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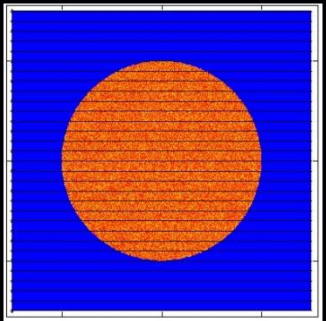
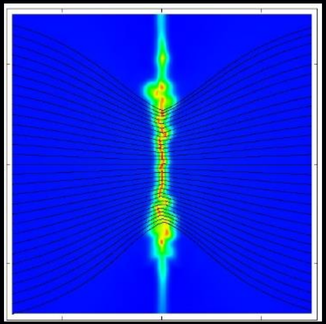
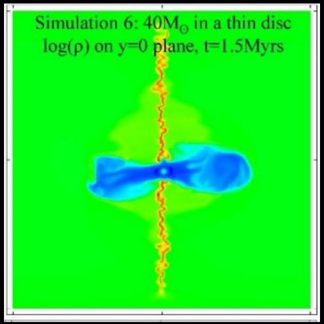
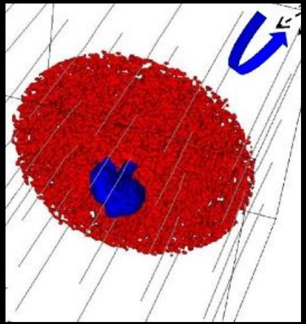
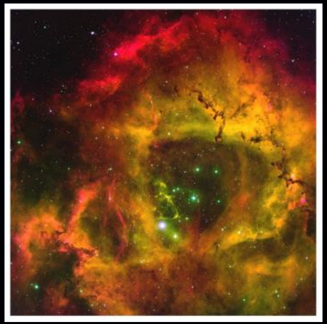
MHD simulation of cloud formation (by the thermal instability) and consequent massive star feedback

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

Indisposed due to injury – back soon!

Session 4: The Theoretical View

'From Gas to Stars: the Links between Massive Star Formation and Star Cluster Formation', StarFormMapper final conf. 17th Sept. 2019

Theoretical models

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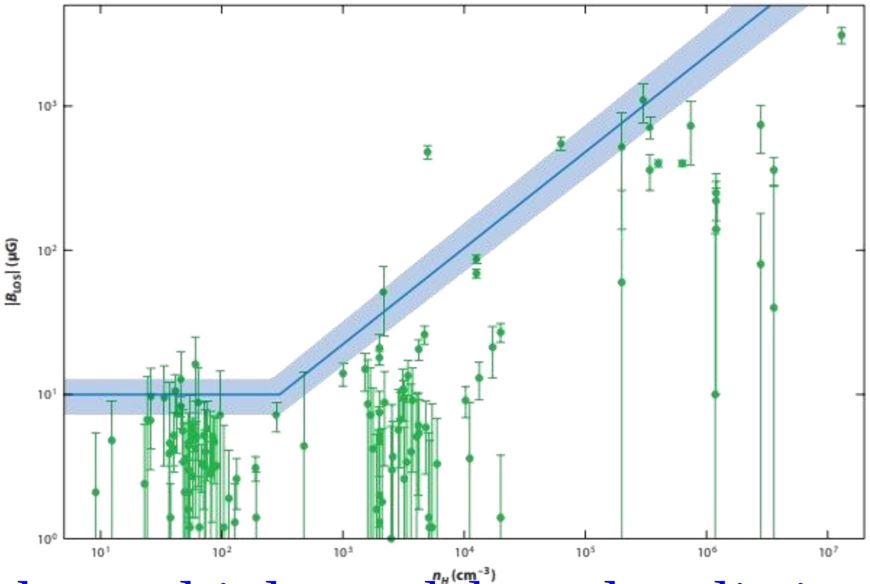
- A senior theoretician in this field recently emphasized that any model should have (1) realistic inputs *and* (2) realistic outputs.
- Anything that fails either (1) or (2) should be ignored by all.

- **Key output 1**: the so-called Crutcher |**B**|-ρ relationship ->
- **Key output 2**: turbulence-like velocity dispersion (albeit with short inertial range: ~1 decade).



If realistic outputs can be generated by multiple models and realistic inputs are difficult to establish with any certainty, how do we truly distinguish between inputs and models?

Outputs: Giant Molecular Clouds (GMCs)

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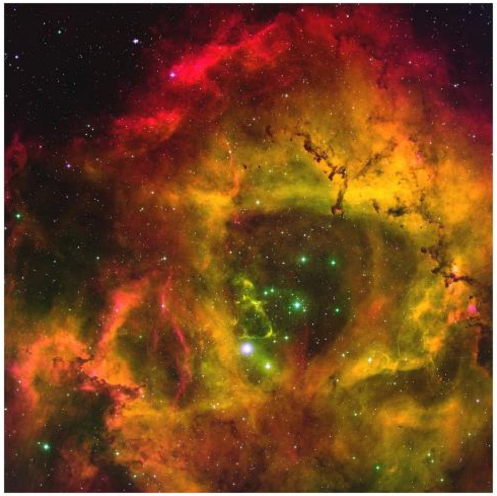
Most stars are formed in GMCs, e.g. Rosette MC

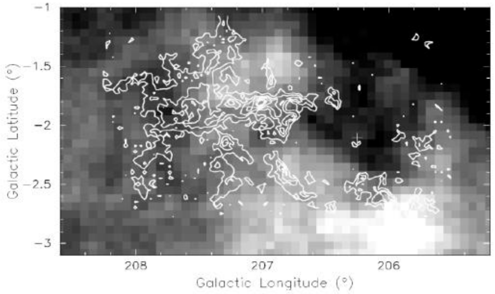
Size	~ 35 pc	
Mass	~ 10^5 $M_\odot$	
Mean density	~ 10^{-22} g cm^{-3}	
Temperature	~ 10 K	-> sound speed ~ 0.2 km s^{-1}
Alfvén speed	~ 2 km s^{-1}	magnetic pressure dominates
Velocity dispersion	~ 10 km s^{-1}	supersonic and super-Alfvénic
Jeans Mass	~ 10^7 $M_\odot$	based on velocity dispersion



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

Size	~ 3.5 – 8 pc
Mass	~ 10^2 – 2x10^3 $M_\odot$
Mean density	~ 10^{-21} g cm^{-3}
Temperature	~ 10 K
Alfvén speed	~ 2 km s^{-1}
Velocity dispersion	~ 1 km s^{-1}
Jeans Mass	~ 3x10^3 $M_\odot$

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



Blitz and Stark 1986

<= Supersonic, but now sub-Alfvénic

Inputs to define our physical model

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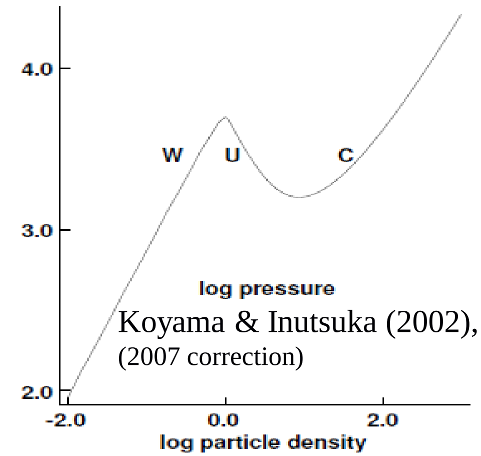
Our Project aim is to develop a realistic initial condition following the formation of molecular clouds to examine the importance of stellar feedback.

We started by taking arguably the minimum number of physically self-consistent inputs 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 include more complex inputs that introduce arguably more realistic velocity conditions for the ISM:-

- 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 up to Mach ~5

but if one can produce results without recourse to extra inputs…

lex parsimoniae / Occam's razor

Inputs: 3d hydro initial condition

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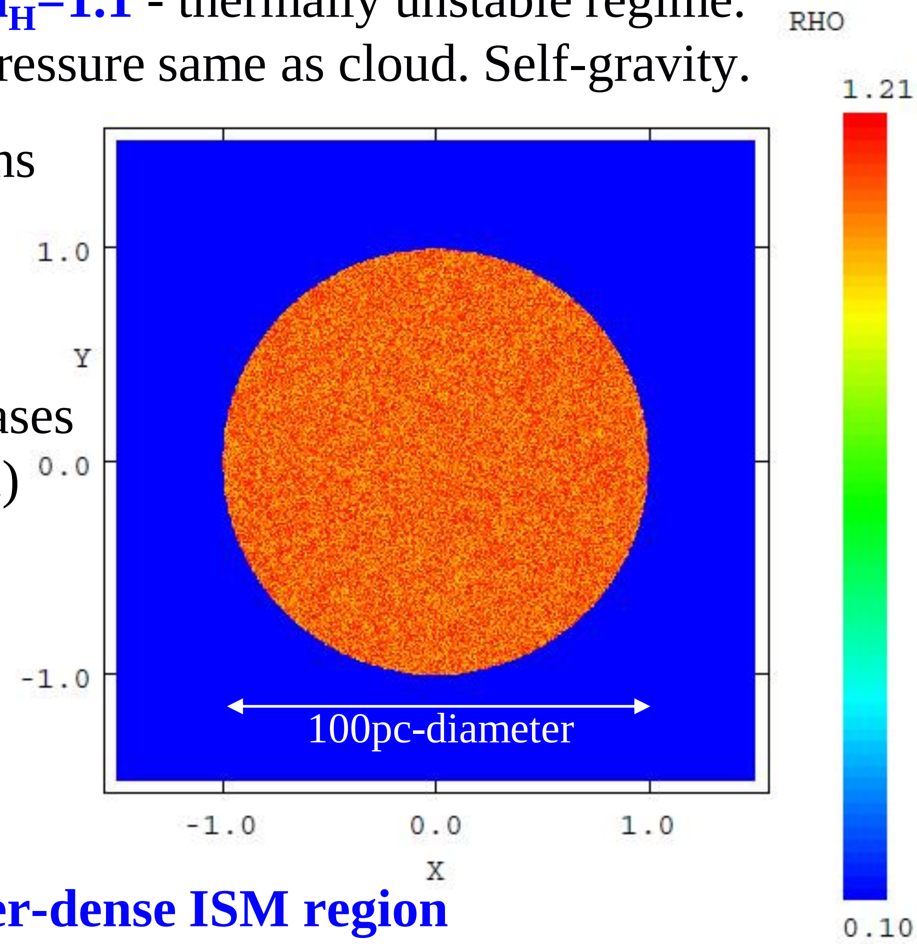
Spherical cloud, radius 50pc, density n_H=1.1 - thermally unstable regime. External medium density n_H=0.1, over-pressure same as cloud. Self-gravity.

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



Summary: our input is a quiescent over-dense ISM region

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

Inputs: enlarged 3D Hydro condition

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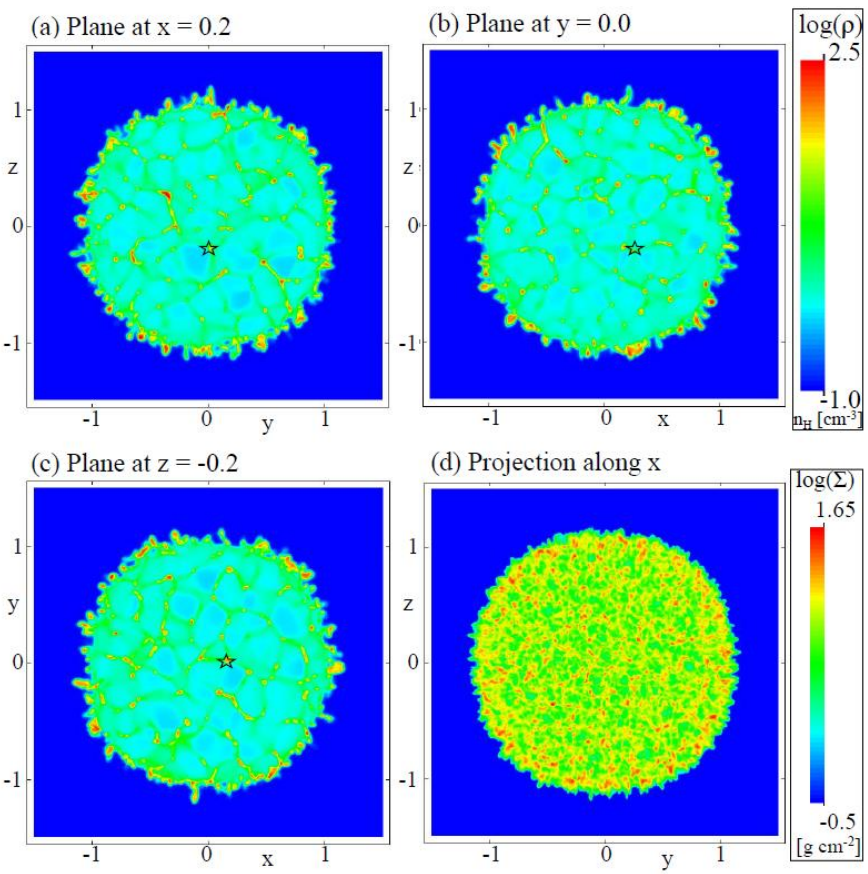
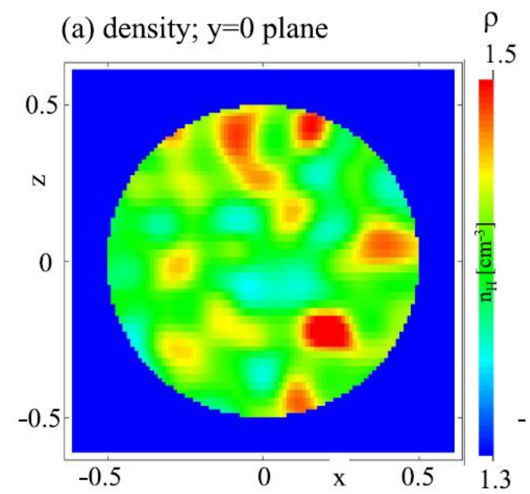
Domain size doubled, **cloud radius increased to 100pc** (r_{init} = 2.0), initial maximum AMR resolution 1024^3 (finest level 0.29pc), Mass 1.35 10^5 $M_\odot$



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

Outputs: clumps, filaments and flows

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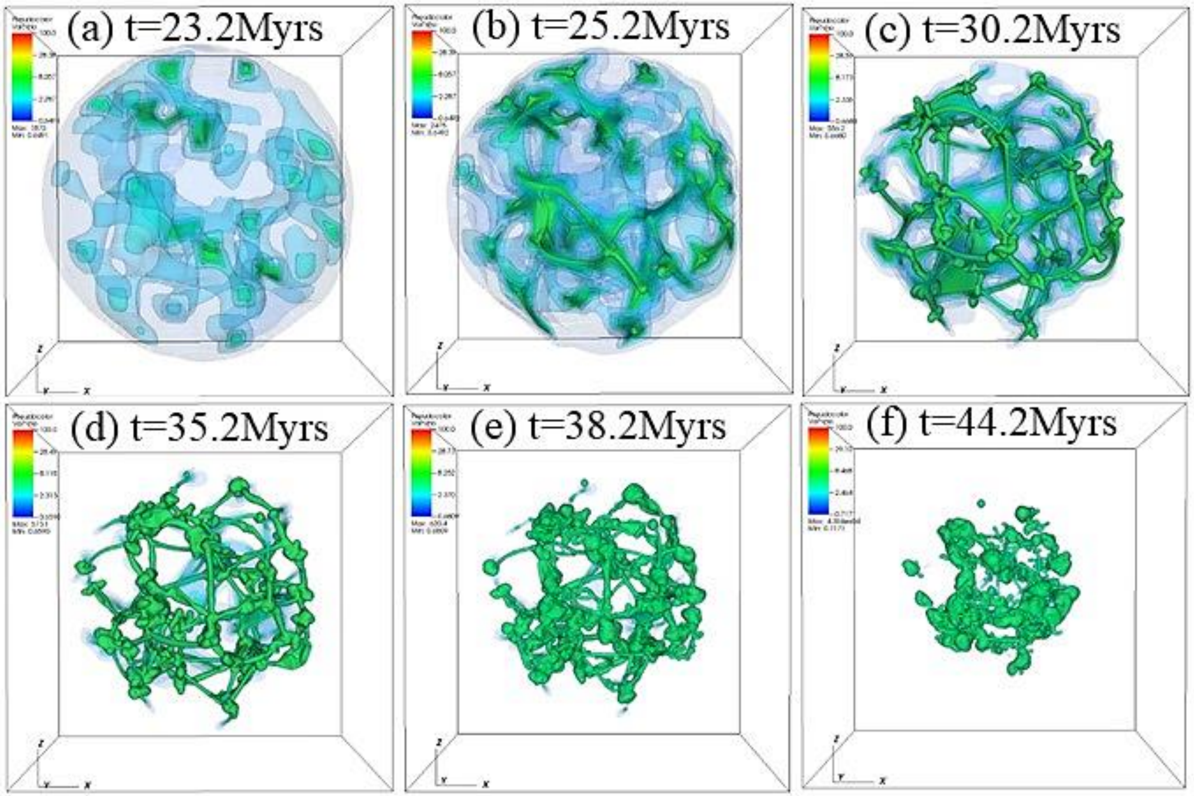
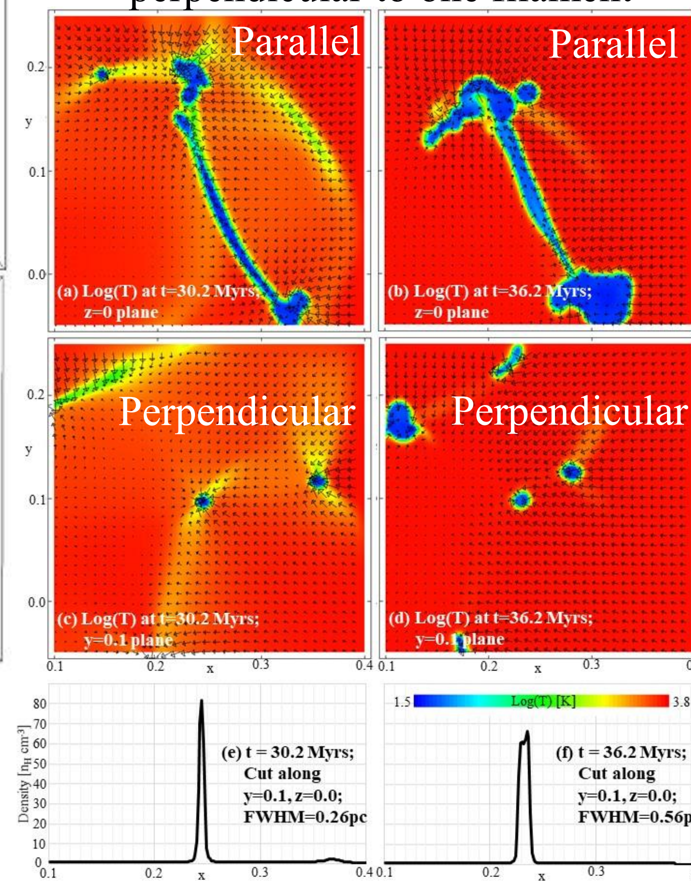


Slices of temperature parallel and perpendicular to one filament



- 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**
- **Near-sonic flow (up to 0.2 km s^{-1}) along the filaments toward the clumps.**

Outputs: realistic clumps

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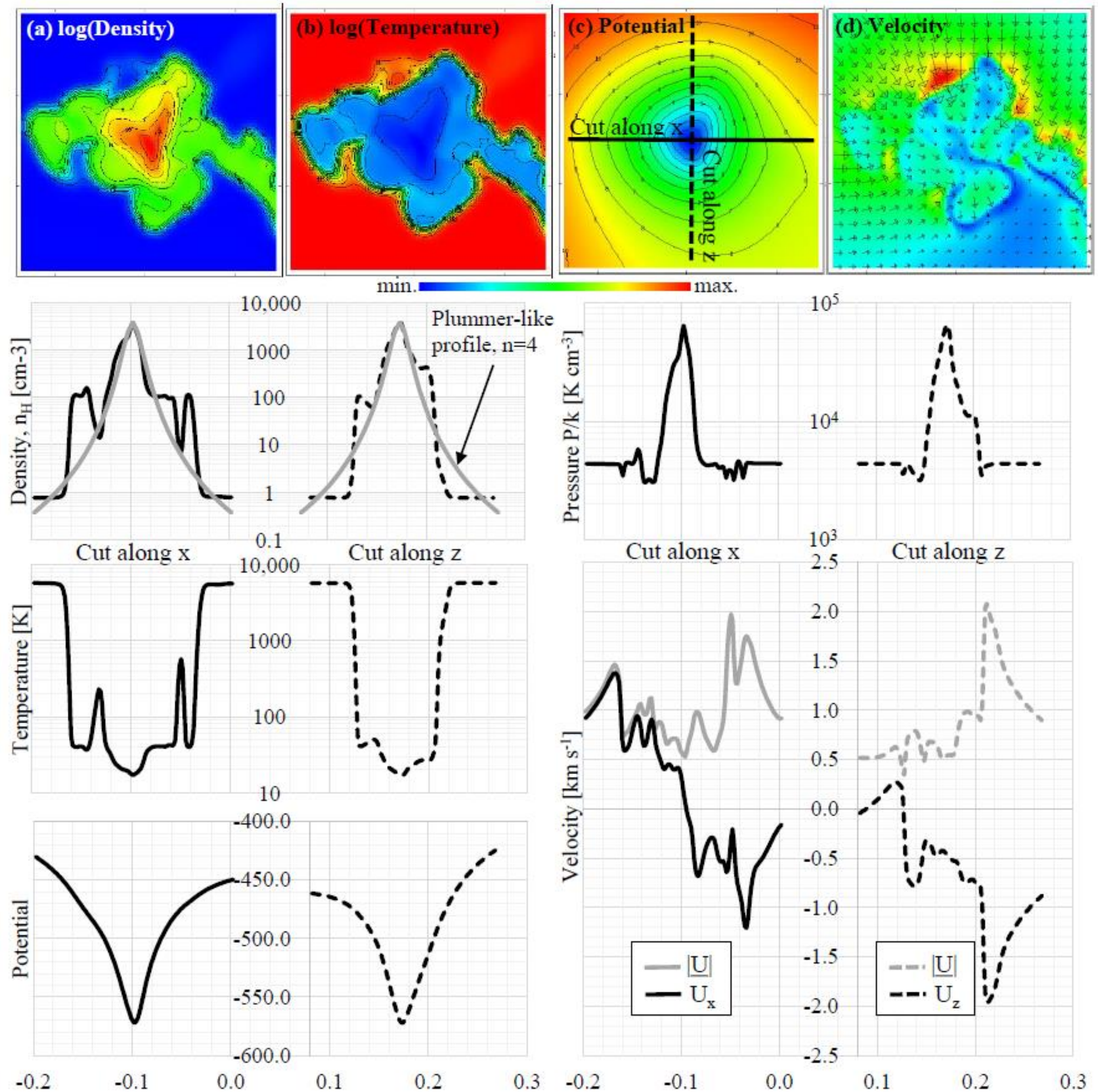
Fellwalker algorithm (Berry 2015) identified **21 distinct clumps with masses >20 $M_\odot$**

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



Outputs: looks like turbulence!

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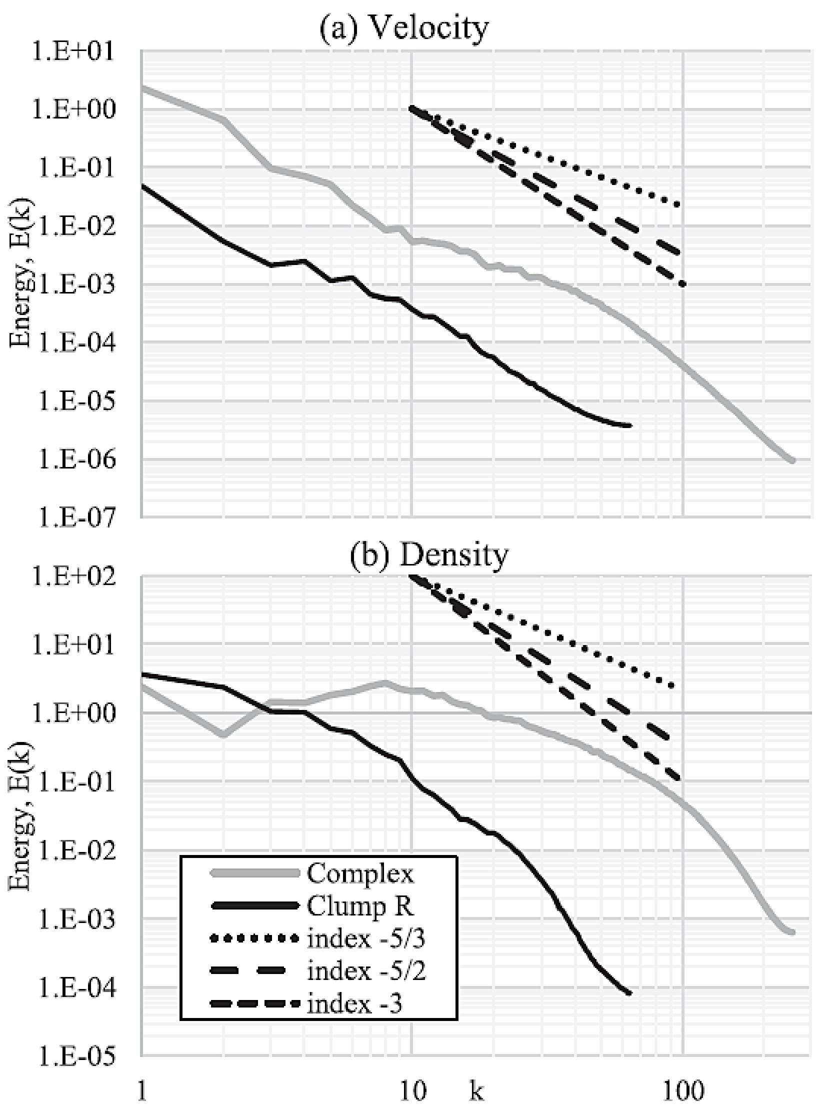
- **Turbulence-like (-5/3) power spectra in the warm stable medium**
- Short inertial range (1 decade) -> by no means fully developed turbulence.
- Should extend to larger scales
- Akin to Larson-like turbulence:- "hierarchy of small-scale irregularities superimposed on larger-scale more systematic motions"
- 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

Compares well with recent observations:

Kalberla & Haud, A&A accepted; arxiv: 1905.08583

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



Power spectra calculated by validated IDL script

Next step: MHD simulations

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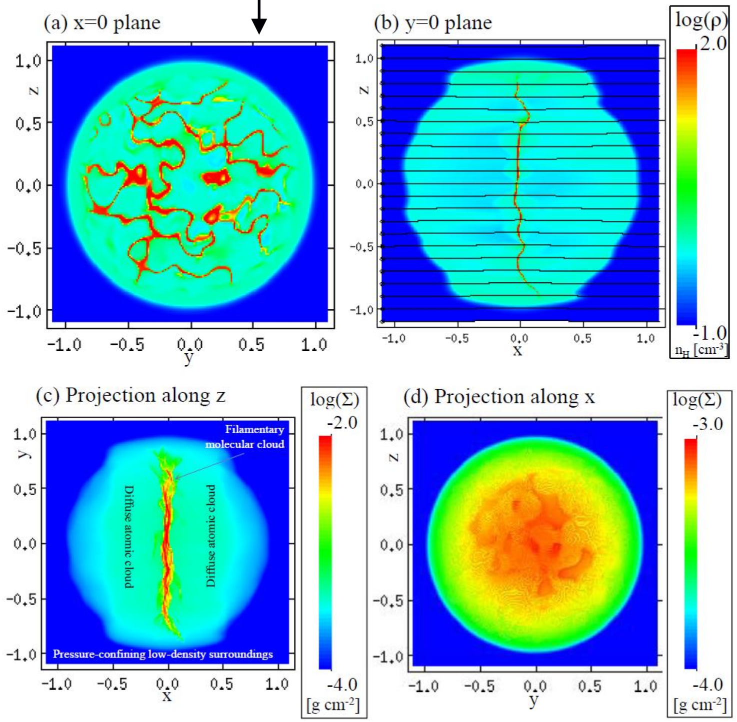
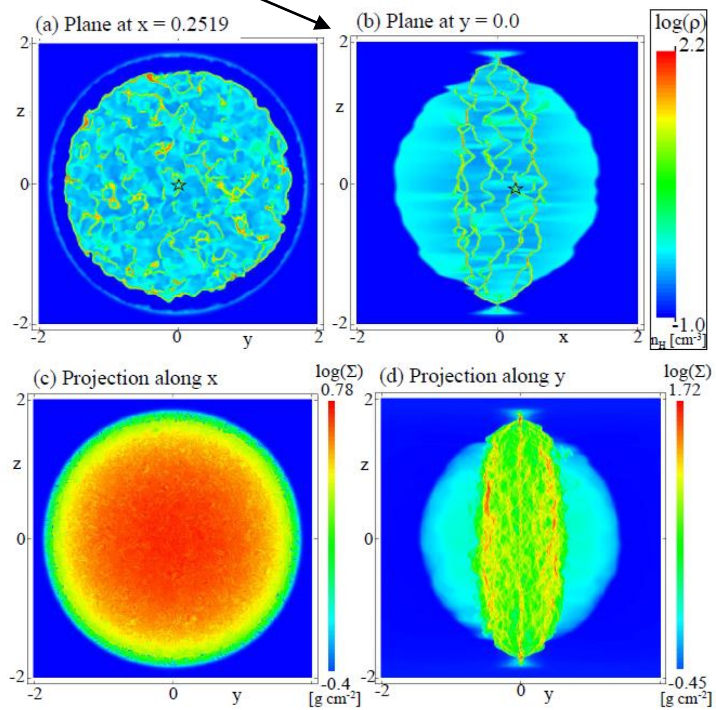
Exactly the same as hydro, but with uniform field in the x-direction

- 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)

Results





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

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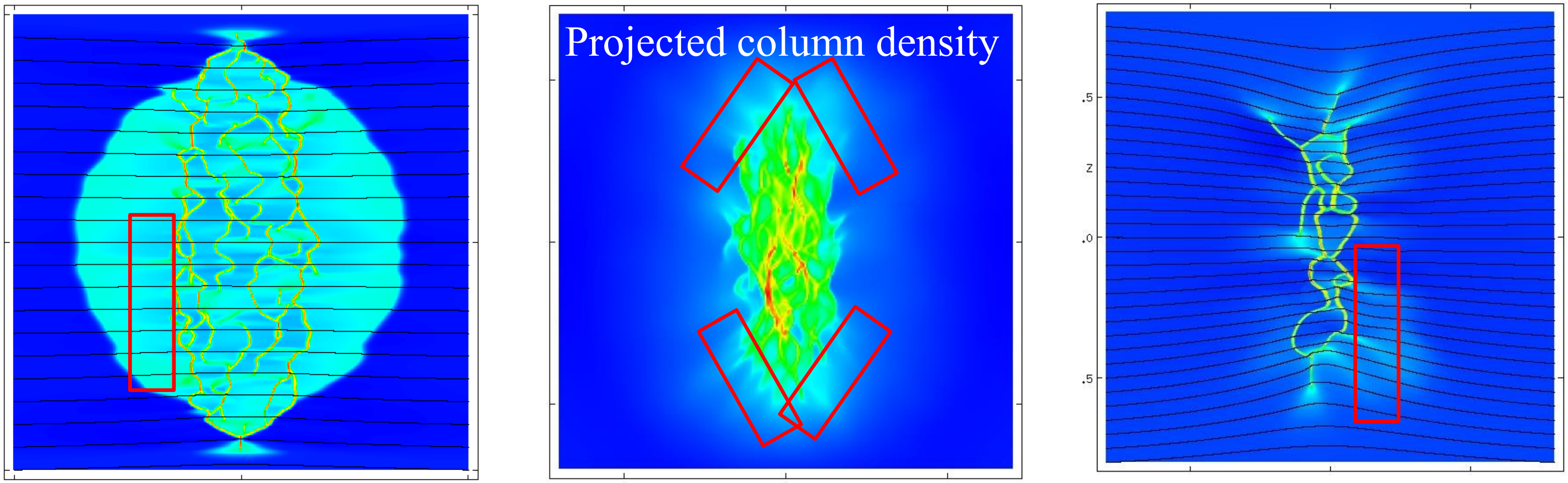
Diffuse material moves along field lines and naturally forms low-density structure parallel to the magnetic field. This is the natural pre-cursor to the high-density filamentary structure that forms in the cloud, perpendicular to the magnetic field.



- 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%) at a range of alignments
- 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 here!

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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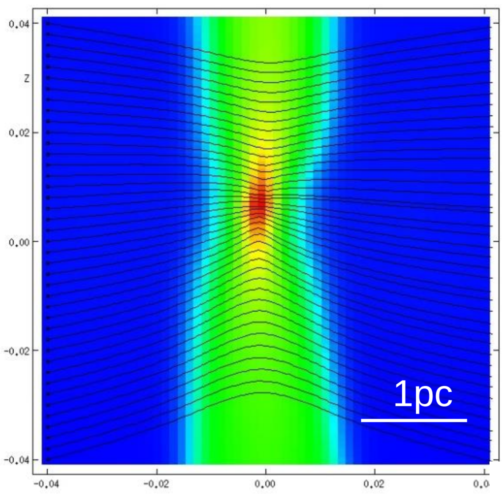
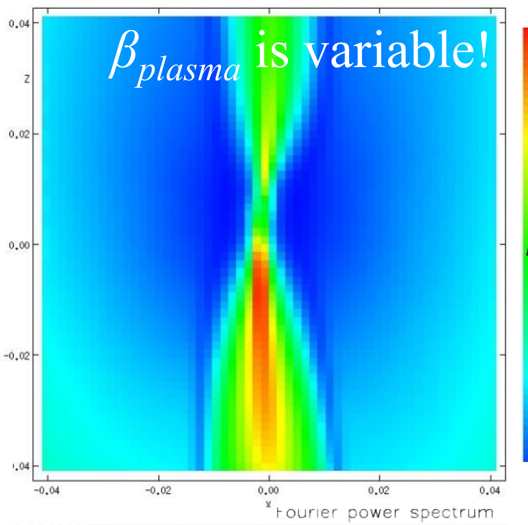
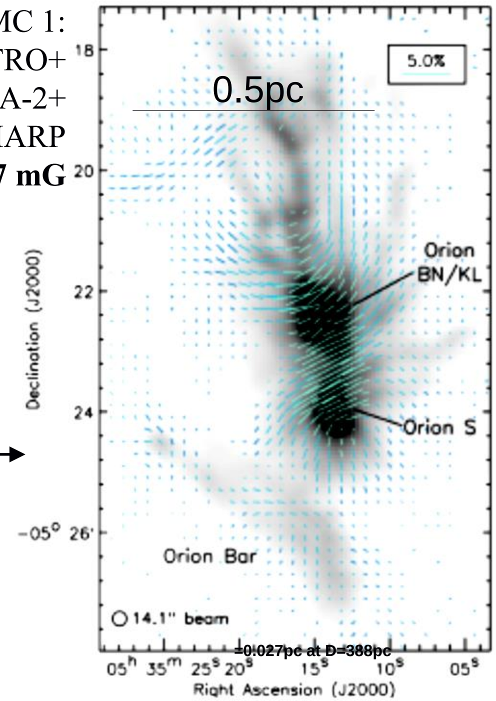
Hour-glass field morphologies naturally form under collapse.





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



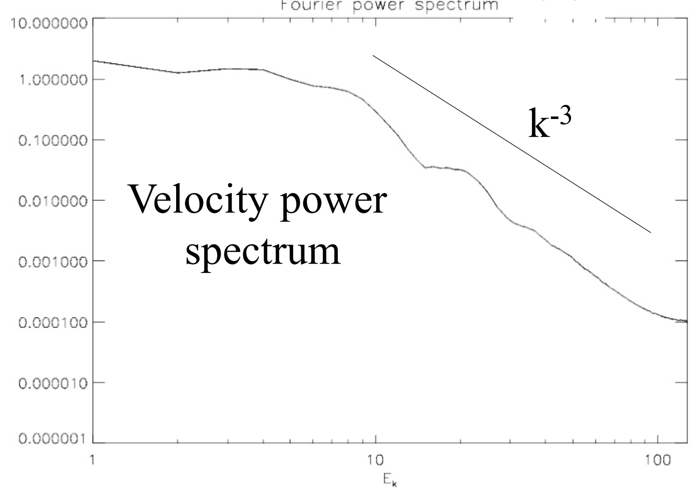
Pattle, Ward-Thompson et al., 2017, ApJ, 846, id.122

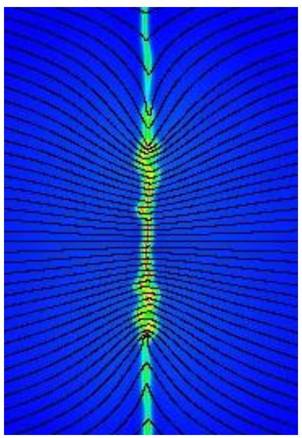
Gravitational collapse
dragging the field.

Field intensified in places from 0.3μG to ~0.1mG

Plasma β changes: 10 to ~1!

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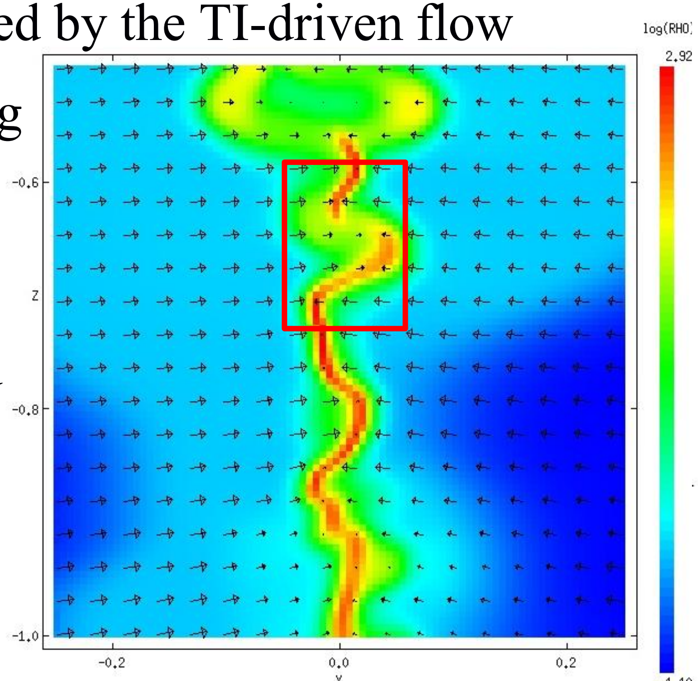
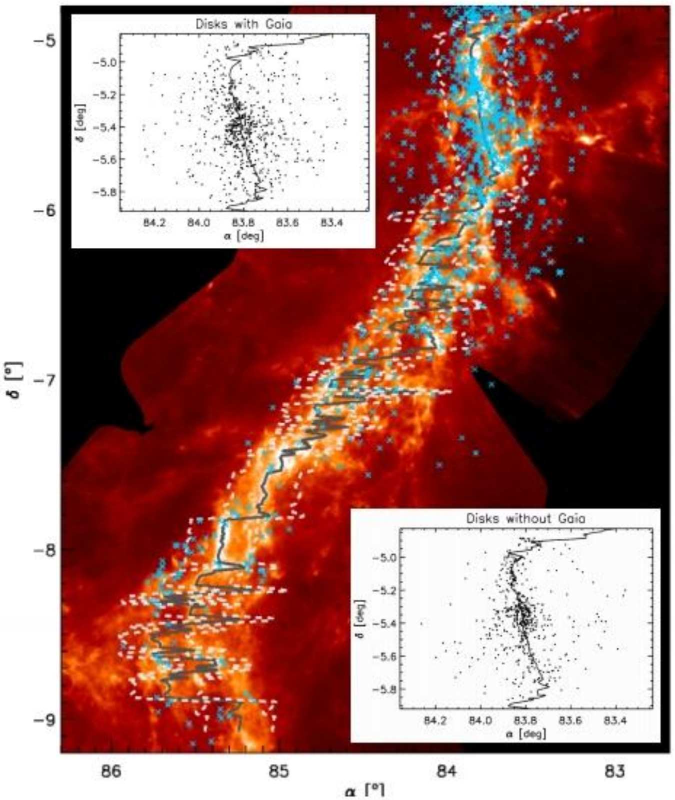
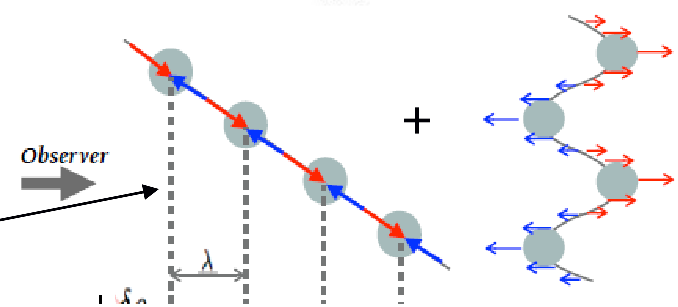
- Recent work **submitted** to MNRAS concludes that an "*integral*"-shaped filament in Orion is a standing wave
- **We obtain apparently similar structure**, with disconnects in the velocity caused by the TI-driven flow
- Not a standing wave – an effect of the initial condition and ISM flow
- Further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





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



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

The Crutcher relationship: comparing models

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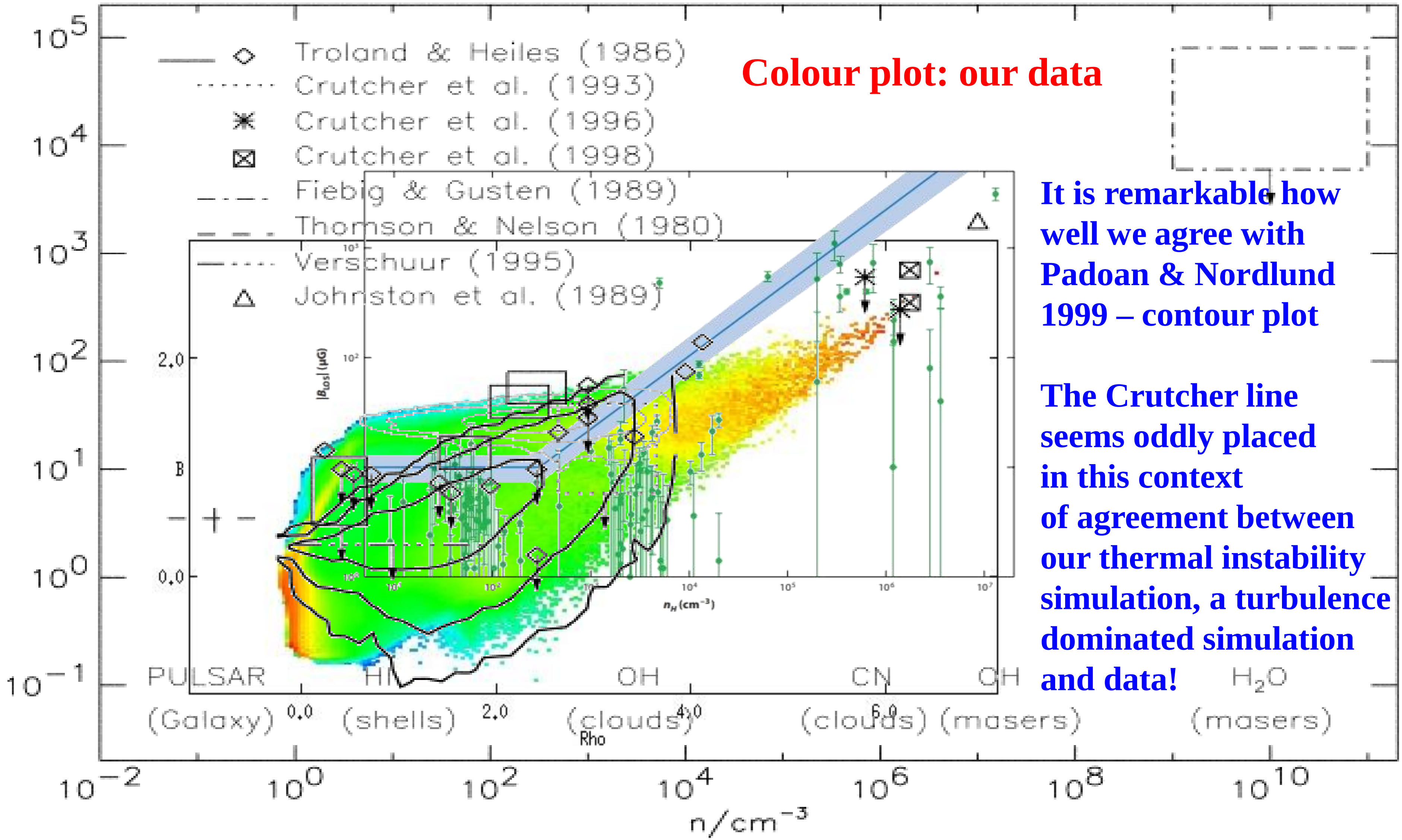

It is remarkable how well we agree with Padoan & Nordlund 1999 – contour plot

The Crutcher line seems oddly placed in this context of agreement between our thermal instability simulation, a turbulence dominated simulation and data!

The Crutcher relationship: comparing models

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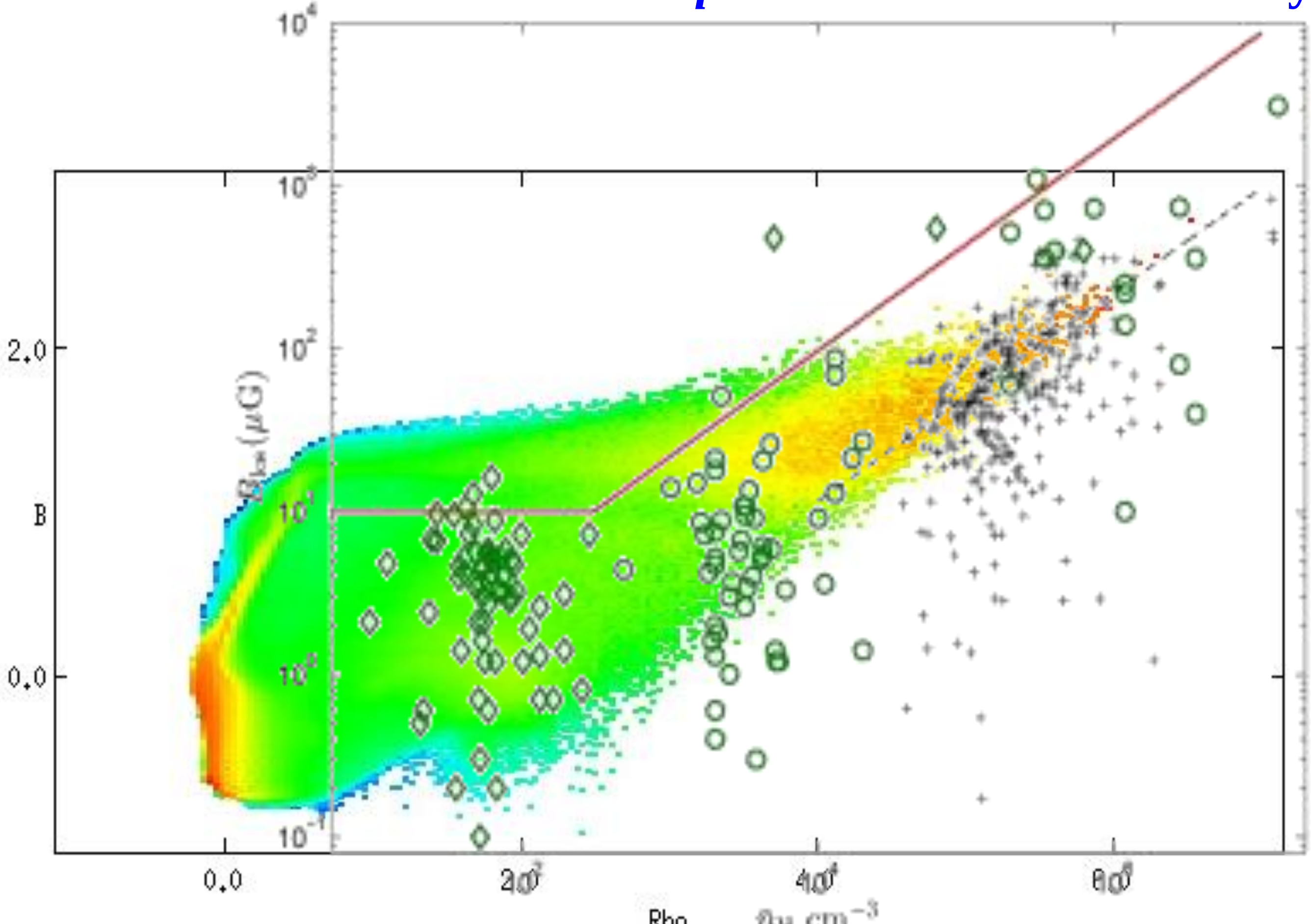
Agreement this time at high density between *driven* turbulence simulation and *quiescent* thermal instability simulation.



Colour plot: our data

Green circles: Crutcher datapoints.

Red line: Crutcher line.

Black crosses: Li, McKee & Klein 2015 simulation of driven Mach 10 turbulence, with M_A ~1.

Black dashed line: best fit by Li et al. to their simulation data.

What should we theoreticians take as the meaning of the red line?

Mechanical stellar wind feedback

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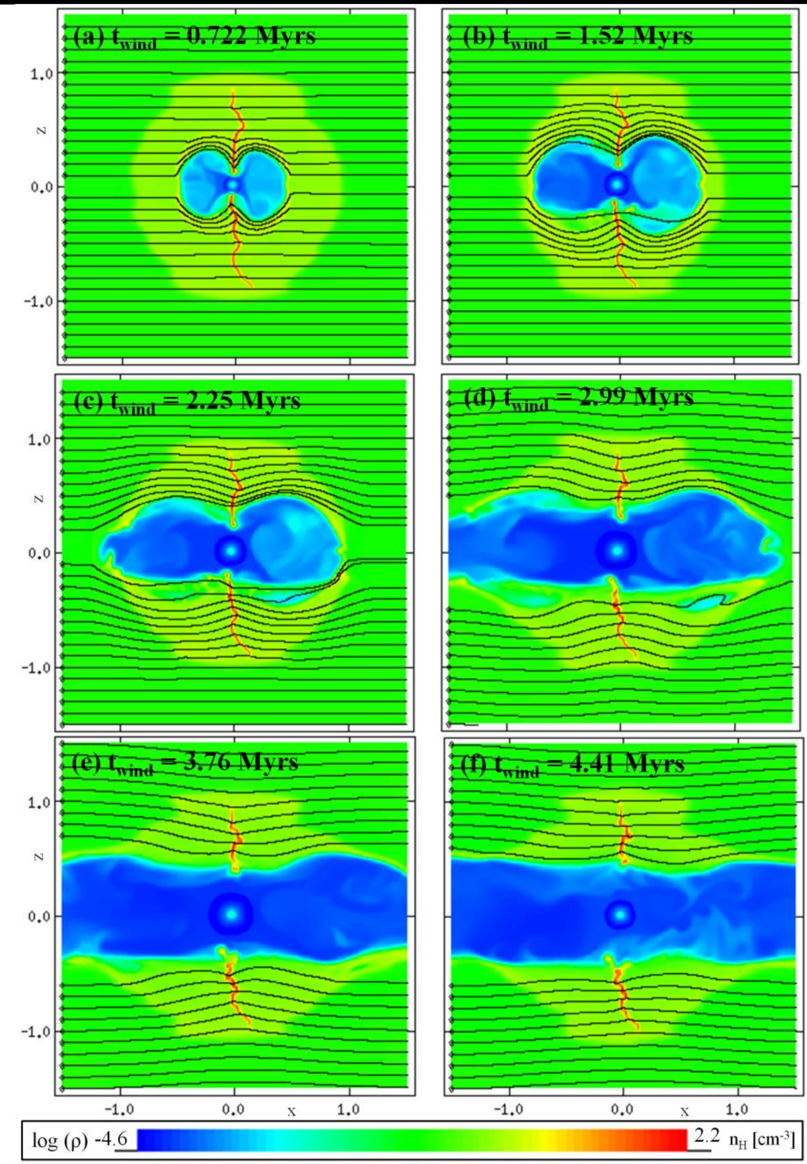
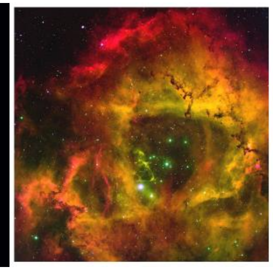
- 40 $M_{\odot}$ star embedded in the sheet
- Realistic Geneva (2012) evolution imposed via density and energy sources
- **Significant impact on a 1.7×10^4 $M_{\odot}$ cloud**
- **Large bipolar cavity evolves into a cylindrical cavity** (diameter~40pc) through the centre of the cloud
- Cavity filled 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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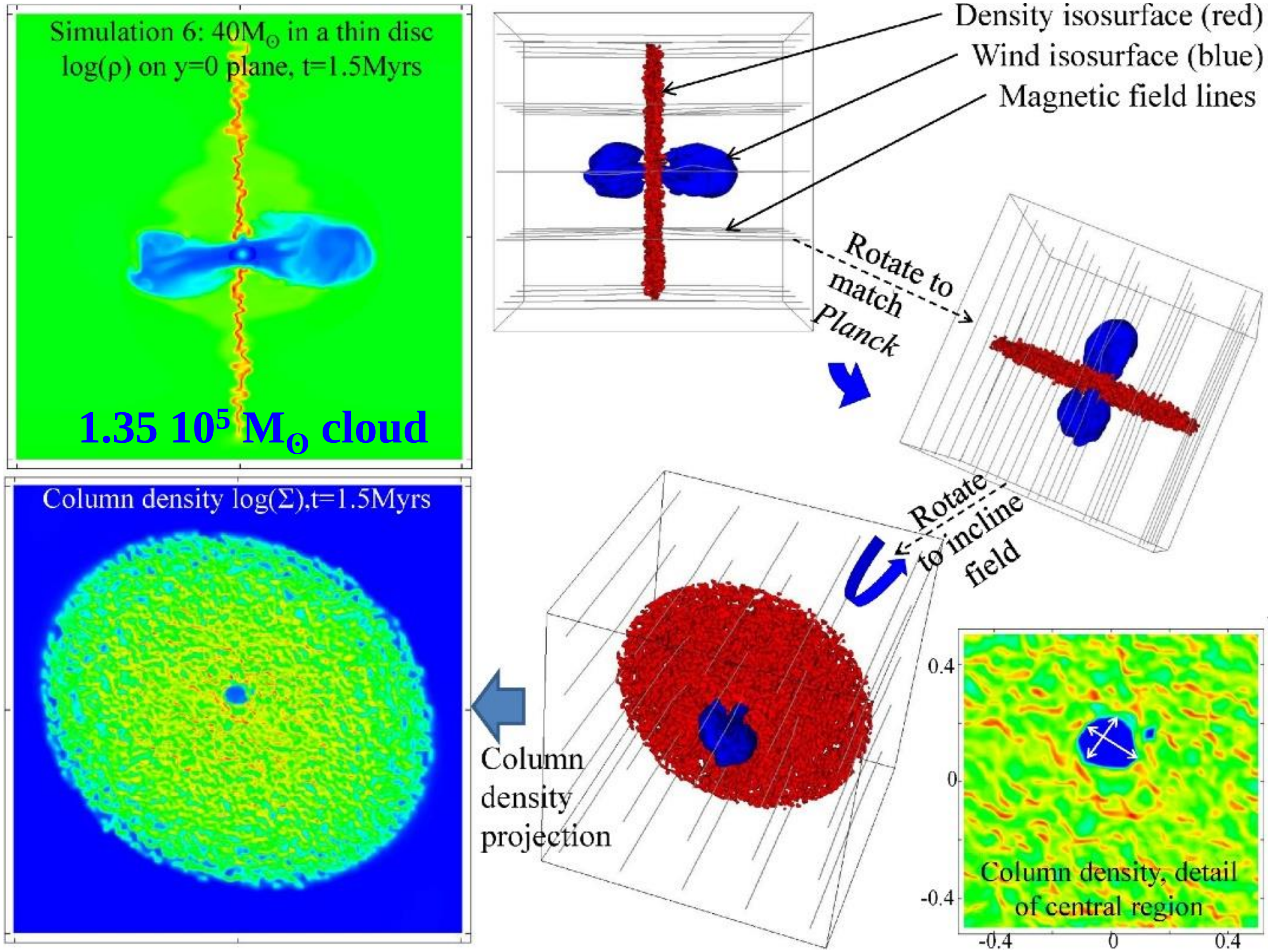
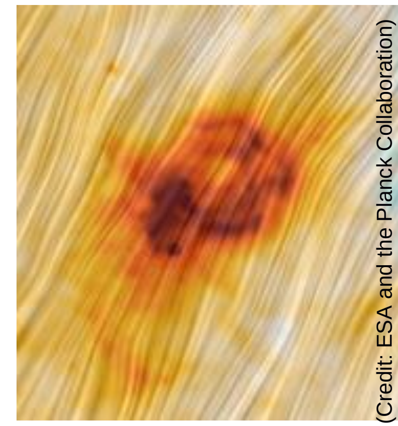
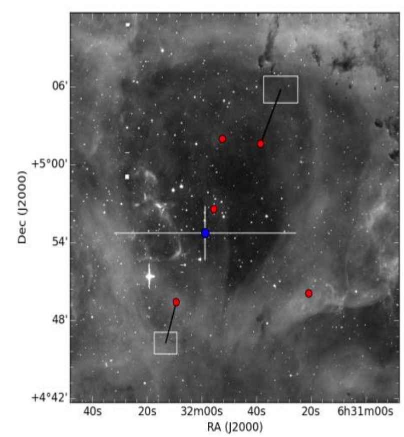
Magnetic field alignment, proper motion and location of possible triggered star formation all support this model.





Evacuated hole

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



Conclusions

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Realistic minimal inputs - the thermal instability in diffuse interstellar medium, 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 and Mach ~1-2.
- There are **near-sonic (0.2 km s^{-1}) flows along the filaments** into the cores, as observed.

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 to tens or more of μG** and creates **hour-glass fields**.
- Disconnects across the sheet, driven by the flow, create integrals and gaps in position-vel. maps.

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, MNRAS *submitted.*
MHD case: striations, hour-glasses & integrals	Wareing, Falle & Pittard, *in prep.*

Revisiting thermal instability

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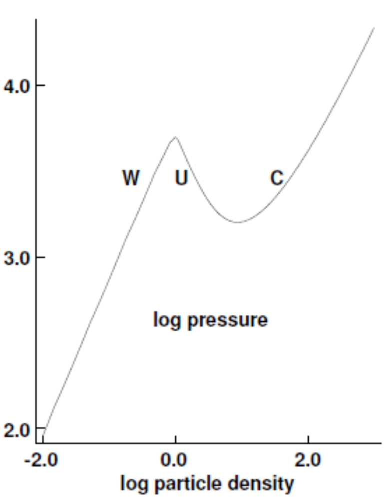
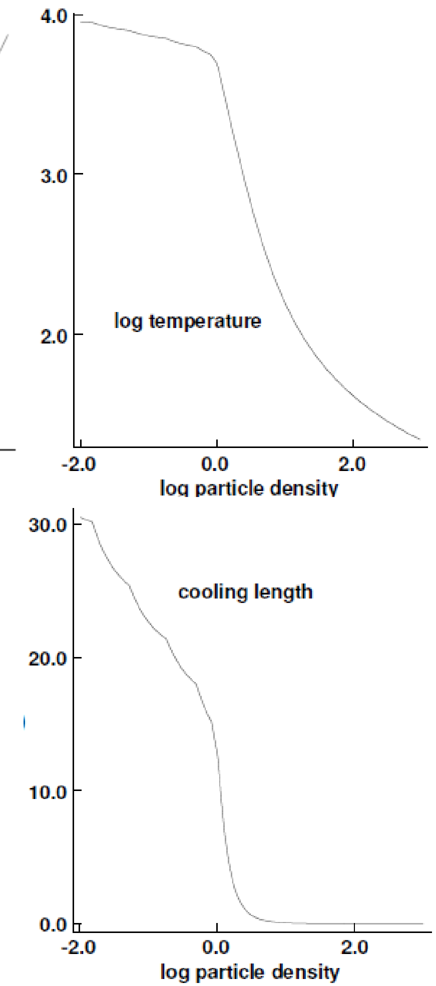
Two stable phases exist in which heating balances cooling (Parker '53, Field '65, Wolfire et al. '95)

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 $\underline{B} = B_o \hat{\underline{I}}_x$

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

  - The hydrodynamic case: $\beta = \infty$
  - Pressure equivalence: $\beta = 1$ - inferred to be the commonest in reality.
  - Magnetically dominated regime: $\beta = 0.1$

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

Simple 3D Hydro condition

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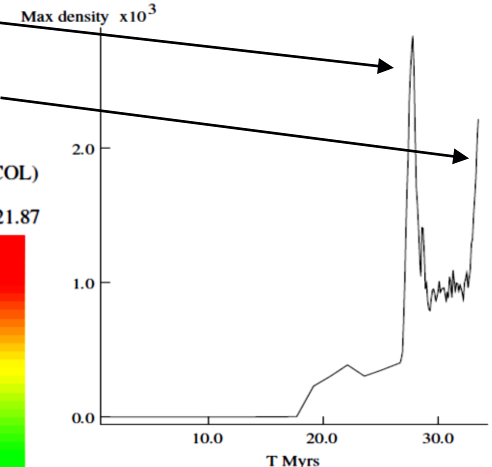
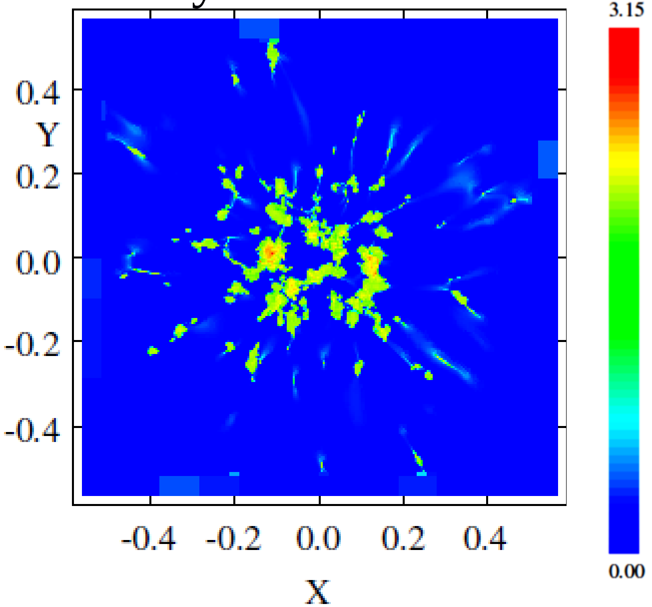
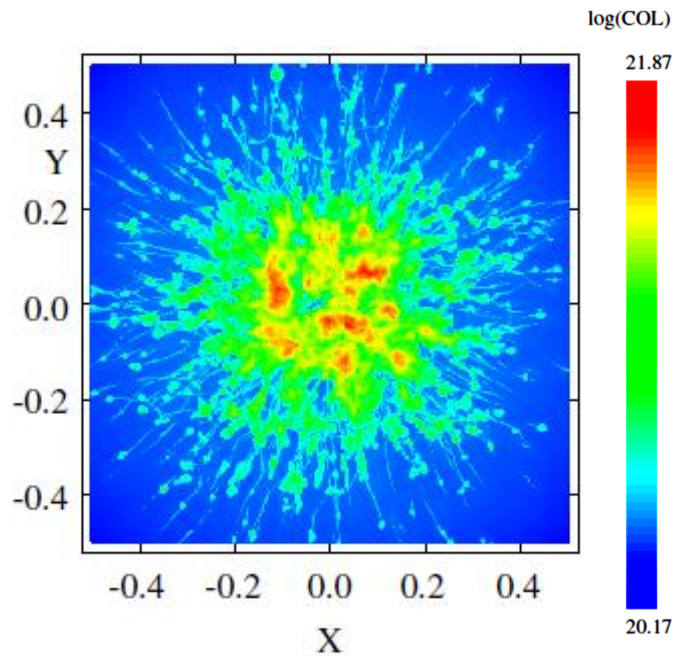
First peak due to TI-driven collapse, not gravity

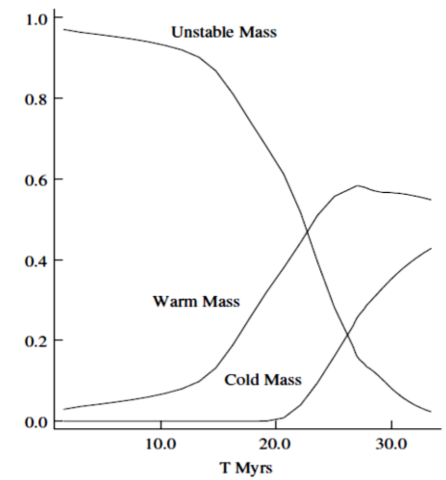
Second peak is due to gravity



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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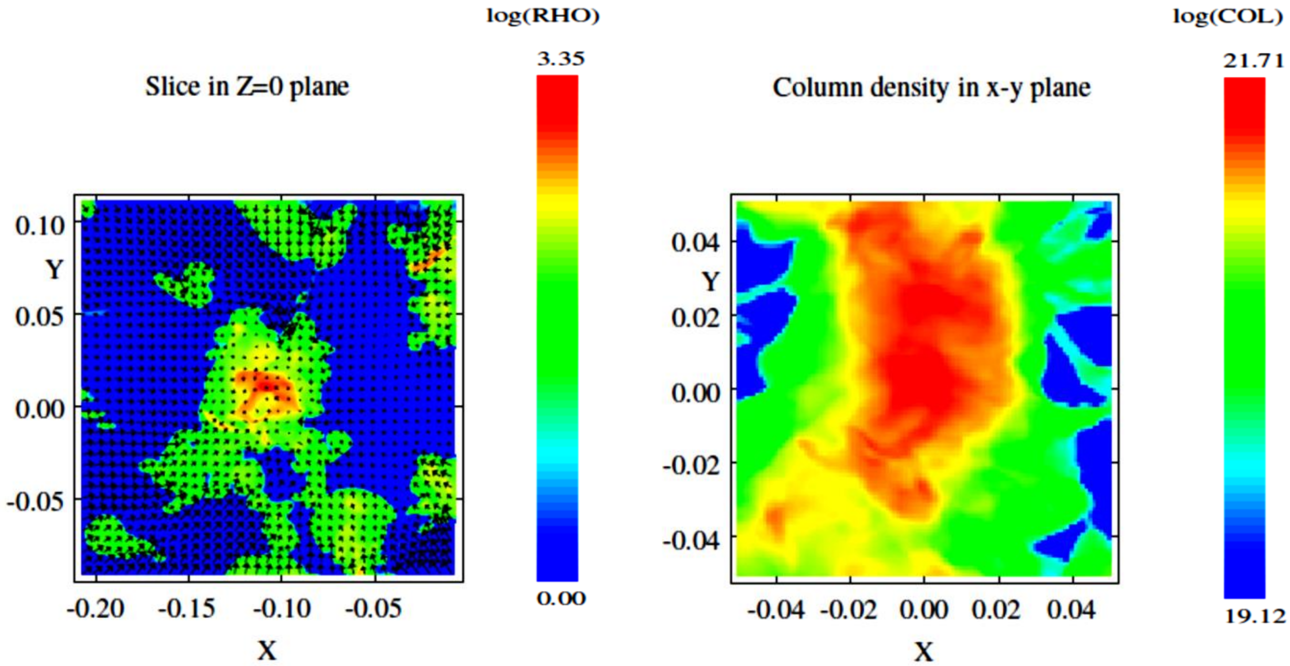

Diameter ~5pc, Mass 182$M_{\odot}$, Max density 2214, Mean density 177,
Max velocity 3.25 km s^{-1} (in frame of dense region), 0.6 km s^{-1} in dense gas.

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

Final evolved enlarged simulation

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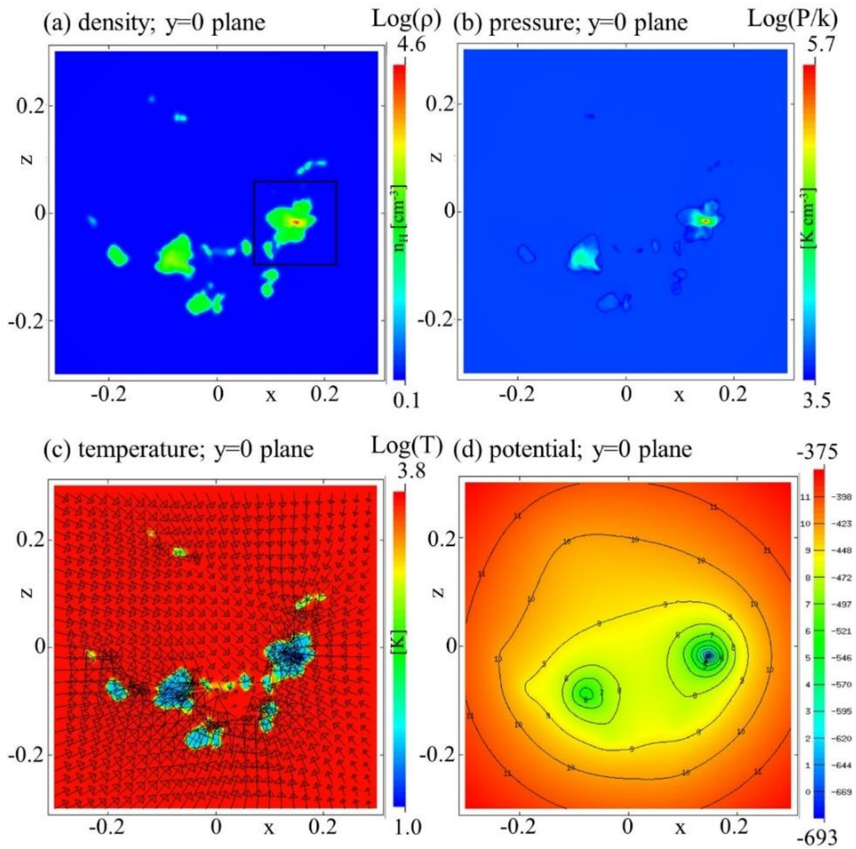
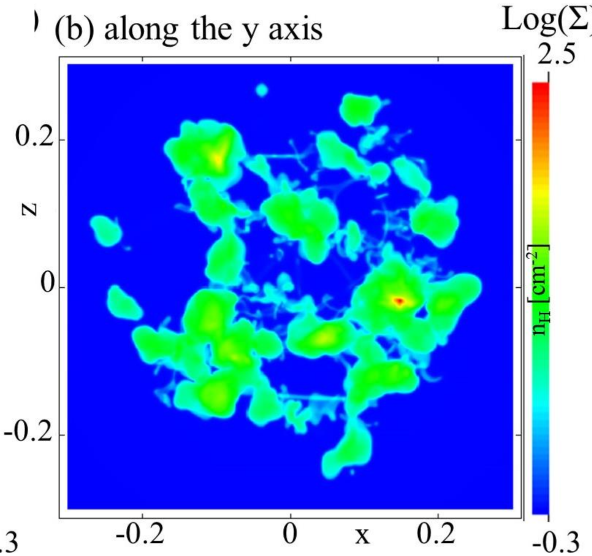
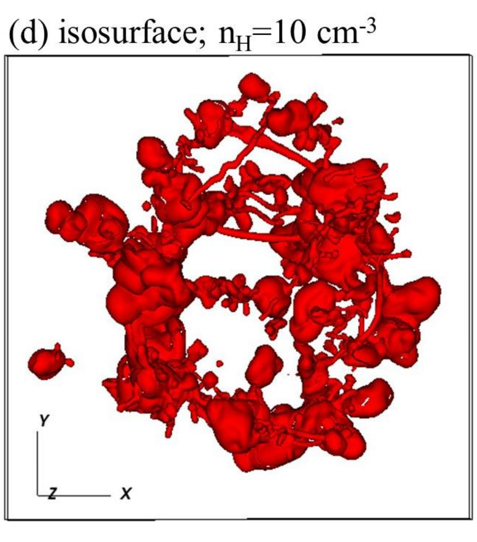
Cloud has contracted under gravity to a radius of ~10 pc







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

Provocative ways to determine between models?

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e.g. I am not convinced by Padoan's latest SN driving models as they produce too weak a B-rho dependence.