Massive star formation: “Un-nesting” the Russian dolls

Nicolas Peretto
Cardiff University

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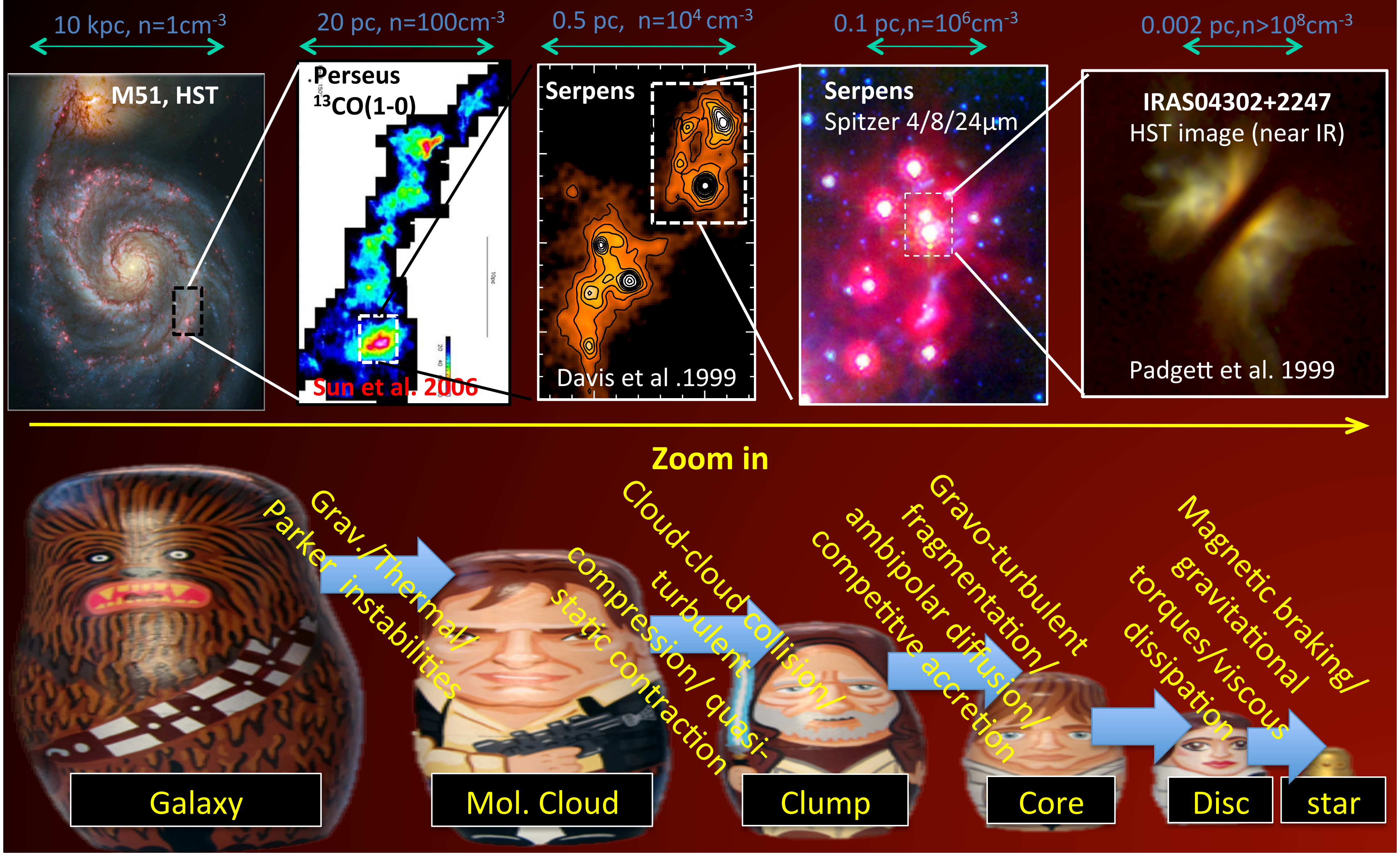
The Russian doll "Model"



Outline

i) Radiation pressure and disc formation

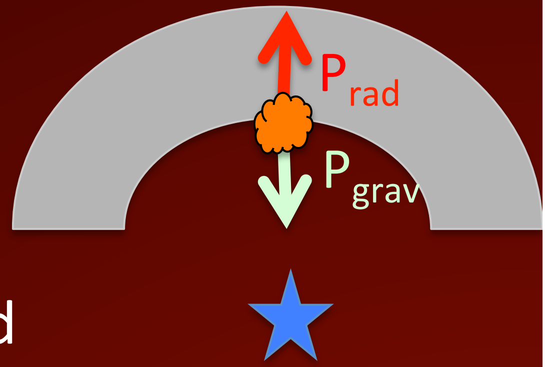
ii) Cloud fragmentation and dynamical evolution

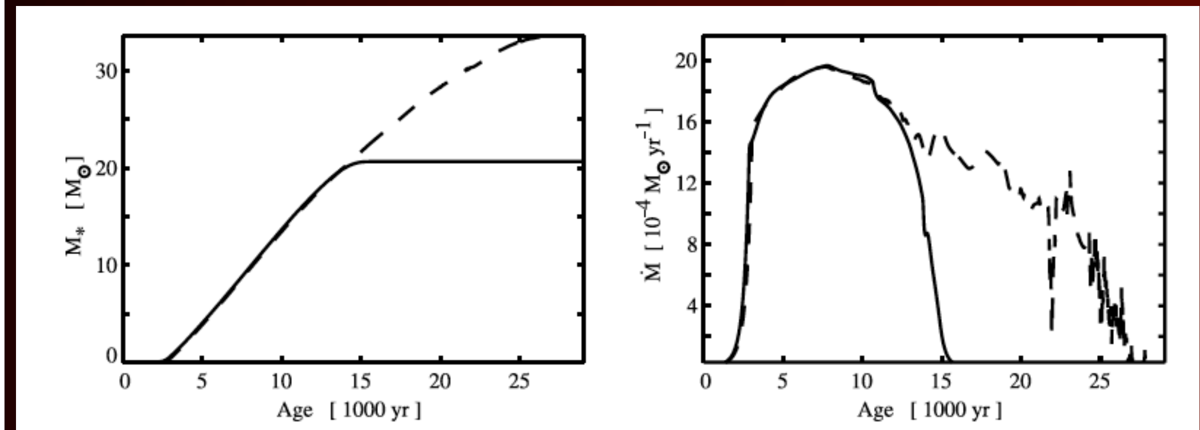
iii) Large scale triggering

The radiation pressure problem

- Kelvin-Helmholtz time < accretion time
- Gravity must overcome radiation pressure

-> Luminosity over mass ratio: L/M < 1000
Large (~10^{-3} M_{sun}/yr) accretion rates are required (Wolfire & Cassinelli 1987)





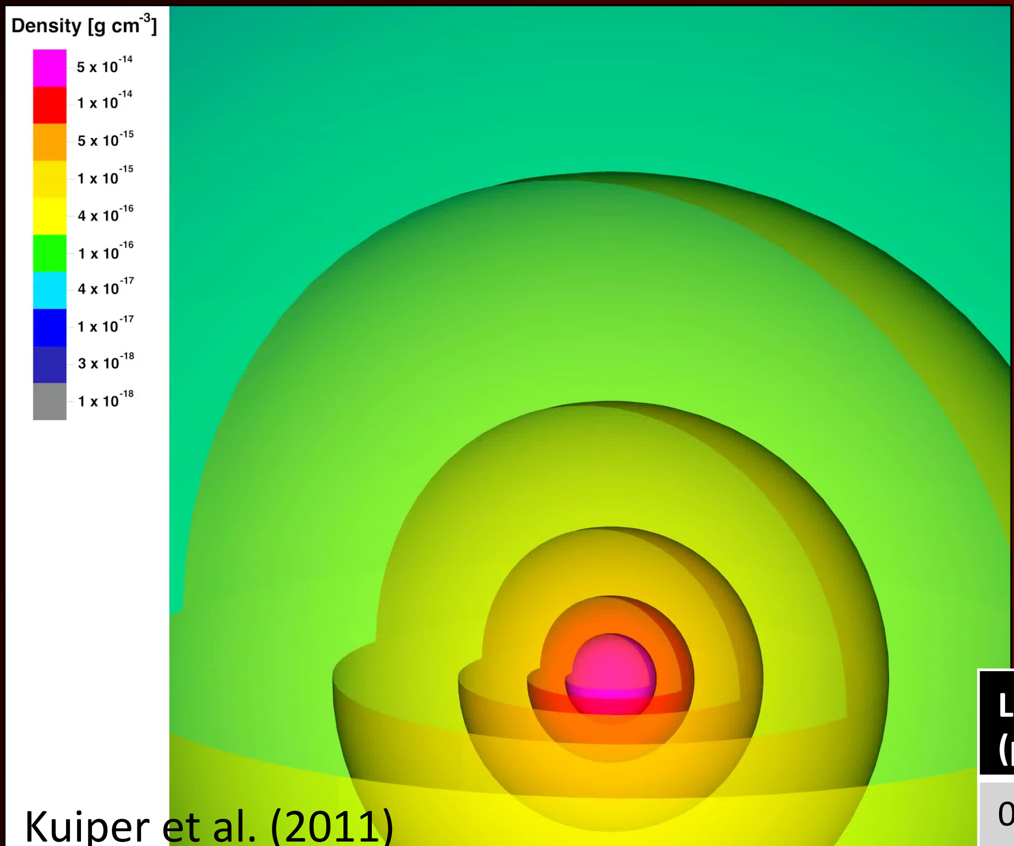
Yorke & Sonnhalter 2002

- Non spherical flows could solve the problem but 2D simulations by Yorke & Sonnhalter (2002) stopped around 40M_{sun}.

L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion.	Δx (AU)
0.4	120	n	y	n	r^{-2}	n	40

The radiation pressure solution

- Krumholz et al. (2009): 3D calculation of a collapsing and rotating massive core forming stellar masses around $40M_{sun}$ (gray FLD)
- Kuiper et al. (2010, 2011): 2D/3D calculations with freq. dependent FLD radiative transport, but no turbulence (see R.Kuiper's talk)



Kuiper et al. (2011)

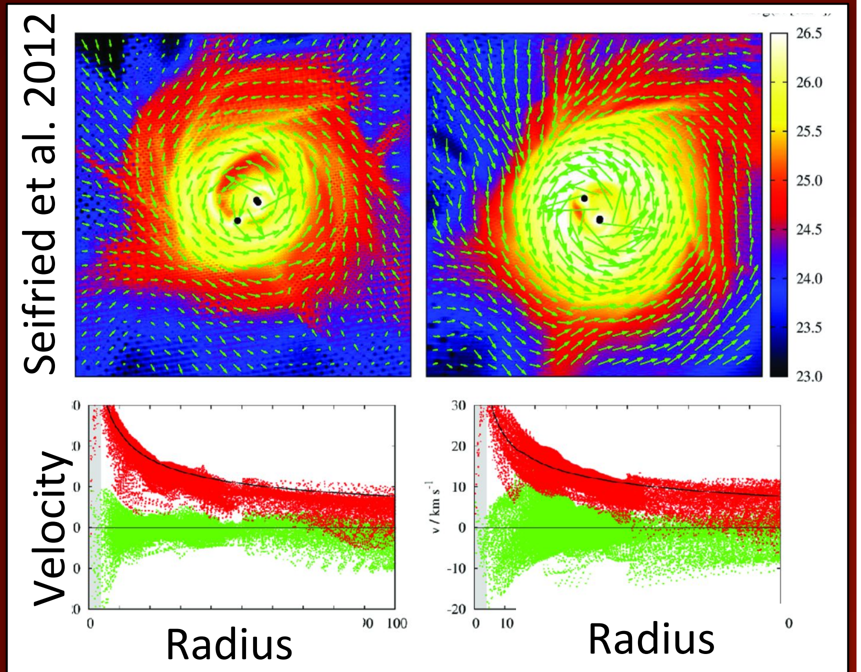
-> Disc mediated accretion, up to 92 M_{sun} in a $240M_{sun}$ core (1D calculation shows a mass limit around $40M_{sun}$)

Details of how accretion proceeds is still controversial (Kuiper & Klessen 2013; Krumholz 2014) but no accretion problem anymore

L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion.	Δx (AU)
0.2	120	n	y	n	r^{-2}	n	1

The formation of a disc

- Discs might be key to the formation of massive stars.
- Radiation MHD simulation of a massive collapsing core (Commerçon et al. 2011) showed that magnetic braking could be very efficient in removing angular momentum: No disc!
- But, misalignment of rotation axis and magnetic field decrease magnetic braking efficiency (Ciardi et al. 2010, Seifried et al. 2011/2012, Myers et al. 2013): Discs can form!
- So, accretion onto the star due to gravitational torques? shear-viscosity?

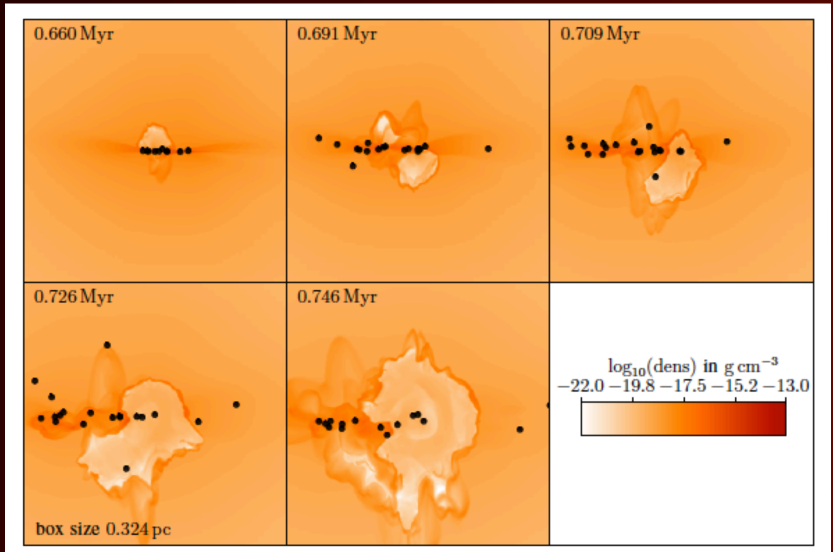


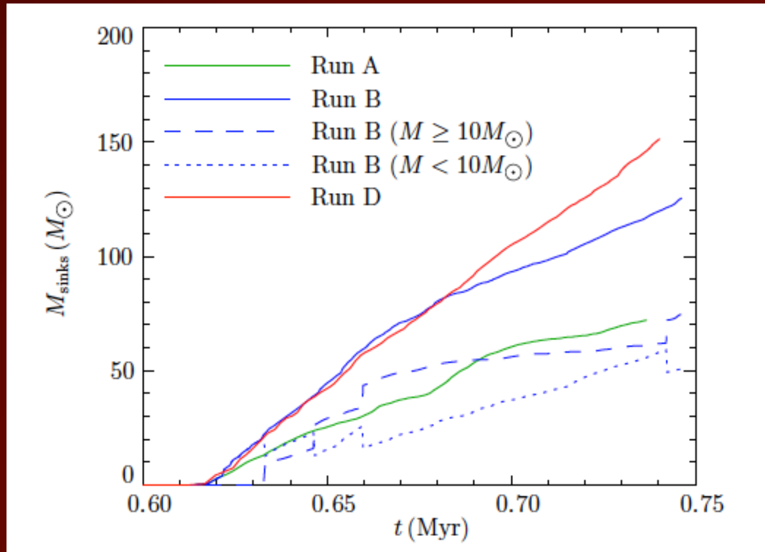
L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion.	Δx (AU)
0.12	100	y	n	y	$r^{-1.5}$	n	1

An end to massive star accretion

- In Kuiper's work, radiation pressure does not limit accretion anymore. So what does (if anything)?

- The growth of the central protostar might be limited Fragmentation-induced starvation (Peters et al. 2010), but not by ionisation. Similar results obtained by Girichidis et al. (2012).

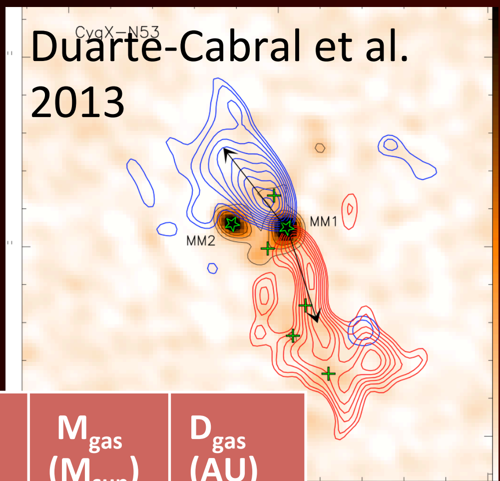




L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion.	Δx (AU)
3.2	1000	y	y	y	R_{flat}=0.5pc $r^{-1.5}$	y	100

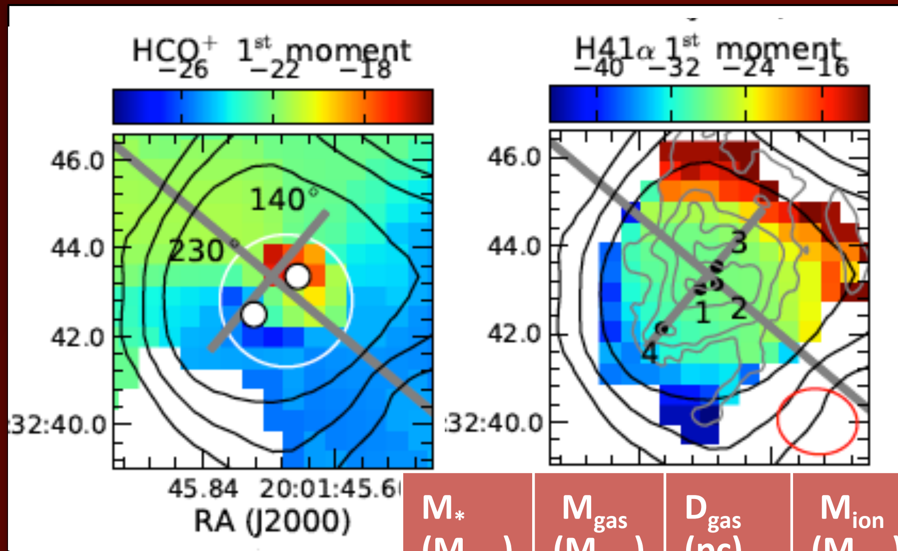
Observational evidence for discs

- Indirect evidence for equatorial accretion is the presence of outflows towards massive protostars.
- Outflows towards massive (proto)stars is a common feature, at different stages, and in different tracers (cf outflow session, P5).



Duarte-Cabral et al. 2013

M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
< 8	34	4000



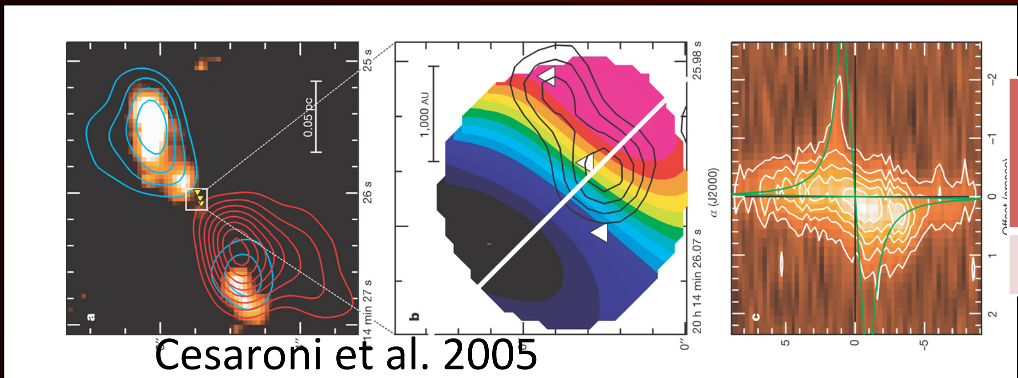
Klaassen et al. (2013)

M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (pc)	M_{ion} (M_{sun})	D_{ion} (pc)
3 x 16	2600	0.7	8	0.1

- But, does this means that Keplerian discs are necessarily present?

Observational evidence for discs

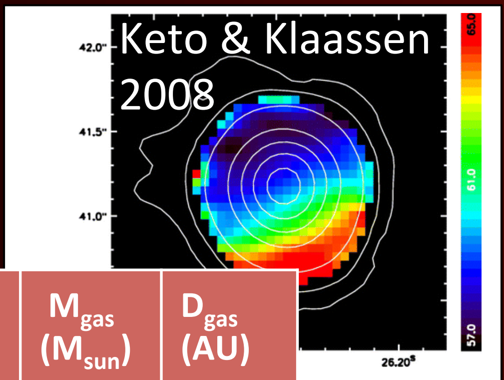
- Keplerian-like velocity structure are observed around early B (proto)stars. Best known is IRAS20126 (Cesaroni et al. 2005; see P4).



Cesaroni et al. 2005

M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
7-8	4	1600

- Rotating ionized gas is found in W51 (Keto & Klaassen 2008), and SED consistent with a disc+envelope (Johnston et al. 2011).

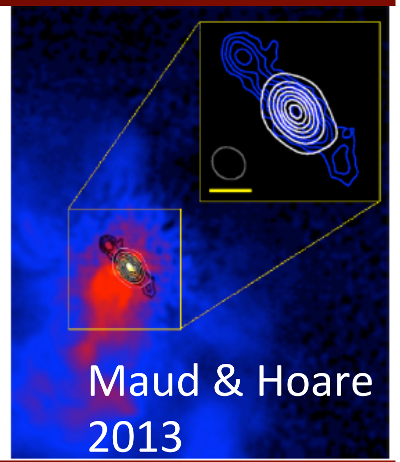


Keto & Klaassen 2008

M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
20	140	4000

- Maud & Hoare (2013) imaged the disc of S140-IRS1, finding evidence for a disc wind.

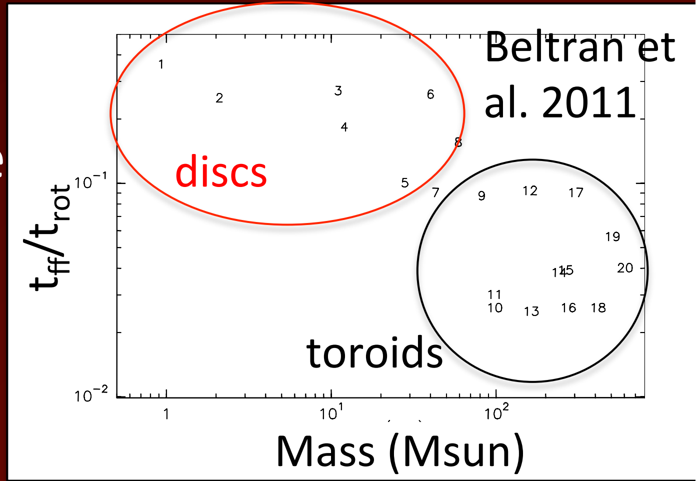
M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
11	3	3000

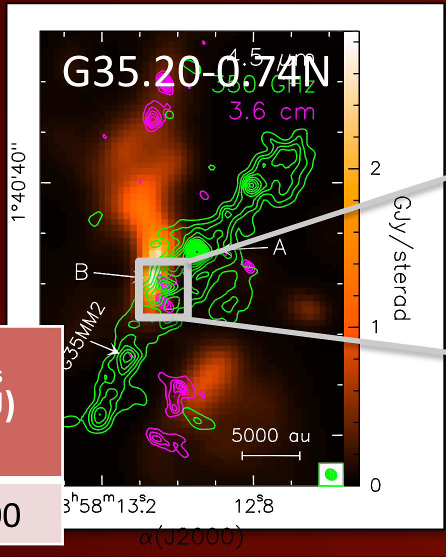


Maud & Hoare 2013

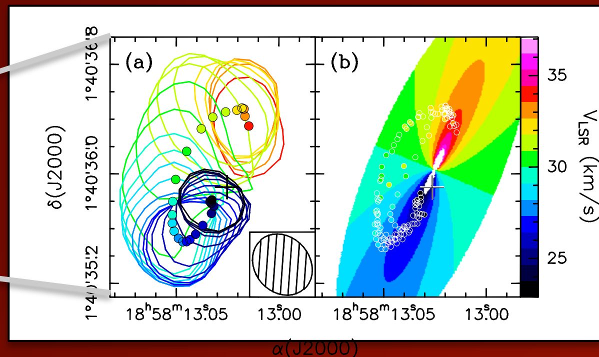
Observational evidence for discs

- Signatures of rotation on small scales (from few 10 of AU to few 1000 AUs) are routinely found (e.g. Sanna et al. 2014; Hunter et al. 2014).
- It seems unlikely that all these sources are true rotationally supported structures
- No Keplerian disc around a O (proto)star has been found yet. But Sanchez-Monge et al. (2013) might have found one (see also Zhan et al. 2013)





M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
18	3	5000



Sanchez-Monge et al. 2013

Outline

i) Radiation pressure and disc formation

ii) Cloud fragmentation and dynamical evolution

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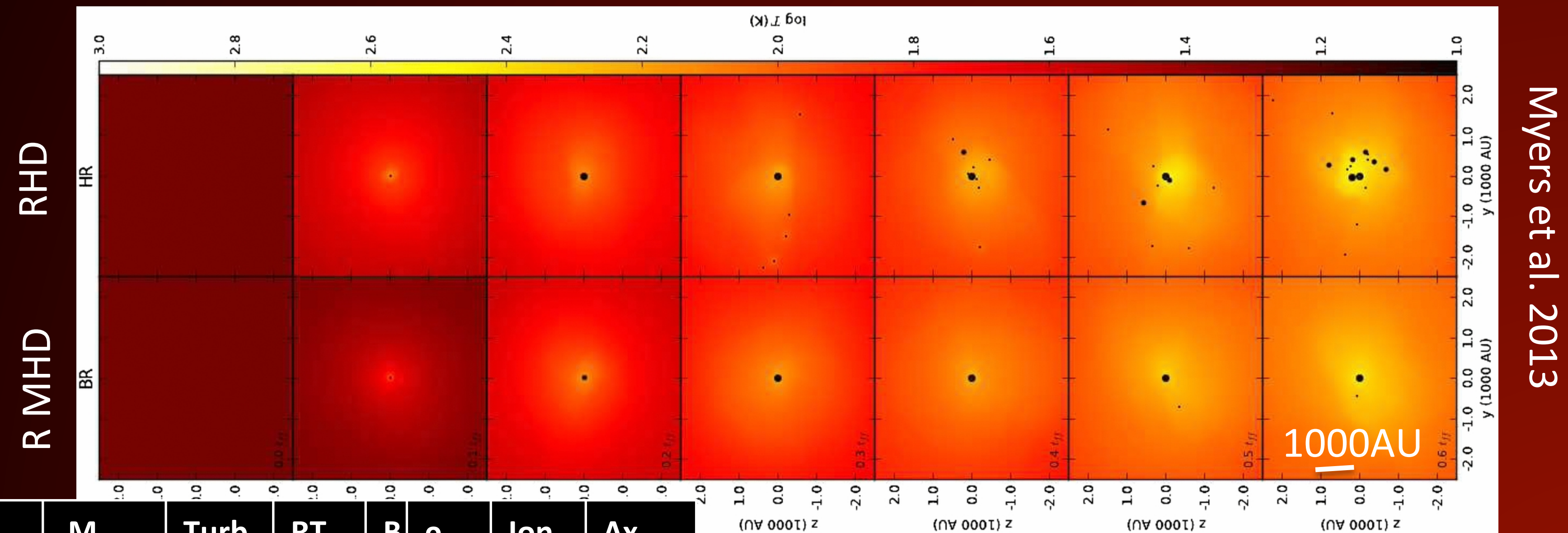
Fragmentation on few hundreds AU scale

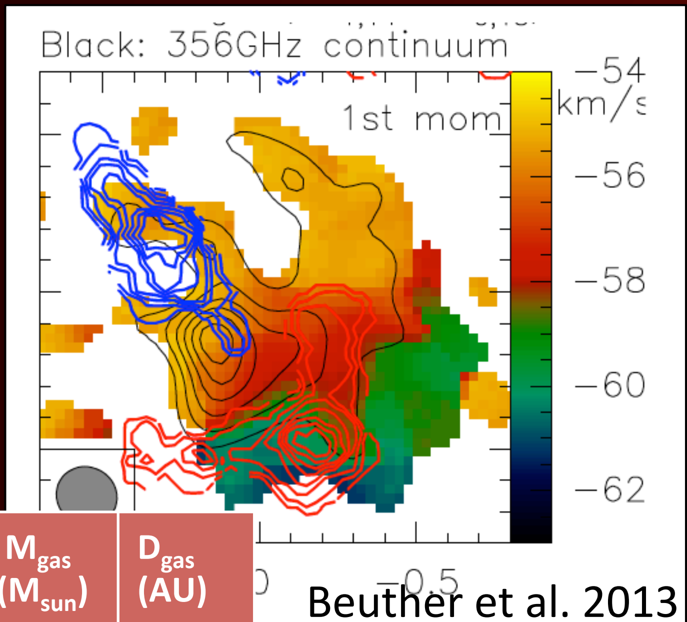
- Radiation MHD simulations show that radiative feedback (heating) and magnetic field act in synergy for preventing fragmentation (Commercon et al. 2011, Peters et al. 2011, Seifreid et al. 2012, Myers et al. 2013).



L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion.	Δx (AU)
0.2	300	y	y	y	$r^{-1.5}$	n	10

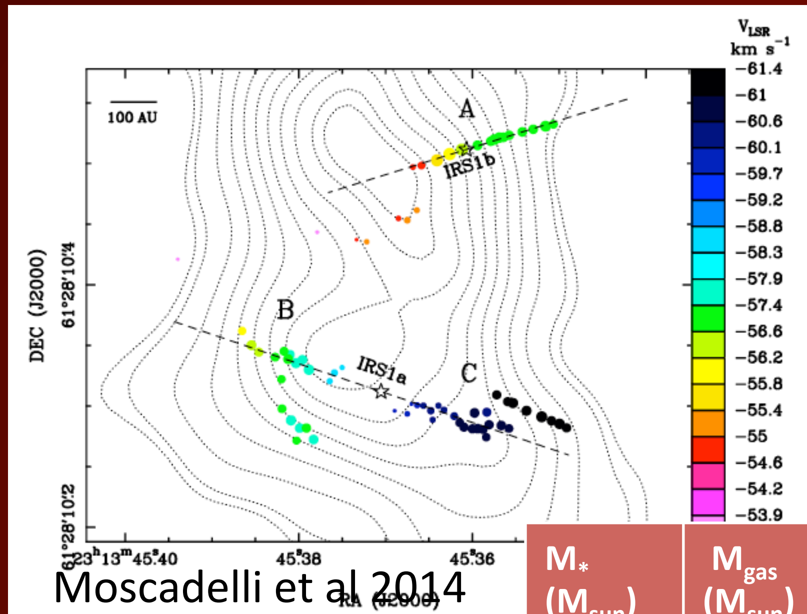
Fragmentation on few hundreds AU scale

- Very high angular resolution (few 0.1”) observations of NGC7538 IRS1 region reveals fragmentation on few 100AUs scale (Beuther et al. 2013).
- Maser emission indicates the presence of rotation on few 10 AUs scale to 100AU scale (Moscadelli et al. 2014).



Beuther et al. 2013

M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
30	1	300

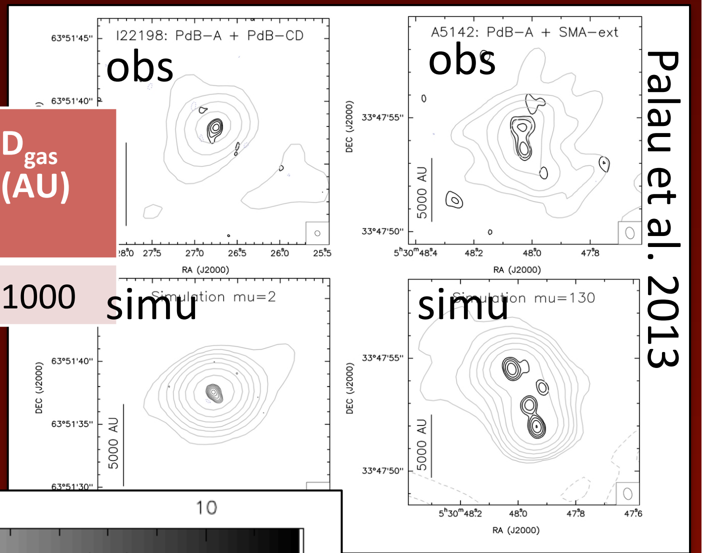


Moscadelli et al 2014

M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
25+16	1	300

Fragmentation on few hundreds AU scale

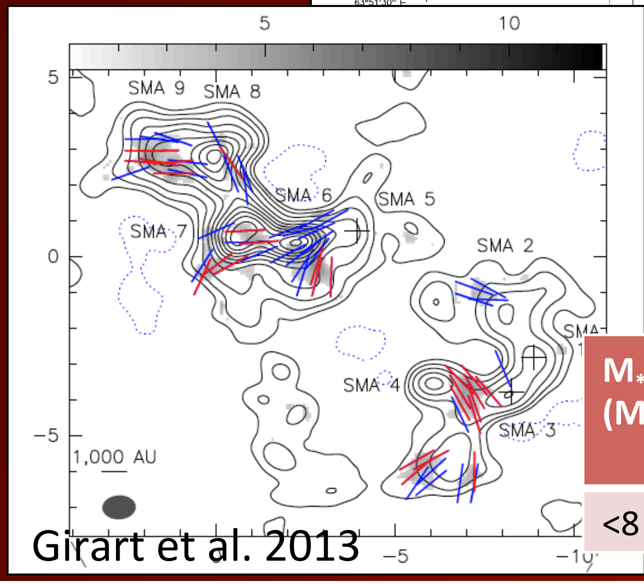
- High-resolution study of 18 massive dense cores reveal different level of fragmentation (30% unfragmented): different levels of magnetic field strengths? (Palau et al. 2013).



M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
<8	5	1000

- For same sources, Palau et al. (2014) find a weak trend of fragmentation level with density profile (see also Girichidis et al. 2011), consistent with Jeans fragmentation (see P33).

- Polarisation observations of DR21 show high level of fragmentation with moderately supercritical gas (Girart et al. 2013; see also Tang et al. 2013; Koch et al. 2013; see P10).



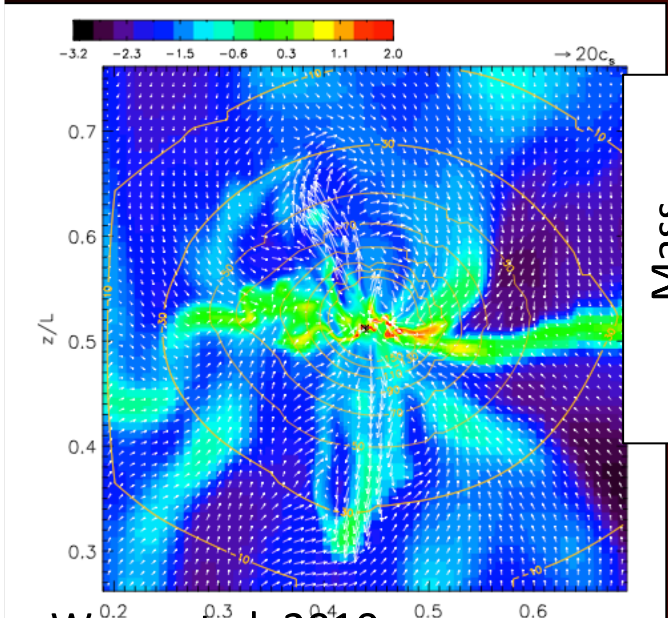
M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
<8	2	4000

The dynamics of dense clouds (Theory)

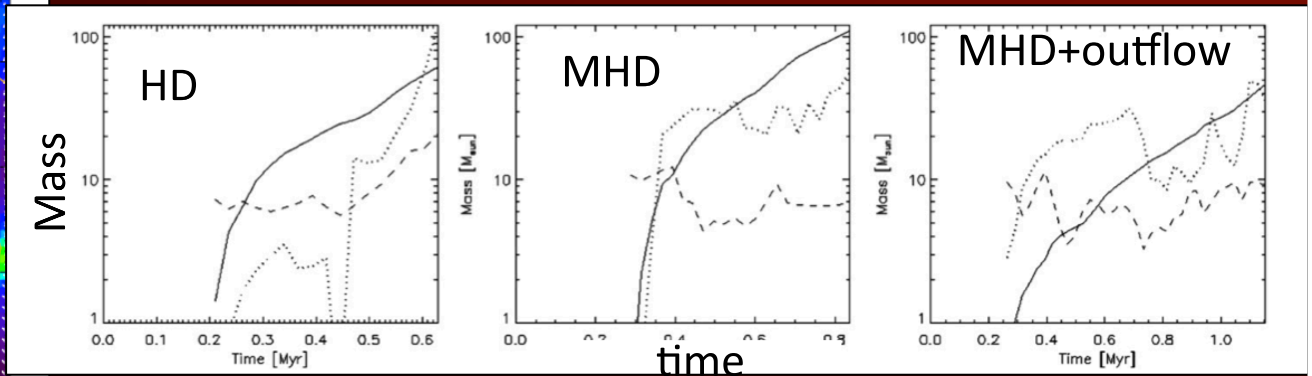
- Wang et al. (2010) performed isothermal MHD simulation of a dense clump, including protostellar feedback (sub-grid model).

- They conclude that the formation of massive stars in their simulation is due to large-scale accretion (clump-fed accretion) due to cloud global collapse. Magnetic field, and protostellar outflow slowing down the process to a few times the cloud freefall time.

But no massive prestellar cores!



Wang et al. 2010

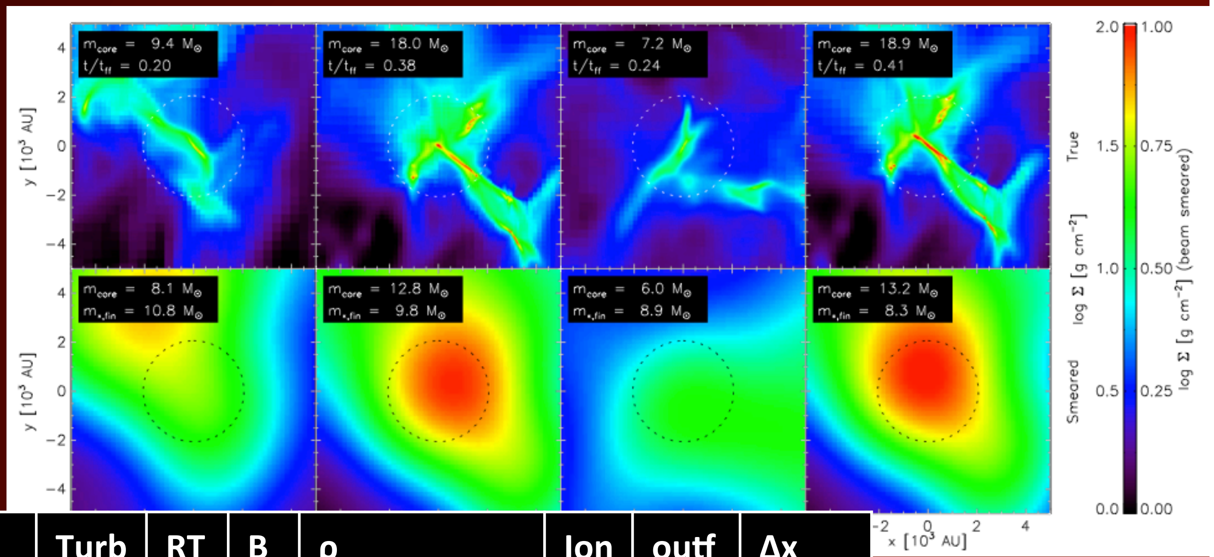


L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion	outf	Δx (AU)
2	1215	y	n	y	R_{flat}=0.3pc r^{-2}	n	y	200

The dynamics of dense clouds (Theory)

- Krumholz et al. (2012) performed a similar set-up but with the inclusion of radiative feedback (but no magnetic field but see Myers et al. 2014, and R.Klein's talk). They find massive prestellar cores.
- But simulations are only ran for a cloud free-fall time, while Wang et al. could run their simulation for 6 free-fall time. And a lot of mass is accreted after 1 t_{ff}.

Krumholz et al. 2012



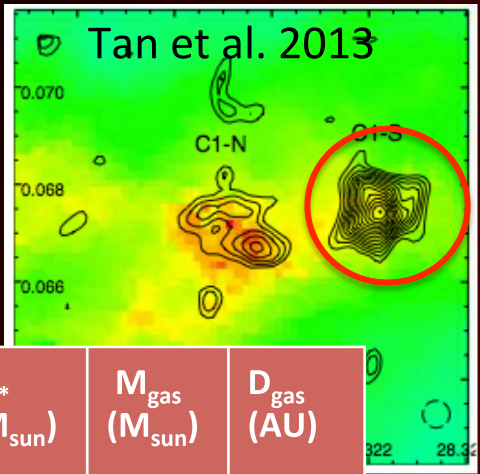
- Initial conditions are key for the outcome of the simulation

L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion	outf	Δx (AU)
0.46	1000	y	y	n	Uni+ turb	n	y	23

Finding Massive presstellar cores

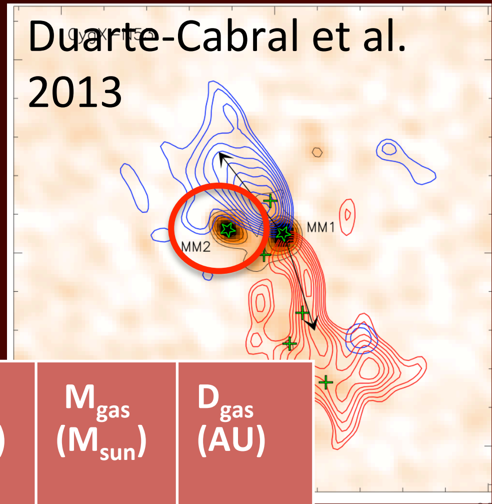
- Only a handful of candidates found so far, and none has the potential to form a, e.g., 100 M_{sun} star.

Tan et al. 2013



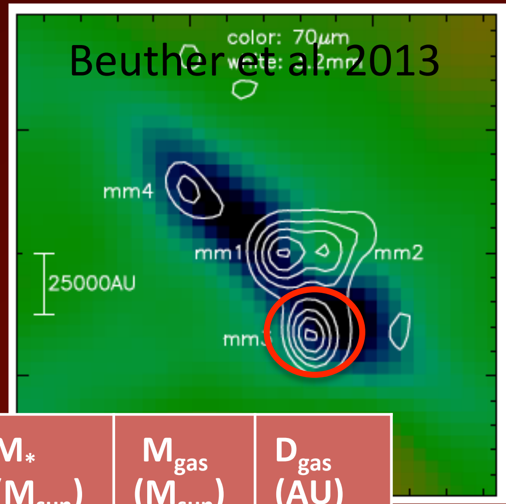
M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
0	60	20000

Duarte-Cabral et al. 2013



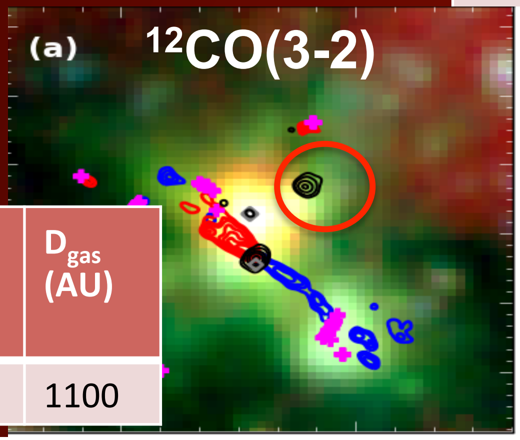
M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
0	6	1200

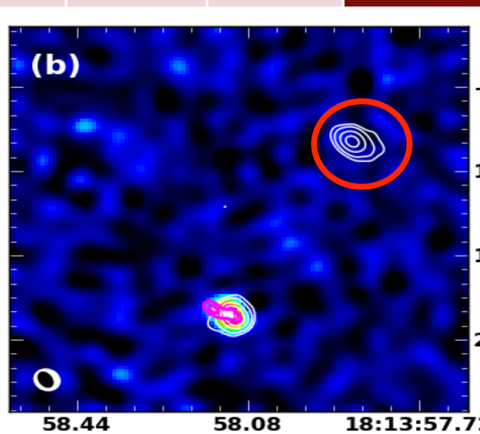
Beuther et al. 2013



M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
0	50	15000

- One real candidate (Cyganowski et al. in prep.), but….

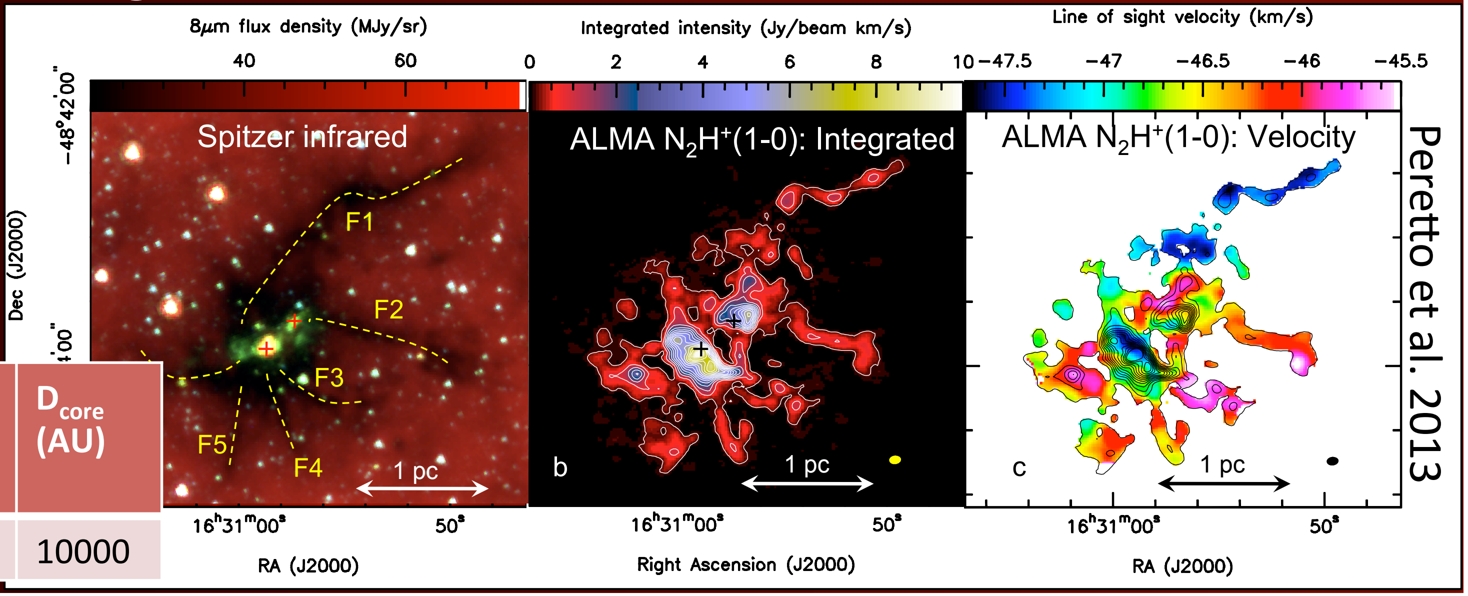




M_* (M_{sun})	M_{gas} (M_{sun})	D_{gas} (AU)
0	200	1100

The dynamics of dense clouds (Obs.)

- IRDCs are dense molecular seen in silhouette against the IR background of the galactic plane (e.g. Perault et al. 1996, Simon et al. 2006, Peretto & Fuller 2009, Ragan et al. 2009; P2, P14, P27, P32, P33; T. Henning's talk).
- Peretto et al. (2013) found a very massive core at the centre of globally collapsing IRDCs. Central 1pc region can be doubled in a million year. This scenario is very similar to the clump-fed picture described by Wang et al. (2010).



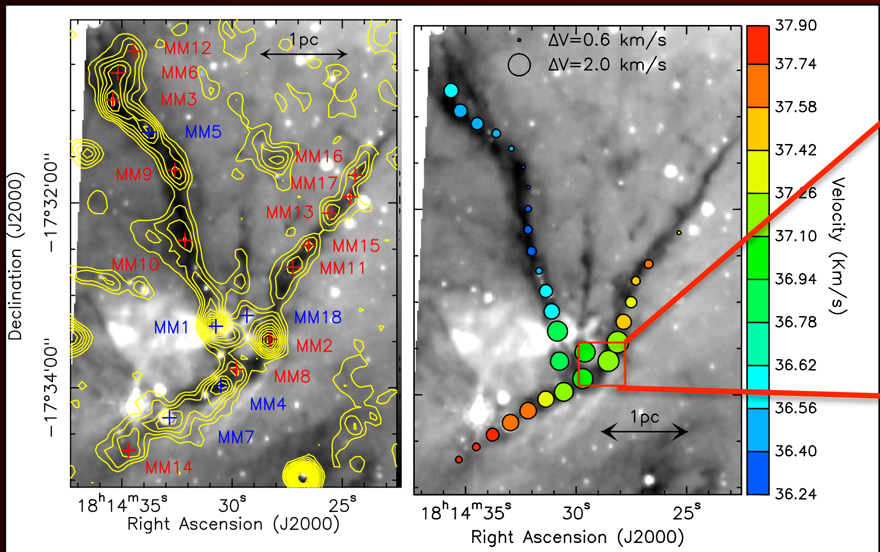
Peretto et al. 2013

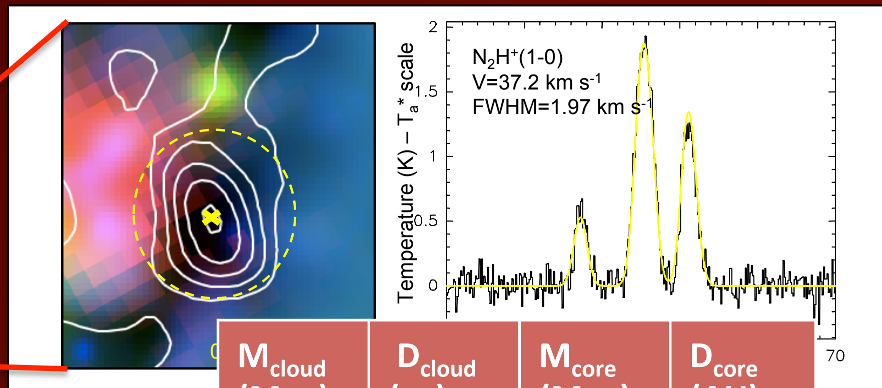
M_{cloud} (M_{sun})	D_{cloud} (pc)	M_{core} (M_{sun})	D_{core} (AU)
5500	4	500	10000

The dynamics of dense clouds (Obs.)

- Peretto et al . (2014) also found indications of large-scale collapse in the filamentary SDC13 IRDC (see also P9, and F. Motte's talk).
- Most massive cores are sitting at the junction of the filaments (see also Schneider et al. 2012)
- One of the central cores is starless, and exhibit the largest velocity dispersion probably as a result of to the large-scale collapse.

Peretto et al. 2014



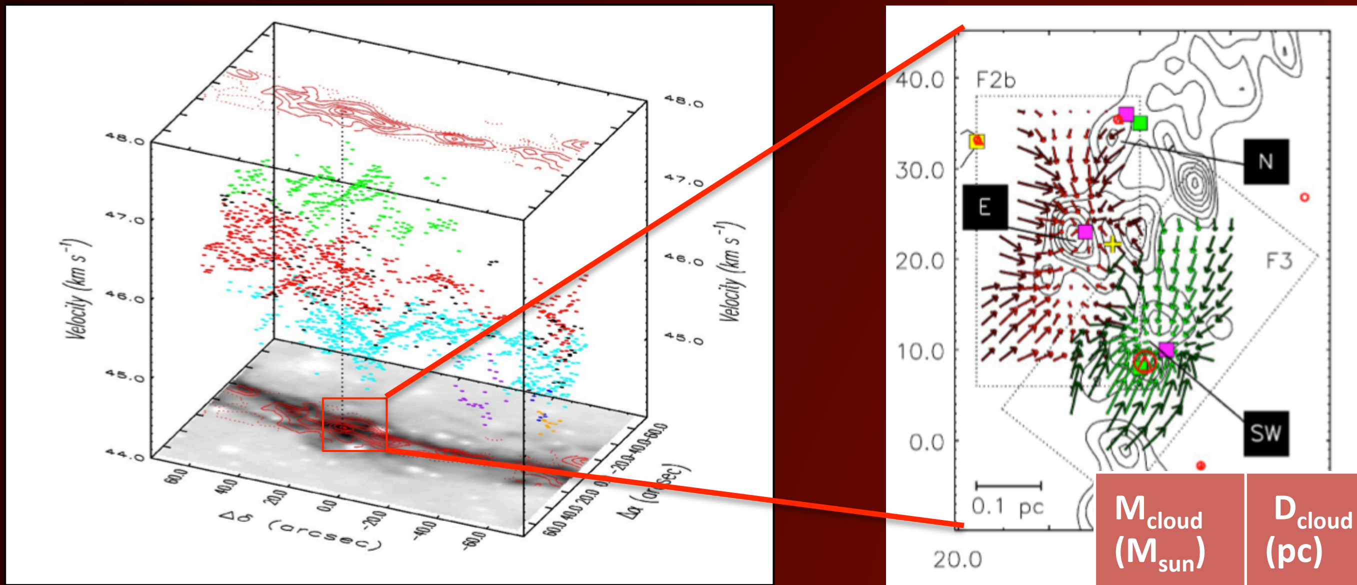


M_{cloud} (M_{sun})	D_{cloud} (pc)	M_{core} (M_{sun})	D_{core} (AU)
1200	5	80	60000

Other evidence: ,e g., Peretto et al. 2006, Schneider et al. 2010, Barnes et al. 2010, Qiu et al. 2012, Galvan-Madrid et al. 2010, Ragan et al. 2012

The dynamics of dense clouds (Obs.)

- Henshaw et al. (2013/2014) show dynamic interactions of a set of at three clouds that has probably lead to the active star formation event (see also Jimenez-Serra et al. 2010; Nguyen-Luong et al. 2012).
- Note that several velocity components on small scales (e.g. Csengeri et al. 2011; Beuther et al. 2013; Hacar et al. 2013 for low-mass).



M_{cloud} (M_{sun})	D_{cloud} (pc)	M_{core} (M_{sun})	D_{core} (AU)
5000	9x1	60	60000

- Interpreted as smooth interaction within a virialised cloud

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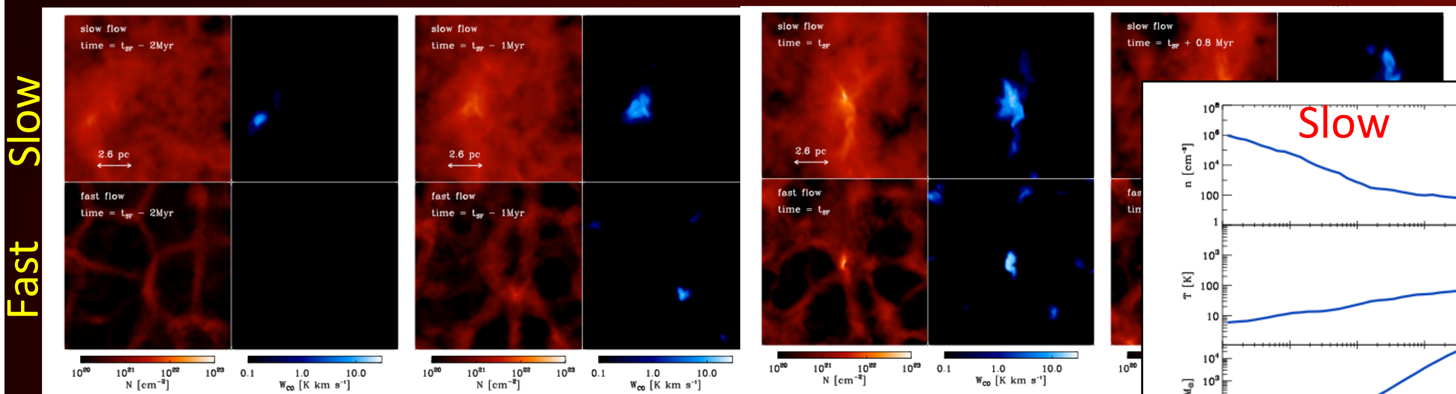
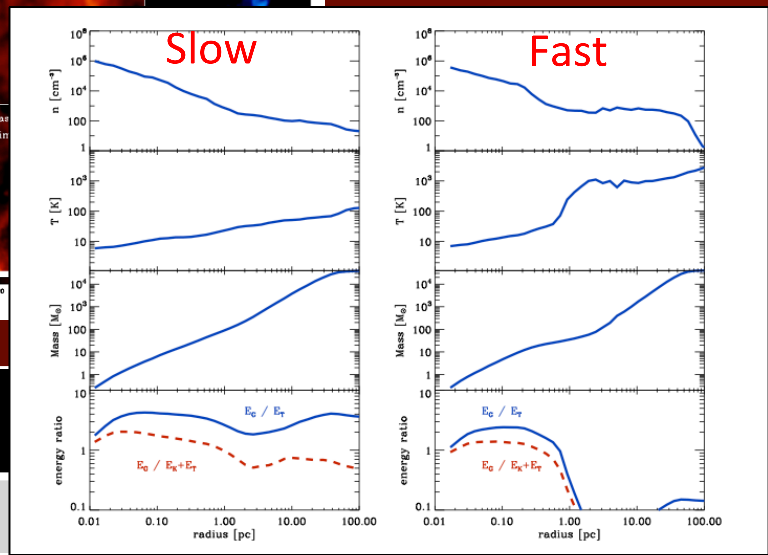
Triggering via colliding flows

- WNM colliding flows have been proposed as a mechanism to trigger thermal instabilities (e.g. Koyama & Inutsuka; Audit & Hennebelle 2005; Vazquez-Semadeni et al. 2007; Banerjee et al. 2009; P34)
- Clark & Glover (2012) performed two colliding flow simulations with CO formation. Flow velocity is key for defining cloud properties (dynamical time scale vs cooling timescale).

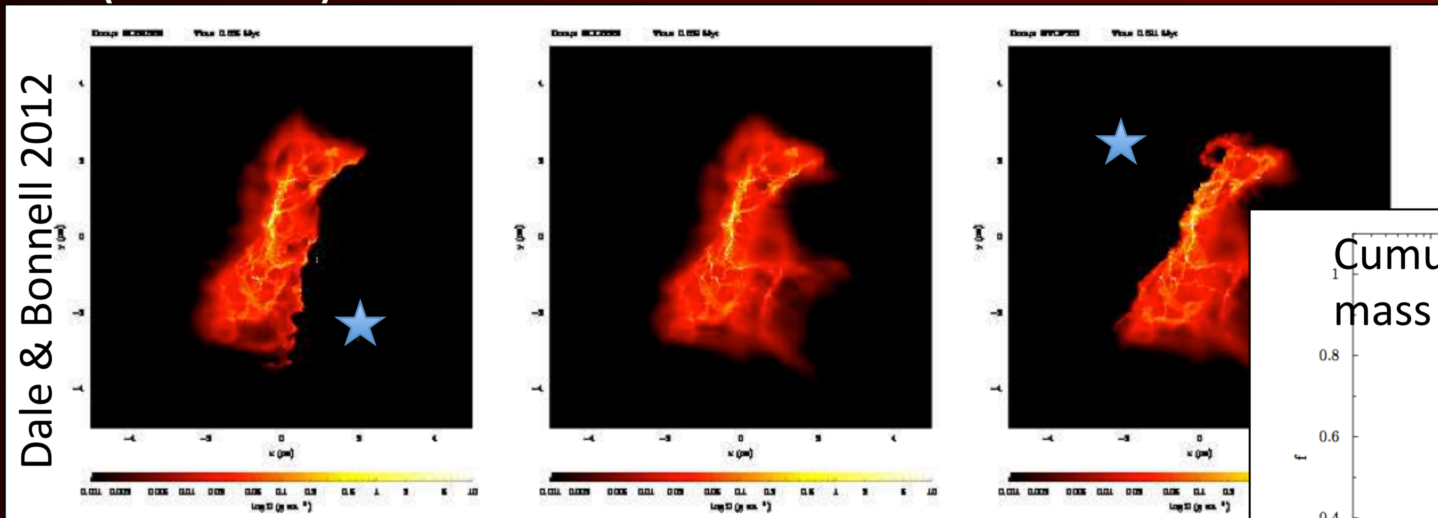




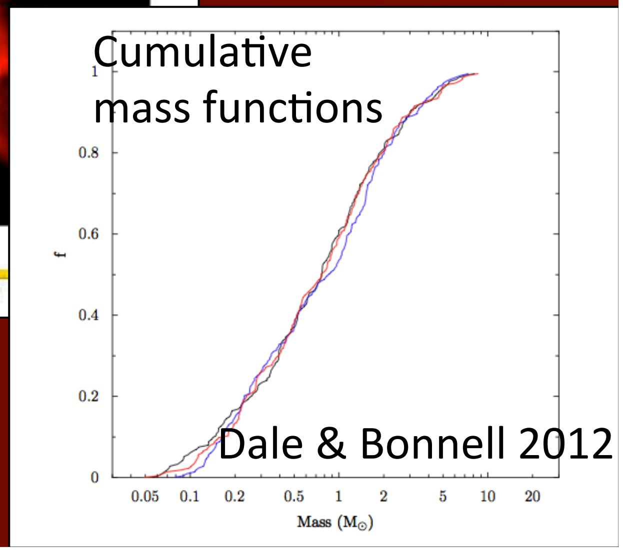
L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion	chem	Δx (AU)
222x72	10^4	y	y	n	Uni	n	y	10000

Triggering by external ionising source

- It has been thought for decades that expanding regions and their ionising front could potentially propagate massive star formation.
- Dale & Bonnell (2012/2013) showed that the impact of ionisation is a strong function of how much gravitationally bound the gas is. Statistically speaking, no impact on the mass distribution of stars (see P20).

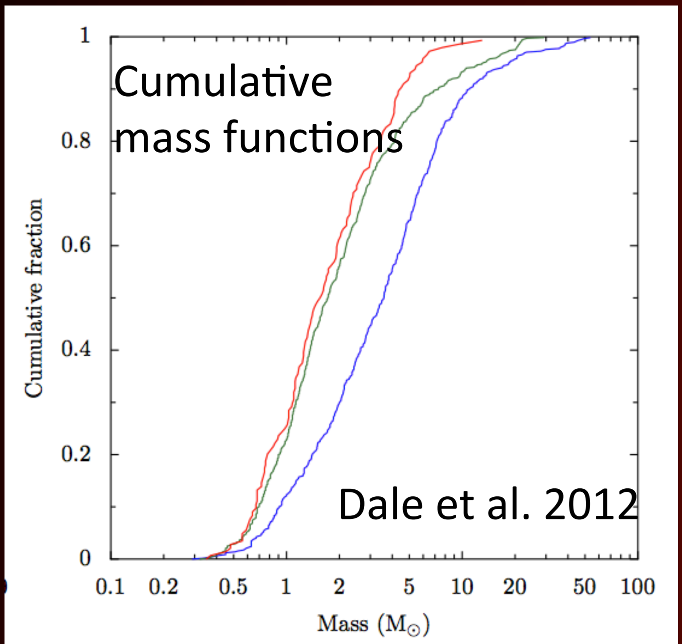


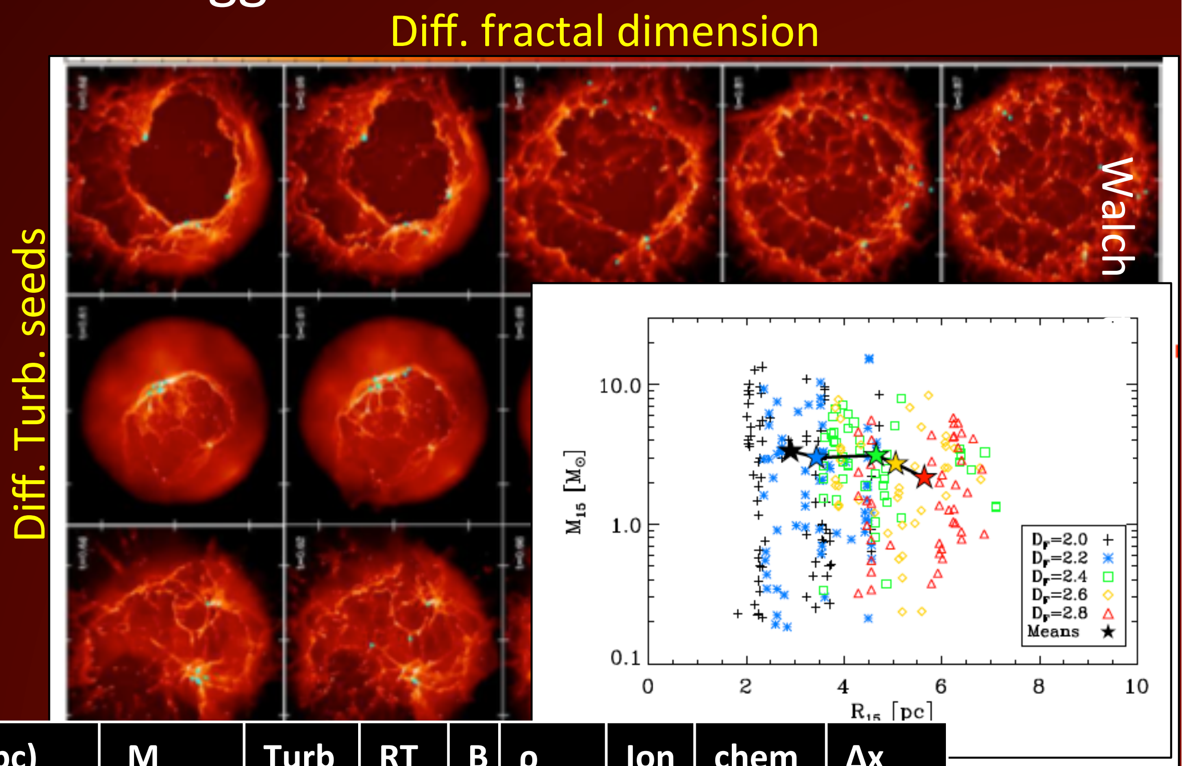
L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion	chem	Δx (AU)
4x2x2	2300	y	n	n	Uni	y	n	1200



Triggering by internal ionising source

- The impact of internal ionising source is negative (Dale et al. 2012)
- But, Walch et al. (2013) investigated the impact of the fractal dimension (i.e. density power spectrum) of clouds on triggering and massive star formation is triggered for low fractal dimension

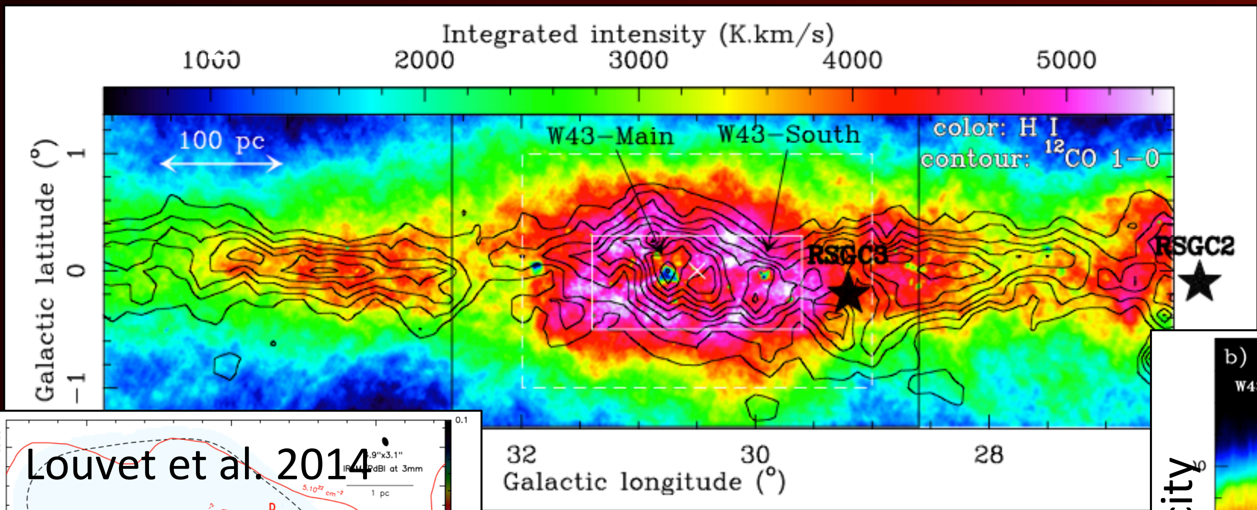




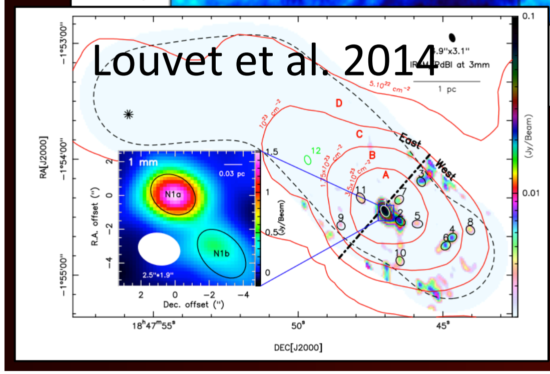
L (pc)	M (M_{sun})	Turb	RT	B	ρ	Ion	chem	Δx (AU)
12	10^4	y	n	n	frac	y	n	1000

Evidence for HI/H_2 flows triggering massive star formation

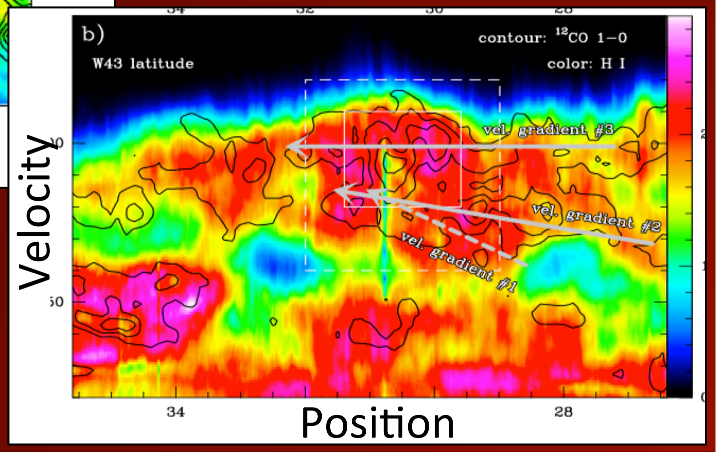
- Finding evidence of HI flows in the Galaxy is very difficult
- Motte et al. (2014) found evidence of large-scale HI and H_2 flows in W43 (see also P3). It turns out that the most massive core ever observed in the Galaxy is located at the converging region (Louvet



Motte et al. 2014

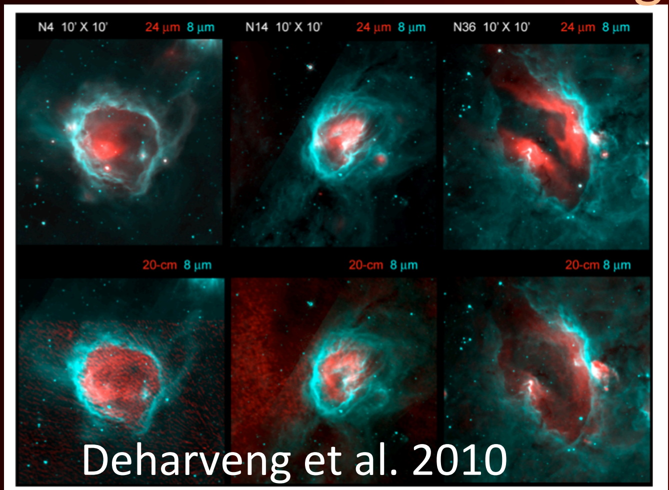


M_{GMC} (M_{sun})	D_{GMC} (pc)	M_{core} (M_{sun})	D_{core} (AU)
10^7	130	1080	6000

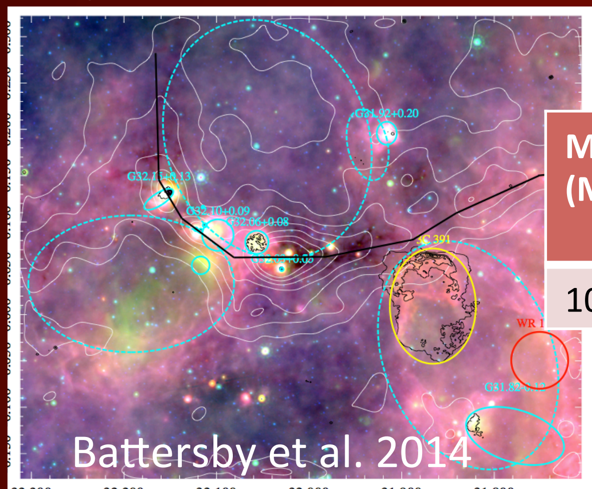


Evidence of dense gas compression via ionisation

- Thompson et al. (2012) showed that between 14% and 30% of all massive star formation happens at the border of HII regions.
- But biased survey of cold dust towards the surrounding of HII regions shows that 40% of roundish HII regions show massive dense cores (see also Zavagno et al. 2010)
- Battersby et al. (2014) suggested that large filamentary molecular clouds might be partially shaped by hot bubbles (see also Ragan et al 2014 and T. Henning's talk)



Deharveng et al. 2010

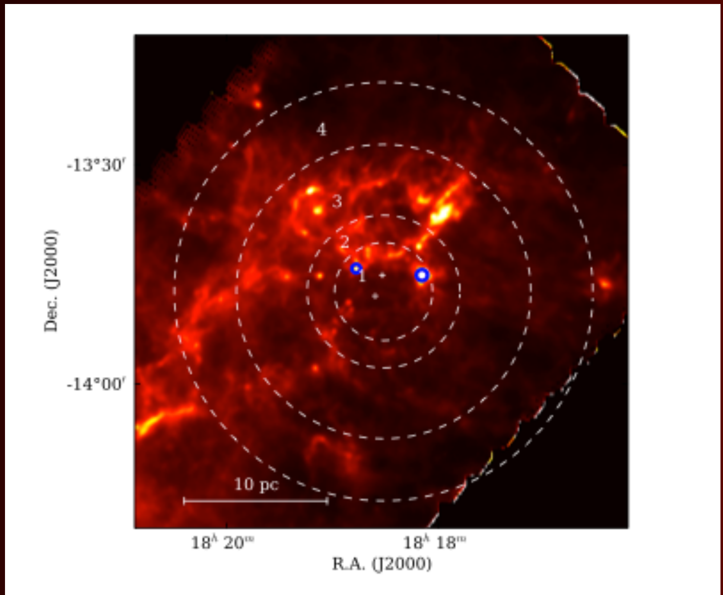

Battersby et al. 2014

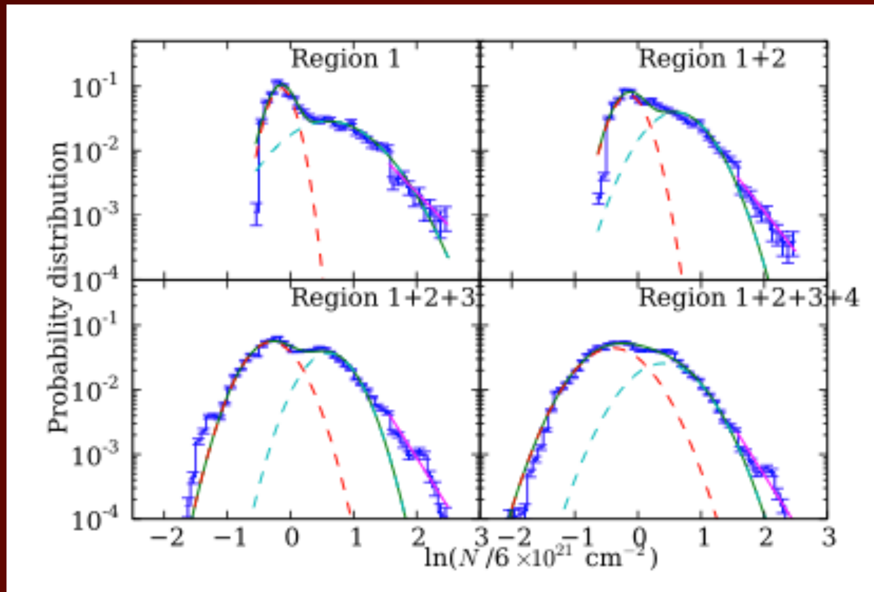
M_{GMC} (M_{sun})	D_{GMC} (pc)	M_{core} (M_{sun})	D_{core} (AU)
10^5	80x5	210	25000

Evidence of dense gas compression via ionisation

- Tremblin et al. (2014) studied the column density PDFs around well known HII regions. They found that such PDFs often shows double peaked PDFs, interpreted as arising from the turbulent cloud and from the compressed layer.
- Double peaked PDFs not always observed: ratio between the pressure of the ionisation front and the turbulent ram pressure.

Tremblin et al. 2014





Summary & conclusions

- Radiation pressure is not an issue. Accretion stopped by fragmentation-induced starvation?
- Rotating structures around massive protostars exist. Are they rotationally supported structures? In simulations it seems so, in real life, not really clear yet...
- Fragmentation is seen down to few hundreds AU scale, but not systematic. Magnetic field amplitude variations?
- Massive prestellar cores probably don't exist.
  But C. Cyganowski's core...
- Star forming clouds are very dynamic (inherited from their formation process), bound (on pc scales), and collapsing. The impact of the collapse probably depends on the cloud properties.
- Triggered star formation has a minor impact on the global stellar population, and on massive stars in particular