School of Physics and Astronomy
FACULTY OF MATHEMATICS AND PHYSICAL SCIENCES
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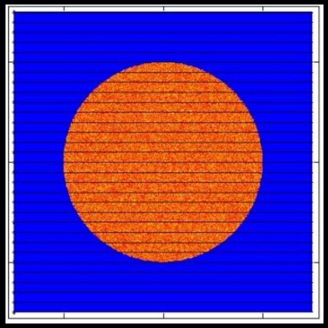
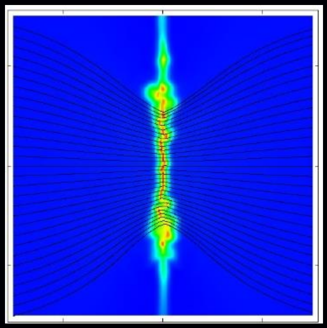
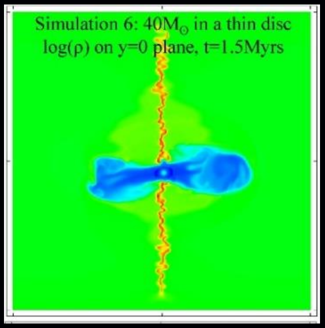
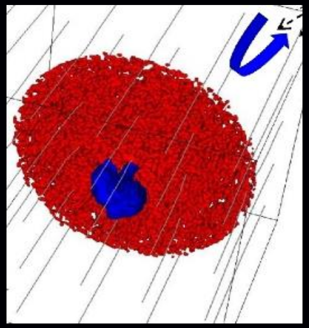
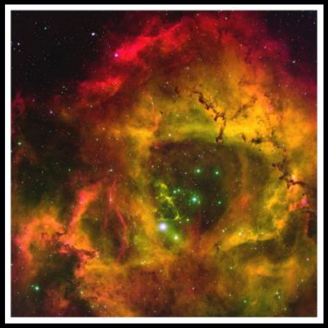
MHD simulation of cloud formation by the thermal instability and consequent massive star feedback

Chris Wareing, J. Pittard, S. Falle, S. Van Loo, M. Kupilas (**see poster!**)

Session III: Molecular cloud formation & properties

‘Zooming in on Star Formation: a conference dedicated to celebrate the career of Prof. Åke Nordlund’, Monday 10th June 2019

Giant Molecular Clouds (GMCs)

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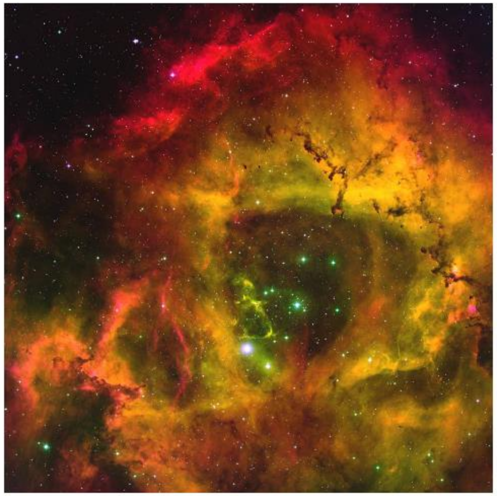
Most stars are formed in GMCs, e.g. Rosette MC

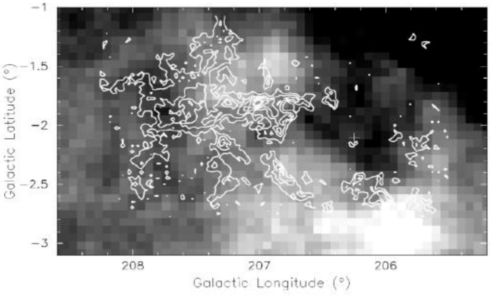
Size	~ 35 pc	
Mass	~ 10^5 $M_\odot$	
Mean density	~ 10^{-22} g cm^{-3}	
Temperature	~ 10 K	-> sound speed ~ 0.2 km s^{-1}
Alfvén speed	~ 2 km s^{-1}	magnetic pressure dominates
Velocity dispersion	~ 10 km s^{-1}	supersonic and super-Alfvénic
Jeans Mass	~ 10^7 $M_\odot$	based on velocity dispersion



But the Rosette MC is not homogeneous: CO maps show it contains ~70 clumps with

Size	~ 3.5 – 8 pc
Mass	~ 10^2 – 2×10^3 $M_\odot$
Mean density	~ 10^{-21} g cm^{-3}
Temperature	~ 10 K
Alfvén speed	~ 2 km s^{-1}
Velocity dispersion	~ 1 km s^{-1}
Jeans Mass	~ 3×10^3 $M_\odot$

Grey-scale: HI, contours CO, 1° ≡ 28pc



Blitz and Stark 1986

<= Supersonic, but now sub-Alfvénic

Physical model

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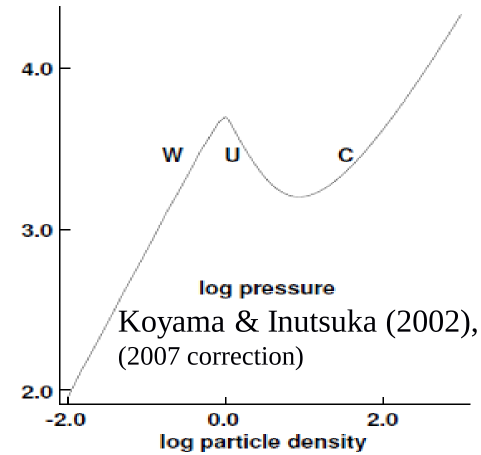
Our first aim is to develop a realistic initial condition following the formation of molecular clouds to allow for the introduction of stellar feedback.

We started by taking the simplest approach with self-consistent physics for the formation of a molecular cloud:-

- **3D HD/MHD**
- **Self-gravity**
- **Multi-phase ISM including thermal instability**



Koyama & Inutsuka (2002), (2007 correction)

In future, we can add complexity:-

- Shear and pressure waves, imitating galactic evolution
- Large-scale flows: SN shock, cloud collision **(see Marcin Kupilas's poster)**
- "Turbulent" initial conditions applying randomised velocities

but if one can produce results without recourse to extra complexity ...

lex parsimoniae / Occam's razor

3D hydro (HD) initial condition

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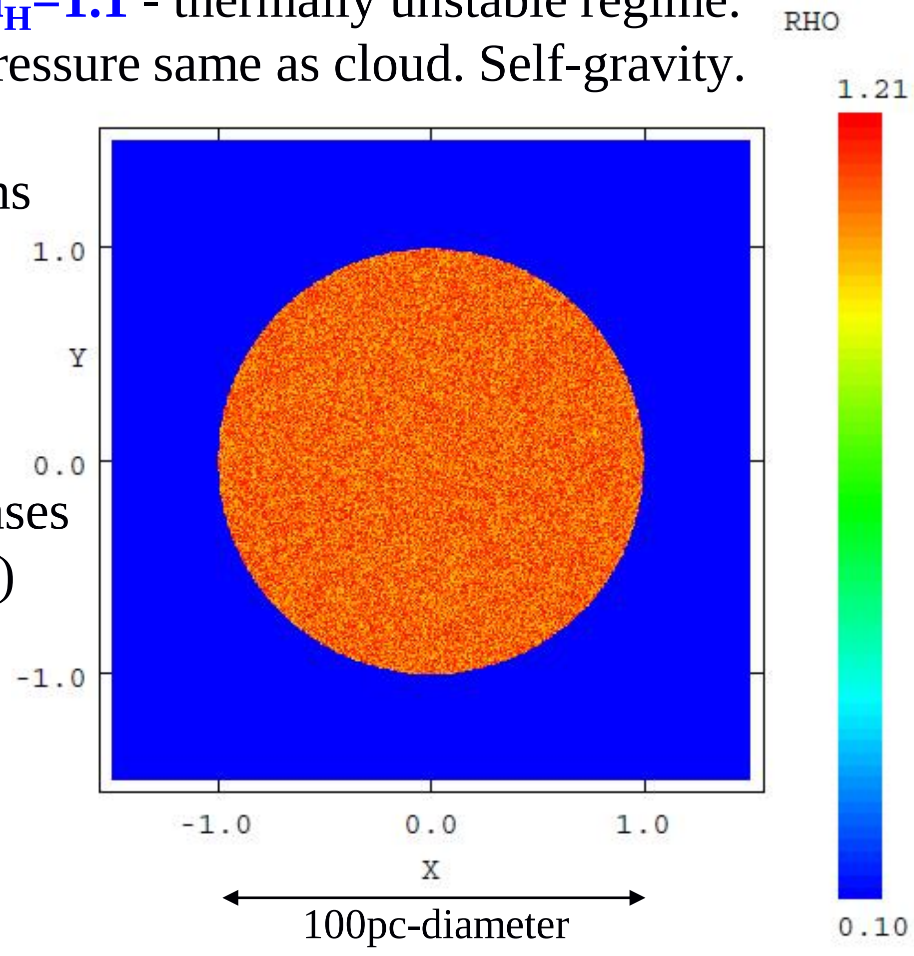
Spherical cloud, radius 50pc, density n_H=1.1 - thermally unstable regime.
External medium density n_H=0.1, over-pressure same as cloud. Self-gravity.

Impose random 10% density perturbations on finest initial AMR grid level (512^3)

Quiescent cloud v=0

Addition of mesh levels as density increases
Up to 10 levels of AMR (4096^3: 0.039pc)

Mass: $1.7\ 10^4\ M_\odot$
Sound crossing time: 6.5 Myrs
Free fall time: 45.0 Myrs
Cooling time: 1.6 Myrs



Code: Magnetohydrodynamic version of Falle's **MG** with self-gravity.

Enlarged 3D Hydro condition

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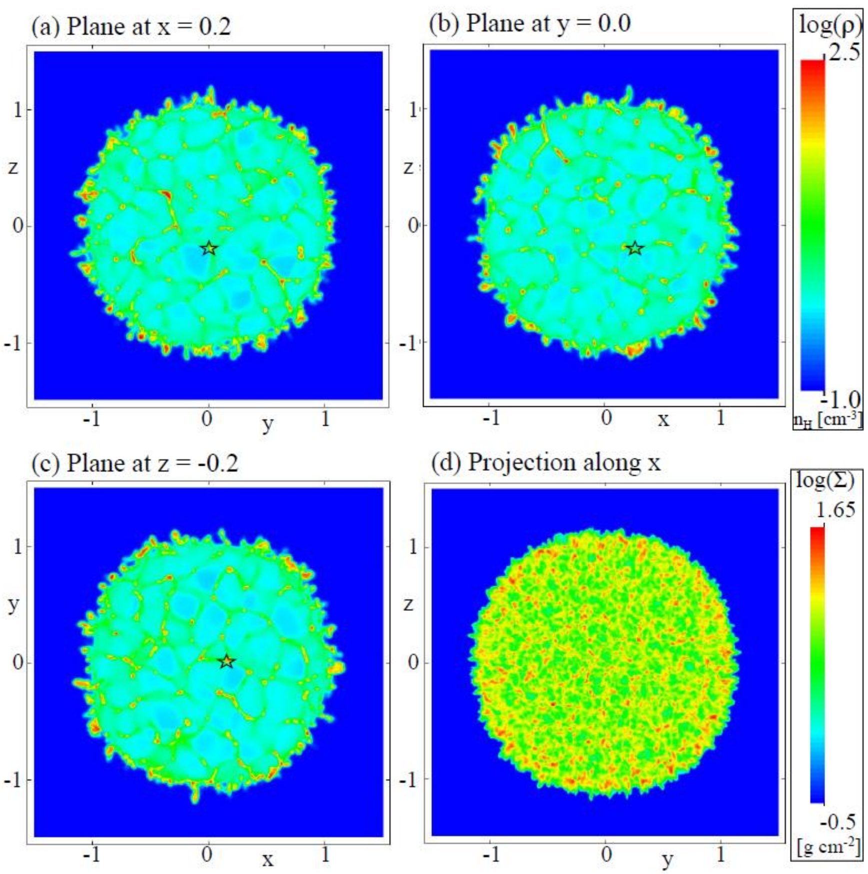
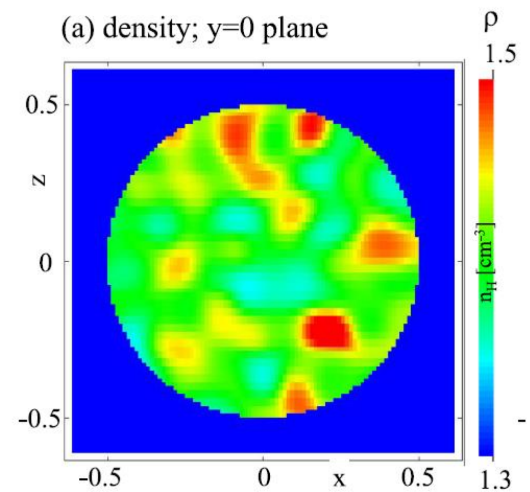
Domain size doubled, **cloud radius increased to 100pc** (r_{init} = 2.0), initial maximum AMR resolution 1024^3 (finest level 0.29pc), Mass $1.35\ 10^5\ M_{\odot}$



Initial cloud diameter (200pc)

High density regions occur after
16.2 Myrs of diffuse cloud evolution

Extract central section at t=16.2 Myrs



Increase resolution and simulate on…

- a further 28.5 Myrs (total ~44.5 Myrs)
- resolution up to 0.039pc

Result: evolution of clumps and filaments

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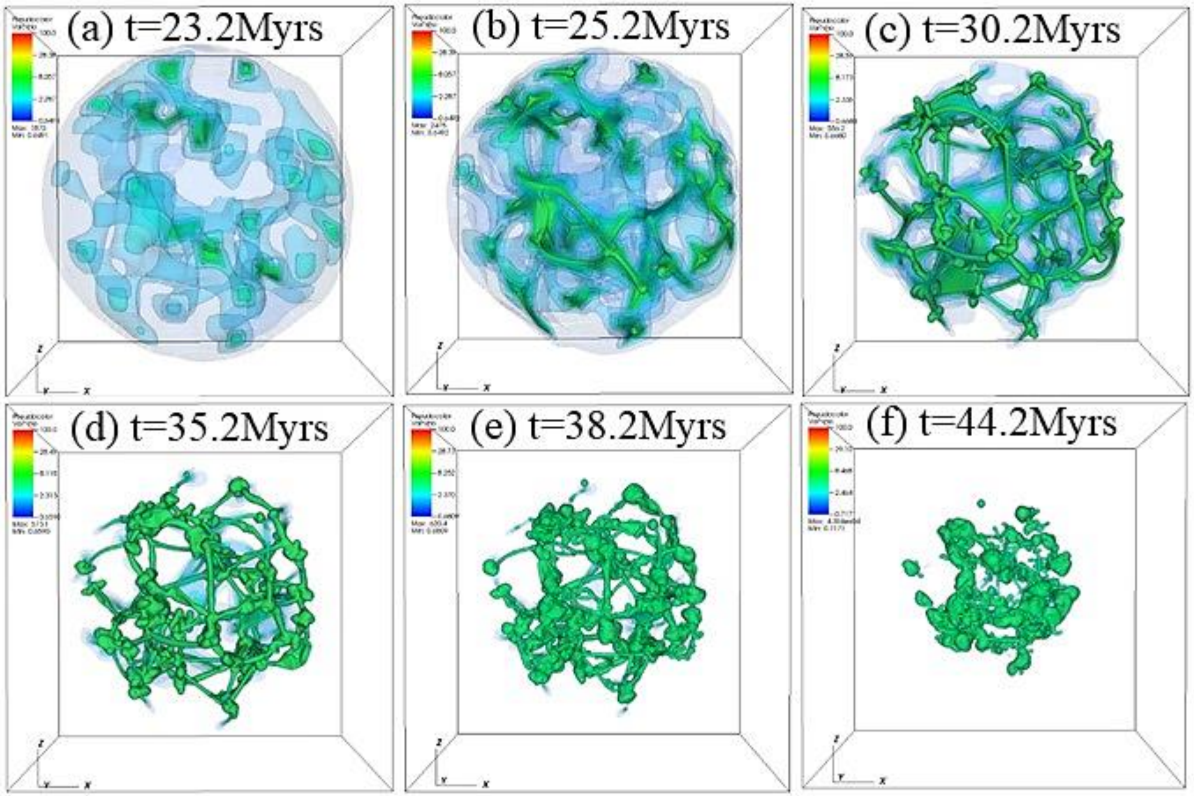
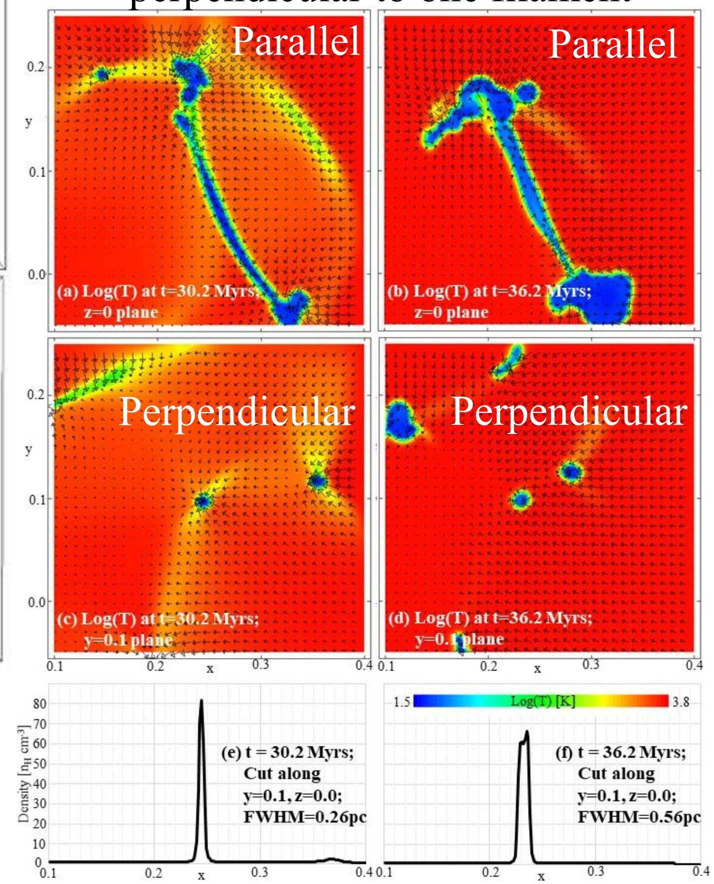


Slices of temperature parallel and perpendicular to one filament



- Creates a network of **cold, dense clumps**, multiply-connected by **filaments**!
- Filaments grow as material falls in, from widths around **~0.1pc to 0.6pc**
- **Flow along the filaments toward the clumps**

Final evolved simulation

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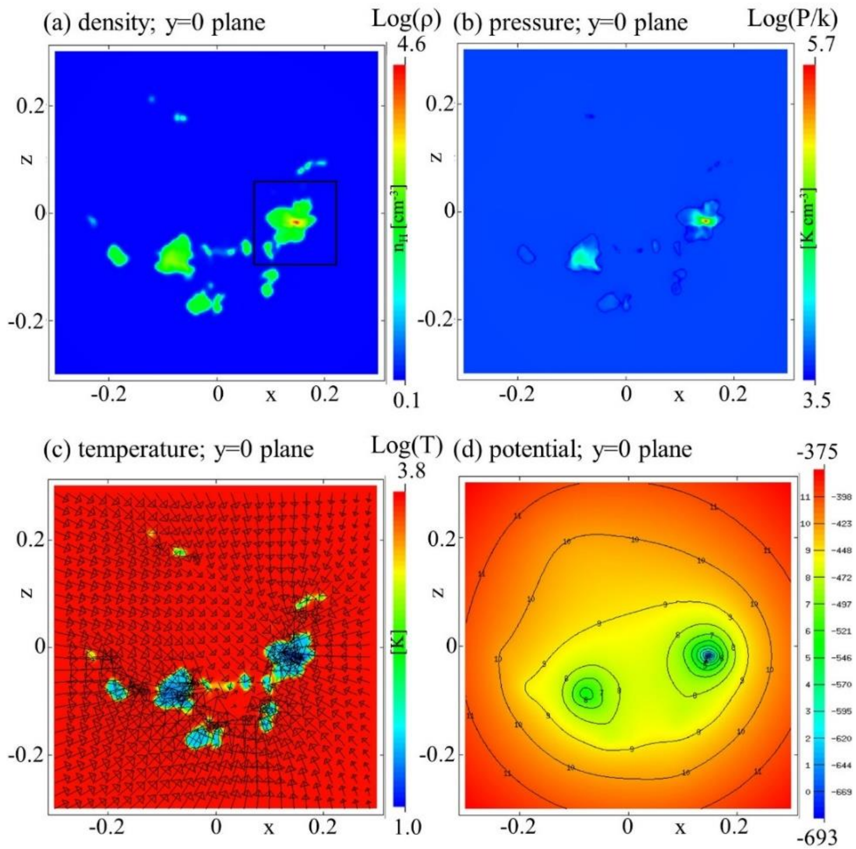
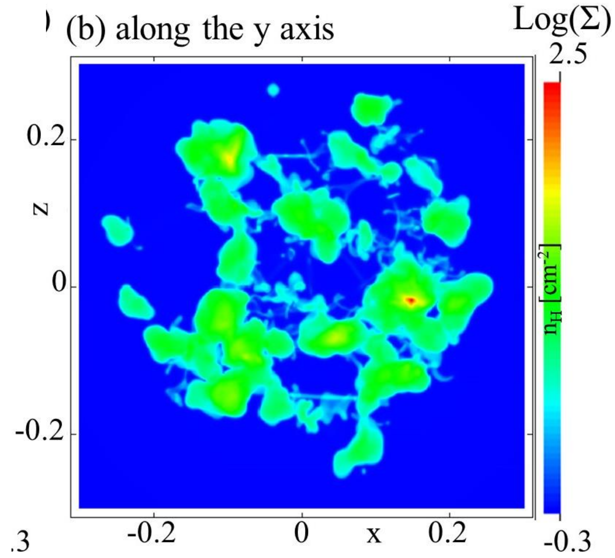
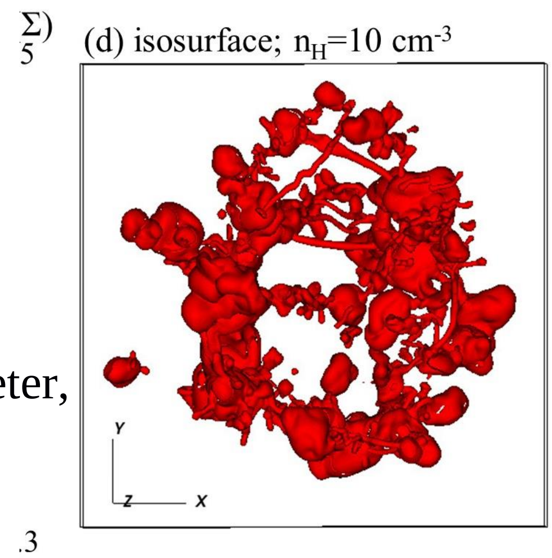
Cloud has contracted under gravity to a radius of ~10 pc







Most massive clump: 354 $M_\odot$ (cold phase: 292 $M_\odot$), 5 pc diameter,
n_{max} ~ 1.5 10^4 (10^{-20} g cm^{-3}), n_{mean} ~ 230 (5x10^{-22} g cm^{-3}),
T_{min} 10.4 K, $v_{in\text{-}flow}$ up to 2.5 km/s, v_{min} 0.2 km/s in cold clumps

Further properties of the clumps

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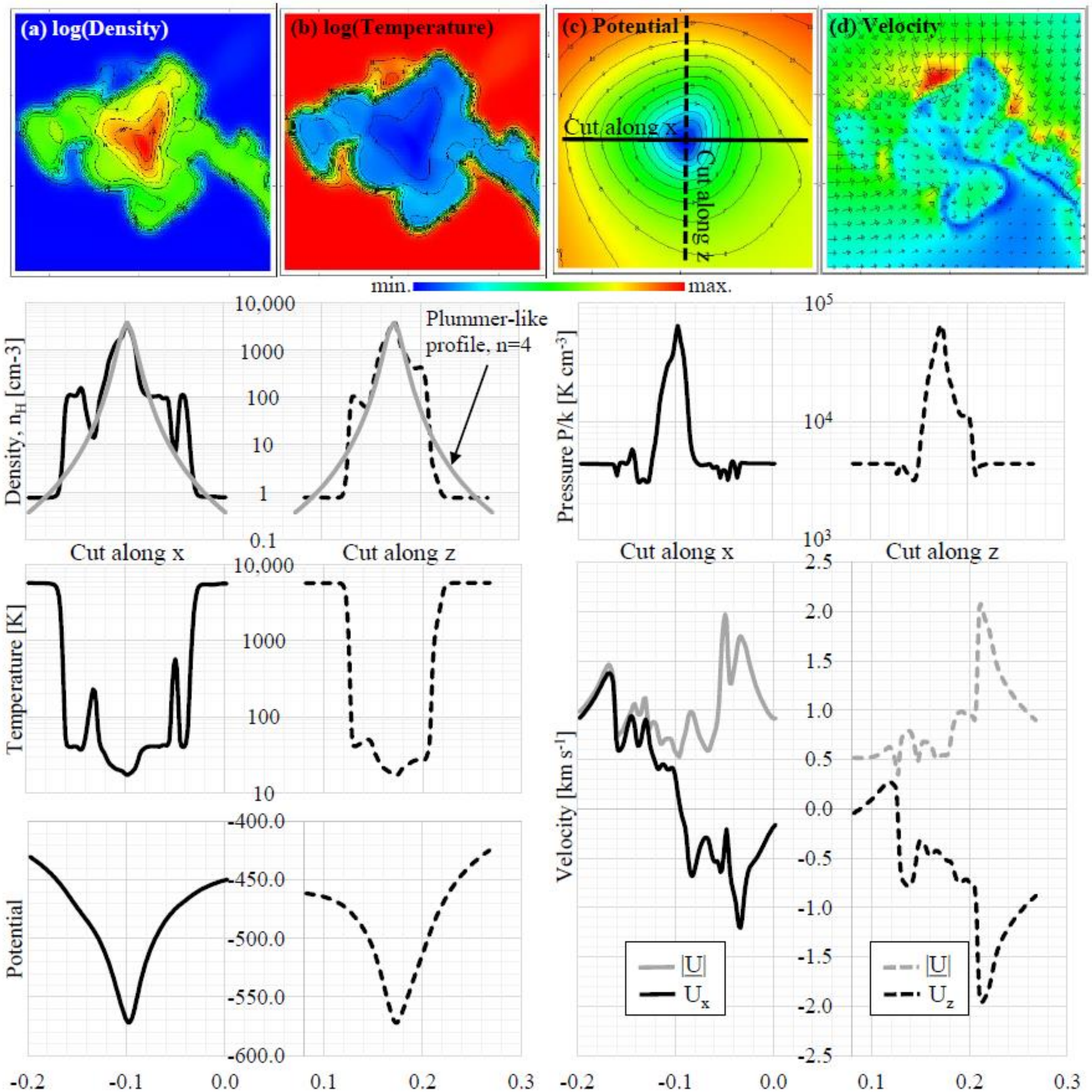
Fellwalker algorithm (Berry 2015) identified **21 distinct clumps with masses >20 $M_\odot$**

Properties in agreement with Bergin & Tafalla (2007) review:- 50-500 $M_\odot$, 0.3-3 pc, 10^3-10^4 cm^{-3}, 0.3-3.0 km/s, 10-20 K

An individual 250 $M_\odot$ clump:

- Complex non-spherical nature
- Central density distribution fits a Plummer-like n=4 curve
- Clearly defined sharp boundary, noticeable in temperature distribution
- Increased internal pressure indicates gravitational collapse



Power spectra of the cloud and a clump

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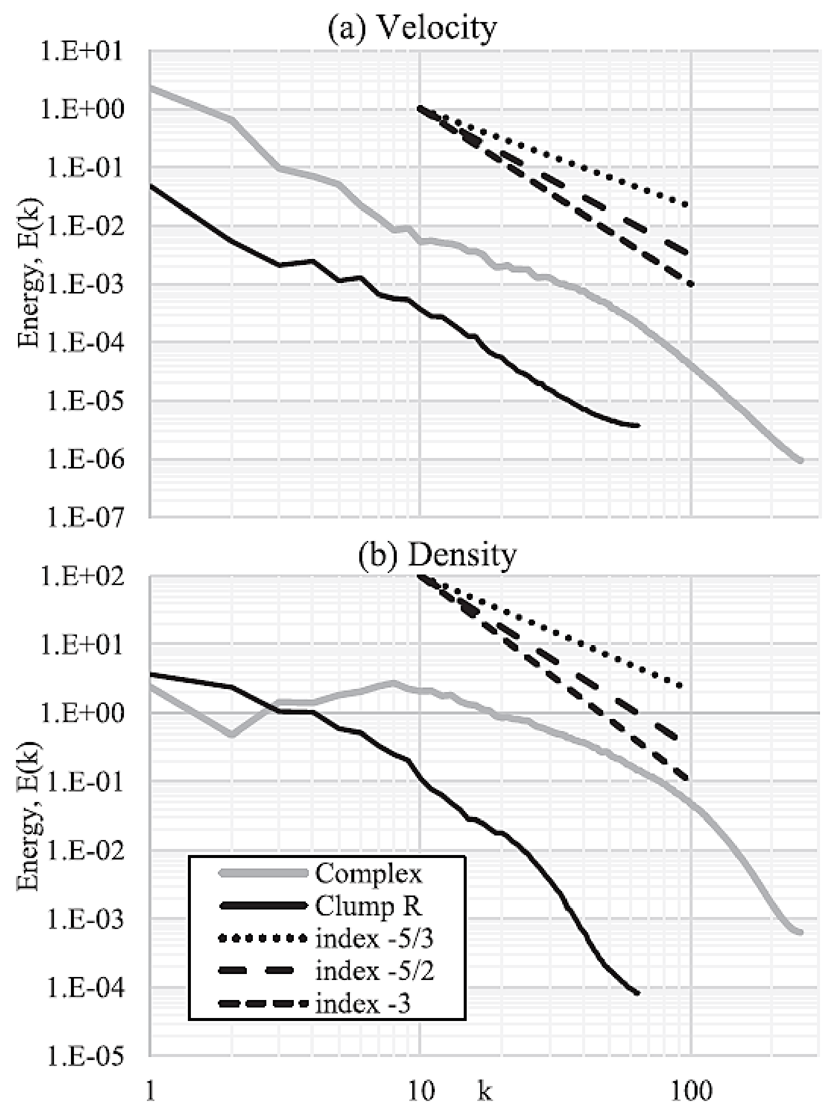
- **Turbulence-like (-5/3) power spectra in the warm stable medium**
- Short inertial range (1 decade) -> by no means fully developed turbulence.
- Should extend to larger scales
- Akin to Larson-like turbulence:- "hierarchy of small-scale irregularities superimposed on larger-scale more systematic motions"
- Spectral break at ~1 pc, on the size-scale of the clumps – could be considered a "dissipative limit"
- Steeper spectral index of -3 implied inside the clumps



Power spectra calculated by validated IDL script

Compares well with recent observations:
Kalberla & Haud, A&A accepted; arxiv: 1905.08583

Cloud complex – 40pc box. Clump R – 10pc box.

MHD simulations

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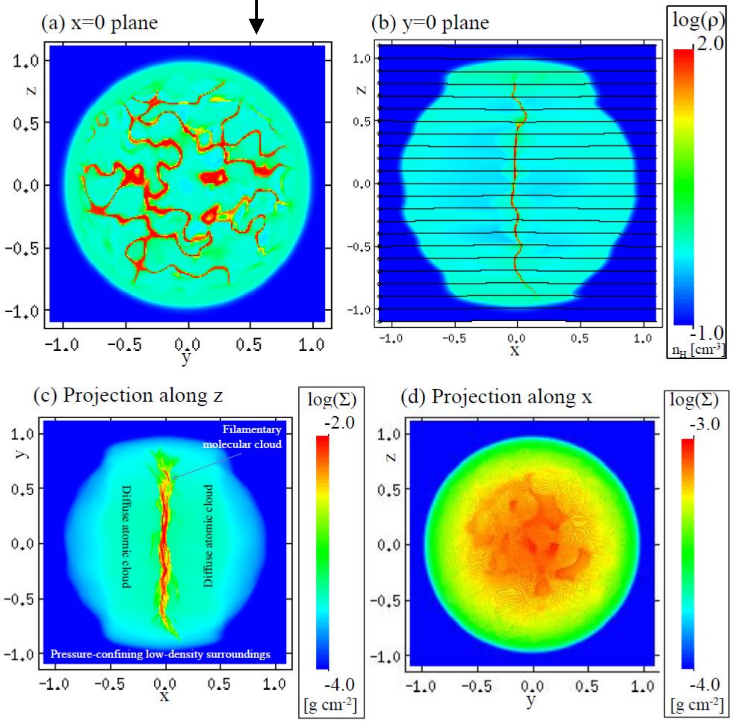
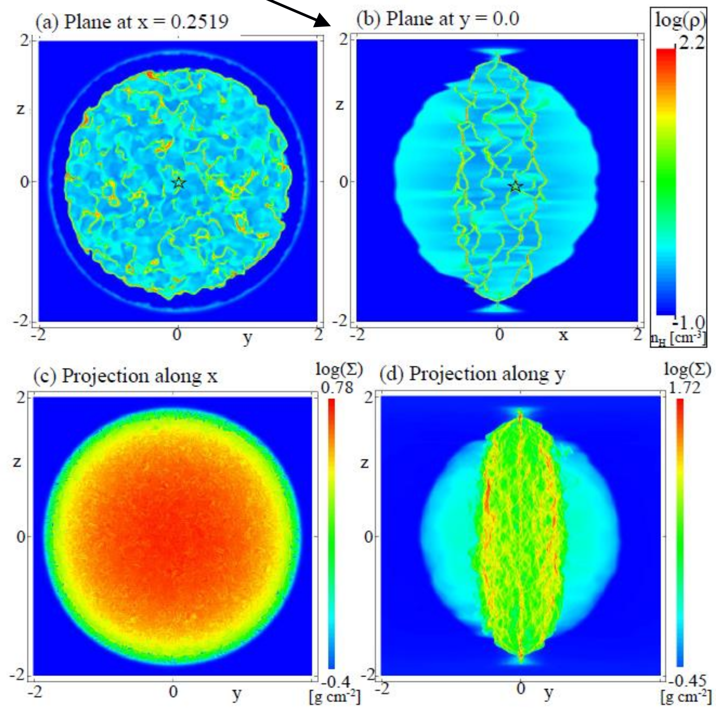
Exactly the same as hydro, but with uniform field in the x-direction

- Regular (1.7 10^4 $M_\odot$) and enlarged (1.35 10^5 $M_\odot$) clouds under consideration
- Plasma β: 0.1 (strong field), 1.0 (plasma/magnetic pressure parity), 10.0 (weak field)





$$\beta = \frac{\rho k_B T}{B^2/2\mu_0}$$

thermal pressure / *magnetic pressure*

Magnetic seismology of Musca 'filament' indicates this structure!

(Tritsis & Tassis 2018, Science, vol 360, Issue 6389, pp.635-638)

Striations, hour-glasses and integrals

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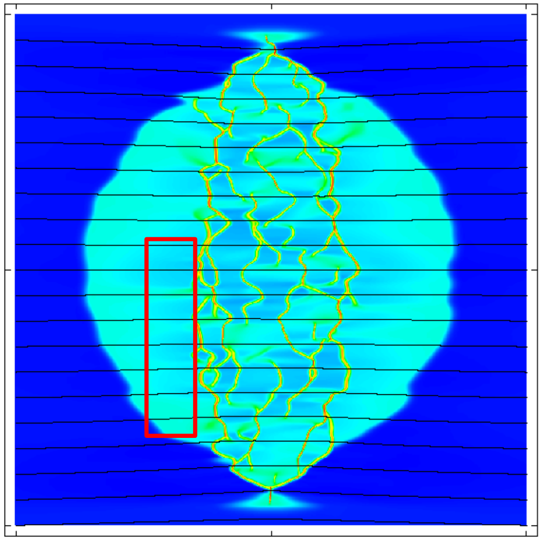
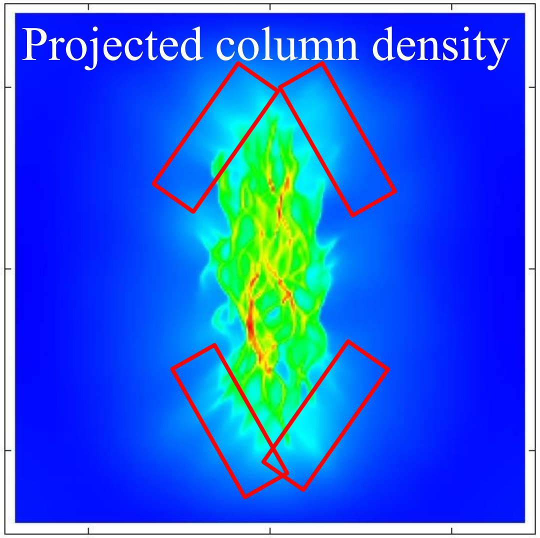
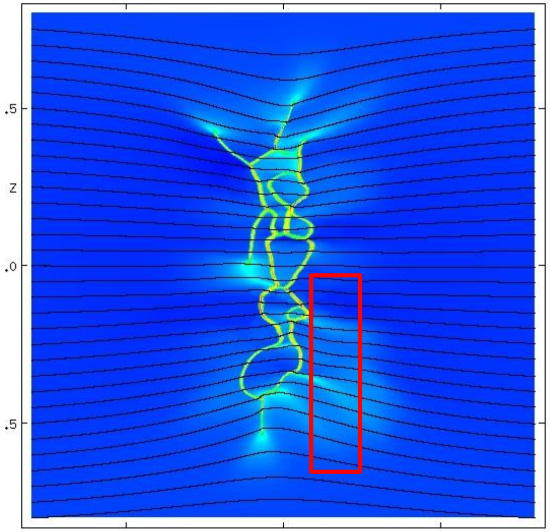
Diffuse material moves along field lines and naturally forms low-density structure parallel to the magnetic field. This is the natural pre-cursor to the high-density filamentary structure that forms in the cloud, perpendicular to the magnetic field.







- Previous work (Tritsis and Tassis 2016) concluded sub-Alfvénic flows would not produce the observed density contrasts (0.03% contrast versus >25% observed)
- However, here we produce a range of density contrast up to factor 3 (400%)
- A further criticism of sub-Alfvénic flows has been the difficulty in which magnetically parallel and perpendicular structure can be produced in the same simulation – no problem!

The difference is in the initial condition. T&T initialised realistic B and ρ, but isothermal throughout at 15K with no gravity.

Striations, **hour-glasses** and integrals

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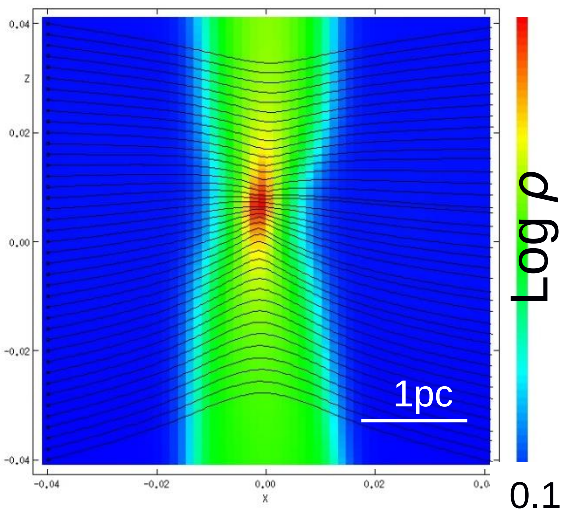
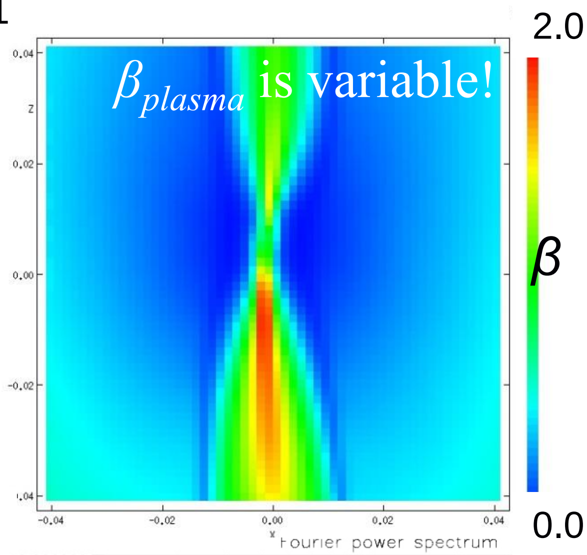
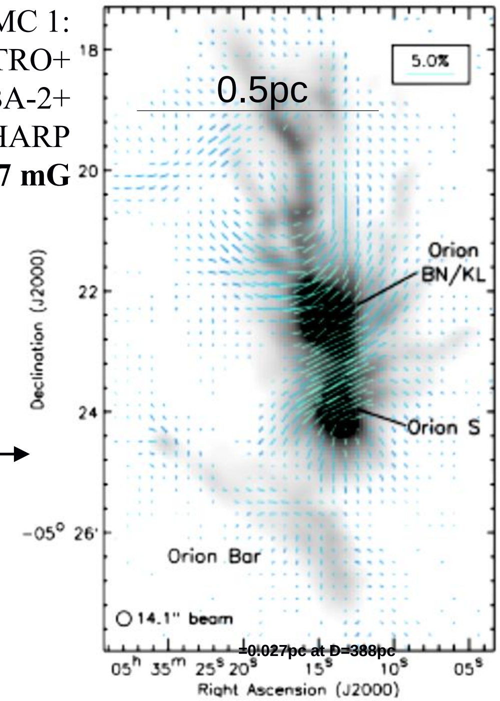
Hour-glass field morphologies naturally form under collapse.





OMC 1:
BISTRO+
SCUBA-2+
HARP
6.7±4.7 mG



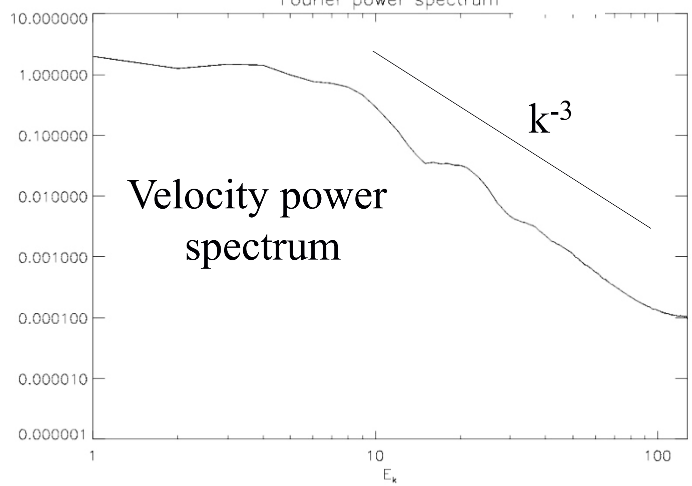
Pattle, Ward-Thompson et al., 2017, ApJ, 846, id.122

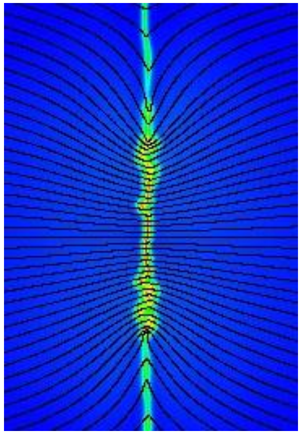
Gravitational collapse once the sheet has formed is dragging the field.

Field intensified in places from 0.3μG to ~0.1mG

V_{max}~3 km s^{-1}, M_{max}~2.9, T~10K, M~150M_{sun}

Density spectrum $k^{-5/2}$





Striations, hour-glasses and **integrals**

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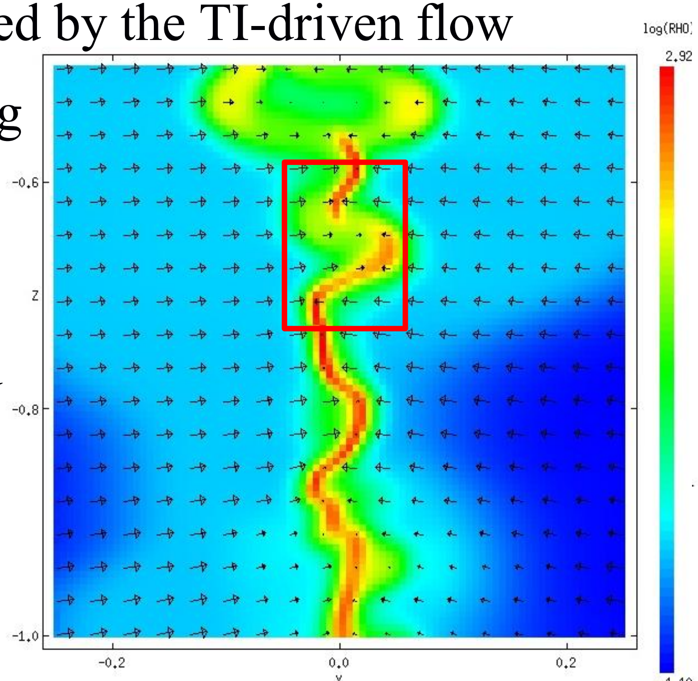
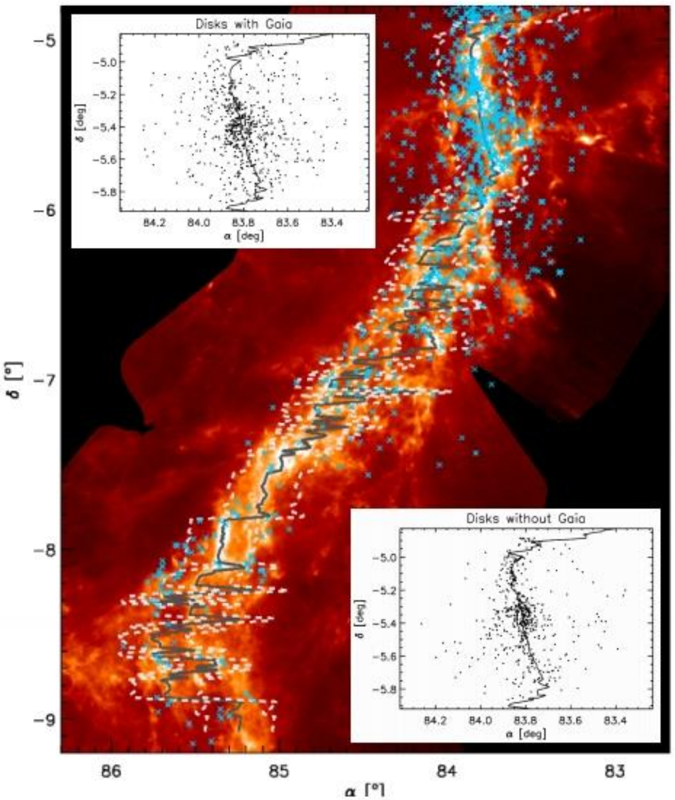
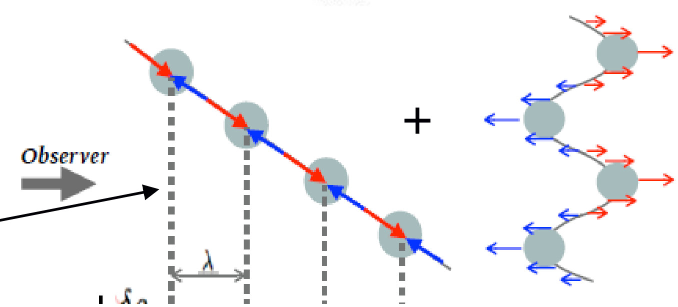
- Recent work **submitted** to MNRAS concludes that an "*integral*"-shaped filament in Orion is a standing wave
- **We obtain apparently similar structure**, with disconnects in the velocity caused by the TI-driven flow
- Not a standing wave – an effect of the initial condition and flow
- Further work required





Stutz et al. MNRAS, **submitted**. arXiv:1807.11496



See also very recent: Liu, Stutz & Yuan, 2019, MNRAS, **487**, 1259; arxiv: 1905.08292

Mechanical stellar wind feedback

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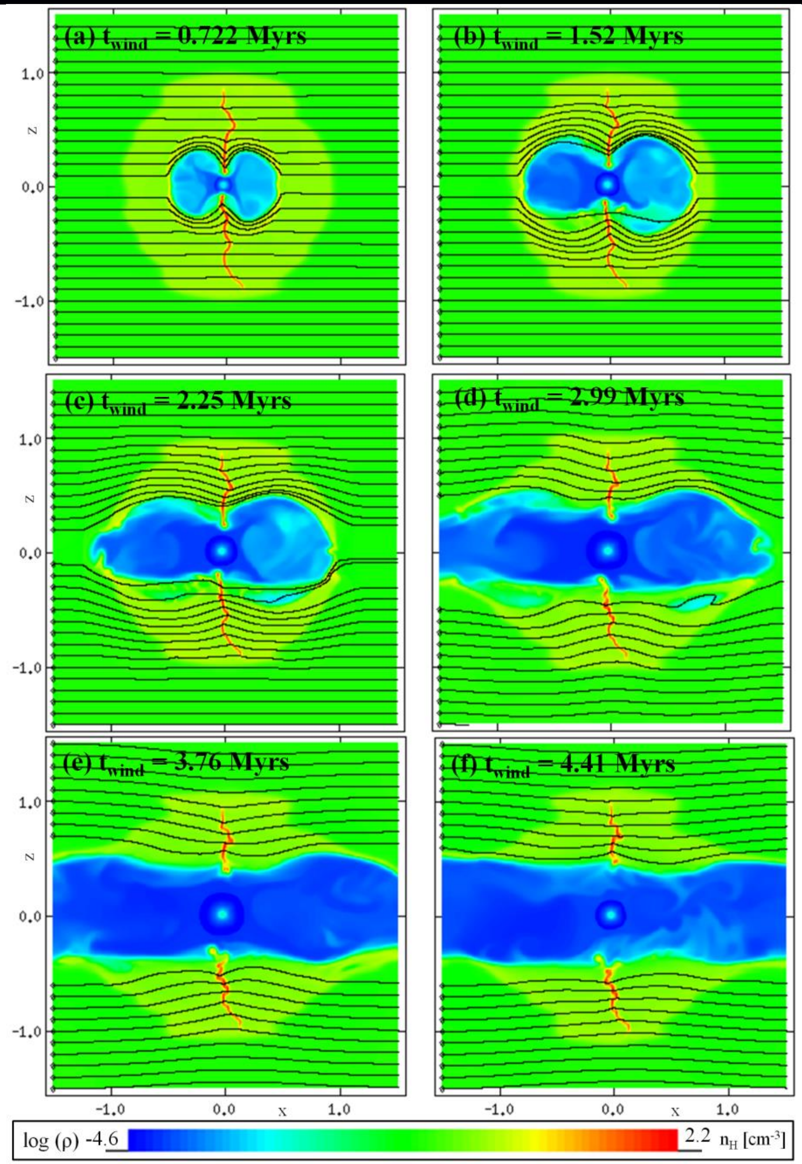
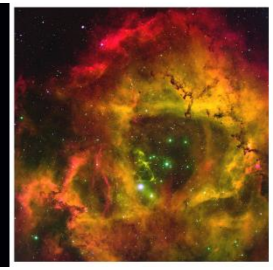
- 40 $M_\odot$ star embedded in the sheet
- Realistic Geneva (2012) evolution imposed via density and energy sources
- **Significant impact on a 1.7×10^4 $M_\odot$ cloud**
- **Large bipolar cavity evolves into a cylindrical cavity** (diameter~40pc) through the centre of the cloud
- Cavity filled with hot, tenuous wind material moving at up to 1000 km/s
- Magnetic field intensified by factors of 3-4 during this wind phase
- **Much of the wind material flows out of the domain along the cavity – this missing wind is simply focussed away!**



Simulating the Rosette Nebula



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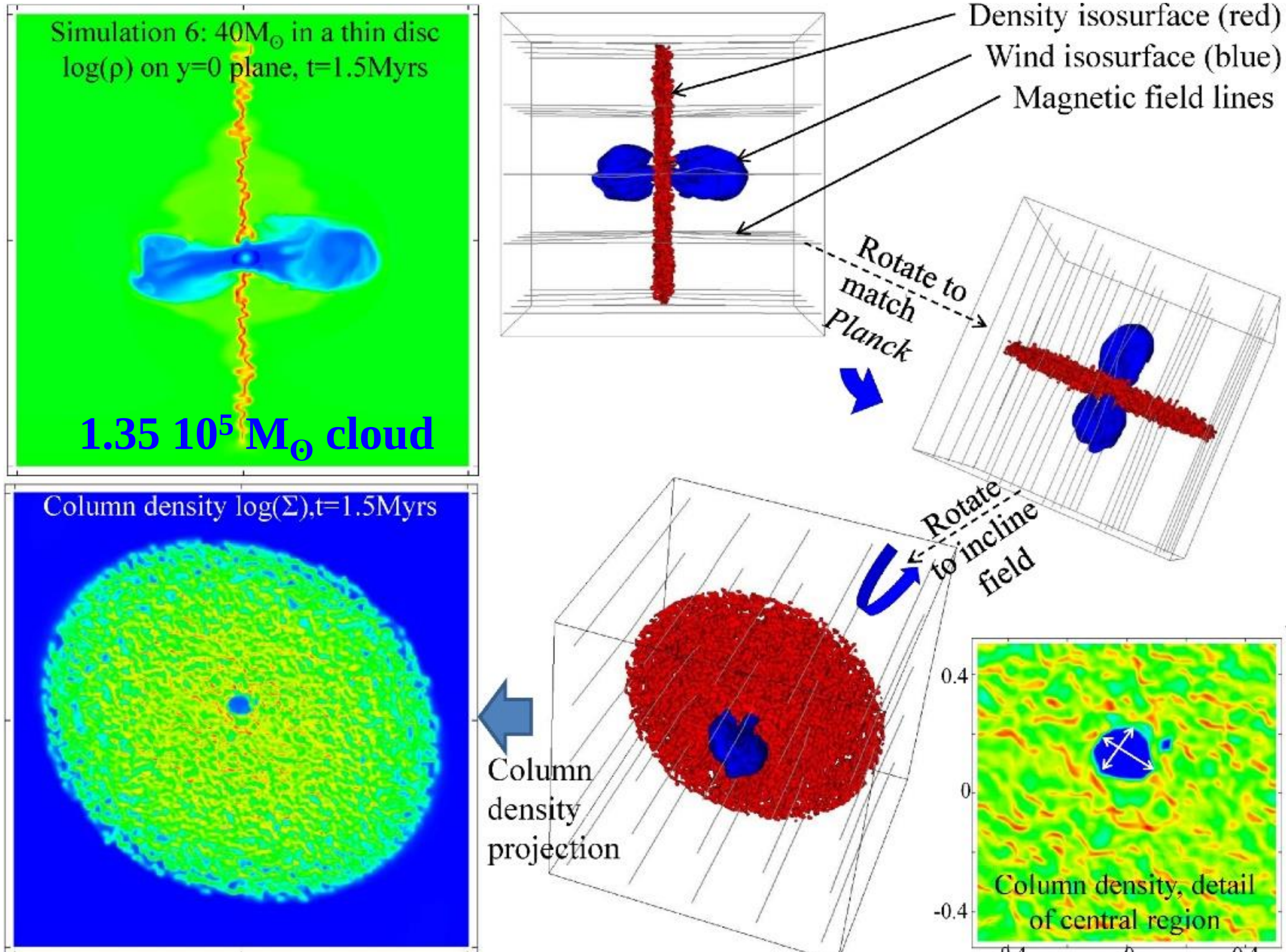
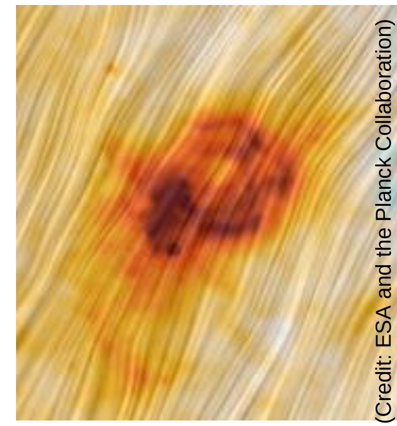
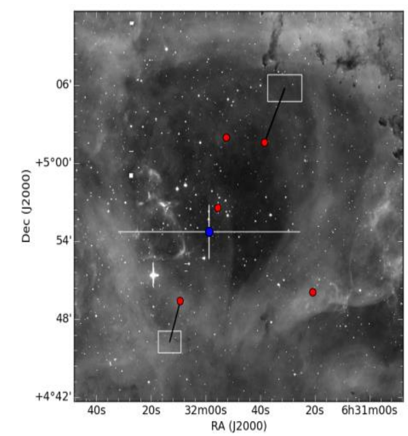
Magnetic field alignment, proper motion and location of possible triggered star formation all support this model.





Evacuated hole

- Simulation: **10x7.5 pc**
- Observations:
  Celnik: d~13pc
  IPHAS: **d~10pc**



Conclusions

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The thermal instability in diffuse interstellar medium, together with self-gravity and magnetic fields, **can create realistic molecular clouds**.

Without magnetic field, the cloud complex contains **realistic cold, dense clumps**.

- The **clumps are connected by a network of cooler, less dense filaments**, with widths 0.2 to 0.6 pc.
- The **quiescent clouds create their own "turbulence"** with realistic spectral indices.

With magnetic field, the cloud flattens into a corrugated sheet-like structure.

- In projection, the clouds appear very filamentary – **parallel striations and perpendicular filaments**.
- Mechanical stellar wind feedback can be directed away from the structure and provide an elegant explanation for the nature of the Rosette Nebula.
- Collapse of the sheet **intensifies magnetic field** (tens of μG) and creates **hour-glass-shaped fields**.
- Disconnects across the sheet, driven by the flow, create integrals and gaps in position-vel. maps.

Thank you for listening. Any comments or questions?

Thermal instability driven initial condition:	Wareing, Pittard, Falle & Van Loo, 2016, MNRAS, **459**, 1803
Magnetic feedback general case:	Wareing, Pittard & Falle, 2017, MNRAS, **465**, 2757
Hydrodynamic feedback general case:	Wareing, Pittard & Falle, 2017, MNRAS, **470**, 2283
Rosette special case:	Wareing, Pittard, Falle & Wright, 2018, MNRAS, **475**, 3598
Hydro case: sheets, filaments and clumps	Wareing, Falle & Pittard, 2019, MNRAS, **485**, 4686
Thermal instability re-visited	Falle, Wareing & Pittard, *in prep.*
MHD case: striations, hour-glasses & integrals	Wareing, Falle & Pittard, *in prep.*

Revisiting thermal instability

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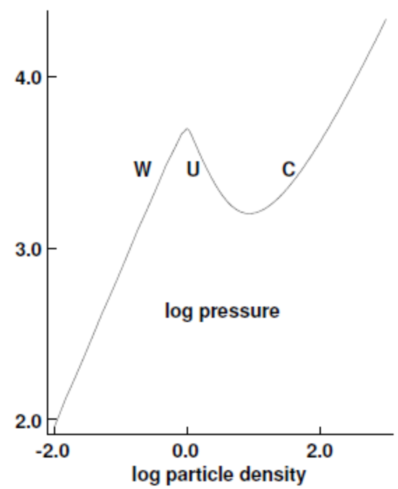
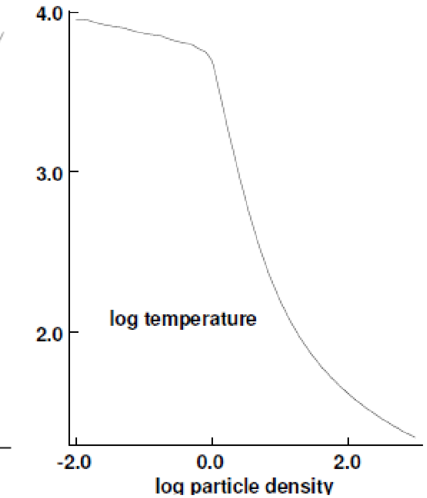
Two stable phases exist in which heating balances cooling (Parker ‘53, Field ‘65, Wolfire et al. ‘95)

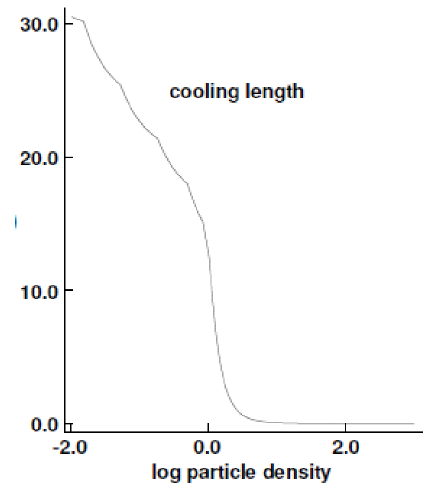
W – warm phase (T > 5000K, ρ < 1, P/k < 5000)
C – cold phase (T < 160K, ρ > 10, P/k > 1600)
U – unstable phase





In the unstable region, can form a length scale from cooling time and sound speed ~ a few pc.

Molecular cloud formation (10K) and stellar feedback (10^8K) requires multi-stage cooling:



<10^4K	Γ : Koyama & Inutsuka (2002), (2007 correction)
10^4K<T<10^8K	Γ : CLOUDY 10.00 Gnat & Ferland (2012)
>10^8K	Γ : MEKAL - free-free bremsstrahlung.

Constant heating rate $\Gamma = 2\times10^{-26}$erg s^{-1} independent of ρ,T

=> Establishes thermal equilibrium P and T by $\rho^2\Lambda = \rho\Gamma$

The (modified) engine

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- Magnetohydrodynamic version of **MG** (*Morris Garages*) with self-gravity.
- Parallelised, upwind, conservative shock-capturing scheme.
- Adaptive mesh refinement uses a coarse base grid (4x4x4) with 7 (or more) levels of AMR to achieve a resolution up to 512^3 (*the Honda bit?*).
  - Why the wide range? Efficient computation of self-gravity.
- Realistic heating and cooling methods
  - Of key importance as it is the balance of these that establishes the initial condition and defines the consequent evolution.
- Three field strengths considered, with $\underline{B} = B_o \hat{\underline{I}}_x$
  - The hydrodynamic case: $\beta = \infty$
  - Pressure equivalence: $\beta = 1$ - inferred to be the commonest in reality.
  - Magnetically dominated regime: $\beta = 0.1$

$$\beta = \frac{\rho k_B T}{B^2/2\mu_0} \qquad \frac{\textit{thermal pressure}}{\textit{magnetic pressure}}$$

Aside: EPSRC and Innovate UK research proposals to apply MG in industry: cryogenic machining.

Simple 3D Hydro condition

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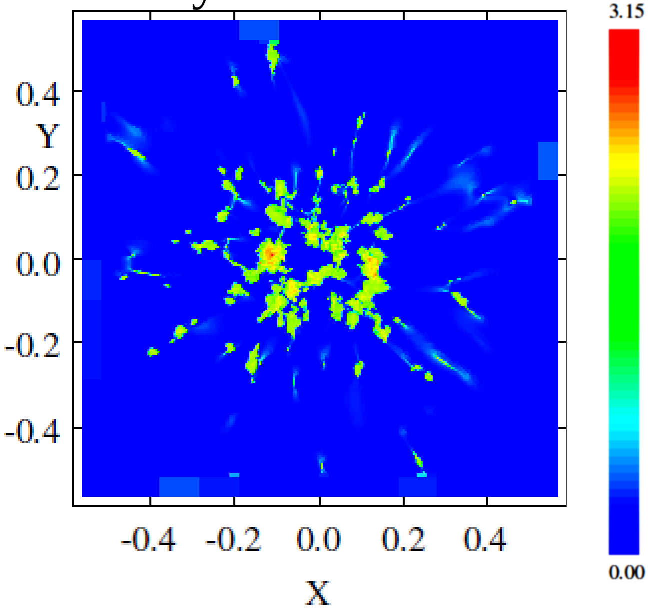
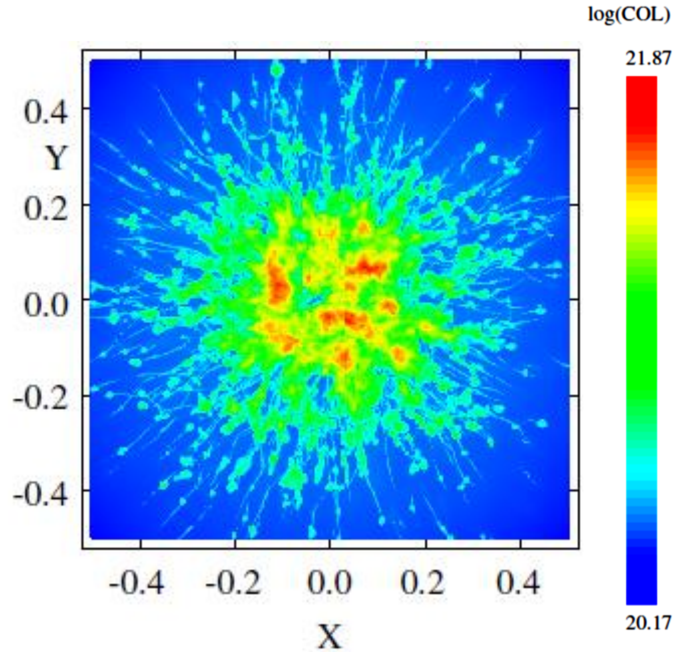
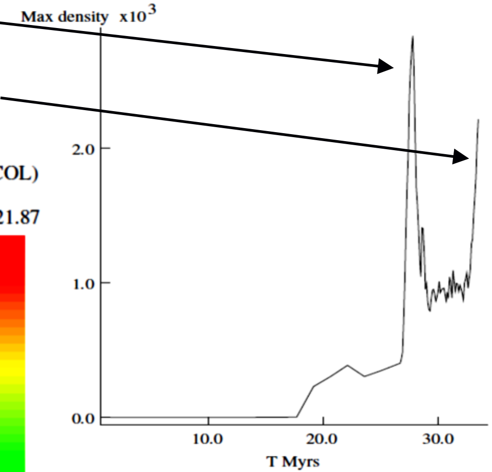
First peak due to TI-driven collapse, not gravity

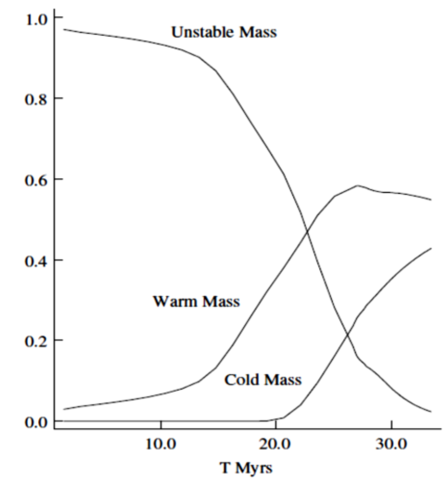
Second peak is due to gravity

t=33.5 Myrs









Collapse is driven first by pressure reduction. Collisions generate high density structure, but true gravitational collapse comes later.

A word of caution though - changing heating and cooling prescriptions changes the equilibrium – it can even suppress the instability!

Detail at t=33.5 Myrs

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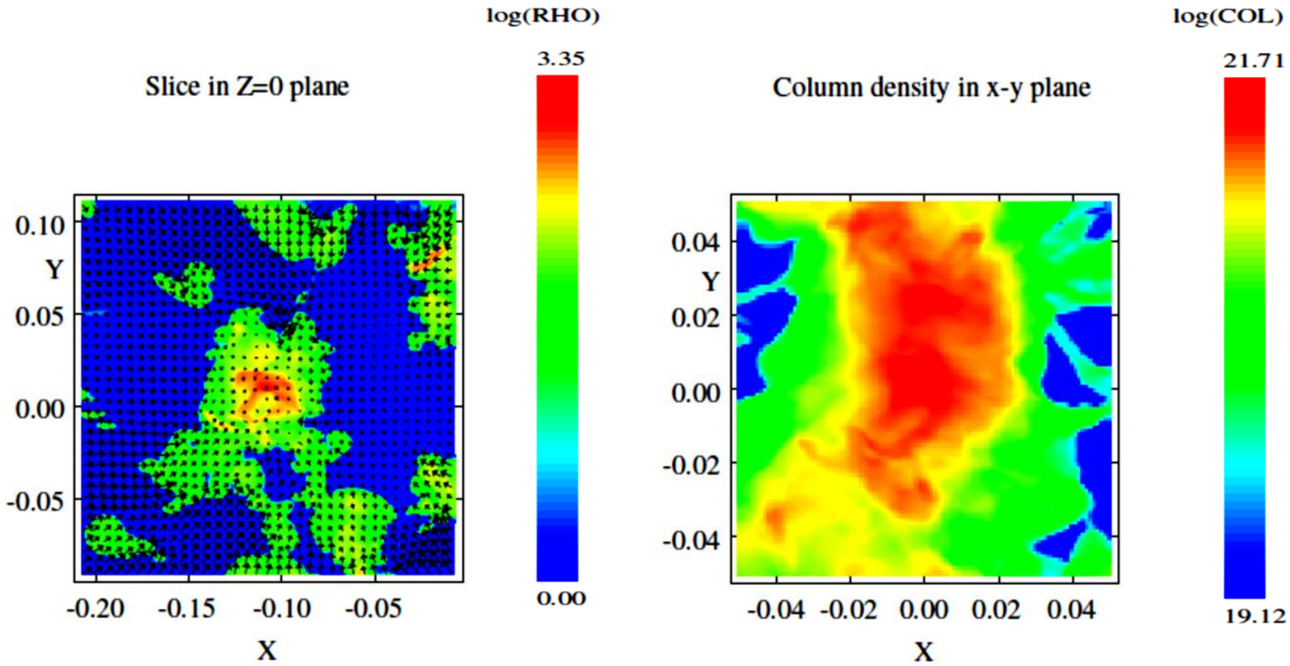

Diameter ~5pc, Mass 182$M_\odot$, Max density 2214, Mean density 177,
Max velocity 3.25 km s^{-1} (in frame of dense region), 0.6 km s^{-1} in dense gas.

Gravitationally bound, but not unstable (Bonnor-Ebert critical mass ~471 $M_\odot$)