School of Physics and Astronomy
FACULTY OF MATHEMATICS AND PHYSICAL SCIENCES

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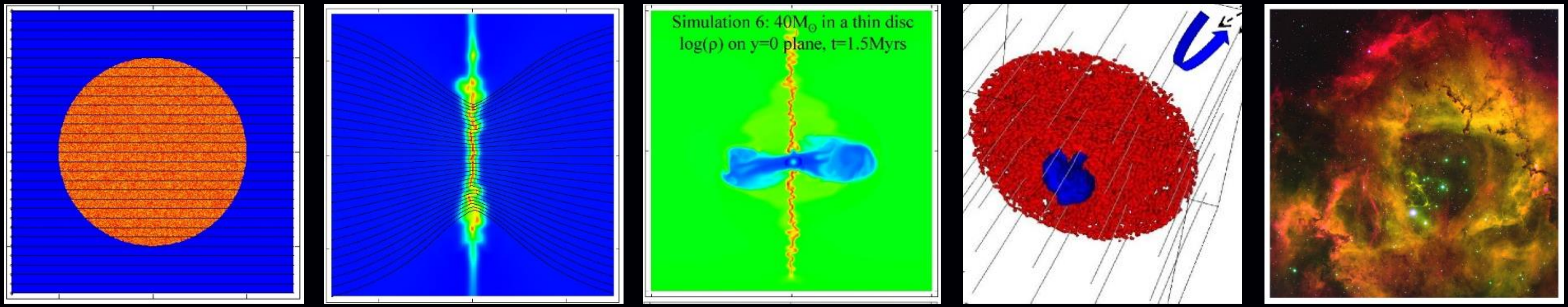
Magnetic fields and star formation:
The interplay of magnetic fields, gravity and thermal instability during the processes of molecular cloud formation and the effect of stellar feedback.



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

Internal seminar

26th March 2021

Star formation: from start to finish?

- Towards a comprehensive understanding of the formation of massive stars and their consequent influence requires multiple elements:-
    - To connect a wide range of environments from ISM to stars;
    - To connect a wide range of physical size scales from kpc to AU;
    - To connect complex, varied, scale and condition-dependent physical processes.
- Observations in principle now allow us to trace the flow of material across all these scales, probing structure, kinematics, chemistry, magnetic fields…
- Numerical simulations do not yet span this range in one go, instead we focus on a subset of the whole range that can be well-resolved.
- This project has focussed on the formation of - and feedback into - molecular clouds on the scale of 100s of pc, resolved down to 10^{-2} pc.
    - Borne out of the Rogers and Pittard (2013,2014) feedback work, in a quest for a realistic initial condition.

Open questions

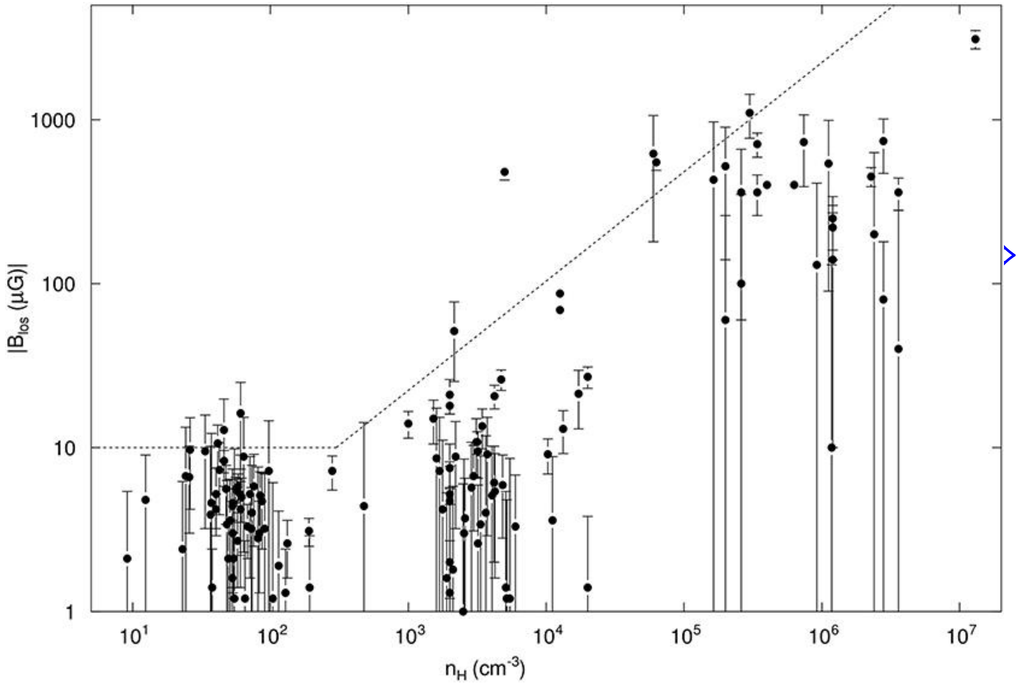
- What roles do magnetic fields play in this whole process?
  - Are they the key agents of evolution?
  - Or can they just be ignored, only a minor perturbation on an otherwise turbulent picture?

- We know that the ISM and star-forming gas clouds are strongly magnetized and their ionization fractions are high enough to place them close to the regime of ideal MHD on all but the smallest size scales.

Lenz’s Law => the fluid is in a sense tied
to the magnetic field lines

Insight from observations…

- We can use the Zeeman effect to measure line-of-sight strength of magnetic fields in molecular clouds and the general ISM, to derive the mass to magnetic flux ratio and whether a cloud is **magnetically supercritical (prone to collapse)** or **sub-critical (supported by the magnetic field)**.
- Below a volume density of ~ **300 cm^{-3}**, B is essentially independent of n, above 300 cm^{-3}, the field strength increases with increasing density ($B \sim n^{0.65}$).



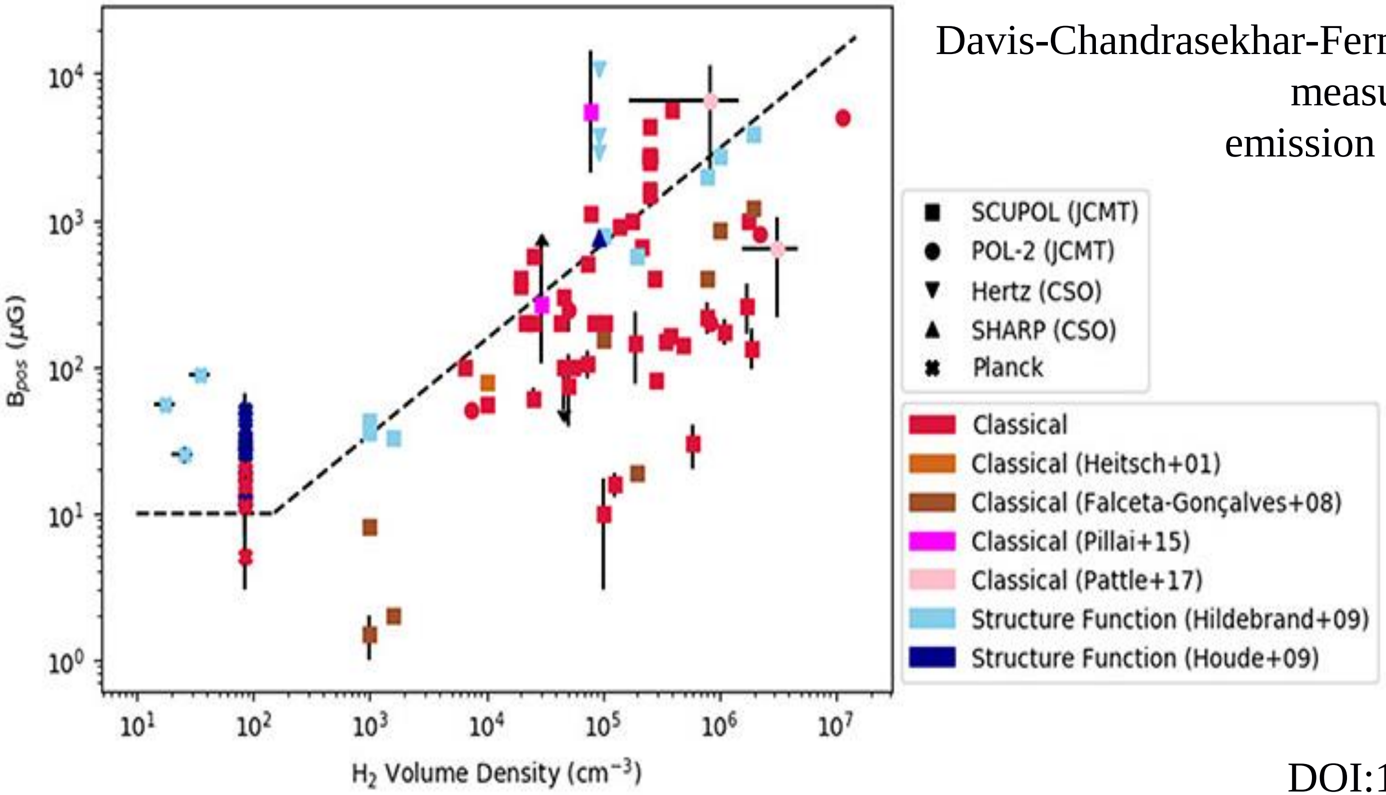
⇒ low-density gas is sub-critical, high-density gas is super-critical.

The dashed line is the upper limit

Crutcher & Kemball
Front. Astron. Space Sci.
17 Oct 2019
DOI:10.3389/fspas.2019.00066

Insight from observations…

- Interestingly, a **very similar result is seen from polarization methods** probing only plane-of-sky magnetic field:-

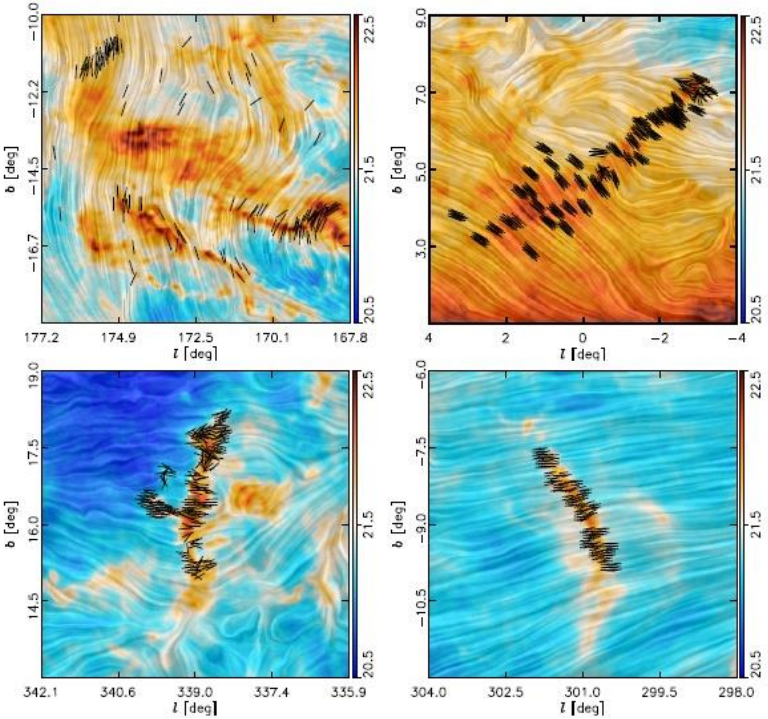


Davis-Chandrasekhar-Fermi magnetic field strength measurements from single-dish emission polarimetry, as a function of volume density

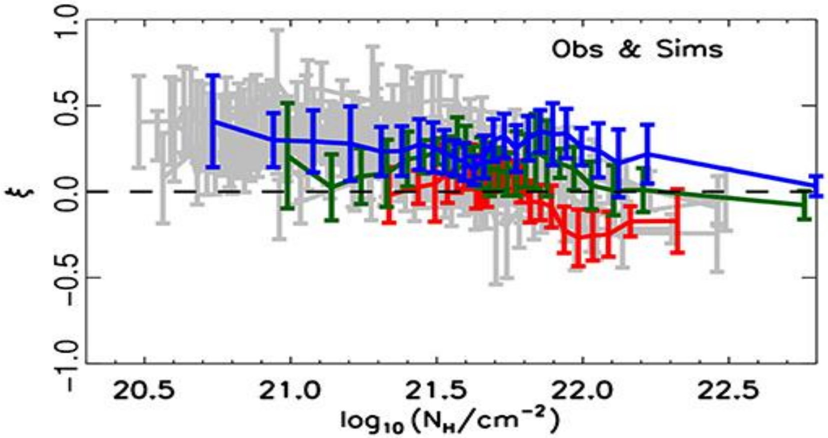
Pattle and Fissel
Front. Astron. Space Sci.
05 April 2019
DOI:10.3389/fspas.2019.00015

Observational alignments…

- There are observations in a variety of environments and growing evidence for **bimodality** in the alignment between fields and filaments.
- Preferentially **parallel at low n_H**, to no preferred orientation or **perpendicular at high n_H**.



Magnetic field morphology in four nearby clouds (Taurus, Pipe, Lupus I and Musca). Drapery: *Planck* sub-mm, vectors: starlight los polarisation.



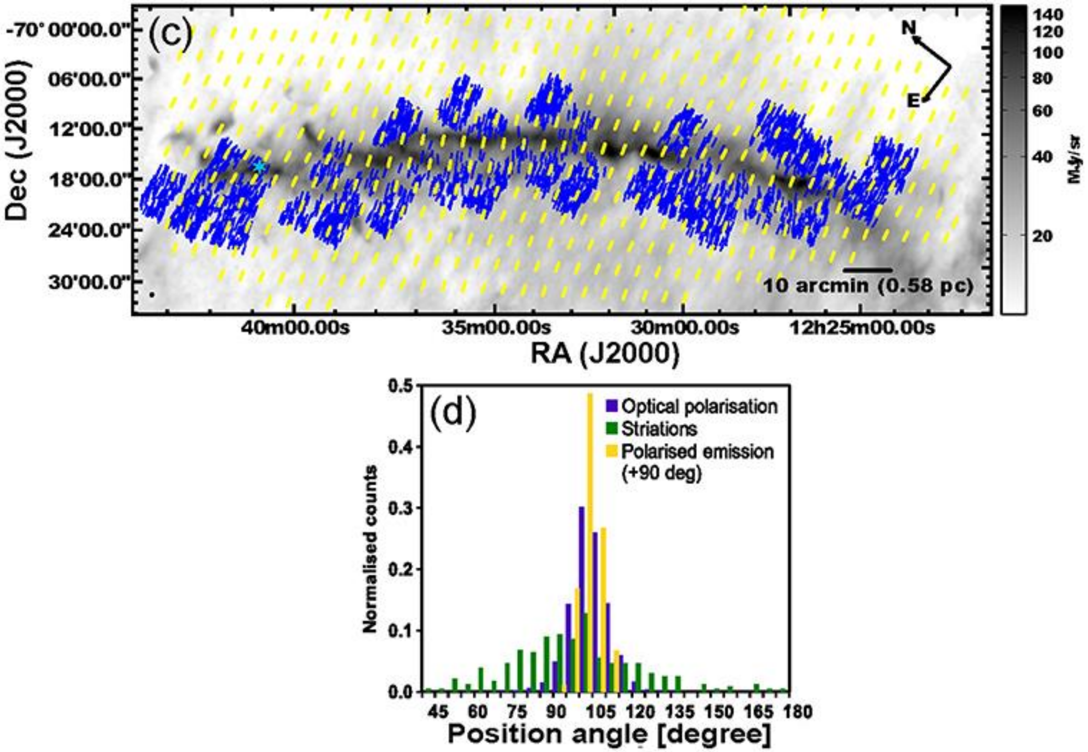
Relative orientation between cloud structure and the magnetic field orientation with increasing column density.

Grey: *Planck* polarisation maps
Synthetic MHD simulations in colour:
Red: B strong compared to turbulent gas motions
Green: equal in energy
Blue: B weak compared to turbulence

(Soler et al. 2013)

Observational alignments…

The magnetic environment of the Musca filament

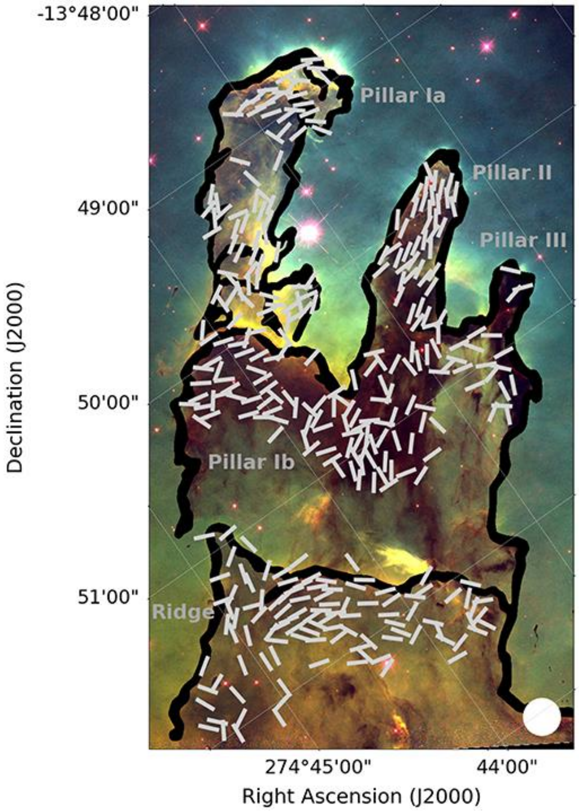


Upper: Herschel SPIRE emission, Planck vectors (yellow) starlight polarisation vectors (blue)

Lower: histograms of optical polarisation showing **magnetic field direction and striation direction to be strongly peaked perpendicular to the direction of the filament**

(Cox et al. 2016)

(Feedback changes everything…)



Magnetic fields in photo-ionised regions JCMT/POL-2 magnetic field vectors overlaid on HST imaging

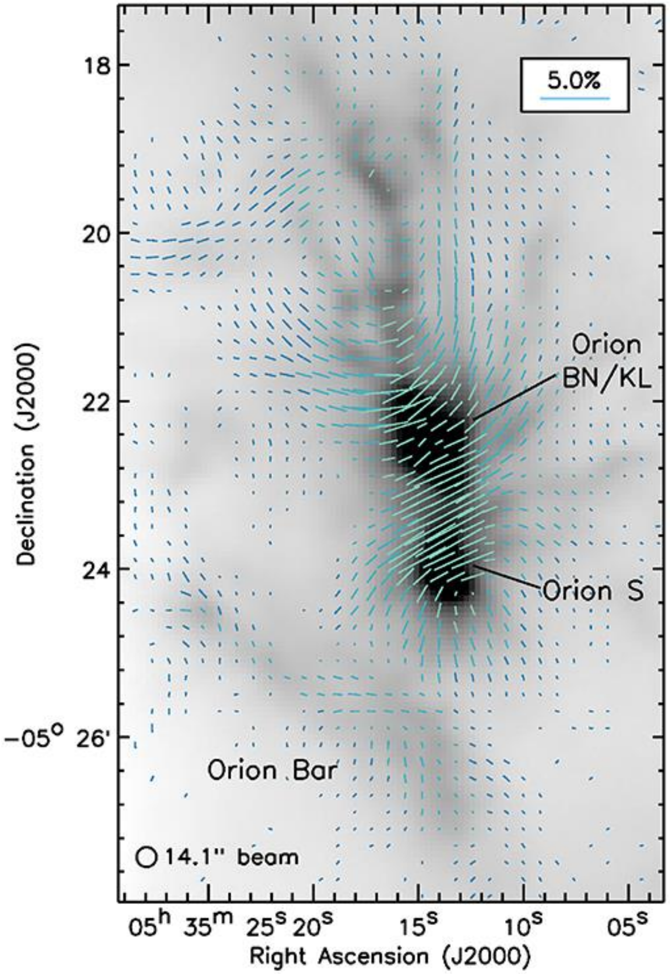
(Pattle et al. 2018)

Observational alignments…

- Magnetic field tends to be perpendicular to self-gravitating filaments, in the low density environment surrounding the filaments
  => **some models predict material is accreted onto such filaments along fieldlines.**

- Observationally, this is well-supported in nearby filaments e.g. Taurus, Musca.

- However, **3D field geometry is not yet well-characterised, significant uncertainties exist** and care needs to be taken to ensure polarisation observations trace the dense material, rather than the low-density envelope.



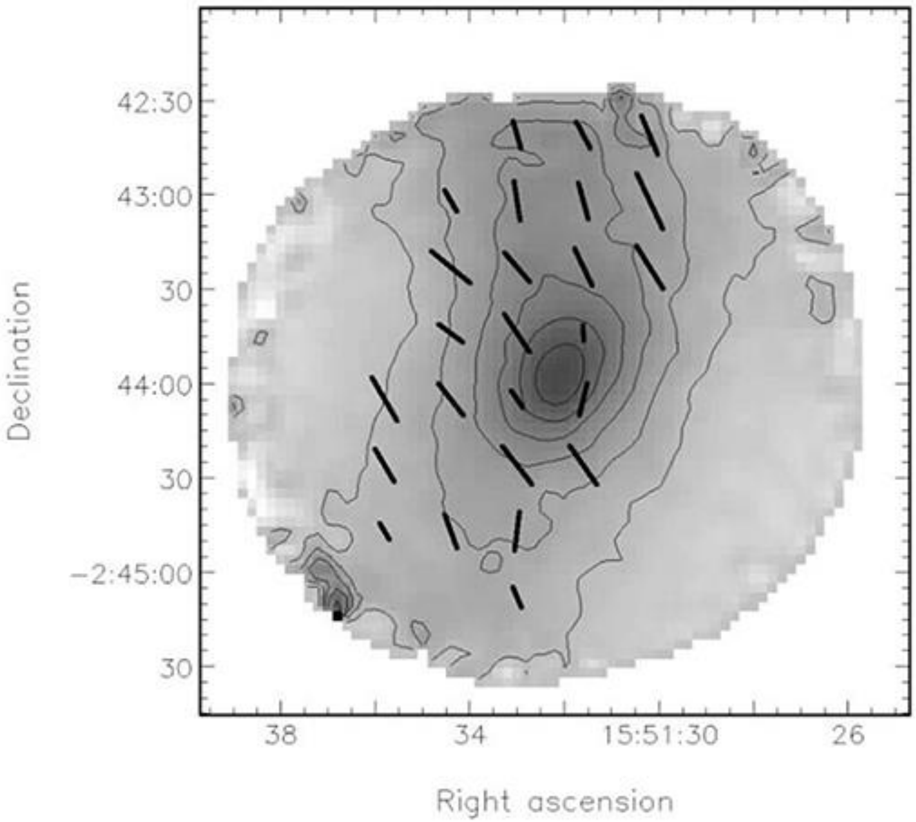
Magnetic field morphology in OMC1.
Hour-glass magnetic field morphology
Pattle et al. (2017)

Observational alignments…

- Magnetic fields detected in isolated starless cores tend to be relatively smooth and well-ordered.
- Field strengths on the order of 100s of µG.
- Note the lack of the hour-glass morphology.

=> Going beyond the ideal MHD limit

- **Interferometric observations of B field in star-forming regions fractions of mG to a few mG**
  Hull and Zhang, Front. Astron. Space Sci., 5 March 2019 DOI:10.3389/fspas.2019.00003

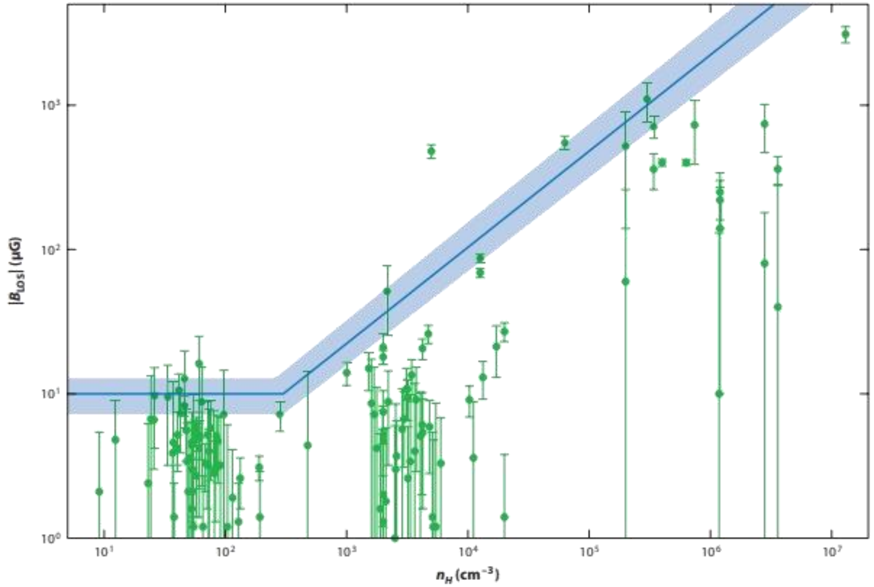


JCMT/SCUPOL magnetic field vectors overlaid on 850µm emission, in the starless core L183 (Crutcher et al 2004)

Theoretical models

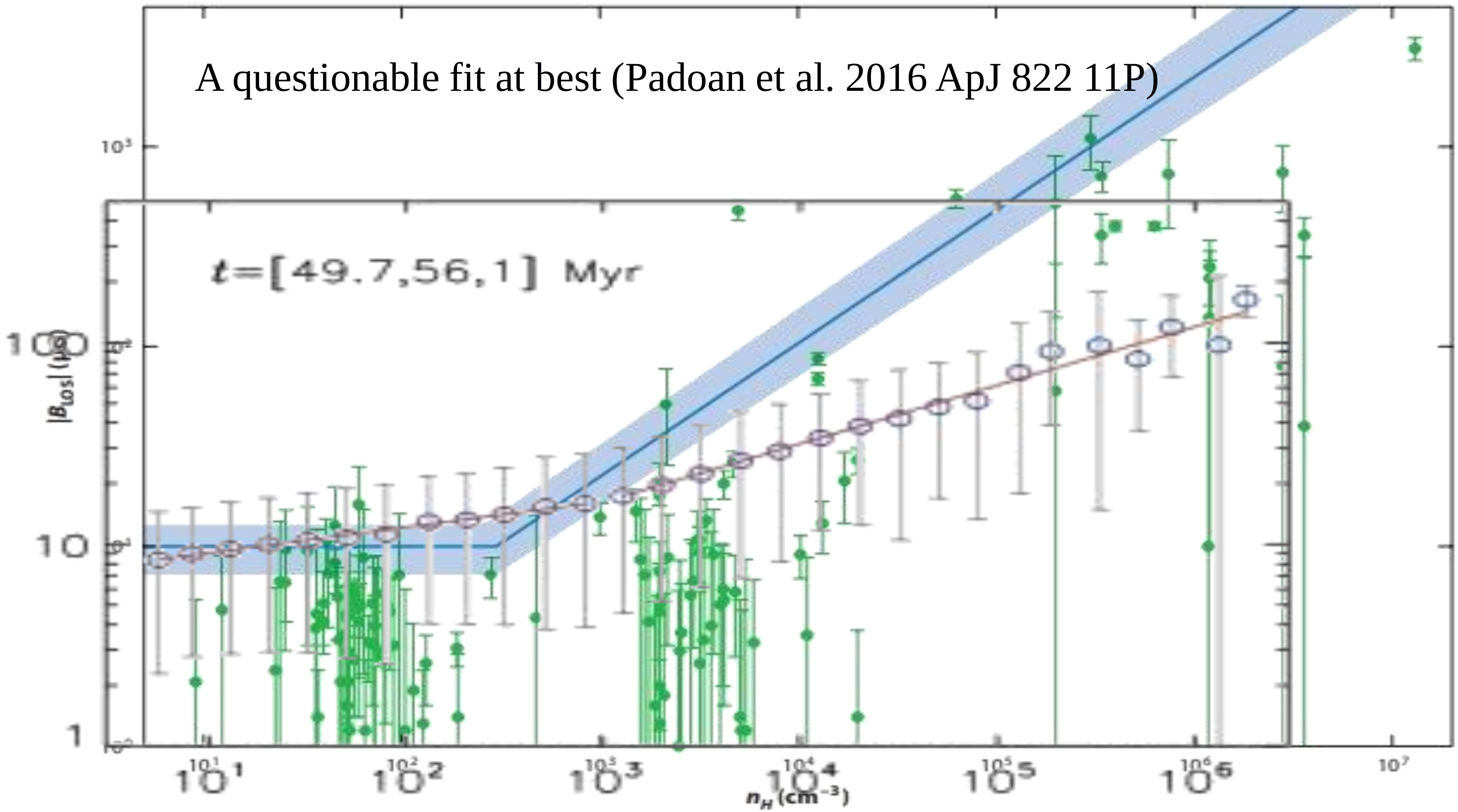
- A senior theoretician in this field recently emphasized that any model should have **(1) realistic inputs** *and* **(2) realistic outputs**.
- Anything that fails either (1) or (2) should be ignored by all.

- **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?

An example…



A questionable fit at best (Padoan et al. 2016 ApJ 822 11P)

…co-authors including said senior theoretician…

Numerical simulations

- Turbulent numerical results suggest that magnetic fields by themselves are minor players in setting either the SFR or IMF
  - They provide resistance to turbulent compression and pressure that opposes gravity, directly reducing the ability of turbulence to gather gas into gravitationally-unstable clumps.
  - Reasonably well understood in supersonic, **super-Alfvénic** flows
  - ***BUT that breaks down in the trans-Alfvénic regime that is more likely to characterise star formation!***

Krumholz & Fedderath Front. Astron. Space Sci. 20 Feb 2019 DOI:10.3389/fspas.2019.0007

- Others comment that it is likely magnetic field strongly shapes the interstellar gas by generating a lot of filaments and reducing the number of clumps

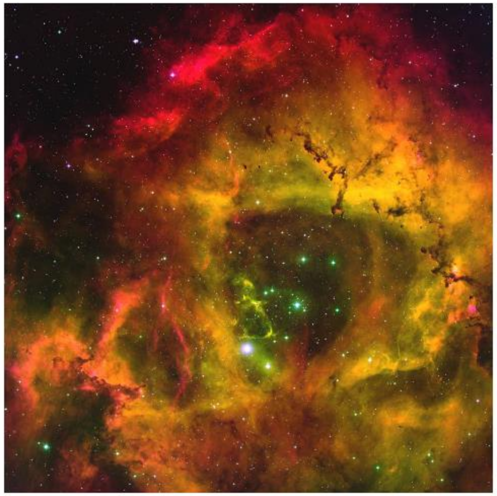
Hennebelle & Inutsuka, Front. Astron. Space Sci. 28 March 2019 DOI:10.3389/fspas.2019.0005

RECALL: Crutcher relationship => low density gas is subcritical!

Outputs: Giant Molecular Clouds (GMCs)

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

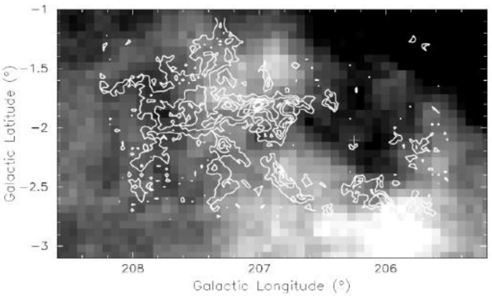
Size	~ 35 pc	
Mass	~ 10^5 $M_\odot$	
Mean density	~ 10^{-22} g cm^{-3}	
Temperature	~ 10 K	-> sound speed ~ 0.2 km s^{-1}
Alfvén speed	~ 2 km s^{-1}	magnetic pressure dominates
Velocity dispersion	~ 5-10 km s^{-1}	supersonic and super-Alfvénic?
Jeans Mass	~ 10^7 $M_\odot$	based on velocity dispersion



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



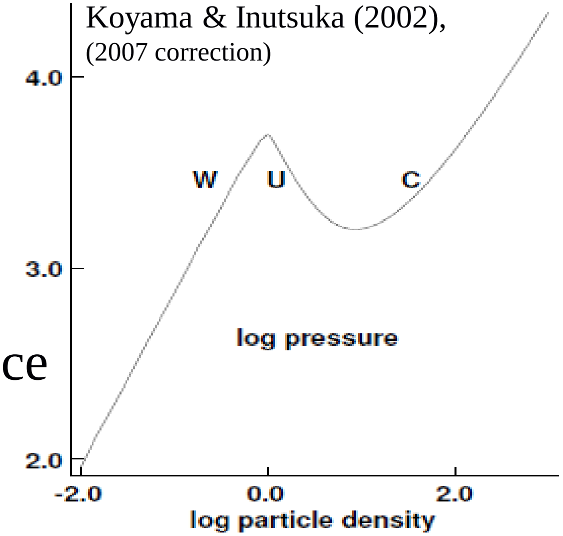
Blitz and Stark 1986

<= Supersonic, but sub-Alfvénic

Where did we come in?

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:-


Koyama & Inutsuka (2002), (2007 correction)

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

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 **(Marcin Kupilas’s project)**
- “Turbulent” initial conditions applying randomised velocities up to Mach ~5

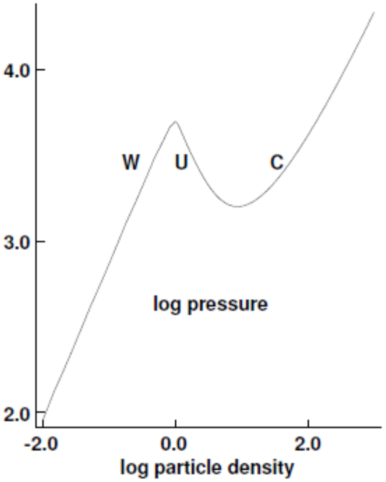
but if one can produce results without recourse to extra inputs...

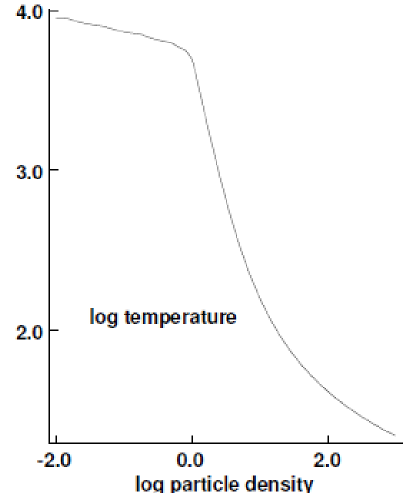
lex parsimoniae / Occam’s razor

Revisiting thermal instability

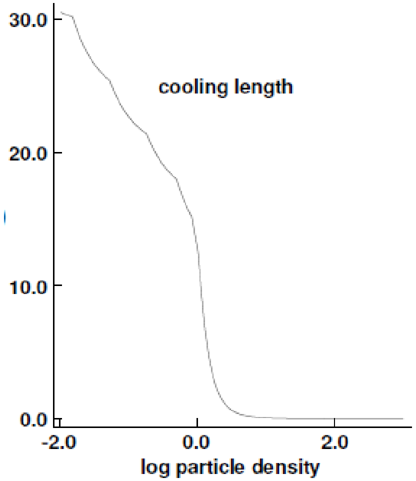
Two stable phases exist in which heating balances cooling (Parker ‘53, Field ‘65, Wolfire et al. ‘95)

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

$<10^4$K	Γ : Koyama & Inutsuka (2002), (2007 correction)
$10^4\text{K}<T<10^8\text{K}$	Γ : CLOUDY 10.00 Gnat & Ferland (2012)
$>10^8$K	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 $\rho^2\Lambda = \rho\Gamma$

Simulating thermal instability

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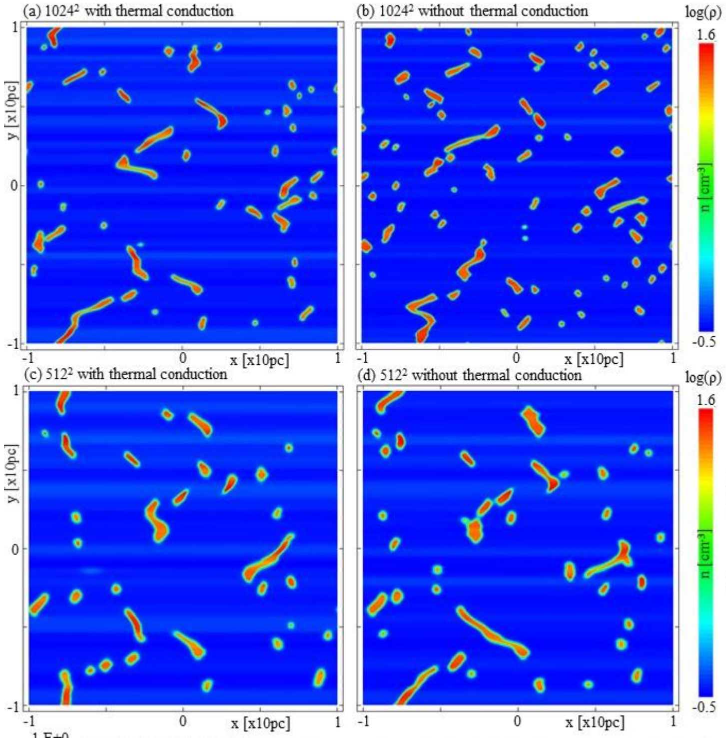
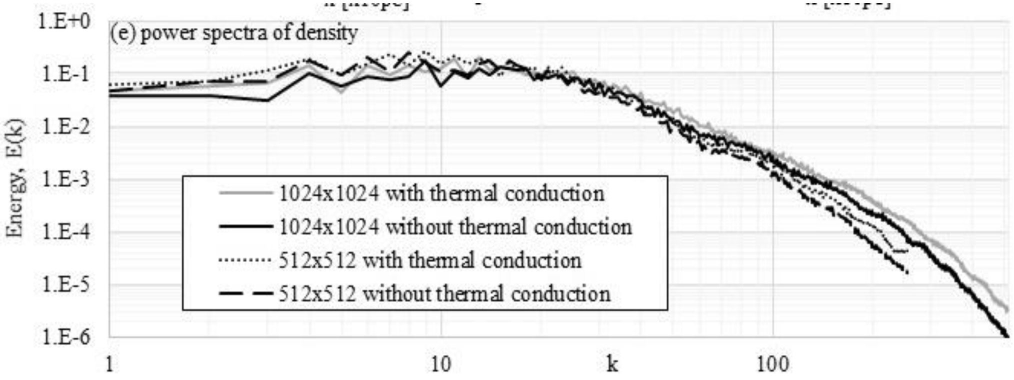
- Koyama & Inutsuka (2004) argued that simulations of thermal instability do not converge, unless one includes thermal conductivity and resolves the Field length.
- Formally, this is true for linear perturbations, but at our initial density of n_H=1.1cm^{-3}, the growth rate has a broad maximum at λ=8.95pc, so there is no particular wavelength that is favoured in the linear regime (Falle et al. 2020).

Wareing et al. 2021

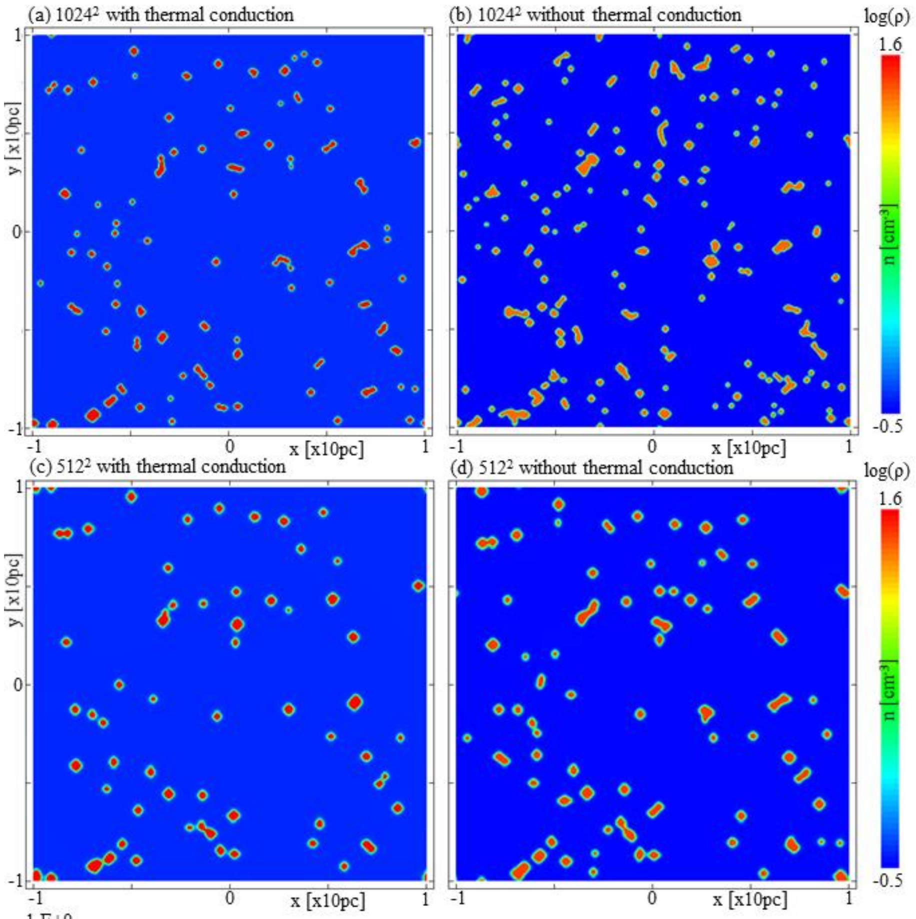


- The results of an MHD resolution test, with and without thermal conduction all give very similar results.
- Thermal conduction reduces the number of small clouds, as expected.



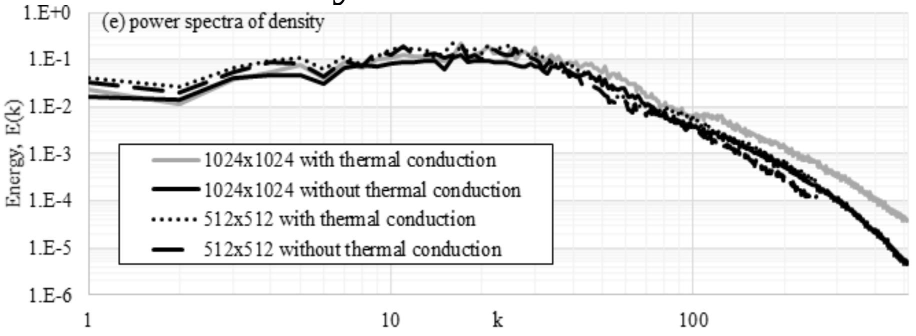
Simulating thermal instability

- Without magnetic field, we again obtain much the same results.
- Other authors (Gazol & Vazquez-Semadini 2002, Piontek & Ostriker 2004, Inoue & Omukai 2015) have also found the same.



Kupilas et al. 2021

- **Properties of the thermally unstable medium converge on large scales**, because most of the mass of the cold gas created is contained in large clumps that are formed by the growth of large-scale fluctuations.
- The final distribution of large clouds is insensitive to the value of thermal conductivity.



Inputs: 3d initial condition

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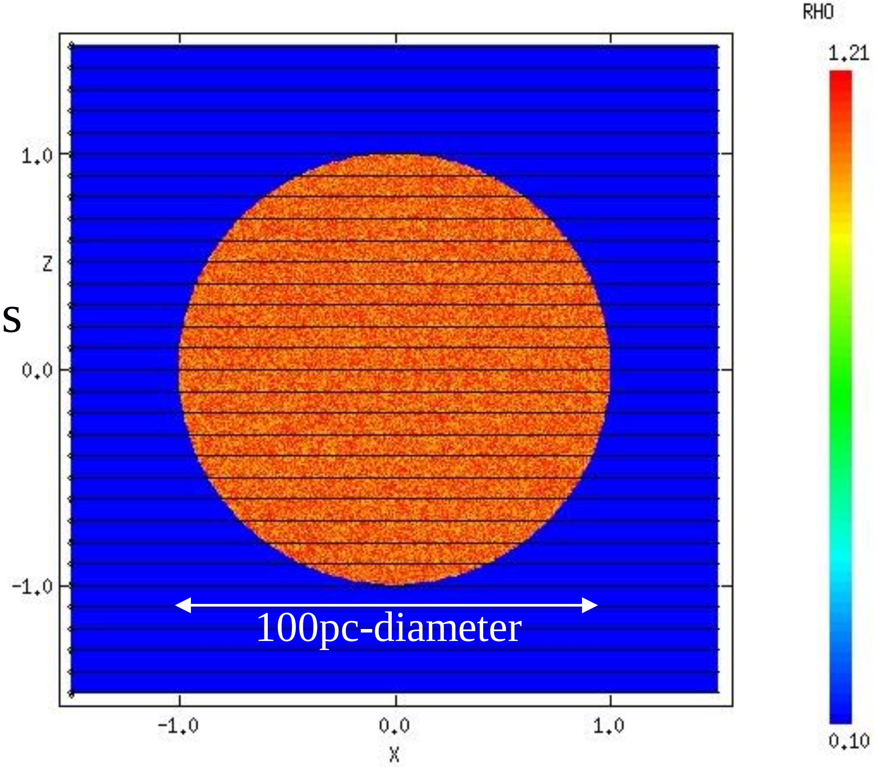
Spherical cloud, radius (1)50, (2)100pc, density n_H=1.1 - thermally unstable. External medium density n_H=0.1, over-pressure same as cloud. Self-gravity.

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

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

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



Threaded by magnetic field along the x-axis,
$\mathbf{B} = B_0\hat{\mathbf{i}}_x$; B_0 = 1.15 μG (β=1), 3.63 μG (β=0.1)

Mass: 1.7 10^4 $M_\odot$ / 1.35 10^5 $M_\odot$
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

The (modified) engine

- 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 $\underline{B} = B_o \underline{\hat{I}}_x$
    - The hydrodynamic case: $\beta = \infty$
    - Pressure equivalence: $\beta = 1$ - inferred to be the commonest in reality.
    - Magnetically dominated regime: $\beta = 0.1$

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

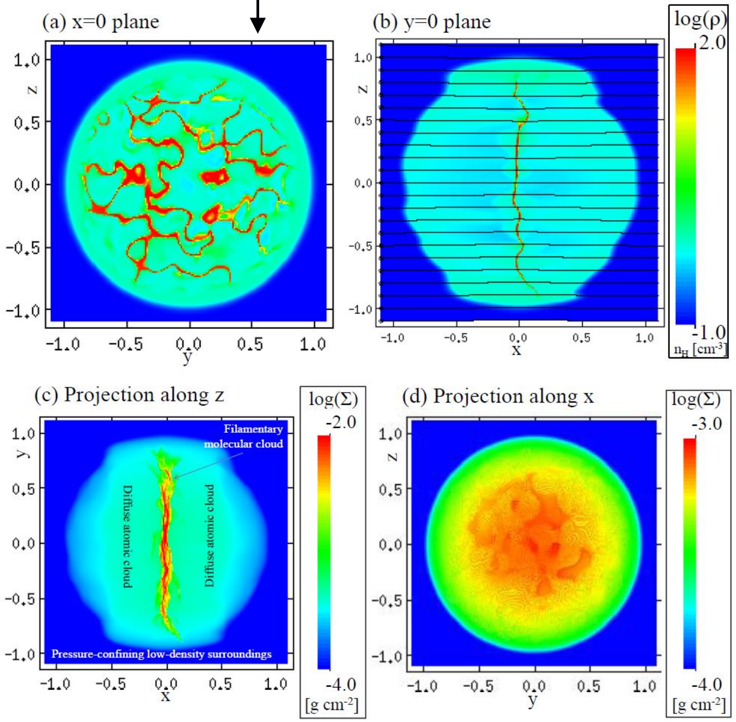
IDEAL MHD

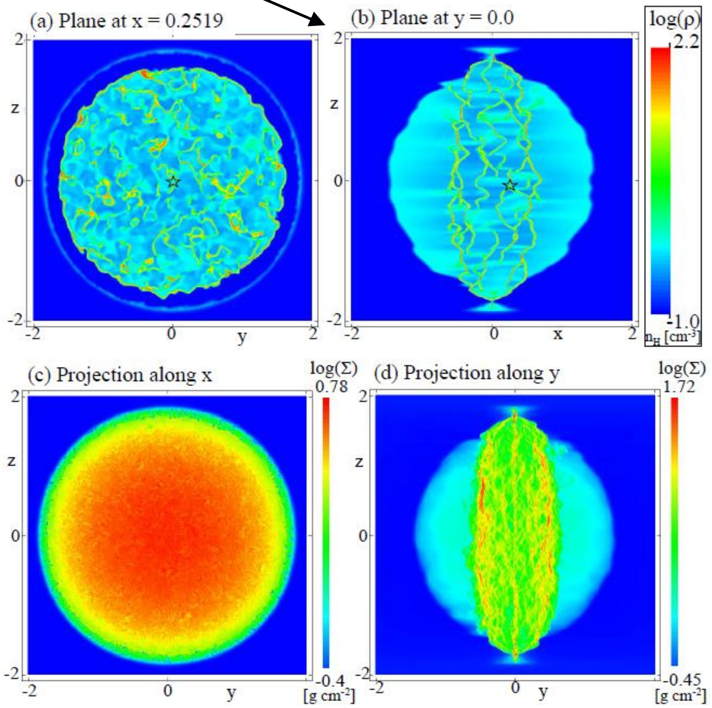
Aside: further EPSRC research proposals to apply MG in industry: CCS, cryogenic machining and latest on fire suppression.

MHD simulations

- 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

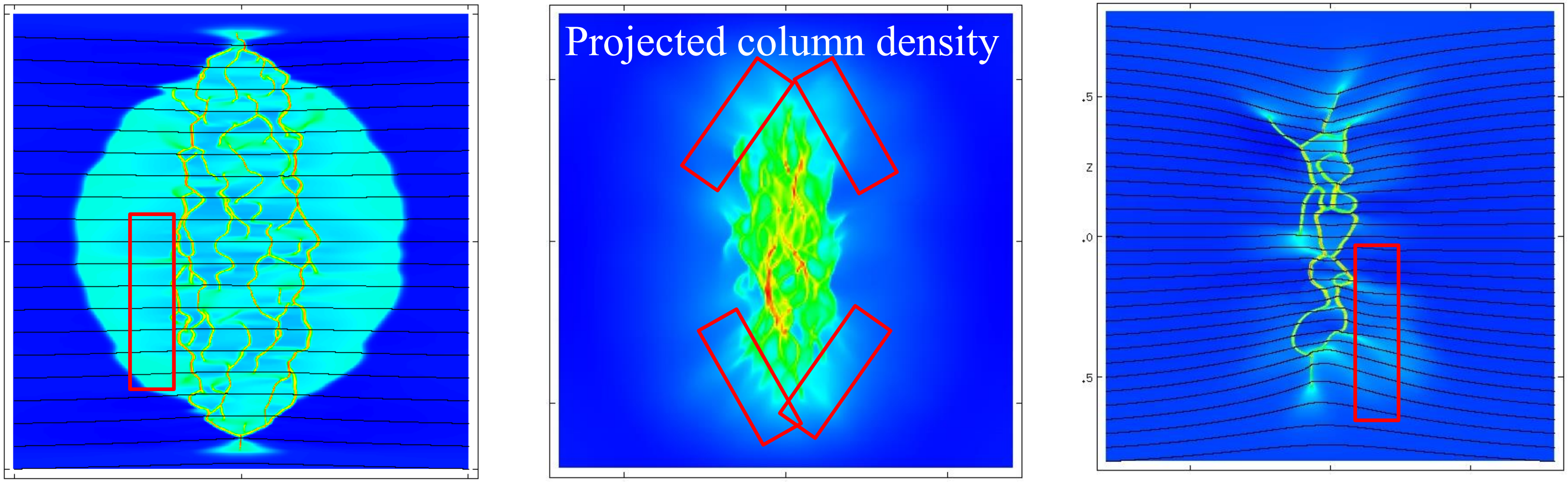
Magnetic seismology of Musca 'filament' indicates this structure!

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

Striations, hour-glasses and integrals

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849

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

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849

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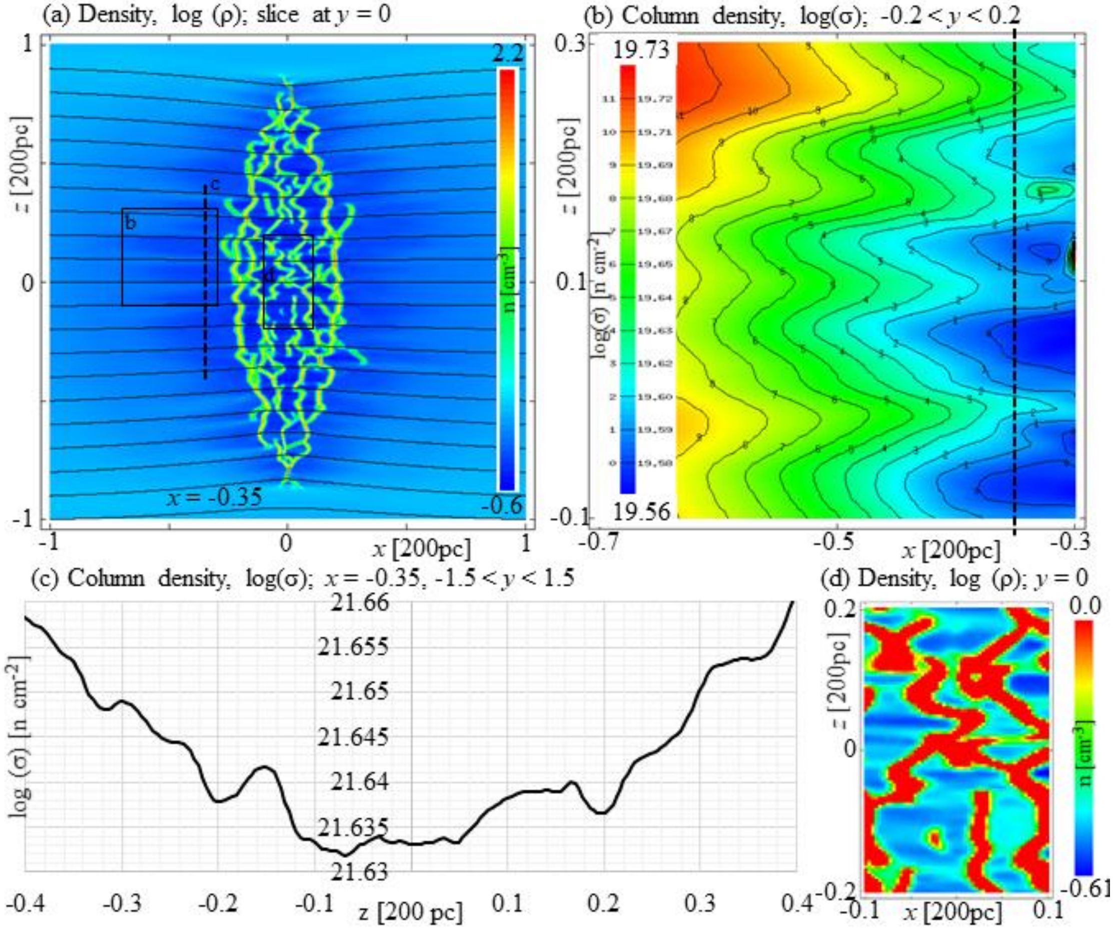
That said, the **striations we observe in the simulations are in the diffuse warm gas** and hence more likely to be linked to elongated fiber structures observed at high Galactic latitudes in the diffuse interstellar medium.



There is some evidence of cold, dense, striation-like structure connected to these structures, but more investigation is required.

Their presence in simulations with and without self-gravity, with and without periodic domains, lends credibility for possible origins in the thermal instability.

Striations, **hour-glasses** and integrals

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849

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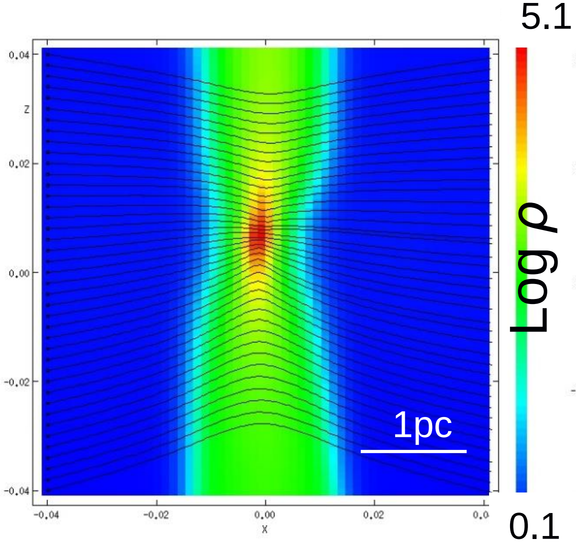
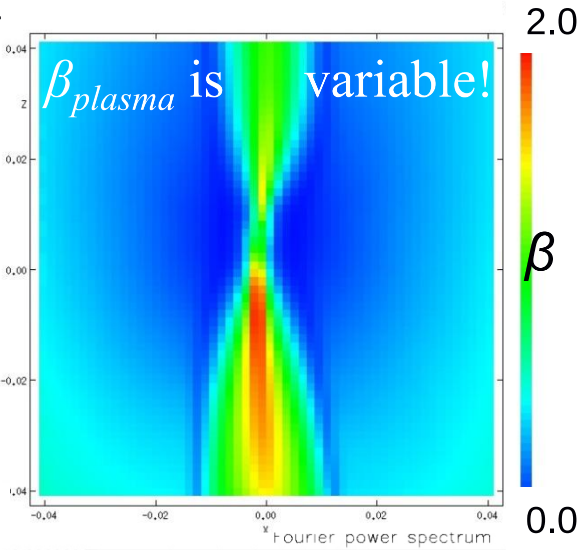
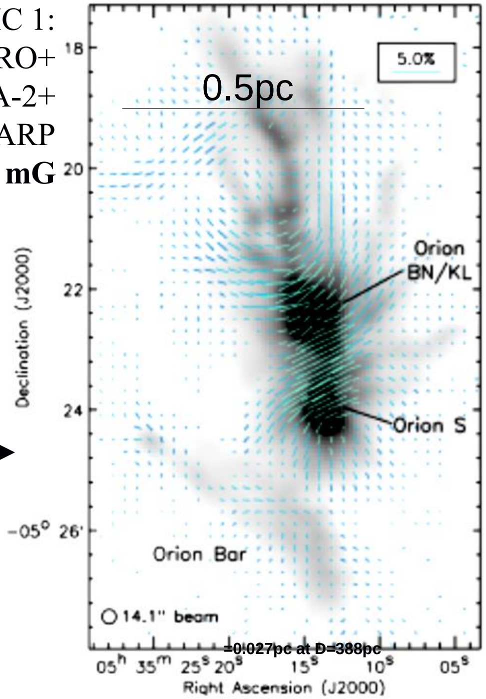
Hour-glass field morphologies naturally form under collapse.





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



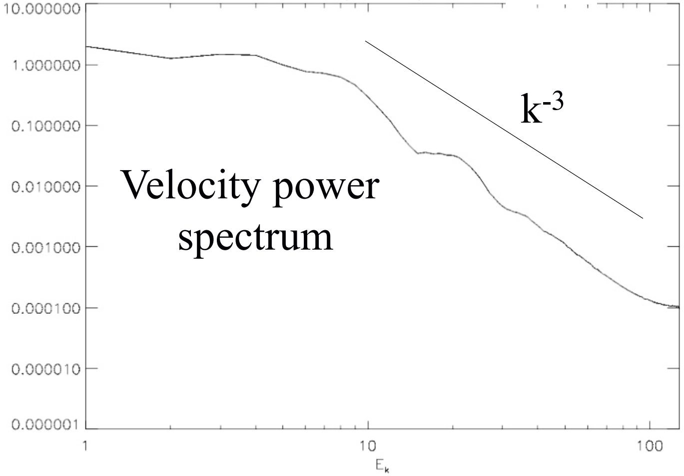
Pattle, Ward-Thompson et al., 2017, ApJ, 846, id.122

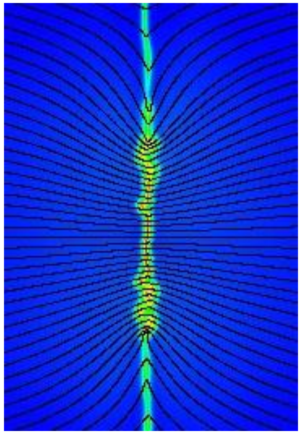
Gravitational collapse
dragging the field.

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 $k^{-5/2}$

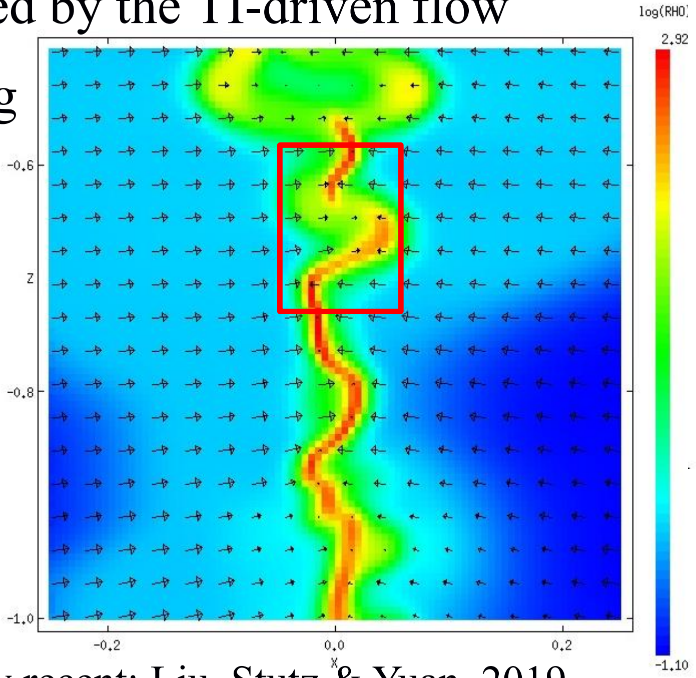




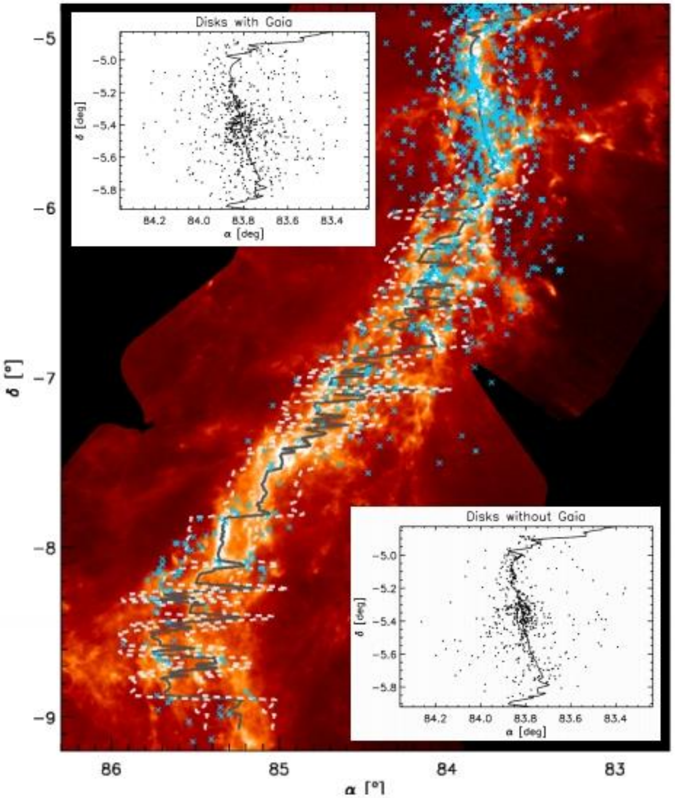
Striations, hour-glasses and **integrals**

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849

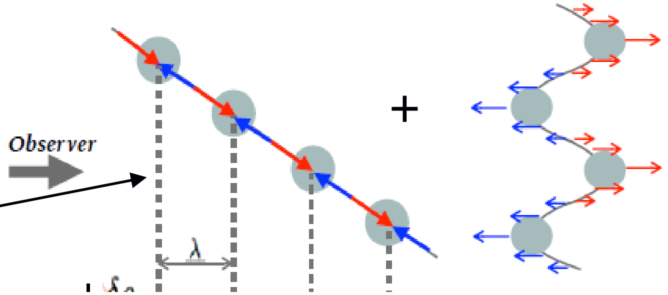
- Recent work **submitted** to MNRAS concludes that an "*integral*"-shaped filament in Orion is a standing wave
- **We obtain apparently similar structure**, with disconnects in the velocity caused by the TI-driven flow
- Not a standing wave –
  an effect of the initial condition and ISM flow
- Further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



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



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



The Crutcher relationship

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849

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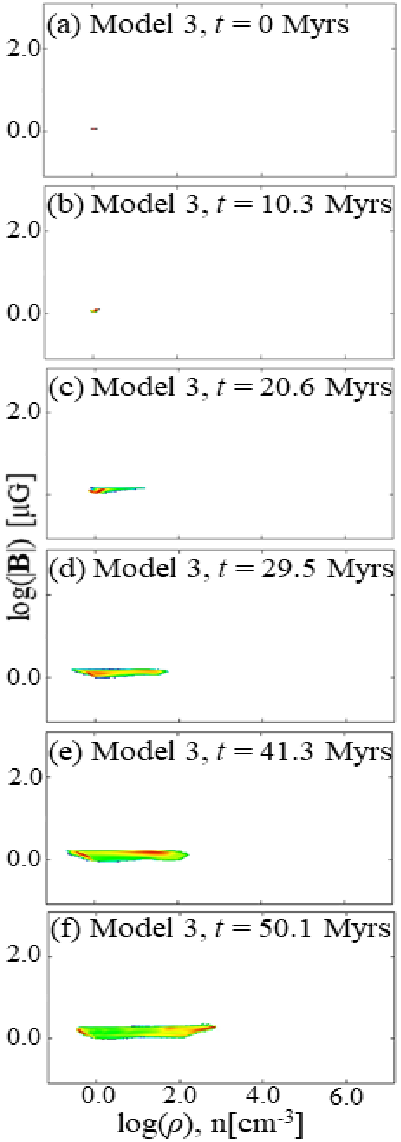
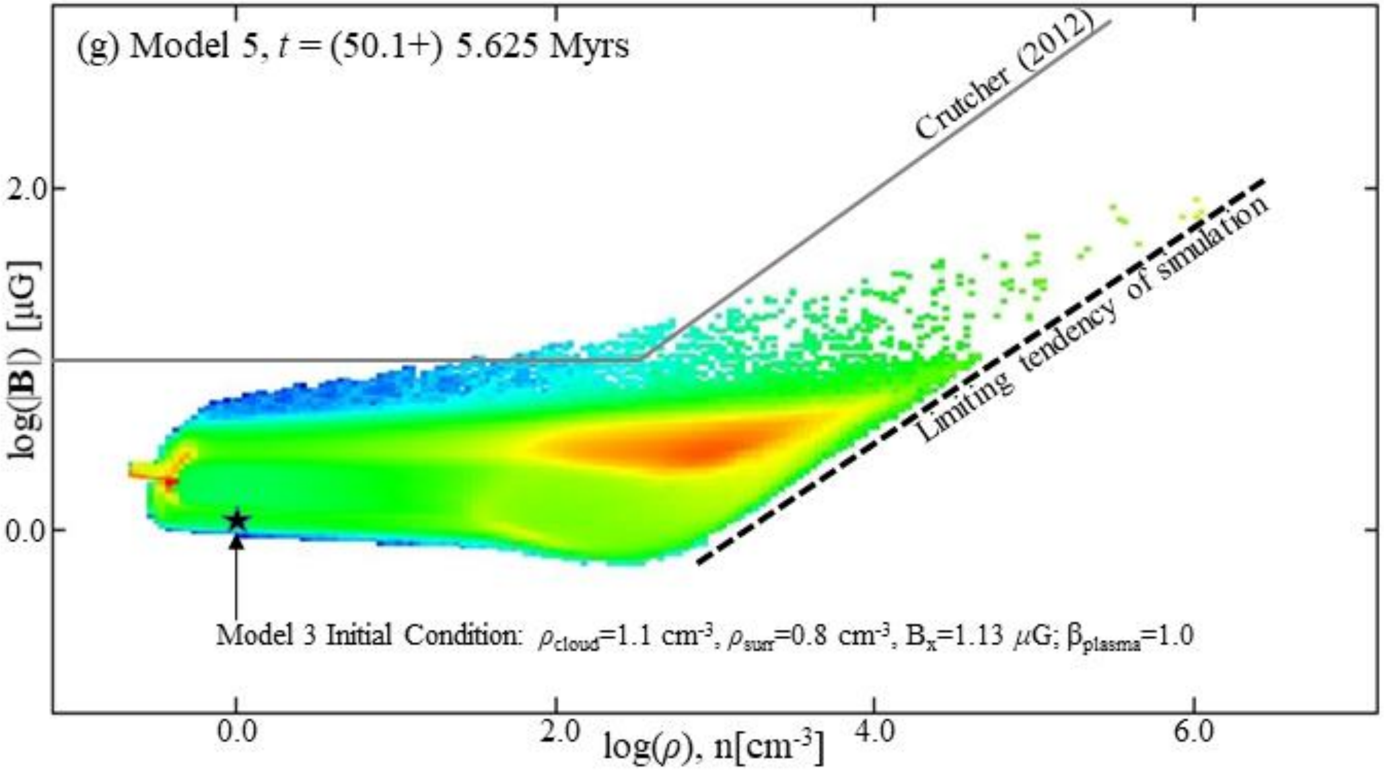


How well do we compare to the Crutcher relationship?

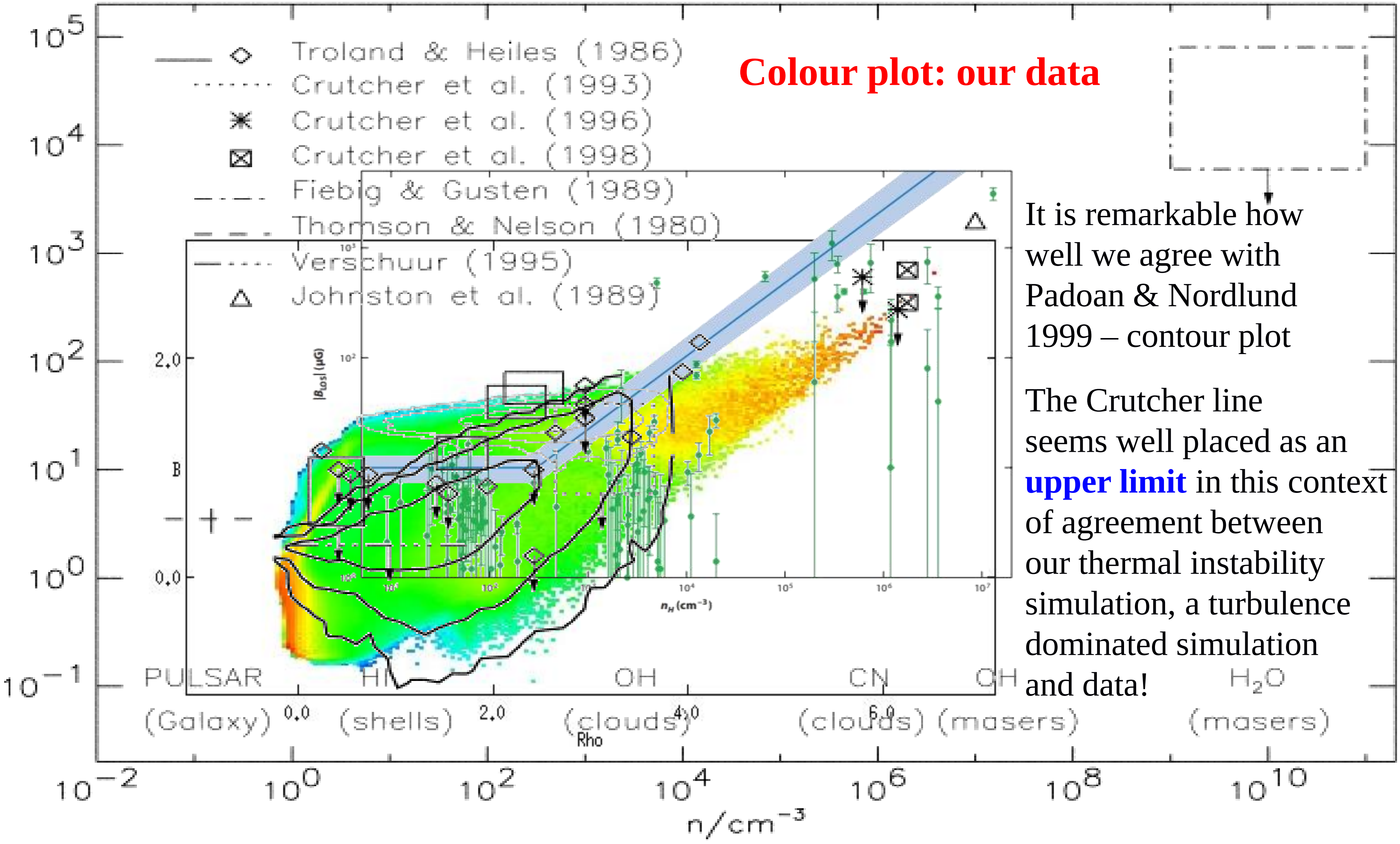


Magnetic field versus density distributions

Colour: frequency of cells with that B and ρ from low (blue) to high (red)

The Crutcher relationship: comparing models

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849



Colour plot: our data

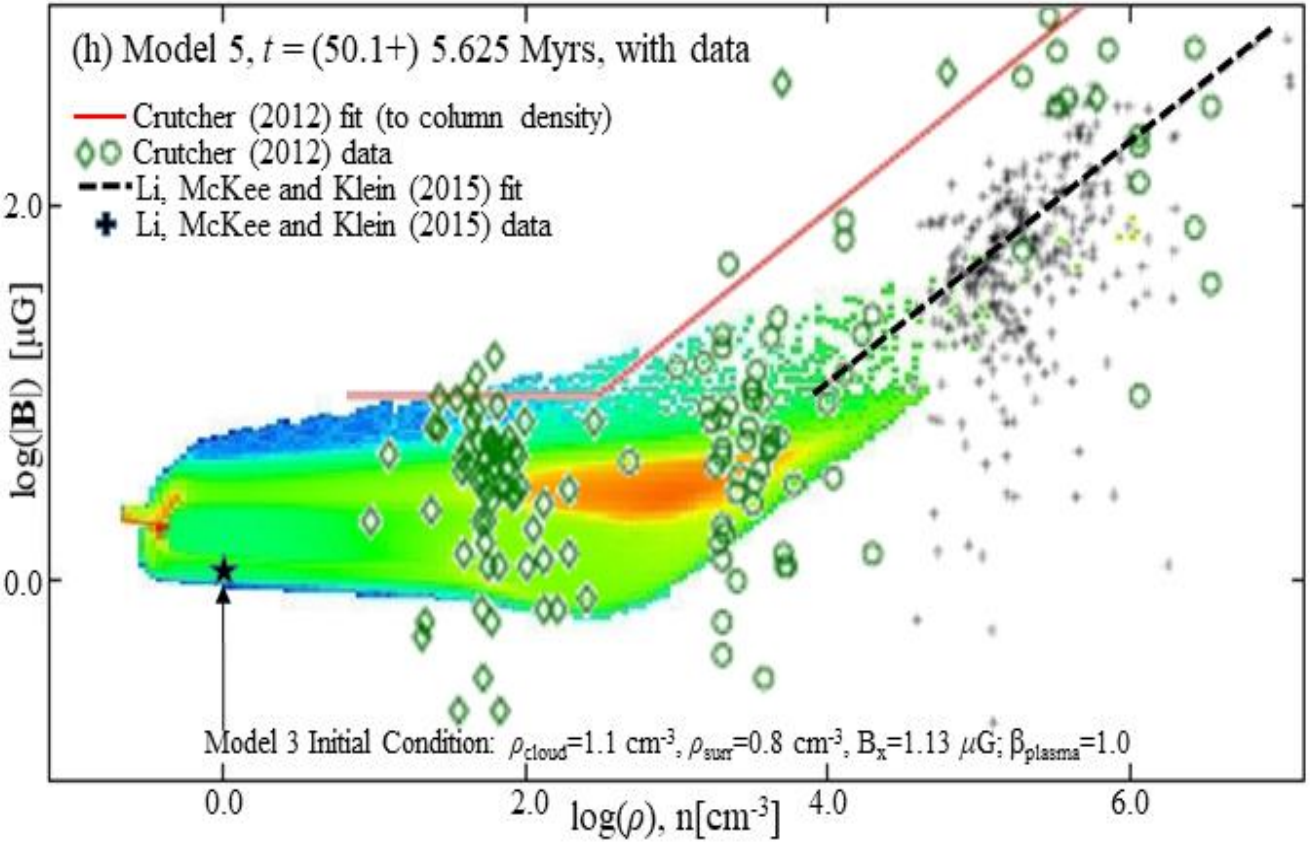
It is remarkable how well we agree with Padoan & Nordlund 1999 – contour plot

The Crutcher line seems well placed as an **upper limit** in this context of agreement between our thermal instability simulation, a turbulence dominated simulation and data!

The Crutcher relationship: comparing models

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849

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.

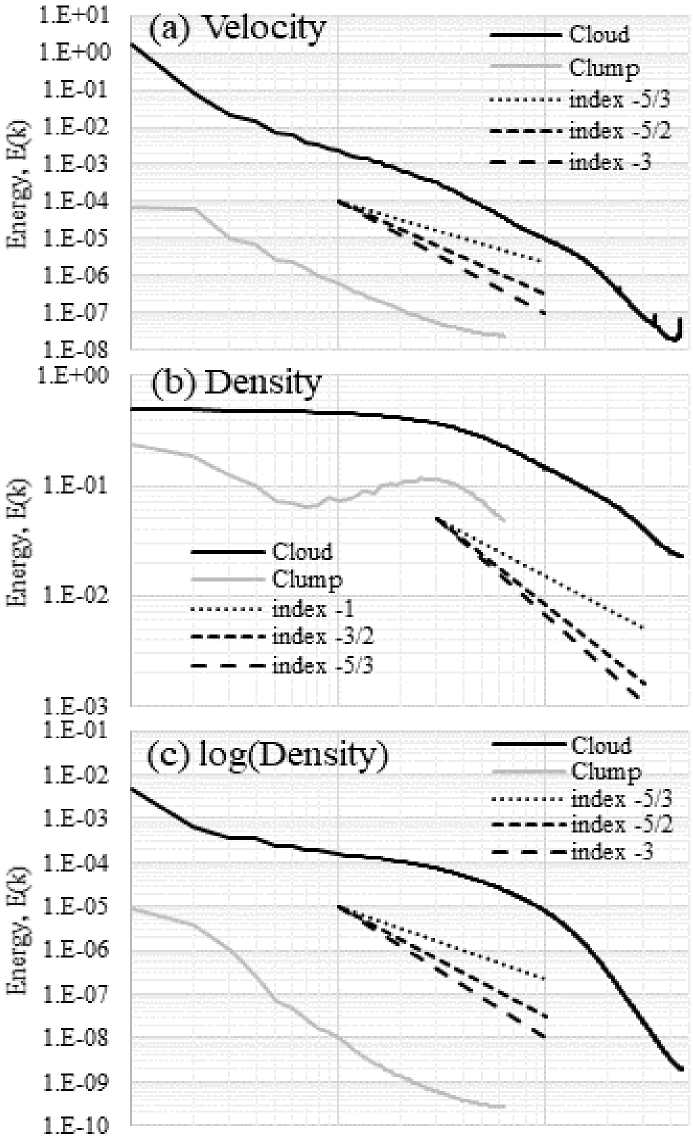
Black crosses: Li, McKee & Klein 2015 simulation of driven Mach 10 turbulence, with M_A ~1.

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? Makes sense as the ‘upper limit’, indicating a clear relationship

Turbulence statistics

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849



Brings us neatly onto power spectra appearances

- Turbulence-like spectra
- Short inertial range
- Spectral index ~ -5/3
- Developed from a stationary initial condition

- This is large-scale laminar-like flow, along the field lines, with structure on small-scales – very Larson (1981)!

- If this model can generate turbulence-like spectra, the only safe conclusion is that 1D power spectra offer only a limited tool to discern between models.

Clump collapse in the MHD case

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849

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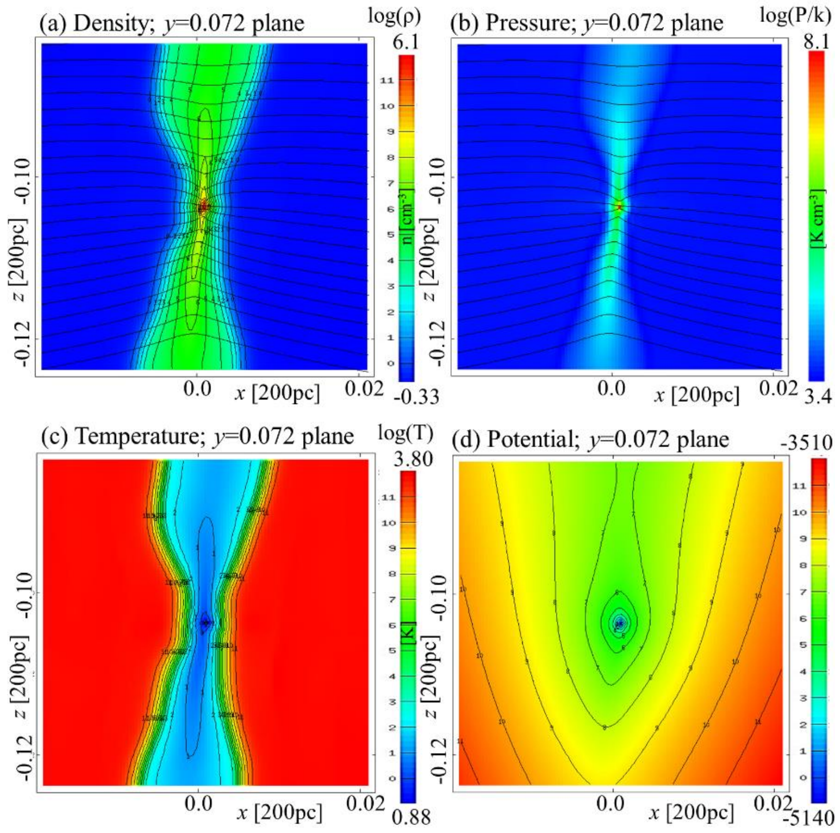
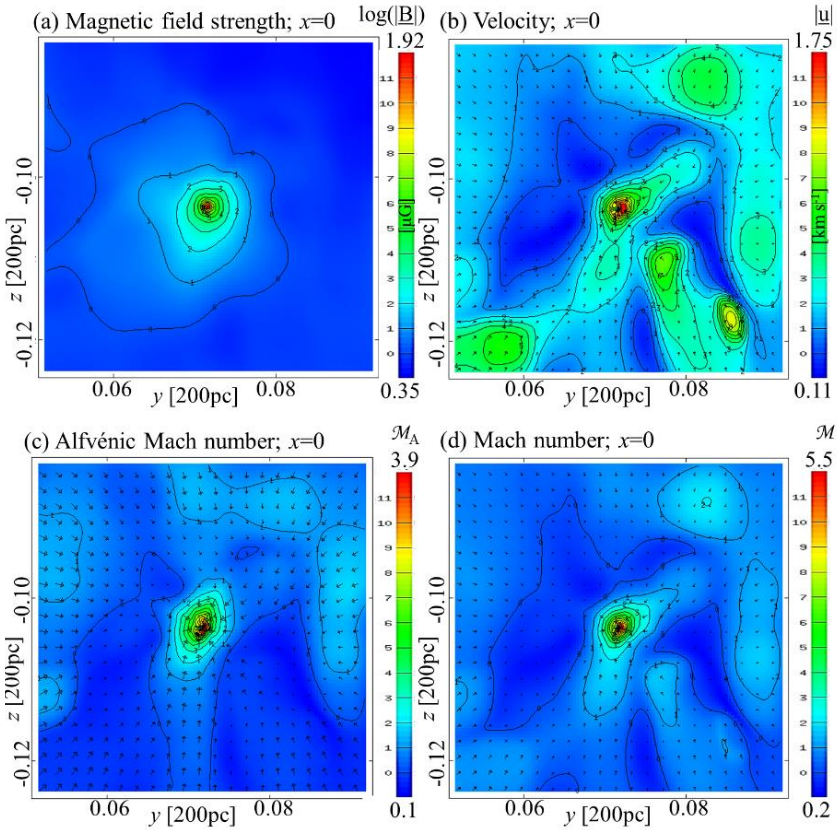
Across the disc-like sheet, clumps form with deep potential wells

Sheet edge-on



Sheet face-on



Sheet compresses as material falls into a clump. Strong B field (100μG),

In-fall velocity ~2 km/s – Mach ~ 5.5, Mach$_A$ ~ 4!

Clump collapse in the MHD case

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849

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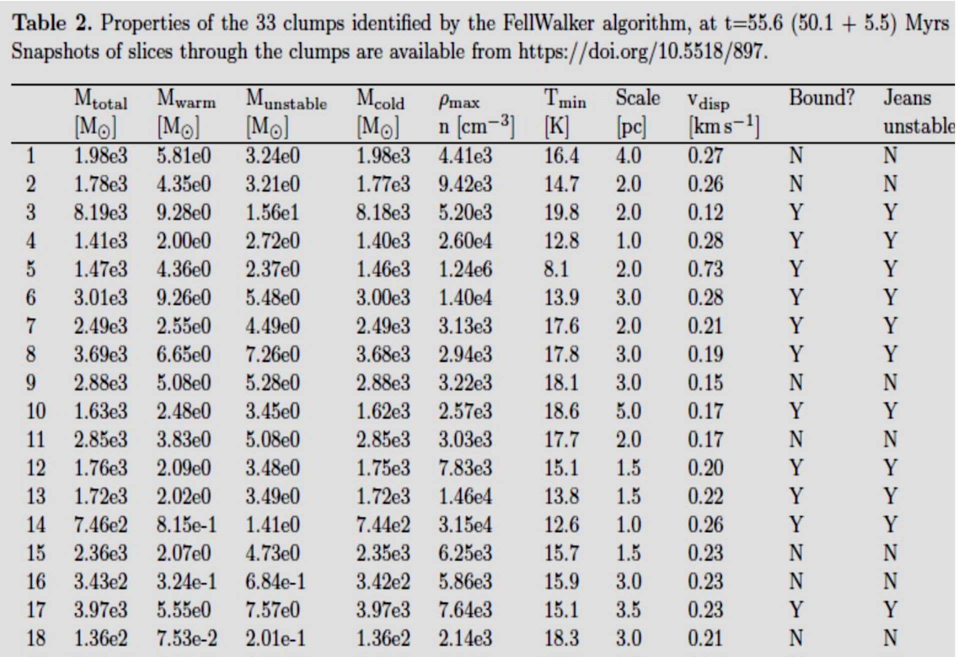


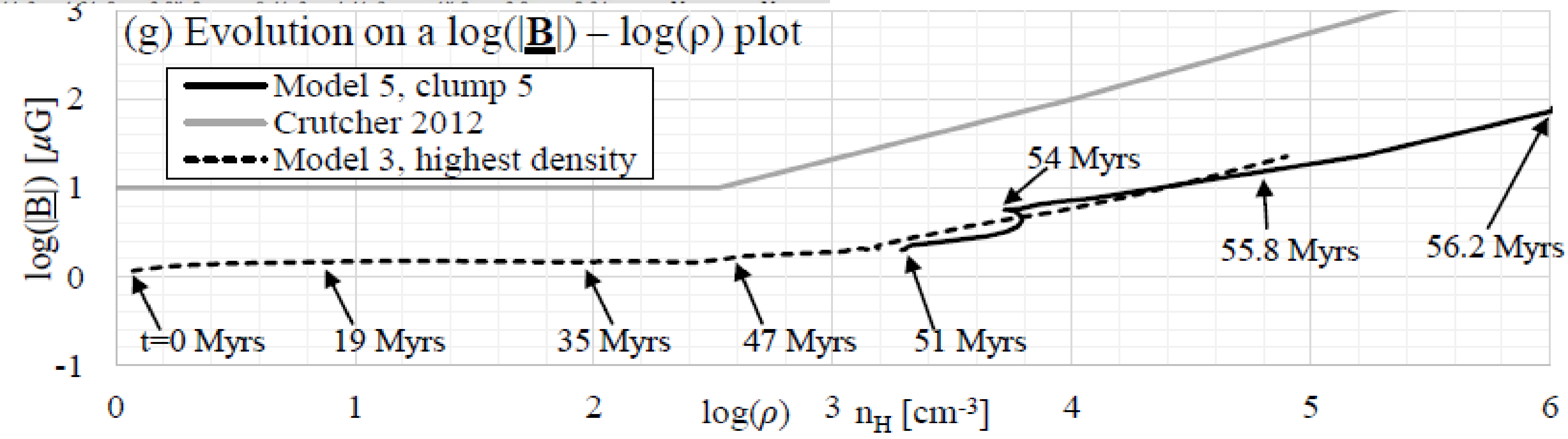
Table 2. Properties of the 33 clumps identified by the FellWalker algorithm, at t=55.6 (50.1 + 5.5) Myrs Snapshots of slices through the clumps are available from https://doi.org/10.5518/897.

	M_{total} $[M_\odot]$	M_{warm} $[M_\odot]$	$M_{unstable}$ $[M_\odot]$	M_{cold} $[M_\odot]$	ρ_{max} n $[cm^{-3}]$	T_{min} [K]	Scale [pc]	v_{disp} $[km\,s^{-1}]$	Bound?	Jeans unstable
1	1.98e3	5.81e0	3.24e0	1.98e3	4.41e3	16.4	4.0	0.27	N	N
2	1.78e3	4.35e0	3.21e0	1.77e3	9.42e3	14.7	2.0	0.26	N	N
3	8.19e3	9.28e0	1.56e1	8.18e3	5.20e3	19.8	2.0	0.12	Y	Y
4	1.41e3	2.00e0	2.72e0	1.40e3	2.60e4	12.8	1.0	0.28	Y	Y
5	1.47e3	4.36e0	2.37e0	1.46e3	1.24e6	8.1	2.0	0.73	Y	Y
6	3.01e3	9.26e0	5.48e0	3.00e3	1.40e4	13.9	3.0	0.28	Y	Y
7	2.49e3	2.55e0	4.49e0	2.49e3	3.13e3	17.6	2.0	0.21	Y	Y
8	3.69e3	6.65e0	7.26e0	3.68e3	2.94e3	17.8	3.0	0.19	Y	Y
9	2.88e3	5.08e0	5.28e0	2.88e3	3.22e3	18.1	3.0	0.15	N	N
10	1.63e3	2.48e0	3.45e0	1.62e3	2.57e3	18.6	5.0	0.17	Y	Y
11	2.85e3	3.83e0	5.08e0	2.85e3	3.03e3	17.7	2.0	0.17	N	N
12	1.76e3	2.09e0	3.48e0	1.75e3	7.83e3	15.1	1.5	0.20	Y	Y
13	1.72e3	2.02e0	3.49e0	1.72e3	1.46e4	13.8	1.5	0.22	Y	Y
14	7.46e2	8.15e-1	1.41e0	7.44e2	3.15e4	12.6	1.0	0.26	Y	Y
15	2.36e3	2.07e0	4.73e0	2.35e3	6.25e3	15.7	1.5	0.23	N	N
16	3.43e2	3.24e-1	6.84e-1	3.42e2	5.86e3	15.9	3.0	0.23	N	N
17	3.97e3	5.55e0	7.57e0	3.97e3	7.64e3	15.1	3.5	0.23	Y	Y
18	1.36e2	7.53e-2	2.01e-1	1.36e2	2.14e3	18.3	3.0	0.21	N	N
19	9.									
20	5.									
21	1.									
22	2.									
23	2.									
24	1.									
25	5.									
26	4.									
27	2.									
28	3.									
29	2.									
30	4.									
31	3.									
32	3.									
33	1.									

Clumps form across the disc-like sheet, developing deep potential wells.

Clump cold mass >10^3Msun
Bound & Jeans unstable
Low temperature
Internal dispersion ~ transonic

Time evolution of a single clump:-



Conclusions I

Wareing, Pittard & Falle 2021, MNRAS, 500, 2831-2849

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1. Diffuse, sub-critical thermally unstable material flows along the field lines, eventually forming sheets.
2. With enough mass, the sheet is supercritical and collapses across the fieldlines. Local supercritical collapse on a globally subcritical sheet can occur.
3. The Crutcher relationship is reproduced, with the correct turning point and agreement with supersonic, super-Alfvénic simulations.
4. Striations appear in the diffuse material, akin to Galactic fibers.
5. Integral shapes form, oscillating along the field lines about the grav. Minimum
6. Hour-glass field morphologies intensify the magnetic field up to mG strengths.
7. Clumps are massive (especially compared to HD case as shown next).
8. Power spectra are not unreasonable, but perhaps a blunt assessment tool.

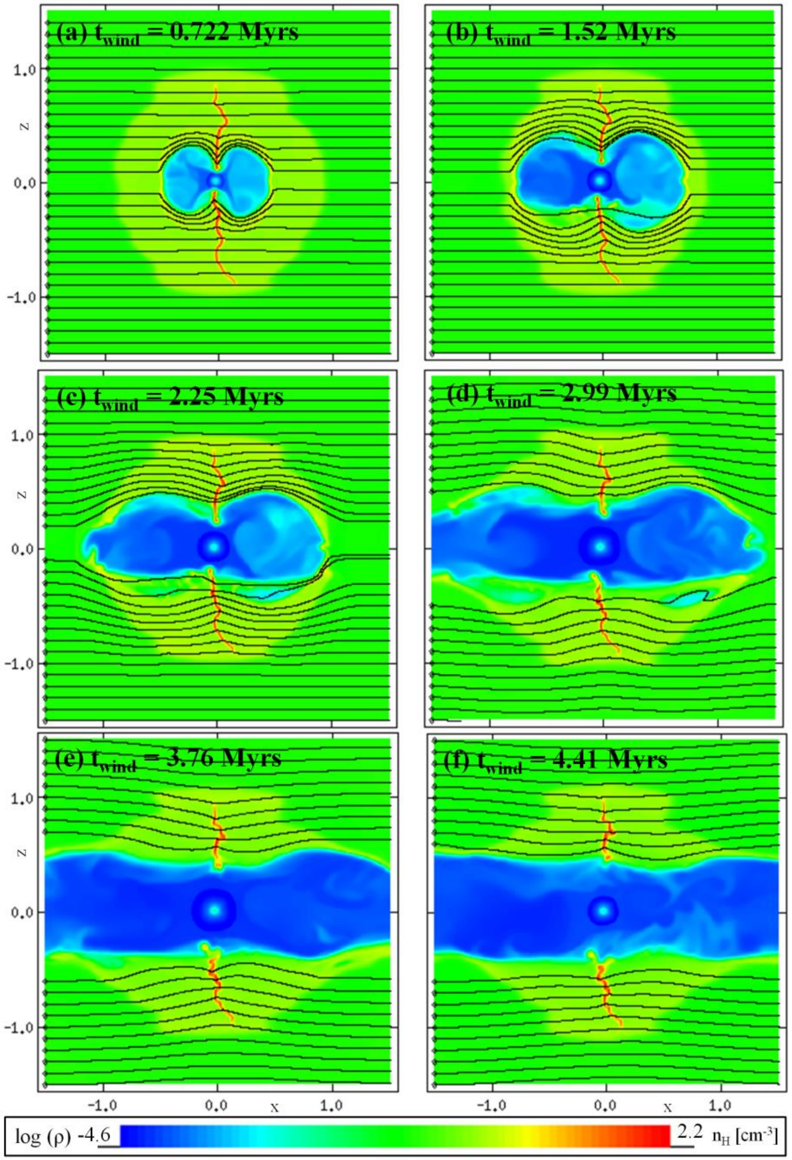
Field length has not been fully resolved, nor have we included thermal conduction, but converged large-scale results are obtained nevertheless.

Future work would need to go beyond ideal MHD and single fluids

Feedback in the magnetic case

Wareing, Pittard & Falle 2017, MNRAS, 465, 2757-2783

- 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!**



The Rosette Nebula

Wareing, Pittard & Falle 2018, MNRAS, 475, 3598-3612

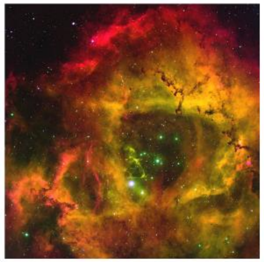
- Large HII region in the Monoceros GMC complex.
- Shocked high velocity cloud? ***(see 1980s Tenorio-Tagle!)*** Or edge of large SN remnant?
- Central cluster is NGC 2244 with age estimates 2-6 Myrs.
- South-Eastern extent is interacting with the Rosette Molecular Cloud.
- Candidate for triggered star formation (controversial!)

IPHAS Hα image (Credit: N.Wright/IPHAS)

- Central cavity r = 6.2pc (Celnik 1985, at 1.4kpc), r ~ 5 pc (IPHAS, at 1.53kpc), D ~ 1.6 kpc +/- 250 pc.
- ***Central cavity is too small!***

Simulating the Rosette Nebula

Wareing, Pittard & Falle 2018, MNRAS, 475, 3598-3612



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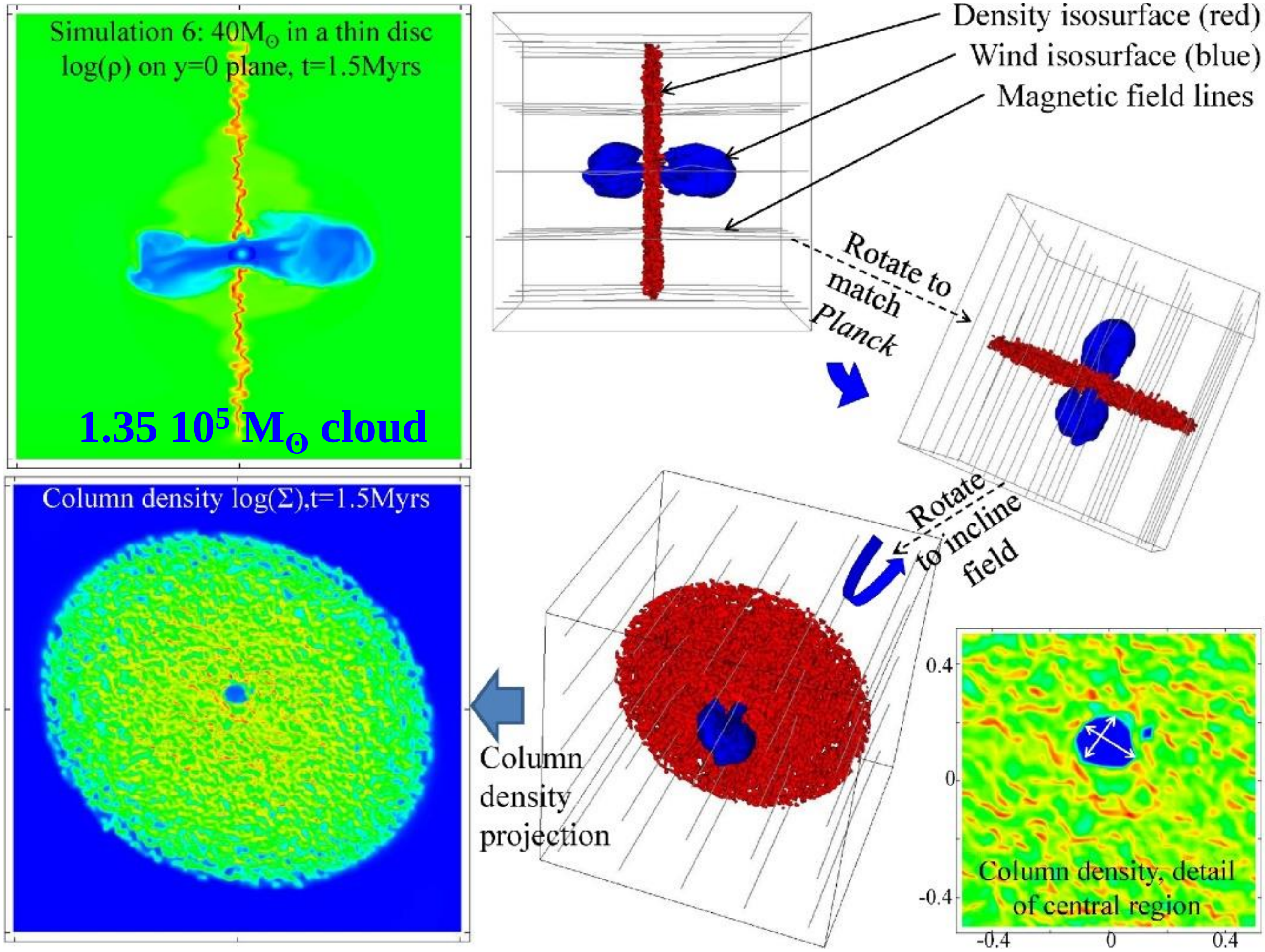
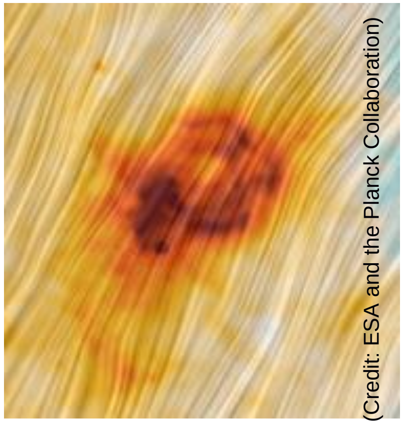
Magnetic field alignment, proper motion and location of possible triggered star formation all support this model.

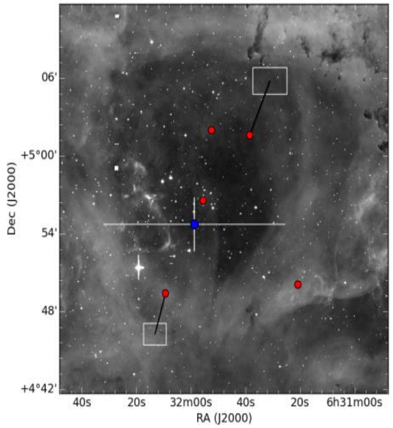




(Credit: ESA and the Planck Collaboration)

Evacuated hole

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



Simulating the Rosette Nebula

Wareing, Pittard & Falle 2018, MNRAS, 475, 3598-3612

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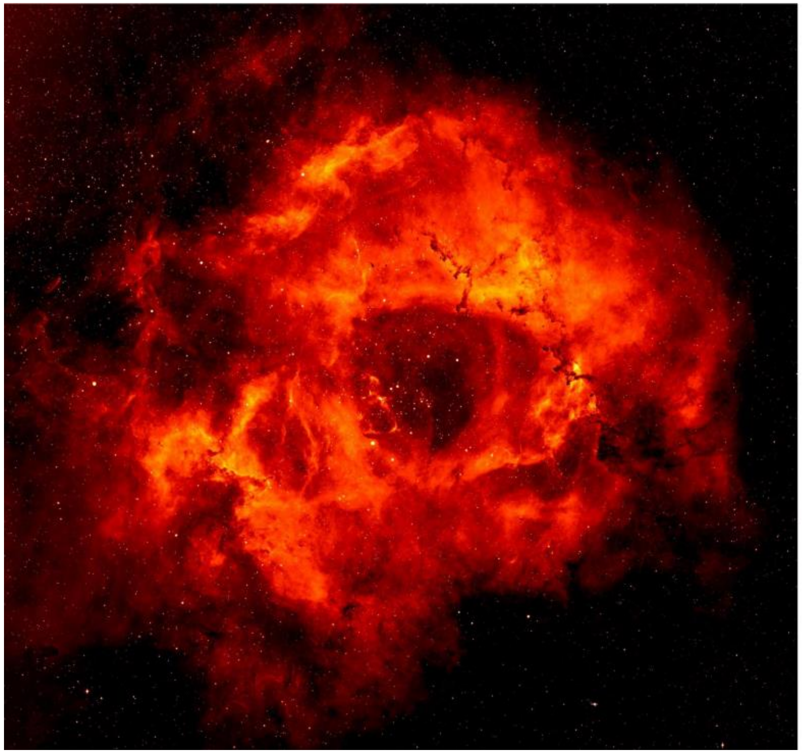
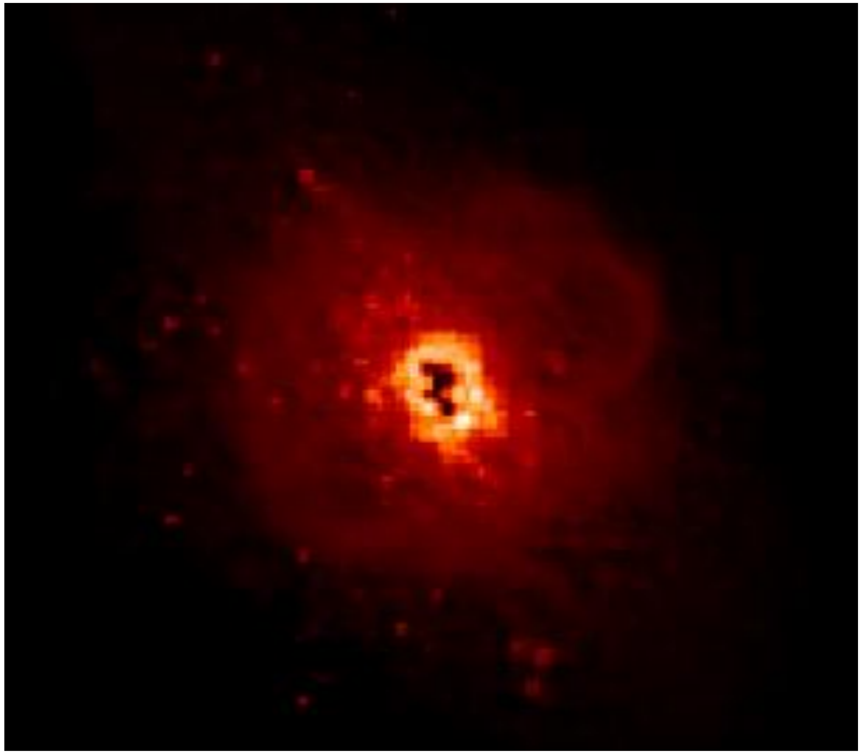


IPHAS observation of the Rosette Nebula and it’s curious central cavity.



A simulated Hα observation derived from the simulation (courtesy of Ahmad and Harries at the University of Exeter).

Zealous PR timing – Valentine’s 2018

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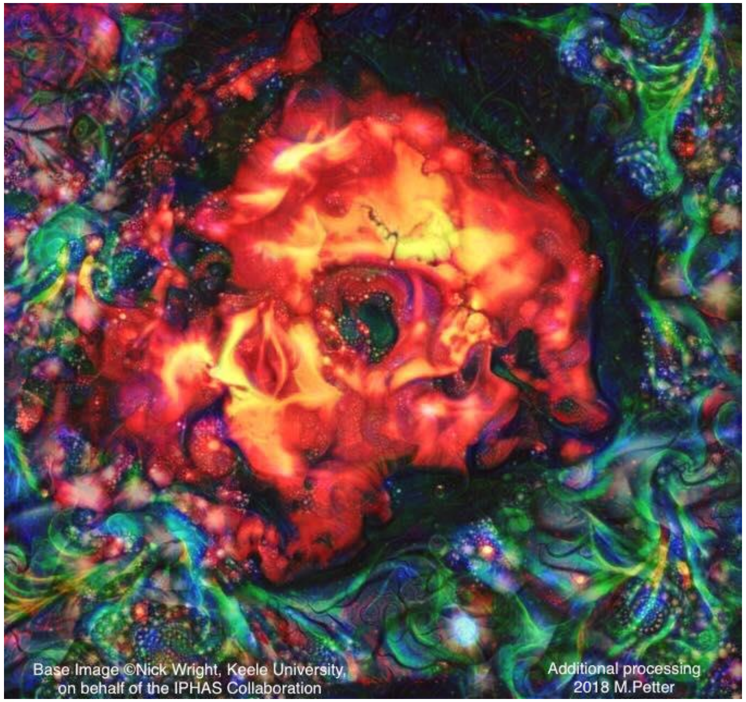

Base Image ©Nick Wright, Keele University, on behalf of the IPHAS Collaboration

Additional processing 2018 M.Petter

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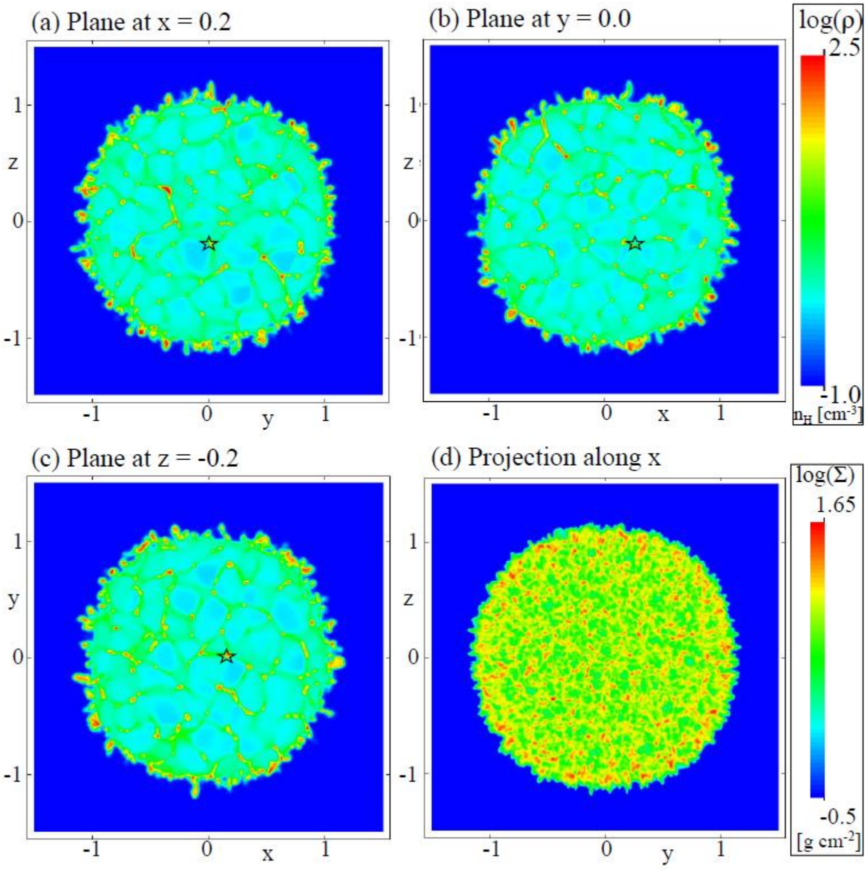
Hydrodynamic case comparison

Wareing, Pittard & Falle 2019, MNRAS, 485, 4686-4702

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

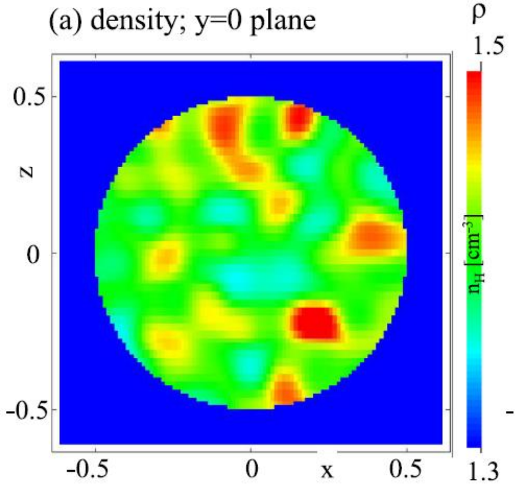


Initial cloud diameter (200pc)

Looking for collapse…

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

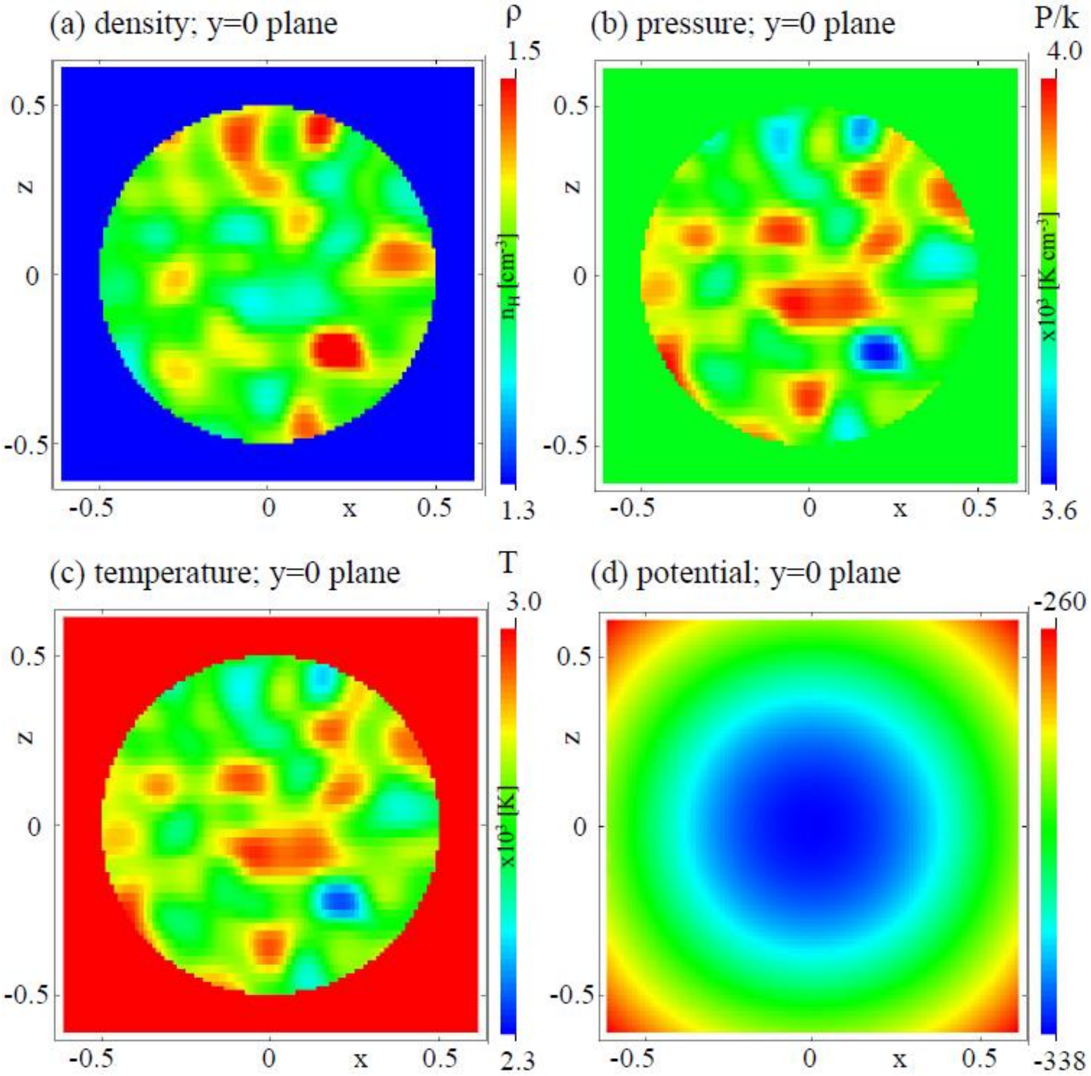
Turning clouds into clumps and cores

Wareing, Pittard & Falle 2019, MNRAS, 485, 4686-4702

Can TI, subsequently dominated by gravity, create truly star-forming collapsing clumps with realistic properties in HD?

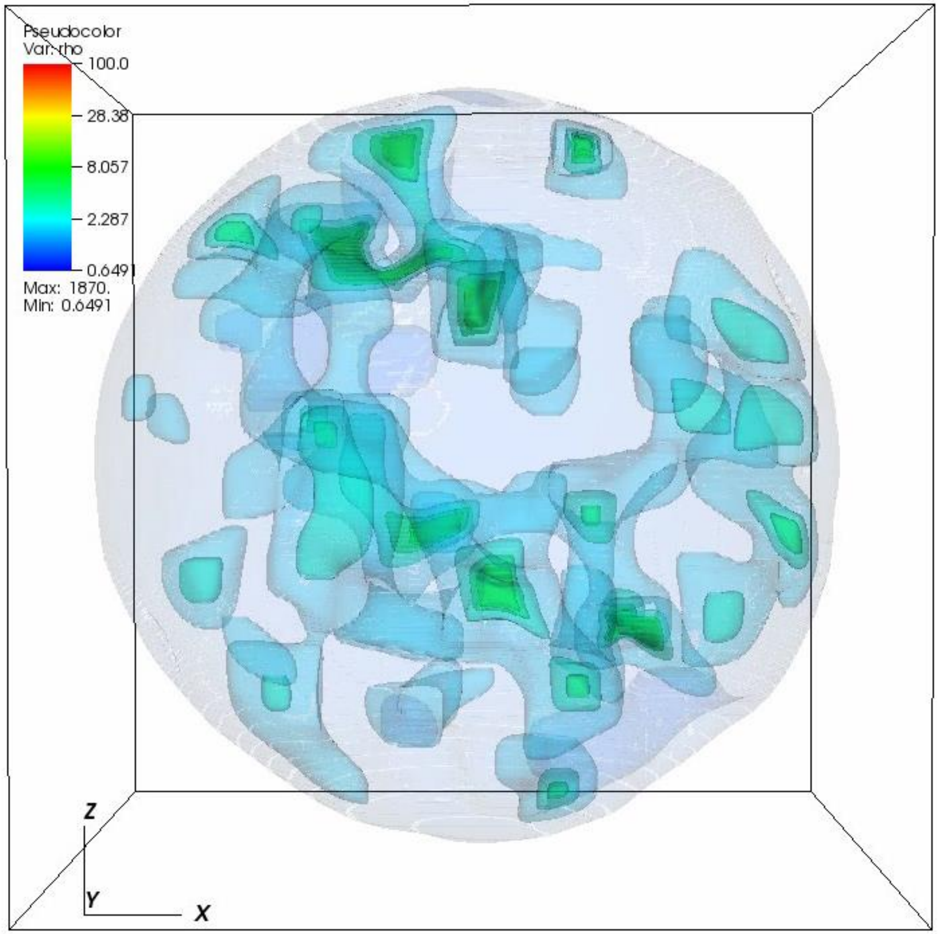
High-resolution simulations

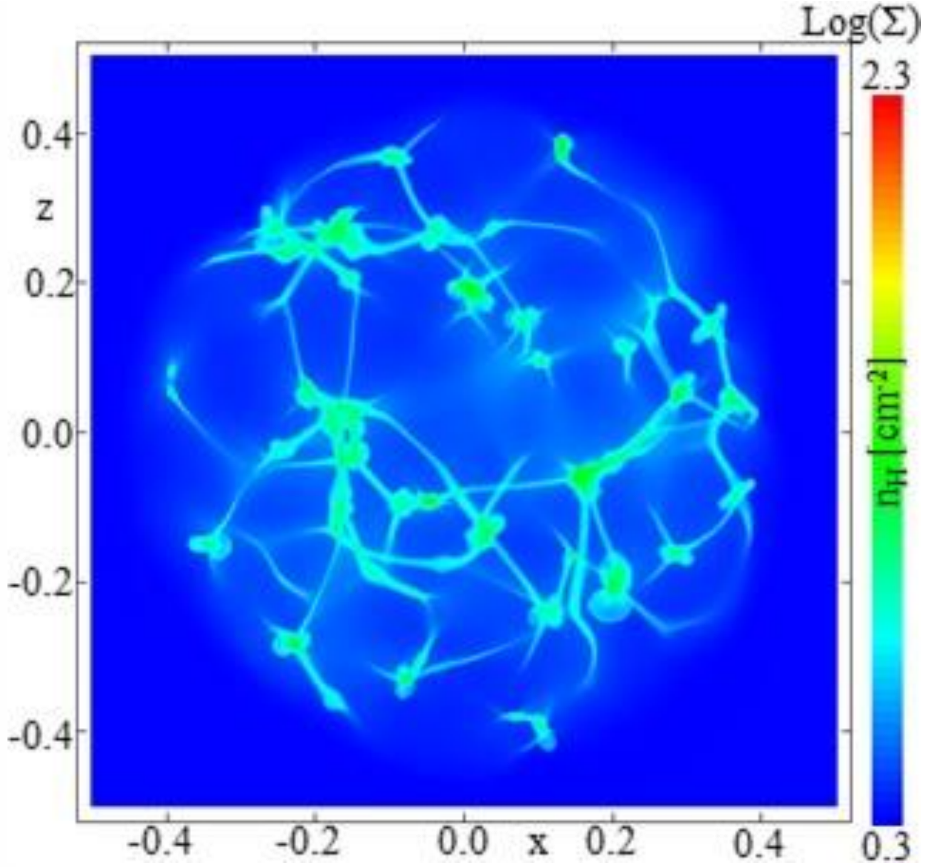
- Central 3000 $M_\odot$ sphere of the HD simulation of large cloud
- Placed in warm stable surroundings to isolate effect of the thermal instability and self-gravity
- Stationary quiescent cloud
- 10x higher resolution:
  0.29 pc -> 0.039 pc (0.016 pc)



Sheets, filaments and clumps

Wareing, Pittard & Falle 2019, MNRAS, 485, 4686-4702





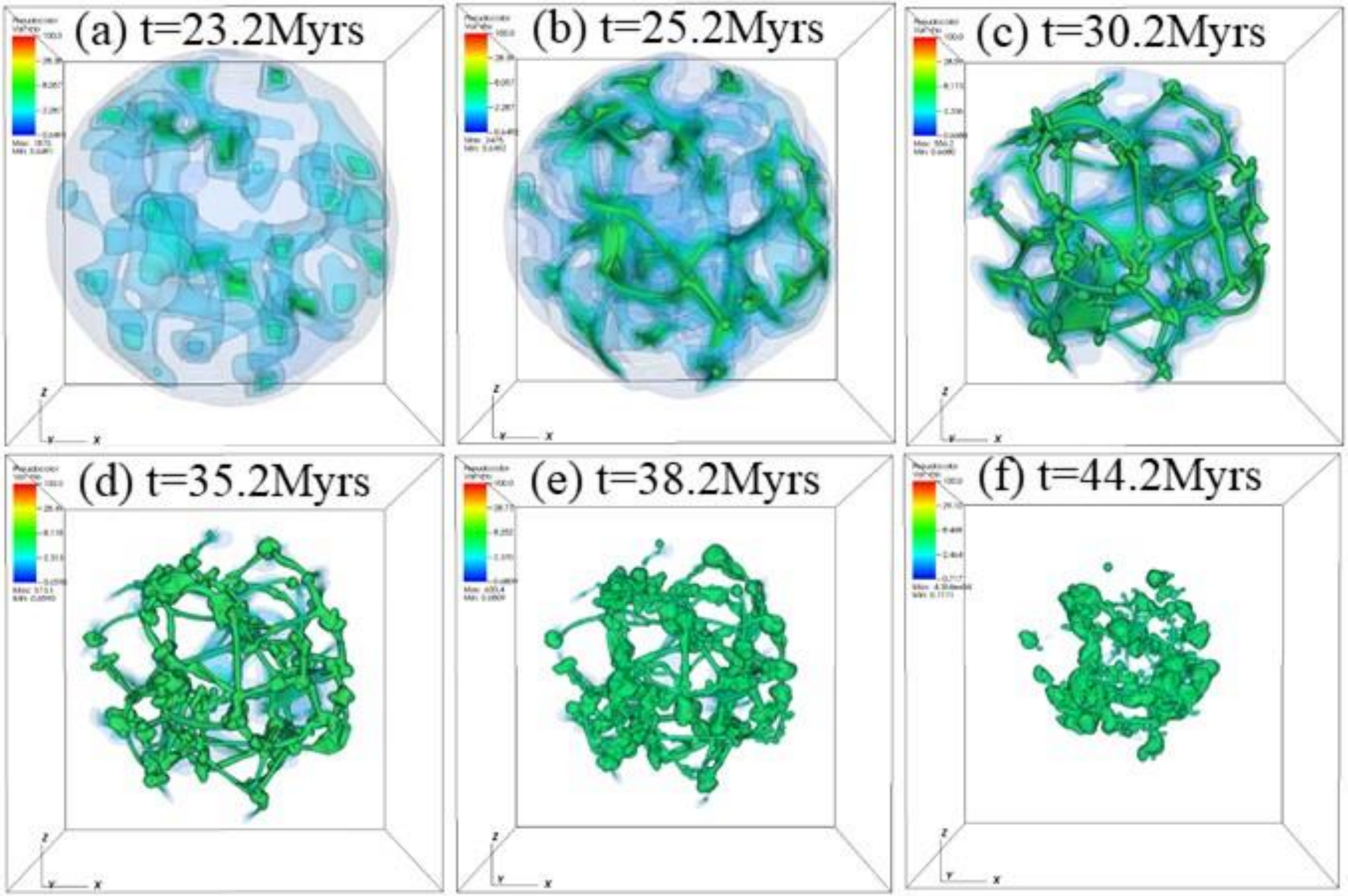
Filament widths 0.1 to 0.3 pc!

At the limit of detectability previously.

Sheets, filaments and clumps

Wareing, Pittard & Falle 2019, MNRAS, 485, 4686-4702

Creates a network of cold, dense clumps, multiply-connected by filaments!



Clumps, filaments and flows

Wareing, Pittard & Falle 2019, MNRAS, 485, 4686-4702

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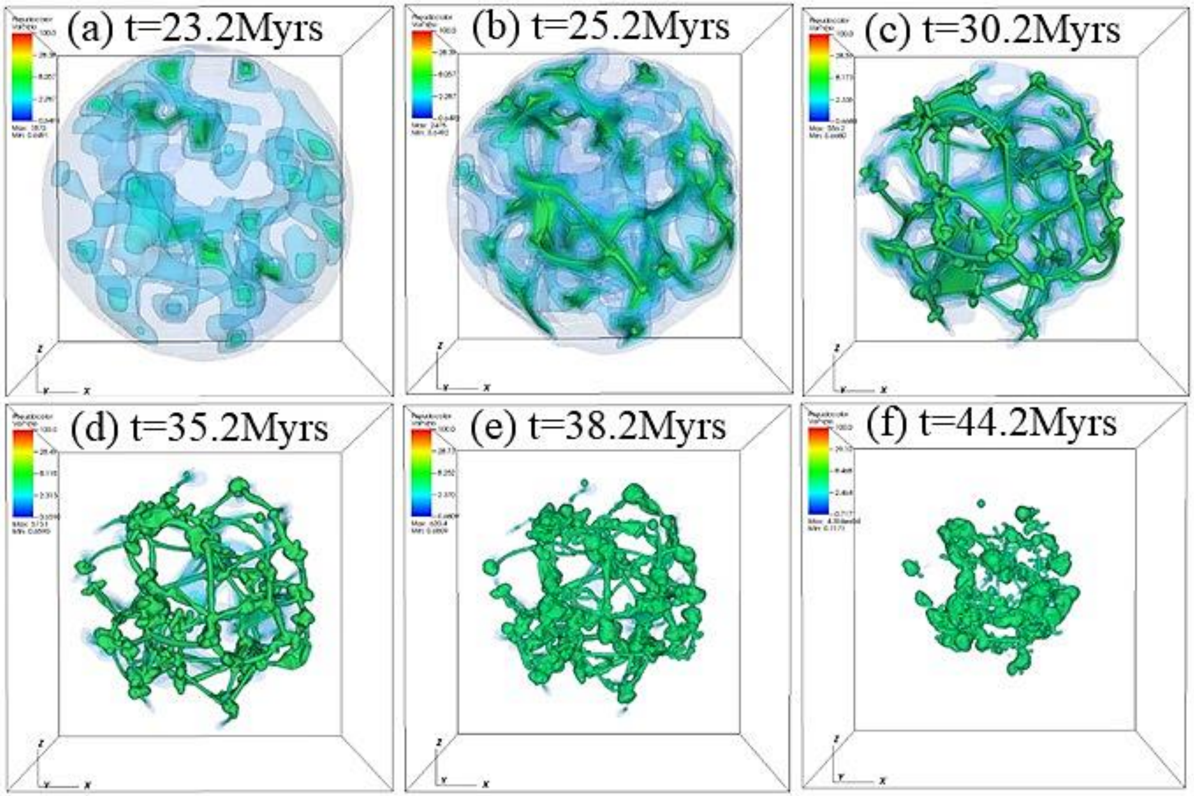
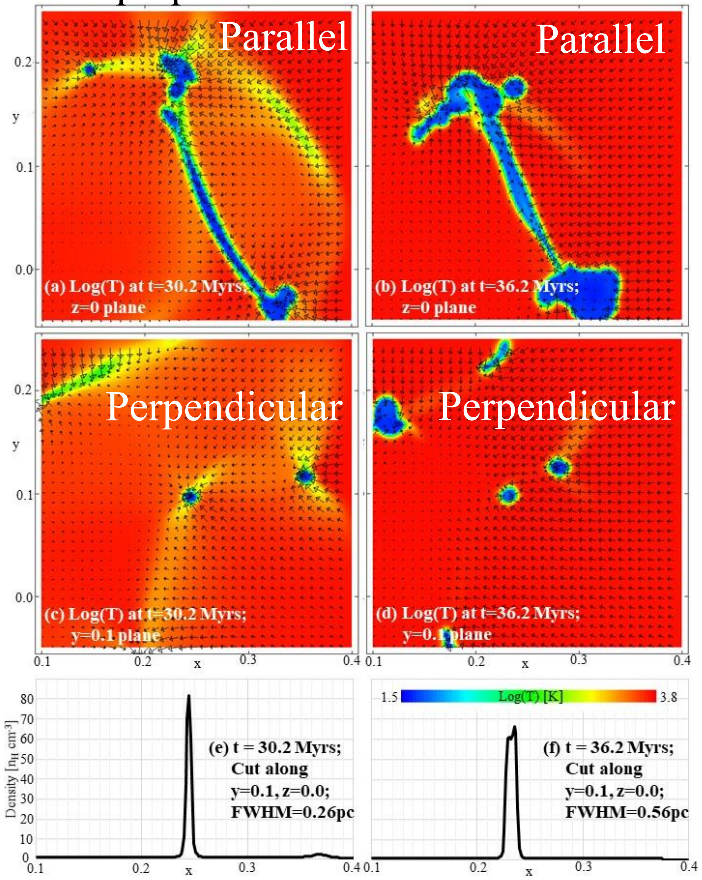


Slices of temperature parallel and perpendicular to one filament



- 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**

Clumps, filaments and flows

Wareing, Pittard & Falle 2019, MNRAS, 485, 4686-4702

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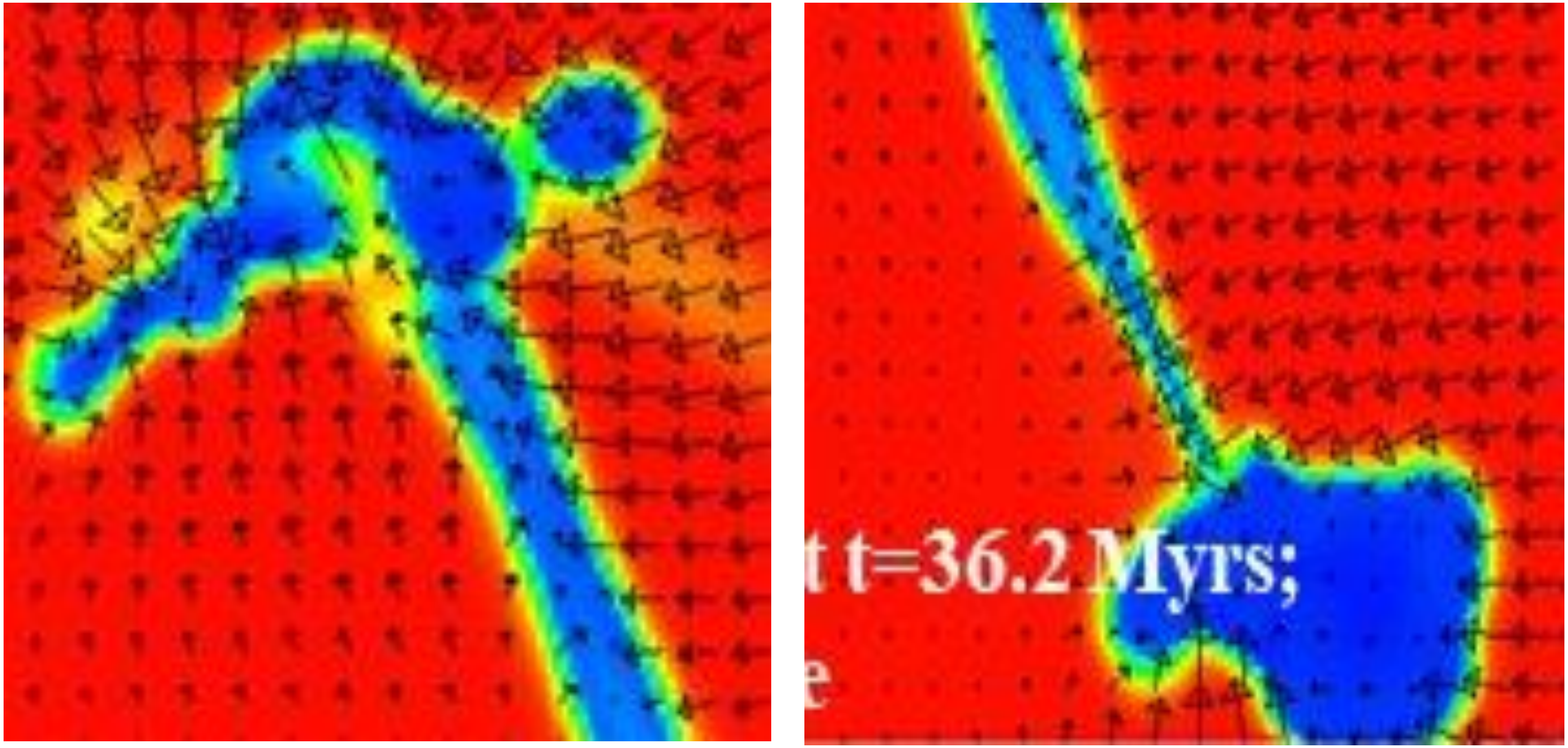
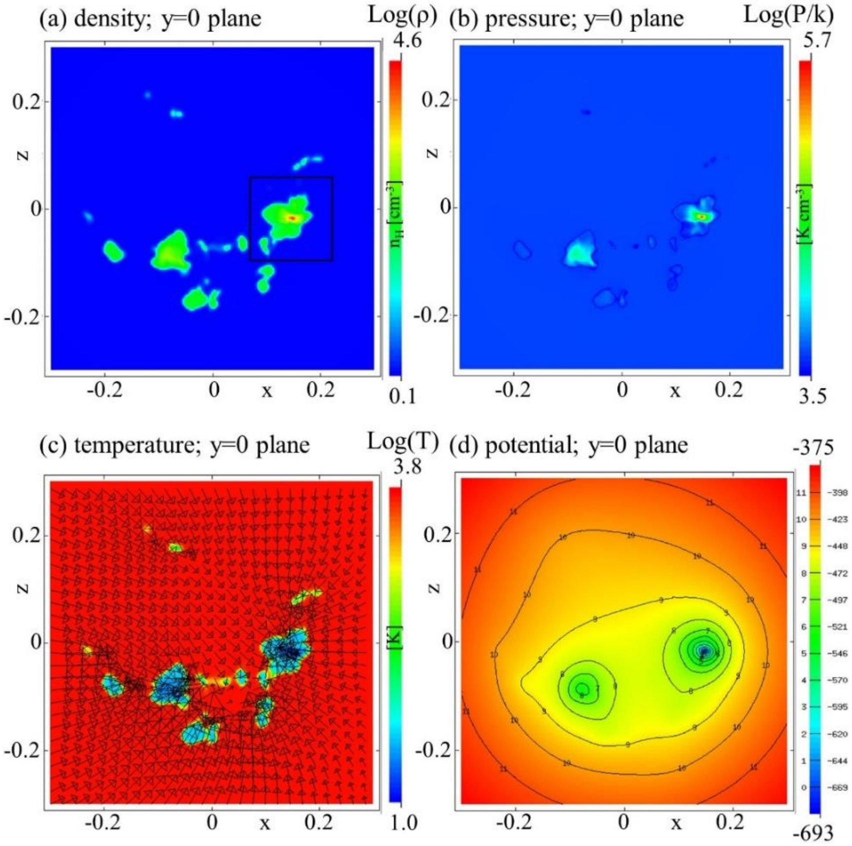
- **Near-sonic flow (up to 0.2 km s^{-1}) along the filaments toward the clumps.**
- Strong correlation with observed velocities along filaments (Traficante et al.)

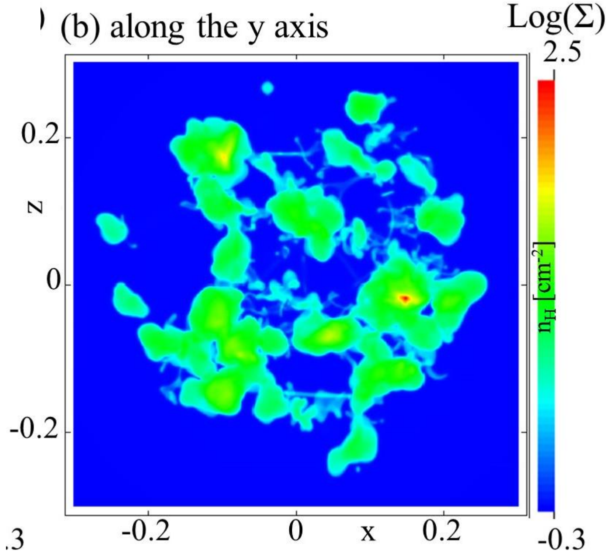


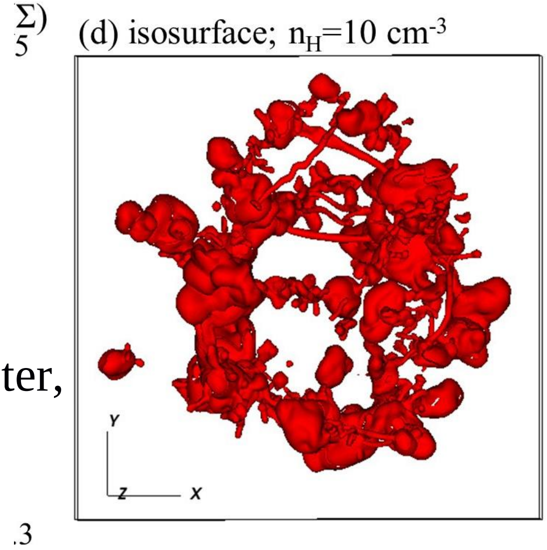
Slices of temperature parallel to one filament

Final evolved enlarged simulation

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

Clump properties

Wareing, Pittard & Falle 2019, MNRAS, 485, 4686-4702

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21 clumps more massive than 20 $M_\odot$.

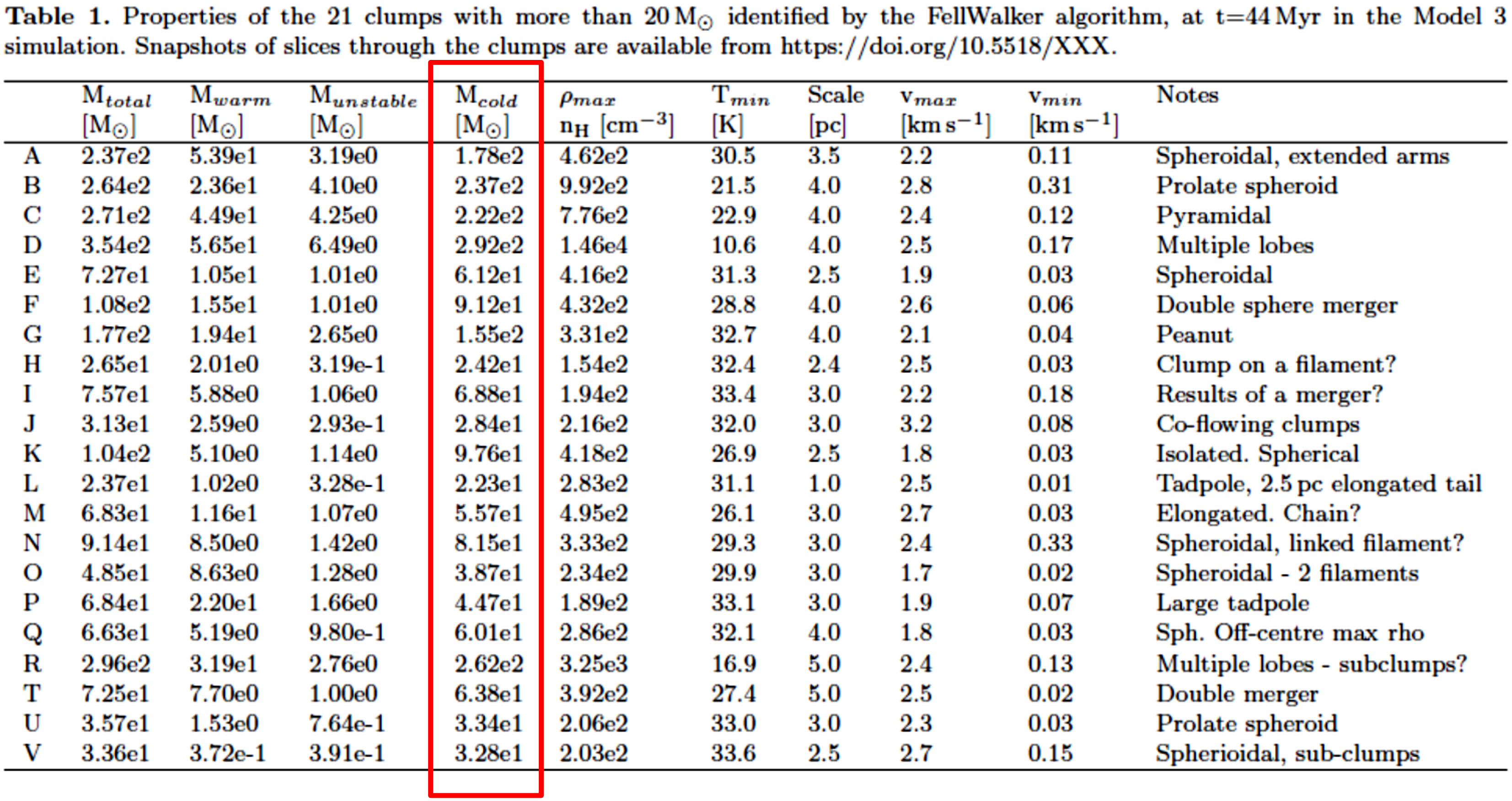


Table 1. Properties of the 21 clumps with more than 20 $M_\odot$ identified by the FellWalker algorithm, at t=44 Myr in the Model 3 simulation. Snapshots of slices through the clumps are available from https://doi.org/10.5518/XXX.

	M_{total} [$M_\odot$]	M_{warm} [$M_\odot$]	$M_{unstable}$ [$M_\odot$]	M_{cold} [$M_\odot$]	ρ_{max} n_H [cm^{-3}]	T_{min} [K]	Scale [pc]	v_{max} [$km\,s^{-1}$]	v_{min} [$km\,s^{-1}$]	Notes
A	2.37e2	5.39e1	3.19e0	1.78e2	4.62e2	30.5	3.5	2.2	0.11	Spheroidal, extended arms
B	2.64e2	2.36e1	4.10e0	2.37e2	9.92e2	21.5	4.0	2.8	0.31	Prolate spheroid
C	2.71e2	4.49e1	4.25e0	2.22e2	7.76e2	22.9	4.0	2.4	0.12	Pyramidal
D	3.54e2	5.65e1	6.49e0	2.92e2	1.46e4	10.6	4.0	2.5	0.17	Multiple lobes
E	7.27e1	1.05e1	1.01e0	6.12e1	4.16e2	31.3	2.5	1.9	0.03	Spheroidal
F	1.08e2	1.55e1	1.01e0	9.12e1	4.32e2	28.8	4.0	2.6	0.06	Double sphere merger
G	1.77e2	1.94e1	2.65e0	1.55e2	3.31e2	32.7	4.0	2.1	0.04	Peanut
H	2.65e1	2.01e0	3.19e-1	2.42e1	1.54e2	32.4	2.4	2.5	0.03	Clump on a filament?
I	7.57e1	5.88e0	1.06e0	6.88e1	1.94e2	33.4	3.0	2.2	0.18	Results of a merger?
J	3.13e1	2.59e0	2.93e-1	2.84e1	2.16e2	32.0	3.0	3.2	0.08	Co-flowing clumps
K	1.04e2	5.10e0	1.14e0	9.76e1	4.18e2	26.9	2.5	1.8	0.03	Isolated. Spherical
L	2.37e1	1.02e0	3.28e-1	2.23e1	2.83e2	31.1	1.0	2.5	0.01	Tadpole, 2.5 pc elongated tail
M	6.83e1	1.16e1	1.07e0	5.57e1	4.95e2	26.1	3.0	2.7	0.03	Elongated. Chain?
N	9.14e1	8.50e0	1.42e0	8.15e1	3.33e2	29.3	3.0	2.4	0.33	Spheroidal, linked filament?
O	4.85e1	8.63e0	1.28e0	3.87e1	2.34e2	29.9	3.0	1.7	0.02	Spheroidal - 2 filaments
P	6.84e1	2.20e1	1.66e0	4.47e1	1.89e2	33.1	3.0	1.9	0.07	Large tadpole
Q	6.63e1	5.19e0	9.80e-1	6.01e1	2.86e2	32.1	4.0	1.8	0.03	Sph. Off-centre max rho
R	2.96e2	3.19e1	2.76e0	2.62e2	3.25e3	16.9	5.0	2.4	0.13	Multiple lobes - subclumps?
T	7.25e1	7.70e0	1.00e0	6.38e1	3.92e2	27.4	5.0	2.5	0.02	Double merger
U	3.57e1	1.53e0	7.64e-1	3.34e1	2.06e2	33.0	3.0	2.3	0.03	Prolate spheroid
V	3.36e1	3.72e-1	3.91e-1	3.28e1	2.03e2	33.6	2.5	2.7	0.15	Spherioidal, sub-clumps

5x to 10x smaller than in the MHD case, as you might expect.

Clumps also take longer to form in MHD than in HD, again as expected.

Realistic clumps

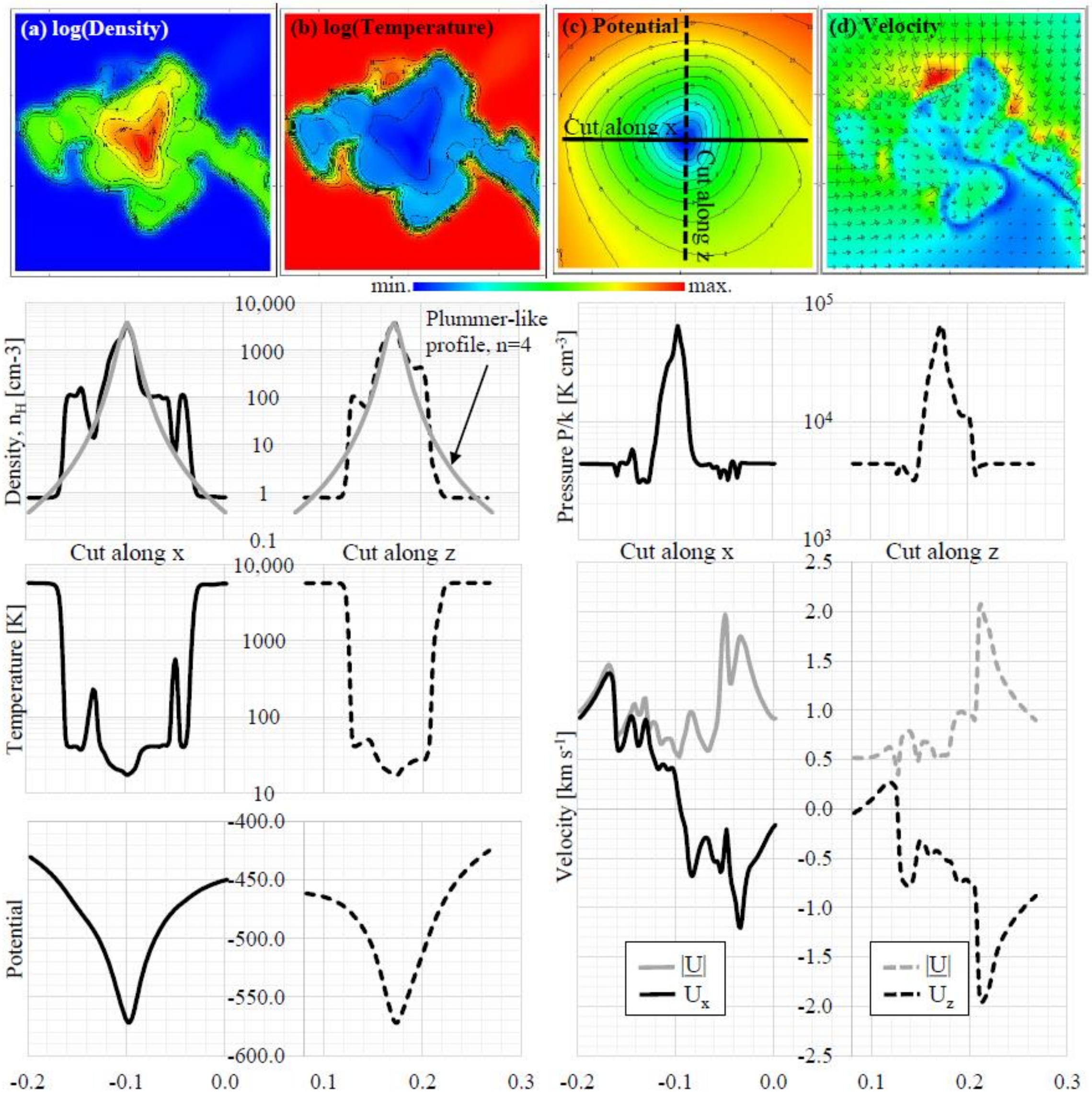
Wareing, Pittard & Falle 2019, MNRAS, 485, 4686-4702

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!

Wareing, Pittard & Falle 2019, MNRAS, 485, 4686-4702

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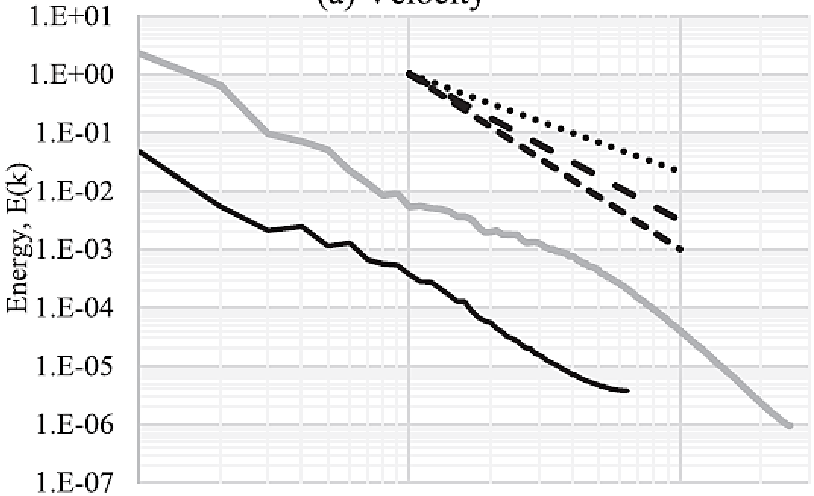
- **Turbulence-like (-5/3) power spectra in the warm stable medium**
- Short inertial range (1 decade) -> **by no means is this fully developed turbulence! …but all that's observed is 1dex!**
- Should extend to larger scales
- **Akin to Larson-like turbulence:- "hierarchy of small-scale irregularities 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

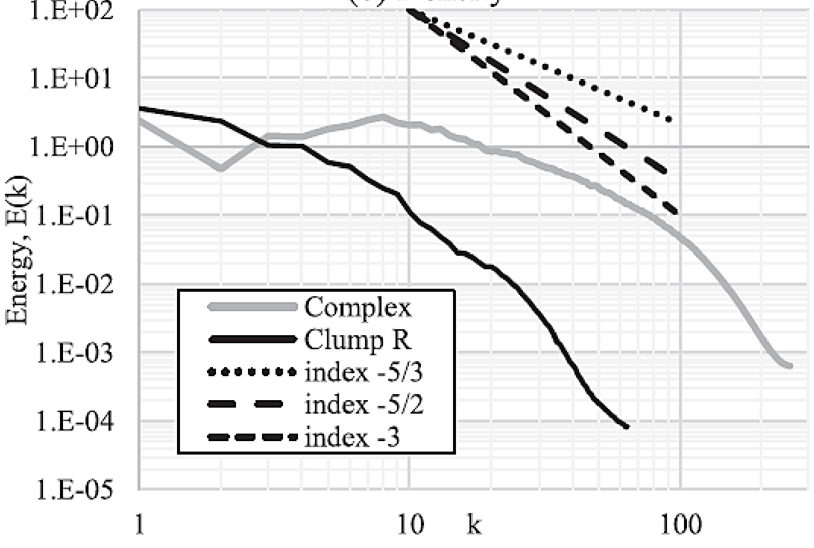
Compares well with recent observations:

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

(a) Velocity



(b) Density



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

Power spectra calculated by validated IDL script – thanks DWH!

Conclusions II

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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.
- The **Crutcher relationship is obtained** with the correct turning point, for the cloud and single clumps.

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, 2020, MNRAS, **492**, 4484
MHD case: striations, hour-glasses & integrals	Wareing, Falle & Pittard, 2021, MNRAS, **500**, 2831
HD Shock-TI cloud interaction	Kupilas, Wareing, Pittard & Falle, 2021, MNRAS, **501**, 3137

My thanks to you all!

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The Hitchhiker’s Guide to the Galaxy (2005 version)
A poor 6.8/10 IMDB score – must be because my bit part was on the cutting room floor!)