# Abundances of low-mass BDs in Upper Scorpius

## *A pilot study*


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# Outline

- The idea
- Sample and setup
- How to analyse the data?
- Summary

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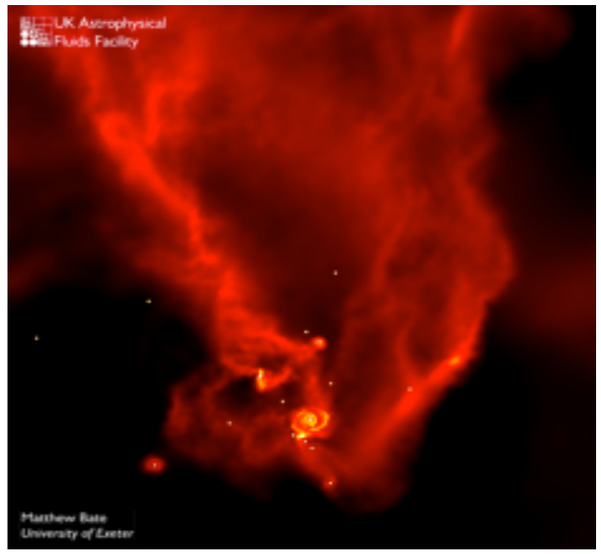
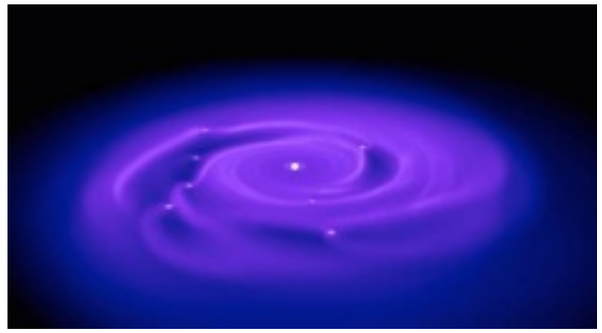
# The idea

*Possible formation scenarios for low-mass brown-dwarfs*

- Collapse/Fragmentation
- Disk fragmentation
- Premature Ejection
- Photo-erosion
- Core-accretion (up to 35 $M_{Jup}$ ⇒ C. Mordasini)



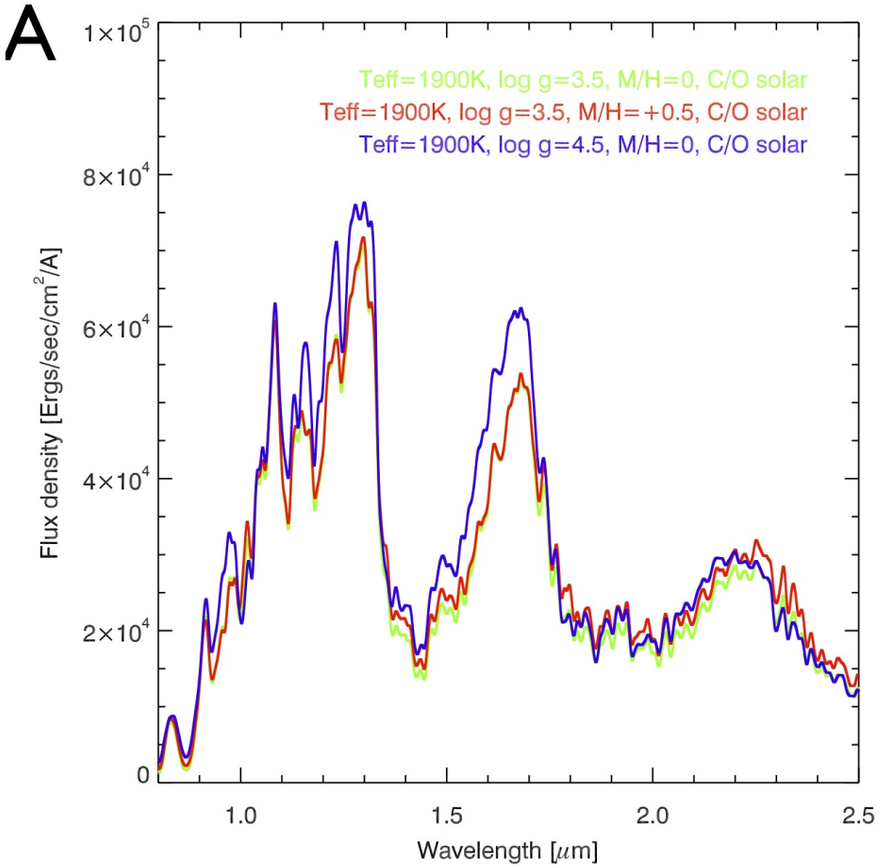
*Wide distribution of compositions for low-mass BDs expected*

# The idea

*How to measure the abundances from emission spectra?*

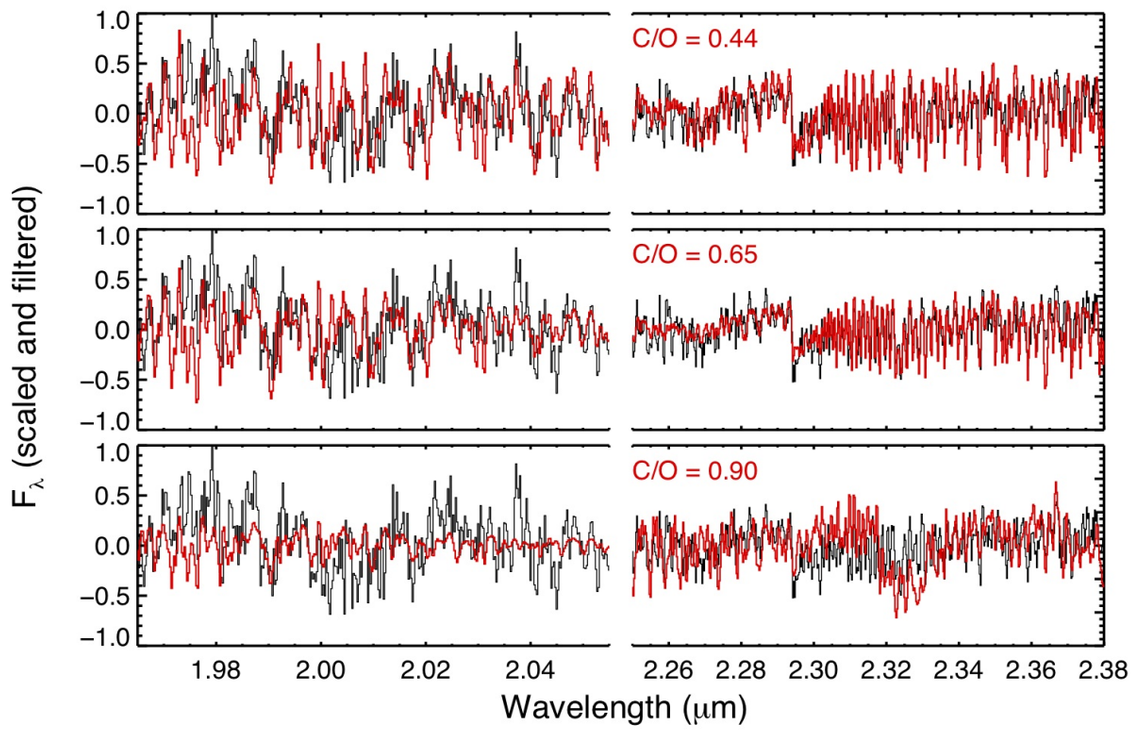
- $T_{eff}$
- log g vs M/H degeneracy
- problem of cloud formation (depletion of chemical species)

A




B

***Konopacki et al. 2013, Science***




*Need for medium-resolution spectroscopy over the widest possible wavelength range*

# The idea

*Idea: explore the relative abundances of a population of BDs with mass < 35 $M_{Jup}$ in a cluster*

⇒ *Need bright enough objects for mid-res spectroscopy*

⇒ *No strong extinction*

⇒ *Different configurations (companions, free-floating)*

⇒ *Eliminate (as much as possible) unresolved binaries*

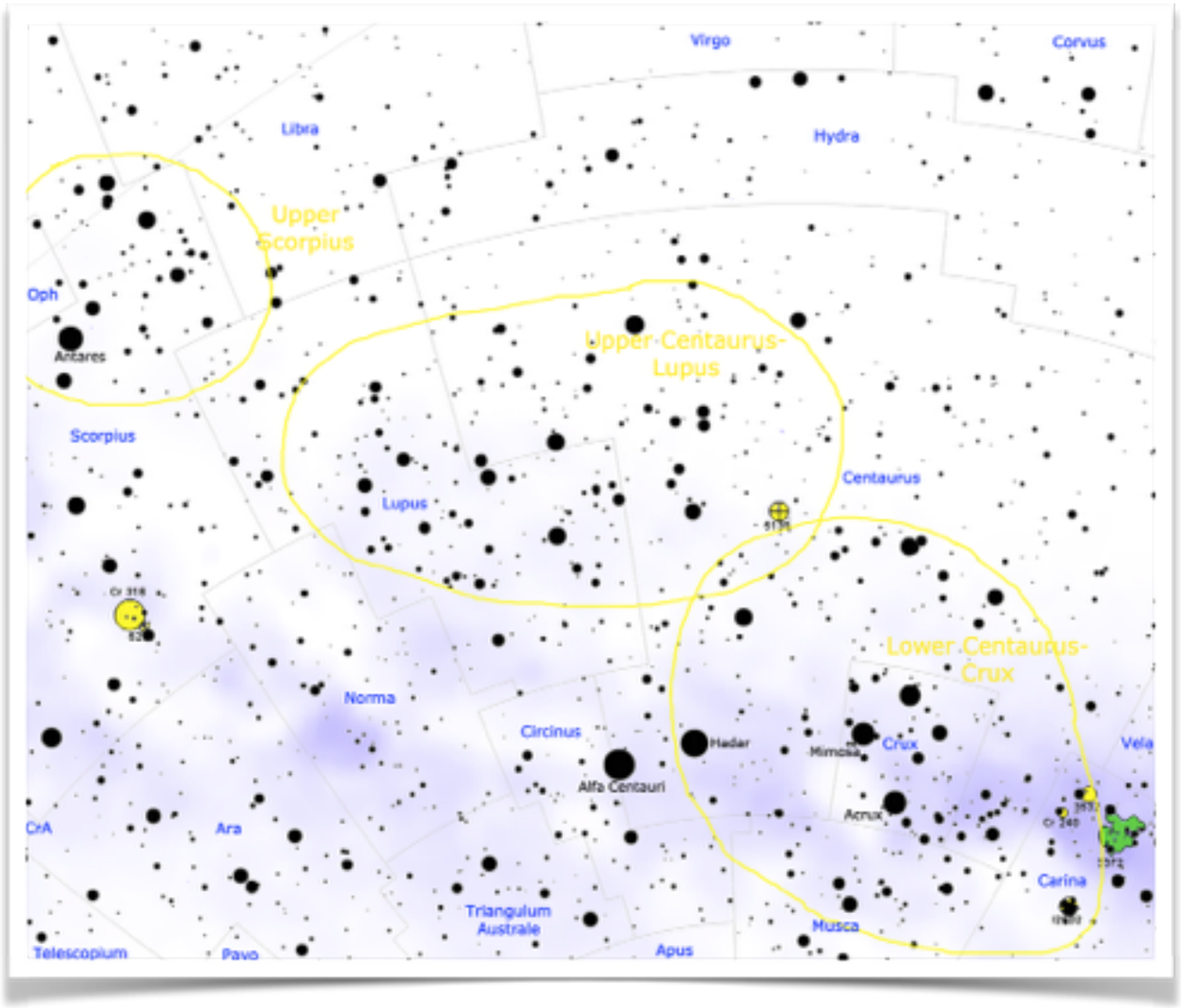
⇒ *Consider early-type/hot objects*

⇒ *Less affected by dust*

⇒ *No non-equilibrium chemistry*

# The idea

## *The choice of Upper Scorpius*




### *1/ Young*

→ 3 to 11 Myr

### *2/ Close*

→ 145 ± 2 pc

### *3/ Perfect for Paranal*

→ RA=16h, DEC=-23.4

### *4/ Wide range of masses*

→ Part of Sco-Cen (OB assoc)

Down to spectral type L2 (0.01 $M_\odot$)

→ Excess of low-mass BDs?

*(Lodieu et al. 2008, 2013 & ref. therein)*

# The idea

## *The choice of Upper Scorpius*

### *5/ Dozens of low-mass BDs with diverse configurations*

- Isolated BDs with spectra indicative of low gravity

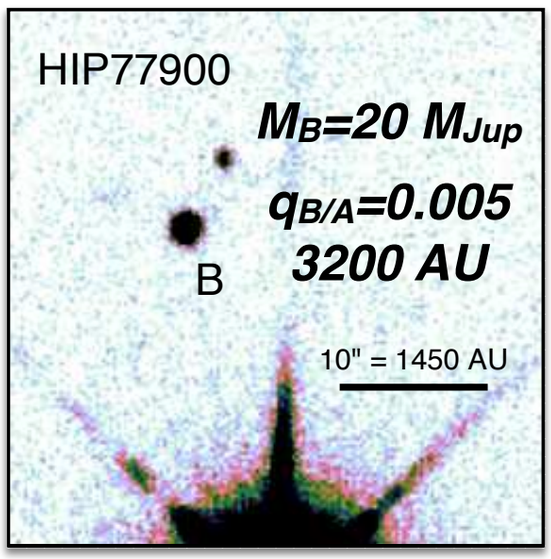
  **M=10-25 $M_{Jup}$**

- Binary low-mass BDs: USCO CTIO 108AB, USco1612-1800B

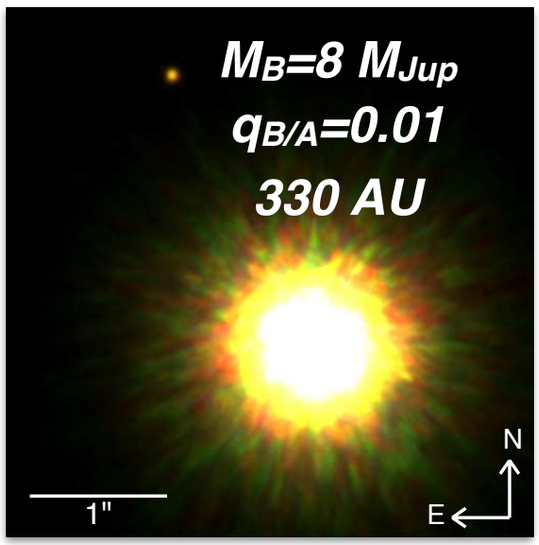
  **$q_{B/A}$=0.1-0.2  separation=430-670 AU  $M_B$=14-26 $M_{Jup}$**

- Companions to stars:

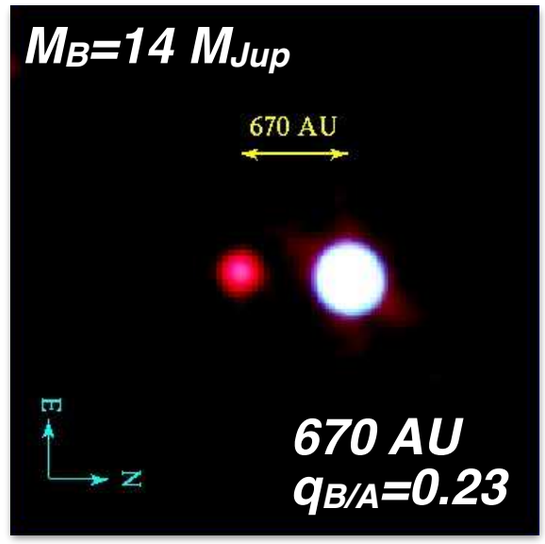
  **$q_{B/A}$=0.005-0.03  separation=330-3200 AU  $M_B$=8-26 $M_{Jup}$**




*Aller et al. 2013, ApJ, 773, 63*




*Lafrenière et al. 2013, ApJ, 689, 153*




*Béjar et al. 2008, ApJ, 673, 185*

# The idea

*A program to try to answer these questions:*

1/ Can we measure the atmospheric M/H, C/O, C/H ?

2/ What is the distribution of C/O and M/H for an homogeneous population of objects?

3/ How is it related to formation scenarios?

*By-product: library of high-quality medium-res. NIR spectra of young M7-M9 dwarfs (SPHERE, GPI, etc)*

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- Sample and setup
- How to analyse the data?
- Summary

# Sample and setup

**European Organisation for Astronomical Research in the Southern Hemisphere**

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49 89 320 06473

APPLICATION FOR OBSERVING TIME PERIOD: **93A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title Category: **C–7**

Chemical hints on the origins of low-mass brown-dwarfs in Upper Scorpius

2. Abstract / Total Time Requested

Total Amount of Time: 0 nights VM, 29 hours SM

Upper Scorpius is the only star forming region where brown dwarfs (BDs) close to the typical deuterium-burning boundary have been discovered in a wide range of configurations (as wide binaries, companions to stars, or free floating). These configurations suggest that multiple BD formation mechanisms (disk instability/fragmentation, core-accretion ? + ejection, photo-erosion of pre-stellar cores, etc) are at play. We propose to use XSHOOTER to obtain high-quality medium-resolution (R$\sim$2700, 3800) $0.8 - 2.5$ $\mu$m spectra of 10 late-type brown-dwarfs members of Upper Sco, found free-floating, in binaries, or orbiting stars. The spectra will be compared to dedicated grids of models in order to derive for the first time the metallicity and C/O ratio in these objects. The comparison of the abundances from object to object will help to understand whether they share a common formation pathway.

3.

| Run | Period | Instrument | Time | Month | Moon | Seeing | Sky | Mode | Type |
|---|---|---|---|---|---|---|---|---|---|
| A | 93 | XSHOOTER | 29h | any | n | 1.0 | CLR | s | |

# Sample and setup

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| Status | Programme ID | Title |
|---|---|---|
| ✔ | 093.C-0769 | Chemical hints on the origins of low-mass brown-dwarfs in Upper Scorpius |

Upper Scorpius is the only star forming region where brown dwarfs (BDs) close to the typical deuterium-burning boundary have been discovered in a wide range of configurations (as wide binaries, companions to stars, or free floating). These configurations suggest that multiple BD formation mechanisms (disk instability/fragmentation, core-accretion ? + ejection, photo-erosion of pre-stellar cores, etc) are at play. We propose to use XSHOOTER to obtain high-quality medium-resolution (R$\sim$2700, 3800) $0.8 - 2.5$ $\mu$m spectra of 10 late-type brown-dwarfs members of Upper Sco, found free-floating, in binaries, or orbiting stars. The spectra will be compared to dedicated grids of models in order to derive for the first time the metallicity and C/O ratio in these objects. The comparison of the abundances from object to object will help to understand whether they share a common formation pathway.

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|---|---|---|---|---|---|---|---|---|---|
| A | 93 | XSHOOTER | 29h | any | n | 1.0 | CLR | s | |

# Sample and setup

**Target properties: companion to star (comp), binaries (bin) or isolated (iso). We give the mass ratio $q_{b/A}$ of bount systems.**

| Source | Config | $K_B$ | SpType | $M_A$ ($M_\odot$) | $M_B$ ($M_{Jup}$) | $q_{b/A}$ | $\rho$ (AU) | Ref. |
|---|---|---|---|---|---|---|---|---|
| HIP 77900B | comp | 14.04 | M9 | 3.8 | $20^{+7}_{-3}$ | 0.005 | 3200 | Aller et al. 2013 |
| HIP 78530B | comp | 14.17 | M8 | 2.5 | $22 \pm 4$ | 0.009 | 710 | Lafrenière et al. 2011 |
| USco 161031.9-191305 B | comp | 12.73 | M9 | 0.88 | $20^{+7}_{-3}$ | 0.023 | 840 | Aller et al. 2013 |
| USCO CTIO 108 AB | bin | 15.11 | M9.5 | 0.06 | $14^{+2}_{-8}$ | 0.23 | 670 | Béjar et al. 2008 |
| USco J161047.13-223949.4 | iso | 14.01 | M8.5 | ... | ~18 | ... | ... | Lodieu et al. 2008 |
| USco J160723.82-221102.0 | iso | 14.01 | M8.5 | ... | ~18 | ... | ... | Lodieu et al. 2008 |
| USco J160828.47-231510.4 | iso | 14.16 | M9.5 | ... | ~17 | ... | ... | Lodieu et al. 2008 |
| USco J160818.43-223225.0 | iso | 14.70 | M9.0 | ... | ~14 | ... | ... | Lodieu et al. 2008 |
| USco J160606.29-233513.3 | iso | 14.97 | M9.0 | ... | ~13 | ... | ... | Lodieu et al. 2008 |
| USco J160737.99-224247.0 | iso | 15.33 | M9.5 | ... | ~11 | ... | ... | Lodieu et al. 2008 |

1/ Different configurations

2/ All spectral type M8.5-M9.5

*CO overtone at 2.29 μm ⇒ C/O ratio*

*Reduced errors in the analysis when abundances compared from one object to another*

3/ No visual binaries (>50 mas)

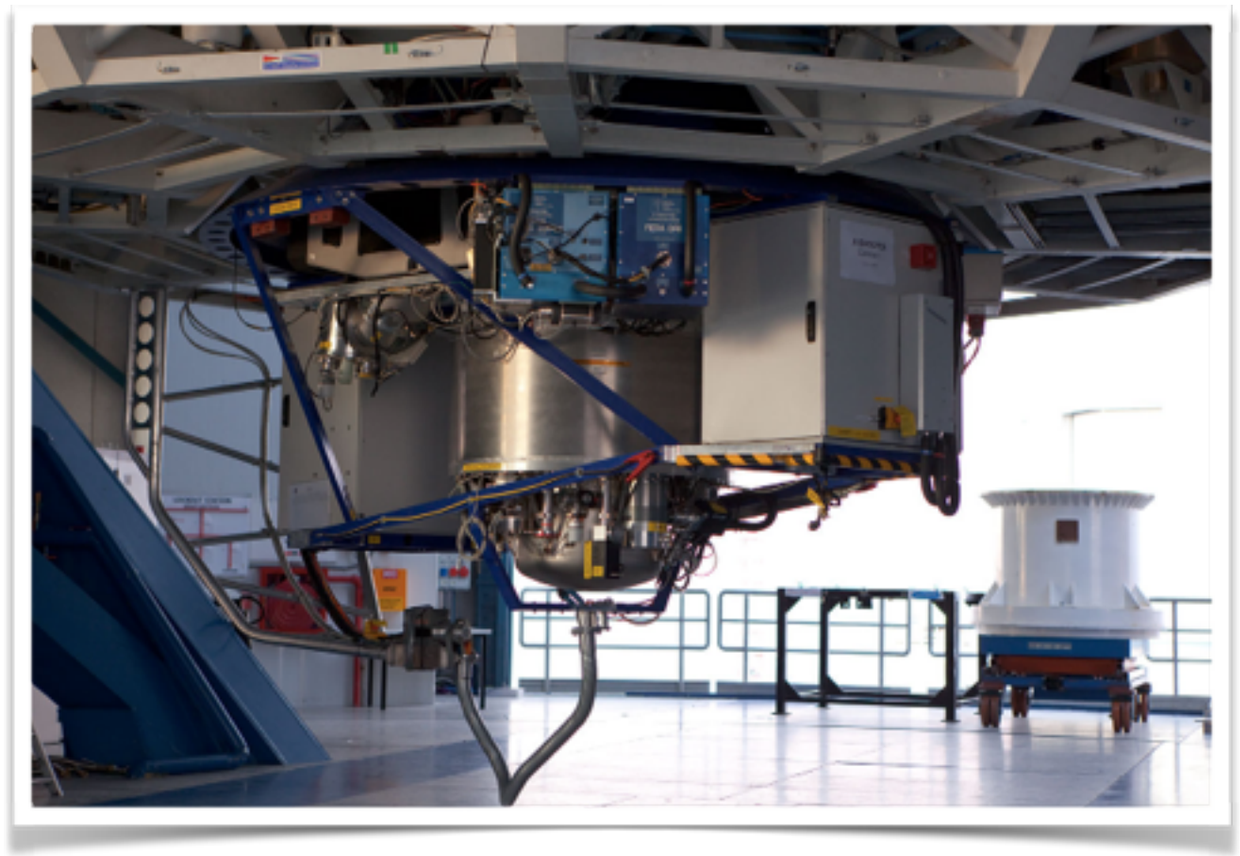
4/ WISE photometry ⇒ no IR excess

# Sample and setup

*The instrument: X-Shooter @ VLT*

a) 300-2500nm coverage in a single shot!

b) R=5400 in the optical, 3890 in the NIR



Tricky data reduction

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- **How to analyse the data?**
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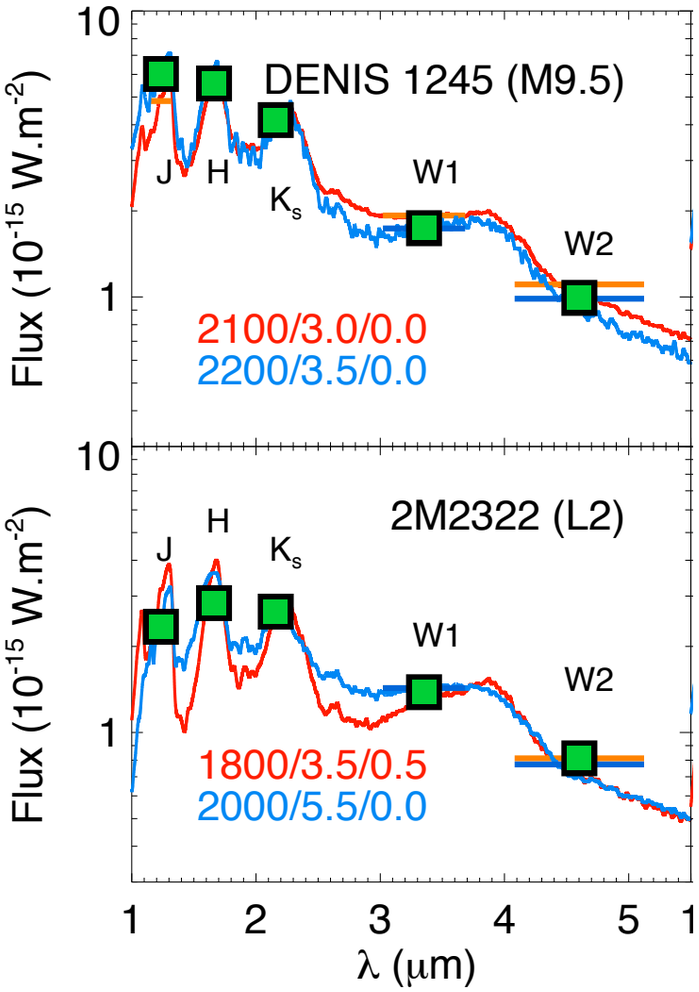
# How to analyse the data?

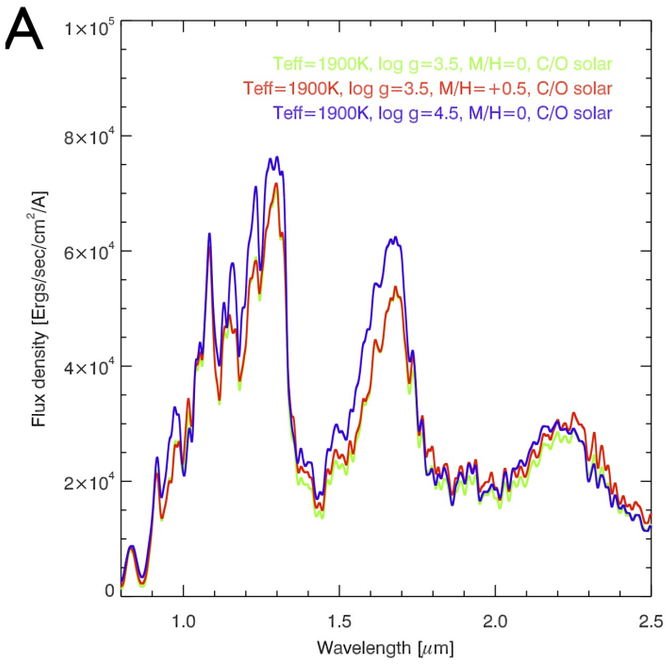
*Atmospheric models:*

## a/ The sequential approach:



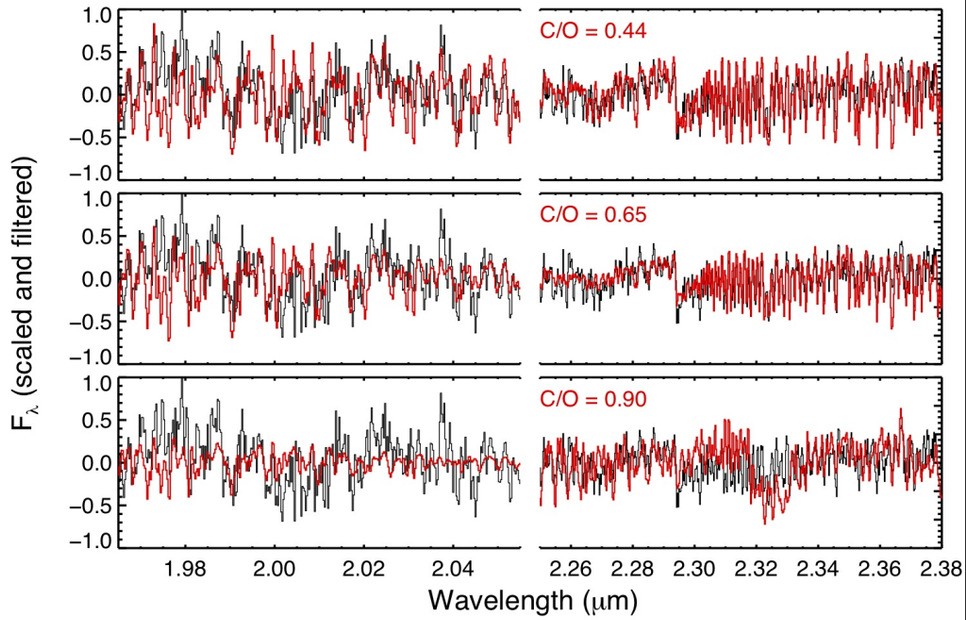

$T_{eff}$ from SED

A




log g & M/H from the pseudo-continuum (optical+NIR)

B




C/O ratio from CO ν=2→0 (K band, R=4000)

# How to analyse the data?

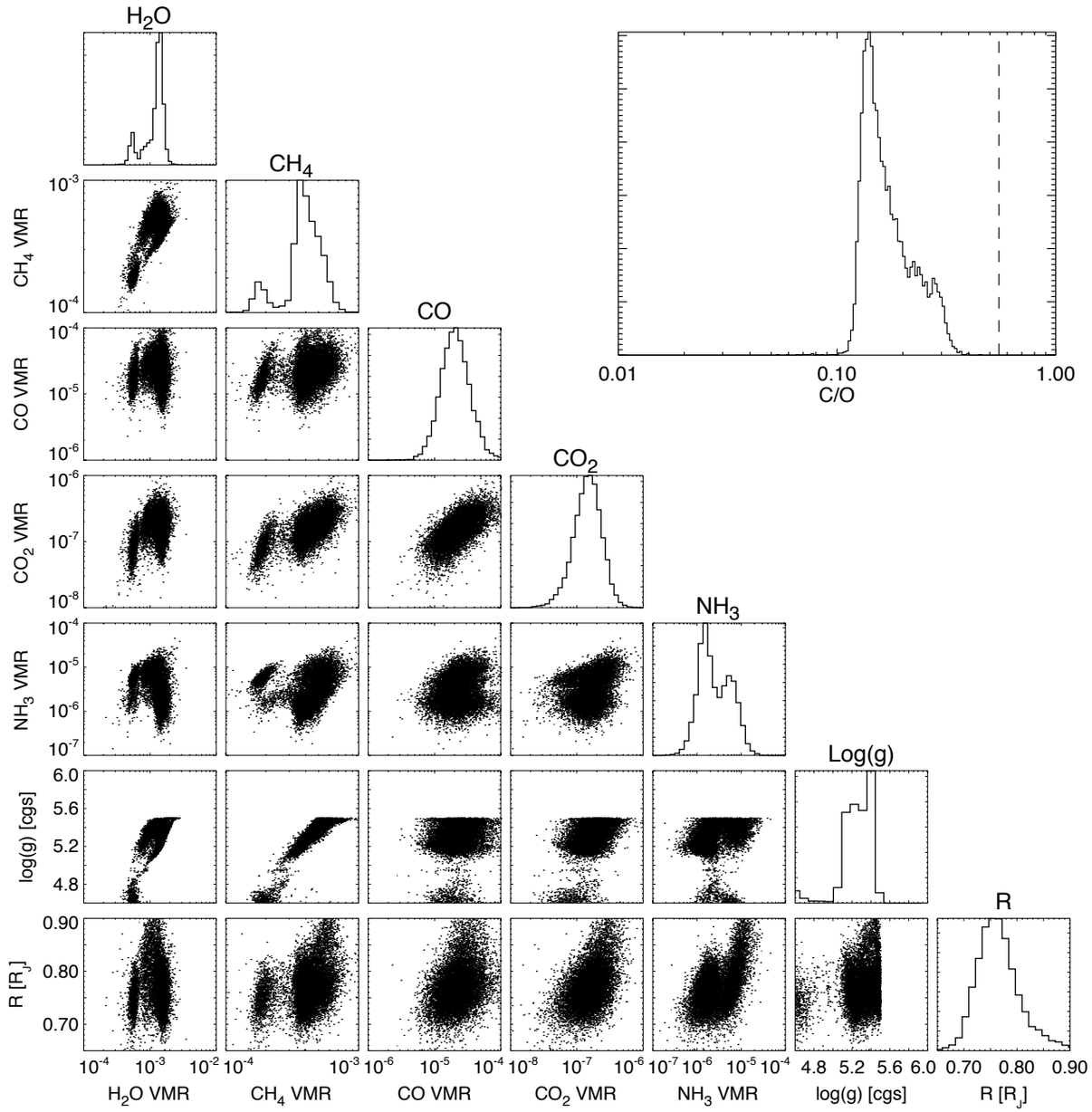
*Atmospheric models:*

## b/ Data-driven retrieval approach

Line et al. 2014, in press

astro-ph: 1403.6412

Lee et al. 2013,ApJ, 778, 87




*Line et al. 2014*

# How to analyse the data?

## *Links with formation models*

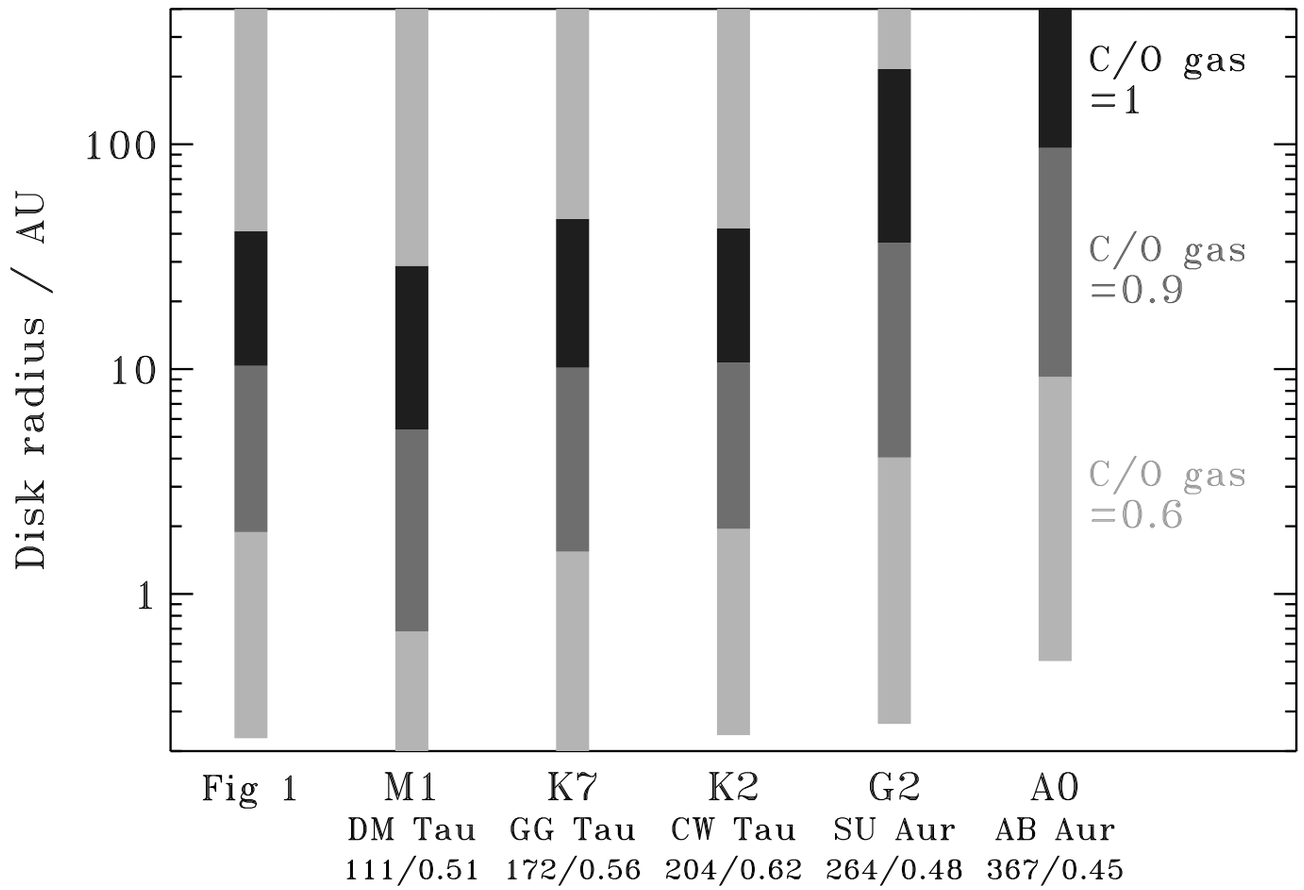



Fig. 2.— The predicted gas phase C/O ratio as a function of radius for five representative disks, ordered by spectral type, compared with the 'typical' disk model in Fig. 1. The derived temperature profile parameters, $T_0$ and $q$, are listed. The C/O ratios are calculated assuming that the stellar C/O ratio is solar, i.e. 0.54, and a static disk.

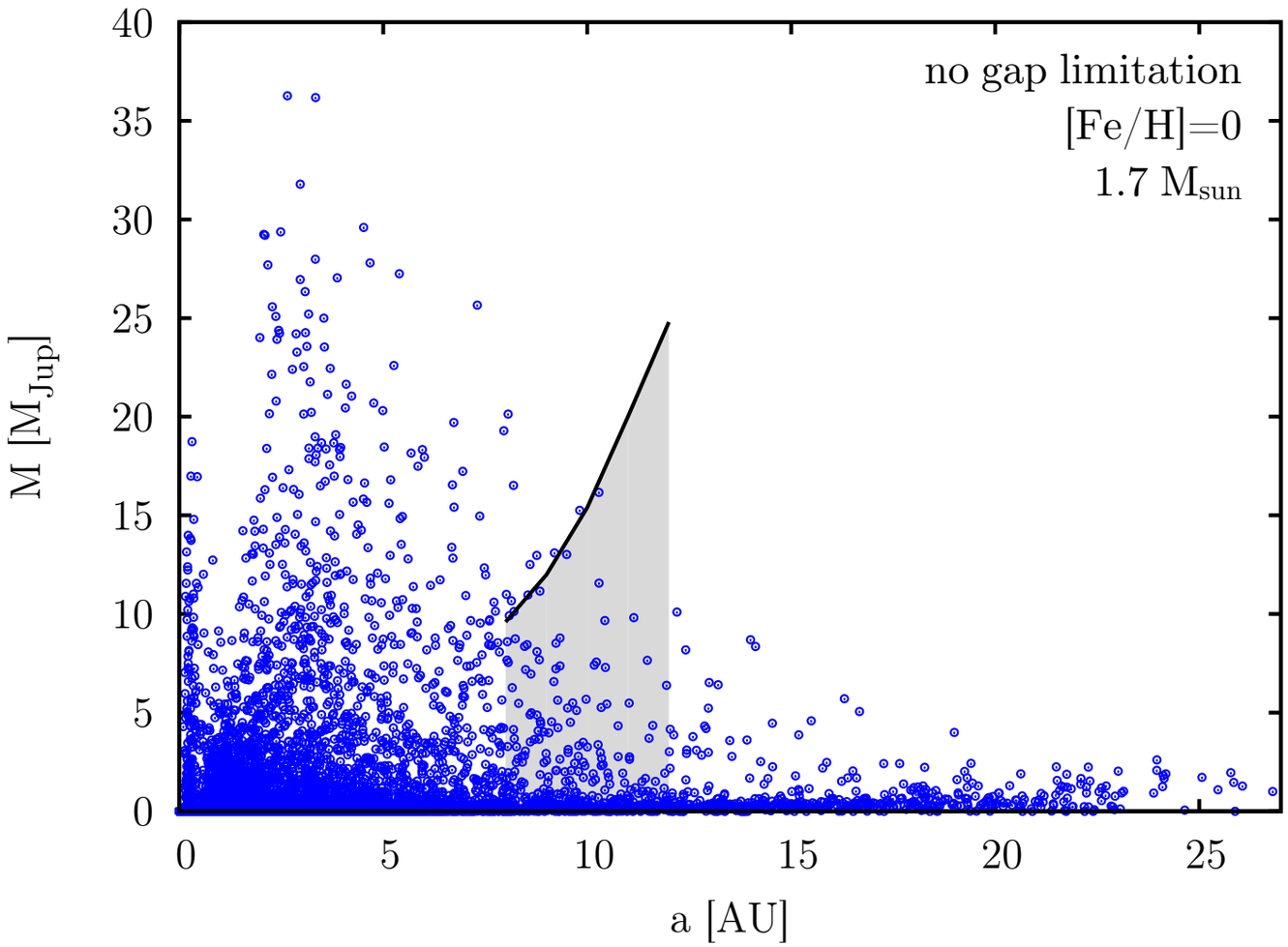
***Öberg et al. 2011***

## Companions: disk model

**K. Öberg (CfA/Harvard)**
**and C. Mordasini (MPIA)**

# How to analyse the data?

## *Links with formation models*




**Planet population synthesis**

**(assuming Up. Sco IMF)**

**C. Mordasini (MPIA)**

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# Summary

- 29hrs program on VLT to measure the relative abundances + M/H of low-mass BDs in Upper Sco
- 10 objects / various configurations ==> possible ≠ origins
- Pilot study: not 100% sure of the outcome(s)!
- Observations ongoing (4 objects observed already)
- People who want to contribute are welcomed!