Substellar Mass Objects in the Belt of Orion – What DECam Does For Us

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How do Substellar Mass Objects (SSMOs) Form?

- In isolation in small cores? (like stars)

- By premature ejection from multiple systems?

- In cores starved in dense environments?

And how we may be able to tell.

OB Associations and the Substellar IMF

- **OB associations**:
  - gravitationally-unbound
  - 1-10 Myr ages
  - Dominated by O and B stars
- **Most stars in the Galaxy have formed in OB associations** (rather than T associations or small clusters).
- The dust and gas are largely dispersed, due to OB star radiation fields, winds, and the occasional supernova.
- Small, slowly-collapsing cores may have been disrupted; their envelopes dispersed.
- Accretion is over: all stars have attained their final masses. There is little chance that an SSMO will accrete enough mass to become a star.

Observing the Substellar IMF
in OB Associations

- Extinctions are low.
- All members are visible and are distinct from the field.
- Members are still spatially concentrated, and can be readily identified.
- Few stars retain optically thick circumstellar disks: colors are generally photospheric.
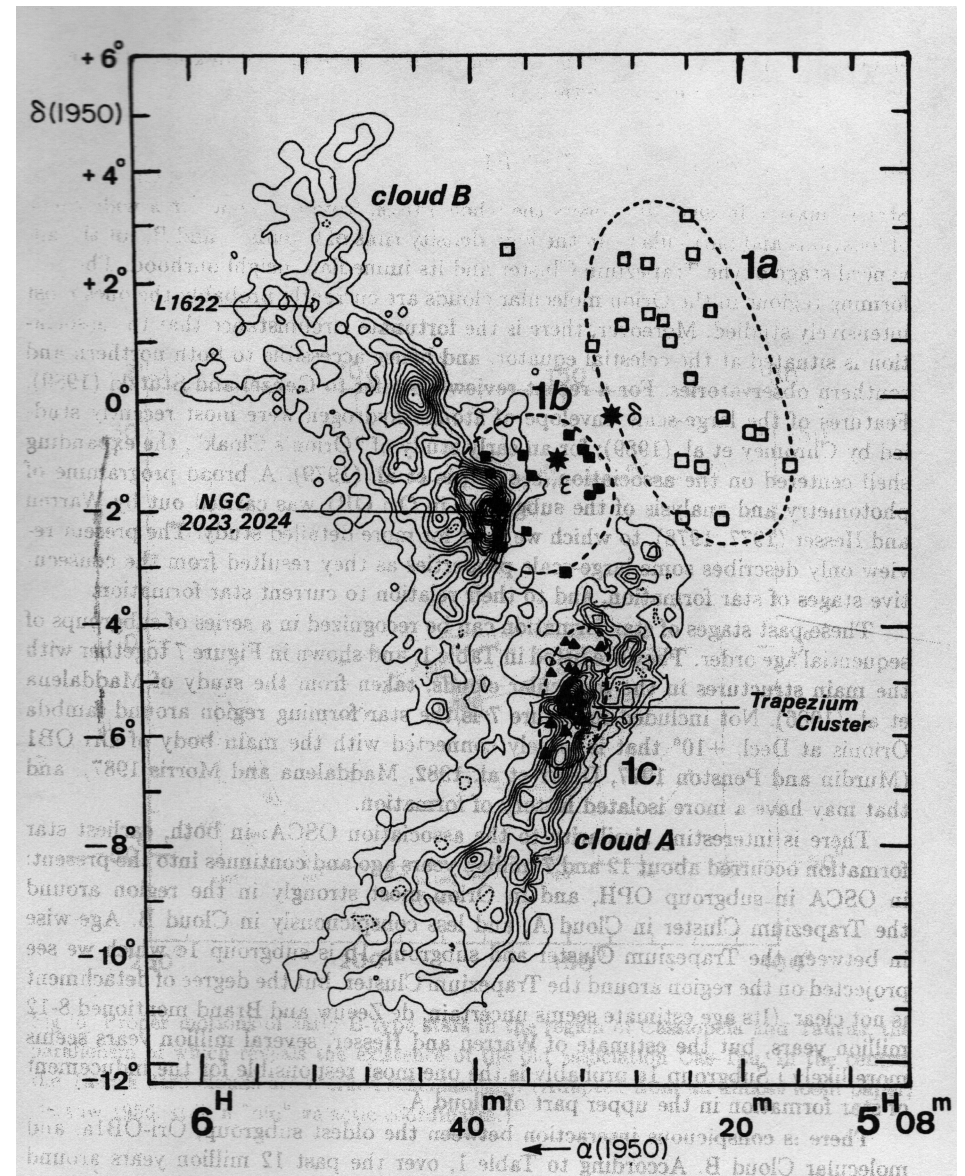
  The stars are nearly coeval.
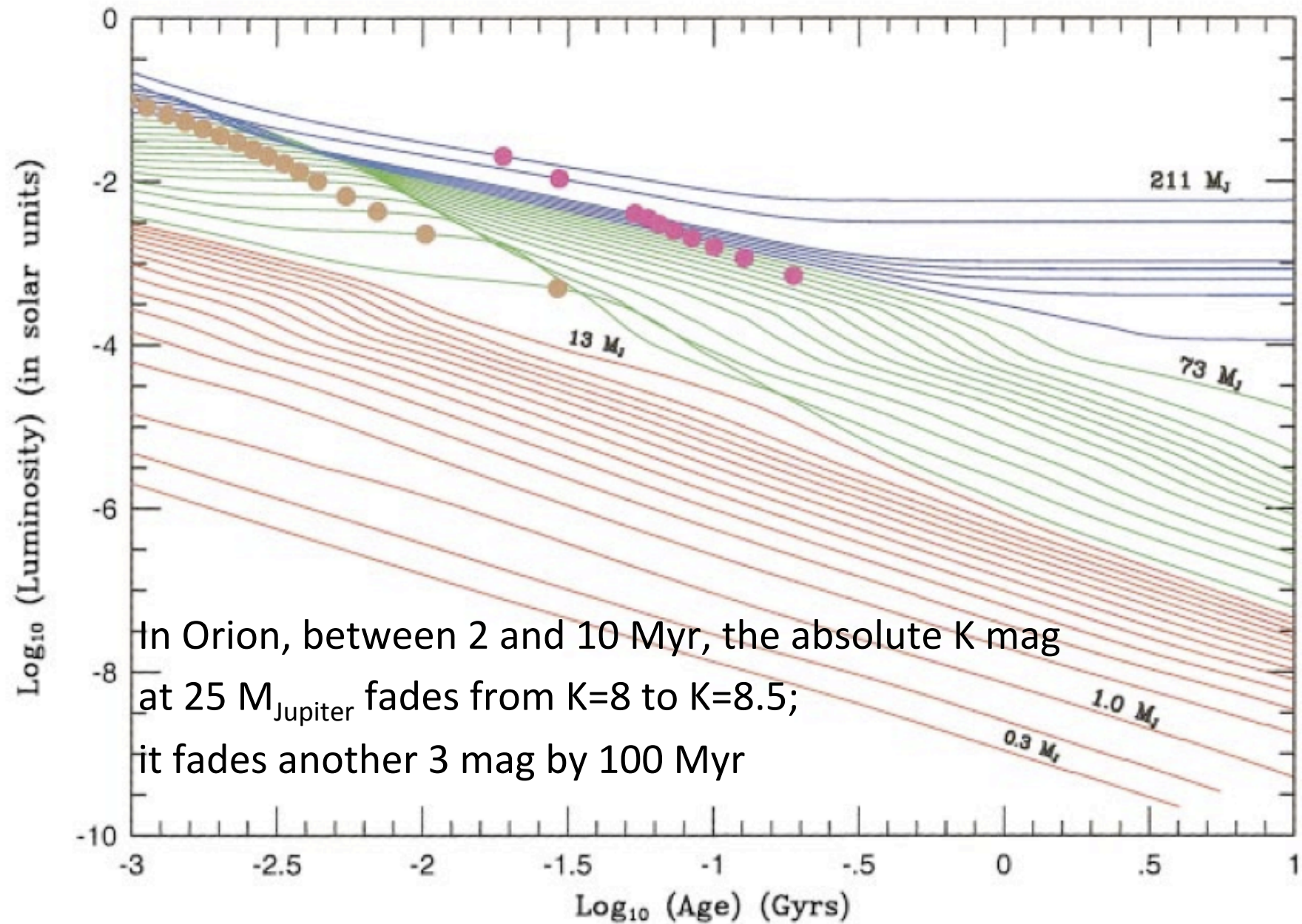 - Differences in absolute ages of order 1 Myr are of much less consequence at 10 Myr than at 1 Myr.

Orion OB1

- The largest nearby OB association
  - ℓ, b ~ 200,-15

- **Ori OB1d**: the Orion Nebula Cluster
  - <1 Myr; 420 pc
- **Ori OB1b**: the Belt
  - 2-5 Myr, 420 pc
- **Ori OB1a, c**
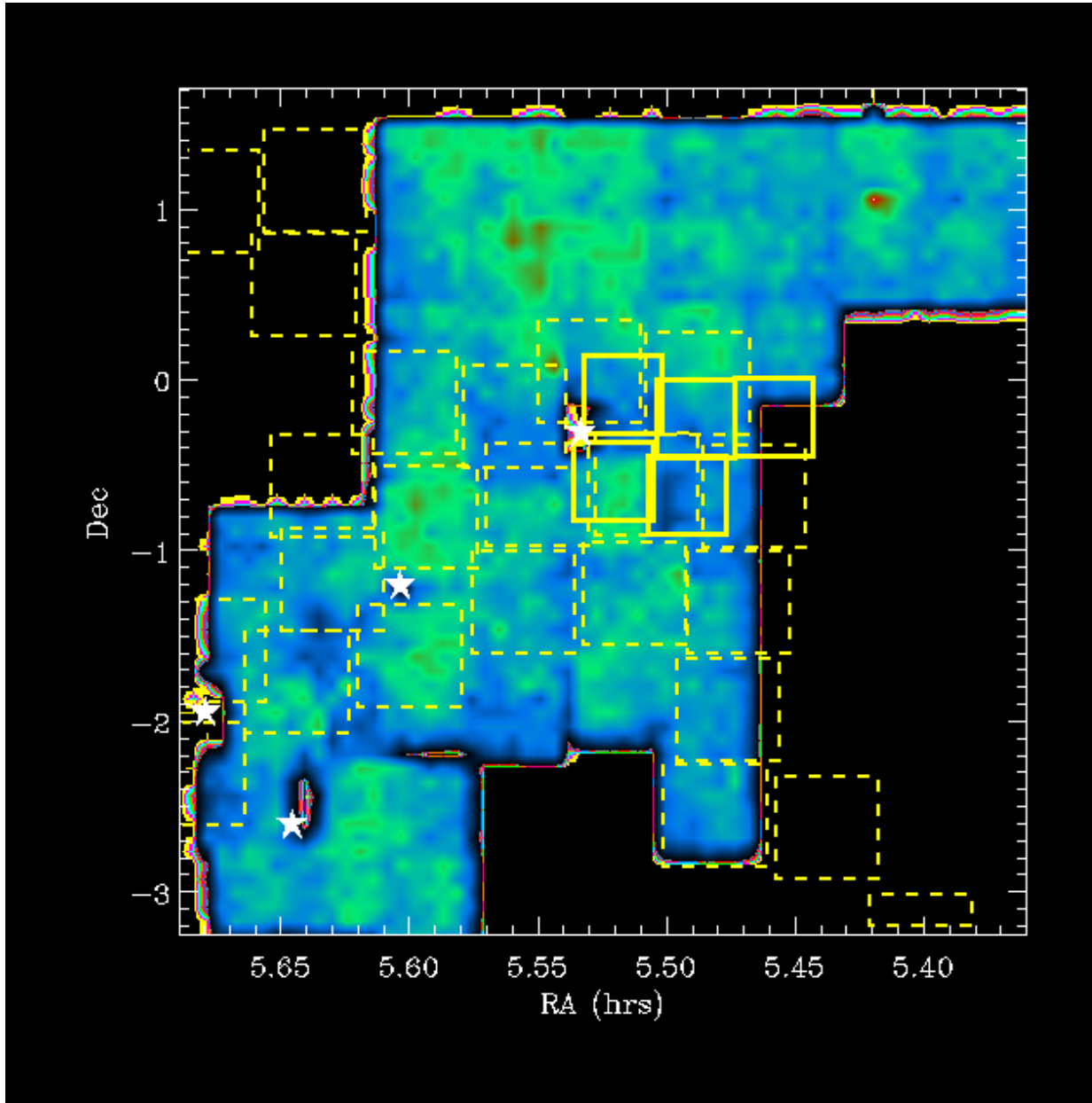 - 10 Myr, 350 pc
  - OB1a: δ>0; OB1c: δ<0

(OB1 Kenobi is in a galaxy far, far away)

Source: Blaauw 1990

Burrows et al.: Theory of brown dwarfs

In Orion, between 2 and 10 Myr, the absolute K mag at 25 M$_{Jupiter}$ fades from K=8 to K=8.5; it fades another 3 mag by 100 Myr

CPAPIR Coverage

Camera Panoramique Proche InfraRouge

Built at Universit'e de Montreal

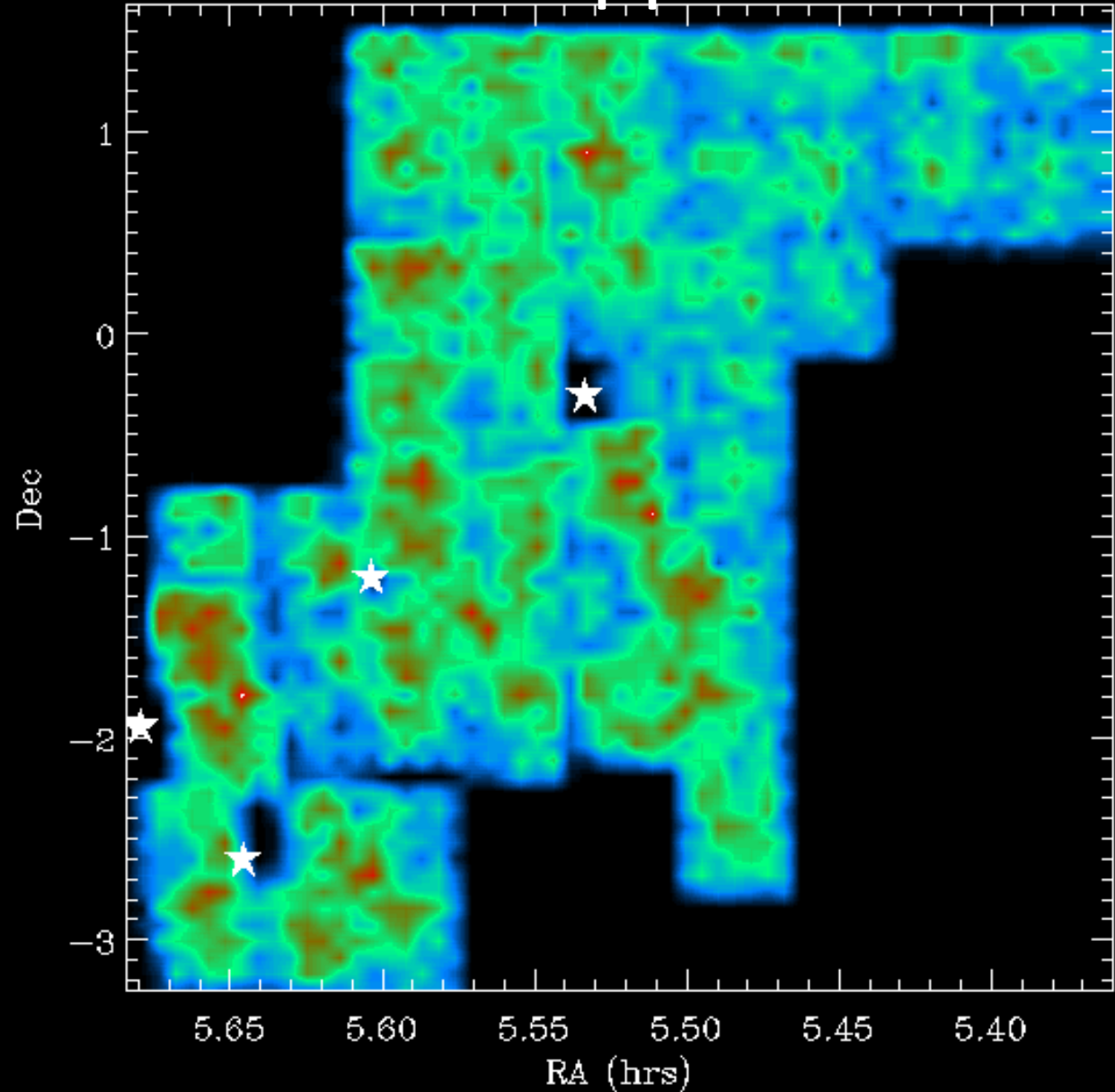Formerly mounted on SMARTS/CTIO 1.5m

2048^2 Hawaii II
0.9 "/pix
30' FoV

Numbers

- 146,905: JHK_s sources in 13 deg^2 from CPAPIR

- 14.4: K_s mag at BD limit in Ori OB1b

- 7,838: CPAPIR sources with

    15.5 > K_s >14.4, 0.8< J-K <1.2

- 4000: estimated background/foreground contamination from background fields

- **4000**: net number of SSMOs in survey region
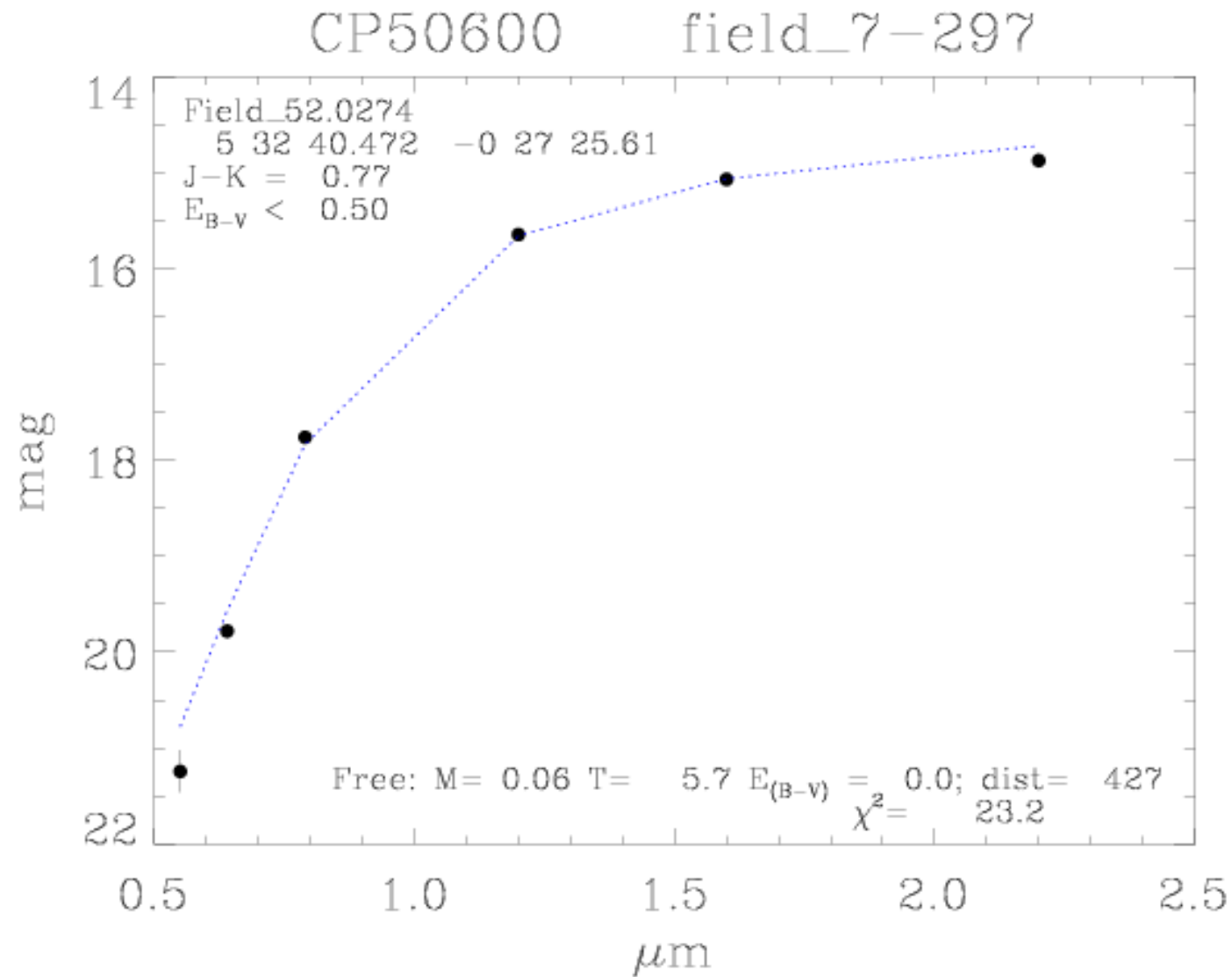
CPAPIR with cuts applied

0.7 < *J-K* < 1.2

K > 14.4

4000 SSMOs? Really?

- Surface density map suggests densities up to $1000/\text{deg}^2$ in places

- This suggests the star:BD ratio in Ori OB1 is closer to 1 than the 4 seen in T associations and young groups

OK - let's confirm

Photometric Corroboration

CP50600   field_7-297

Field_52.0274
  5 32 40.472   -0 27 25.61
J-K =   0.77
E_{B-V} <   0.50

Free: M= 0.06 T=   5.7 $E_{(B-V)}$ =   0.0; dist=   427
                                    χ^2 =   23.2

Spectroscopic Confirmation

nIR spectra from:

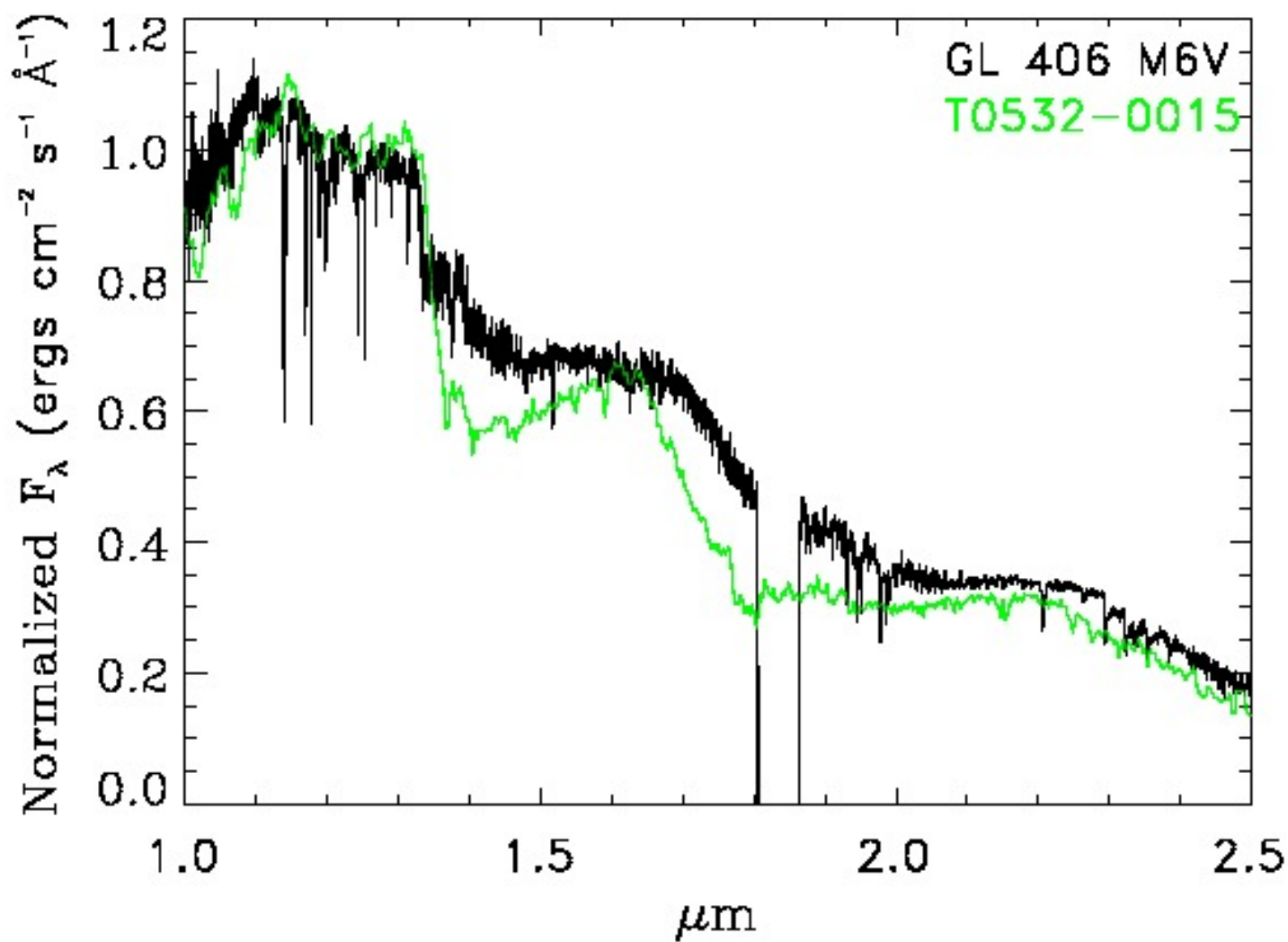- IRTF Spex

- Palomar TripleSpec

- SOAR OSIRIS

Signatures of youth (or at least low gravity):

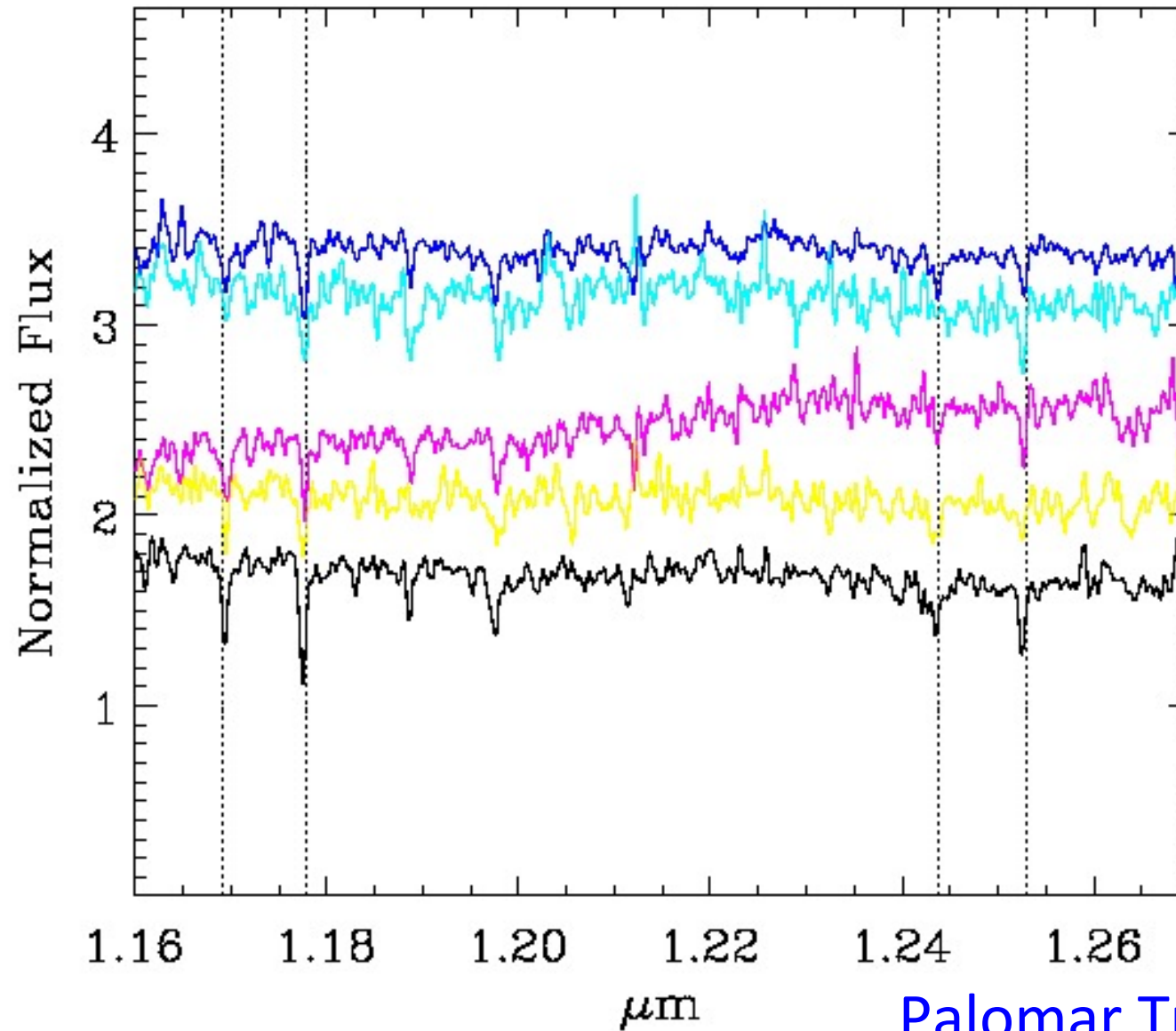- Triangular H bands

- Narrow alkali lines

Triangular H band
indicative of low g, or youth

Narrow Gravity-sensitive Alkali Lines

Palomar TripleSpec

Spectroscopic Confirmation

13 of 19 spectroscopic targets have

- Triangular H bands
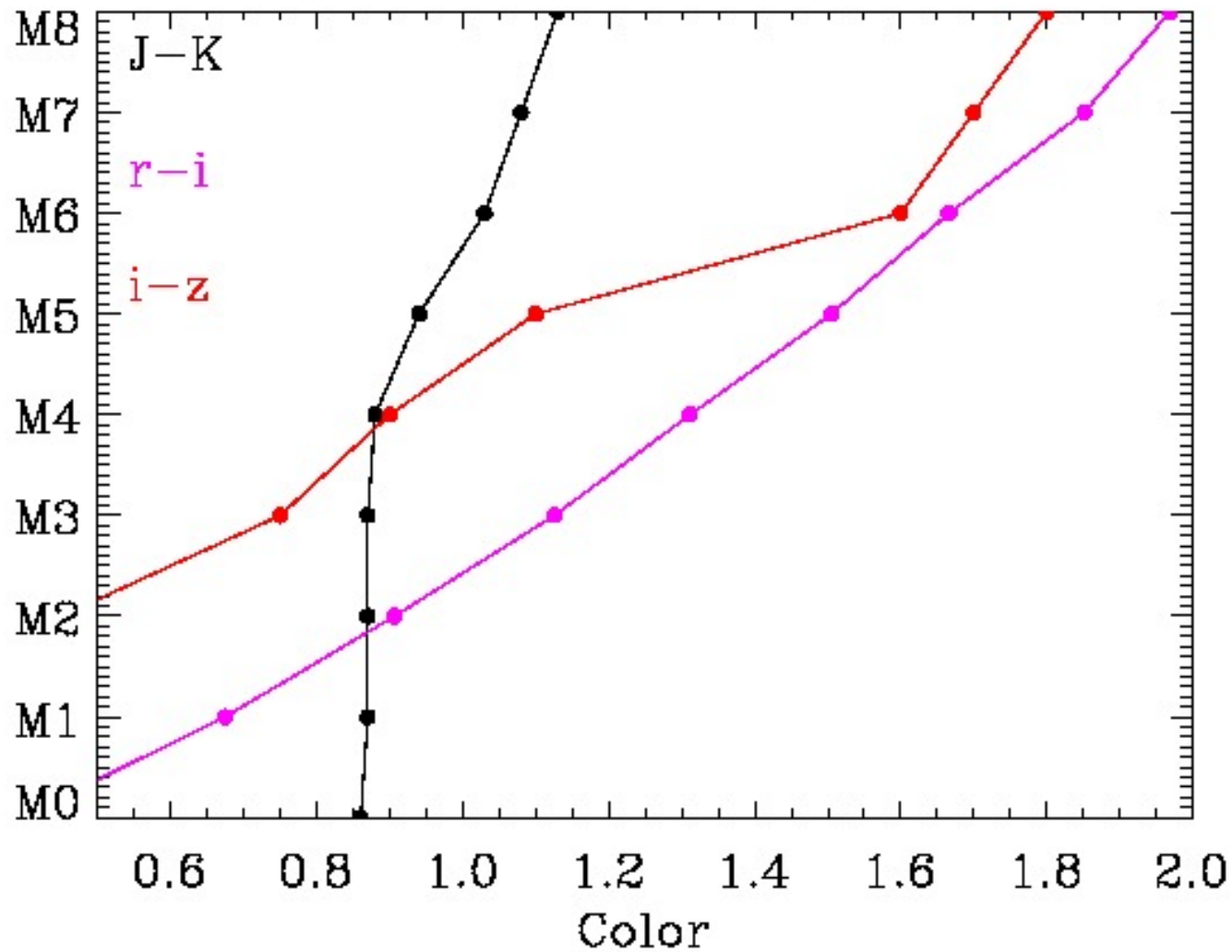- Alkali line indices (Aller & Liu 2013) consistent with low gravity

Not so fast...

At 2-5 Myr:

- SSMOs have M6-M7 spectral types

- All foreground M dwarfs have ~ same *J-K* color

- Late M PMS stars (foreground OB1a members) are low gravity

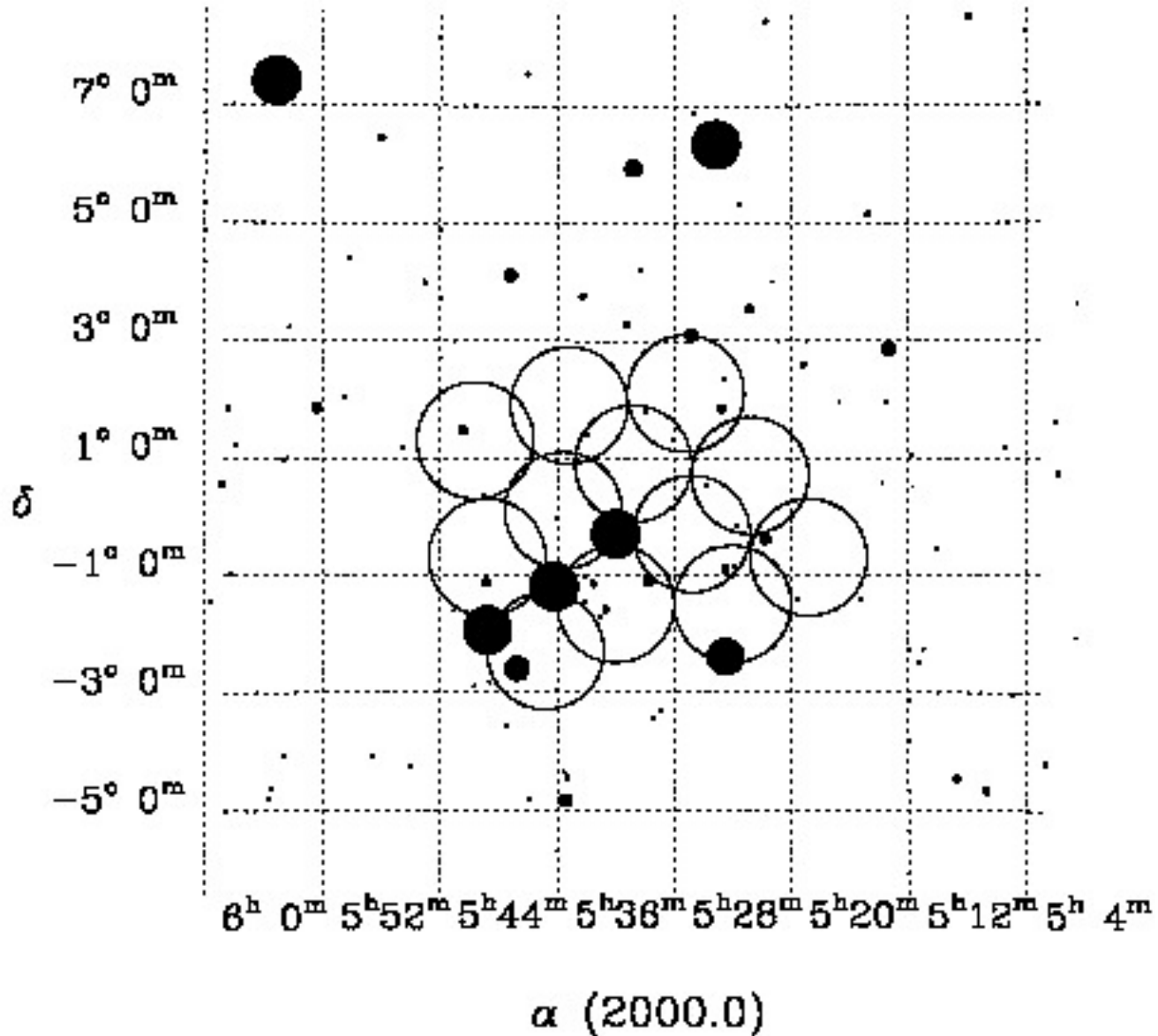**What is the foreground M star contamination?**

Why Go to the Optical?

DECam Observing Strategy

- *grizY*, 4 point dither, 10 seconds per pointing
- Repeat, 100 sec/pointing
- Tile region to avoid the bright stars of the belt
- 12 fields observed; ~ 35 deg^2
- SDSS standard fields every 1-2 hours

Where We Observed

Big Data!

900 Gb of compressed processed data

- /dev/sda3   1917666416 1353737844 466510128 75% /
- tmpfs   1990236   228 1990008   1% /dev/shm
- /dev/sda1   999320   120488   826404 13% /boot
- /dev/sdc1   1922728752 1684710904 140342176 93% /data1
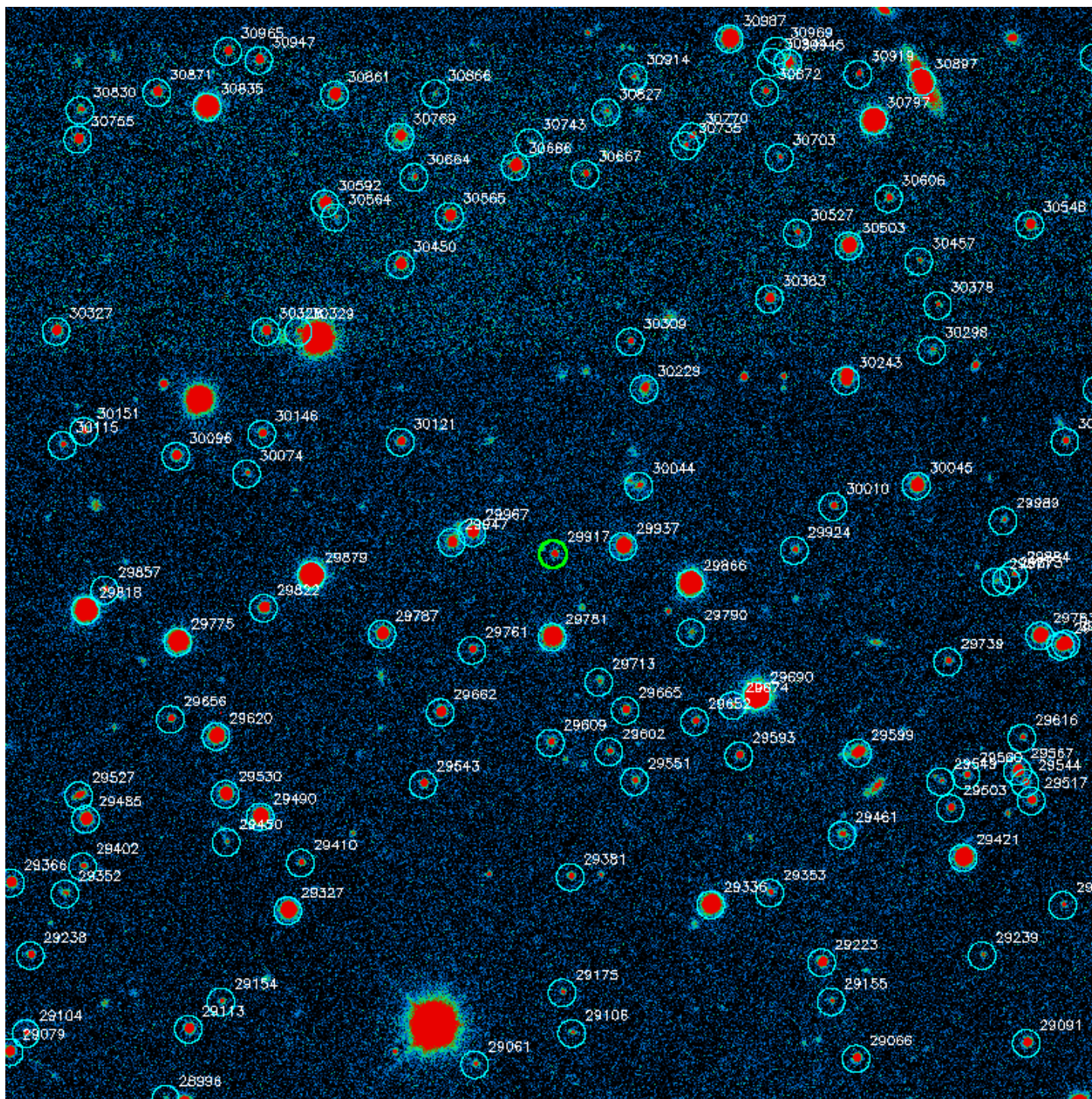- /dev/sdb1   1922727280 1714425436 110626244 94% /data2

Current Reduction Plan

- Find targets in Σ of Stacked (osi) $i+z+Y$ images
- Use aperture photometry to measure count rates in individual InstCal frames
- Match sources in individual CCDs and by filter
- Measure known standards in standard fields in the same way to produce photometric solution
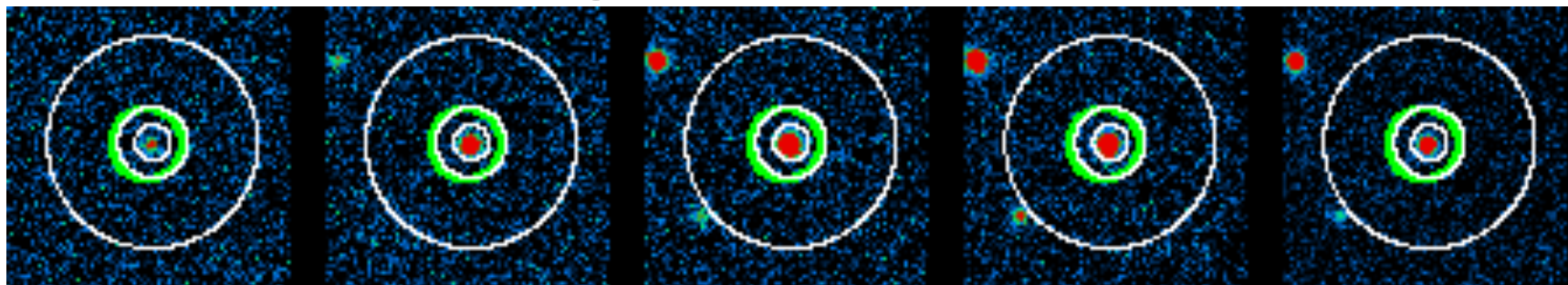- Make CMDs

800x800 subarray. Stacked *i*. 400 sec. Find with σ=6.

800x800 subarray. Stacked *i*. 400 sec. Find with σ=4.

Matching a random source

g   r   i   z   Y

Other sources within image:
    366611 -25.2 -20.3
    366715 -37.7 23.8

Pr_SListV: statistics for source   366666   FJ053753.927-022526.081
Tile position: tile22 4021.89 2531.35
FIND f,r,s: 2621.13 0.13 0.43

filt	cts	sigma	back	mag	flag
g	1648.1	3.0	3733.6	23.42	0
r	7445.1	13.0	4188.1	22.14	0
i	12058.1	22.0	3682.1	21.57	0
z	12213.8	24.4	3055.3	21.26	0
Y	5053.8	13.6	1698.4	21.06	0

Matching an interesting source

g   *r*   *i*   *z*   Y

Other sources within image:
    366666 37.7 -23.8 2621.1
    366824 -18.4 37.6 3003.7

Pr_SListV: statistics for source   366715   FJ053754.606-022519.664
Tile position: tile22 3984.21 2555.11
FIND f,r,s: 2112.84 0.08 0.44

filt	cts	sigma	back	mag	flag
g	113.5	0.2	3734.1	>24.64	0
r	1209.5	2.1	4190.2	24.11	0
i	6223.1	11.5	3683.4	22.29	0
z	10559.9	21.2	3057.5	21.42	0
Y	4860.2	13.1	1701.2	21.11	0

SSMO candidate!

g>21.5

r > 20

i > 18

r-i ~ 1.8 (M6)

Still Needed

- Photometric calibration
  - Await PS1 release?
- Efficient photometry and source matching algorithms
- Up-to-date photospheric models for objects near the planetary mass limit

What do we expect?

- Limiting magnitudes TBD, but crudely about 26th mag (from *magzpt* keyword)
  - SSMO limit = 21.5, 20, 18 in *g, r, i*
  - Planetary mass limit is in reach at *r, i, z, Y*

- Millions of stars; thousands of SSMOs
- An awesome IMF of Orion OB1a and Ori OB1b from 20 solar masses to 20 Jovian masses

Suggestions Welcome

- Thanks to
  - Kathy Vivas for hand-holding the first night,
  - Kathy and Frank Valdes for answering questions about the pipeline

- Collaborators on this program:
  - Jackie Faherty
  - Serena Kim
  - Bill Sherry