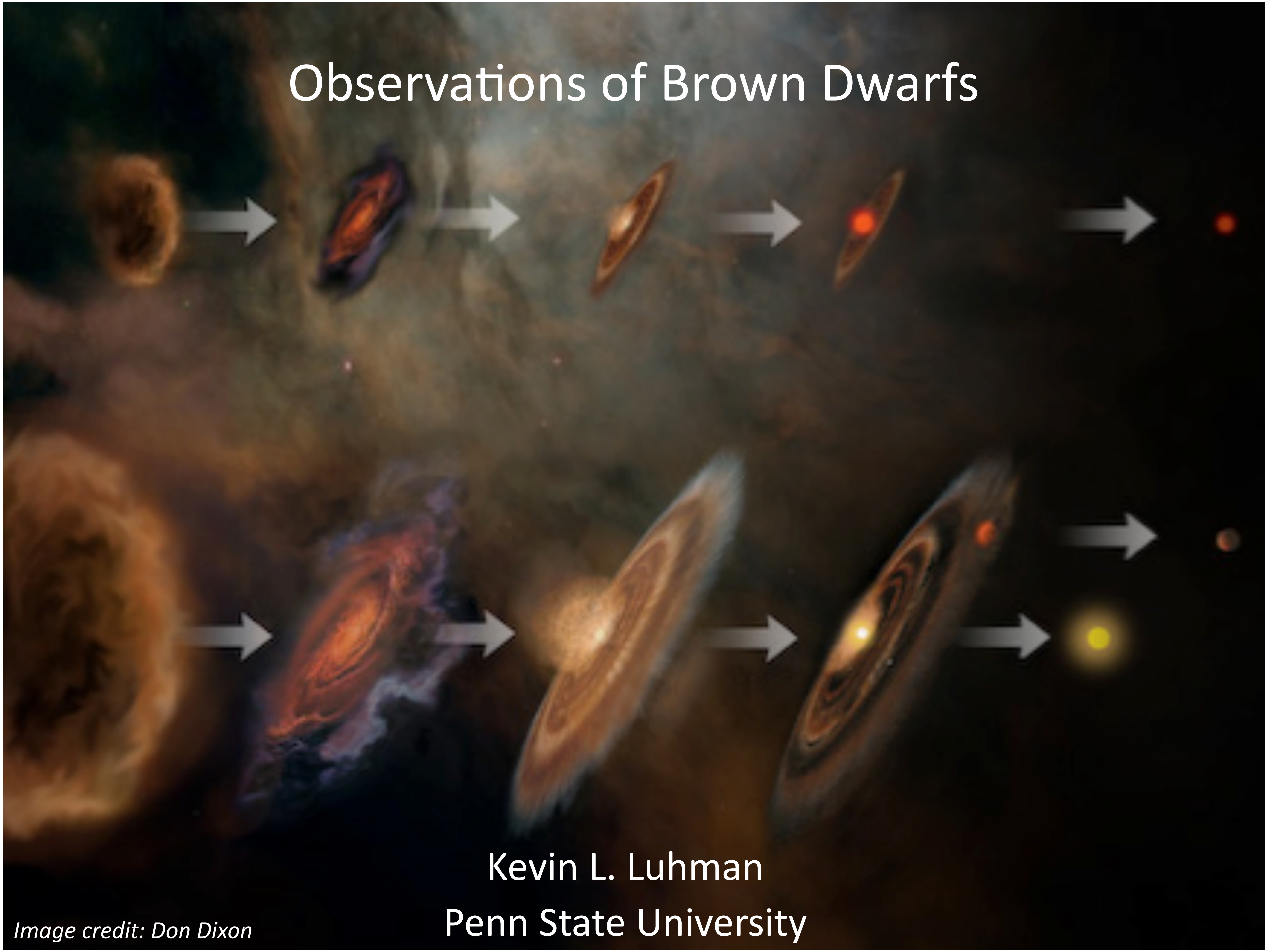
# Observations of Brown Dwarfs

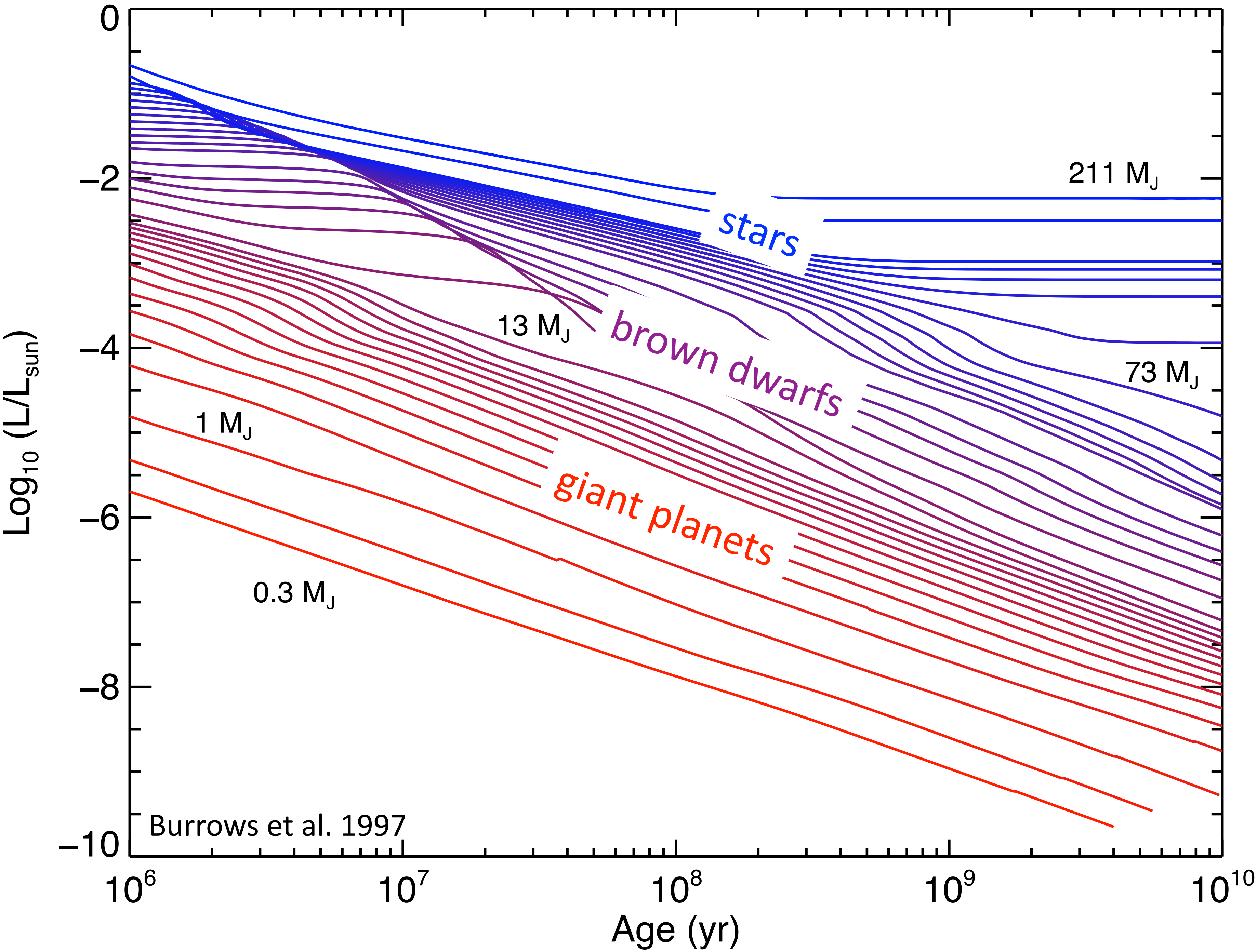


Kevin L. Luhman
Penn State University

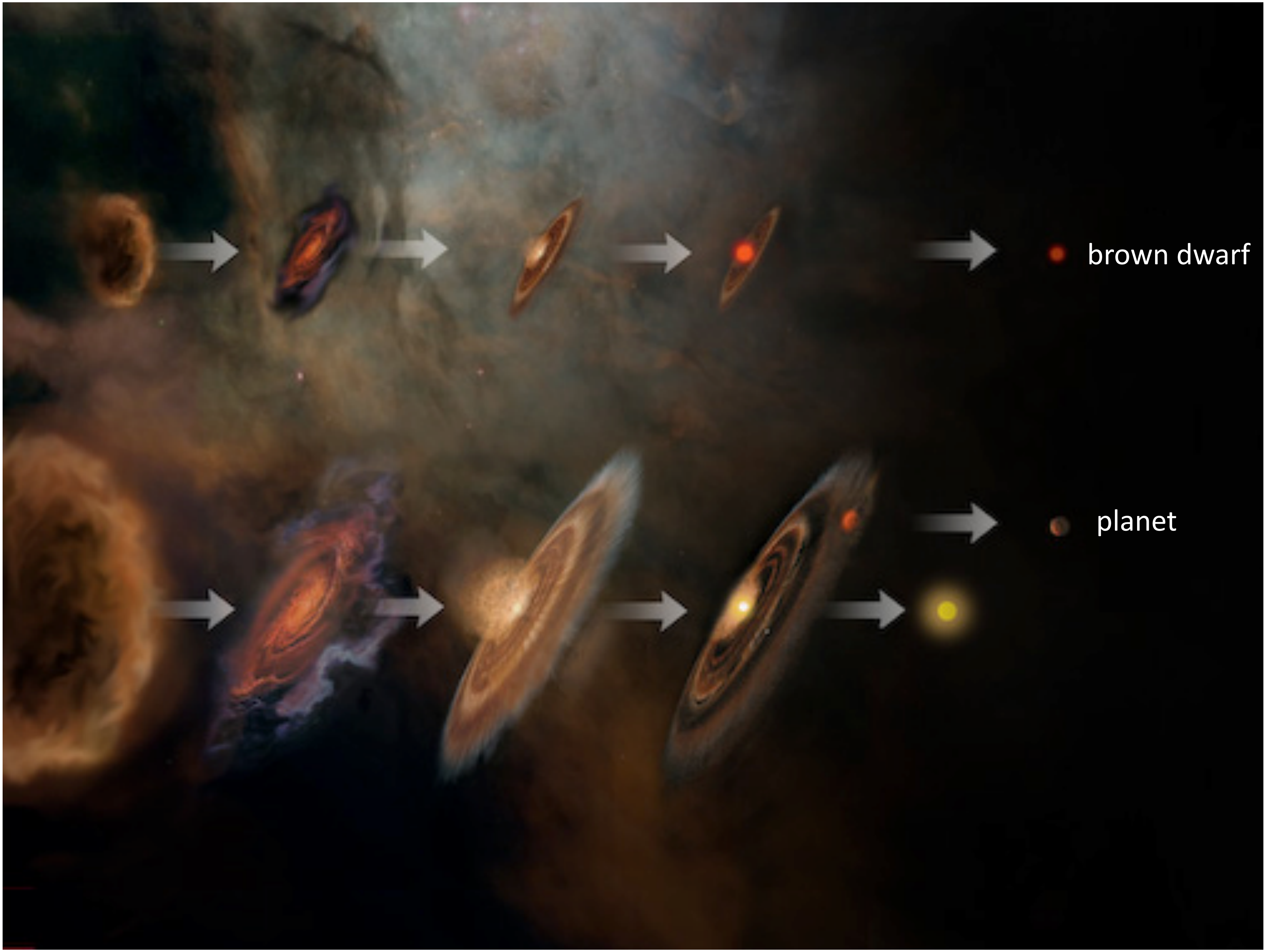
*Image credit: Don Dixon*

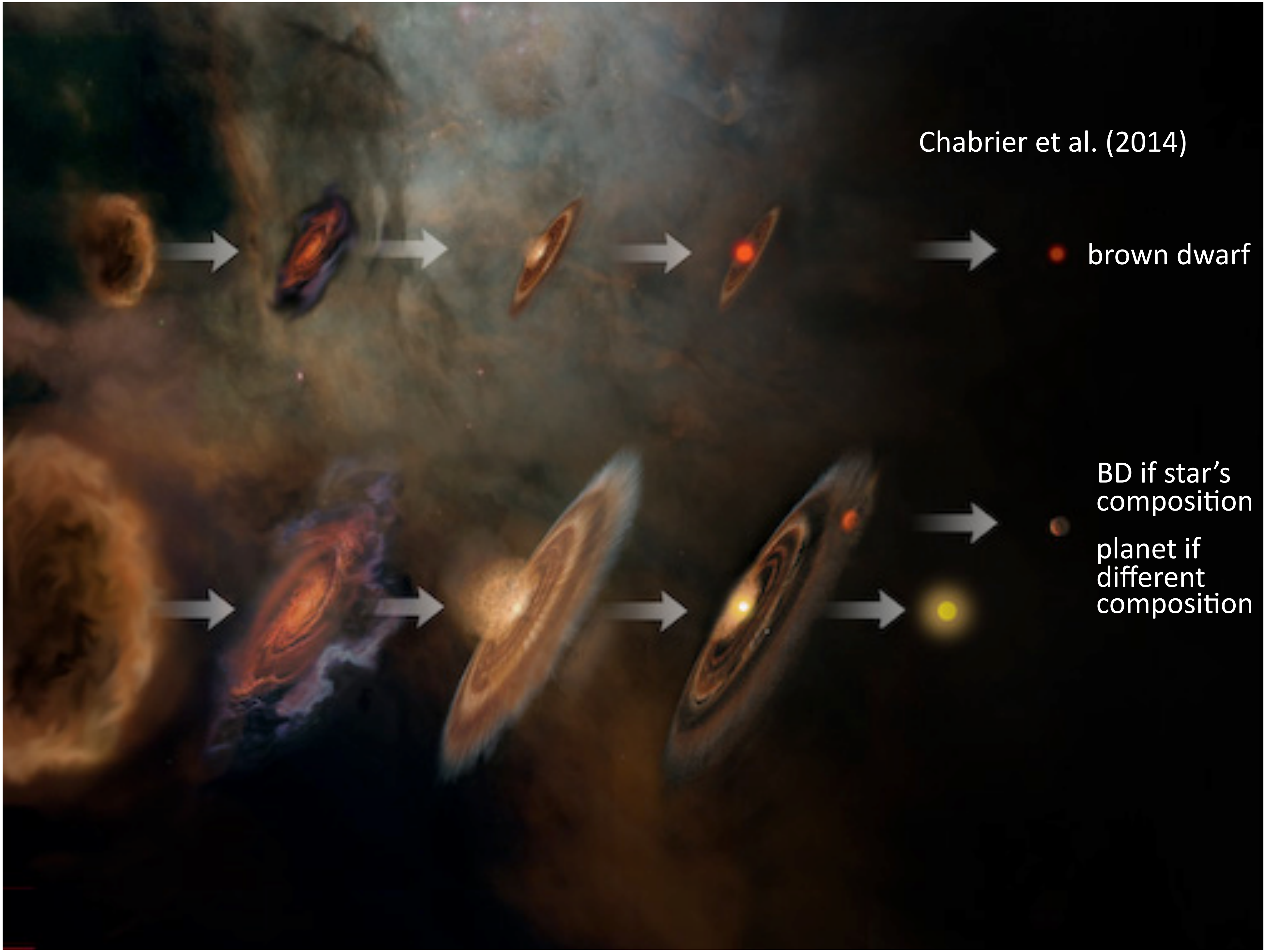
# Outline

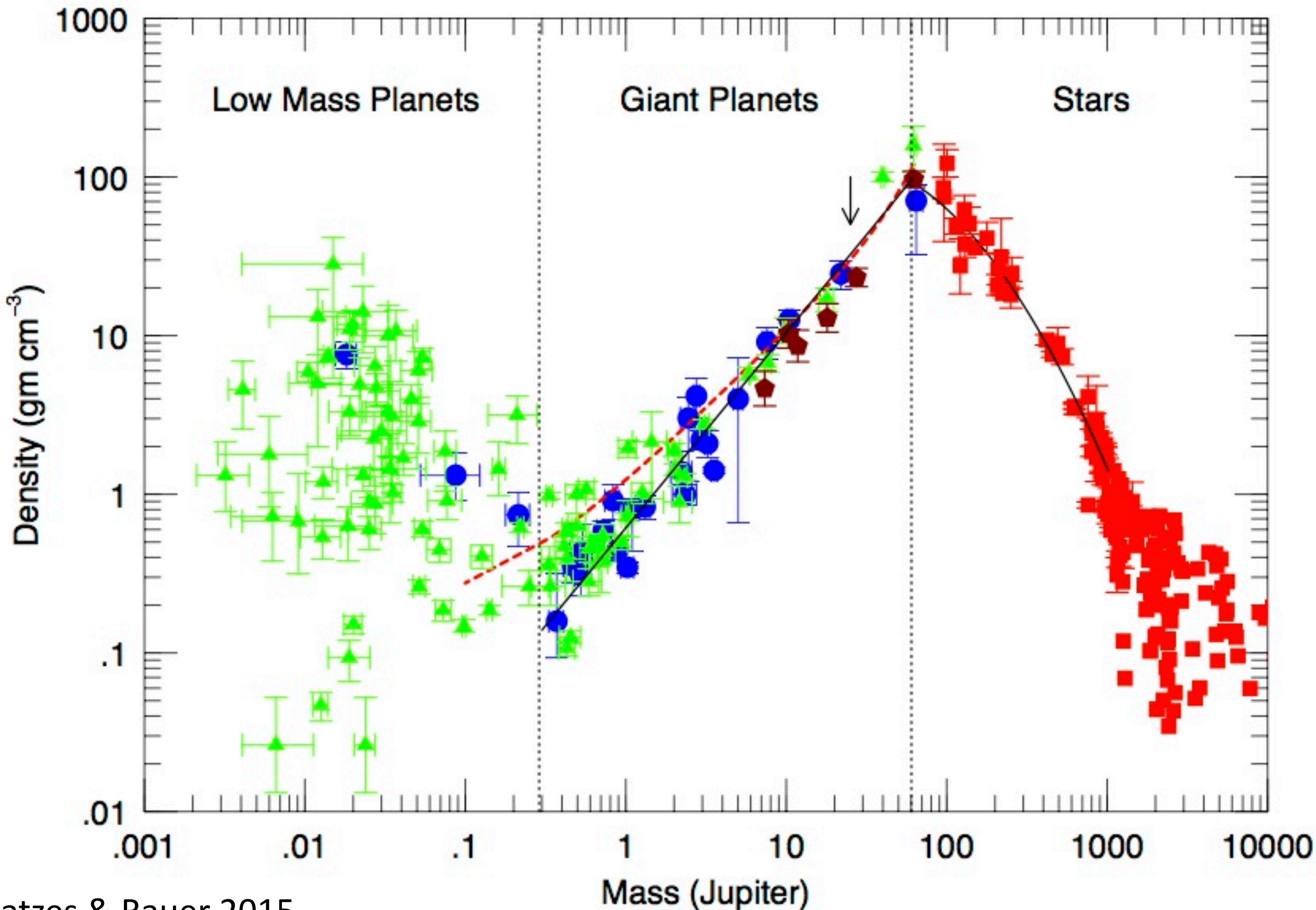
- Definitions
- Models of brown dwarf formation
- Mass functions
- Circumstellar Disks
- Binary properties



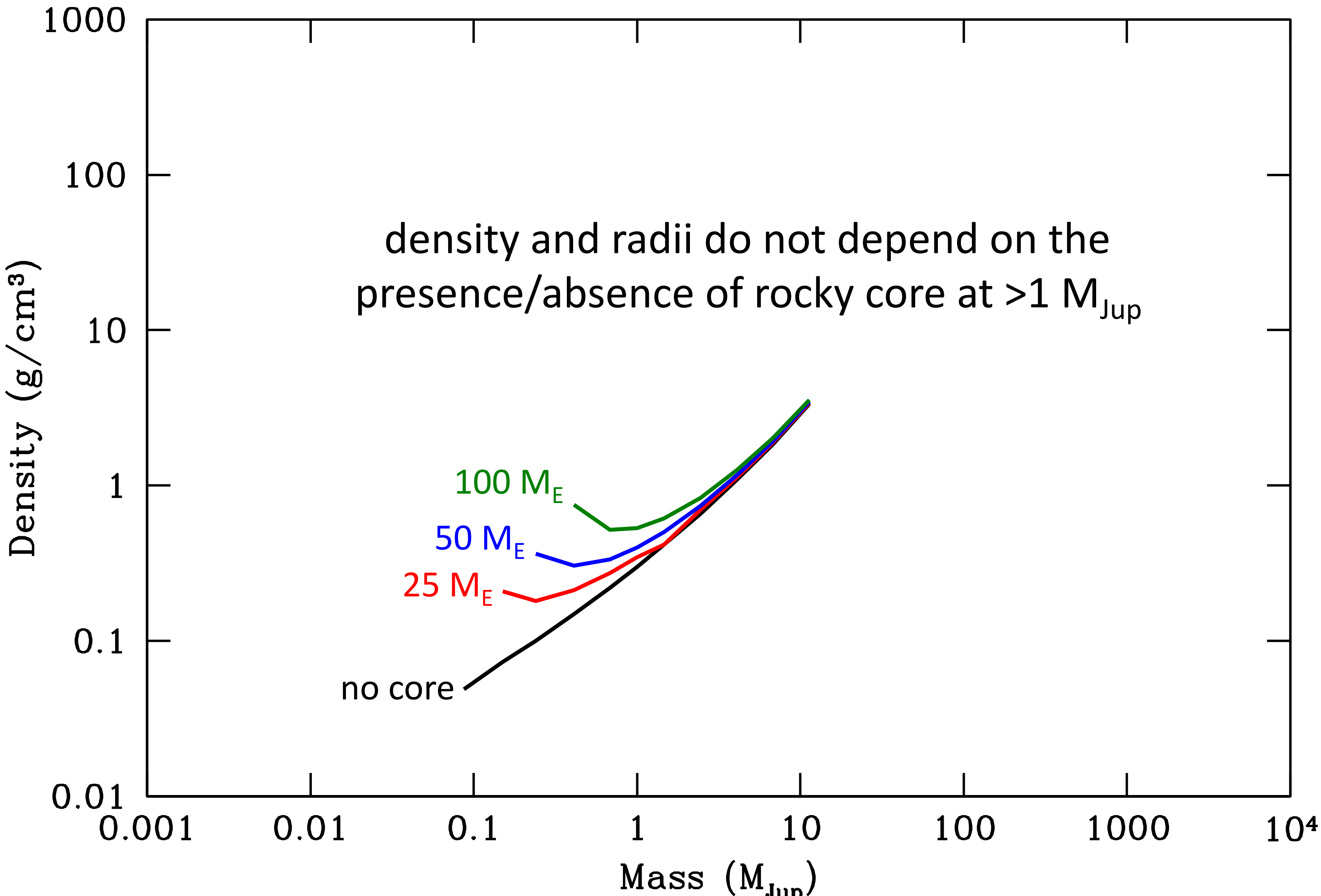
0
−2
−4
−6
−8
−10
$10^6$
$10^7$
$10^8$
$10^9$
$10^{10}$
Age (yr)
$\mathrm{Log_{10}}\ (L/L_{sun})$
211 $M_J$
stars
13 $M_J$
brown dwarfs
73 $M_J$
1 $M_J$
giant planets
0.3 $M_J$
Burrows et al. 1997


brown dwarf
planet


Chabrier et al. (2014)
brown dwarf
BD if star's composition
planet if different composition



Hatzes & Rauer 2015




Fortney et al. 2007

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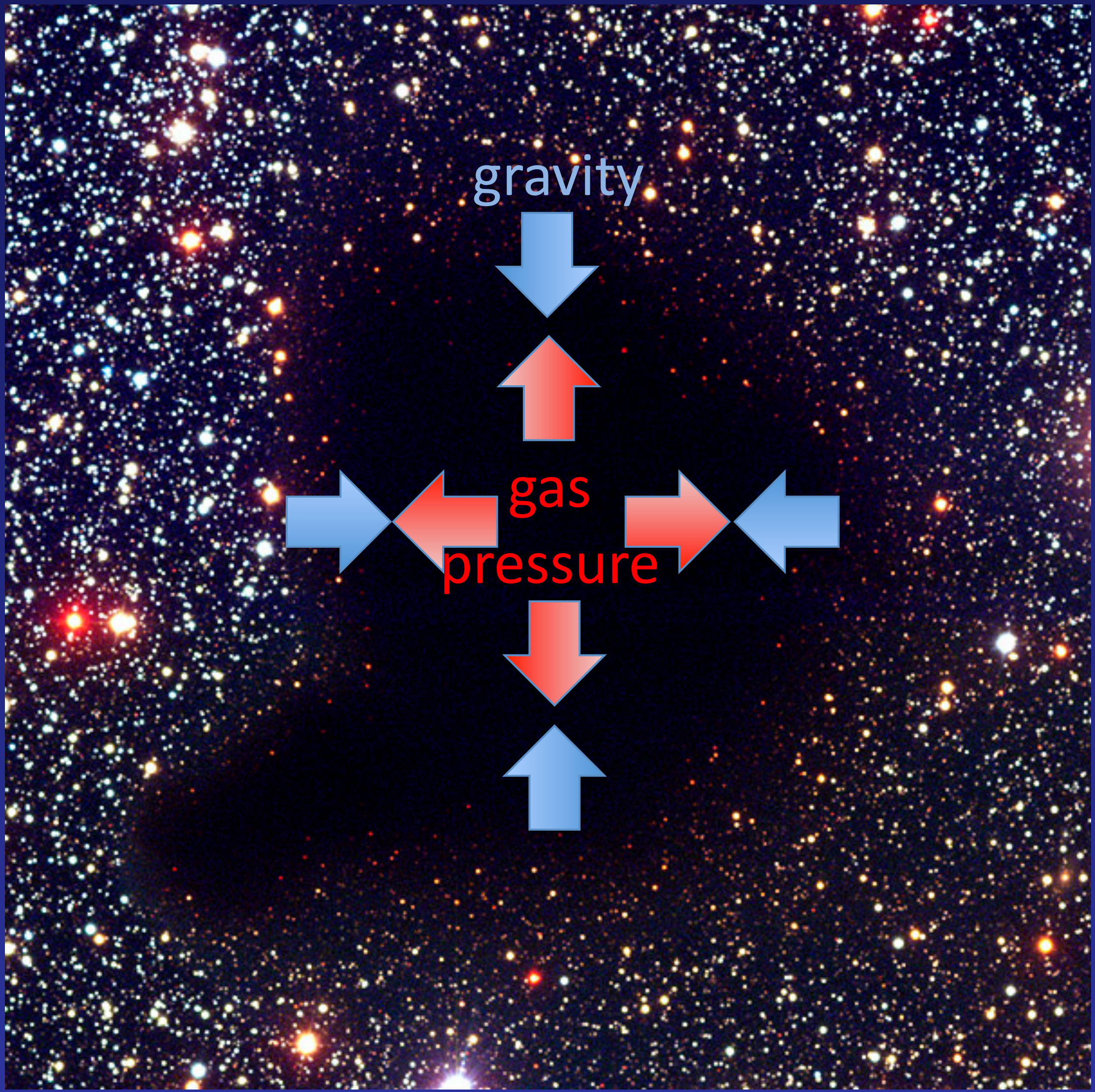
# What makes it possible for brown dwarfs to form?

Barnard 68 Alves et al. 2001

# What makes it possible for brown dwarfs to form?

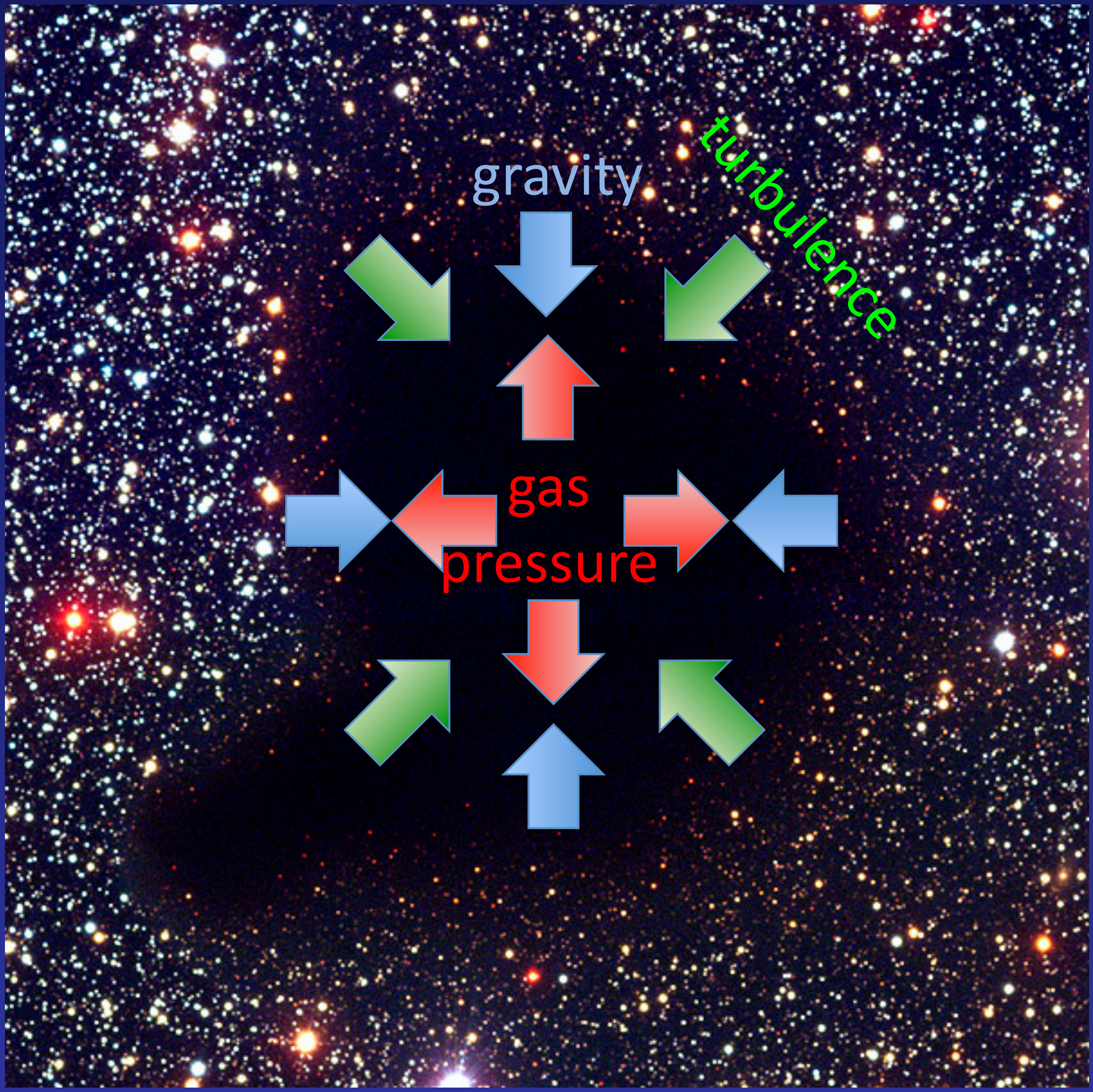



Barnard 68

Alves et al. 2001

# Turbulent fragmentation?

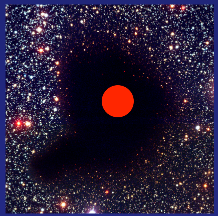
e.g., Padoan & Nordlund 2004




Barnard 68

Alves et al. 2001

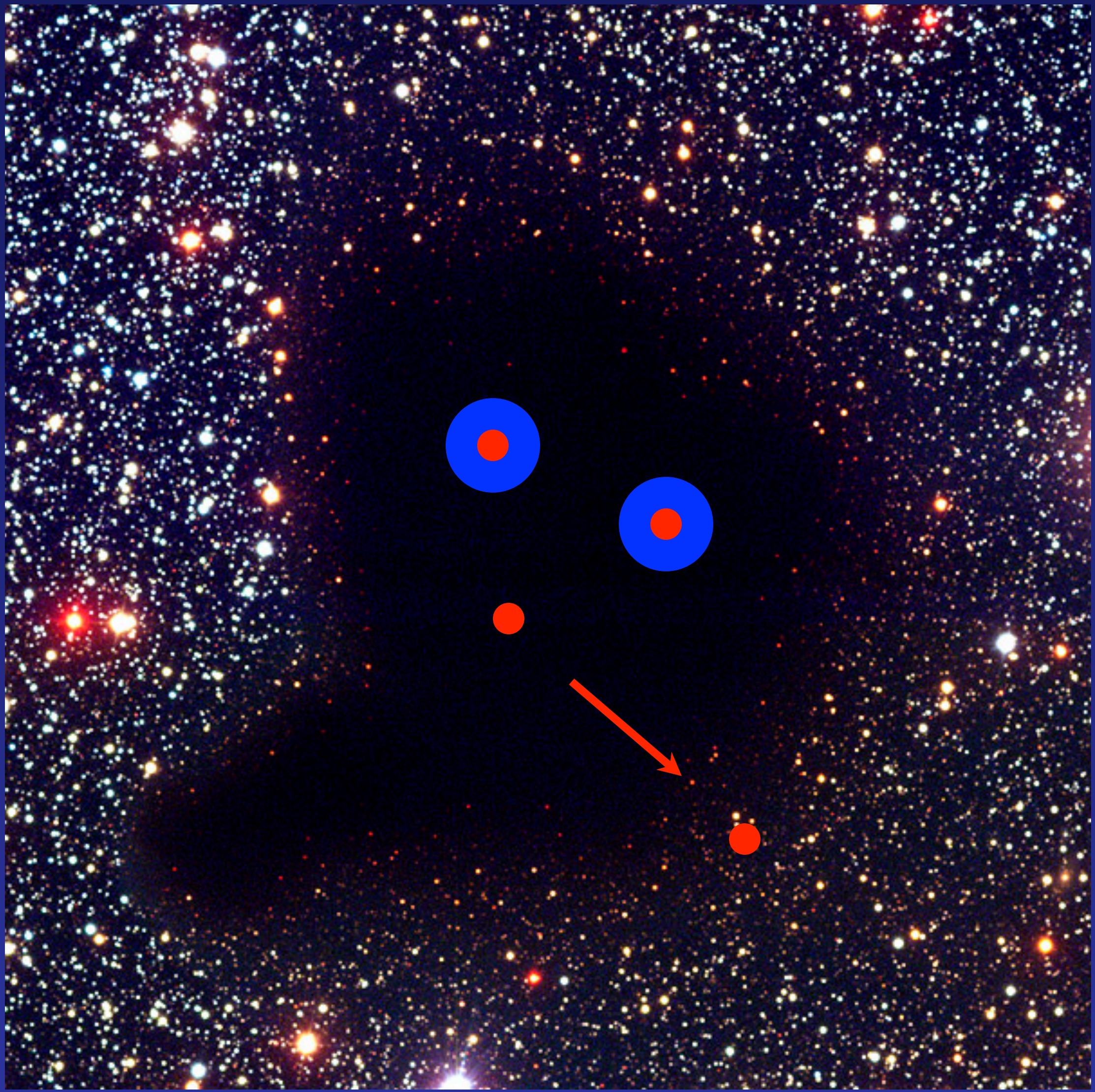
# Turbulent fragmentation?
e.g., Padoan & Nordlund 2004



Barnard 68 Alves et al. 2001

# Dynamical interactions?

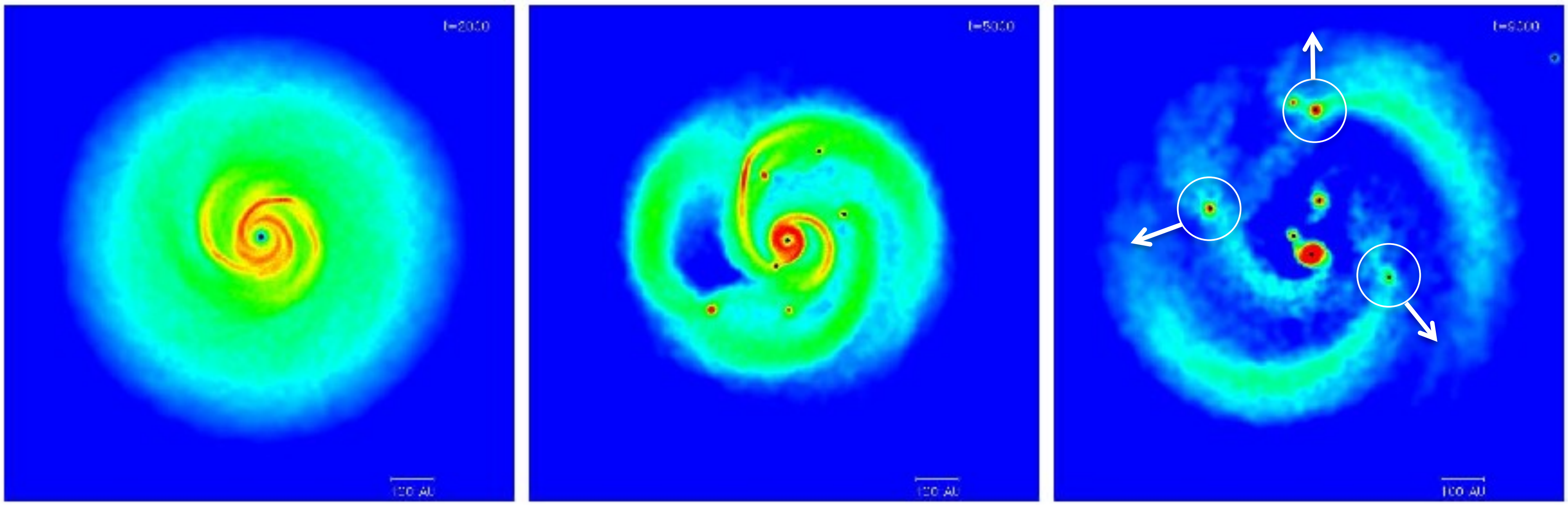
e.g., Reipurth & Clarke 2001, Bate et al. 2002



Barnard 68 Alves et al. 2001

# Dynamical interactions?

e.g., Boss 2001, Stamatellos et al. 2007



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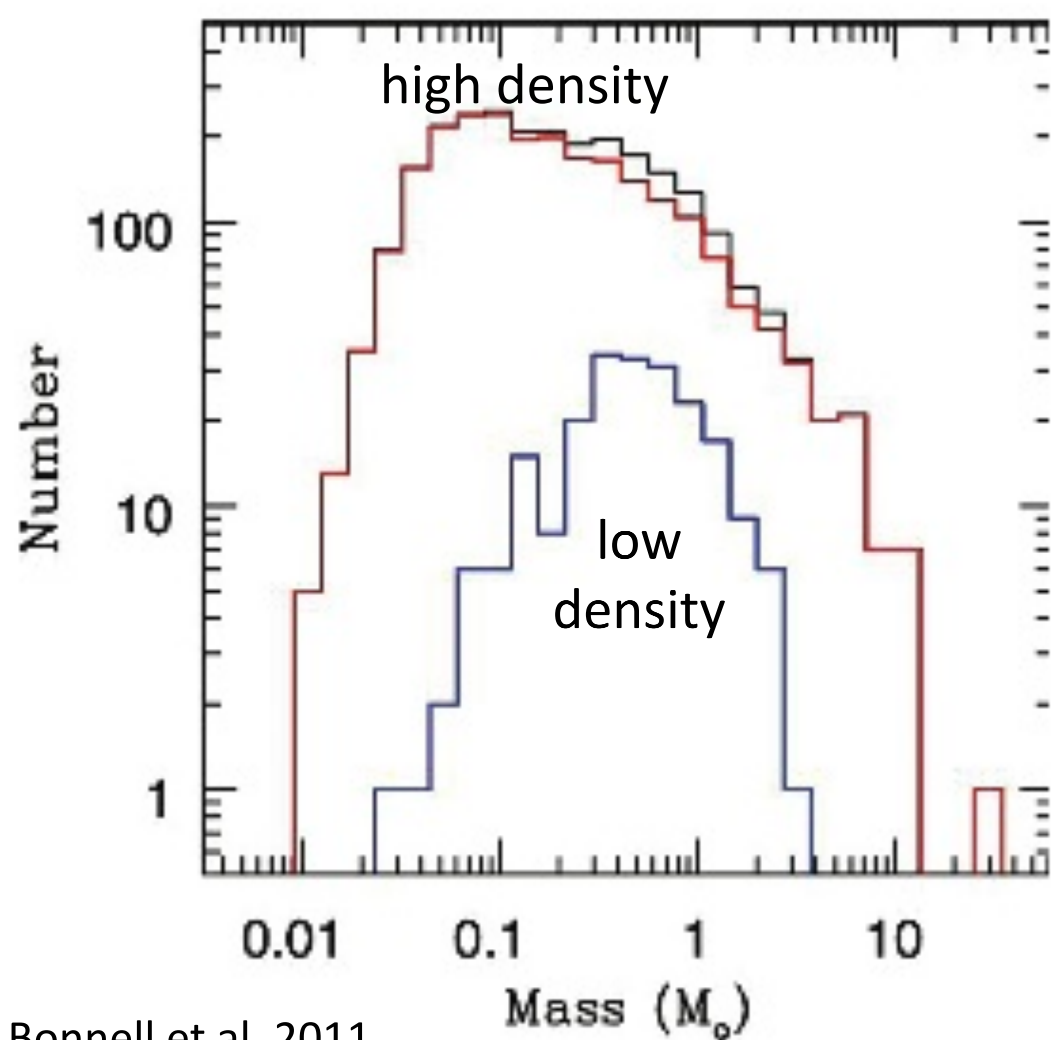
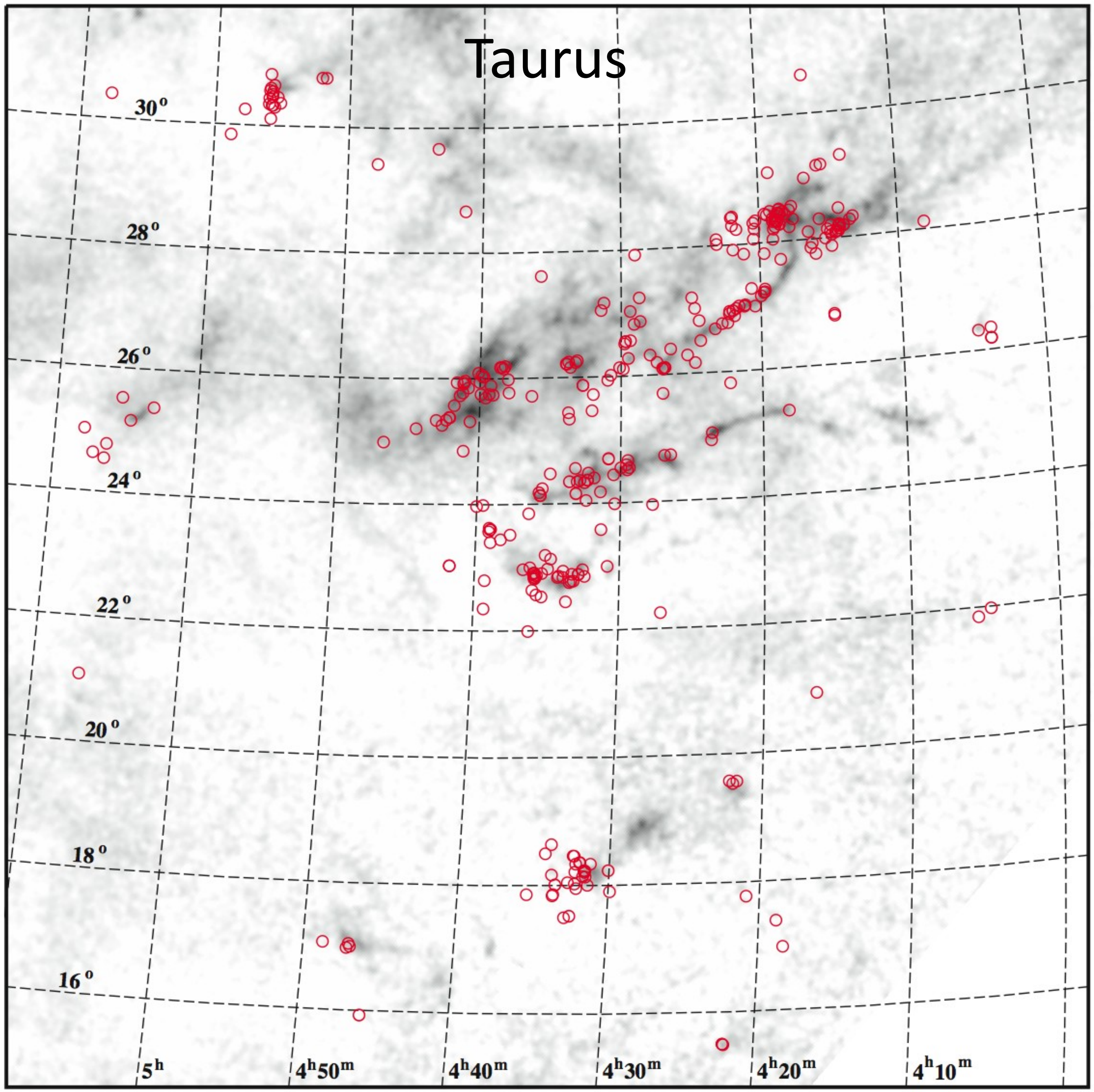
If dynamical interactions determine masses, then IMF should be broader at higher stellar densities (more BDs)

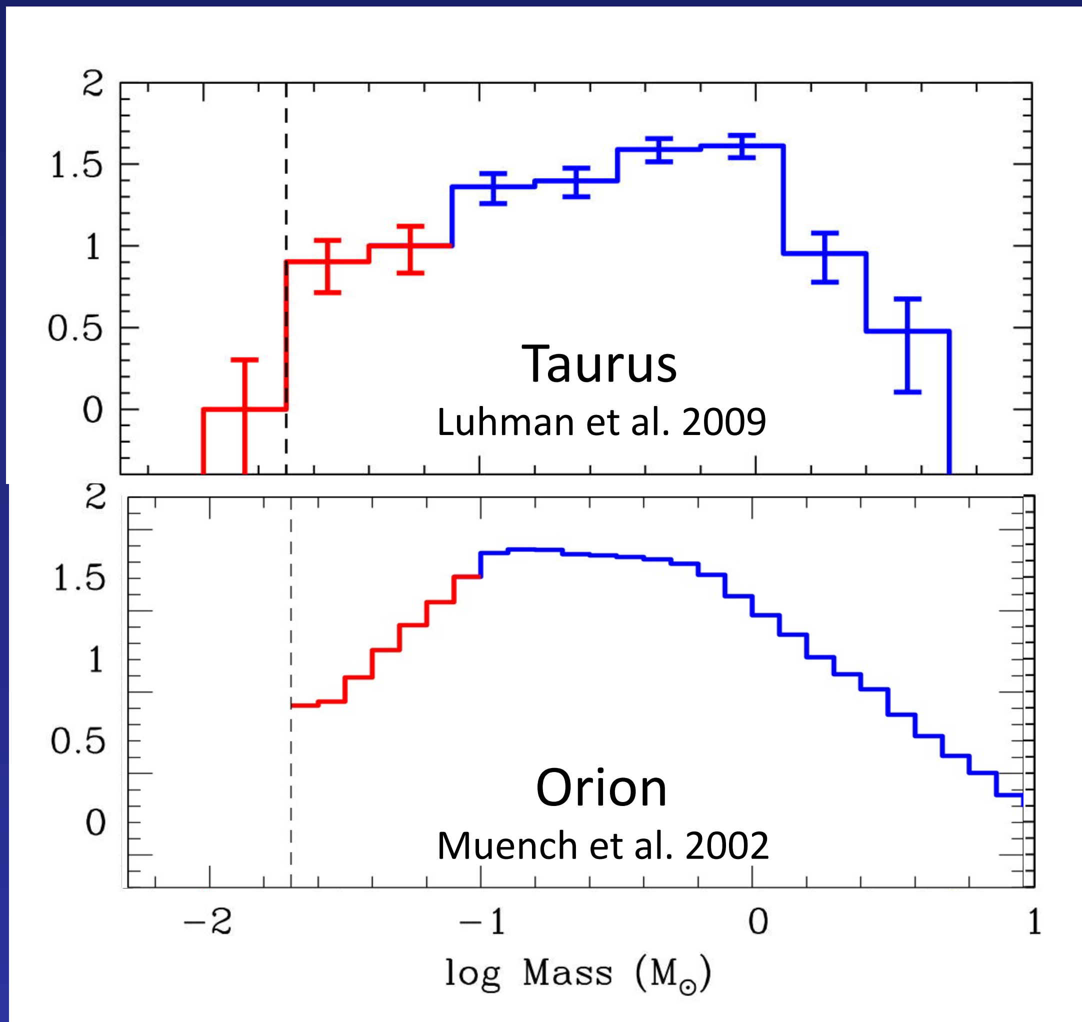



Bonnell et al. 2011

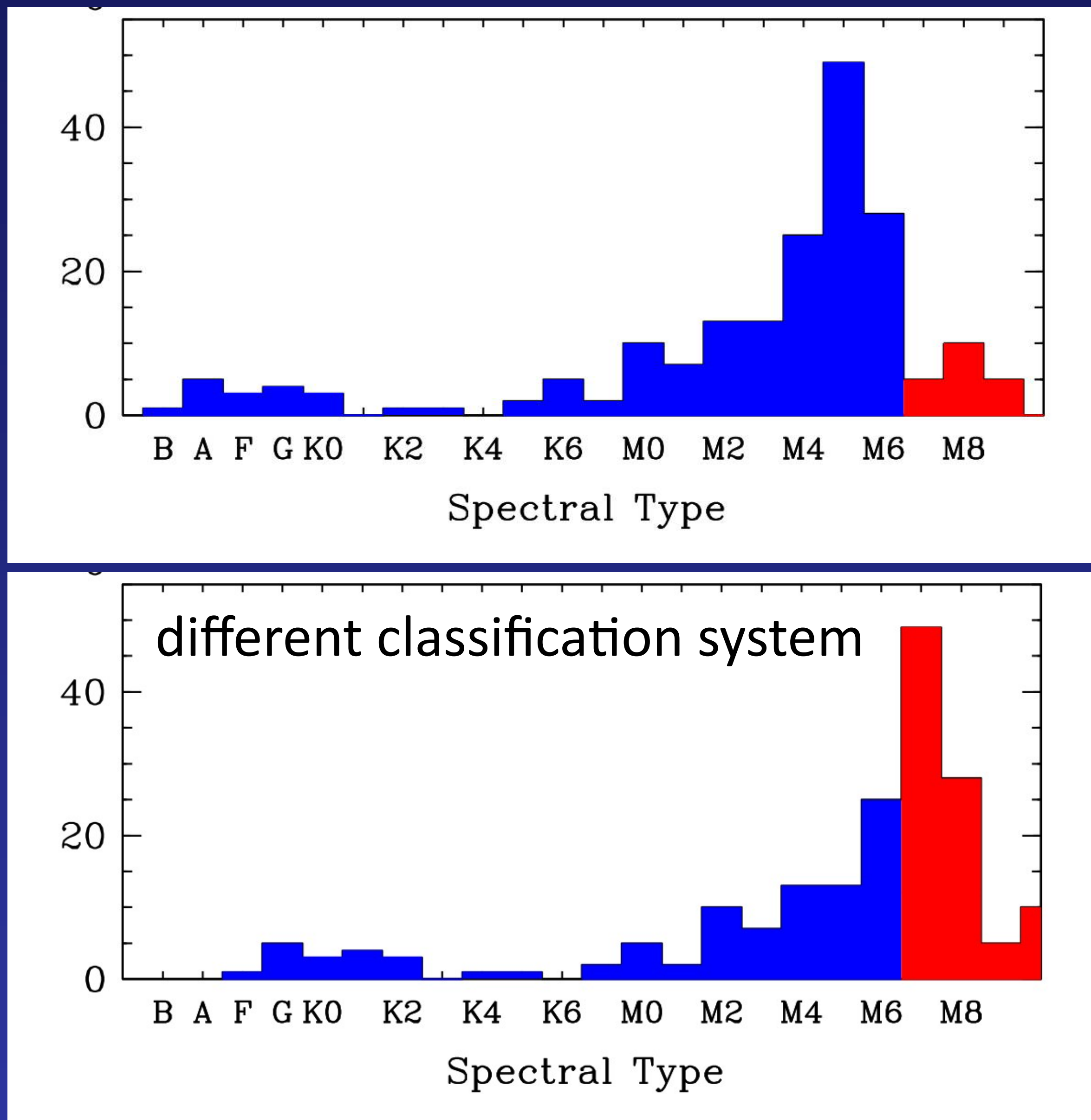



Orion

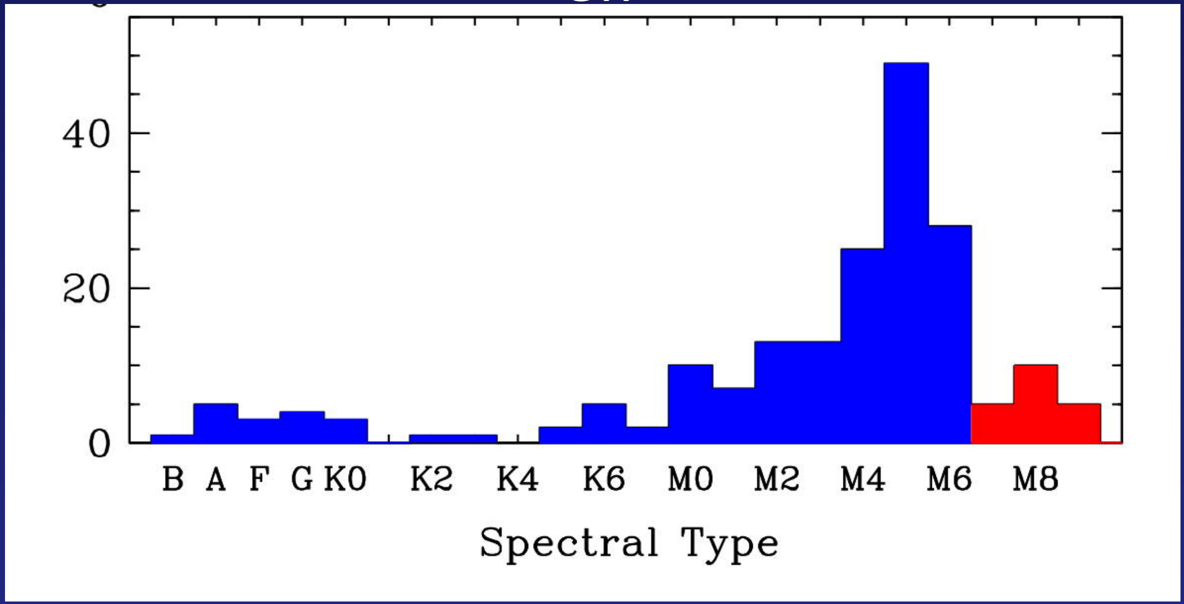
# Width of IMF & abundance of BDs similar across a factor of 1000 in stellar density

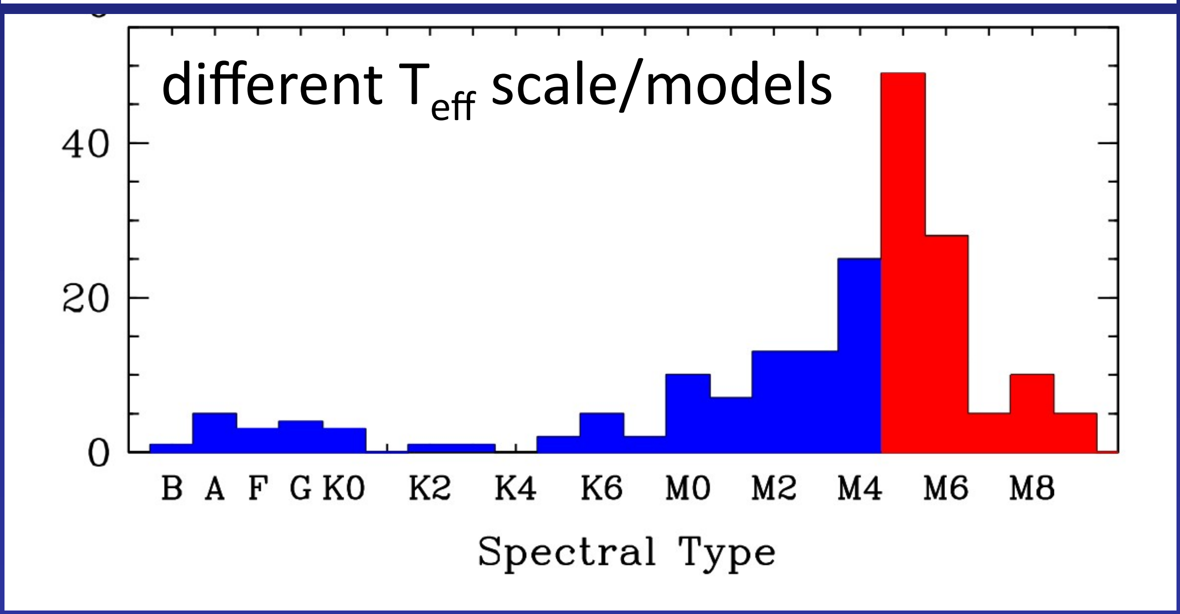


# IMF sensitive to spectral classifications

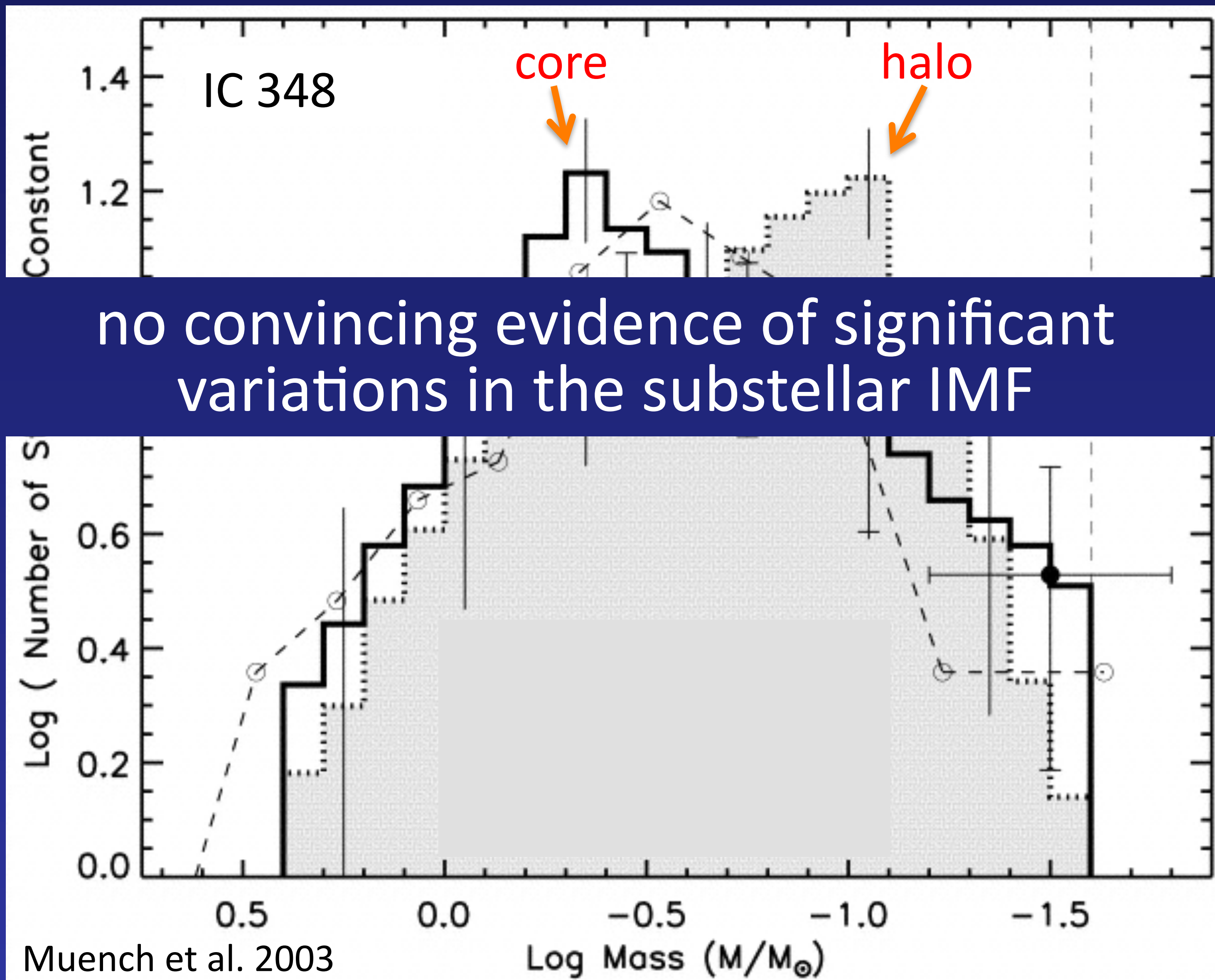


# IMF sensitive to $T_{eff}$ scale & models

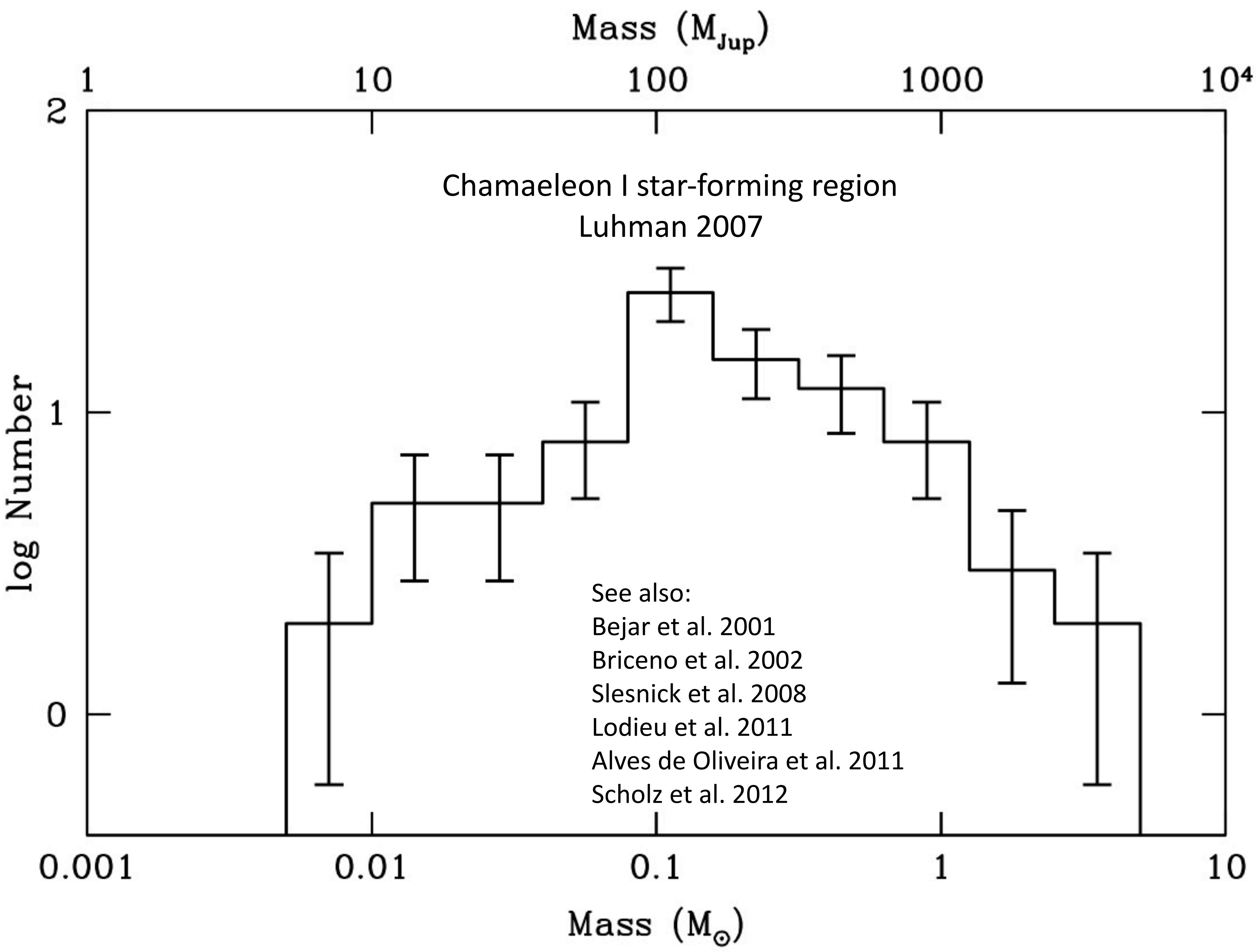


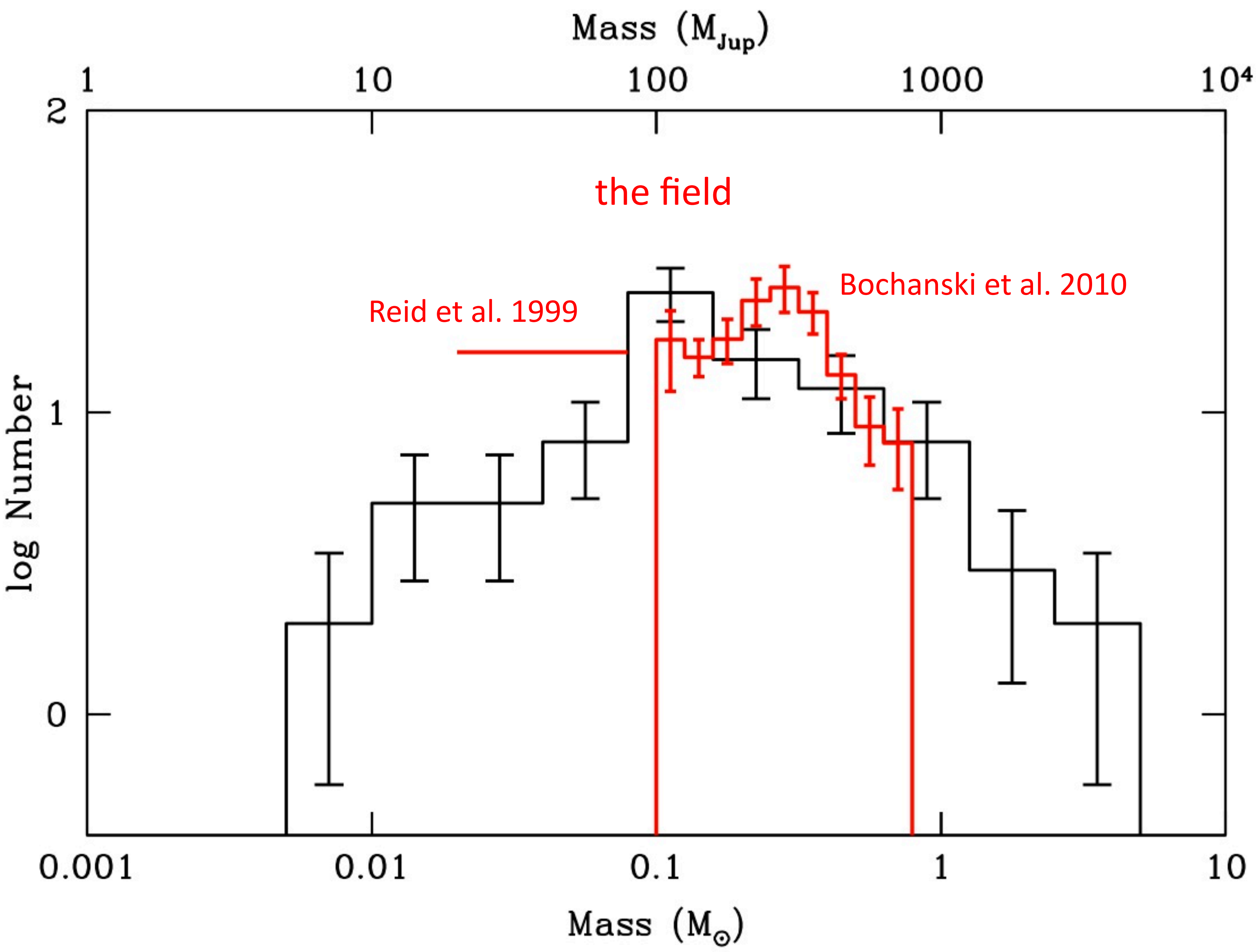



# IMF sensitive to field size

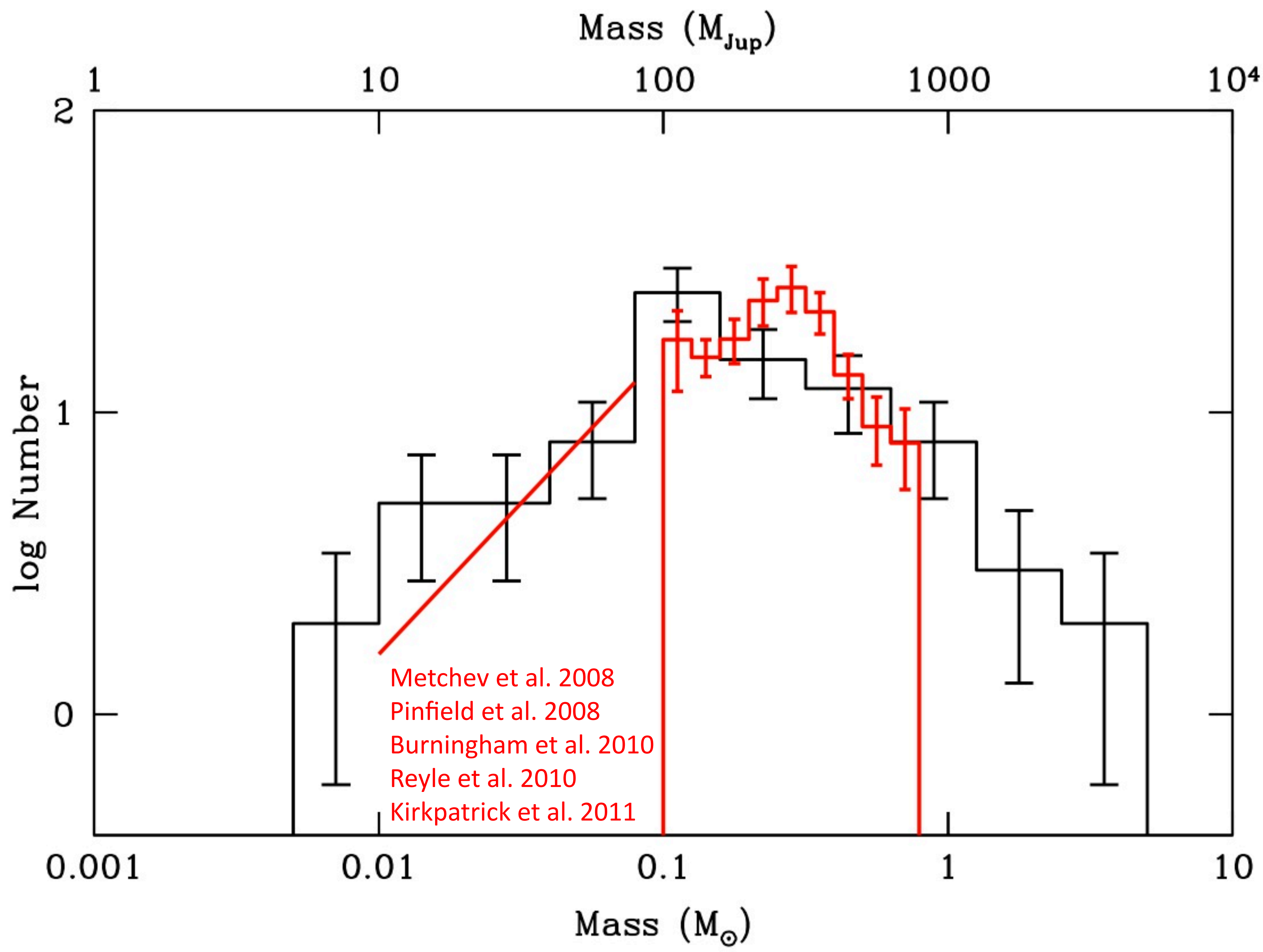



no convincing evidence of significant variations in the substellar IMF

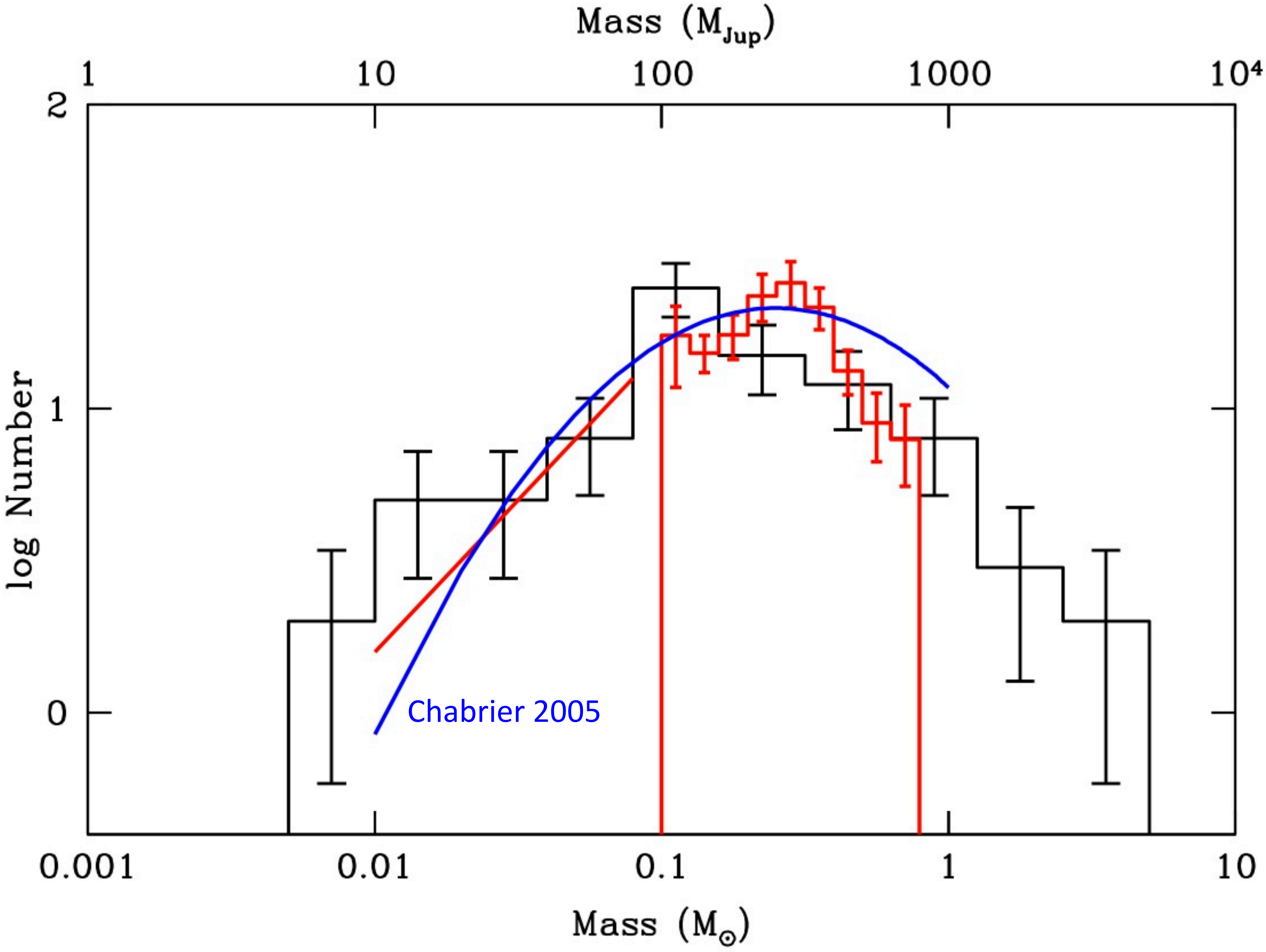

Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
Chamaeleon I star-forming region
Luhman 2007
See also:
Bejar et al. 2001
Briceno et al. 2002
Slesnick et al. 2008
Lodieu et al. 2011
Alves de Oliveira et al. 2011
Scholz et al. 2012
0.001
0.01
0.1
1
10
Mass ($M_\odot$)

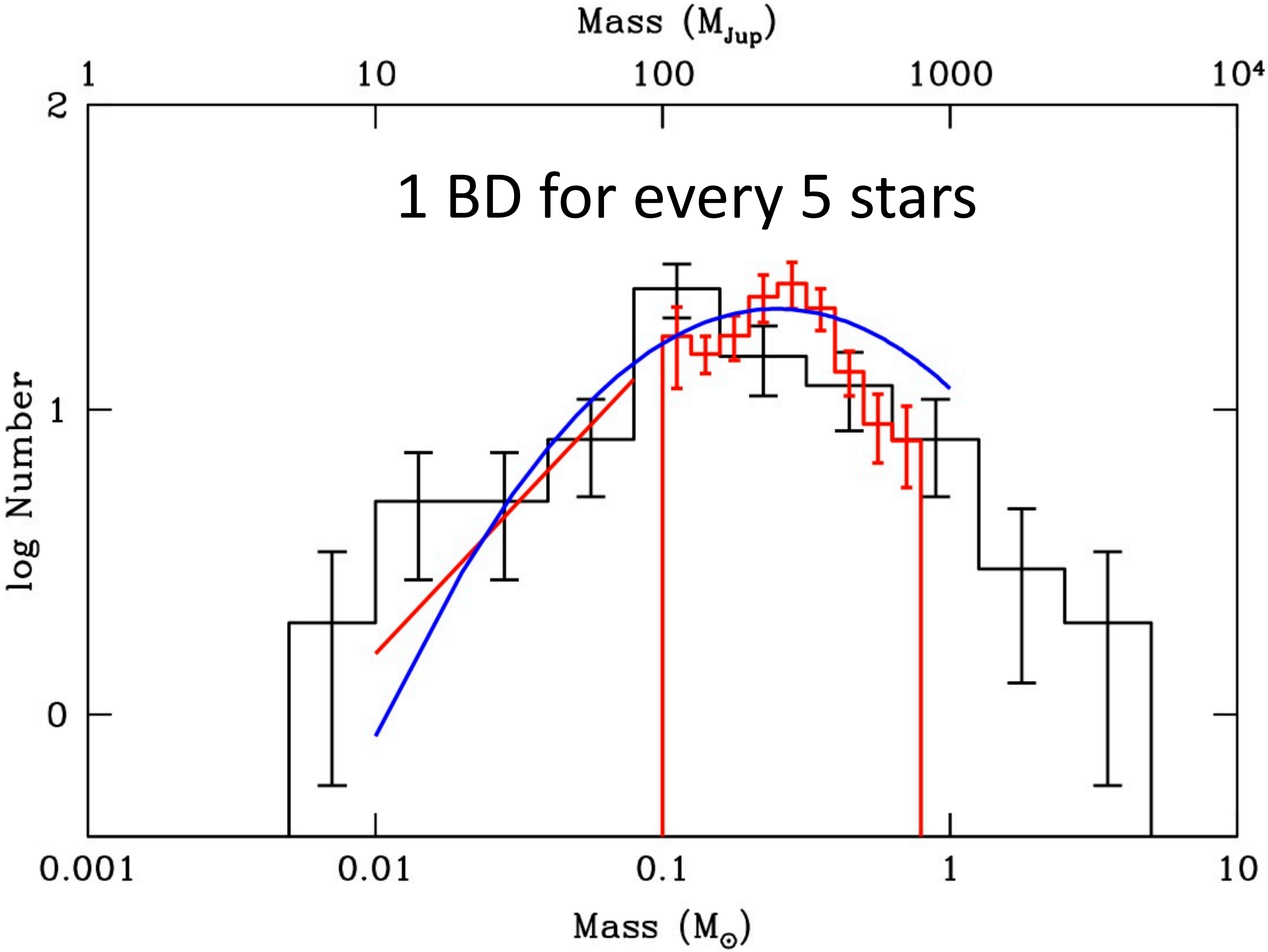


Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
the field
Reid et al. 1999
Bochanski et al. 2010
0.001
0.01
0.1
1
10
Mass ($M_\odot$)

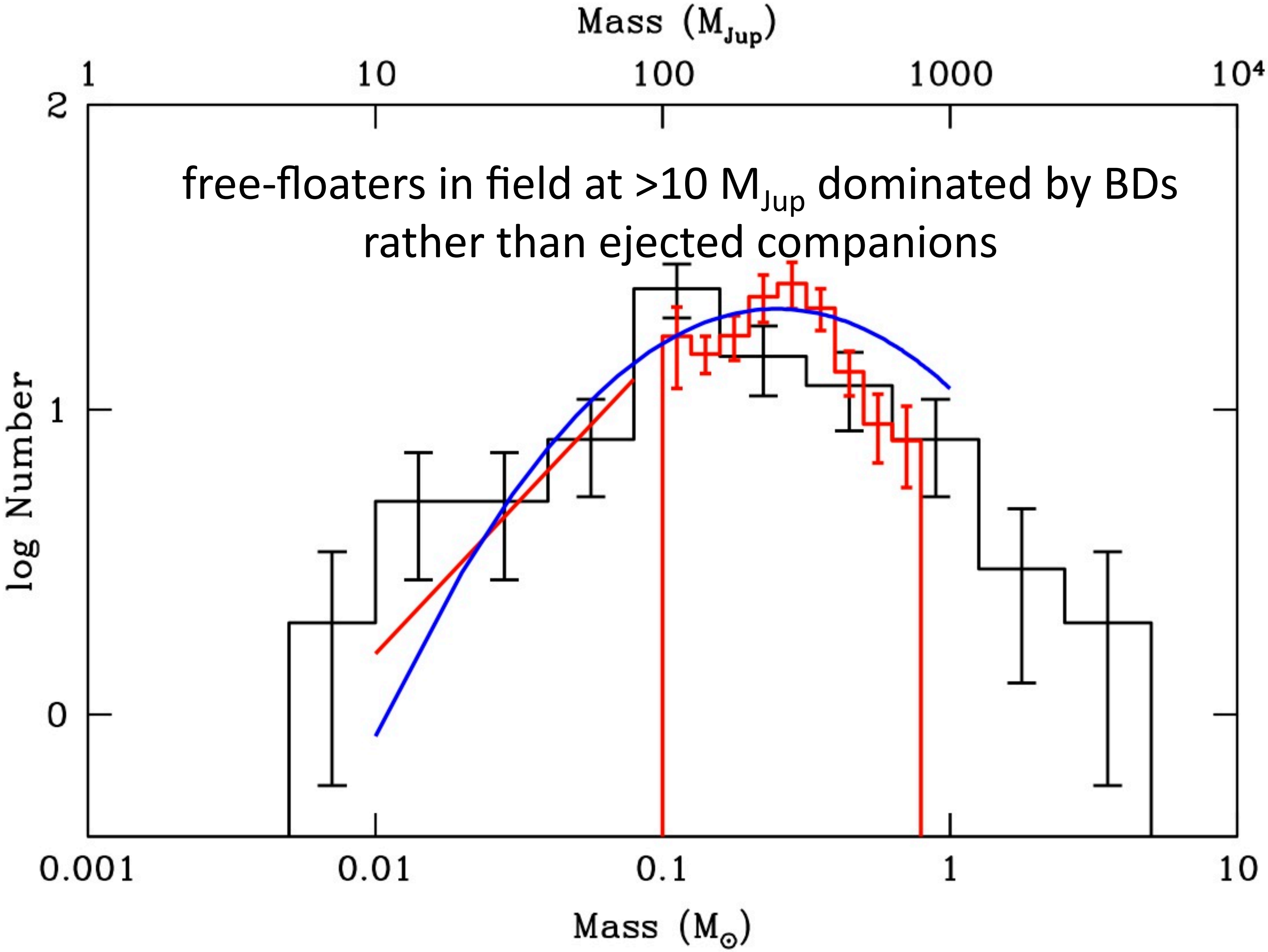


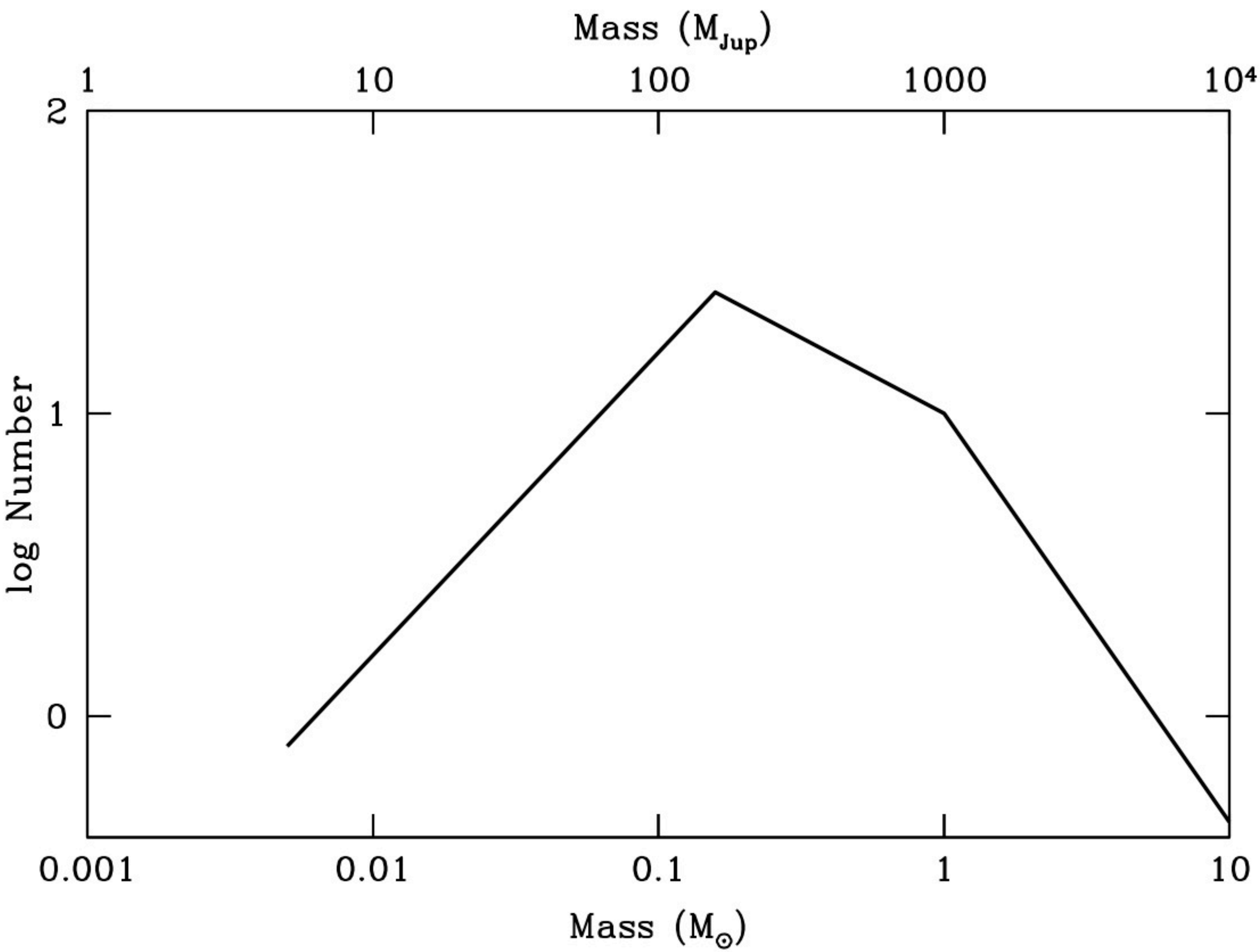
Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
Metchev et al. 2008
Pinfield et al. 2008
Burningham et al. 2010
Reyle et al. 2010
Kirkpatrick et al. 2011
0.001
0.01
0.1
1
10
Mass ($M_\odot$)

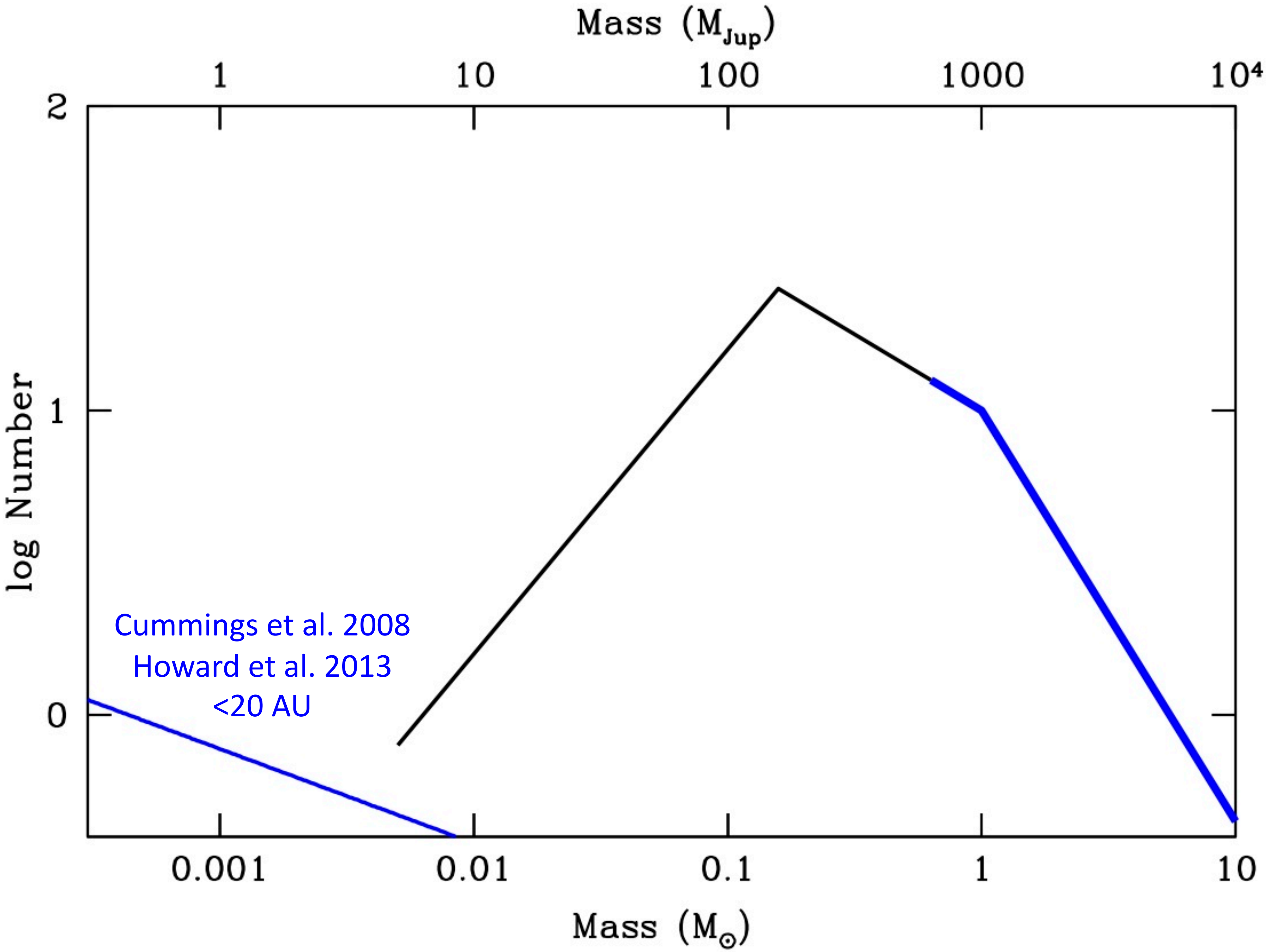

Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
Chabrier 2005
0.001
0.01
0.1
1
10
Mass ($M_\odot$)



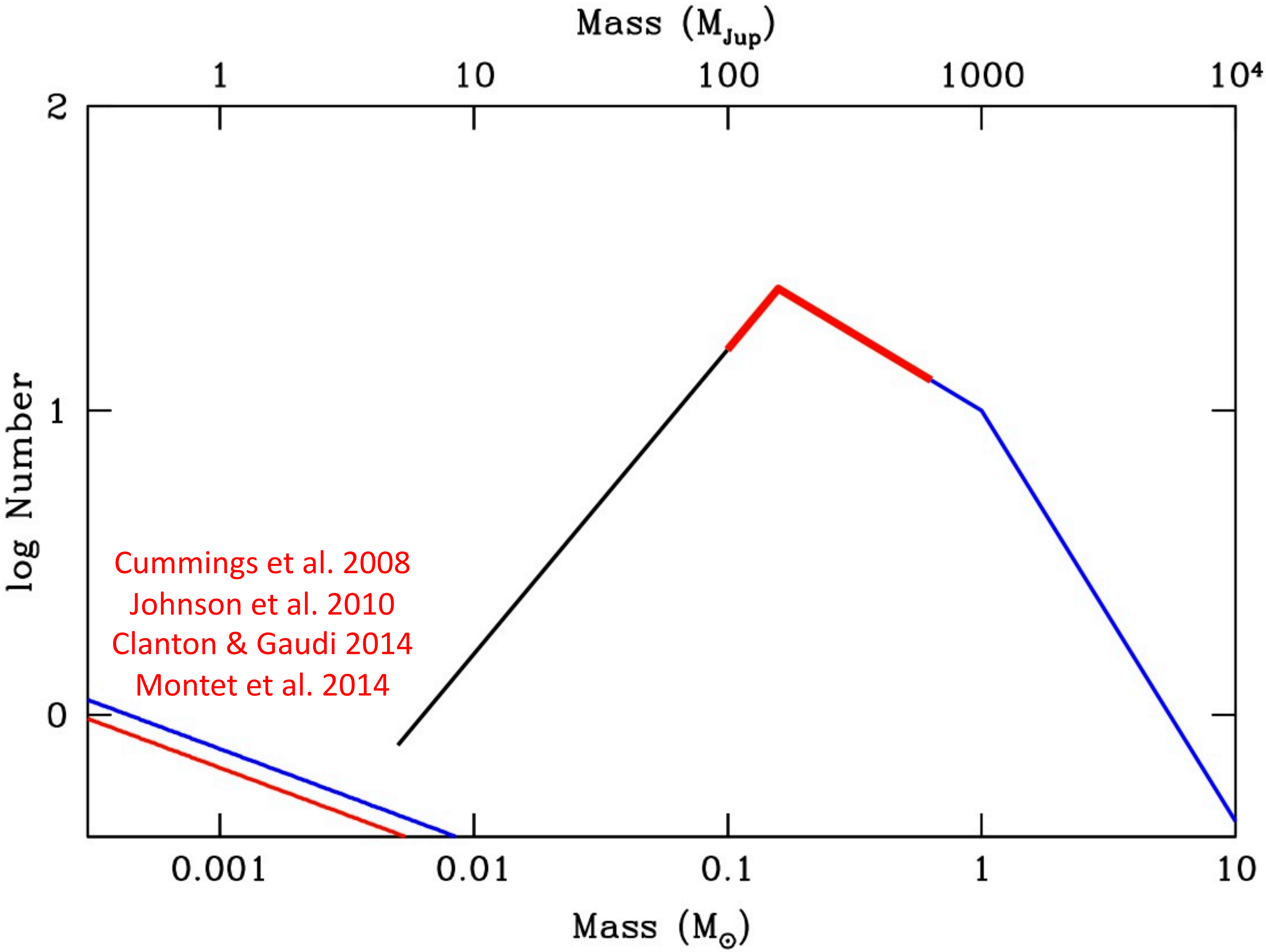
Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
1 BD for every 5 stars
log Number
2
1
0
0.001
0.01
0.1
1
10
Mass ($M_\odot$)


free-floaters in field at >10 $M_{Jup}$ dominated by BDs rather than ejected companions
Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
0.001
0.01
0.1
1
10
Mass ($M_\odot$)

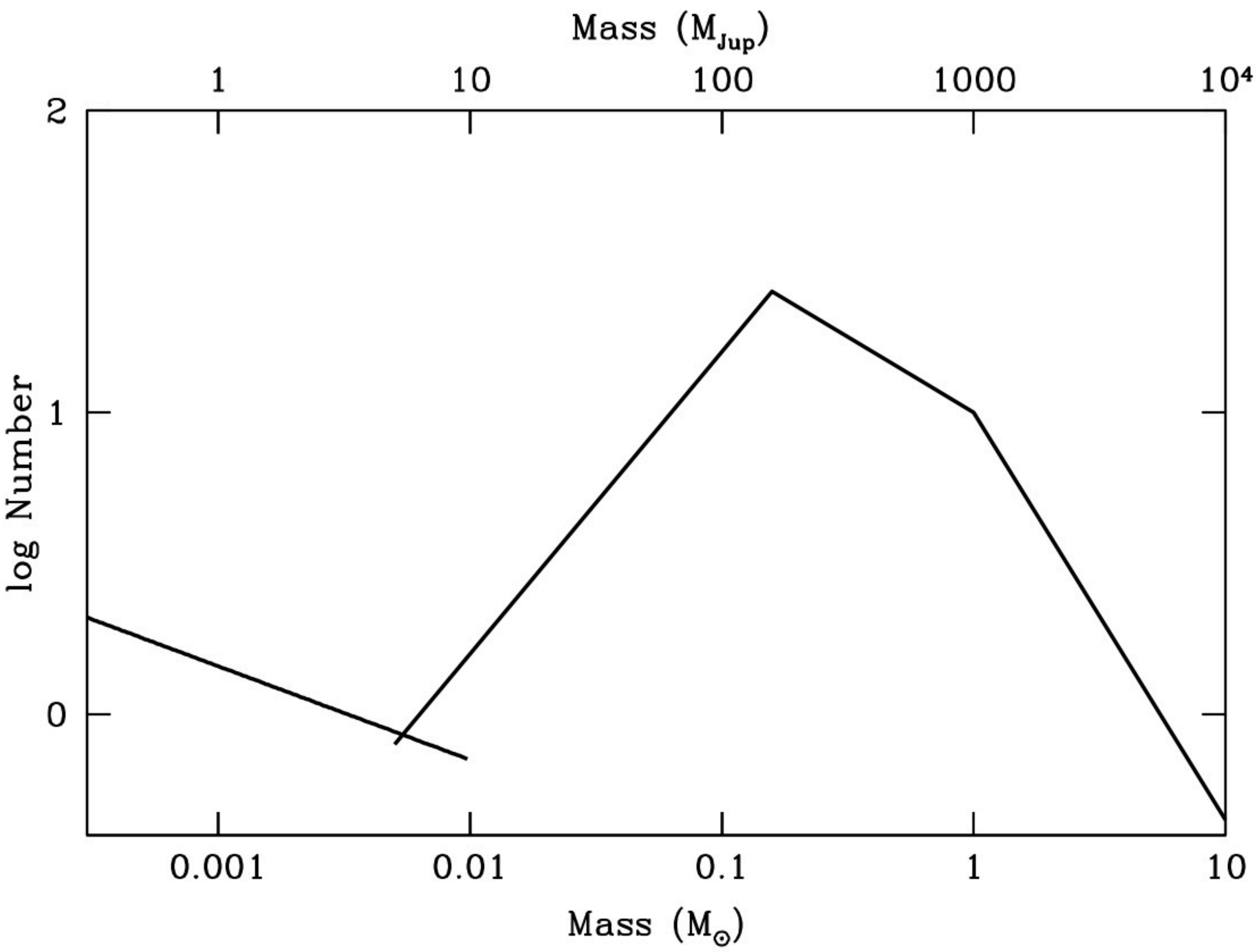

Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
0.001
0.01
0.1
1
10
Mass ($M_\odot$)



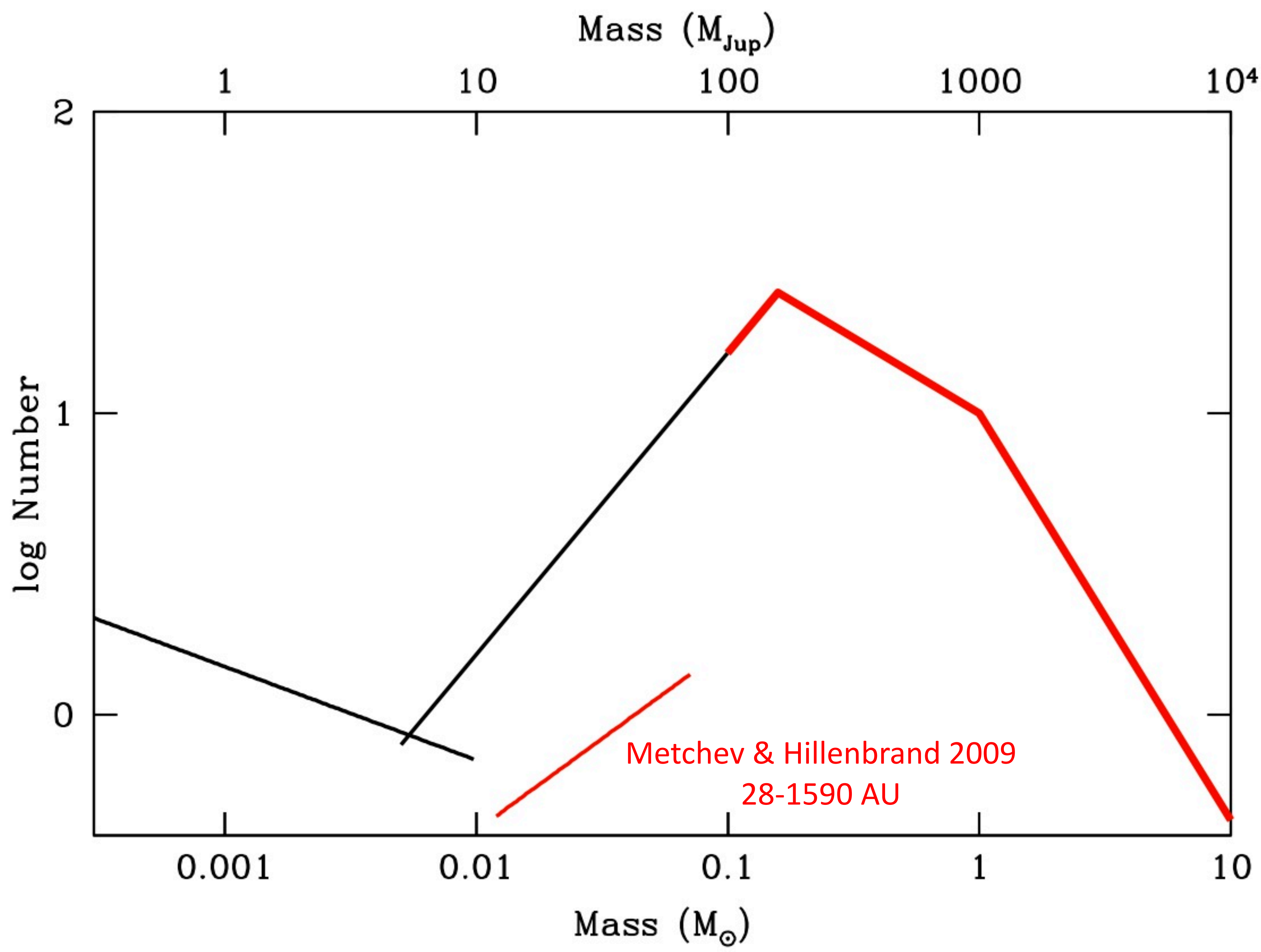
Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
Cummings et al. 2008
Howard et al. 2013
<20 AU
0.001
0.01
0.1
1
10
Mass ($M_\odot$)



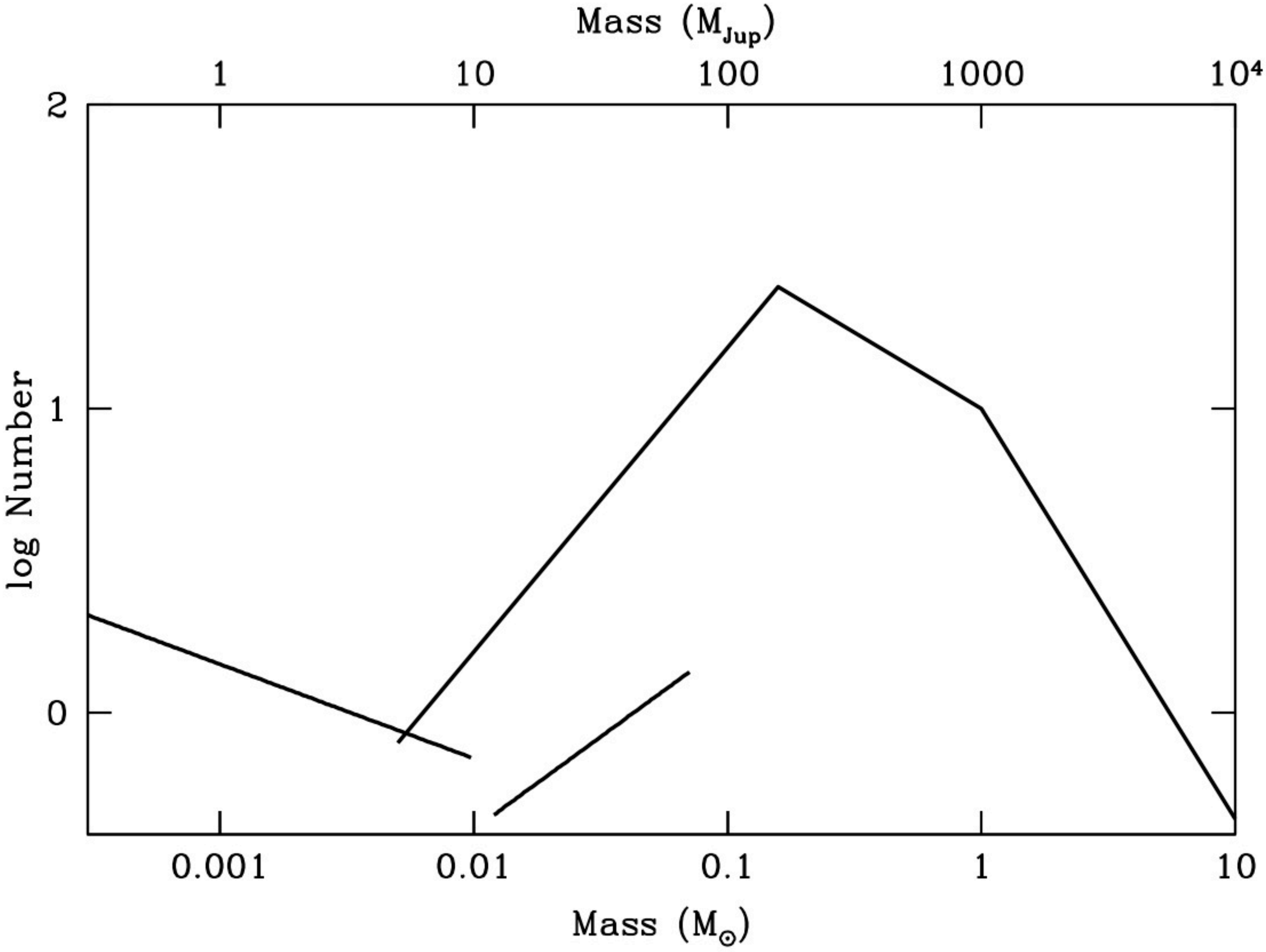
Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
Cummings et al. 2008
Johnson et al. 2010
Clanton & Gaudi 2014
Montet et al. 2014
0.001
0.01
0.1
1
10
Mass ($M_\odot$)



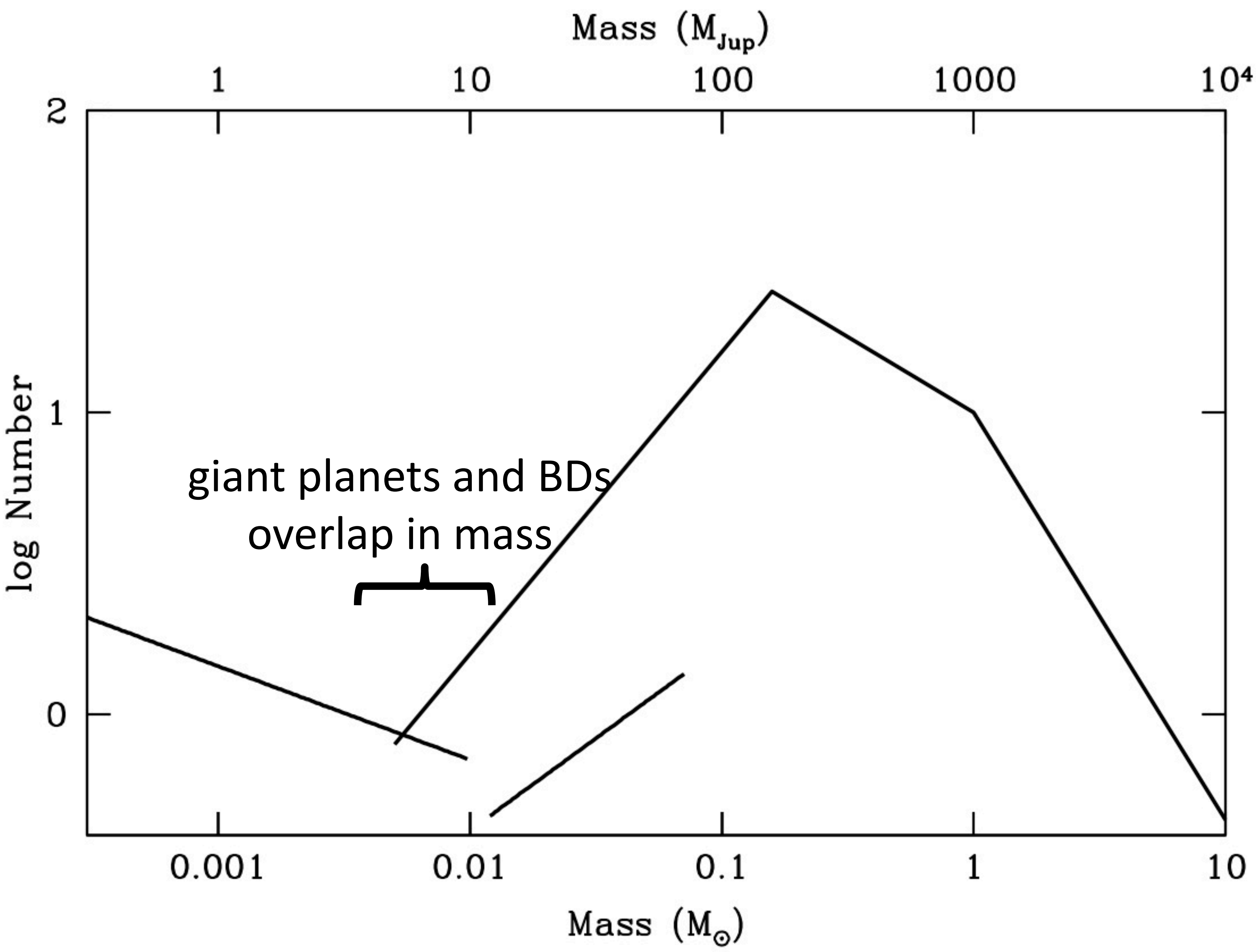
Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
0.001
0.01
0.1
1
10
Mass ($M_\odot$)



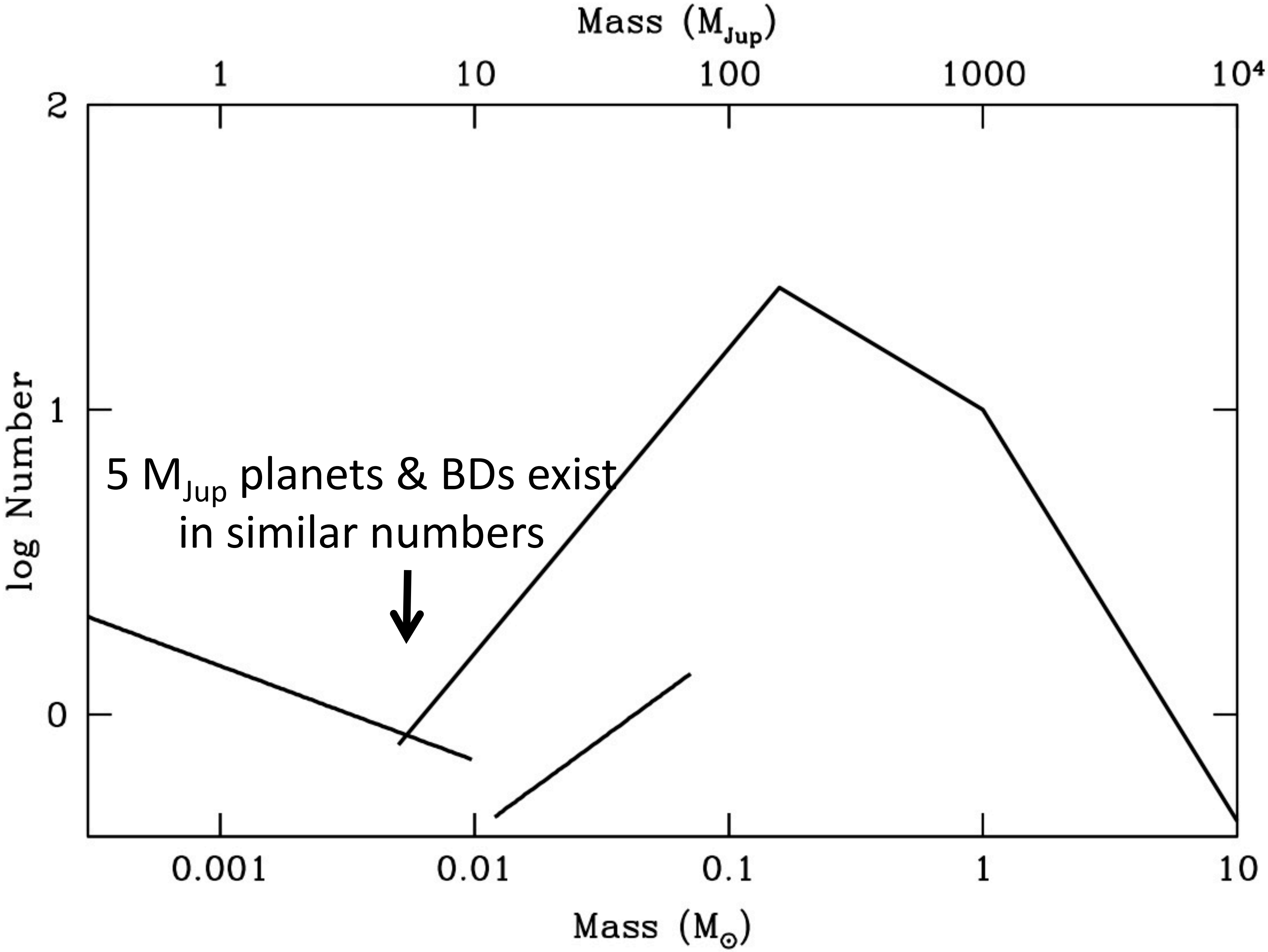
Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
Metchev & Hillenbrand 2009
28-1590 AU
0.001
0.01
0.1
1
10
Mass ($M_\odot$)



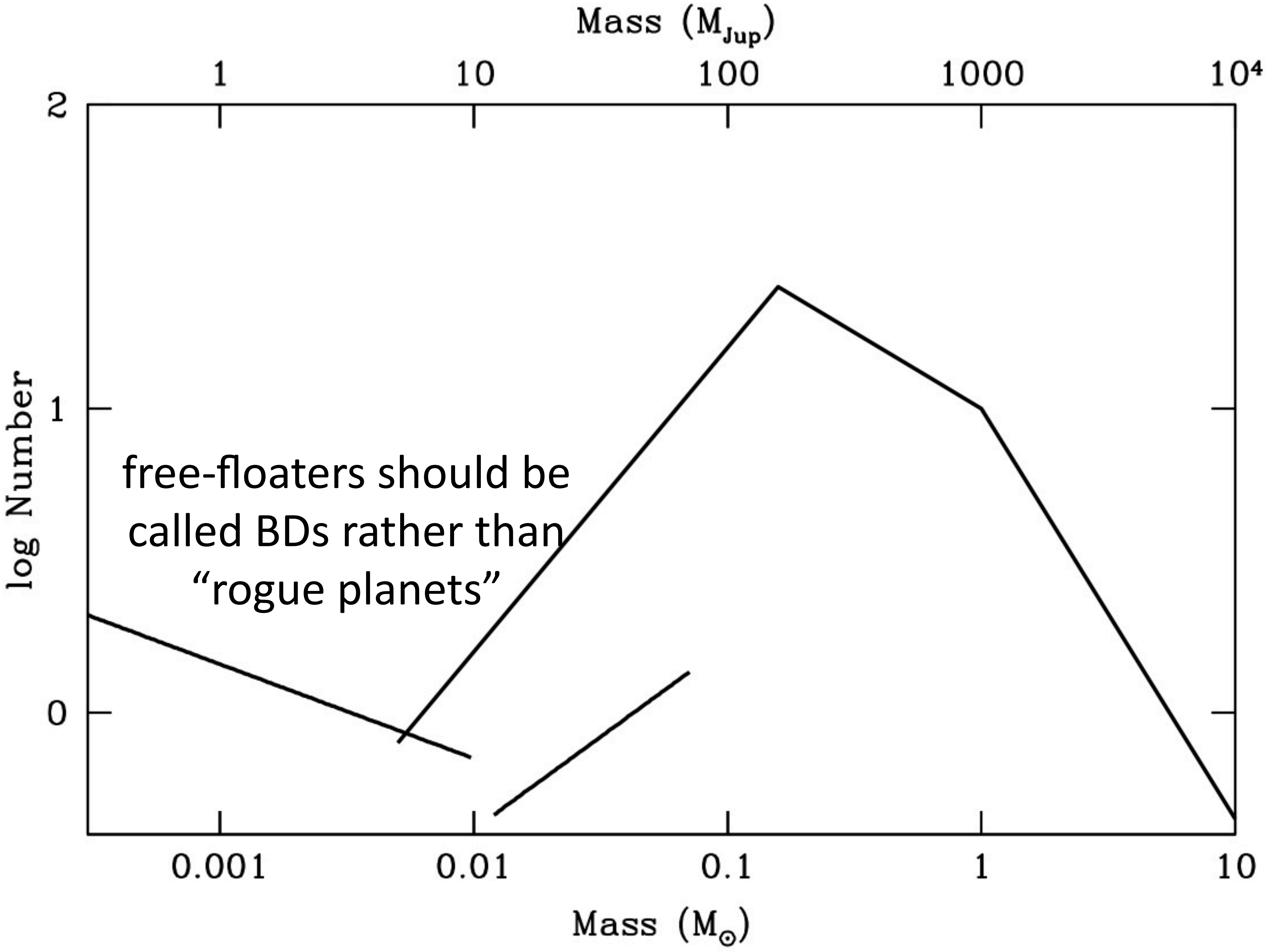
Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
0.001
0.01
0.1
1
10
Mass ($M_\odot$)

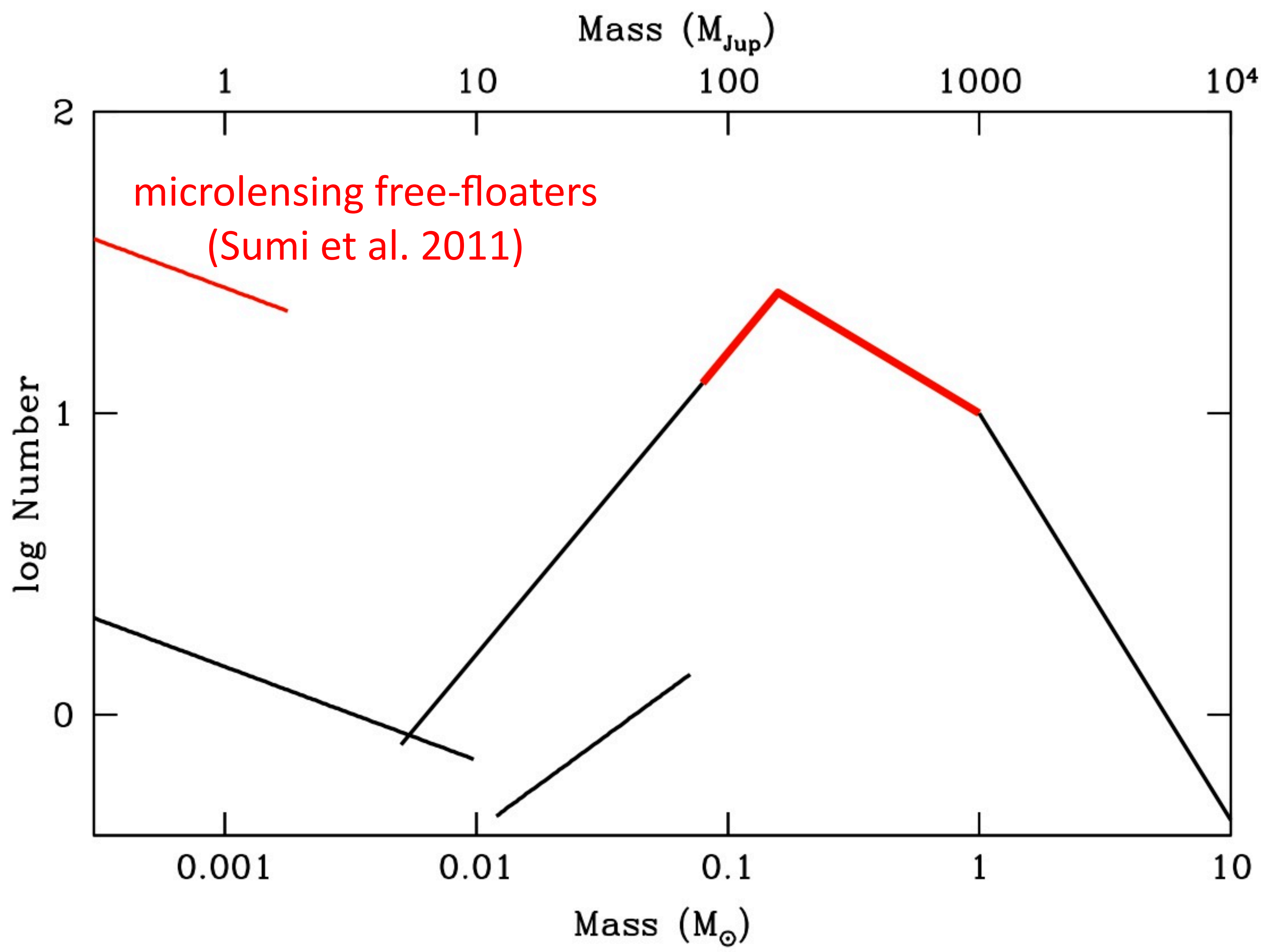


Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
giant planets and BDs
overlap in mass
0.001
0.01
0.1
1
10
Mass ($M_\odot$)



Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
5 $M_{Jup}$ planets & BDs exist
in similar numbers
0.001
0.01
0.1
1
10
Mass ($M_\odot$)


Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
free-floaters should be
called BDs rather than
"rogue planets"
0.001
0.01
0.1
1
10
Mass ($M_\odot$)



Mass ($M_{Jup}$)
1
10
100
1000
$10^4$
2
1
0
log Number
microlensing free-floaters
(Sumi et al. 2011)
0.001
0.01
0.1
1
10
Mass ($M_\odot$)

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- Mass Functions
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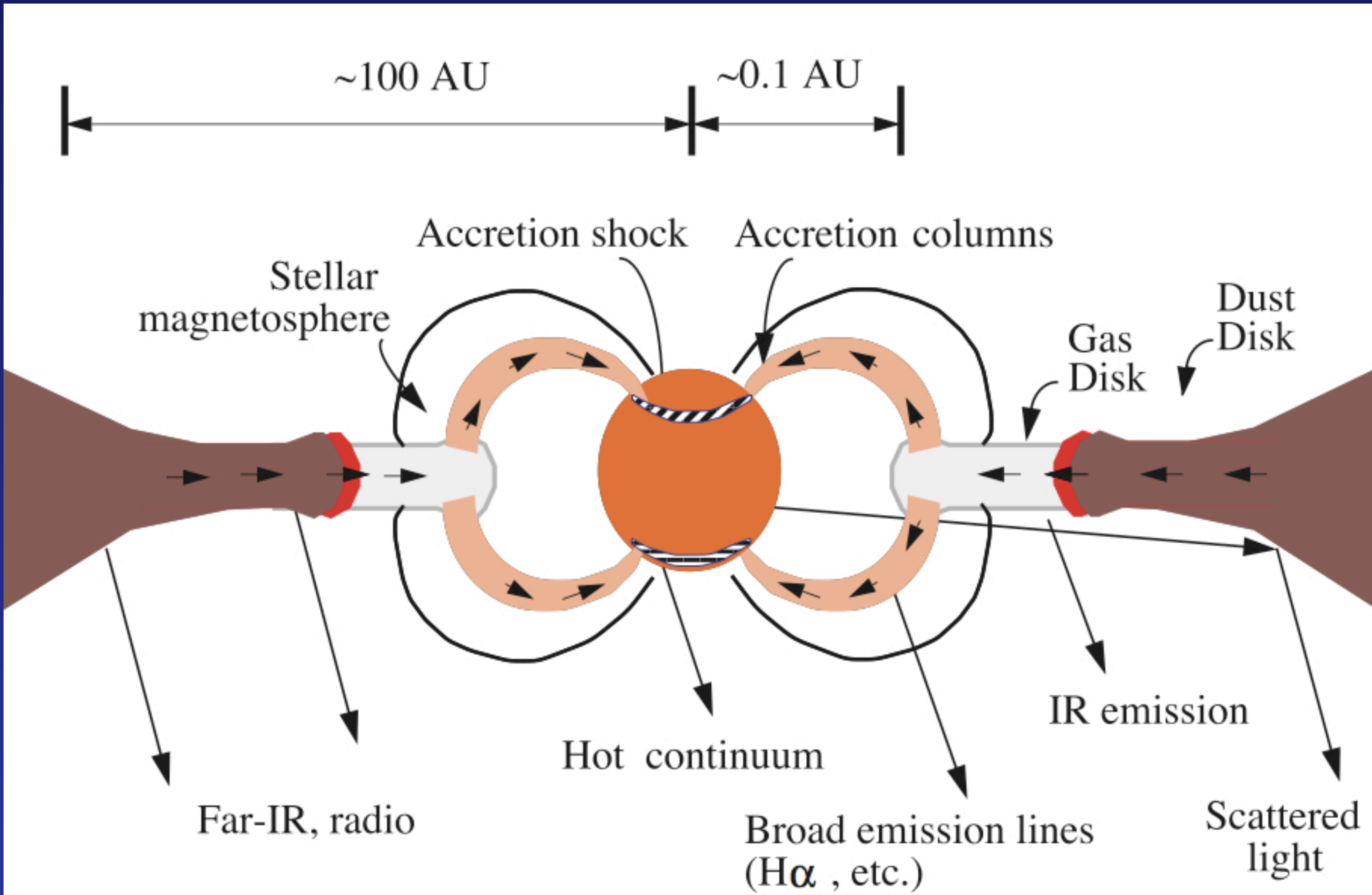
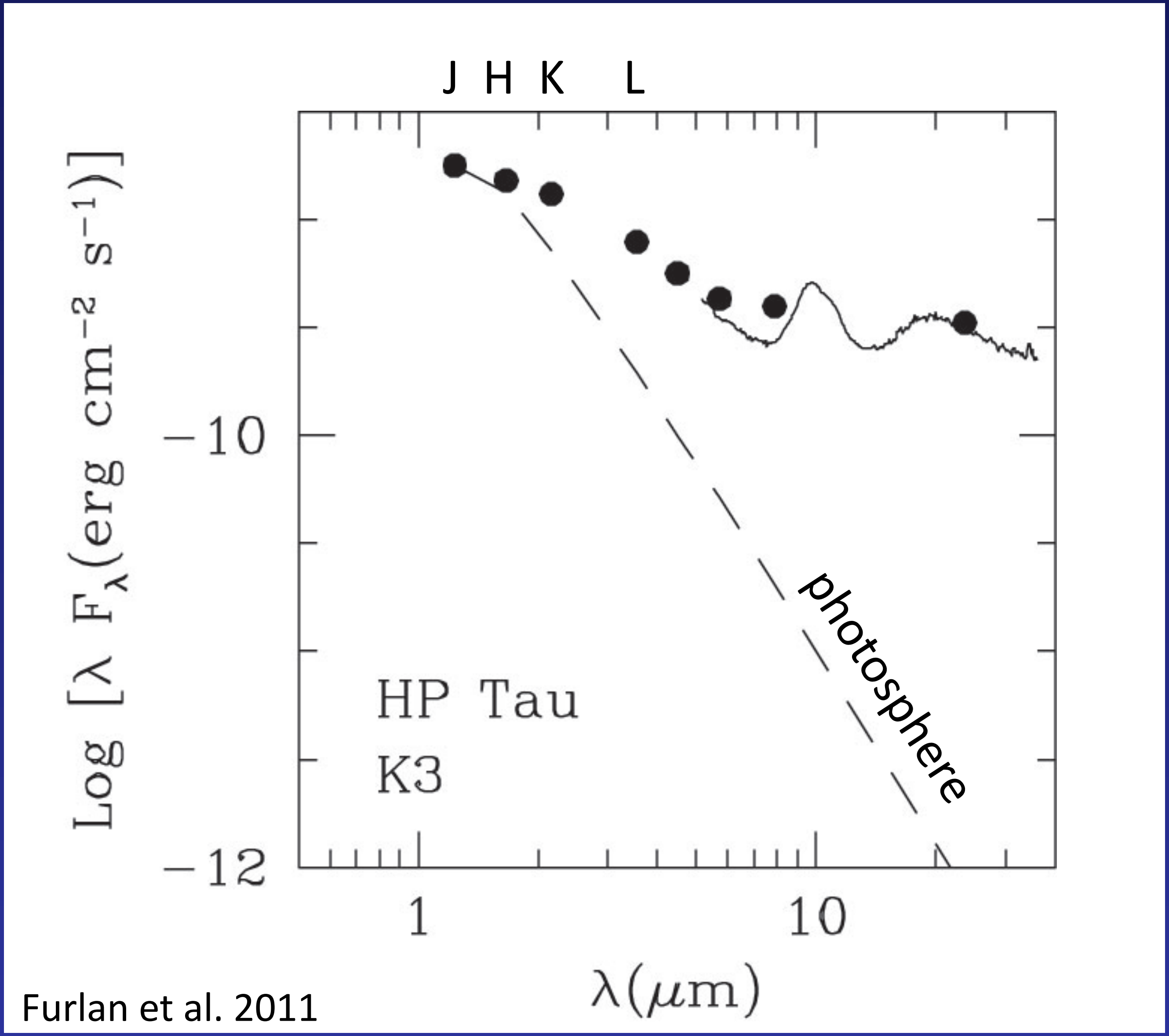
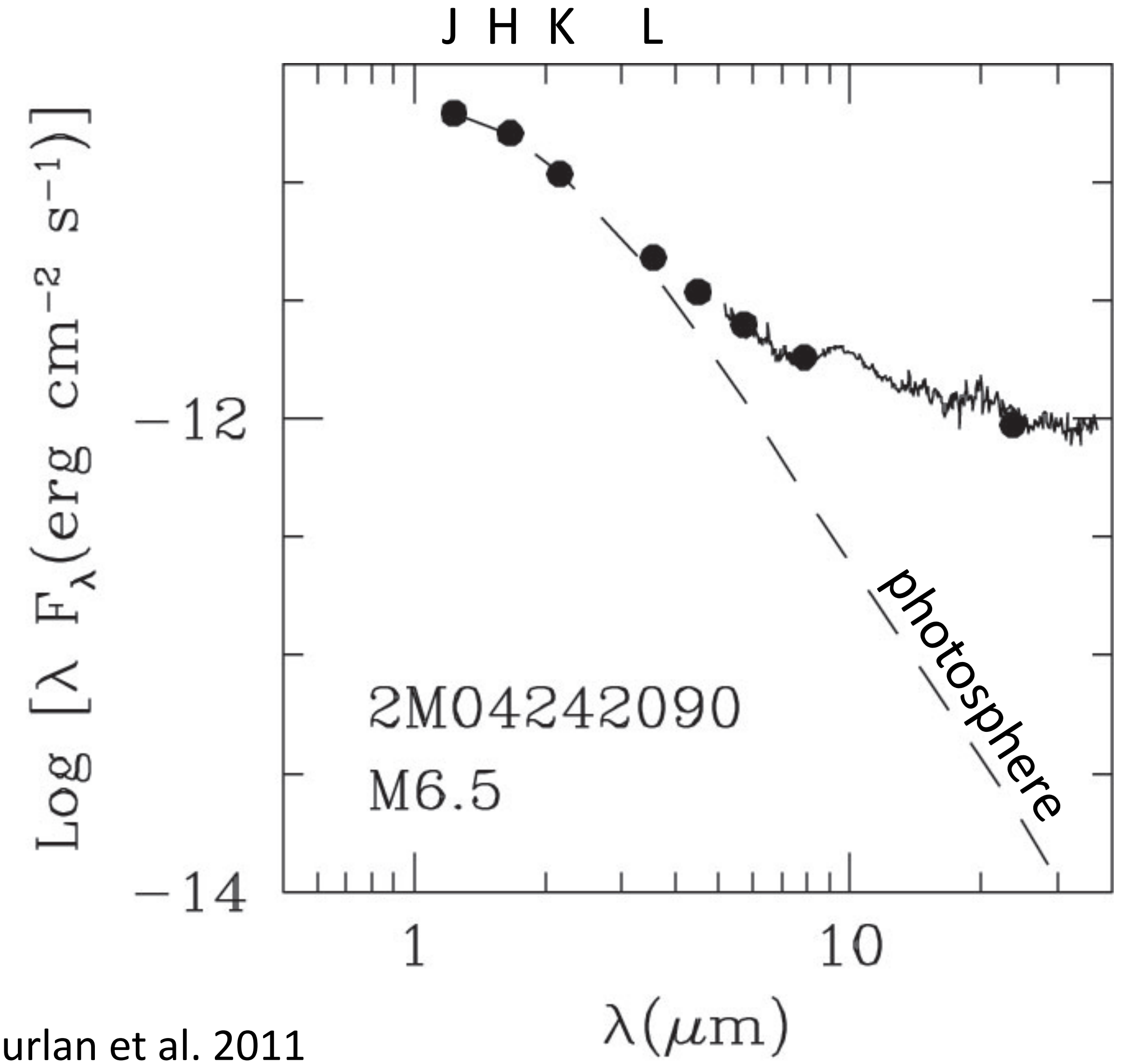
# Easiest method of detecting disks: IR imaging



# Disks detected around solar-type stars with JHKL

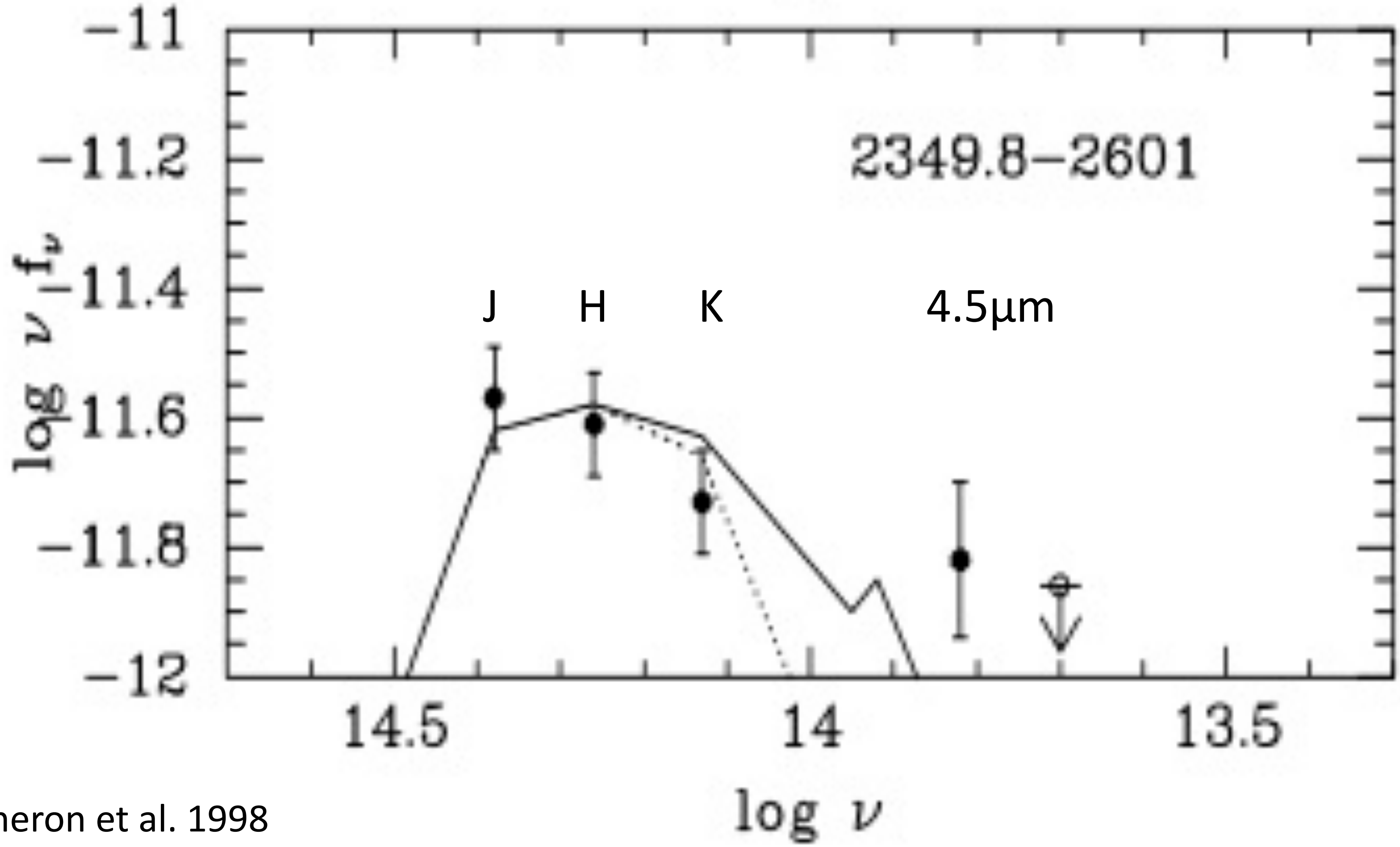


# Longer wavelengths needed for most BD disks



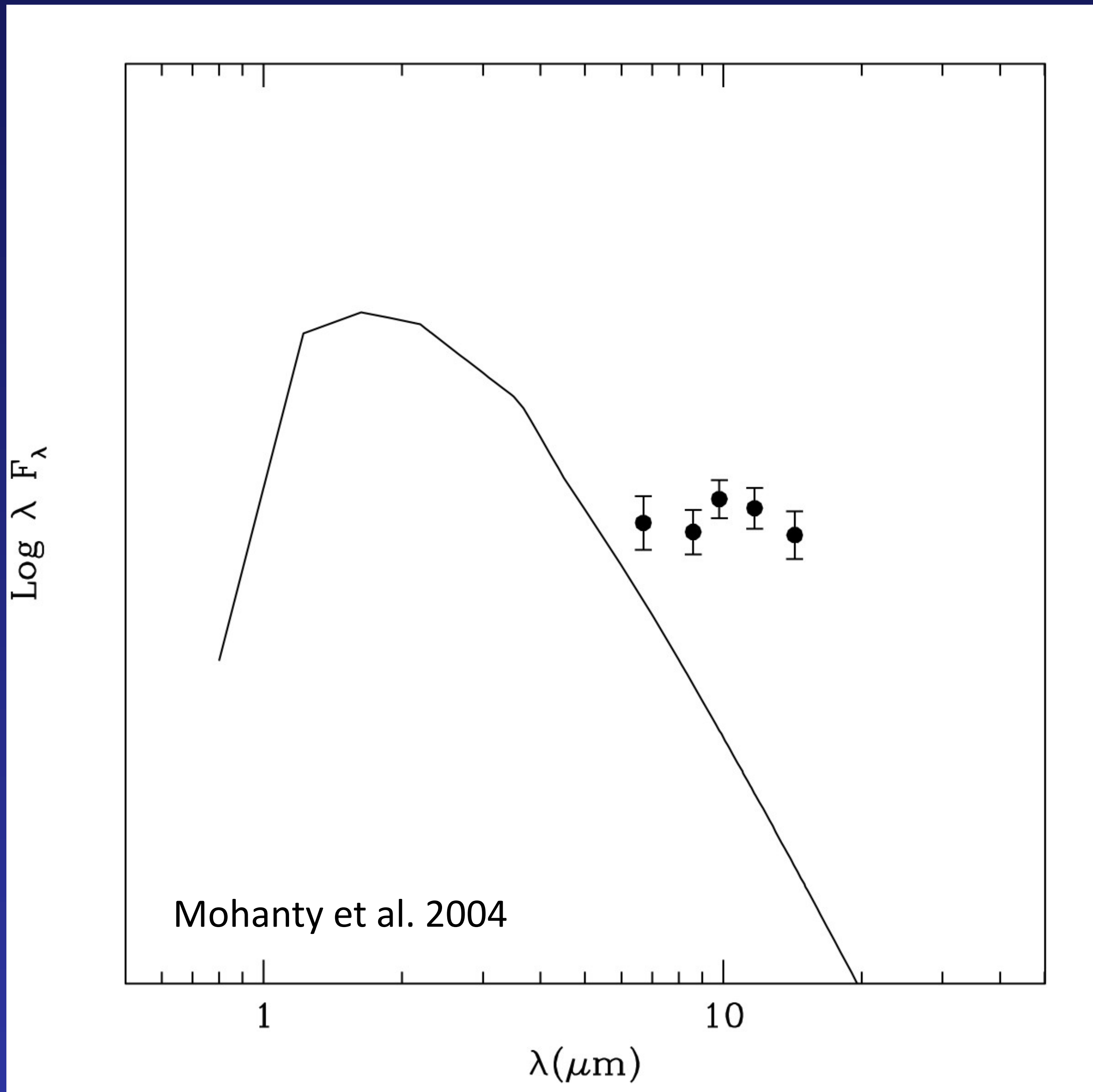

Furlan et al. 2011

# ISO detected a 4.5 μm excess from a young BD

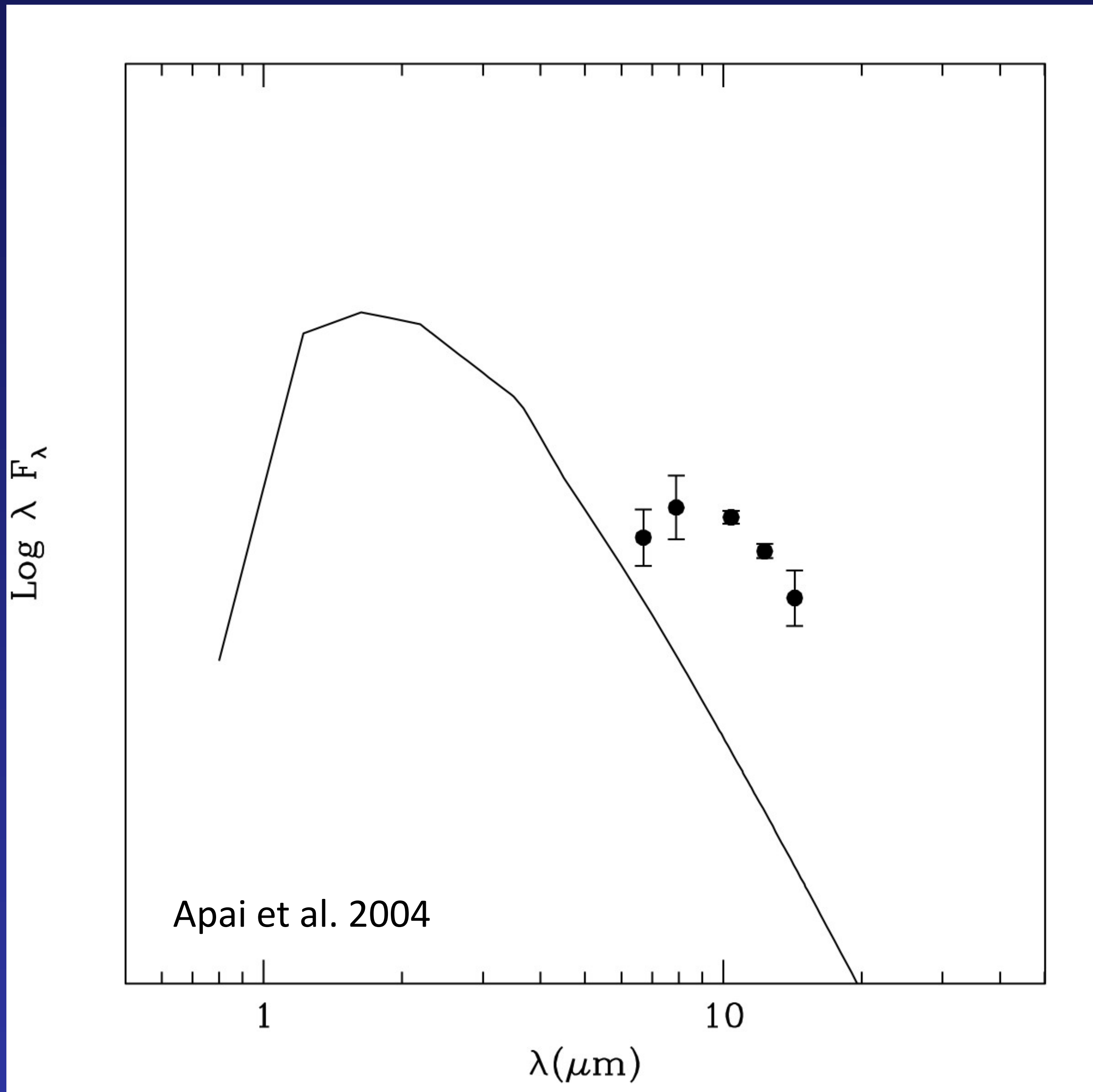



Comeron et al. 1998

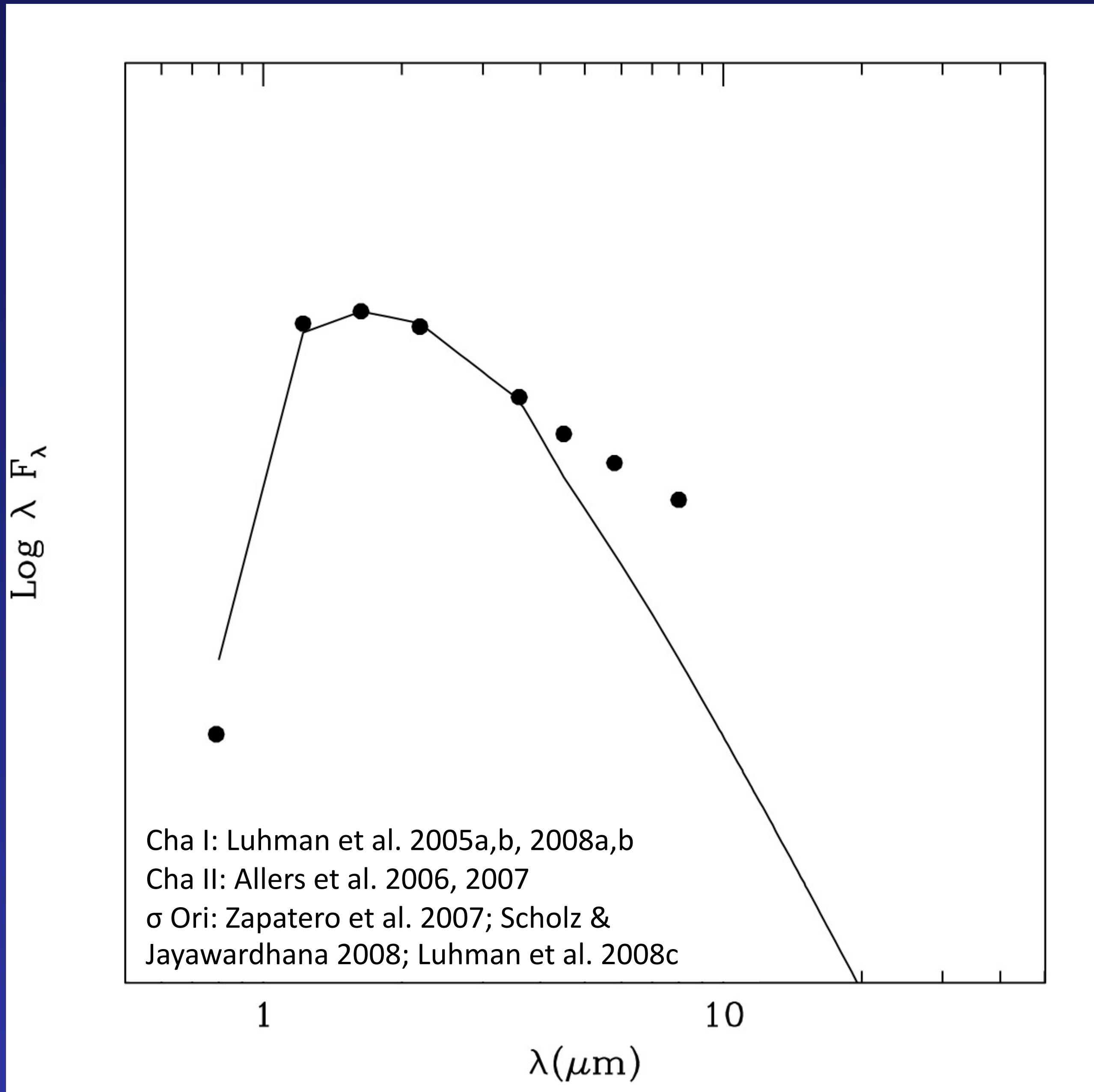
# A few BD disks detected at >4 μm from ground



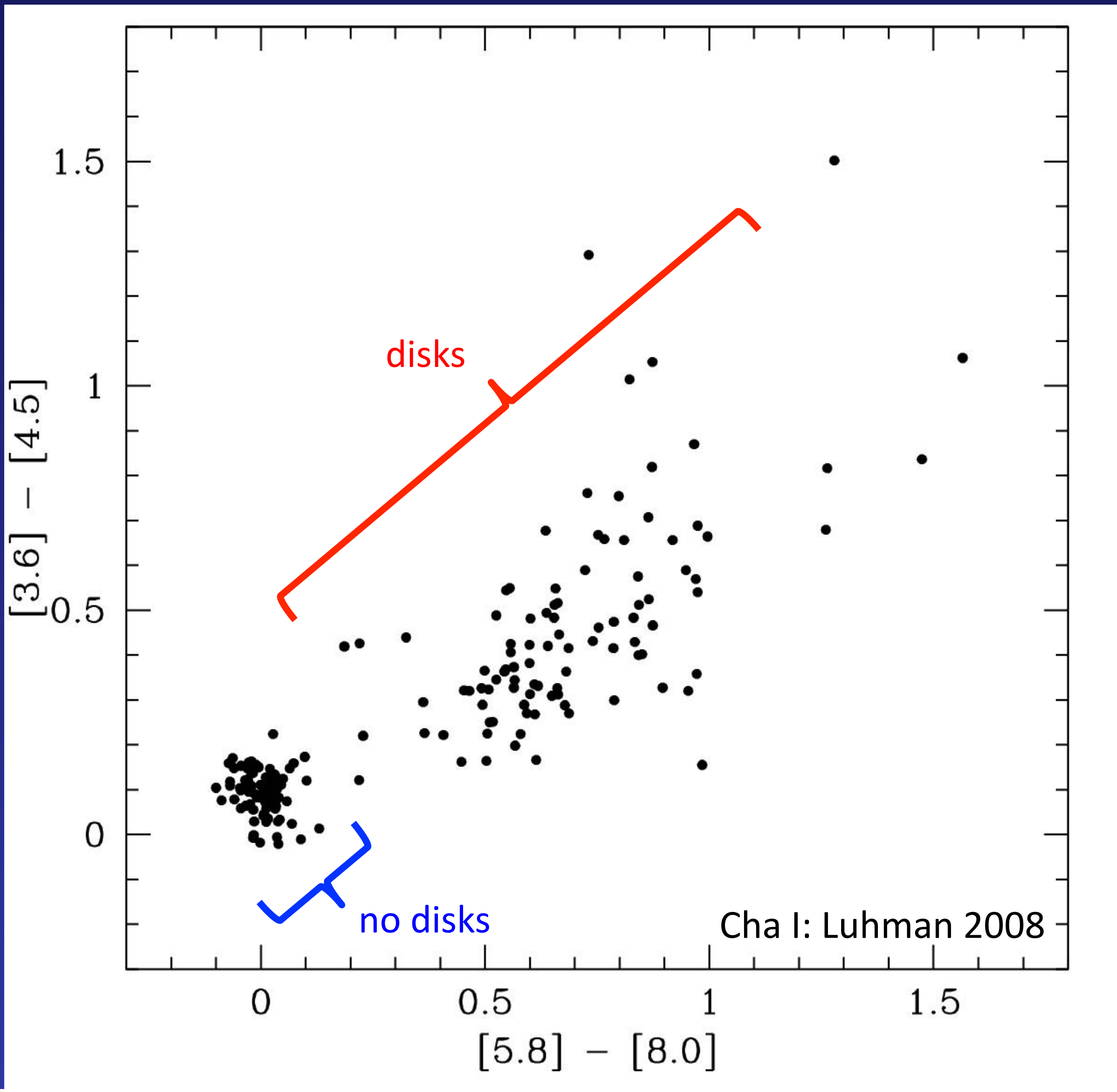
# A few BD disks detected at >4 μm from ground



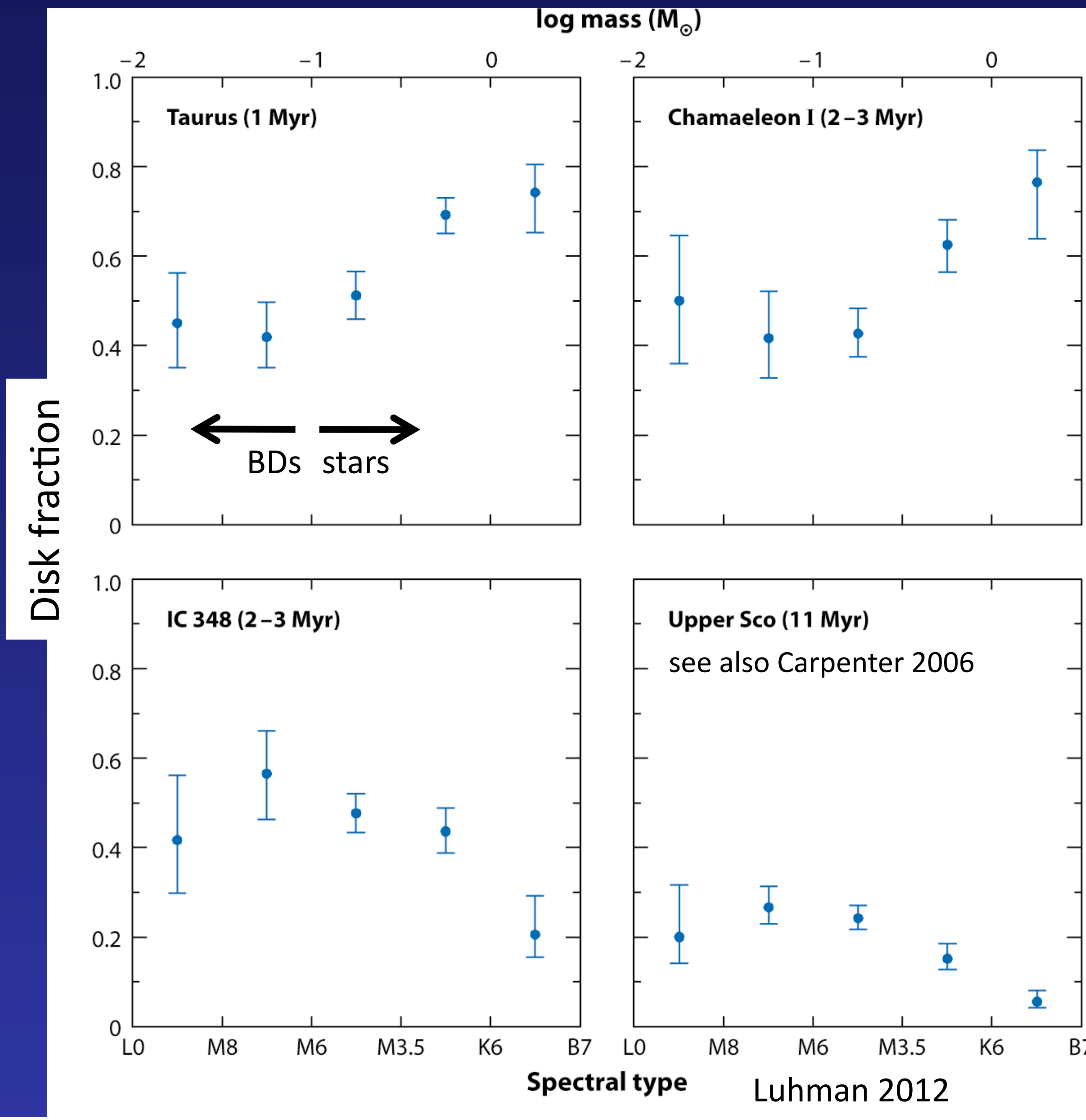
# Spitzer detected disks for smallest known BDs (~8 $M_{Jup}$)



# Spitzer detected disks in large numbers & at faint levels

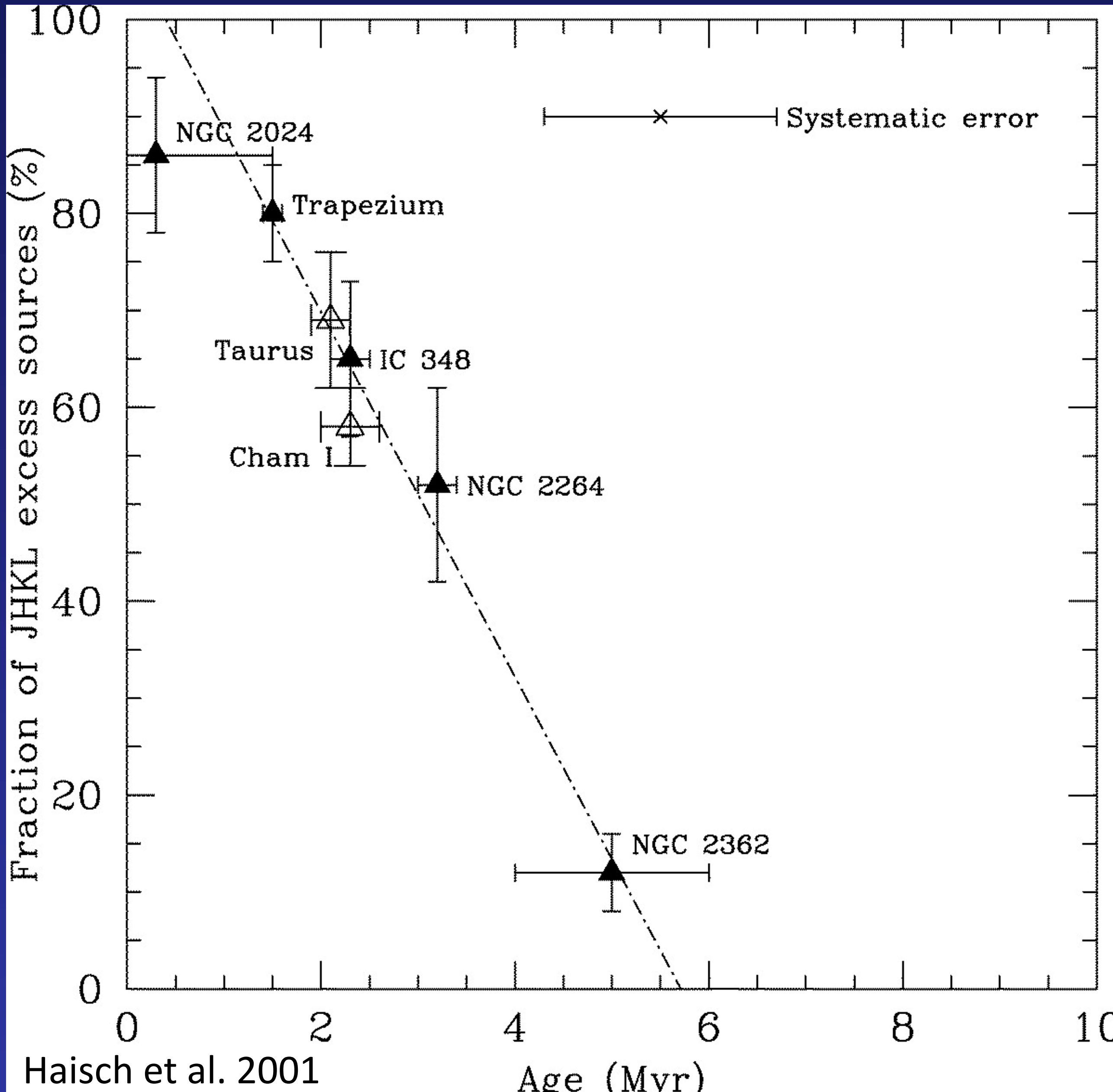


# BDs and low-mass stars have similar disk fractions

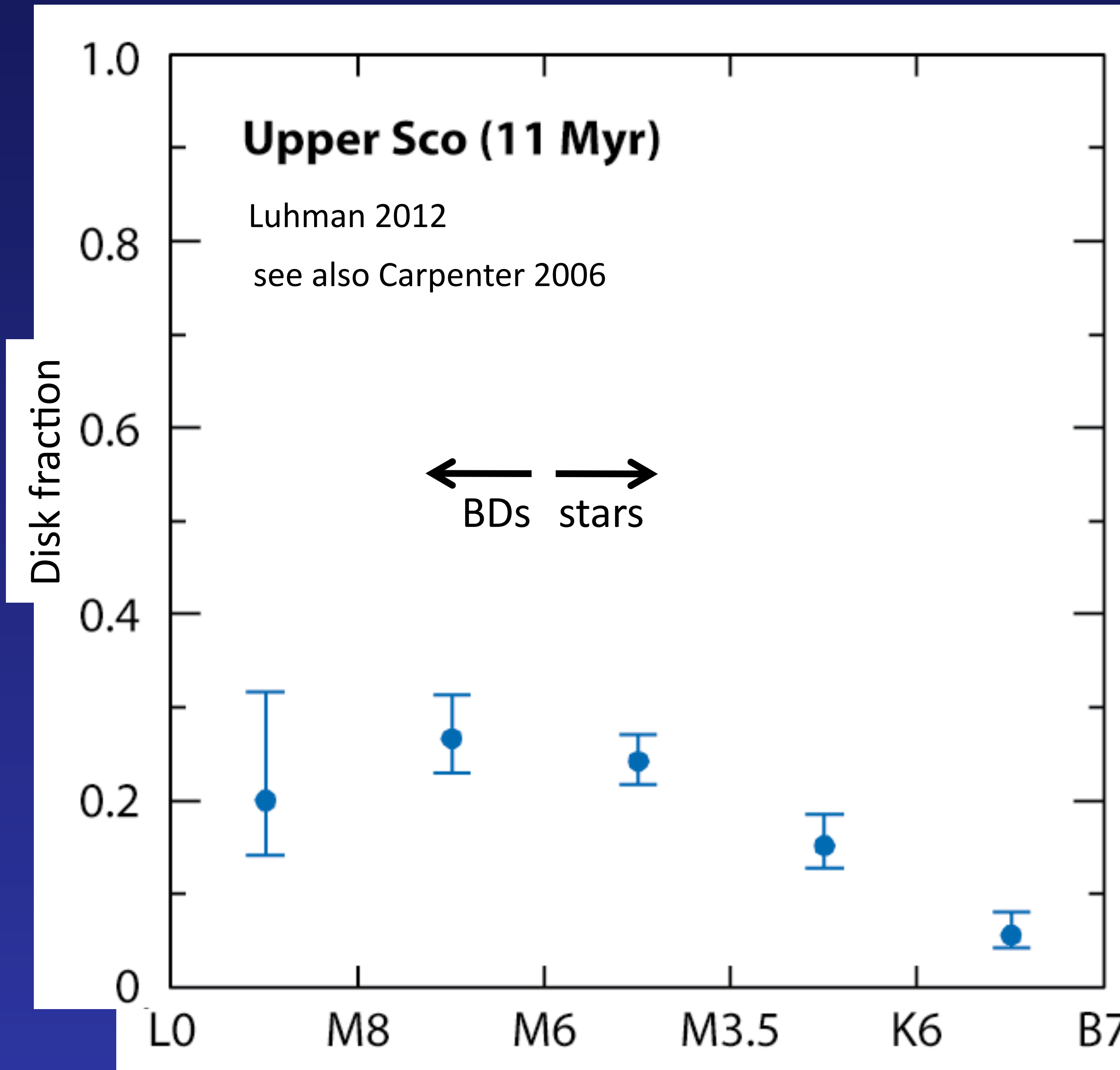



Luhman KL. 2012.
Annu. Rev. Astron. Astrophys. 50:65–106

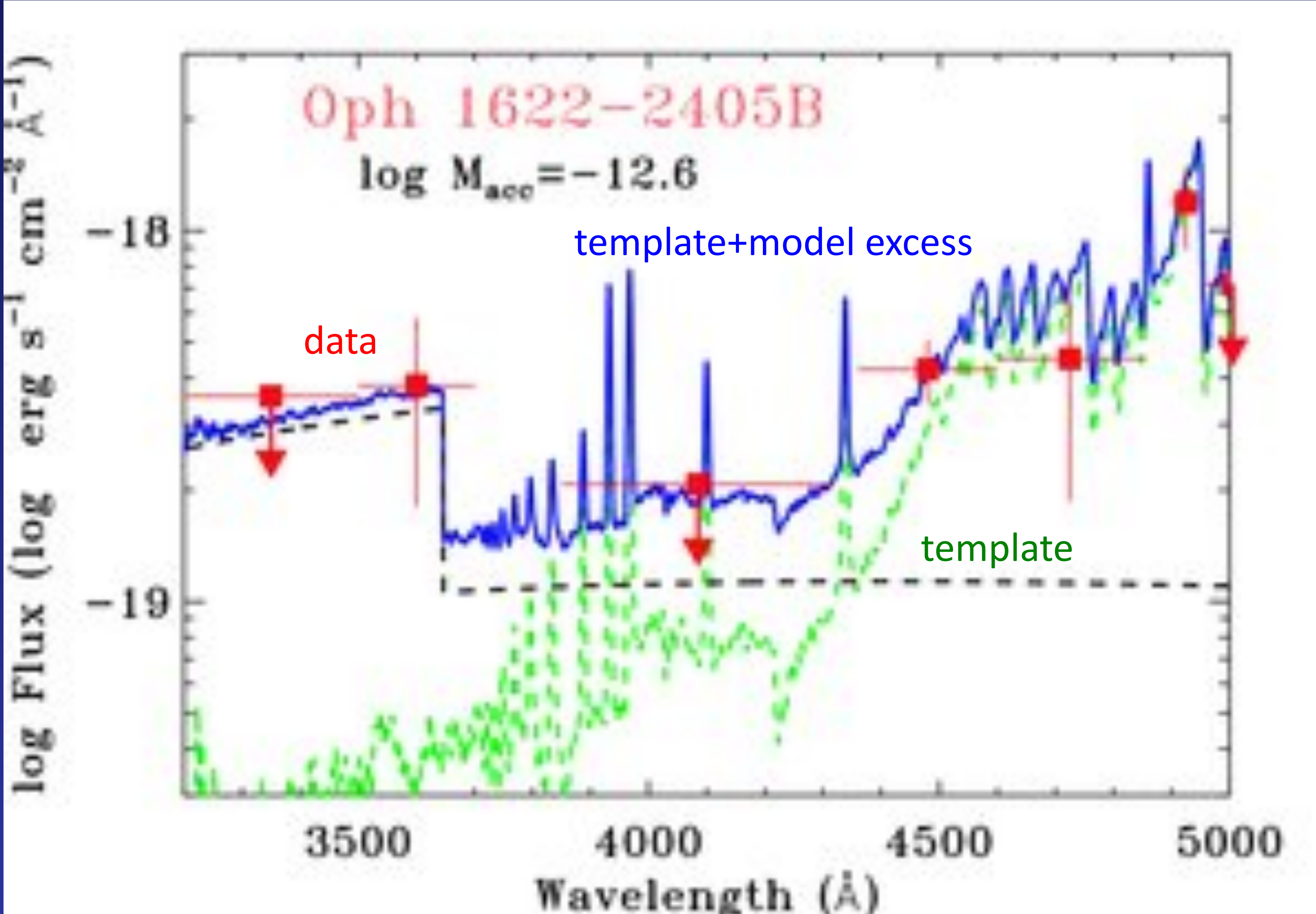
# Disk lifetimes from disk fractions vs. age



# Disk lifetimes longer for lower stellar masses

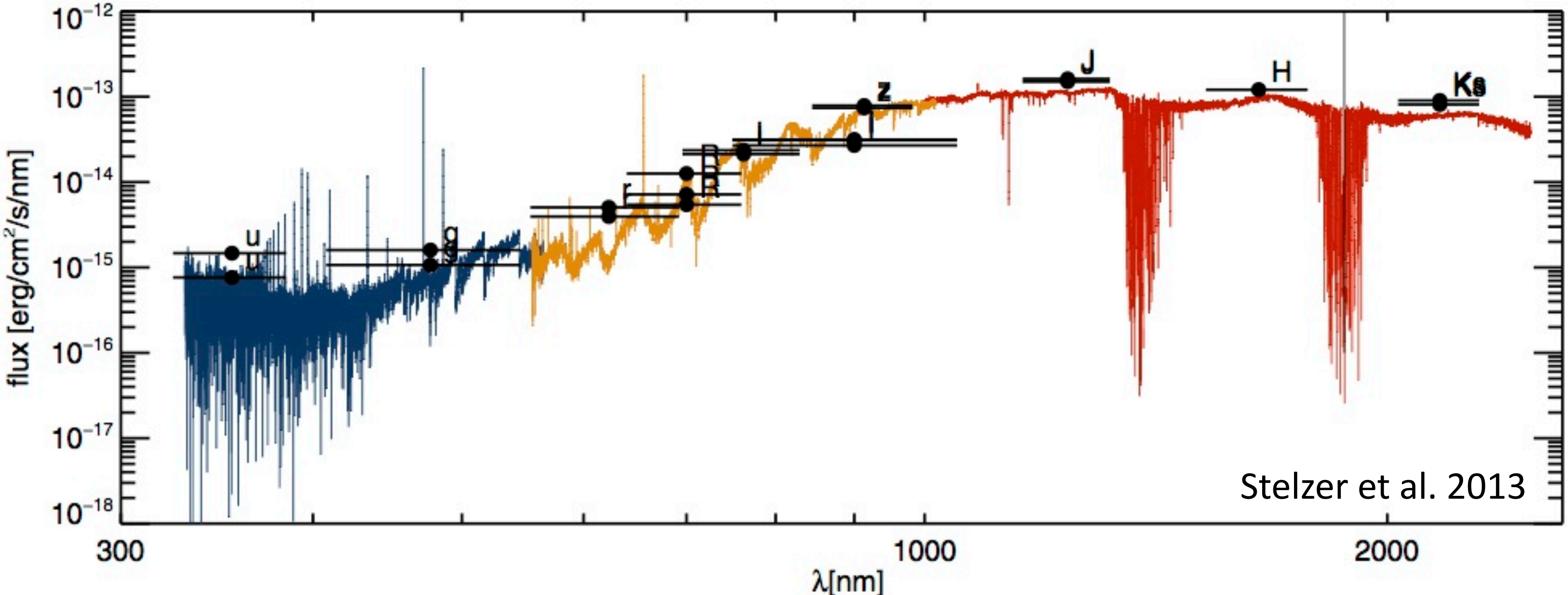


# UV excess emission from accreting BDs

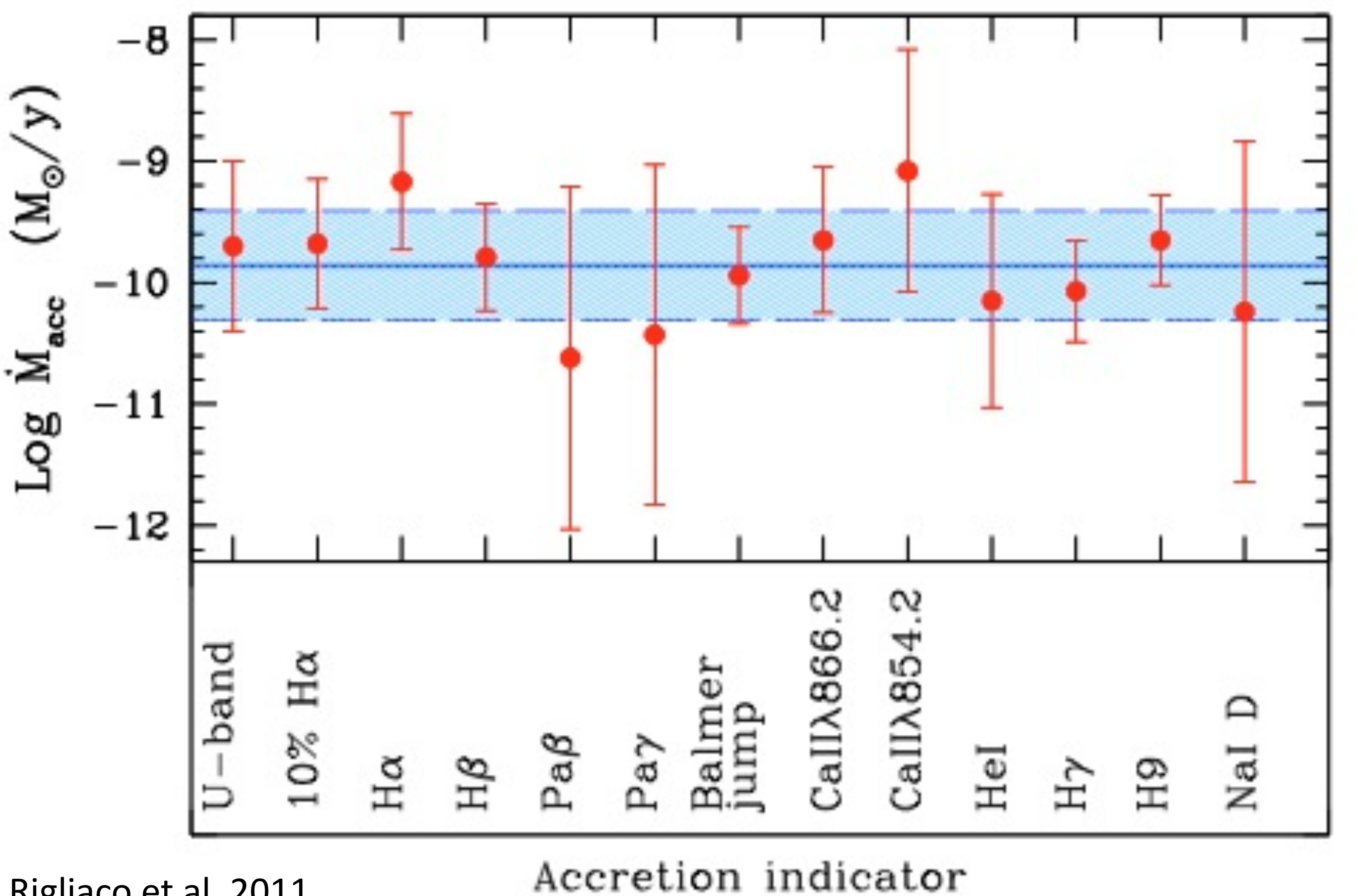



Herczeg & Hillenbrand 2008; Herczeg et al. 2009

# X-shooter: UV excess + many lines + near-IR excess

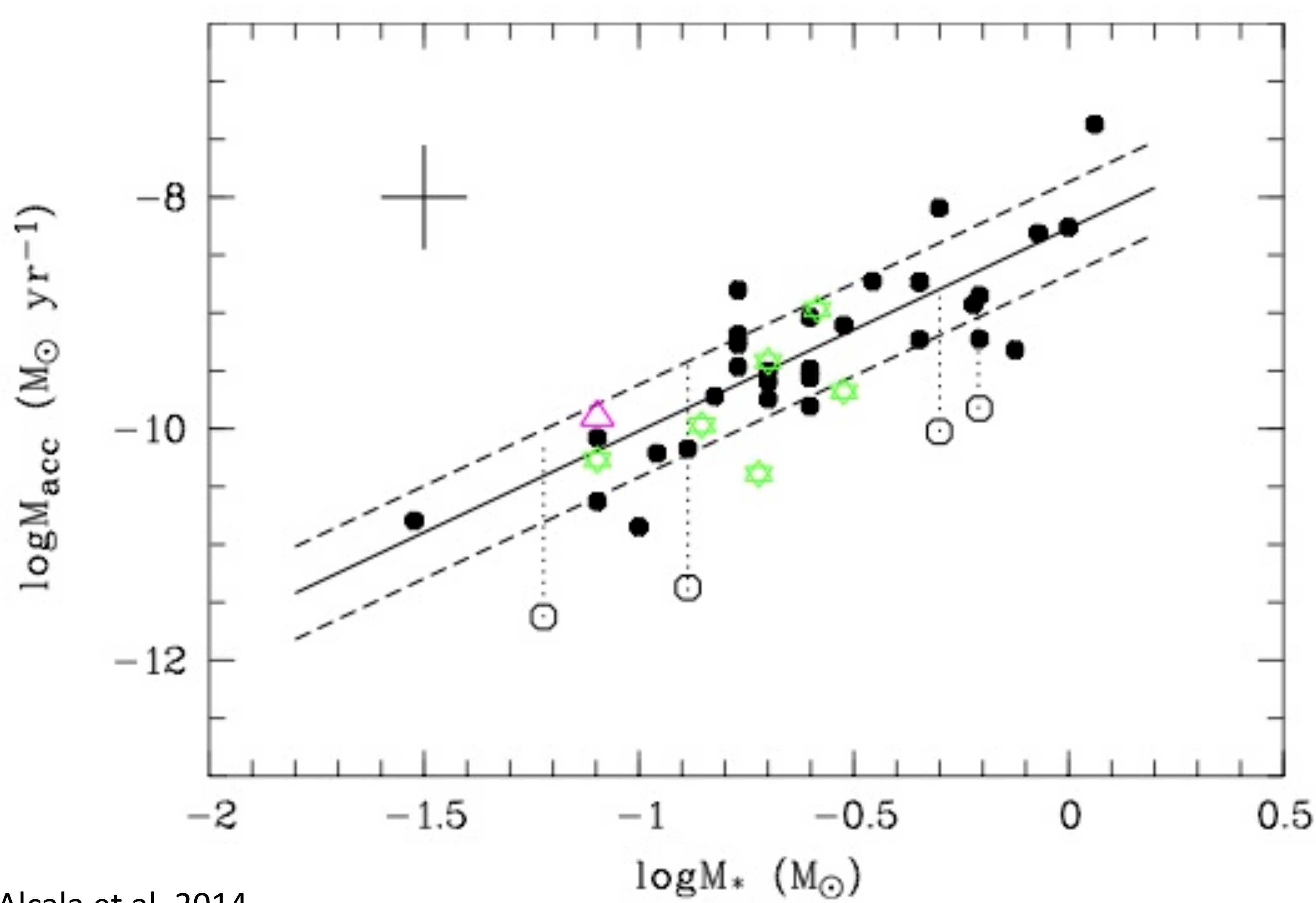


# X-shooter: UV excess + many lines + near-IR excess




Rigliaco et al. 2011

# Accretion rates decrease steadily from stars to BDs

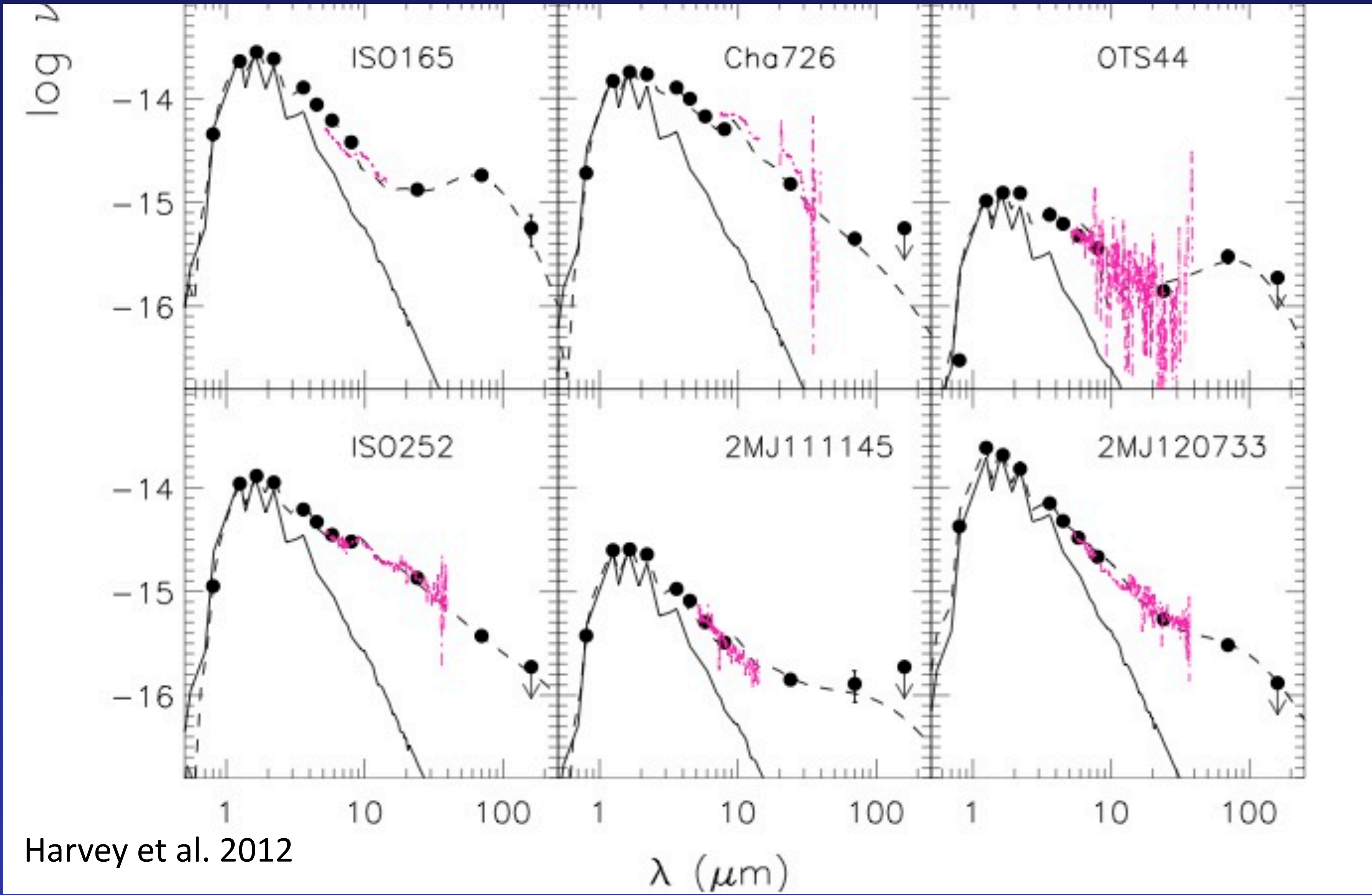



Alcala et al. 2014

# Far-IR and mm: BD disk masses ~ 0.001-10 $M_{Jup}$

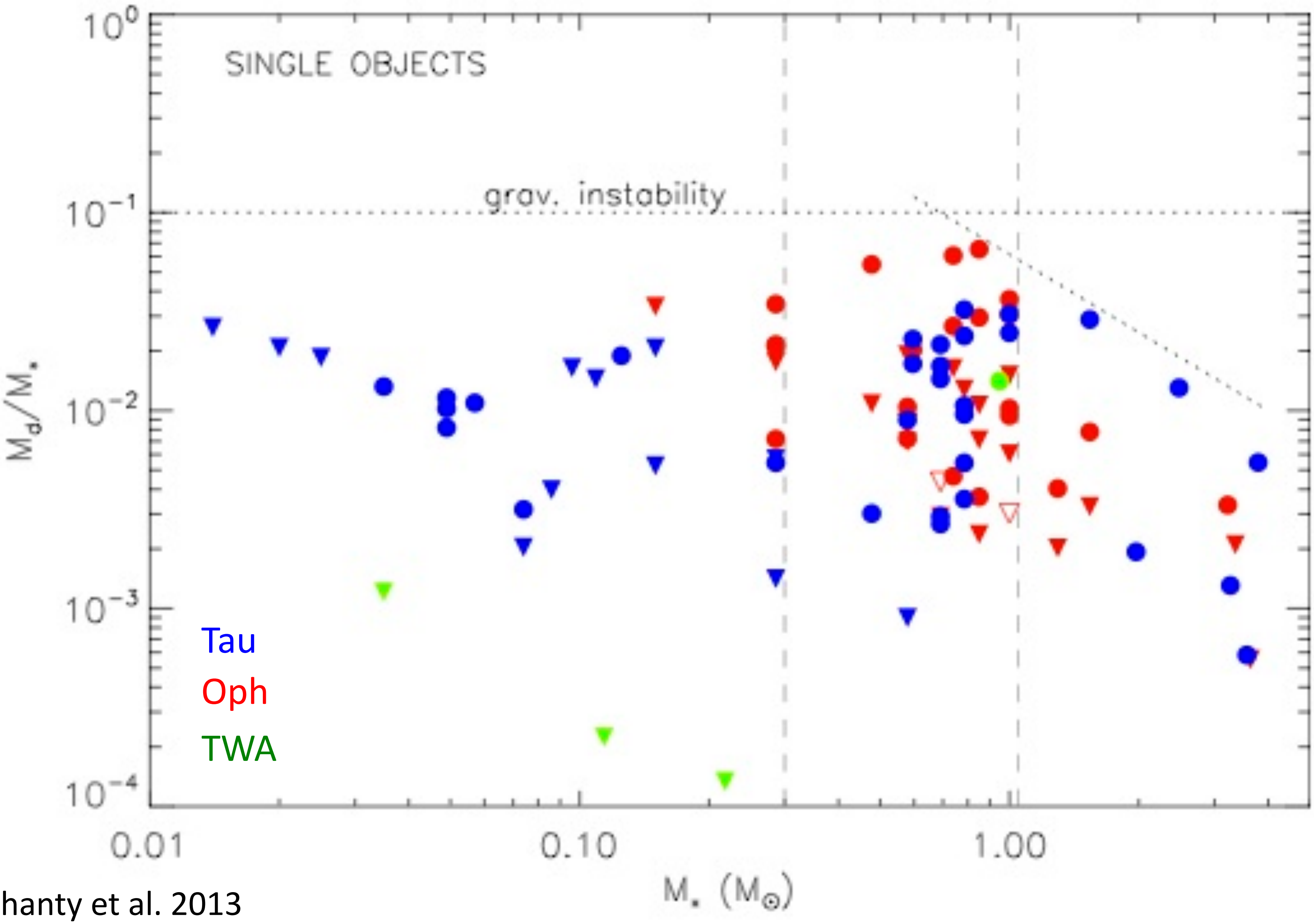
Far-IR: Harvey 2012a,b; Alves de Oliveira 2013

mm: Klein 2003; Scholz 2006; Ricci 2012, 2013; Mohanty 2013; Andrews 2013



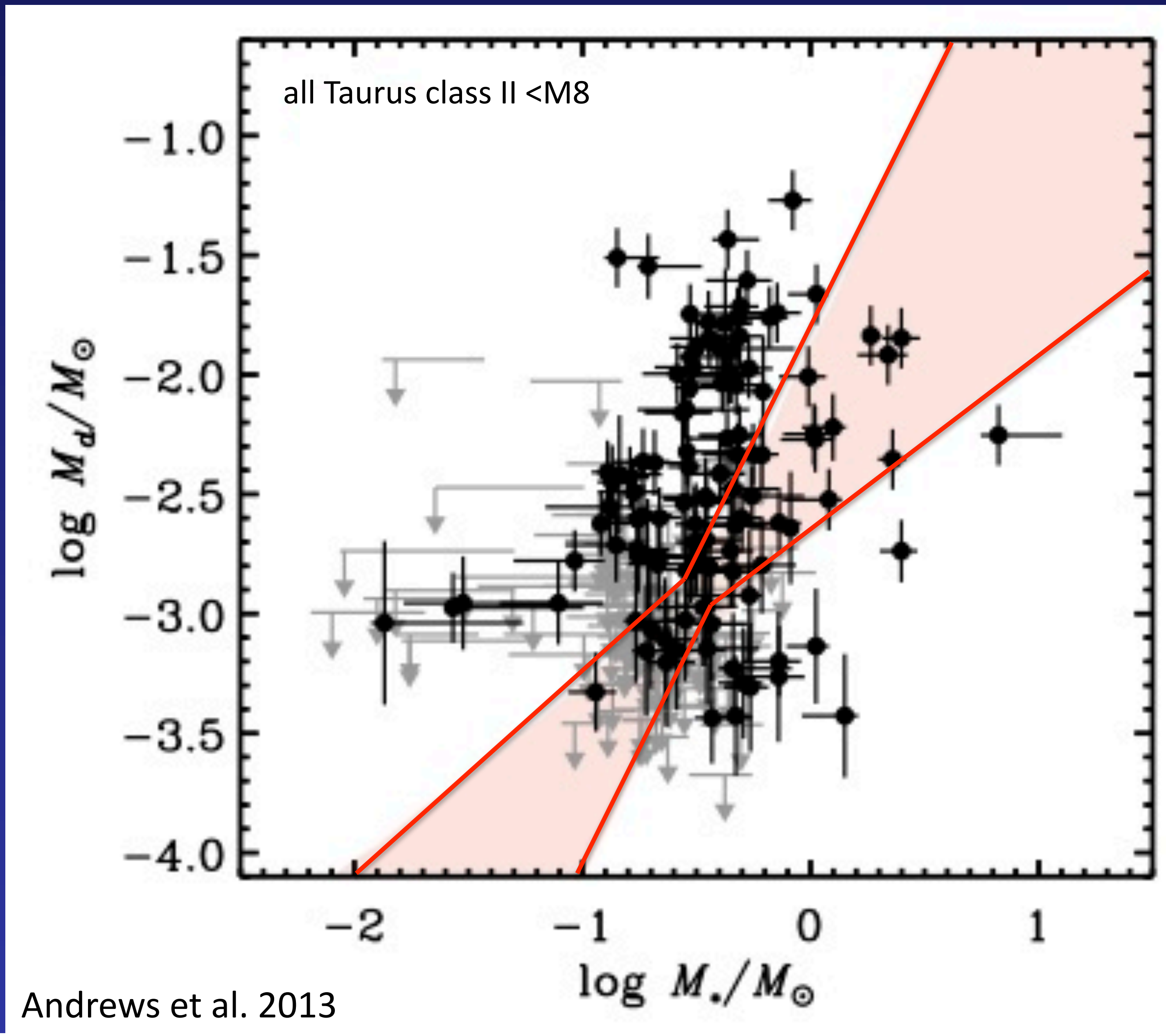

Harvey et al. 2012

# Disk mass/star mass roughly constant at ~ 0.4%




Mohanty et al. 2013

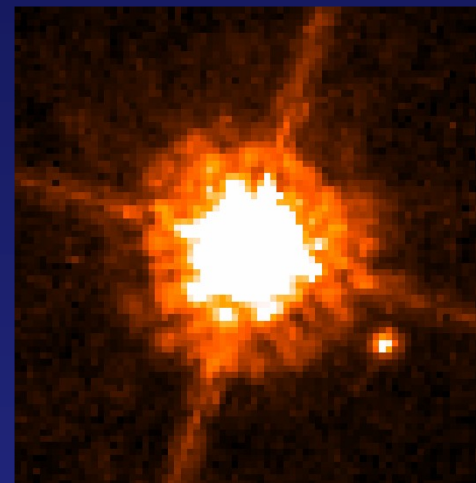
# Disk mass/star mass roughly constant at ~ 0.4%



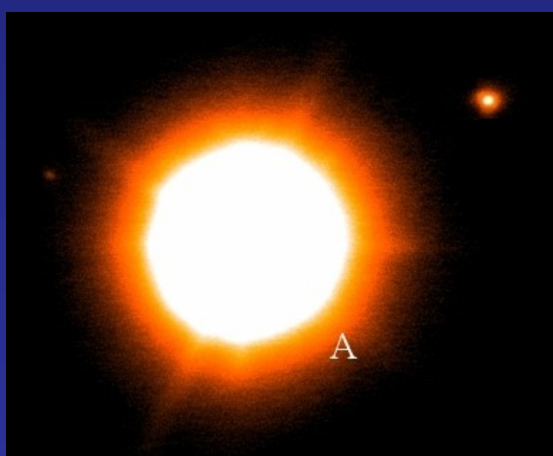

Andrews et al. 2013

# Companions that are young, wide, and $<20\ M_{Jup}$

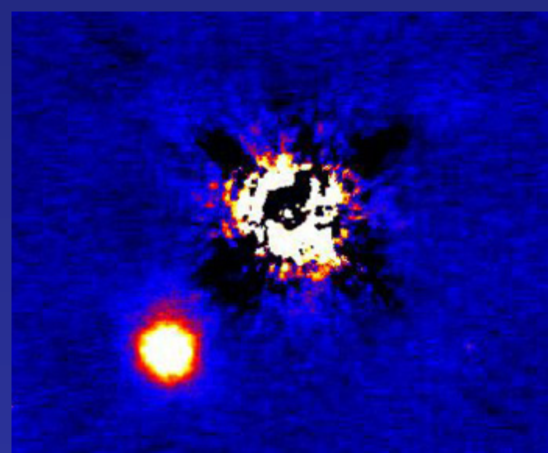
2M 1207B
Chauvin et al. 2004



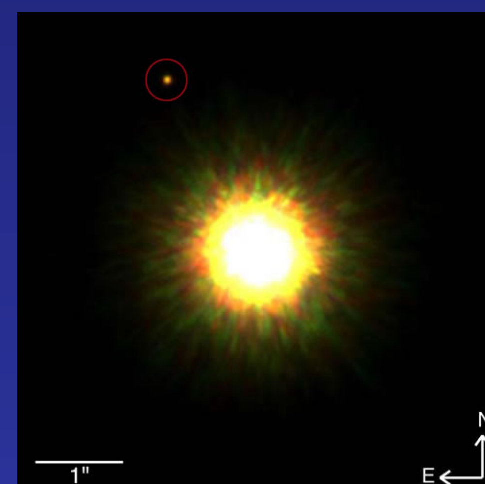
CHXR73B
Luhman et al. 2006




CT Cha B
Schmidt et al. 2008

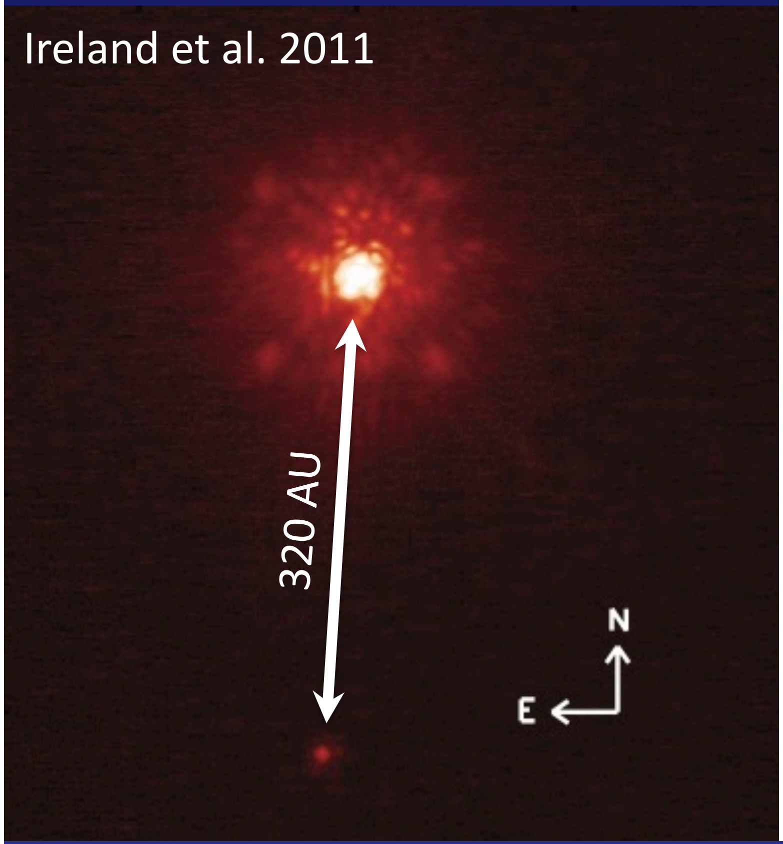


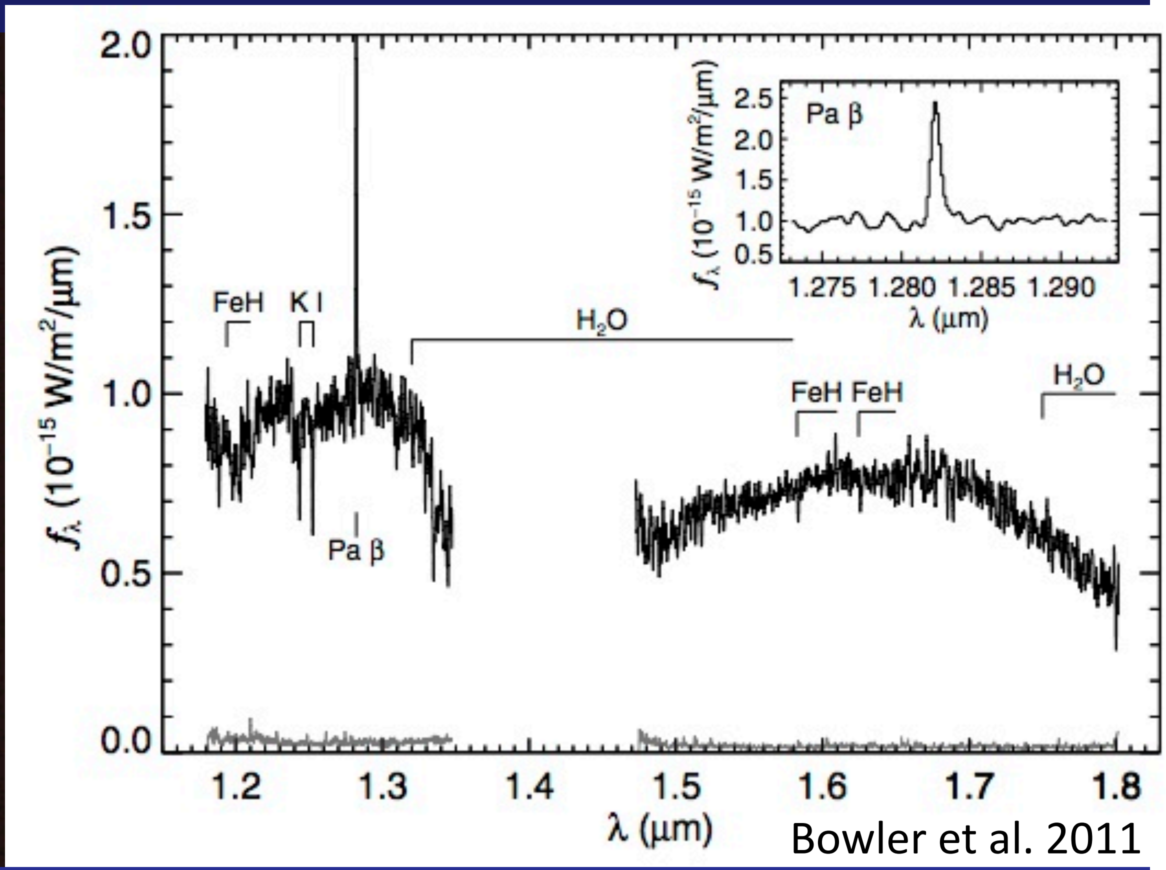
DH Tau B
Itoh et al. 2005



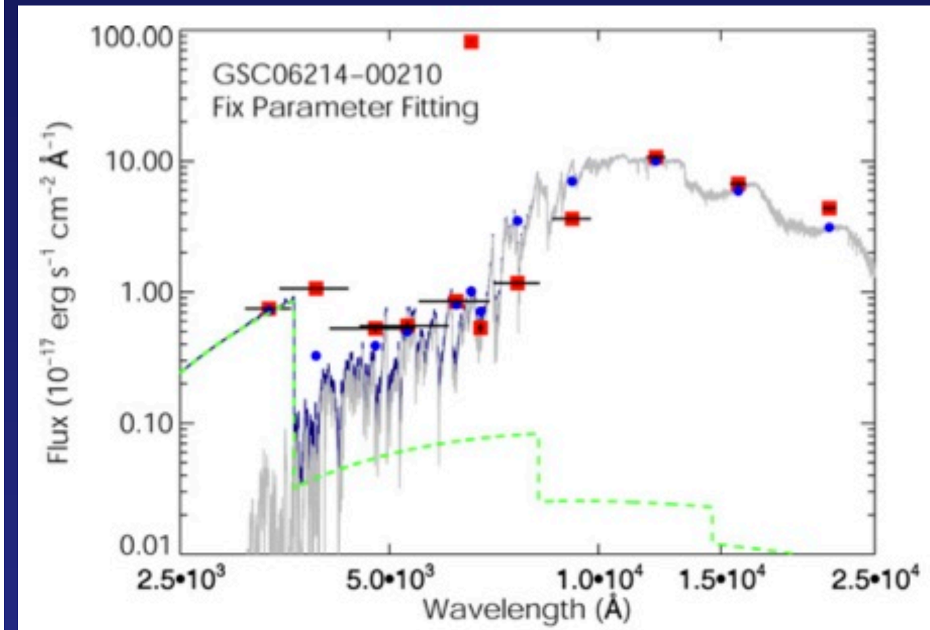

1609-2105B
Lafreniere et al. 2008

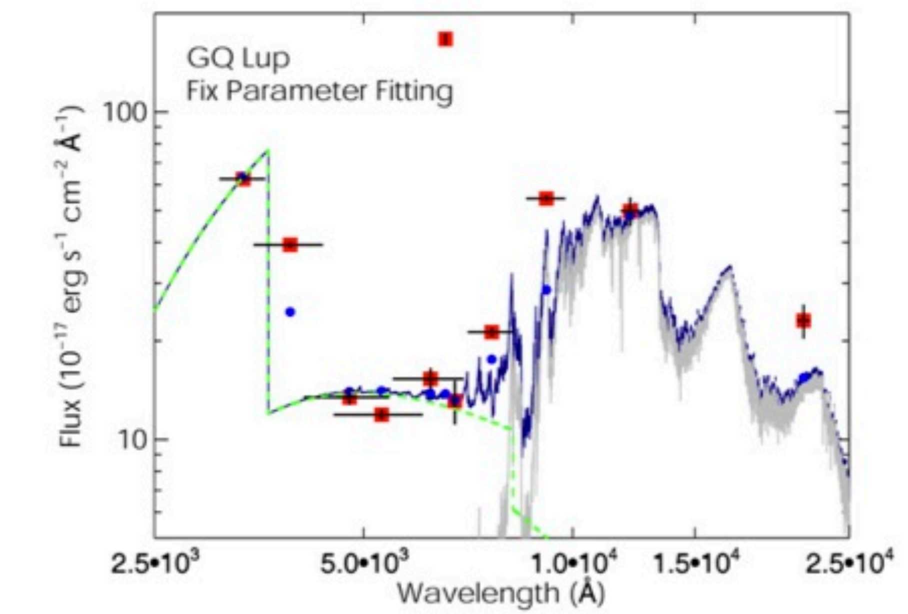
# Accretion detected in wide 15-30 $M_{Jup}$ companions

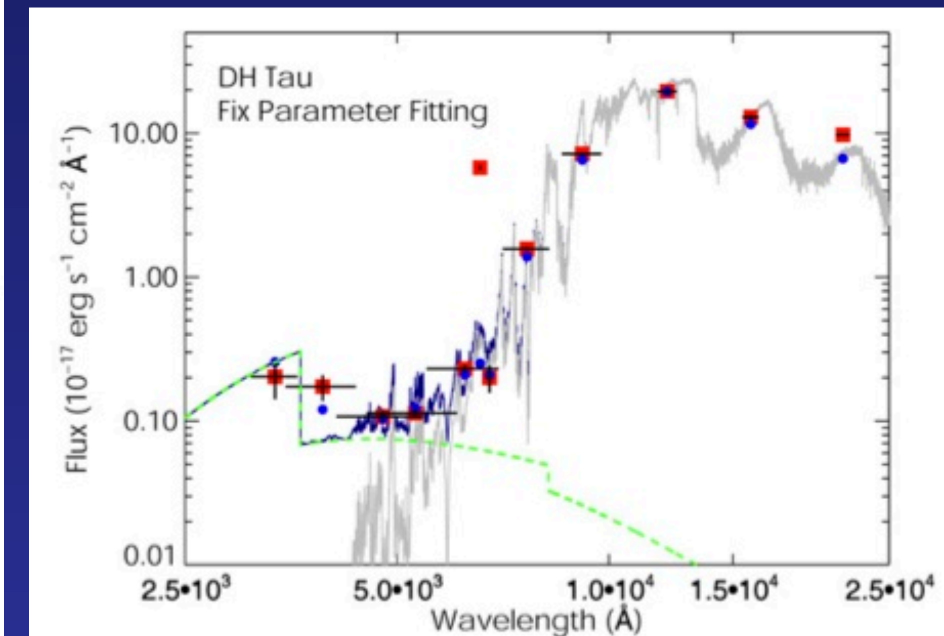


# Accretion detected in wide 15-30 $M_{Jup}$ companions

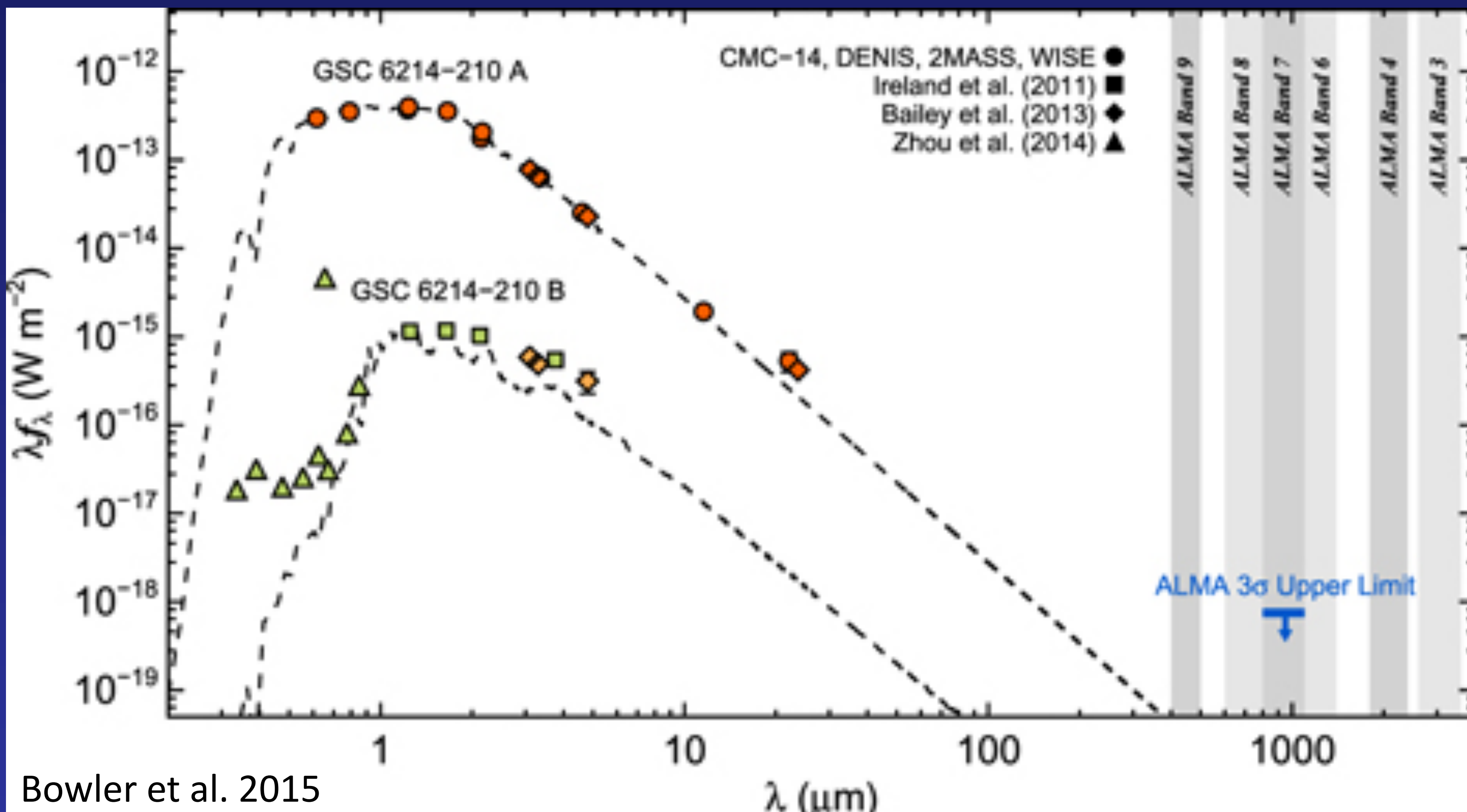


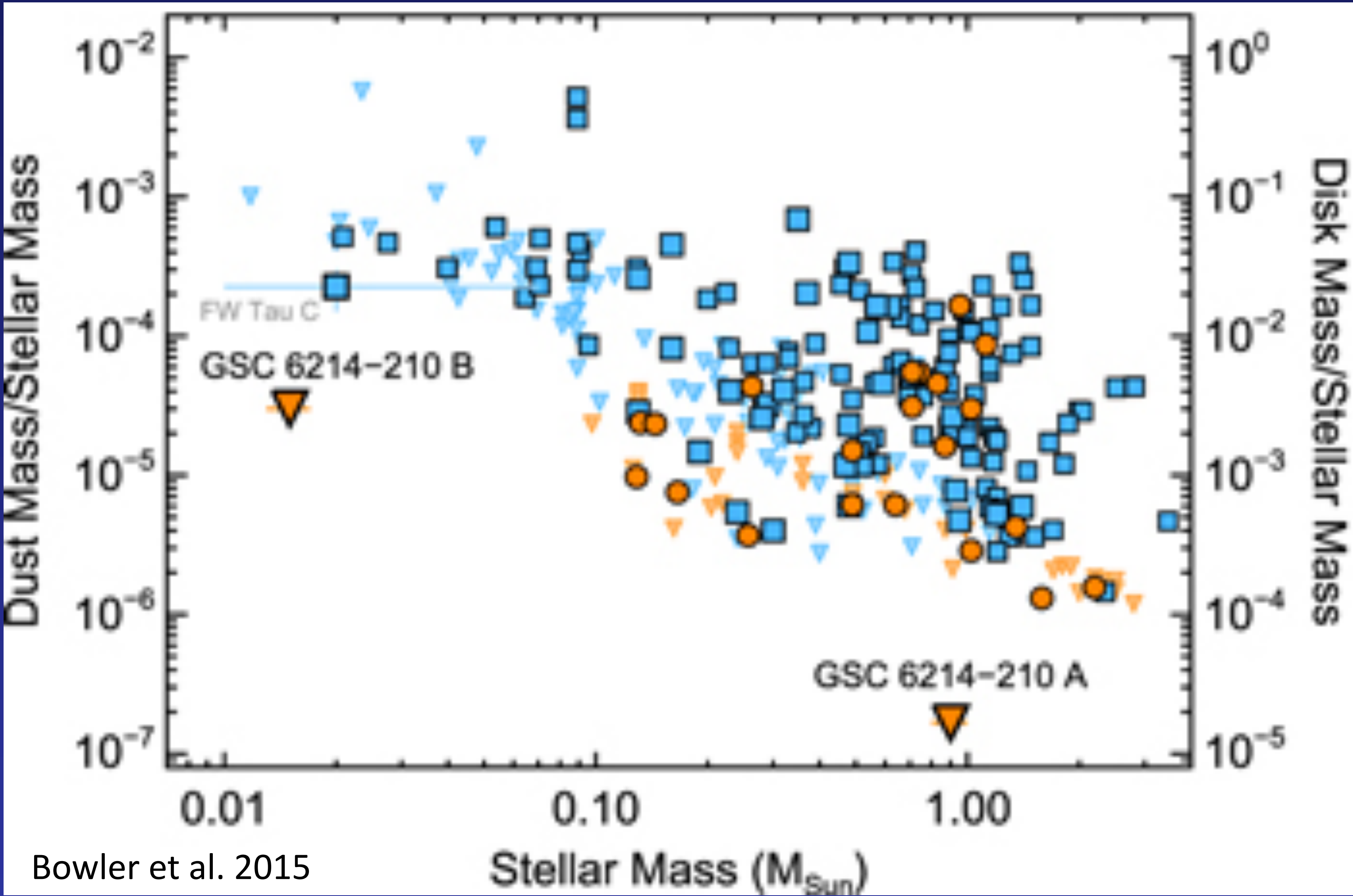

Zhou et al. 2014

# ALMA non-detection: $M_{disk} < 0.05\ M_{Jup}$



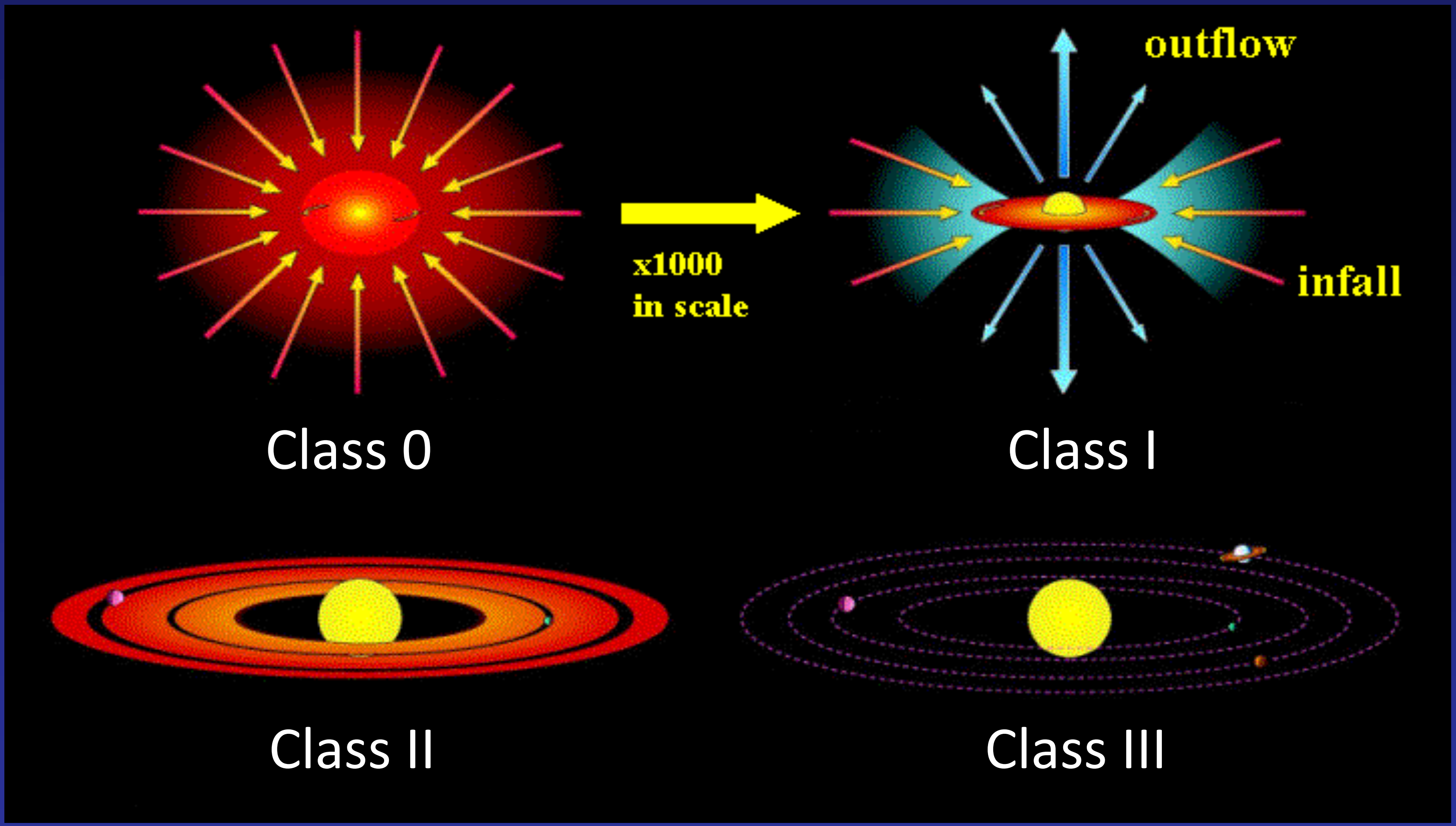

Bowler et al. 2015

ALMA non-detection: $M_{disk}/M_{BD} < 0.3\%$



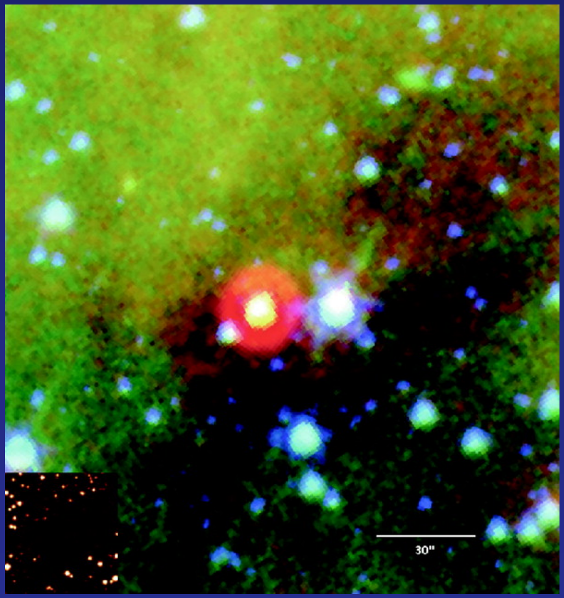

Bowler et al. 2015

# Do brown dwarfs undergo the protostellar phases like stars?



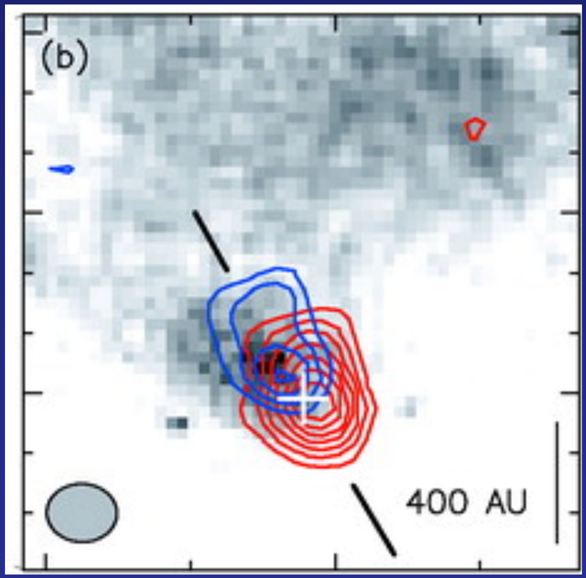
# Spitzer has found possible protostellar brown dwarfs, which are not predicted by dynamical models

Spitzer image of L1014




Young et al. 2004

CO outflow in L1014



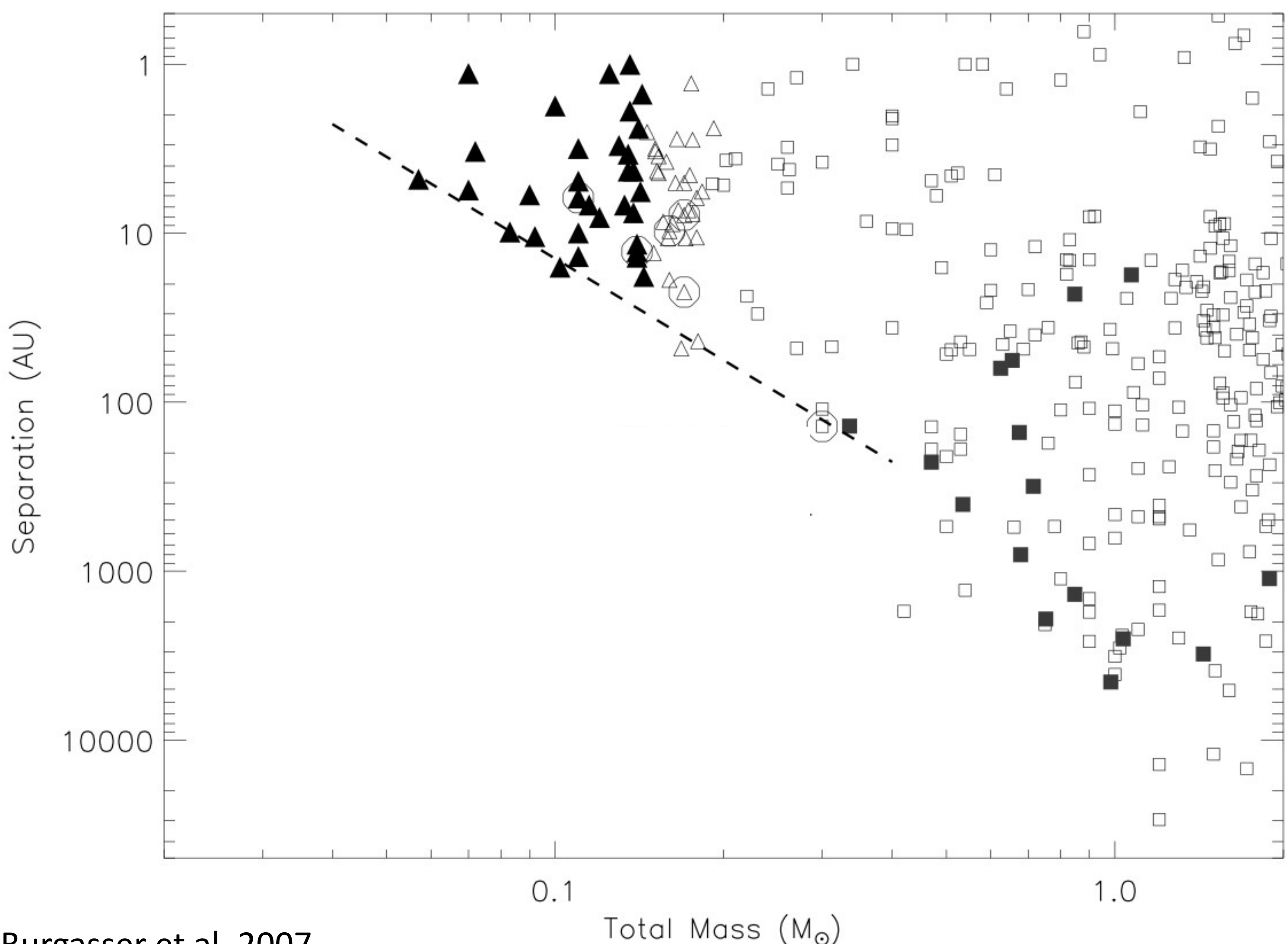

Bourke et al. 2005

See also: Huard et al. 2006, Dunham et al. 2006, 2008, André et al. 2012

# Outline

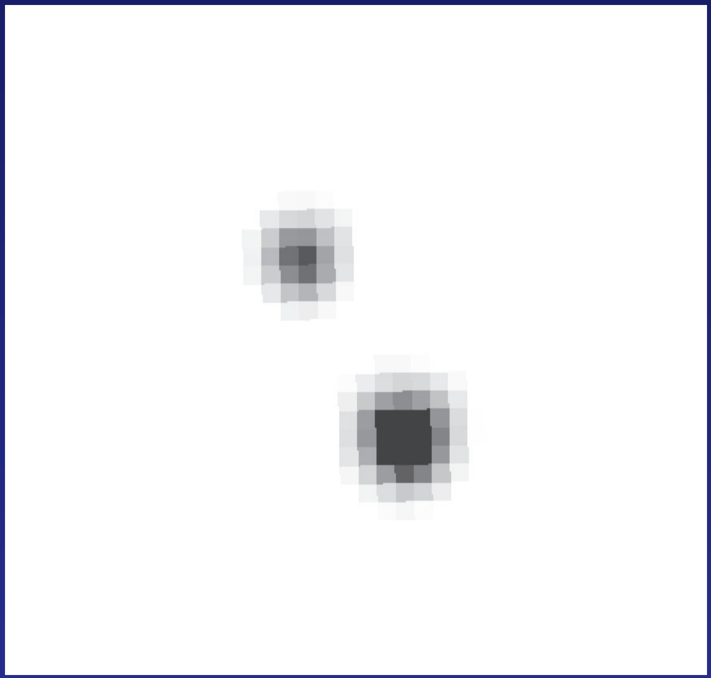
- Definitions
- Models of Brown Dwarf Formation
- Mass Functions
- Circumstellar Disks
- Binary Properties

# Most binary brown dwarfs have small separations (<20 AU)

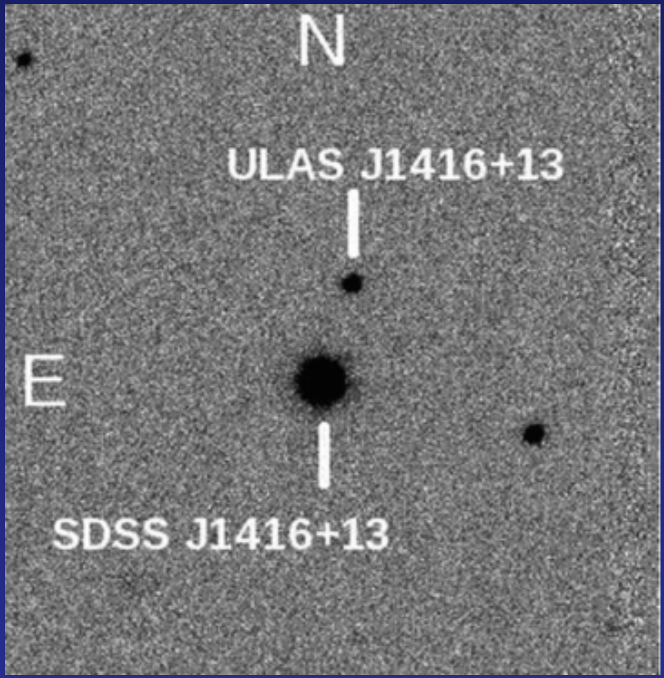



Burgasser et al. 2007

# But a few binary brown dwarfs are wide (>100 AU)

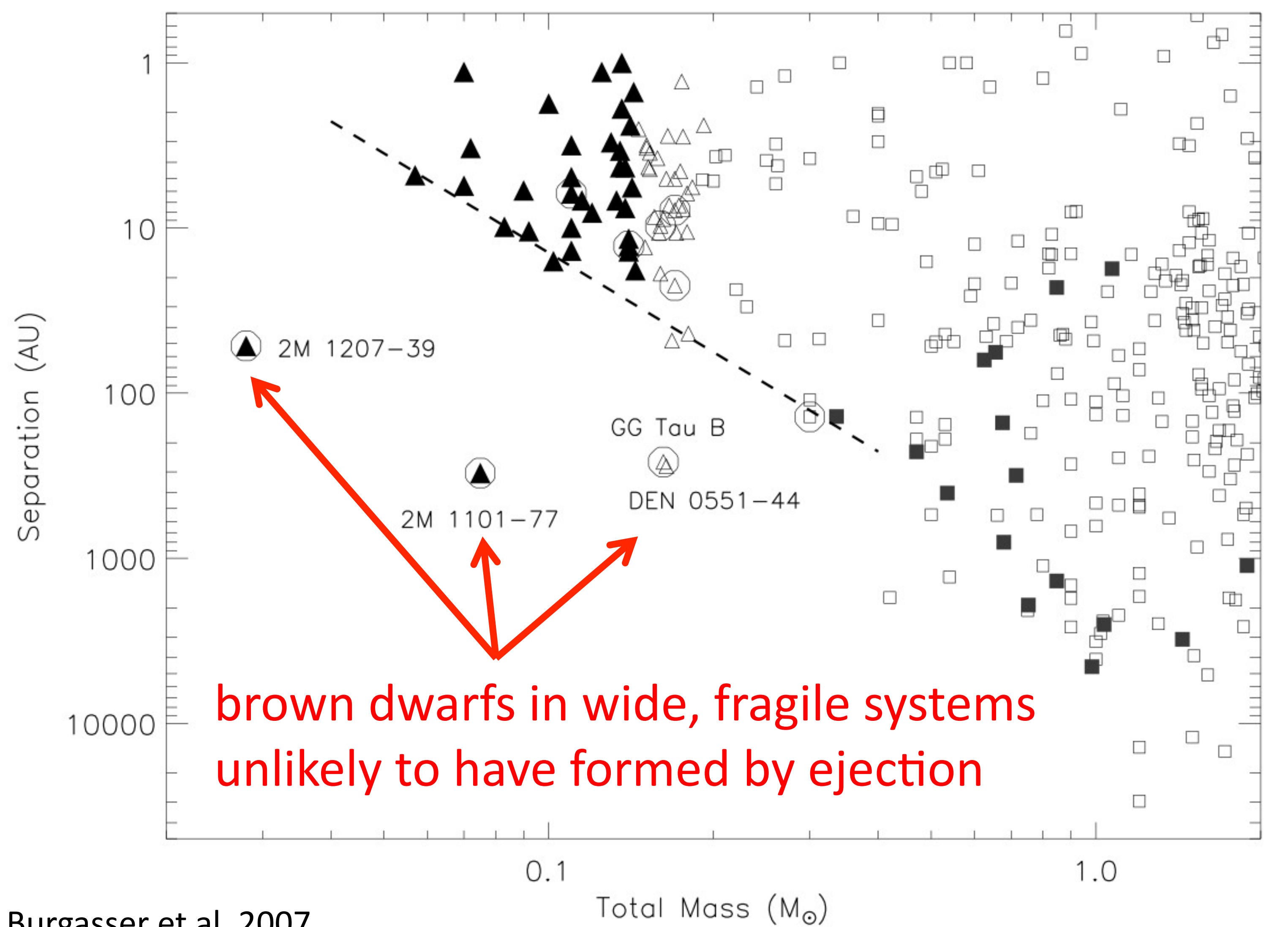


Young Clusters
Luhman 2004



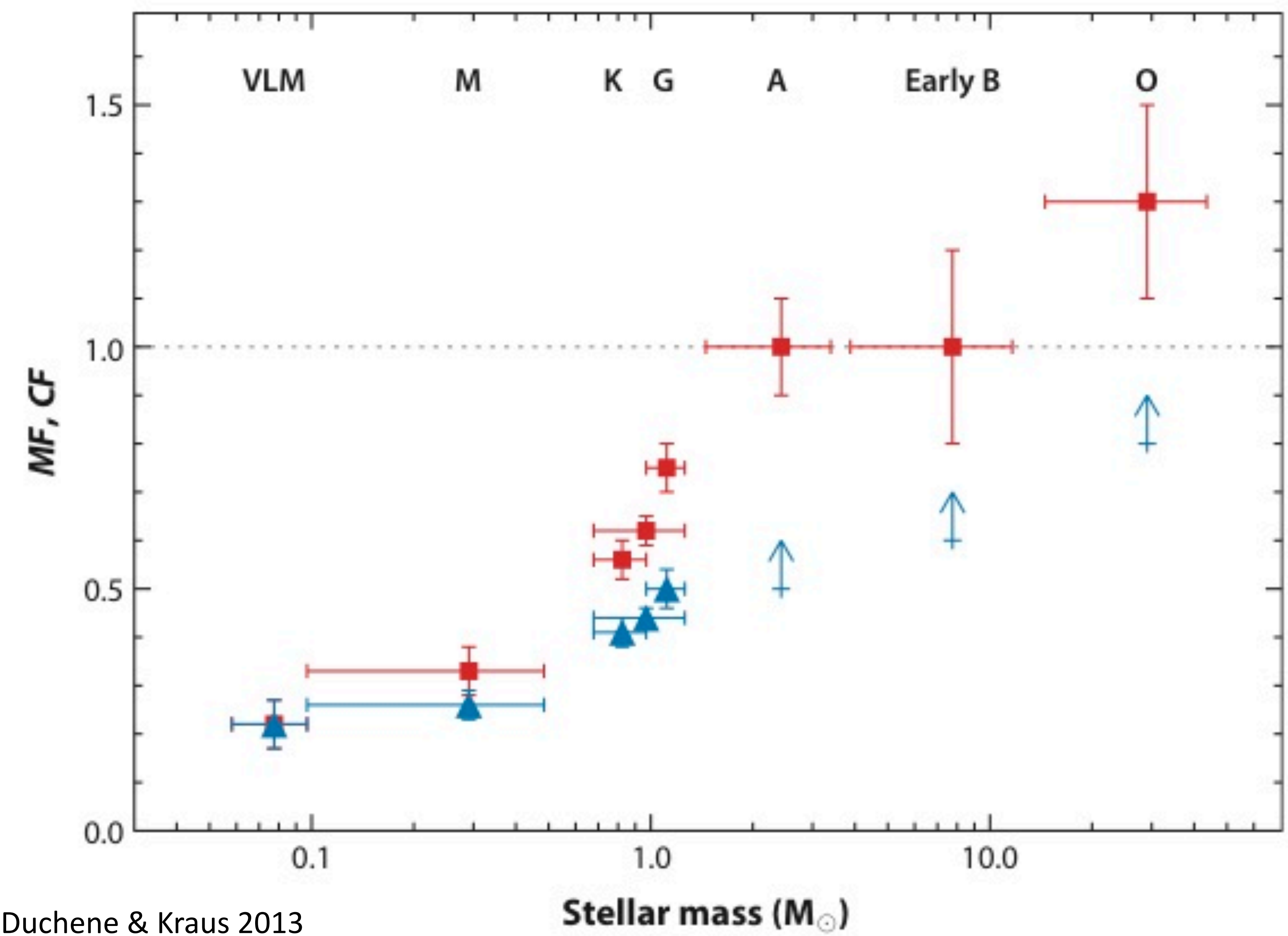

Field
Burningham et al. 2010
Scholz et al. 2010

# But a few binary brown dwarfs are wide (>100 AU)



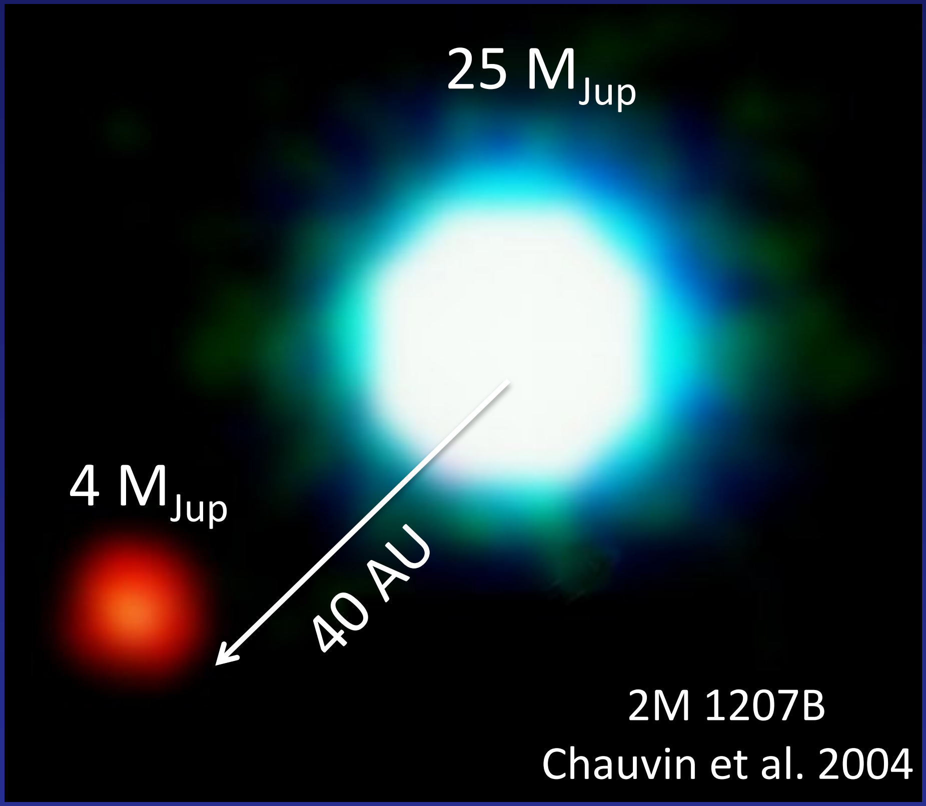

Burgasser et al. 2007

# Binary frequency decreases steadily with lower mass



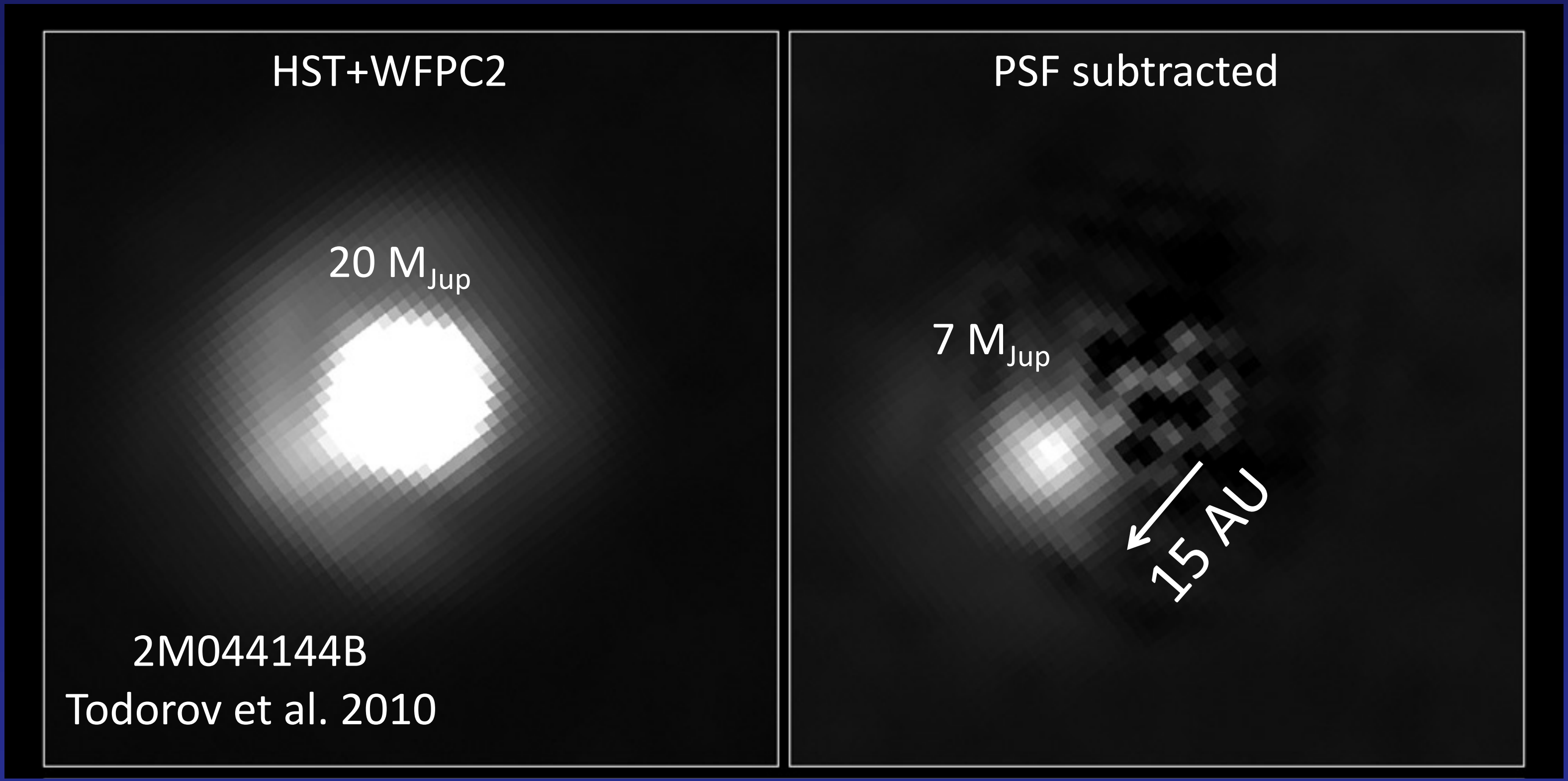

Duchene & Kraus 2013

# Indicator of formation mechanism: mass ratio ($M_2/M_1$)



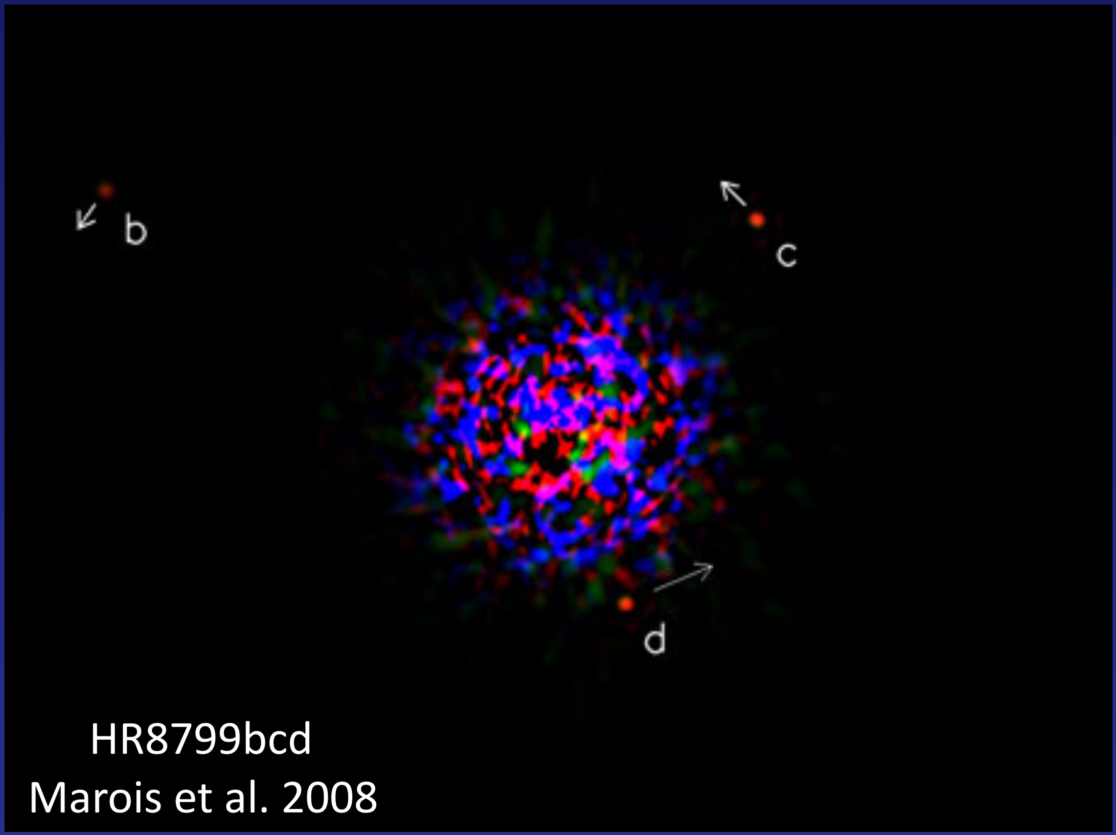

Large mass ratio ➔ formed like a binary star

# Indicator of formation mechanism: mass ratio ($M_2/M_1$)



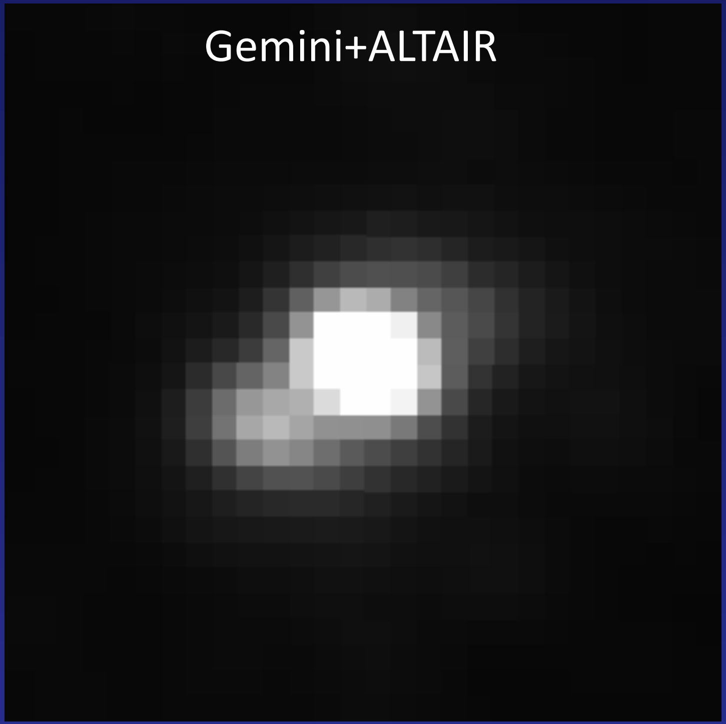

Large mass ratio ➔ formed like a binary star

# Indicator of formation mechanism: configuration of orbits

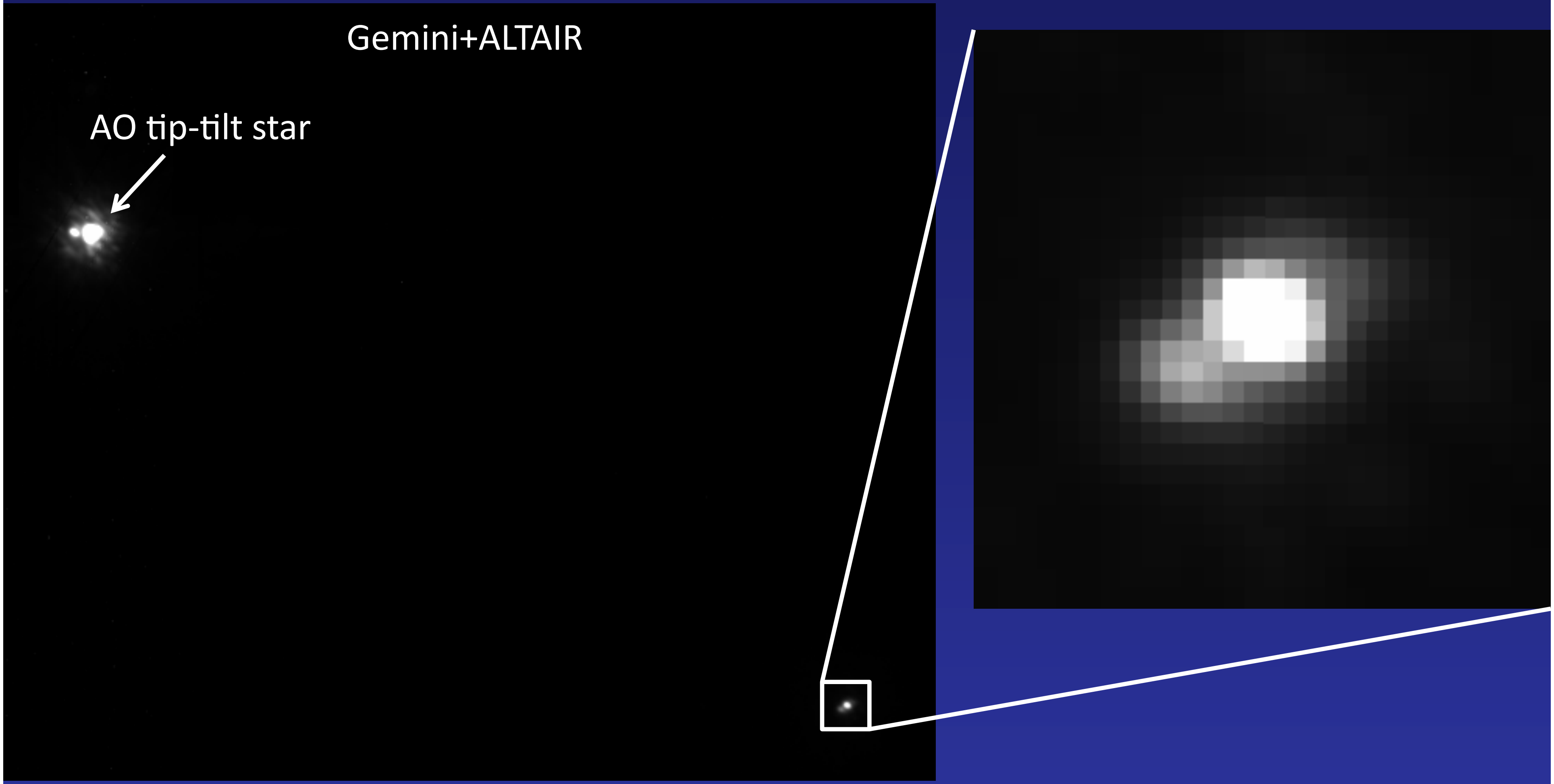



Three small objects orbiting a much larger primary
➔ formation in a disk

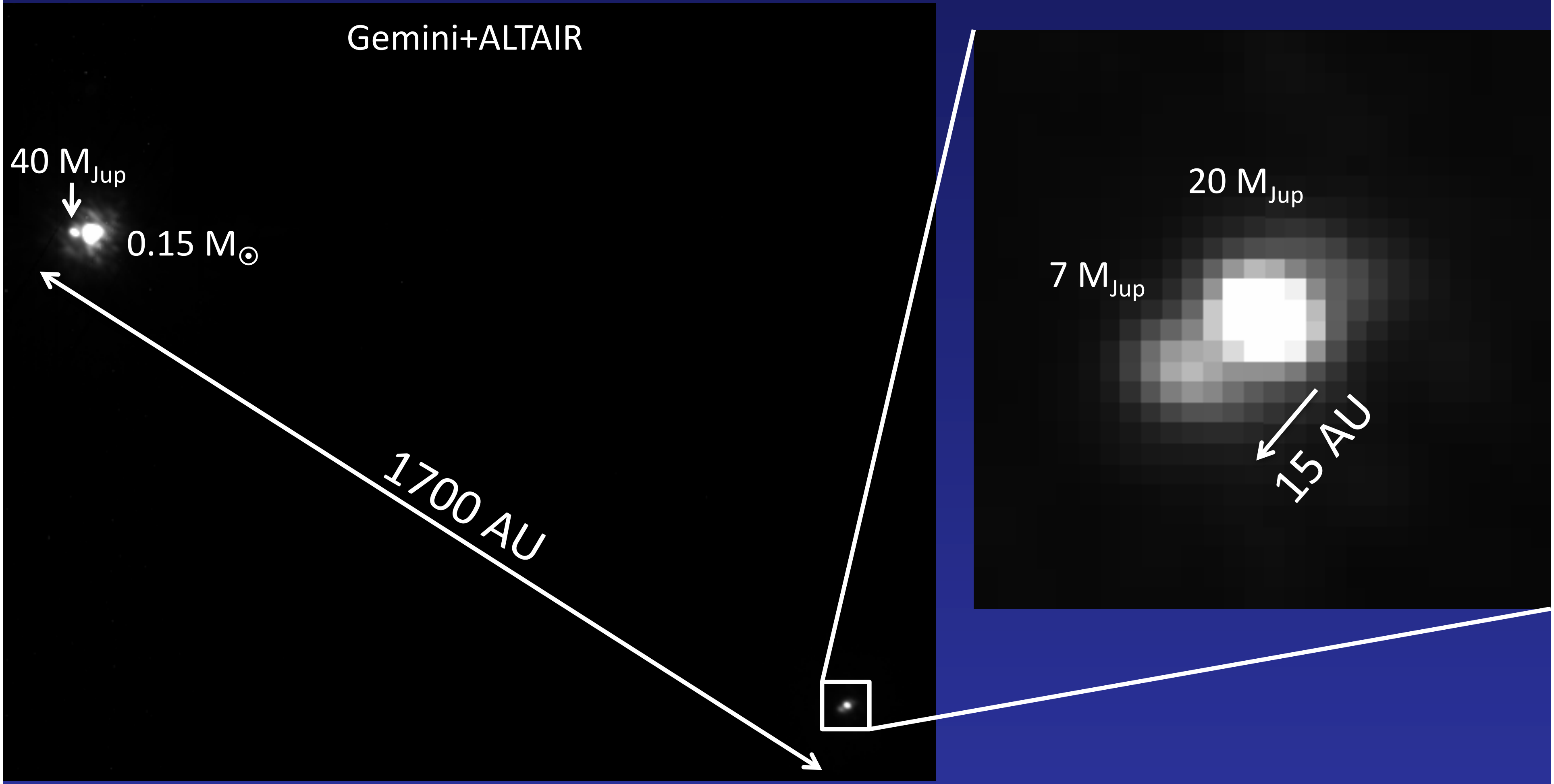
# Indicator of formation mechanism: configuration of orbits

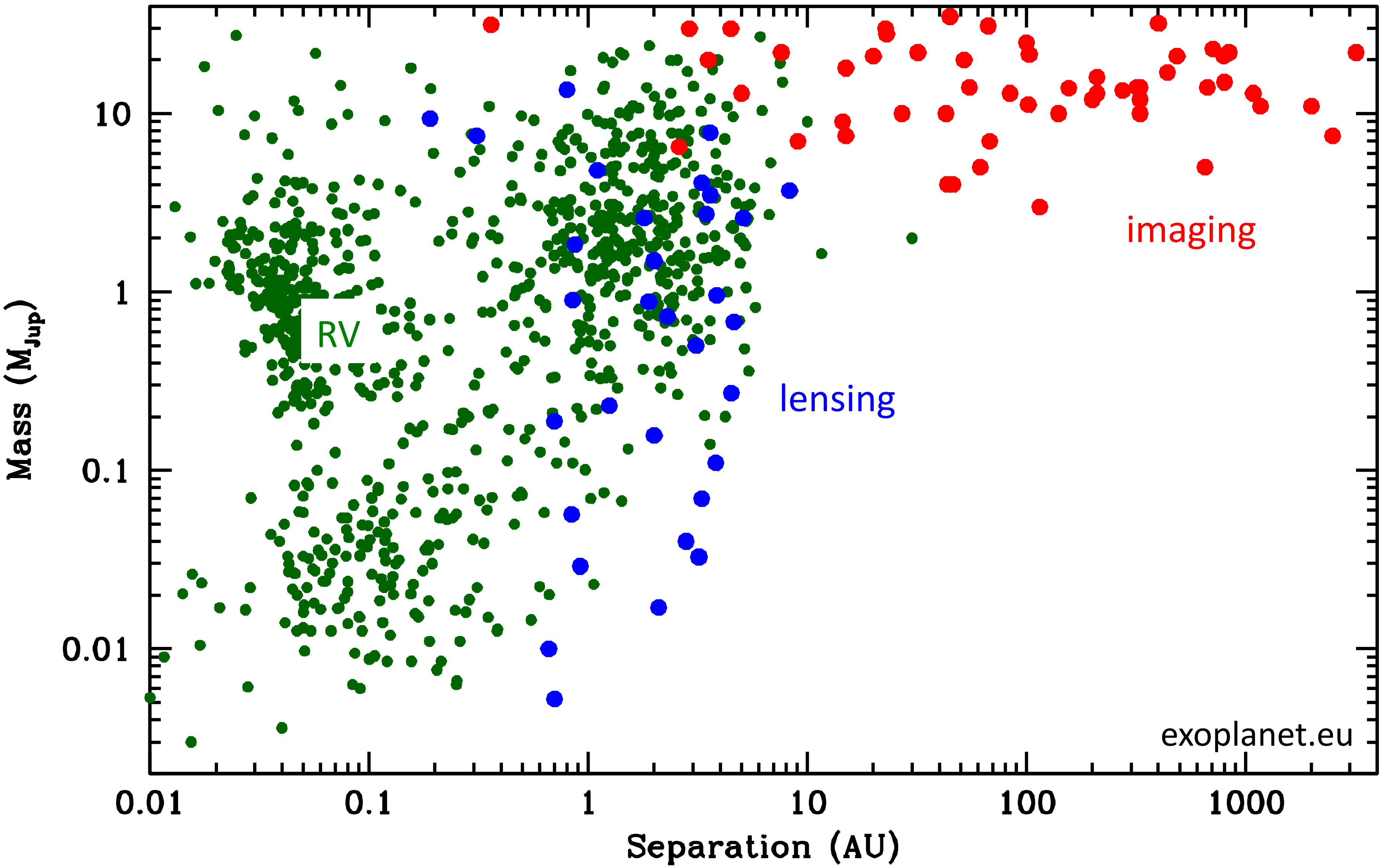
# Indicator of formation mechanism: configuration of orbits



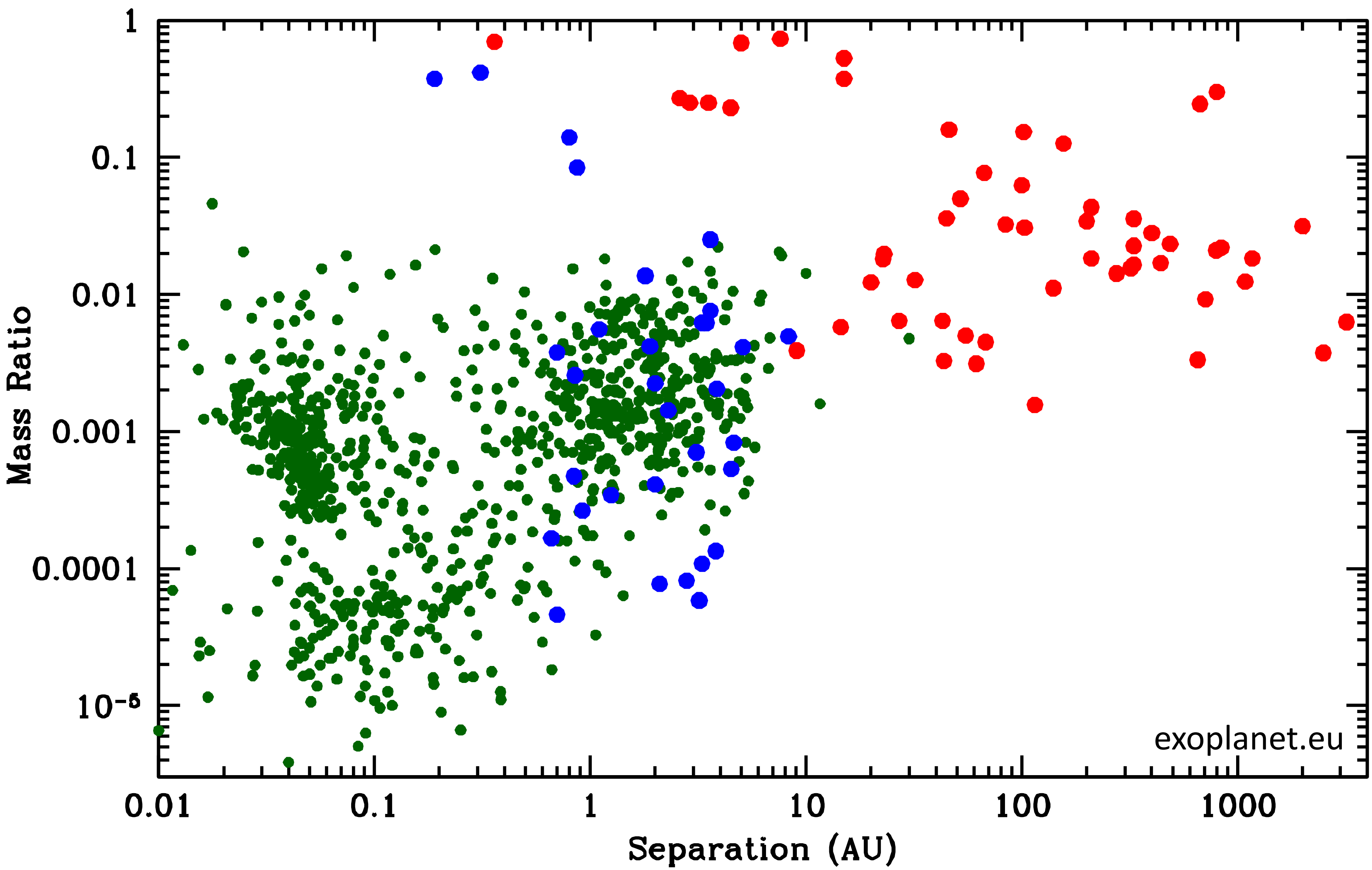
# Indicator of formation mechanism: configuration of orbits



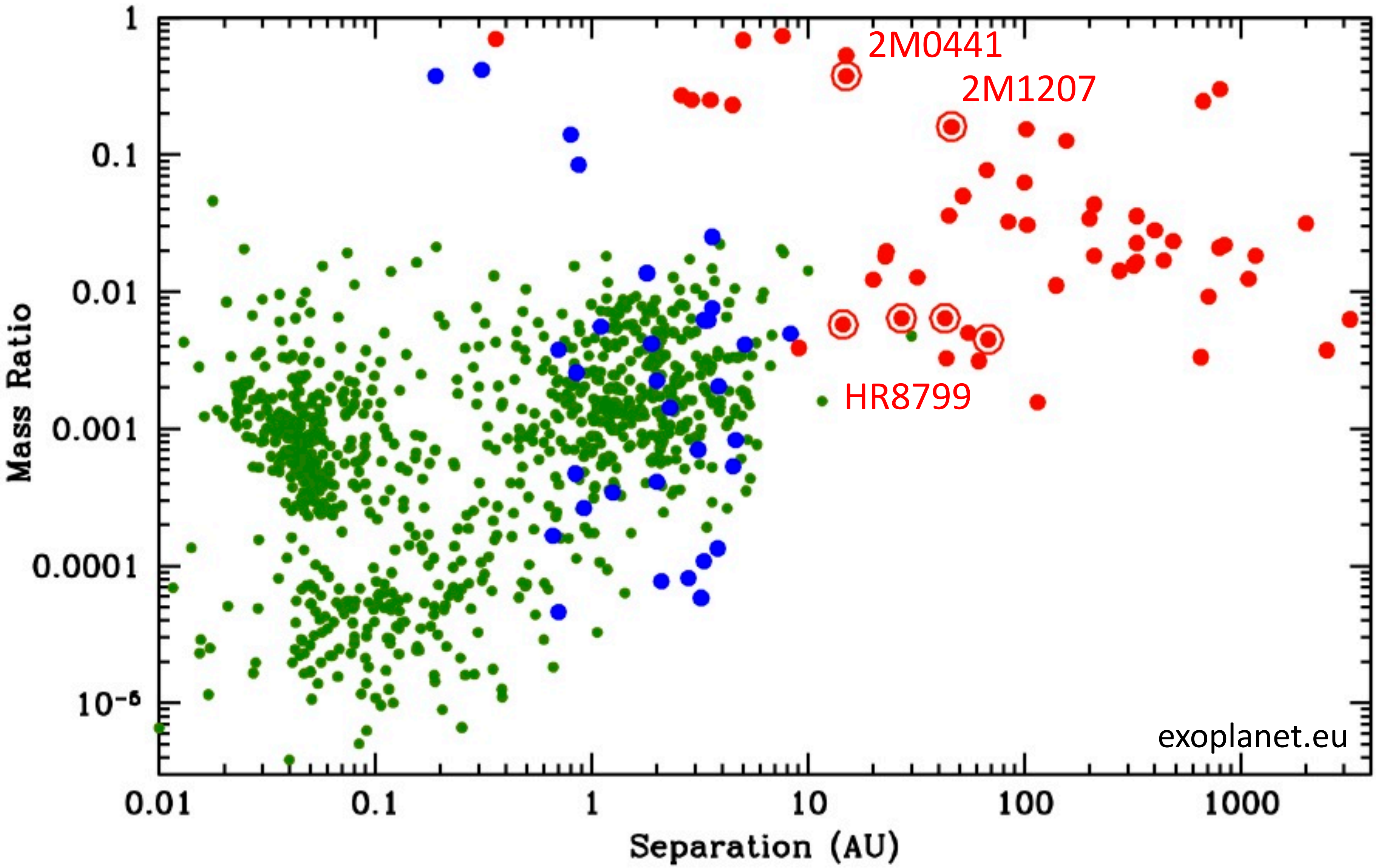

Hierarchical configuration ➔ cloud core fragmentation



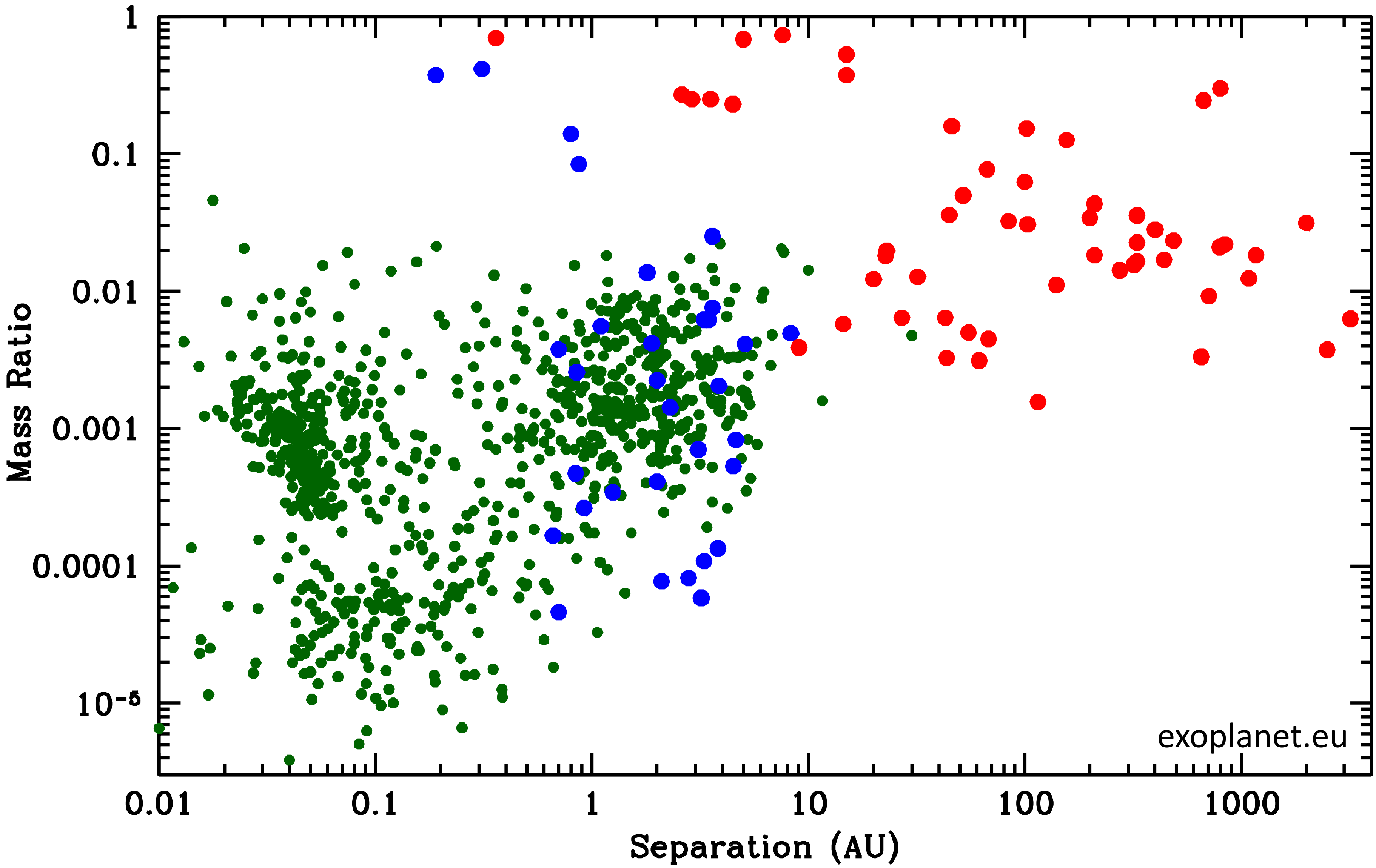
10
1
0.1
0.01
Mass ($M_{Jup}$)
0.01
0.1
1
10
100
1000
Separation (AU)
RV
lensing
imaging
exoplanet.eu



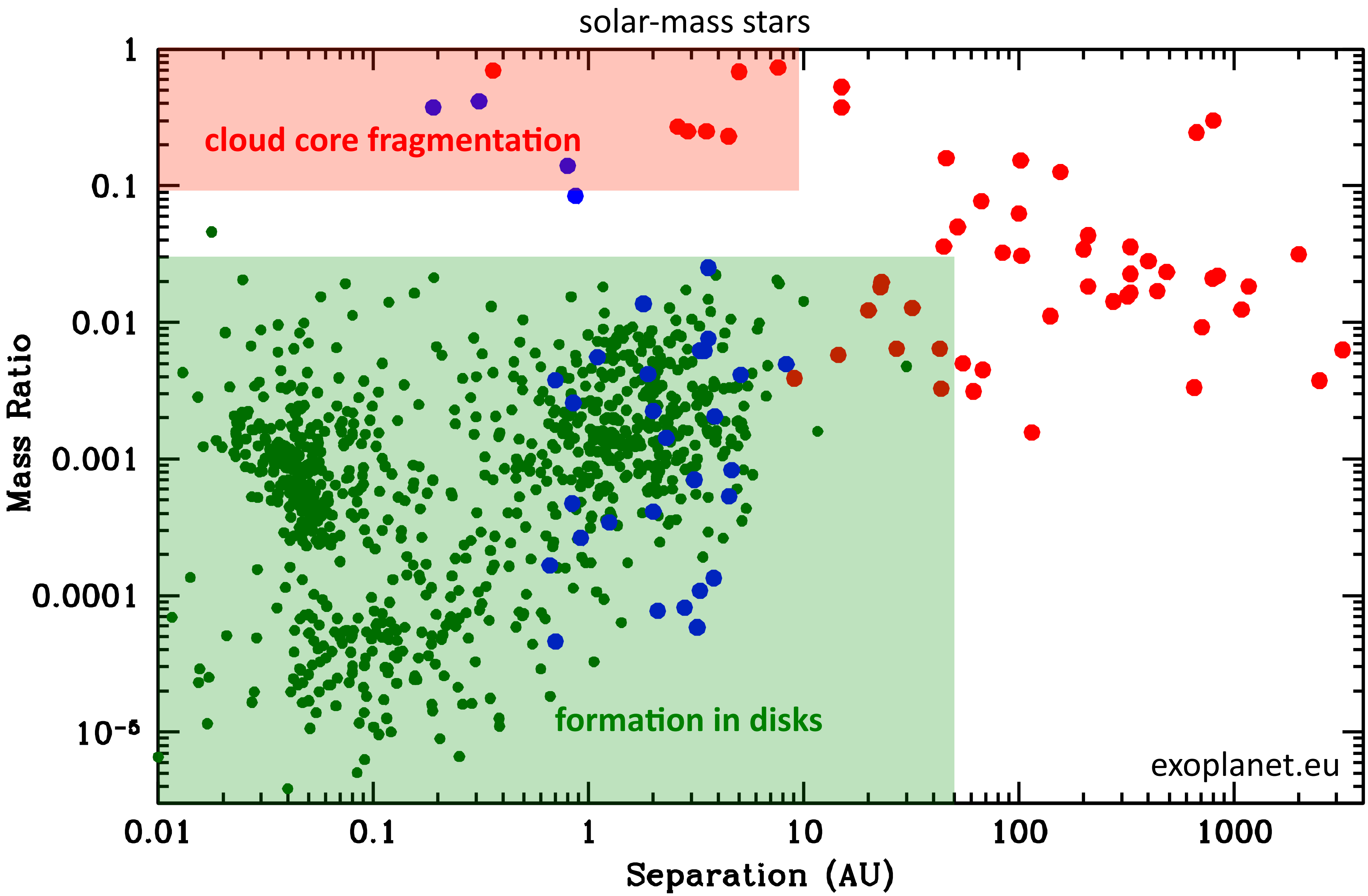
1
0.1
0.01
0.001
0.0001
$10^{-5}$
Mass Ratio
0.01
0.1
1
10
100
1000
Separation (AU)
exoplanet.eu

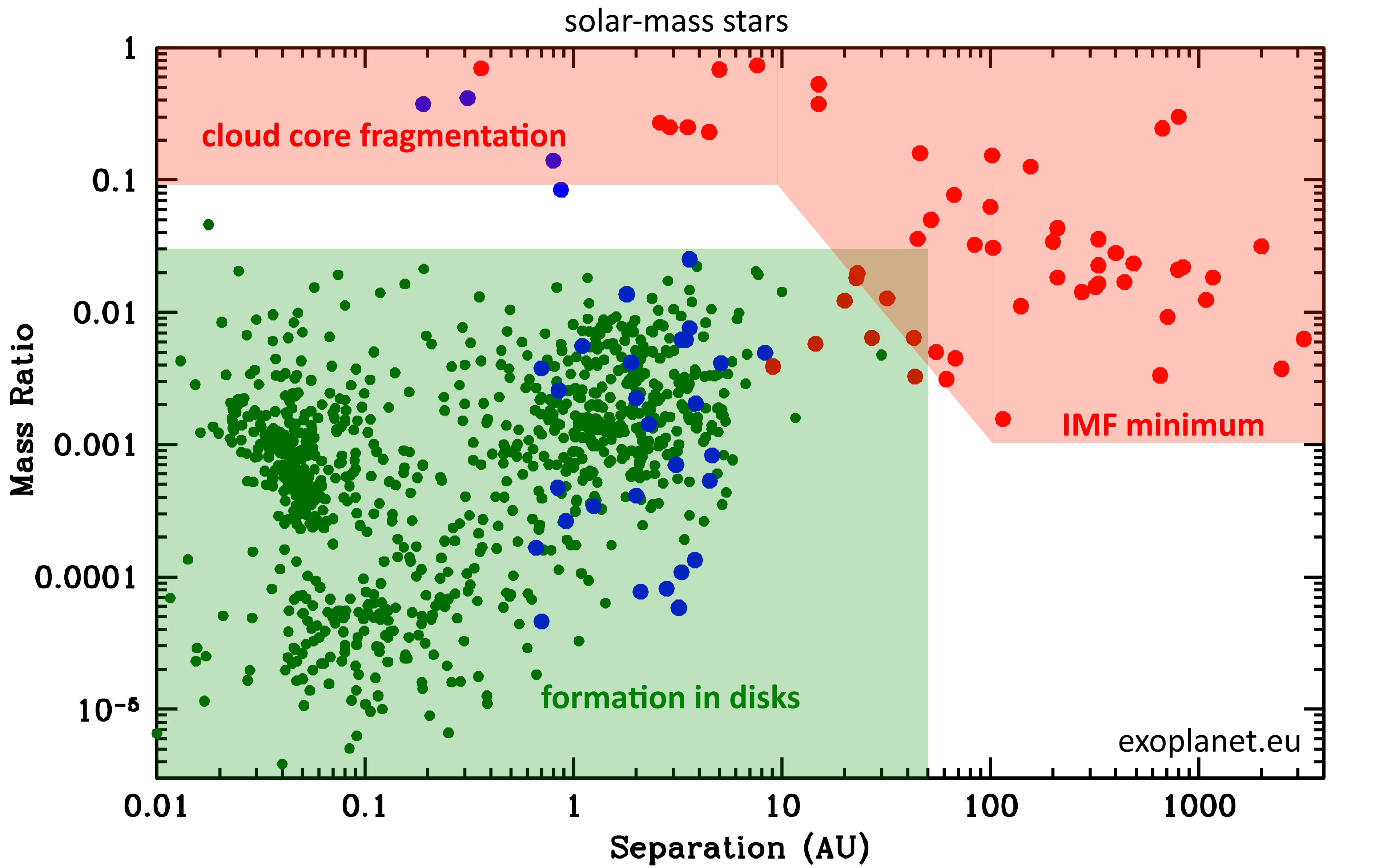


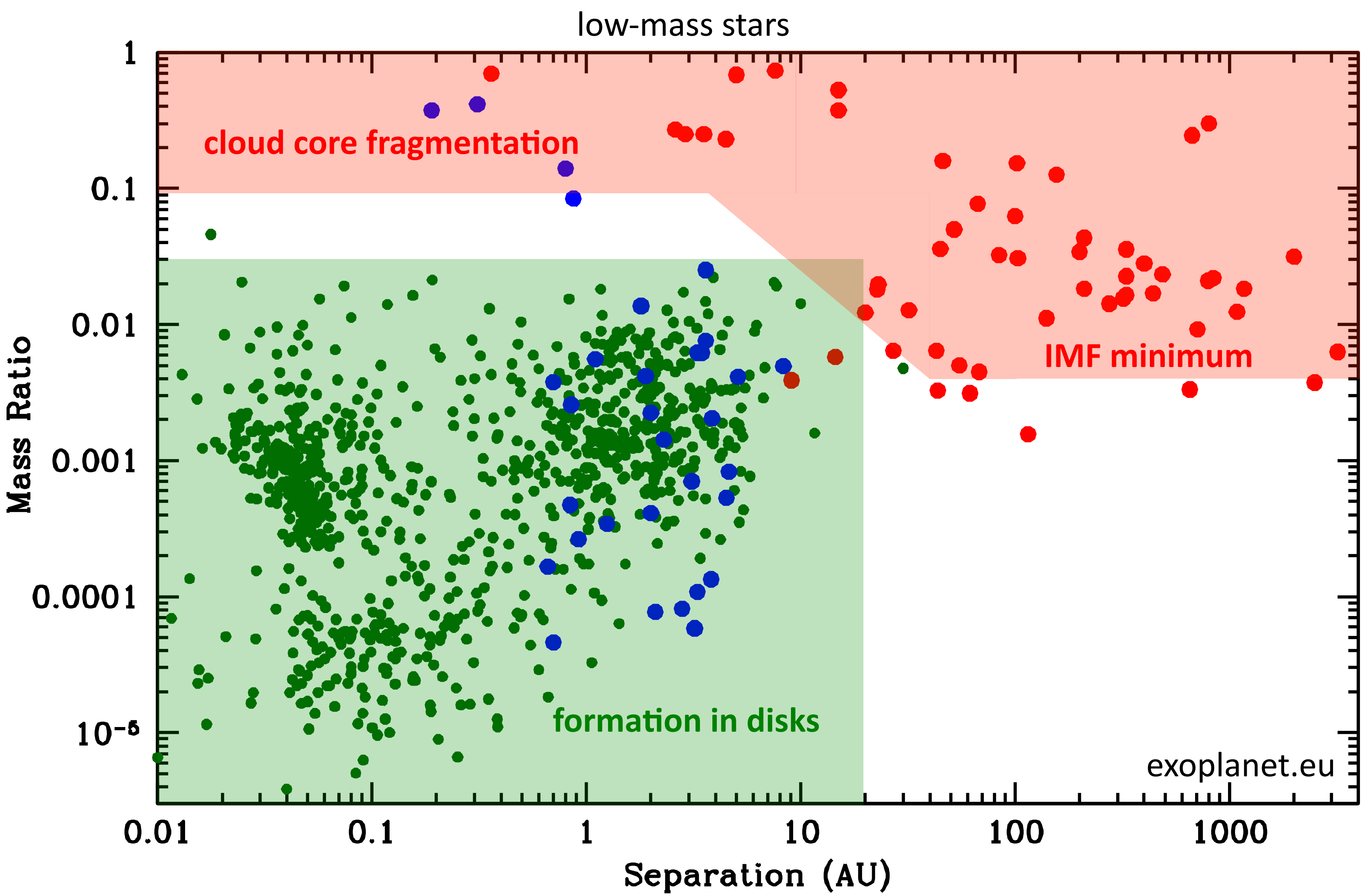
2M0441
2M1207
HR8799
exoplanet.eu
Mass Ratio
1
0.1
0.01
0.001
0.0001
$10^{-5}$
0.01
0.1
1
10
100
1000
Separation (AU)



1
0.1
0.01
0.001
0.0001
$10^{-5}$
Mass Ratio
0.01
0.1
1
10
100
1000
Separation (AU)
exoplanet.eu


solar-mass stars
cloud core fragmentation
formation in disks
exoplanet.eu
Mass Ratio
1
0.1
0.01
0.001
0.0001
10⁻⁵
0.01
0.1
1
10
100
1000
Separation (AU)


solar-mass stars
cloud core fragmentation
IMF minimum
formation in disks
exoplanet.eu
Mass Ratio
1
0.1
0.01
0.001
0.0001
10⁻⁵
Separation (AU)
0.01
0.1
1
10
100
1000



low-mass stars
cloud core fragmentation
IMF minimum
formation in disks
exoplanet.eu
Mass Ratio
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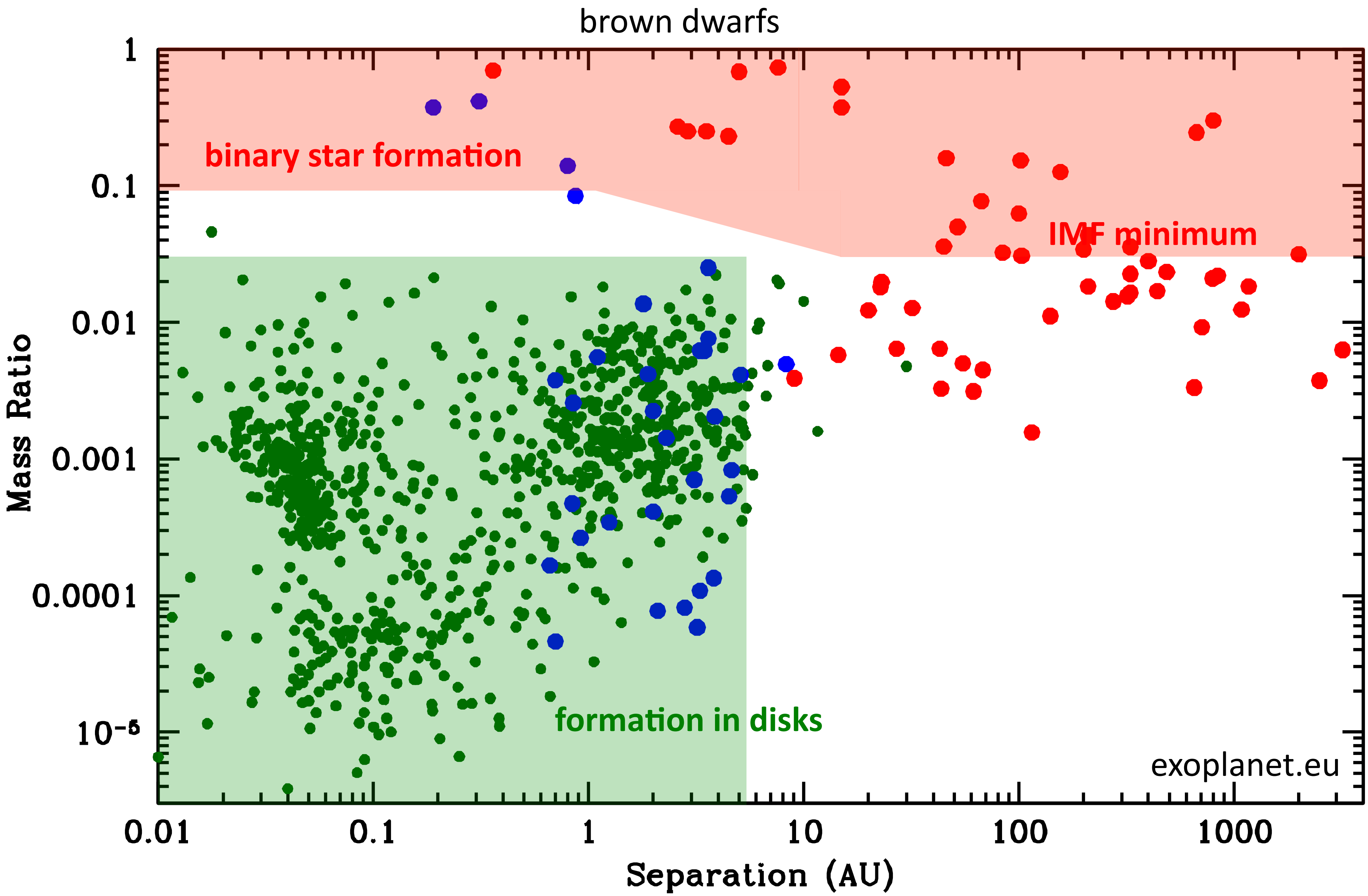
0.1
0.01
0.001
0.0001
10⁻⁵
Separation (AU)
0.01
0.1
1
10
100
1000


brown dwarfs
binary star formation
IMF minimum
formation in disks
exoplanet.eu
Mass Ratio
1
0.1
0.01
0.001
0.0001
10⁻⁵
Separation (AU)
0.01
0.1
1
10
100
1000

# Summary

- IMF, disks, & binarity indicate that BDs form like stars without the need for dynamical interactions
- BDs and giant planets overlap in mass and exist in similar numbers at 5 $M_{jup}$
- Free-floating objects are probably BDs unless there is evidence indicating formation in a disk
- Binary star formation extends down to ≤5 $M_{jup}$