The substellar initial mass function

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Outline

- Introduction
- Pleiades
- σ Orionis
- Upper Sco
- The field
- Final remarks

I thank Catarina Alves de Oliveira, Koraljka Muzic, and Trent Dupuy for their excellent presentations

The mass function

- Original definition of the **mass function** by Salpeter (1955):

$$\frac{dN}{d\log(M)} \propto M^{-\Gamma}$$

Power law

- Miller & Scallo (1979):

$$\frac{dN}{d\log(M)} \propto \exp\left(-\frac{(\log M - \log M_c)^2}{2\sigma^2}\right)$$

Lognormal

- The **mass spectrum** definition:

$$\frac{dN}{dM} \propto M^{-\alpha}$$

Power law

- Relation between exponents (power law):

$$\Gamma = \alpha - 1$$

The mass function

- (Initial) mass function/spectrum is not directly observable.
- To build it from observations, it can be broken down into two terms:

$$\frac{dN}{dM} = \frac{dN}{dL} \times \frac{dL}{dM}$$

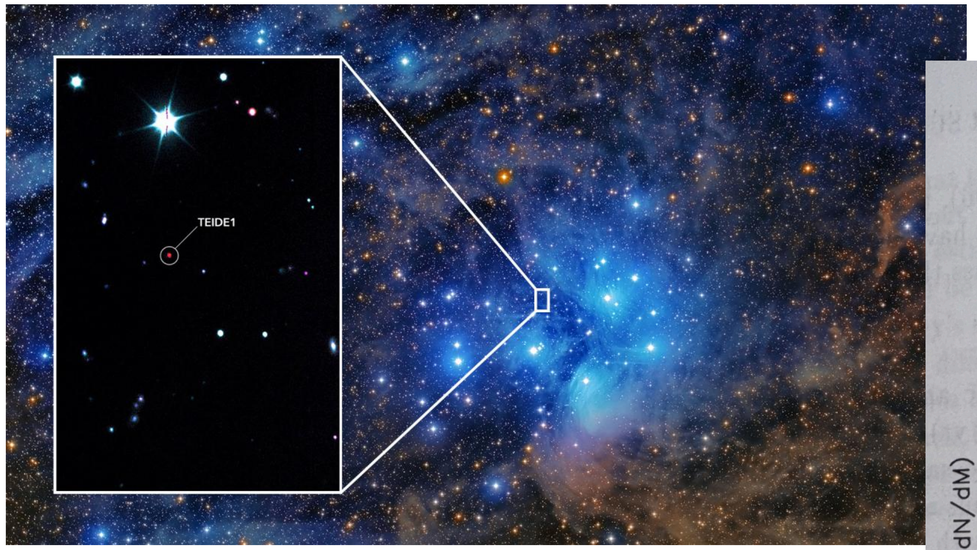
Luminosity function,
which is constructed from observations.

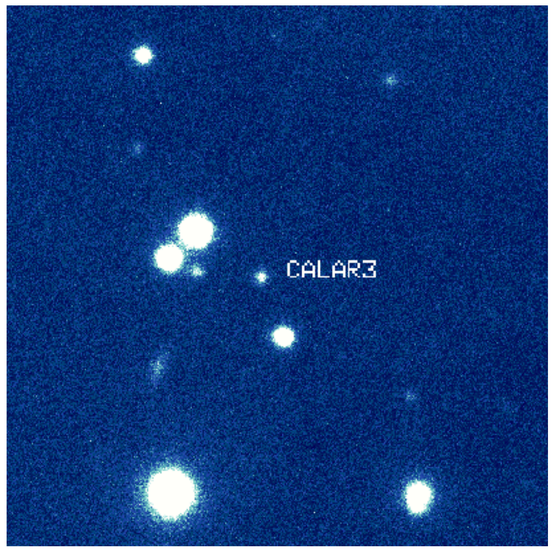
Mass - luminosity relationship,
which can be obtained from evolutionary models
or relations from objects with dynamical masses.

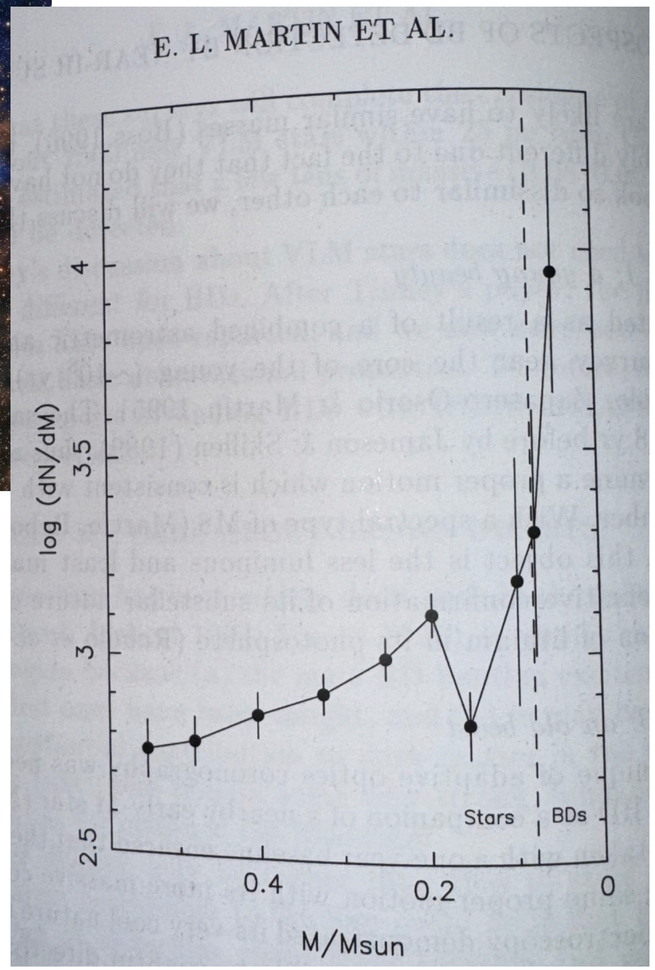
- Both terms have their own complexities, uncertainties, and systematics.

The first substellar mass function in the Pleiades

Martín et al. (1997)





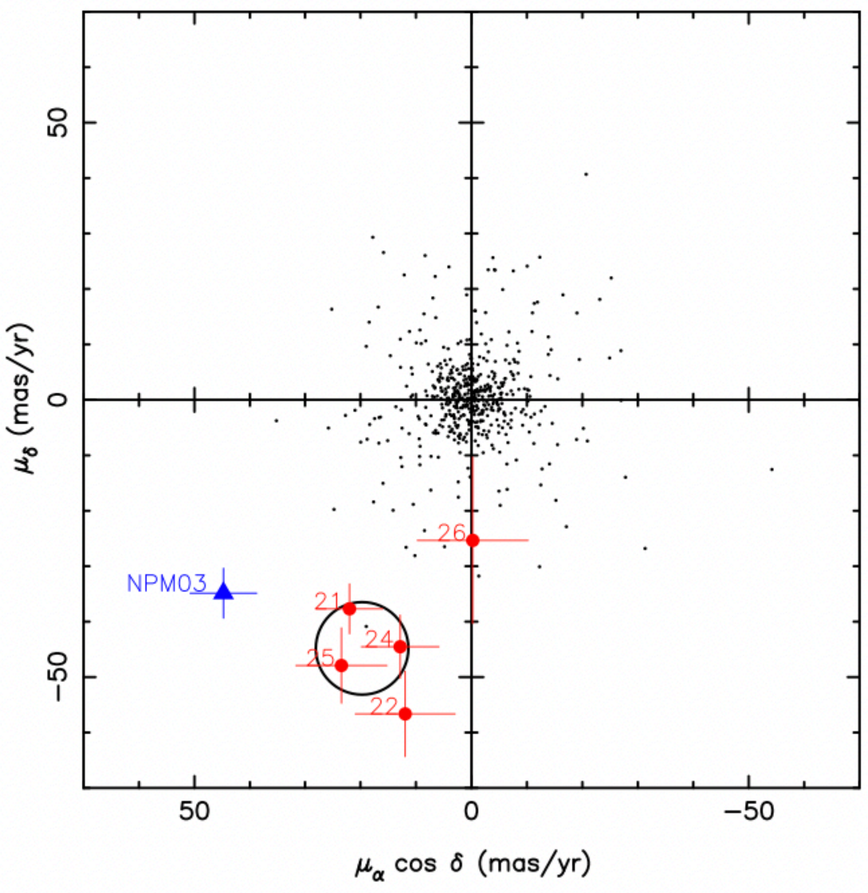


- 125 Myr
- ~130 pc
- No extinction, except at the Merope cloud

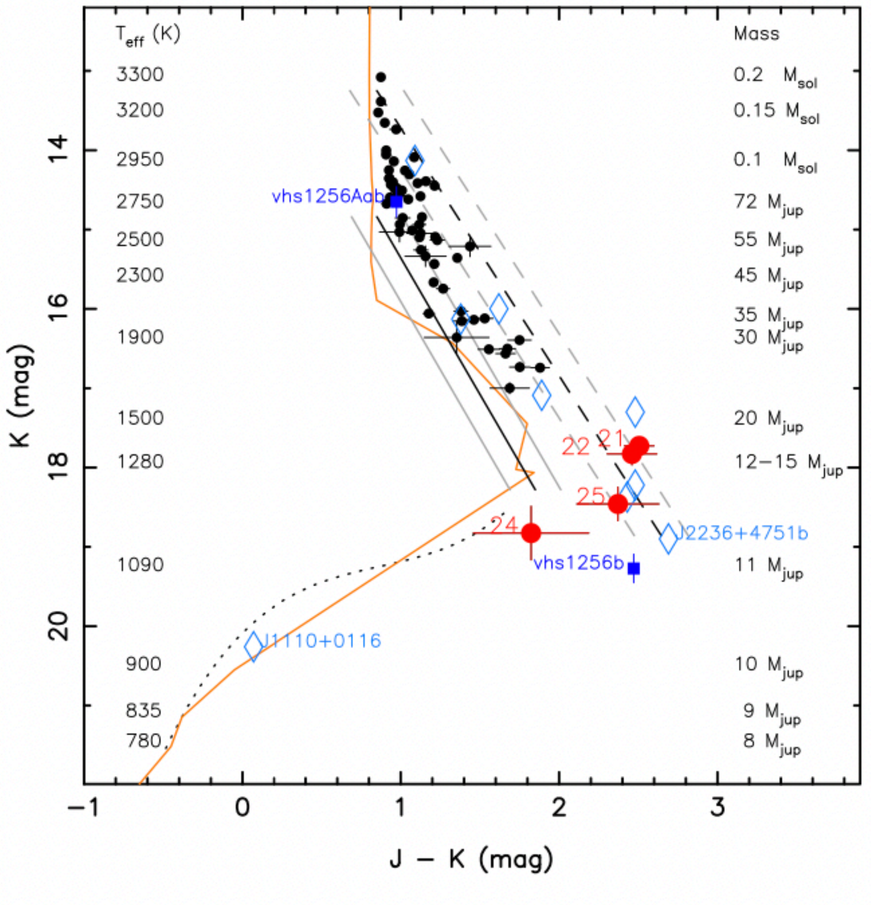
- Mass function shows continuity across the substellar borderline, and
- Suggests that brown dwarfs can be as numerous as low mass stars in the cluster.
- However, mass contribution of massive brown dwarfs to the cluster mass is < 1% (Rebolo et al. 1995).

The substellar mass function in the Pleiades

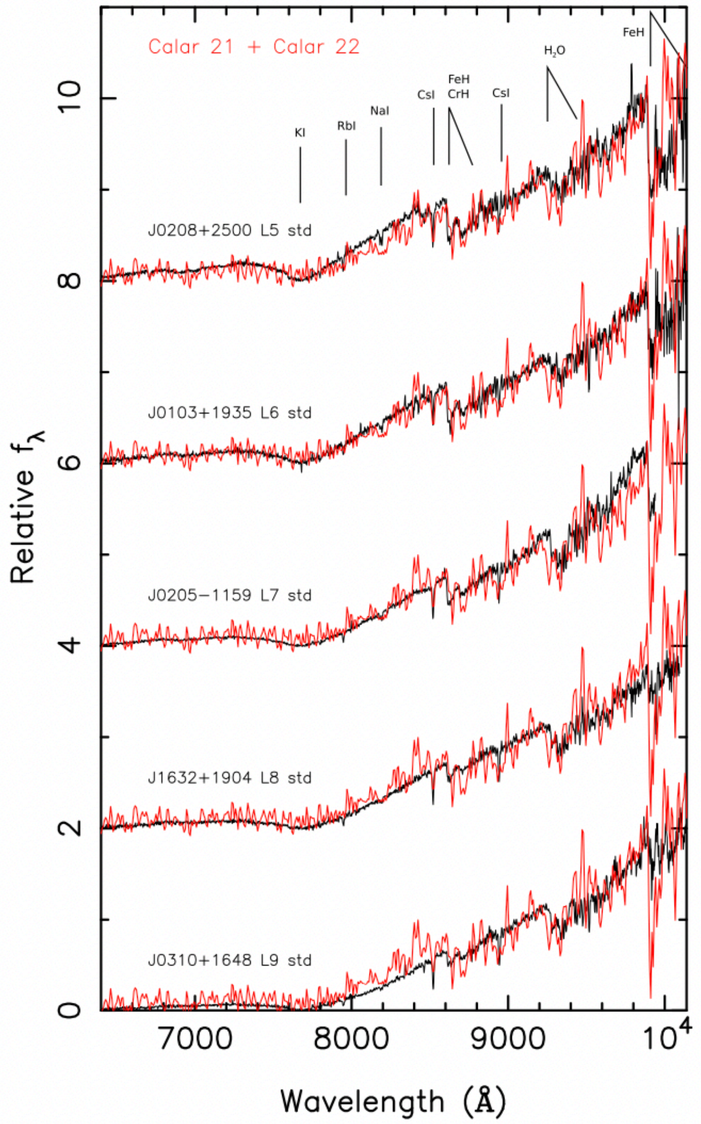
Zapatero Osorio et al. (2018)



Cluster proper motion

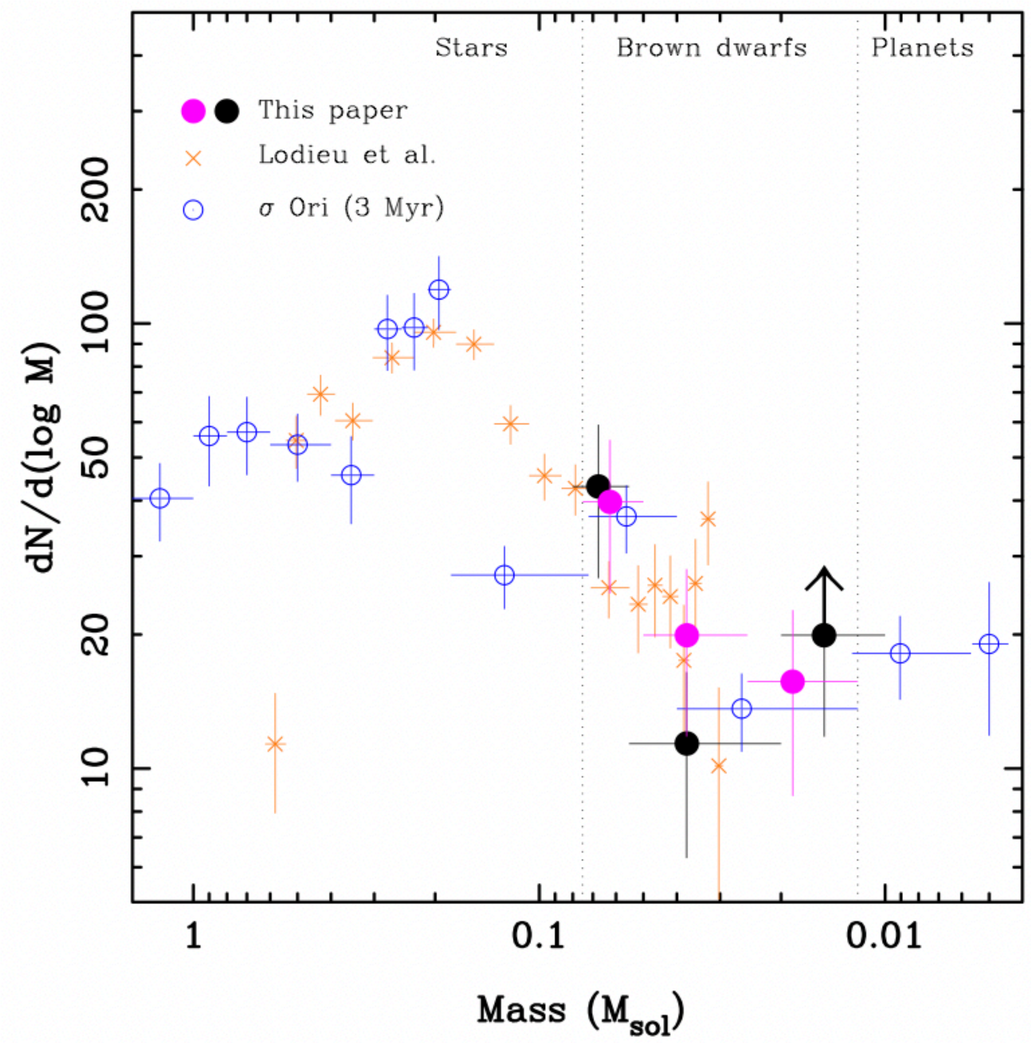


Cluster photometric sequence

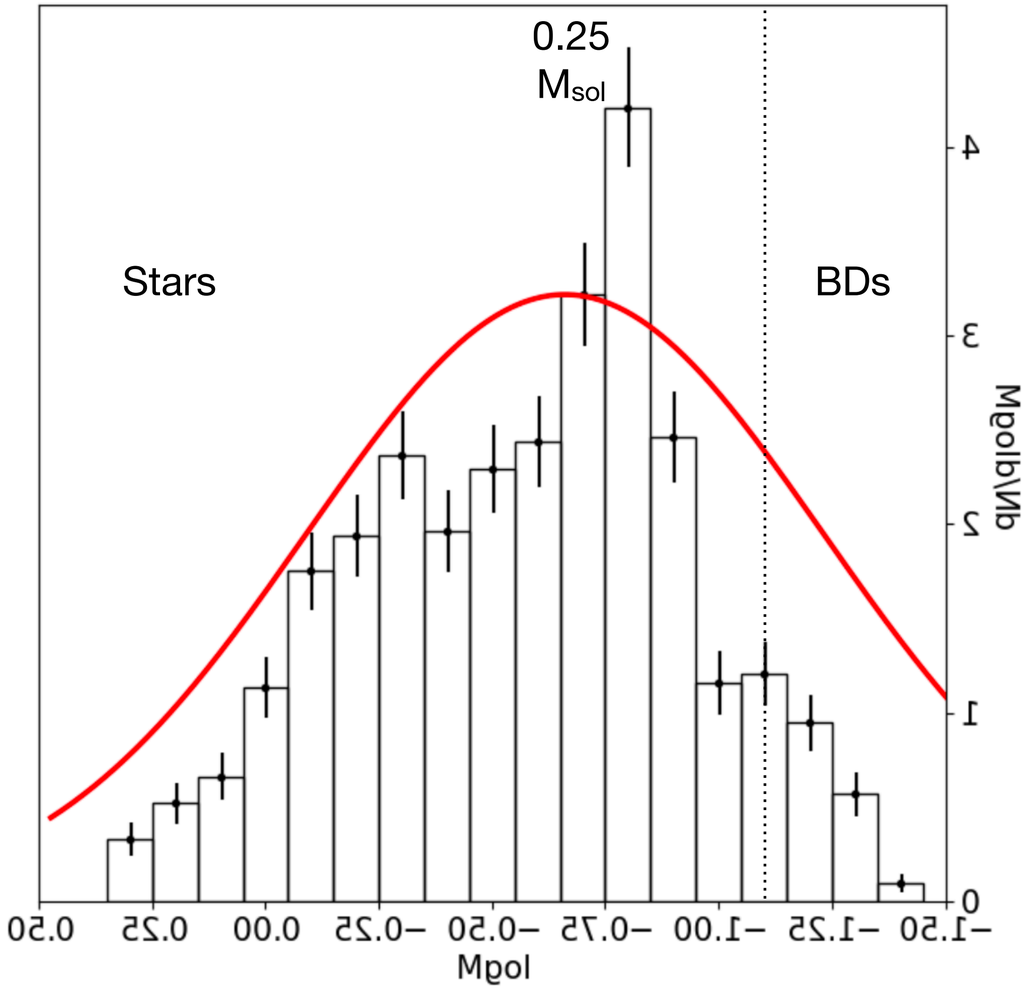


The substellar mass function in the Pleiades

Zapatero Osorio et al. (2014), complete down to 0.012 M_{sol}



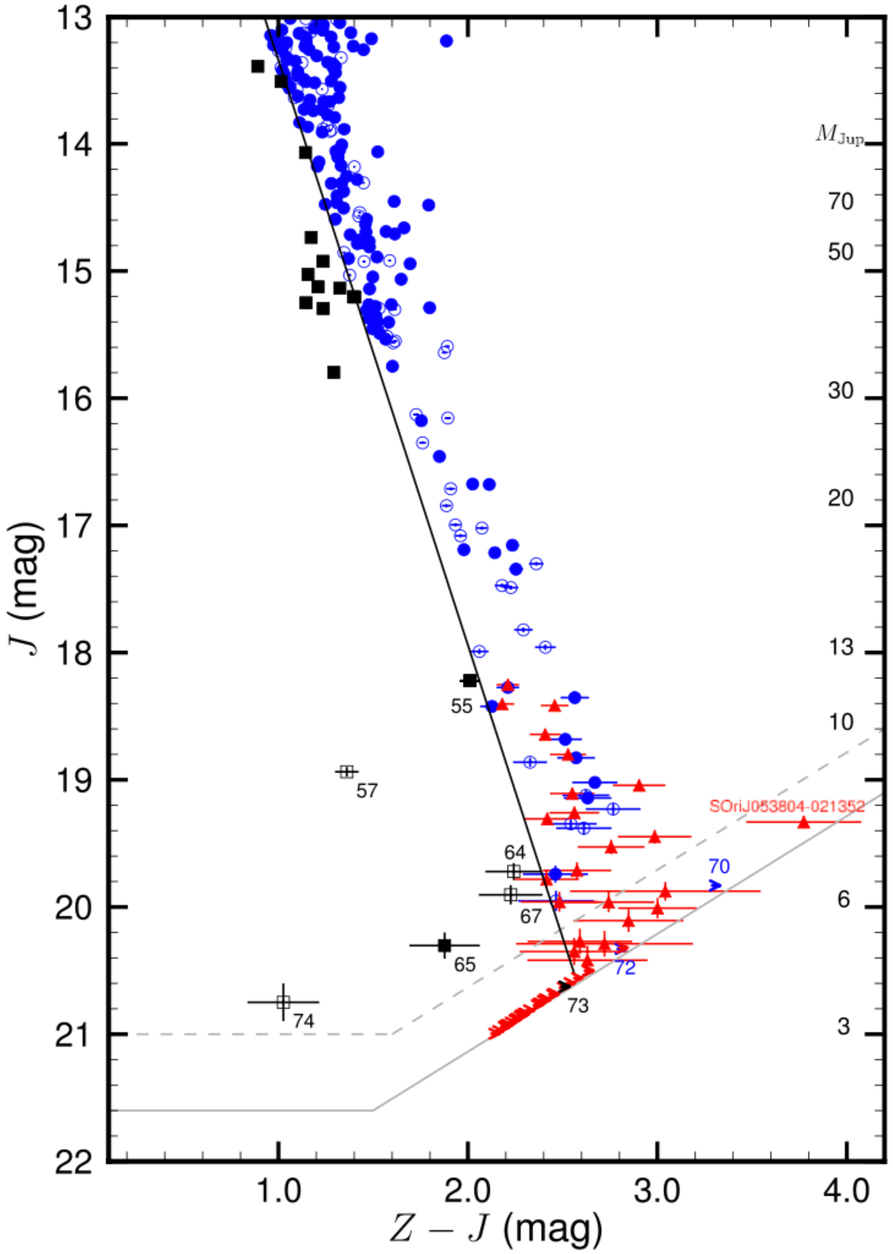
Lodieu et al. (2019): complete down to 0.040 M_{sol}



Pleiades mass function softly increases toward the planetary-mass domain

σ Orionis cluster

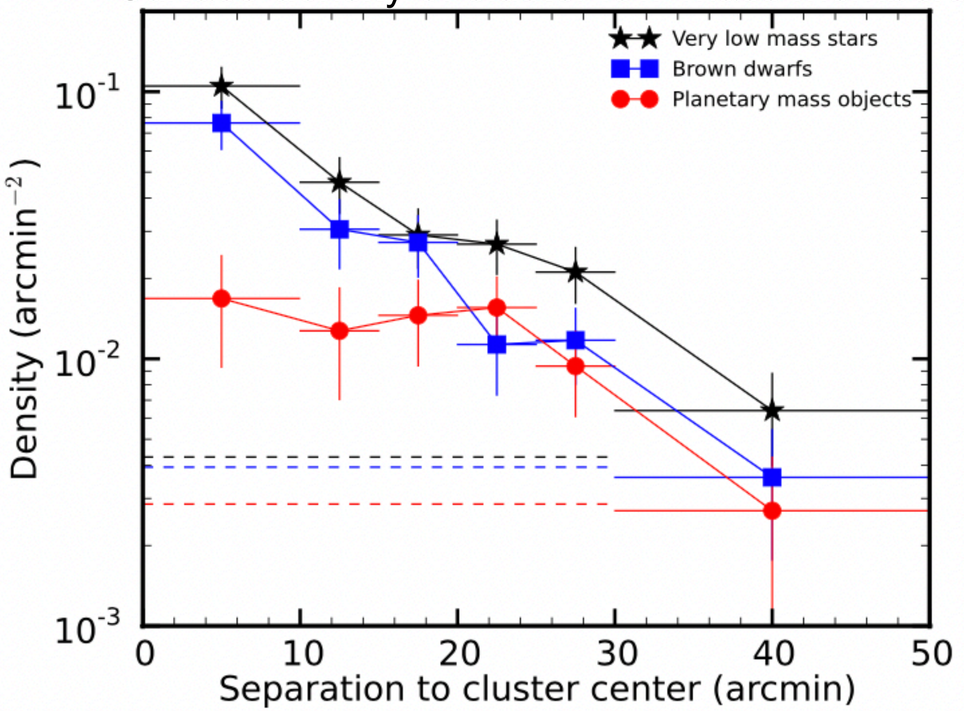
The initial mass function of the σ Orionis cluster



Peña Ramírez et al. (2012)

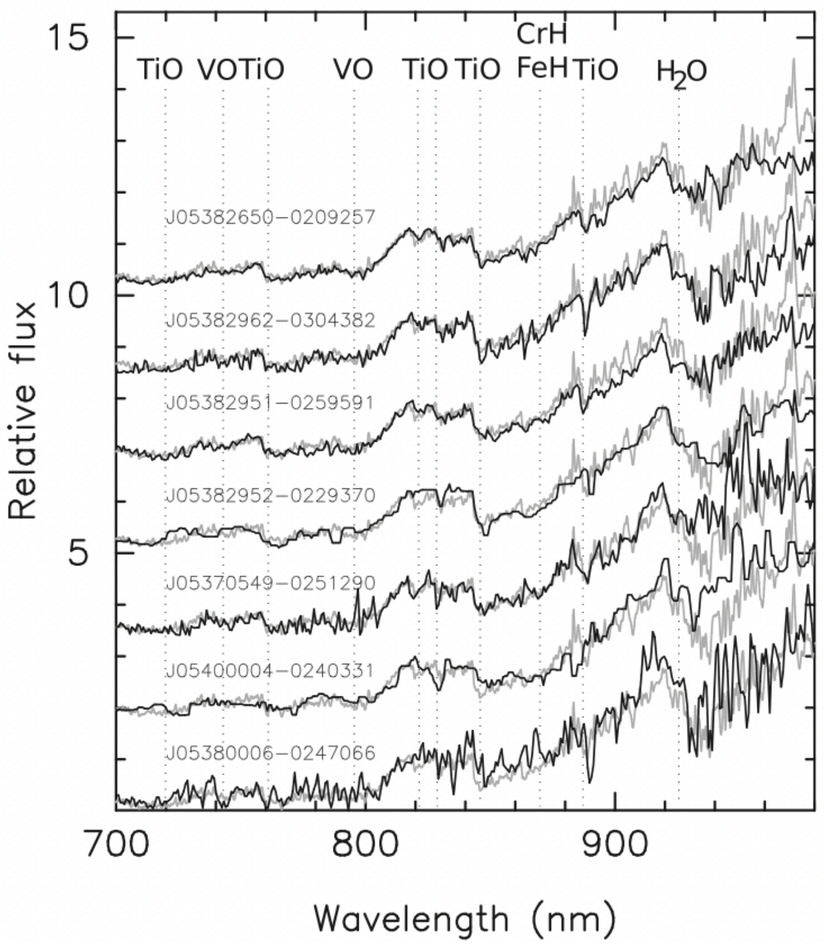
- 3 Myr
- 352 pc
- No extinction
- 0.78 deg^2
- 210 members with masses 0.004 - 0.25 M_{sol}
- 71% are fully confirmed cluster members

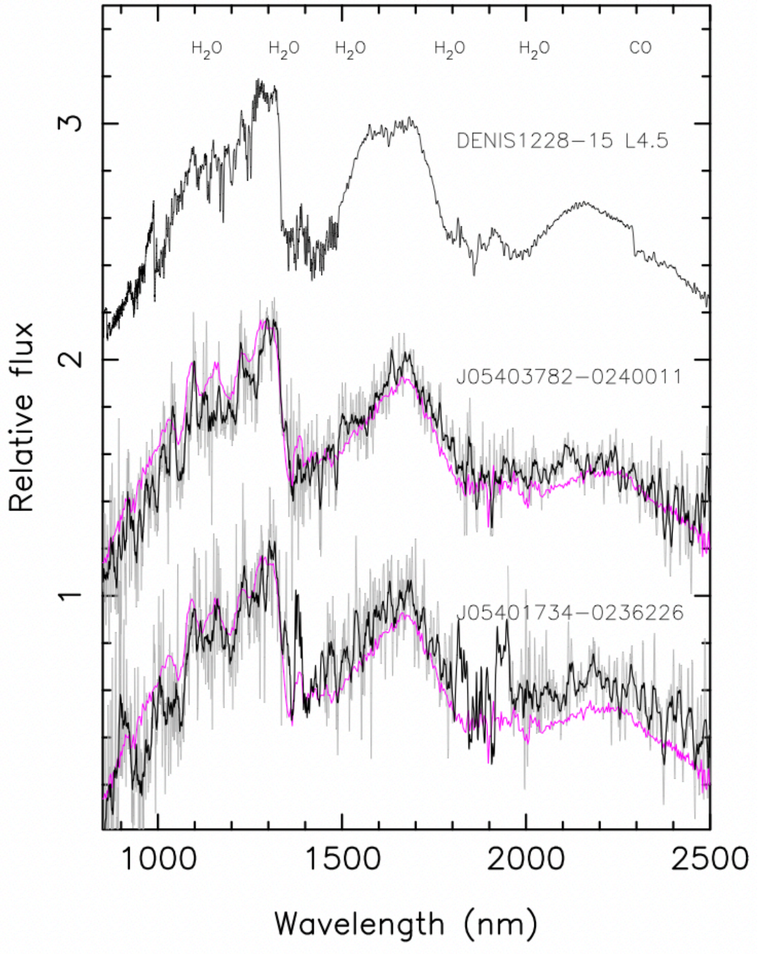
Surface density of cluster low-mass members

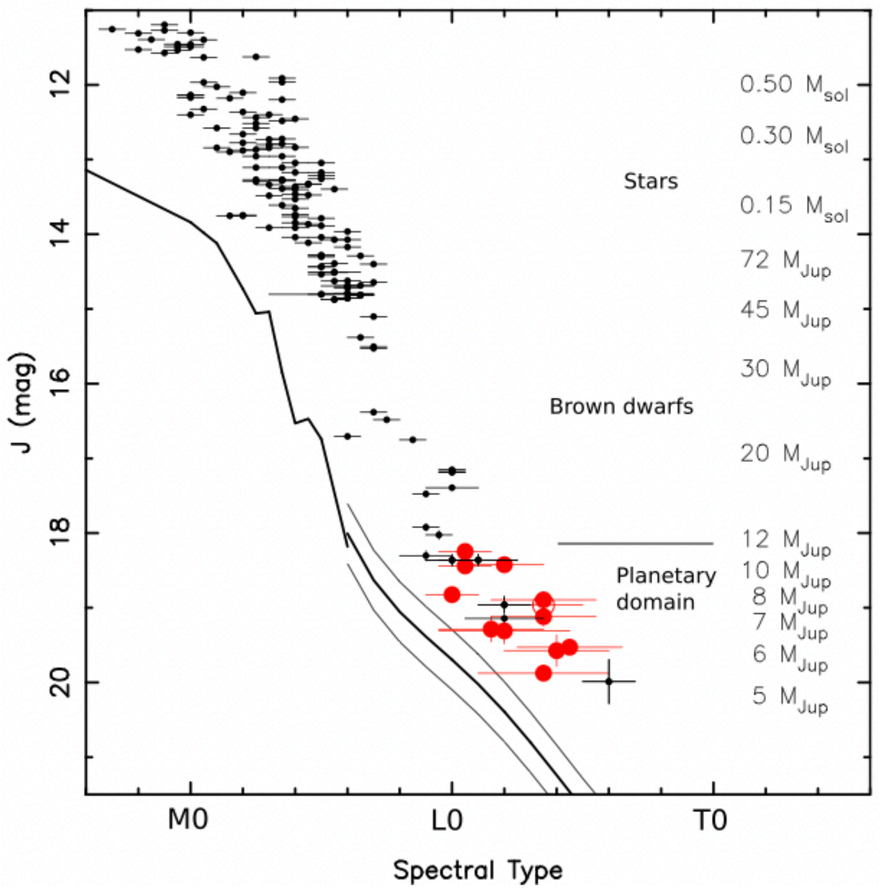


The initial mass function of the σ Orionis cluster

Zapatero Osorio et al. (2017)





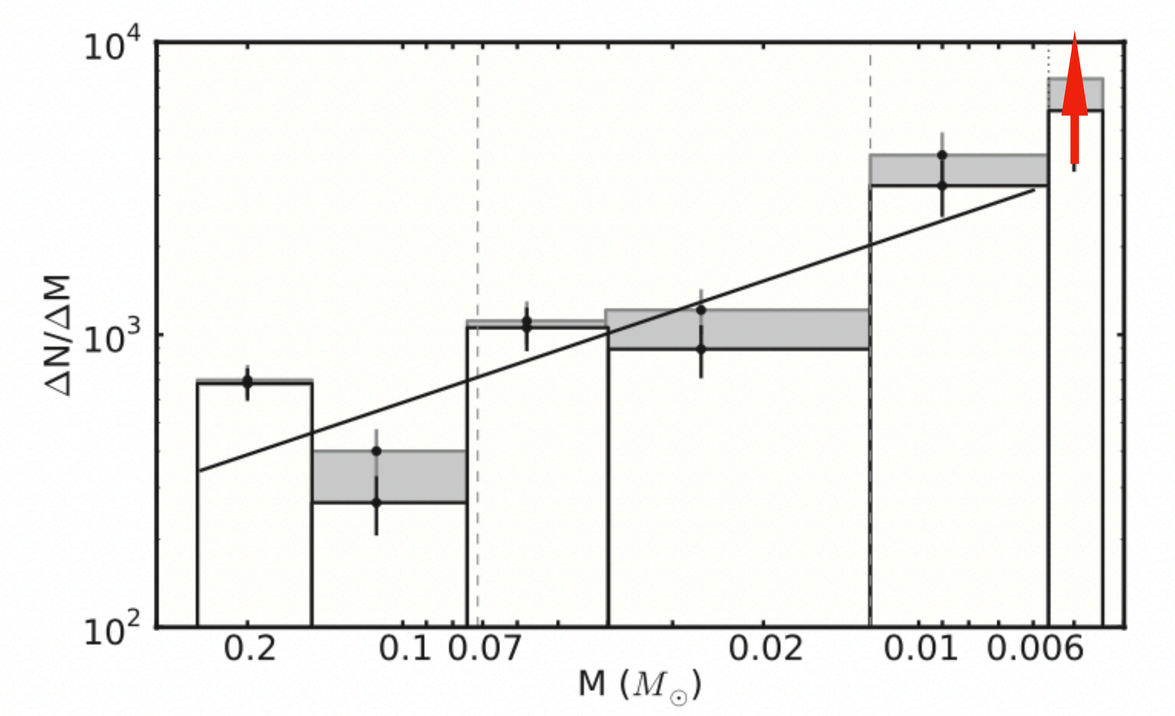


Confirmation of cluster membership in the planetary-mass domain is at the level of ~80%

The initial mass function of the σ Orionis cluster

Peña Ramírez et al. (2012)

Mass spectrum of the low-mass tail $\frac{dN}{dM} \propto M^{-0.6\pm0.2}$

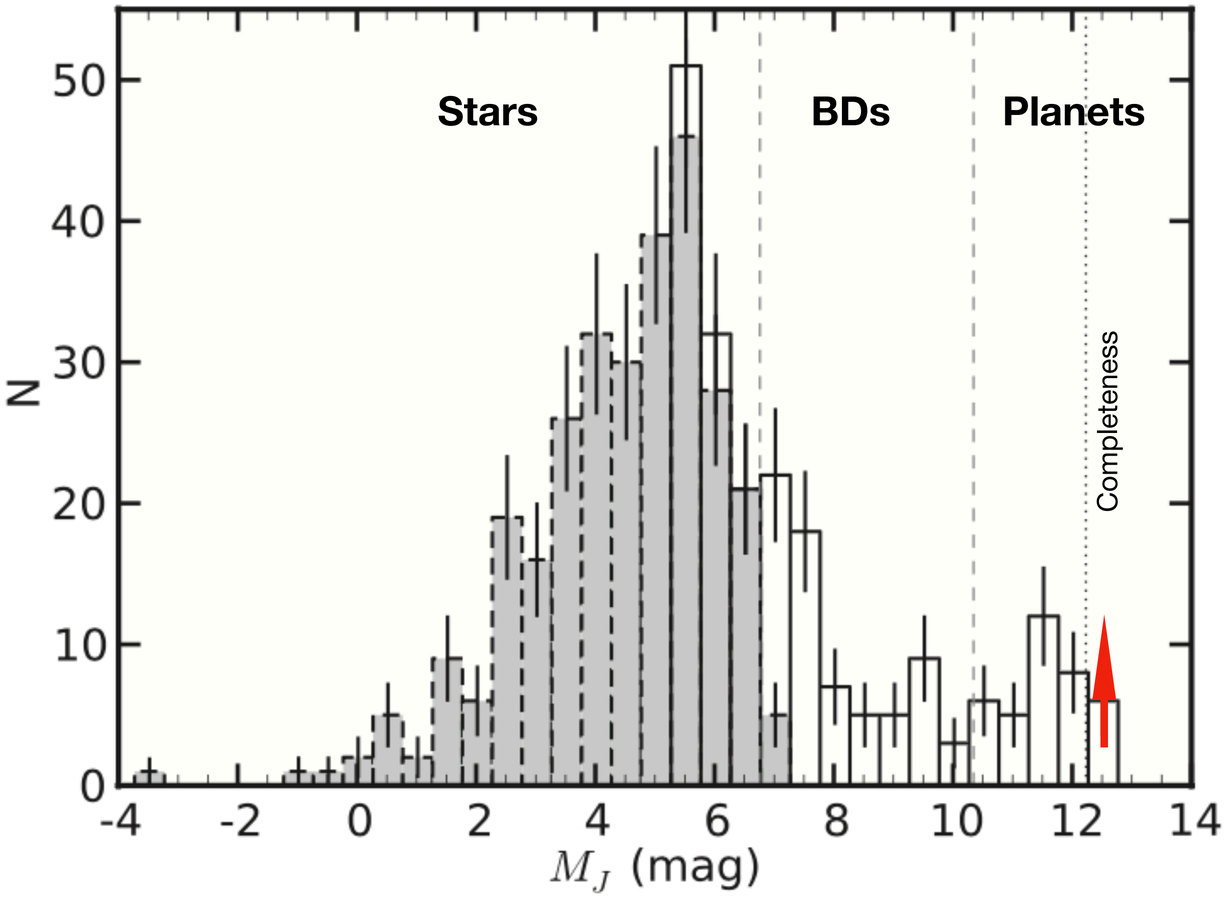


Completeness in the mass interval: 0.006 - 0.25 M_{sol}

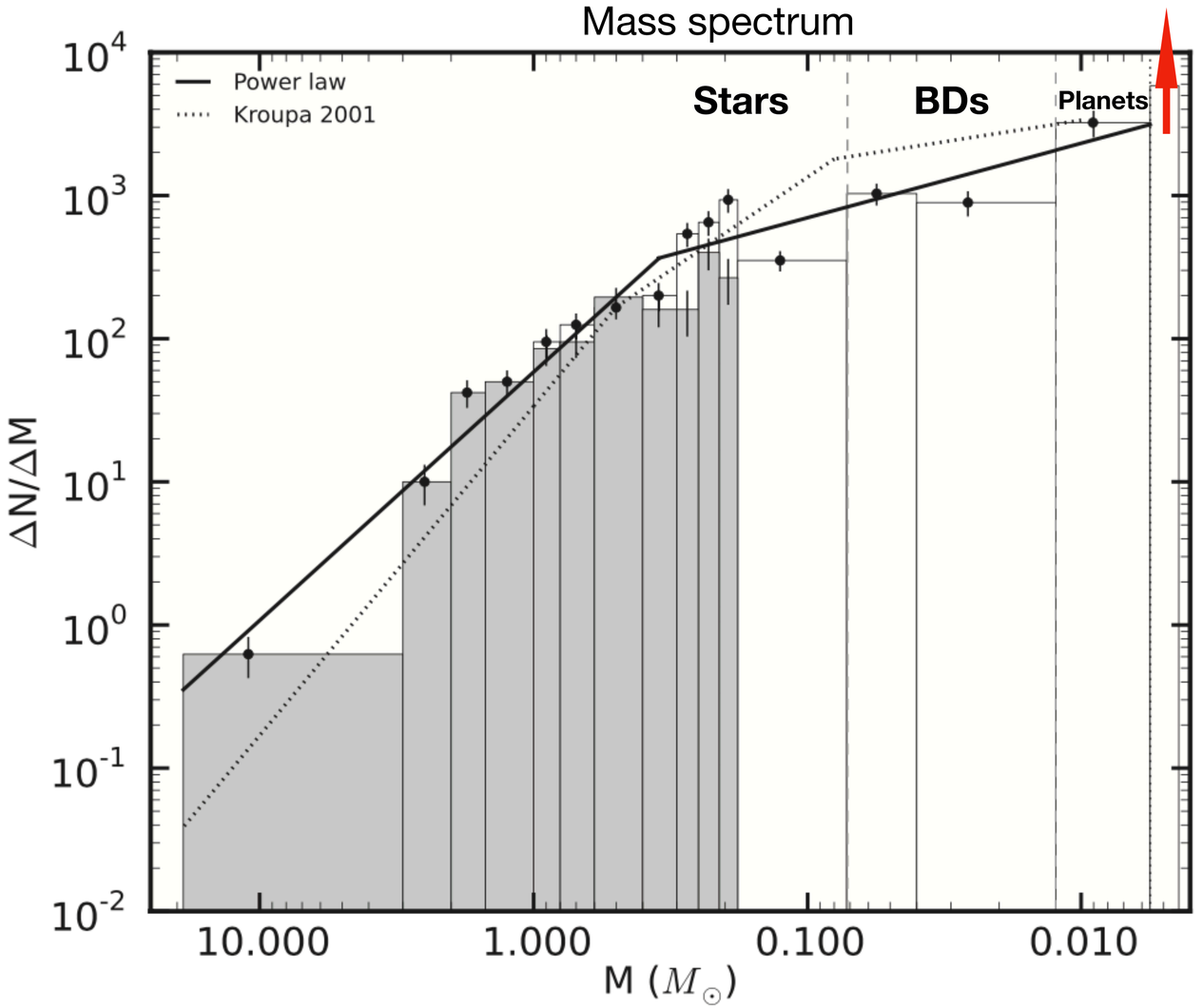
The initial mass function of the σ Orionis cluster

Peña Ramírez et al. (2012)

J-band luminosity function



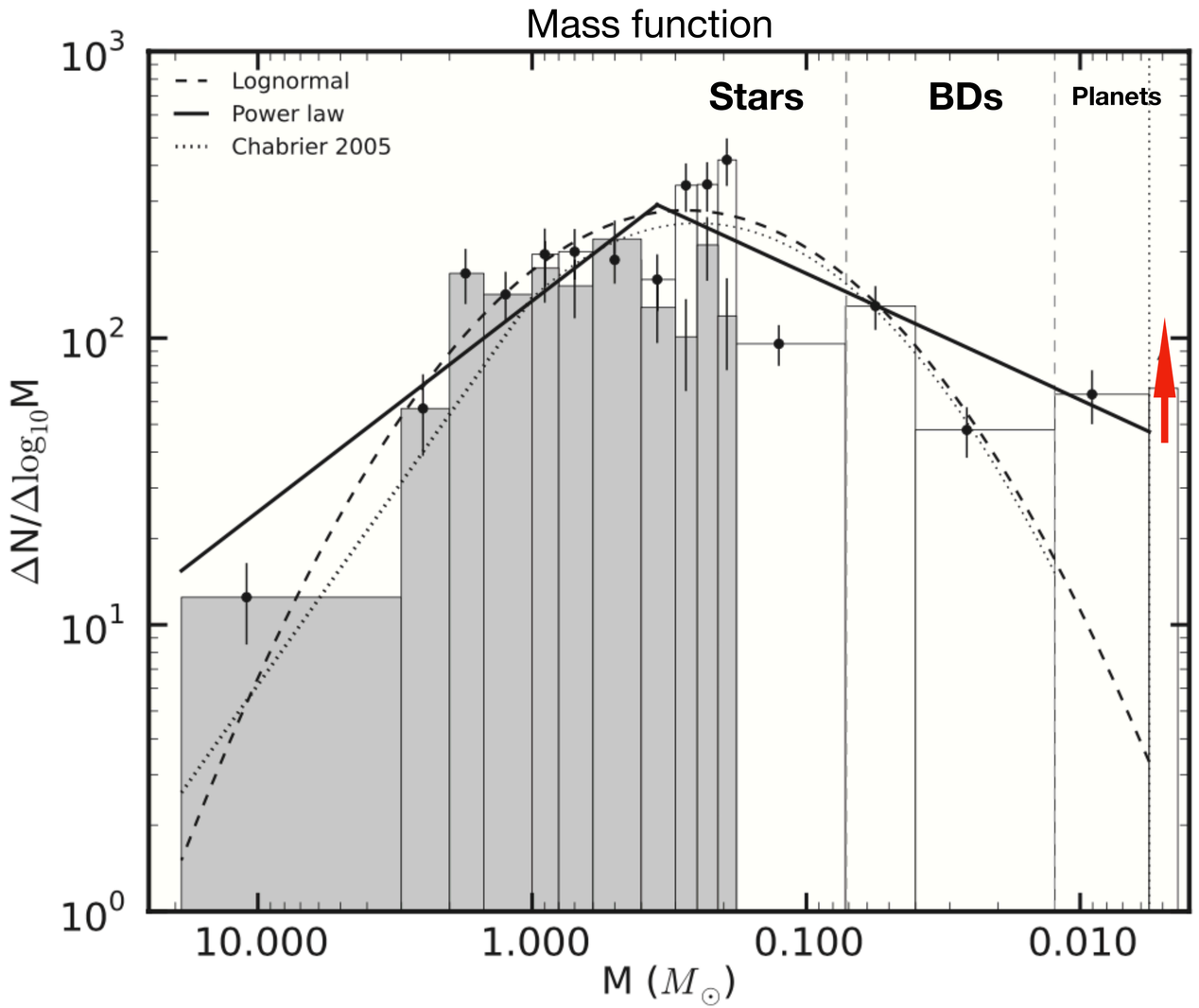
Mass spectrum

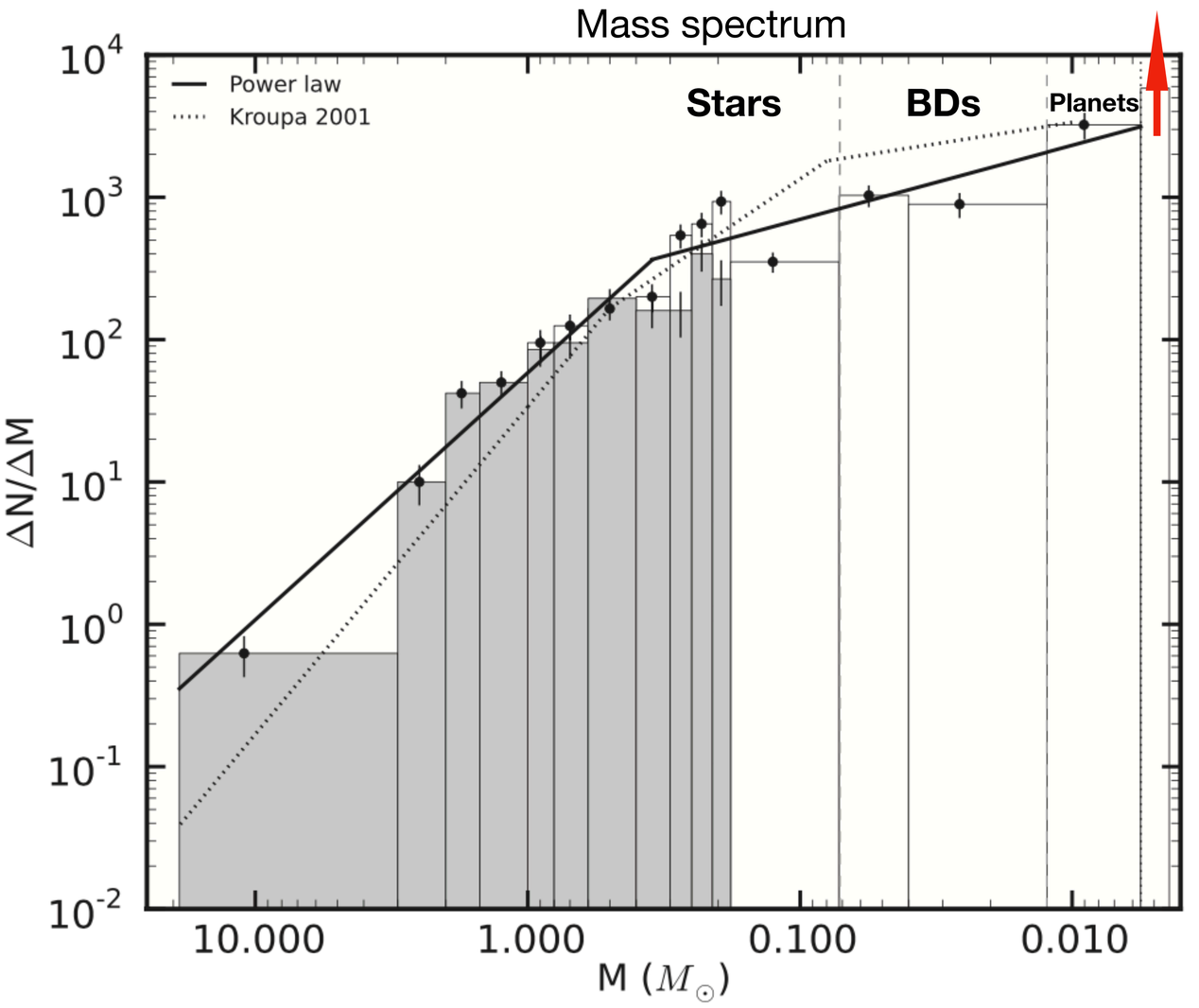


- **Completeness** in the mass interval: 0.006 - 19 M_{sol}
- Mass-luminosity relations (3 Myr, solar metallicity) from Siess et al. (2000) and Baraffe et al. (1998)

The initial mass function of the σ Orionis cluster

Peña Ramírez et al. (2012)





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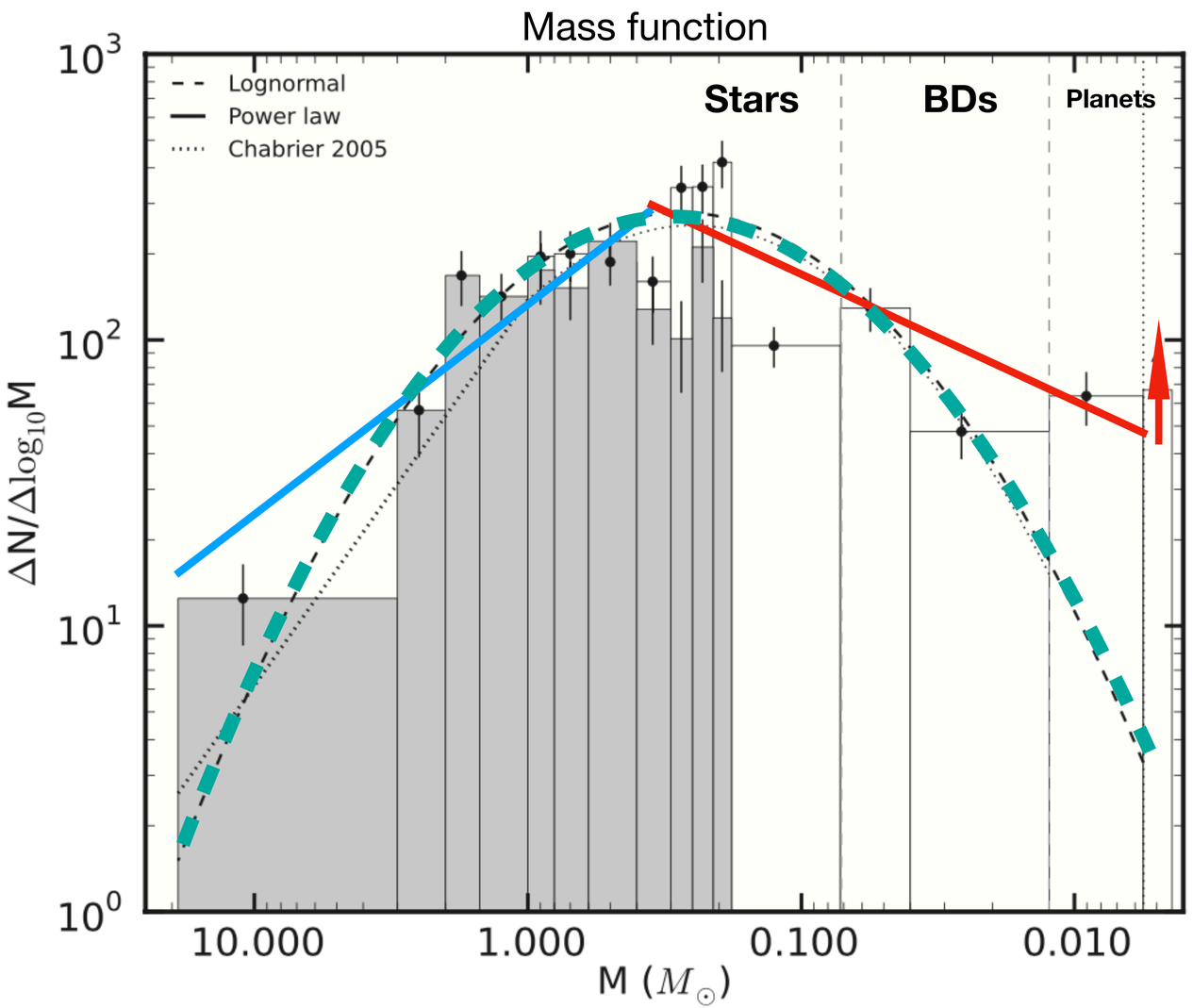
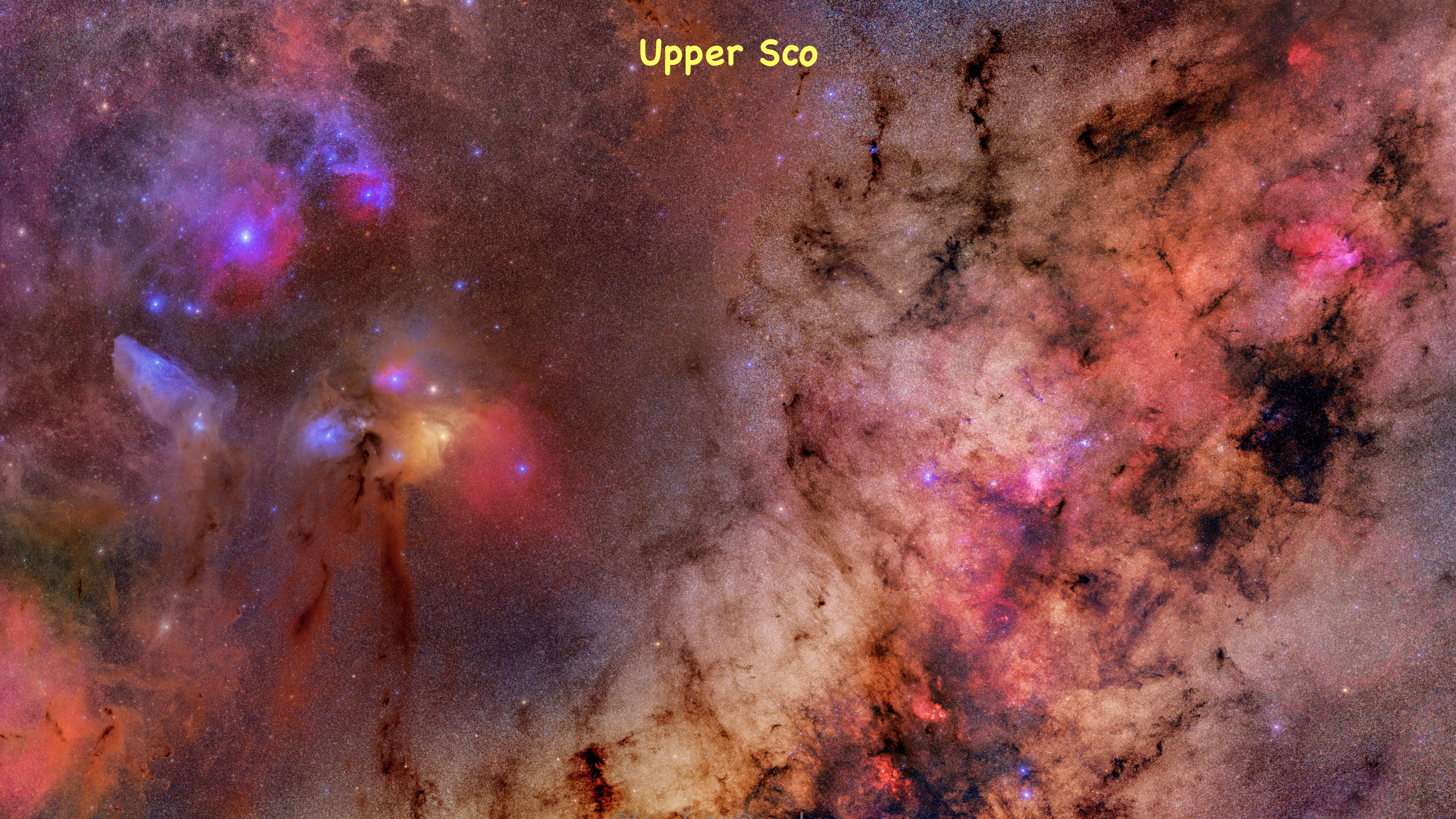
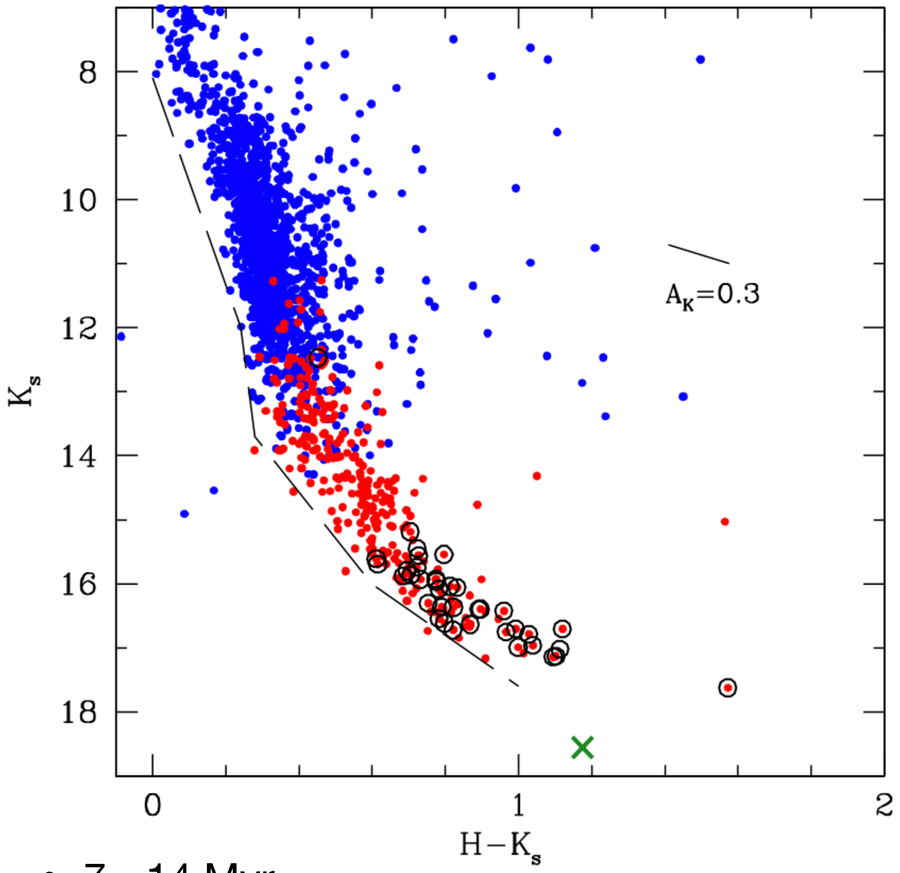
Peña Ramírez et al. (2012)



- **Completeness** in the mass interval: 0.006 - 19 M_{sol}
- Power-law fit:
  - α = 1.7 ± 0.2 for 0.35 - 19 M_{sol}
  - α = 0.6 ± 0.2 for 0.006 - 0.35 M_{sol}
- Lognormal fit:
  - M_c = 0.27 ± 0.11 M_{sol}
  - σ = 0.68 ± 0.19 M_{sol}

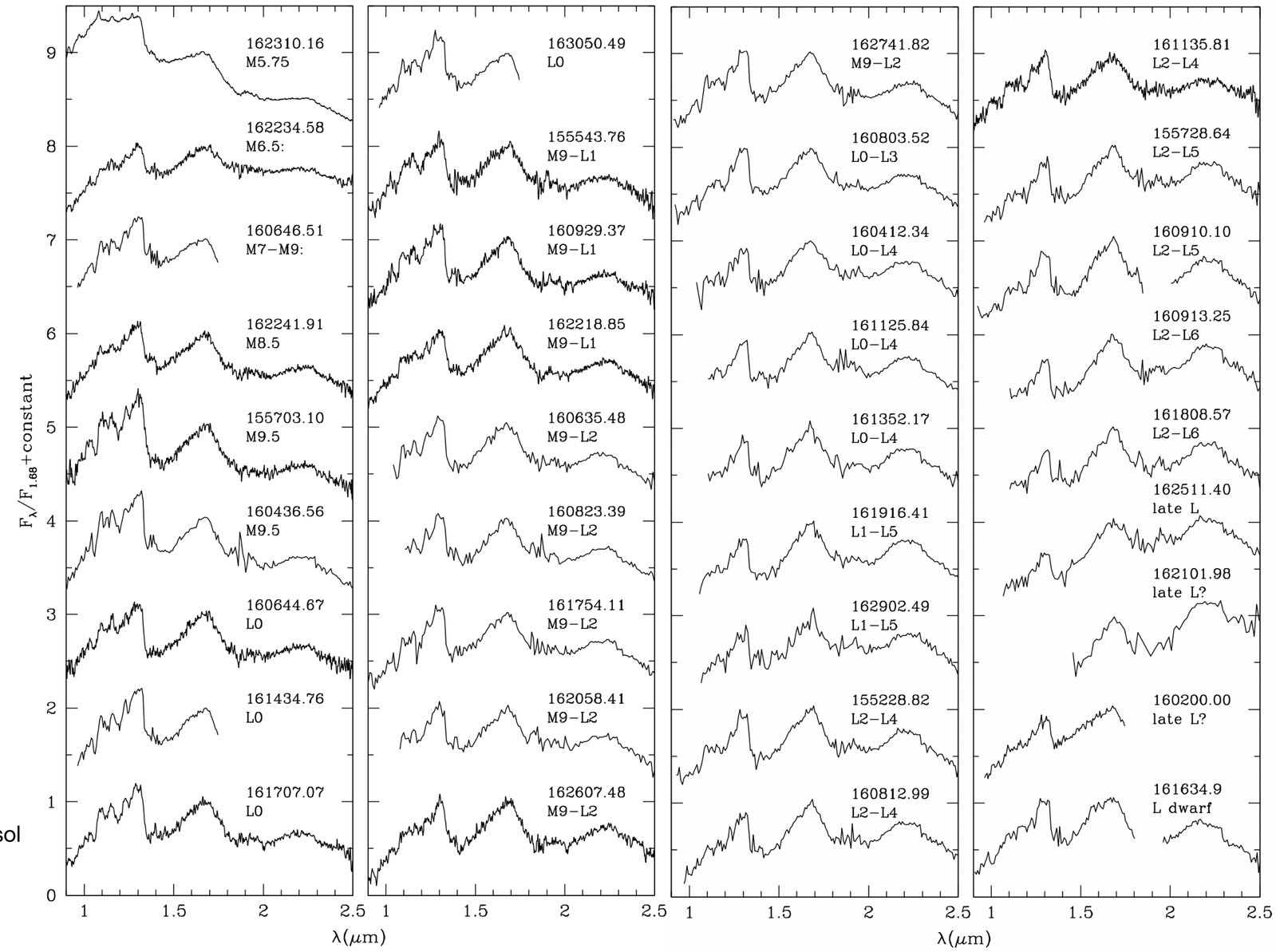

Upper Sco

The initial mass function of the Upper Sco Association



- 7 - 14 Myr
- 145 pc
- ~100 deg^2
- Some extinction
- 1753 members with masses ~0.007 - 1.3 M_{sol}
- 274 of which are substellar, all spectroscopically classified
- **Completeness** down to 0.01 M_{sol}

Luhman (2025)



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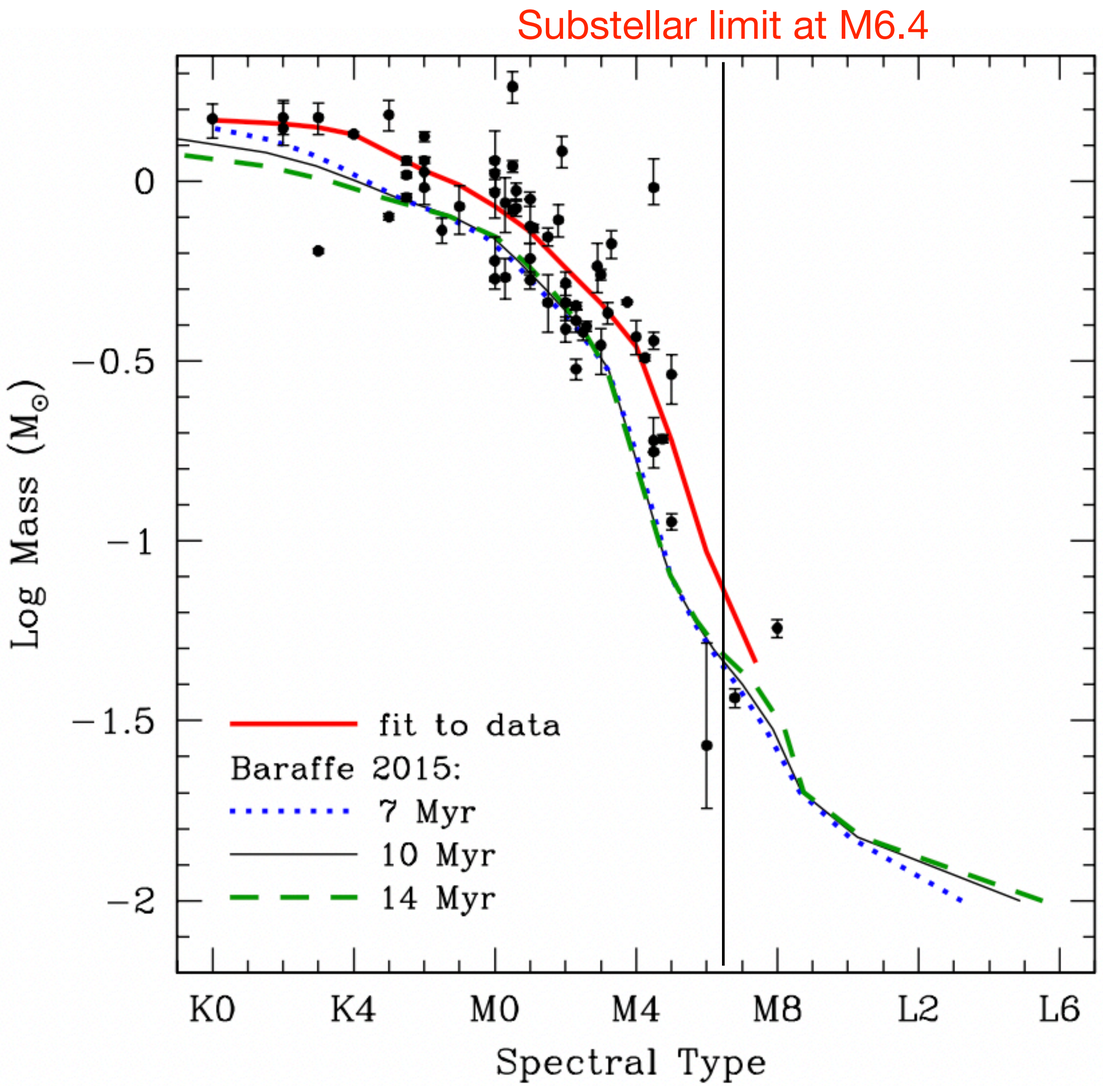
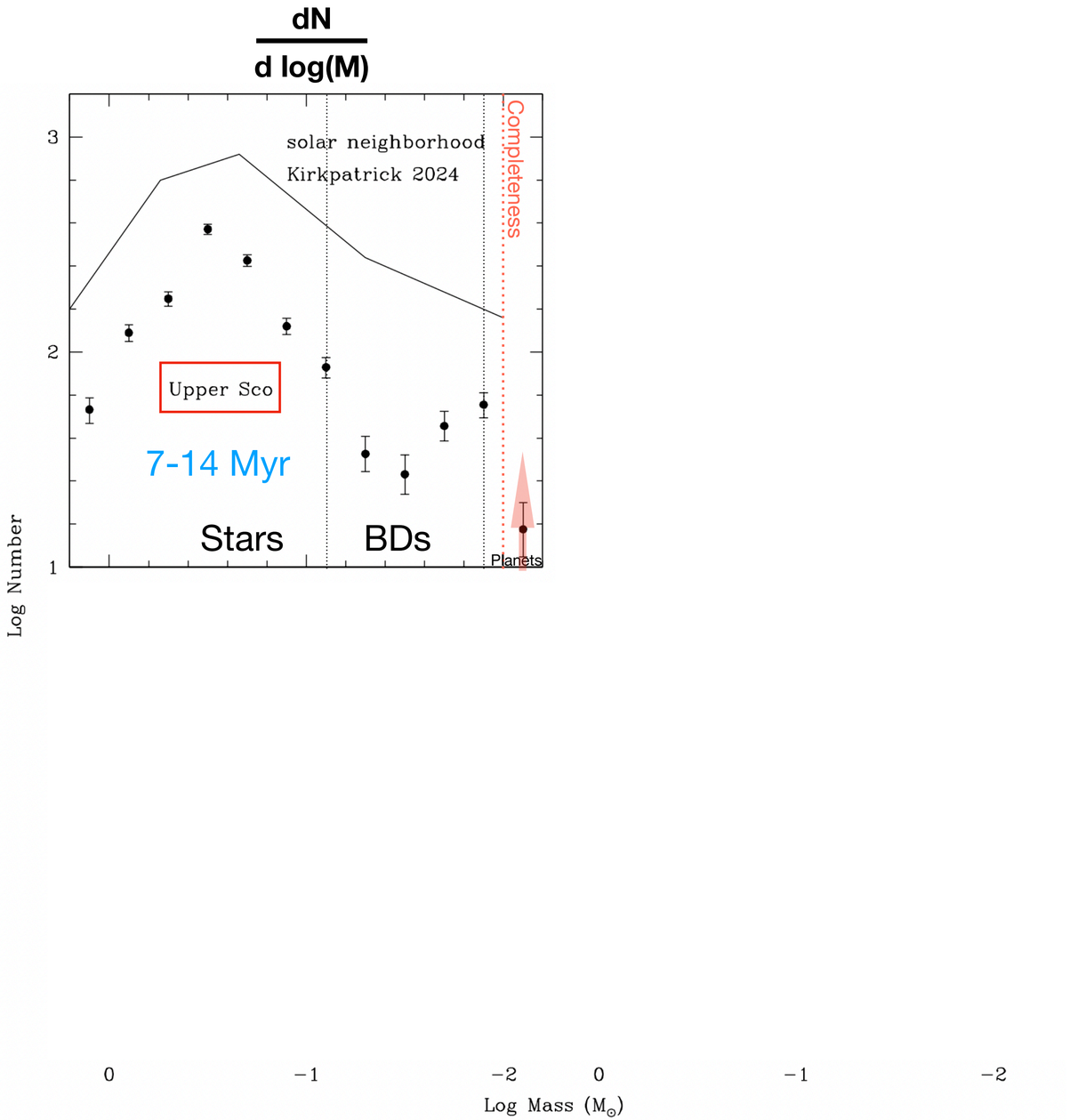


- K0 - M7.4: Mass - SpT relation from dynamical masses based on binary orbits or rotation or circumstellar disks.
- >M7.4: Masses from M(K) using Baraffe et al. (2015) for > 0.015 M_{sol} and Chabrier et al. (2023) for < 0.015 M_{sol}.

The initial mass function of the Upper Sco Association

Luhman (2025)



- Peak at 0.03 $M_{sol,}$ declines to lower masses, and rises below 0.03 M_{sol}.
- Number ratio of stars to BDs above 0.02 M_{sol} is:
  - 12 for Upper Sco,
  - ~9 for IC 348.
- This contrasts with the star-to-BD ratio of the σ Ori cluster (4-5) and the solar neighborhood (~4).
- This ratio is sensitive to the location of the substellar limit.

The initial mass function of the Upper Sco Association

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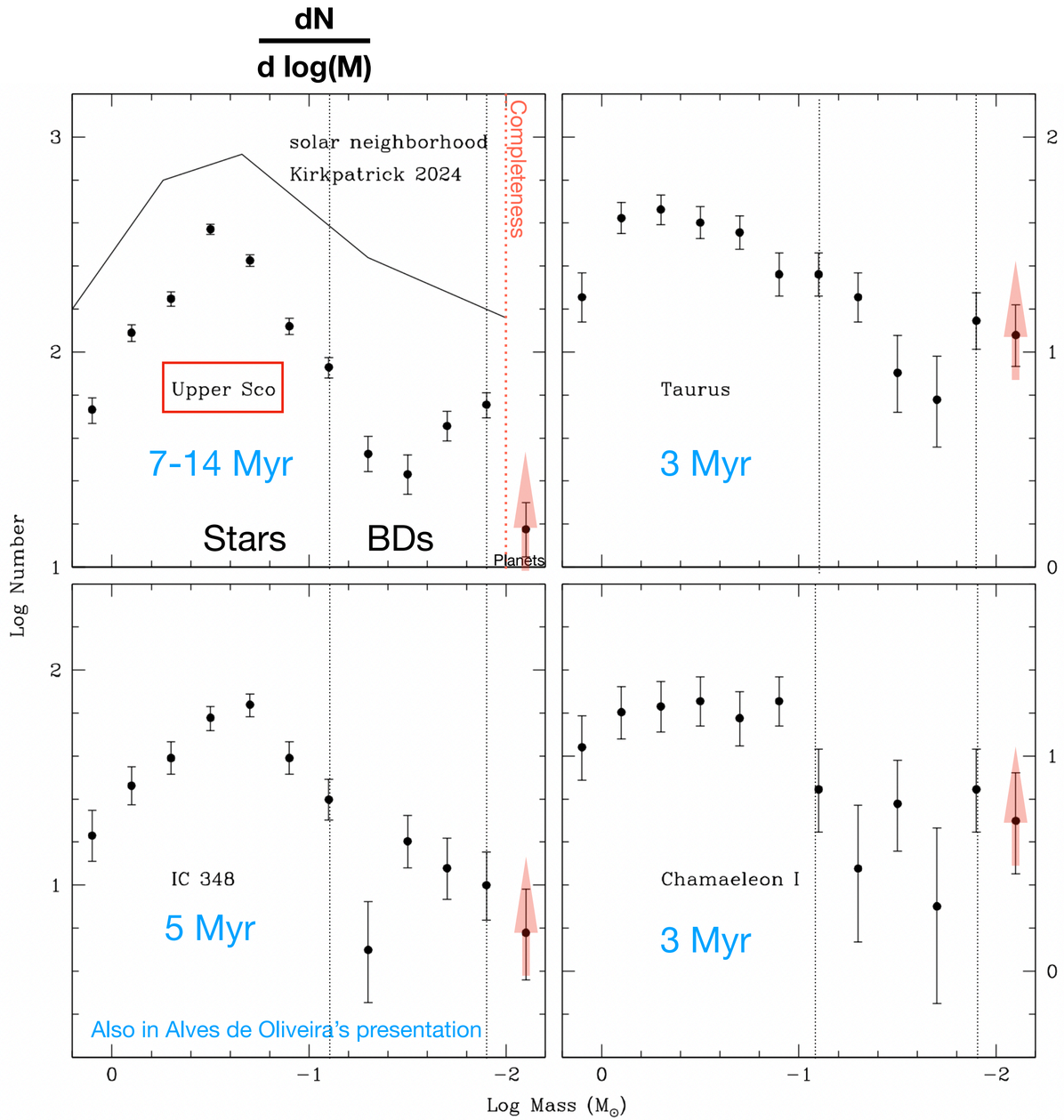

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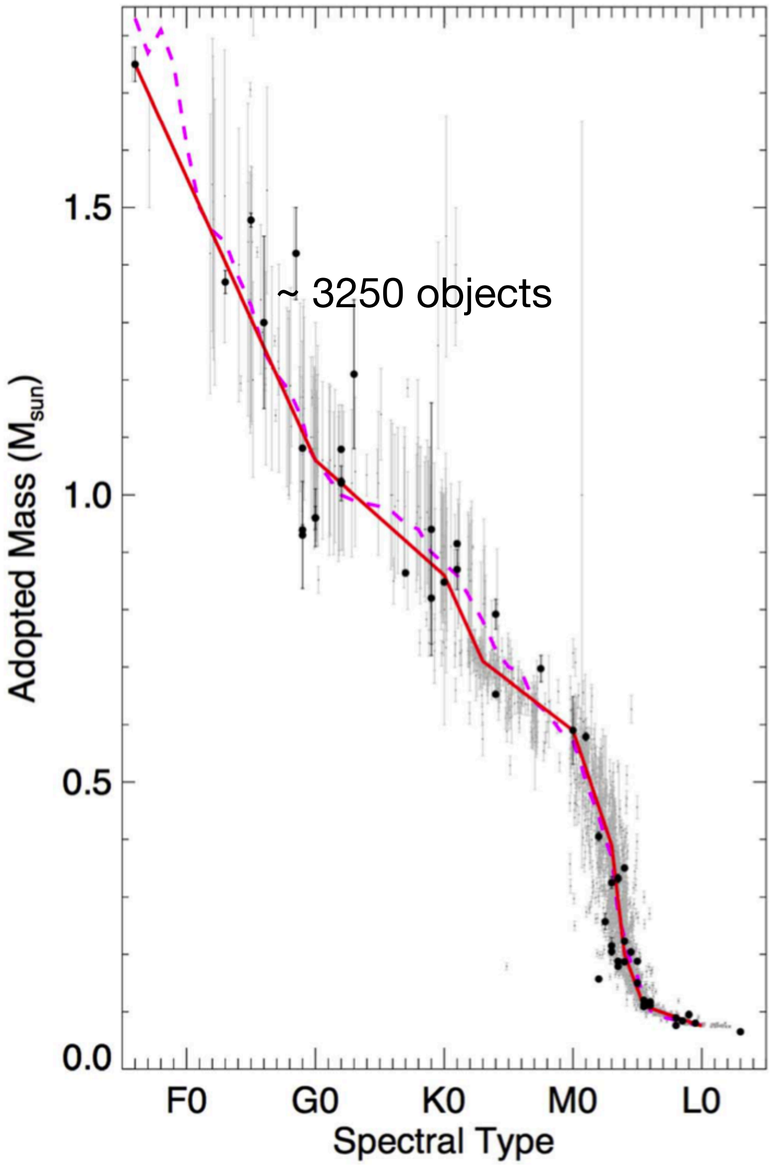
The solar neighborhood

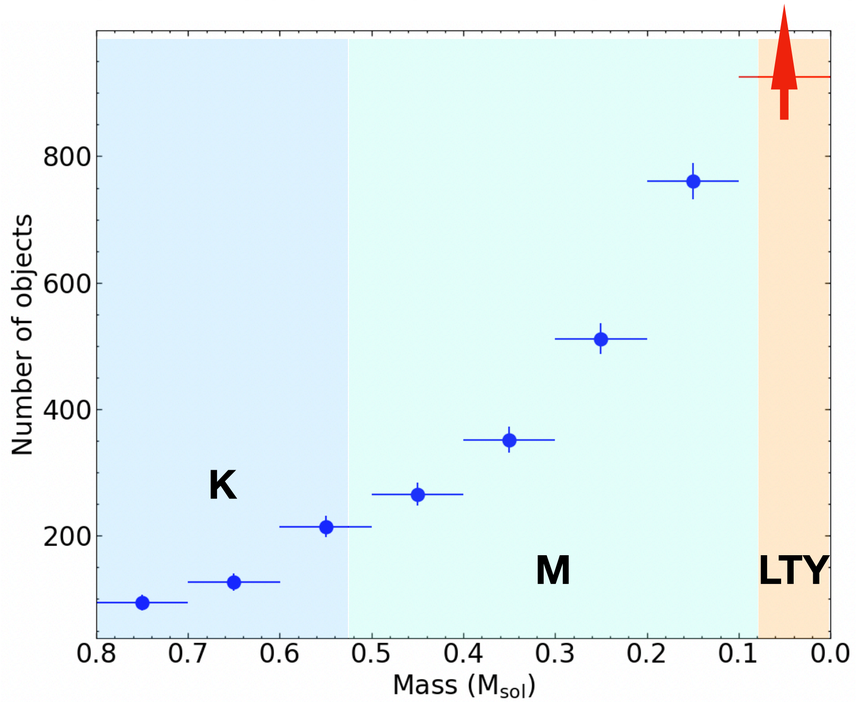
The initial mass function of the solar neighborhood



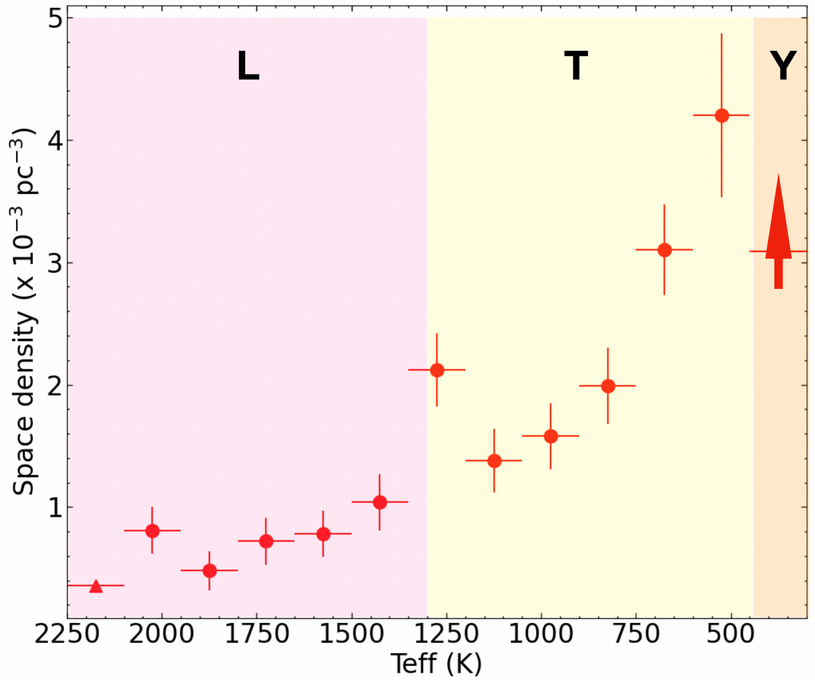
- Based on the full-sky 20 pc census of ~3600 stars and brown dwarfs.
- **0.005 - 8 M_{sol}**
- Completeness:
  - up to 20 pc for SpT earlier than T8.5,
  - up to 15 pc for T8.5 - Y0,
  - up to 11 pc for > Y0.

Kirkpatrick et al. (2024)

LOW-MASS STARS and BROWN DWARFS



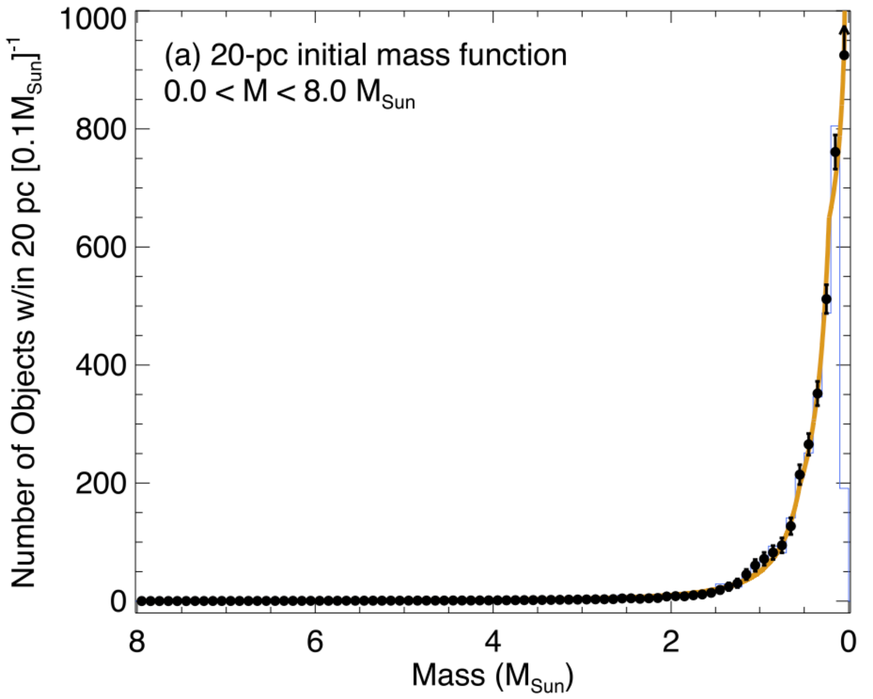
BROWN DWARF space density

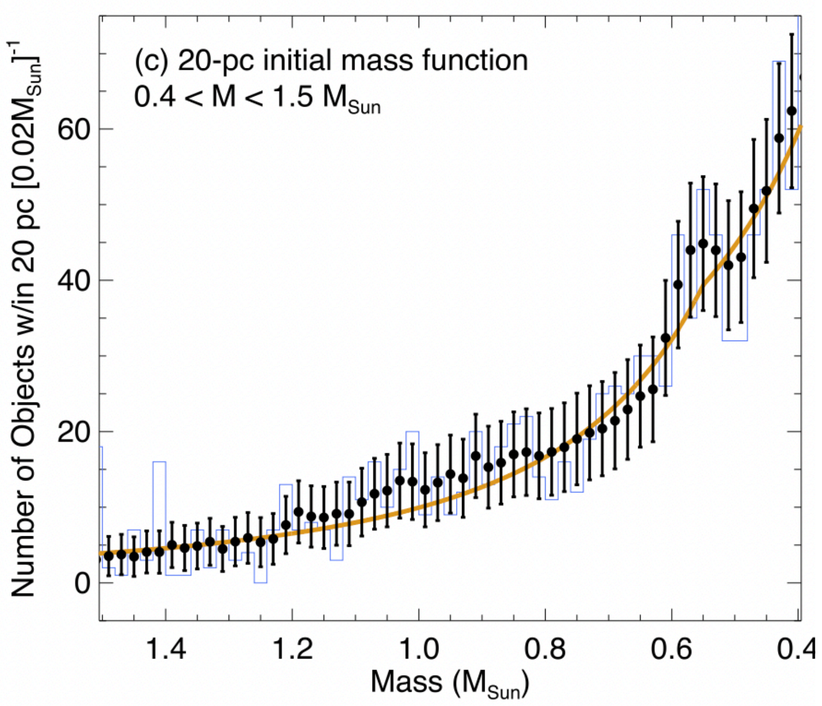


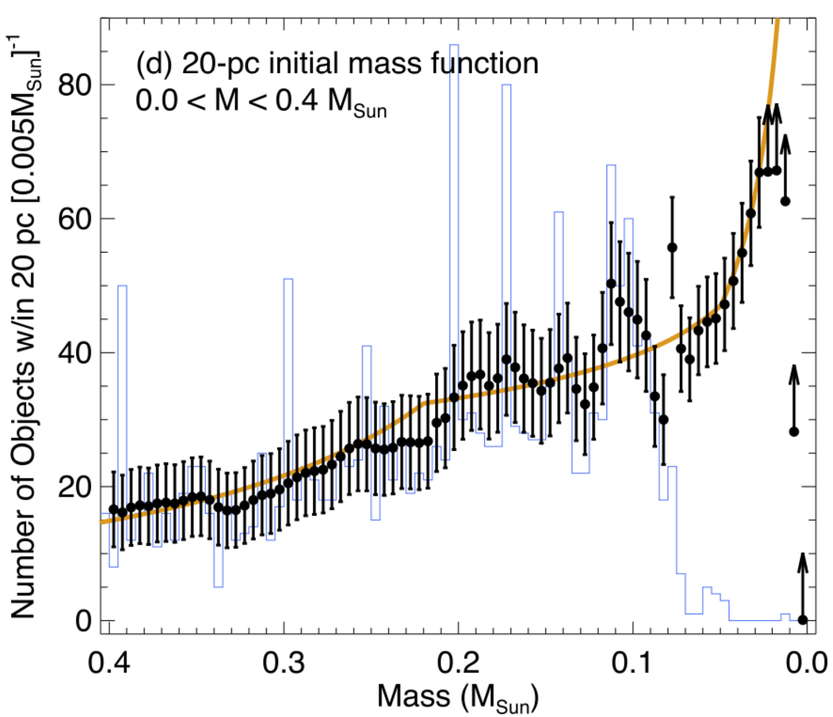
- Fraction stars (≤ 0.4 M_{sol}) to BDs ≈ 2.0
- Fraction stars (≤ 8 M_{sol}) to BDs ≈ 4.0

The initial mass function of the solar neighborhood

Kirkpatrick et al. (2024)





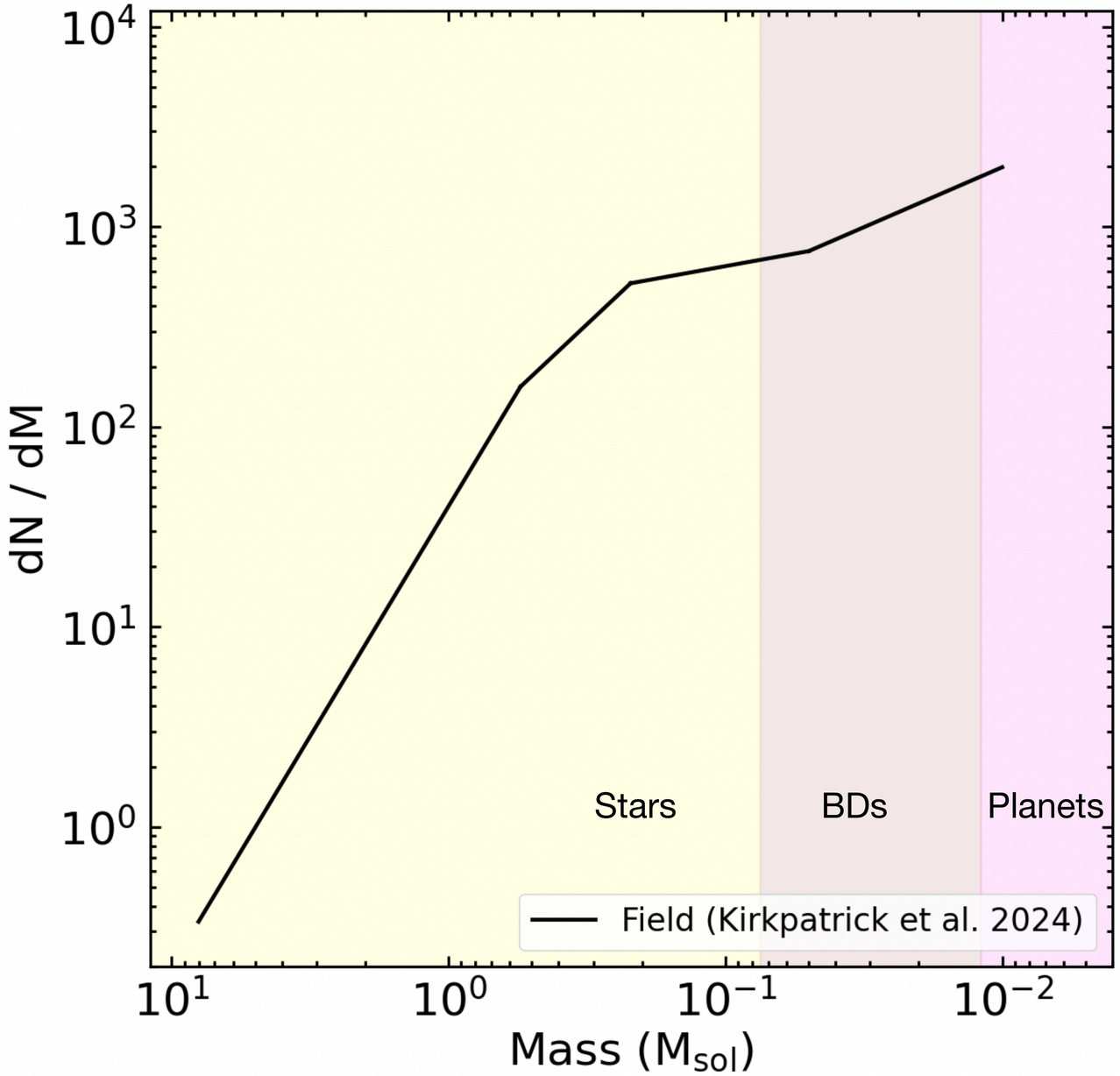


$$\frac{dN}{dM} \propto M^{-\alpha}$$

Mass interval (M_{sol})	α
0.55 - 8.00	2.3 (Salpeter)
0.22 - 0.55	1.3
0.05 - 0.22	0.25
0.01 - 0.05	0.6

The initial mass function of the solar neighborhood

Kirkpatrick et al. (2024)



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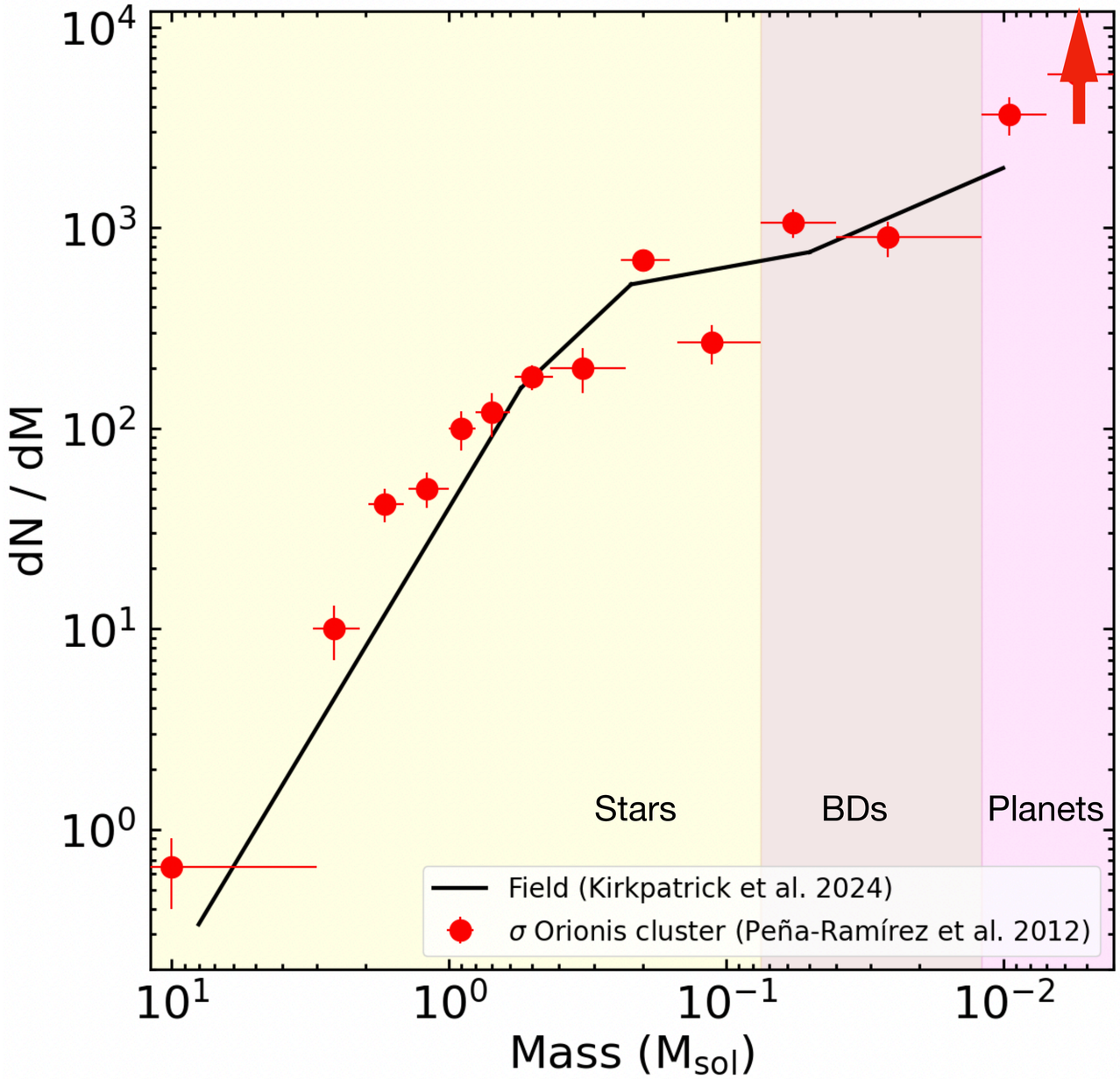
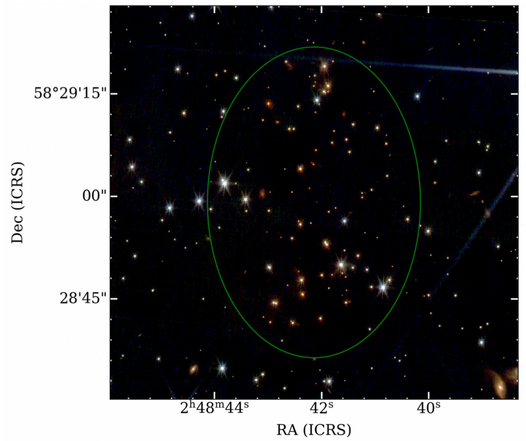
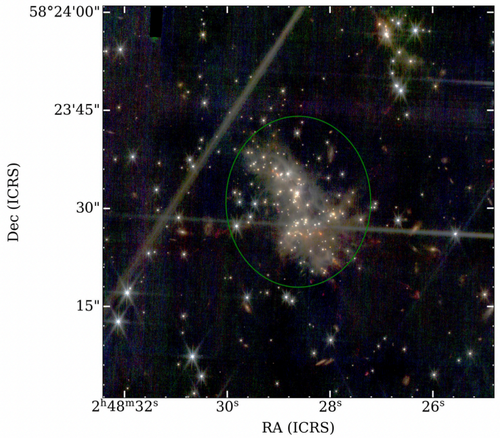


- Extrapolation to **1 - 5 M_{jup}**
  - ~ 800-900 “free-floating planets” with “solar metallicity” up to 20 pc,
  - most would have < 1000 K and therefore very faint at optical and near-infrared wavelengths.

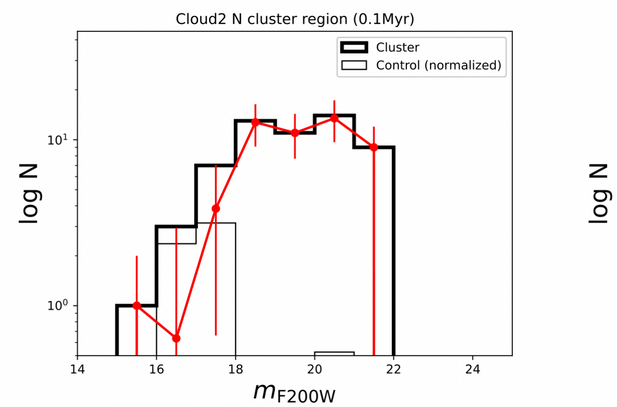
The initial mass function at slightly low metallicity

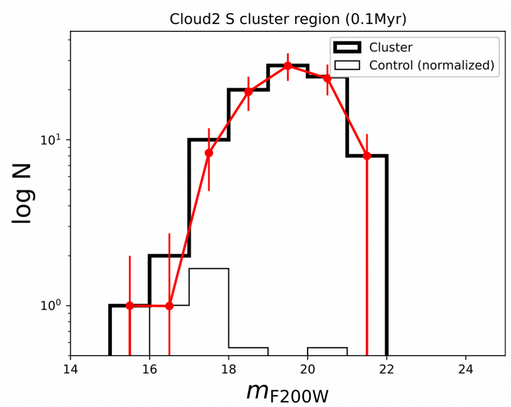




Yasui et al. (2024)

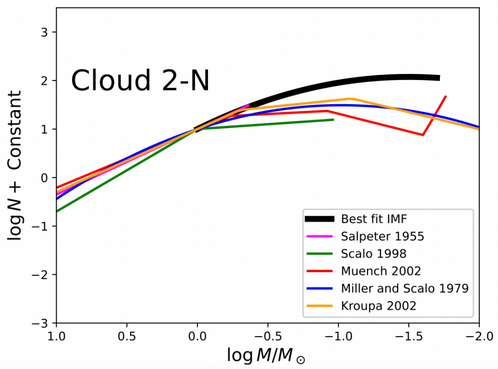
- Digel Cloud 2
- [Fe/H] ~ -0.7 dex
- 7.9 kpc (Gaia).
- There is extinction

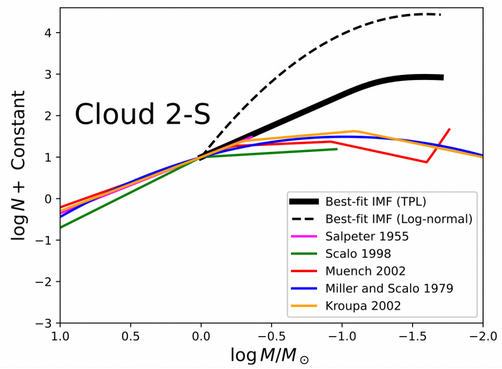




- JWST NIRCCam and MIRI
- Mass detection limit: 20 M_{jup}

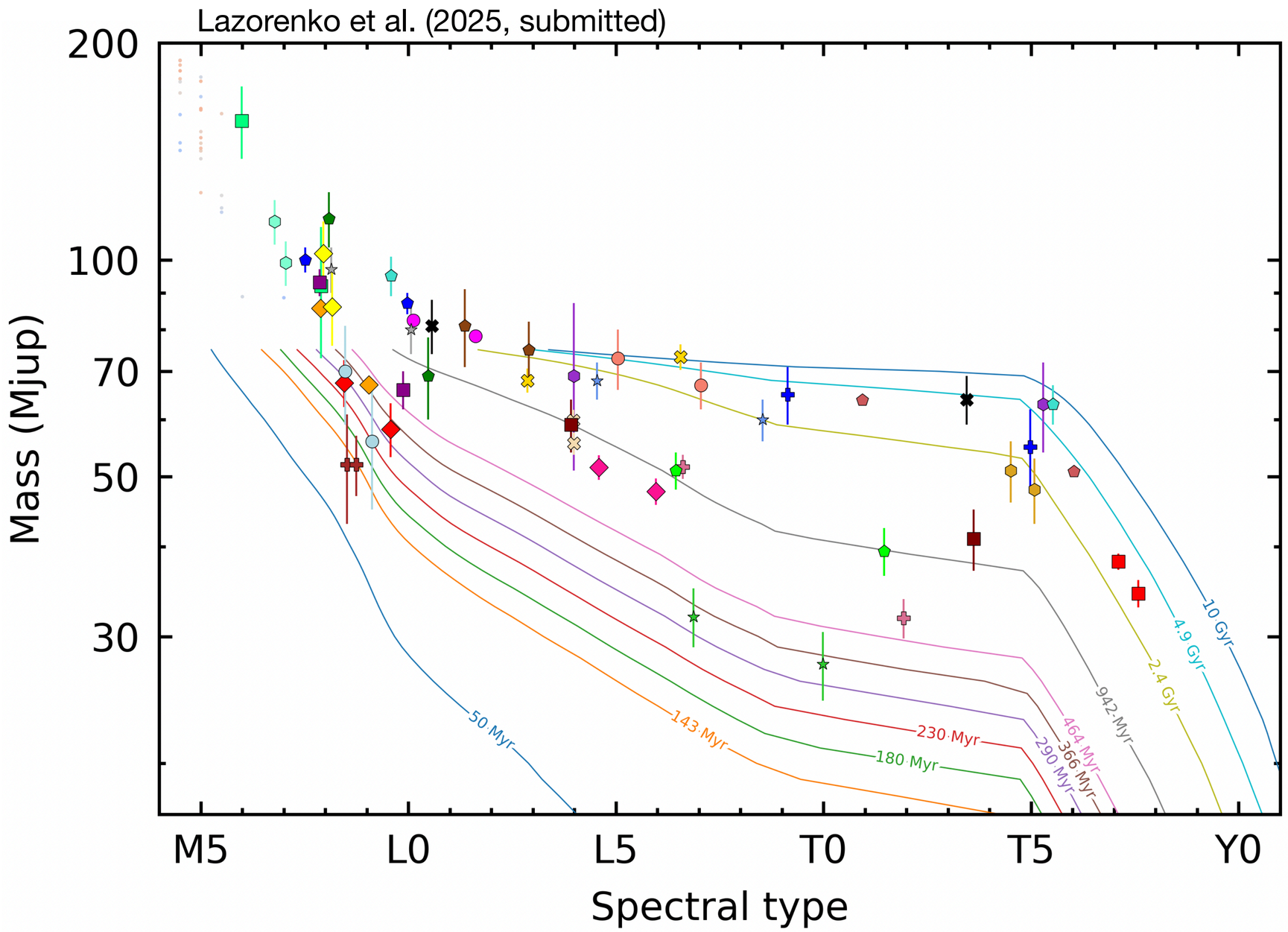
$$\frac{dN}{d\log(M)}$$





- M_c = 0.032 ± 0.010 M_{sol}
- Strongly in contrast with M_c = 0.25 M_{sol} in the solar neighborhood

Dynamical masses of very low-mass dwarfs



Lazorenko et al.
Sahlmann et al.
Xuan et al.
Chen et al.
Dupuy et al.
Curiel et al.
Brandt et al.
Liu et al.
Cardoso et al.
Bouy et al.
etc.

The substellar initial mass function

Final remarks

- IMF (mass spectrum) is smoothly rising towards smaller masses in the substellar regime, but slope is moderate.
- Contribution of BDs (13-75 M_{jup}) to the total mass ≤ 1%.

- Extension of the IMF below 4-6 M_{jup} is now possible with the JWST: contradicting recent works on whether there are planetary-mass objects below ~5 M_{jup} [De Furio et al. 2025; Langeveld et al. 2024; Luhman 2025].

- Universality of the substellar IMF is an open question.
- Substellar IMF at different metallicities is also an open issue (hints for a MF peak at smaller masses.

Talks by Almendros-Abad, Tsilia, Rom