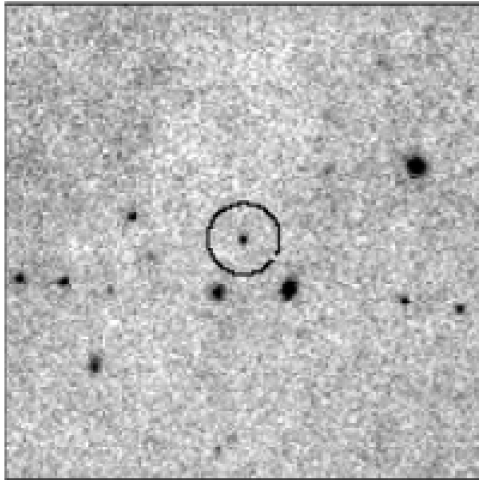




Low-Mass Brown Dwarfs and the Initial Mass Function

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Overview

- Introduction
- Objectives and Observations
- Extraction and Data Quality
- Candidate IC 4665 members
 - Calibration and Selection
- Young T-Dwarfs in IC 348
 - Candidates and Initial Mass Function
- Perspectives



Overview

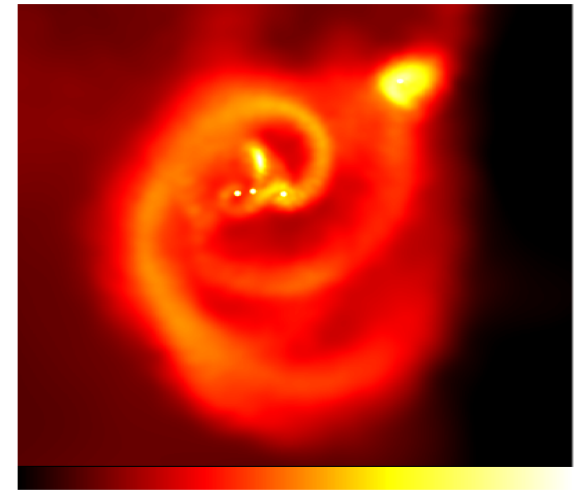
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Low-Mass Star Formation

Collapse of a molecular cloud:-

- Quiescent
 - many larger mass cores
 - photoerosion of prestellar cores by nearby stars
 - lower dynamical ejection
- Turbulent
 - fragmentation
 - reduces Jean's mass
 - many lower mass cores



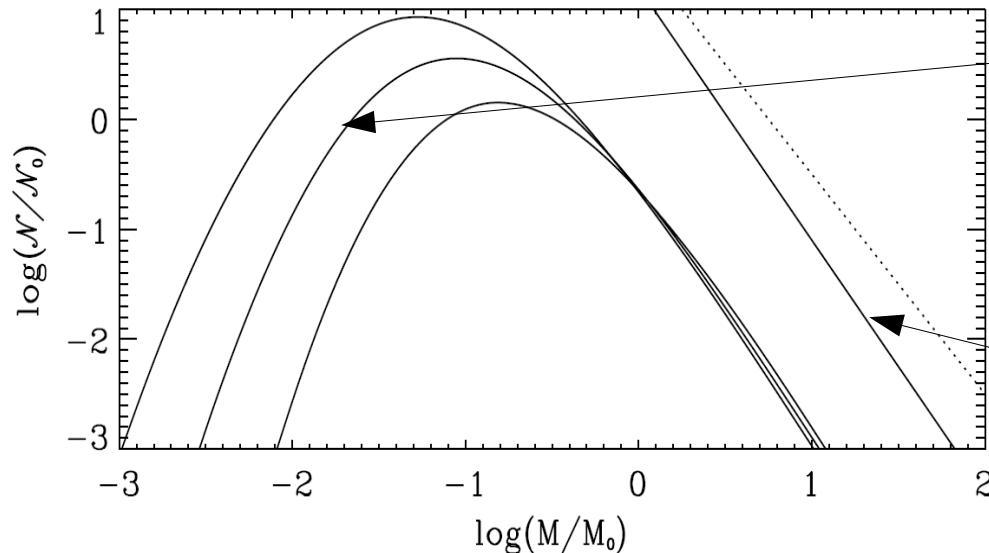
Bate 2009: $\log(\text{column density})$, 600AU across



Initial Mass Function (IMF)

is the outcome of the star formation process, and can be found from the prediction of the present day MF

- Depends on initial state of the cloud



Log-normal:

$$\xi(m) \propto e^{\left[-\frac{(\log m - \log m_0)^2}{2\sigma^2} \right]}$$

Power law:

$$\frac{dn}{d \log m} \propto m^{-x}$$

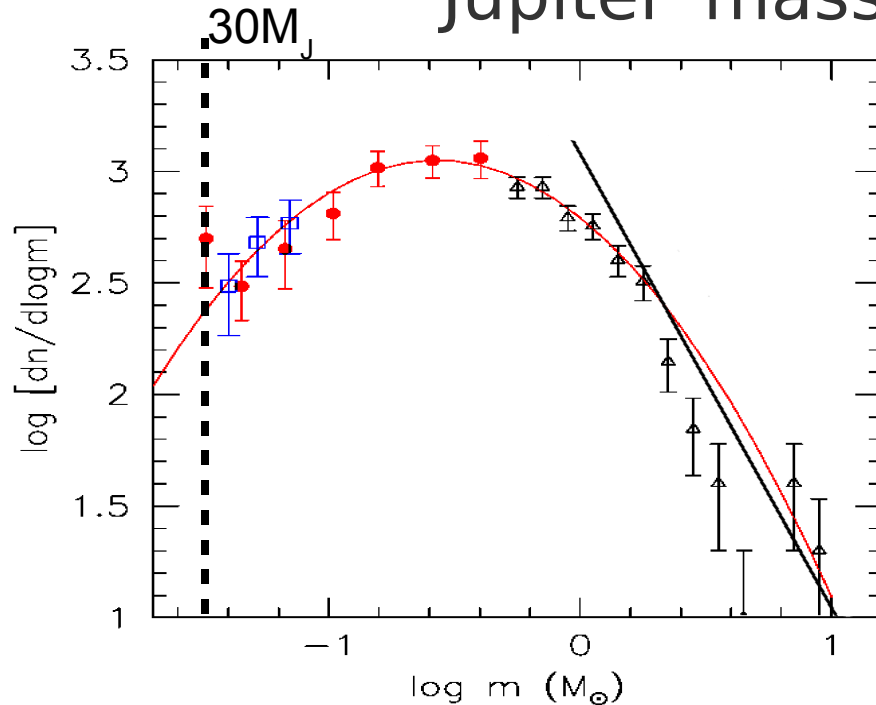
$x=1.35$ (Salpeter distribution)

Hennebelle & Chabrier 2009: normalised mass function vs mass for predicted MF for different numerical simulations.



Observed IMF

Generally known for many clusters down to 30 Jupiter masses ($\sim 0.03M_{\odot}$)



No apparent variations with log-normal fits

e.g. Pleiades:

- Peak mass: $m_0 \sim 0.25M_{\odot}$
- Dispersion $\sigma = 0.52$

Moraux et al '03: mass function vs mass

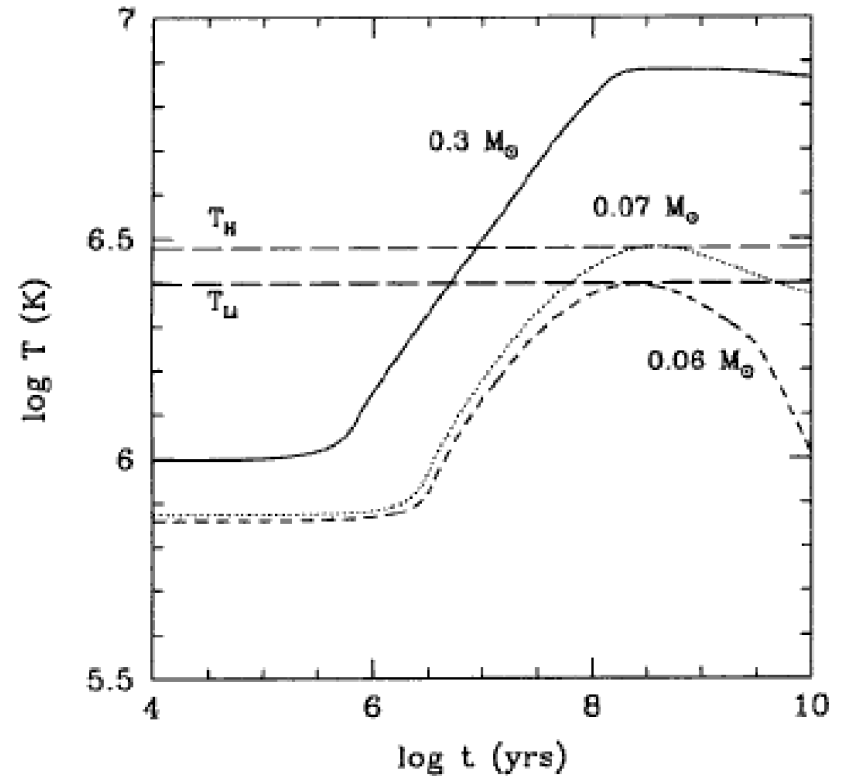
Need to investigate the IMF for masses lower than $\sim 30M_J$



Sub-Stellar Objects

Properties:-

- between planets and stars
- No stable H-fusion
- $\sim 0.07 M_{\odot}$
- Deuterium burning
- $\sim 0.012 M_{\odot}$
- $T_{\text{effective}}$ decreases with age



Chabrier '98: core temp v.s. Time:
0.06, 0.07 $0.3 M_{\odot}$



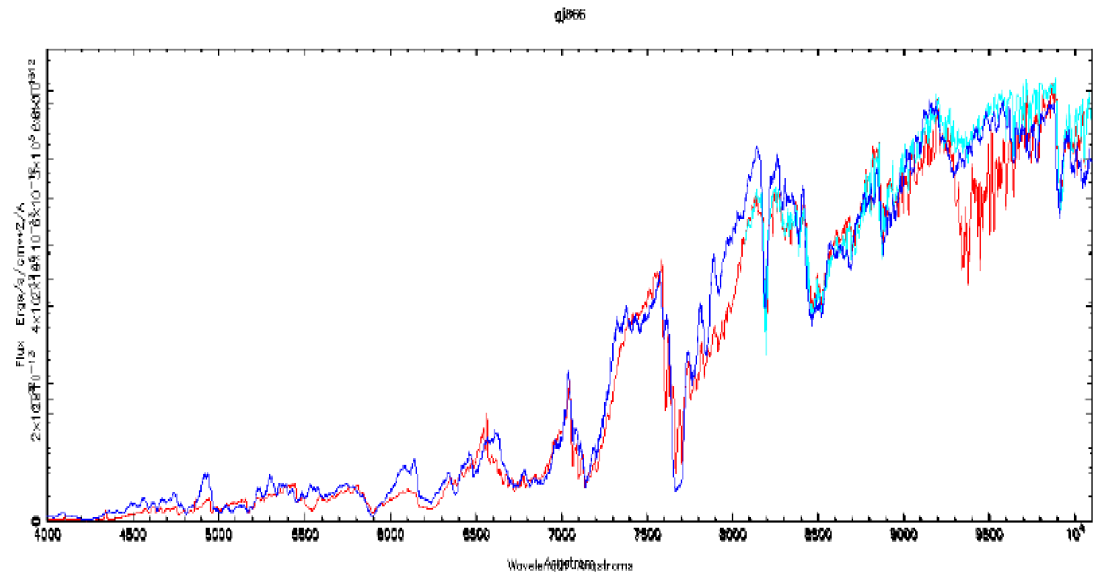
Models

Atmospheres

- Molecular species
 - Define M L T Y dwarfs
- Dust formation
- Settling
- Sedimentation
- Mixing

Allard et al '10: absolute flux vs wavelength: cool dwarf GJ866 (red) vs model (dark blue) ($T_{\text{eff}}=2900\text{K}$, $\log(g)=5.0$, solar metallicity) cyan=

- AMES
 - NextGen: solar to hot BDs, $\sim 3700\text{K}$
 - Dusty, Cond: grains/settling
- BT-Settl
 - Abundances & Opacities





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Motivation

How do/can the lowest mass objects form?

How do these objects overlap with planets?

How do these objects contribute to the IMF?

CONSTELLATION Work Package 3



Objectives & Strategy

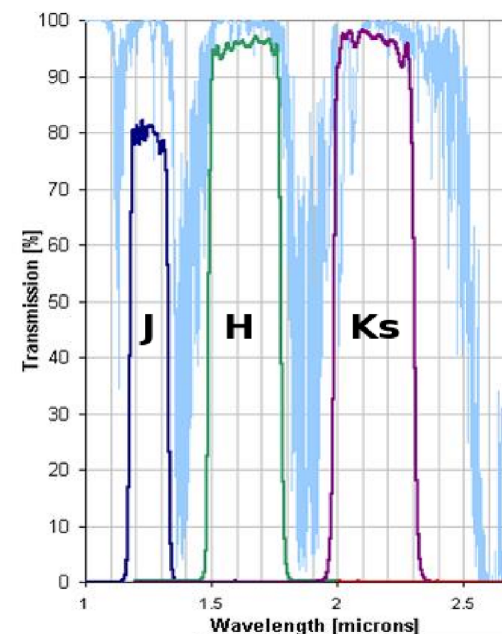
Constrain the low-mass end of the Initial Mass Function

- Where are the best places to observe these lowest mass objects?
 - IC 4665 – ~40Myr open cluster:
 - low mass objects earlier than ~L3, ~15M_J
 - IC 348 – 3Myr star forming region:
 - T dwarfs later than spectral type ~T3, ~10M_J



Observational Strategy

- These clusters require deep *and* wide field photometric observations:
 - Field of View (different footprints)
 - Infrared (cool objects brighter in IR than optical)
- Photometric considerations
 - PSF (Seeing)
 - Atmospheric considerations
 - Extinction

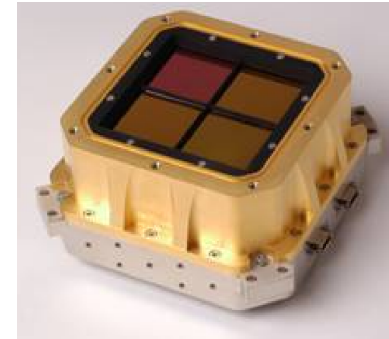




Instrumentation

Canada France Hawaii Telescope 3.6m

- WIRCam:
 - 20'x20' FOV
 - Y, J, H, K_s + methane narrowbands
- MegaCam
 - 1°x1° FOV
 - z'





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- Conclusions & Perspectives



Data Treatment Overview

CFHT/TERAPIX pipelines (2MASS calibrated)

Extraction (SExtractor, PSFEx)

Detection and Photometry

Zero-point/intrafield calibration

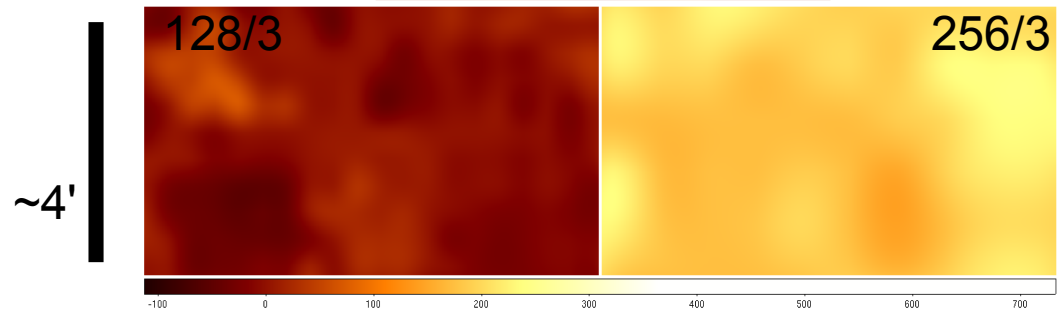
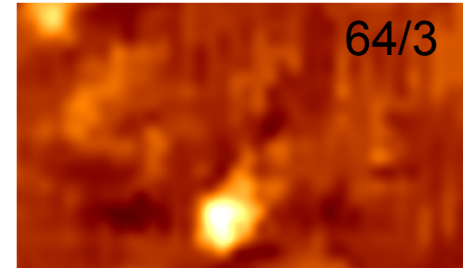
Amalgamation





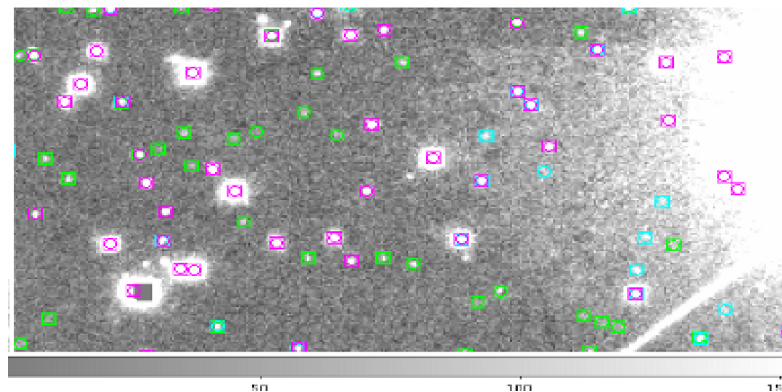
Detection and Photometry

- Sky background estimation



- Detection band, threshold and filter optimisation

- Aperture and PSF modeling

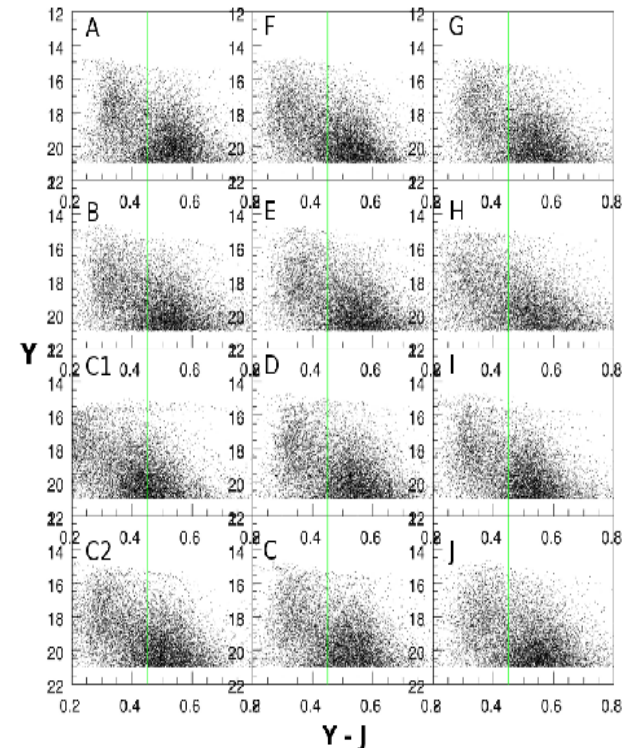


~1'
green: 1σ
cyan: 3.5σ
purple: 5σ



Calibration

- 2MASS or UKIDSS zero point adjustment
 - Median of good, bright overlapping objects
 - If required
- Intrafield calibration

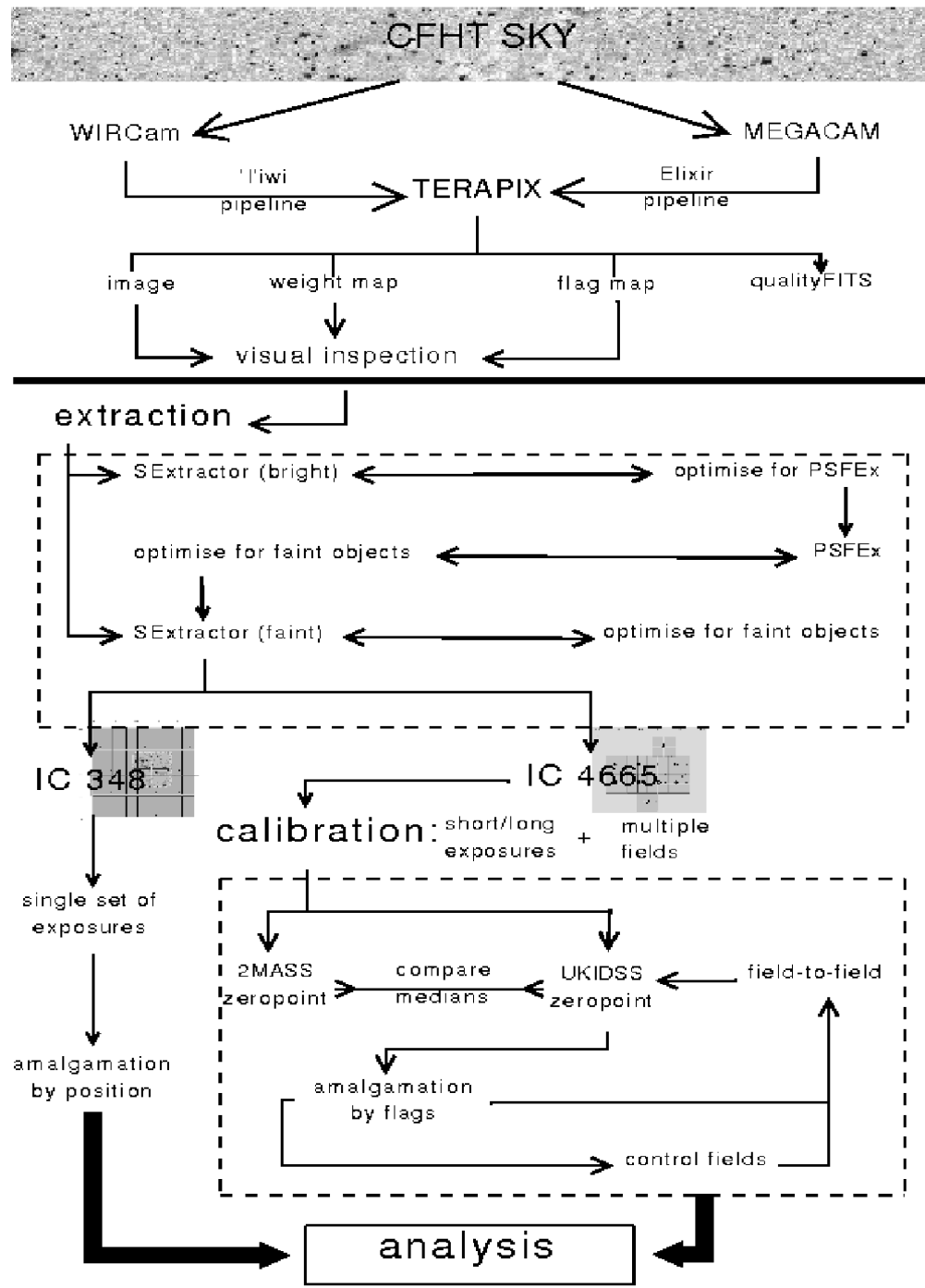




Catalogue Amalgamation

TOPCAT/STILTS and shell scripts:

- All bands for each position of detection image
- Also based on saturation/IMA flags
- For short+long required either/or for bands
- 1 catalogue uniquely populated for each field



My Ph.D. Work



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IC 4665



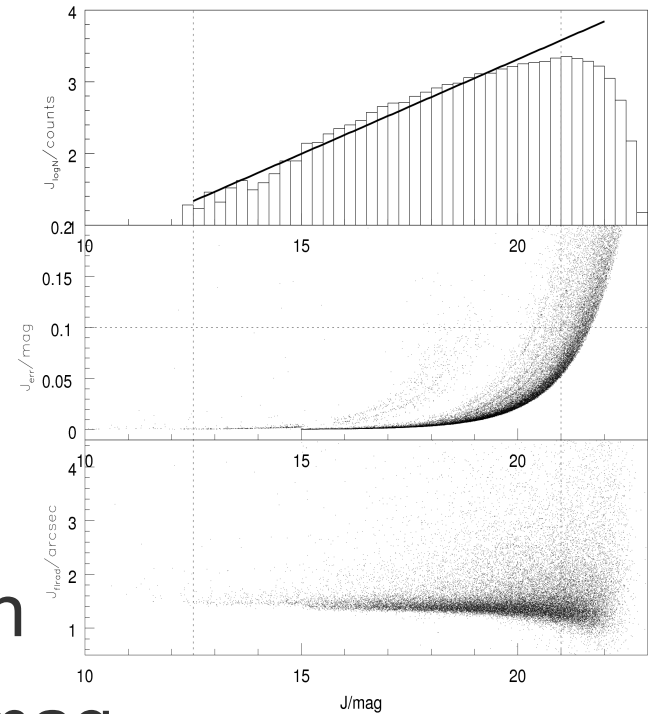
Image: Stefan Binnewies and Josef Pöpsel



IC 4665

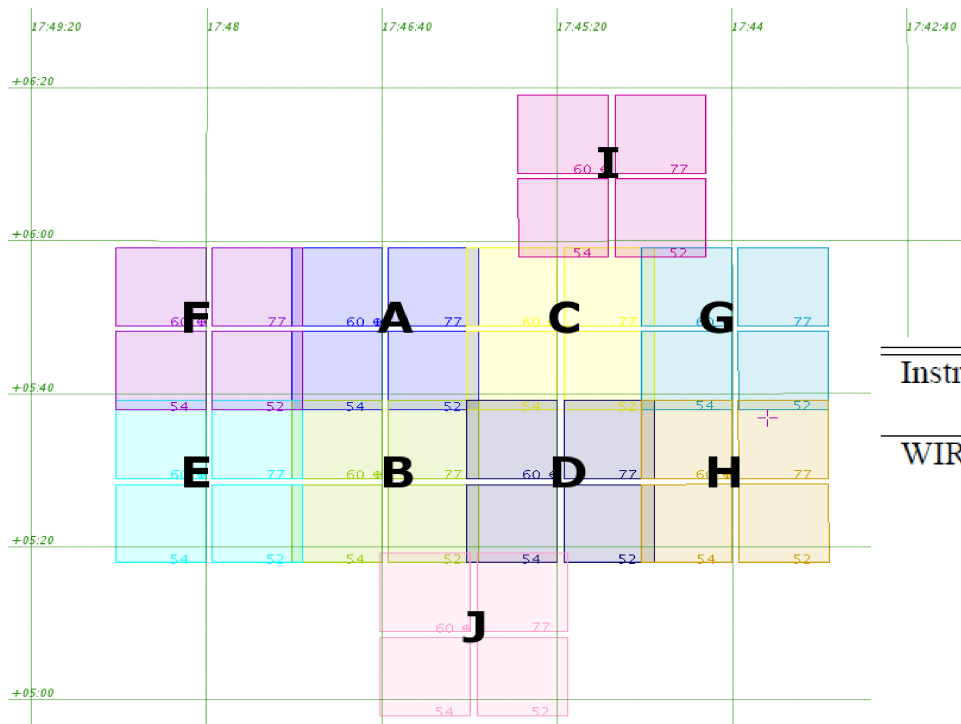
Open cluster

- $17^{\text{h}}46^{\text{m}}18^{\text{s}} +05^{\circ}43'0''$ (J2000)
- 350 ± 15 pc
- ~ 30 - 40 Myr, low proper motion
- Average extinction $A_V \sim 0.59$ mag
- Y J H Ks (21, 20.5, 19.75, 18.5 mag)
- $0.012 M_{\odot}$ (YJH) and $0.015 M_{\odot}$ (Ks)
- 10 fields + 2 control fields
 - ~ 1.1 sq. deg.





Field of View



Instrument	Field of View (FOV)	Field	Coordinates (J2000)
WIRCam	20' × 20'		
		A	17 ^h 46 ^m 42 ^s .00 +05°49'23".0
		B	17 ^h 46 ^m 42 ^s .00 +05°29'23".0
		C	17 ^h 45 ^m 22 ^s .00 +05°49'23".0
		D	17 ^h 45 ^m 22 ^s .00 +05°29'23".0
		E	17 ^h 48 ^m 02 ^s .40 +05°29'23".0
		F	17 ^h 48 ^m 02 ^s .40 +05°49'23".0
		G	17 ^h 44 ^m 02 ^s .40 +05°49'23".0
		H	17 ^h 44 ^m 02 ^s .40 +05°29'23".0
		I	17 ^h 44 ^m 58 ^s .54 +06°09'23".0
		J	17 ^h 46 ^m 01 ^s .60 +05°09'23".0
		Control1	17 ^h 51 ^m 03 ^s .00 +08°05'54".0
		Control2	17 ^h 40 ^m 53 ^s .00 +02°50'14".0



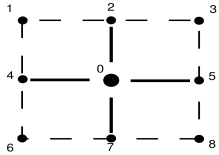
Candidates

- Selection (from ~380,000)
 - Use BT-Settl 30 & 50 Myr isochrones for selection over 6 CMDs and 15 COLDs Y-J/J-H etc
 - Two isochrones to address age uncertainty
 - Y-J colour most constraining
(~4,500 potential cluster members)
 - J-H least (~140,000 objects)

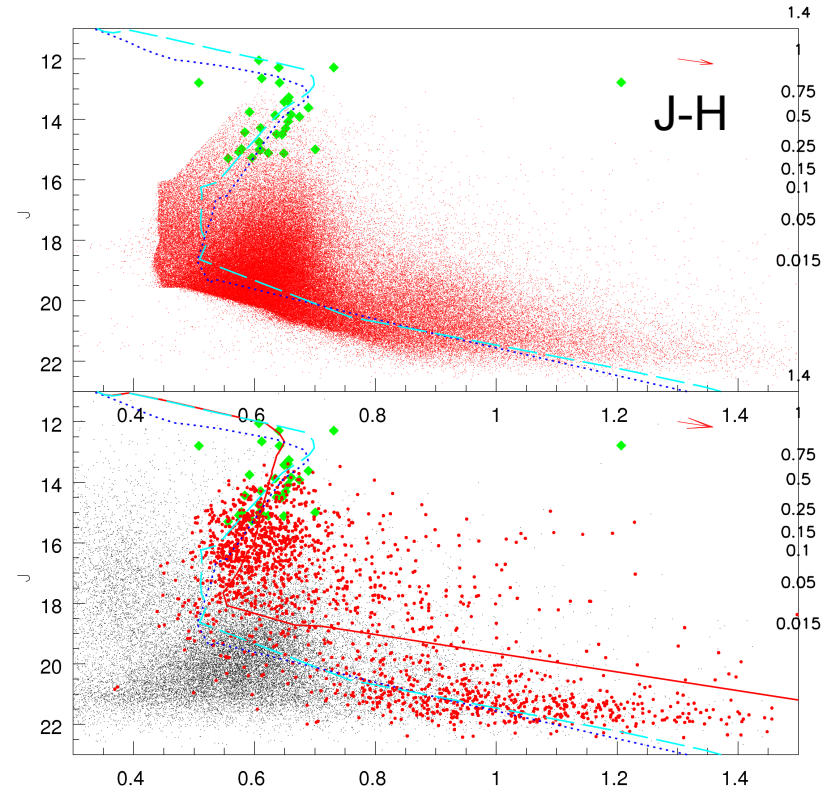
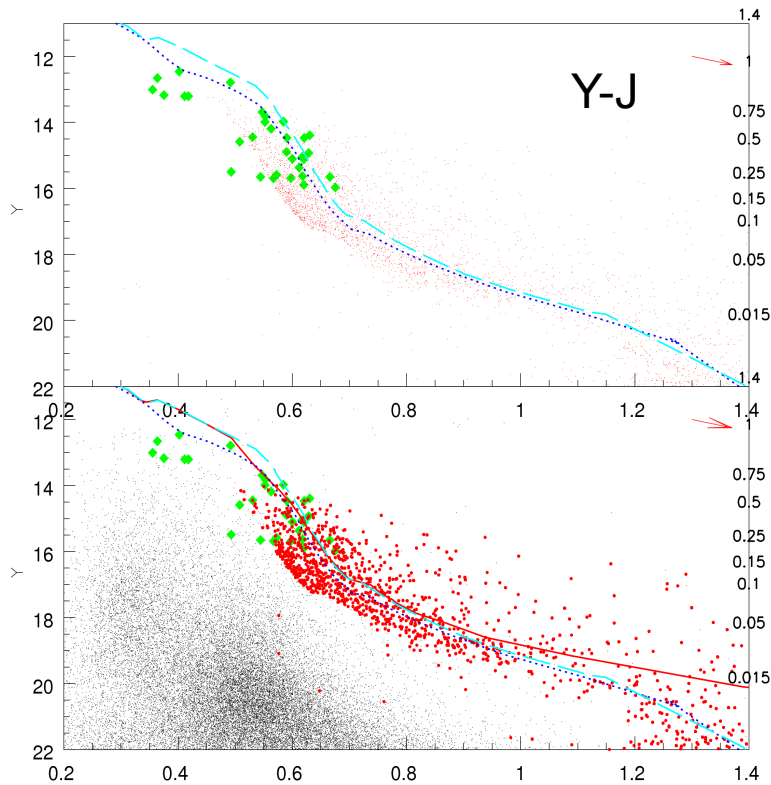
Field	Identifier	RA	DEC	Y	Yerr	J	Jerr	H	Herr	K	Kerr
				/ mag	/ mag	/ mag	/ mag	/ mag	/ mag	/ mag	/ mag
D	168841111	266.46933	5.47968	20.131	0.141	18.974	0.141	18.327	0.141	17.818	0.142
B	6280000	266.82553	5.31048	17.305	0.141	16.309	0.140	15.811	0.140	15.207	0.140
A	8280000	266.75516	5.65025	19.200	0.148	18.138	0.144	17.493	0.144	17.059	0.140
...



CMD Selection - 2278



Top: one field one colour (Y-J); bottom all fields all colours (J-H)



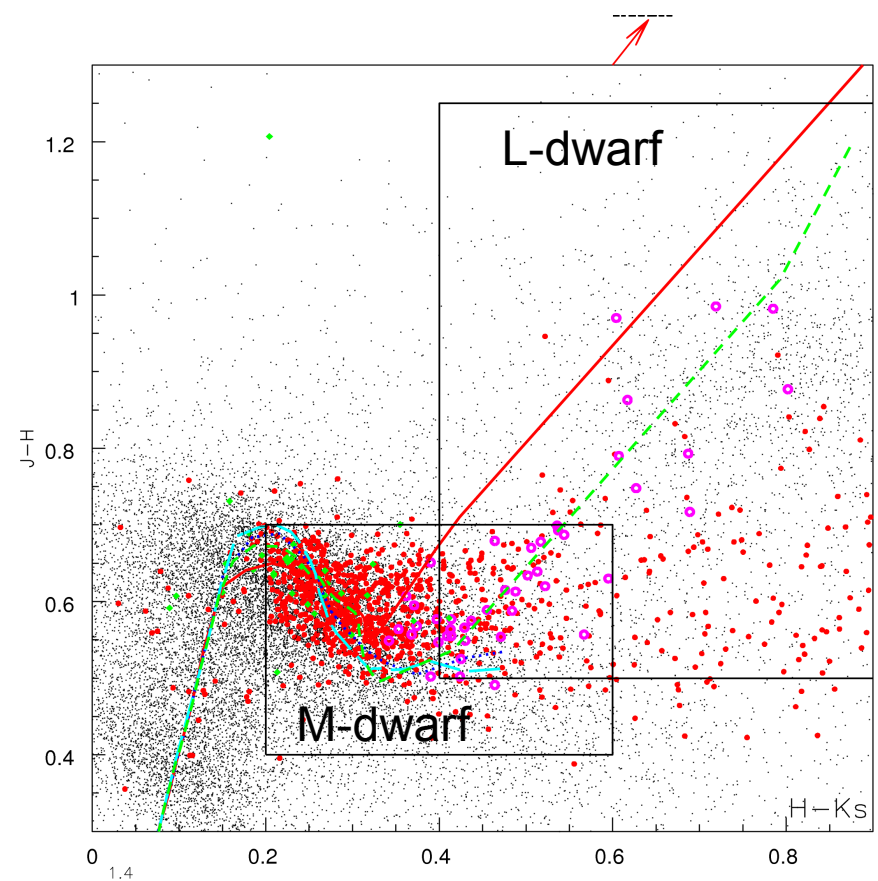
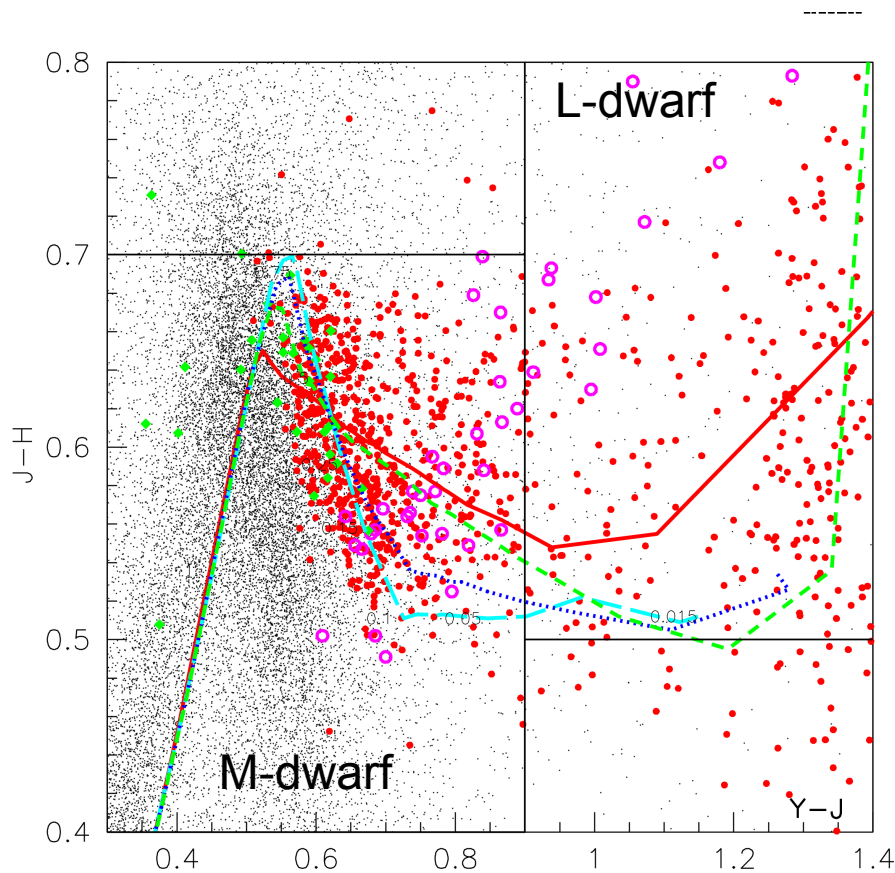
— 30Myr BTDUSTY
 — 30Myr BTSETTL
 50Myr BTSETTL

• IC 4665 Candidates
 ◆ Manzi et al 2008 R.V. members=Y



COLD Selection - 1163

Possible discrepancy wrt the Y-band in the theoretical models. Requires testing.



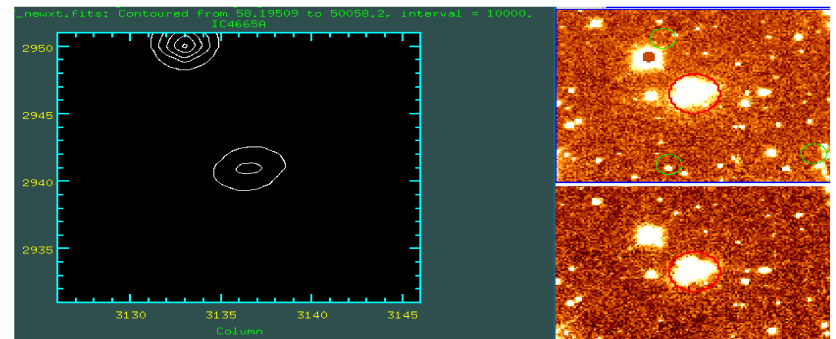
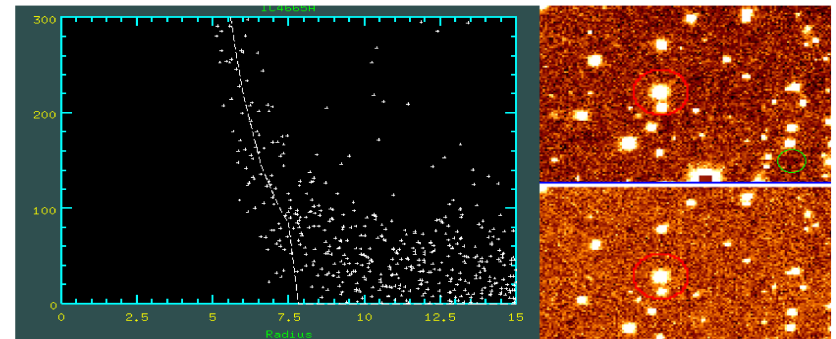
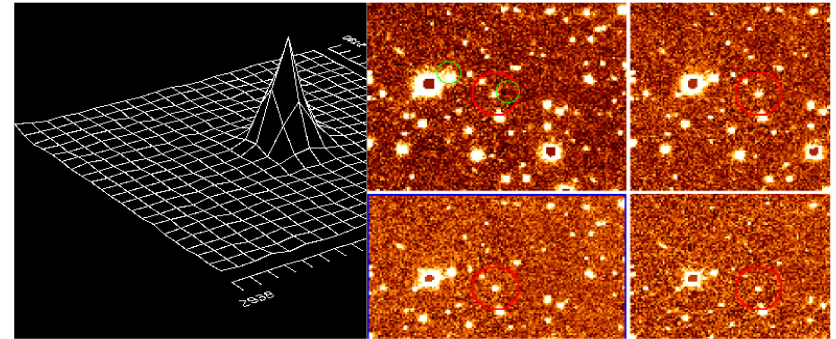
- 30Myr BTDUSTY
- 30Myr BTSETTL
- 50Myr BTSETTL
- - - 120Myr BTSETTL
- IC 4665 Candidates
- ◆ Manzi et al 2008 R.V. members=Y
- Bihan et al 2010 PLEIADES(UKIDSS)

Regions: Hewett et al '06



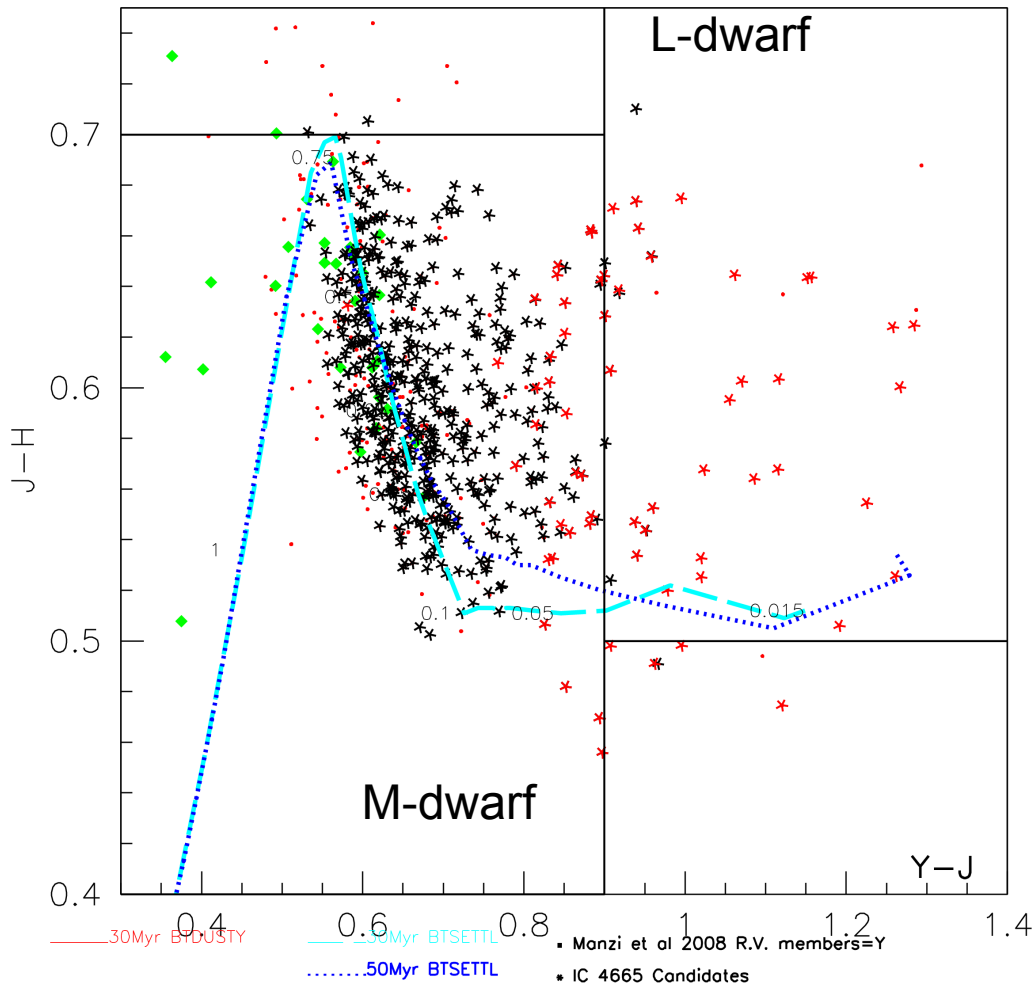
Visual Inspection

- Filtering to 590:
 - PSF FWHM < 5.0 pix
 - Completeness
 - No sat/IMA flags
 - No duplicates
 - Visually inspected with these criteria
- 510 'OK'





Spectral Type



- Empirical selection (Hewett+2006)
 - YJ/JH and JH/HK empirical locations
 - 63 L, 485 M-dwarf 'OK'
 -



Conclusions:

IC 4665: Detection of candidate members down to the L-dwarf regime.

Work in Progress.

- Empirical candidate selection and model testing also required
- Contamination (at least 20% from control field analysis), further spectral type analysis, IMF, *Spitzer* data, spectroscopy
- Collaboration (Selection and UKIDSS), with N. Lodieu from the IAC.



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IC 348



Image: Adam Block and Tim Puckett



IC 348 Overview

Aim to constrain the low-mass IMF e.g.

- **ONC:** 15 low-mass objects $\sim 8-15M_J$ (Lucas et al. 2001)
- **σ Ori:** 7 objects $\sim 6-8M_J$; Power law IMF
 $110-6M_J$ with $x=-0.4\pm 0.2$ (Caballero et al. 2007)
- One T-dwarf (T6) - S Ori 70 (Zapatero Osorio et al. 2002, 2008)

Search for young and low-mass objects

- Masses \sim few M_{Jup}
- Nearby star forming region IC 348



IC 348

Clustered star forming region

- $03^{\text{h}}44^{\text{m}}34^{\text{s}} +32^{\circ}09'8''$ (J2000) in Perseus
- 300+/-15pc, ~40pc in front of Per OB2 association
- ~1-3Myr, low proper motion; $\sim 2 < A_V < 20$ mags
- IMF complete to $\sim 35M_J$ (though for $A_V < 4$ mag)
- **WIRCam IR survey to find the lowest mass objects**

Cernis 1993, Herbig 1998, Herbst 2008, Luhman et al. 2003, Muench et al. 2003, Scholz et al. 1999.



Observations

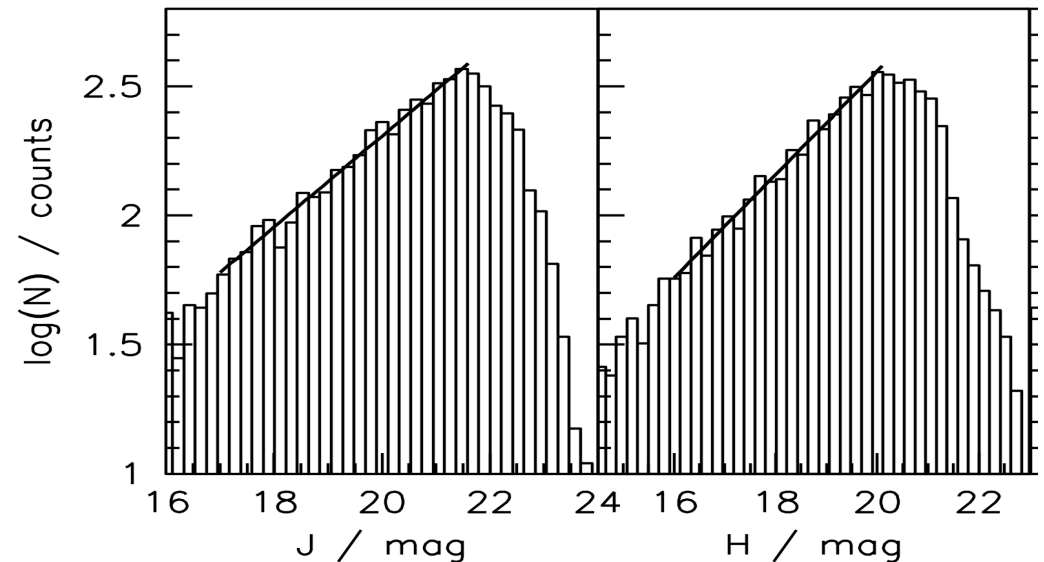
CFHT

WIRCam

- CH₄ on/off narrowbands
- J, H, K bands
- Depth ~H~20mag

MegaCam

- z' band
- Depth ~z'~24mag



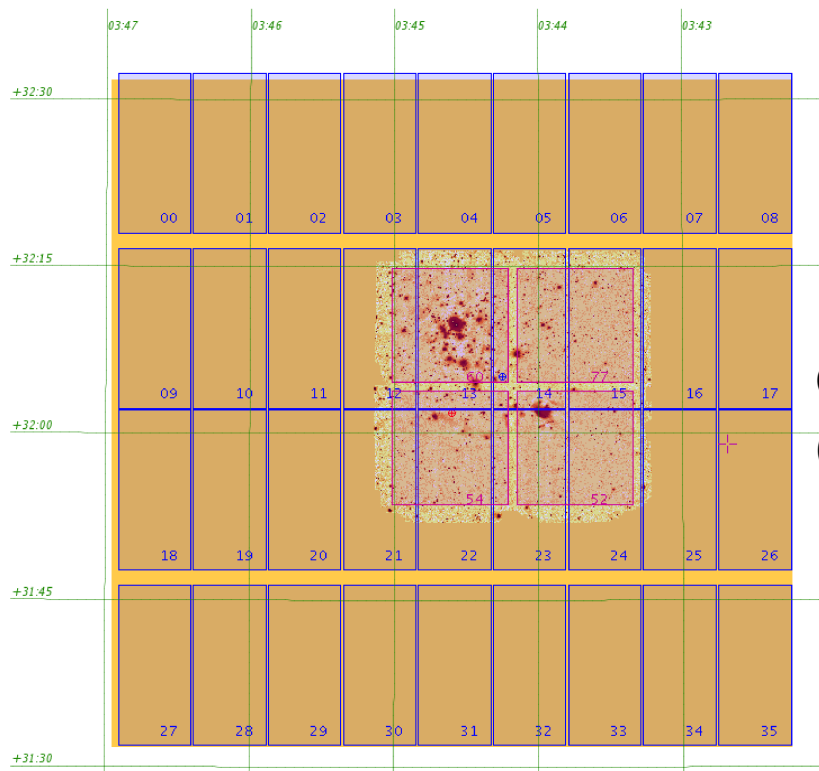
Thibault et al. 2003, Boulade et al. 2003



Field of View

Telescope	FOV	Filter	Integration time (h)	Pointing coordinates (J2000)
MegaCam	$0.96^\circ \times 0.94^\circ$	z'	2.5	$03^{\text{h}}44^{\text{m}}36^{\text{s}}.00 +32^\circ 01' 50'' 0$
WIRCam	$20' \times 20'$	CH_4 off, on	3.7, 1.4	$03^{\text{h}}44^{\text{m}}14^{\text{s}}.80 +32^\circ 05' 06'' 0$
WIRCam	$20' \times 20'$	J, H, K_s	0.35, 0.16, 0.12	

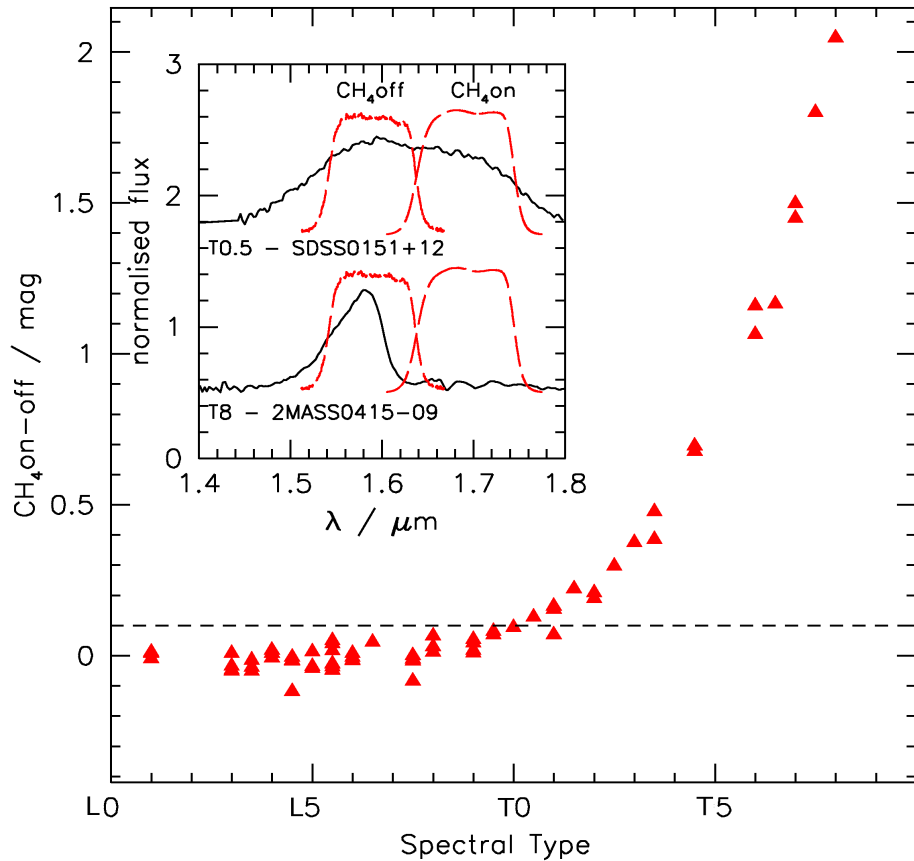
A	$03^{\text{h}}44^{\text{m}}14^{\text{s}}.80 +32^\circ 05' 06'' 0$
B	$03^{\text{h}}44^{\text{m}}14^{\text{s}}.80 +32^\circ 15' 06'' 0$
C	$03^{\text{h}}45^{\text{m}}02^{\text{s}}.00 +32^\circ 05' 06'' 0$
D	$03^{\text{h}}45^{\text{m}}02^{\text{s}}.00 +32^\circ 15' 06'' 0$



CH_4 Off WIRCam image
(used for detection base)



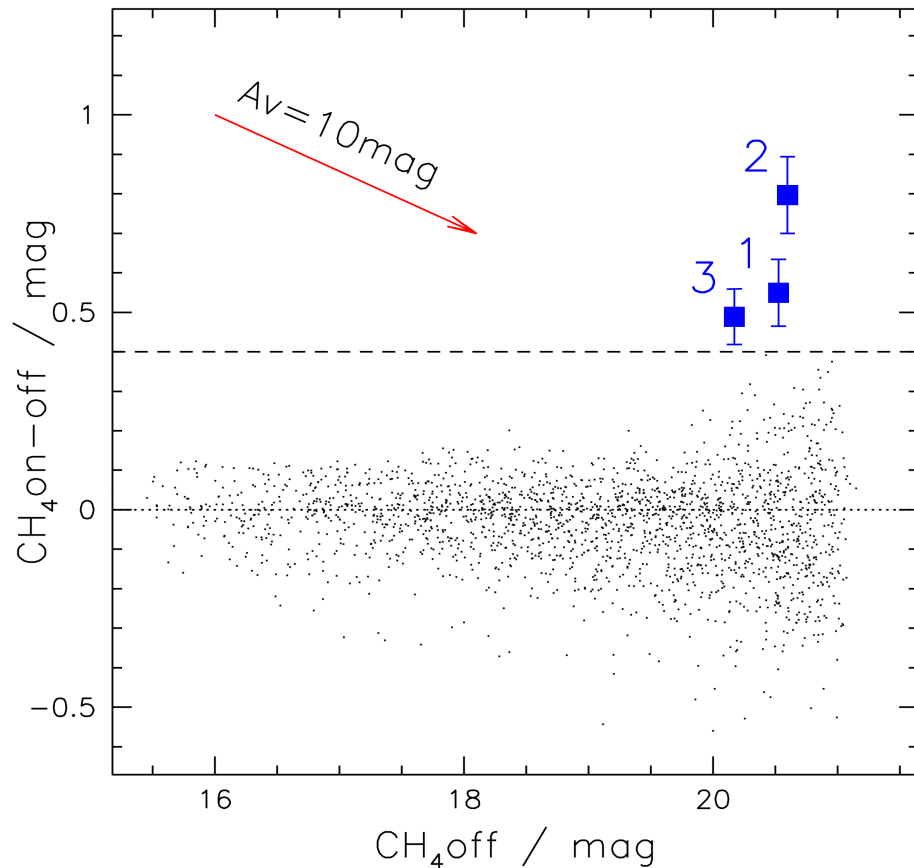
Methane



$\text{CH}_4\text{on-CH}_4\text{off}$ colour
($1.69\mu\text{m}-1.58\mu\text{m}$) vs SpT
L & T 5Gyr field dwarf
spectra - convolved
SpT latens with colour
e.g. T3 => $\sim 0.4\text{mag}$



T-Dwarf Selection



CH₄on-CH₄off vs CH₄off

Asymmetry from local reddening

0.4mag equates to a confidence of $\sim 3.5\sigma$

3 good candidates all above 4σ



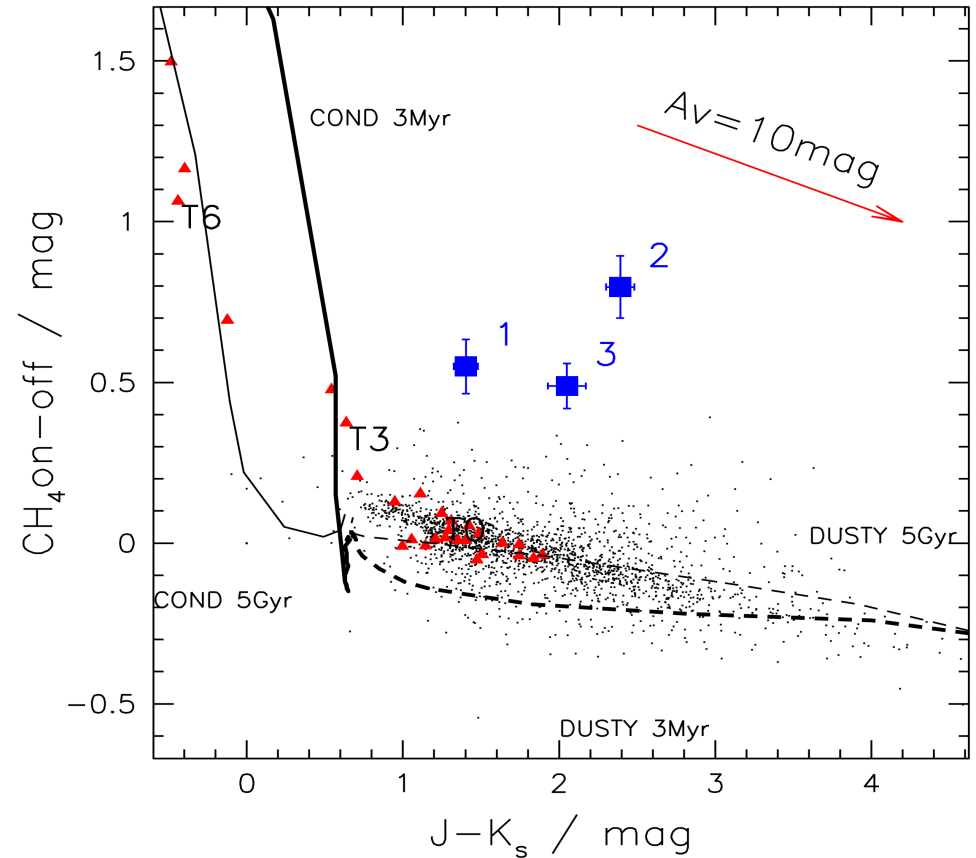
Extinction

Extinction vector

Dereddened to COND
3Myr model

SpT found from
dereddened colours

Candidates have SpT
T4-T7



Allard et al. 2001, Chabrier et al. 2000

SVO extinction co-efficients (svo.laeff.inta.es/theory/filters)



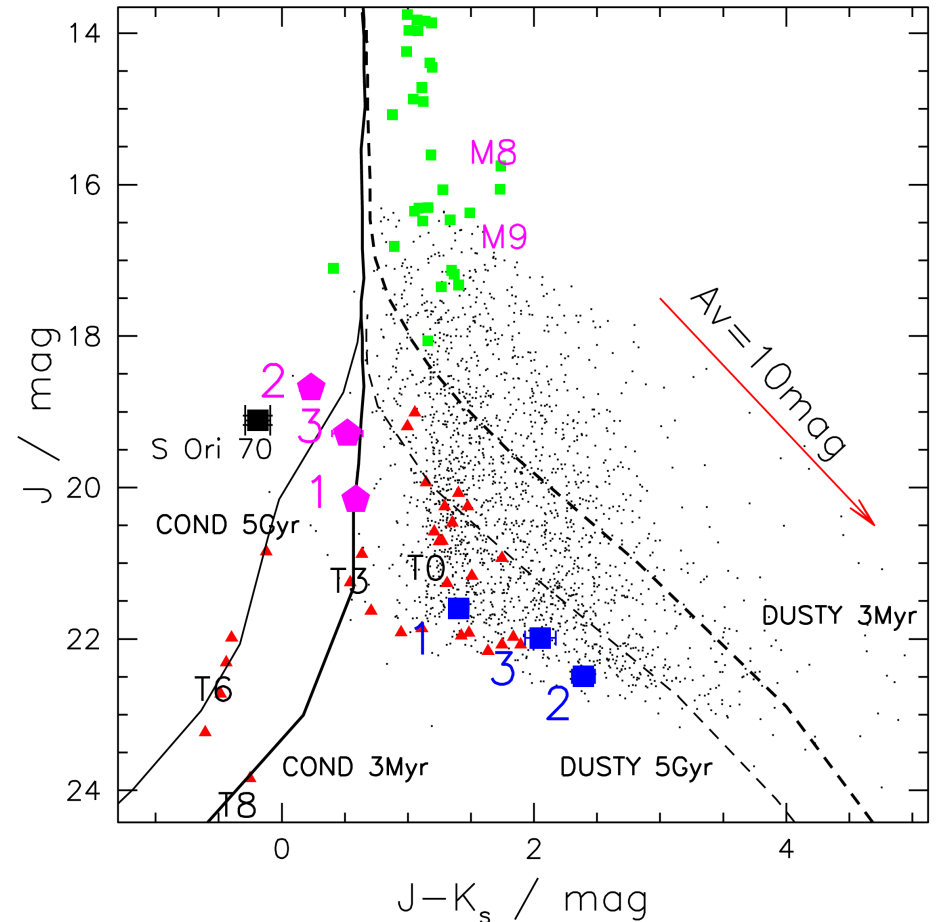
Three Candidates

Follows 3Myr model

Younger objects are brighter than field objects from larger radii

Comparison: \sim T6 S Ori 70, 1-8Myr, 350pc

IC348_CH4_2 close to S Ori 70



Luhman et al 2006, Zapatero Osorio et al. 2002, 2008.



Candidate Rejection

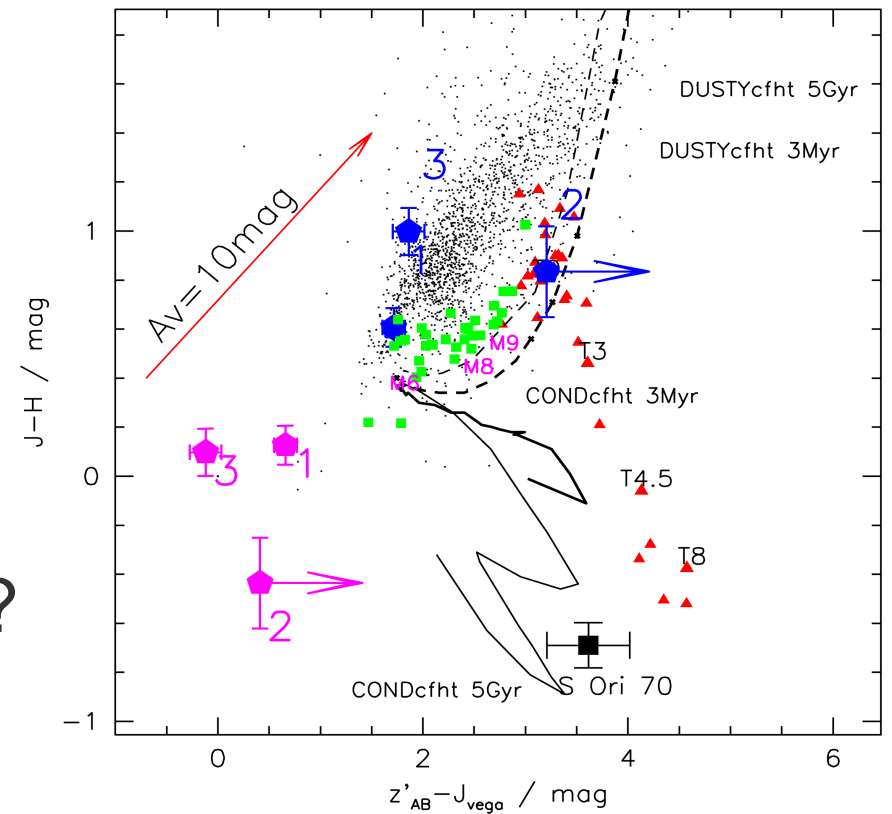
Inconsistent location

IC348_CH4_1 & 3 rejected

Far too blue in $z'-J$

IC348_CH4_2 upper limit

Identity unknown for rejected candidates – cool sub-dwarfs?



Luhman et al 2006, Zapatero Osorio et al. 2002, 2008.



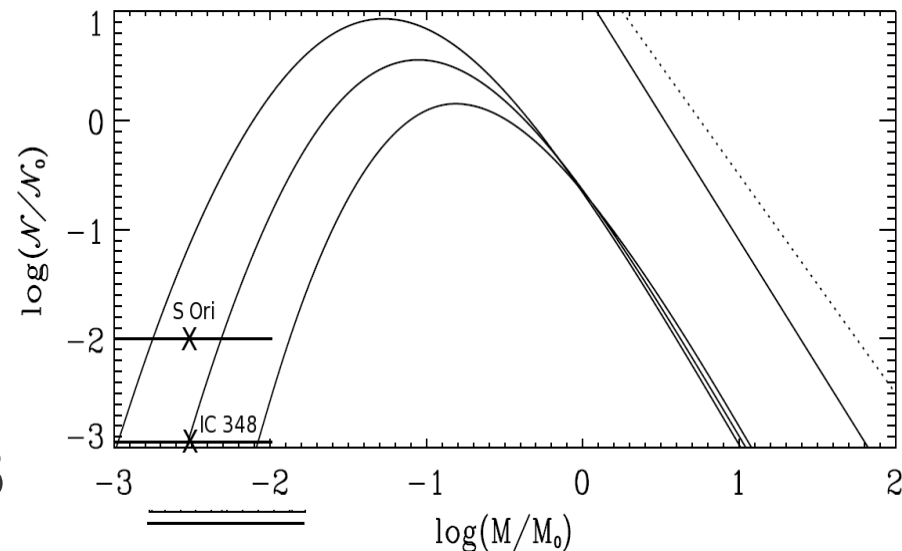
Membership

- Remaining candidate is very close to the core (4')
- Extinction ~ 12 mag consistent with membership rather than field
- Dereddened object brighter than field objects
- Statistically expect < 1 foreground field T3-T5.5 dwarfs in our FOV (Metchev et al. 2008)



IMF

- One candidate with mass estimated $<7M_J$ ($\pm 50\%$)
- ~ 420 members in IC 348
- Log-normal IMF extrapolated to $1-10M_J$ (1.6-4 expected)
- 10x fewer objects in this mass bin when compared to σ Ori
- This candidate is consistent with log-normal extrapolation to low mass domain for IC 348



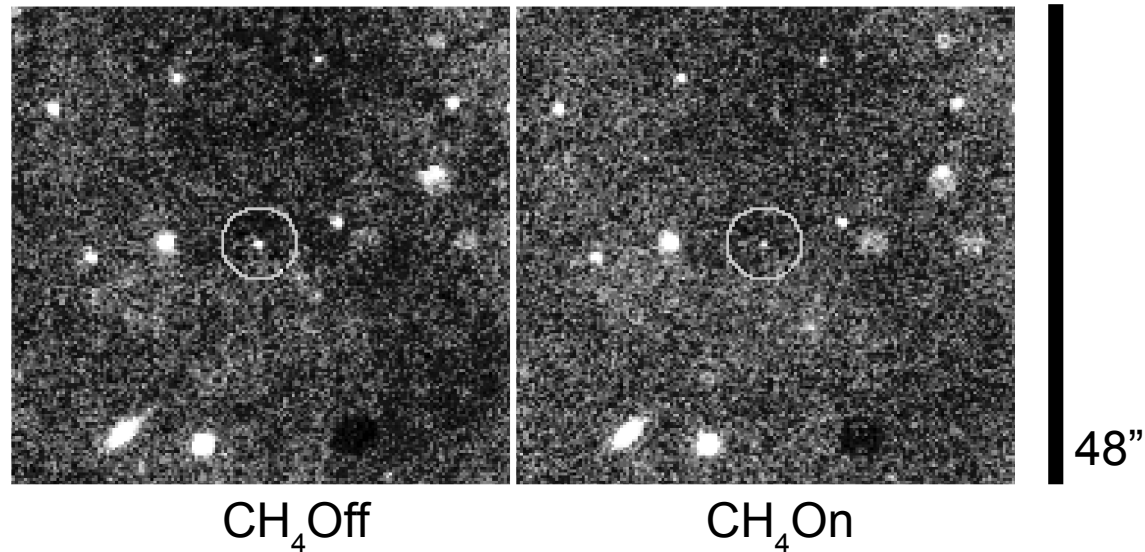
Hennebelle & Chabrier 2009



IC 348 Summary

“Young T-Dwarf Candidates in IC 348” published: Burgess et al. 2009 (2009A&A...508..823)

- Three objects based on methane colours detected
- Two rejected by too blue z'-J colours – unknown ident
- One very likely a member of IC 348 and consistent for a 3Myr old, ~T6 Dwarf
- Among lowest-mass T-dwarf detected so far





Conclusions:

One good T6 candidate: supports the extrapolation of the log-normal IMF to a few M_J

Supports variations of the low mass end of the IMF, e.g. σ Ori with 10x more objects

- Spectroscopy of all three candidates
- Ascertain identity of 2 rejected – cool subdwarfs?
- Full census using zJHK data to extend confirmed IMF to masses $< 30M_J$



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How does this work fit in with current scientific understanding?

T6 dwarf possibly formed in isolation

Helped constrain the lower mass IMF:

One object (IC 348) v.s. ~ 10 objects (σ Ori)

Requires more clusters for wider picture

Information on initial conditions – cloud state

Simulations/models v.s. Observations:

e.g. Y-band discrepancy





Advantages

- Constellation Network
 - Schools
 - International Conferences
 - Presenting work
 - Networking
 - Languages
 - Friends





Questions



Wednesday, 15th December 2010

Andrew Burgess

Ph.D. Defense
LAOG