School of Physics and Astronomy
FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

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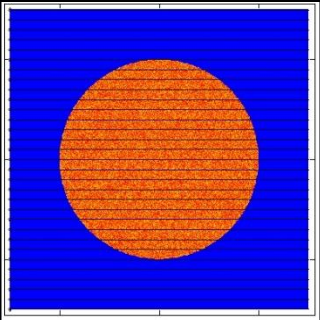
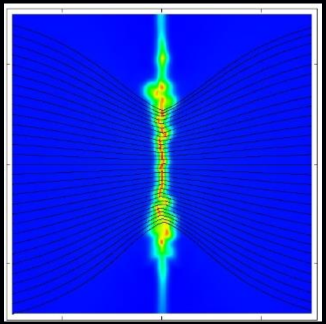
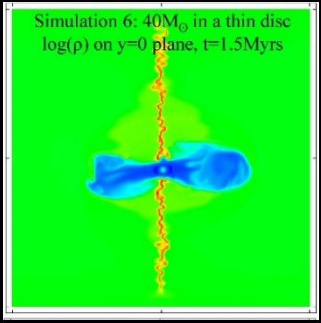
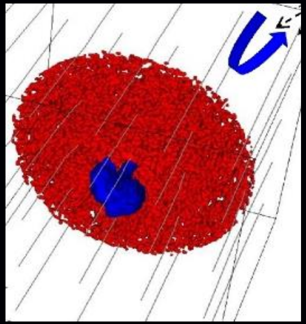
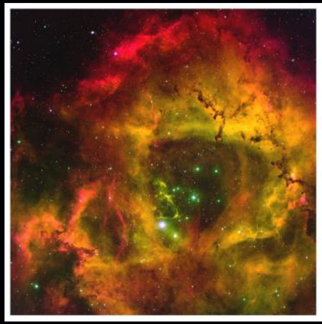
Simulations of thermal instability in the ISM

Chris Wareing, J. Pittard, S. Falle, S. Van Loo, M. Kupilas

Solar1: Non-equilibrium thermodynamics across scales:
from the solar corona to the intracluster medium

National Astronomy Meeting 2022, University of Warwick, 12/7/2022

History: models for stellar feedback

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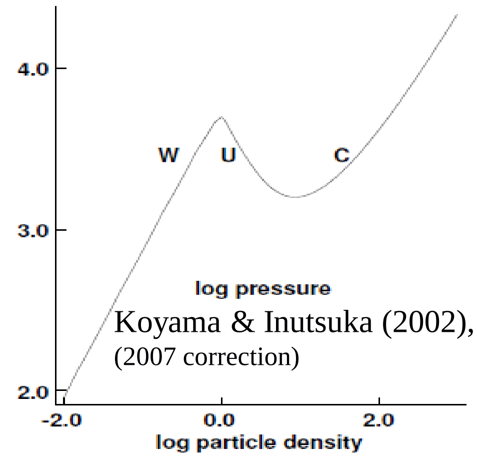
The original project aim was to develop a realistic initial condition following the formation of molecular clouds from the ISM to examine the importance of subsequent massive star feedback.

Started by taking arguably the minimum number of physically self-consistent inputs for the formation of a molecular cloud:-

- **Multi-phase ISM including thermal instability**
- **Self-gravity**
- **Magnetic field**

employing 3D HD/MHD simulations



Koyama & Inutsuka (2002), (2007 correction)

Add more complexity later if necessary:-

- Large-scale flows: shocks and SNRs (see Kupilas et al. 2021,2022), cloud collision
- Shear and pressure waves, imitating galactic evolution
- “Turbulent” initial conditions applying randomised velocities up to Mach ~5

but if one can produce realistic clouds without recourse to extra inputs...

lex parsimoniae / Occam’s razor

Theory: thermal instability in the ISM

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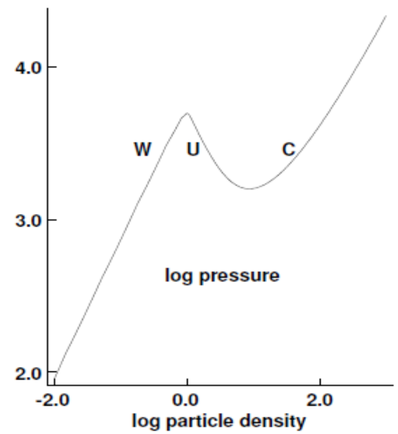
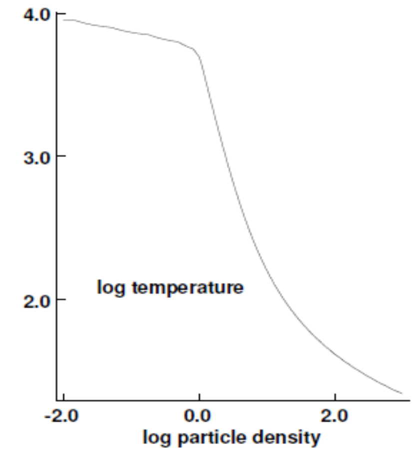
Two stable phases exist in which heating balances cooling (Parker '53, Field '65, Wolfire et al. '95)

W – warm phase ($T > 5000$K, $\rho < 1$, $P/k < 5000$)
C – cold phase ($T < 160$K, $\rho > 10$, $P/k > 1600$)

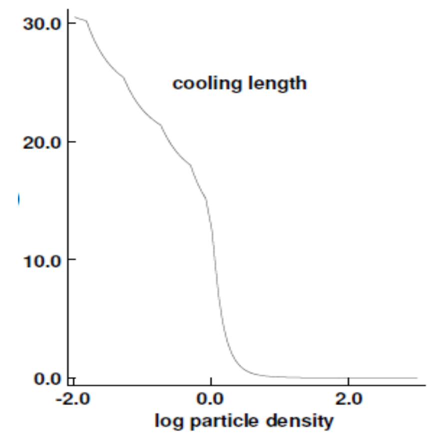
In between is an unstable region (U), where perturbations to equilibrium grow at a scale from cooling time and sound speed ~ few pc.





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

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



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

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

Note: altering heating and cooling functions can change, even suppress, this behaviour!

Growth of cold, dense structure

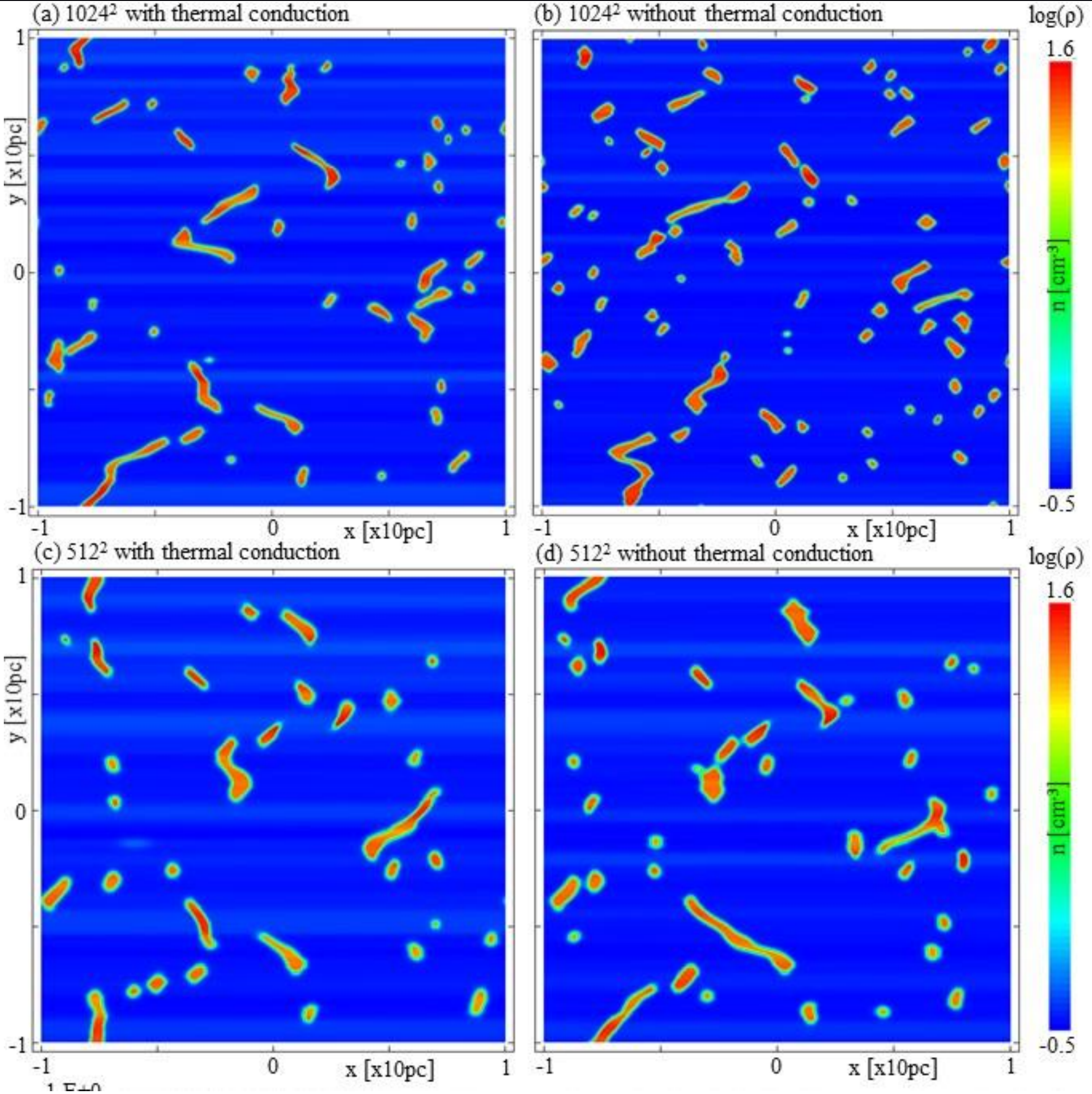
Idealised case

- Periodic boundary conditions.
- Approximately 30 cells across the initial Field length at 1024^3, 15 at 512^3.

Results

- Similar with and without thermal conduction.

Agreement amongst many groups that neither thermal conduction nor resolution have much effect on the final large-scale result.



Initial condition for the ISM

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Spherical cloud, radius 100pc, density n_H=1.1 – in the thermally unstable regime. External medium density n_H=0.1, over-pressure same as cloud. Self-gravity.

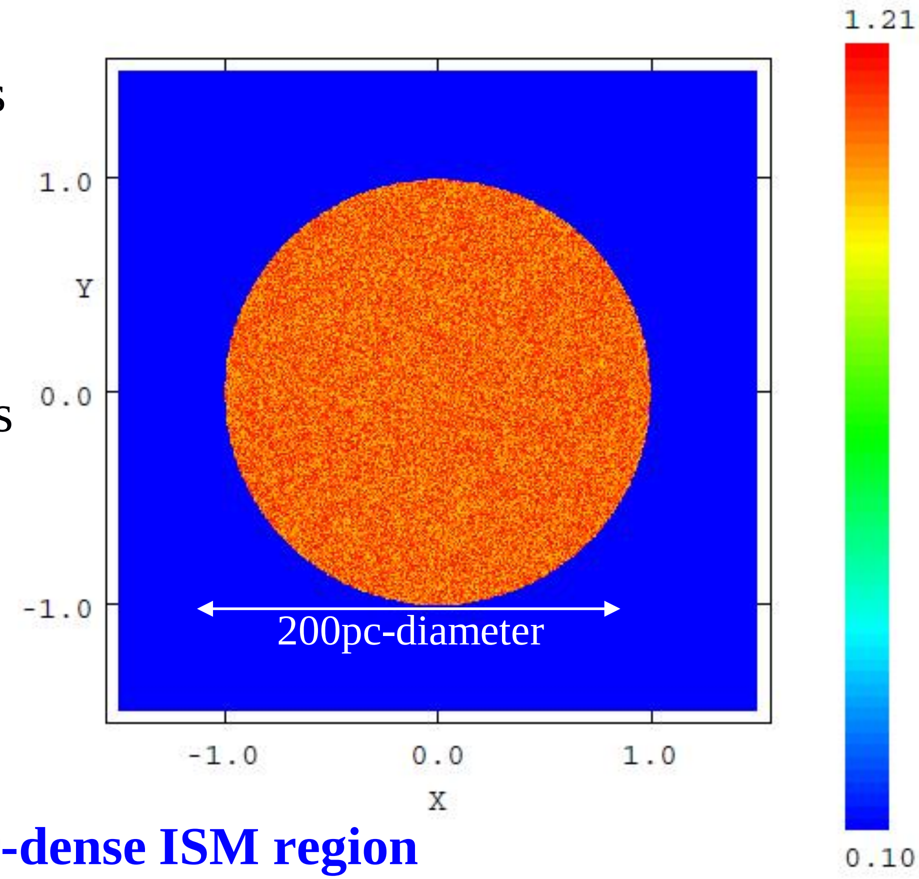
Impose random 10% density perturbations on finest initial AMR grid level (512^3)

Quiescent cloud <u>v</u>=0

Extract and resimulate as density increases
Up to 10 levels of AMR (4096^3: 0.039pc)

Mass: 135,000 $M_{\odot}$

Initially no magnetic field



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

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

Result via non-equilibrium evolution

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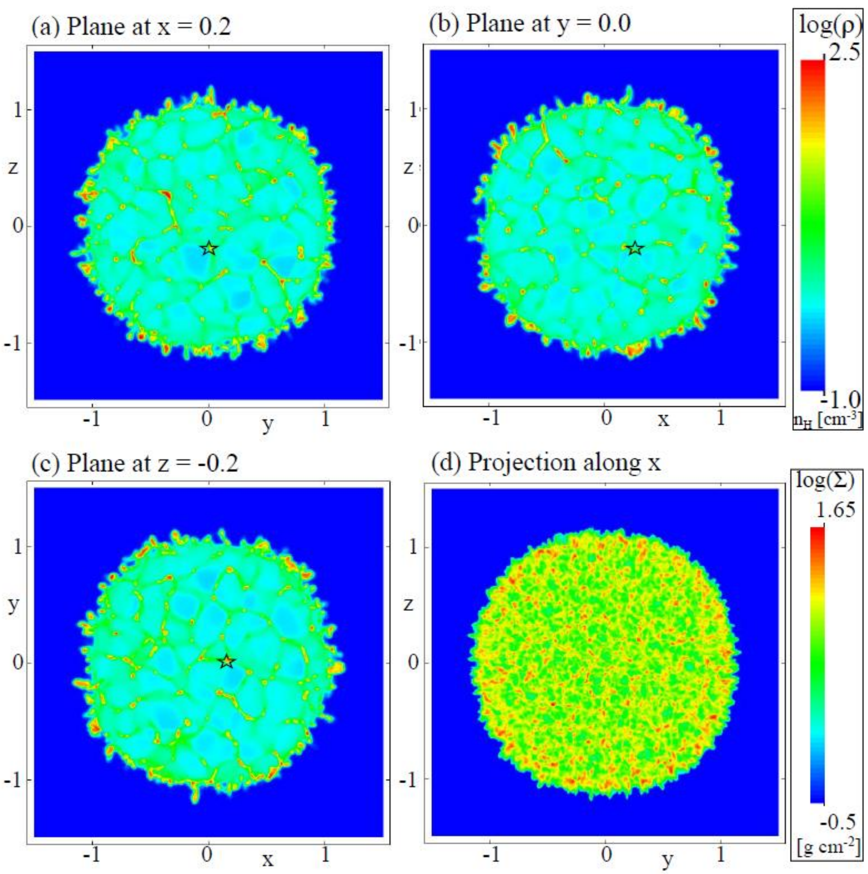
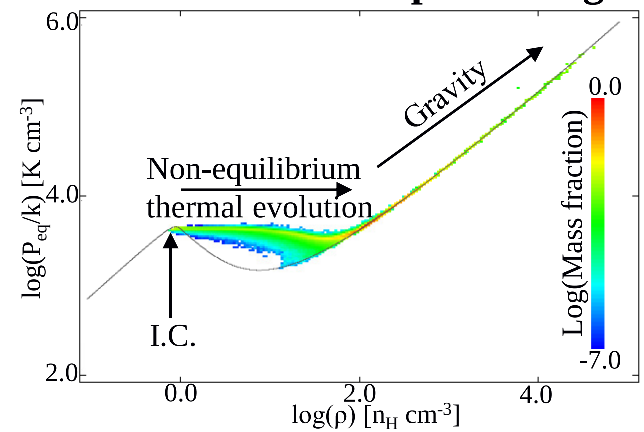
Cold, dense, stable condensations form across the cloud surrounded by warm, diffuse, stable medium…



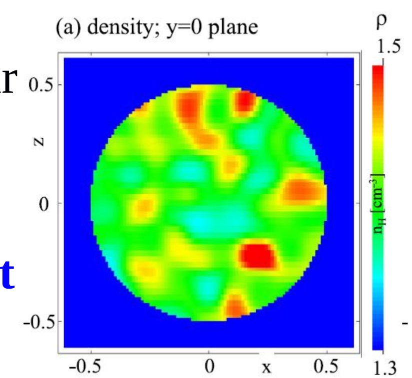
Initial cloud diameter (200pc)

Evolution across the phase diagram



Phase plot shown at late time

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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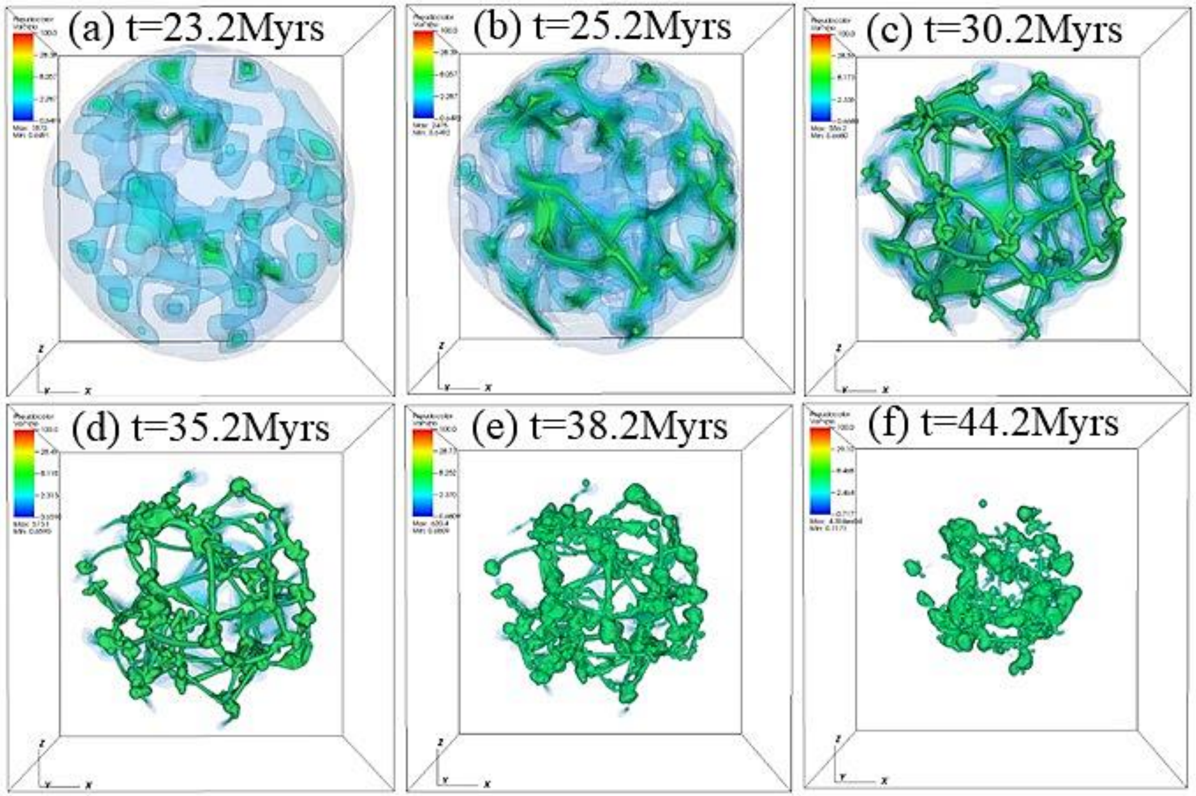
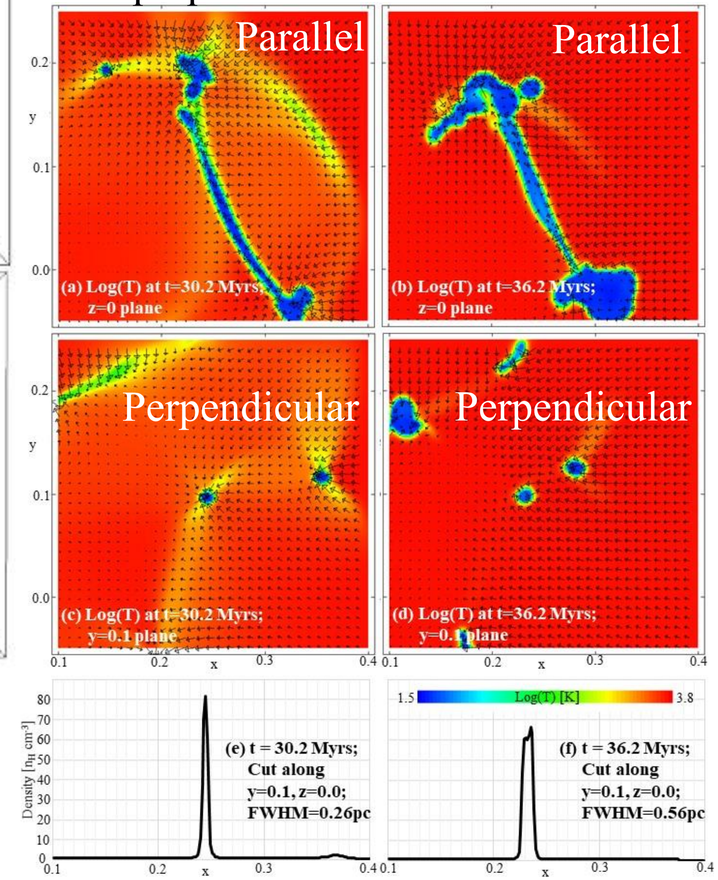


Slices of temperature parallel and perpendicular to one filament



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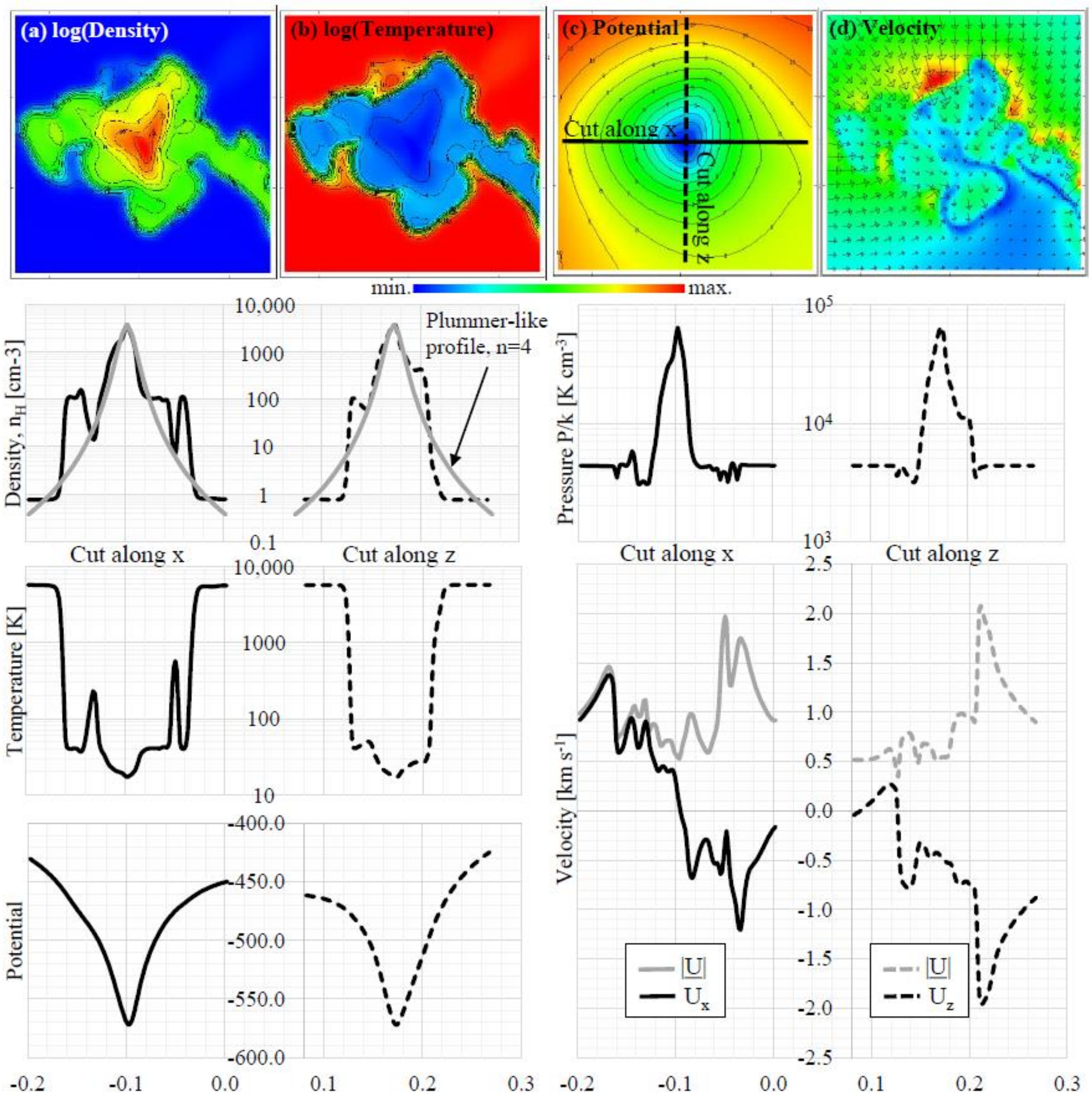
Fellwalker algorithm (Berry 2015) identified **21 distinct clumps with masses >20 $M_\odot$**

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, most noticeable in temperature distribution
- Increased internal pressure indicates gravitational collapse



Addition of magnetic field

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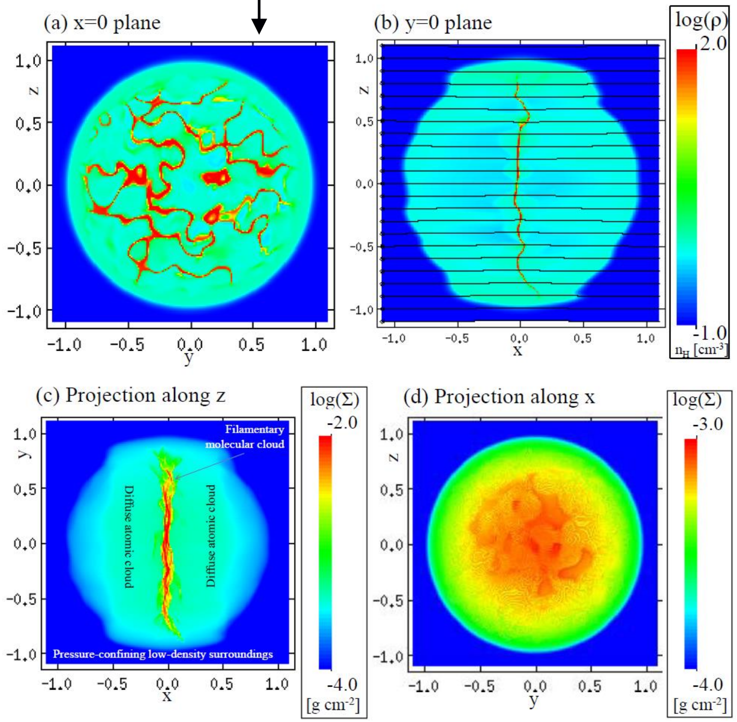
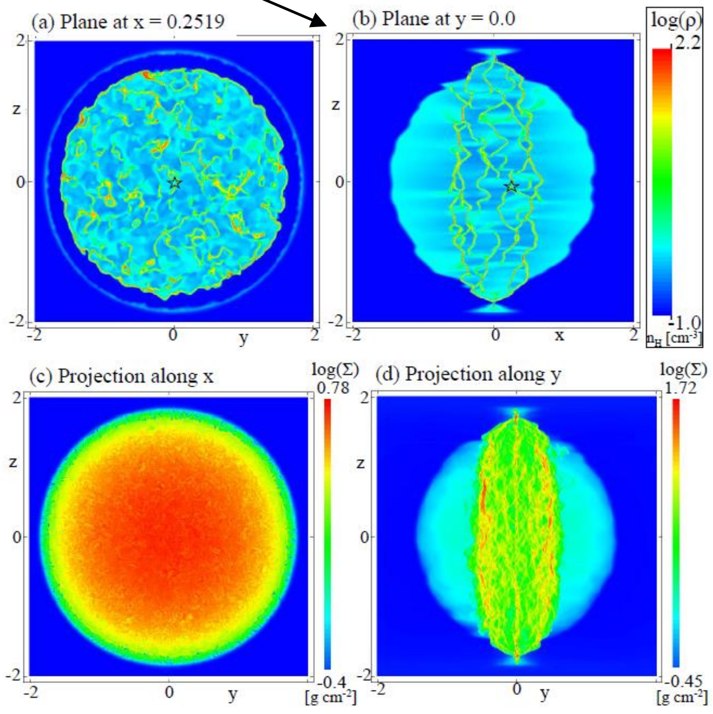
Exactly the same as hydro, but with uniform field in the x-direction

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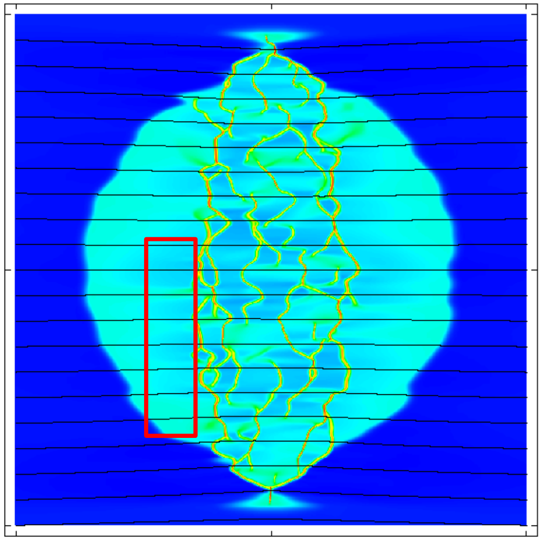
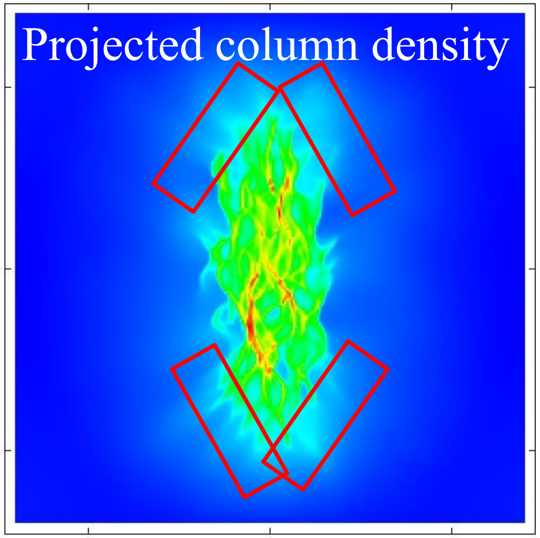
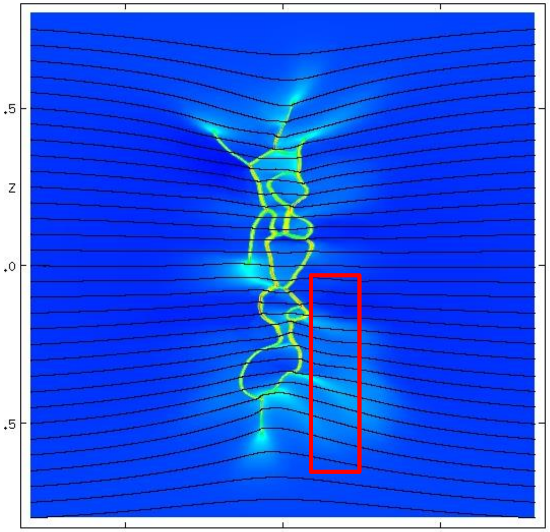
Diffuse material moves along field lines and naturally forms low-density structure parallel to the magnetic field. This is the natural pre-cursor to the high-density filamentary structure that forms in the cloud, perpendicular to the magnetic field.





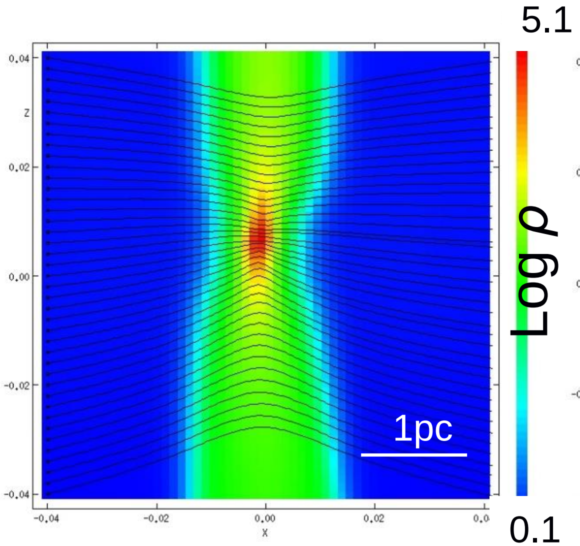


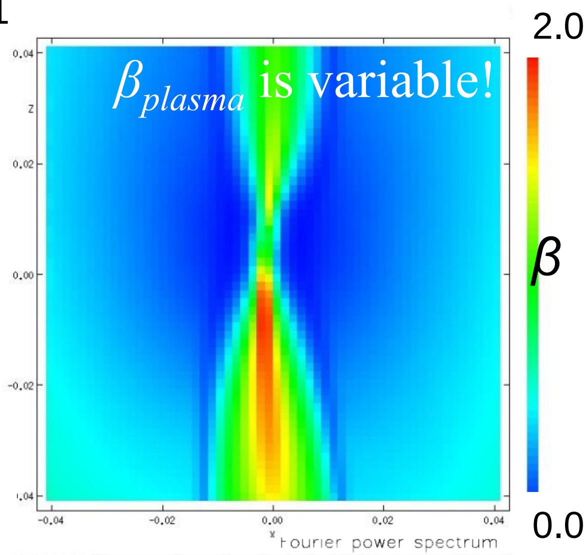
- Previous work (Tritsis and Tassis 2016) concluded sub-Alfvénic flows would not produce the observed density contrasts (0.03% contrast versus >25% observed)
- However, here we produce a range of density contrast up to factor 3 (400%) at a range of alignments
- A further criticism of sub-Alfvénic flows 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.

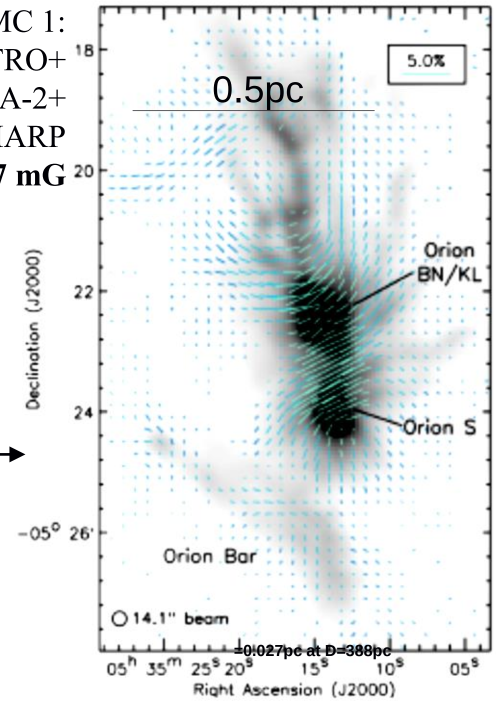
Striations, **hour-glasses** and integrals

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

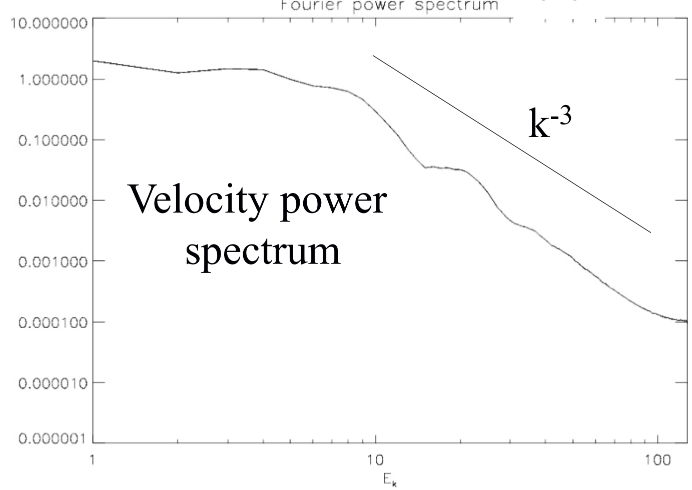
Gravitational collapse dragging the field.

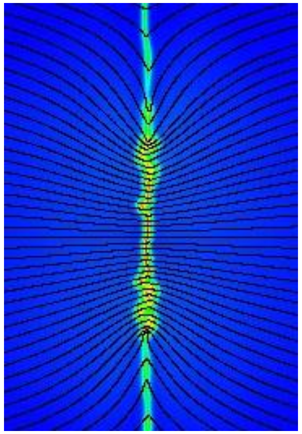
Field intensified in places from 0.3μG to ~0.1mG

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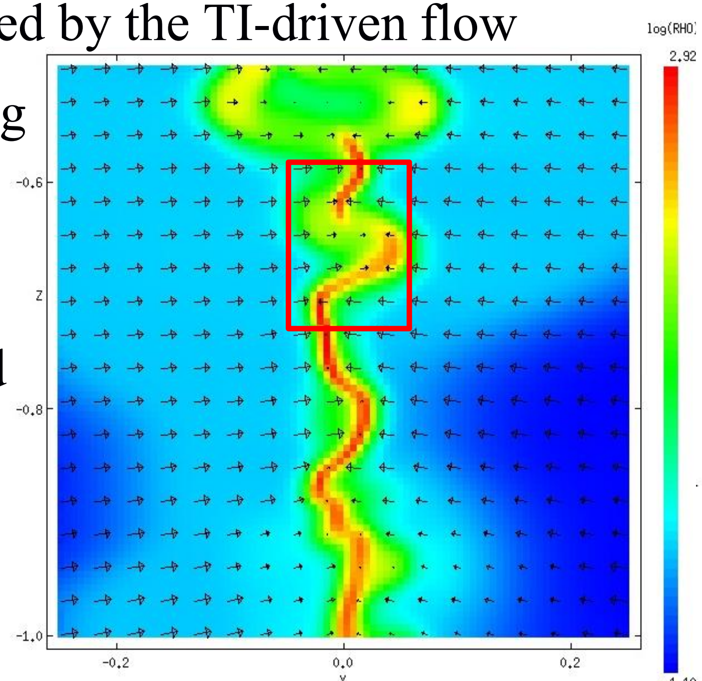
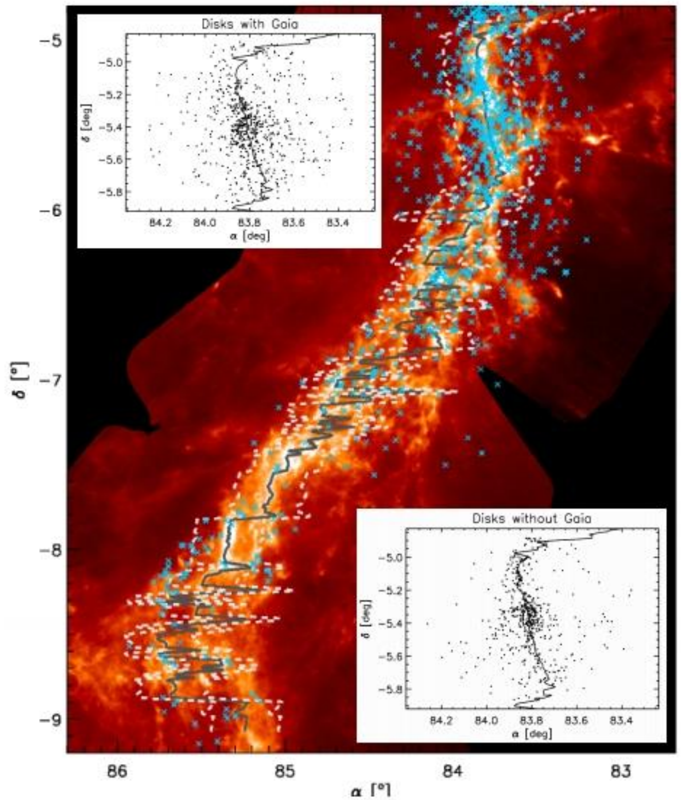
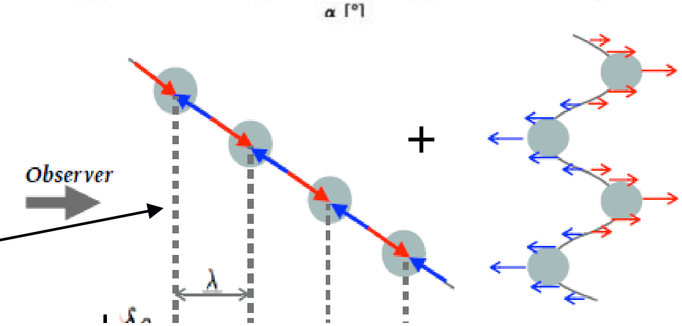
- Recent work **submitted** to MNRAS concludes that an "*integral*"-shaped filament in Orion is a standing wave
- **We obtain apparently similar structure**, with disconnects in the velocity caused by the TI-driven flow
- Not a standing wave – an effect of the initial condition and ISM flow
- Further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





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



See also: Liu, Stutz & Yuan, 2019, MNRAS, **487**, 1259

Conclusions

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Realistic minimal inputs - 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 feedback 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, 2020, MNRAS, **492**, 4484
MHD case: striations, hour-glasses & integrals	Wareing, Falle & Pittard, 2021, MNRAS, **500**, 2831
Shock-cloud interaction:	Kupilas, Wareing, Pittard & Falle, 2021, MNRAS, **501**, 3137
SNR-cloud interaction:	Kupilas, Pittard, Wareing & Falle, 2022, MNRAS, **513**, 3345

Outputs: Giant Molecular Clouds (GMCs)

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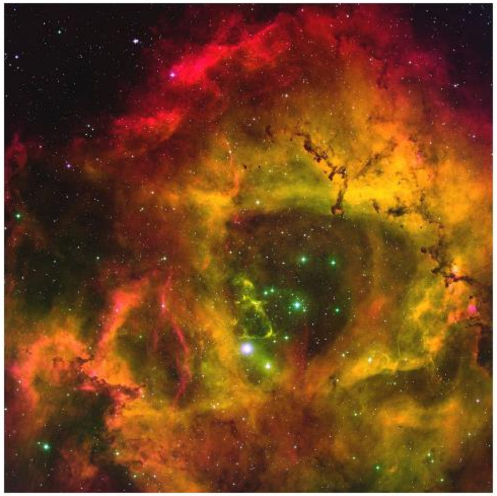
Most stars are formed in GMCs, e.g. Rosette MC

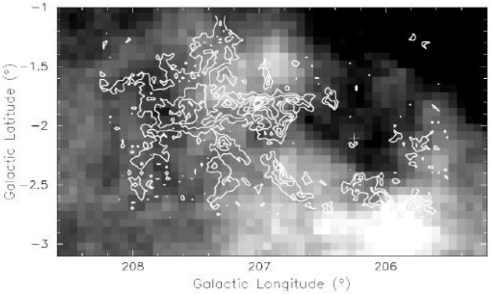
Size	~ 35 pc	
Mass	~ 10^5 $M_\odot$	
Mean density	~ 10^{-22} g cm^{-3}	
Temperature	~ 10 K	-> sound speed ~ 0.2 km s^{-1}
Alfvén speed	~ 2 km s^{-1}	magnetic pressure dominates
Velocity dispersion	~ 10 km s^{-1}	supersonic and super-Alfvénic
Jeans Mass	~ 10^7 $M_\odot$	based on velocity dispersion



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

Size	~ 3.5 – 8 pc
Mass	~ 10^2 – 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, 1º ≡ 28pc



Blitz and Stark 1986

<= Supersonic, but now sub-Alfvénic

Theoretical models

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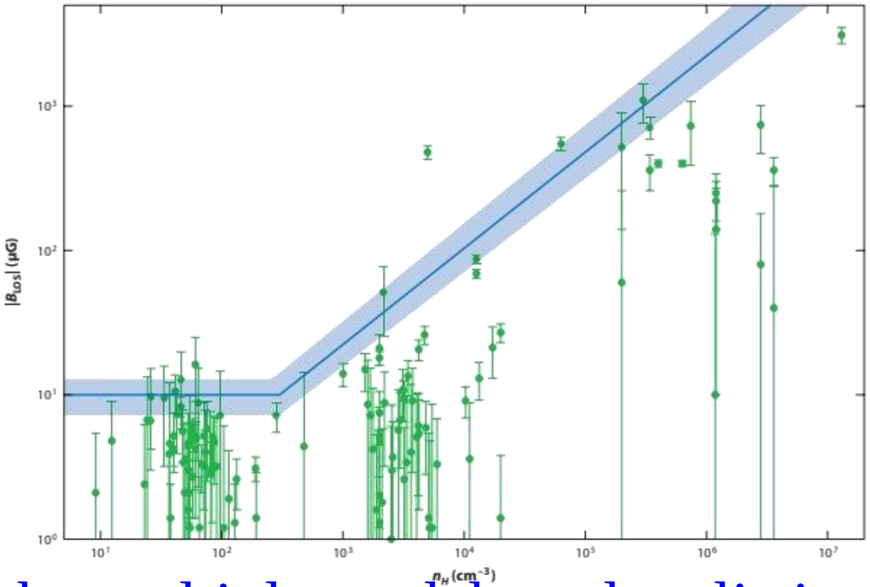
- A senior theoretician in this field recently emphasized that any model should have (1) realistic inputs *and* (2) realistic outputs.
- Anything that fails either (1) or (2) should be ignored by all.

- **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?

The Crutcher relationship: comparing models

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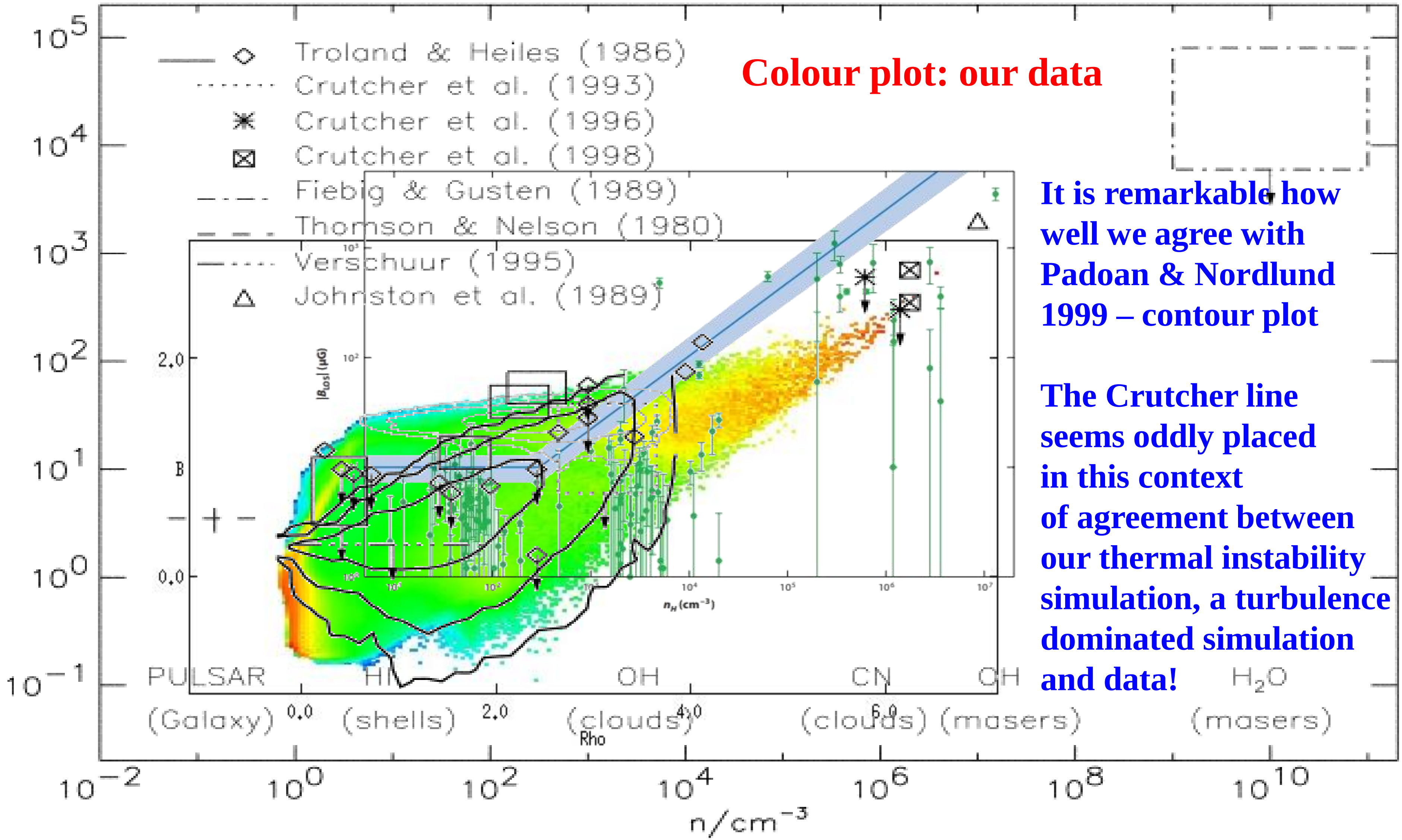

Colour plot: our data

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!

Reproducing the Crutcher relationship: |B| vs. ρ

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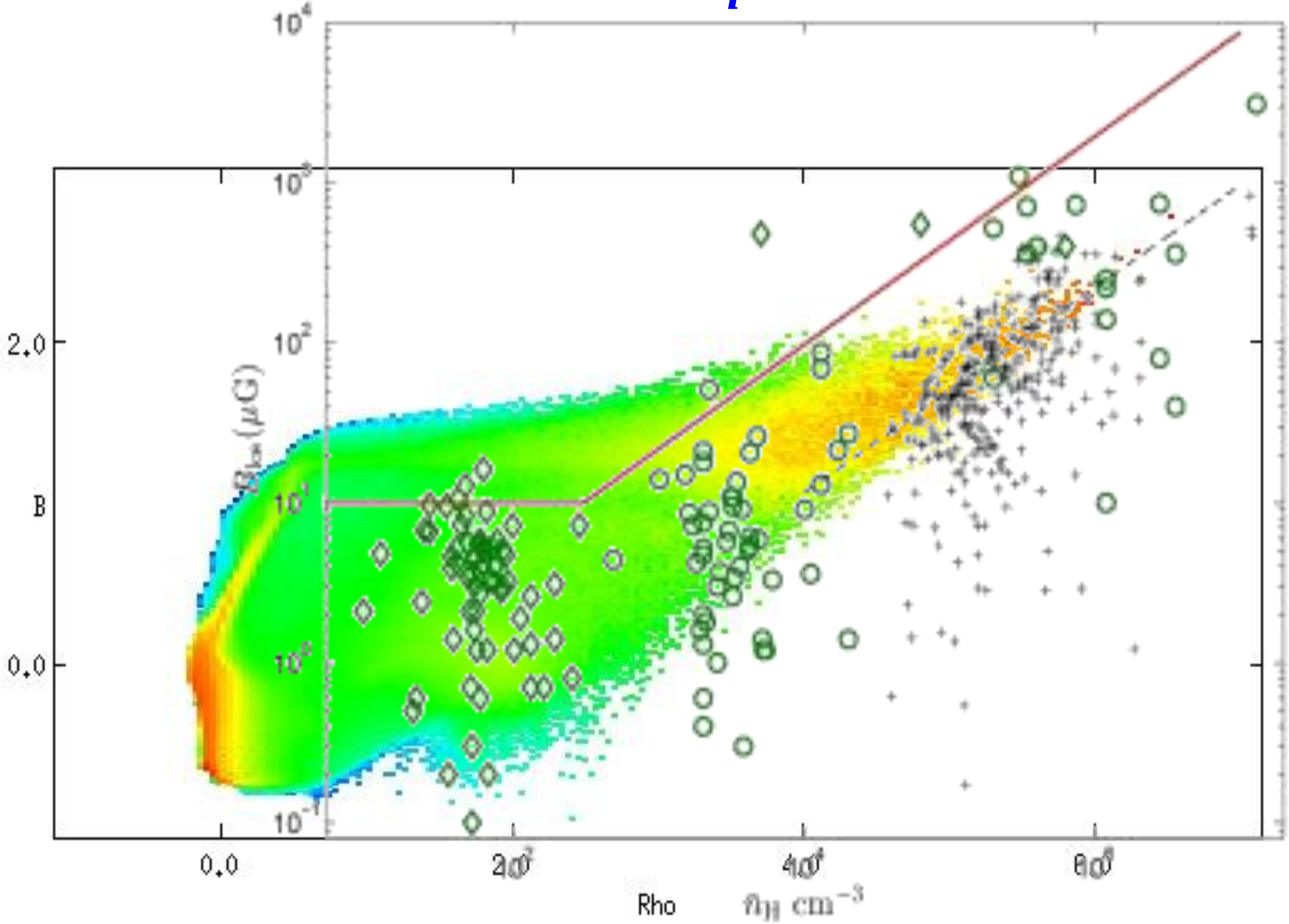
Agreement at high density between others' *driven* turbulence simulation and our *quiescent* thermal instability simulation.



Colour plot: our data

Green circles: Crutcher datapoints.

Red line: Crutcher Relationship

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

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

Outputs: a turbulent appearance!

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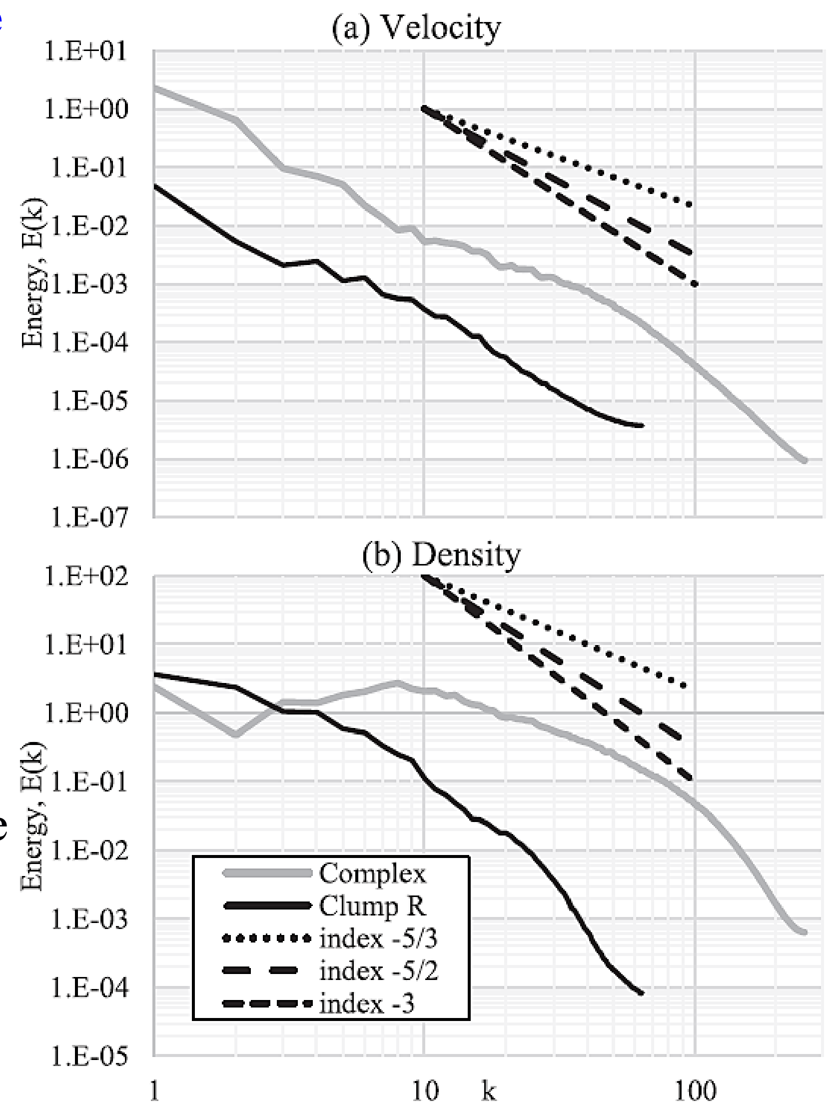
- **Turbulence-like (-5/3) power spectra in the warm stable medium**
- Short inertial range (1 decade) -> by no means fully developed turbulence.
- Should extend to larger scales
- Akin to Larson-like turbulence:- "hierarchy of small-scale irregularities superimposed on larger-scale more systematic motions"
- 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, 2019, A&A, 627, A112

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



Power spectra calculated by validated IDL script

Mechanical stellar wind feedback

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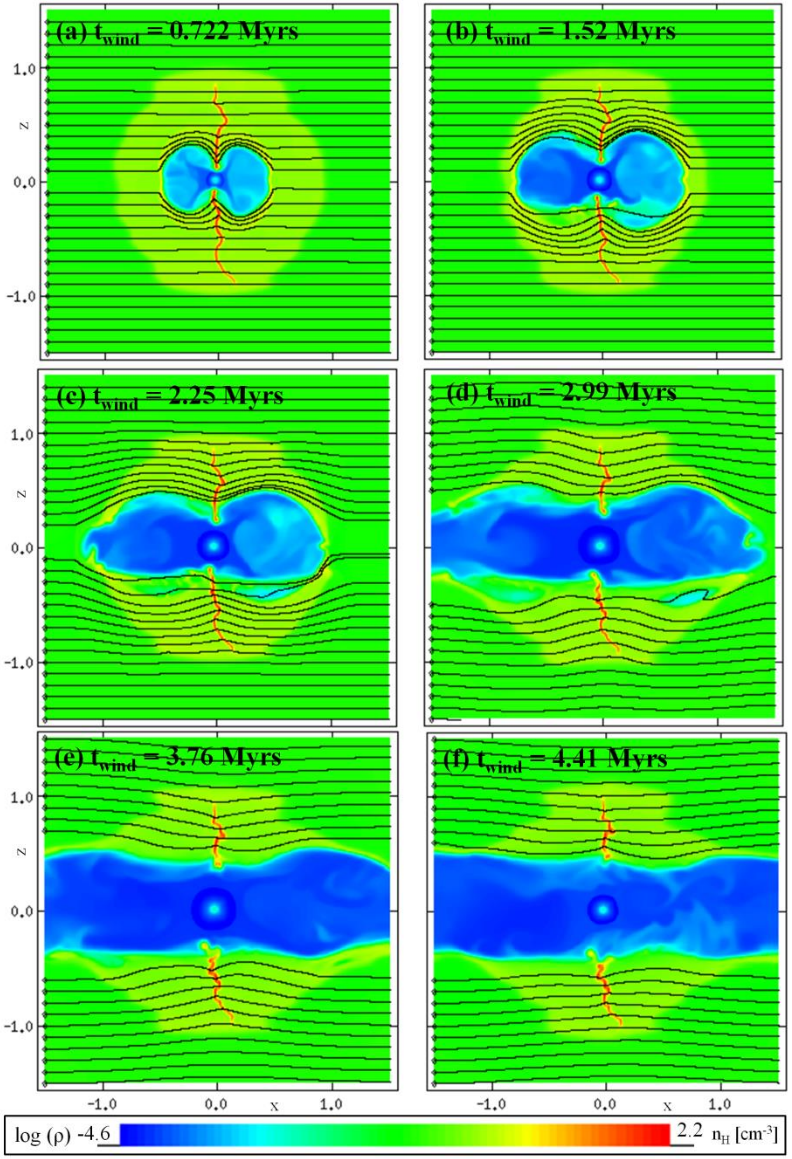
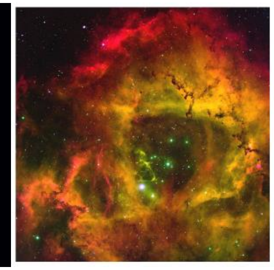
- 40 $M_\odot$ star embedded in the sheet
- Realistic Geneva (2012) evolution imposed via density and energy sources
- **Significant impact on a 1.7×10^4 $M_\odot$ cloud**
- **Large bipolar cavity evolves into a cylindrical cavity** (diameter~40pc) through the centre of the cloud
- Cavity filled with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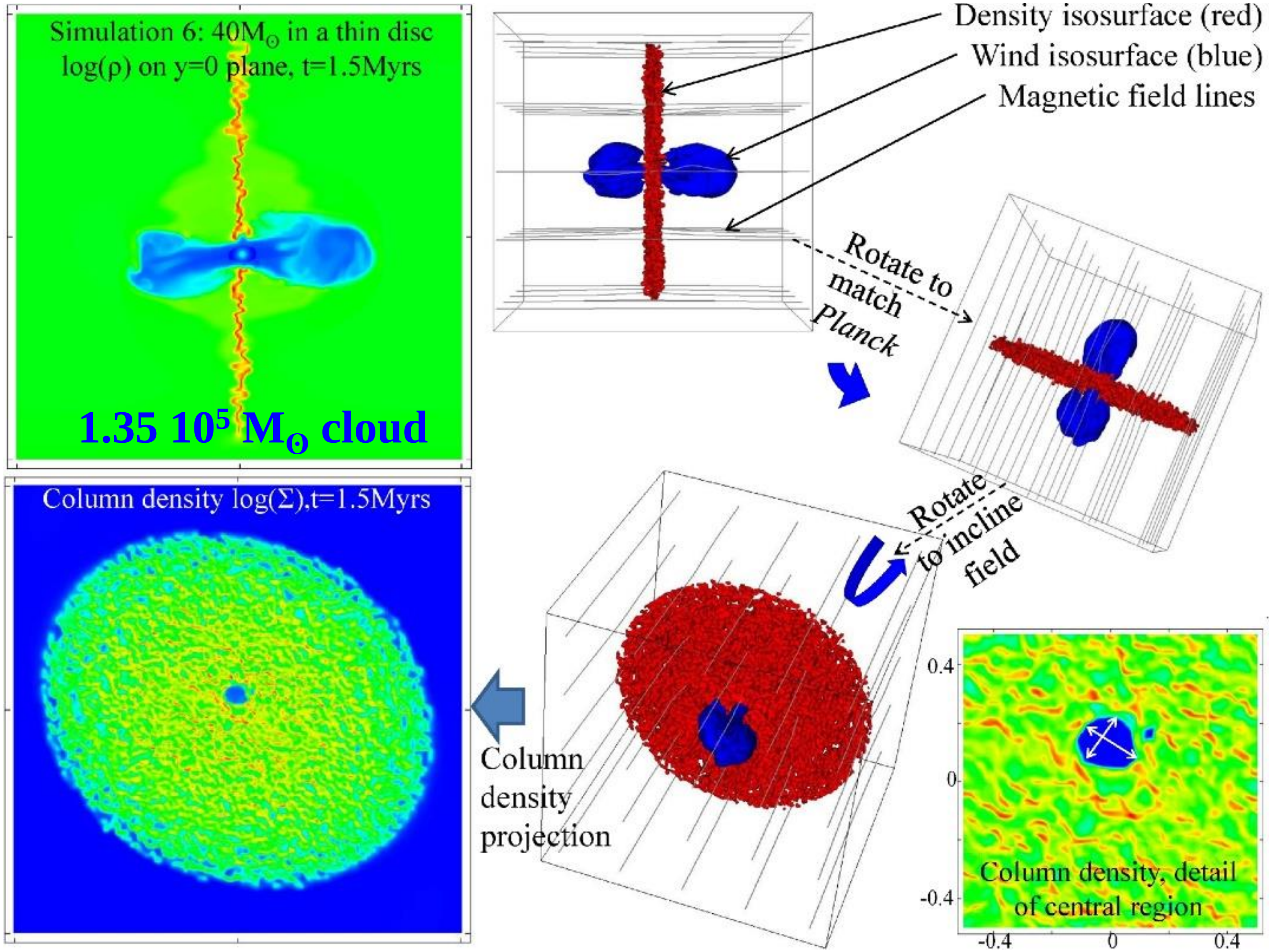
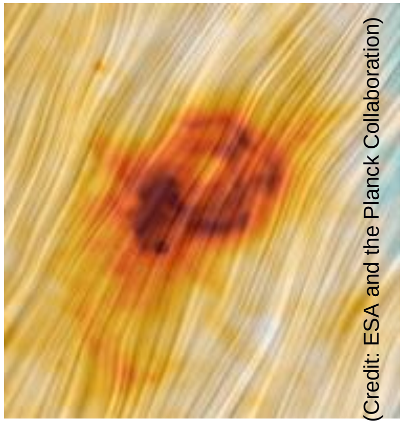
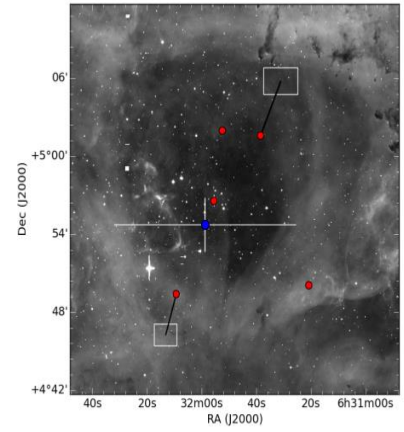
Magnetic field alignment, proper motion and location of possible triggered star formation all support this model.





Evacuated hole

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



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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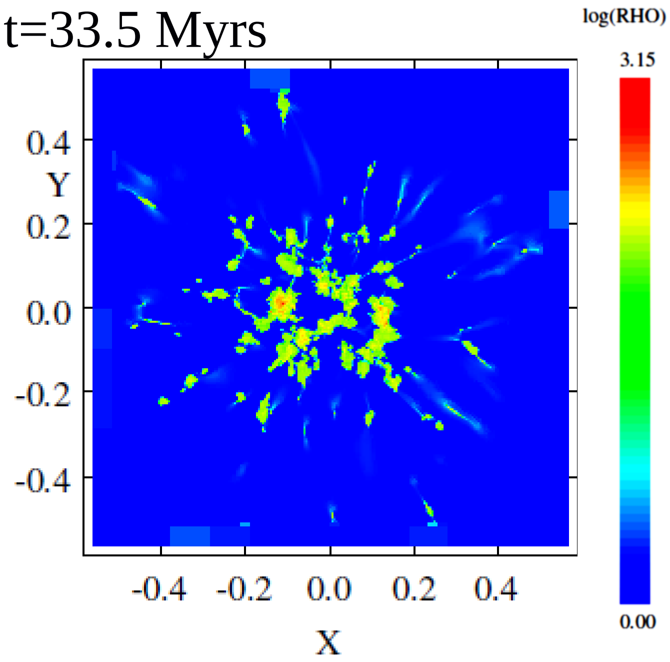
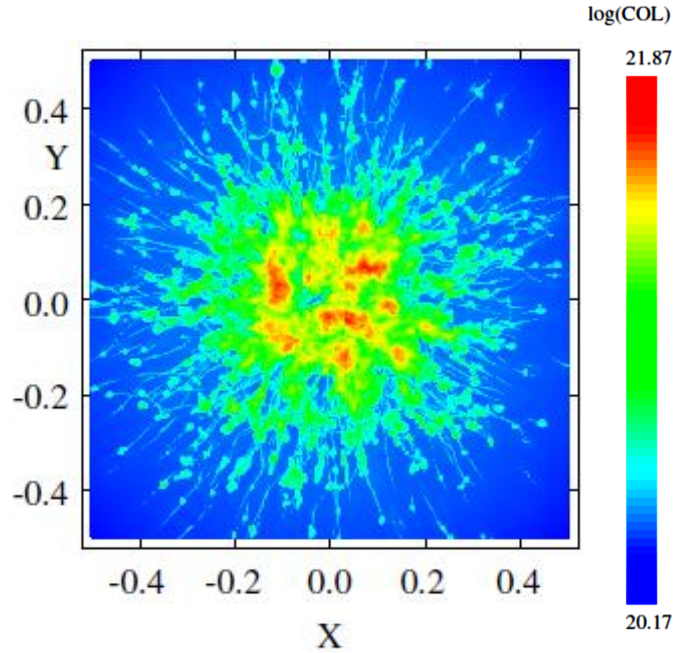
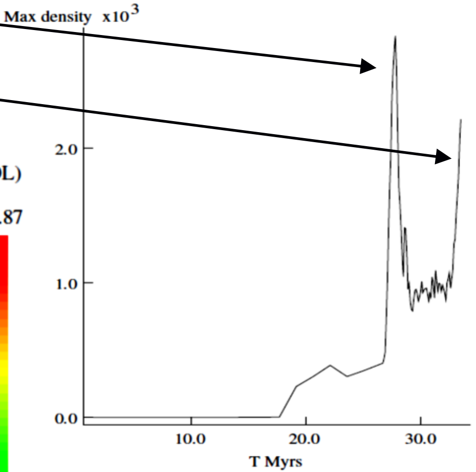
First peak due to TI-driven collapse, not gravity

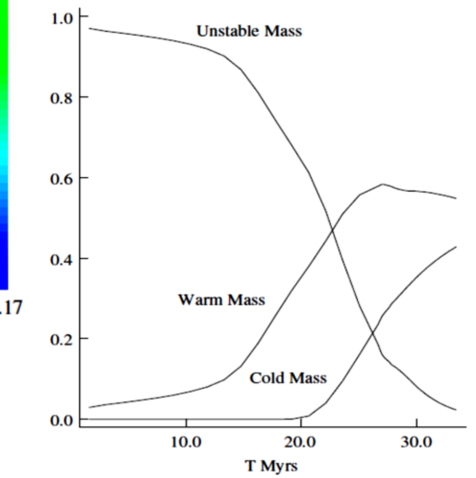
Second peak is due to gravity

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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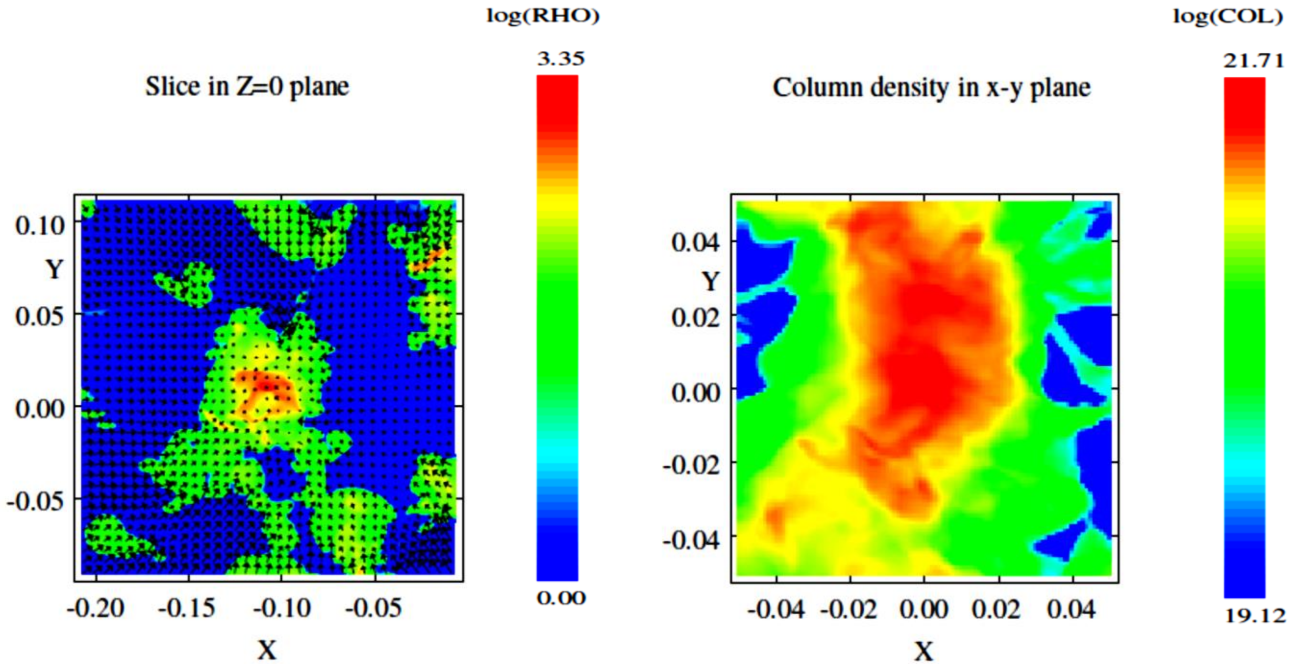

Diameter ~5pc, Mass 182$M_{\odot}$, Max density 2214, Mean density 177,
Max velocity 3.25 km s^{-1} (in frame of dense region), 0.6 km s^{-1} in dense gas.

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

Final evolved enlarged simulation

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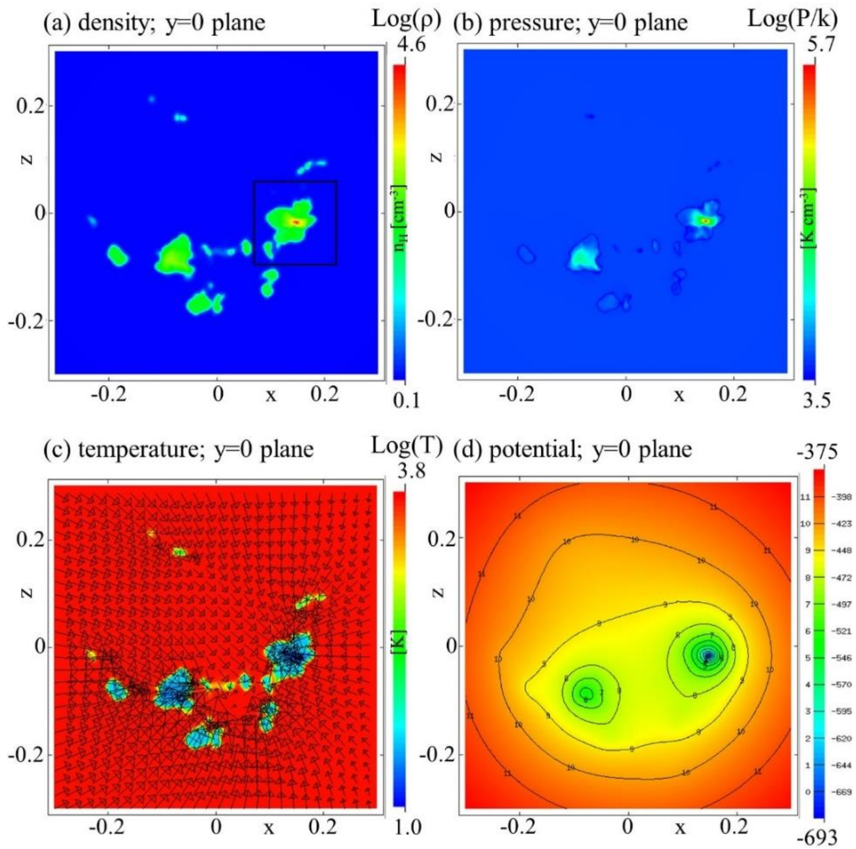
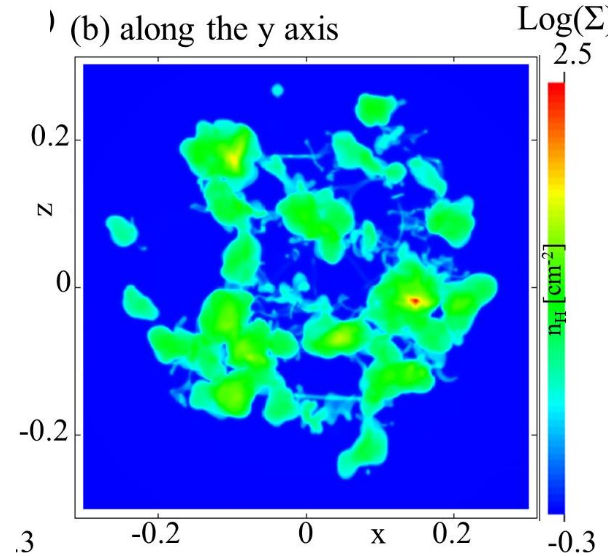
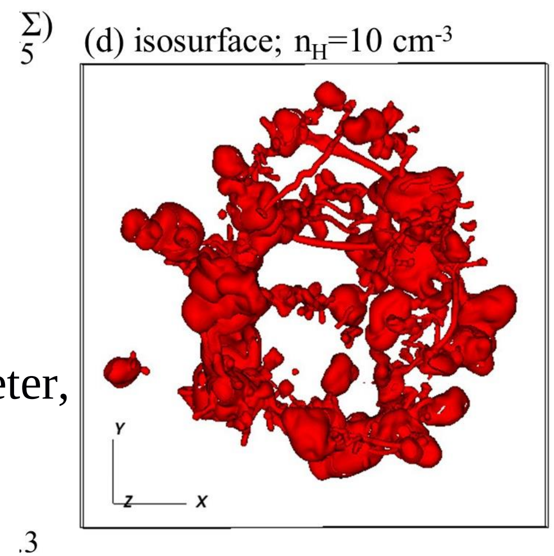
Cloud has contracted under gravity to a radius of ~10 pc







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