Mutual influence of supernovae and molecular clouds

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Cosmic rays from MeV to TeV energies
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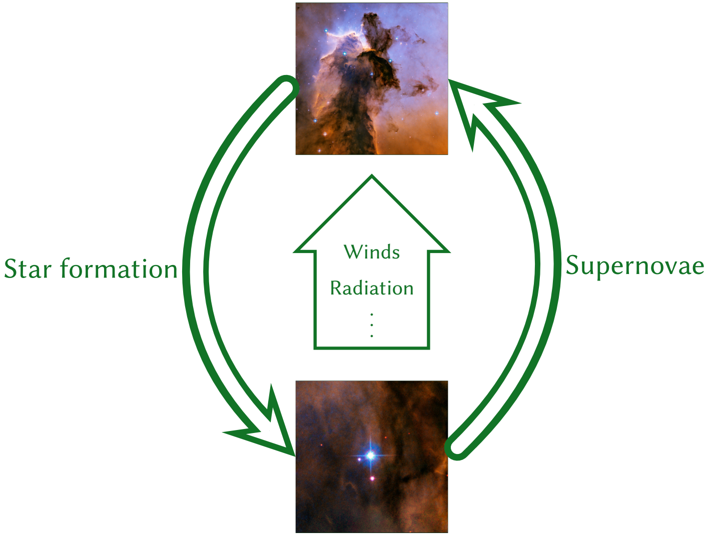
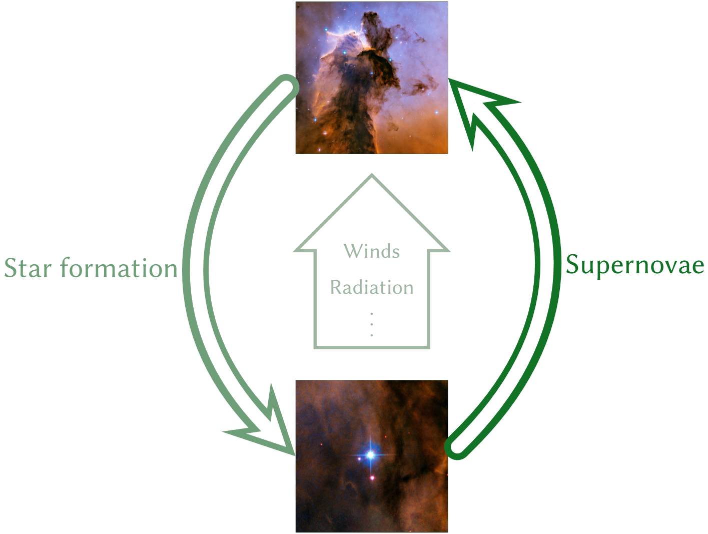
Introduction

Context



Context



About supernovae

- 3 propagation phases :
  - Free expansion until $\frac{4}{3}\pi\rho_{ISM}R_s^3 \sim M_{ej}$
  - Adiabatic (Sedov-Taylor) phase untill cooling becomes efficient ($T_s < 10^6$ K)
  - Radiative phase
- During the radiative phase, a dense shell forms

Method

General information

Technical data

- RAMSES MHD code with custom patch
- Parallel environment: 64 – 256 computing cores
- Grid size: 256^3 – 1024^3
- Wall time: 24 – 120 hours

Simulation types

- Uniform medium
- Cloud-like (turbulent) medium
- Both without and with magnetic field

Simulations

Features

- Box size: 40 — 160 pc (uniform), 50 pc (cloud)
- Resolution: 0.04 — 0.15 pc

Physics

- Hydrodynamics

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{v} \otimes \vec{v} + \left(P \right) \mathbb{I} \right) = 0$$

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot \left(\left(E + P \right) \vec{v} \right) = 0$$

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$$\frac{\partial (\rho \vec{v})}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{v} \otimes \vec{v} + \left(P + \frac{B^2}{8\pi} \right) \mathbb{I} - \frac{\vec{B} \otimes \vec{B}}{4\pi} \right) = 0$$

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot \left(\left(E + P - \frac{B^2}{8\pi} \right) \vec{v} + \frac{1}{4\pi} \vec{B} \times \left(\vec{v} \times \vec{B} \right) \right) = 0$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) = 0$$

Simulations

Features

- Box size: 40 — 160 pc (uniform), 50 pc (cloud)
- Resolution: 0.04 — 0.15 pc

Physics

- Hydrodynamics
- Magnetic field
- Self-gravity (cloud)

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{v} \otimes \vec{v} + \left(P + \frac{B^2}{8\pi} \right) \mathbb{I} - \frac{\vec{B} \otimes \vec{B}}{4\pi} \right) = -\rho \vec{\nabla} \phi$$

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot \left(\left(E + P - \frac{B^2}{8\pi} \right) \vec{v} + \frac{1}{4\pi} \vec{B} \times \left(\vec{v} \times \vec{B} \right) \right) = -\rho \vec{v} \cdot \vec{\nabla} \phi$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) = 0$$

$$\Delta \phi - 4\pi G \rho = 0$$

Simulations

Features

- Box size: 40 — 160 pc (uniform), 50 pc (cloud)
- Resolution: 0.04 — 0.15 pc

Physics

- Hydrodynamics
- Magnetic field
- Self-gravity (cloud)
- Heating (UV background)

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{v} \otimes \vec{v} + \left(P + \frac{B^2}{8\pi} \right) \mathbb{I} - \frac{\vec{B} \otimes \vec{B}}{4\pi} \right) = -\rho \vec{\nabla} \phi$$

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot \left(\left(E + P - \frac{B^2}{8\pi} \right) \vec{v} + \frac{1}{4\pi} \vec{B} \times \left(\vec{v} \times \vec{B} \right) \right) = -\rho \vec{v} \cdot \vec{\nabla} \phi + \Gamma_t$$

$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) = 0$$

$$\Delta \phi - 4\pi G \rho = 0$$

Simulations

Features

- Box size: 40 — 160 pc (uniform), 50 pc (cloud)
- Resolution: 0.04 — 0.15 pc

Physics

- Hydrodynamics
- Magnetic field
- Self-gravity (cloud)
- Heating (UV background)
- Cooling (important for the shell)

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v}) = 0$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{v} \otimes \vec{v} + \left(P + \frac{B^2}{8\pi} \right) \mathbb{I} - \frac{\vec{B} \otimes \vec{B}}{4\pi} \right) = -\rho \vec{\nabla} \phi$$

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$$\vec{\nabla} \cdot \vec{B} = 0$$

$$\frac{\partial \vec{B}}{\partial t} - \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) = 0$$

$$\Delta \phi - 4\pi G \rho = 0$$

Preliminary study: supernova in a uniform medium

Initial conditions

- Uniform density $n = 1, 10, 100, 1000\ \text{cm}^{-3}$
- Gas at cooling / heating equilibrium
- 10^{51} erg of thermal energy injected at the center

Box size (pc)	Density (cm^{-3})	Temperature (K)
160	1	4907.8
80	10	118.16
80	100	36.821
40	1000	19.911

SN in MCs

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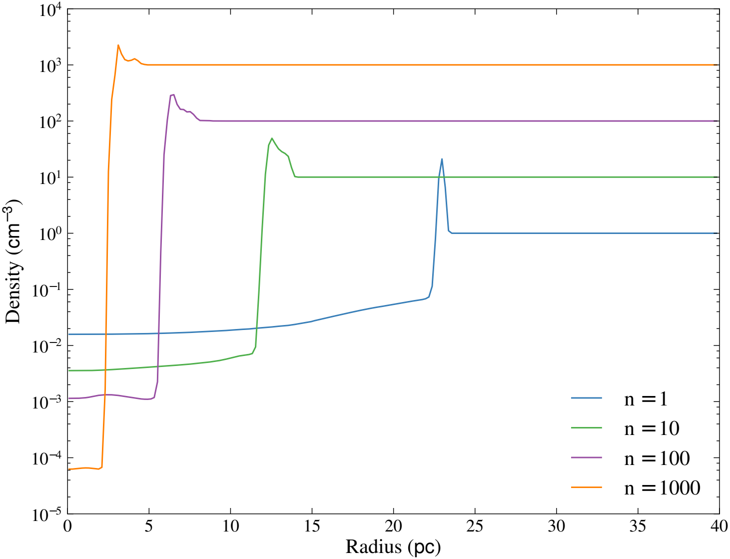
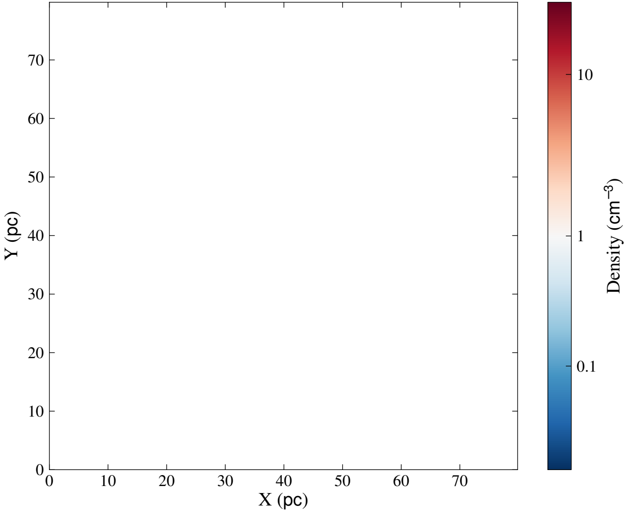
Structure



0.1 Myr after the explosion

Structure



0.1 Myr after the explosion

Ambient density: 1 cm^{-3}

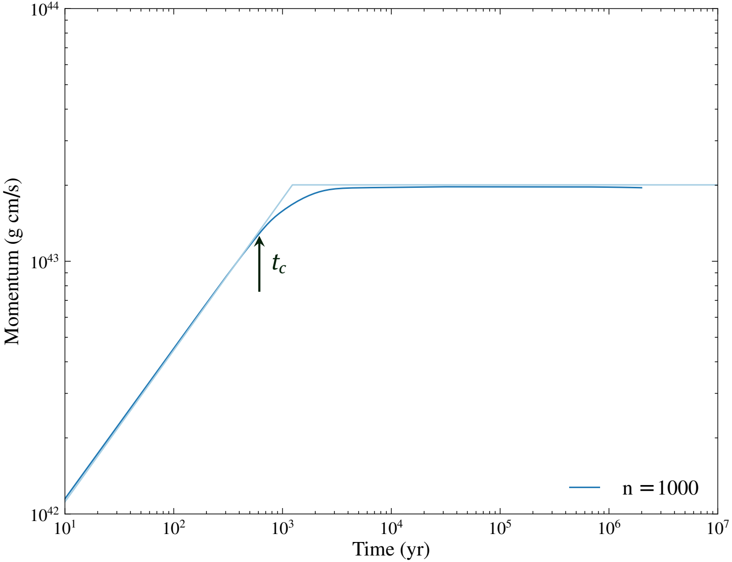
Model

- Adiabatic (S-T) phase:

$$p_{43} = 1.77\ n_0^{1/5} E_{51}^{4/5} t_4^{3/5} \qquad E_{K,51} = 0.28\ E_{51}$$

- Transition at t_c such that $\frac{3}{2} k_B \frac{n_s T_s}{\Lambda_s}\Big|_{t_c} = t_c.$

Model


10^{44}
10^{43}
10^{42}
Momentum (g cm/s)
t_c
n = 1000
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
Time (yr)

Model

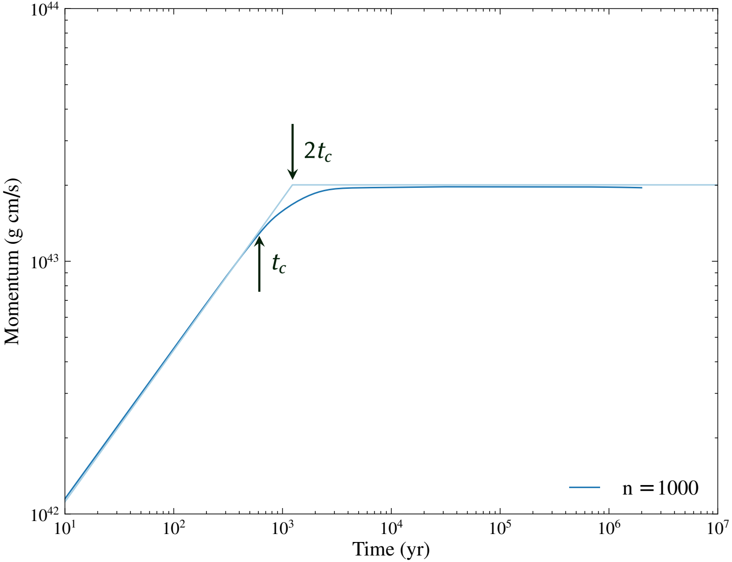
- Adiabatic (S-T) phase:

$$p_{43} = 1.77\ n_0^{1/5} E_{51}^{4/5} t_4^{3/5} \qquad E_{K,51} = 0.28\ E_{51}$$

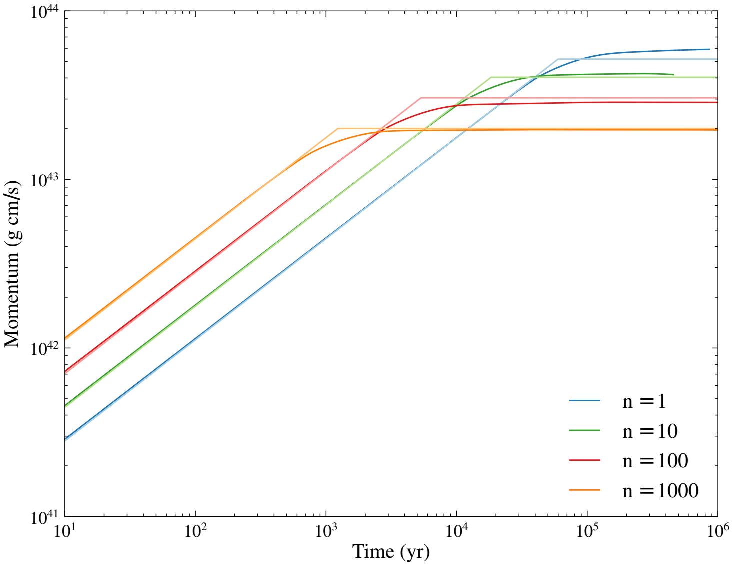
- Transition at t_c such that $\left.\frac{3}{2} k_B \frac{n_s T_s}{\Lambda_s}\right|_{t_c} = t_c$.
- Radiative phase: references from a S-T blast wave at $2t_c$

$$p_{43} = 1.77\ n_0^{1/5} E_{51}^{4/5} \left(2t_{c,4}\right)^{3/5} \quad E_{K,51} = 0.28\ E_{51} \left(\frac{t}{2t_c}\right)^{-3/4}$$

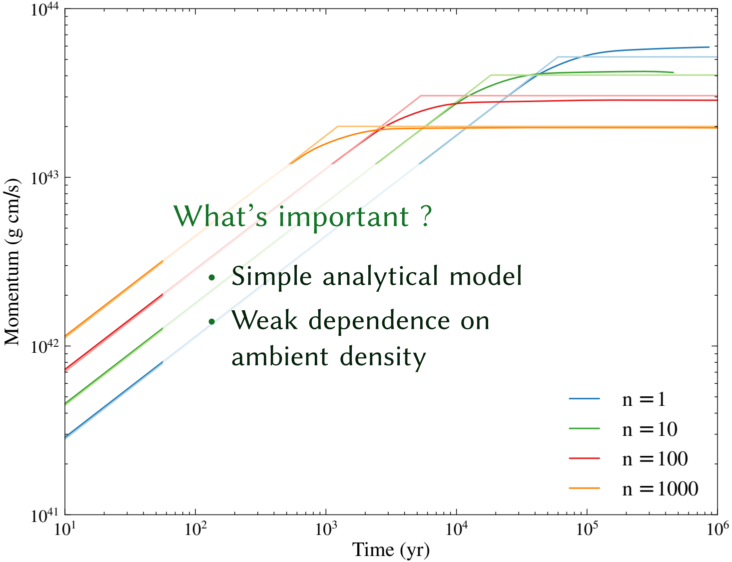
Model


Momentum (g cm/s)
Time (yr)
10^{44}
10^{43}
10^{42}
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
10^{7}
$2t_c$
t_c
n = 1000

Momentum


10^{44}
10^{43}
10^{42}
10^{41}
Momentum (g cm/s)
10^{1}
10^{2}
10^{3}
10^{4}
10^{5}
10^{6}
Time (yr)
n = 1
n = 10
n = 100
n = 1000

Momentum



What's important ?

- Simple analytical model
- Weak dependence on ambient density

Impact of a supernova on a molecular cloud

Initial and boundary conditions

Initial conditions

- Problem: no "standard" initial conditions
- Our choice: spherical cloud with turbulent velocity field, $M = 10^4\ \mathrm{M}_\odot$, $R \sim 10$ pc
- MHD: uniform magnetic field, 5 µG
- We let the cloud evolve before triggering the supernova

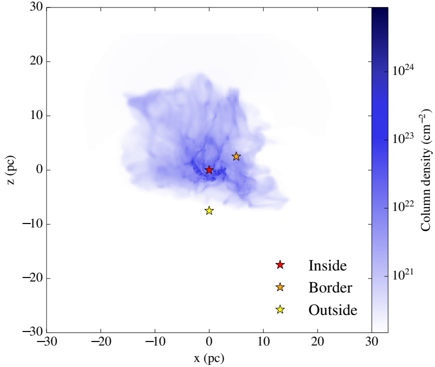
Boundary conditions

- Free outflow (vanishing gradient)
- No inflow possible
- MHD: vanishing divergence applied to the normal component

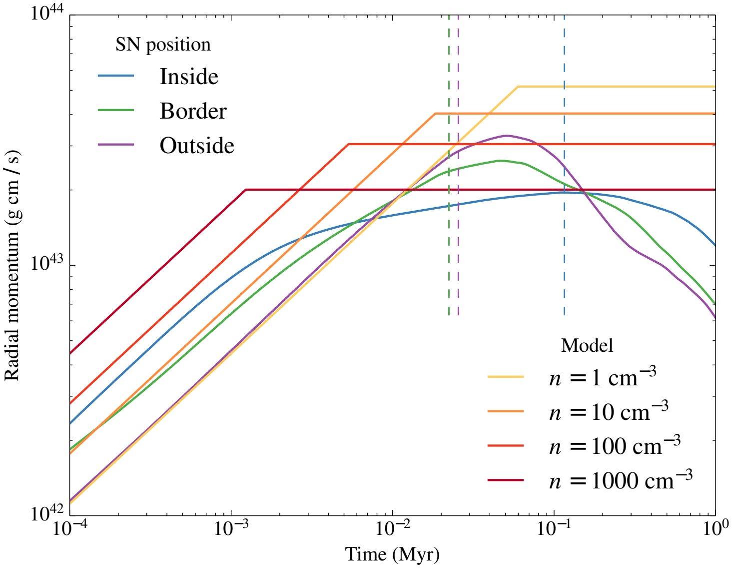
Simulations

Configurations :

(I) Supernova in the cloud (7.7 Myr)
(II) Supernova at the border of the cloud (7.7 Myr)
(III) Supernova outside the cloud (8.2 Myr)
(IV) Cloud without supernova (10.2 Myr)

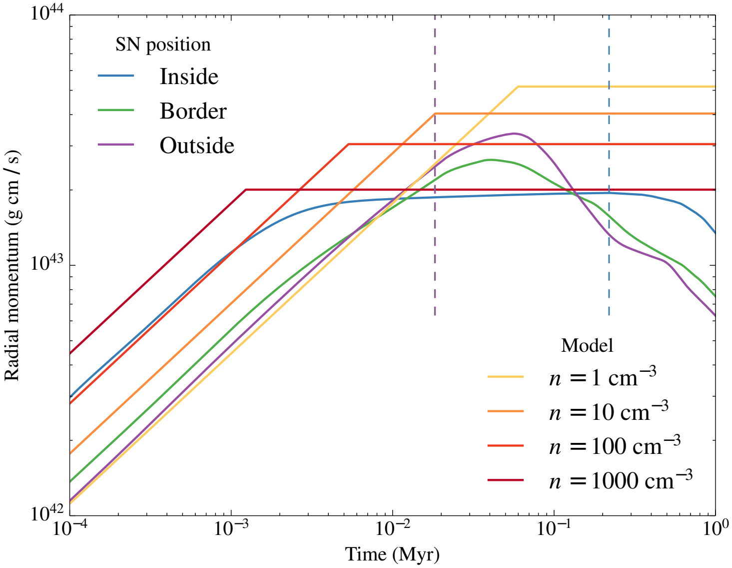


Momentum injection



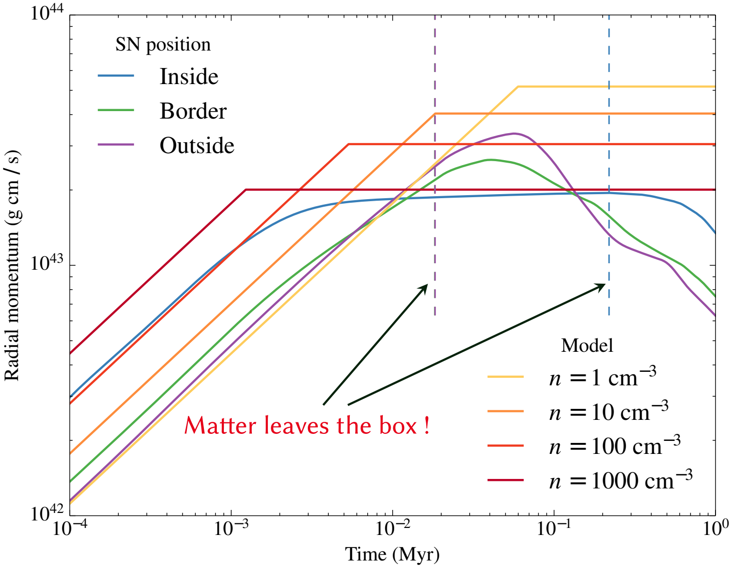
HD

Momentum injection



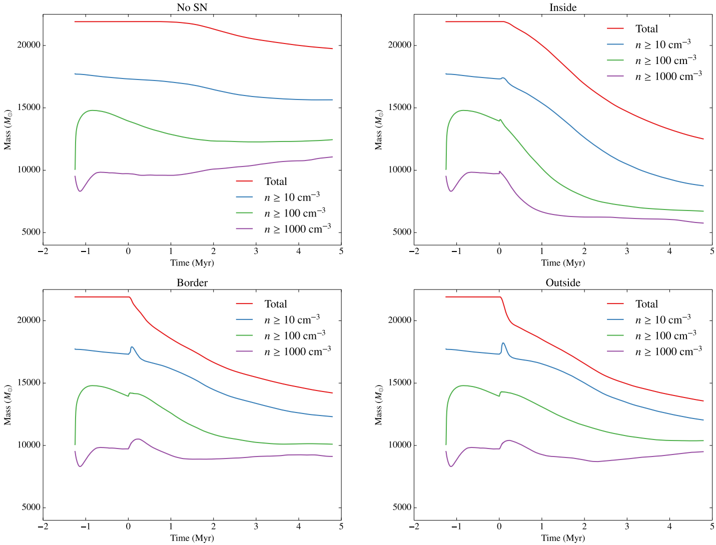
MHD

Momentum injection



MHD

Mass distribution



HD

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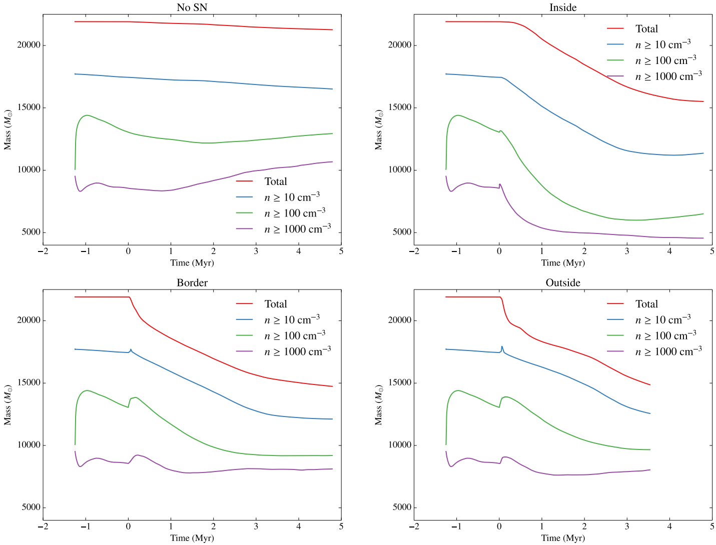
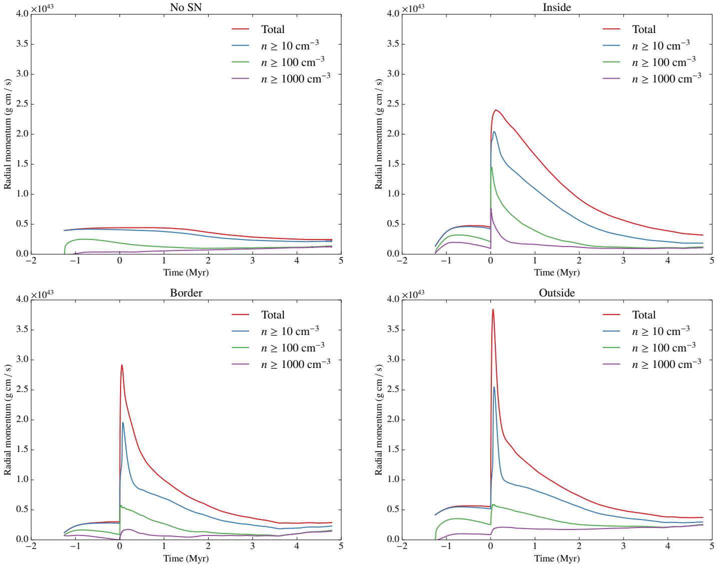
Mass distribution



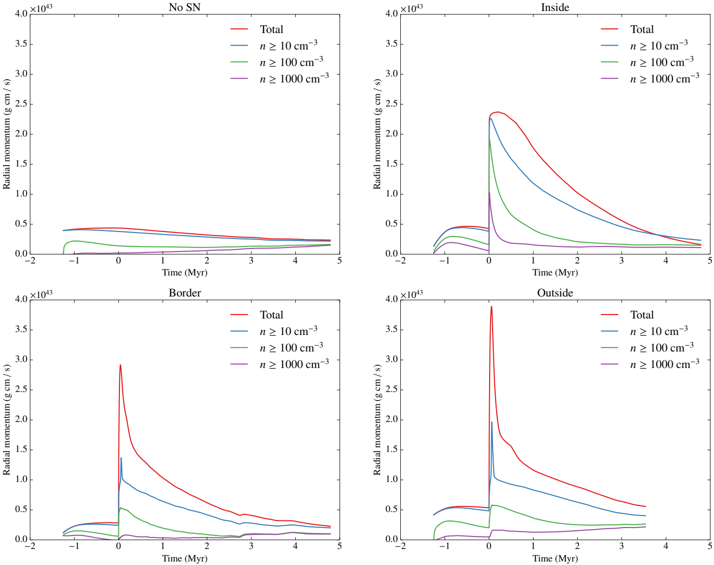
MHD

Momentum distribution



HD

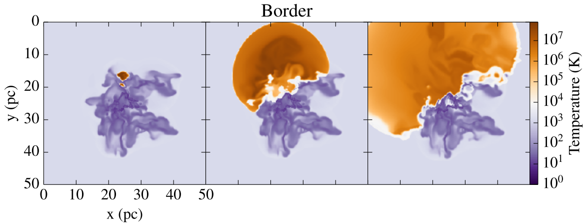
Momentum distribution



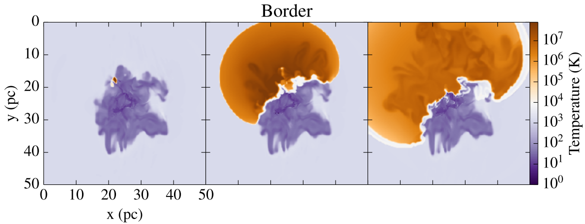
MHD

HD / MHD comparison

HD



MHD



Conclusion

Results

We have

- Larger scale feedback model
- Valid in cloud-like turbulent medium
- Remains valid in the turbulent MHD case
- Momentum $\sim 10^{43}$ g cm s^{-1}

But

- Dynamics strongly depend on the location
- The exact location depends on the star's movement
- Stellar feedback may push the medium before

Results

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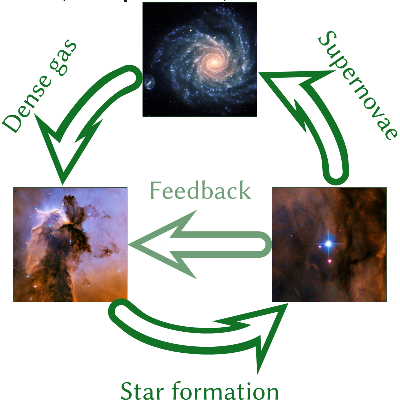
We need the larger scales to be self-consistent

What's next ?

Self-consistent simulations (in progress)

- ✓ 1 kpc simulation box, 1 pc resolution
- ✓ Gravity, magnetic field, disk structure
- ✓ Follow star-forming regions (sink particles)
- ✍ Stellar feedback
- ✓ Trigger supernovae



More physics

- Winds
- Ionization
- Cosmic rays, . . . ?

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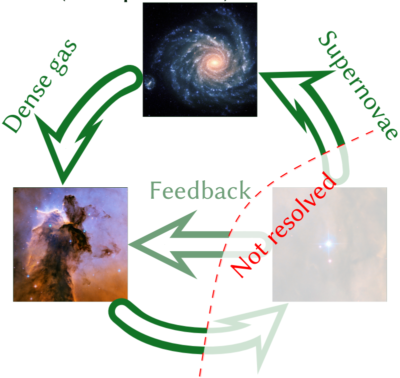

More physics

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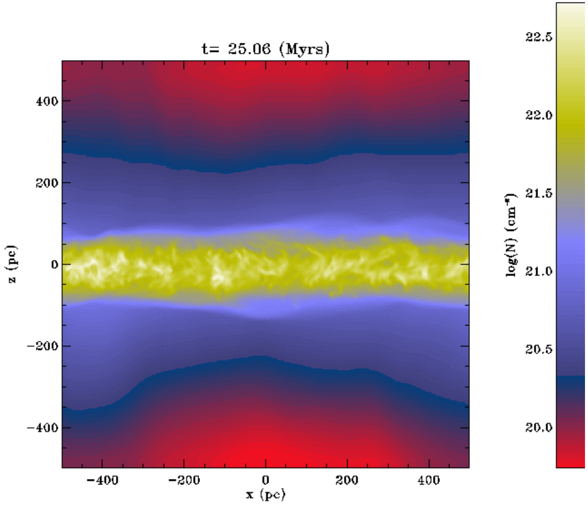
t= 25.06 (Myrs)
400
200
0
−200
−400
z (pc)
−400
−200
0
200
400
x (pc)
22.5
22.0
21.5
21.0
20.5
20.0
log(N) (cm⁻²)

Thanks for your attention!

arXiv:1410.7972