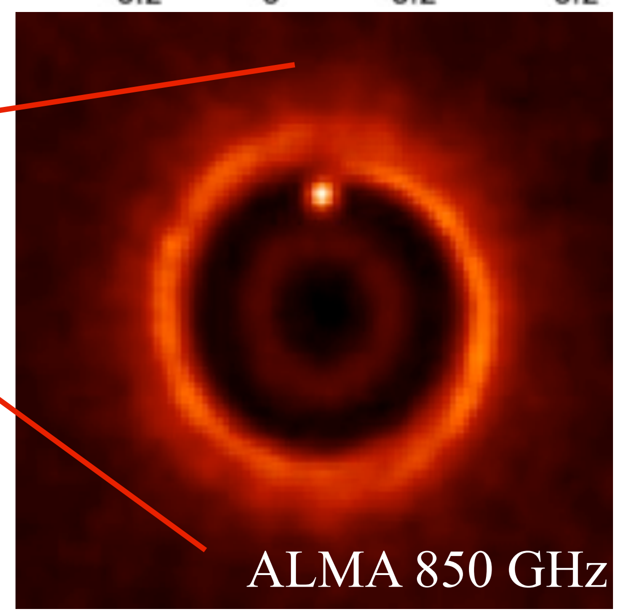






(Cossins, Lodato, Testi 2010)

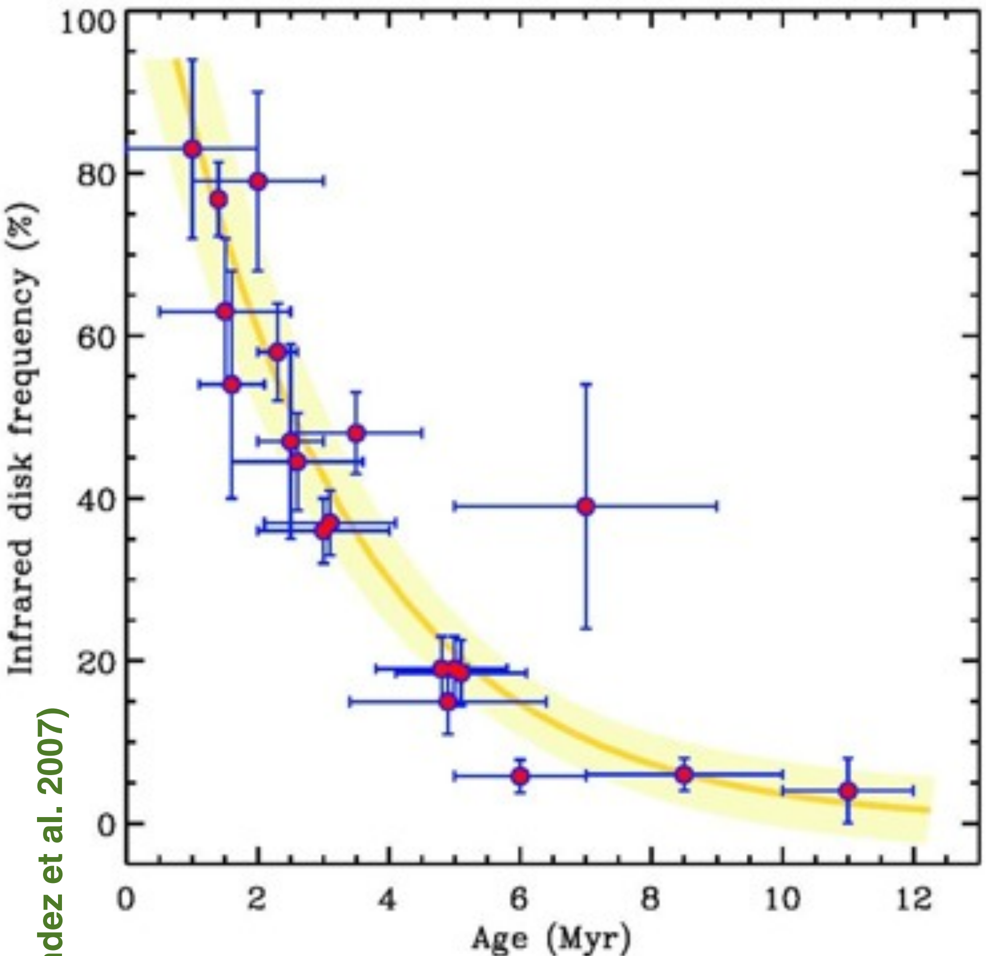




(Wolf & D'Angelo)

- <u>Disk structures, grain trapping, planet formation</u>

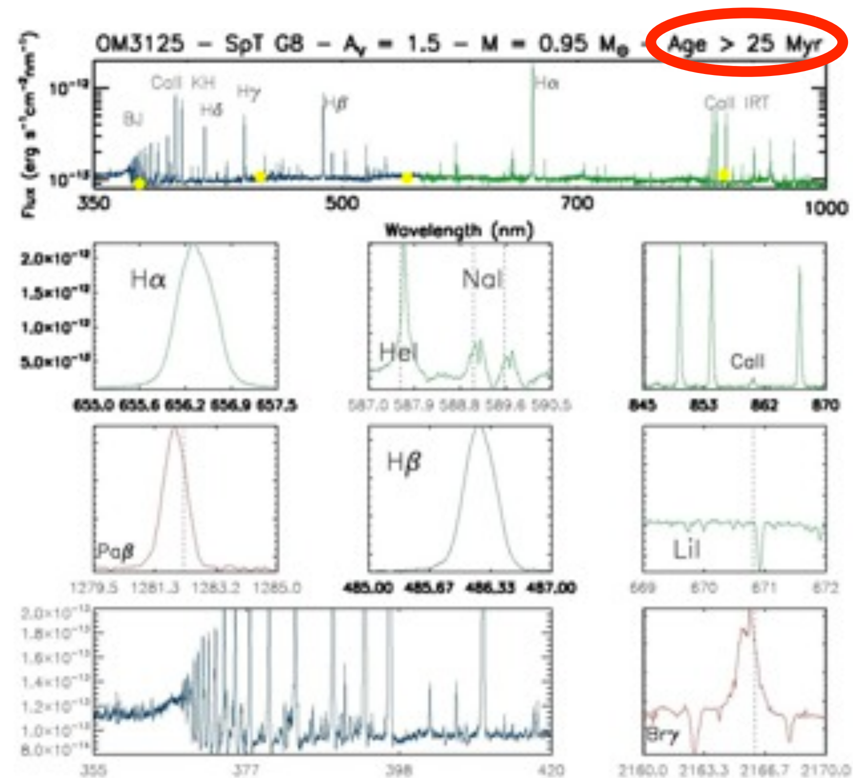
A problem of timescales



(Hernandez et al. 2007)

Inner disk clearing:
e-folding time t~2-3 Myr

- Evolution too fast to reconcile with SS meteoritic evidence
- Need to study the (small) population of long-lived disks



(Manara et al. 2012)