School of Physics and Astronomy
FACULTY OF MATHEMATICS AND PHYSICAL SCIENCES

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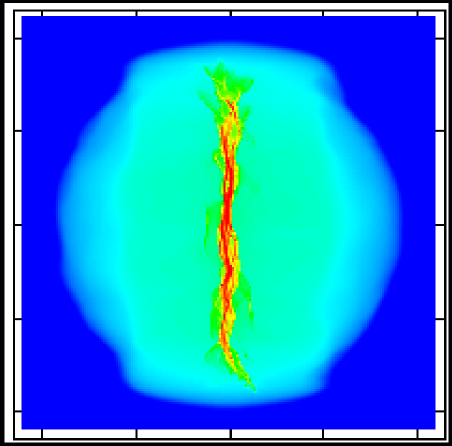
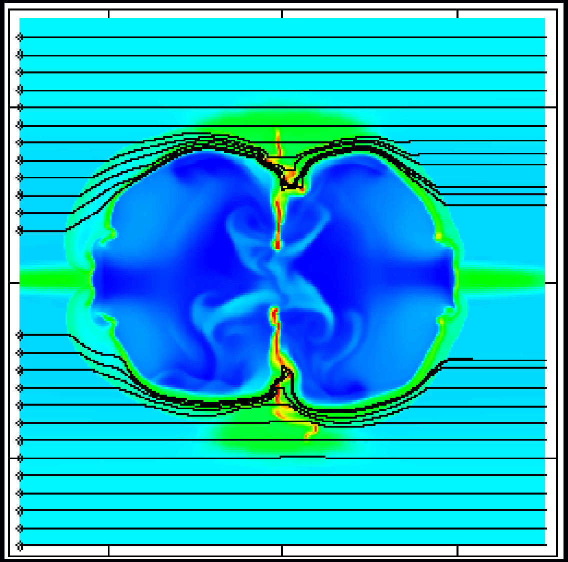
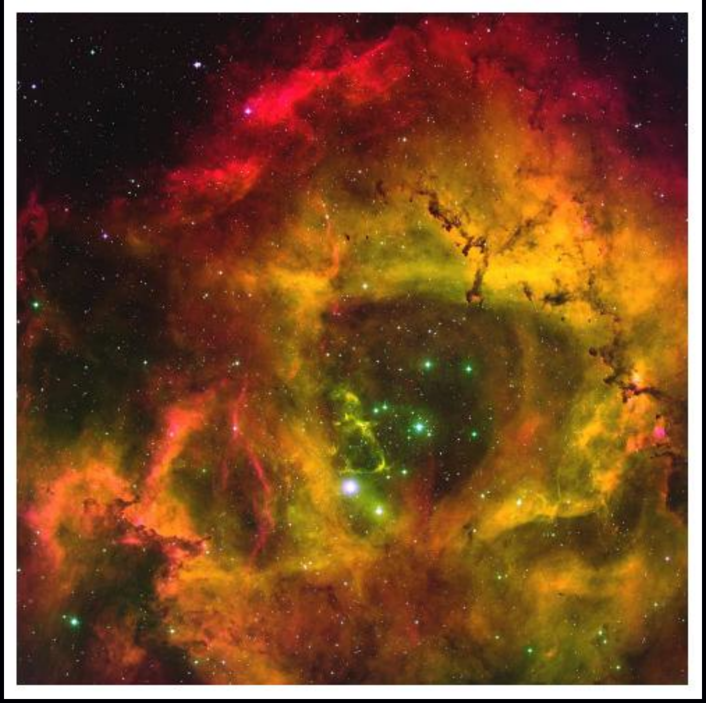
Filaments, feedback and forming the Rosette

MHD simulation of stellar feedback in a sheet-like molecular cloud formed by the thermal instability







Chris Wareing,

Julian Pittard, Sam Falle, Sven Van Loo

Northern Star Formation Meeting 8/9/2016

Context and overview

Our **aim is to elucidate the effects of stellar radiation, stellar winds and SNe on the evolution of gas where stars and stellar clusters are born, with further regard to the study of triggered star formation** .

Method: hydrodynamic simulations with realistic initial conditions that include magnetic fields, self-gravity & realistic stellar feedback.

Today, I will concentrate on simulations including magnetic fields and self-gravity, examining the mass, momentum and energy effects of stellar winds and SNe.

- The physics we include in our models.
- Developing a realistic initial condition as a starting point for feedback.
- The stellar evolution models and resulting feedback.
- Comparisons to previous work and observations.
- An intriguing suggestion for the Rosette Nebula!

Winds are important
CONTEXT AND OVERVIEW

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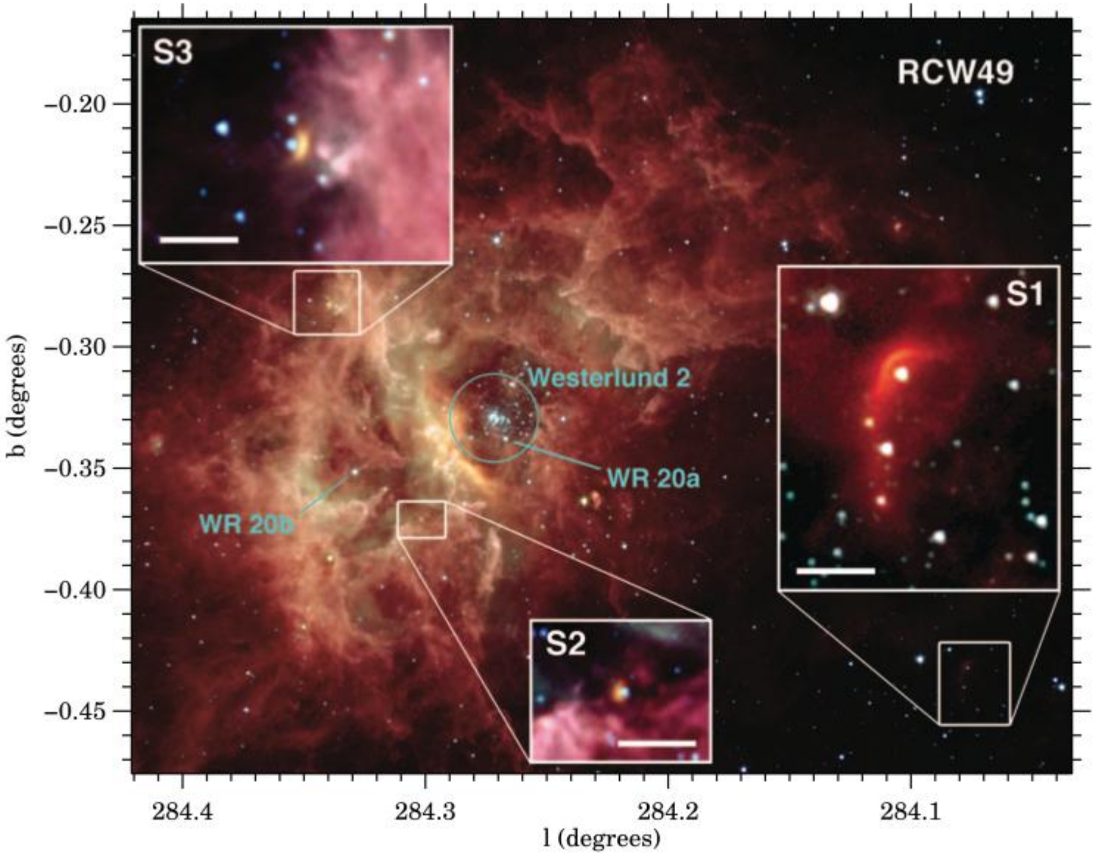
- Total energy injected is less than SNe, but in many clusters no SNe yet.
- Stellar winds create bow shocks around nearby stars, e.g. in RCW49.

- GLIMPSE full colour image of RCW49.
- The scale bars are 0.6 pc at 4.2kpc.
- Bow shocks are indicated S1-3.
- Three energy sources that could drive large-scale interstellar flows are indicated.



Povich et al. 2008, ApJ, **689**, 242-248

Physical model & engine

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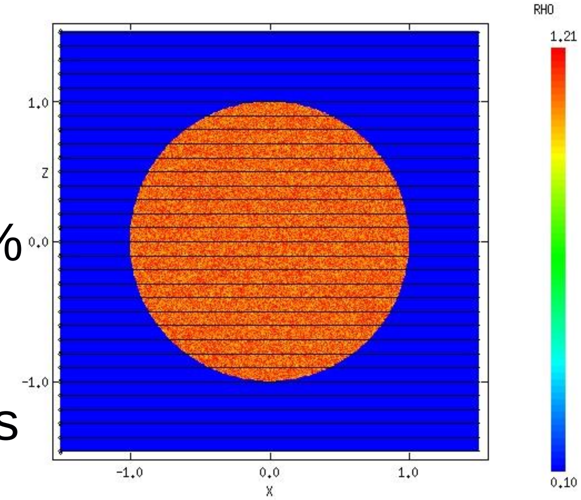
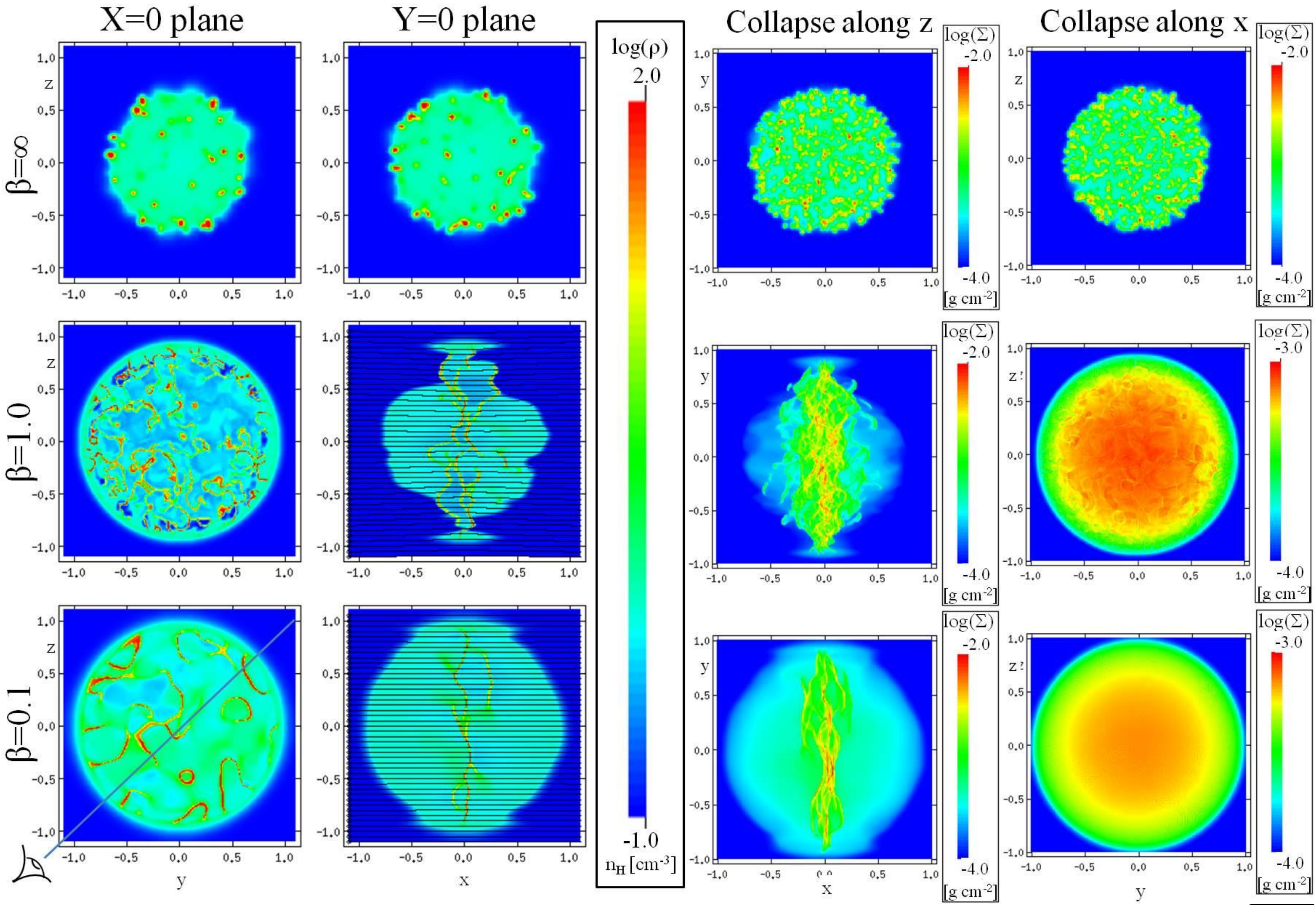
- We wish to start from the simplest set of self-consistent physics for the formation of our molecular cloud and examine what's possible from there. Specifically **3D MHD, self-gravity and multi-phase ISM** (i,e. realistic heating and cooling).
- We used a magnetohydrodynamic version of MG with self-gravity - a parallelised upwind, conservative shock-capturing scheme, with adaptive mesh refinement.

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

- Three field strengths were considered, all with: $\underline{B} = B_o \underline{\hat{I}}_x$
  - The hydrodynamic case: $\beta = \infty$
  - Pressure equivalence: $\beta = 1$ - commonest.
  - Magnetically dominated regime: $\beta = 0.1$
- 100-pc diameter diffuse cloud, n_H=1.1 cm^{-3} +/- 10%
- For $\beta = 1$, B_0 = 1.15 μG. For $\beta = 0.1$, B_0 = 3.63 μG
- Pressure equilibrium with low-density surroundings



More details on my poster.



Logarithmic mass density on planar slices

Logarithmic column density

- t=35.4 Myrs. Only looked like an MC for last 10Myrs

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Results

INITIAL CONDITION

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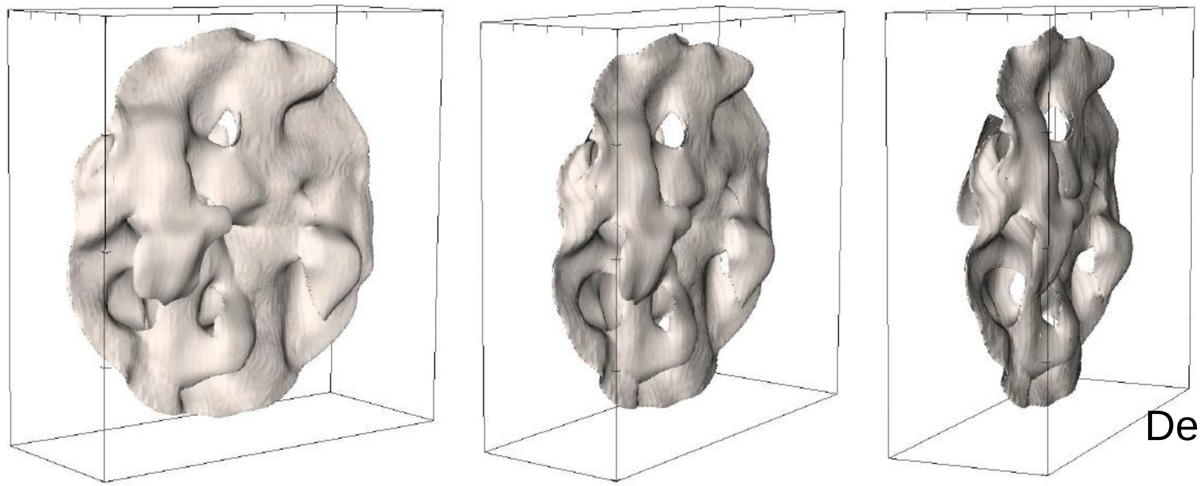
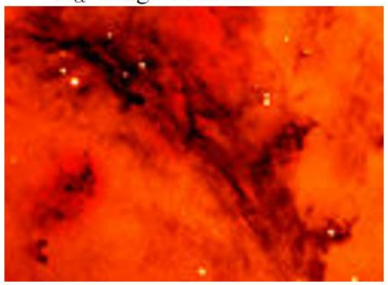
- In the magnetic case, the model forms corrugated sheets...

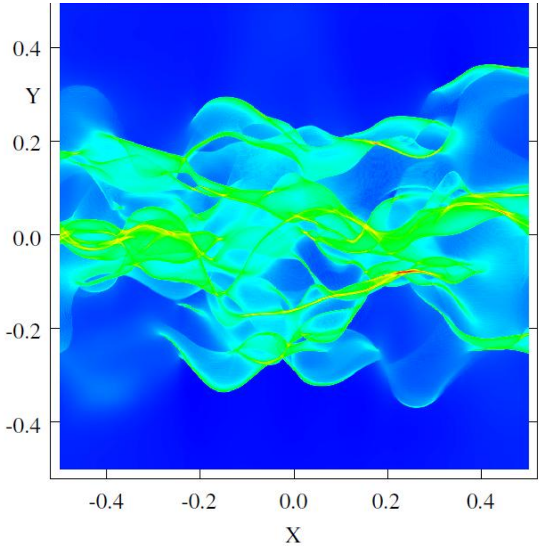


Density isosurface

...that in projection appear filamentary.

H_α image of Rosette





Results

INITIAL CONDITION FOR FEEDBACK

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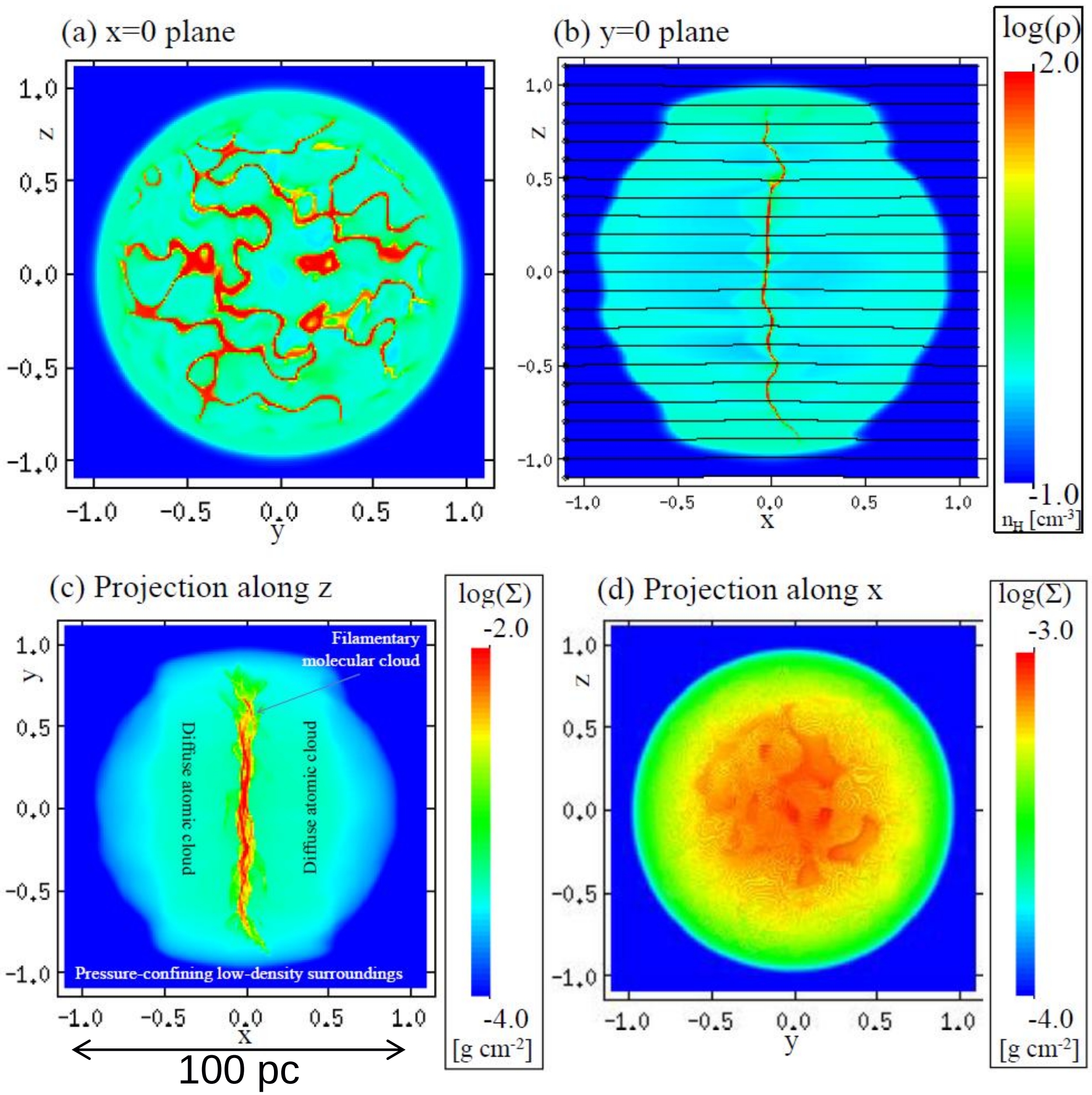
- New initial condition.
- 100 pc-diameter ‘corrugated’ sheet
- Filamentary in projection
- 17,000 $M_{\odot}$
- Density >100 cm^{-3} after 32.9 Myrs of evolution
- Assume free-fall time of 5.89 Myrs to forms stars
- Inject stars at t=38.8Myrs
- Position of central star (-0.025, 0.0, 0.0125)
- Total mass in excess of star formation mass



$15M_\odot$ star: wind phase

FEEDBACK RESULTS

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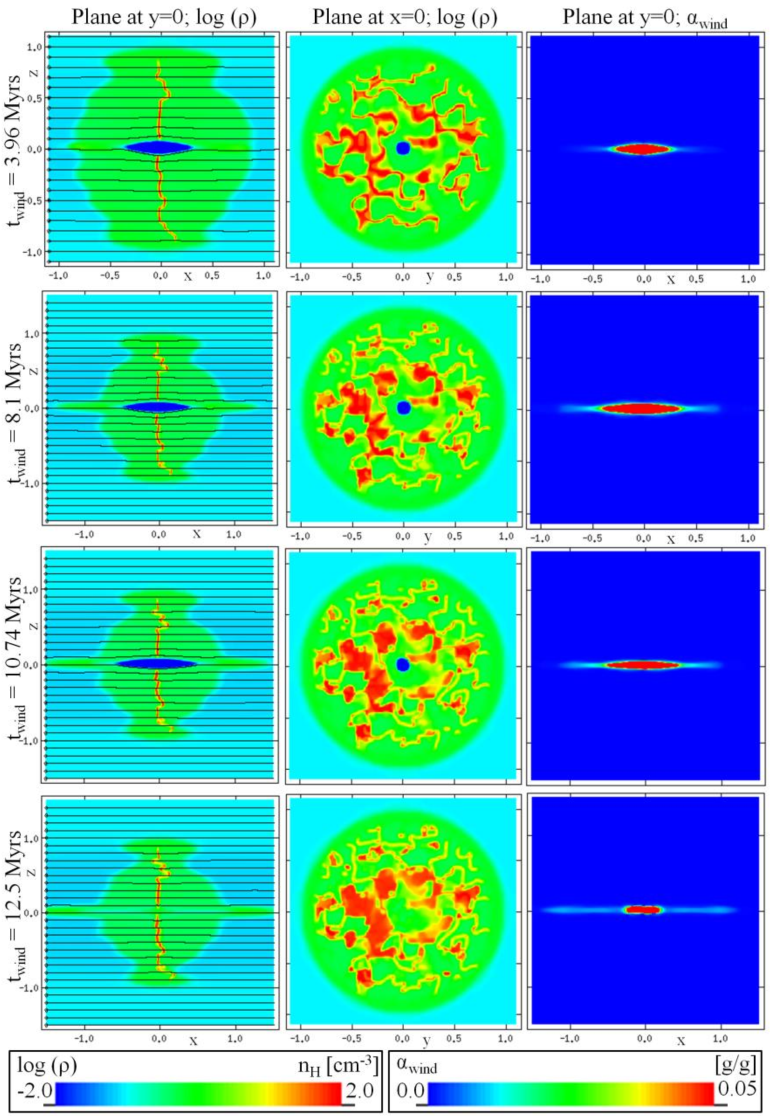
- 15 $M_\odot$ star, following Geneva 2012 track (*more details on poster*).
- Showing the wind evolution during the MS at three times and finally at the end of the RSG phase.
- **Low mass-loss rate and low wind energy have minimal effect.**
- Small, local cavity driven through the parental molecular cloud.
- RSG phase deposits considerable material into this cavity.
- RSG affects early evolution of the SN, but only small perturbation.
- Total mass injected 1.75 $M_\odot$, total energy injected of 1.05x10^{49} erg



$15M_{\odot}$ star: early SN phase

FEEDBACK RESULTS

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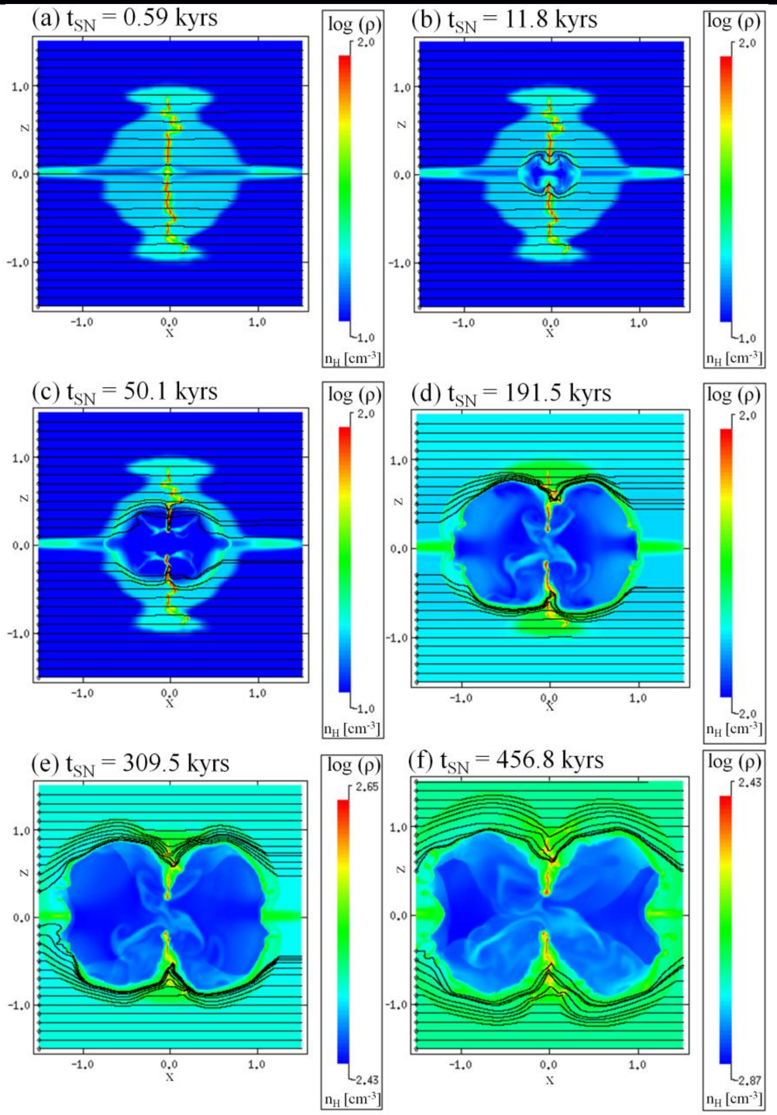
- Explodes in a SN after 12.5 Myrs, releasing 10 $M_{\odot}$ and 10^{51} erg.
- SN rapidly exits the wind cavity.
- **Expansion is hindered by the high density corrugated molecular cloud.**
- High density filamentary structure is ablated by the expanding SN remnant.
- Magnetic field intensified by a factor of 4 around the shell away from cloud.
- Intensified temporarily by a factor of up to 10 (16 μG) at the edges of the corrugated molecular cloud.
- Hot, dense, ablated molecular material exists inside the remnant and is likely to be emitting strongly.



$15M_{\odot}$ star: late SN phase
FEEDBACK RESULTS

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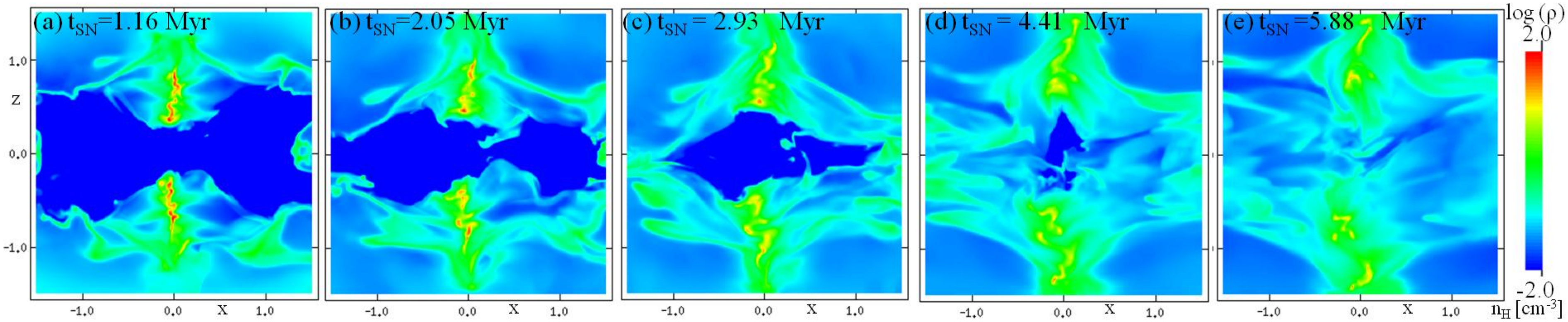

- SN-wind-cloud interaction at late time, once the SN forward shock has left the computational domain.
- Indicative results only – boundary effects now present.
- Considering only the fate of the molecular cloud, after 1.16Myr, the cloud is still recognisable.
- **After 6Myrs post SN, the molecular cloud has been dispersed.**
- Simulations with a larger computational volume are required.

40$M_\odot$ star: wind phase

FEEDBACK RESULTS

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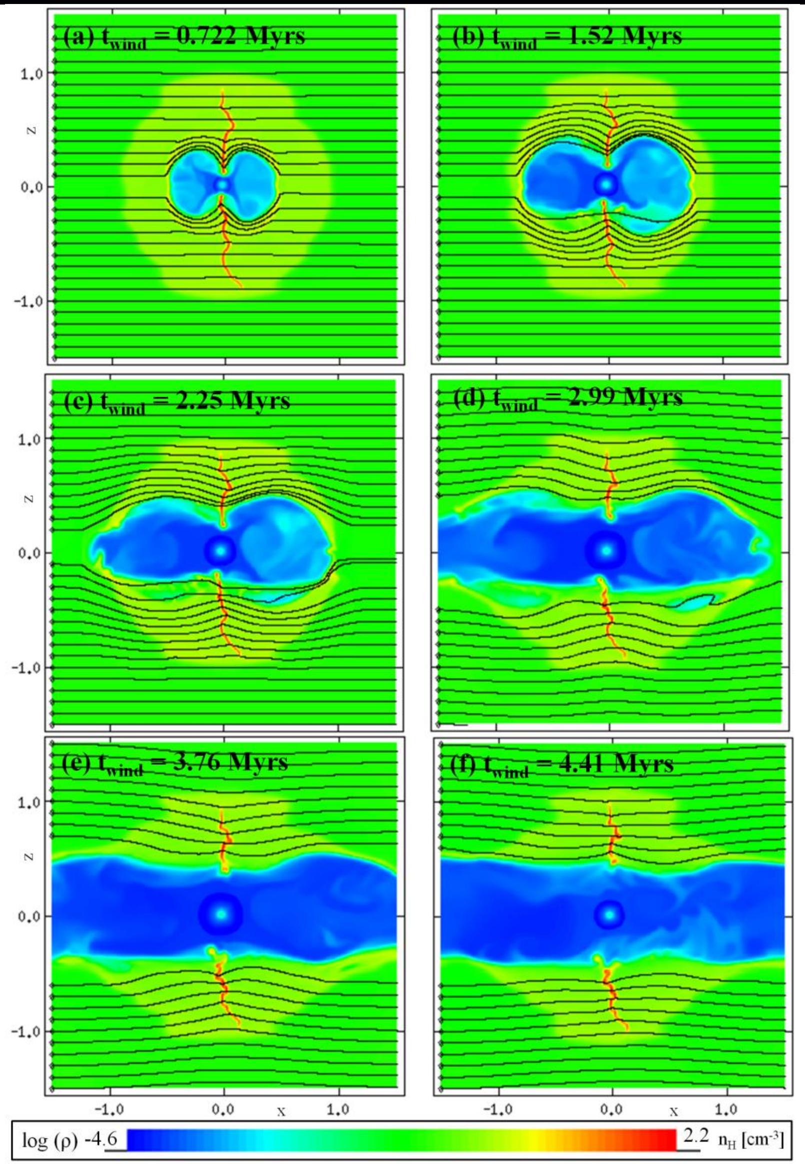
- 40 $M_\odot$ star, following Geneva 2012 track (*more details on poster*).
- **For this star, there's a significant impact on the molecular cloud.**
- Large bipolar cavity evolves into a cylindrical cavity (D~40pc) through the centre of the cloud.
- Cavity filled with hot, tenuous wind material moving 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.
- Total mass injected 27.2 $M_\odot$, total energy injected of 2.5x10^{50} erg



$40M_\odot$ star: SN phase

FEEDBACK RESULTS

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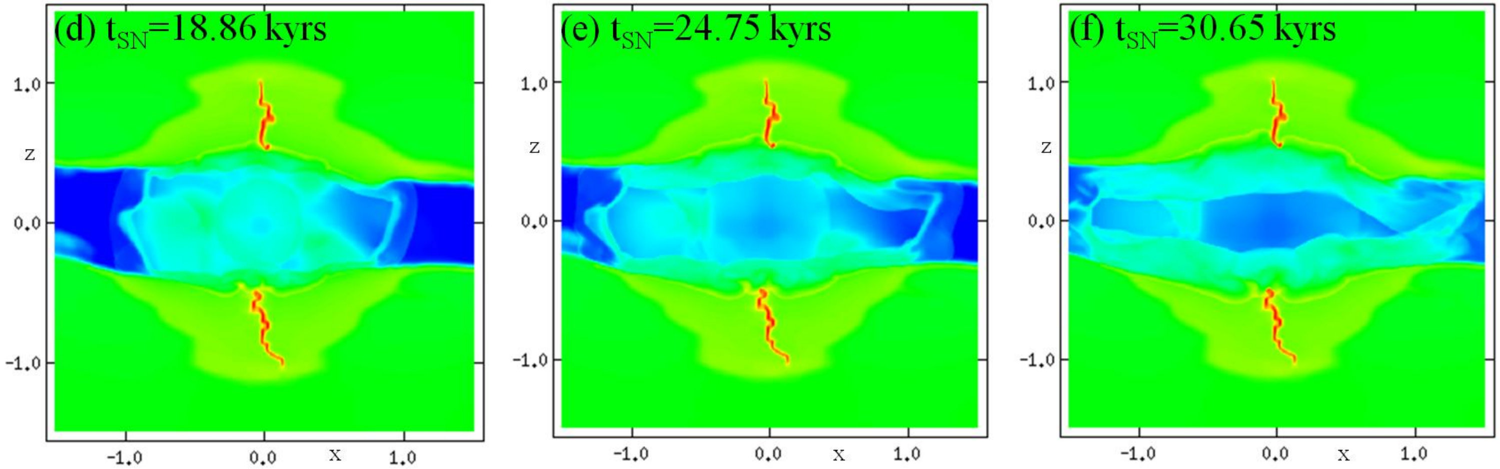
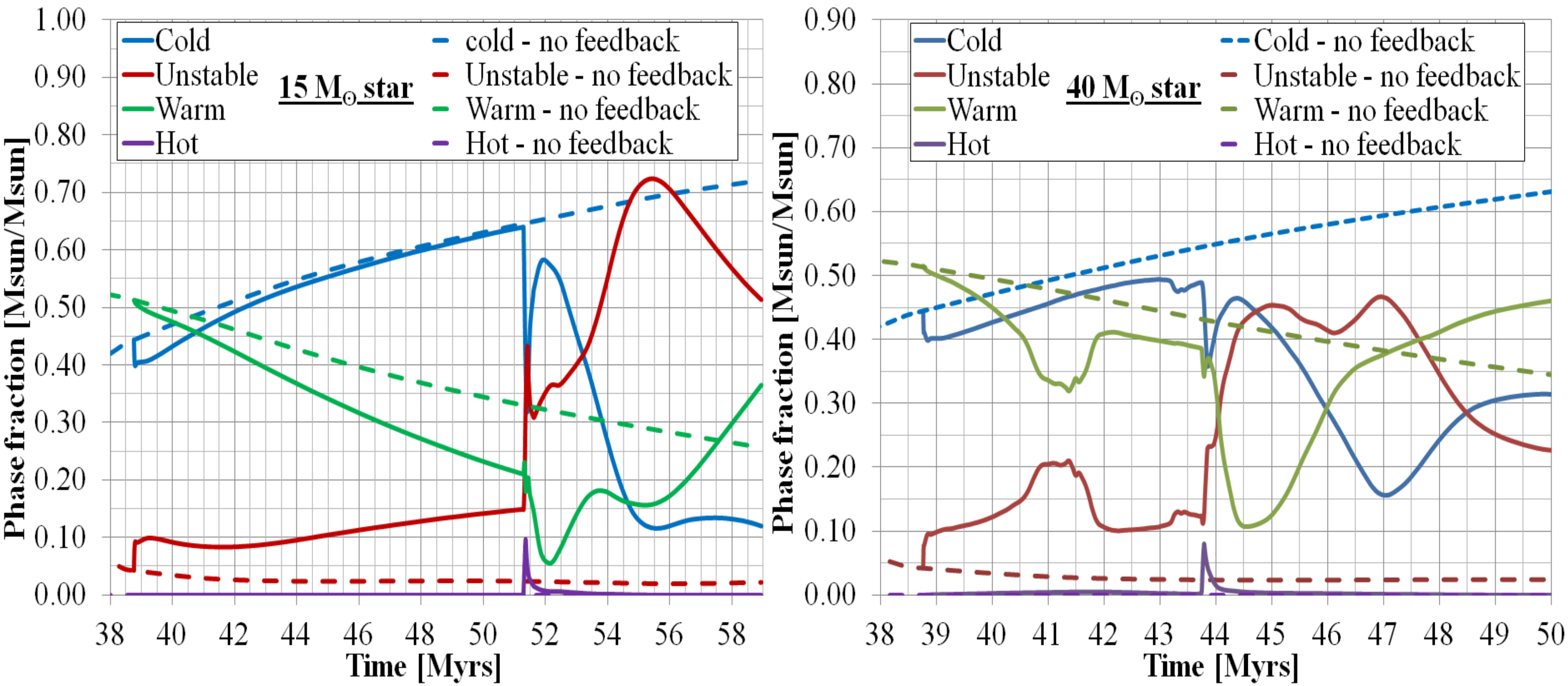


- Final LBV phase results in a high-density environment around star.
- WR wind creates a D=25pc shell, into which SN explodes (t_{star}=4.97 Myrs).
- It is a spherical SN remnant until it reaches the cavity wall (8 kyrs).
- SNR then accelerates away through the cavity, whilst slowing into the denser diffuse cloud and molecular sheet.
- SN forward shock leaves domain in 30kyrs; c.f. 400kyrs for $15M_\odot$ star.
- **Majority of SN energy and material leaves the cloud unhindered.**

More details on my poster.

Phase fractions

FEEDBACK RESULTS



- Fragments of the molecular cloud survive these single star evolution scenarios, with increasing amounts of post-SN cold phase material in the 40 $M_{\odot}$ case.

Comparisons to previous works

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- There are large differences, especially in the initial condition, compared to our previous work (Rogers & Pittard) – no straightforward comparison.
  - In R&P a multitude of porous channels allow wind escape.
  - Here: expansion of a coherent bubble.
- Similarities occur: the SN can transport large fractions of energy without strongly affecting the parent cloud.
- Key factor**: the shaping effect of the pre-SN winds**
- There's agreement with other authors:
  - Lower mass stars (low mass-loss rates) have little effect on parent cloud.
- High levels of turbulence have been shown to resist shaping effects of winds.
  - Are these appropriate? We generate transsonic structured large-scale flows in this scenario, as observed, without the introduction of turbulence.

Wareing et al. MNRAS submitted

Comparisons to observations

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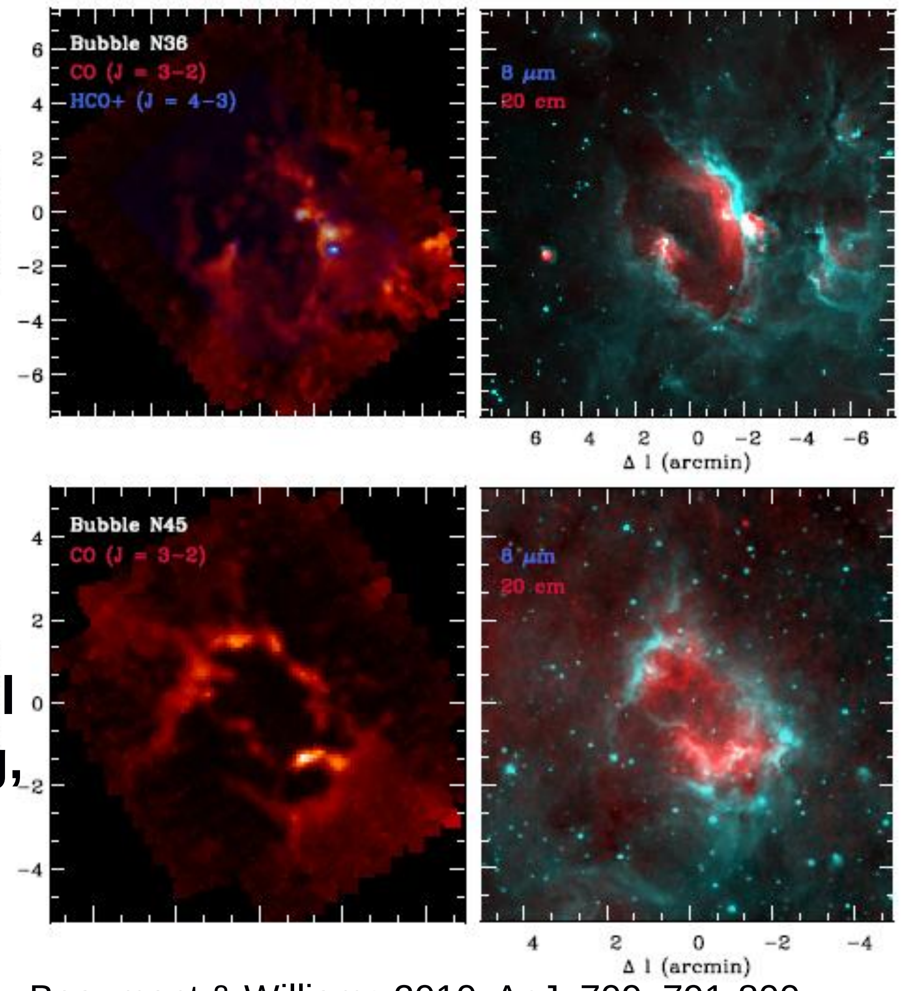
- Bubbles interacting with flattened clouds and bipolar HII regions.
- Observations of wind-blown bubbles often reveal the surrounding gas has a **ring-like** rather than spherical morphology (controversial!).
- Observations detect little CO with the implication that the molecular clouds have thicknesses of few ~pc.
- Bipolar HII regions would form if we had included photoionization.
- Beaumont & Williams found **43 small *Spitzer*-GLIMPSE objects with ring, not spherical, cloud structures.**
- Looked hard, but failed to identify l.o.s. velocity components.



Beaumont & Williams 2010, ApJ, 709, 791-800

A thought experiment: the Rosette Nebula

COMPARISONS TO OBSERVATIONS

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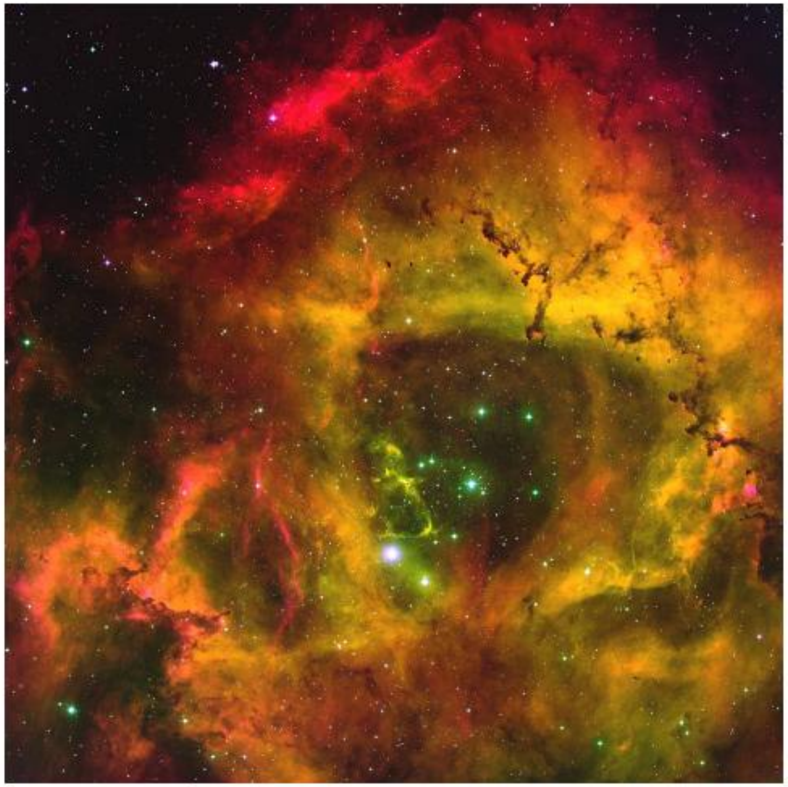
- Large HII region in the Monoceros GMC complex at a distance of 1.6+/-0.2 kpc.
- Central cluster NGC 2244 dominated by a single star, ages 2-6 Myrs.
- Triggered star formation SE of region.
- Even though the stars are **quite young (2-4Myr)**, both the radius and expansion velocity point to a far younger dynamical age of the cavity: around **64,000 years**!
- **Strong contradiction** between theory of a Strömgren sphere and modelling.



- **Solution?** Bruhweiler et al postulate “an ejection event formed the cavity”.
- But Bruhweiler et al. emphasize they cannot rule out that there is not an asymmetric cavity where the much larger axis is directed toward observer.
  - They find an axis ratio >17, which they find “**uncomfortably large**”.

A new model...
THE ROSETTE NEBULA

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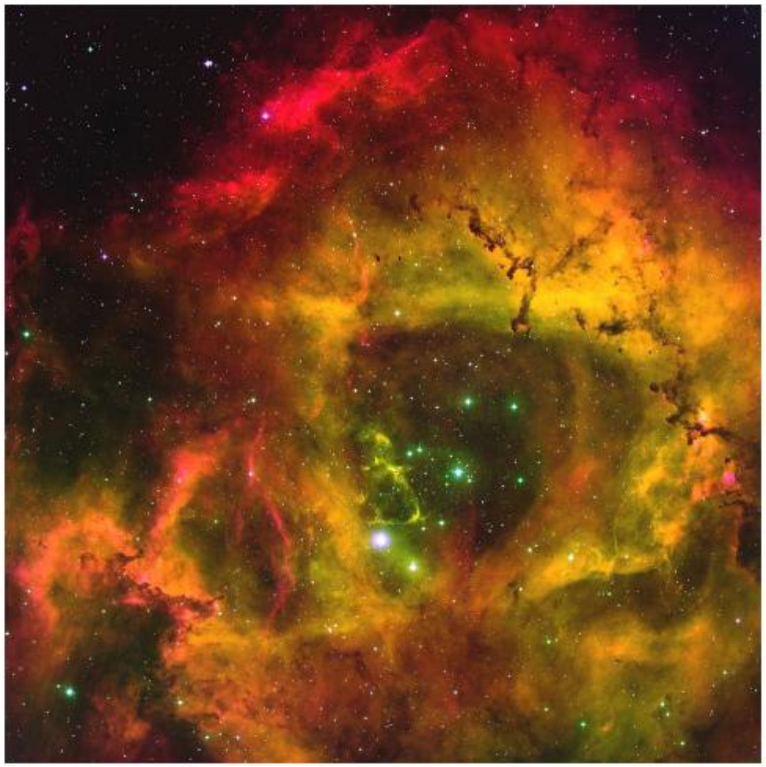
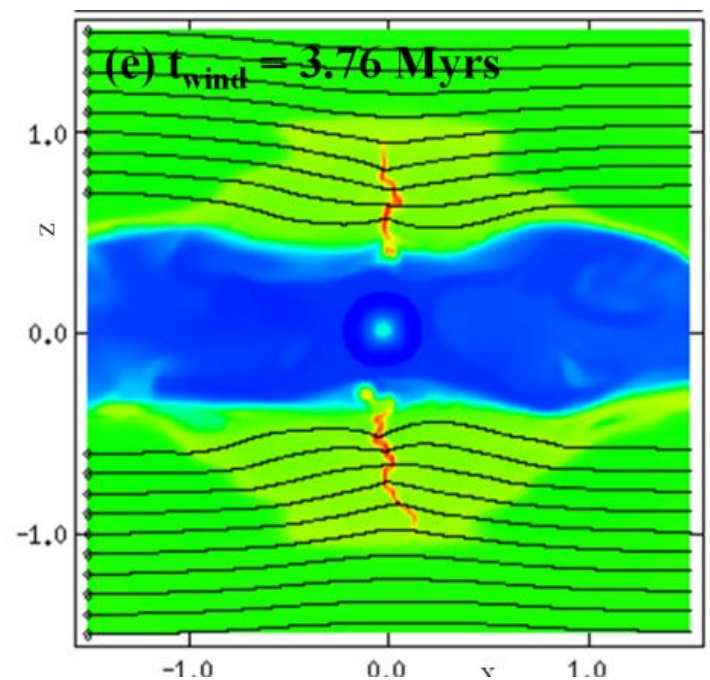
- What if this...

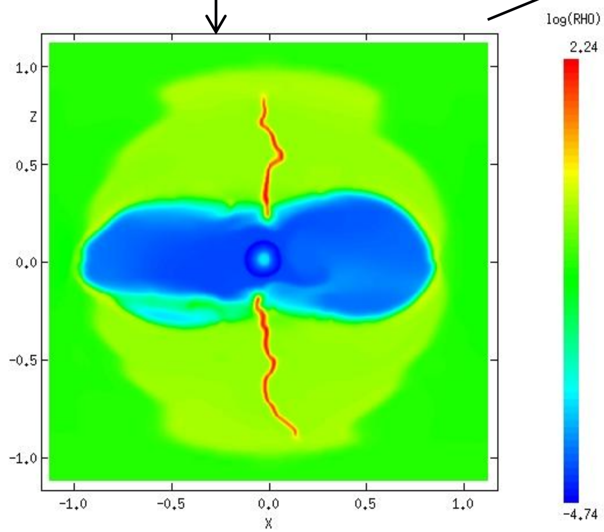


...was formed like this.

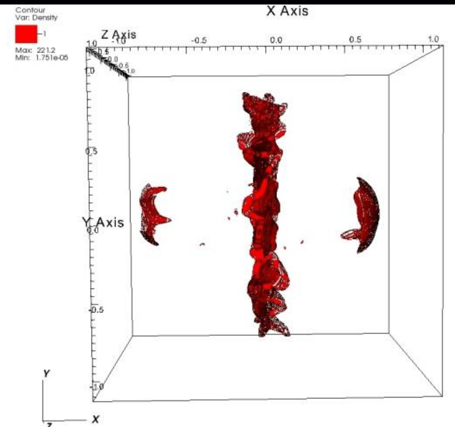


- Our simulations have shown it's possible to clear a central cavity from a parent molecular cloud.
- **Instantly solve the dynamical age problem!**

- New simulation of a 32 $M_{\odot}$ star in the same initial condition.
- Contoured surface of density
- Slice at y=0

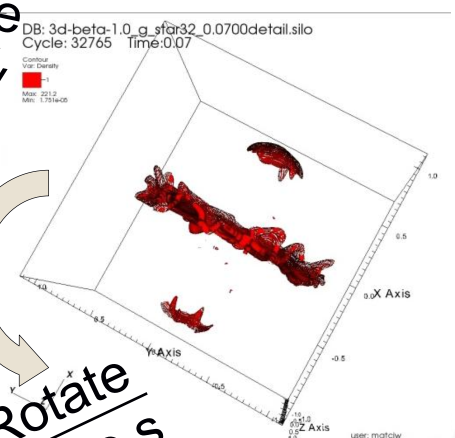


- Central hole: D=18-20pc (c.f. 13pc for the Rosette)

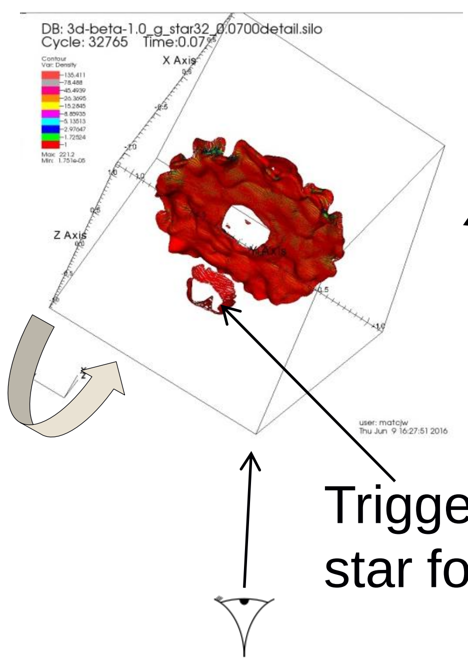


t=2.5 Myrs

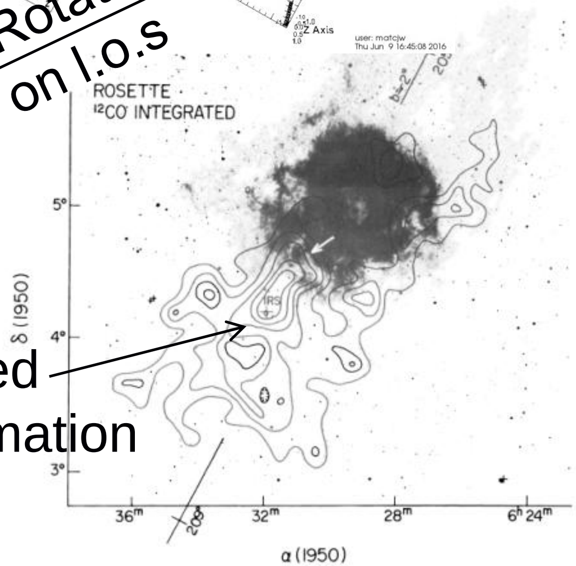
Rotate on sky



Rotate on l.o.s



Triggered star formation



Final remarks

THE ROSETTE NEBULA

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Do we have a decent model for the formation of the Rosette Nebula?

We have a solution for:

- The overall structure.
- The mismatch of stellar and dynamical ages.
- The missing wind luminosity problem.
- The position and localised nature of the triggered star formation.
- The obscuration of any other triggered star formation.
- The angle to the line of sight.

- And we naturally require the background field to be in the most likely position, along the Galactic Plane.

Thank you for listening. Any comments or questions?

References

Wareing, Pittard, Falle & Van Loo, 2016, MNRAS, **459**, 1803-1818

Wareing, Pittard & Falle, MNRAS submitted. Arxiv: 1605.04706

Wareing, Pittard & Falle, in preparation – submit to Nature? Nature Astronomy?