A submillimeter study in Chamaeleon II: Searching for the youngest substellar objects

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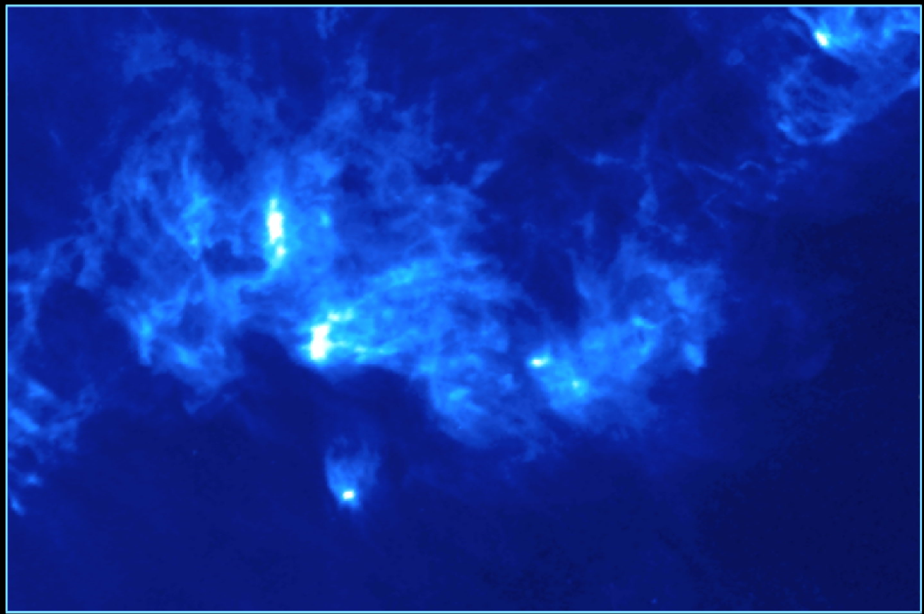
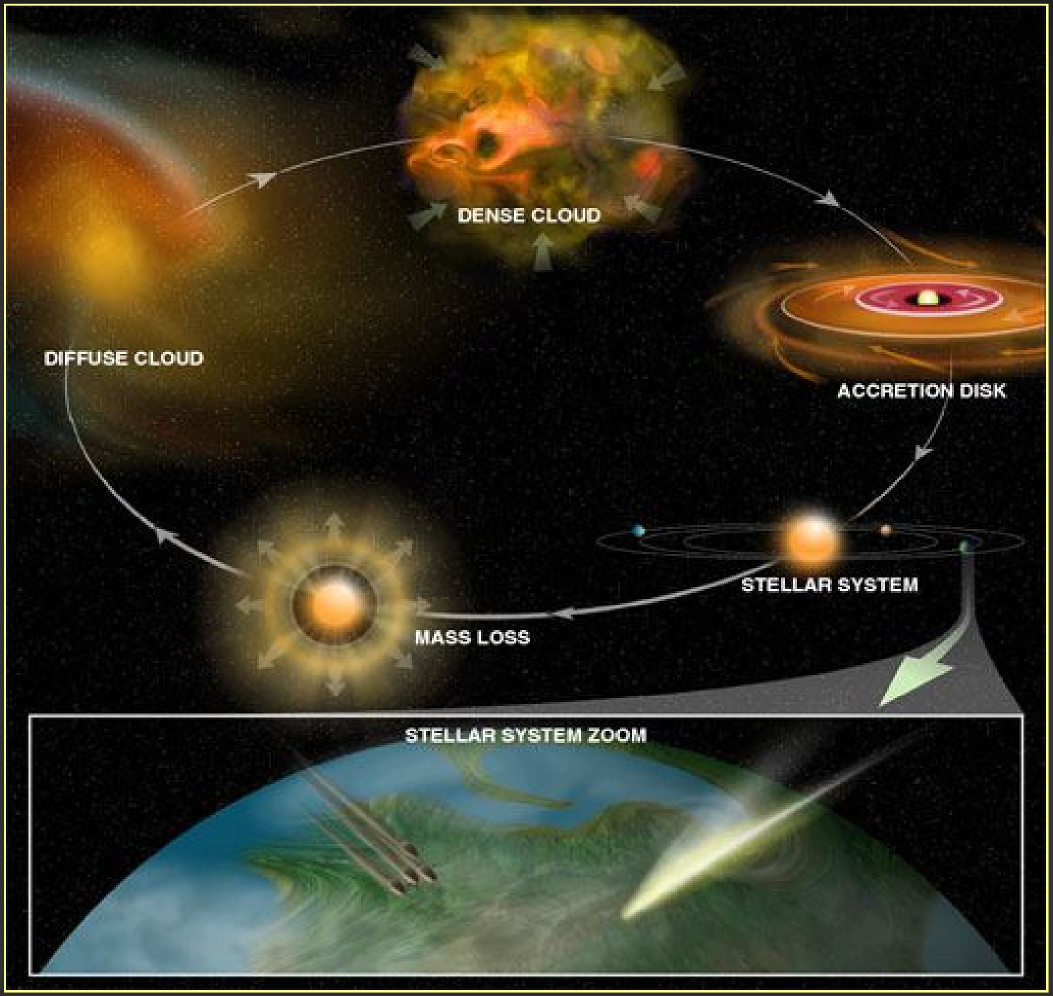


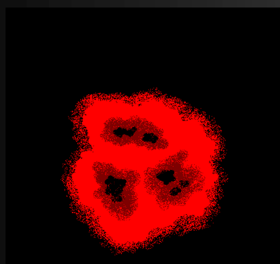
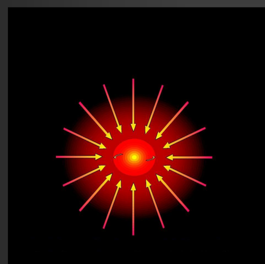
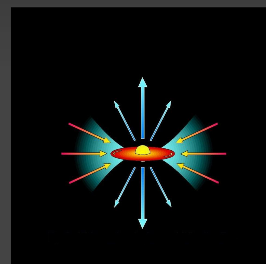
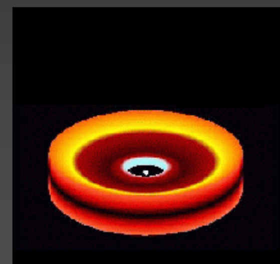
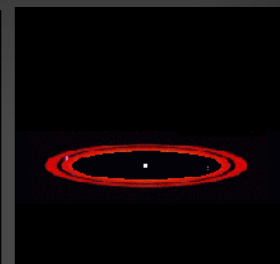
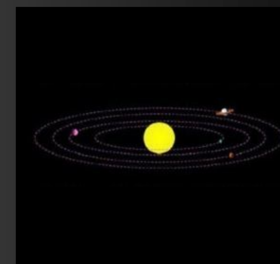
D. Barrado, H. Bouy, N. Huelamo (LAEX-CAB, Madrid), A. Bayo, (ESO, Chile), M. Morales-Calderón (Caltech), A. Palau (IEEC-CSIC, Barcelona), O. Morata (U. Of Taiwan), C. Eiroa (UAM, Madrid).

Why Star Formation is interesting?



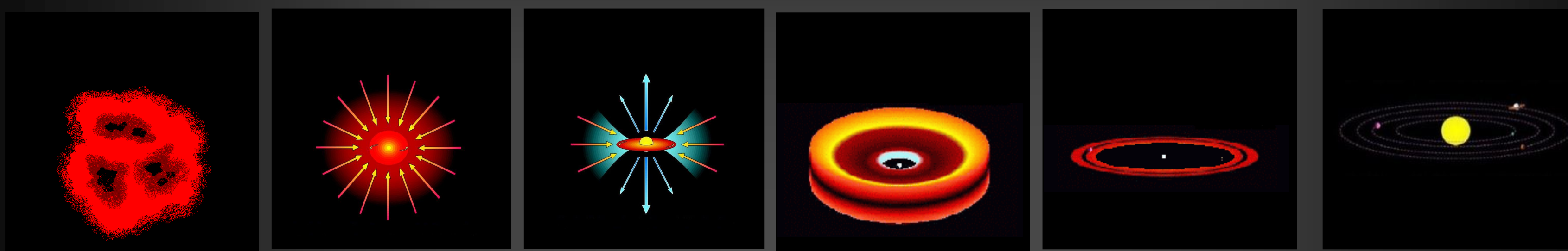
- Stars are the chemical factories of the Universe
- Our planet and all the life forms are literally stardust

Star Formation Theory

Dark cloud	Collapse	Protostars	T Tauri	PMS+Debri	Planetary system
					
$10^{5\text{-}6}$ AU	10^4 AU	500 AU	100 AU	100 AU	50 AU
	0 yr	$10^{4\text{-}5}$ yr	$10^{5\text{-}6}$ yr	$10^{6\text{-}7}$ yr	$>10^7$ yr

Star Formation Theory

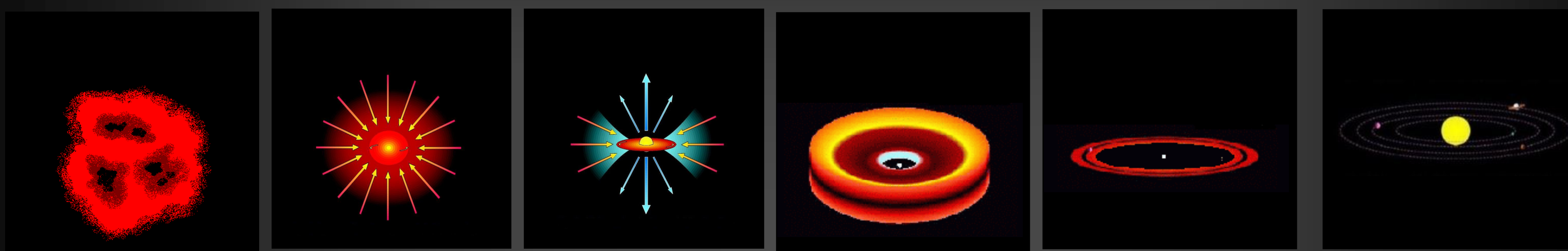
Dark cloud | Collapse | Protostars | T Tauri | PMS+Debri | Planetary system



Low mass

Star Formation Theory

Dark cloud | Collapse | Protostars | T Tauri | PMS+Debri | Planetary system



High mass (> 8 Msun)

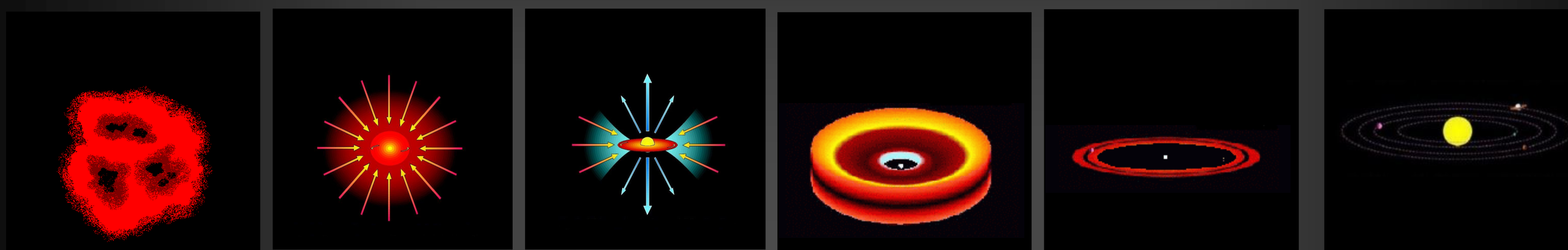
⇕

Low mass

⇕

Substellar mass (< 0.08 Msun)

Star Formation Theory



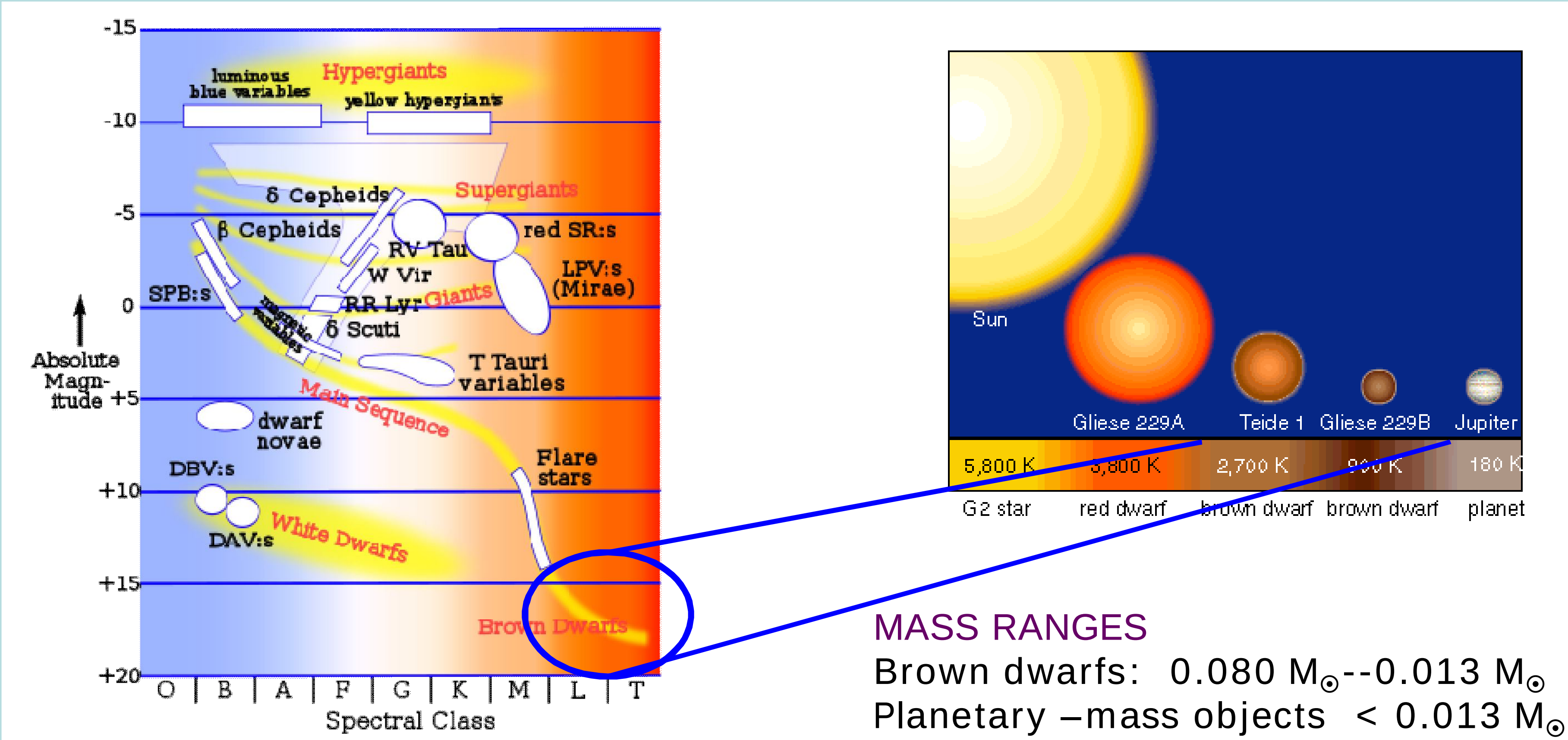
High mass (> 8 Msun) YES???

Low mass

Substellar mass (< 0.08 Msun) ???

Substellar Objects

Sub-stellar objects do not have enough mass to maintain nuclear reactions in their cores, as do stars on the main sequence.



MASS RANGES

Brown dwarfs: $0.080\ M_{\odot}$--$0.013\ M_{\odot}$

Planetary –mass objects $< 0.013\ M_{\odot}$

Discovery of the first BDs: Nakajima et al. (1995), Rebolo et al. (1995)

Substellar Objects: how do they form?

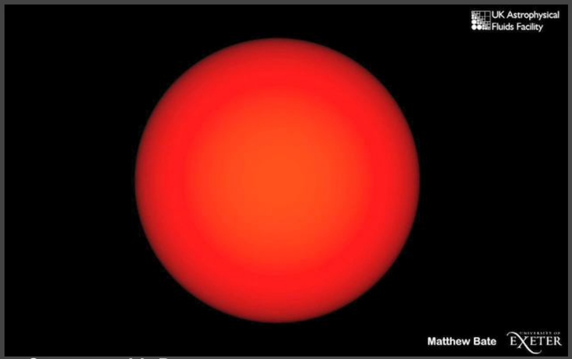
1. Like low-mass stars?

Cloud fragmentation &
Gravitational Collapse

2. Aborted Stellar embryos

Ejection?

Dynamical processes in stellar clusters
(ejection of the least massive objects.)



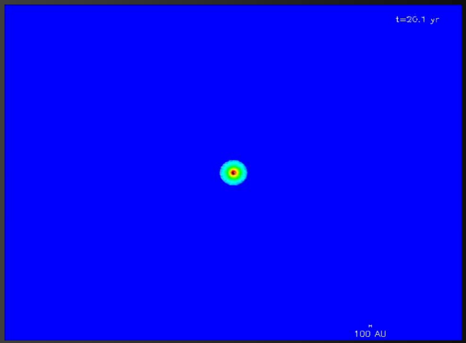
Courtesy: M. Bate

Photo-evaporation

Presence of high-mass stars

Courtesy: NASA

3. In circumstellar disks (like planets)?



Courtesy: D. Stamatellos

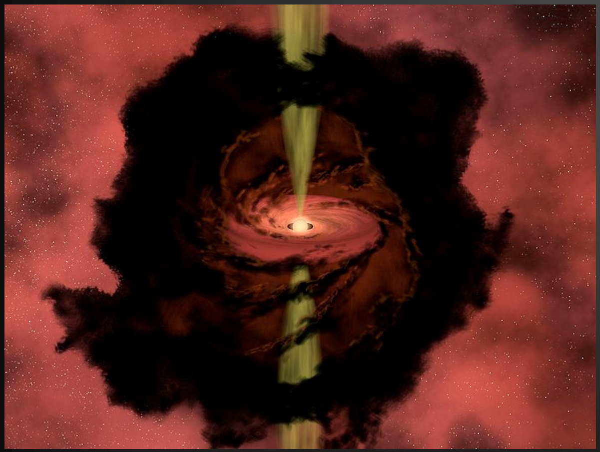
Substellar Objects: how do they form?

All mechanisms can form brown dwarfs, but is fragmentation the most efficient one?

Signatures of formation evolve with time, it is better to observe them when they are young.

- Can we find brown dwarfs with the properties of the youngest low-mass stars?
    - BDs associated with dusty cold envelopes, molecular outflows, ...
    - SEDs peaking at sub(mm) and far-IR regime, etc...

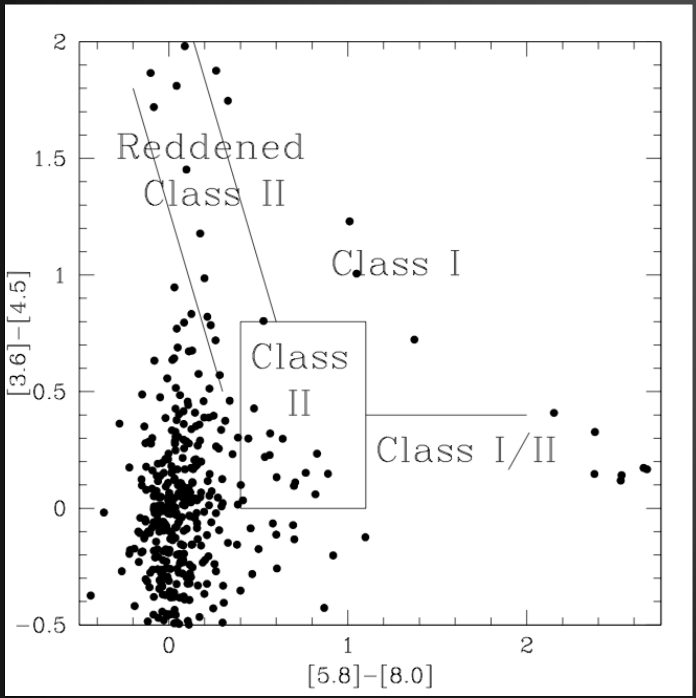
- Observations to discriminate between different scenarios, in the millimeter and submillimeter regime.

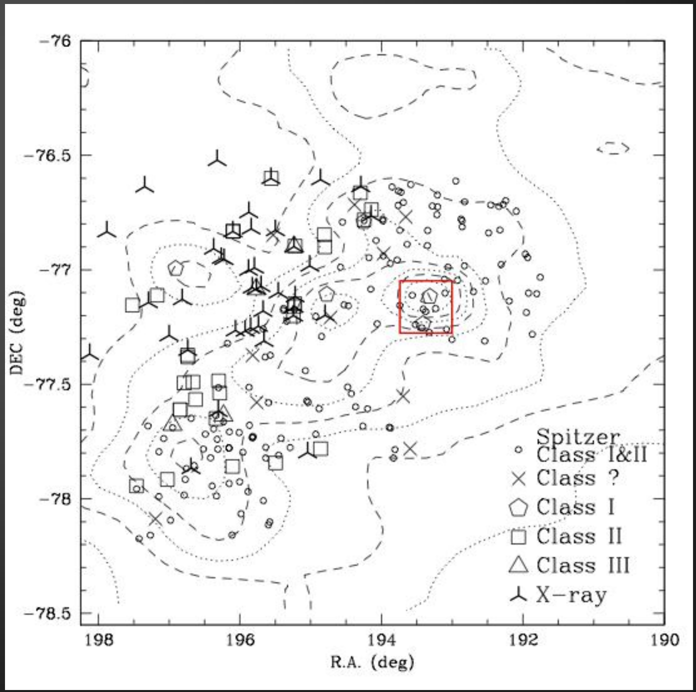


If we find proto-BD surrounded by cold dusty envelopes, similar to low-mass stars, they would provide direct support for in-situ formation.

Searching for proto-BD's in Chamaeleon II: strategy

1. We used IRAC/Spitzer (3.6-8.0 micron) color-color diagram to classify the stage of the evolution of Cha II members (following Allen et al. 2004).
2. We represented the distribution of the known candidate members of the Cha II cloud.
3. We selected a region of 14'×14', where the highest density of low mass Class I and Class I/II objects is observed.





Contours: IRAS map at 100 microns

Searching for proto-BD: strategy

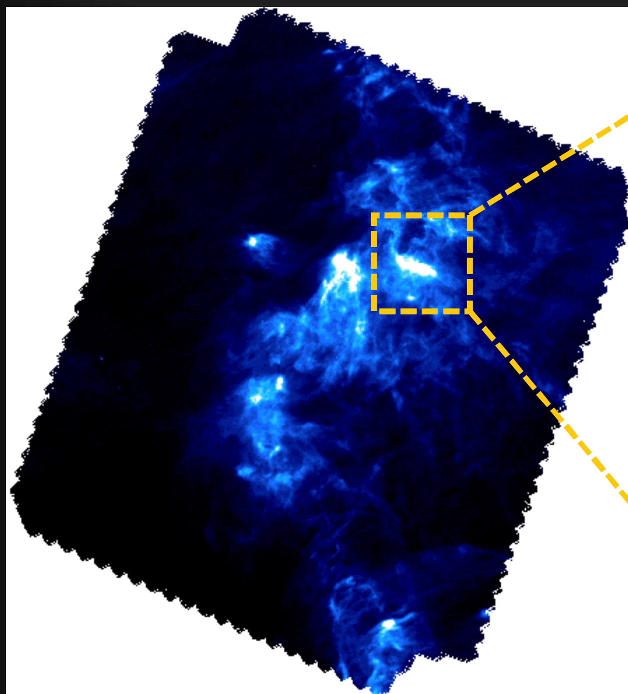
4. Two out of the three Class I sources in the area, fall in the region we have selected to study, being this region the place of the cloud with most recent star formation.

5. Very deep continuum observations at 870μm were carried out with LABOCA bolometer array at APEX telescope to detect faint cold dust emission.

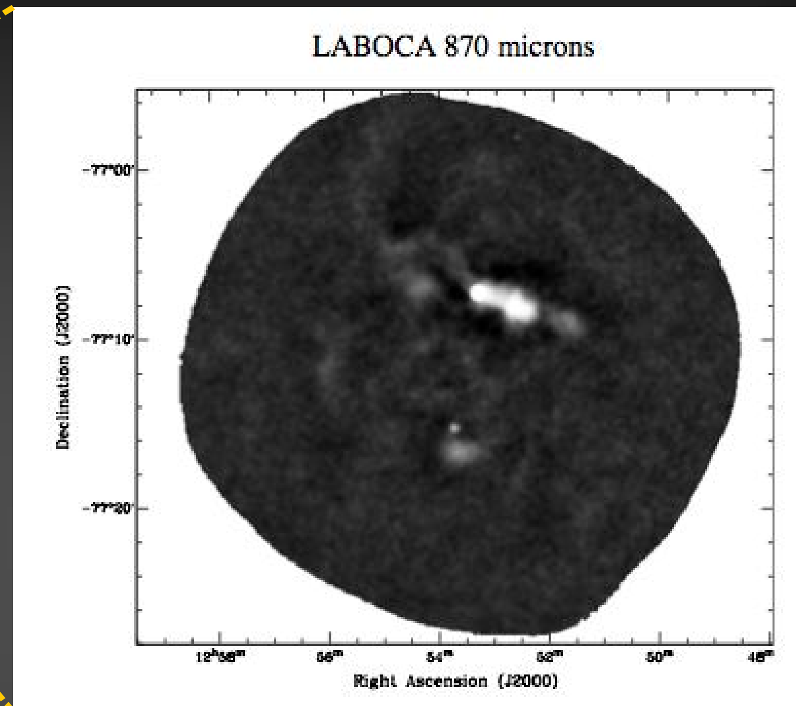
LABOCA
- Multichannel bolometer array
- 295 pixels, 26" separation
- Angular Resolution: 18.6"
- FOV 11.4'

MAPPED AREA
- Area ~14' x 14', 13 hours
- Very deep (rms ~4.5 mJy)

LABOCA observations at 870 µm



Herschel SPIRE 250 microns

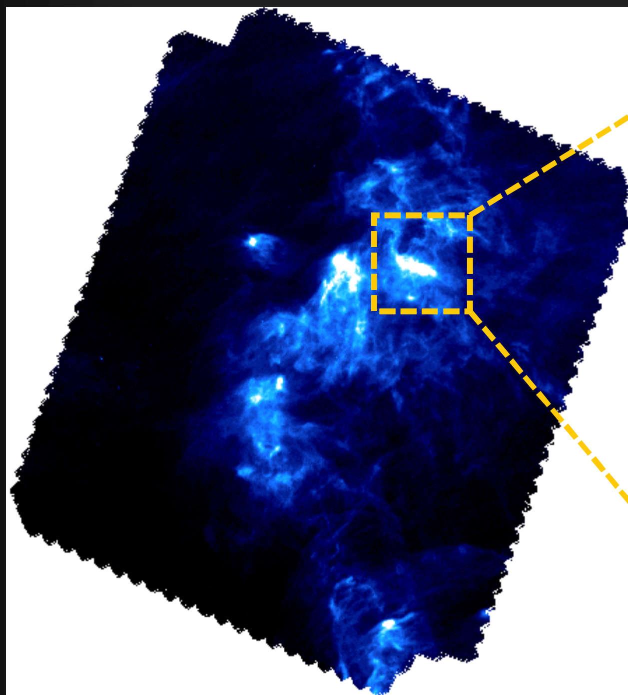


APEX LABOCA 870 µm (rms=4.5 mJy)

Map at 870 µm: 2 strong point-like objects surrounded by diffused emission and several faint isolated objects (point-like and extended)

- 21 clumps/point-like objects were detected at >4σ
- Masses range from ~1 $M_\odot$ to 12 M_{JUP}
- Six clumps show extended structure (~35”-80” → 6000 – 14000 AU)

LABOCA observations at 870 µm



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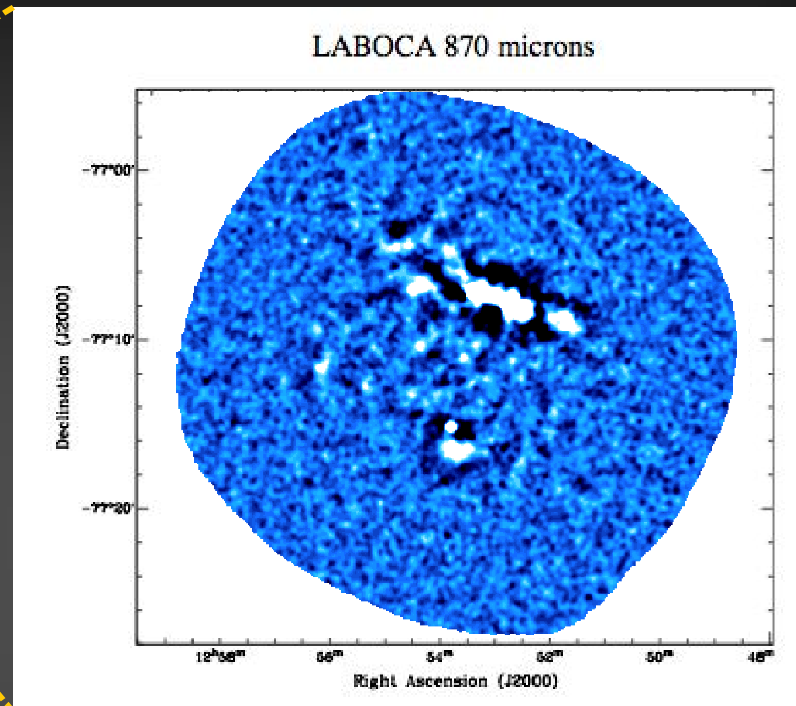

APEX LABOCA 870 µm (SNR map)

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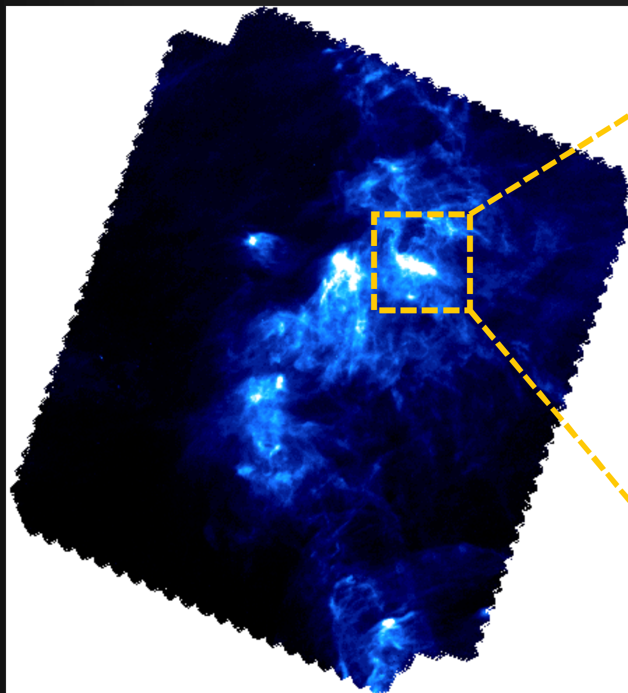

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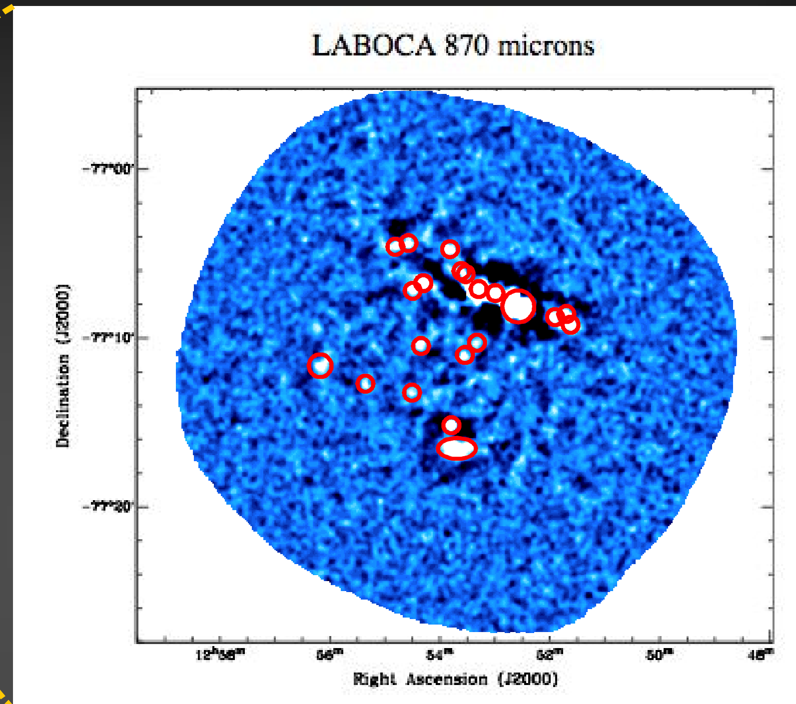

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Multiwavelength approach: searching for counterparts

Telescope/ Instrument or survey	Filter$_1$ (λ_1)	Filter$_2$ (λ_2)	Filter$_3$ (λ_3)	Filter$_4$ (λ_4)	Filter$_5$ (λ_5)
ESO 2.2m/WFI	Rc (651.7 nm)	Hα (658.8 nm)	NB665 (665.6 nm)	SII (676.3 nm)	Ic (783.8 nm)
ESO 2.2m/WFI	I (826.9 nm)	MB856 (856.2 nm)	MB914 (914.8 nm)	Z (964.8 nm)	
VLT/VIMOS	I (817.1 nm)				
ESO 1m/DENIS	I (0.8 μm)	J (1.2 μm)	Ks (2.1 μm)		
Mt. Hopkins-CTIO/2MASS	J (1.2 μm)	H (1.7 μm)	K (2.2 μm))		
WISE	W1 (3.4 μm)	W2 (4.6 μm)	W3 (12 μm)	W4 (22 μm)	
Spitzer/IRAC	I1 (3.6μm)	I2 (4.5 μm)	I3 (5.8 μm)	I4 (8.0 μm)	
Spitzer/MIPS	M1 (24 μm)	M2 (70 μm)			
Akari/IRC	S9W (9 μm)	L18W (18 μm)			
Akari/FIS	N60 (65 μm)	WIDE-S (90 μm)	WIDE-L (140 μm)	N160 (160 μm)	

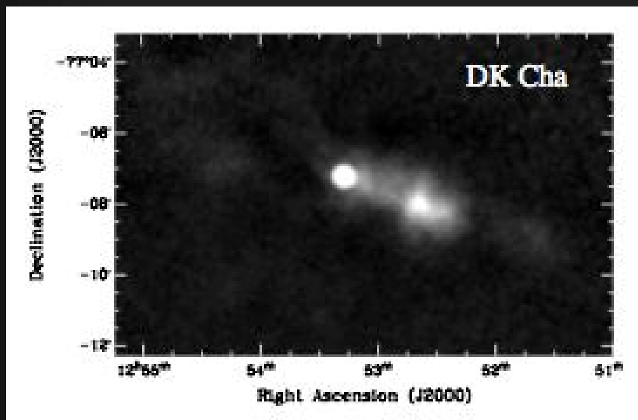
Nature of these objects:

- Positions were crossmatched with a multiwavelength catalogue (optical to far-IR)
- SEDs were used to identify reliable candidates
- Robitaille 2006, 2007 SED models were used to identify background stars and young stellar objects.

Results on found counterparts:

- 10% of the sources are associated to a YSO
- 67% do not show any evidence of active star formation
- 24% need more observations to support the presence of a YSO

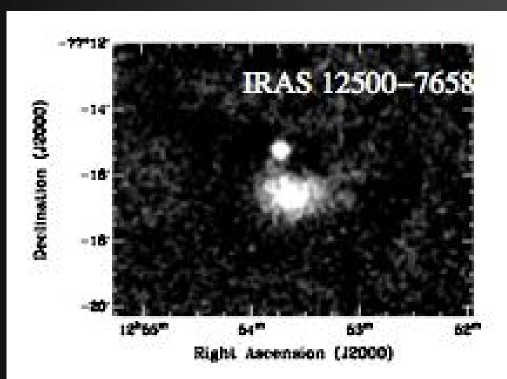
YSO's: DK Cha and IRAS 12500-7658



DK Cha:

- Herbig Ae, Class I/II. Face-on disk-outflow system (Van Kempen et al 2010).

- Immerse in elongated structure with multiple subpeaks → very likely tracing the natal cloud



IRAS 12500-7658:

- Class I object in the substellar regime ($M_*=0.06M_\odot$) that emits in the optical (Spezzi et al. 2008).

- L_{bol} higher than VeLLOs → Class I objects + optical very low mass companion

- At the edge of a clump of dust of ~7000AU size
    - Produced by a molecular outflow?
    - Expelled from parental cloud?

- We need more observations to study the characteristics of the possible molecular outflow.

Clumps with no counterparts: Pre-proto BDs?

- In-situ formation of BDs via turbulent fragmentation (Padoan & Nordlund, 2004)
- Cores of any size can be formed if $n_{core} > n_{critical}$
- Critical density inferred from the mass of the critical Bonnor-Ebert isothermal sphere

$$m_{BE} = 3.3\ M_{\odot}\ (T/10\ K)^{3/2}\ (n_{critical}/10^3 cm^{-3})^{-1/2}$$

$$n_{core} > n_{critical}$$

a) For extended (spatially resolved) starless clumps we found $n_{core} < n_{critical}$, so they are very likely transient clumps.

b) For point-like starless sources:

- For the less massive clumps (~12 M_{JUP}), $n_{critical}$ = 7.6 X 10^7 cm^{-3}, and a size of the clump smaller than 150 AU is needed for having a density higher than $n_{critical}$
- For the more massive clumps (~47 M_{JUP}), $n_{critical}$ = 4.4 X 10^6 cm^{-3}, and a size of the clump smaller than 1000 AU would be needed.
- For intermediate clumps (~20-30 M_{JUP}), sizes of 300-500 AU would be needed

How to solve the problem?

- Such as small and faint objects need subarsec resolution high-sensitivity observations to do a follow up study → ALMA will provide the right answers.

Conclusions:

- We have performed a very deep observations (rms ~ 4.5 mJy) at 870 µm aiming to search for young sub-stellar objects in the Cha II region.

- We identified 21 clumps/point-like sources, two of them associated with YSOs. One of them is a sub-stellar object candidate.

- The found extended starless sources are very likely transient clumps.

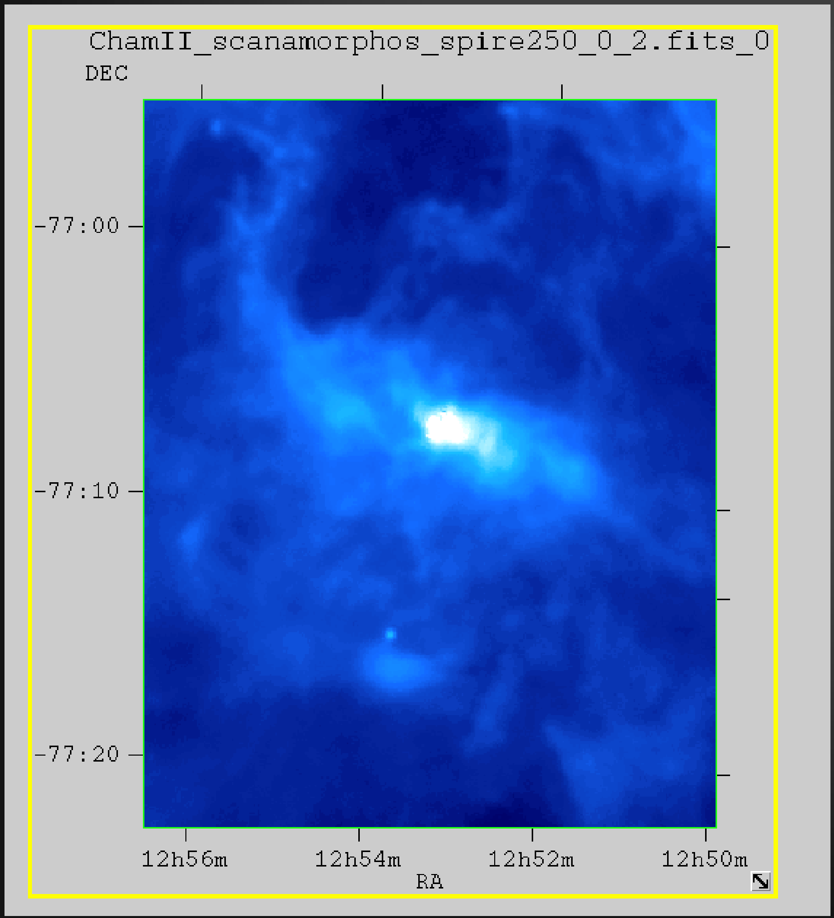
- The point-like starless sources, could grow in mass and became pre-stellar objects if they have sizes between 150-1000 AU, depending on their mass.

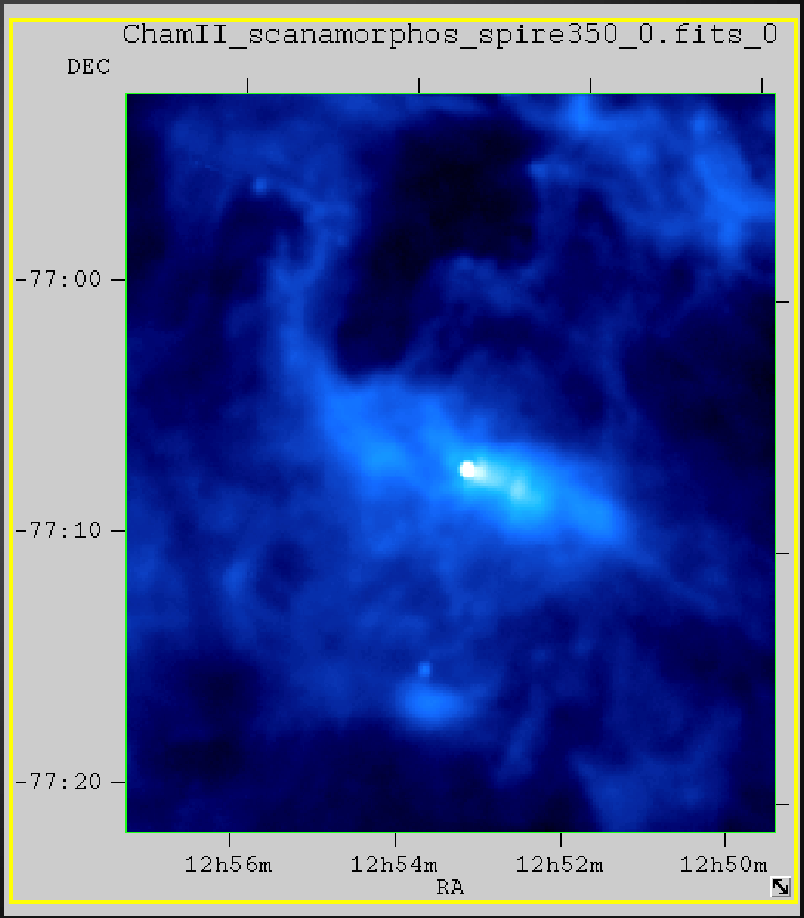
- ALMA observations are needed to resolve spatially these objects. We also need spectral line information to infer the kinematics and the energetic state of these pre-sub-stellar cores candidates.


Thank you!!

COUNTERPARTS:

- 2 young stellar objects (DK Cha and IRAS 12500-7658)
- 3 clumps with no reliable counterpart
- 3 counterparts with rising fluxes between IRAC bands (I2>I1)
- Most of them background stars → i.e. no counterparts
- 4 inconclusive





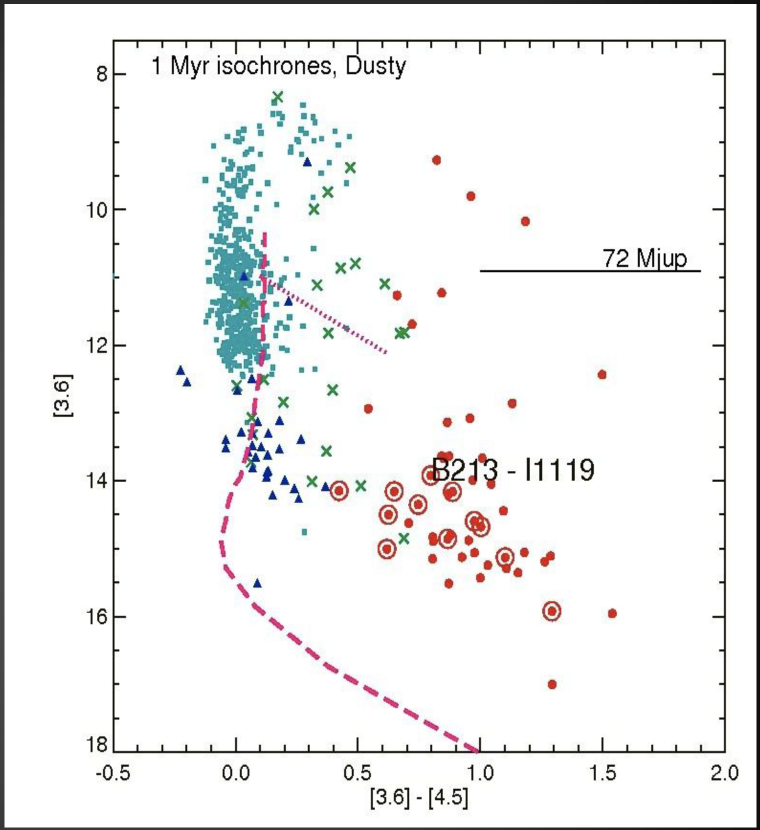
Searching for proto-BD: strategy

B213 in Taurus:

Color-magnitude diagram
- comparison with evolutionary tracks (Baraffe et al. 2003): SUBSTELLAR population

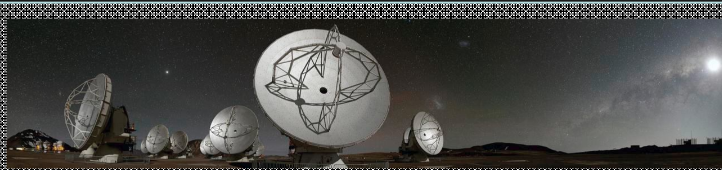
- Rejection of clear extragalactic contaminants (Gutermuth et al. 2008)

Cross IRAC with 2MASS & MIPS:
- Steep SED (1-24mic)



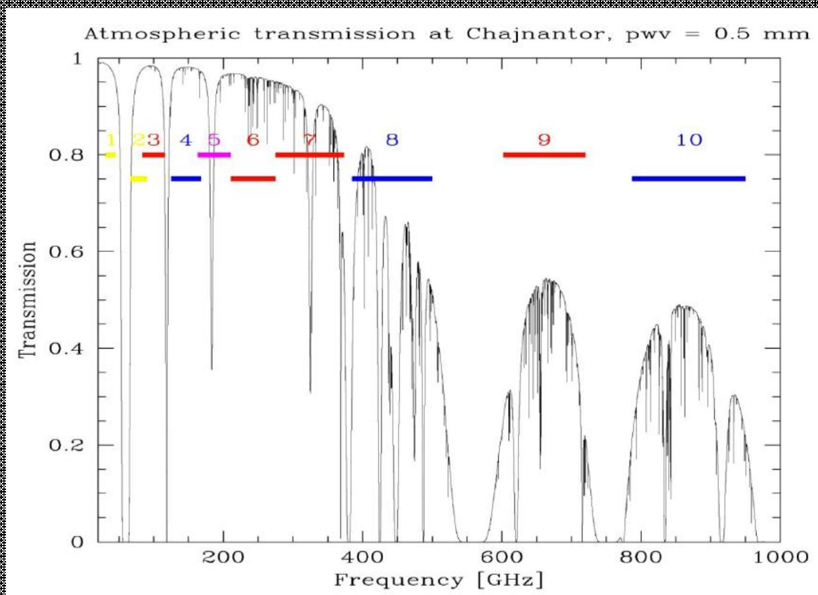
We isolated a total of 12 substellar sources in B213, deeply embedded and apparently non-background

Herschel and ALMA synergies



Atacama Large Millimeter Array

66 antennas at 5000m in Chile



Wavelength	1cm – 300 µm
FOV	145" – 6.4"
Spatial Resolution	13-0.14" - 0.5-0.005"
Max. Bandwidth	16 GHz
Max. Spec. resolution	0.001 – 0.02 km/s
Sensitivity (5σ, 1hr)	0.1 – 3.2 mJy

Herschel

PACS, SPIRE, HIFI

PHOTOMETRY	PACS	SPIRE
Wavelength	75,110,170 µm	250,360,520 µm
FOV	1.75'x3.5'	4'x8'
Spatial Resolution	3-6"	18-36"

SPECTROSCOPY	PACS	SPIRE	HIFI
Wavelength	55-210µm	194-671µm	157-625µm
FOV	47"	2.6'	39"-13"
Spatial Resolution	9"	17-29"	39"-13"
Max. Spec. resol. (km/s)	75-300	300-24000	0.02-0.6