BD30: Conference Summary

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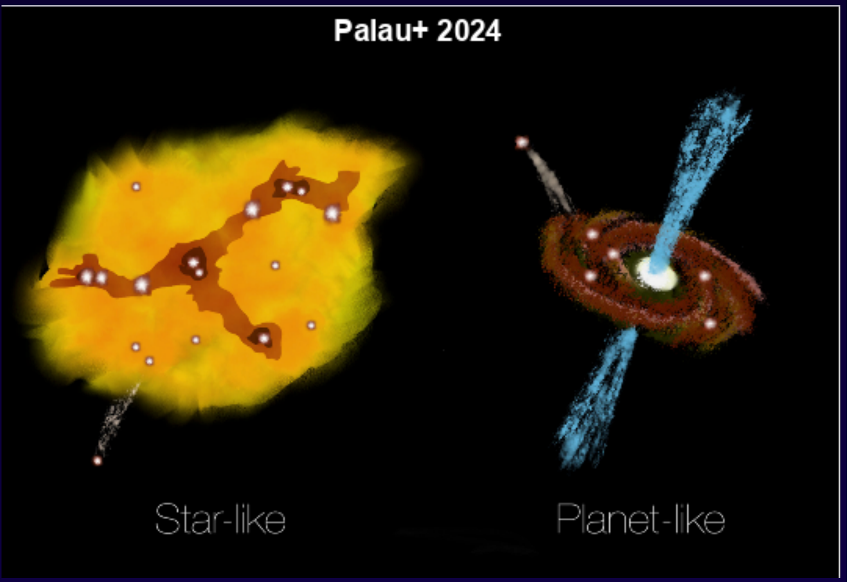
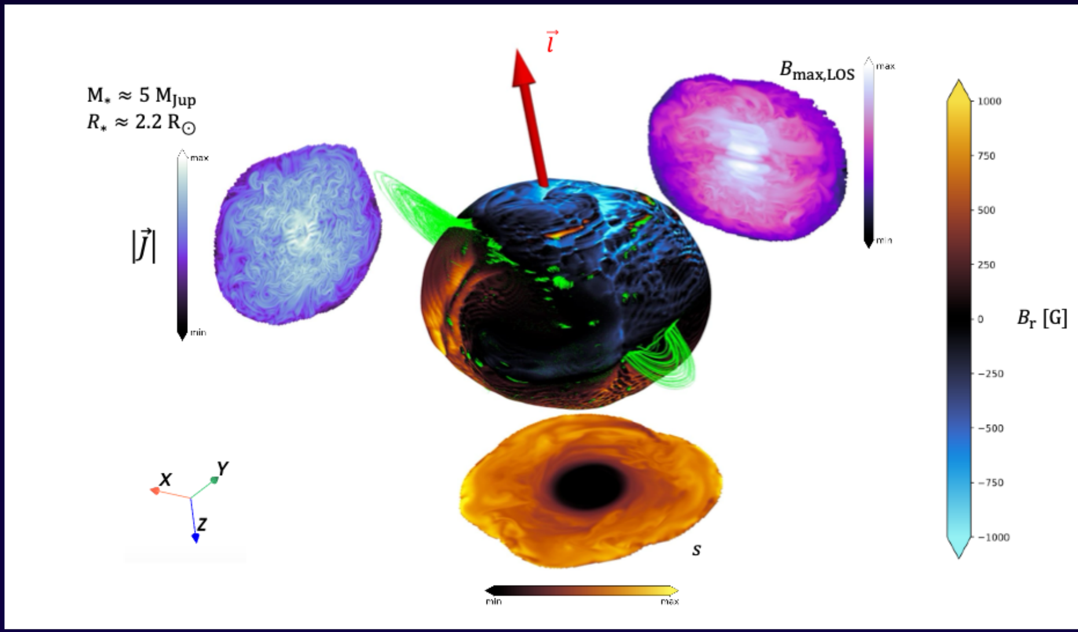
La Gomera, Sep 5, 2025

TOPICS

- Formation/early evolution of brown dwarfs :the lower end of the IMF
- Large scale surveys are Deep surveys
- Modelling Atmospheres
- Spectroscopy of brown dwarfs :
  - Ultracool
  - Ultrapoor
  - The brown dwarfs-exoplanet connection
- Brown dwarfs in binary systems
- BD companions: close and wide
- Time domain phenomena in brown dwarfs: rotation, activity and weather
- Proper motion searches
- Radio searches
- Planets around brown dwarfs
- Future projects impacting the substellar world

Formation and early evolution: protoBDs



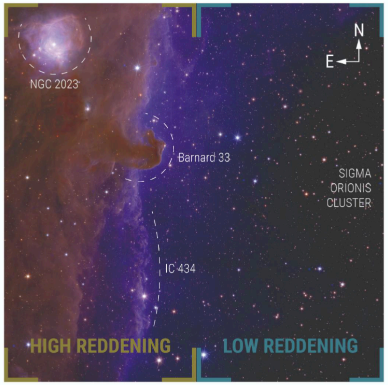


- Brown Dwarf formation through gravitational collapse indeed possible
- Nascent proto-BDs early evolution is highly dynamical
- Interior structure of proto-BDs sensitive to initial conditions
- Nascent BDs should have magnetic fields of kGauss strength

Adnan Ali Ahmad´s talk

The lower end of the IMF

Example star forming regions: σ Orionis



Euclid multi-colour mosaic (Credit: Martín et al. 2025)

Properties: Distance: ~400 pc, Age: 2–4 Myr, Low extinction, solar metallicity

Why Important:

- Very young, nearby, low extinction → ideal for substellar searches
- First photometric brown dwarfs discovered in 1999 (Béjar et al. 1999)
- Rich stellar population revealed by ROSAT (Walter et al. 1997)

Scientific Impact:

- Spectroscopic follow-up defined substellar sequence M6–L6 (Zapatero Osorio et al. 2000, 2002a,b, 2017; Damian et al. 2023)
- Brown dwarfs mass range: **0.075–0.006 M⊙**, spanning stellar limit → planetary regime
- First confirmed **isolated planetary-mass objects** in a cluster (Zapatero Osorio et al. 2000)

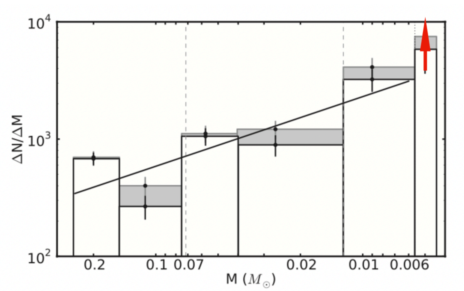
Today: a unique laboratory where **25 $M_\odot$ massive stars** coexist with **6 M_{Jup} objects**

THE EUROPEAN SPACE AGENCY

The initial mass function of the σ Orionis cluster

Peña Ramírez et al. (2012)

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



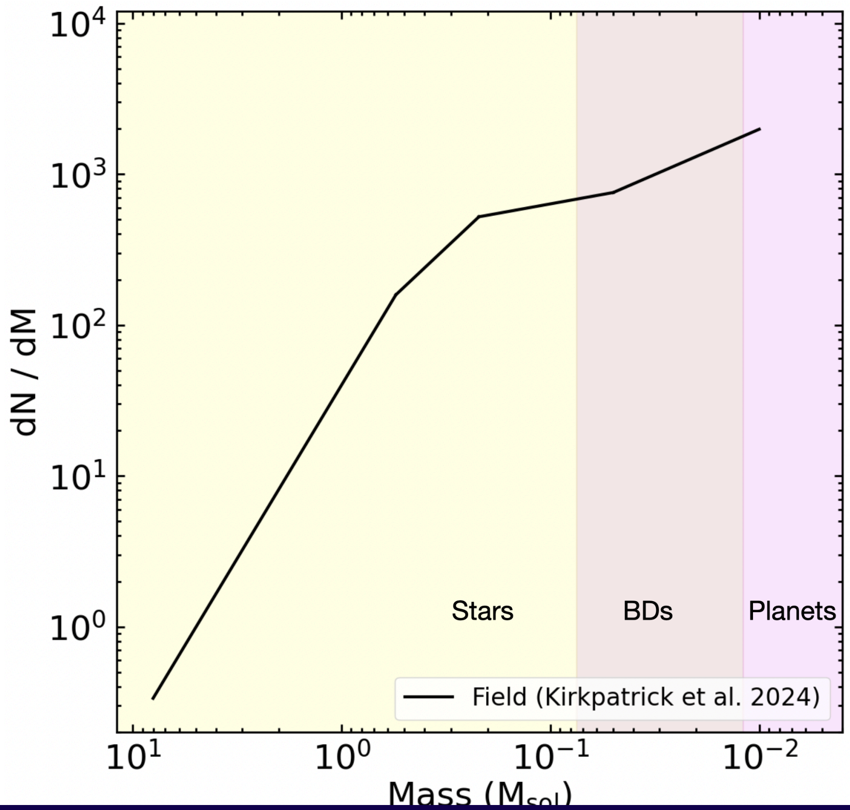
Completeness in the mass interval: 0.006 - 0.25 M_{sol}

- Pleiades
- σ Orionis
- Upper Scorpius
- Praesepe
- Hyades
- Trapezium
- Taurus
- IC 348
- NGC 1333
- Chamaeleon I
- ρ Ophiuchus
- α Persei
- NGC2024
- Lupus
- …

Talks Alves-de Oliveira, Zapatero-Osorio, Muzic, Tsilia,Martin/Zerjal,Rom…

The lower end of the IMF

The initial mass function of the solar neighborhood



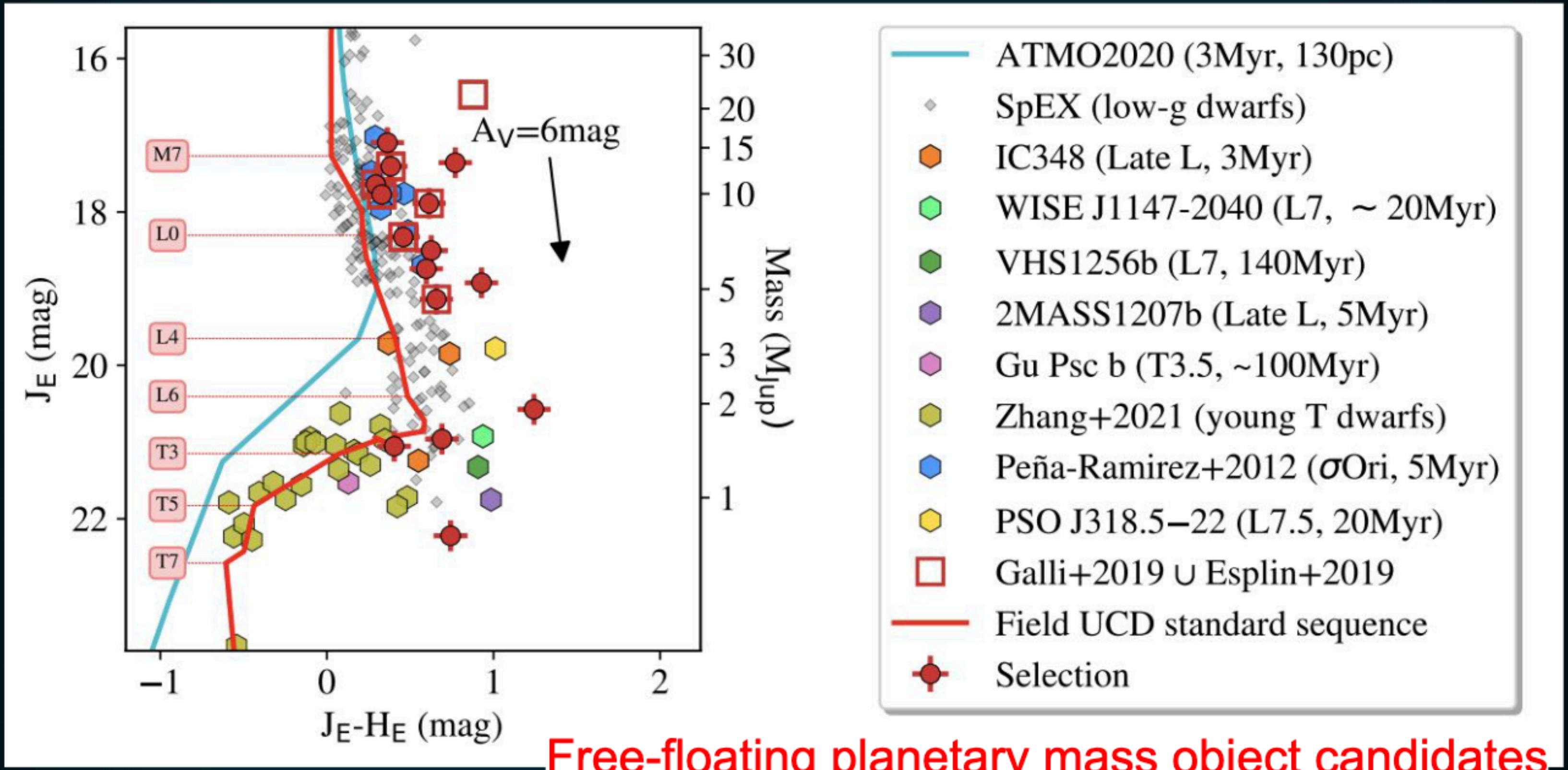
Kirkpatrick et al. (2024)

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

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 lower end of the IMF

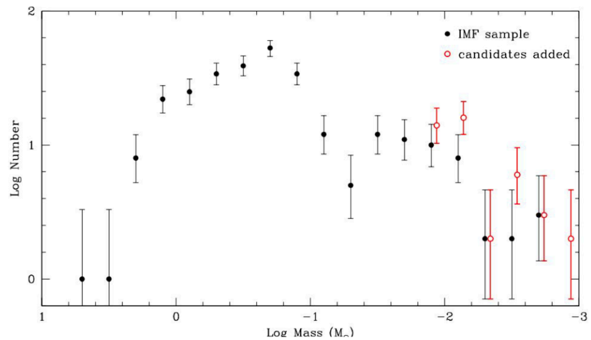
Taurus region LDN 1495 (Bouy et al. 2025)



Free-floating planetary mass object candidates

The lower end of the IMF

The IMF in IC 348



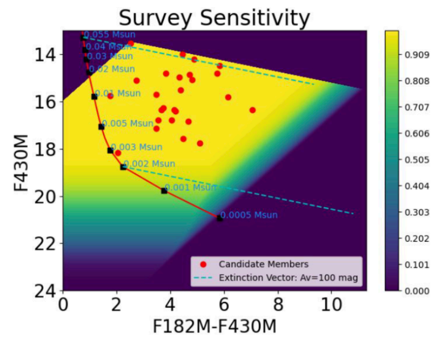
down to ~2 M_{JUP}

(but, without methane absorption)

talk by C. Alves de Oliveira

Luhman & Alves de Oliveira (2025)

NGC 2024



- 400 pc, 1 Myr

survey sensitivity:

1- 2 M_{Jup} @ AV < 50 - 30 mag

no detections below ~ 3 M_{Jup}

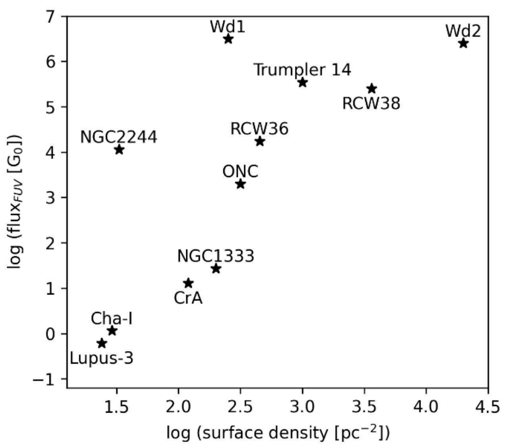
awaiting spectroscopy

- GO 5409 (PI De Furio)

De Furio et al. (2024)

Pushing the frontier with JWST

Star forming environments



RCW 38
- GO 7607 (PI Muzic)
- down to 2-3 M_{JUP}

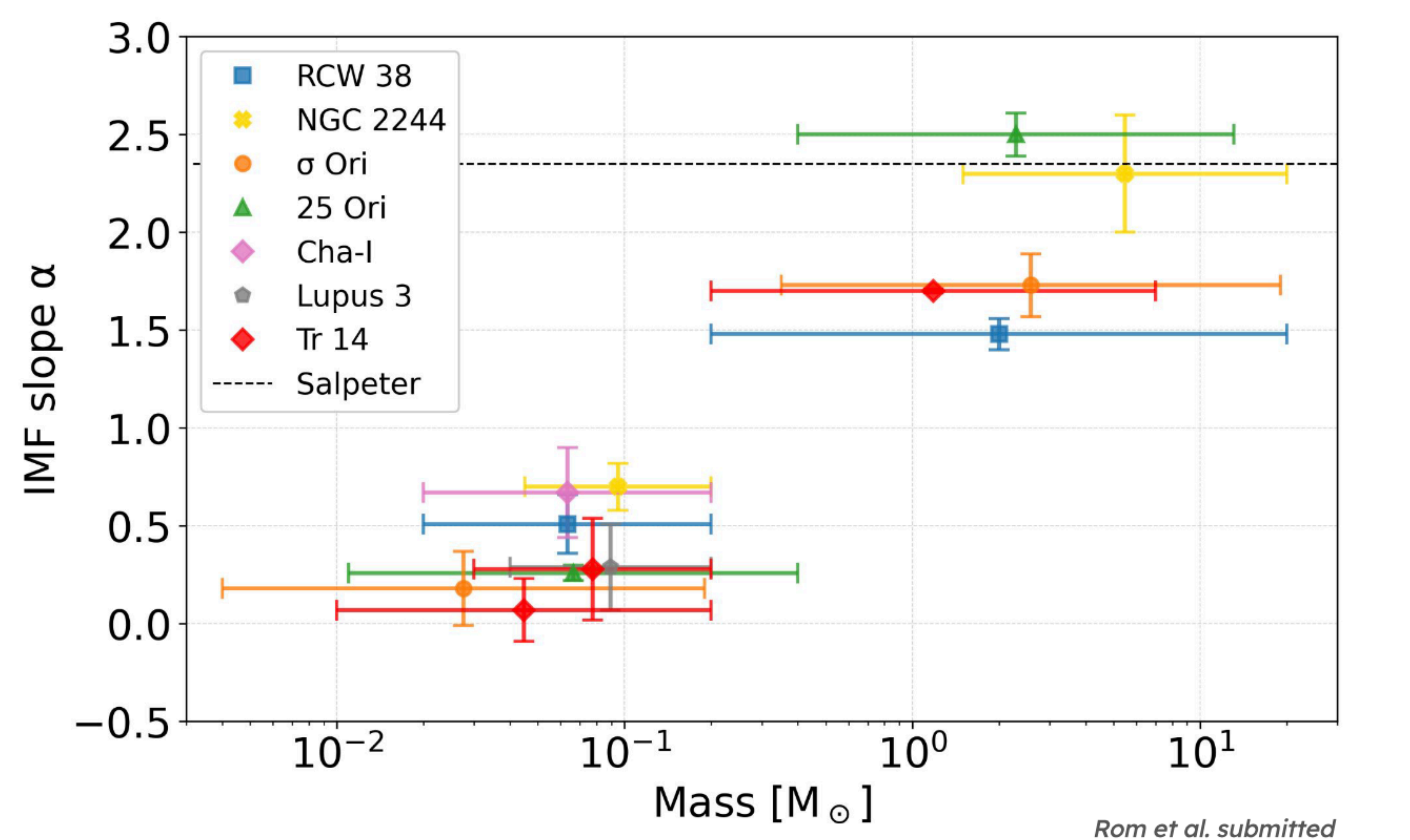
Westerlund 1 & 2
- EWOCS (PI M. Guarcello)
- sensitive to BDs, but not PMOs

talk by V. Almendos-Abad

NGC 2244
- GTO 4545 (PI McCaughrean)
- down to 1 M_{Jup}

Muzic, Almendros-Abad talks

Substellar IMF slopes



Rom et al. submitted

Large Scale Surveys

DENIS
2MASS
SDSS
Pan-starrs
UKIDSS
VHS
WISE

Conclusions

Best-effort estimates:

- Spectral type ≥ M7 (spectroscopically confirmed all-sky): ~4,000 – 8,000
- L dwarfs (spectroscopically confirmed): ~1,500 – 3,500
- T dwarfs (spectroscopically confirmed): ~1,100
- Y dwarfs (confirmed): ~40

Estimated numbers within 100 pc:

- ≥M7: a few ×10^3 — ~10^4
- L dwarfs within 100 pc: ~2,000 – 5,000
- T dwarfs within 100 pc: ~800 – 2,000
- Y dwarfs within 100 pc: Hundreds-Thousands

Lodieu´s talk

Euclid: Large and Deep

Wide survey 15000 sq. deg, YHJ 24 mag

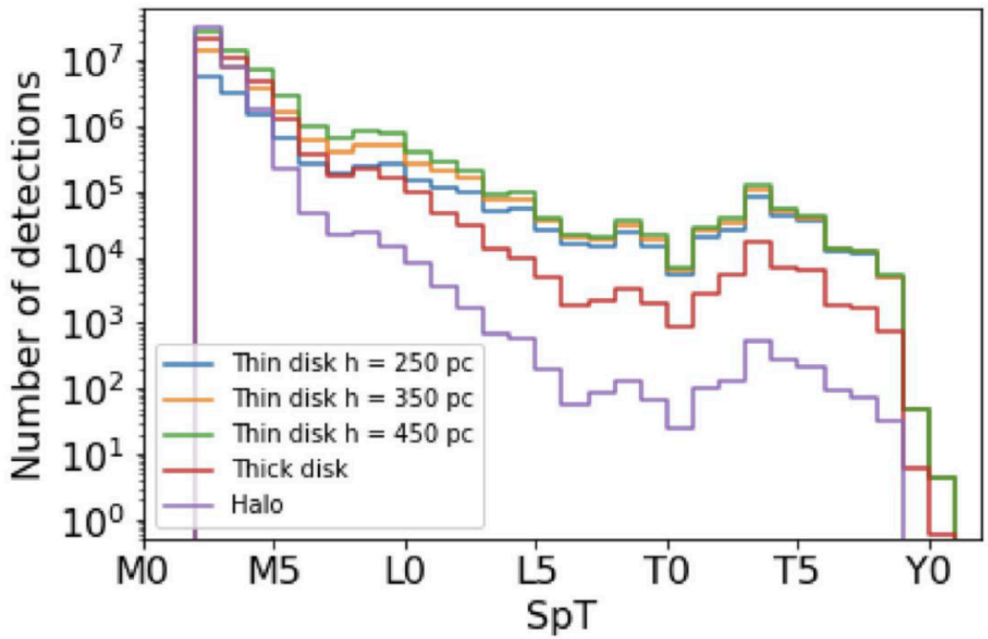


Figure 9. Simulated number counts of UCDs detected by the Euclid wide survey (15 000 deg^2) in the NISP *J* band for a constant galactic latitude of 45° for all objects.

Predicted numbers in the J band (Wide Survey):

- L dwarfs: 2 million
- T dwarfs: 1 million
- Y dwarfs: a handful

All three NISP bands: Around 1 million

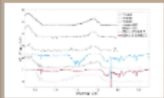
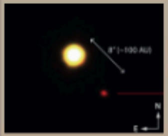
Solano et al. 2021: 2021MNRAS.501..281S

Zerjal, Martin, Domínguez Anjana talks

Large and Deep

Eu

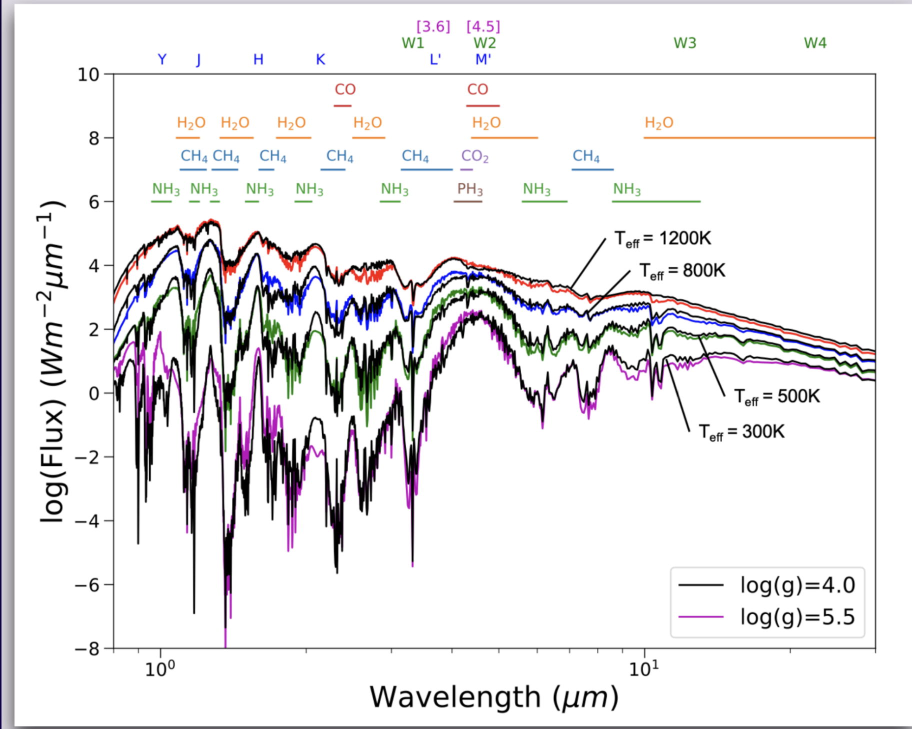
STATE OF THE ART / CHALLENGE

	STATE OF THE ART	CHALLENGE
Substellar objects (with spectra)	 (2x10^3)	2x10^6 (2x10^5)
Substellar binaries (dynamical masses)	150 (40)	2x10^4 (400)
Substellar wide companions to stars	 50	1000
Planets around substellar primaries	10	100
Halo substellar objects	0	few x10^2

Zerjal/Martin, talk

Modelling atmospheres

Model Grids



Equilibrium Chemistry + No Clouds
- ATMO 2020 (Phillips+ 2020)
- Sonora Bobcat (Marley+ 2021)
- Lacy & Burrows (2023)
- Linder+ (2019)

Disequilibrium Chemistry + No Clouds
- Lacy & Burrows (2023)
- Sonora Elf Owl (Mukherjee+2024)
- ATMO 2020 (Phillips+2020)

Equilibrium Chemistry + Clouds
- MARCS-DRIFT (Campos Estrada+2025)
- Sonora Diamondback (Morley+2024)
- Linder+ (2019)
- Morley+ 2012,2014
- BT-Settl (Allard 2014)
- Saumon & Marley (2008)

Disequilibrium Chemistry + Clouds
- Exo-REM (Charnay+2019)

Disequilibrium Chemistry + Diabatic Thermal Structure
- ATMO 2020++ (Leggett+2021, Meisner+2023)

Low-metallicity
- Phoenix (Gerasimov+2020)
- LowZ (Meisner+2021)

M. Phillips talk

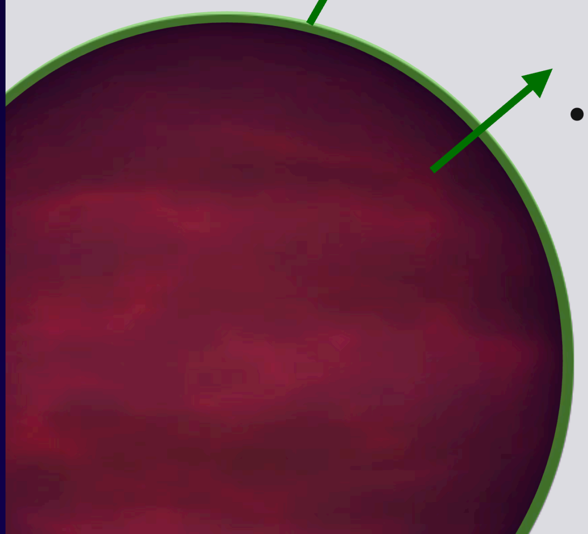
Modelling atmospheres

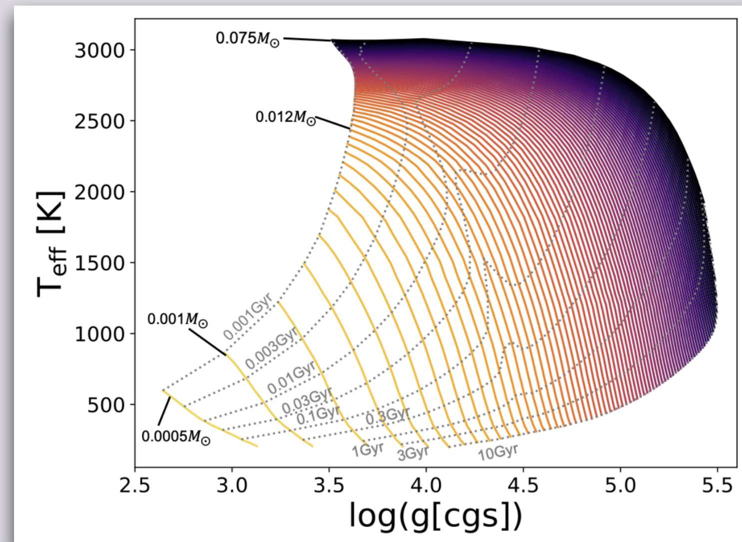
Coupled Atmosphere & Evolution Models

Radiative-convective atmosphere models
Inputs: T_{eff}, log(g), [M/H]
Outputs: PT profiles, abundances, emission spectra

Evolution models

- Calculate the interior structure, nuclear burning, Time evolution
- Provide mass, age, radius, luminosity



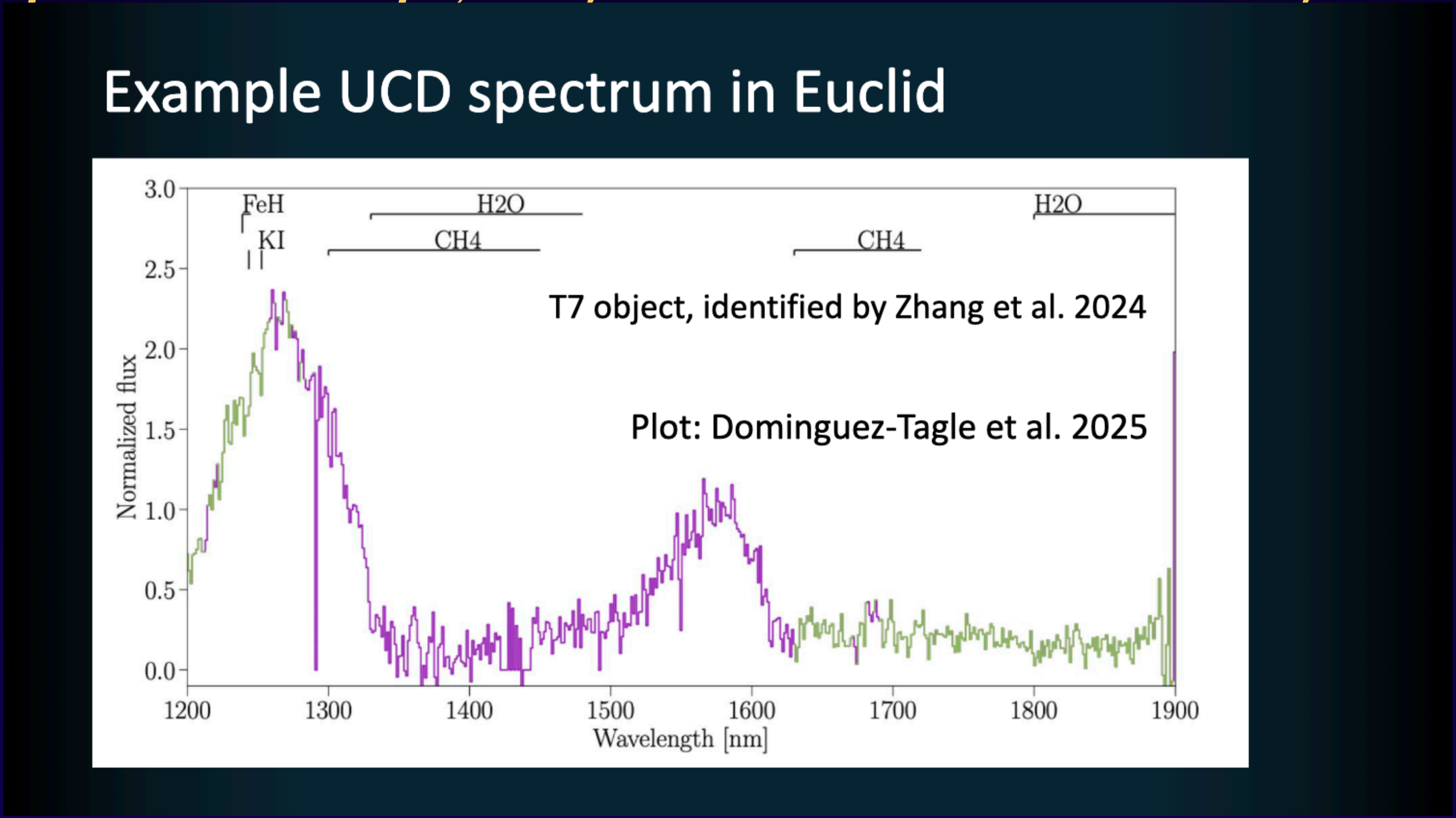


Cloud-free evolution to ~Jupiter masses
ATMO 2020 (Phillips+ 2020)
Sonora Bobcat (Marley+ 2021)

Cloudy Evolution
Sonora Diamondback (Morley+ 2024)
BHAC (Baraffe+2015)
Saumon & Marley 2008

M. Phillips talk

Spectroscopy of cool Brown dwarfs

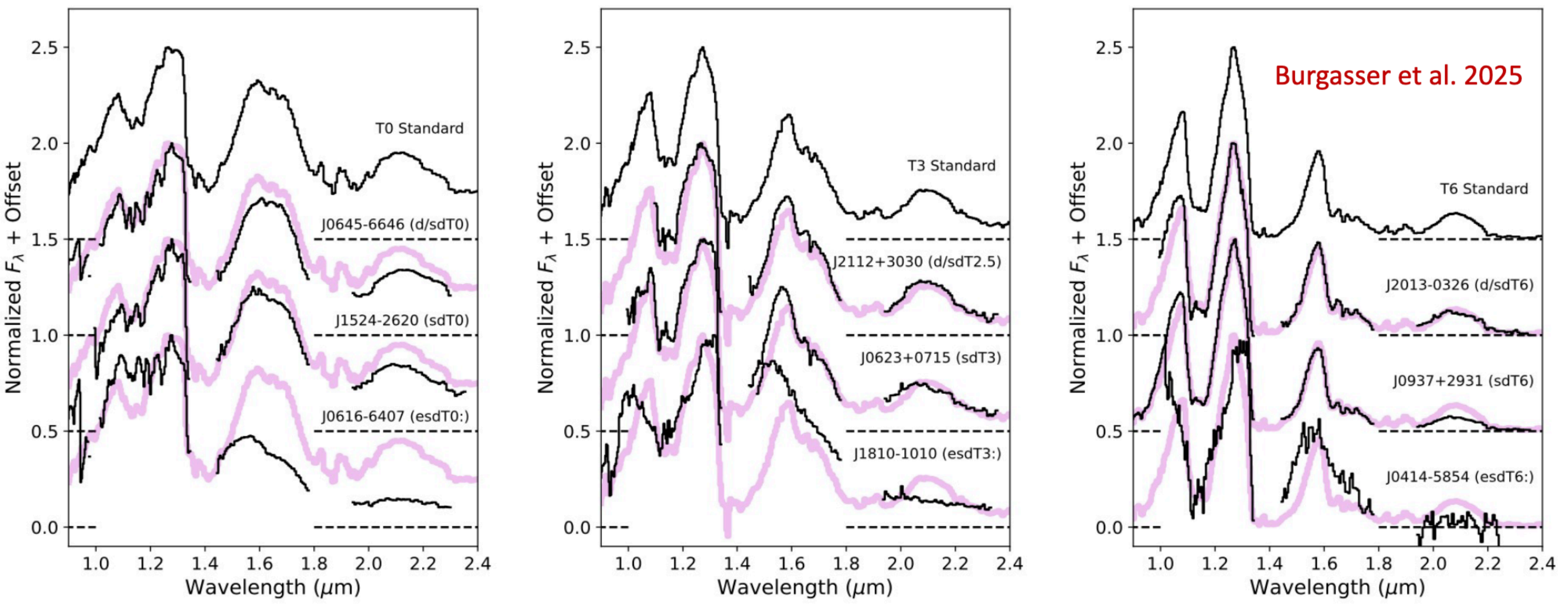


Ongoing Large effort to obtain and model Euclid UCDs

Dominguez Tagle and Nafise Sedighi´s talk

Spectroscopy of metal-poor Brown Dwarfs

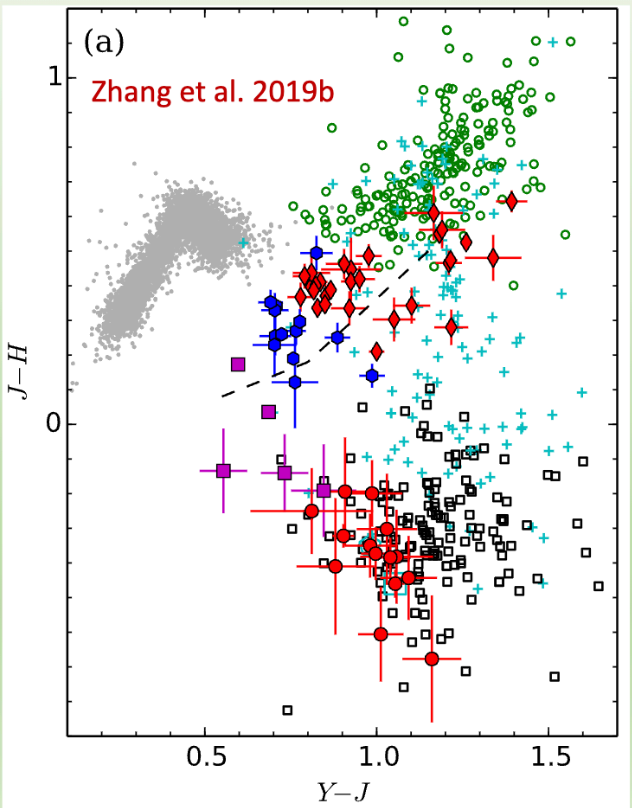
T subdwarf classification

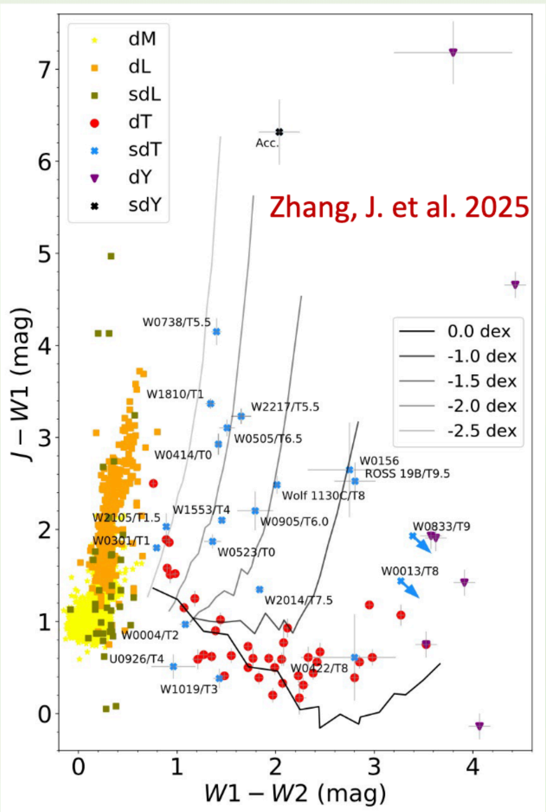


Zenghua Zhang´s talk

Photometry of metal-poor Brown Dwarfs

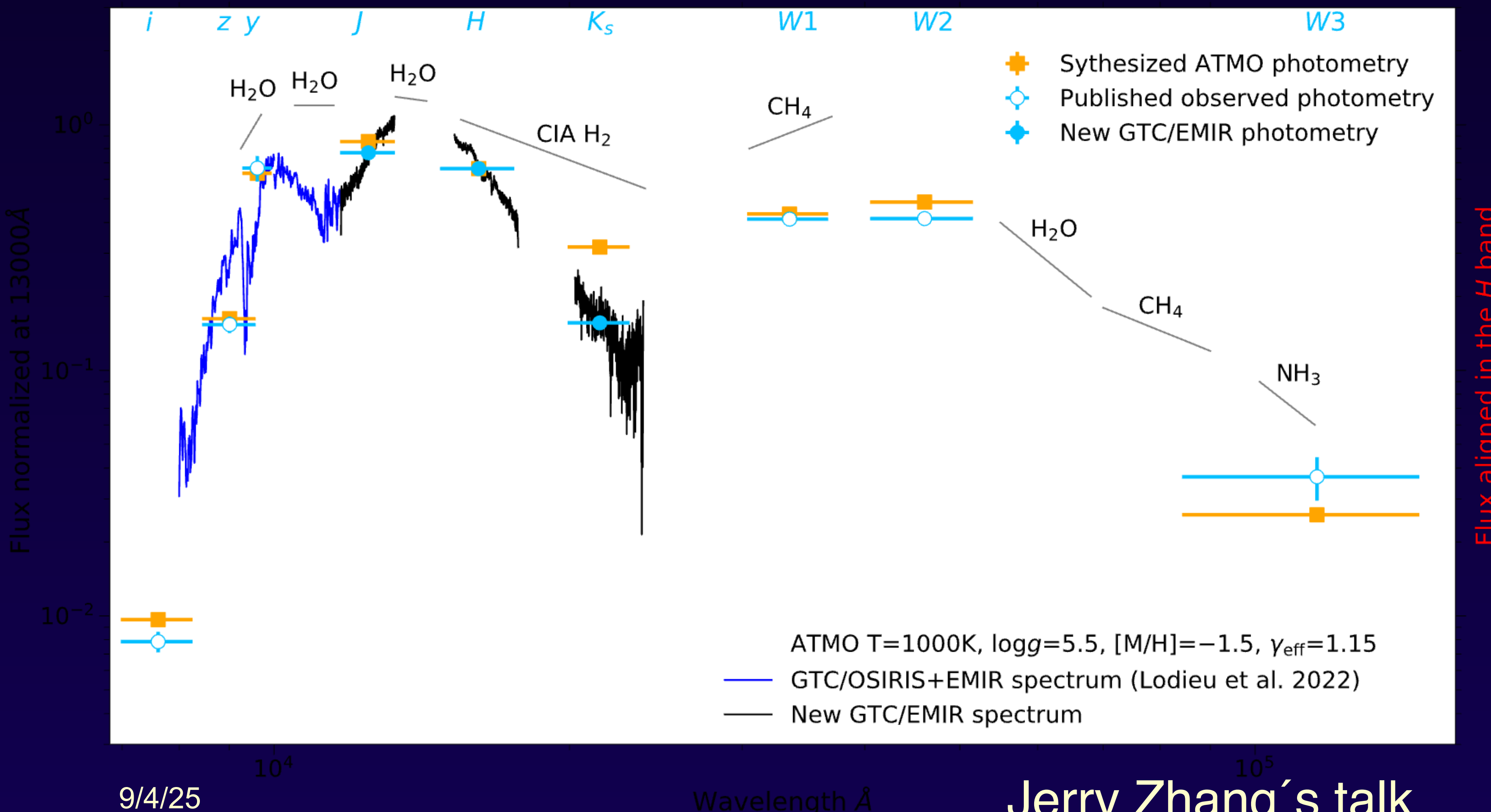
Colours of T subdwarfs





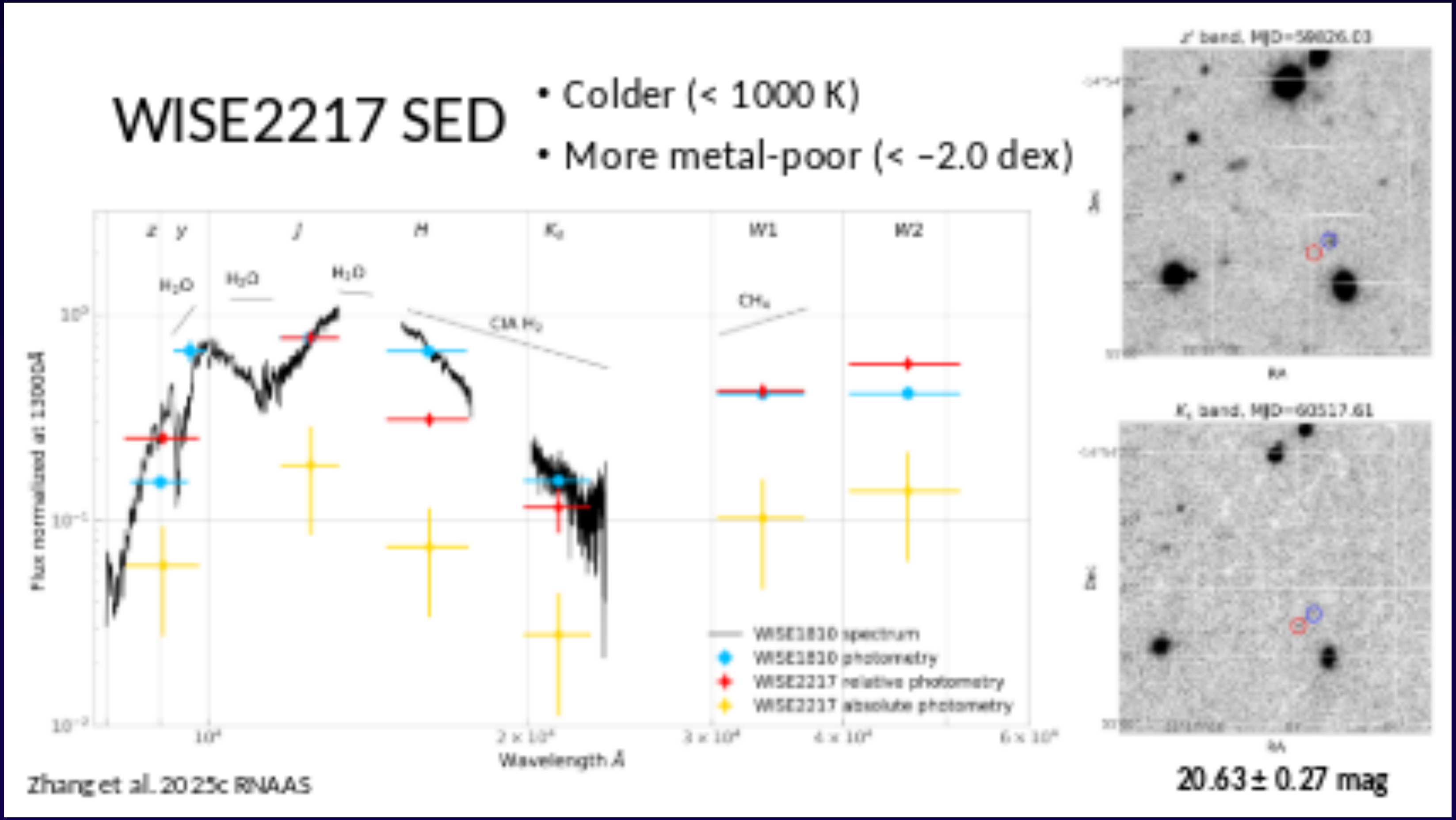
Zenghua Zhang´s talk

Spectroscopy of metal-poor Brown Dwarfs



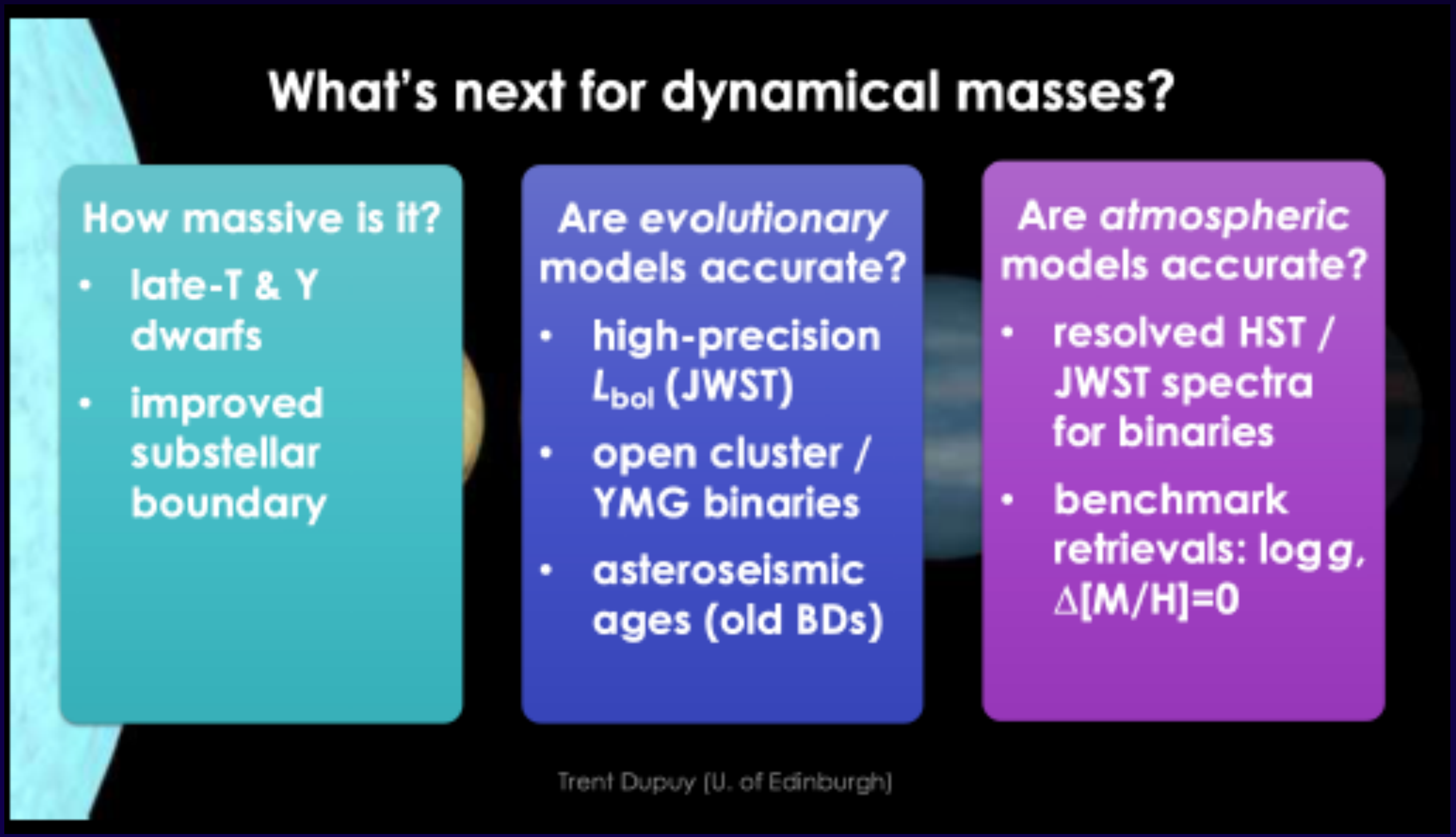
Jerry Zhang´s talk

Metal-poor BDs



Zhang et al. 2025c RNAAS

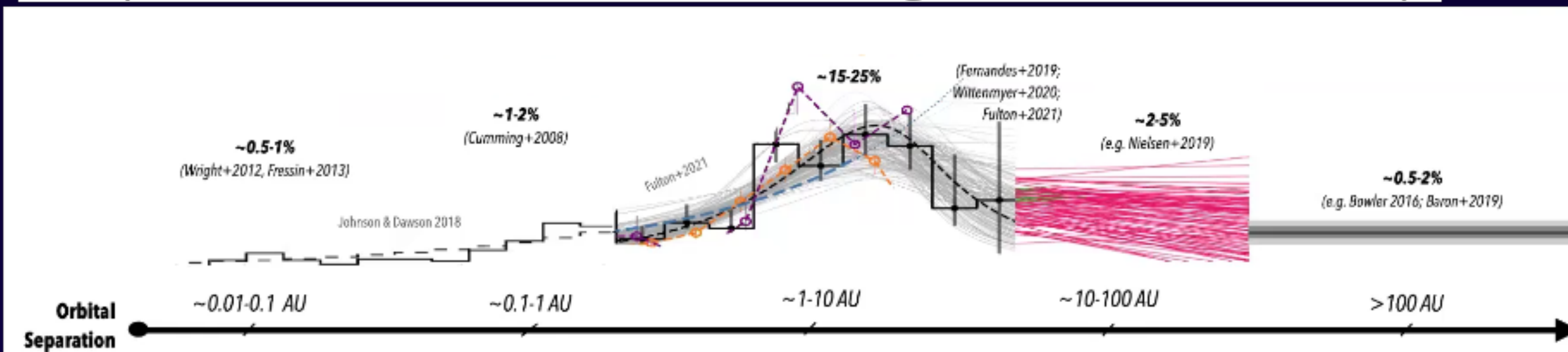
Brown dwarf companions: accurate masses

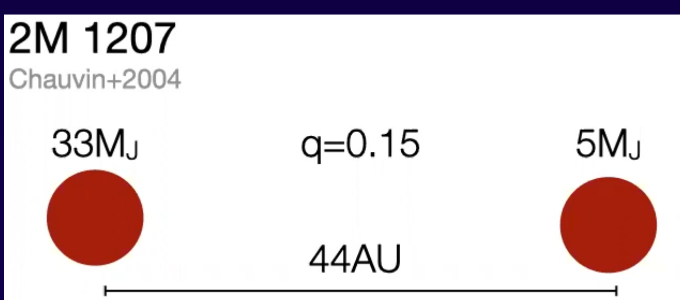


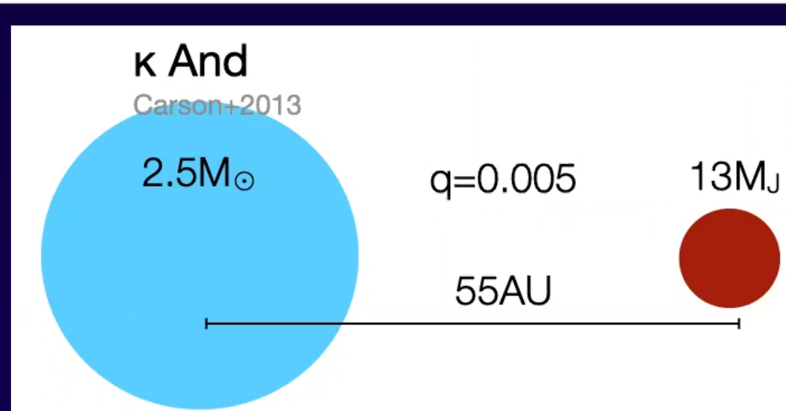
Brown dwarf wide companions

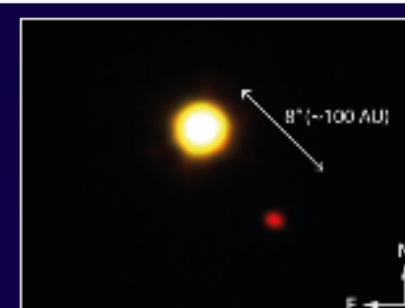
Gauza´s talk

Compilation credits: B. Bowler (2025, Sagan Summer Workshop)







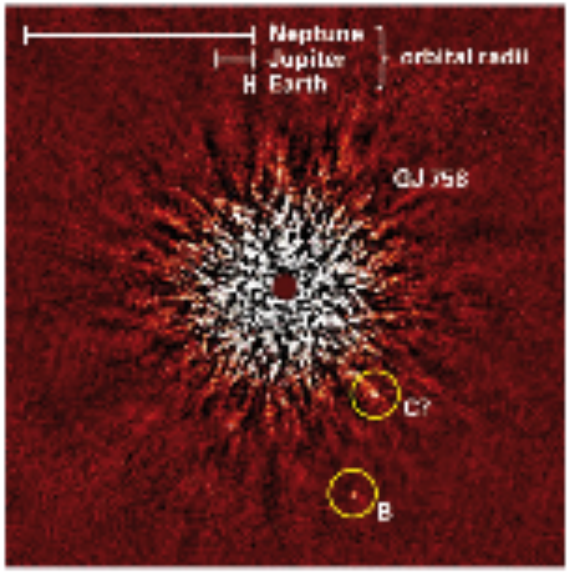


•VHS 1256 (Gauza et al. 2015

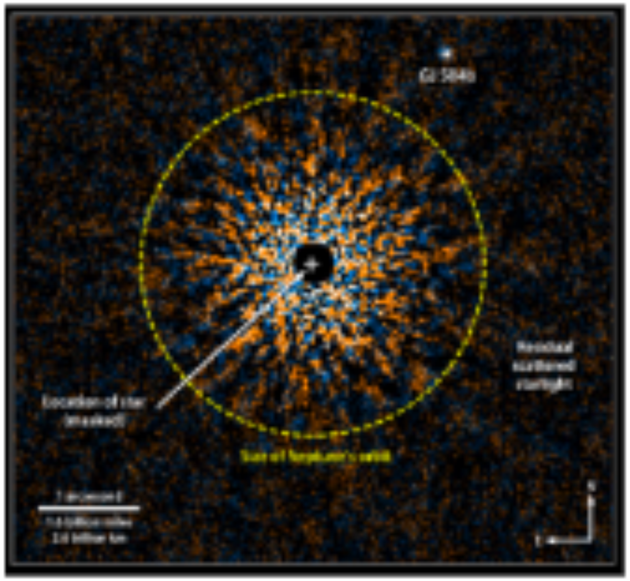
Brown dwarf companions

The coolest substellar companions

- Late T and Y companions: Teff <750 K



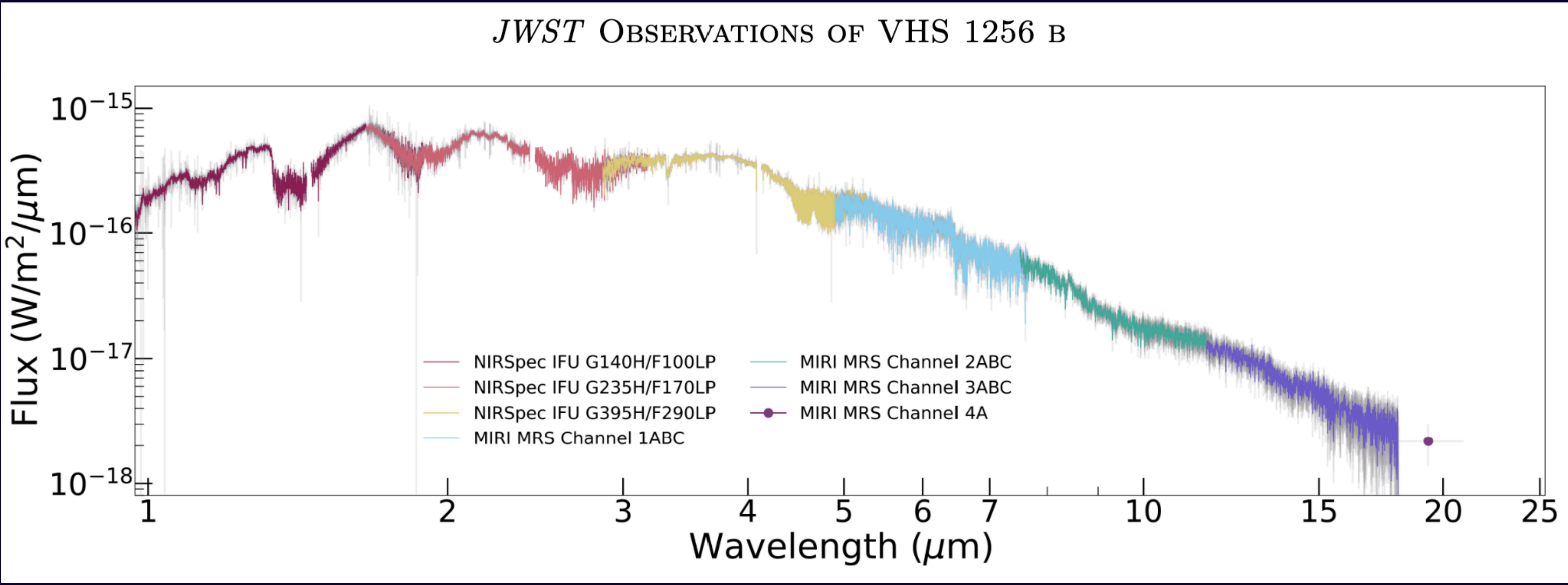
GJ758: G8V at 15.5pc
GJ758B: Sep. = 1.9" (29UA)
M_{comp} = 38 M_{Jup}
SpT~ late T/early Y



GJ504: G0V at 17.6pc
GJ504b: Sep. = 2.5" (43.5 AU)
M_{comp} ~ 4 M_{Jup}
SpT~ late T/early Y

Bejar´s talk

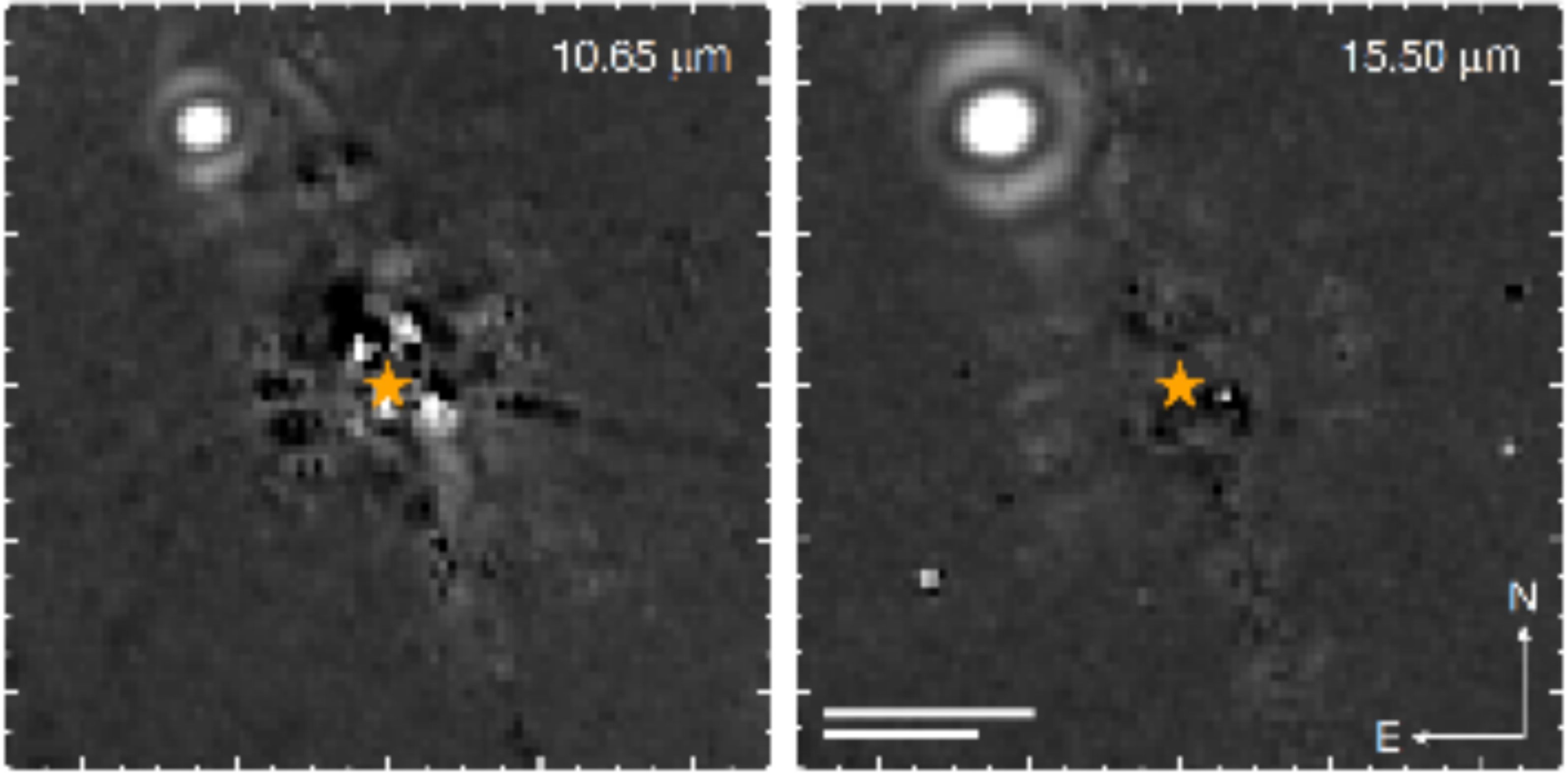
Brown dwarf companions



Bejar´s talk

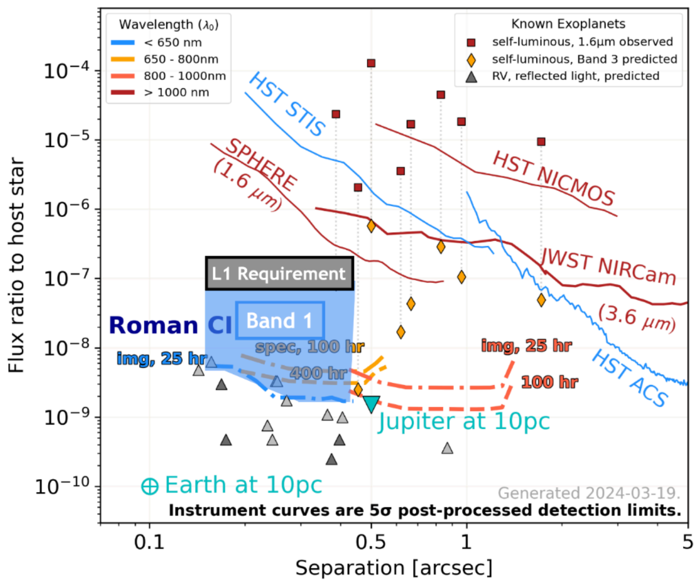
JWST detection of the coolest planets

Discovery of a 6 M_{Jup} planet of ~300 K at 15 AU of Eps Indi A in the mid-IR (Matthews et al. 2024)



Future detection of mature planets

- Detection of old Jupiter-like planets require contrast of 10^{-8}-10^{-9} in the VIS/



For V~ 5 stars

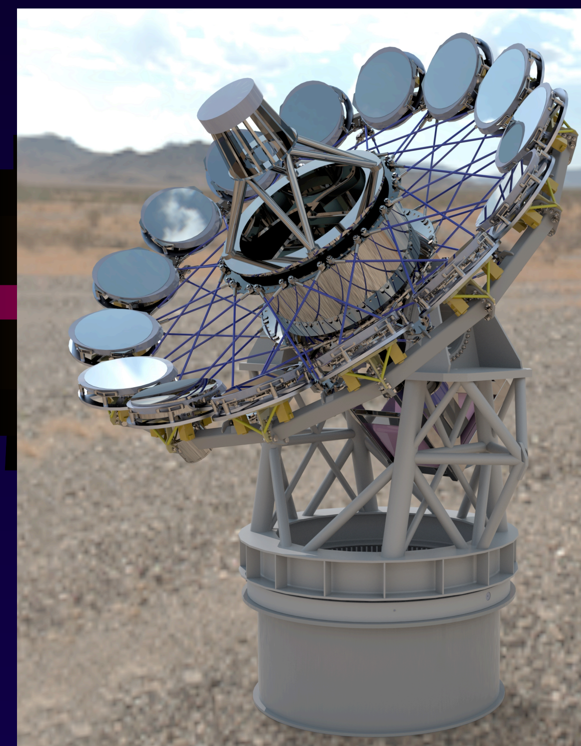
The expected contrast is

< 10^{-7} (L1 requirement)

~ 10^{-8} - 10^{-9} (predicted/goal)

100 to 1,000 times better than current facilities. Optimistically, image mature "Jupiters"

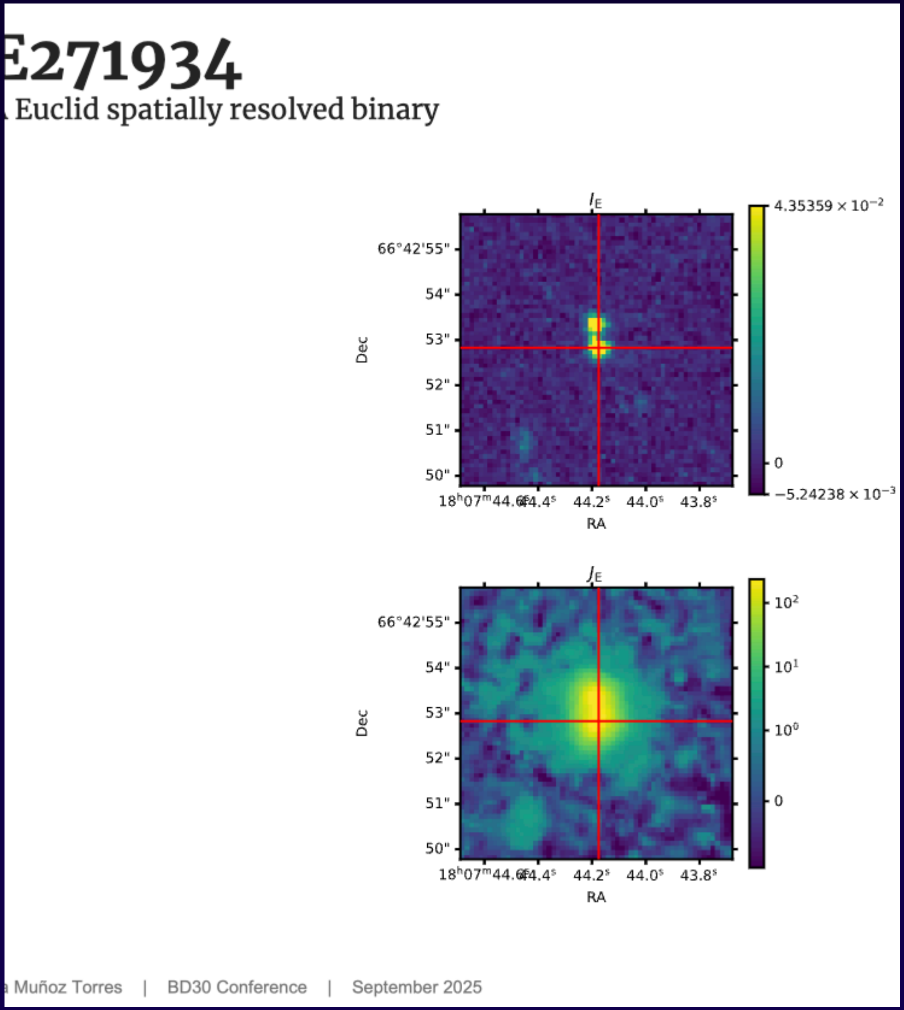
@ 10-50pc in reflected light!



Small ELF

(Loideu et al.2023)

Brown Dwarf Binaries

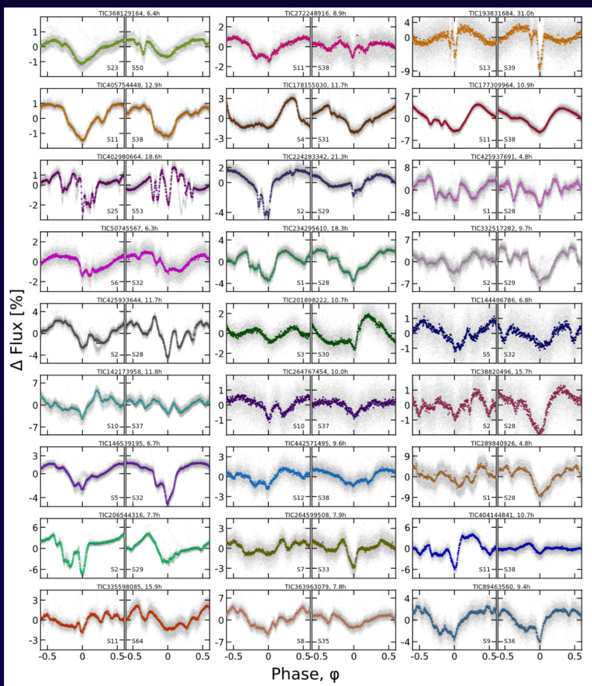


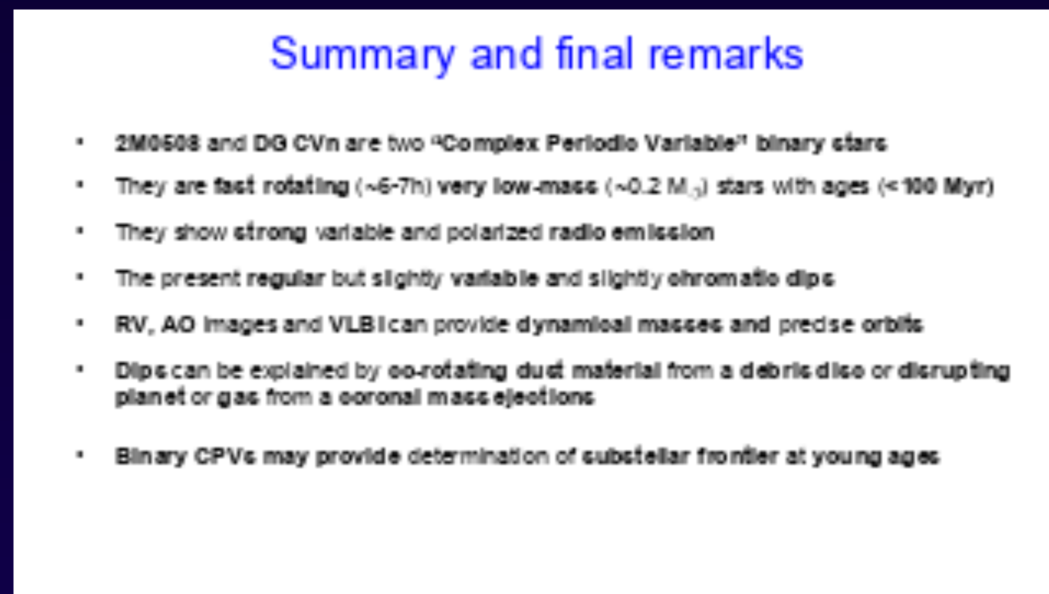
Euclid first
BD binary

Thousands
to be detected
at sep>0.2"

S. Muñoz

Complex periodic variable binaries



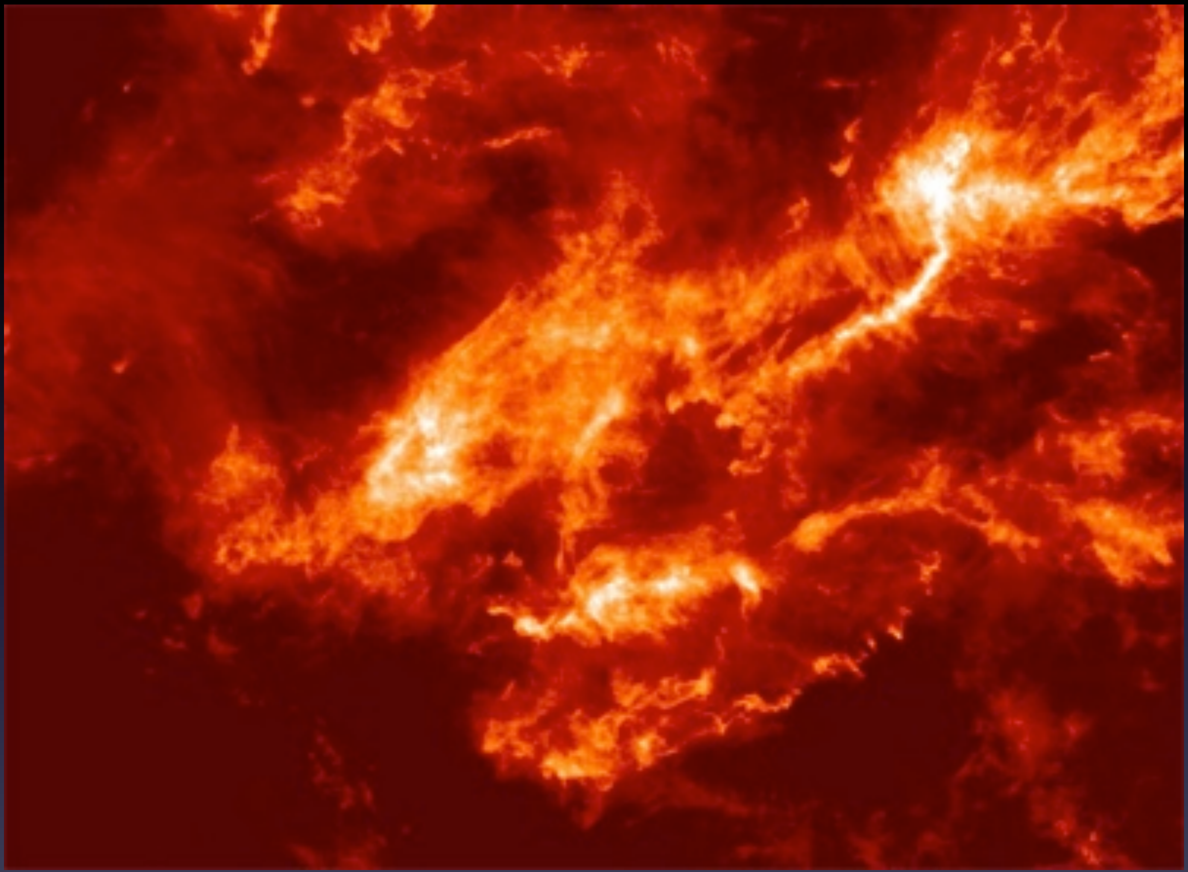

Summary and final remarks

- 2M0508 and DG CVn are two "Complex Periodic Variable" binary stars
- They are fast rotating (~6-7h) very low-mass (~0.2 $M_{\odot}$) stars with ages (<100 Myr)
- They show strong variable and polarized radio emission
- The present regular but slightly variable and slightly chromatic dips
- RV, AO images and VLBI can provide dynamical masses and precise orbits
- Dips can be explained by co-rotating dust material from a debris disc or disrupting planet or gas from a coronal mass ejections
- Binary CPVs may provide determination of substellar frontier at young ages

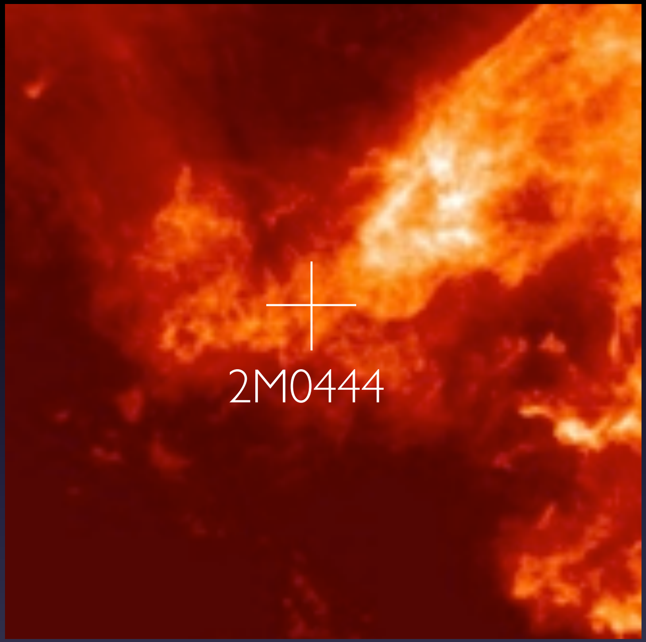
Bejar´s talk

Brown dwarfs have disks when they form

2M0444+2512



FCRAO, G. Narayanan / M. Heyer

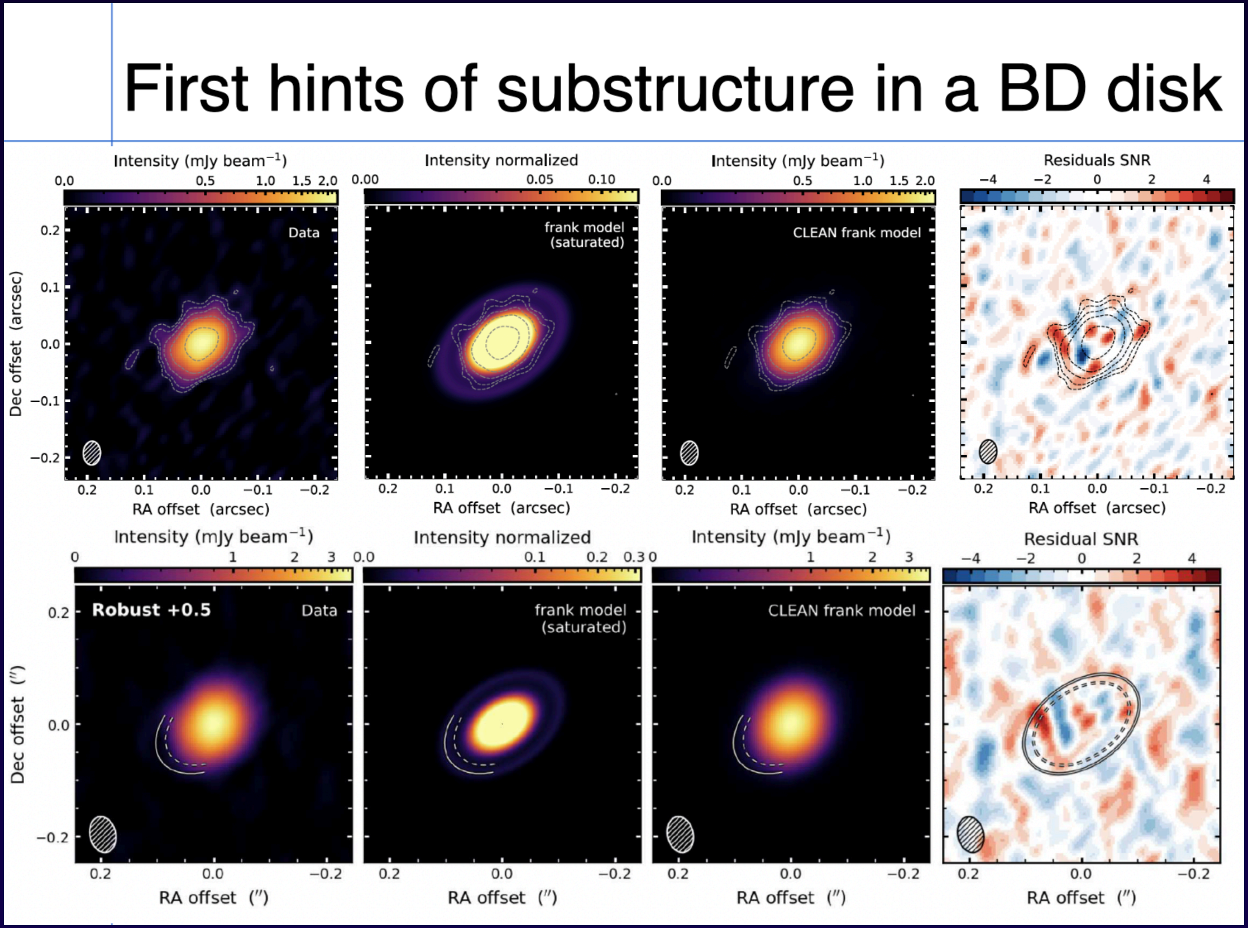


$M_{BD} \approx 50\ M_{Jup}$, $Age \sim 1$ Myr

…and ALMA can see them

L. Ricci

BD Disks also show Gaps



ALMA

Mass of the planets?

Challenge to theory?

Talk by Santamaria

BD disks

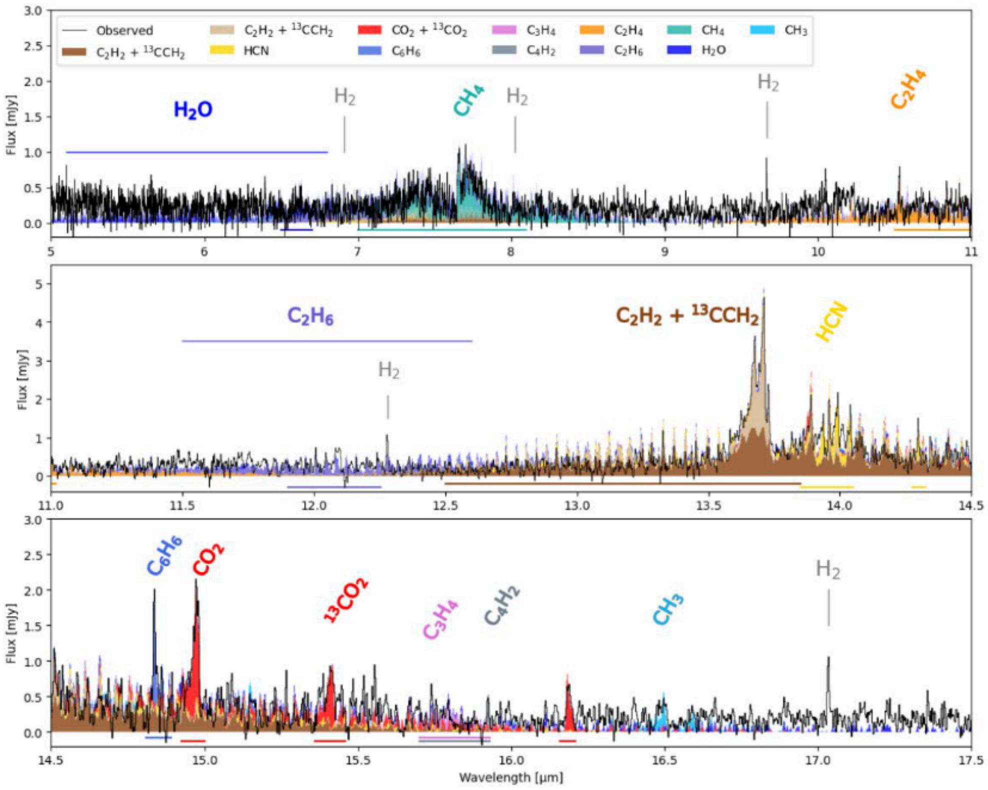
BD disks and chemistry

MINDS (MIRI mid-INfrared Disk Survey) + others

- VLMS/BDs: rich hydrocarbon chemistry
- BD disks:
  - hydrocarbons
  - typically, C/O > 1
  - silicates

Tabone et al. 2024, Arabhavi et al. 2024, Morales-Calderón et al. 2025, Patapis et al. 2025, Kanwar et al. (2025)

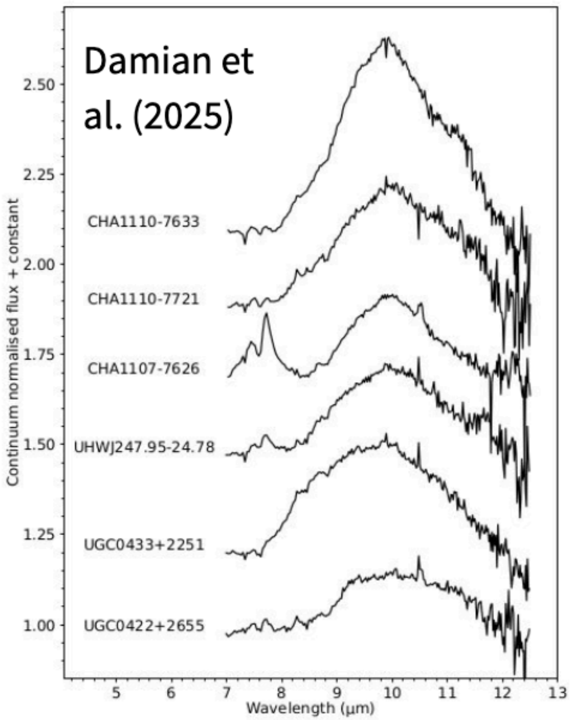
Morales-Calderón et al. (2025)



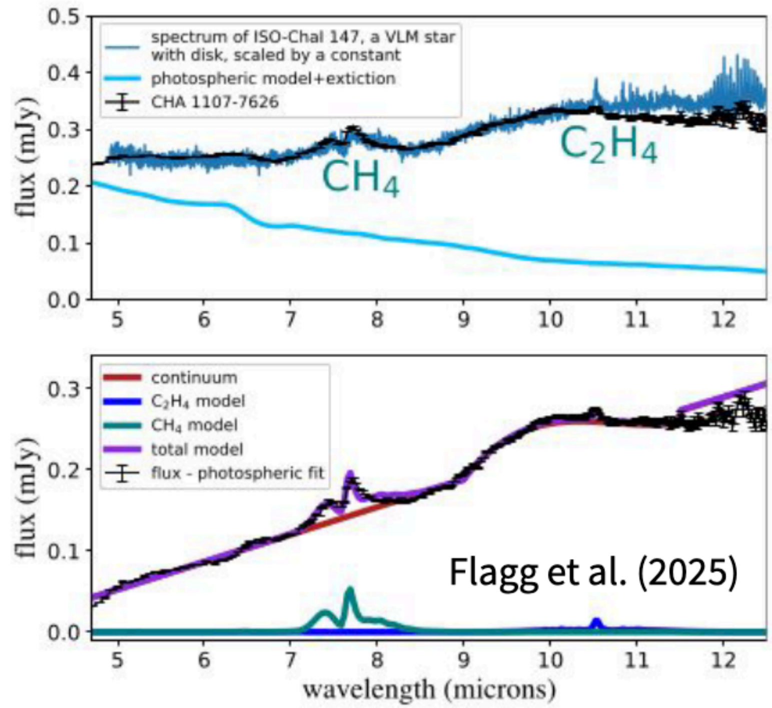
Disks in Planetary mass objects

PMO disks

silicates



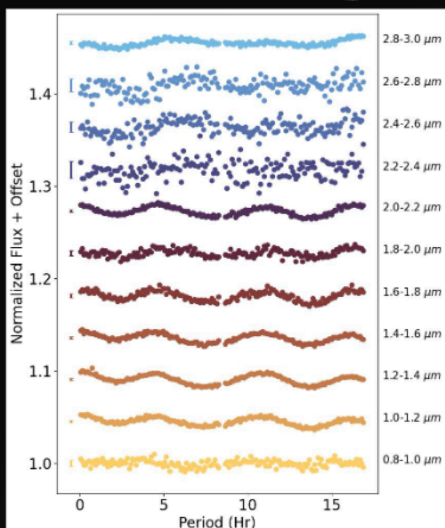
hydrocarbons in Cha 1107-7626



Time domain phenomena: rotation, activity and weather

Summary

Jared Bull
September 4, 2025



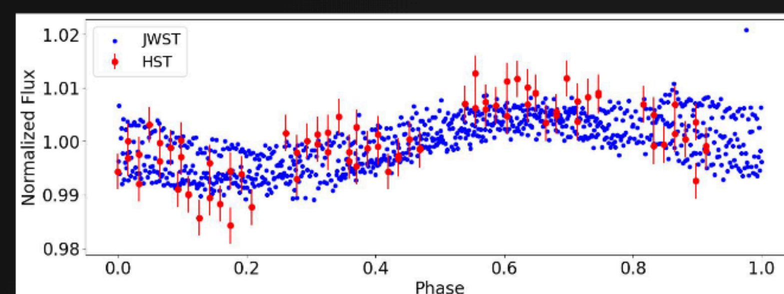
➔ **Distinct** LC behavior across wavelengths

- Multiple mechanisms at play?

Ross 458c, T8

➔ Variability **stable** across epochs (400+ rotations)

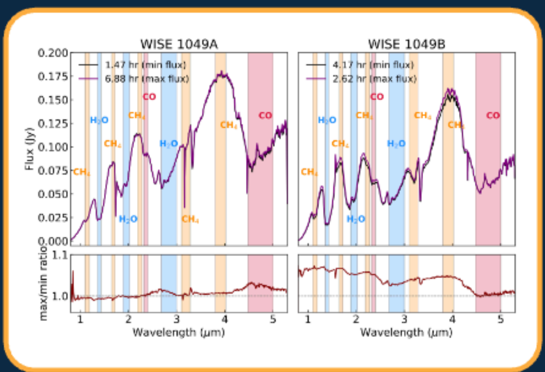
- Period constraint of **5.66 +/- 0.08 hr**

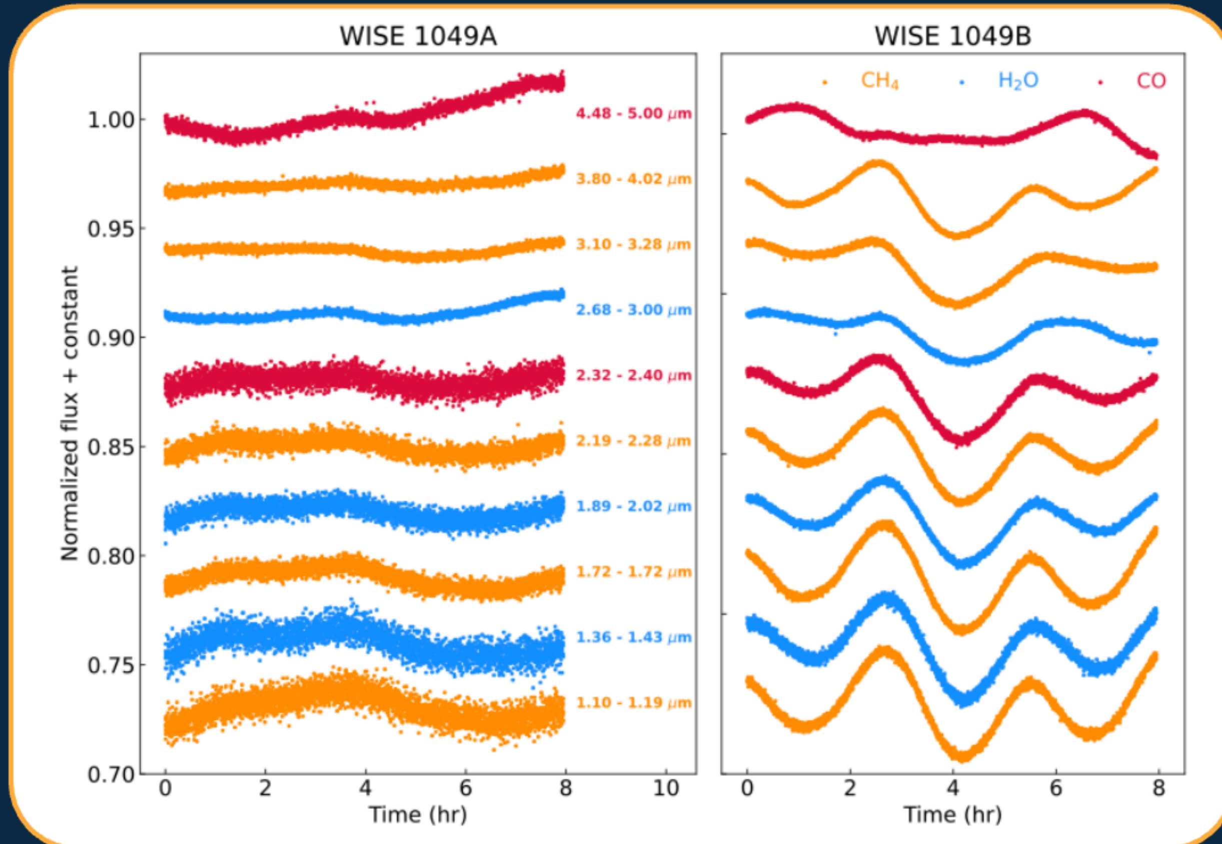


Time domain phenomena: rotation, activity and weather

Time-resolved spectroscopy

Oliveros-Gomez + under review



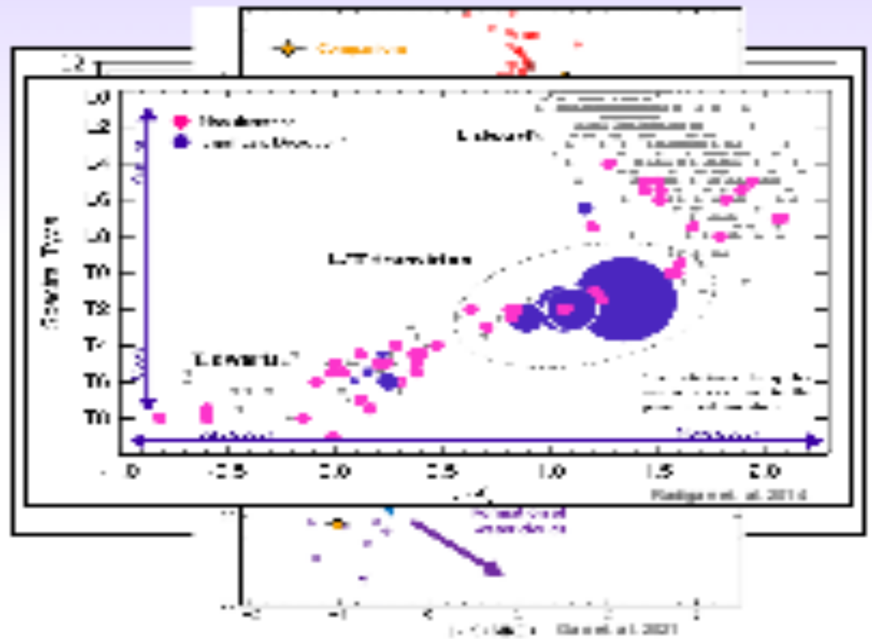


JWST spectrosc.

Time domain phenomena: rotation and variability

SPECTRAL TYPE DEPENDENCE OF VARIABILITY

- L dwarfs modelled best by cloud atmospheres
  - Thick silicate and irons clouds suppressing irradiation of flux from interior
- L/T transition is best described by patchy, segmented cloud structures
  - Works such as Radigan 2014 have explained that the silicate cloud breakup causes the highest amplitudes of variability in the J-band.
- T dwarfs modelled best by cloudless atmospheres
  - Clouds have broken fully and descended beyond photosphere



Brown Dwarf Light Curve Library !

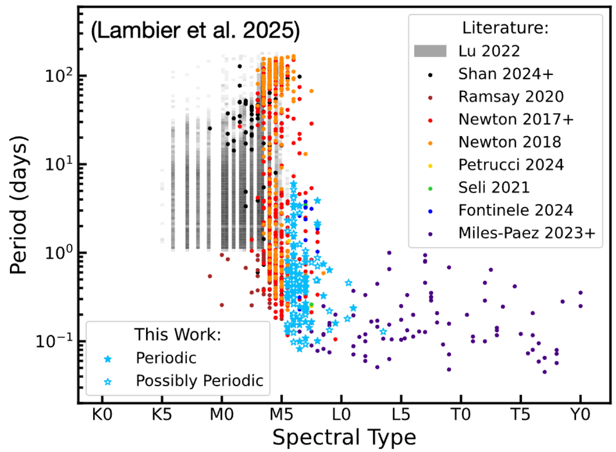
Manjrawala´s talk

Time domain phenomena: rotation and variability

Take-home messages

Studying brown dwarf variability has been a mix of careful technique and serendipitous discovery. Sometimes we know what we are looking for, sometimes the objects surprise us.

- Variability is ubiquitous in brown dwarfs.
- Rotation reveals how brown dwarfs spin up with age, losing angular momentum only moderately compared to stars.
- Multi-wavelength variability probes clouds, temperature gradients, chemistry, and magnetism in 3D.
- Brown dwarfs as exoplanet analogs — with JWST and ELTs turning light curves into weather maps.

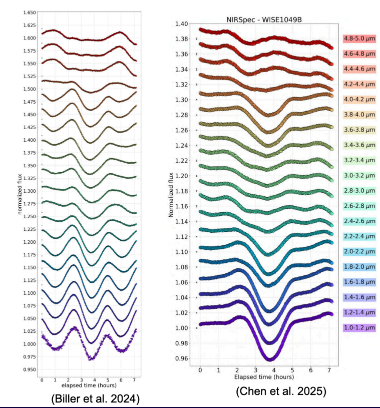


What's Missing?

- More Y dwarf rotation periods! Is there a Y-dwarf analogue to the L/T transition peak in variability?
- How slowly/fast can field brown dwarfs rotate? Pulsations?
- Variability studies in subdwarfs.
- Potential correlations between radio and optical/IR variability.
- Sun-like magnetic cycle analogues?

Luhman 16A and B: No Two Epochs Alike

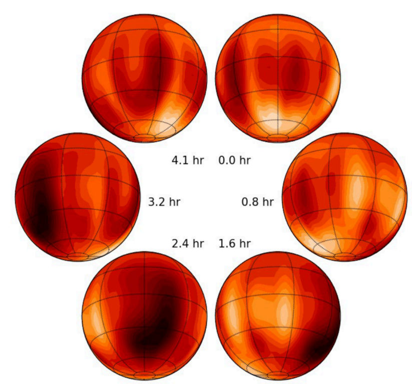
Modeling suggests that, at the same wavelength chunk, light-curve shapes evolve across epochs but arise from the same mechanism.



(Biller et al. 2024)

(Chen et al. 2025)

Doppler imaging: When Variability Becomes a Map



Crossfield et al. (2014)

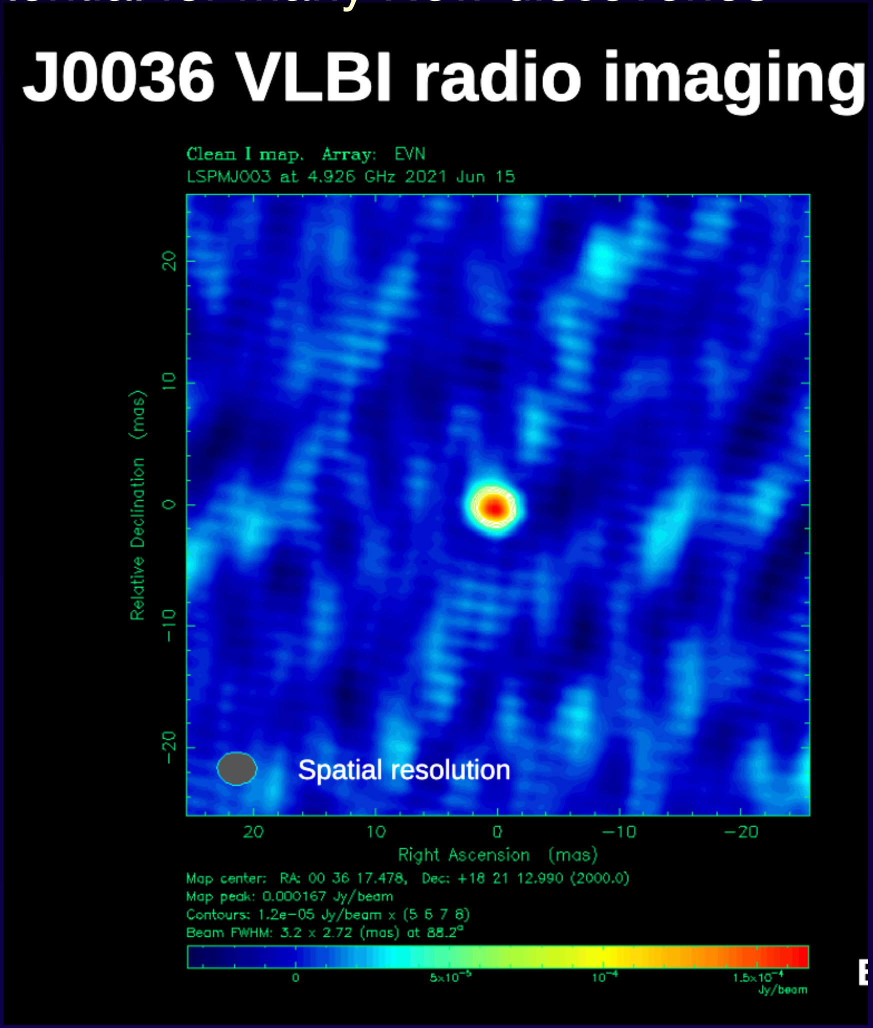
Paulo Miles talk

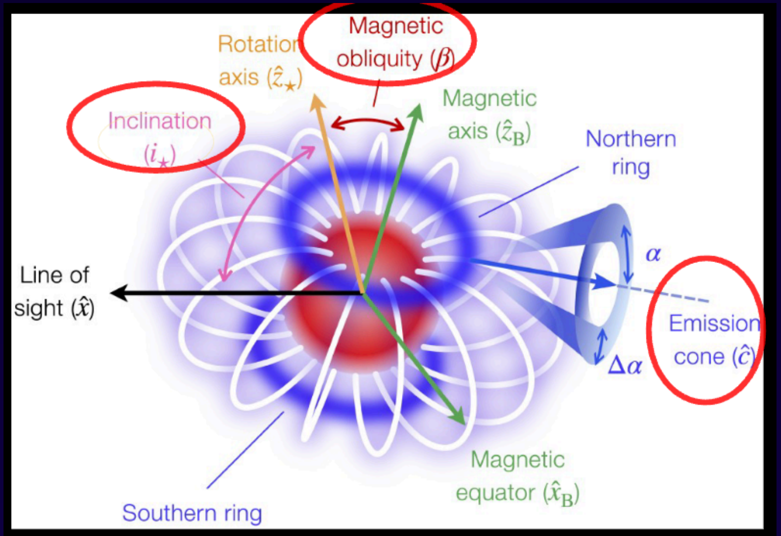
Proper motion searches

- Likely to find the nearest peculiar objects using surveys at different epochs.
- Free-floaters VHS, WISE, Euclid (Pérez Garrido)
- Common proper motion companions with GAIA (Gauza´s talk)
- Euclid, Rubin, Roman: the key for new discoveries down to J=24

Auroral emissions
Belt emissions
Potential for many New discoveries

Radio searches



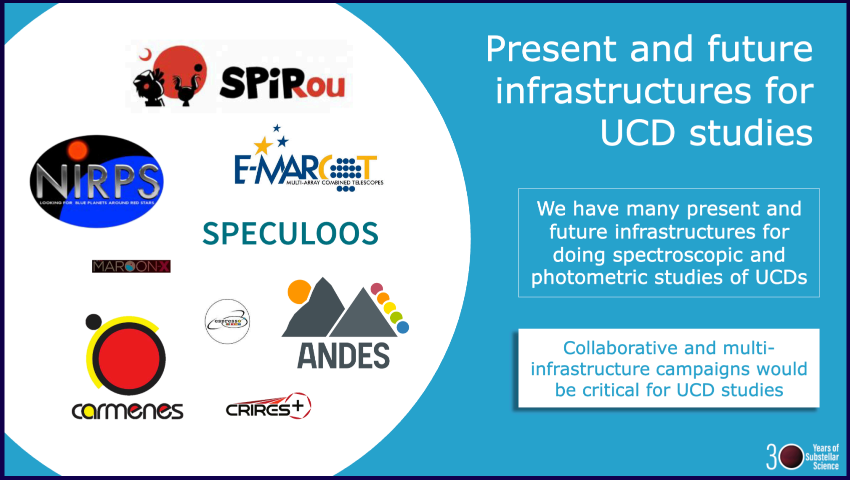


Bloot et al. (2024)

Talks by
Carrero
Guirado
Kavanagh

Planets around Brown dwarfs

- Radial Velocity searches
- Direct imaging of young planetary companions with JWST
- Earth-like transiting planets:
  - space missions with small space telescopes DUNE, POET



Suarez-Mascareño, Metchev , Bejar and Varas talks

Future projects impacting the substellar field

- New Space missions Roman, Plato, Ariel, POET, DUNE
- New Ground-based
  - Mid-class 3.5m SELF fully dedicated
  - Large telescopes 8m Rubin
  - Extremely Large Telescopes 39m ELT, GMT
  - SKA

In a few years they will start operation
expanding the current suit of amazing telescopes:
JWST, 8-10 m telescopes, Euclid, ALMA, VLBI etc

With all these facilities the next 30 years promise
to be filled with exciting discoveries!

- Many thanks for your atention!

Additional slides

Formation Mechanisms: Stars vs BDs vs Planets

Observations

BDs can be born in relative isolation, in binaries, in multiple systems

Stars vs BDs: Properties of LMS/VLMS extend smoothly into the BD regime → same mechanism for LMS/VLMS stars and high-mass BDs…

• **BDs vs Planets:** Observed frequencies of objects with M~13 M_J around solar-type stars behave smoothly with no special pattern → single

Formation and early evolution of brown dwarfs : the lower end of the IMF

- Substellar mass function extended down to 3 M_Jup
- BDs mostly form like VLMSs
- Dynamical interactions & disk fragmentation may occur at some level
- "Taurus-mode" of formation produces sufficient # of BDs
- Revision of concepts: filaments and gravo-turbulent models

"…turbulence is driven by gravity…"

Formation and evolution of BDs

- BDs can form as giant planets via disk gravitational fragmentation
- BDs can form as scale down process for stars

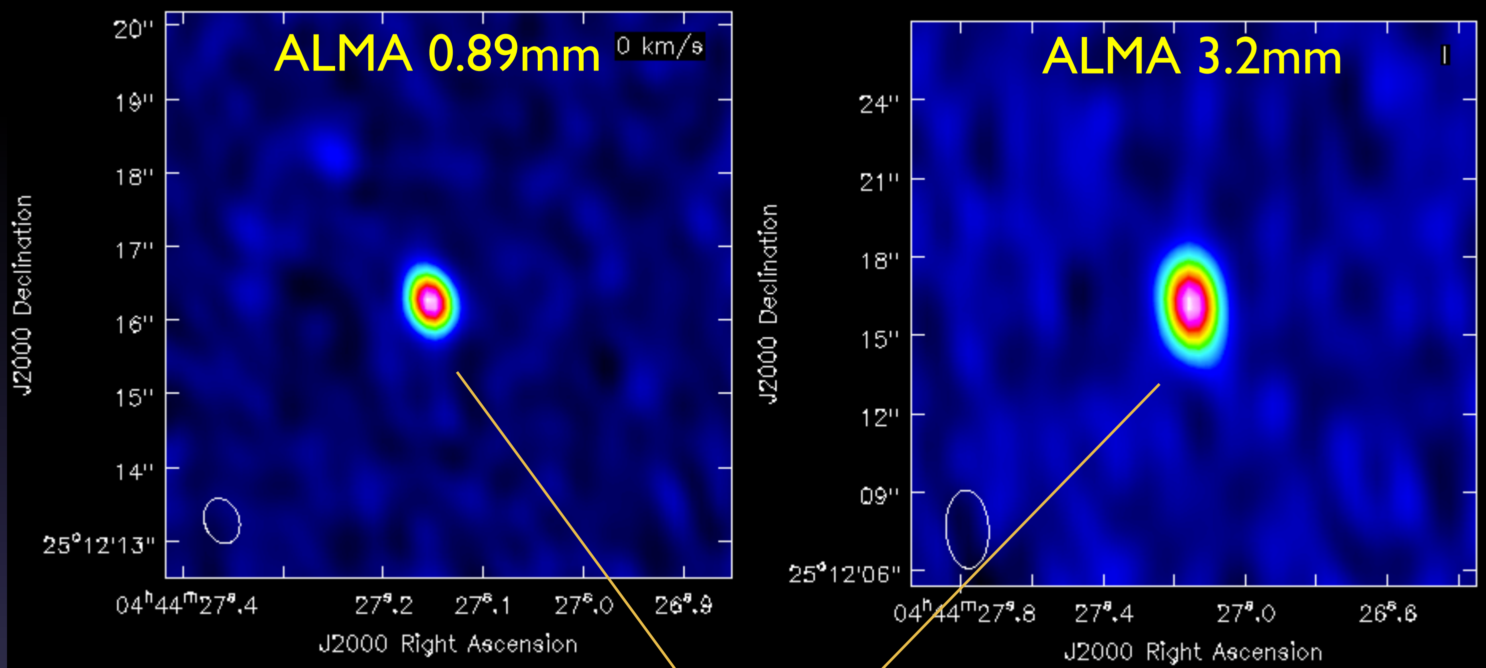
- Hybrid scenario : ejection of fragments from protostellar disks followed by cooling and contraction to stellar densities. Ejected fragments are surrounded by an envelope or mini-disk. No high-velocity ejections

(Eduard Vorobyov, Olga Zakhozhay)

Role of ALMA

The disk around the young BD 2M0444

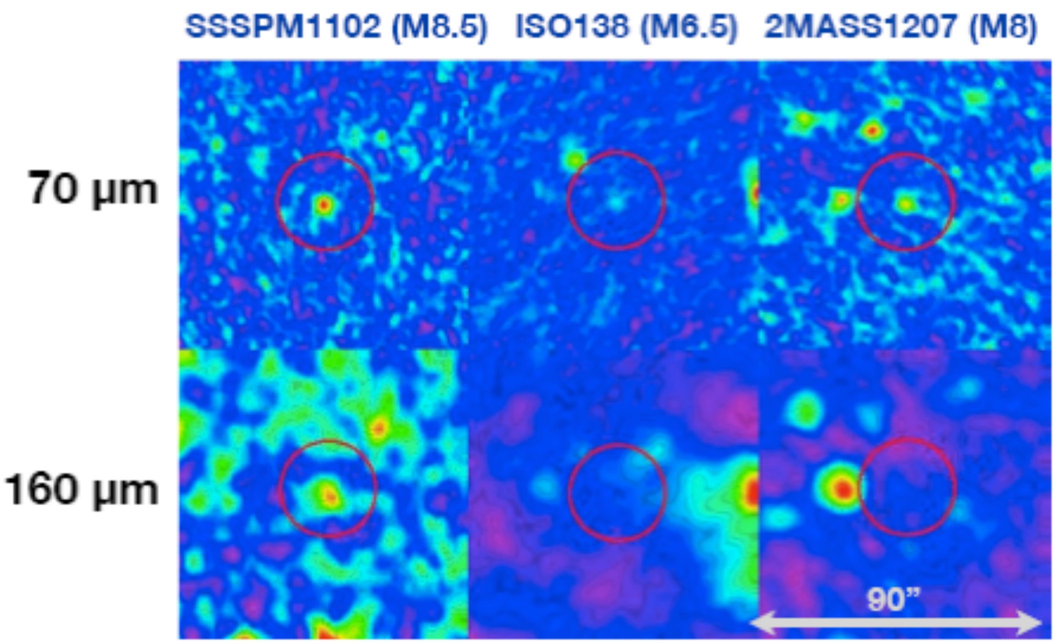
Dust



α

Ricci + 13b, in prep

Disks of brown dwarfs by Herschel / PACS



(Harvey, Henning et al. 2012a, APJL
Harvey, Henning et al. 2012b, ApJ)

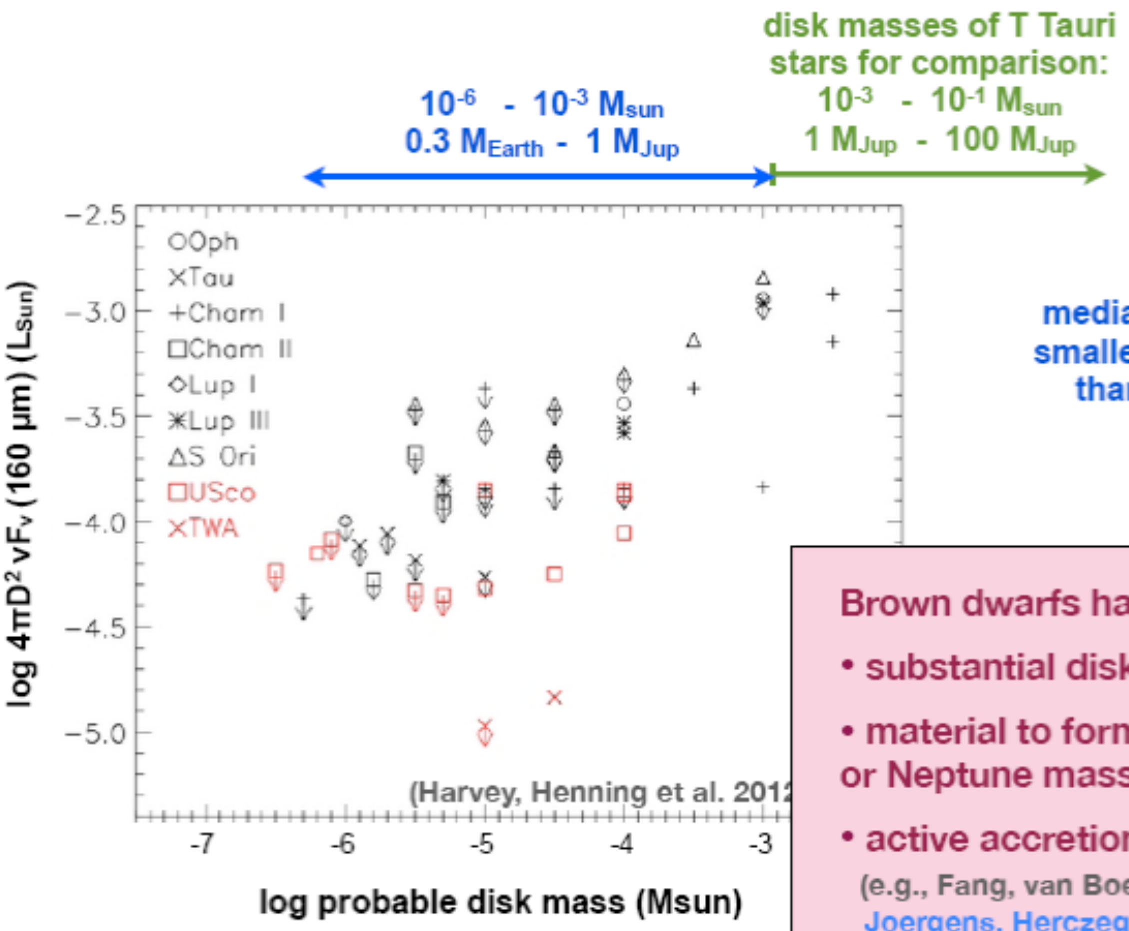
Survey of 47 BD / VLMS (M3-M9.5) in young star-forming regions with Spitzer detections of disks

77% detected at 70 µm
30% detected at 160 µm

V. Joergens

First far-IR survey of cold dust and of disk properties for a statistically significant sample of young brown dwarfs

Brown dwarf disk masses by Herschel



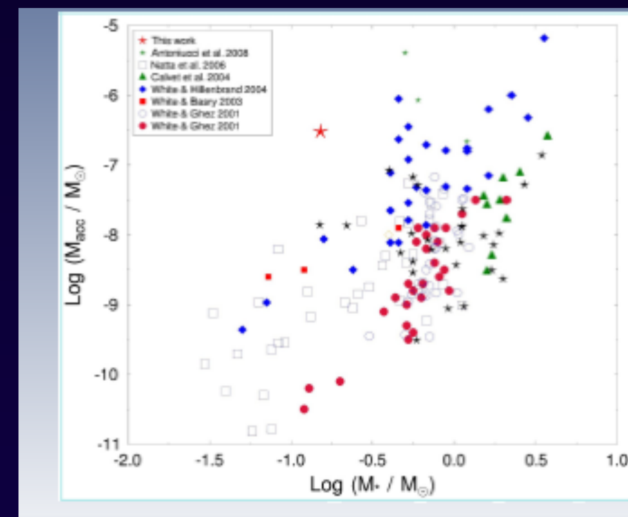
median ratio M_{disk} / M_{Star} smaller for brown dwarfs than for T Tauri star

Brown dwarfs have:

- substantial disks
- material to form Earth mass or Neptune mass planets
- active accretion (10^{-9}-10^{-12} M_{Sun}/yr)
  (e.g., Fang, van Boekel et al. 2009; Joergens, Herczeg, Liu et al. 2013)

Accretions and Outflows in BDs

- 10 Jets/outflows discovered since 2005 (Forbidden emission lines, spectral-astrometry)
- Mass accretion rates vs. Mass outflow rate

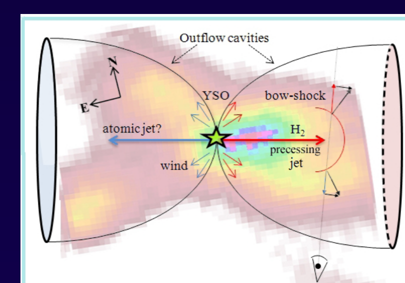


$$\dot{M}_{[FeII]}/\dot{M}_{acc} \sim 0.1$$

R. García López

Other reported 0.5-0.05
Possible observational bias due to selection of bright targets

B. Riasz



Bipolar outflows in ISO 143 and ISO 217 V. Joergens

García López et al. 2013

Angular momentum and disk evolution

- Disk braking happens in BDs
- Wind braking does not

A. Scholz

Mass function

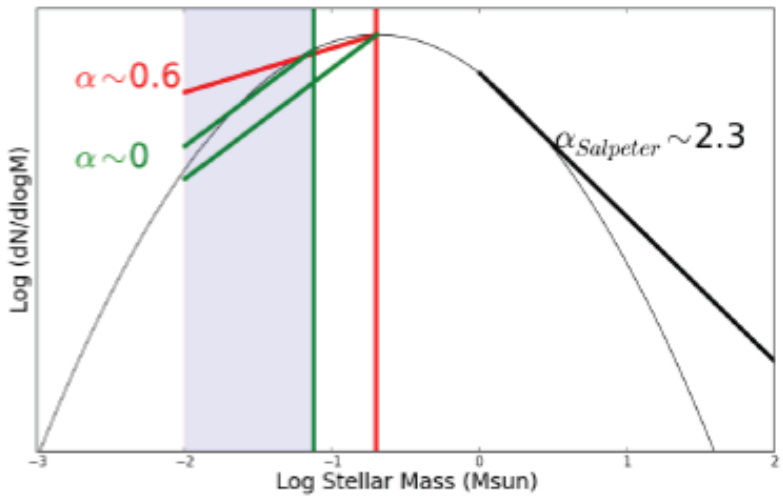
Mass Function: summary

field:	$\alpha < 0$
young clusters:	$\alpha \sim 0.6$

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

$$dN / d\log M \propto M^{-\Gamma}$$

$$\alpha = \Gamma + 1$$



Catarina Alves de Oliveira

European Space Agency

Open questions

Observations: substellar MFs measured from field BDs and clusters seem to differ, but are they comparable?

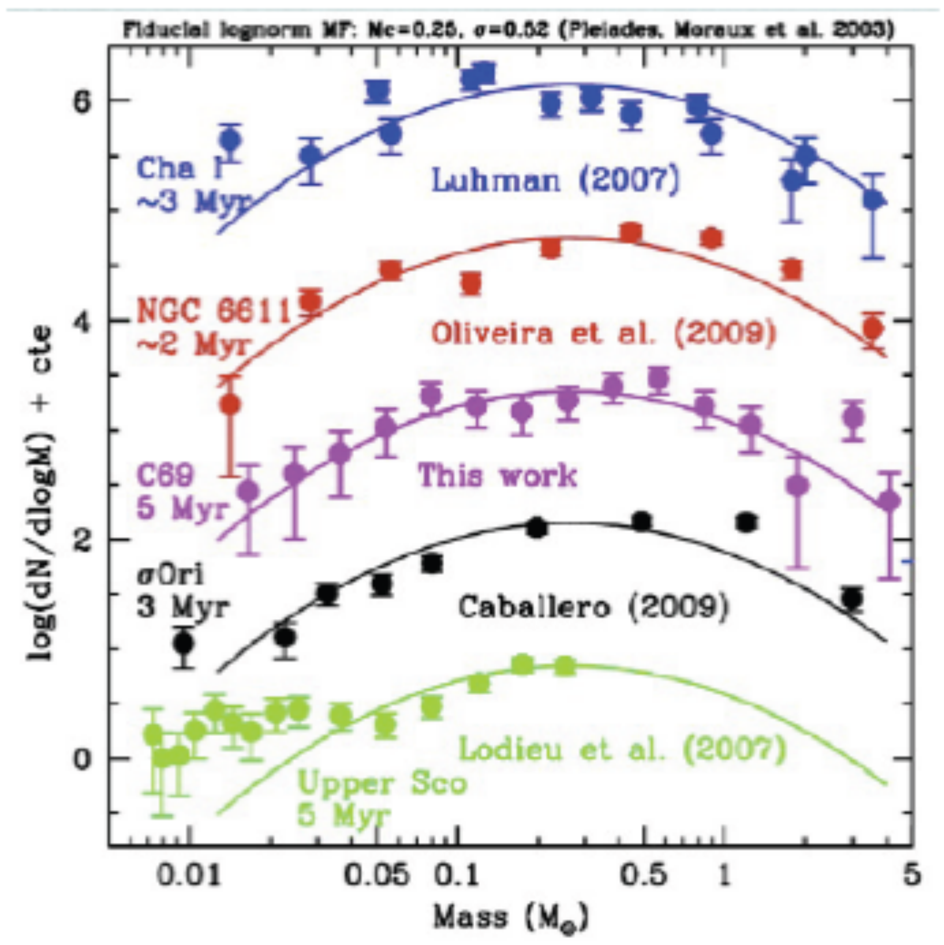
- Clusters: different methods / spectral typing / evolutionary models / completeness corrections
- Field: different methodology / large spread when fitting entire temperature range

Are the current results mature and accurate enough to claim a difference in the observed substellar mass function?

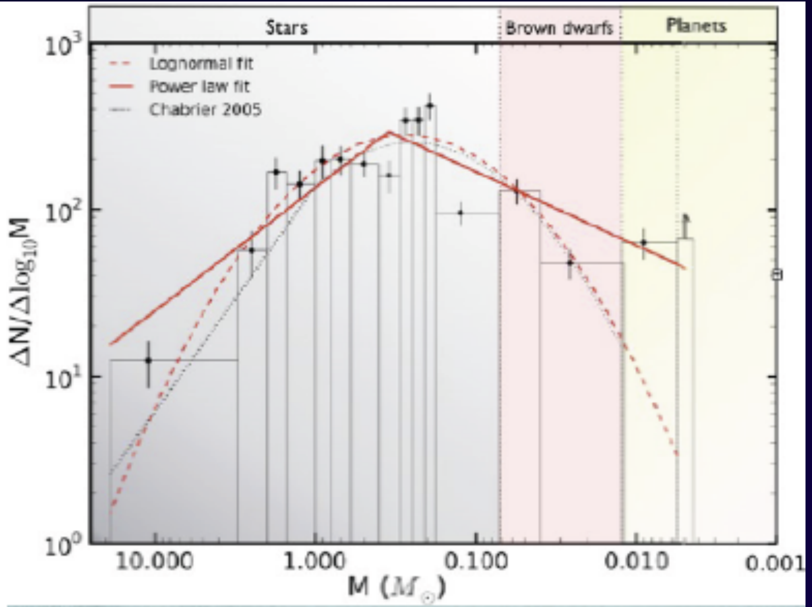
My answer is … No

European Space Agency

Mass functions of star forming regions essentially agree

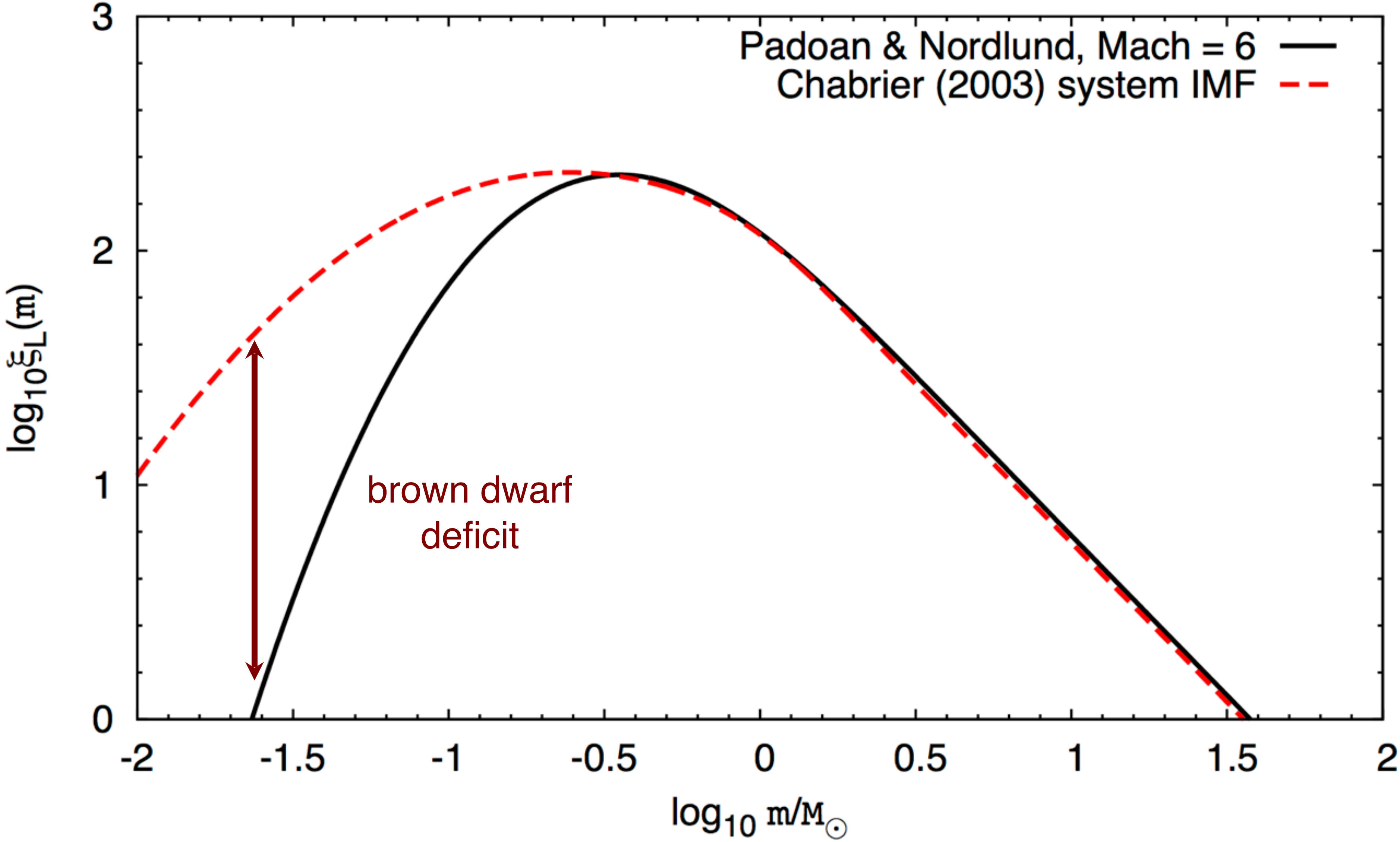


Bayo et al. 2011



Peña Ramírez et al. 2012

Model vs. empirical IMF



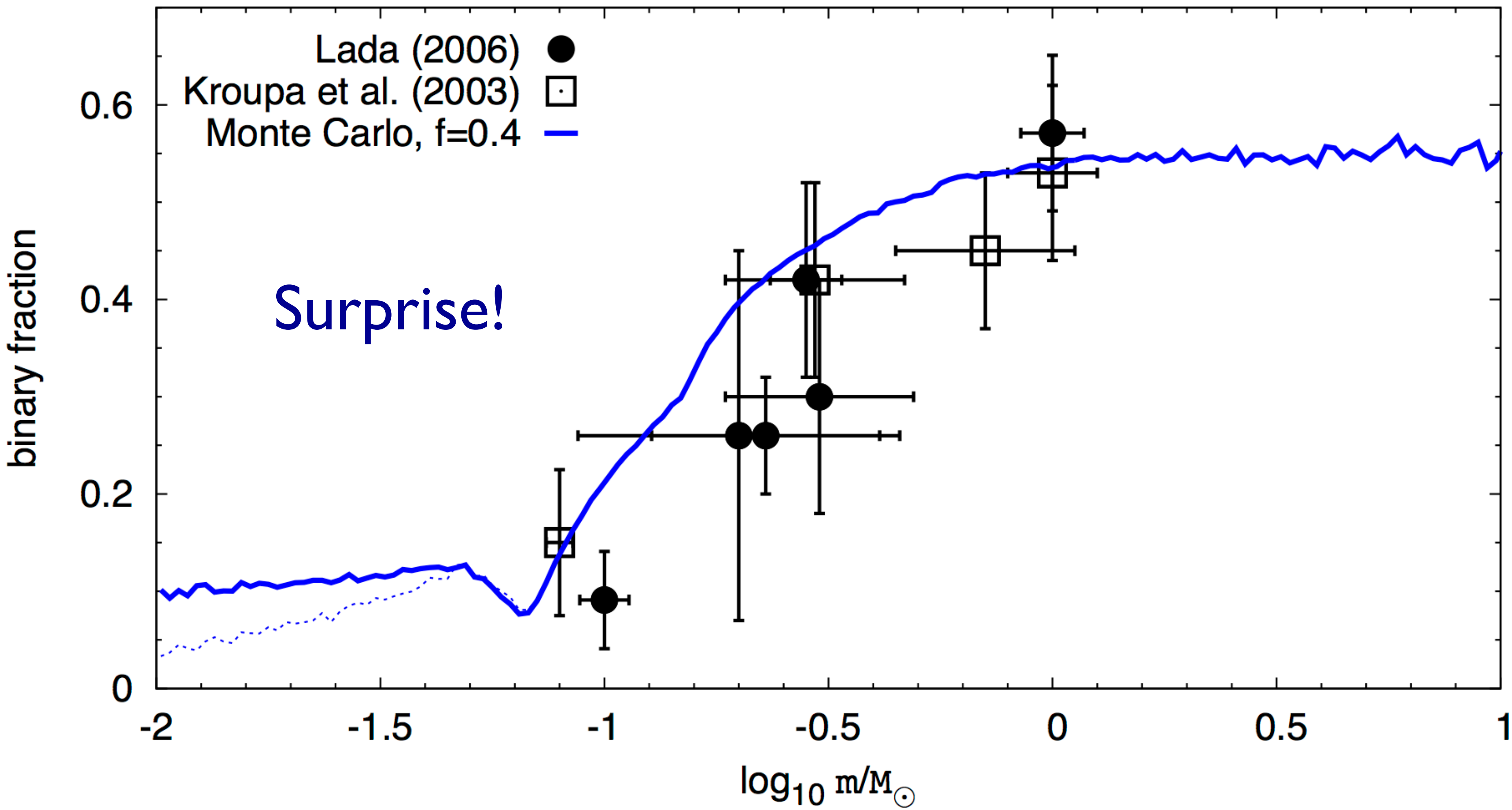
Residual MF summary

- Analytical star-formation models fail to produce BDs
- Residual MF of model vs. observations match BD-part of composite IMF *and* SPH results.

→ **Brown dwarfs are special!**

Ingo Thies

Binarity fraction vs. mass

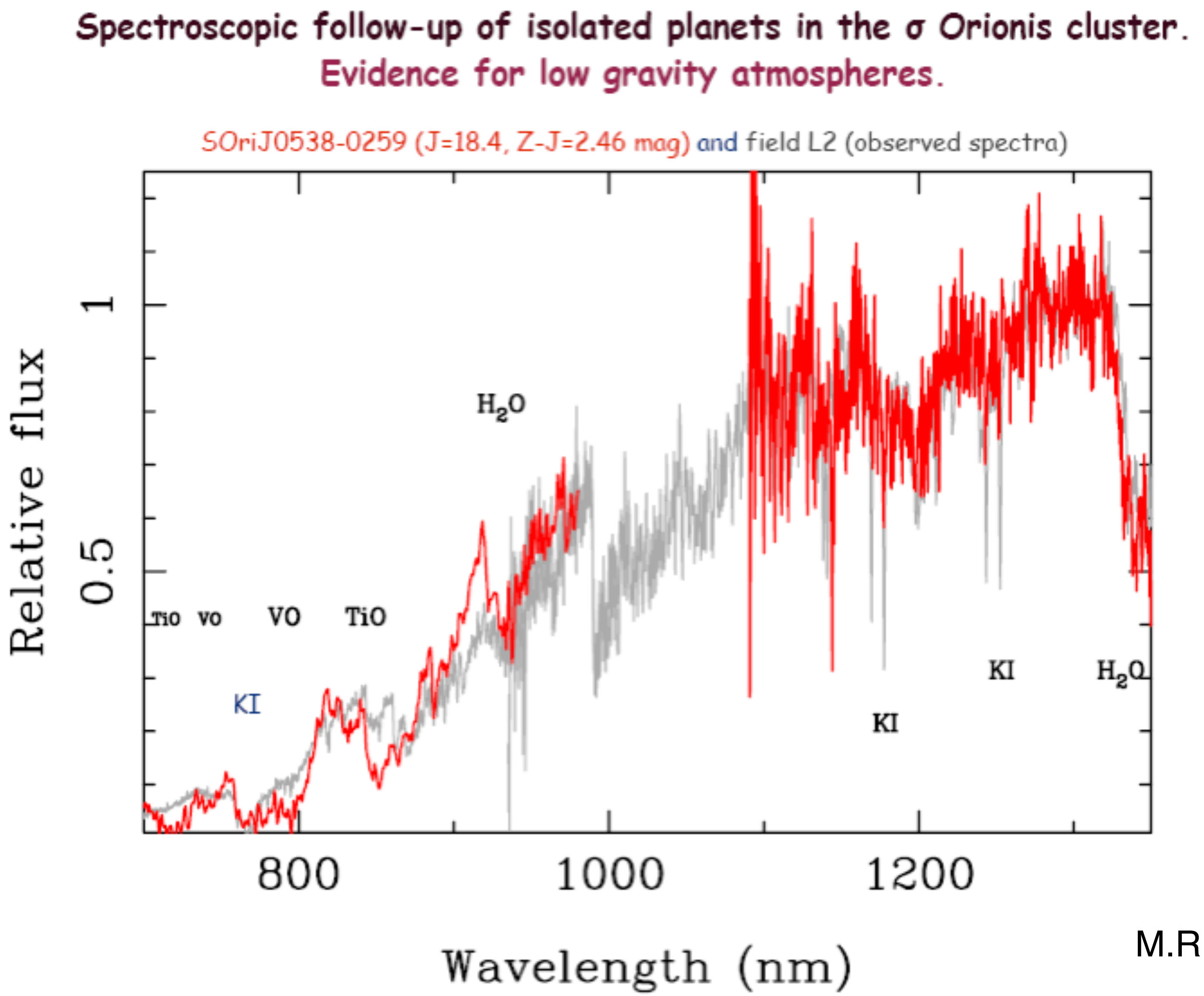


Bds preferably form from disks… (I. Thies)

BD surveys

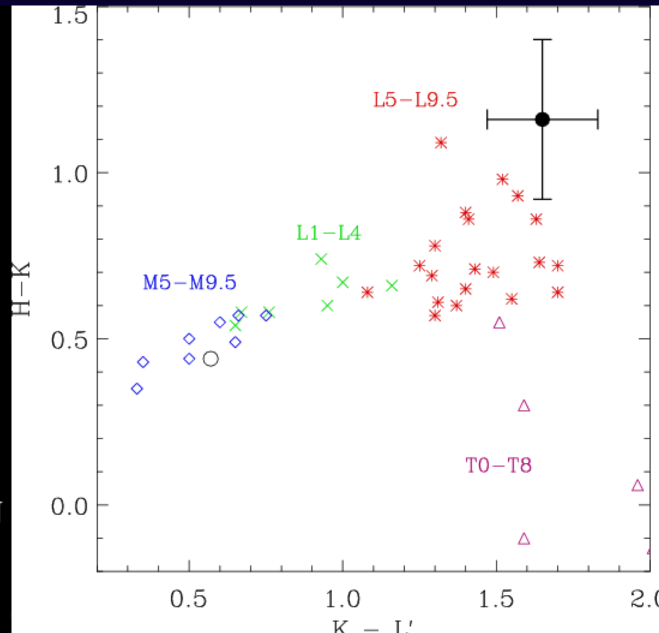
- Low gravity BDs (Maria Rosa Zapatero Osorio, Jacqueline Faherty, Jonathan Gagné)
- Cool Y dwarfs (Trent Dupuy, Joana Gomes)
- Subdwarfs (Marcela Espinoza)
- Large scale surveys (Ben Burningham, Avril Day-Jones, Leigh Smith)

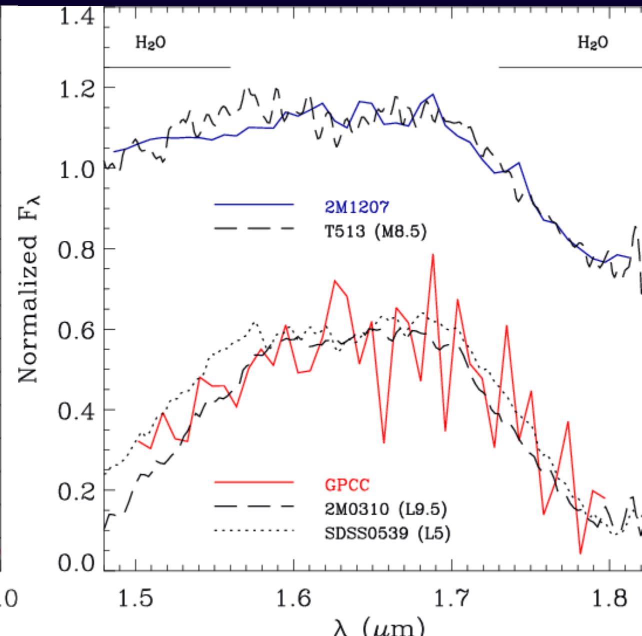
Low gravity planetary mass objects



M.R. Zapatero-Osorio

How does it compare with other imaged planetary-mass companions ?





Primary: A M8-type brown dwarf with proper motion consistent with membersip in TW Hydrae Association (age 8 ± 4 Myr) → mass of the primary~ 25 Mjup

A candidate companion of 5 ± 2 Mjup

Chauvin et al. 2004

Upper Scorpius: A massive giant planet?

Distant companion at the planetary mass boundary 5

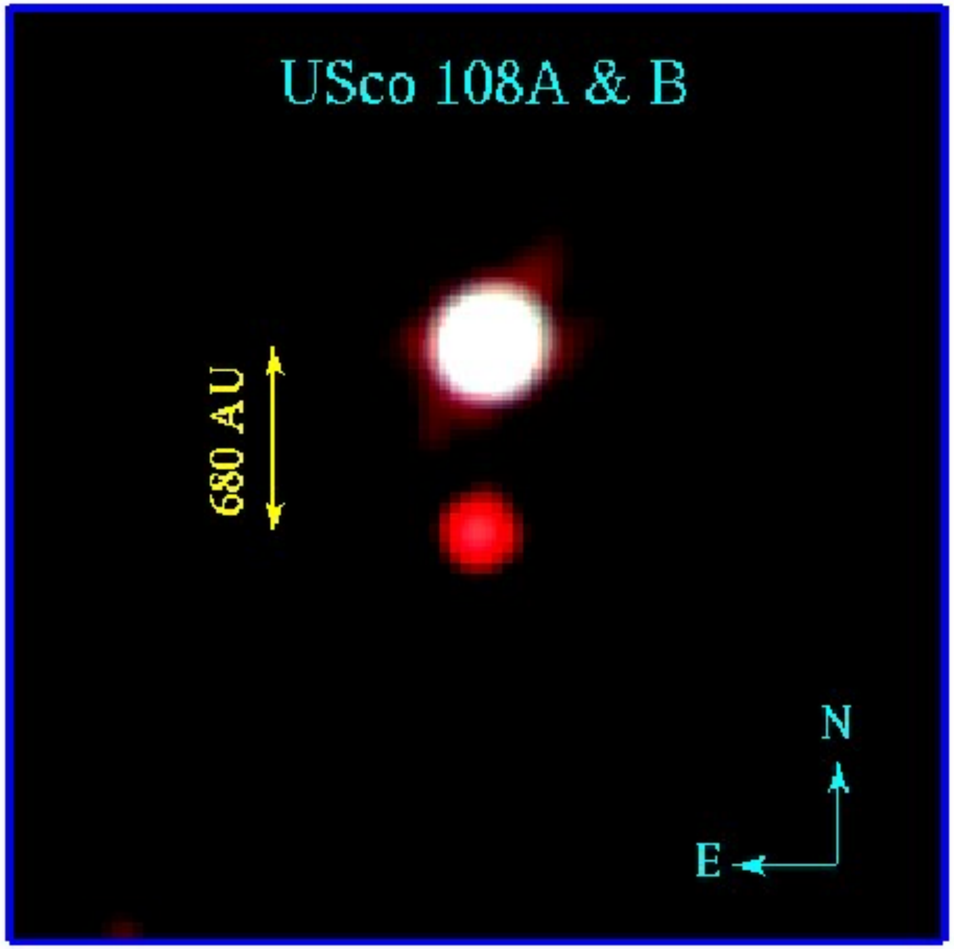
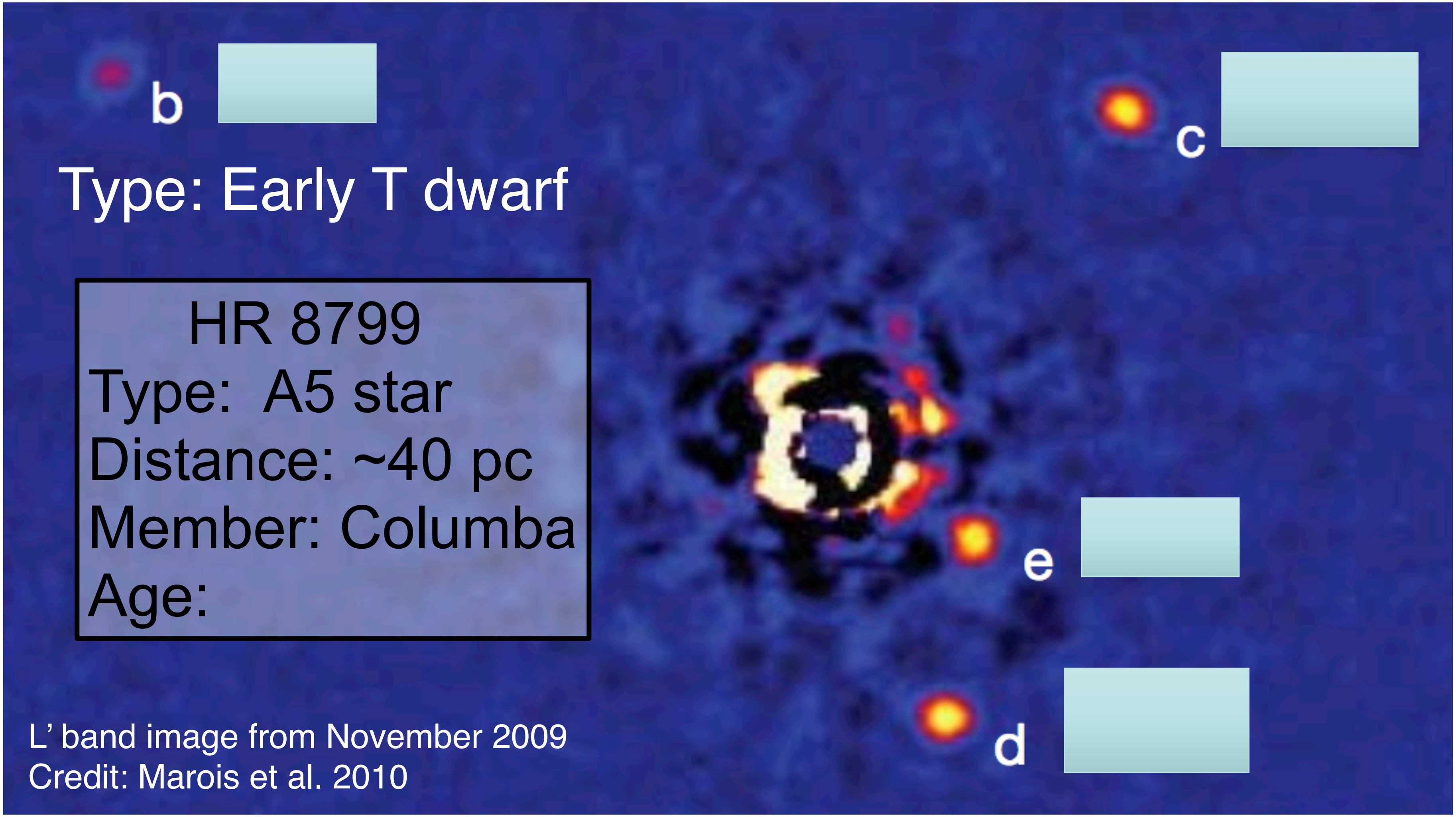


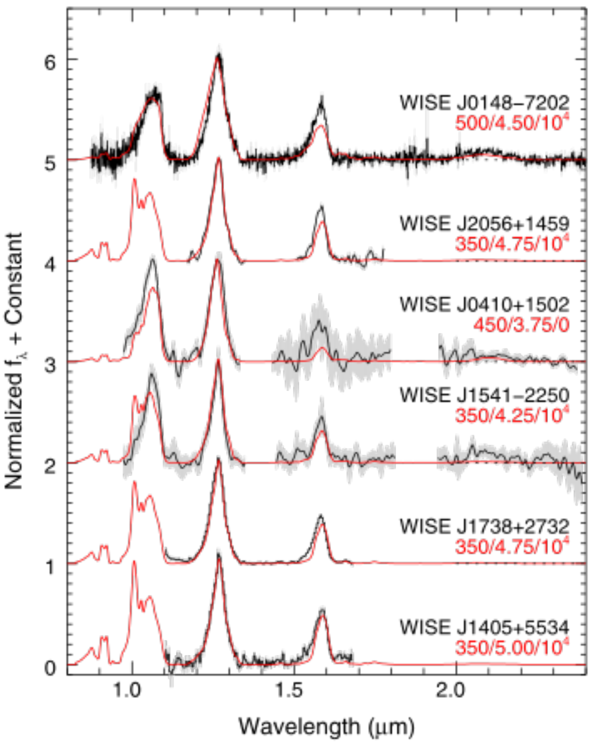
FIG. 1.— Simulated colour IZK image of UScoCTIO 108A and UScoCTIO 108B (I = blue, Z = green, and K' = red). IZ images are from AUX intrument on the WHT and the K' image from NICS on the TNG. All images were convolved with a gaussian to a spatial resolution of 1.1 arcsec.

Béjar et al. 2008 Ap J Lett


b
c
Type: Early T dwarf
HR 8799
Type: A5 star
Distance: ~40 pc
Member: Columba
Age:
e
d
L' band image from November 2009
Credit: Marois et al. 2010

Y dwarfs: cool

- Parallaxes measured with Spitzer. Revision of Temperatures of Y dwarfs (reported by T. Dupuy). Most likely 400 K.
- New WISE w2 searches for Y dwarfs and new findings (reported by J. Gomez)



Large Scale BD surveys

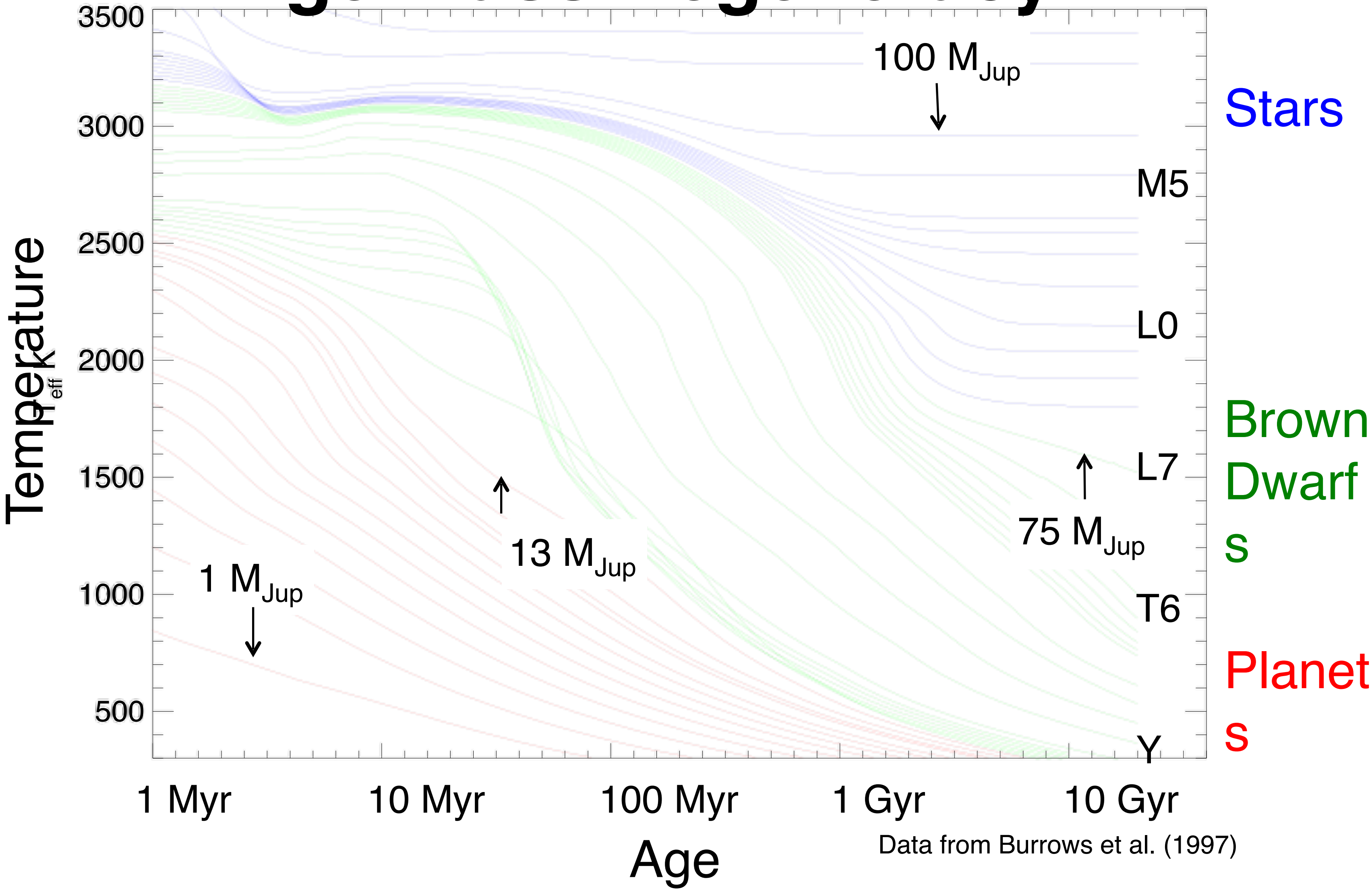
- Impressive amount of work in 20 years: DENIS, 2MASS, SDSS, UKIDSS, WISE (review by Ben Burningham)

Survey league table

Survey	L dwarfs	T dwarfs	Y dwarfs
DENIS	49	1	0
2MASS	403	55	0
SDSS	381	57	0
UKIDSS	50	230	0
CFBDS(IR)	170(?)	45	1
WISE	10	176	14
VISTA-VHS	0	5	0

B. Burningham

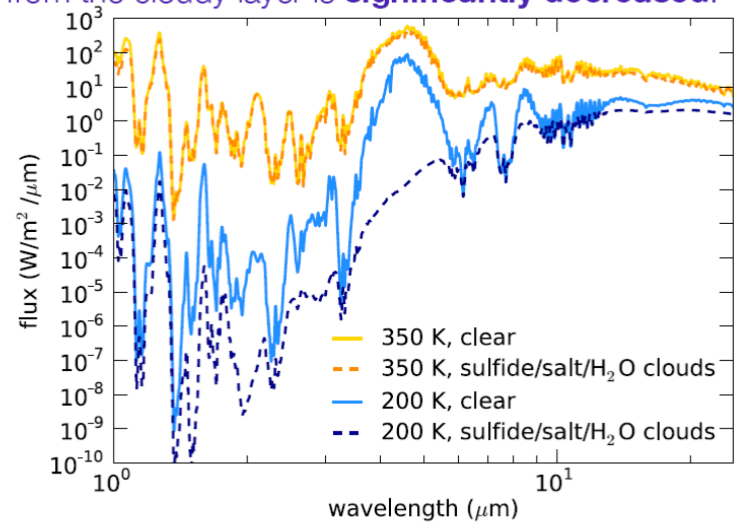
We may need them to fully explore the Age-Mass Degeneracy



Data from Burrows et al. (1997)

Water clouds in 300 K atmospheres!

For the coldest models (200-275 K), the flux emerging from the cloudy layer is **significantly decreased**.



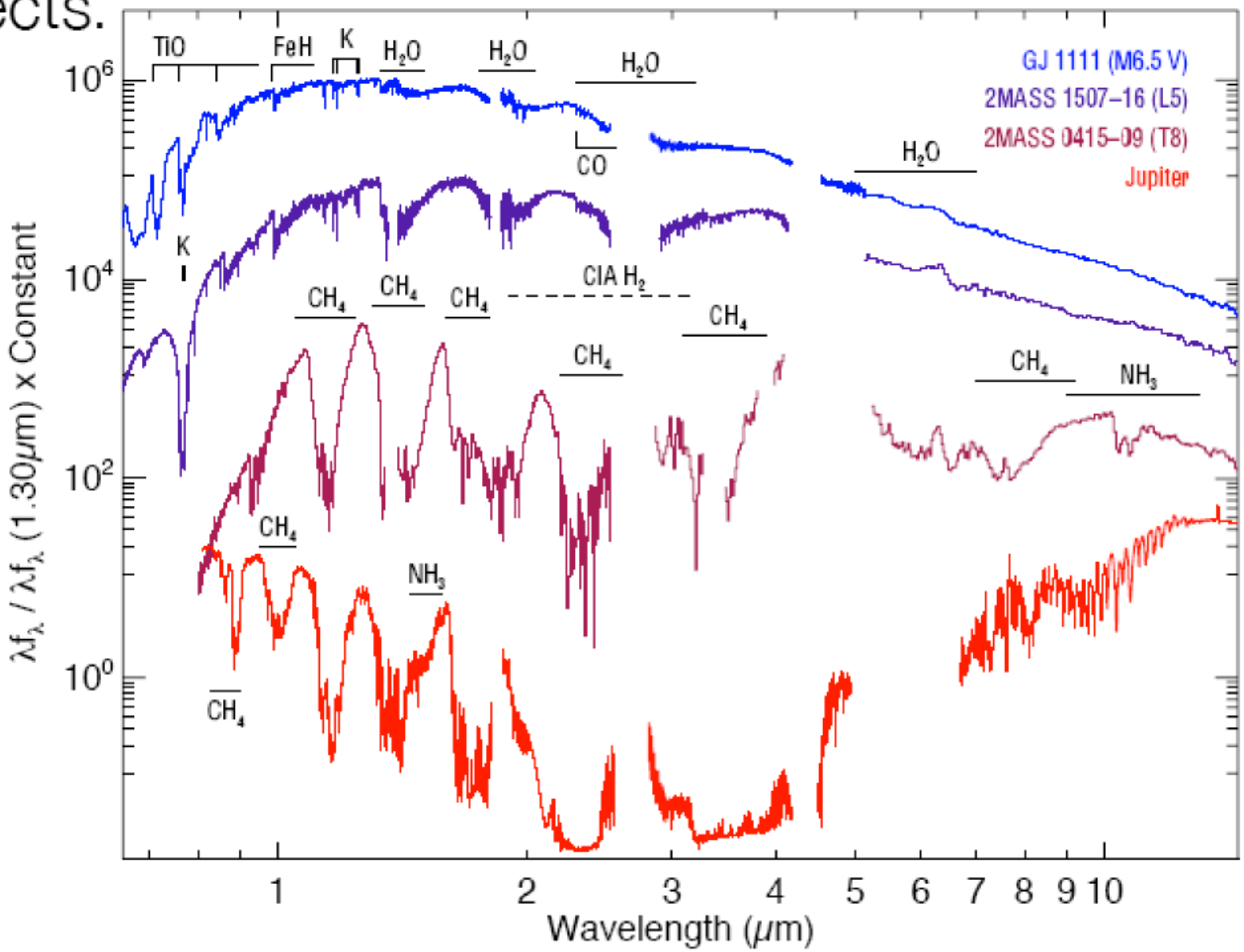
Water clouds could be extremely important for objects **colder than ~350 K**.

C. Morley

Spectroscopy

- Talks by V. Béjar and K. Allers shows how fundamental spectroscopy is for understanding BDs…but it is more and more difficult for low-luminosity objects

objects.



What is the spectral type of Jupiter?

Is Jupiter a Y dwarf? (V. Béjar)

Brown dwarf/Planet Connection (Panel)

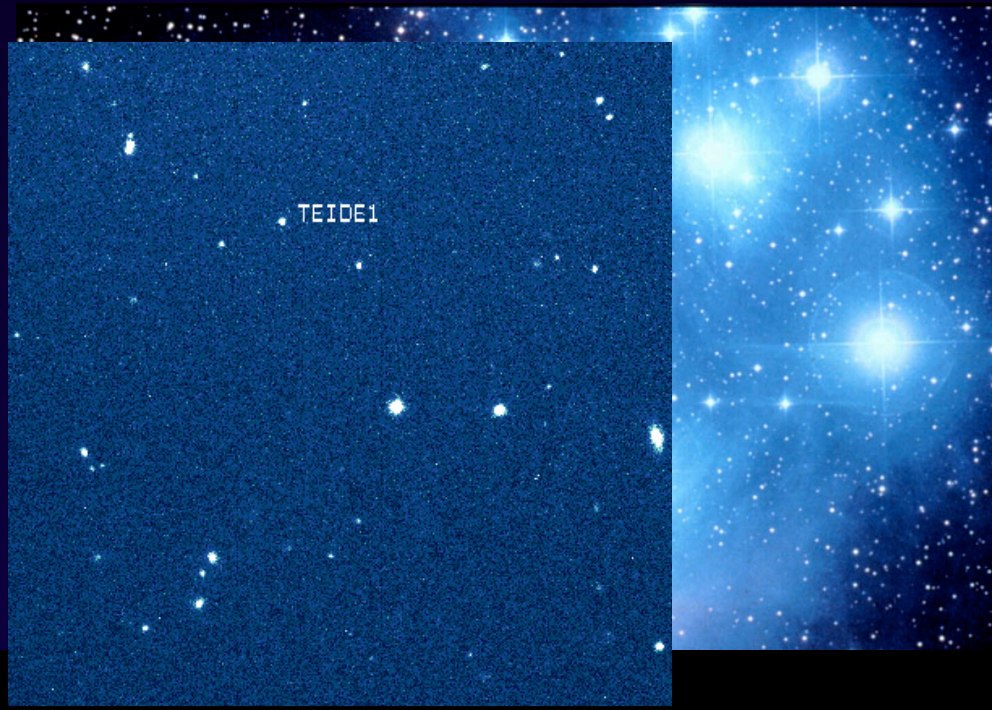
- How might we define the fundamental differences between brown dwarfs and giant planets?
- What are the priorities for improving theory to differentiate brown dwarfs and planets?
- Does the field population contain free-floating planetary mass objects?

1995: First direct detections of Brown dwarfs

“Discovery of a brown dwarf in the Pleiades star cluster” Rebolo, Zapatero Osorio, Martín. 1995 (Nature 377, 129)

Teide 1: a photometric/spectroscopic proper motion/radial velocity cluster member with spectral type M8, mass ~ 50 M_{Jup}

submitted May 22th,
published September 14th, 1995

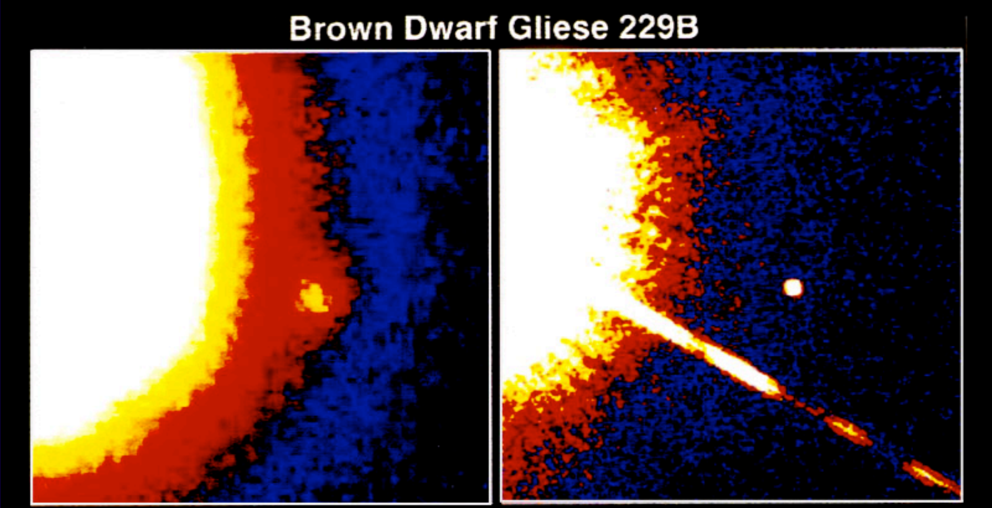


“Discovery of a cool brown dwarf” Nakajima, Oppenheimer Kulkarni et al. 1995 (Nature 378, 463)

Gl 229B, a very cool faint proper motion companion of a nearby M-dwarf new spectral type T
mass 30-50 M_{Jup}

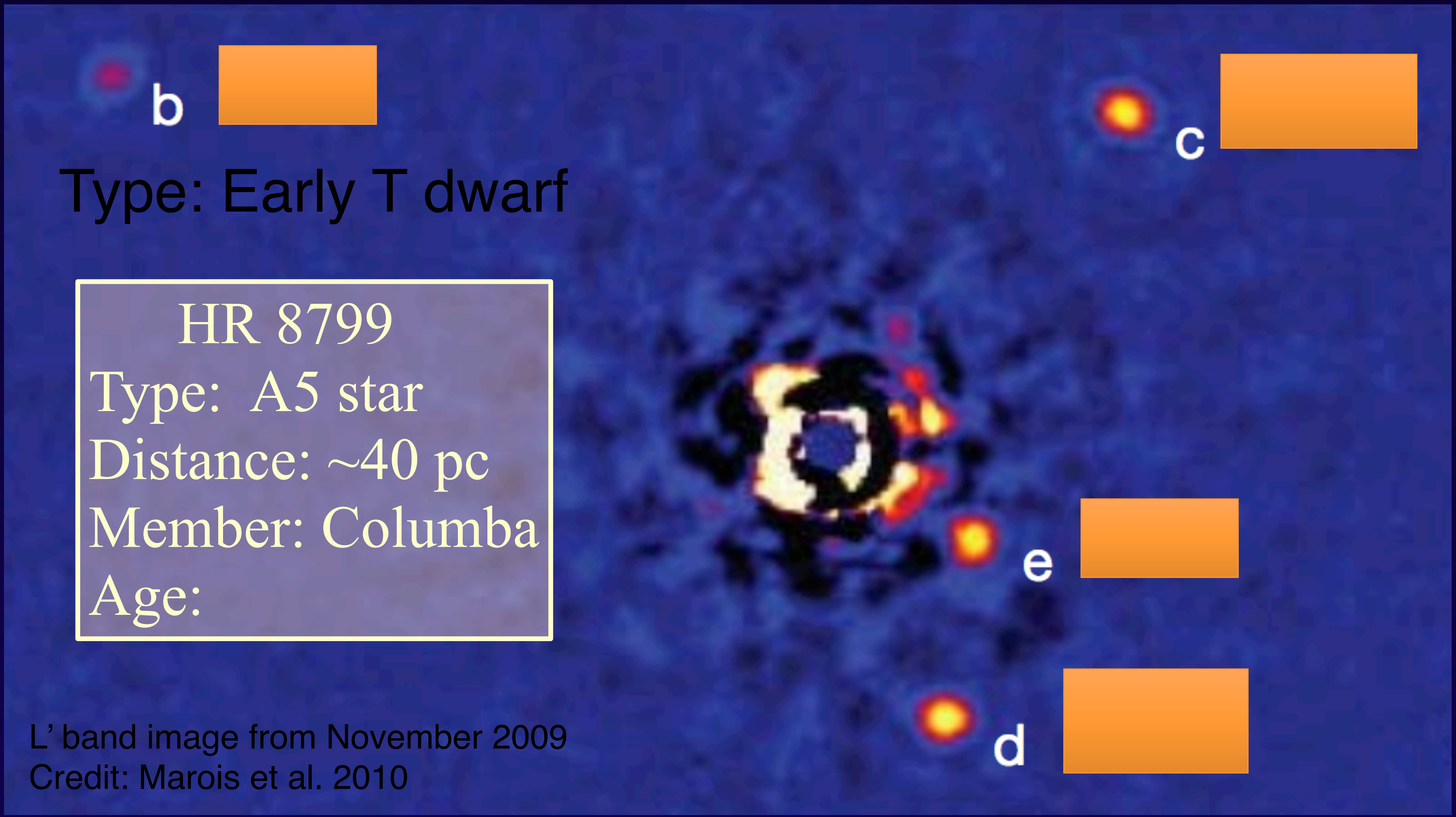
submitted September 25th,
published November 30th, 1995

See also Oppenheimer et al. Science, December 1st, 1995



Brown Dwarf-Exoplanet Overlap

The HR8799 Planets



HR 8799
Type: A5 star
Distance: ~40 pc
Member: Columba
Age:

Age-Mass Degeneracy