School of Physics and Astronomy
FACULTY OF MATHEMATICS AND PHYSICAL SCIENCES
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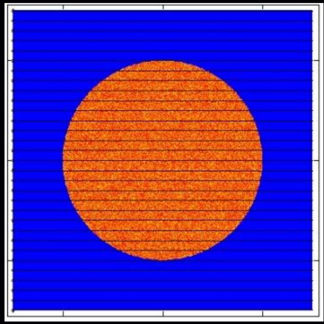
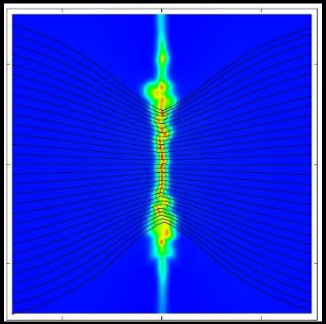
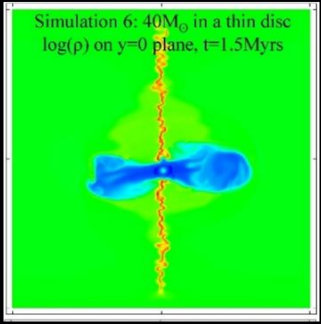
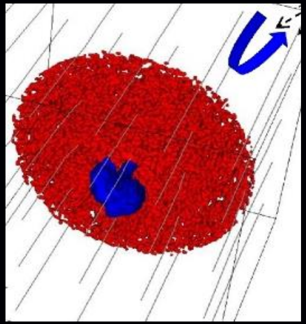
MHD simulation of cloud and clump formation triggered by the thermal instability

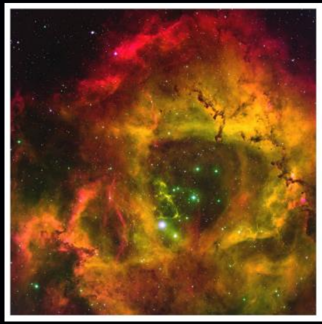
(and consequent massive star feedback)











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

'Tracing the Flow', Tuesday 3rd July 2018

Giant Molecular Clouds (GMCs)

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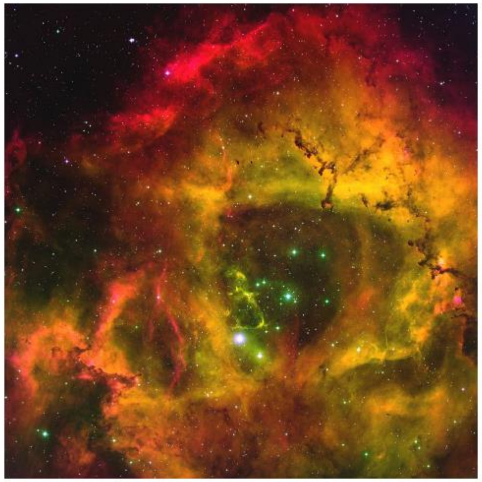
Most stars are formed in GMC e.g. Rosette Molecular Cloud



Size	$\simeq 35$ pc
Mass	$\simeq 10^5\ M_\odot$
Mean Density	$\simeq 10^{-22}$ gm cm^{-3}
Temperature	$\simeq 10$ K $\Rightarrow$ sound speed $\simeq 0.2$ km s^{-1}
Alfvén speed	$\simeq 2$ km s^{-1} $\Rightarrow$ magnetic pressure dominates
Velocity dispersion	$\simeq 10$ km s^{-1} - Supersonic and super Alfvénic
$\Rightarrow$ Jeans Mass	$\simeq 10^7\ M_\odot$ (based on velocity dispersion)

Translucent Clumps

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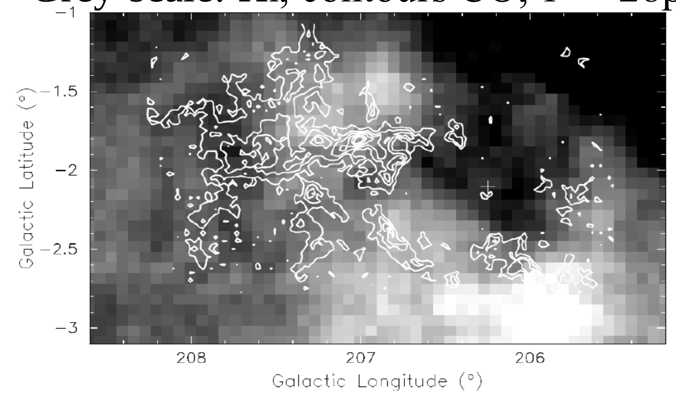
Rosette GMC not Homogeneous: CO maps show that it consists of $\simeq$ 70 clumps with

Grey-scale: HI, contours CO, $1^{\circ} \equiv 28$pc



Blitz and Stark 1986

Sizes	$\simeq 3.5 - 8.0$ pc
Masses	$\simeq 10^2 - 2\ 10^3\ M_\odot$
Densities	10^{-21} gm cm^{-3}
Temperature	$\simeq 10$ K $\Rightarrow$ Sound speed $\simeq 0.2$ km s^{-1}
Alfvén speed	$\simeq 2$ km s^{-1} $\Rightarrow$ magnetic pressure dominates (Crutcher 1999)
Velocity dispersion	$\simeq 1$ km s^{-1} - Supersonic and sub Alfvénic
$\Rightarrow$ Jeans Mass	$3\ 10^3\ M_\odot$ (based on velocity dispersion)

Physical model

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

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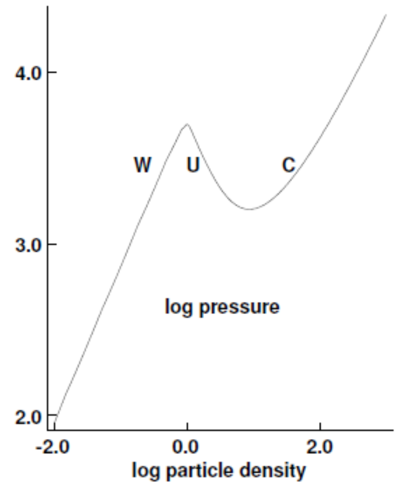
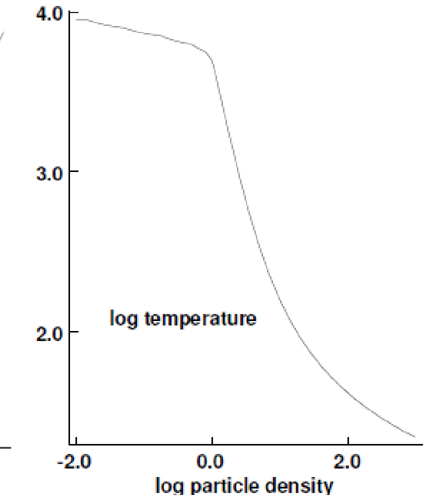
Two stable phases exist in which heating balances cooling (Wolfire et al. 1995)

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

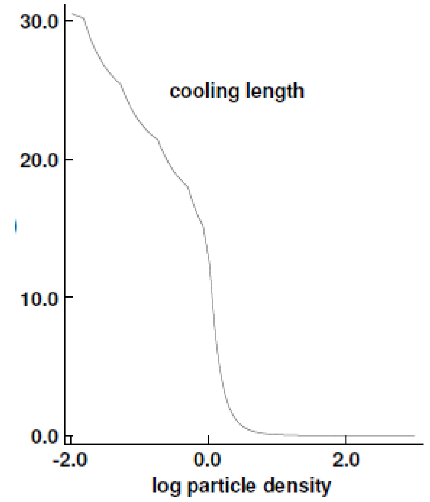
In the unstable region, can form a length scale from cooling time and sound speed ~ a few pc.





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

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

Simple 3D Hydro condition

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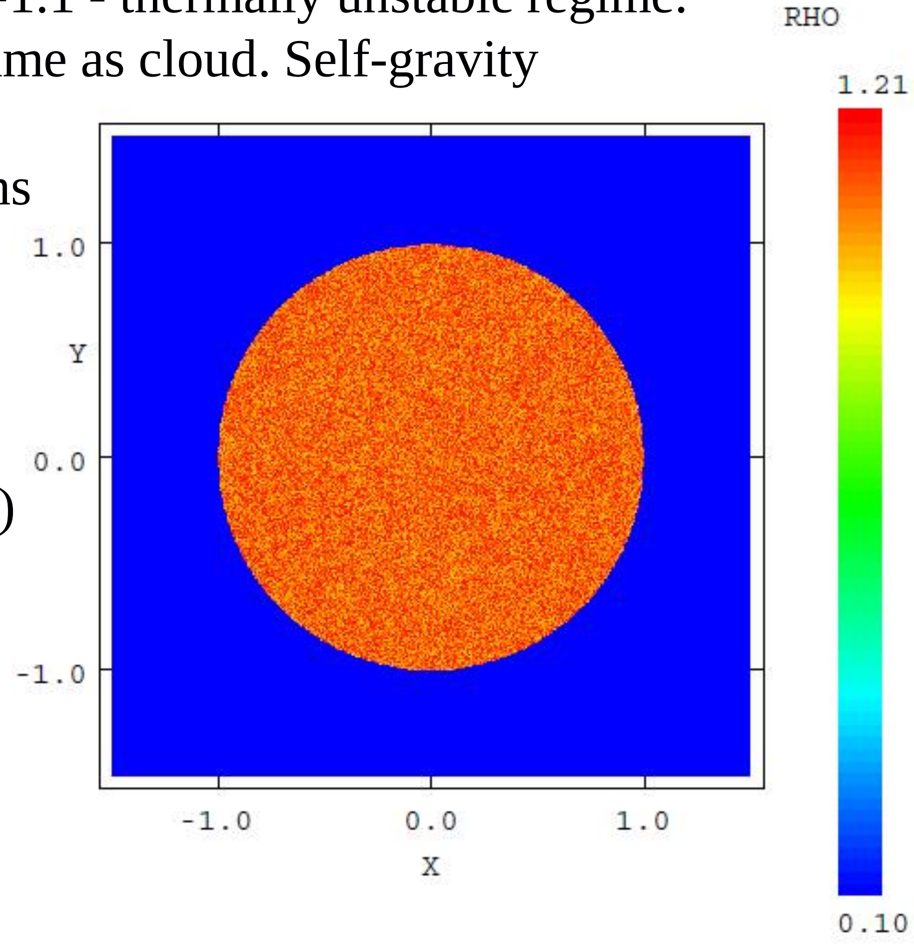
Spherical cloud, radius 50pc, density n_H=1.1 - thermally unstable regime. External medium density 0.1, pressure same as cloud. Self-gravity

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

Quiescent cloud v=0

Up to 10 levels of AMR (4096^3: 0.037pc)

Mass: 1.7 10^4 M_{sun}
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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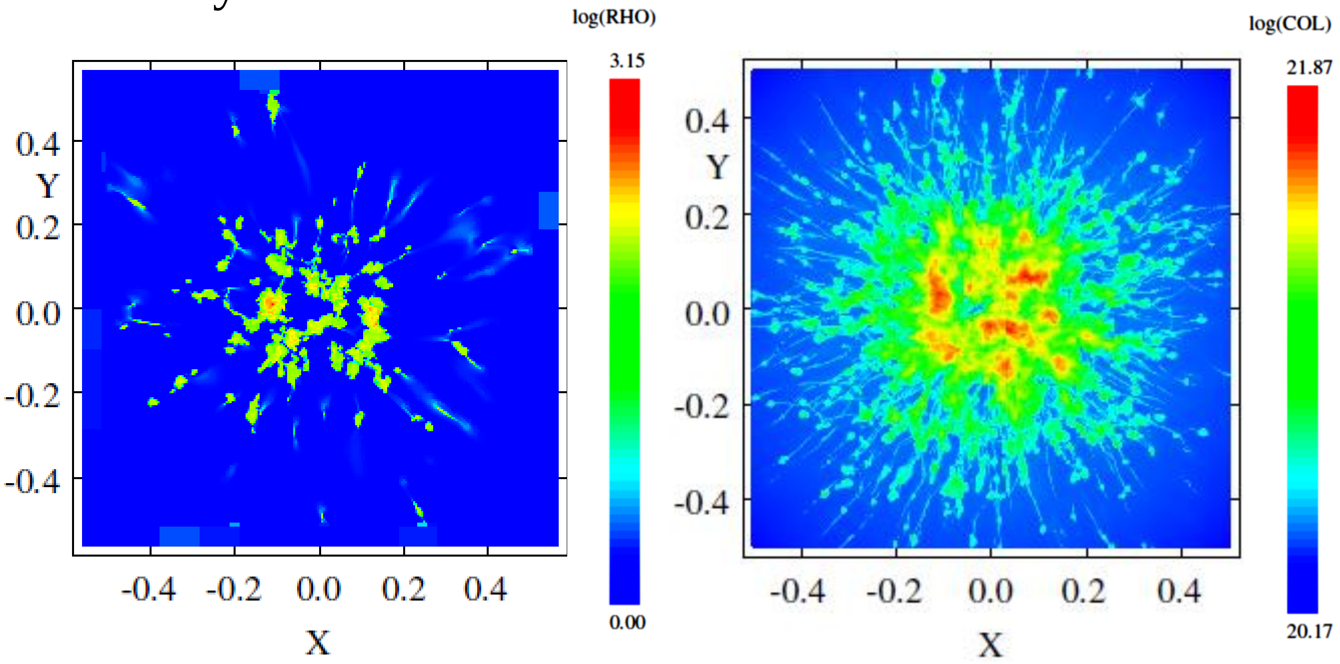
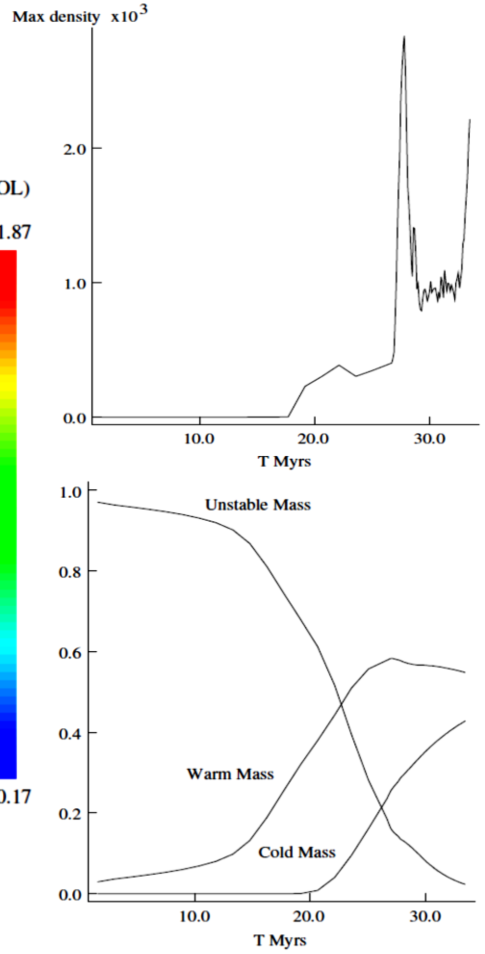
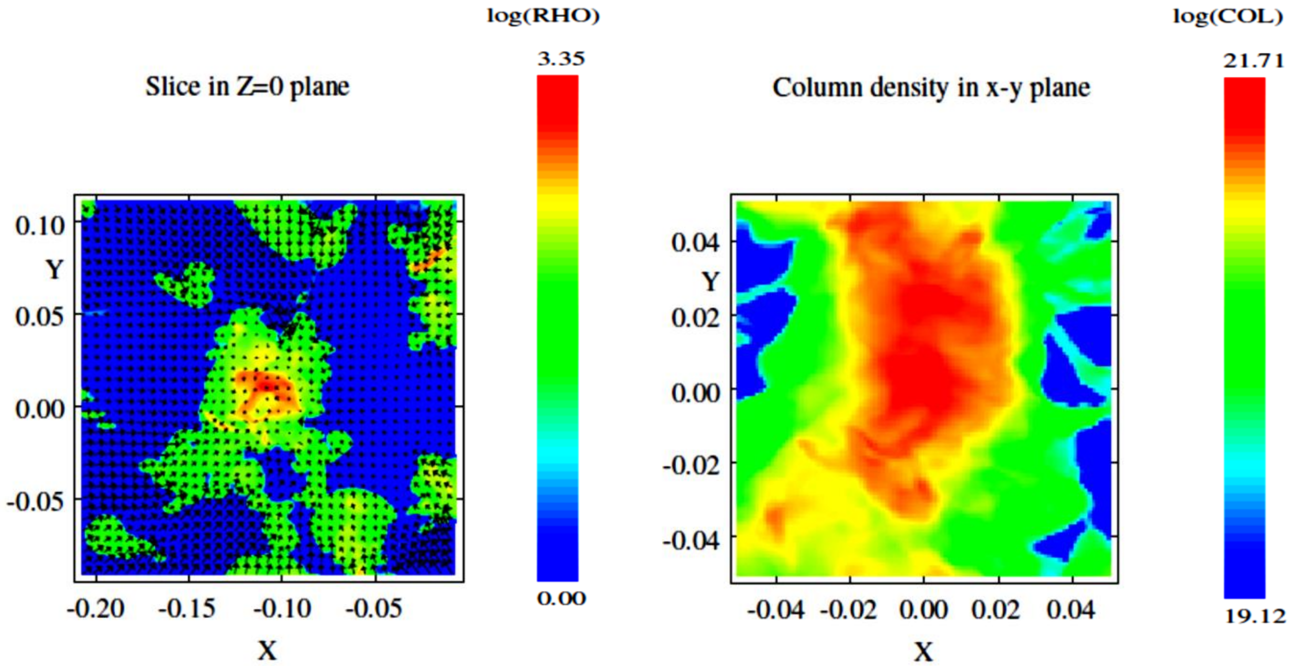
First peak not due to gravity, second one is =>

t=33.5 Myrs





Detail at t=33.5 Myrs



Diameter ~5pc, Mass 182M_{sun}, 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_{sun})

Enlarged 3D Hydro condition

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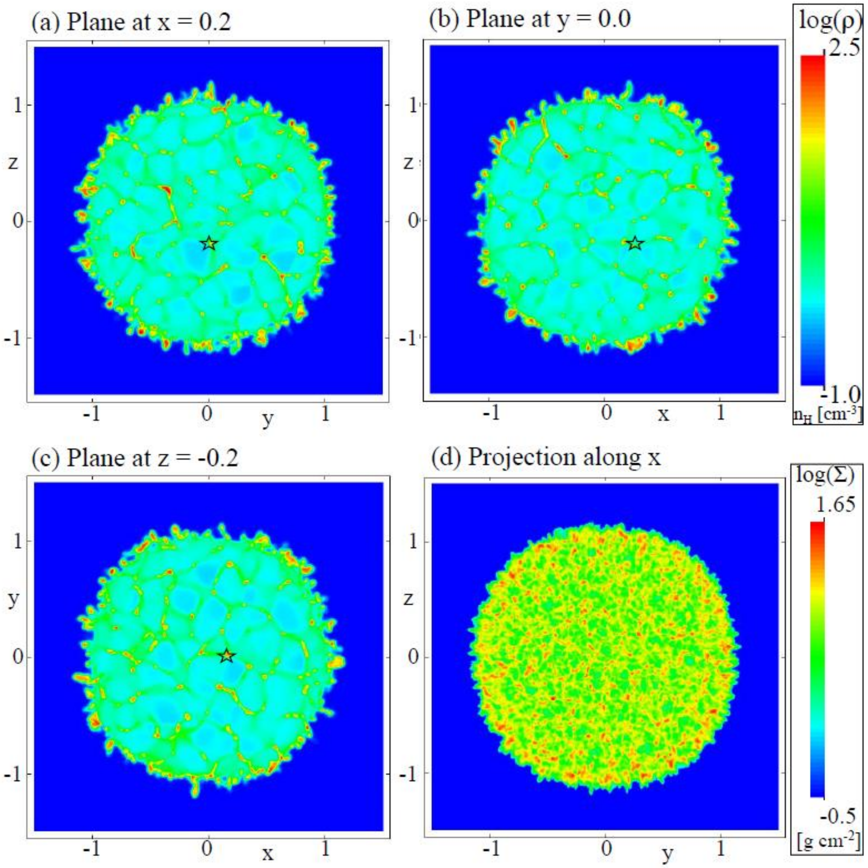
Domain size doubled, cloud radius increased to 100pc (r_{init} = 2.0), initial maximum AMR resolution 1024^3 (finest level 0.29pc), Mass 1.35 10^5 M_{sun}



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

Will collapse to form clusters

Detail

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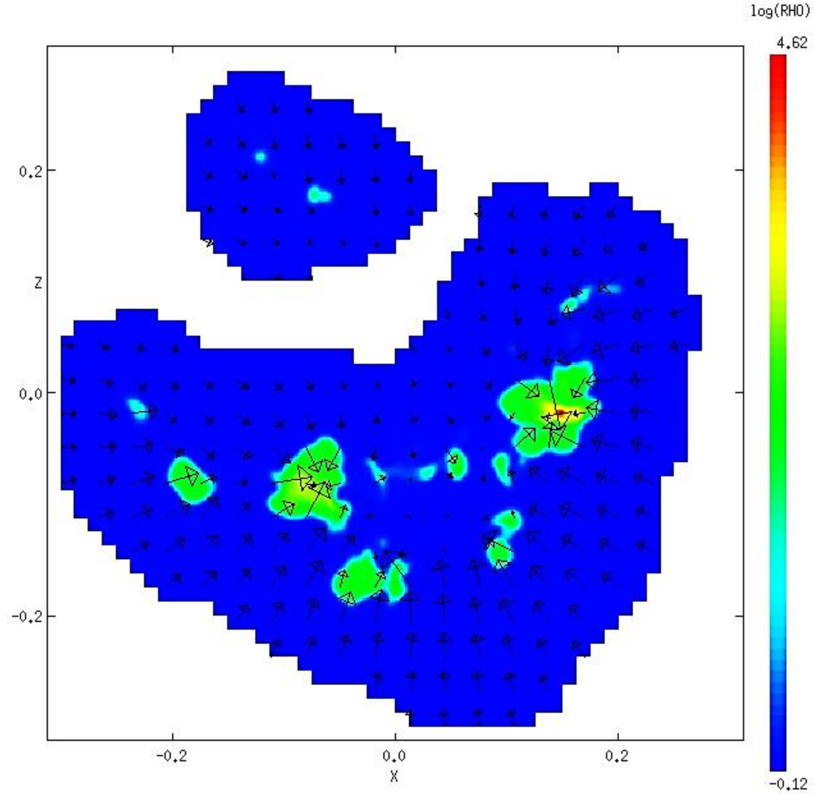

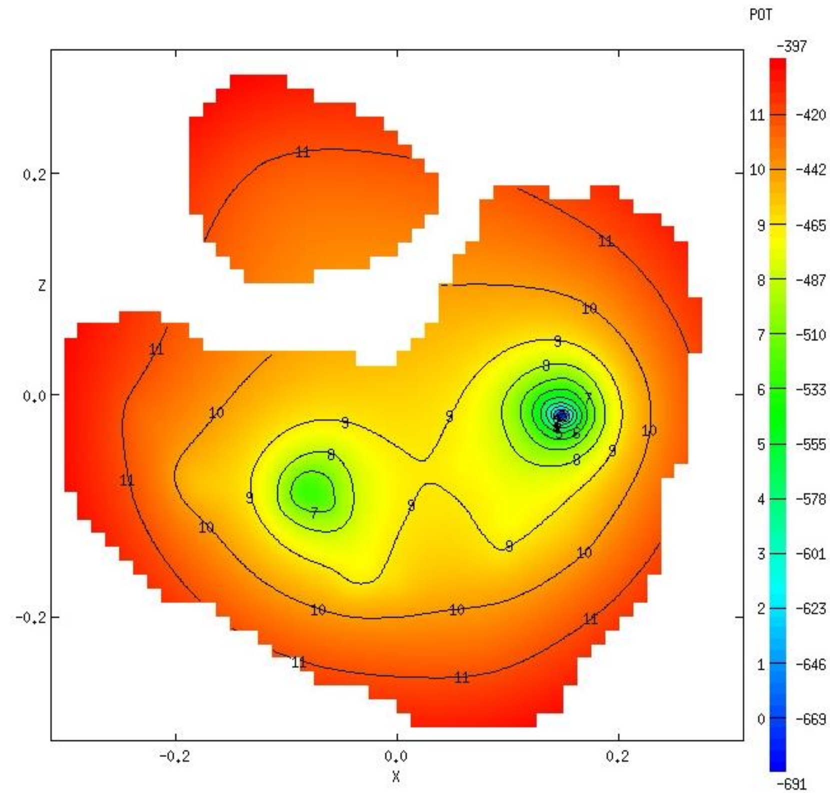

Most massive clump: 354 M_{sun} (cold phase: 292M_{sun}), 5 pc diameter, max rho 1.5 10^4 (10^{-20} gm cm^{-3}), mean rho ~230 (5 10^{-22} gm cm^{-3}), dispersion 6.2 km s^{-1}.

3D MHD condition

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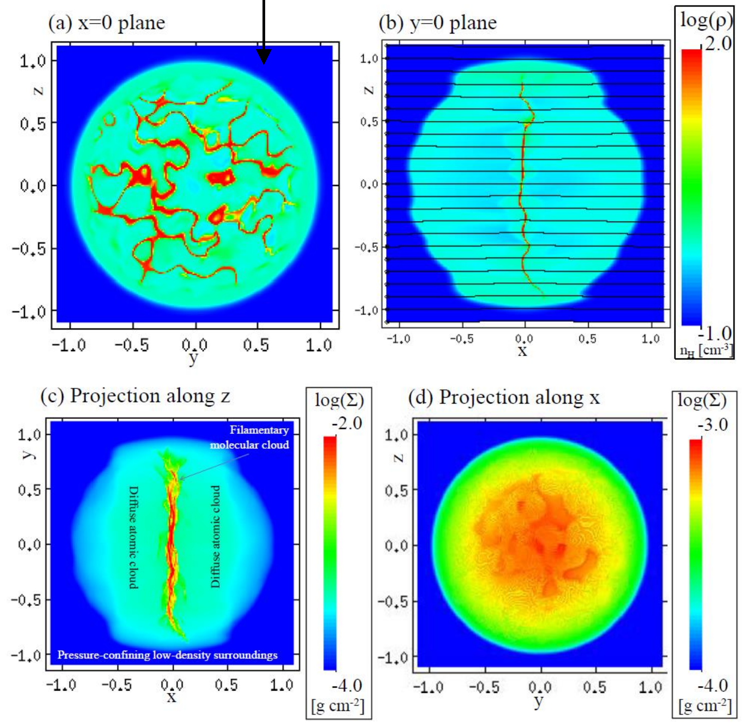
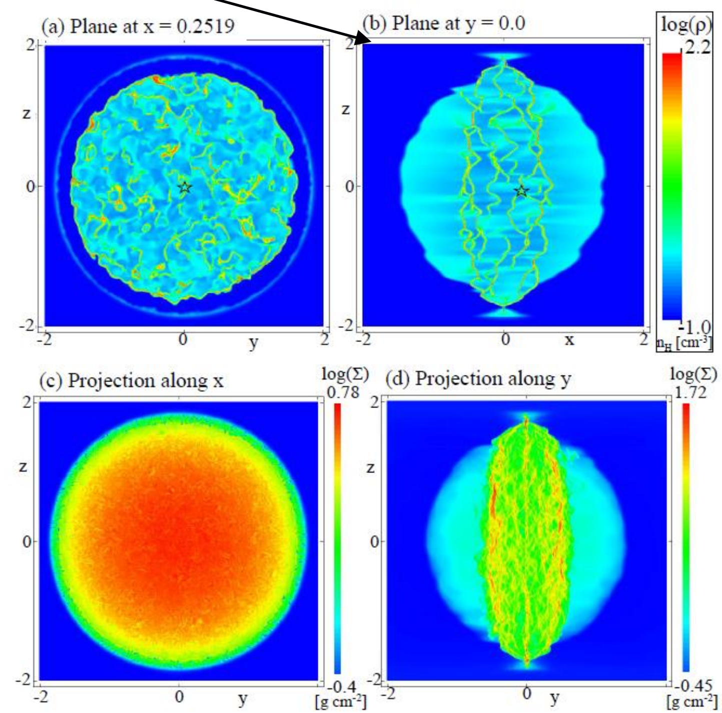
Exactly the same as hydro, but with uniform field in the x-direction.

- Regular (1.7 10^4 M_{sun}) and enlarged (1.35 10^5 M_{sun}) 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)

3D MHD condition – *in progress*

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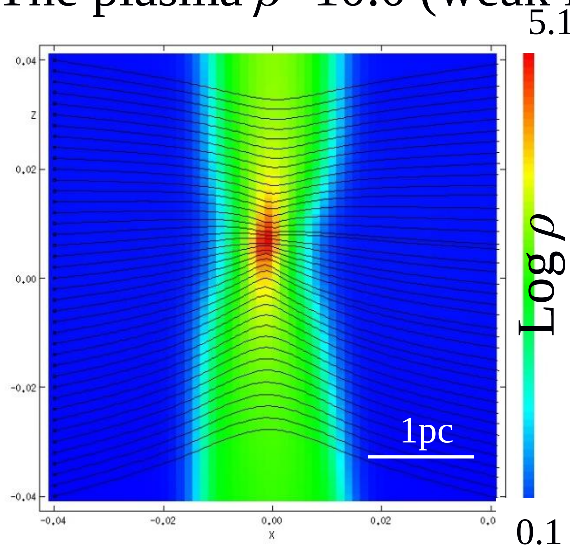
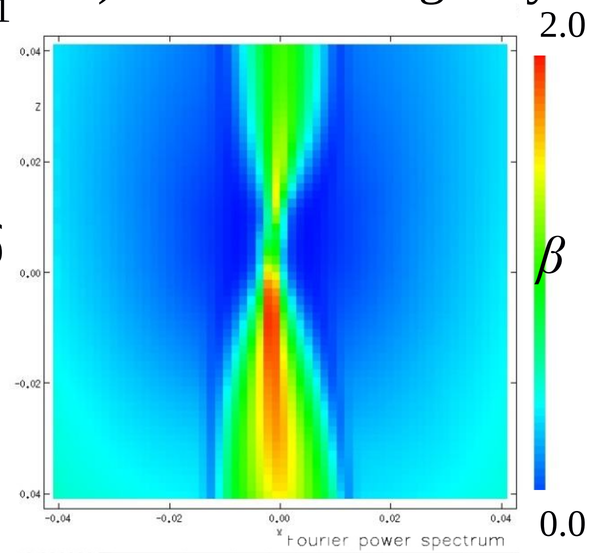
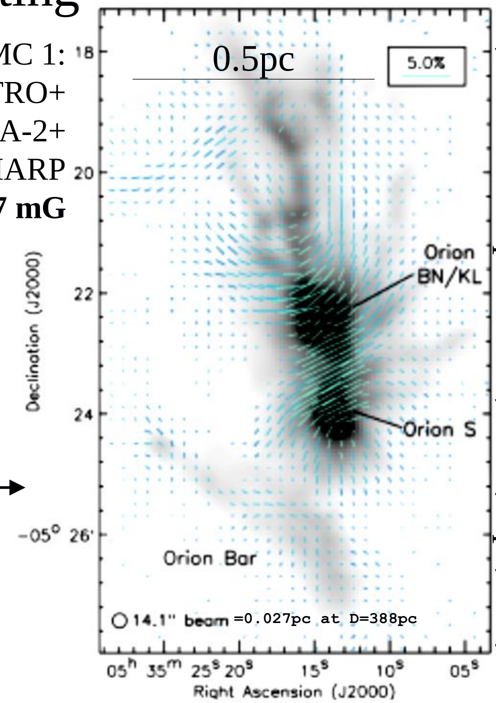
The plasma β=10.0 (weak field) case is looking very interesting





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



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

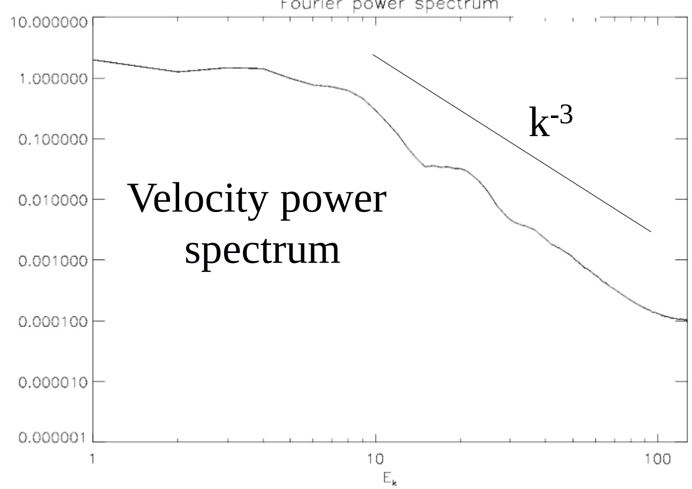
Gravitational collapse once the sheet has formed is dragging the field.

Field intensified in places from 0.3μG to ~0.1mG

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

T~10K, M~150M_{sun}

Density power spectrum $k^{-2.5}$



Beginning to show similarities?

=> Next step: re-simulate central section; sinks

Mechanical stellar wind feedback

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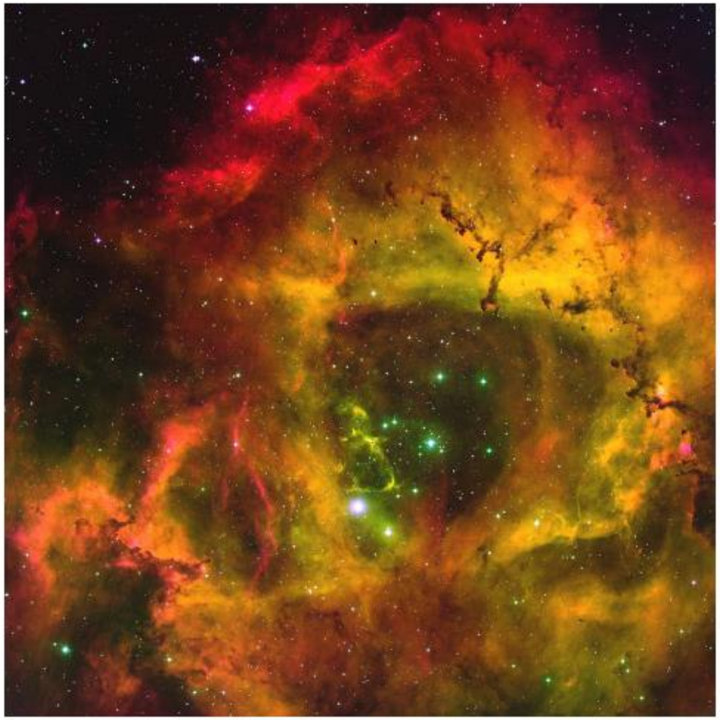
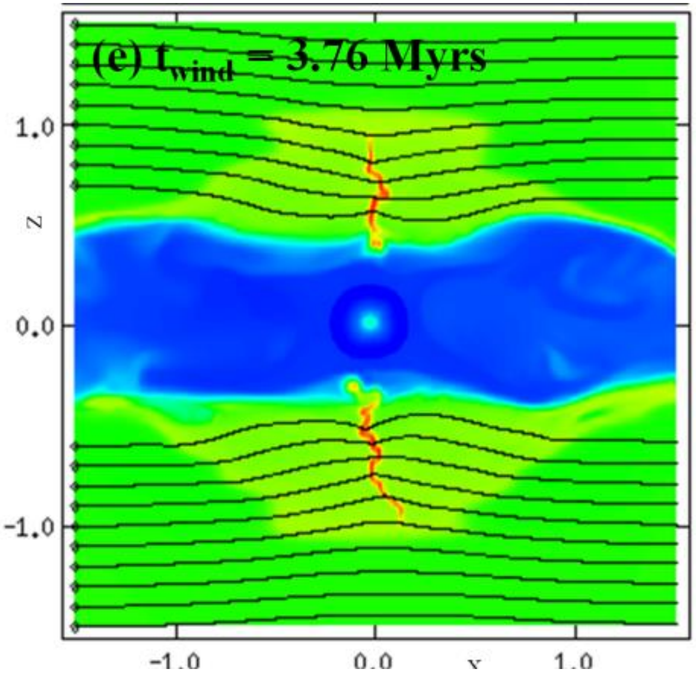
Feedback simulations into these clouds have shown it's possible to clear a relatively small central cavity from a sheet-like parent molecular cloud.

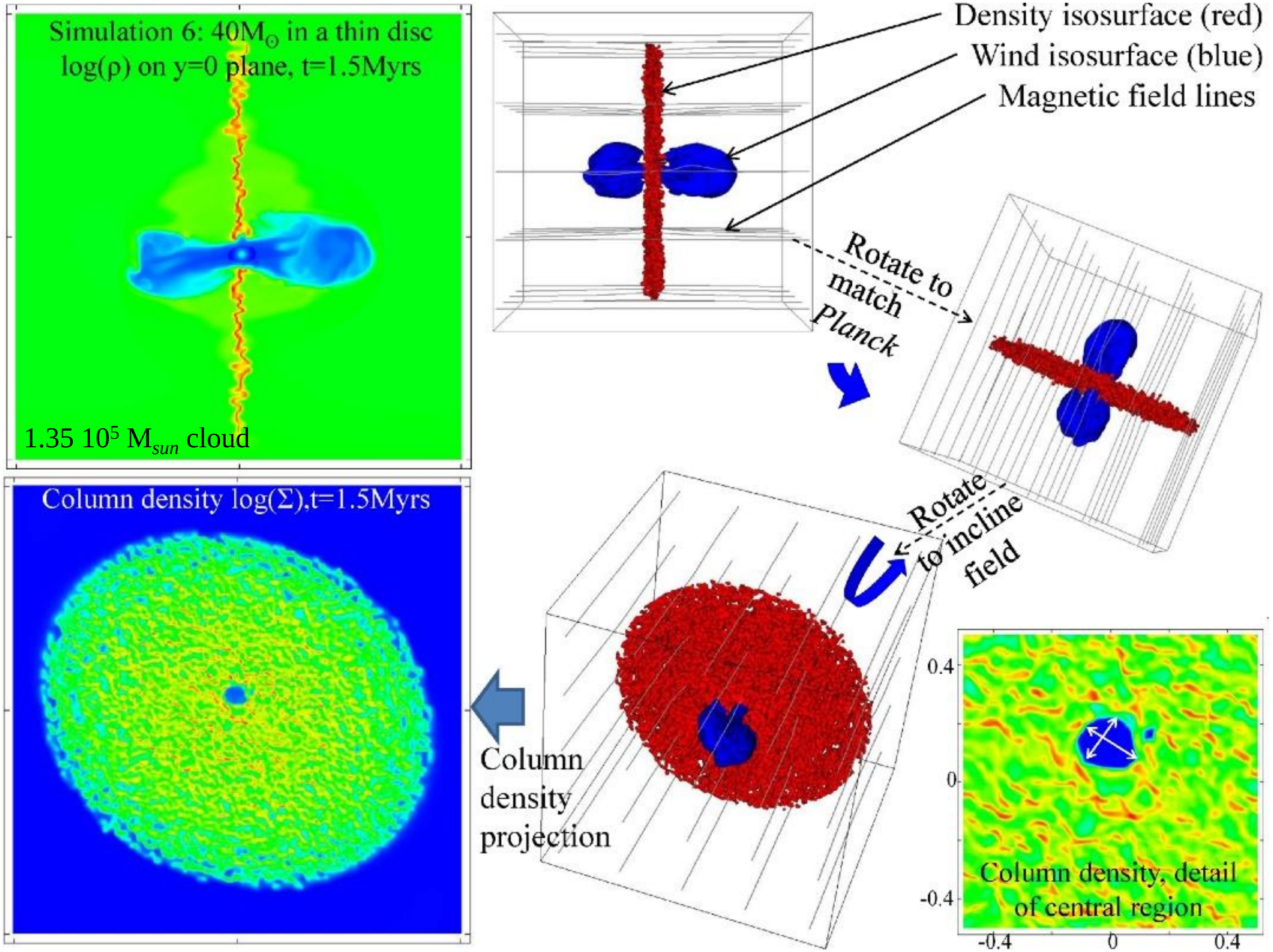
What if the Rosette nebula...



...was formed by something like this:
(β=1 cloud, 40M_{sun} feedback)



Simulating the Rosette Nebula



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, sheets form, 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.

But, how to create very low plasma β conditions? Pressure waves next!

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*

The engine

Physical model

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

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

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