School of Physics and Astronomy
FACULTY OF MATHEMATICS AND PHYSICAL SCIENCES

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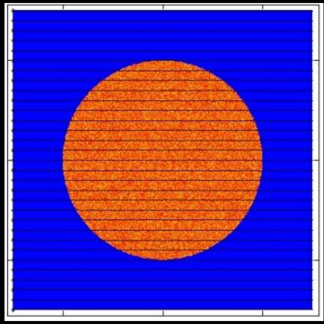
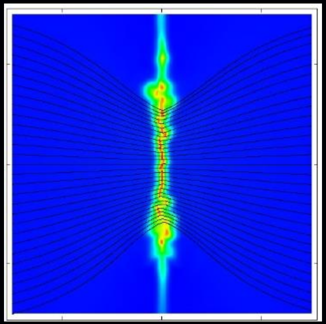
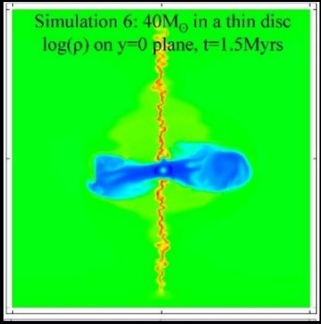
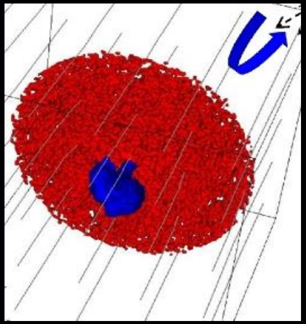
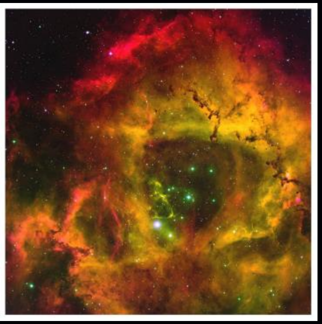
MHD simulation of cloud and clump formation triggered by the thermal instability and consequent massive star feedback

Chris Wareing, J. Pittard, S.A.E.G. Falle, S. Van Loo
Astrophysics Group

'The Wonders of Star Formation', Thursday 6th September 2018

Physical model

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Aim first to develop a realistic initial condition for the introduction of feedback.

Simplest approach with self-consistent physics for the formation of a molecular cloud and examine the results, before adding extra complexity

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

In future, extra additions may be necessary:

- Shear and pressure waves, imitating galactic evolution
- Large-scale flows: SN shock, cloud collision
- “Turbulent” initial conditions applying randomised velocities

but if one can find a solution without recourse to extra complexity ...

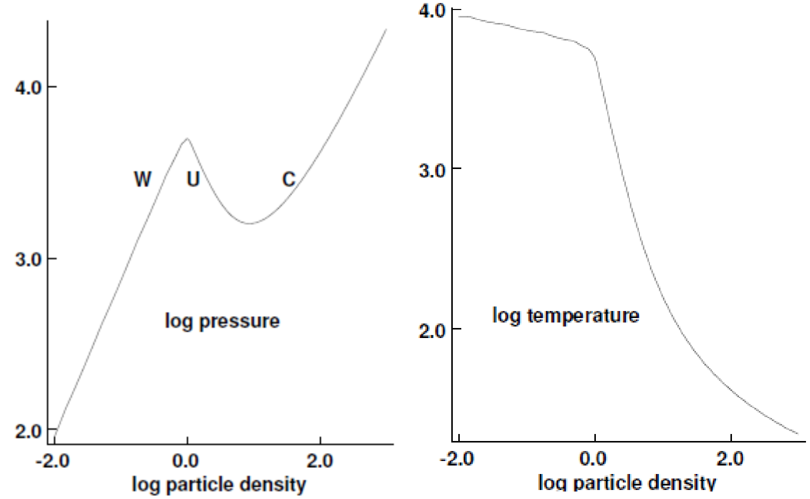
lex parsimoniae / Occam’s razor

Thermal instability

Two stable phases exist in which heating balances cooling (Field 1965, Wolfire et al. 1995)

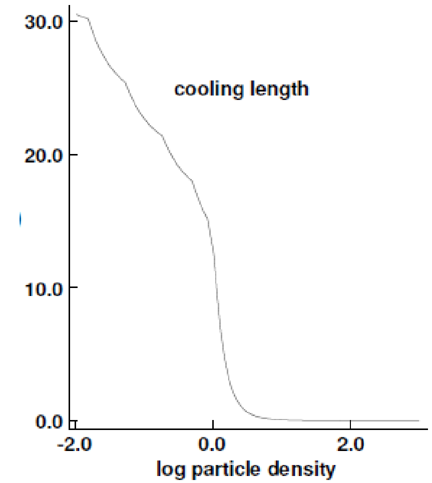
W – warm phase (T > 5000K, ρ < 1, P/k < 5000)
C – cold phase (T < 160K, ρ > 10, P/k > 1600)
U – unstable phase

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:

$<10^4$K	Γ : Koyama & Inutsuka (2002), (2007 correction)
10^4K<T<10^8K	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 $\rho^2\Lambda = \rho\Gamma$

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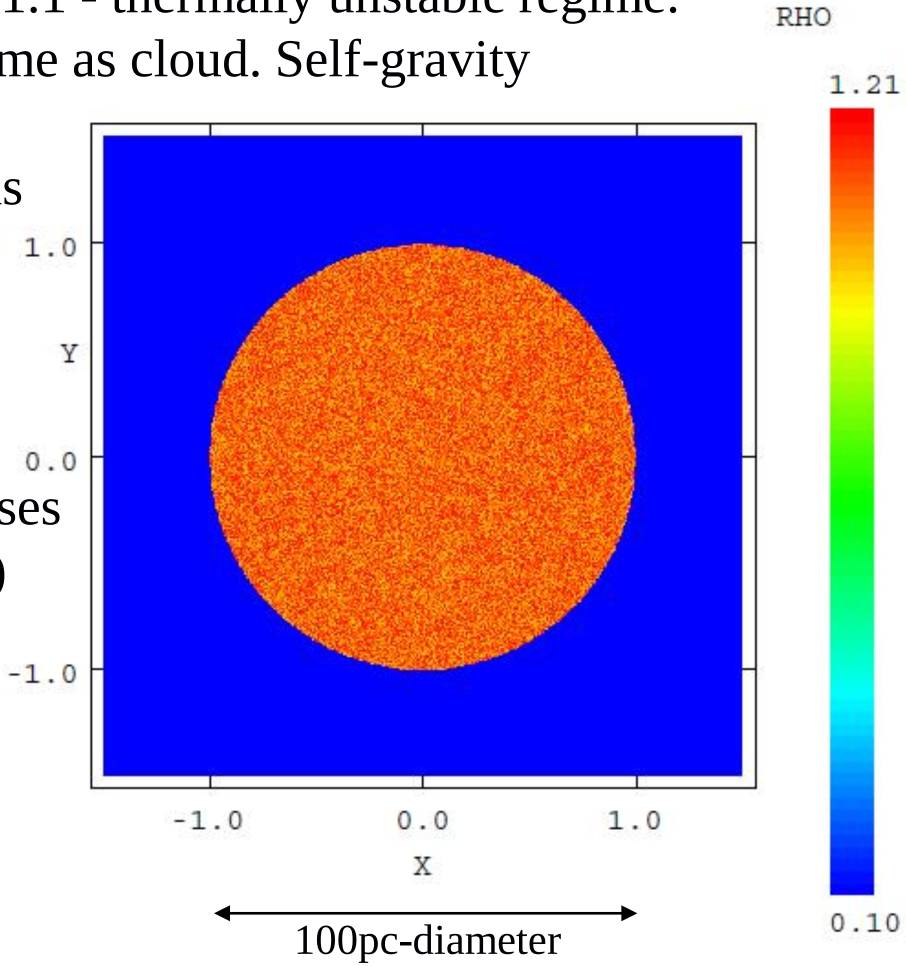
Spherical cloud, radius 50pc, density n_H=1.1 - thermally unstable regime. External medium density 0.1, pressure same as cloud. Self-gravity

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)

Mass: 1.7 10^4 $M_\odot$
Sound crossing time: 6.458 Myrs
Free fall time: 44.92 Myrs
Cooling time: 1.642 Myrs



Simple 3D Hydro condition

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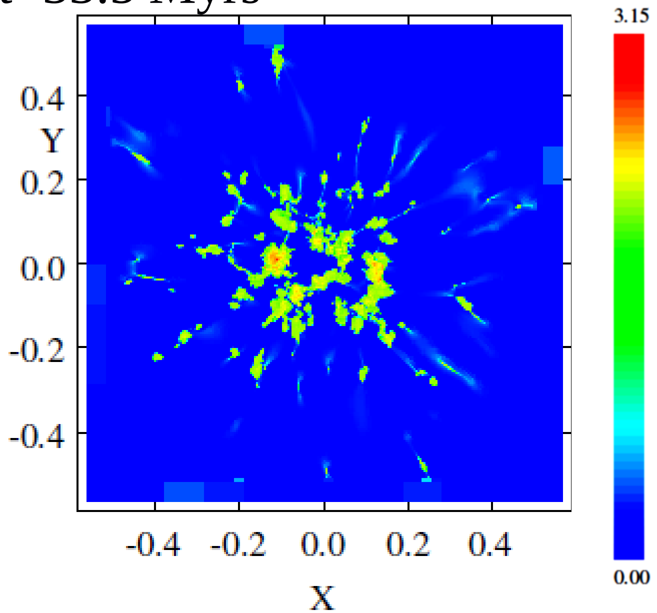
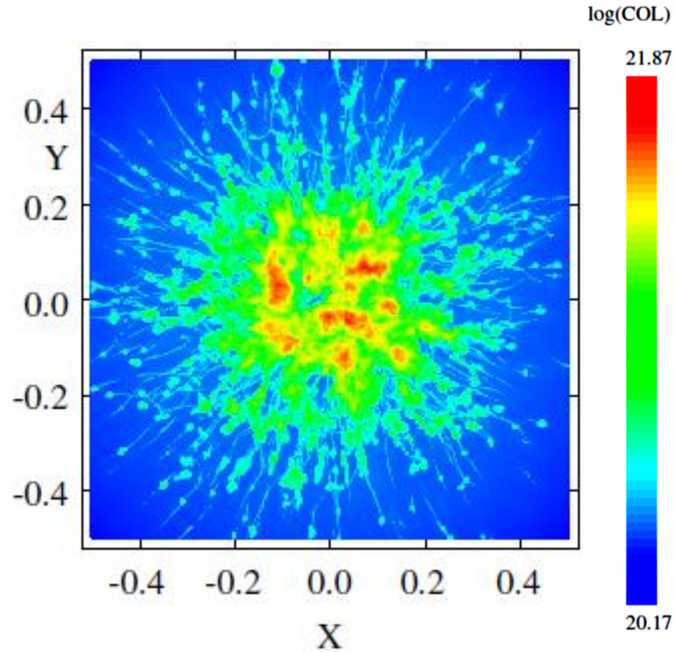
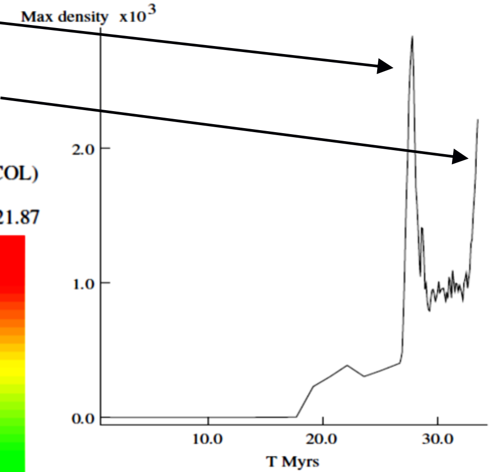
First peak due to TI-driven collapse, not gravity

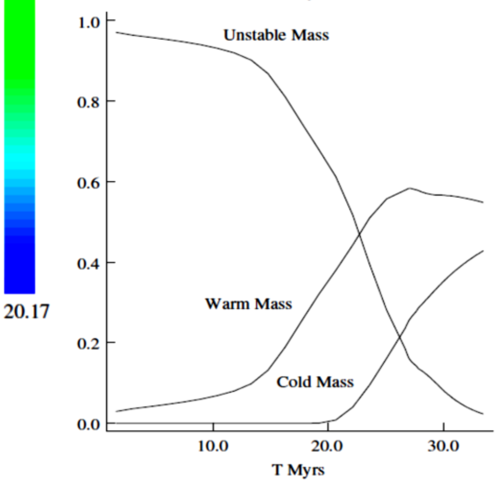
Second peak is due to gravity

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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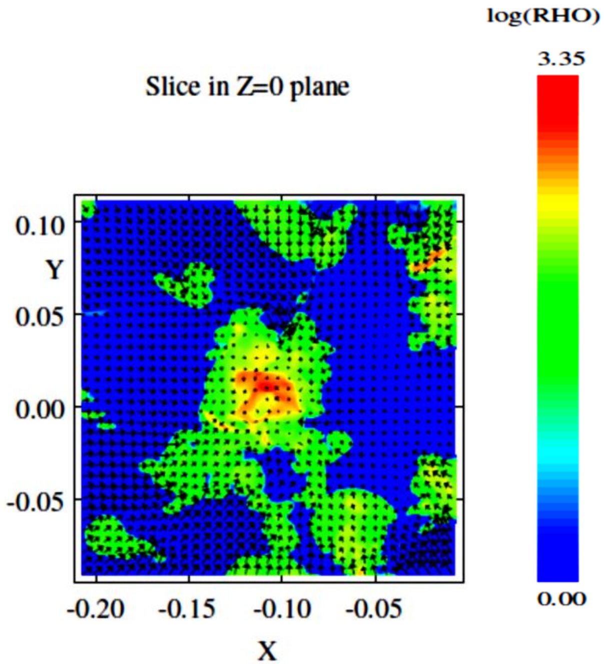

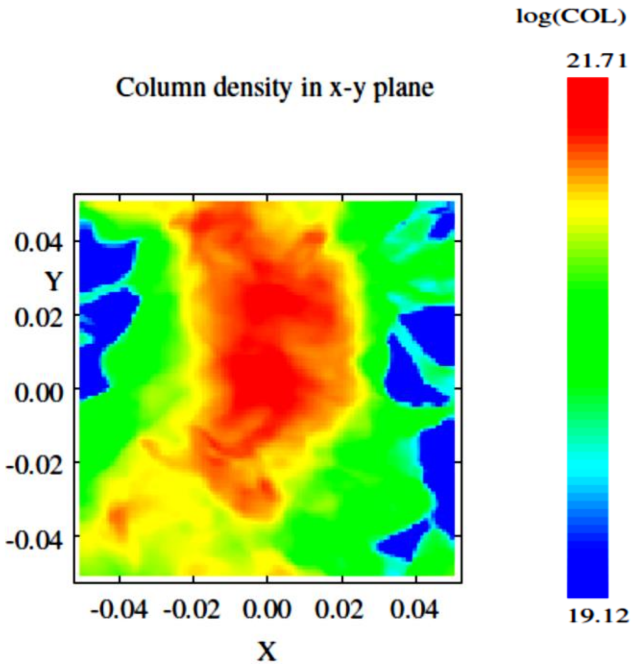

Diameter ~5pc, Mass 182$M_{\odot}$, Max density 2214, Mean density 177,
Max velocity 3.25 km s^{-1} (in frame of dense region), 0.6 km s^{-1} in dense gas.

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

Enlarged 3D Hydro condition

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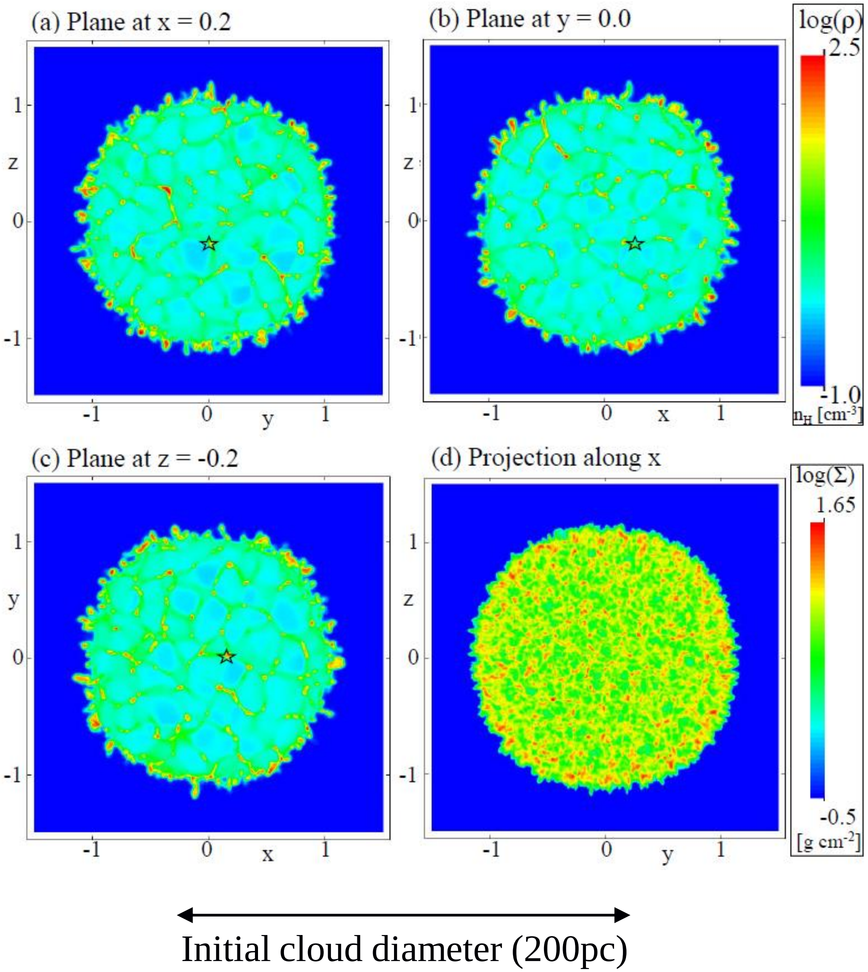
Domain size doubled, cloud radius increased to 100pc (r_{init} = 2.0), initial maximum AMR resolution 1024^3 (finest level 0.29pc), Mass 1.35 10^5 $M_\odot$



High density regions occur after
16.2 Myrs of diffuse cloud evolution

Increase resolution and simulate on…
- a further 28.5 Myrs
- resolution up to 0.039pc

Fellwalker clump identification watershed algorithm (Berry 2015)
- 28 gravitationally isolated clumps
- size scale ~5pc
- masses 50-300 $M_\odot$, >80% cold phase
- inward flow, dispersion 4-6 km s^{-1}
- ***unstable***

Will collapse to form clusters

Detail

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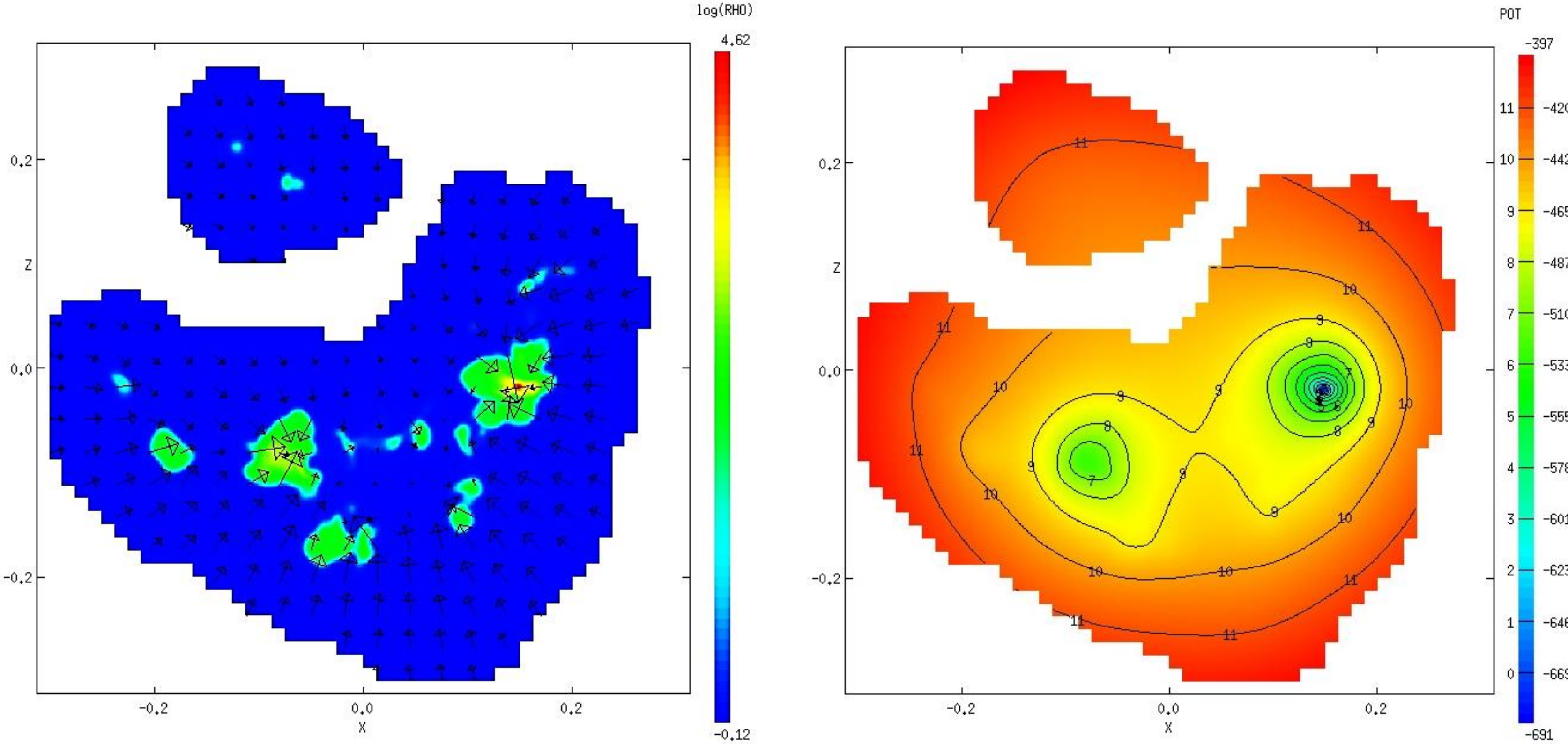

Most massive clump: 354 $M_\odot$ (cold phase: 292$M_\odot$), 5 pc diameter, max rho 1.5 10^4 (10^{-20} g cm^{-3}), mean rho ~230 (5×10^{-22} g cm^{-3}), dispersion 6.2 km s^{-1}.

3D MHD condition

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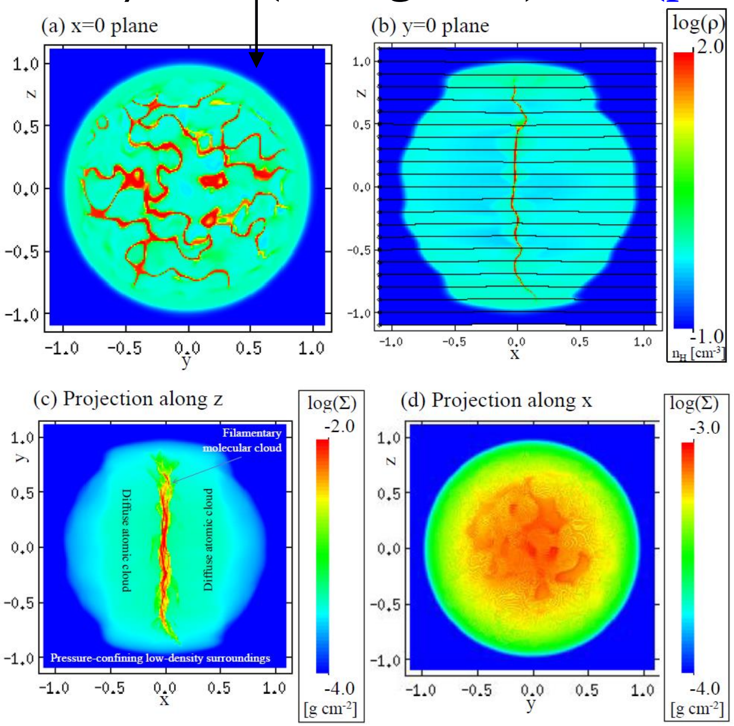
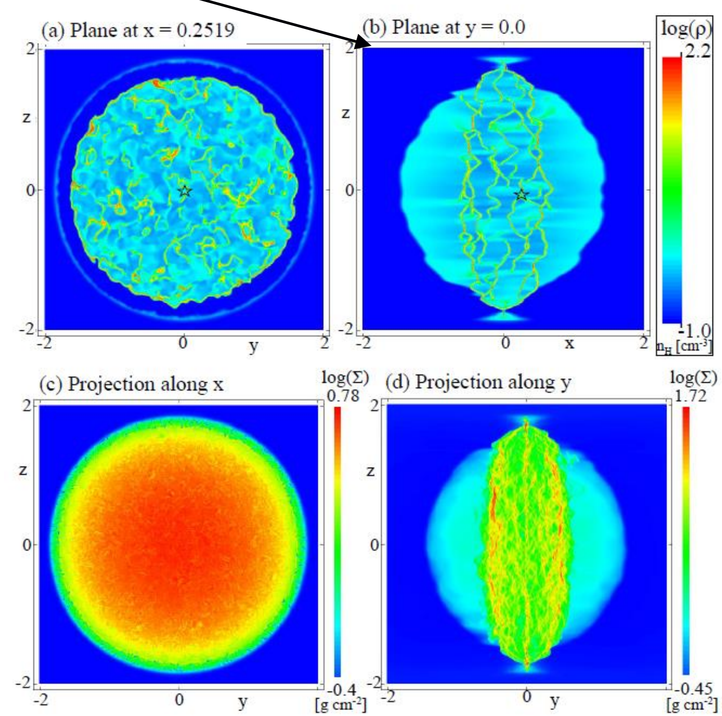
Exactly the same as hydro, but with uniform field in the x-direction.

- 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)



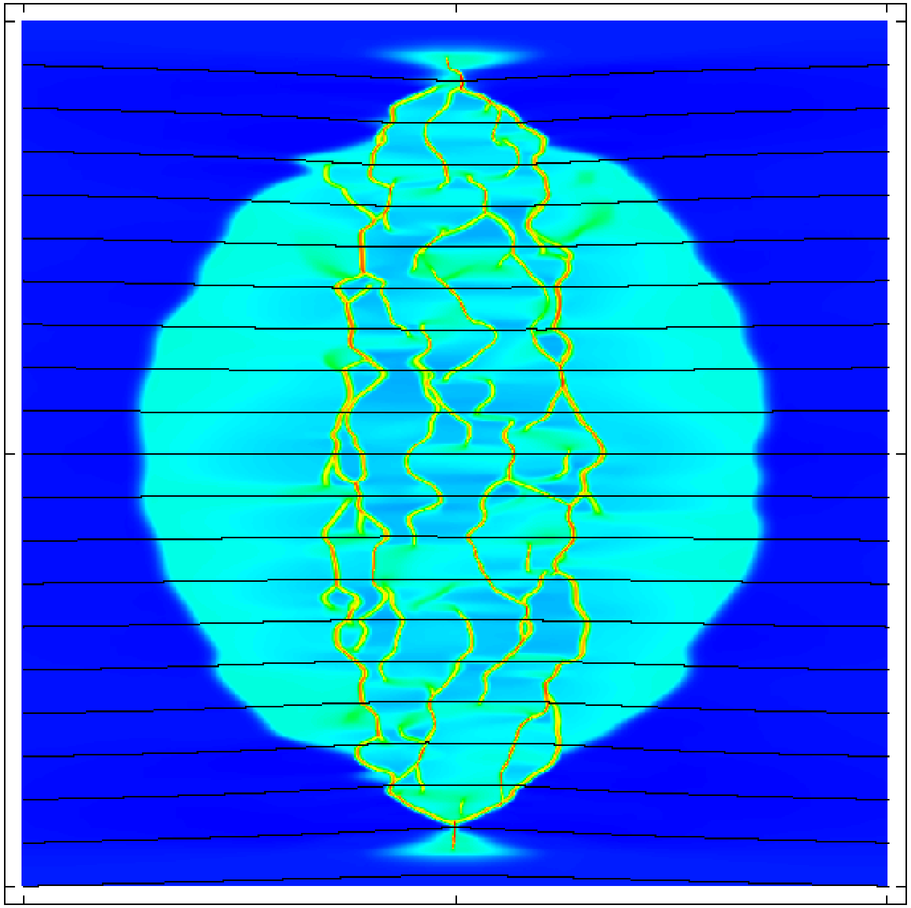


Magnetic seismology of Musca 'filament' indicates it is like this!

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

Naturally occurring striations

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



- Previous work (Tritsis and Tassis 2016) concluded sub-Alfvénic flows would not produce the observed density contrasts (0.03% contrast versus >25% observed).

- However, here we produce a range of density contrast up to factor 3 (400%).

- A further criticism of sub-Alfvénic flows has been the difficulty in which magnetically parallel and perpendicular structure can be produced in the same simulation – no problem!

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

Final collapse – *in progress*

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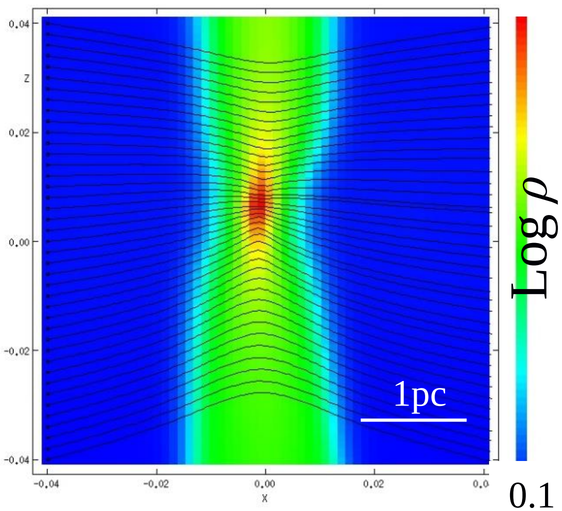
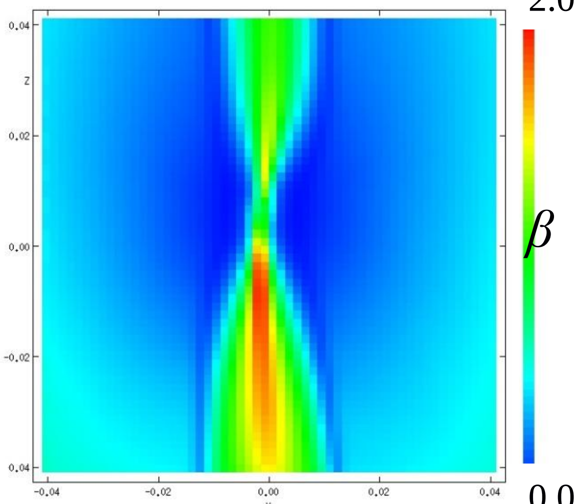
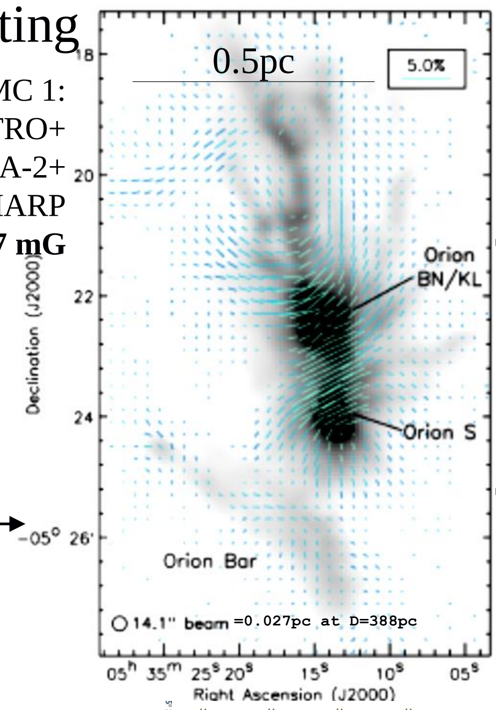
The plasma β=10.0 (weak field) case is looking very interesting





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



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

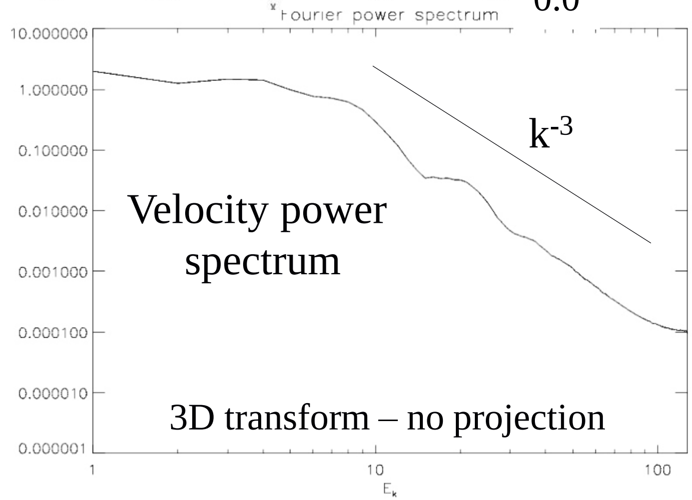
Gravitational collapse once the sheet has formed is dragging the field.

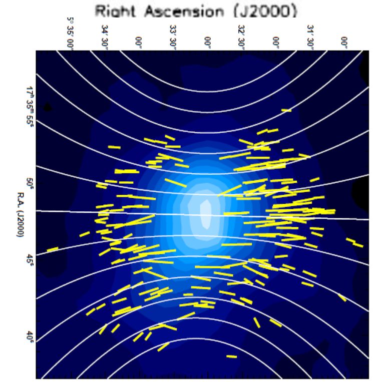
Field intensified in places from 0.3μG to ~0.1mG

V_{max}~3 km s^{-1}, $\mathcal{M}_{max}$~2.9,

T~10K, M~150$M_\odot$

Density power spectrum $k^{-2.5}$





Core-scale: FeSt 1-457 0.2pc x 0.2pc
Kandori et al. 1808.05327

=> Next step: re-simulate central section; add sink particles?

Mechanical stellar wind feedback

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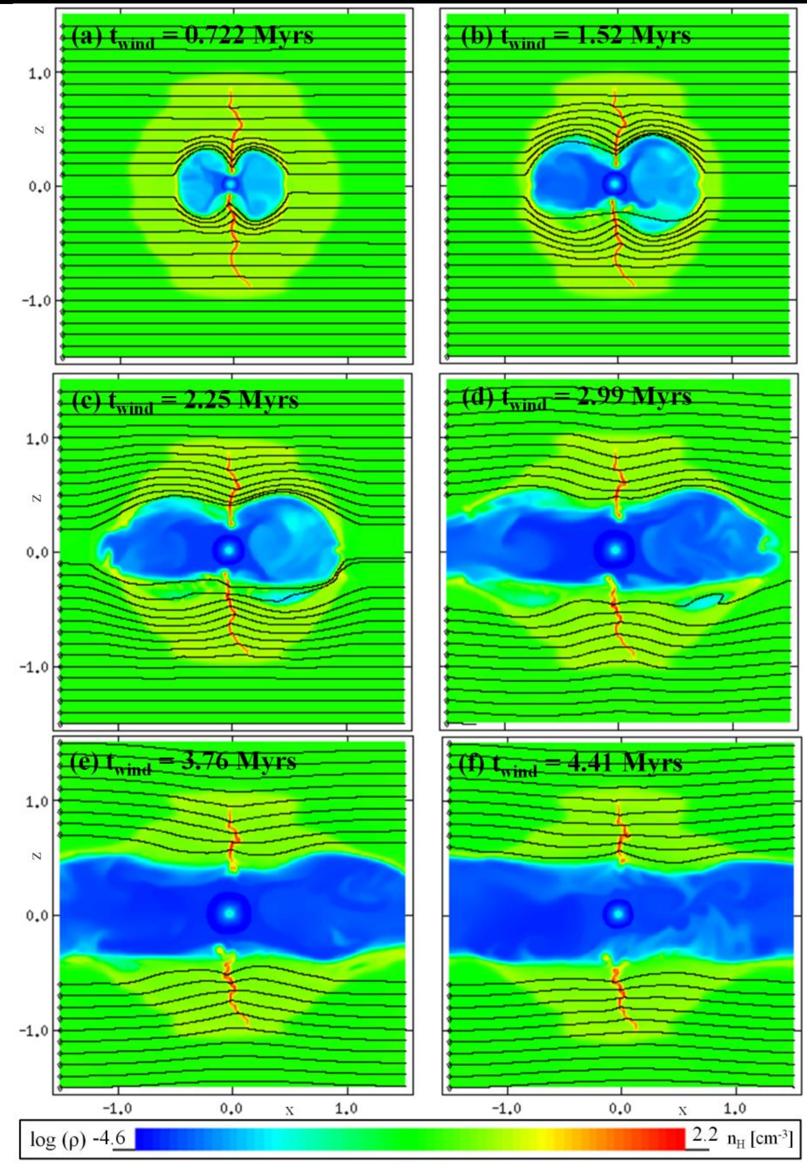
- 40 $M_\odot$ star embedded in the sheet.
- Realistic Geneva (2012) evolution.
- **Significant impact on the 1.7×10^4 $M_\odot$ cloud.**
- Large bipolar cavity evolves into a cylindrical cavity (diameter~40pc) through the centre of the cloud.
- Cavity filled with hot, tenuous wind material moving at 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 – the wind is not missing!



Solving a missing wind problem?

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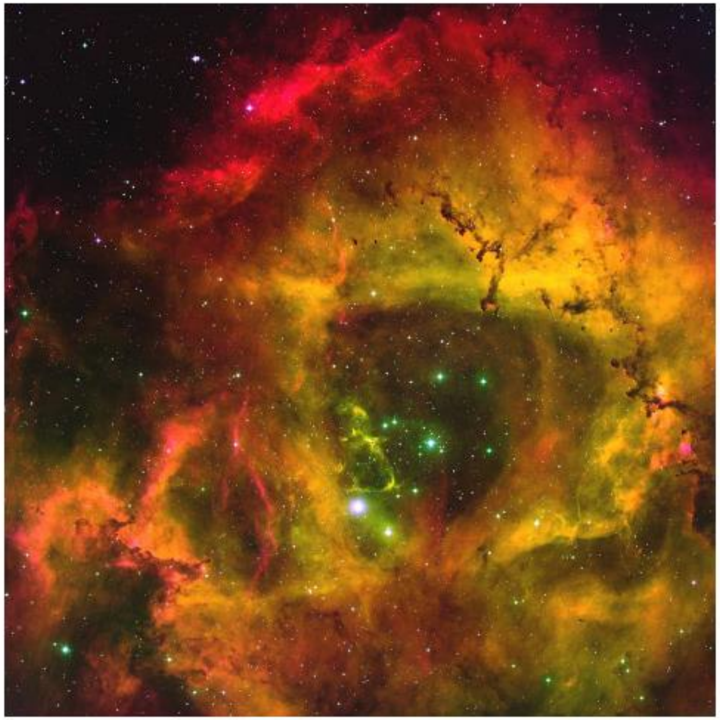
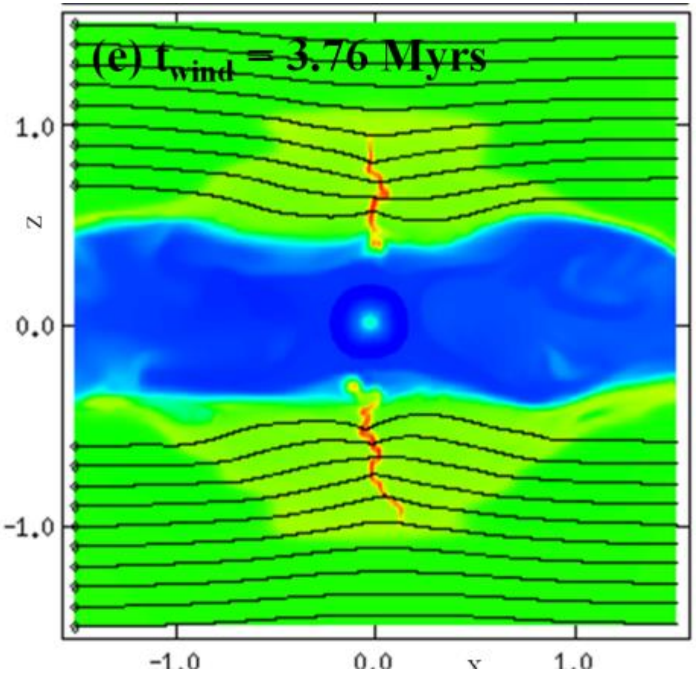
Feedback simulations into these clouds have shown it's possible to clear a relatively small central cavity from a sheet-like parent molecular cloud.

What if the Rosette nebula...



...was formed by something like this:
(β=1 cloud, 40$M_\odot$ feedback)



Simulating the Rosette Nebula

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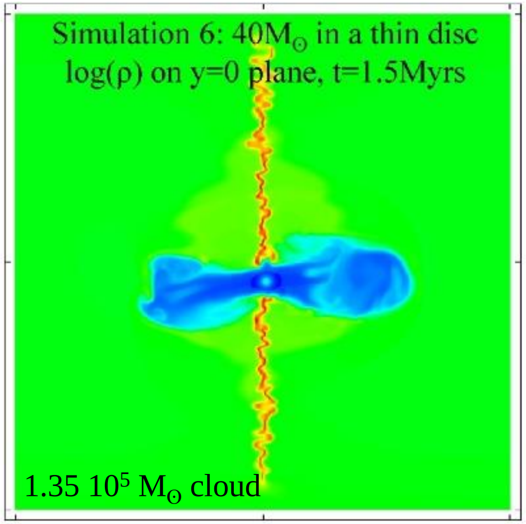
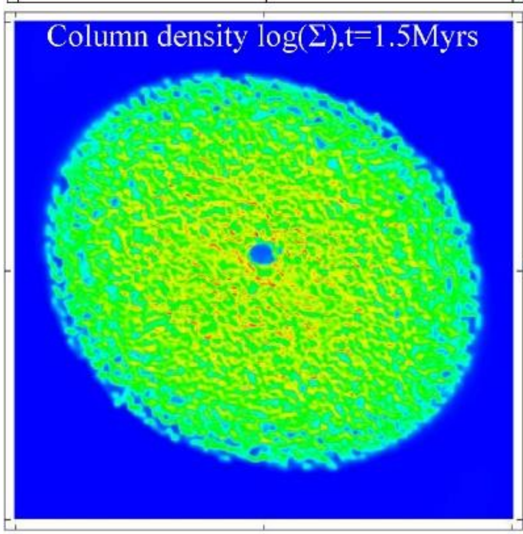
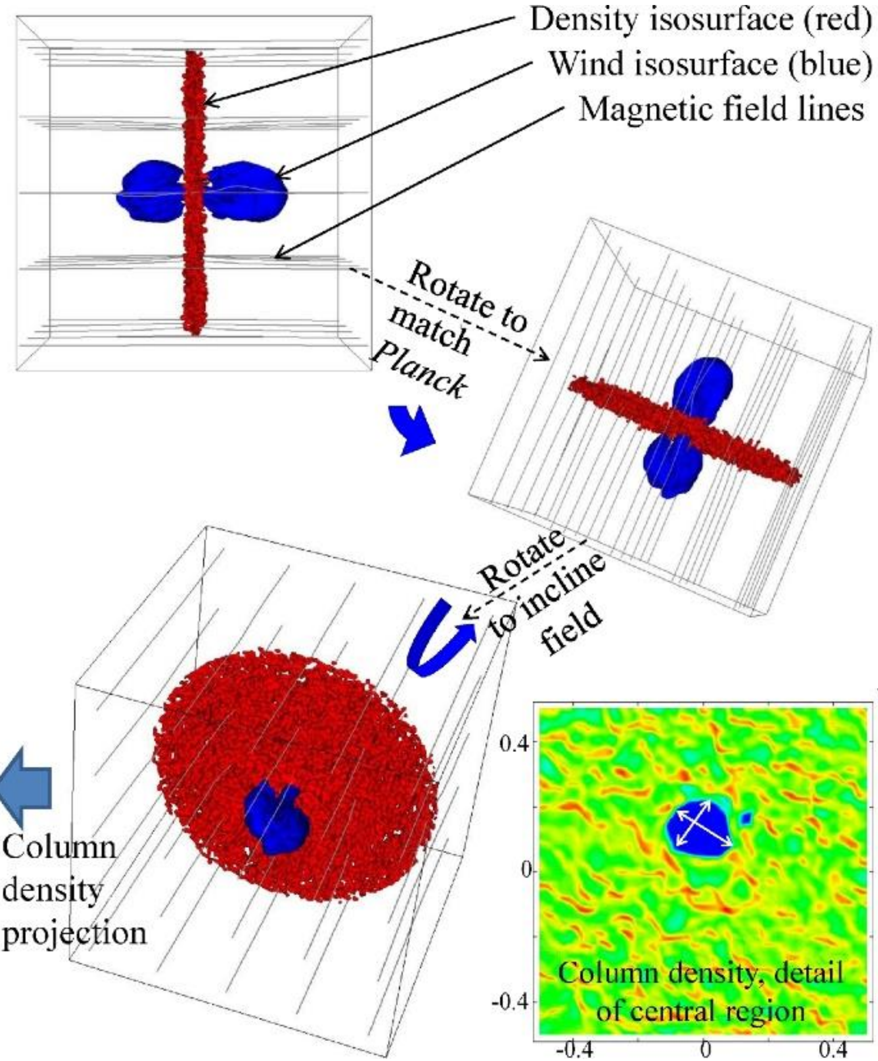
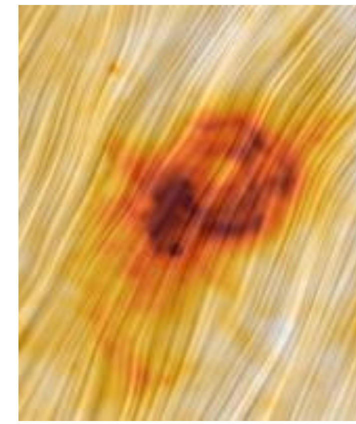


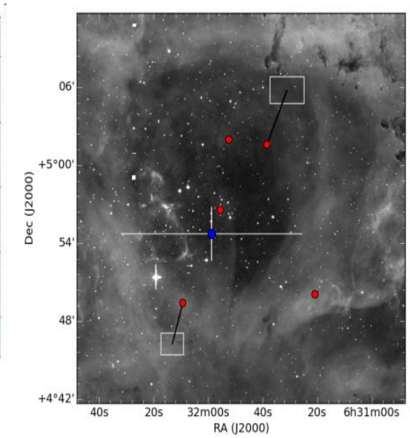






(Credit: ESA and the Planck Collaboration)

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



Conclusions

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Adopting only 3D hydrodynamics, thermal instability and self-gravity, it is possible to generate star-forming clumps from diffuse large-scale initial conditions.

With magnetic fields, interconnected sheets form, fragmented in projection, as recently inferred in the Musca cloud.

In the weak magnetic case, gravitational collapse intensifies field strength towards mG magnitudes and eventually will create double-horseshoe field structure.

A thin, extended molecular cloud in a magnetic field can host the Rosette Nebula.

Thank you for listening. Any comments or questions?

Thermal instability driven initial condition:	Wareing, Pittard, Falle & Van Loo, 2016, MNRAS, **459**, 1803
Magnetic feedback general case:	Wareing, Pittard & Falle, 2017, MNRAS, **465**, 2757
Hydrodynamic feedback general case:	Wareing, Pittard & Falle, 2017, MNRAS, **470**, 2283
Rosette special case:	Wareing, Pittard, Falle & Wright, 2018, MNRAS, **475**, 3598
Clumps formed by TI + gravity	Wareing, Pittard, Falle *in preparation*

Giant Molecular Clouds (GMCs)

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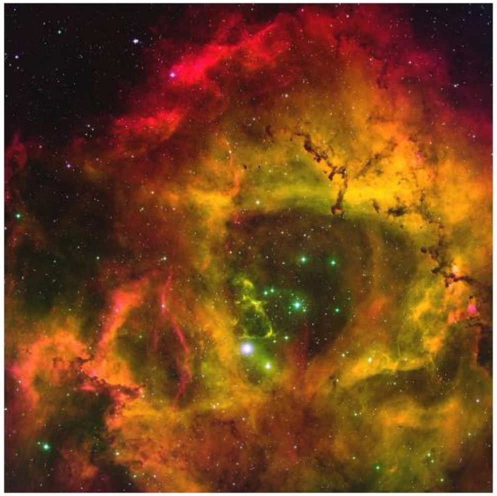
Most stars are formed in GMCs, e.g. Rosette MC

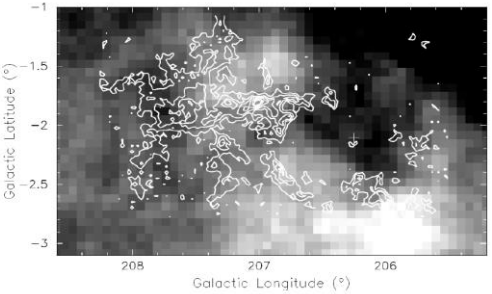
Size	~ 35 pc	
Mass	~ 10^5 $M_\odot$	
Mean density	~ 10^{-22} g cm^{-3}	
Temperature	~ 10 K	-> sound speed ~ 0.2 km s^{-1}
Alfvén speed	~ 2 km s^{-1}	magnetic pressure dominates
Velocity dispersion	~ 10 km s^{-1}	supersonic and super-Alfvénic
Jeans Mass	~ 10^7 $M_\odot$	based on velocity dispersion



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, 1º ≡ 28pc



Blitz and Stark 1986

<= Supersonic, but now sub-Alfvénic