

Embedded Substellar Candidates and their Environments

Ultra-low Mass Star Formation Workshop

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Harvard-Smithsonian CfA



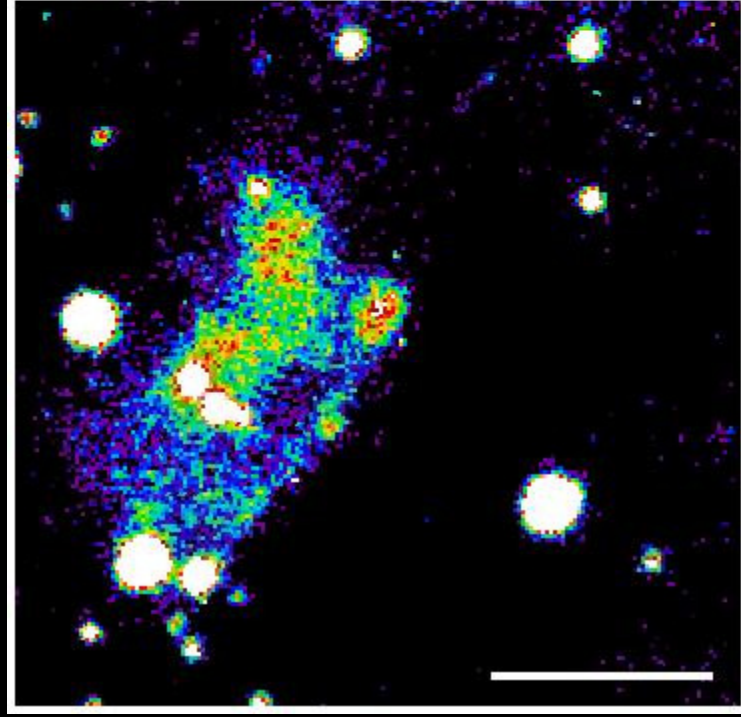
L1014-IRS

Angular extent of nebulosity detected strongly suggests that L1014-IRS is associated with L1014 at 200 pc

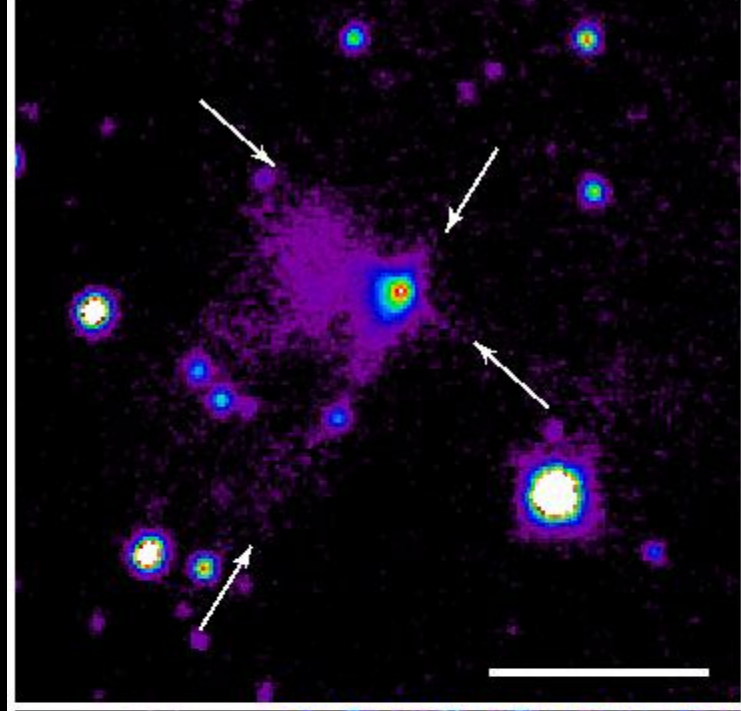
With luminosity of $0.025 - 0.050 L_{\text{sun}}$ and age of 10^5 years, L1014-IRS is consistent with having a mass of $20-25 M_{\text{Jupiter}}$

Chabrier et al. 2000

H Band



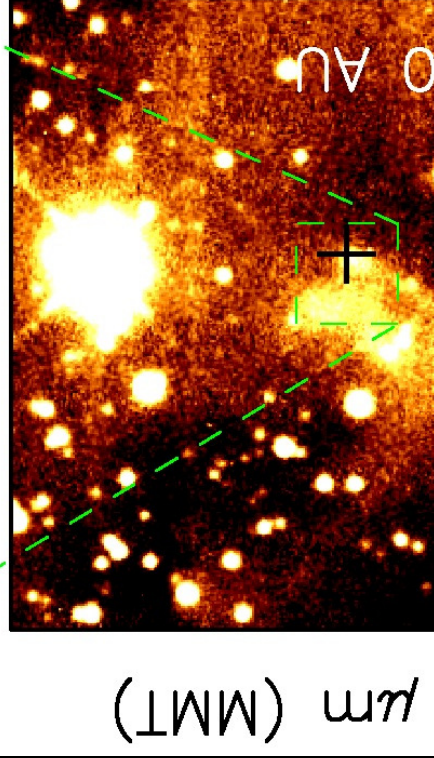
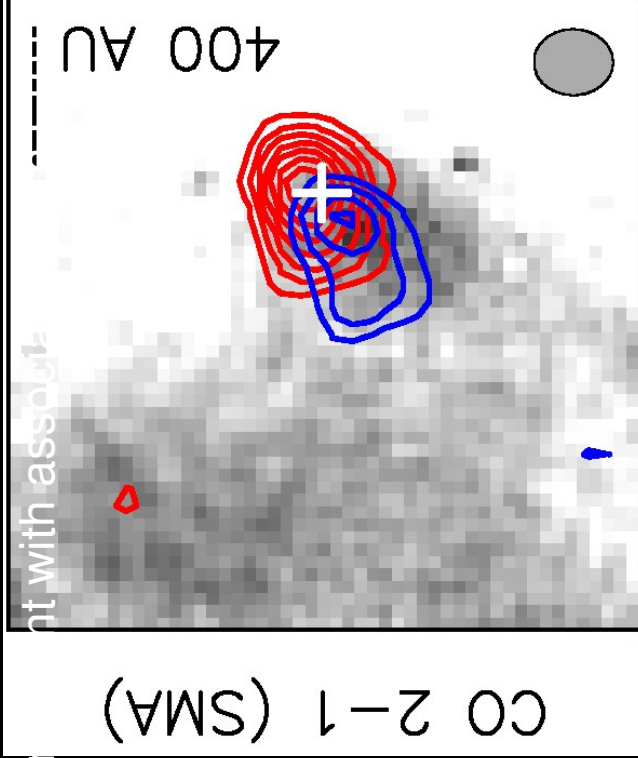
K Band



Huard et al. (in prep.)

L1014-IRS

CO outflow detected with orientation similar to near-IR nebulosity,
and Vlsr cor



sun and age of 10^5 years,
ing a mass of 20-25 M_{Jupiter}

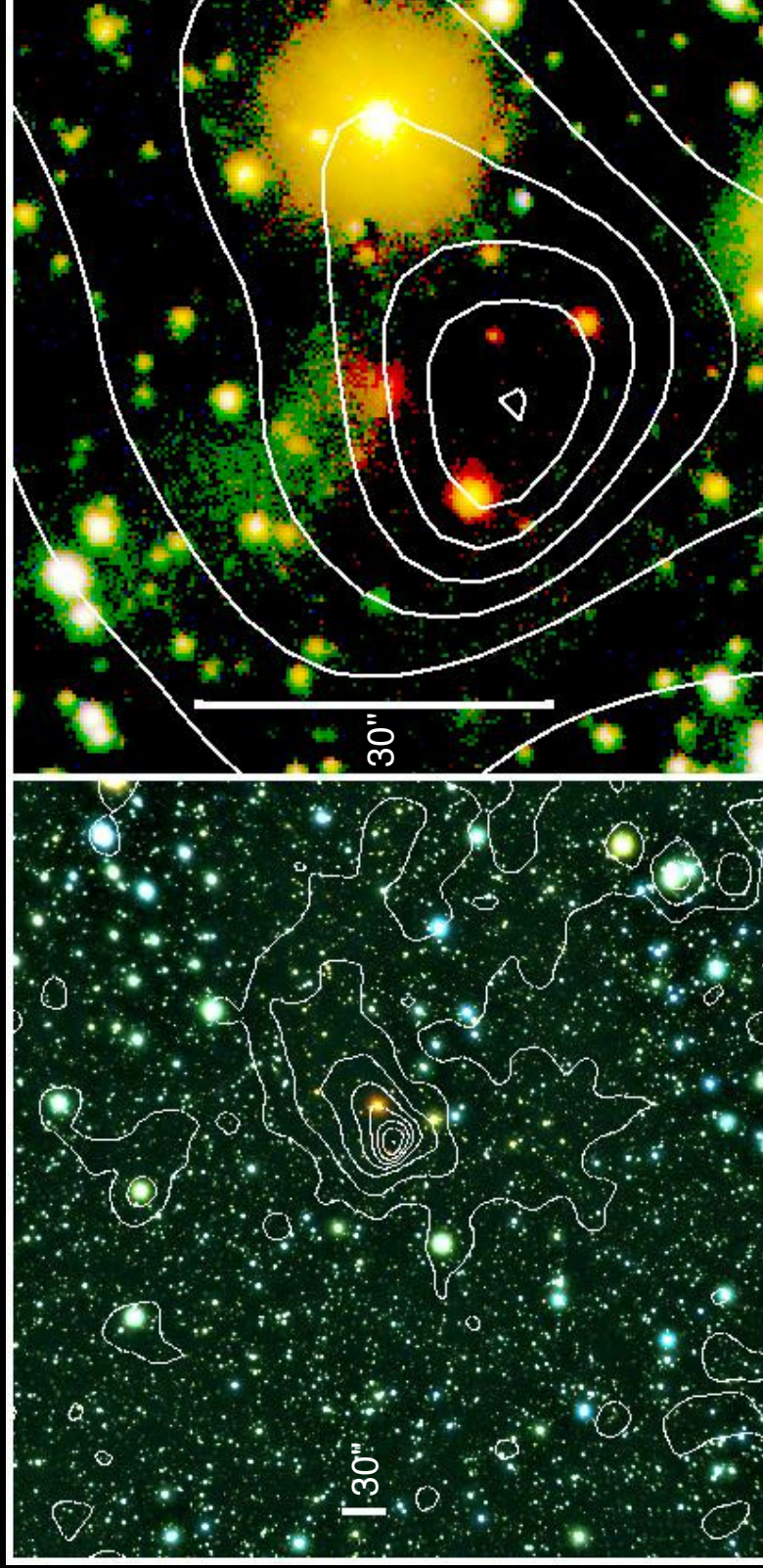
Chabrier et al. 2000

Bourke et al. (in prep.)

L1014-IRS

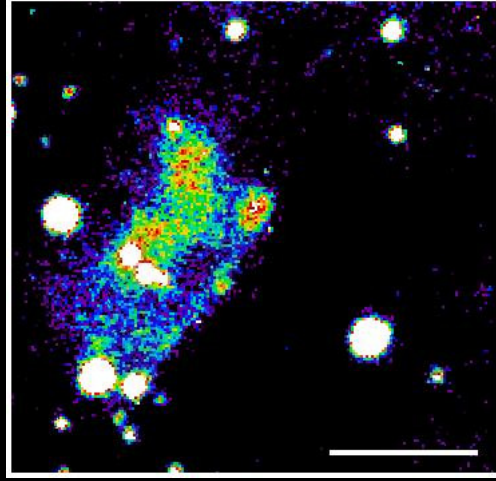
Near-IR colors of background stars used to construct a high angular resolution map of extinction. (*NICE* method; e.g., Lada et al. 2004)

$A_V = [2, 5, 10, 15, 20, 25, 30, 35]$

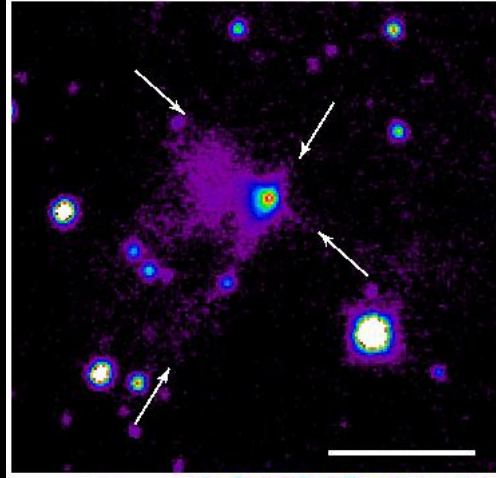


L1014-IRS

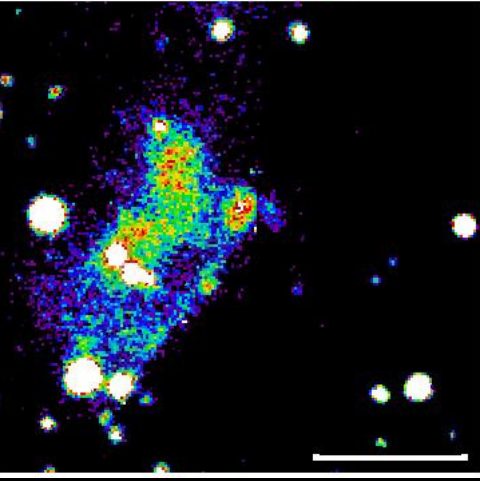
H Band



K Band



Observations



After removing differential extinction

Inclination not quite edge-on,
but not more than 30° from
an edge-on orientation.

Questions...

How common are sources like L1014-IRS ?

What are their physical properties ?

Do they typically form in isolation or in systems ?

Search for More Candidates

89 isolated molecular cloud cores in *c2d* Legacy project

73 Cores Searched

B 18-2	DC 2742-04	L 1155C-2	L 260
B 35A	DC 275.9+1.9	L 1155E	L 328
B 72	DC 2910-35	L 1165	L 429-C
BHR 14	DC 3002-35	L 1197	L 43
BHR 16	DC 302.1+7.4	L 1221	L 462-1
BHR 22	DC 3023-177	L 1228	L 492
BHR 47	DC 3026-159	L 1251C	L 63
BHR 59	DC 303.8-14.2	L 1251E	L 673-7
BHR 76	DC 3272+18	L 134A	L 673
Bern 48	DC 3369+83	L 1355	L 675
CB 130-3	DC 3386+95	L 1507A	L 723
CB 188	DC 3391+117-2	L 1521-2	TMC 1-1C-2
CG 30	DC 3460+78	L 1521B-2	TMC 1
CG 31A	DC 3463+78	L 1521F	
CG 31B	DC 3464+79	L 1524-4	
CG 31C	IRAM 04191+1522	L 158	
DC 2573-25	L 100	L 1694-2	
DC 2660-75-1	L 1014	L 1772	
DC 2675-74	L 1021	L 204C-2	
DC 2694+30	L 1148	L 234E	

Search for More Candidates

89 isolated molecular cloud cores in c2d Legacy project

73 Cores Searched

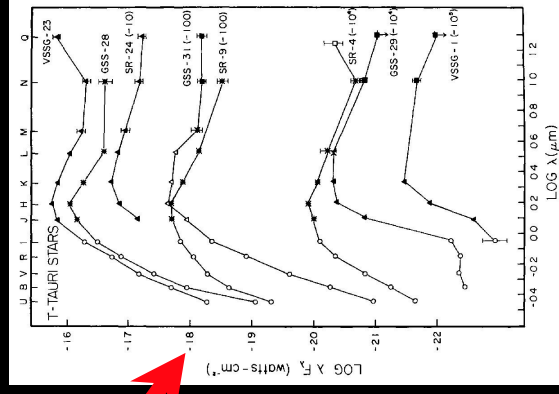
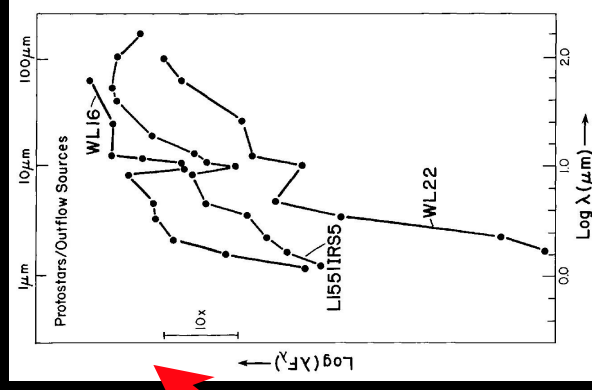
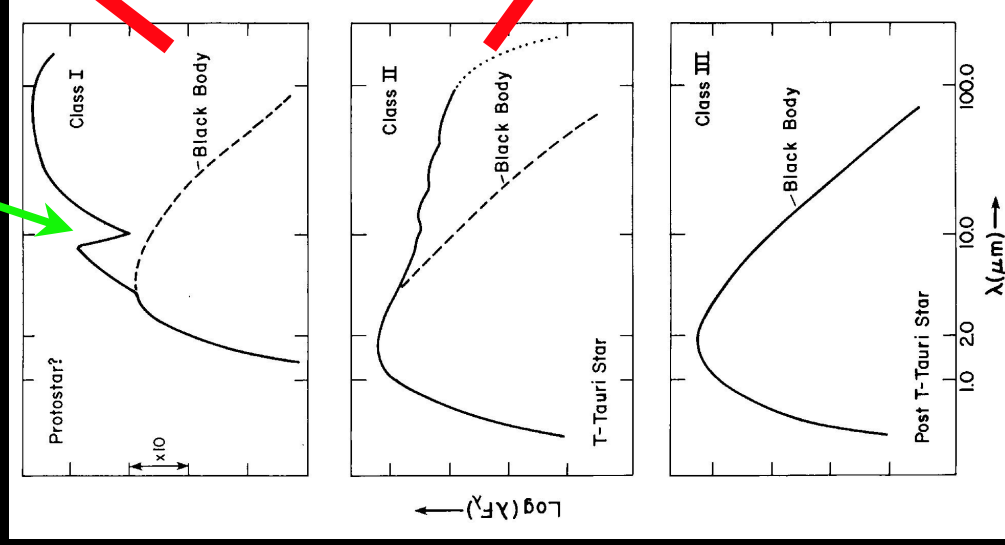
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54 Starless Cores

Criteria for Candidates

10- μm Si absorption

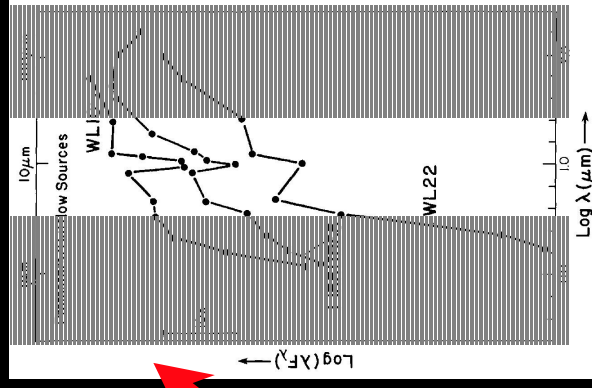
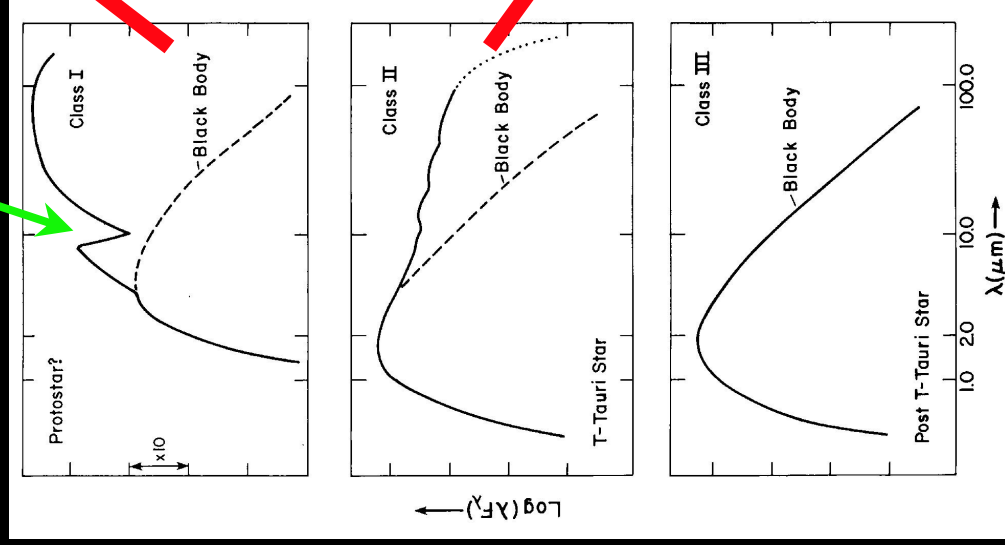
Lada 1987



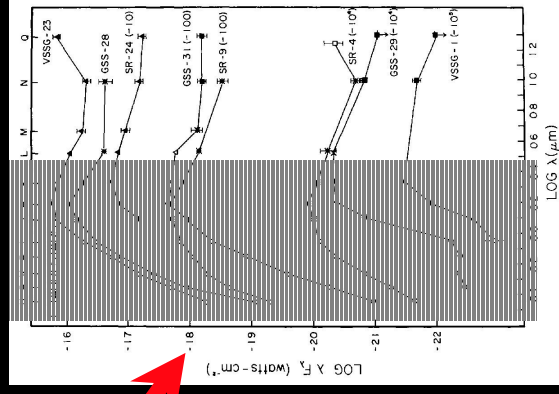
Criteria for Candidates

10- μm Si absorption

Lada 1987

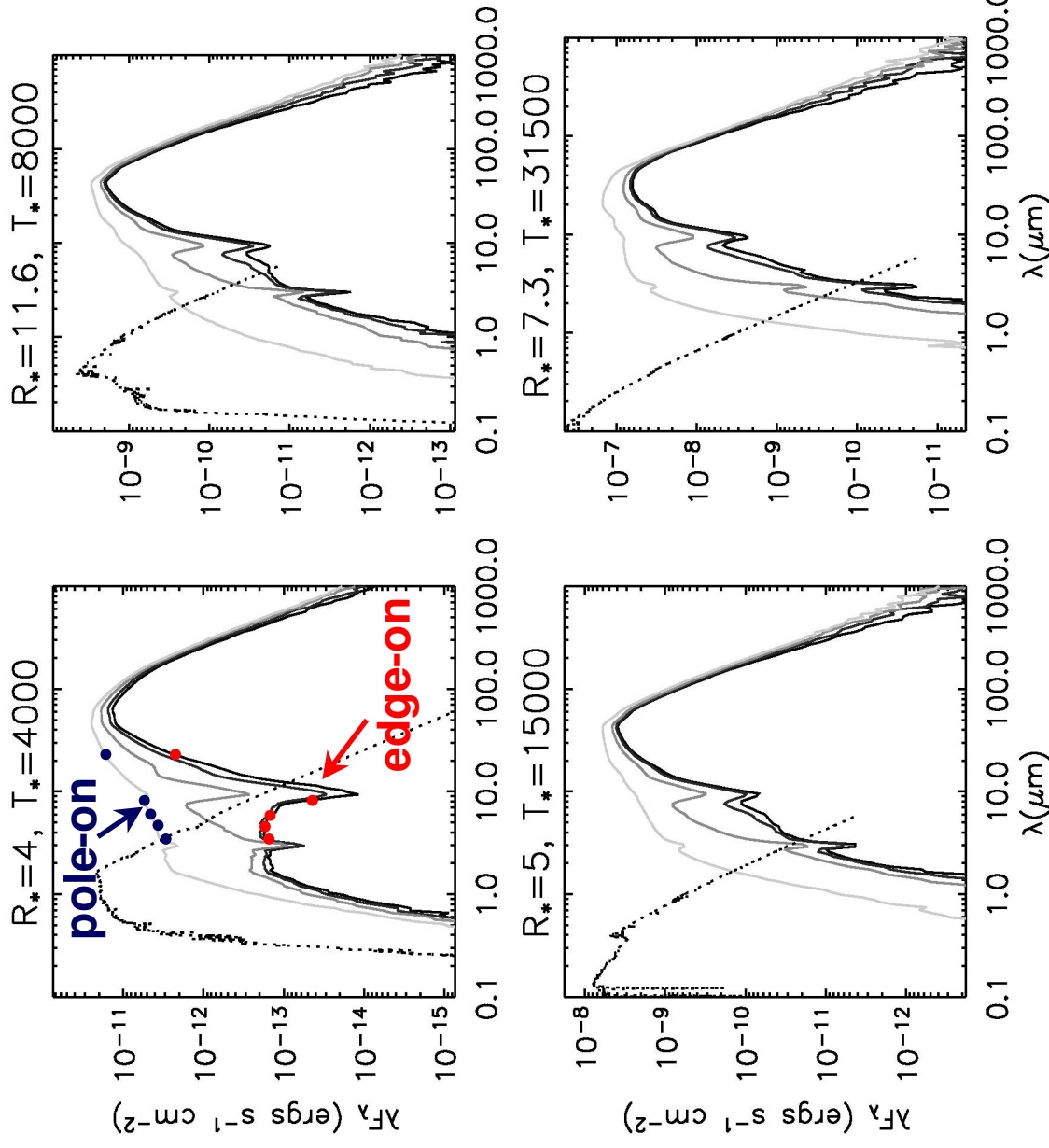


Youngest protostars exhibit generally increasing mid-IR SEDs



YSOs exhibit generally decreasing mid-IR SEDs

Criteria for Candidates



Mid-IR SEDs of protostars depend on temperature and inclination.

Criterion #1

Generally flat or rising mid-IR SED

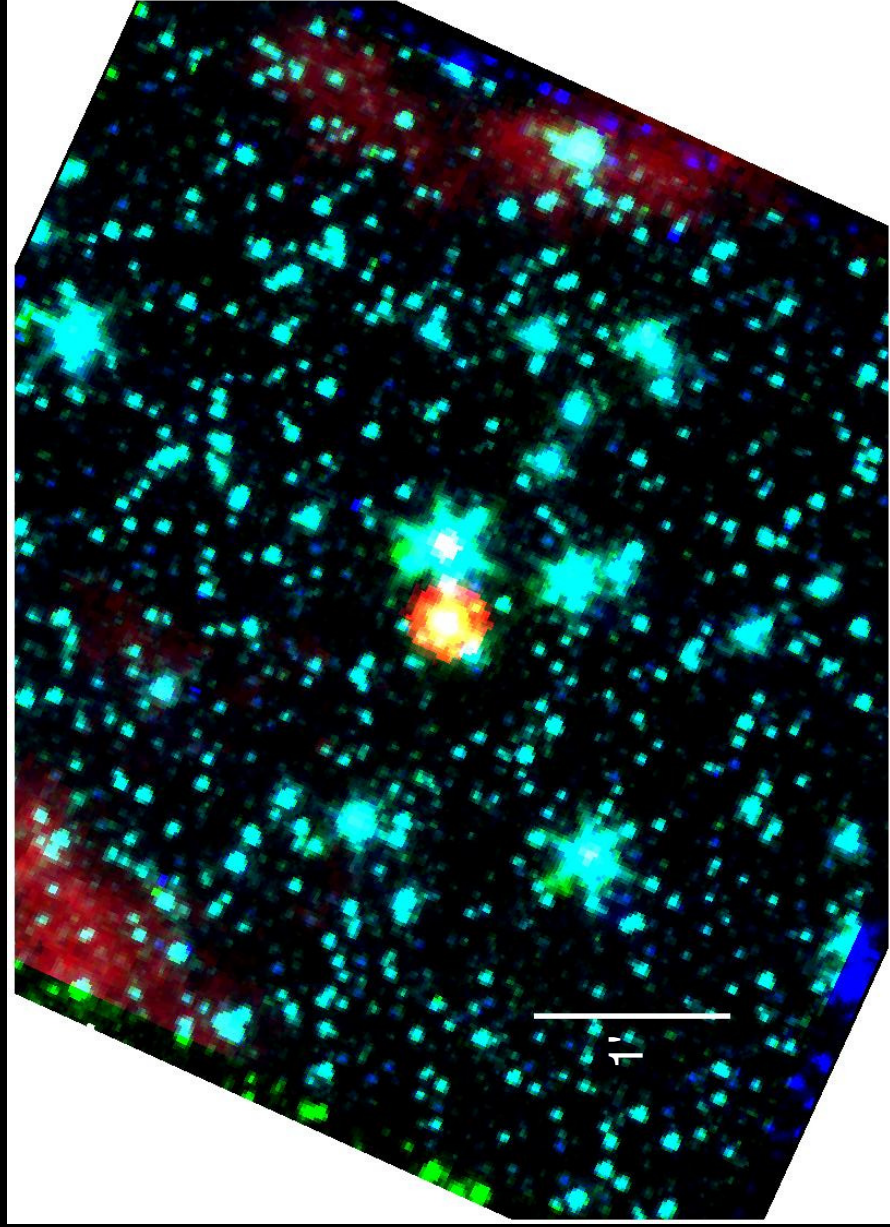
(in at least 2 of the 4 independent Spitzer colors)

Whitney et al. 2004

Criteria for Candidates

L1014

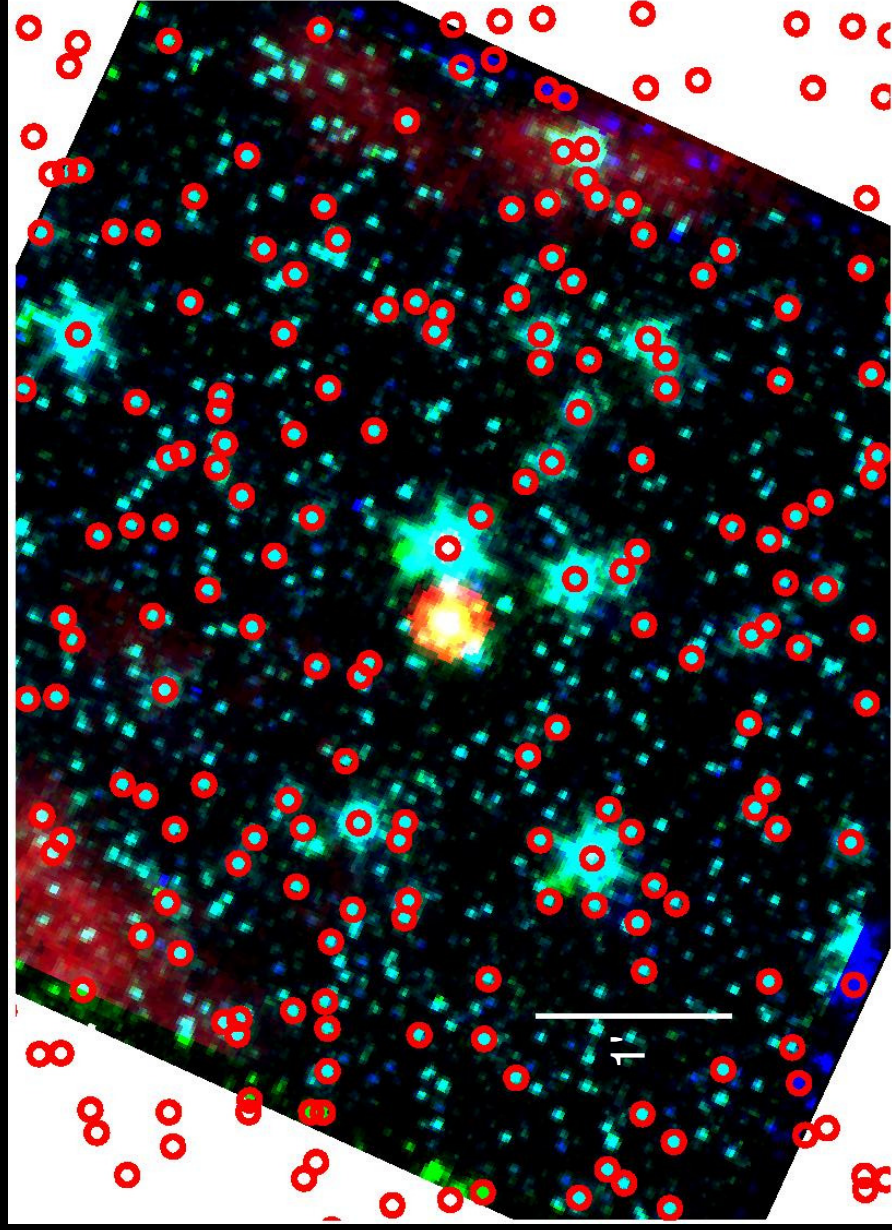
3.6, 4.5, 24 μm



Criteria for Candidates

L1014

3.6, 4.5, 24 μm



Criteria for Candidates

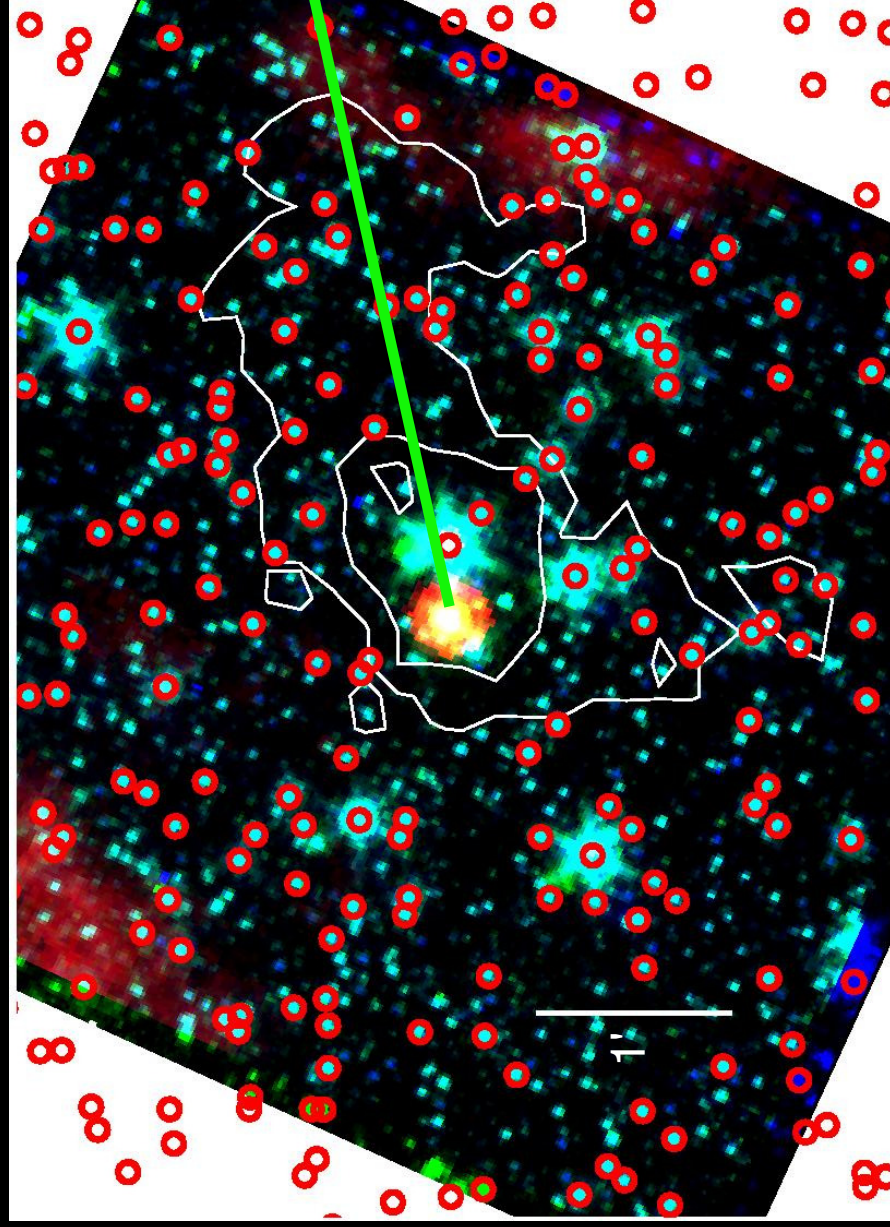
$$A_V = 15.9 [(H-K)_{\text{observed}} - (H-K)_{\text{intrinsic}}]$$

Rieke & Lebofsky 1985
Lada et al. 2004

$$(H-K)_{\text{intrinsic}} \approx 0.15 \text{ mag}$$

L1014

3.6, 4.5, 24 μm



$A_V = [5, 10] \text{ mag}$

2MASS $A_V = 12 \text{ mag}$

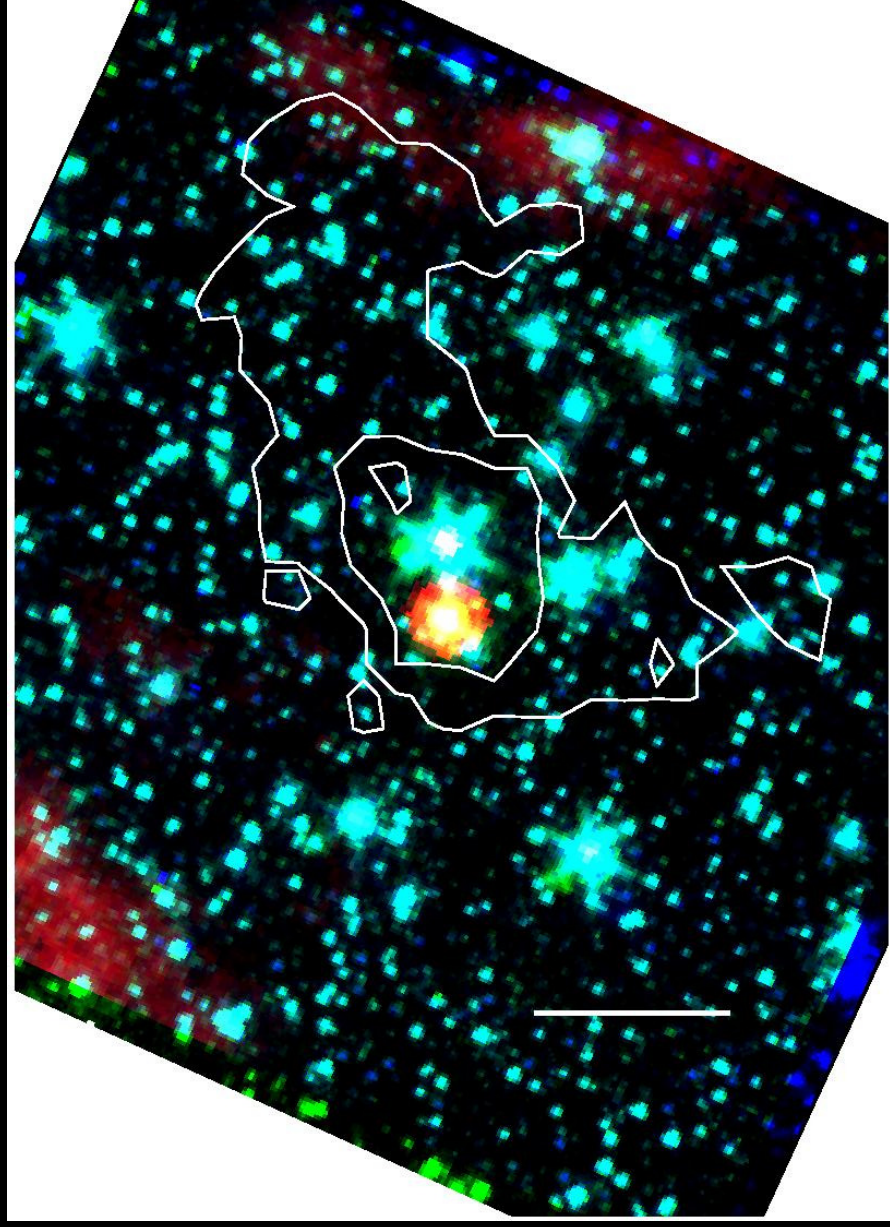
From deep near-IR
observations,
 $A_V = 25 \text{ mag}$

2MASS A_V is
typically an
underestimate of
extinction, by at
least a factor of 2

Criteria for Candidates

L1014

3.6, 4.5, 24 μm



$A_V = [5, 10]$ mag

Criterion #2

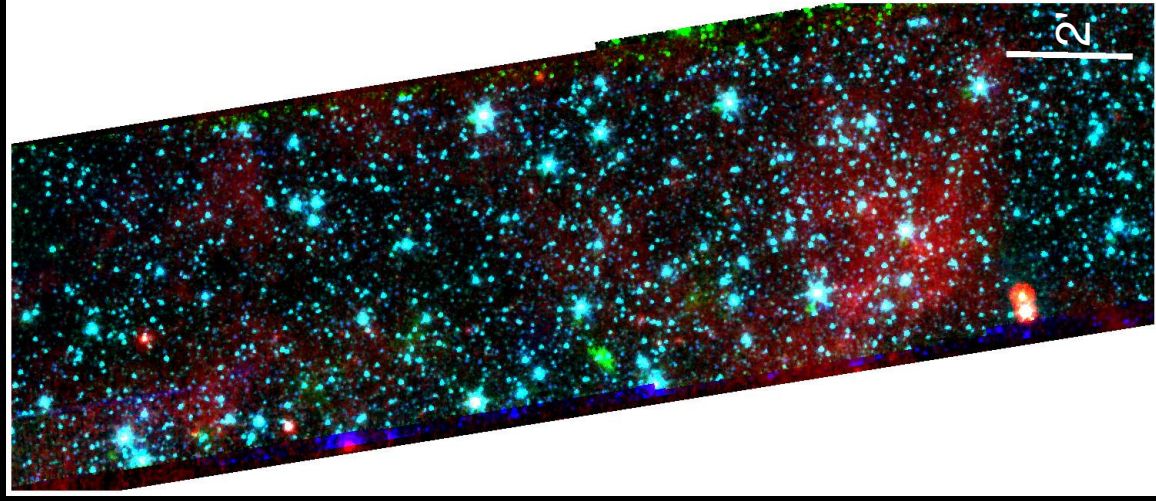
Associated with at
least moderate
extinction

(at least $A_V > 8$ mag, as
determined by 2MASS
photometry)

Searching...

CB130-3

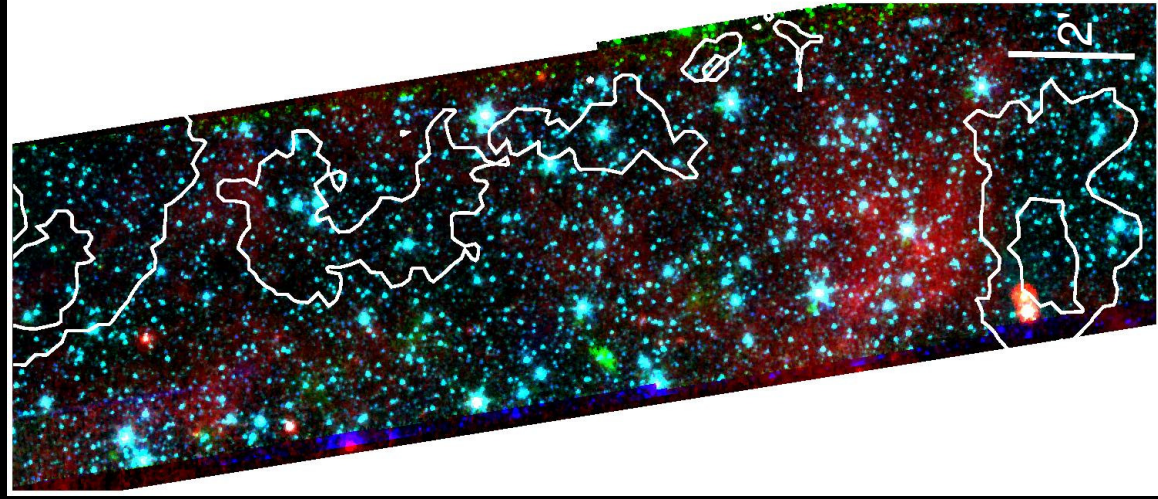
3.6, 4.5, 24 μm



Searching...

CB130-3 3.6, 4.5, 24 μm

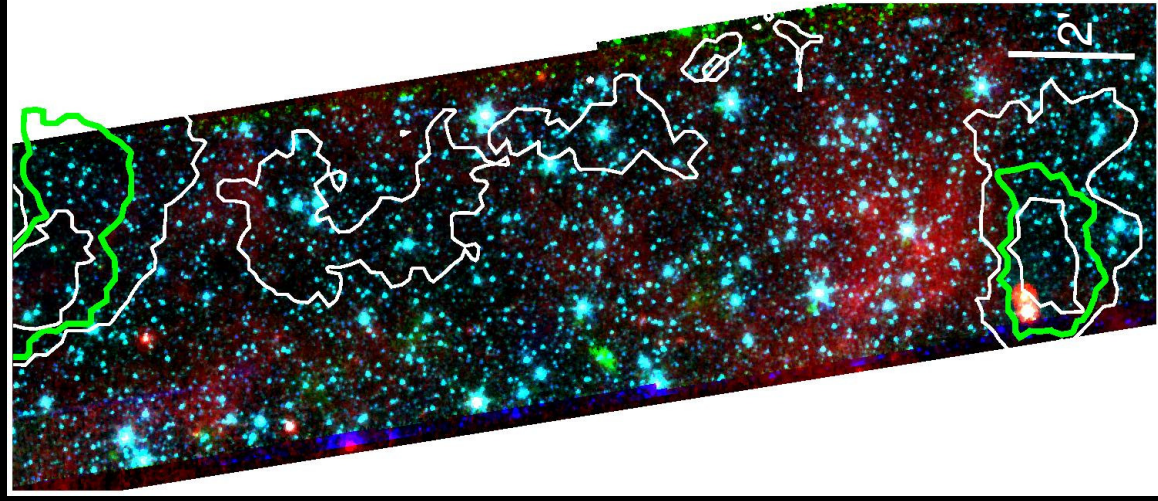
$A_V = [5, 10]$ mag



Searching...

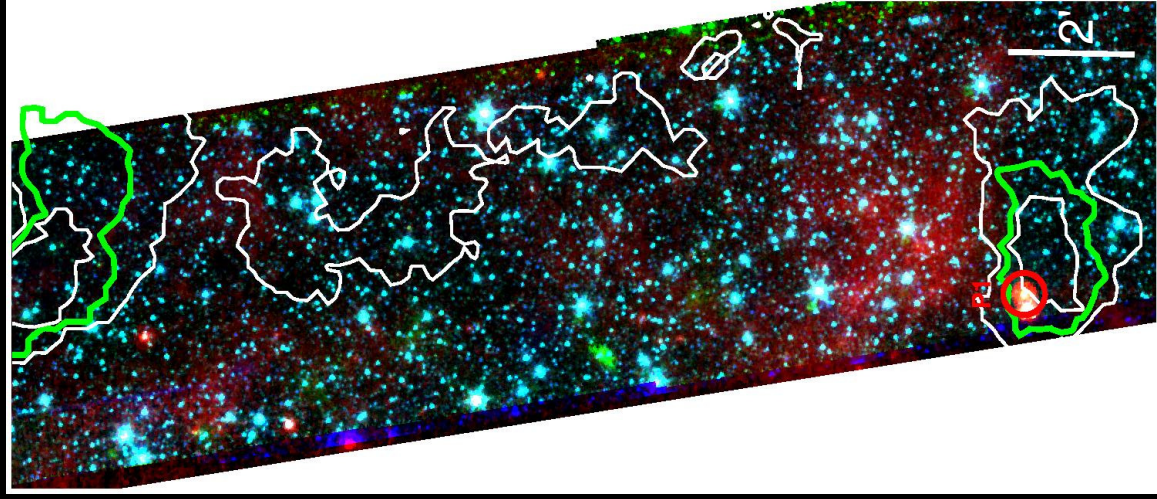
CB130-3 3.6, 4.5, 24 μm

$A_V = [5, 8, 10]$ mag

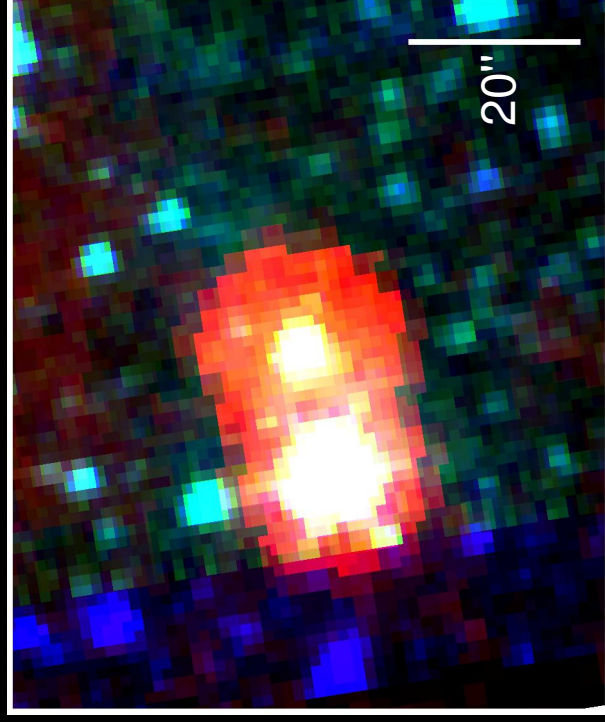


Searching...

CB130-3 3.6, 4.5, 24 μm

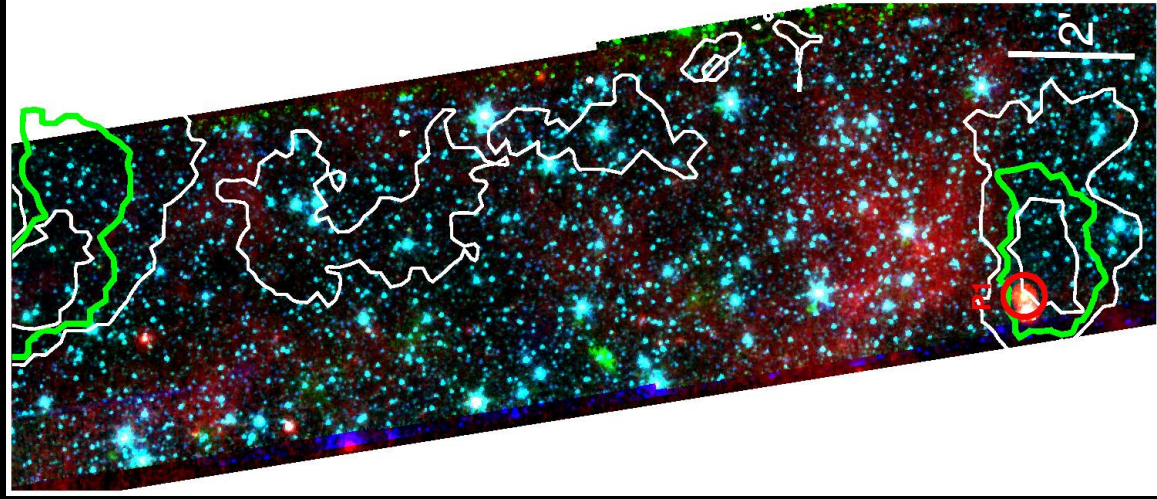


$A_V = [5, 8, 10]$ mag

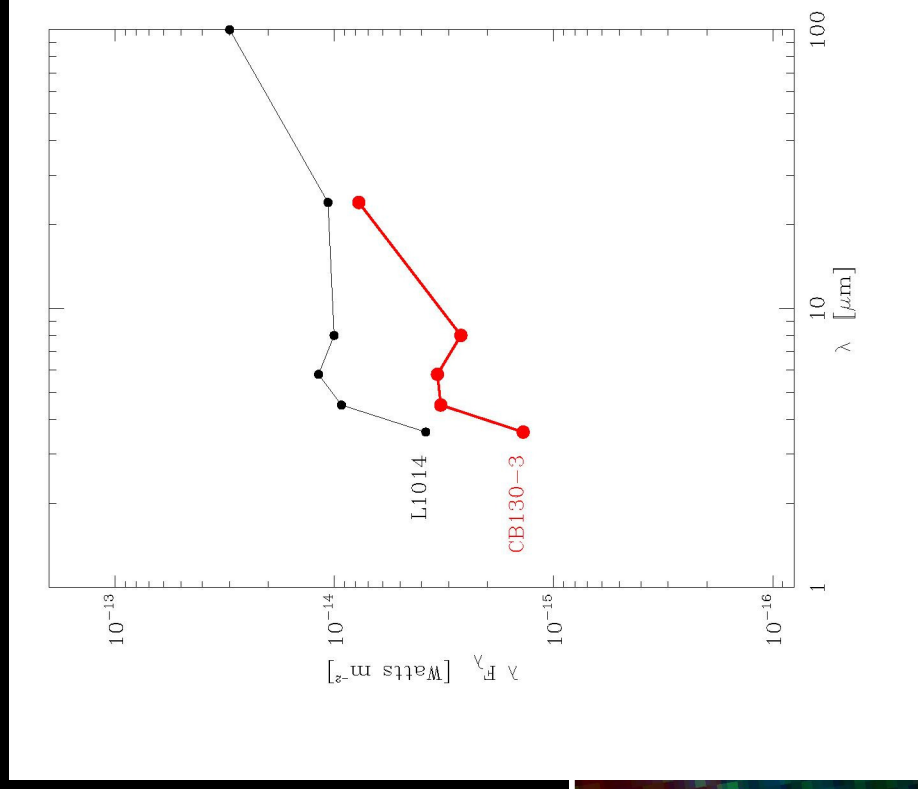
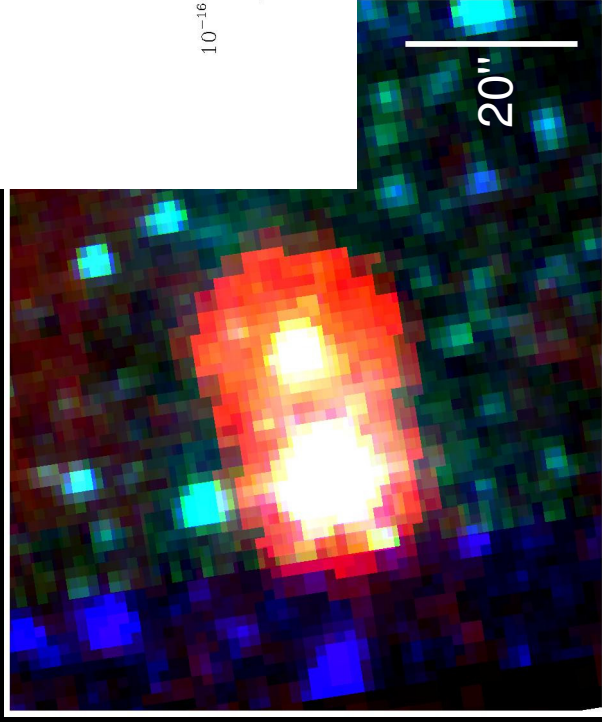


Searching...

CB130-3 3.6, 4.5, 24 μm



$A_V = [5, 8, 10]$ mag



Results of Search

14 Candidates in 10 of the 54 “Starless” Cores

4 Categories of Candidates

Rising with Si absorption

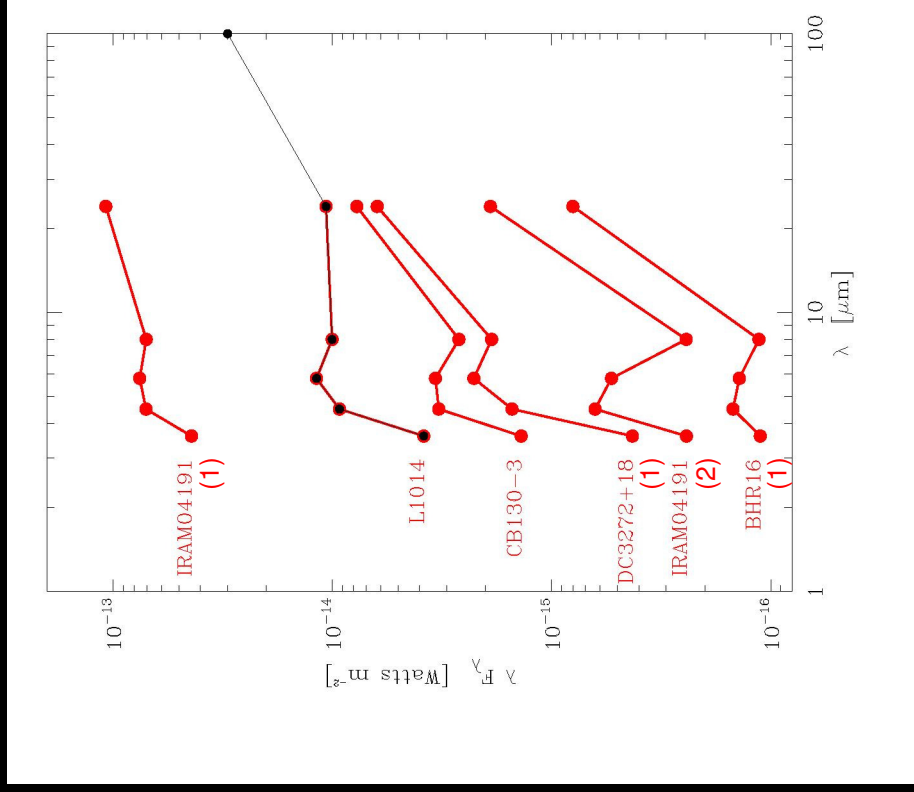
Decreasing-Rising

Rising with no Si absorption

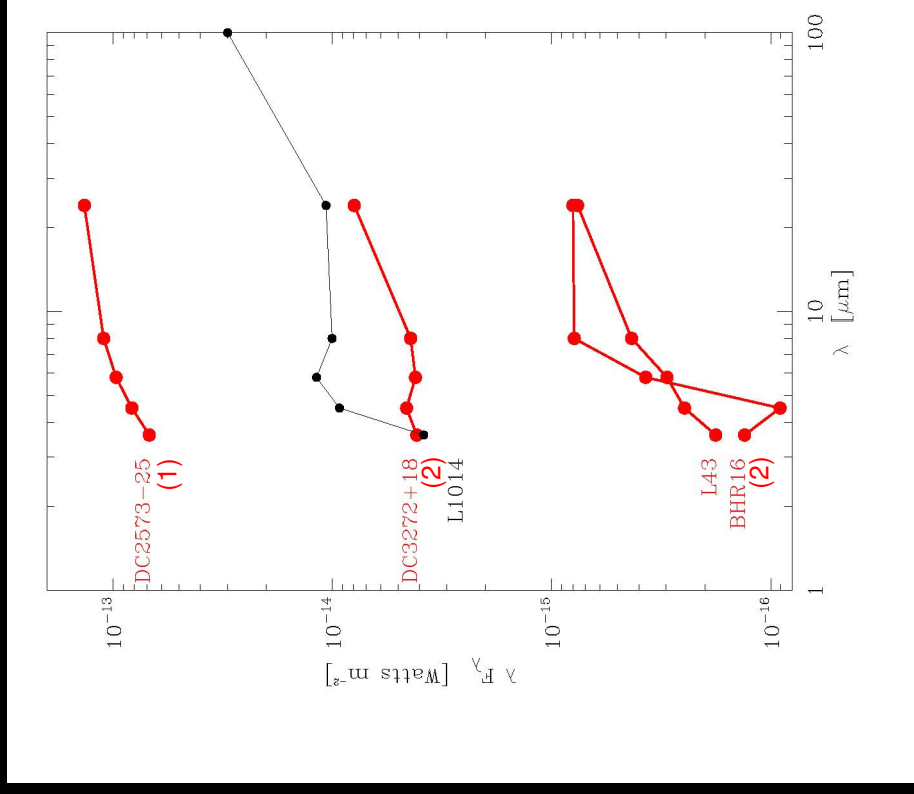
Dunnos

Results of Search

Rising with Si absorption

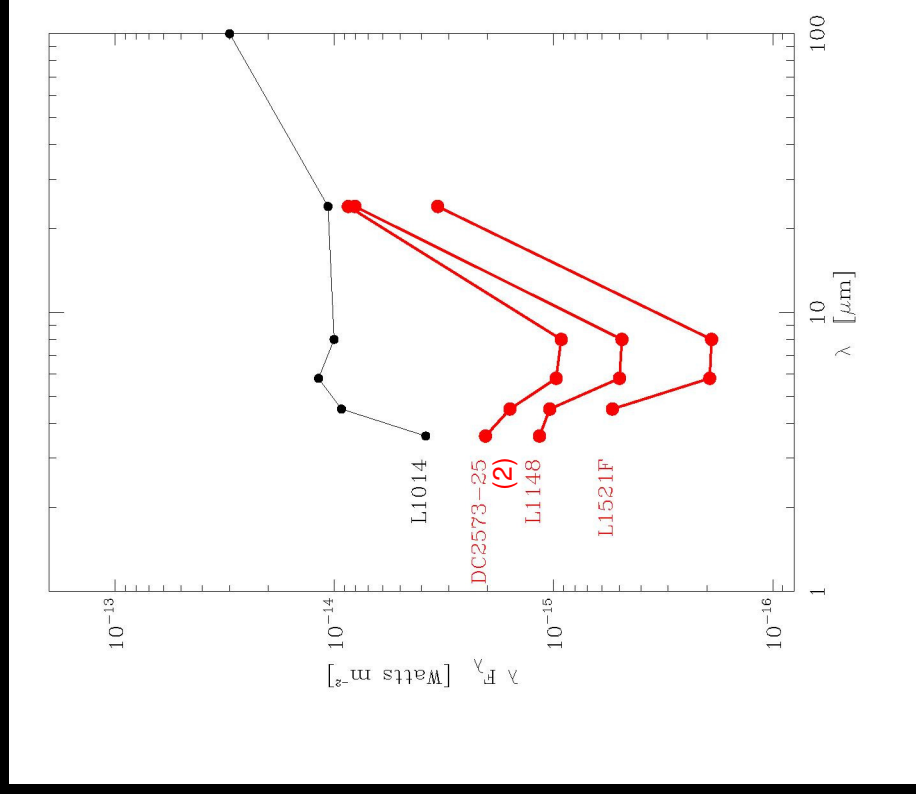


Rising with no Si absorption

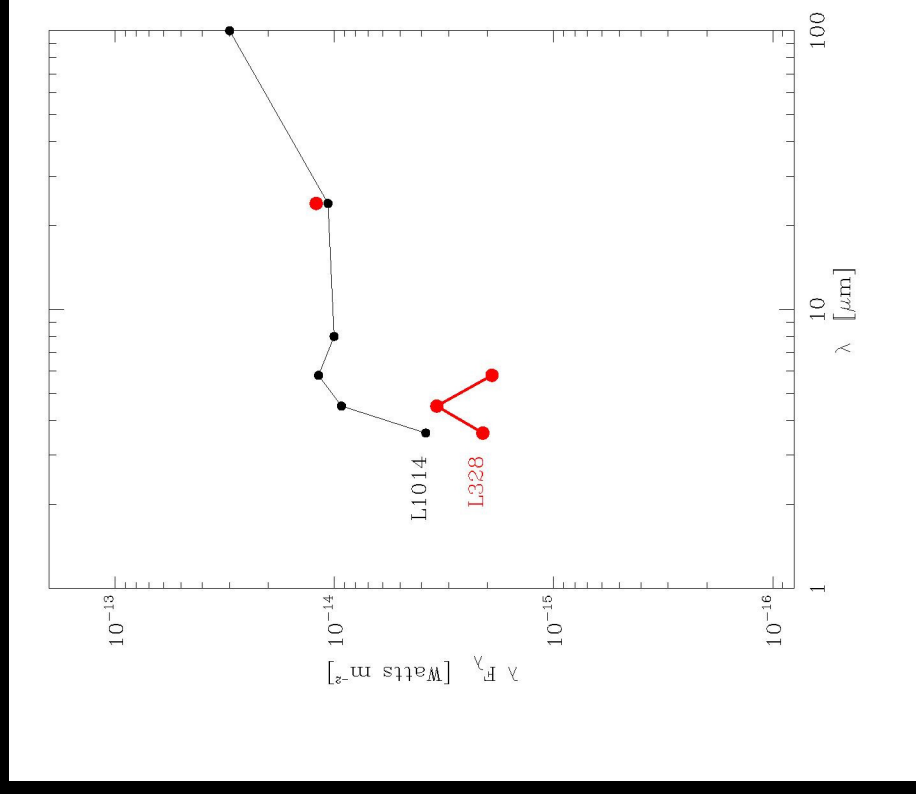


Results of Search

Decreasing-Rising



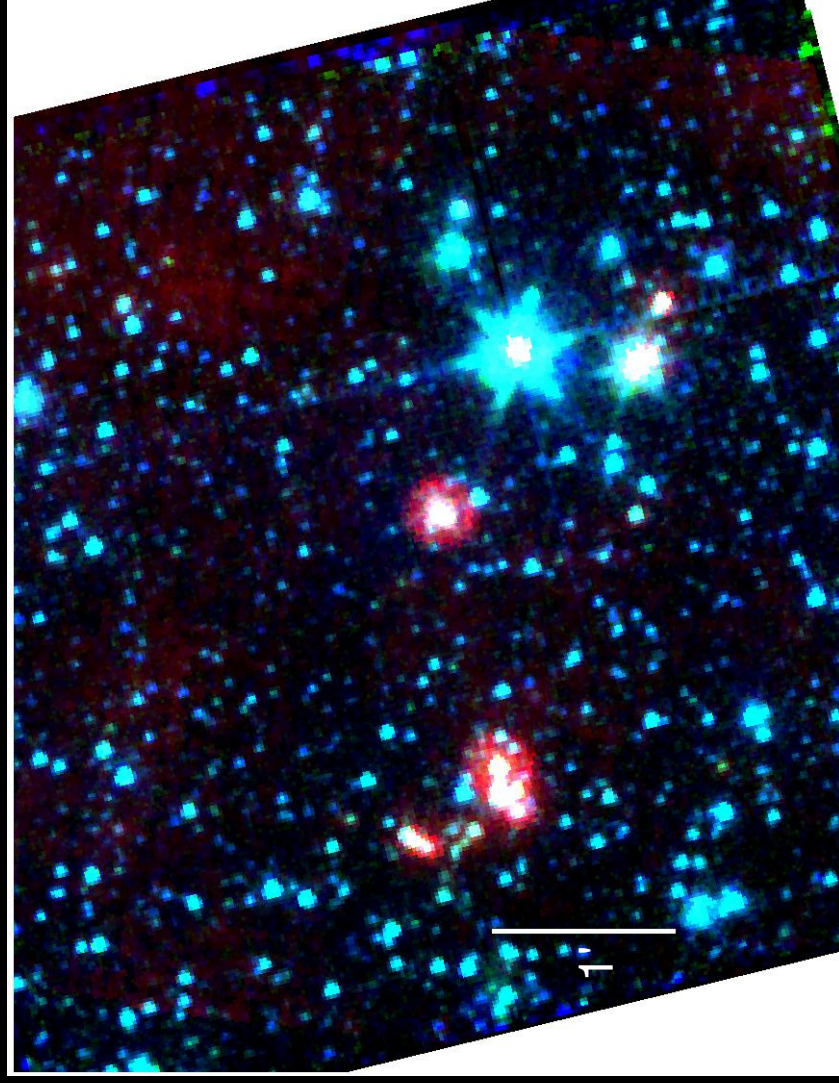
Dunnos



Results of Search: Rising with Si absorption

BHR16

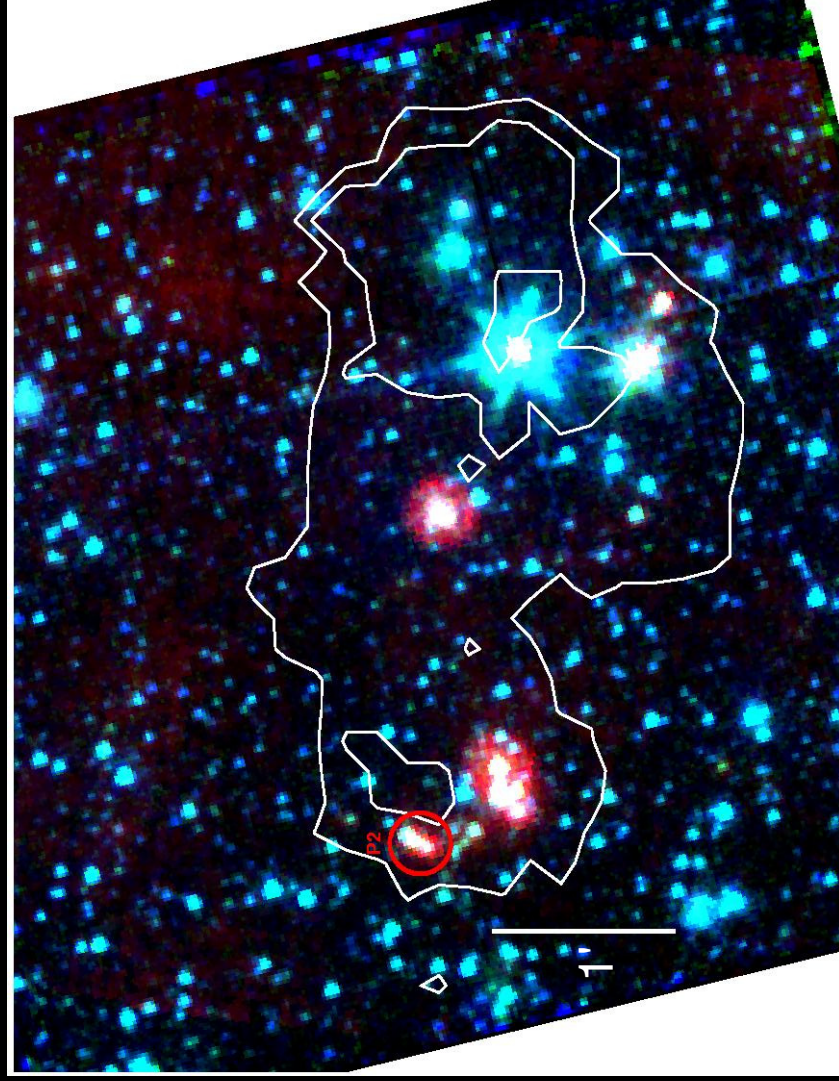
3.6, 4.5, 24 μm



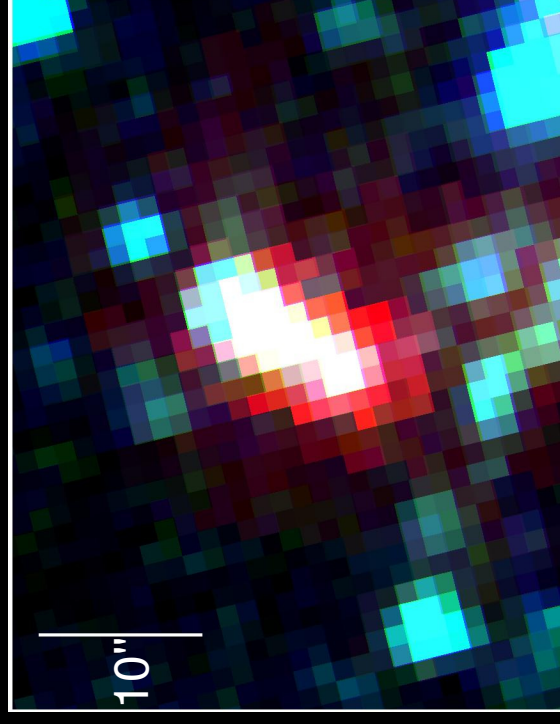
Results of Search: Rising with Si absorption

BHR16

3.6, 4.5, 24 μm



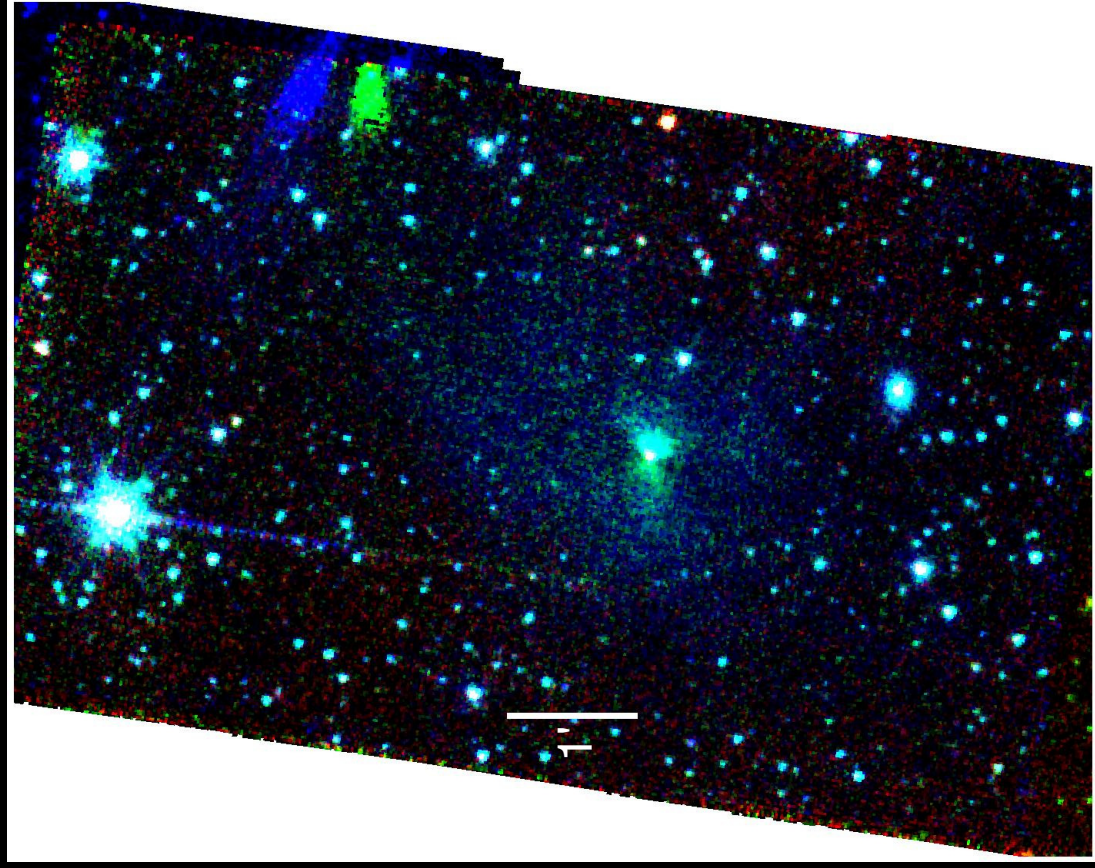
$A_V = [5, 10]$ mag



Results of Search: Decreasing-Rising

L1521F

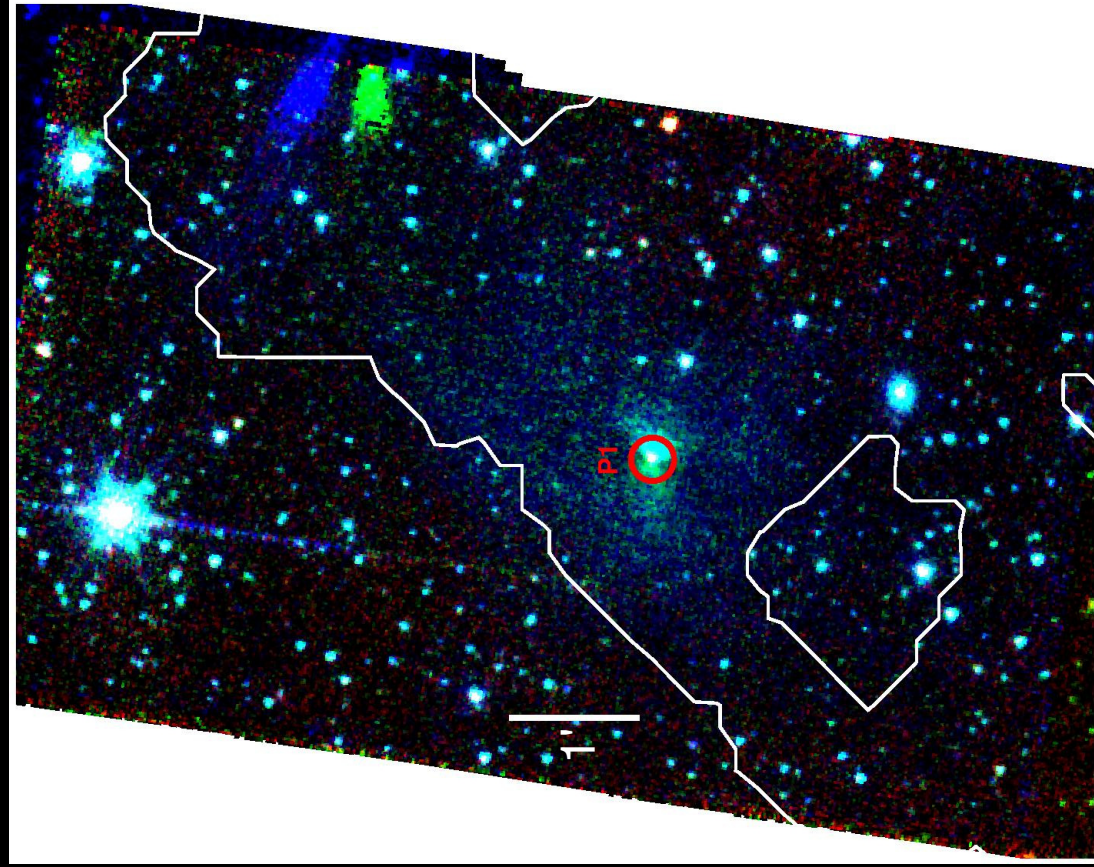
3.6, 4.5, 8.0 μm



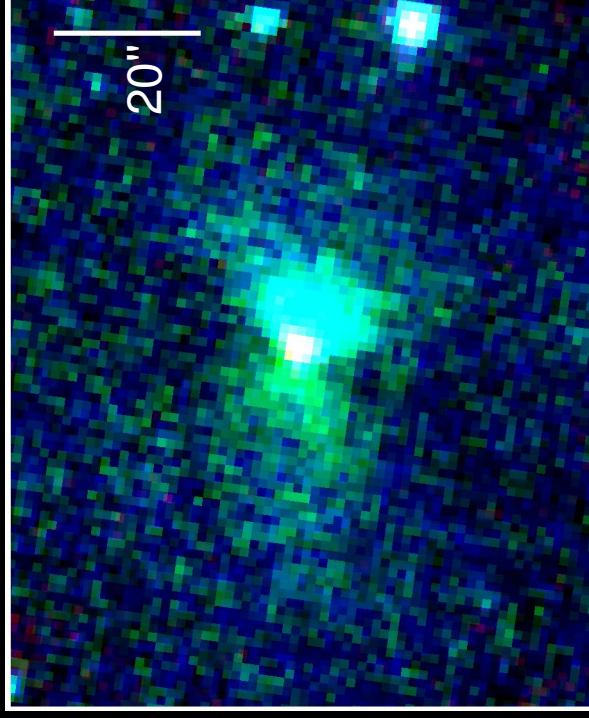
Results of Search: Decreasing-Rising

L1521F

3.6, 4.5, 8.0 μm



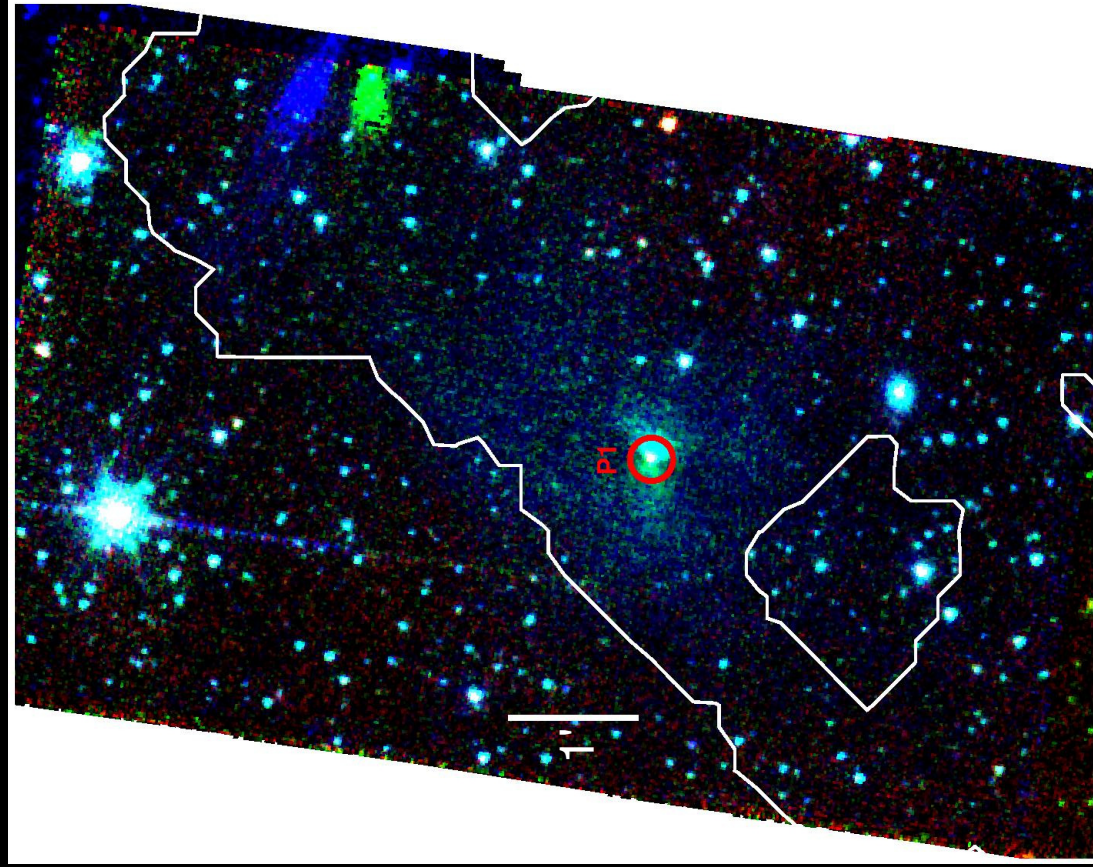
$A_V = [5, 10]$ mag



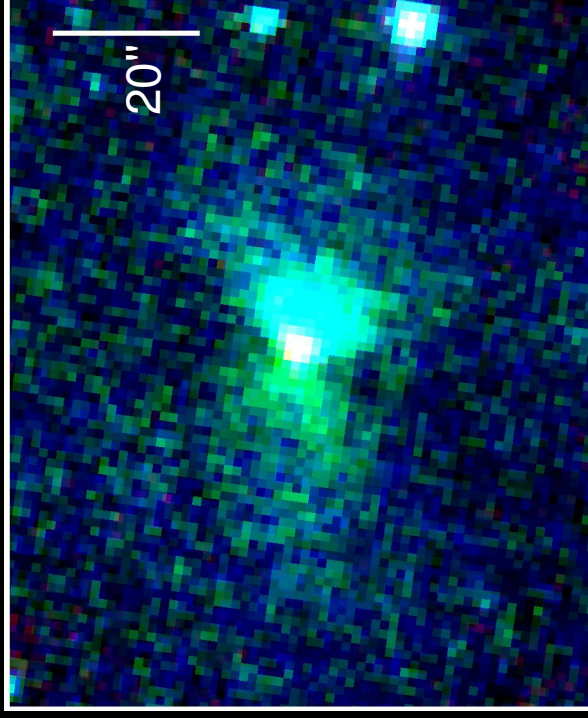
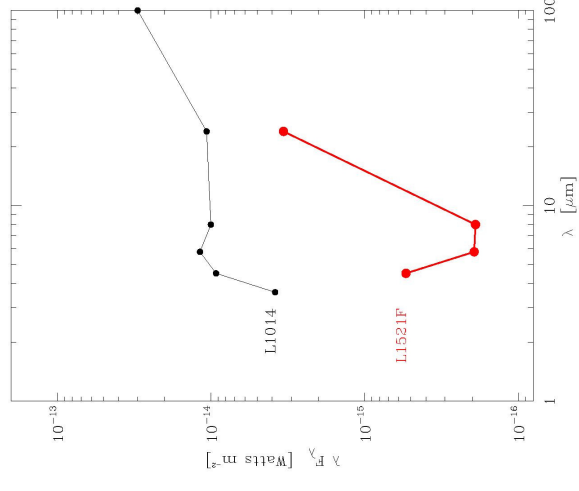
Results of Search: Decreasing-Rising

L1521F

3.6, 4.5, 8.0 μm



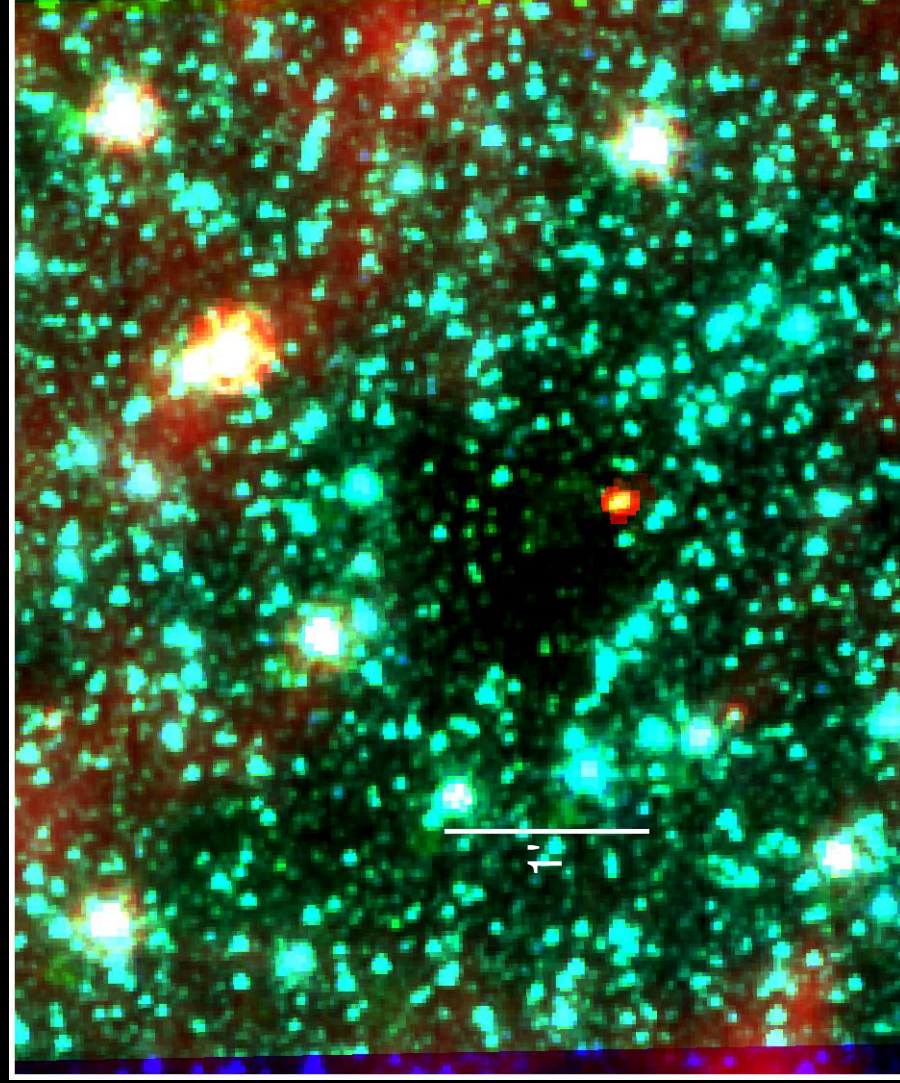
$A_V = [5, 10]$ mag



Results of Search: Durnnos

L328

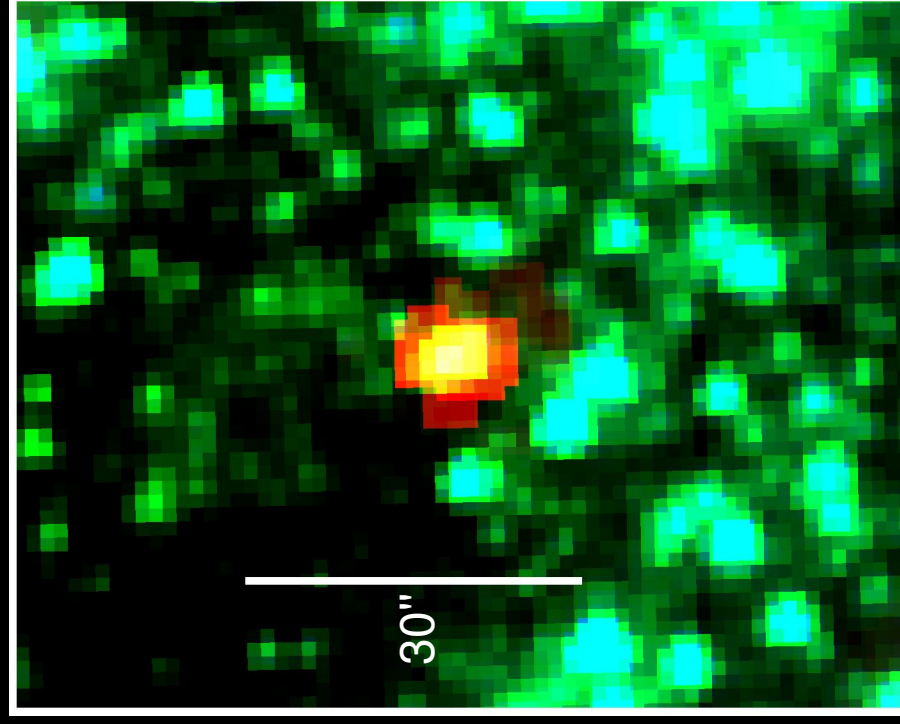
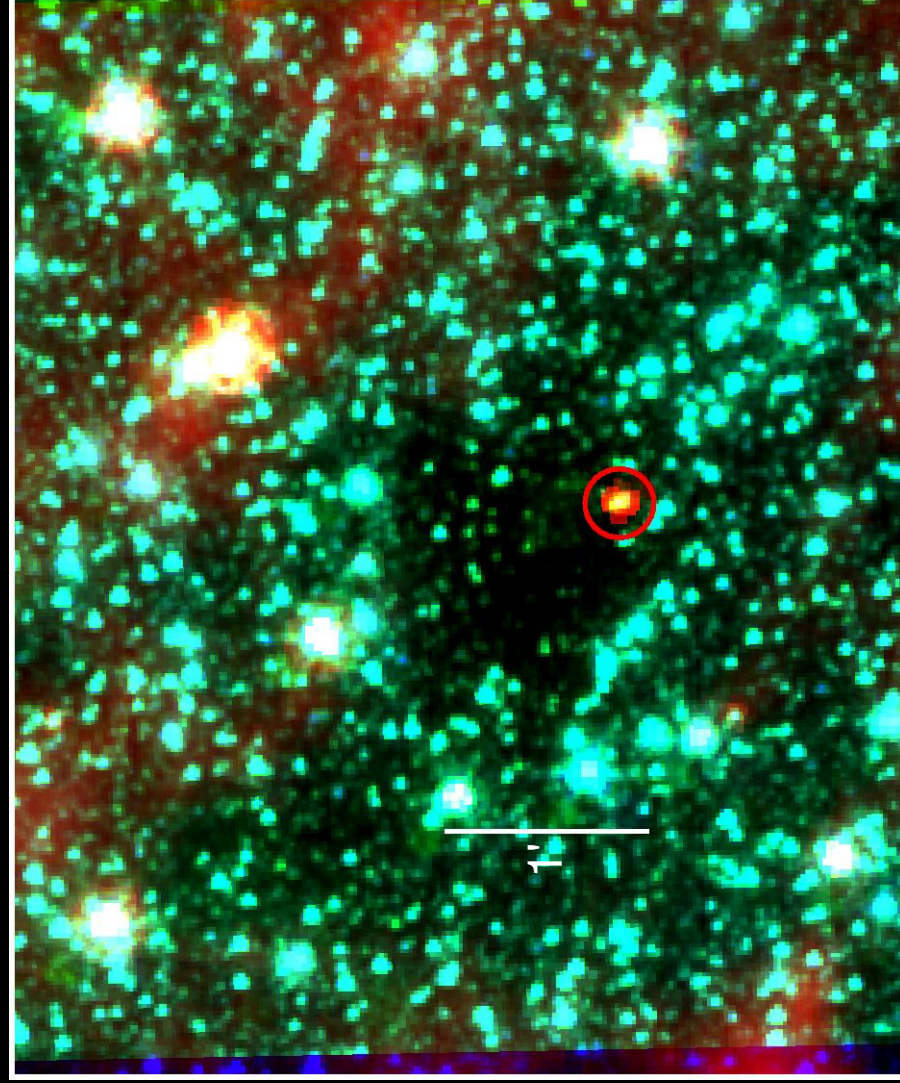
3.6, 4.5, 24 μm



Results of Search: Durnnos

L328

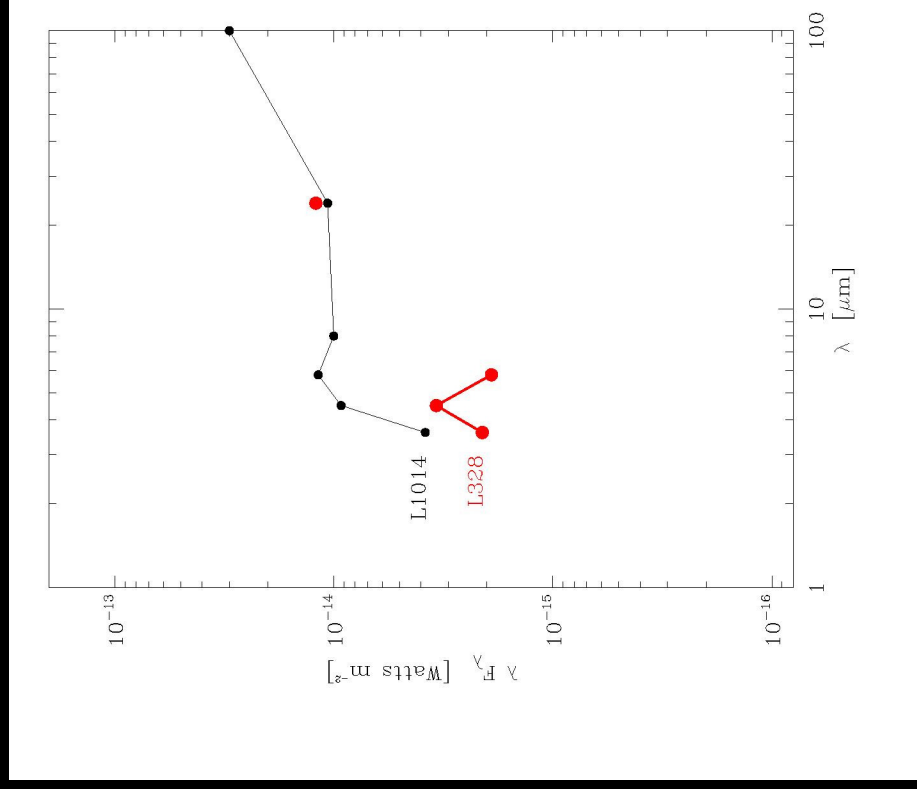
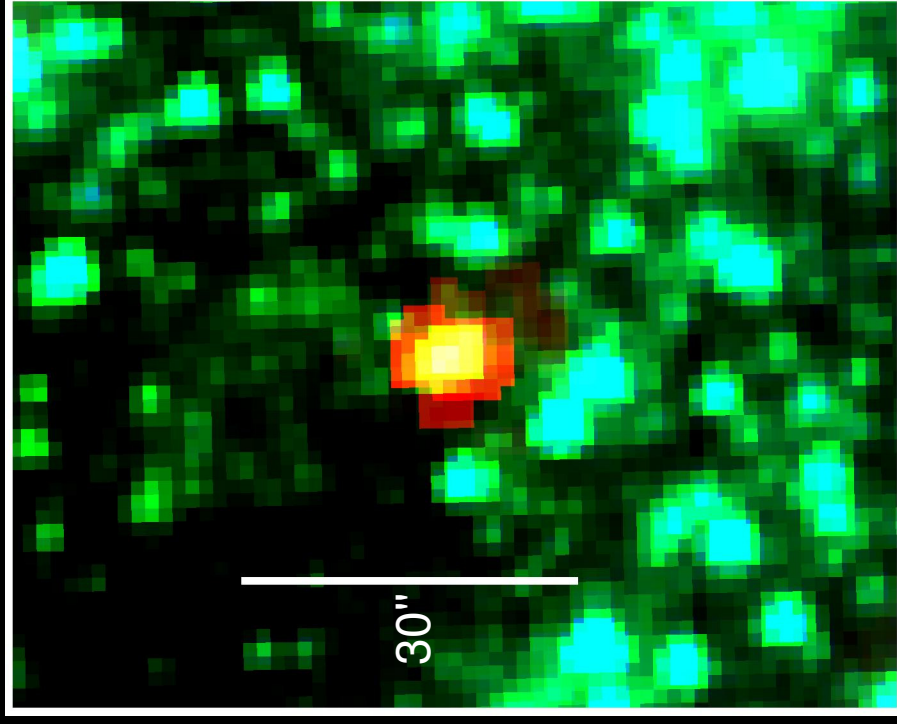
3.6, 4.5, 24 μm



Results of Search: Durnnos

L328

3.6, 4.5, 24 μm



Results of Search: Specifics

14 Candidates in 10 of the 54 “Starless” Cores

4 Categories of Candidates

	Rising with no Si absorption	Rising with Si absorption	Decreasing- Rising	Dunno
BHR16	1	1	0	0
CB130-3	0	1	0	0
DC2573-25	1	0	1	0
DC3272+18	1	1	0	0
IRAM 04191+1522	0	2	0	0
L43	1	0	0	0
L328	0	0	0	1
L1014	0	1	0	0
L1148	0	0	1	0
L1521F	0	0	1	0

Results of Search: Contamination by Galaxies

14 Candidates in 10 of the 54 “Starless” Cores

...but how many are galaxies?

Results of Search: Contamination by Galaxies

14 Candidates in 10 of the 54 “Starless” Cores

...but how many are galaxies?

Spatial distribution of galaxies independent of extinction in cores

Results of Search: Contamination by Galaxies

$A_v < 8$ mag ← | → $A_v \geq 8$ mag

~ 4% of all 24- μ m sources expected to be 'red' galaxies

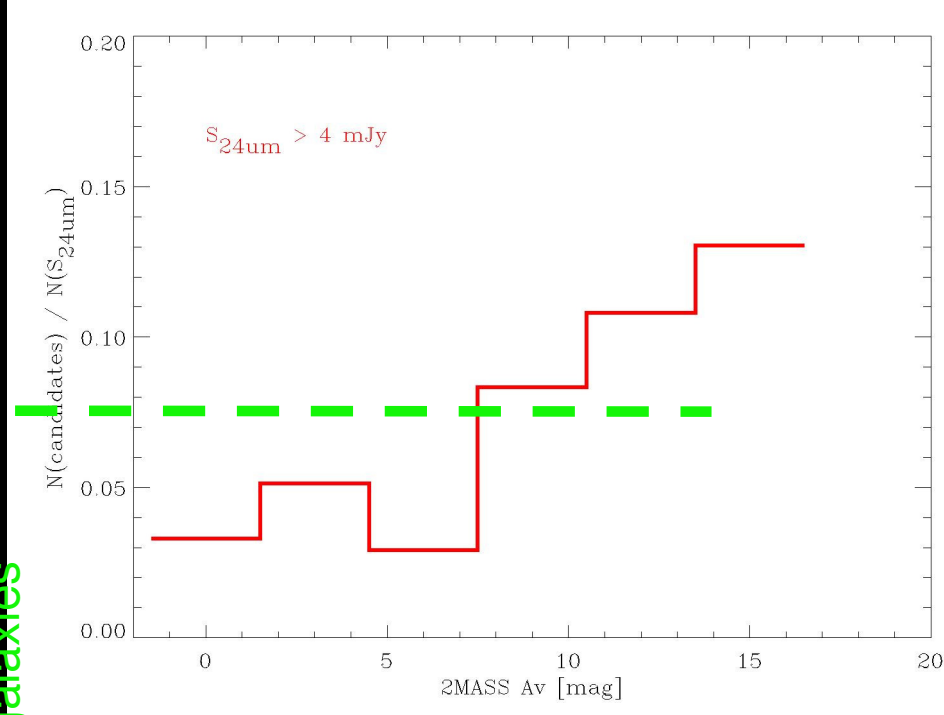
Number of 24- μ m sources projected onto extinction, $A_v \geq 8$ mag

= 144
x 4%

Expected number of 'red' galaxies = 6

Number of Candidates Found ('red' sources) = 14

Expected number of previously unknown protostars and embedded brown dwarfs = 8



Summary

Recent observations of L1014-IRS are consistent with it having an ultra-low mass, perhaps substellar.

More than a dozen candidates for ultra-low mass, embedded sources have been found.

At least half of these candidates are expected to be Truly low-mass sources, not galaxies.

Follow-up near-IR spectroscopic observations and two-dimensional radiative transfer models are necessary to confirm their classification