Fragmentation of Molecular Clumps and Formation of Protoclusters

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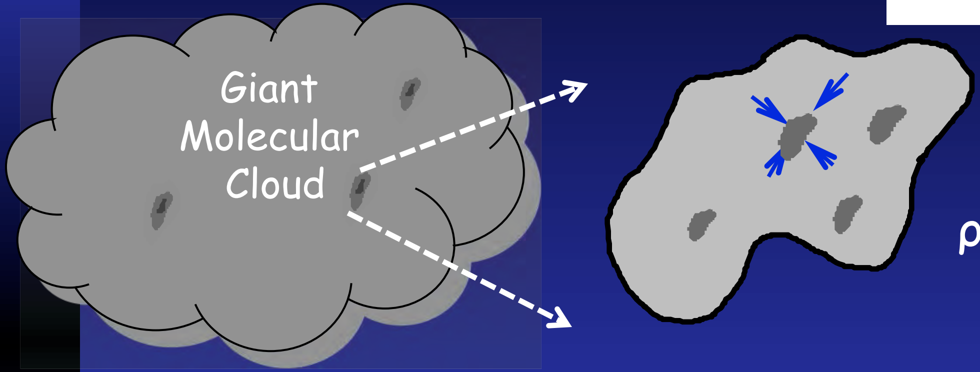
Massive Star (Cluster) Formation



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

M_J ~ 1 Msun

??

- - - - - - ->

ρ, T, ΔV, B,
feedb

r

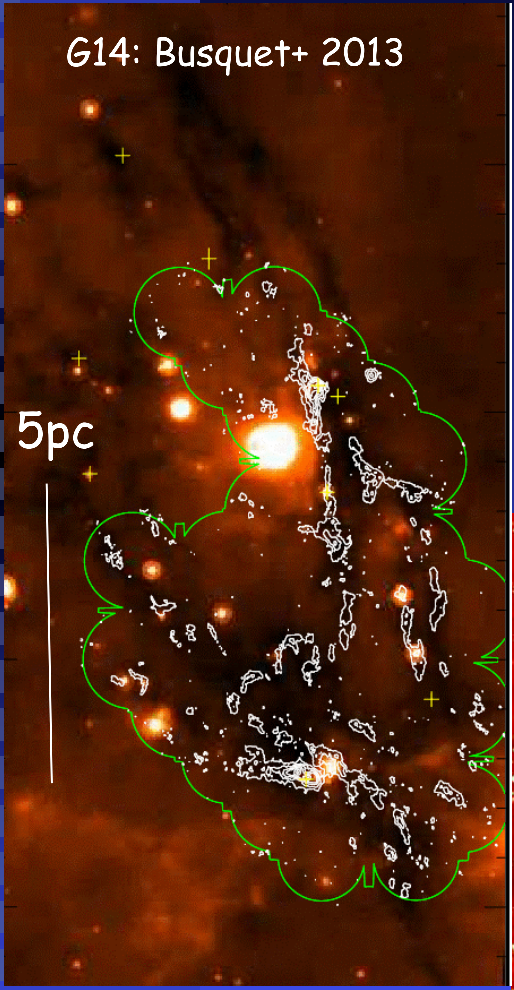
ge

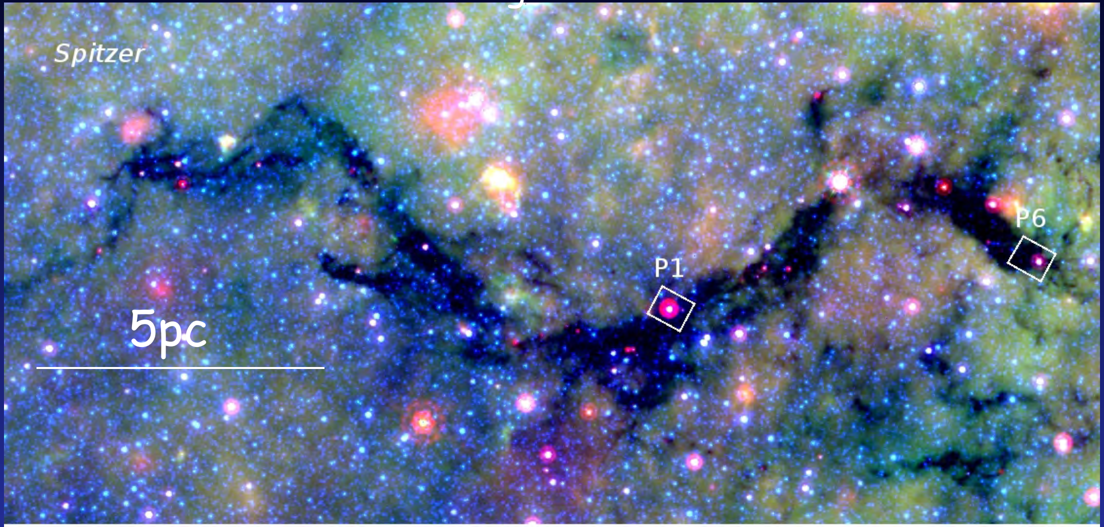
10^2 pc
$n(H_2)$ ~ 10^2 cm^{-3}
M ~ 10^5 Msun

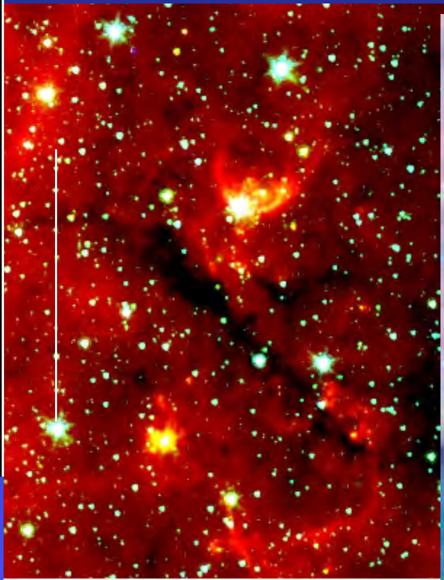
- **What is the initial conditions (physical/chemical) for cluster star formation?**
- **How do massive clumps fragment & which processes control fragmentation?**
- **How to make massive cores?**
- **Does cluster star formation proceed in equilibrium?**

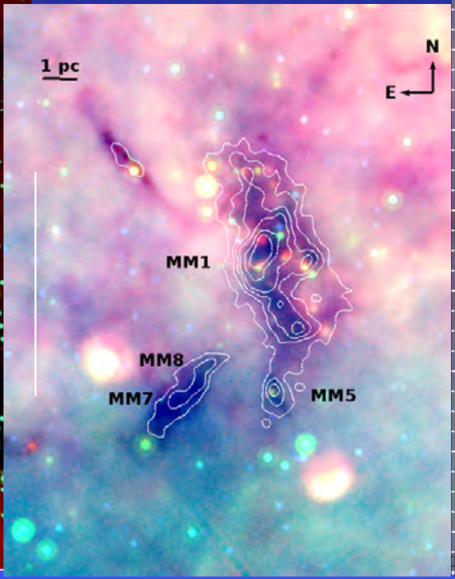
See review by
Zinnecker & Yorke 2007

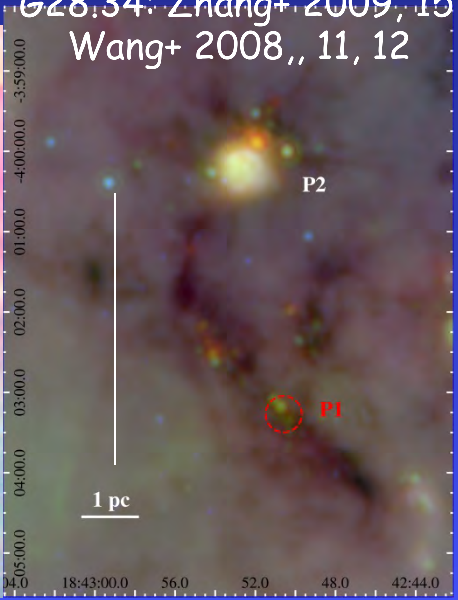
Recent High-Res Imaging of IRDCs


G14: Busquet+ 2013

G11.11: Wang+ 2014


G30.88: Zhang+ 2011


G28.53: Lu + 2015


G28.34: Zhang+ 2009, 15
Wang+ 2008,, 11, 12


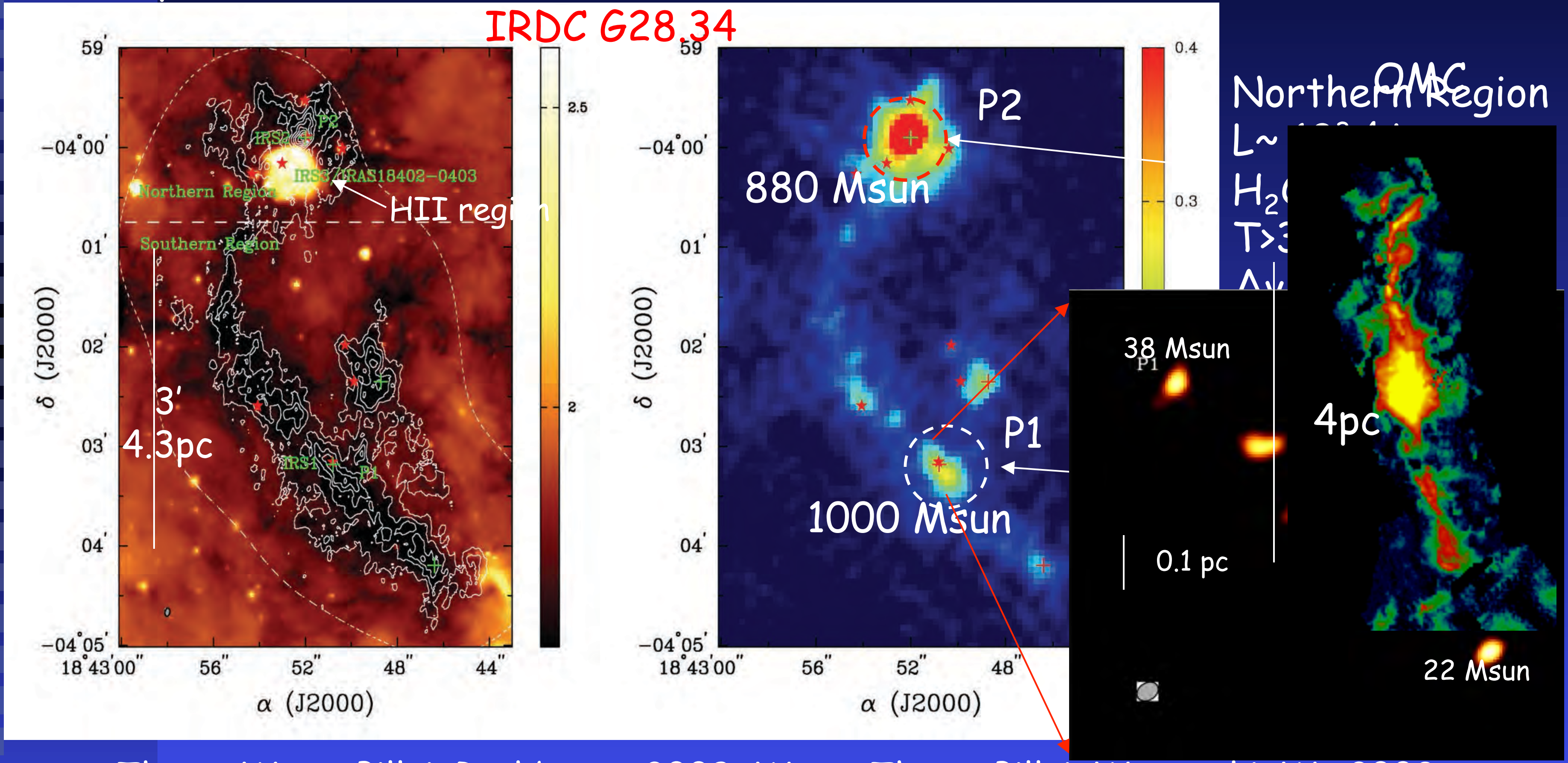
Clump Fragmentation: IRDC G28.34

VLA NH_3 (Contours) d=4.8kpc

Spitzer 8μm(color)

1.2mm continuum

P1 will evolve into P2



Zhang, Wang, Pillai, Rathborne 2009; Wang, Zhang, Pillai, Wyrowski, Wu 2008
Wang, Zhang, Rathborne, Jackson, Wu 2006; Rathborne et al. 2010

Cores contain many Jeans mass

$n(H_2)=7\times10^4$ cm^{-3}, T=15K
M_J (thermal) = 2 Msun
L_J = 0.1 pc

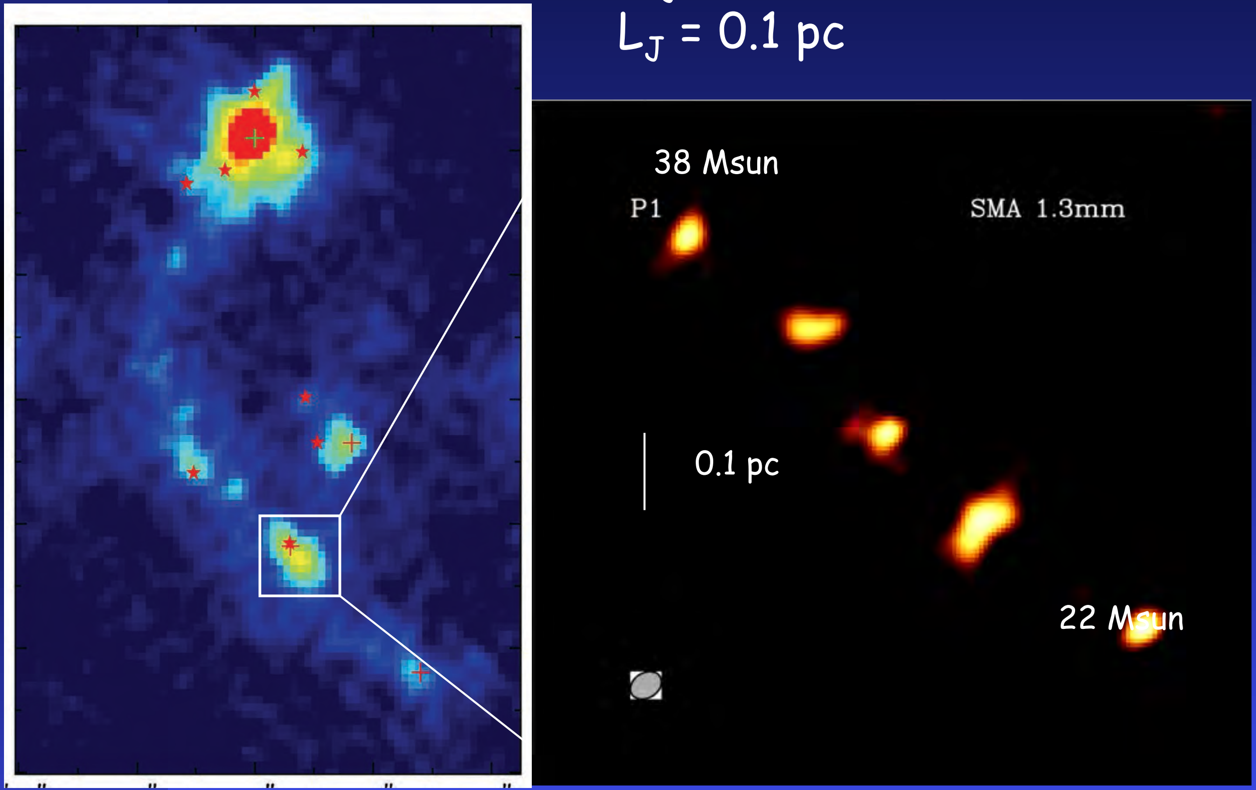
➔

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?

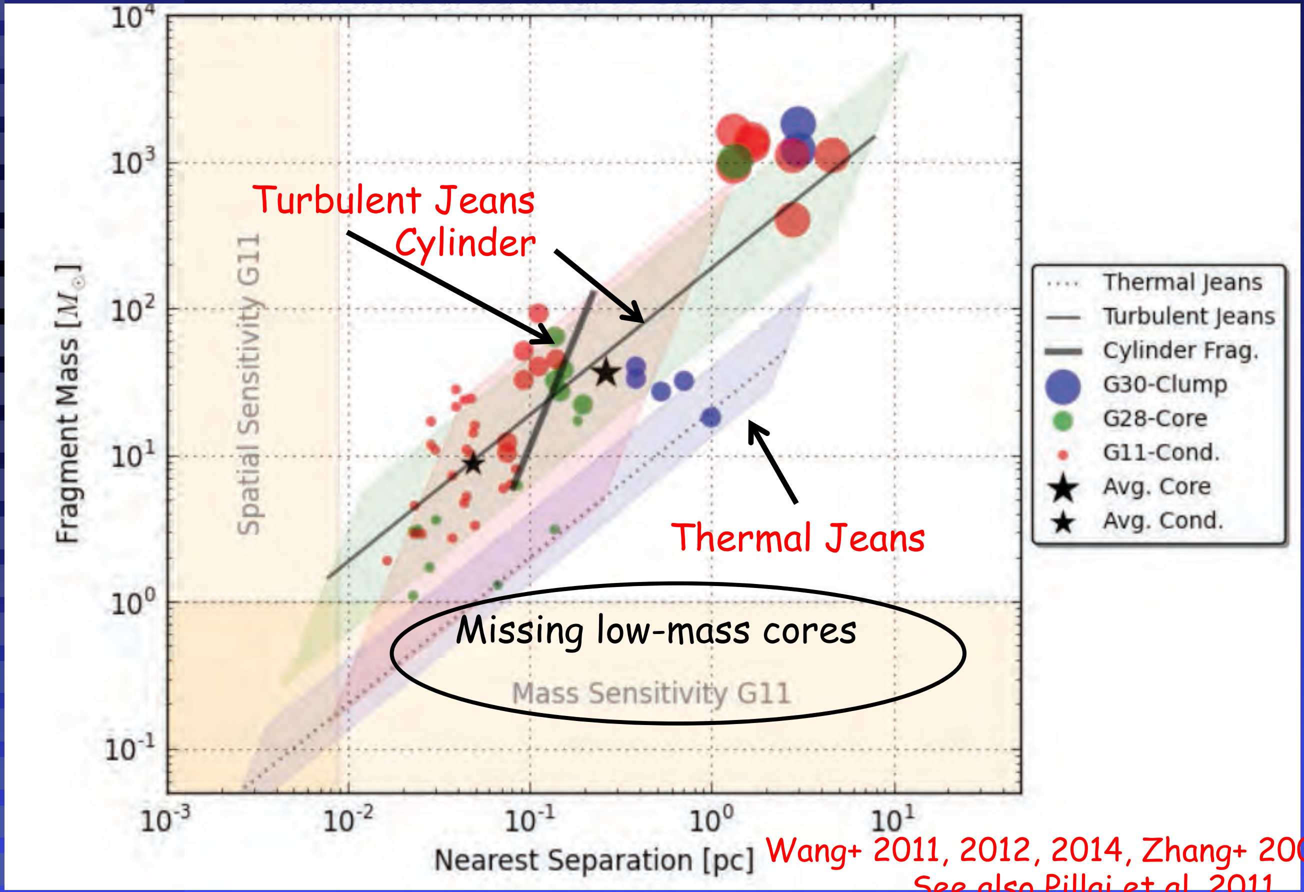


Zhang, Wang, Pillai, Rathborne 2009

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



Turbulent Jeans
Cylinder

Thermal Jeans

Missing low-mass cores

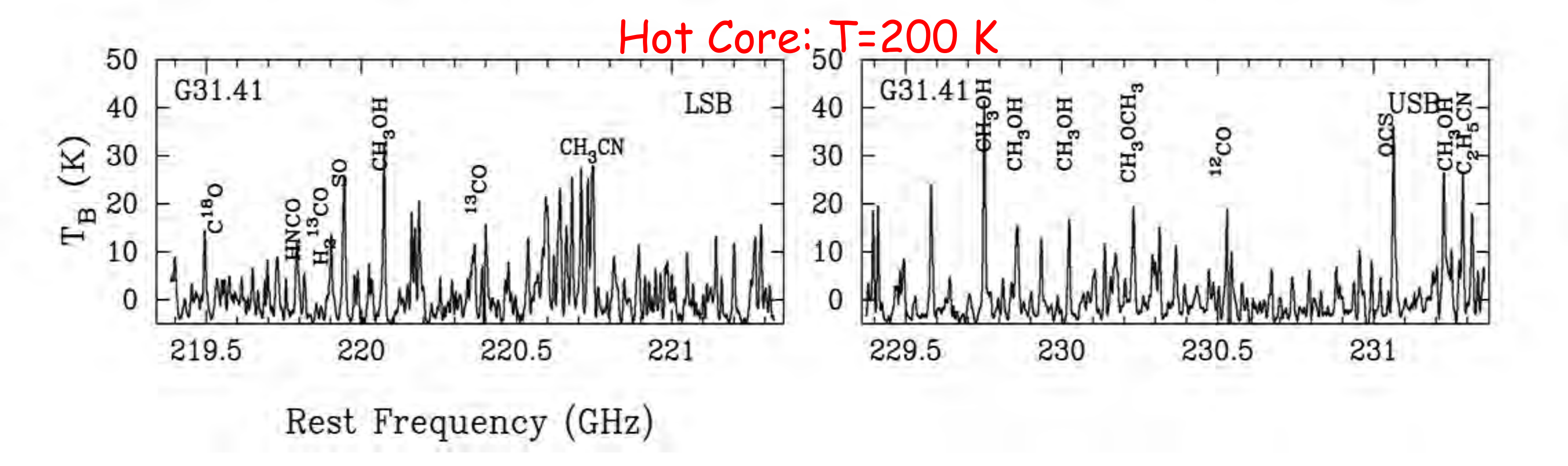
Wang+ 2011, 2012, 2014, Zhang+ 2009, 2011
See also Pillai et al. 2011

$$M/L = \left(\frac{2\delta_v}{G}\right)$$

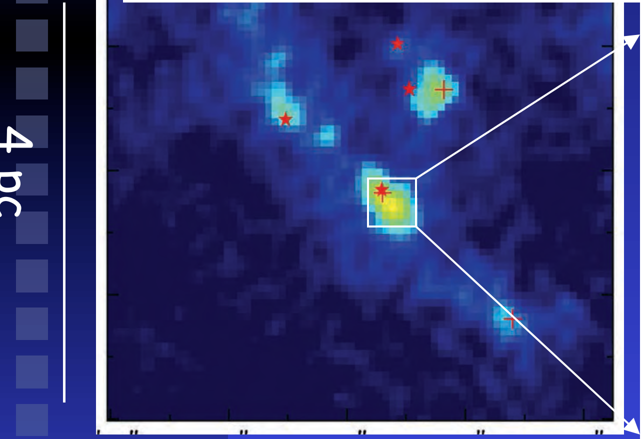
$$\lambda_{\max} = \begin{cases} 0.15\,\mathrm{pc}\left(\frac{c_s}{0.21\,\mathrm{km\,s^{-1}}}\right)\left(\frac{n}{3\times10^5\,\mathrm{cm^{-3}}}\right) & \text{for thermal support,} \\ 0.13\,\mathrm{pc}\left(\frac{\sigma}{0.72\,\mathrm{km\,s^{-1}}}\right)\left(\frac{n}{5\times10^6\,\mathrm{cm^{-3}}}\right) & \text{for turbulent support.} \end{cases}$$

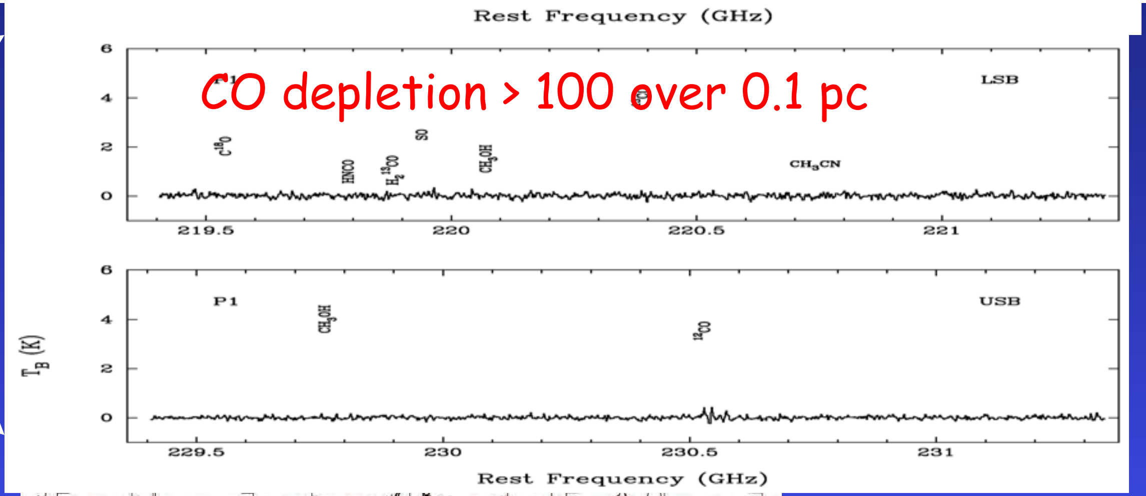
See Chandrasekhar & Fermi 1953;
Larson 1985; Nagasawa 1987

G28.34+0.06: Chemical Evolution

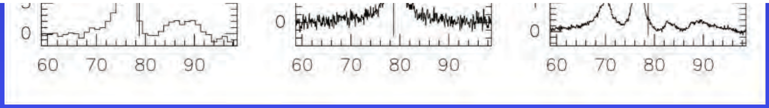


Hot Core: T=200 K



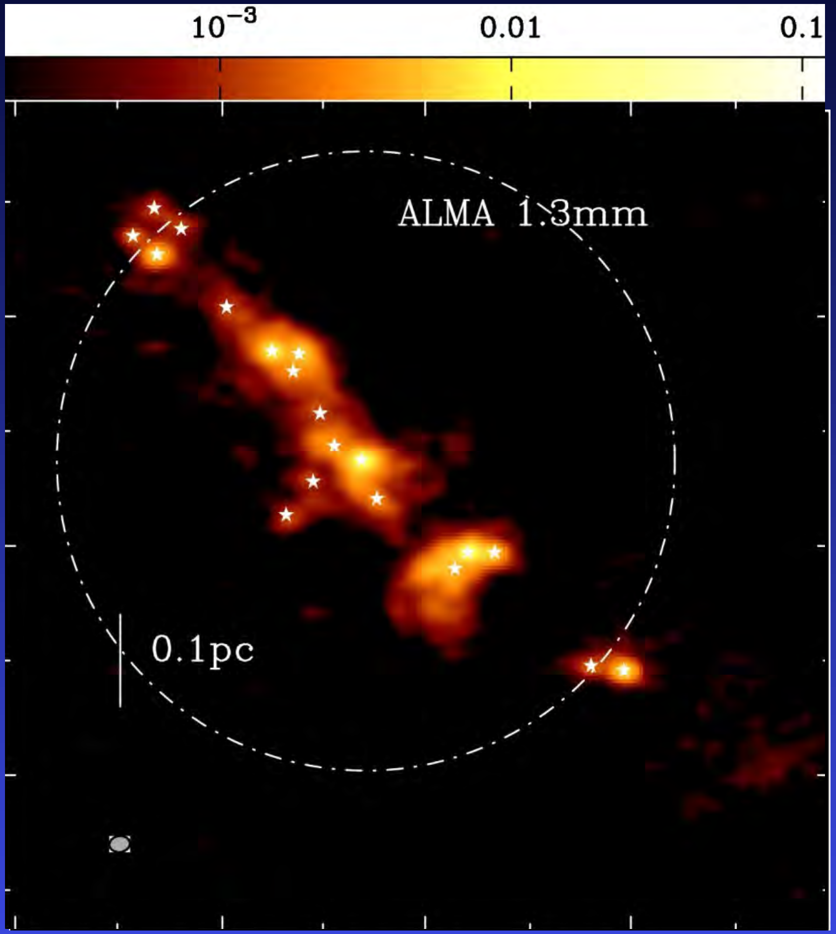


CO depletion > 100 over 0.1 pc



Rathborne et al. 2006
Zhang et al. 2009
See also Rathborne et al. 2008; Sanhueza et al. 2013

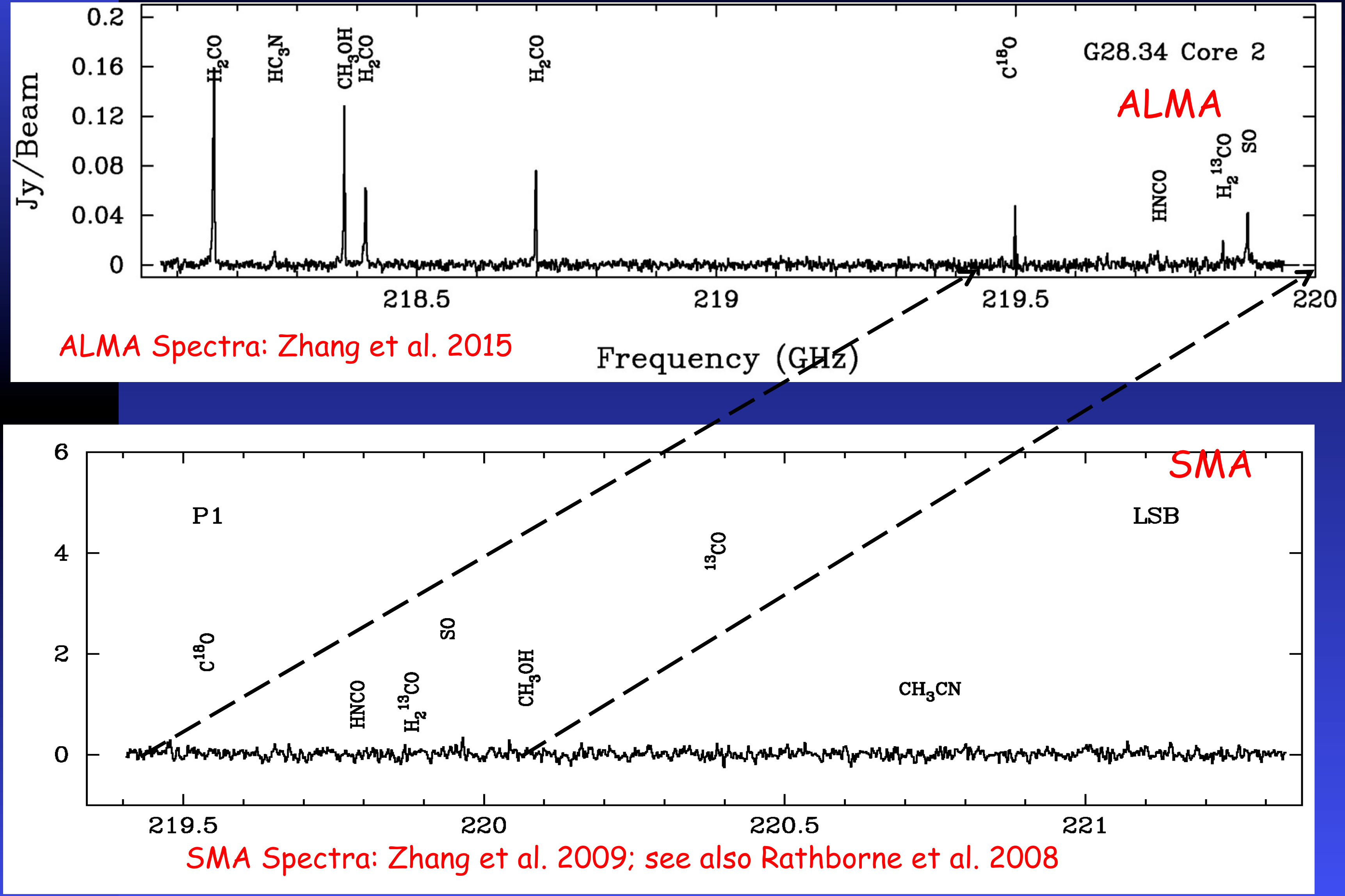
G28.34: ALMA Observations



ALMA observations reached a 3σ mass sensitivity of 0.2 Msun, far below the global Jeans mass of 2 Msun.

Zhang et al. 2015 (arxiv: 1503.03017)

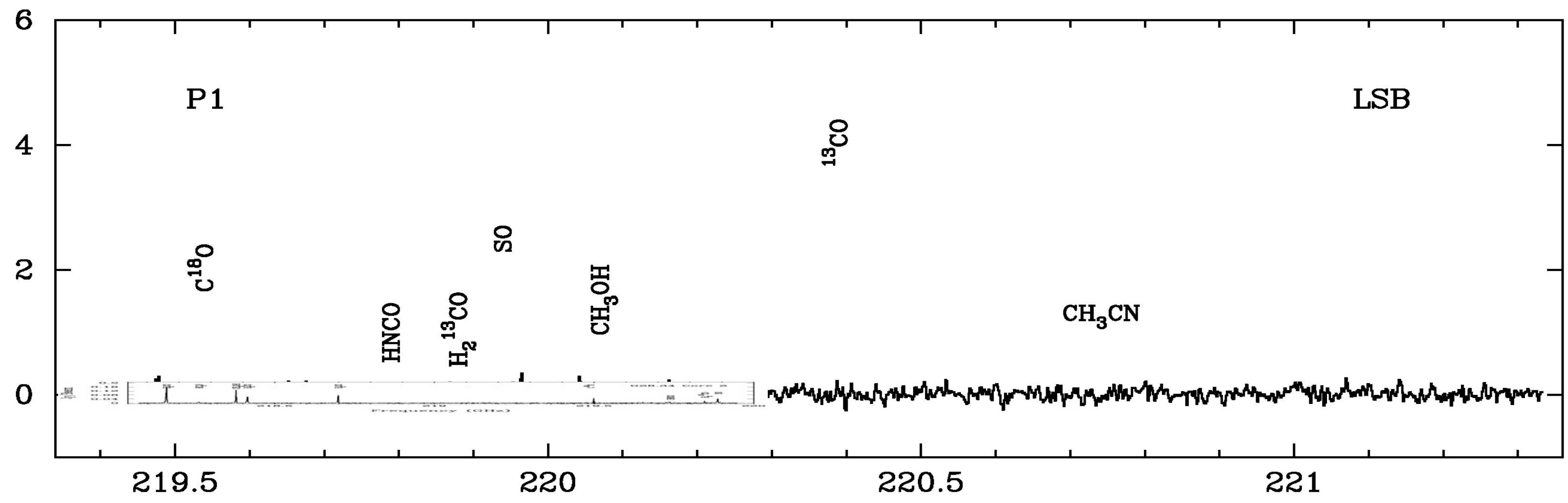
Time for Some Chemistry:



ALMA Spectra: Zhang et al. 2015

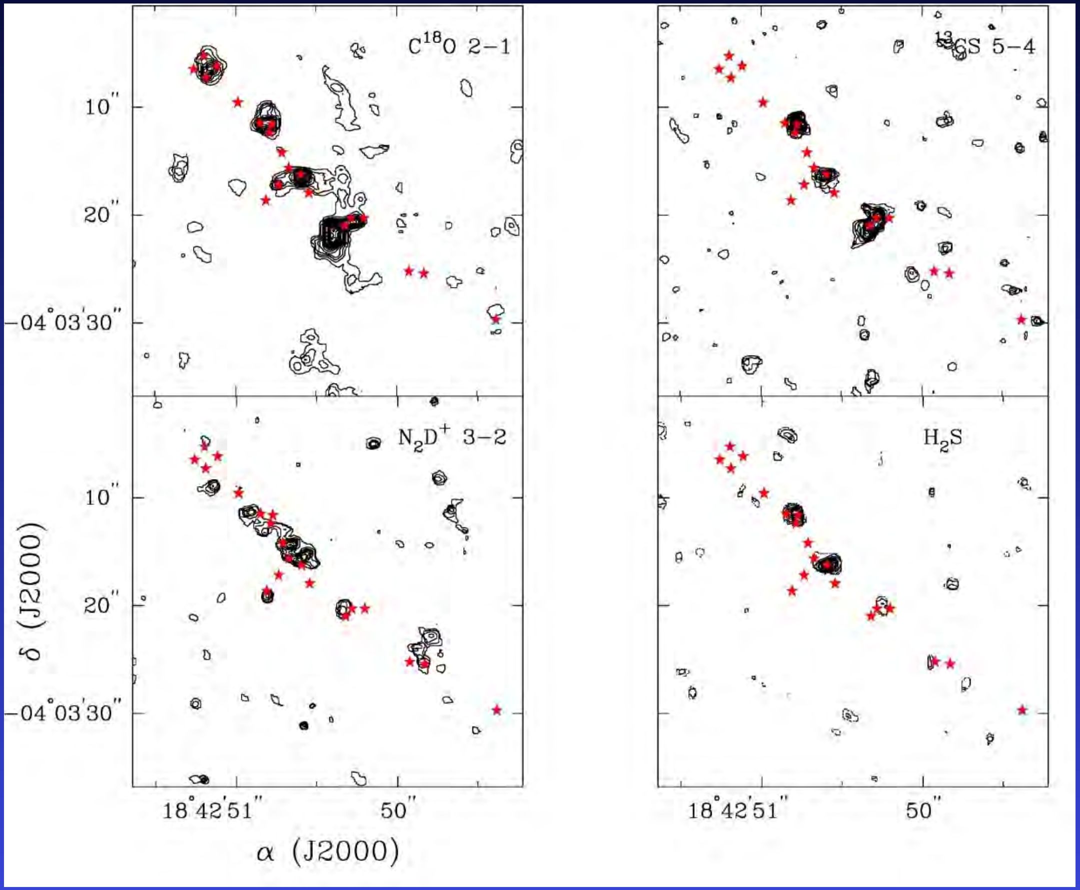
SMA Spectra: Zhang et al. 2009; see also Rathborne et al. 2008

Time for Some Chemistry:



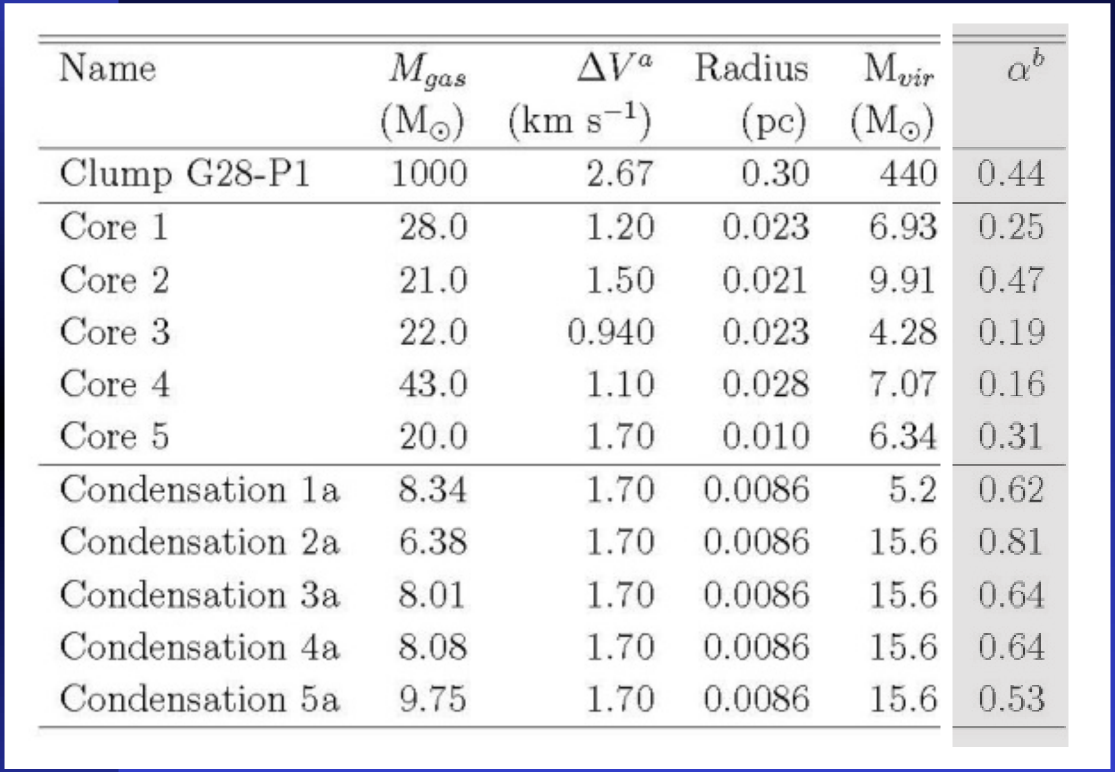
SMA Spectra: Zhang et al. 2009

Emission from Dense Cores:



Zhang et al. 2014

Does cluster formation from equilibrium gas



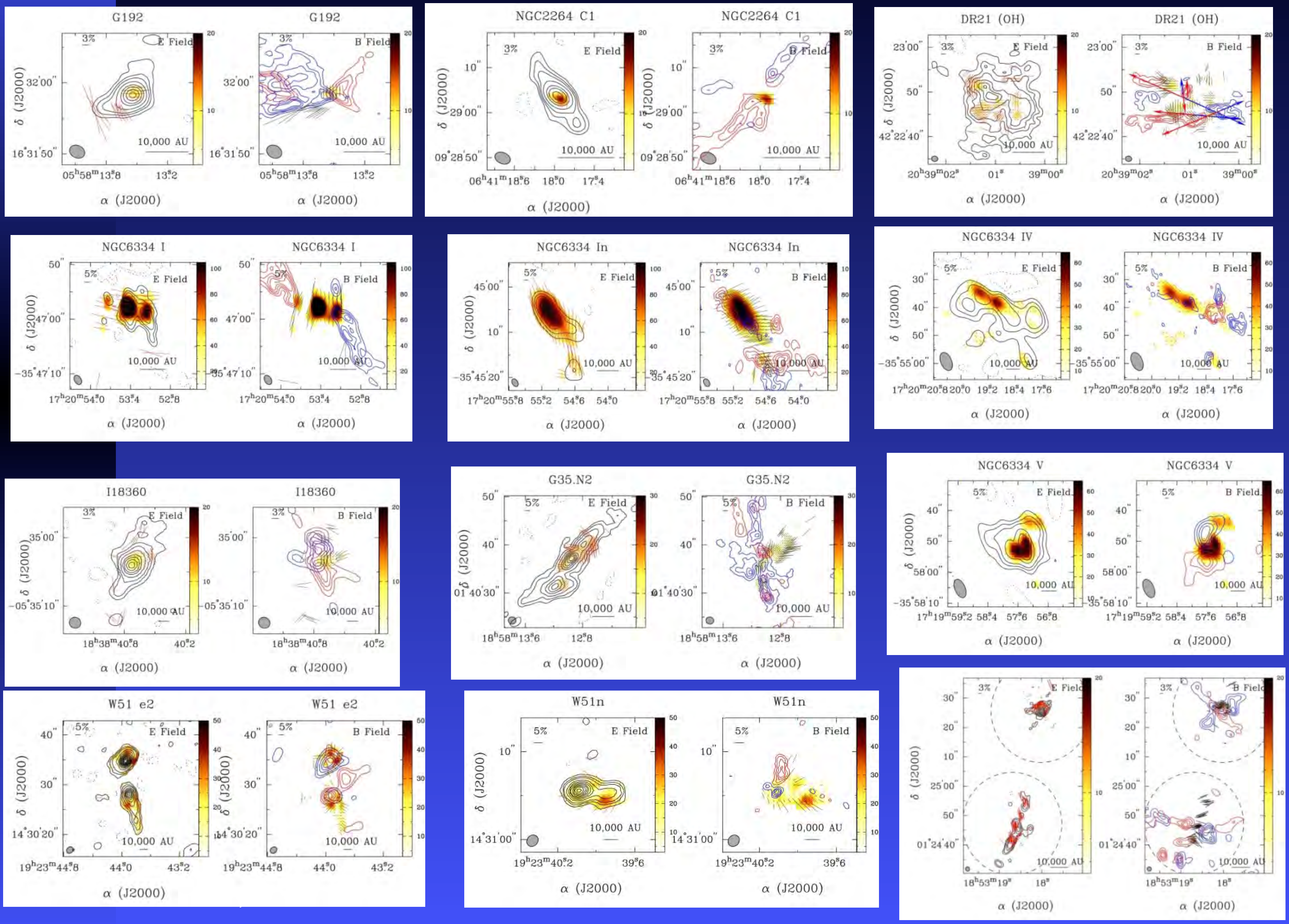
Name	M_{gas} ($M_\odot$)	ΔV^a (km s^{-1})	Radius (pc)	M_{vir} ($M_\odot$)	α^b
Clump G28-P1	1000	2.67	0.30	440	0.44
Core 1	28.0	1.20	0.023	6.93	0.25
Core 2	21.0	1.50	0.021	9.91	0.47
Core 3	22.0	0.940	0.023	4.28	0.19
Core 4	43.0	1.10	0.028	7.07	0.16
Core 5	20.0	1.70	0.010	6.34	0.31
Condensation 1a	8.34	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, 2015; Tan et al. 2013

Magnetic Fields ??

SMA Polarization Survey of Massive SF Regions



Zhang et al. 2014 See also talk by Girart

Role of Magnetic Fields in Cluster formation

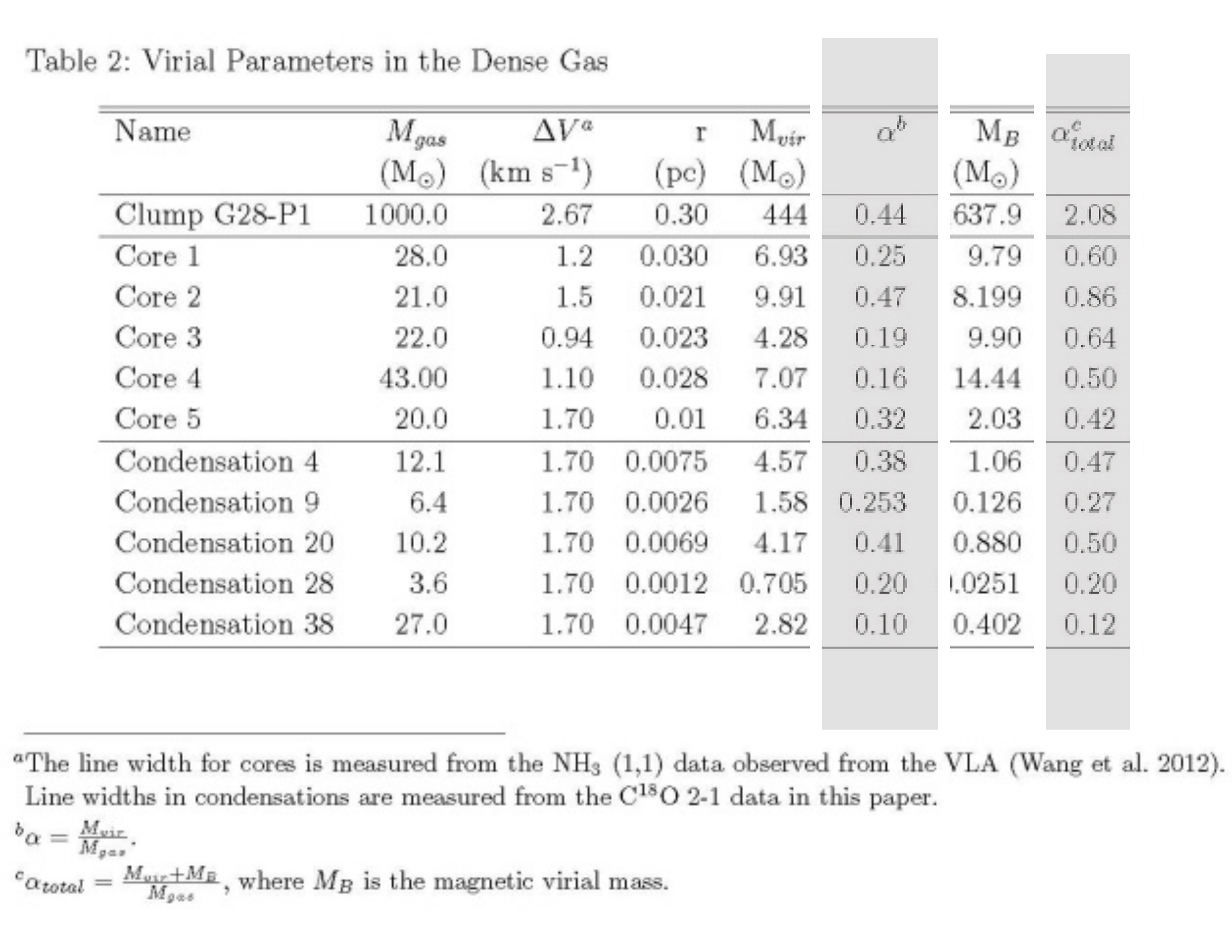


Table 2: Virial Parameters in the Dense Gas

Name	M_{gas} ($M_\odot$)	ΔV^a (km s^{-1})	r (pc)	M_{vir} ($M_\odot$)	α^b	M_B ($M_\odot$)	α^c_{total}
Clump G28-P1	1000.0	2.67	0.30	444	0.44	637.9	2.08
Core 1	28.0	1.2	0.030	6.93	0.25	9.79	0.60
Core 2	21.0	1.5	0.021	9.91	0.47	8.199	0.86
Core 3	22.0	0.94	0.023	4.28	0.19	9.90	0.64
Core 4	43.00	1.10	0.028	7.07	0.16	14.44	0.50
Core 5	20.0	1.70	0.01	6.34	0.32	2.03	0.42
Condensation 4	12.1	1.70	0.0075	4.57	0.38	1.06	0.47
Condensation 9	6.4	1.70	0.0026	1.58	0.253	0.126	0.27
Condensation 20	10.2	1.70	0.0069	4.17	0.41	0.880	0.50
Condensation 28	3.6	1.70	0.0012	0.705	0.20	.0251	0.20
Condensation 38	27.0	1.70	0.0047	2.82	0.10	0.402	0.12

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[a] The line width for cores is measured from the NH_3 (1,1) data observed from the VLA (Wang et al. 2012). Line widths in condensations are measured from the $C^{18}O$ 2-1 data in this paper.

[b] $\alpha = \frac{M_{vir}}{M_{gas}}$.

[c] $\alpha_{total} = \frac{M_{vir}+M_B}{M_{gas}}$, where M_B is the magnetic virial mass.

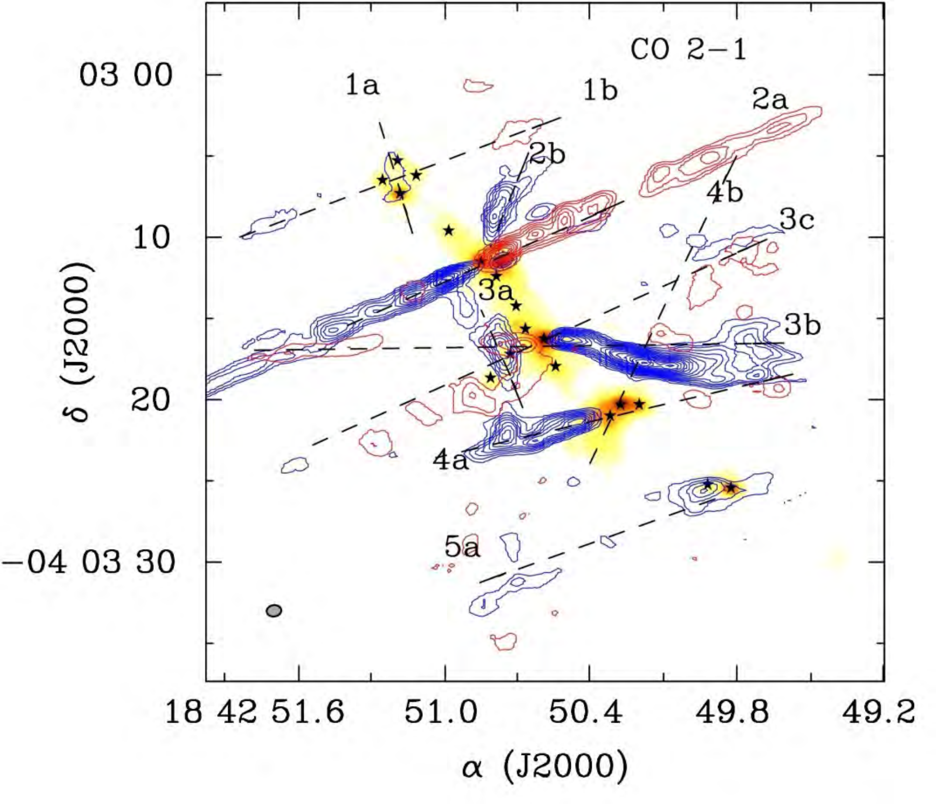
$$\alpha = \frac{M_{vir}}{M} = \frac{5\sigma^2 R}{GM}$$

Magnetic fields may play an important role in cloud support

If B(clump)=0.27 mG
α_{total}(clump)=2
Pillai et al. 2015

B(cores) ~> 1-10 mG see Zhang et al 2014.
See Girart's talk

CO Outflows



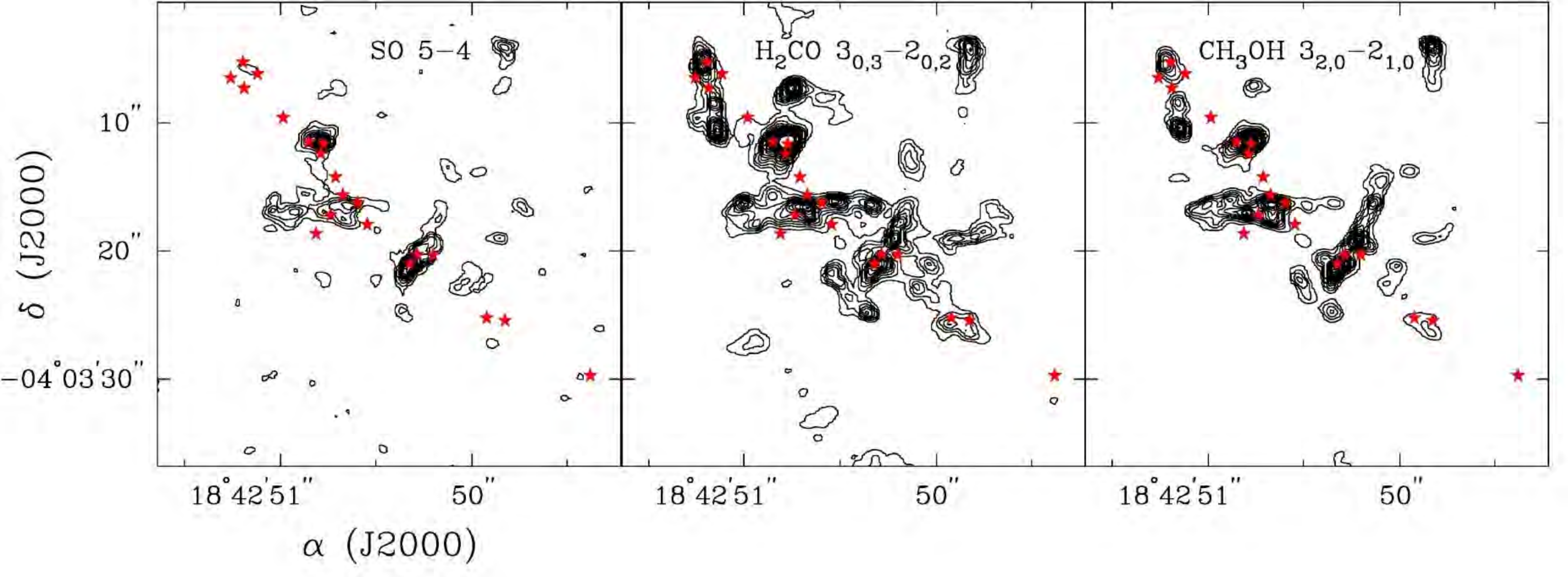
10 molecular outflows
Outflow energetics consistent with those of intermediate stars

Outflow energy ~ turbulent energy

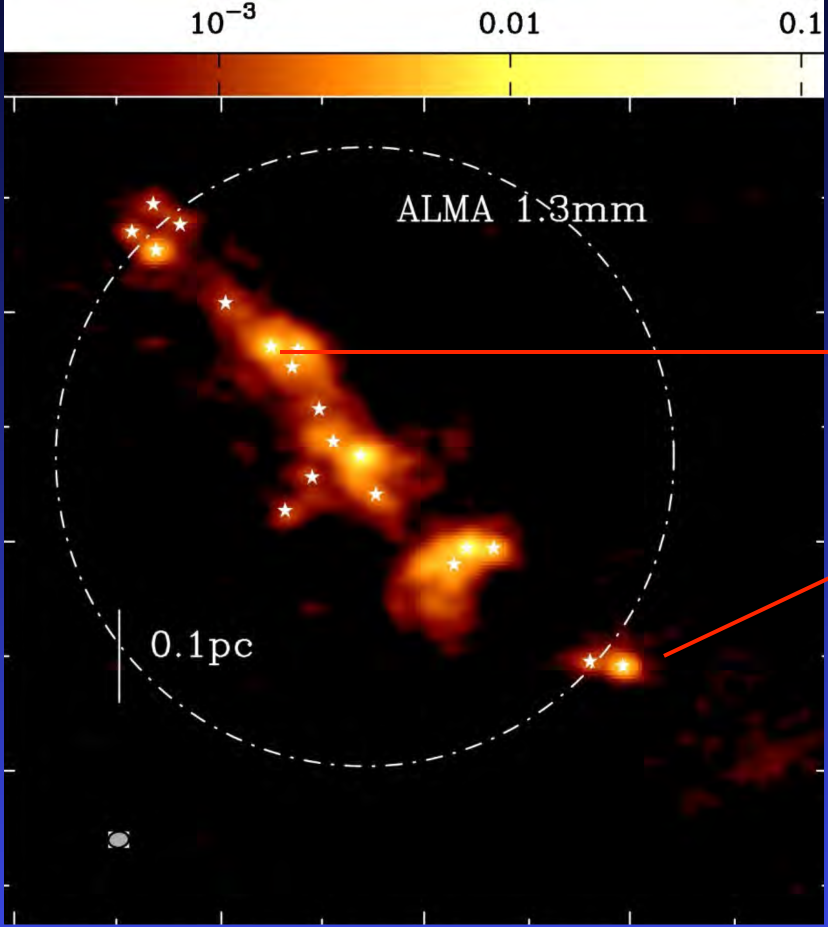
M_{acc} ~ 10^{-5} Msun/yr

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

Emission from Outflows:

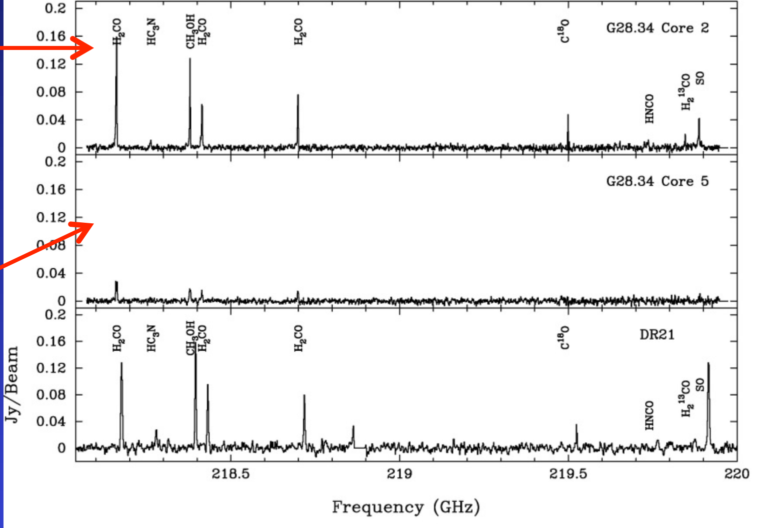


Chemical Differentiation



Cores 2,3,4 are chemically more advanced than Cores 1,2

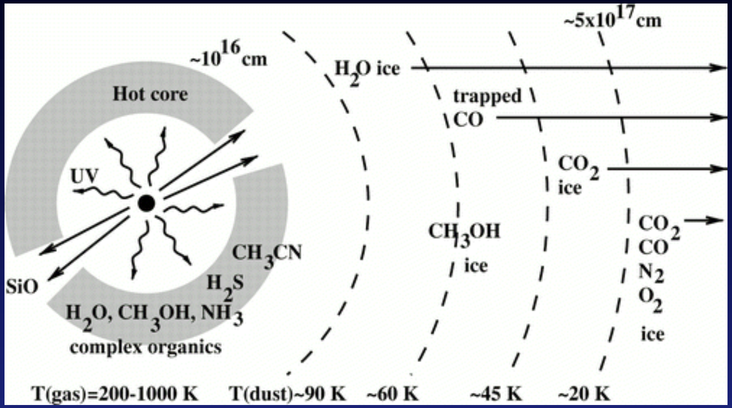
Comparison with protostellar cores in DR 21 filament suggests Cores 2,3,4 harbor intermediate mass protostars!



Zhang et al. 2015

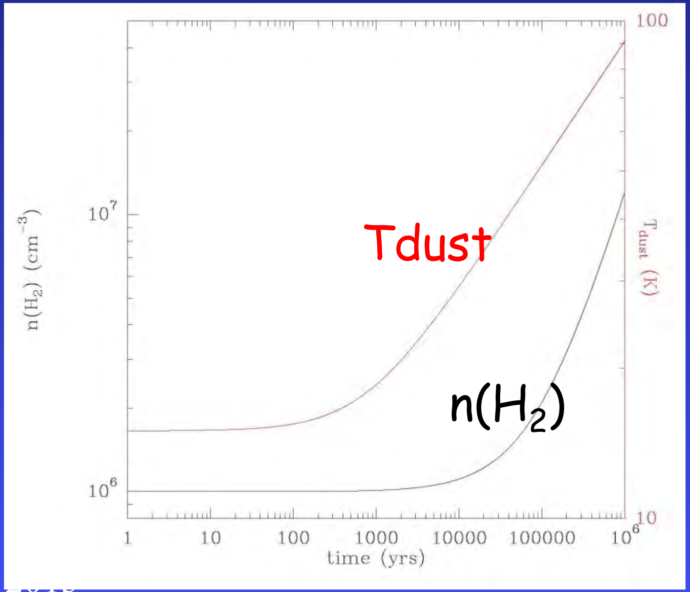
Chemical Evolution: Cold Core to Hot Core

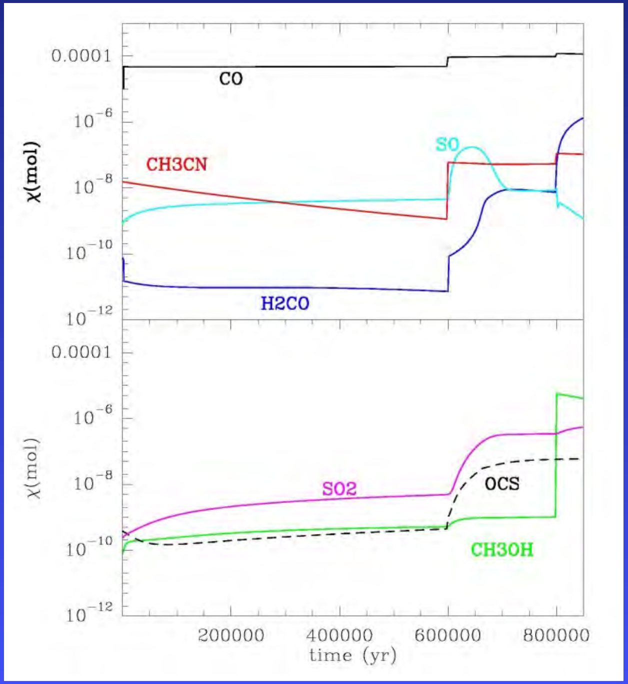
Follow dynamic collapse and chemical evolution (depletion) under a constant T
Turn on protostellar heating and follow chemical evolution in gas phase
See Viti et al. 2004



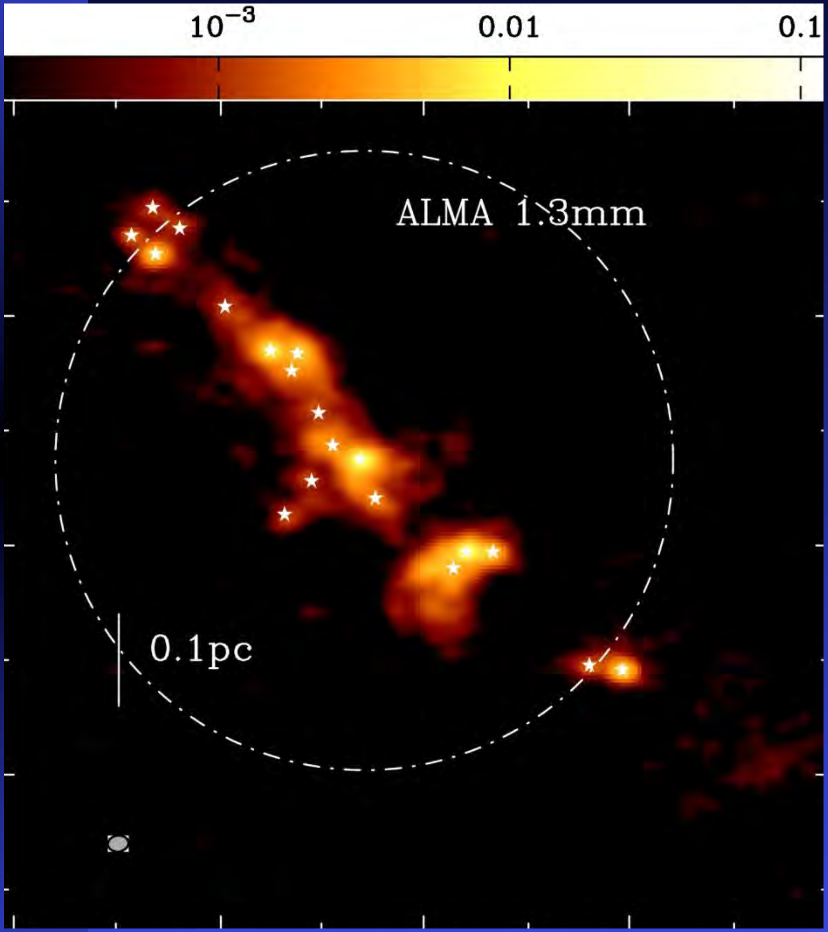
van Dishoeck & Blake 1998

With Jimenez-Sierra, Viti et al.

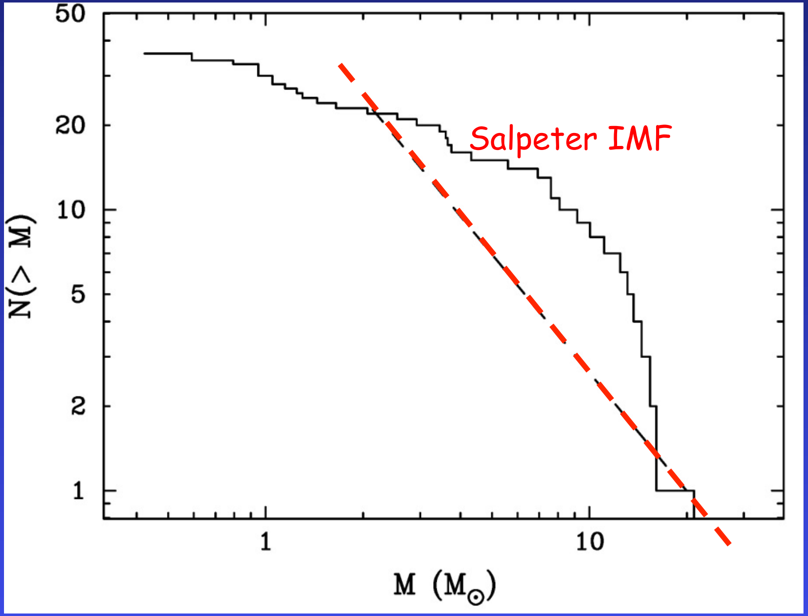




Where are low-mass protostars?



Clump mass 10^3 Msun → 100 stars
from 0.5 – 20 Msun
Identified 38 cores
Core mass function top heavy
Lack of low-mass cores by >x5!

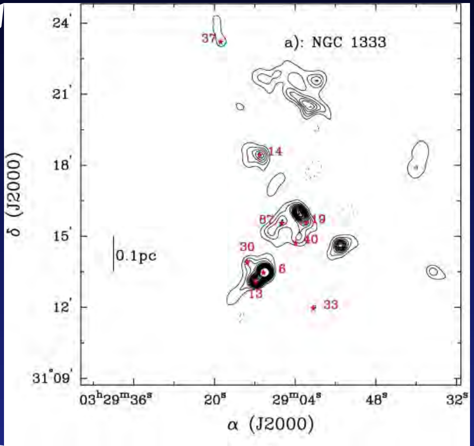


Zhang et al. 2015

Where are low-mass protostars?

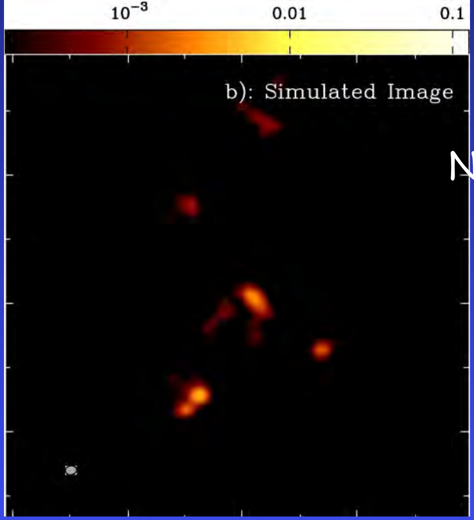
Low-mass cluster NGC 1333 in Perseus
D=235pc

Gutermuth et al. 2009



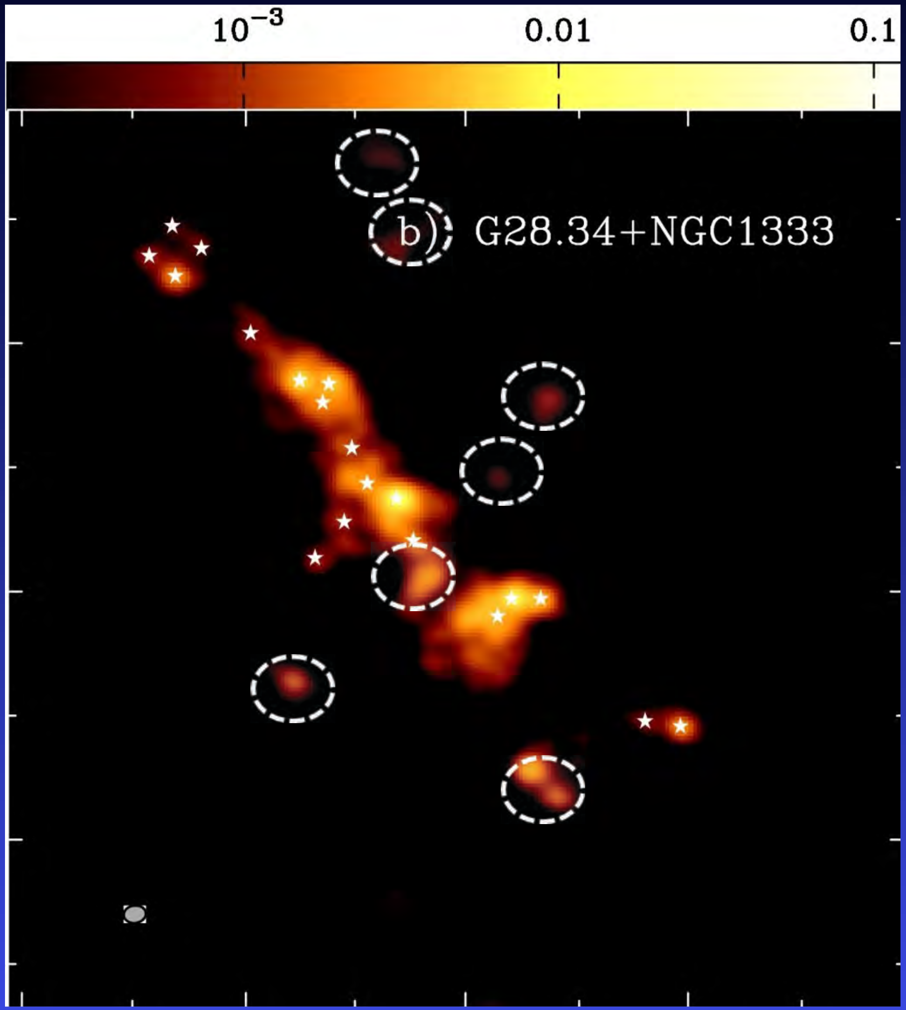
Kirk et al. 2006
SCUBA 870 μm

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

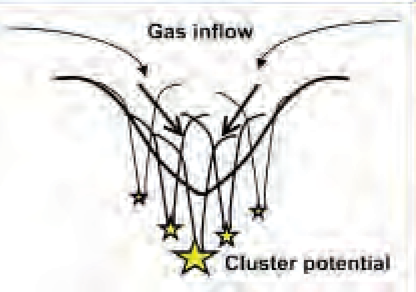
A low-mass such as NGC1333 can be reliably detected if present

Low-mass protostars form after massive ones in a cluster

Conclusions

- 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.

How to Make Massive Cores: Initial Fragmentation

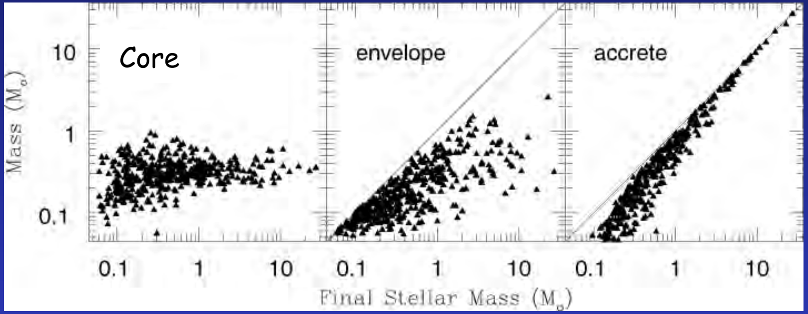


Competitive Accretion

Start with cores with 0.5 Msun

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

Bonnell et al. 2001, 2004

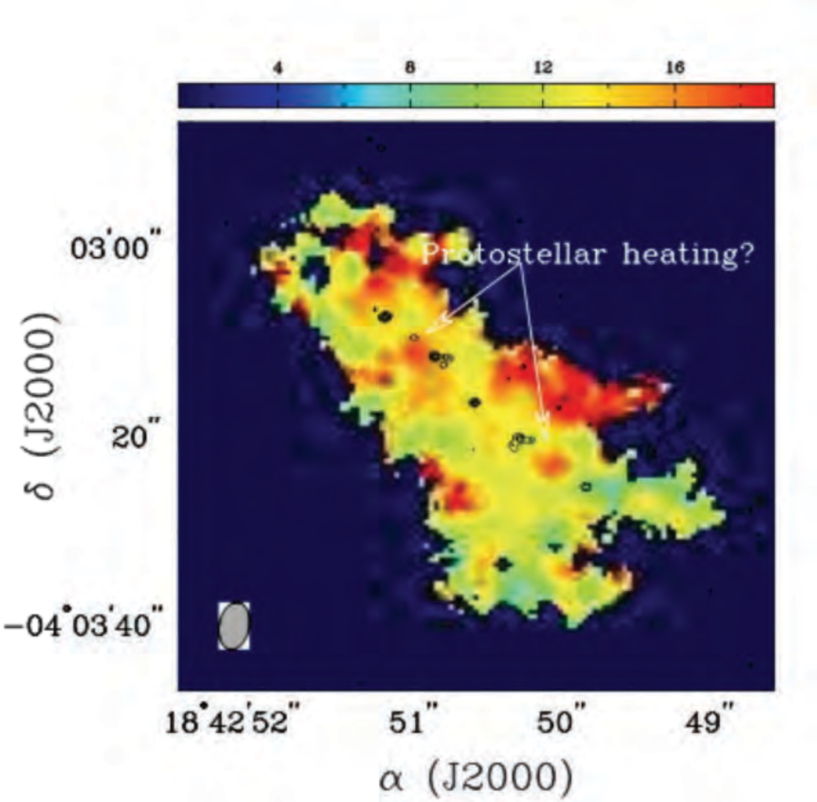


Monolithic Collapse

Stellar heating increase M_J $f * M_{core} \sim M_*$

McKee & Tan 2002; Krumholz et al. 2007

Is heating sufficient to increase M_J ?



T = 10- 20 K
No enhanced heating at dense cores

Stellar heating is not
enough to increase thermal M_J

Wang, Zhang, et al. 2012

Polarization Map for G240