From the structure of molecular clouds to the formation of massive stars

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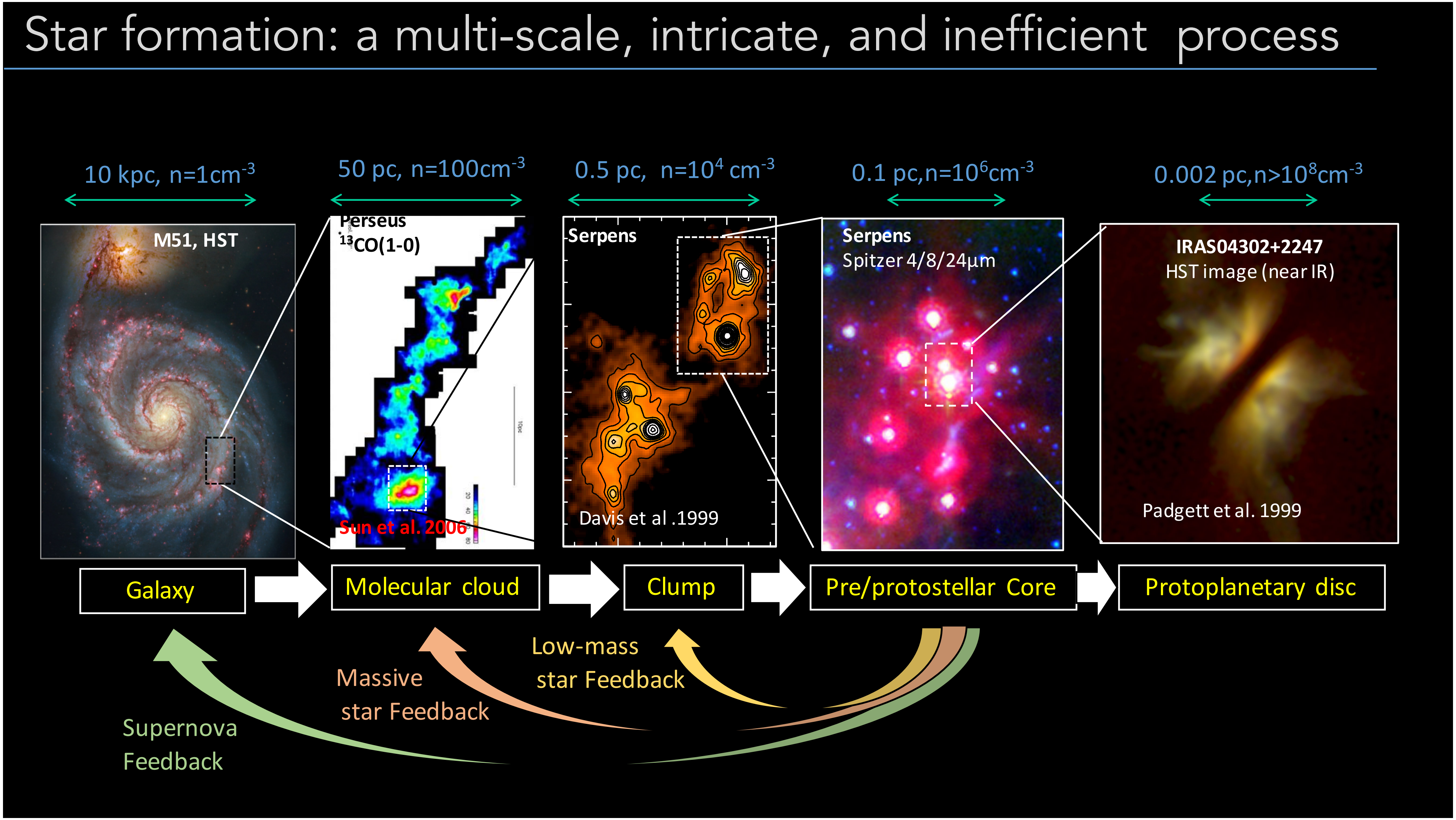
17th of December 2019, CEA, Saclay


Star formation: a multi-scale, intricate, and inefficient process
10 kpc, n=1cm-3
50 pc, n=100cm-3
0.5 pc, n=104 cm-3
0.1 pc,n=106cm-3
0.002 pc,n>108cm-3
M51, HST
Perseus
13CO(1-0)
Sun et al. 2006
Serpens
Davis et al .1999
Serpens
Spitzer 4/8/24µm
IRAS04302+2247
HST image (near IR)
Padgett et al. 1999
Galaxy
Molecular cloud
Clump
Pre/protostellar Core
Protoplanetary disc
Low-mass
star Feedback
Massive
star Feedback
Supernova
Feedback

Outline

- The energy balance of molecular clouds
- The structure and dynamics of hub filament systems
- The impact of OB stars on their parent cloud

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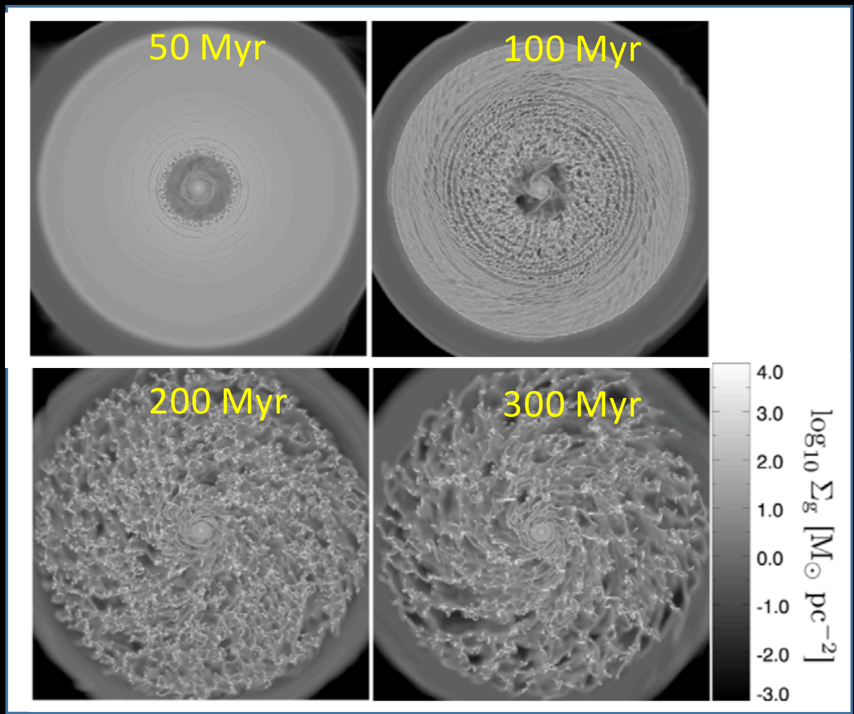
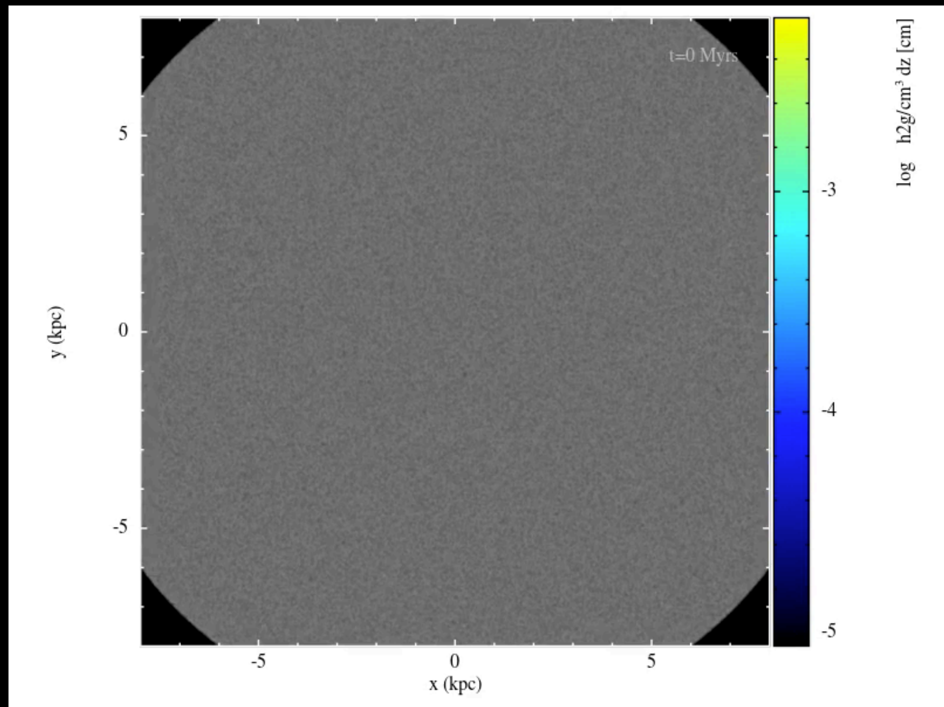
The energy balance of molecular clouds

- Formation of GMCs requires the presence of converging flows: Gravity (e.g. Kim & Ostriker 2002); SN/HII region compression (e.g. Ntormousi+ 2011; Inutsuka+ 2015); Galactic dynamics (e.g. Dobbs+ 2013)



Tasker & Tan 2009



Dobbs & Pringle 2013

The energy balance of molecular clouds

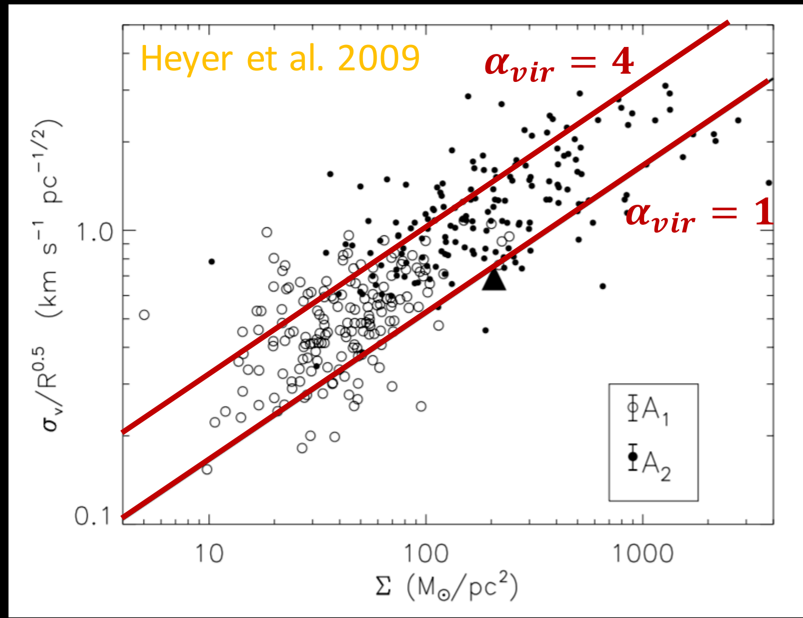
- Virial balance: $E_G=2E_K$ -> $\alpha_{vir}=2E_K/E_G=1$

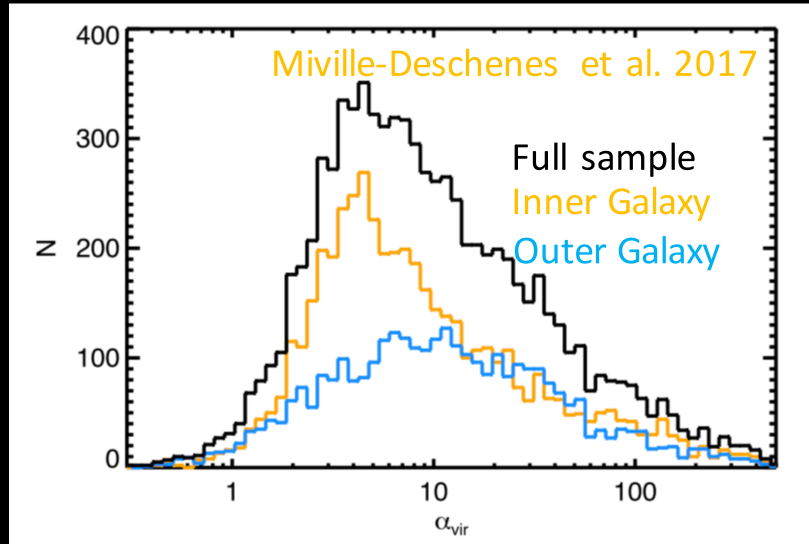
  → $\sigma_v^2 \propto \Sigma\, R$

- Heyer et al (2009, 2015) proposed that GMCs are all self-gravitating and compatible with virial equilibrium

- However, one expects very similar relationship for clouds in free-fall (Ballesteros-Paredes et al. 2011/2017)

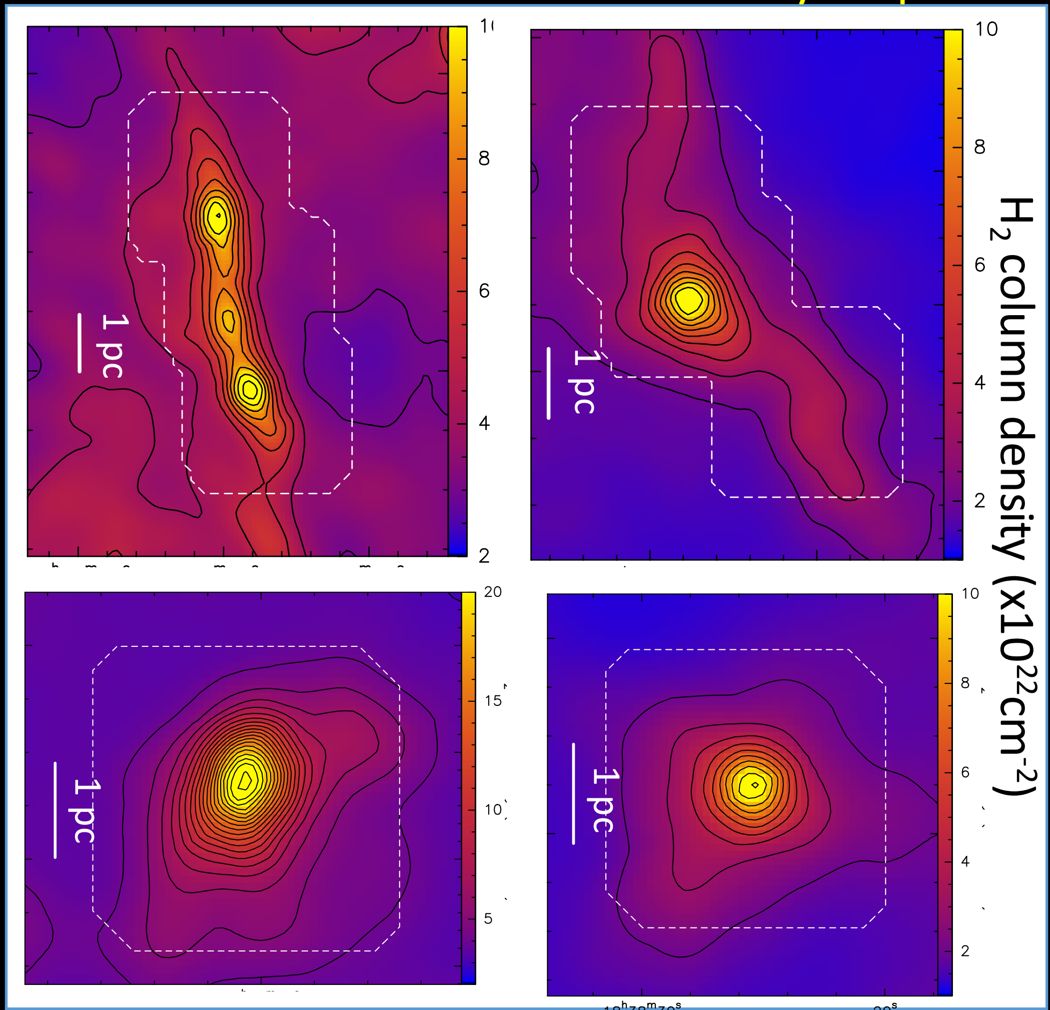
- A majority of unbound clouds ($\alpha_{vir} > 2$) (e.g. Miville-Deschenes + 2017; Schuller+2017)





The energy balance of molecular clouds

PPMAP Herschel column density maps

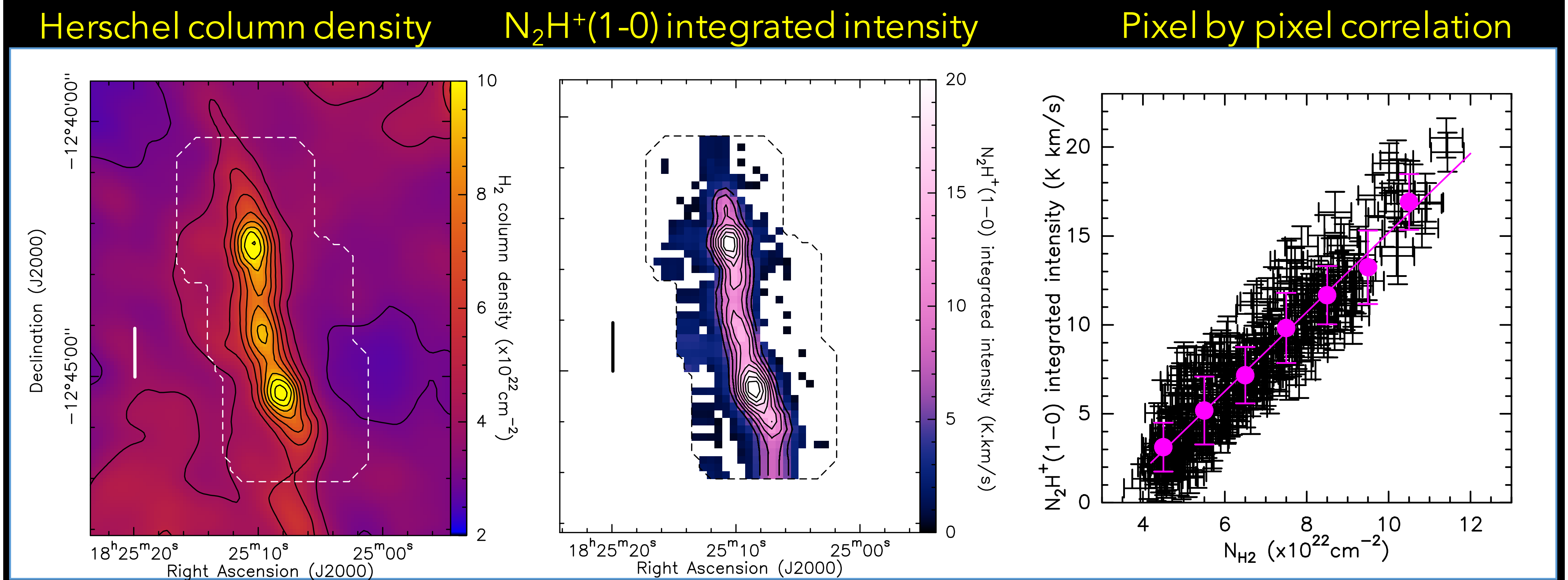


- Sample of 27 IRDCs from Peretto & Fuller 2009 catalogue
- Kinematic distances: 3 to 5 kpc (using Reid + 09 model)
- Masses: 300 to 20,000 Msun in 1 to 6 pc diameters
- Aspect ratio: 1 to 6

Peretto et al., in prep

The energy balance of molecular clouds

- All detected, with excellent correlation with column density

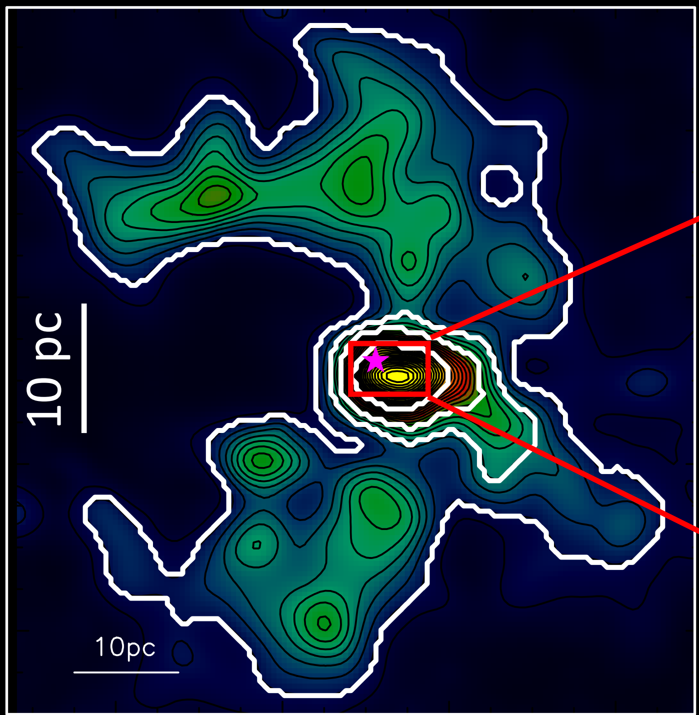


Peretto et al., to be subm

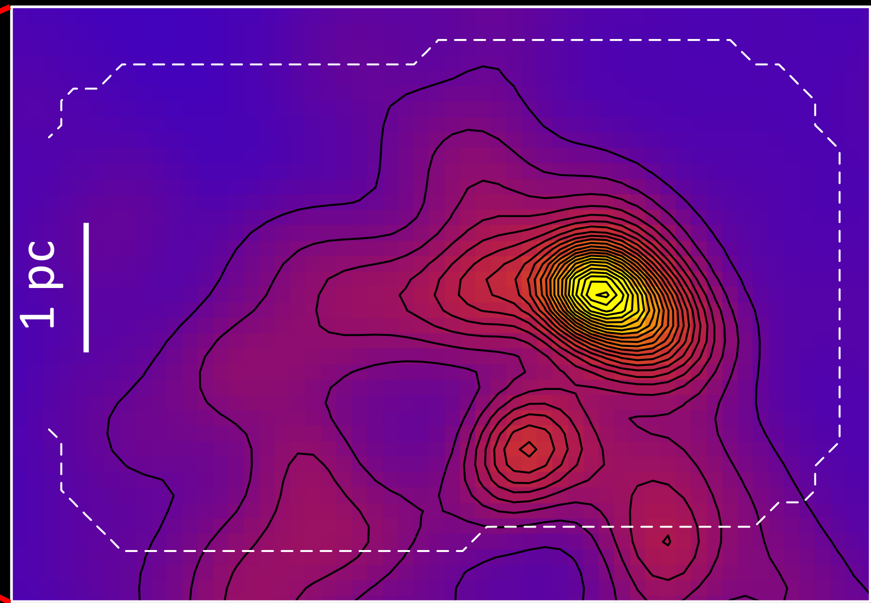
The energy balance of molecular clouds

- Following up clouds from few tenths to few tens of pc using 2D dendrogrammes .....

Large (^{13}CO(1-0) GRS)



Small scales (Herschel/N_2H^+ IRAM 30m)



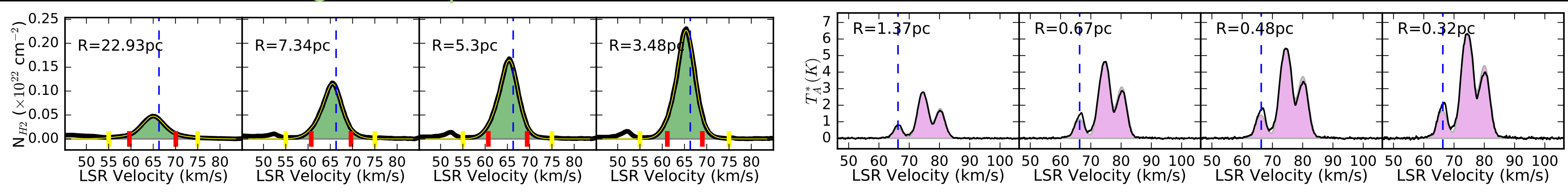
Peretto et al., to be subm

The energy balance of molecular clouds

- .... and line fitting all the way

^{13}CO large scale points

N_2H^+ small scale points



Largest scale
R = 23 pc

Decreasing radius

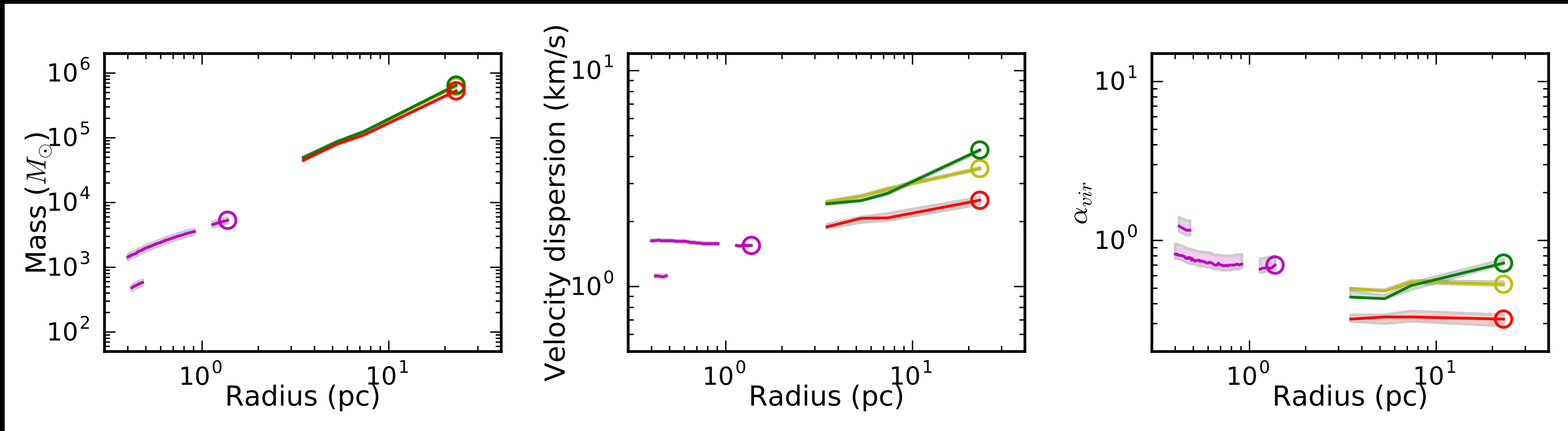
Smallest scale
R=0.3 pc

- Test of several methods for ^{13}CO(1-0) velocity dispersion estimates

Peretto et al., to be subm.

The energy balance of molecular clouds

- Profiles of m(R), σ(R), α_{vir}(R) for every individual cloud

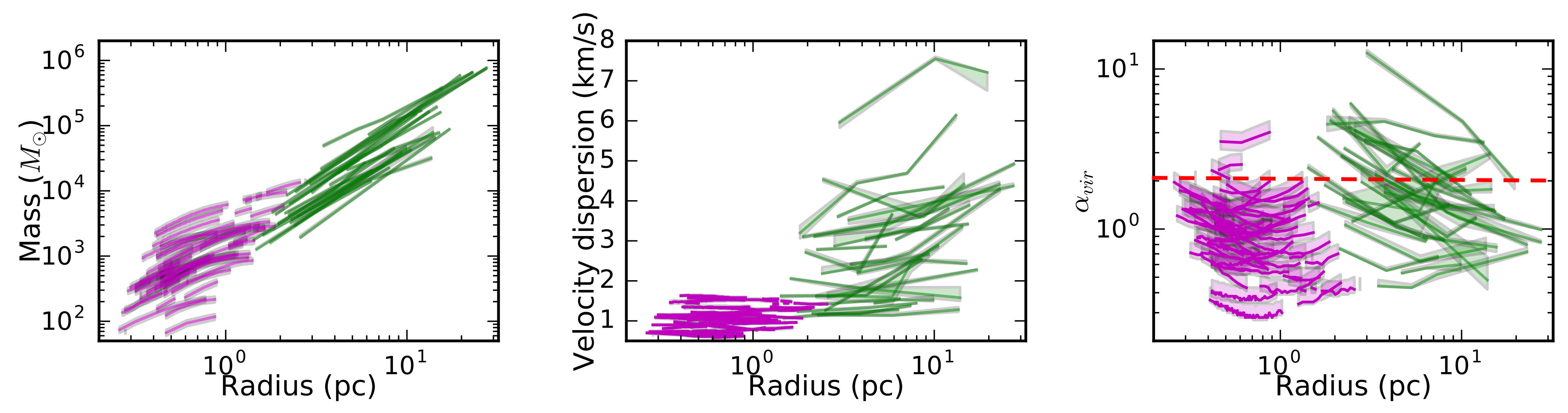


- In simple cases all three methods provide consistent values and transition between small and large scales is continuous

Peretto et al., to be subm.

The energy balance of molecular clouds

- Putting it altogether

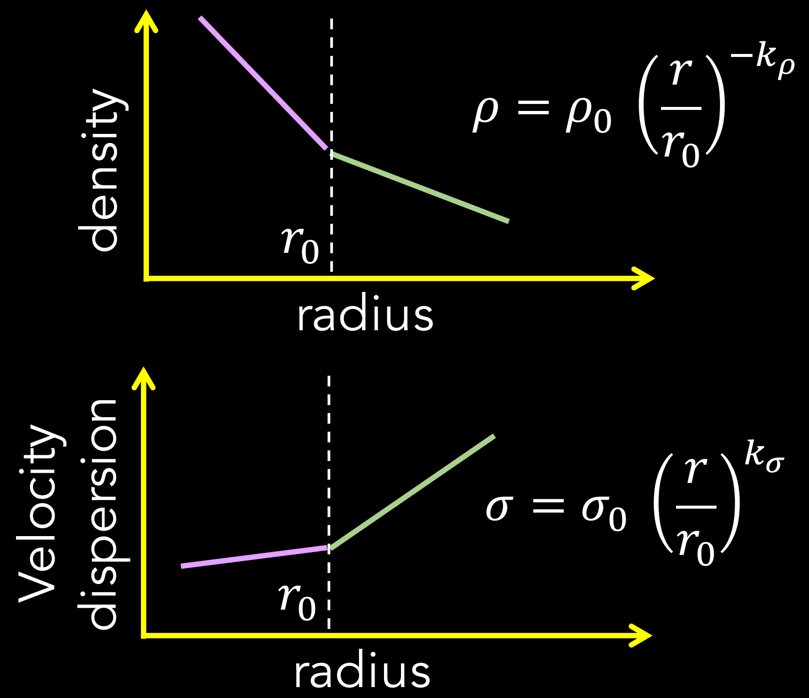


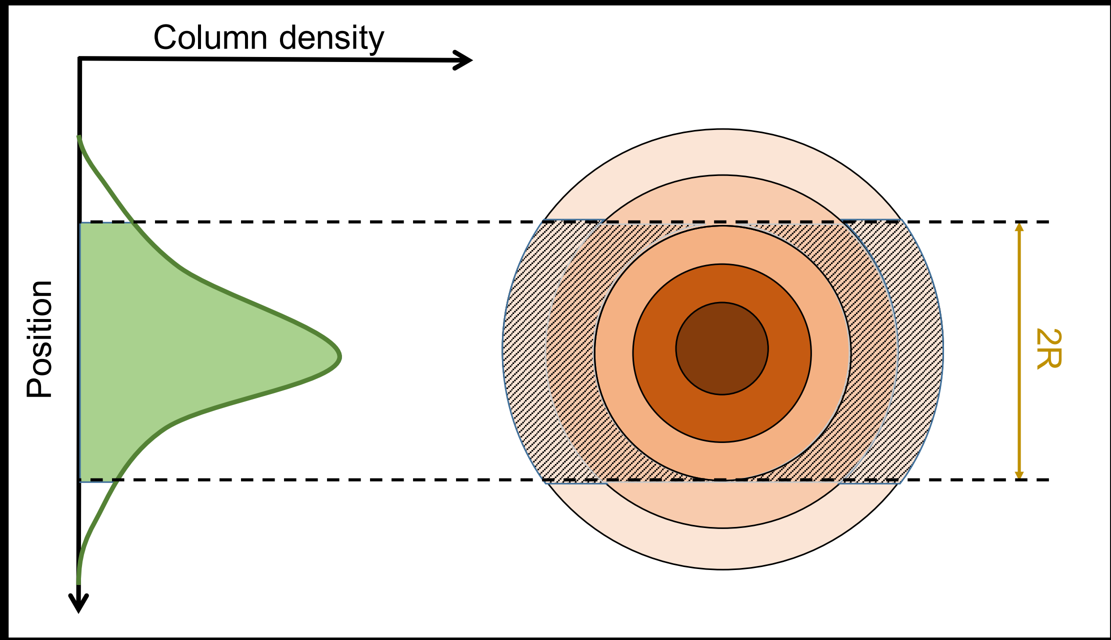
- Discontinuities in the dense (purple) and diffuse (green) parts of the profiles: What is the origin of these?

Peretto et al., to be subm.

The energy balance of molecular clouds

- 1D modelling of observed cloud profiles



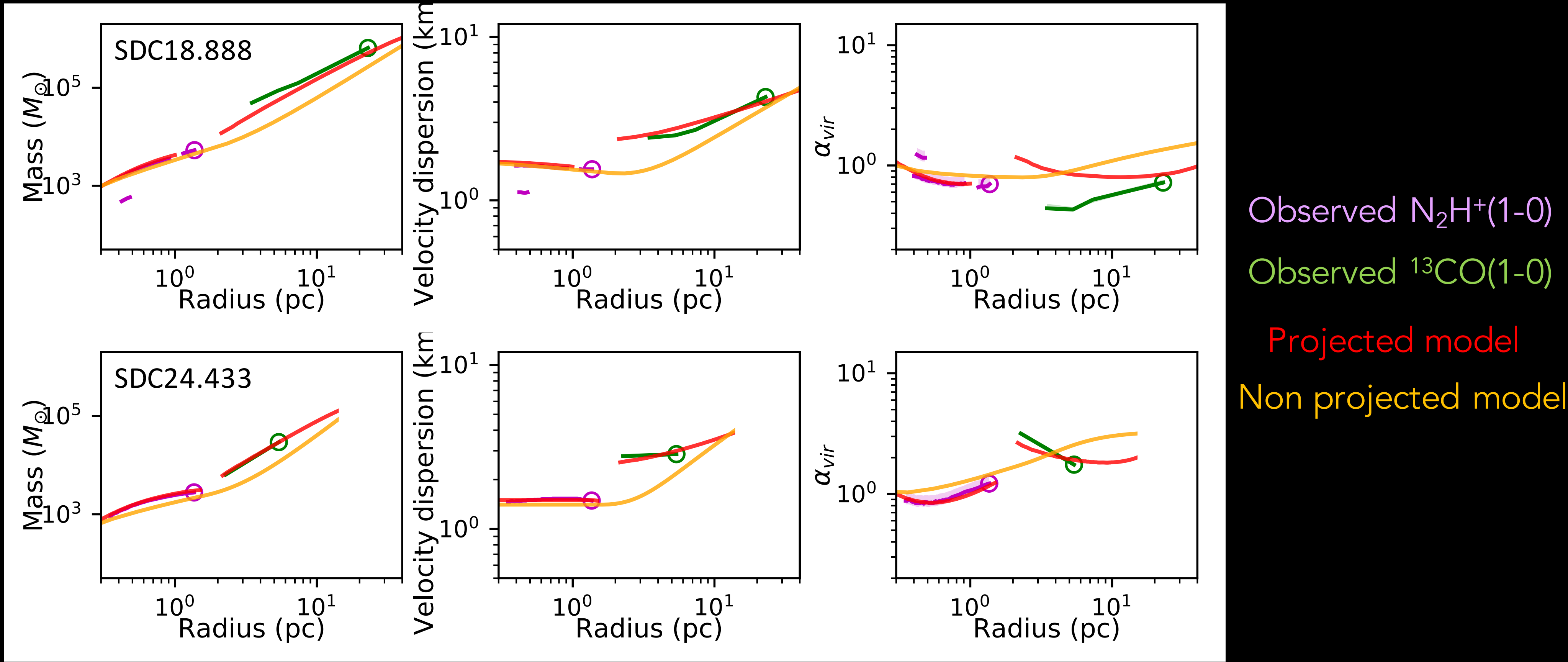


Peretto et al., to be subm.

- N_2H^+(1-0) observations only trace the inner part of the model
- Can the model, once projected on the sky and convolved at the resolution of the observations, explain the observed profiles?

The energy balance of molecular clouds

- Modelled Profiles of m(R), σ(R), α_{vir}(R) for every individual cloud

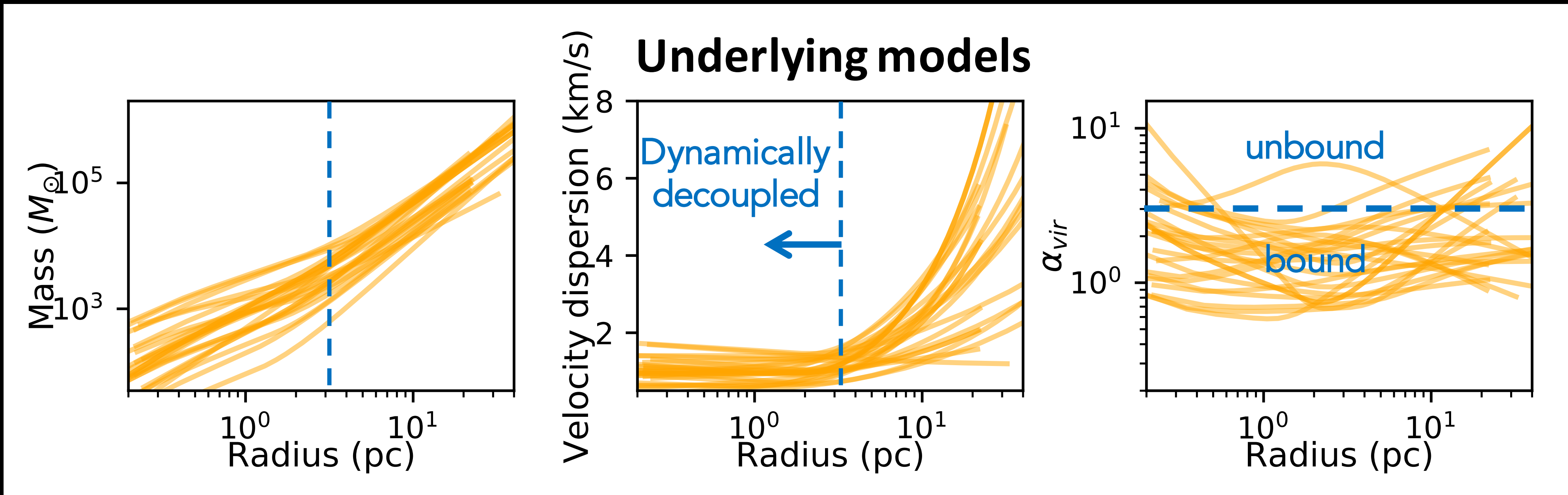


Peretto et al., to be subm

- Models do reproduce most observed features

The energy balance of molecular clouds

- Overall comparison



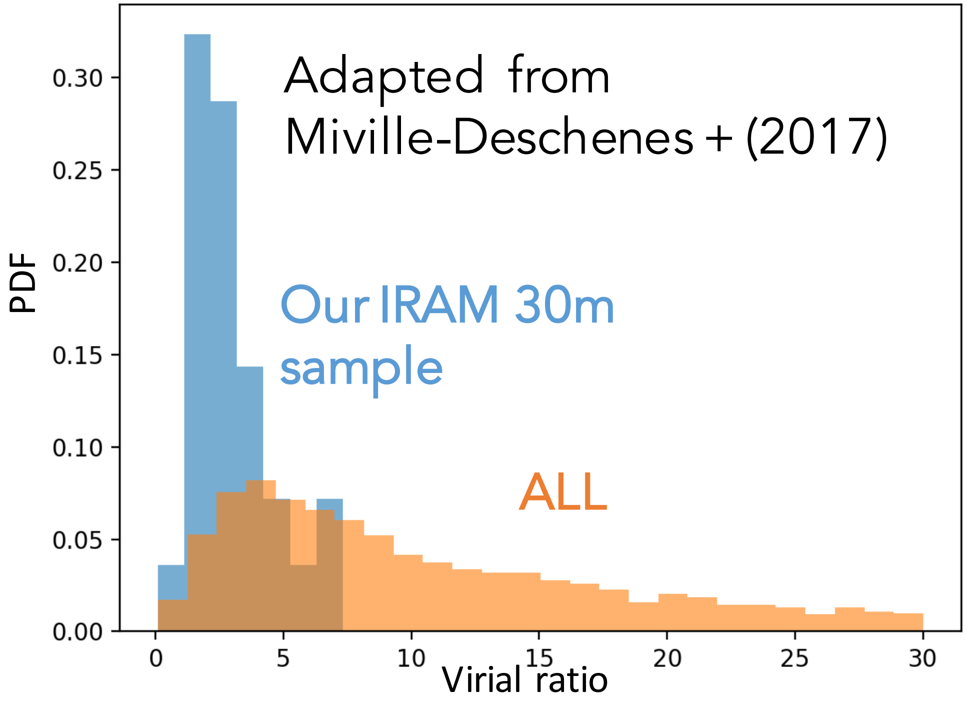
Peretto et al., to be subm.

- The dense clumps are dynamically decoupled from their parent, gravitationally bound, molecular clouds.
- What is the physical origin of such decoupling? Working on it.

Sample bias compared to MW cloud population

- But what about complete samples of clouds showing that the majority are unbound?
- Our IRAM 30m sample compared to the global population using Miville-Deschenes+ (2017) cloud properties from the ^{12}CO(1-0) Dame et al. (2001) survey
- Our sample is clearly biased towards low virial ratio values

virial ratio distribution of MW ^{12}CO clouds



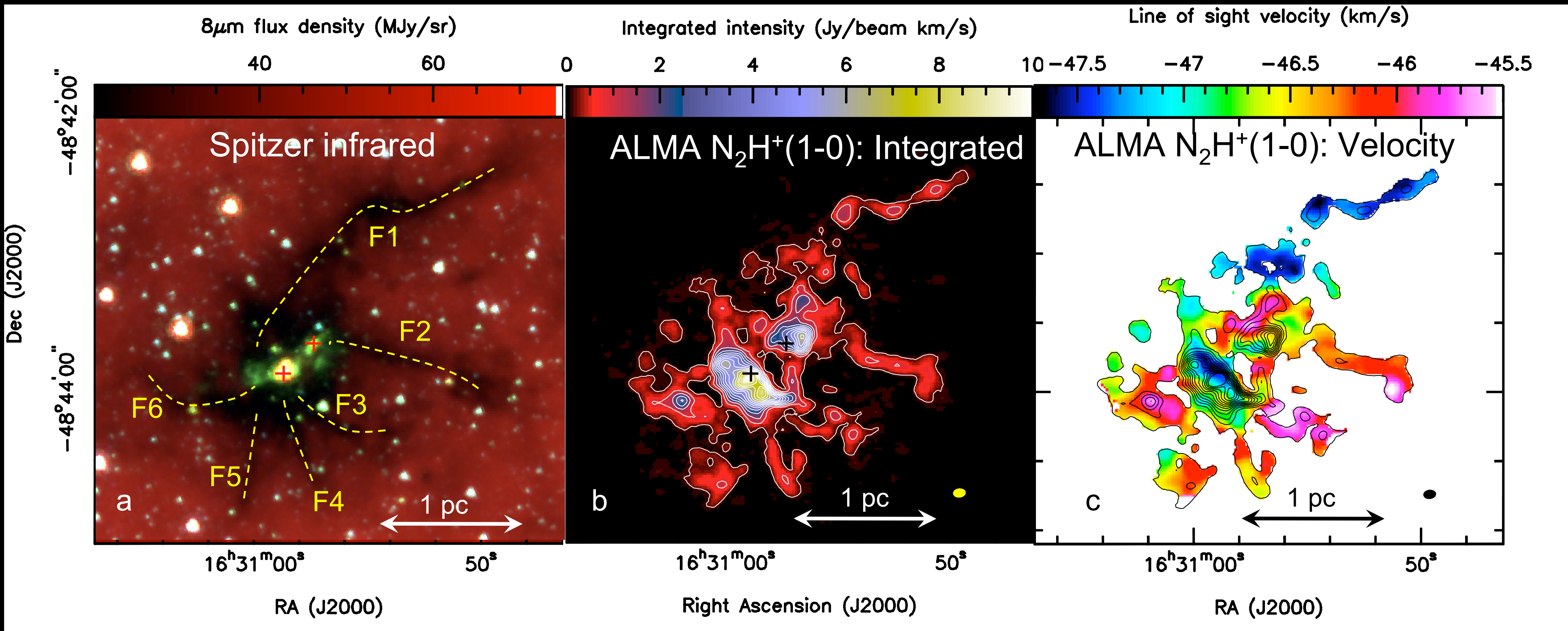
Peretto et al., to be subm

Outline

- The energy balance of molecular clouds
- The structure and dynamics of hub filament systems
- The impact of OB stars on their parent cloud

Structure and dynamics of hub filament systems

- ALMA observations of the SDC335 hub (M_{H2}=5500M_{sun} in D=2.4pc)



Peretto et al, 2013

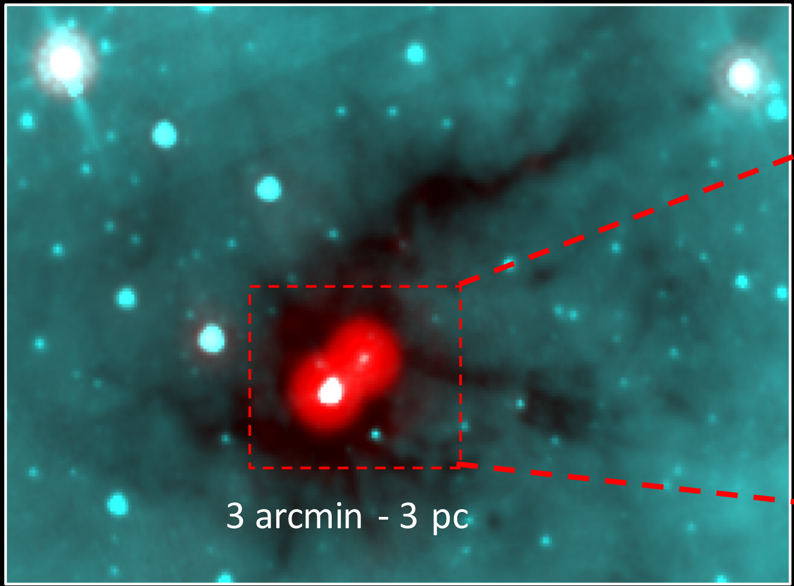
- Combined with single data: Infall velocity of ~ 0.7 km/s, only 1.6 times slower than the expected freefall velocity: Rapid collapse!!!

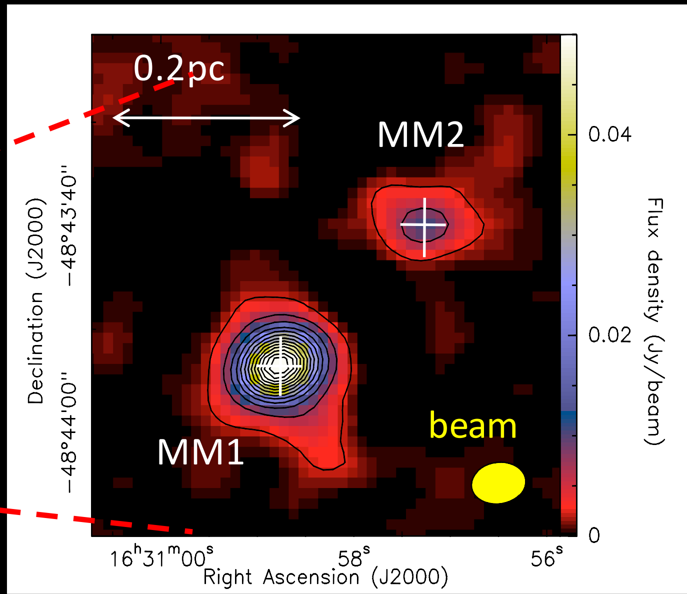
Structure and dynamics of hub filament systems

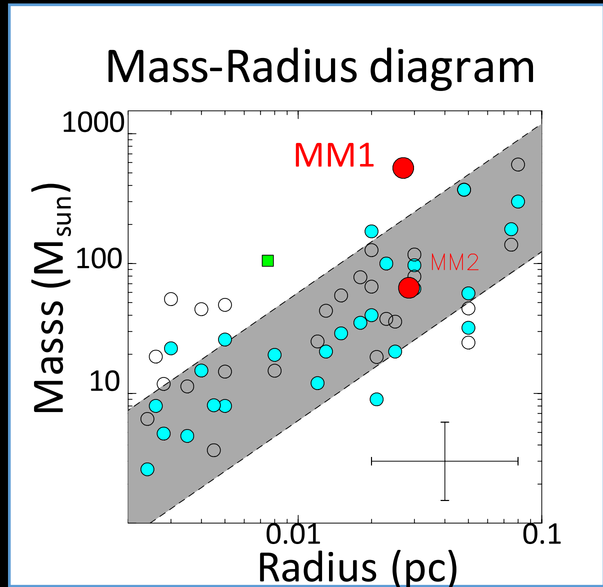
- A 500 M_{sun} protostellar core at the centre of a globally collapsing clump

Spitzer two colour 8 & 24 µm

3.2mm dust cont.







- A OB star cluster is currently forming at the centre of SDC335 (Avison+2015, Avison+ submitted.)

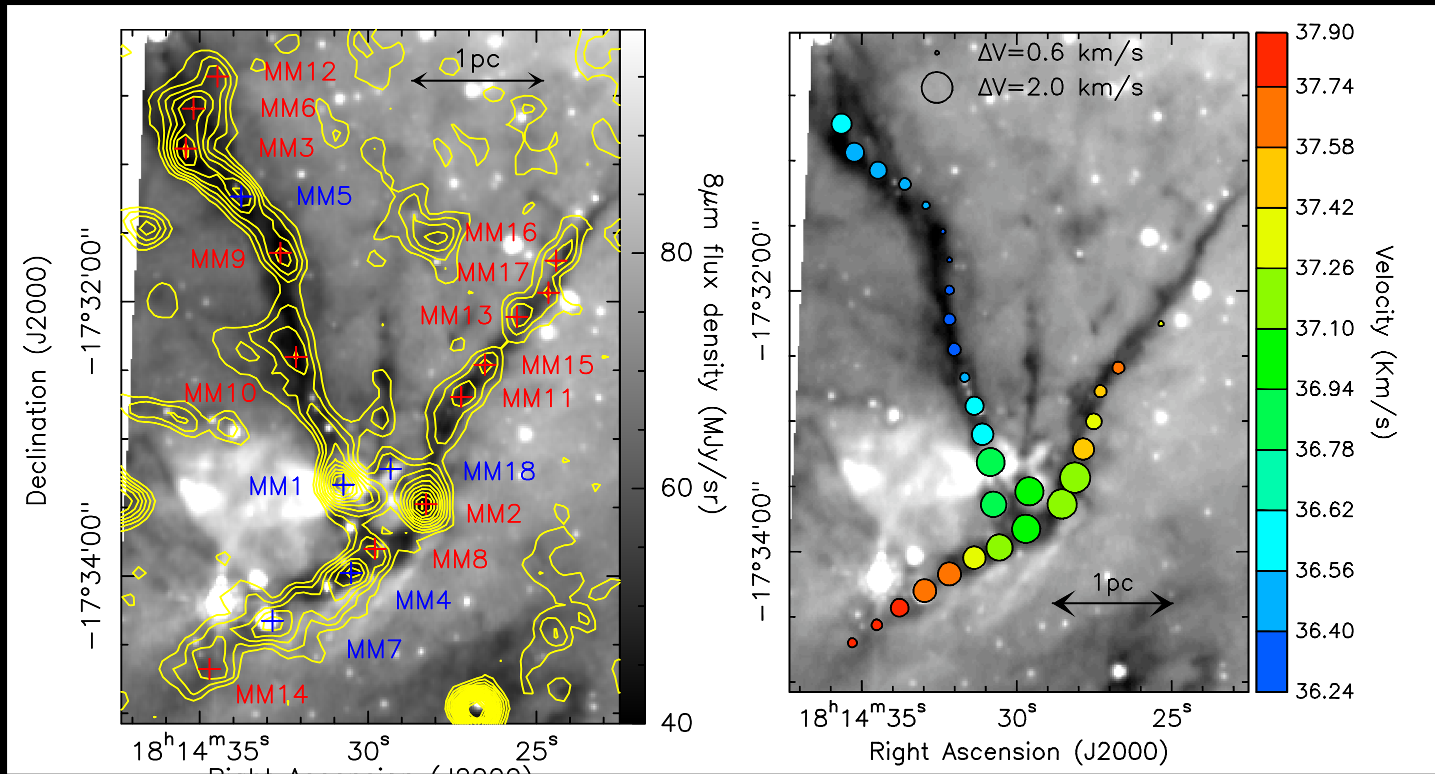
Structure and dynamics of hub filament systems

- Characterisation of the SDC13 hub ($M=1200M_{sun}$ in $D=3pc$)

- "Massive" cores at the junction

- Velocity gradients in all filaments

- Increased velocity dispersion at junction

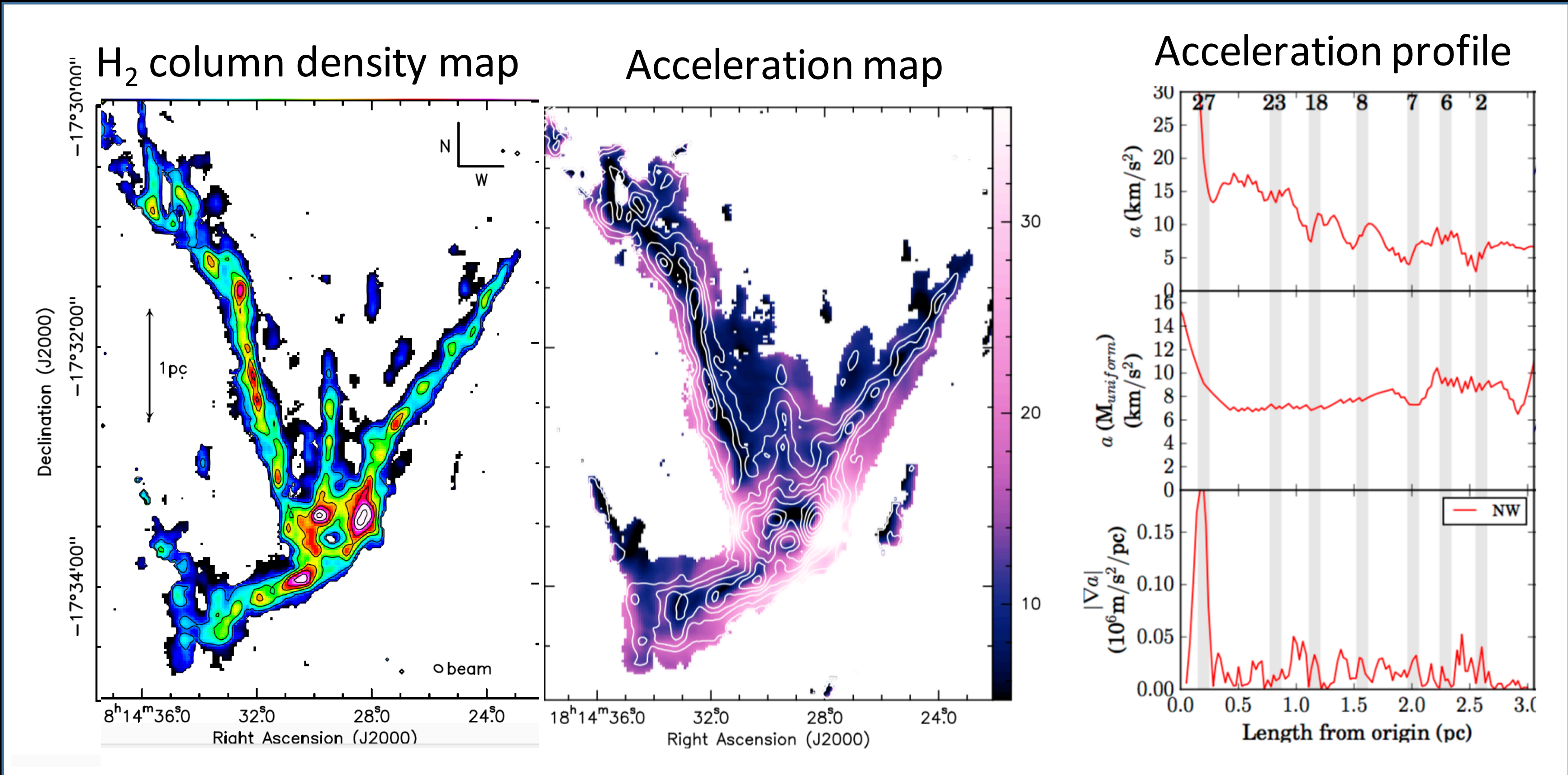


Peretto et al. 2014

- Consistent with longitudinal free-fall collapse of large aspect ratio filaments (Pak+2019 propose alternative scenario)

Structure and dynamics of hub filament systems

- NH$_3$ JVLA observations of SDC13

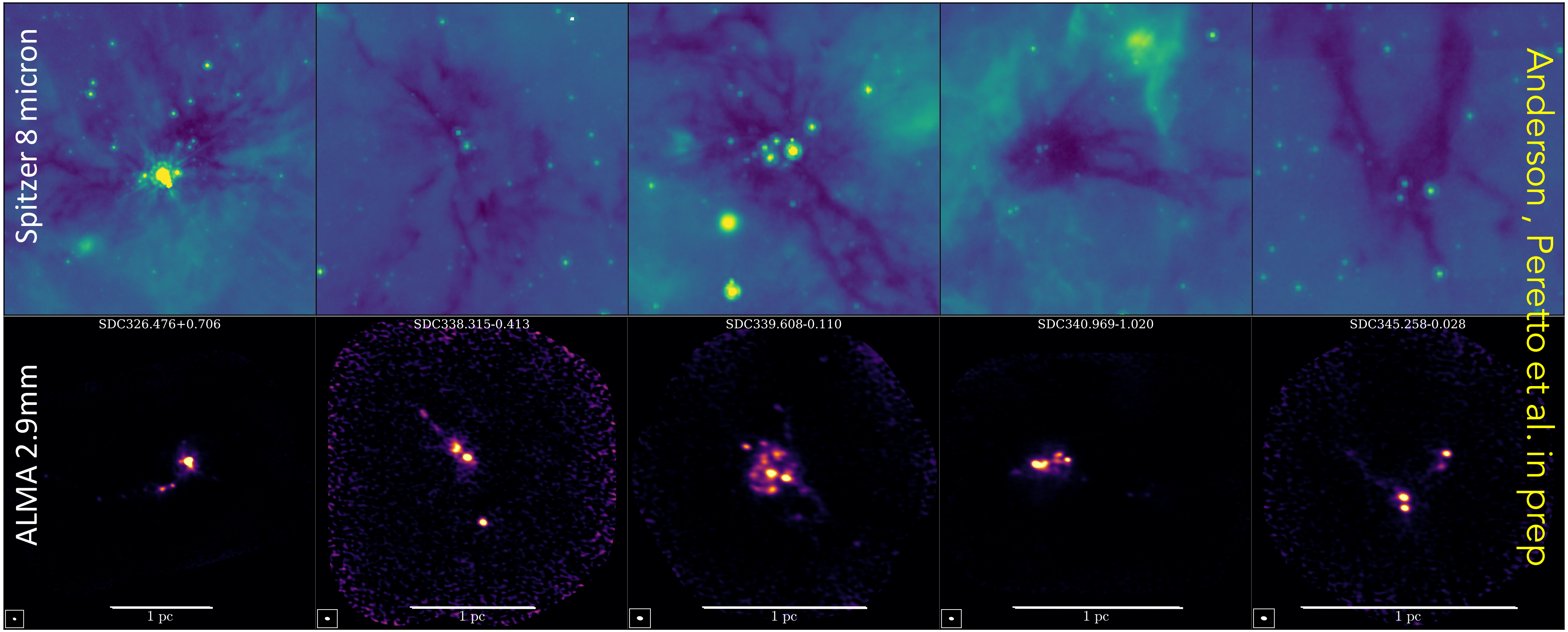


Williams, Peretto et al. 2018

- Junction is a favored location for the formation of massive cores

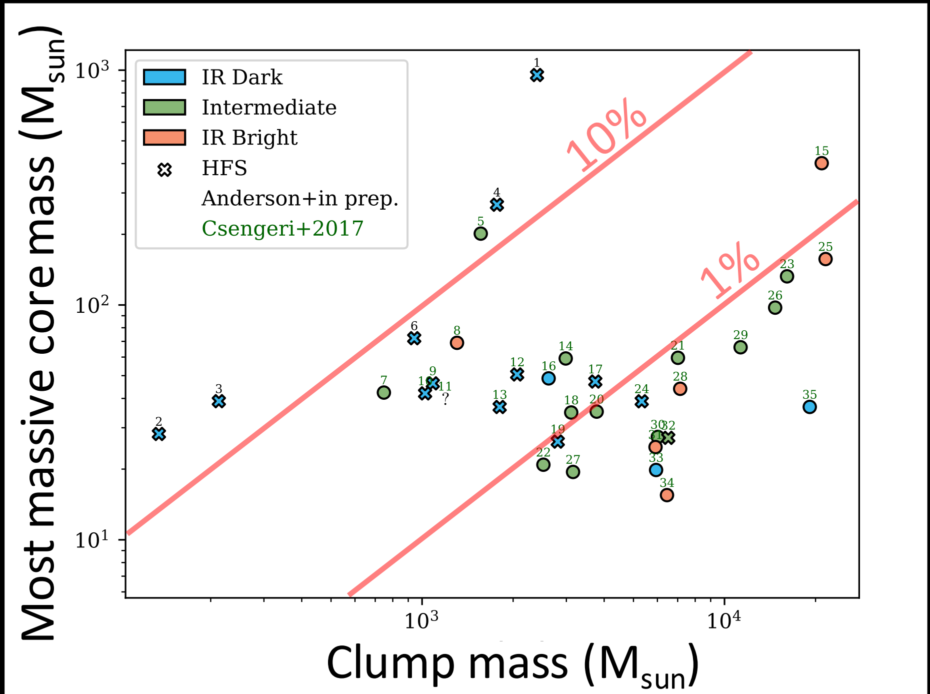
Structure and dynamics of hub filament systems

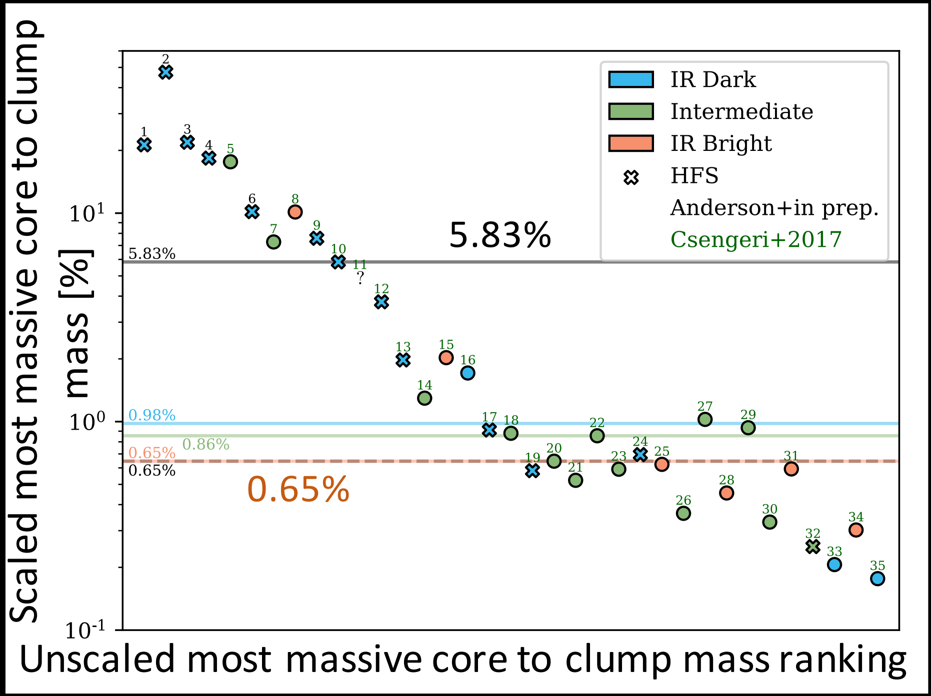
- ALMA mapping of 5 IRDC with narrow distance range (2.1kpc to 2.9kpc) and large mass range (~200 to 2000 M_{sun})



Structure and dynamics of hub filament systems

- Comparing core / clump masses as a function of cloud IR darkness and morphology – Csengeri et al. (2017) sample used for statistics





Anderson, Peretto et al. in prep

- No correlation between core and clump masses, but hubs concentrate more of the clump mass into the most massive core

Outline

- The energy balance of molecular clouds
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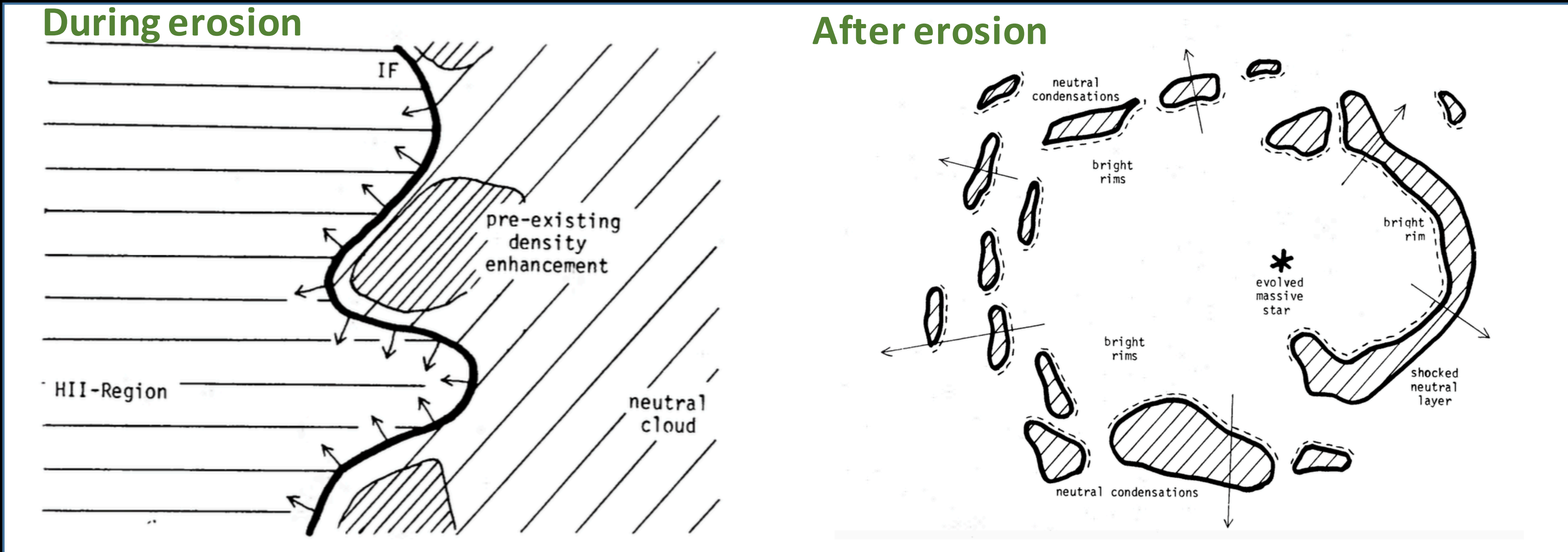
- The impact of OB stars on their parent cloud

The impact of OB stars on their parent cloud

- Feedback from massive stars is responsible for dispersing their host clouds and limiting the cloud SFE (e.g. Whitworth 1979; Elmegreen 1983; Williams & McKee 1997)

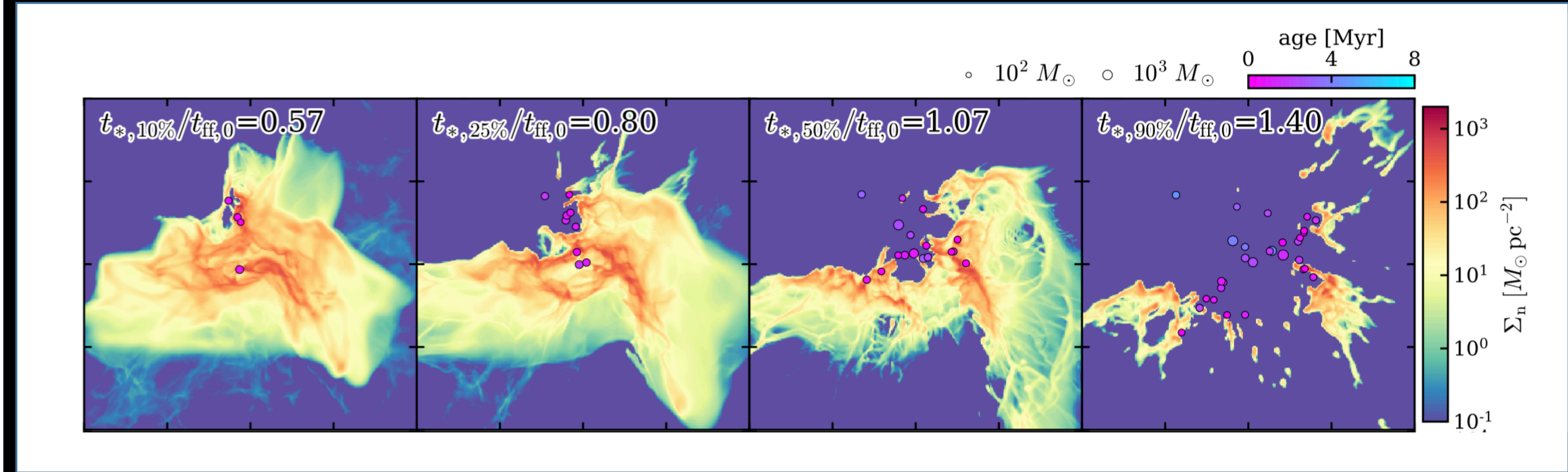


Whitworth 1979

- But what type dominates? Ionisation, radiation pressure, winds (see Krumholz et al. 2014 for a review).

The impact of OB stars on their parent cloud

- Large number of simulations that investigate the impact of certain type of feedback on their host cloud (e.g. Dale+2005 to 2017; Peters+2010/2011; Geen+2016/2018; Kim+2018; and many others)

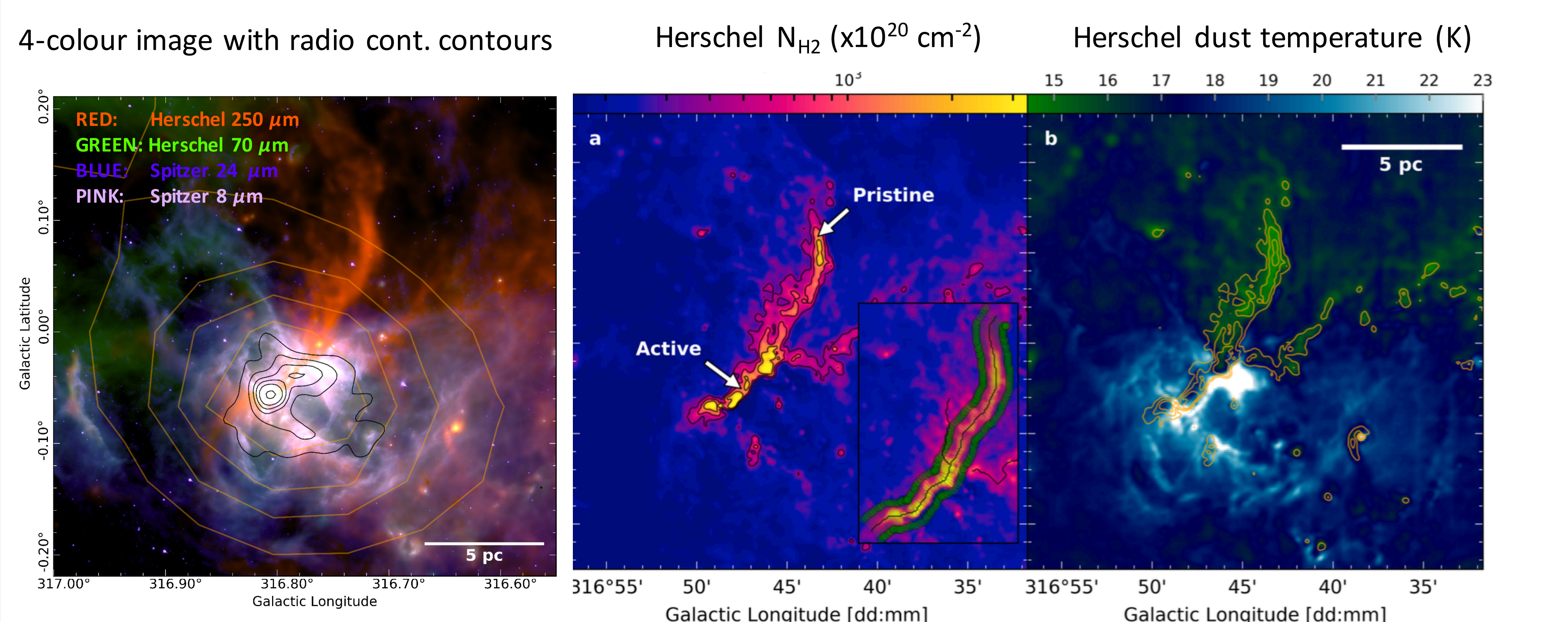


Kim et al. 2018

- The spatial mass distribution is key (see also Thompson & Krumholz 2016)

The impact of OB stars on their parent cloud

- The G316.75 ridge: A O star-forming 20,000 M_{sun} ridge, half IR bright half IR dark



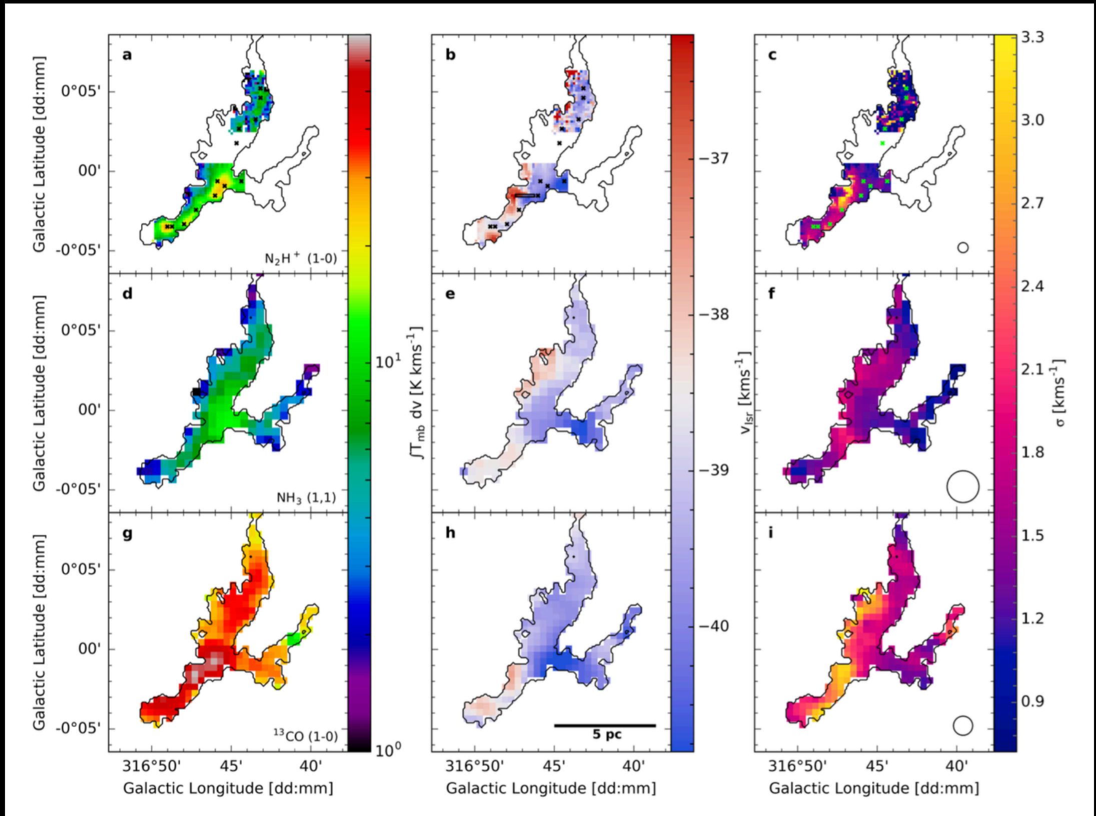
Watkins, Peretto +, 2019

- Use the IR dark gas properties as initial conditions for IR bright part

The impact of OB stars on their parent cloud

- Use of ^{13}CO(1-0), NH_3(1,1) N_2H^+(1-0) archive data to probe gas kinematics at different density regime (from ~10^2 to 10^5 cm^{-3})

Integrated Velocity V dispersion



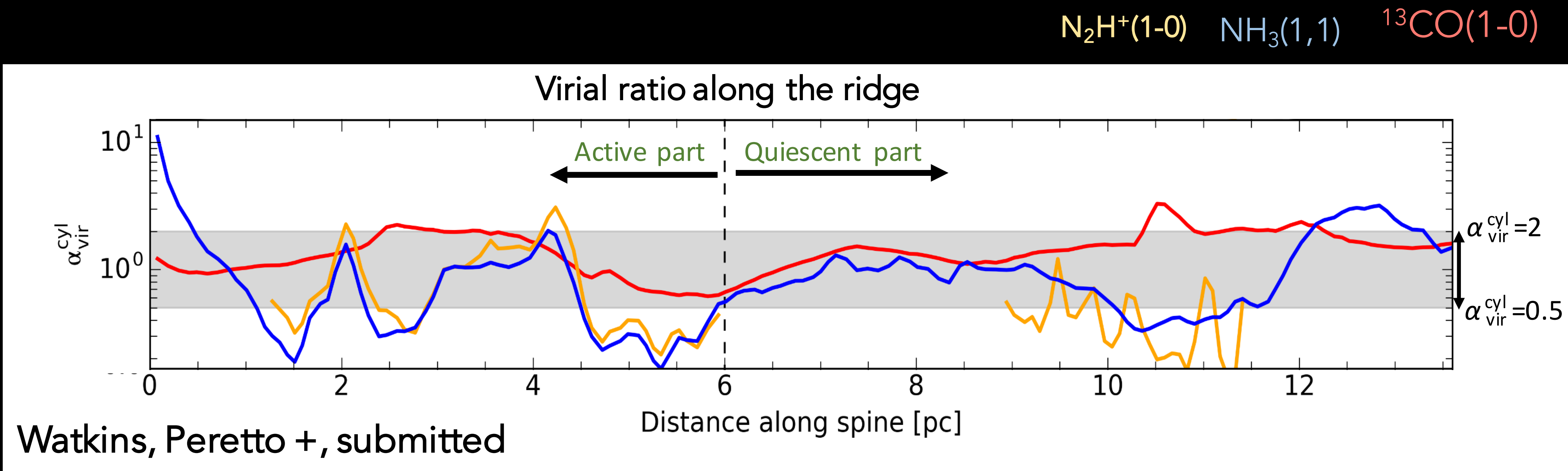
Watkins, Peretto +, 2019

N_2H^+(1-0) NH_3(1,1) ^{13}CO1-0)

- Velocity fields are similar
- Velocity dispersions are larger for lower density tracers
- Localised peaks of very large (6km/s) velocity dispersion in the active part of the ridge

The impact of OB stars on their parent cloud

- Computing the energy balance of the G316.75 ridge

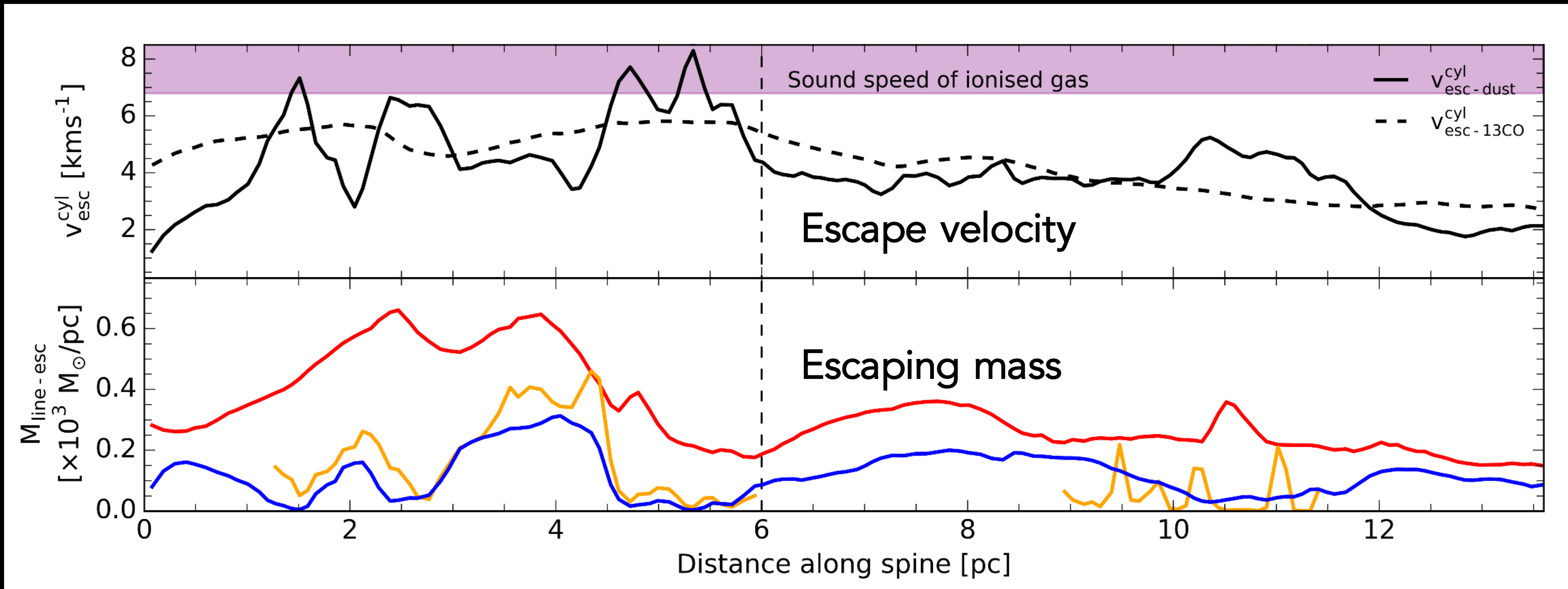


- The vast majority of the gas is bound, in all tracers (i.e. densities), and little differences between the active and quiescent parts of the ridge

The impact of OB stars on their parent cloud

- Computing the escape velocity, and escape mass fraction of the G316.75 ridge

Watkins, Peretto +, 2019



$^{13}CO(1-0)$

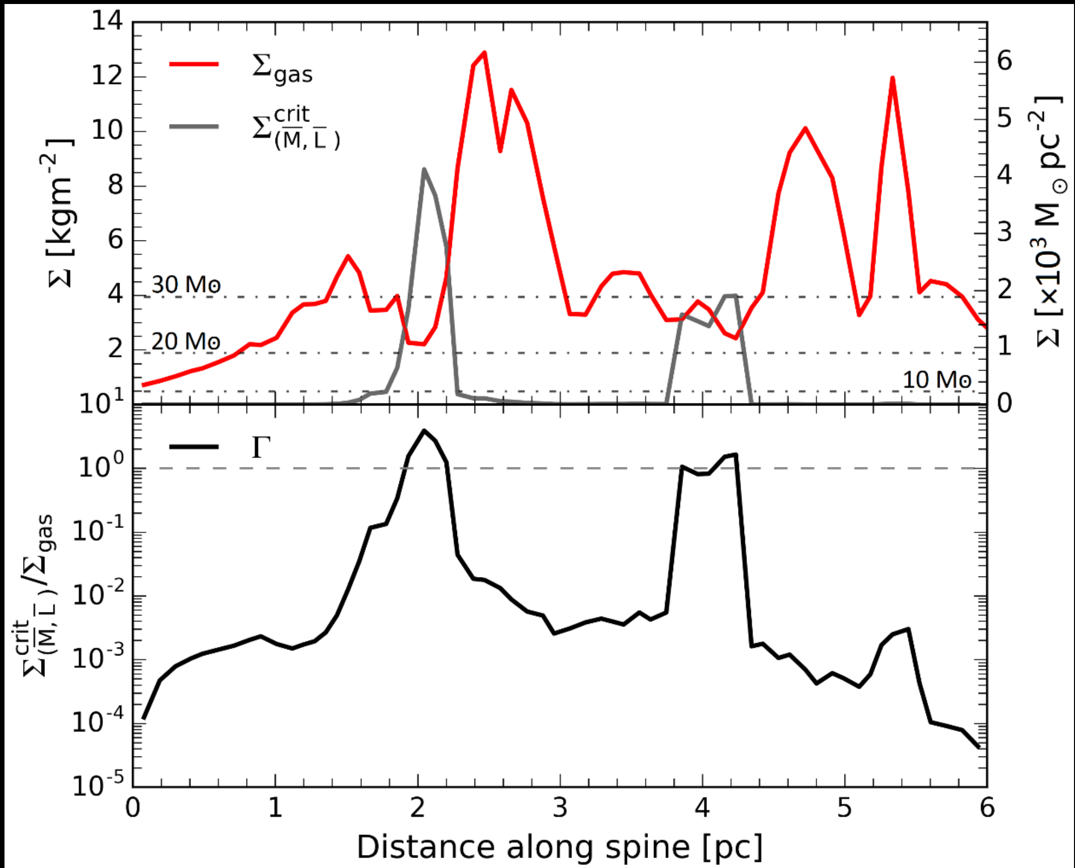
$NH_3(1,1)$

$N_2H^+(1-0)$

- 5% to 10% of the dense gas is currently escaping, 20% of the more diffuse. Far from numerical predictions after 2Myr (~70%).

The impact of OB stars on their parent cloud

- Testing radiation pressure



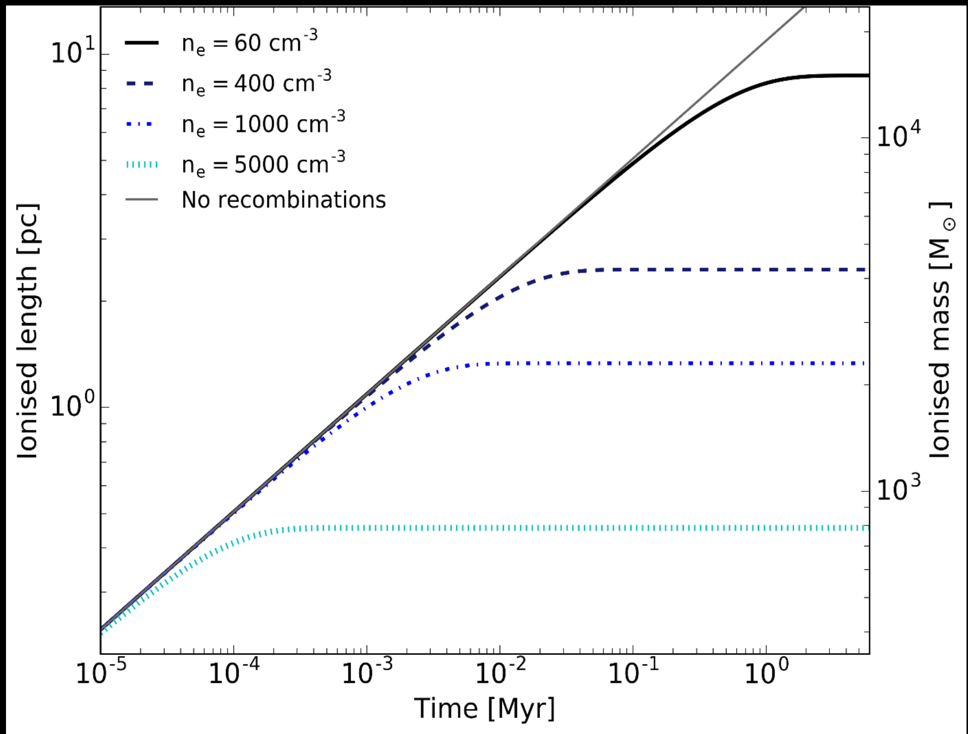
Watkins, Peretto +, 2019

- Gas should be blown away if:
  $L_{star} > L_{Edd}$
- Equivalent to (Thompson & Krumholz 16):
  $\boldsymbol{\Sigma_{gas} < \Sigma_{crit}(L_{star})}$
- Suppose a fully sampled IMF, with 2 to 4 O stars, that we randomly place
- The ridge is super-Eddington nearly everywhere

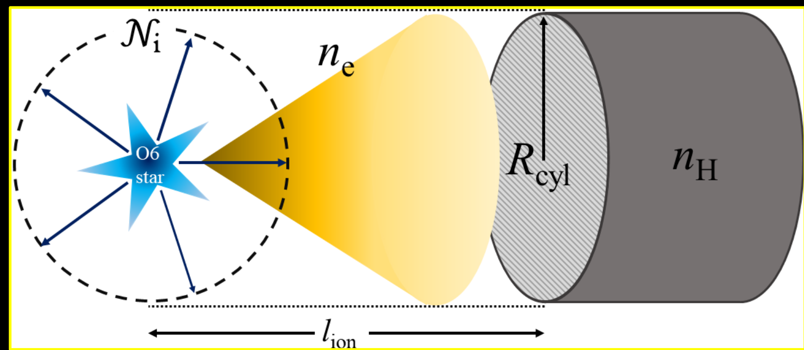
The impact of OB stars on their parent cloud

- Testing ionisation feedback

Watkins, Peretto +, 2019



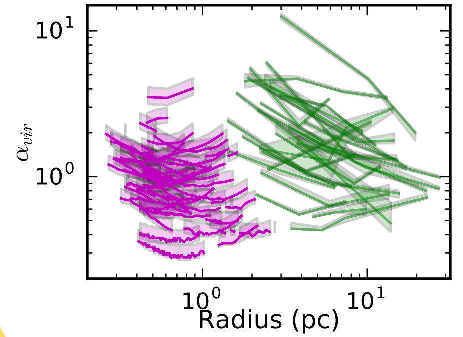
- Only 8% of the G316.75 ridge mass has been ionised
- The erosion of the ridge by the ionising photons of an embedded star

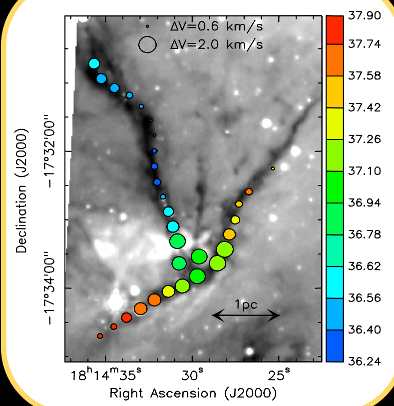


- Erosion stalls very quickly for the ridge density: Ionisation from O stars do not manage to disperse the ridge.

Summary & conclusions

- Dense clumps are dynamically decoupled from their parent, self-gravitating, molecular clouds. Is that a result from clump collapse? Rotational support? Removal of B field support?





- Massive hub filamentary systems are rapidly collapsing clumps in which the converging point of filaments represent a favored location for the formation of massive cores/stars. Is that true across all hub masses?

- The impact of O star feedback is rather to limit the formation of more dense gas onto the ridge. How does feedback impact gas properties as a function of cloud morphology?