Infrared Dark Clouds seen by *Herschel* and ALMA

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IR-dark clouds: shadows in infrared sky

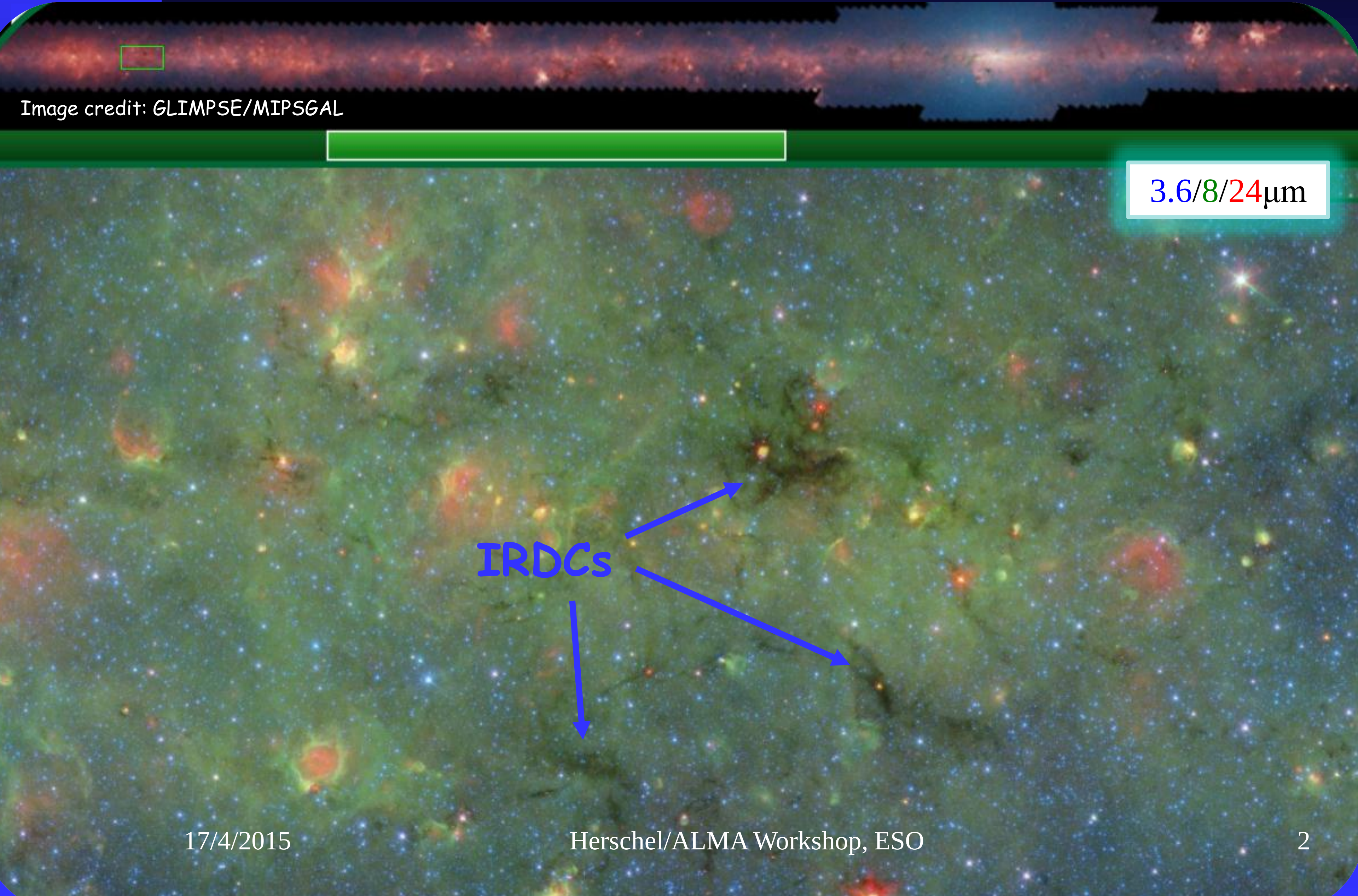
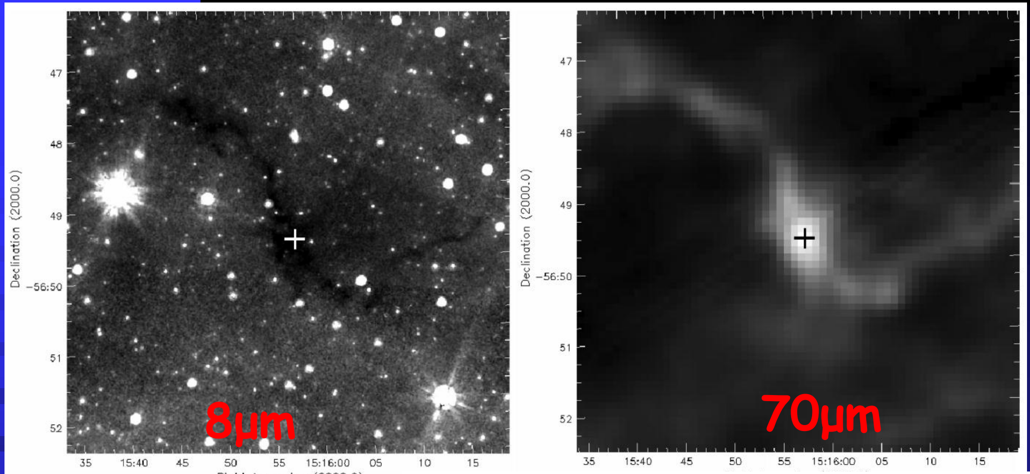


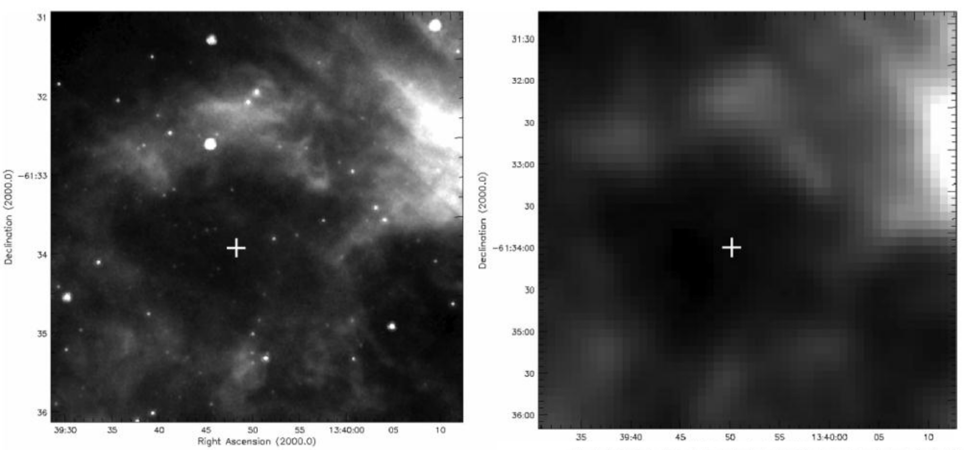
Image credit: GLIMPSE/MIPSGAL

IRDC Catalogues

- Simon+06 identified 11,000 IRDCs from MSX images
- Peretto & Fuller 09: similar number of IRDCs from Spitzer data
- 80% of the two catalogues do not overlap

- Wilcock+12: about 2/3 of these IRDC candidates not seen at far-IR with Herschel (cf. Jackson+08) → genuine IRDCs are overestimated


8μm
70μm
Declination (2000.0)
Right Ascension (2000.0)
47
48
49
−56:50
51
52
35
15:40
45
50
55
15:16:00
05
10
15


Declination (2000.0)
Right Ascension (2000.0)
31
32
−61:33
34
35
36
39:30
35
40
45
50
55
13:40:00
05
10
31:30
32:00
30
33:00
30
−61:34:00
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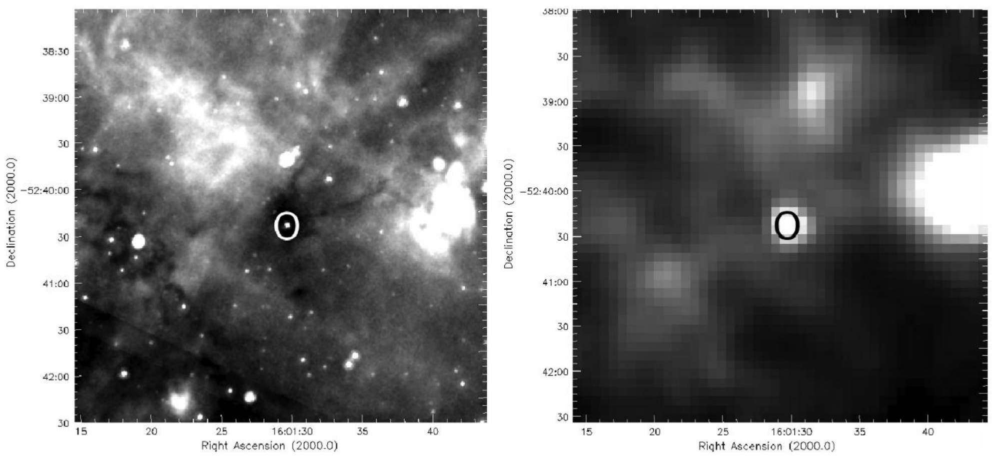
35:00
30
36:00
35
39:40
45
50
55
13:40:00
05
10


Declination (2000.0)
Right Ascension (2000.0)
38:00
38:30
39:00
30
−52:40:00
30
41:00
30
42:00
30
15
20
25
16:01:30
35
40

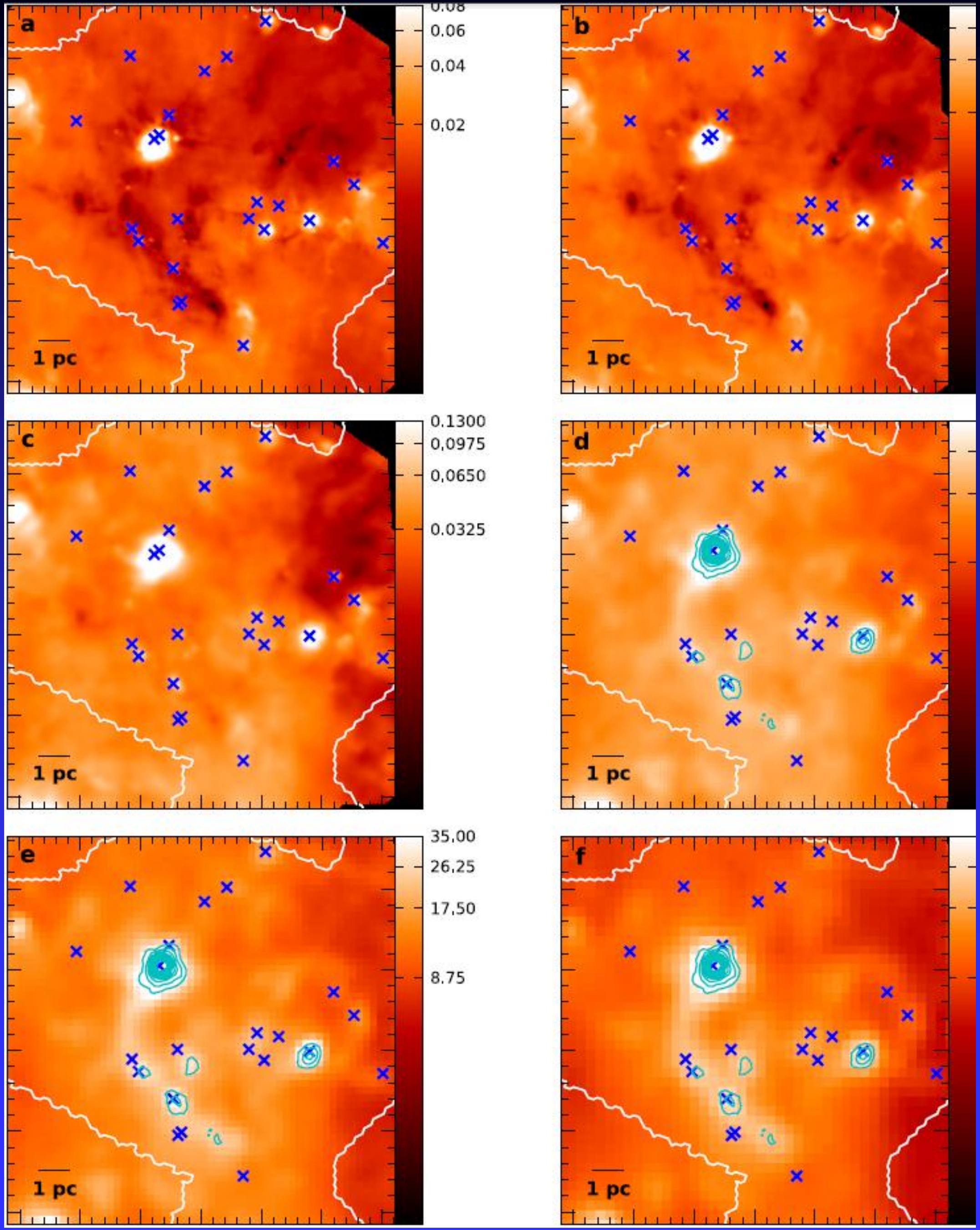
Wilcock+12

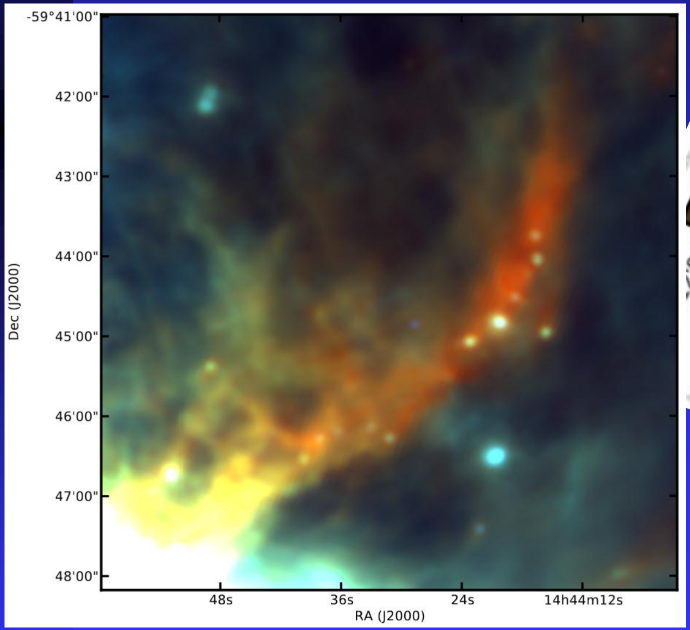
Ragan+2012

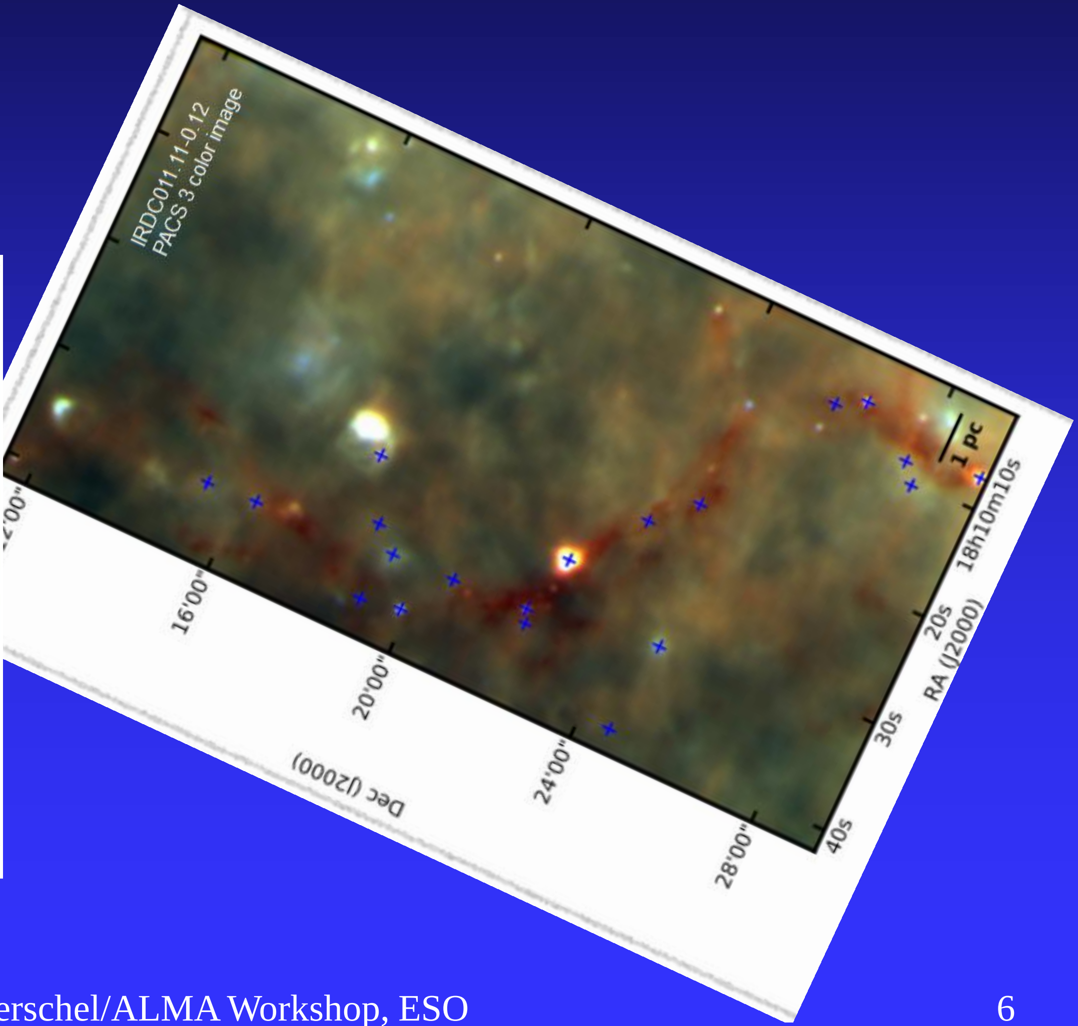
EPoS

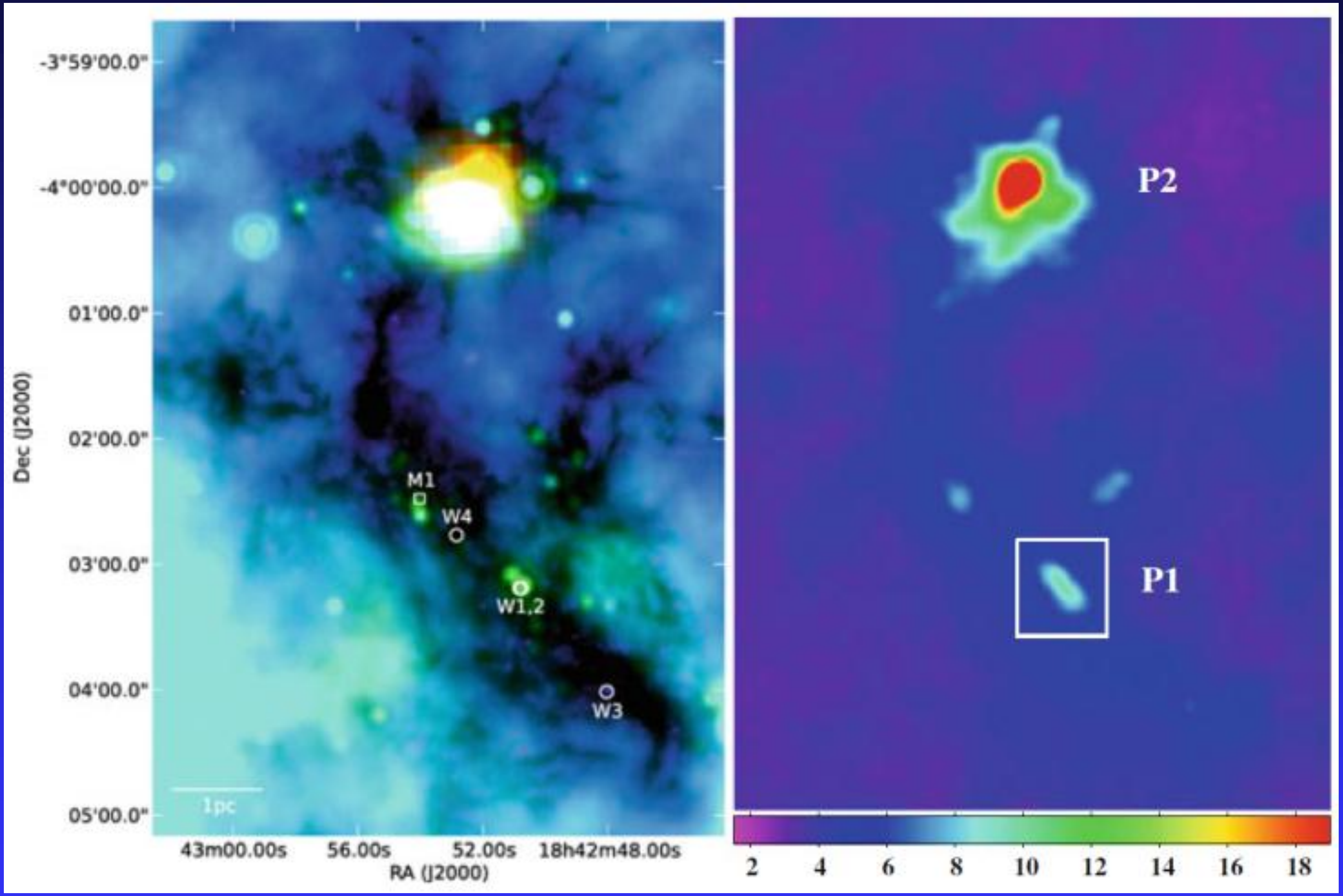
Molinari+2010

Hi-GAL




-59°41'00"
42'00"
43'00"
44'00"
45'00"
46'00"
47'00"
48'00"
Dec (J2000)
48s
36s
24s
14h44m12s
RA (J2000)

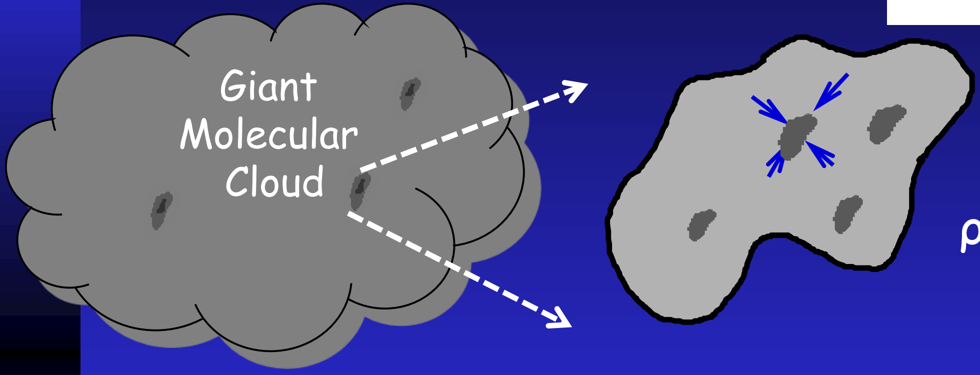

IRDC011.11-0.12
PACS 3 color image
1 pc
16'00"
20'00"
24'00"
28'00"
Dec (J2000)
18h10m10s
20s
30s
40s
RA (J2000)


-3°59'00.0"
-4°00'00.0"
01'00.0"
02'00.0"
03'00.0"
04'00.0"
05'00.0"
Dec (J2000)
M1
W4
W1,2
W3
1pc
43m00.00s
56.00s
52.00s
18h42m48.00s
RA (J2000)
P2
P1
2
4
6
8
10
12
14
16
18

Massive Star (Cluster) Formation

$$M_J = \frac{\pi}{6}\left(\frac{\pi C_s^2}{G}\right)^{3/2}\rho_o^{-1/2}$$

M_J ~ 1 Msun



??

ρ, T, ΔV, B,
feedb ck

r

10^2 pc
$n(H_2)$ ~ 10^2 cm^{-3}
M ~ 10^5 Msun

ge

- **What is the initial conditions (physical/chemical) for cluster star formation?**
- **How do massive clumps fragment & which processes control fragmentation?**
- **How to make massive cores?**
- **Does cluster star formation process in equilibrium?**

See review by
Zinnecker & Yorke 2007

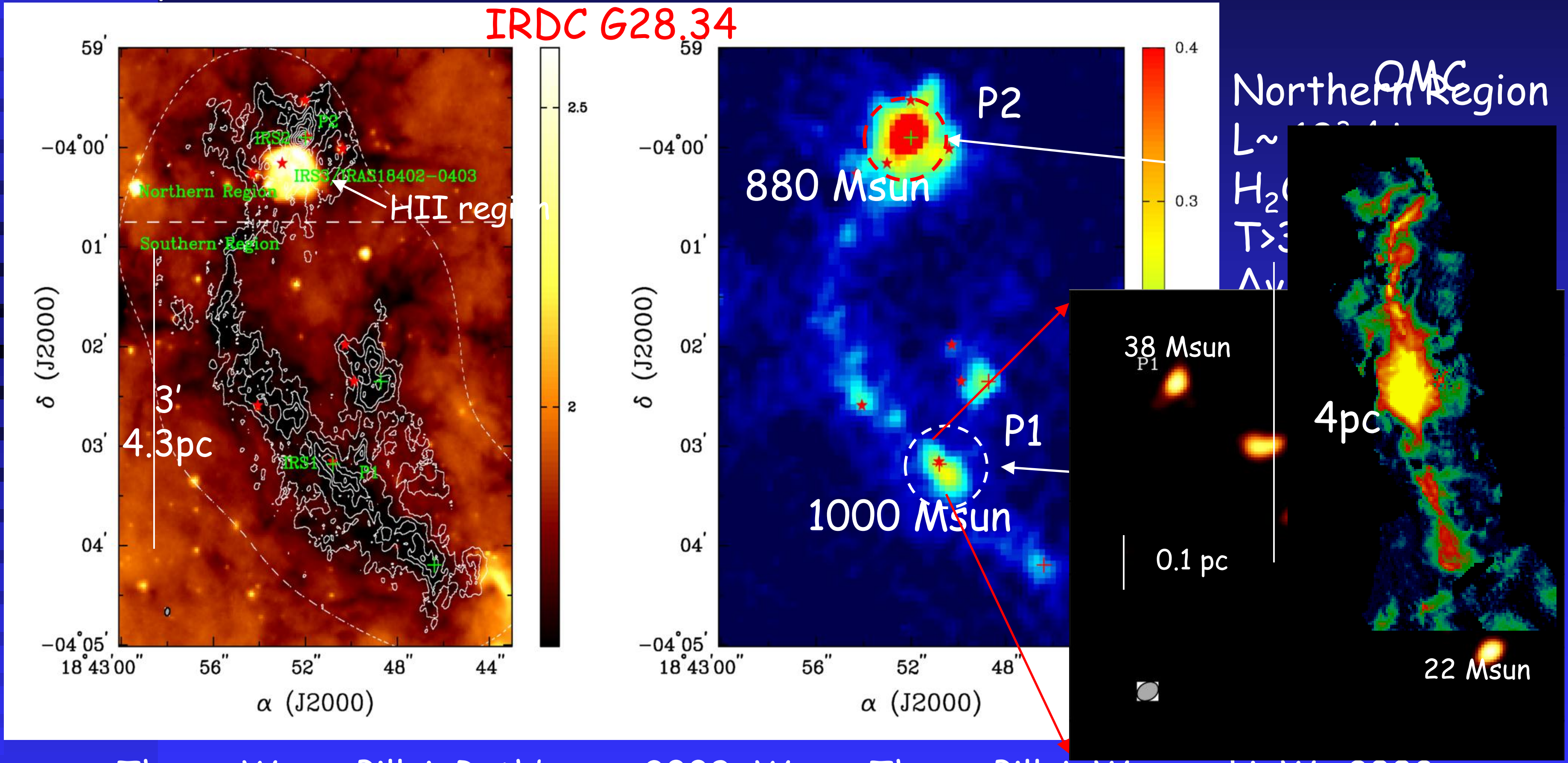
Clump Fragmentation: IRDC G28.34

VLA NH_3 (Contours) d=4.8kpc

Spitzer 8μm(color)

P1 will evolve into P2

1.2mm continuum



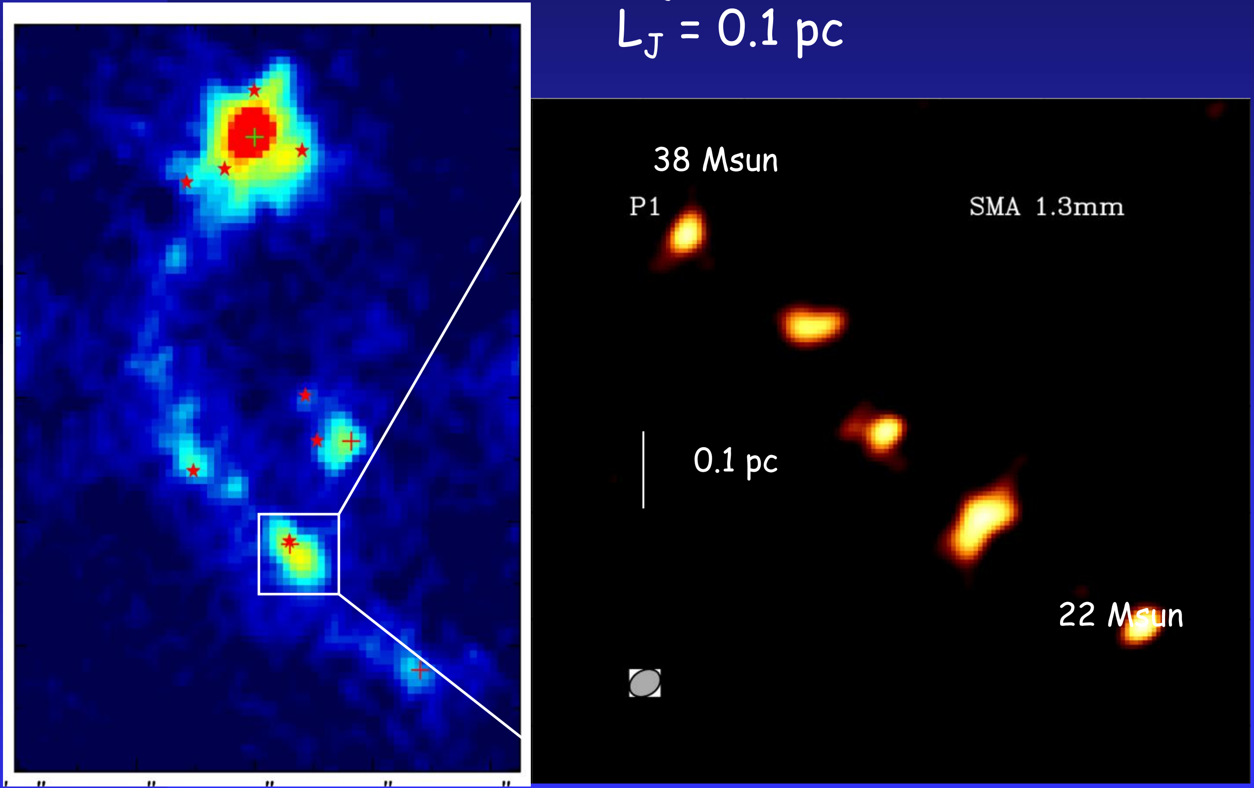
Zhang, Wang, Pillai, Rathborne 2009; Wang, Zhang, Pillai, Wyrowski, Wu 2008
Wang, Zhang, Rathborne, Jackson, Wu 2006

Cores contain many Jeans mass

$n(H_2)=7x10^4$ cm^{-3}, T=15K
M_J (thermal) = 2 Msun
L_J = 0.1 pc

➔

For spatially resolved cores (res < L_J)
$M_{core}/M_J > 10$,



$$M_J = \frac{\pi}{6}\left(\frac{\pi C_s^2}{G}\right)^{3/2} \rho_o^{-1/2}$$

σv=0.7 km/s
M_{turb_J} ~ 30 Msun
L_{turb_J} ~ 0.3 pc

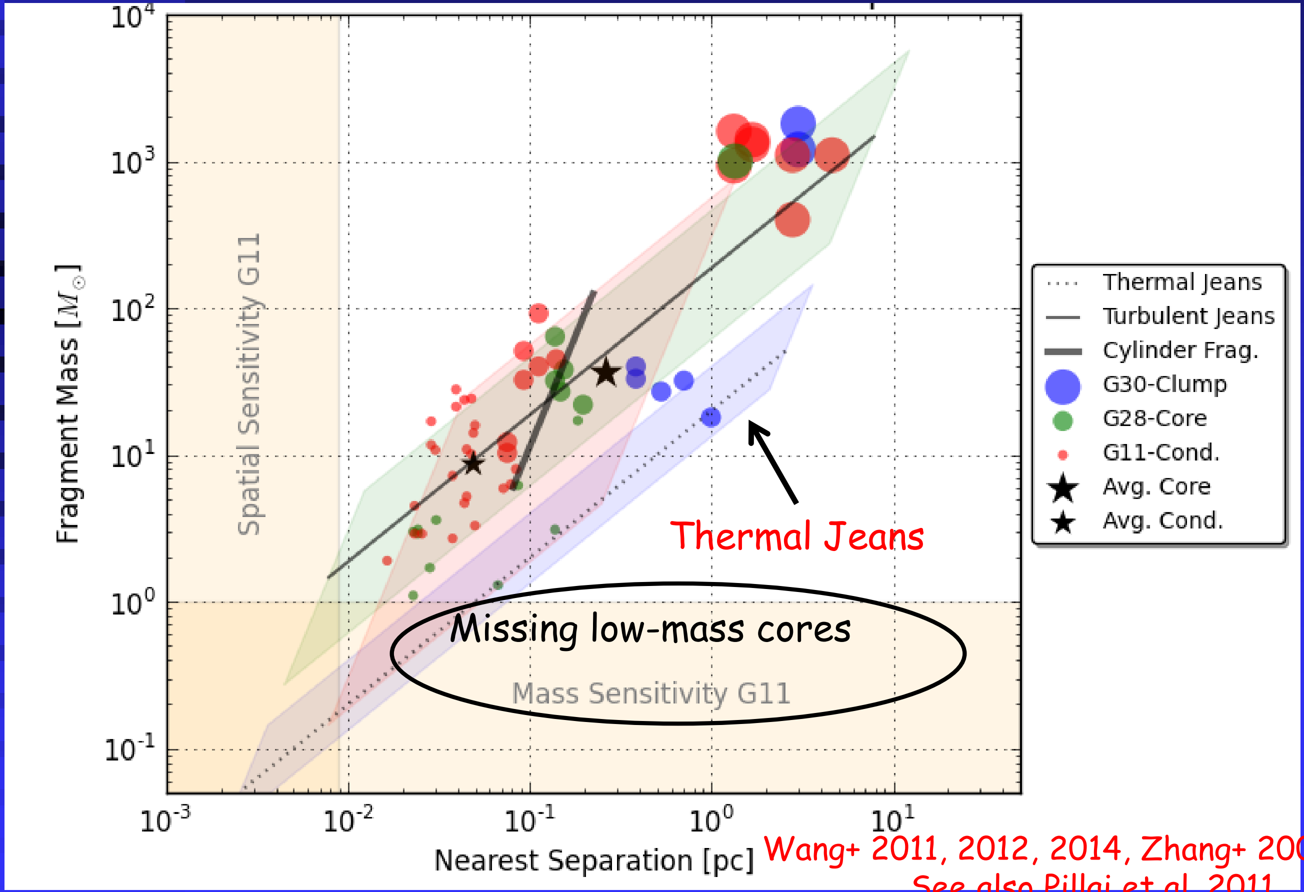
Turbulence (and B field)
Supported fragmentation?

Zhang, Wang, Pillai, Rathborne 2009

See also Brogan et al. 2009; Longmore et al 2010; Csengeri et al. 2010, 11; Pillai et al. 2011; Tan et al. 2013

Hierarchical Fragmentation

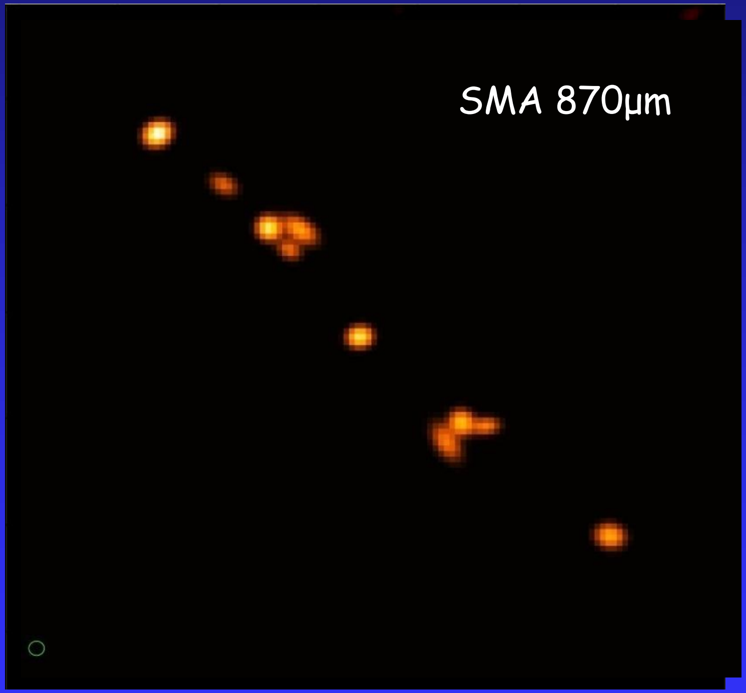
Comparison with Jeans fragmentation:
Thermal fragmentation does not explain massive cores
Additional support from turbulence and/or magnetic field



See Chandrasekhar & Fermi 1953;
Larson 1985; Nagasawa 1987

Wang+ 2011, 2012, 2014, Zhang+ 2009, 2011
See also Pillai et al. 2011

G28.34: Further Fragmentation:



Cores further fragment into
condensations at a res ~ 0.5"
M = several – 10 Msun

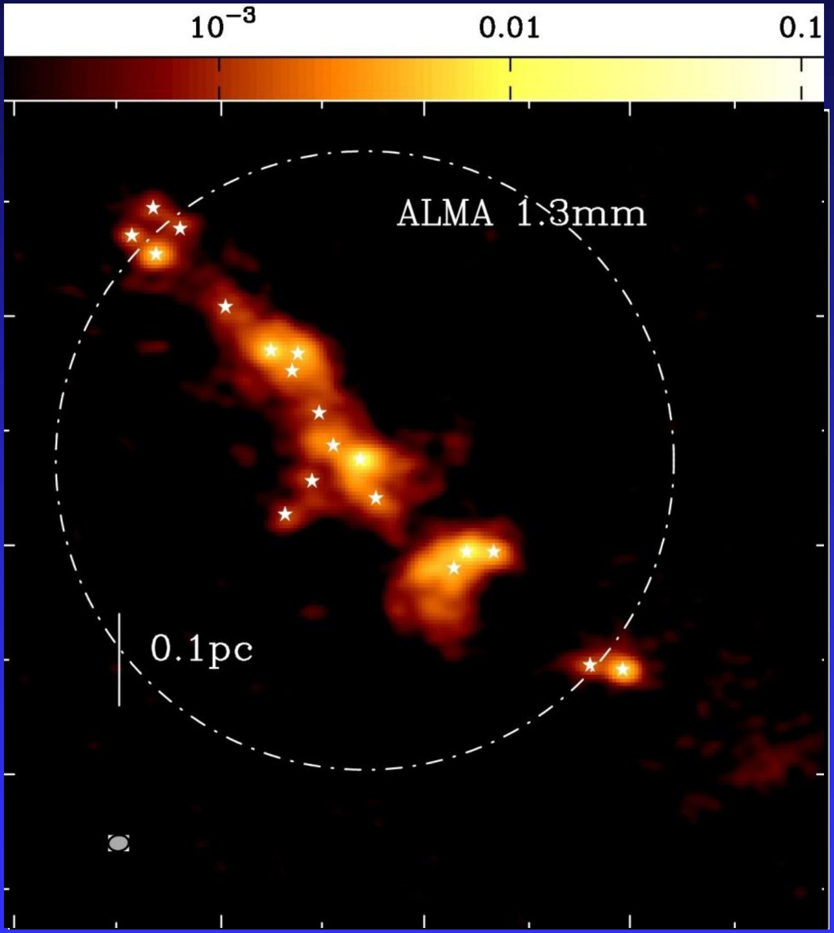
$n(H_2)=10^6\ cm^{-3}$, T=16K
M_J (thermal) = 0.5 Msun
L_J = 0.025 pc (1")

For Spatially resolved
condensation (res < L_J)
$M_{frag}/M_J > 10$

See also Brogan et al. 2009; Longmore
et al 2010' Csengeri et al. 2010, 11

Wang, et al. 2011

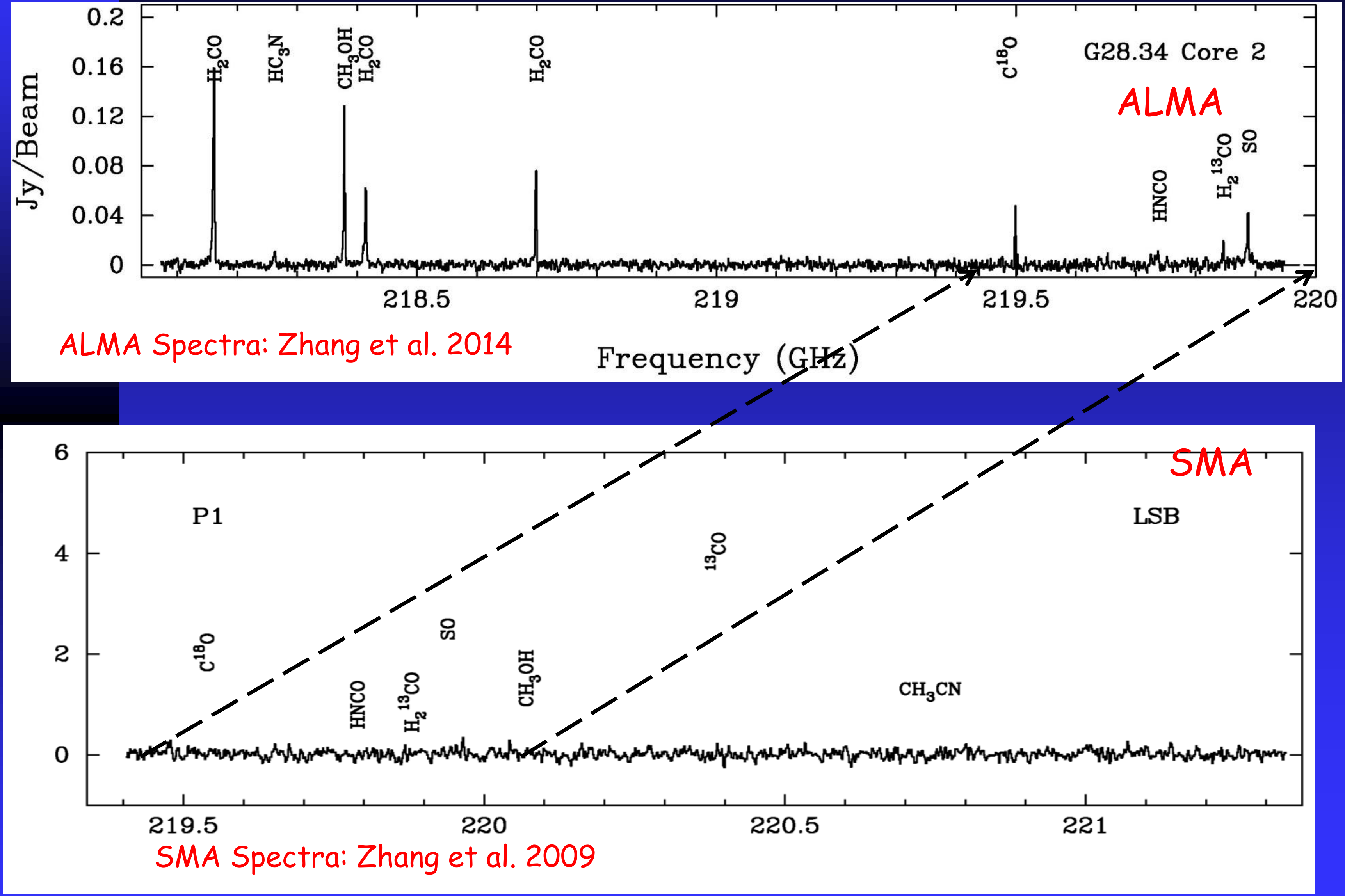
G28.34: ALMA Observations



ALMA observations reached a 3σ mass sensitivity of 0.15 Msun, far below the global Jeans mass of 2 Msun.

Zhang Wang, et al. 2015

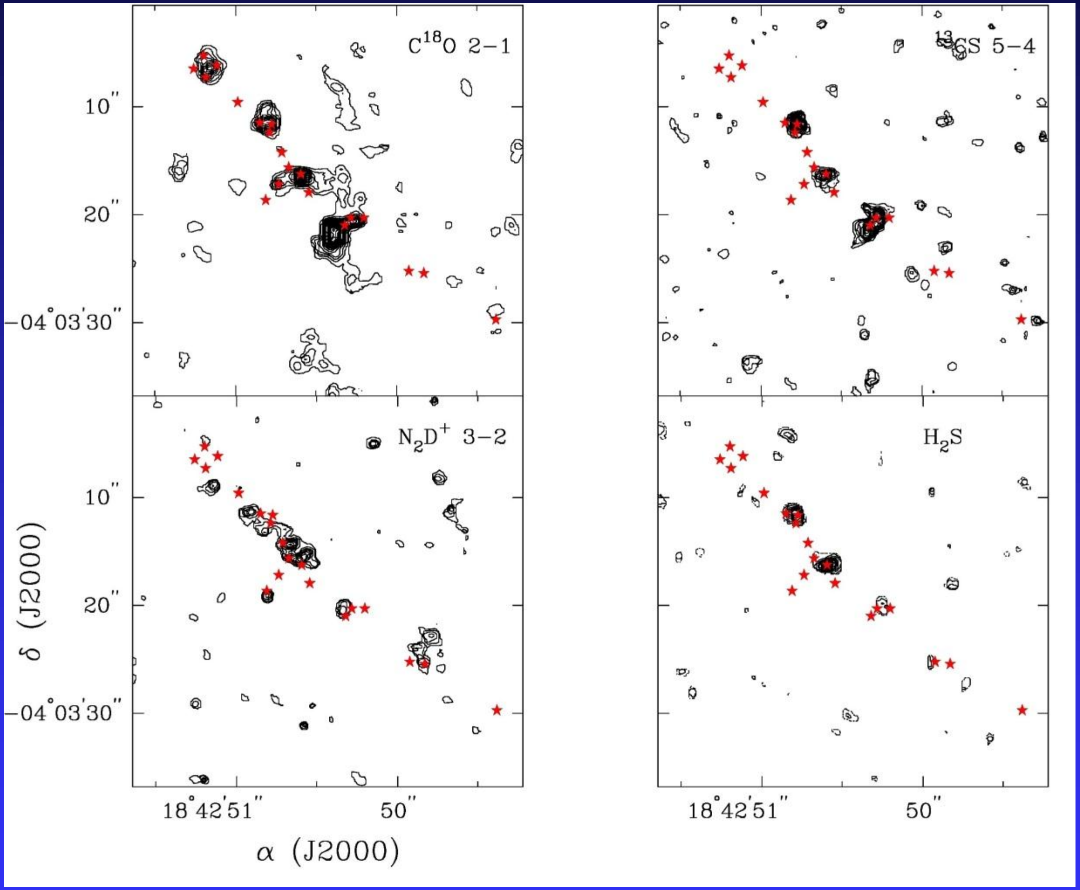
Chemistry:



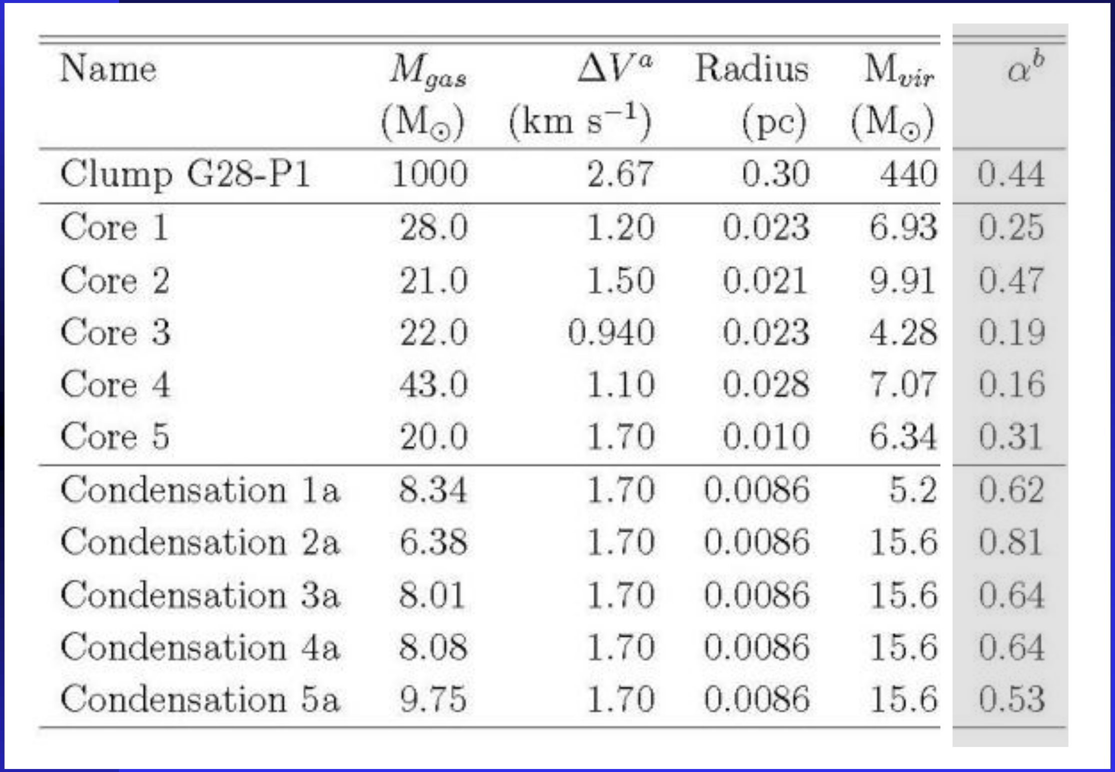
ALMA Spectra: Zhang et al. 2014

SMA Spectra: Zhang et al. 2009

Emission from Dense Cores:



Does cluster formation from equilibrium gas



Name	M_{gas} ($M_\odot$)	ΔV^a (km s^{-1})	Radius (pc)	M_{vir} ($M_\odot$)	α^b
Clump G28-P1	1000	2.67	0.30	440	0.44
Core 1	28.0	1.20	0.023	6.93	0.25
Core 2	21.0	1.50	0.021	9.91	0.47
Core 3	22.0	0.940	0.023	4.28	0.19
Core 4	43.0	1.10	0.028	7.07	0.16
Core 5	20.0	1.70	0.010	6.34	0.31
Condensation 1a	8.34	1.70	0.0086	5.2	0.62
Condensation 2a	6.38	1.70	0.0086	15.6	0.81
Condensation 3a	8.01	1.70	0.0086	15.6	0.64
Condensation 4a	8.08	1.70	0.0086	15.6	0.64
Condensation 5a	9.75	1.70	0.0086	15.6	0.53

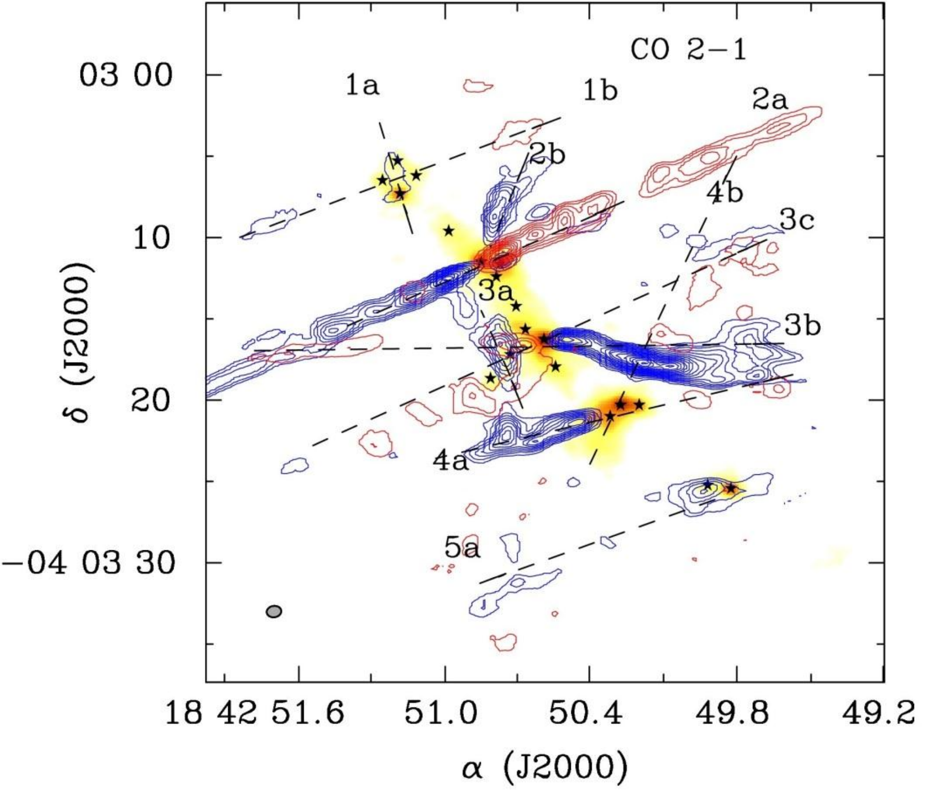
$$\alpha = \frac{M_{vir}}{M} = \frac{5\sigma^2 R}{GM}$$

See also Csengeri et al. 2011, Pillai et al. 2011, Tan et al. 2013

Magnetic fields may play an important role in cloud support

B ~> 1 mG see Zhang et al 2014.

CO Outflows



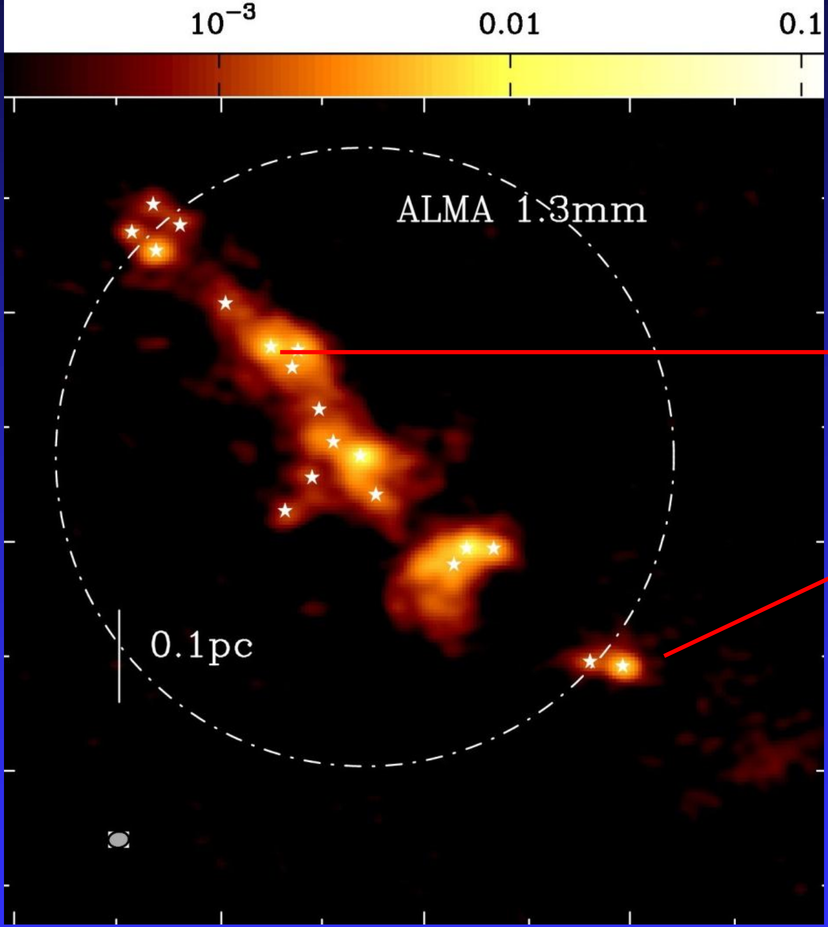
10 molecular outflows
Outflow energetics consistent with those of intermediate stars

Outflow energy ~ turbulent energy

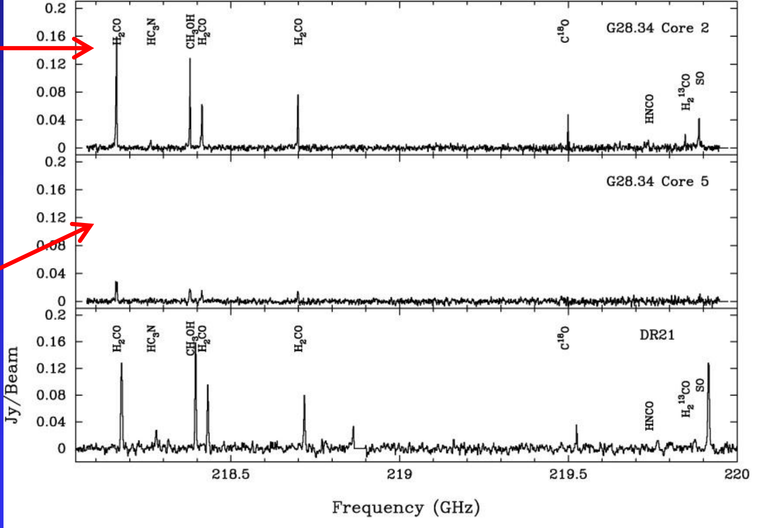
M_{acc} ~ 10^{-5} Msun/yr

Need 10^6 yrs to form 10 Msun *if* M_{acc} = cont.

Chemical Differentiation



Cores 2,3,4 are chemically more advanced than Cores 1,2 Comparison with protostellar cores in DR 21 filament suggests Cores 2,3,4 harbor intermediate mass protostas!

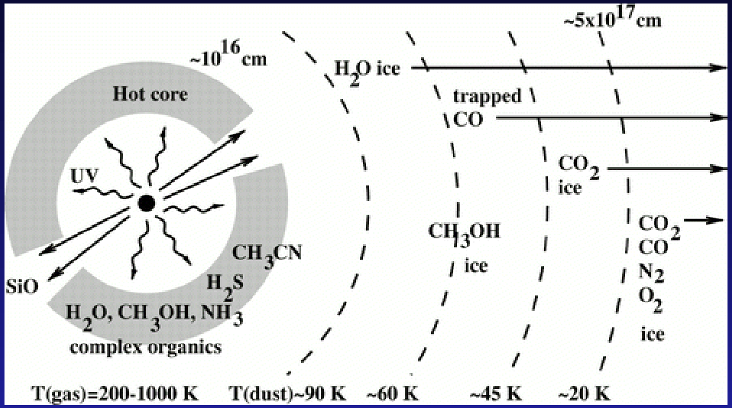


Chemical Evolution: Cold Core to Hot Core

Follow dynamic collapse and chemical evolution (depletion) under a constant T

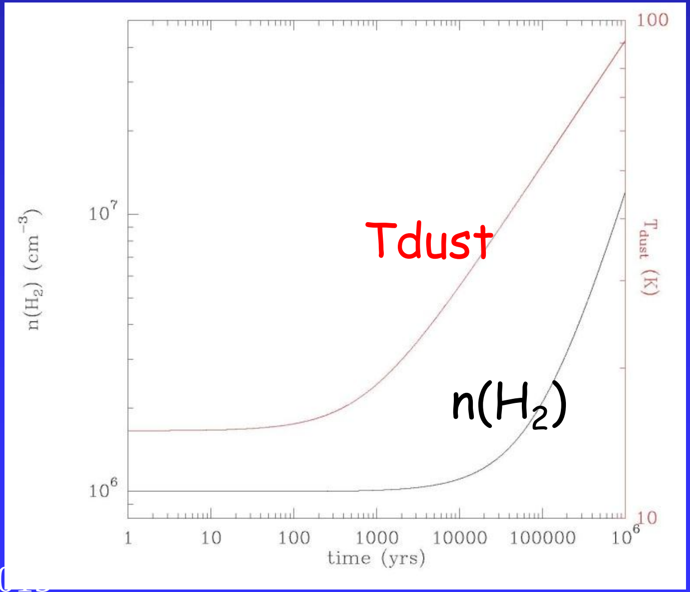
Turn on protostellar heating and follow chemical evolution in gas phase

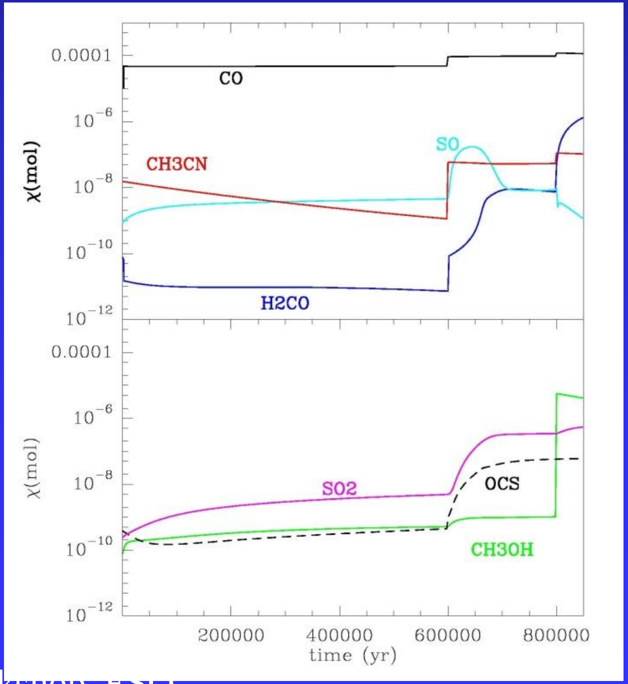
See Viti et al. 2004



van Dishoeck & Blake 1998

With Jimenez-Serra, Viti et al.

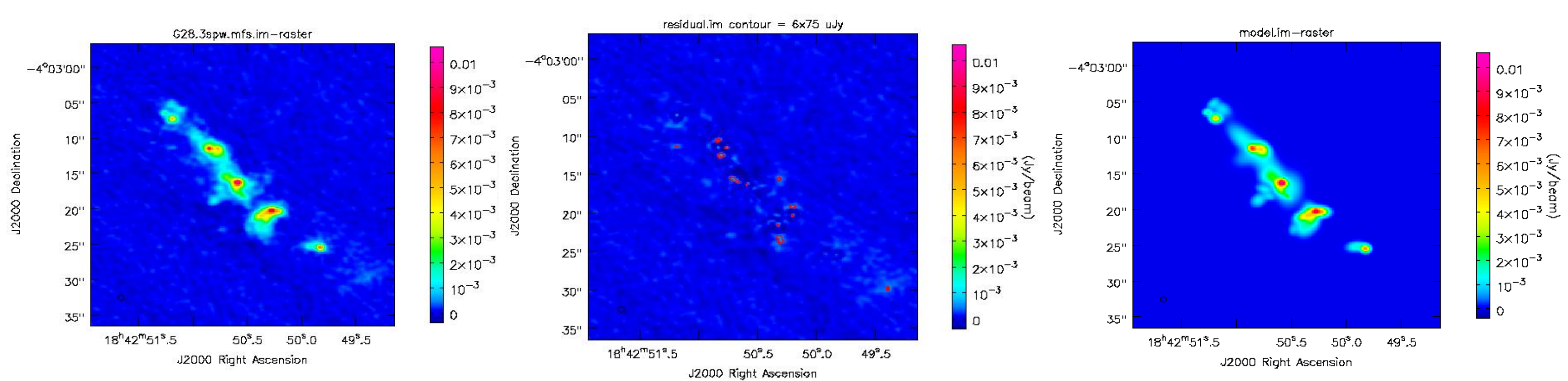




ALMA 1.3mm

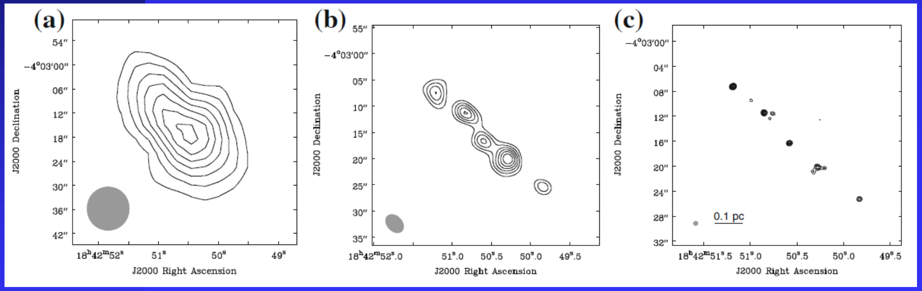
Residual

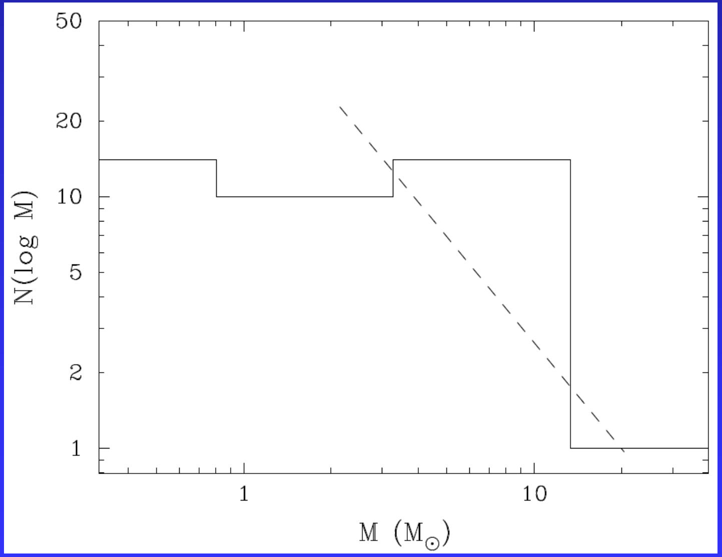
Model (38 sources)



Zhang, Wang, Lu, Jiminez-Serra, 2015

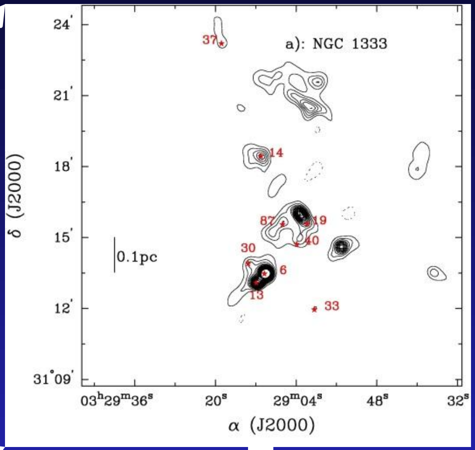
Wang et al. 2011,2012,2015





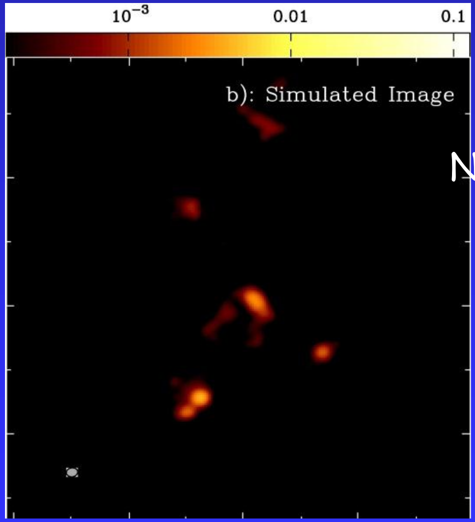
Where are low-mass protostars?

Gutermuth et al. 2009



Kirk et al. 2006
SCUBA 870 μm

ALMA simulated observations at 1.3mm



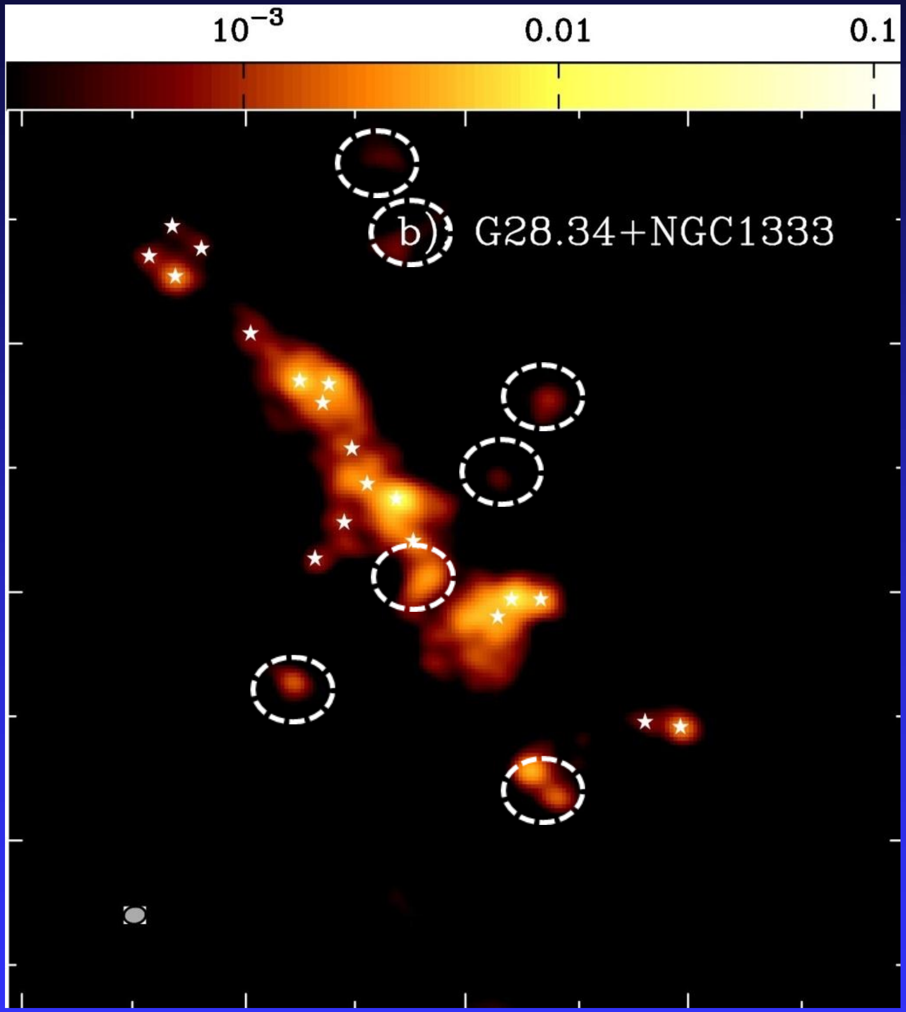
NGC 1333 Class 0 protostars
detected at distance
of G28.34

Where are low-mass protostars?

Simulated ALMA observations using G28 and NGC1333

A low-mass such as NGC1333 can be reliably detected if present

Low-mass protostars form after massive ones in a cluster



Conclusions

- *Hershel* is the right telescope to identify intrinsically cold and dense molecular clumps, better than just IR-dark!
- Massive cores formed during early fragmentation are 10x to 10^2x more massive than thermal Jeans mass → Important role of turbulence support and perhaps magnetic fields.
- Gas in cluster forming clumps is sub-virial, unless magnetic fields are strong (~ mG)
- Massive protostars grow from low-intermediate mass protostars.
- Dense cores harboring massive stars undergo significant increase in temperature (and perhaps mass). As a result, they undergo chemical change during the early evolution.
- Low-mass protostars appear to form after the formation of massive stars.