Phantom workshop 2025

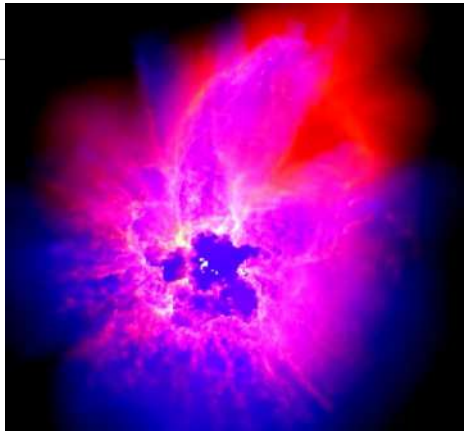
Stellar feedback in Molecular Clouds

Semi-confined Supernova in H II region bubbles

and how it differs to 1-D SN models in galaxy sims

Cheryl Lau

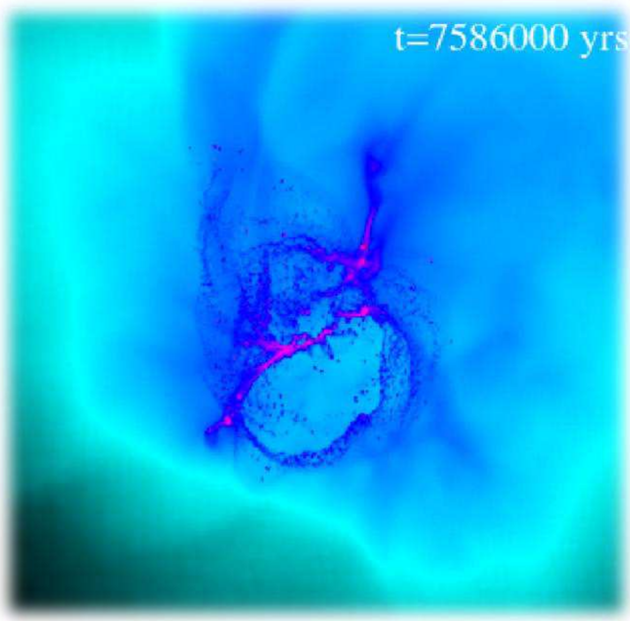
Prof. Ian Bonnell
University of St Andrews, Scotland, UK



(Dale et al. 2014)

Stellar feedback

- ❑ Photoionization
- ❑ Stellar winds
- ❑ Supernovae
- ❑ Jets
- ❑ Radiation pressure



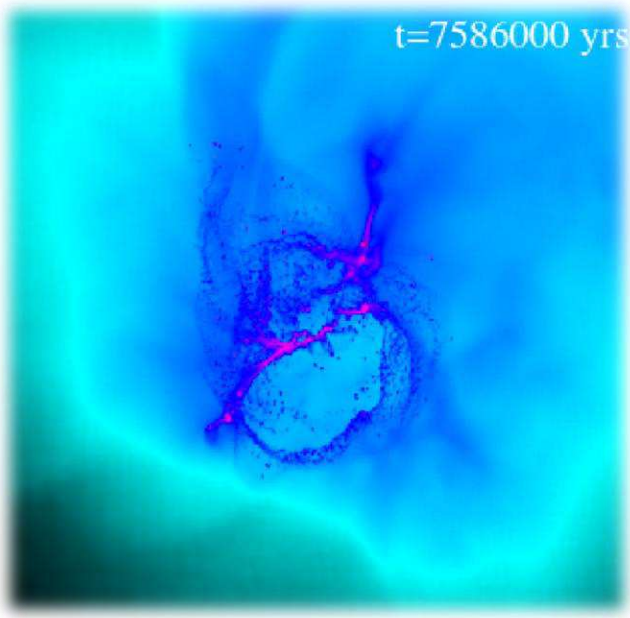
The largest source of energy and momentum in the ISM

- ❖ Sweep gas into shells and pillars
- ❖ Create bubbles
- ❖ Heats gas to hinder fragmentation

Stellar feedback

- ❑ Photoionization
- ❑ Stellar winds
- ❑ Supernovae
- ❑ Jets
- ❑ Radiation pressure

10^{51} ergs of KE

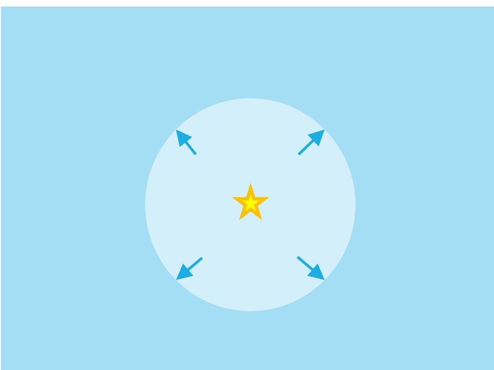


- ❖ Sustain turbulence
- ❖ Disperse molecular clouds to regulate star formation
- ❖ Launch galactic winds to halo

➢ **How much of the SN energy is transferred to the ISM?**

SNe are always affected by pre-SN feedback

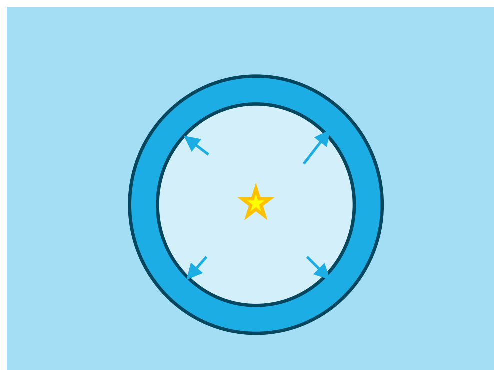
Stellar winds



Wind-blown bubbles

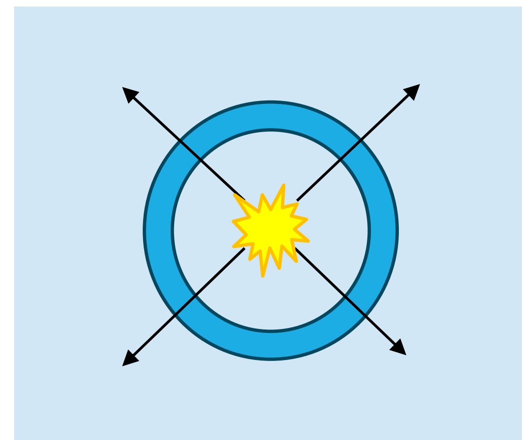
+

Ionizing radiation



H II regions

SN



Explodes in a cavity

Determines cooling of SN

But usually not resolved in galaxy sims…

Sub-grid models for galaxy sims

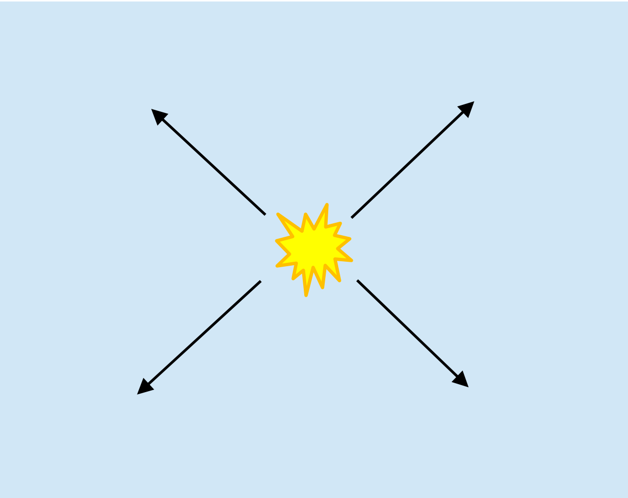
Sub-grid models are **prescriptions / recipes** of impact of feedback on small-scales

Otherwise…. lack of resolution leads to **numerical overcooling** –

- Feedback energy is distributed to too much mass
- Cannot resolve the hot phase of ISM
- Becomes subjected to high cooling rates

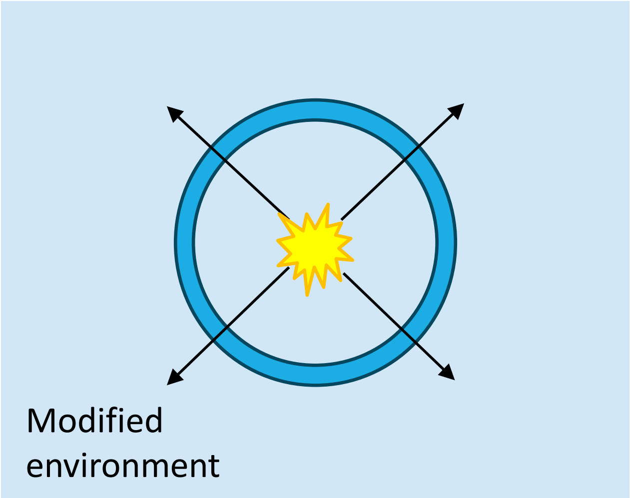
Current SN sub-grid models (typically)

Based on **spherical blast wave** solutions (Sedov/Snowplough)



+ cooling
+ stellar models ..... etc.

+ Interaction with **pre-SN feedback** bubble

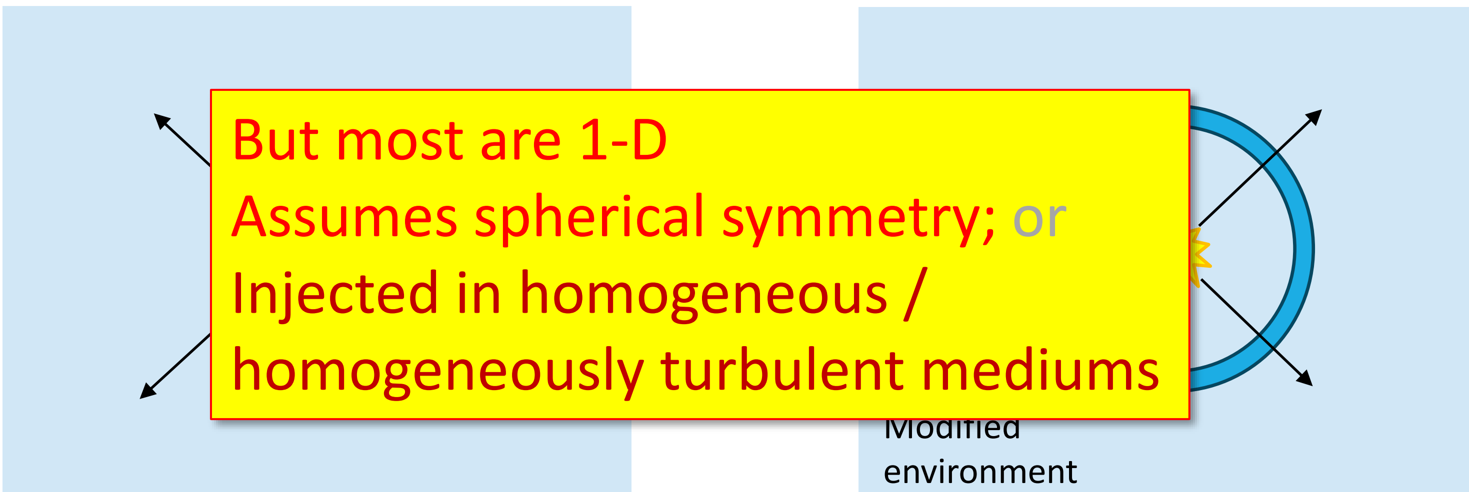


E.g. Wind-blown bubbles, HII regions

Current SN sub-grid models (typically)

Based on **spherical blast wave** solutions (Sedov/Snowplough)

+ Interaction with **pre-SN feedback** bubble

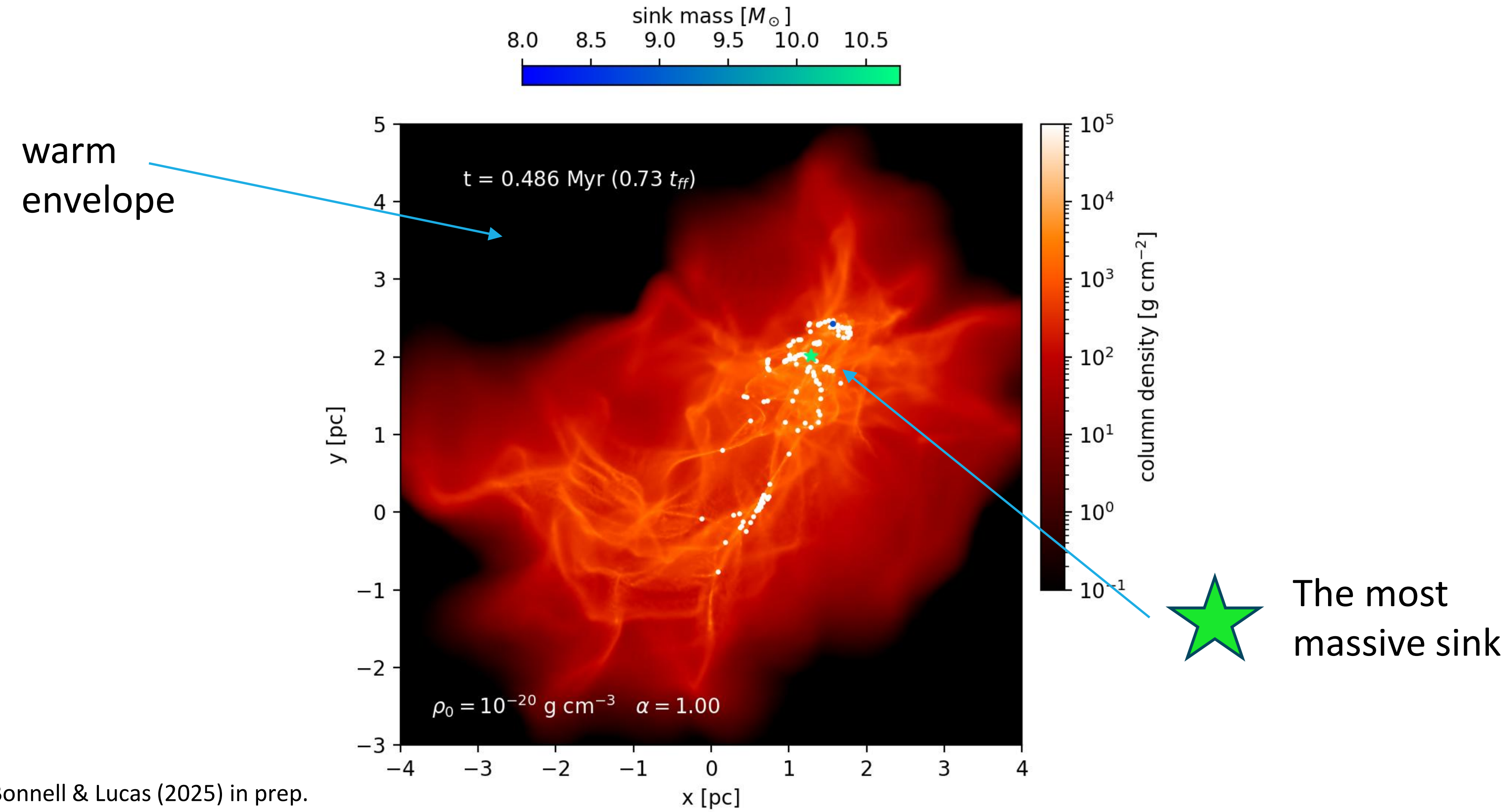


But most are 1-D
Assumes spherical symmetry; or
Injected in homogeneous / homogeneously turbulent mediums

+ cooling
+ stellar models ..... etc.

E.g. Wind-blown bubbles, HII regions

Before SN: HII region in GMC

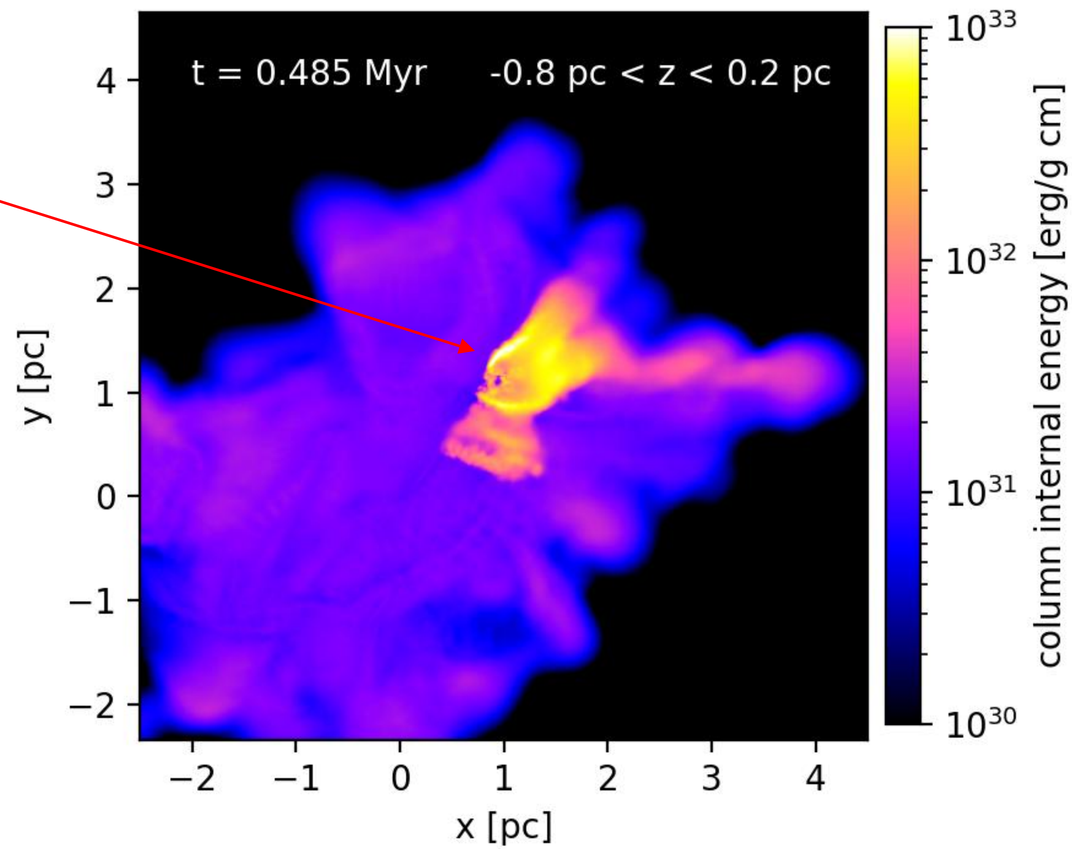


Lau, Bonnell & Lucas (2025) in prep.

Before SN:
HII region bubble in GMC

Heated by photoionization

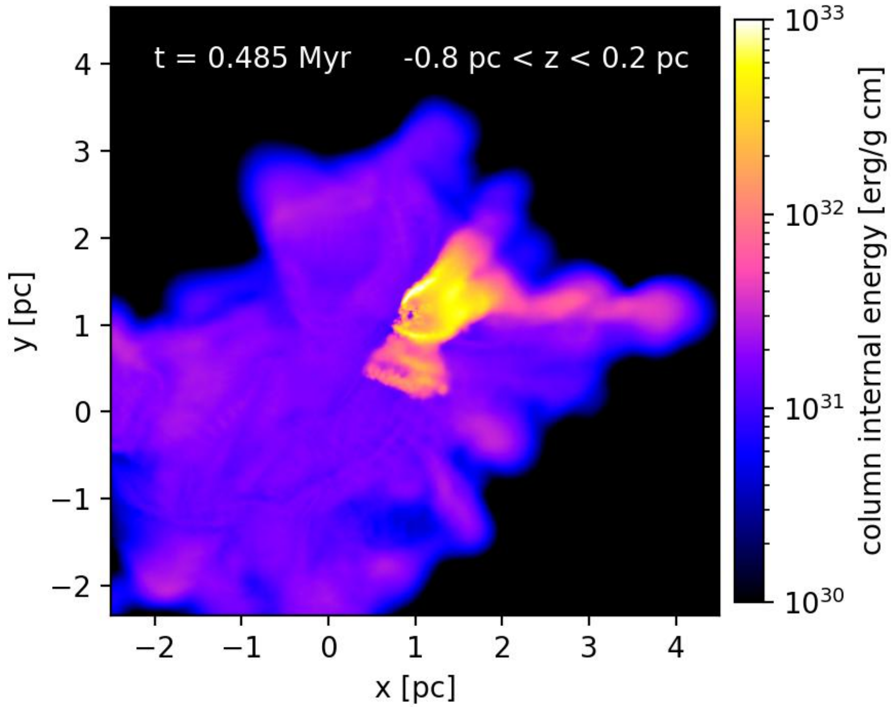
Internal energy of a slice



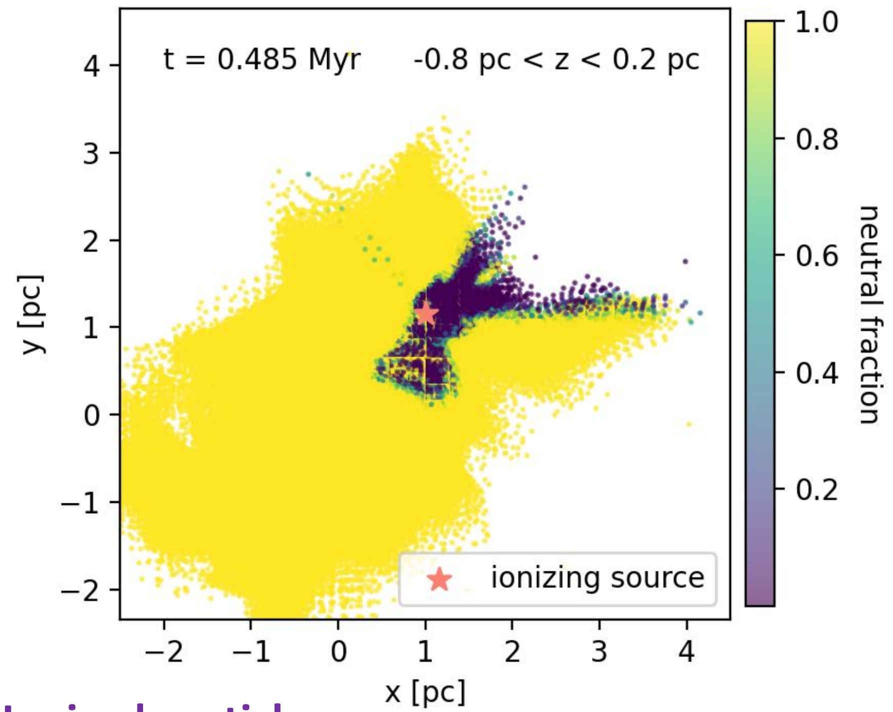
Lau, Bonnell & Lucas (2025) in prep.

Before SN: Ionized channels in GMC

Internal energy



Ionic fractions



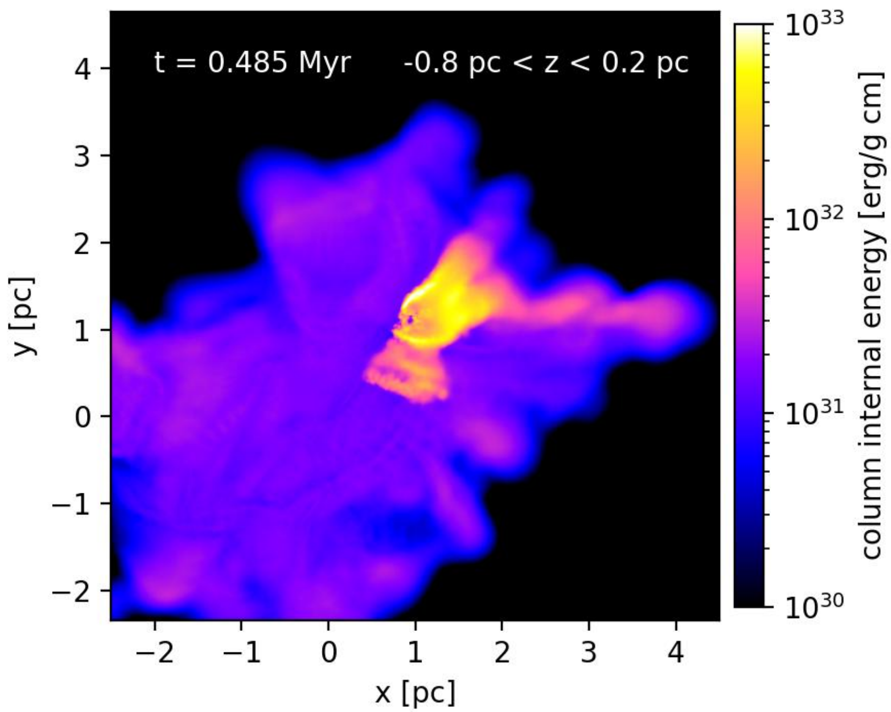
Ionized particles
Neutral particles

Lau, Bonnell & Lucas (2025) in prep.

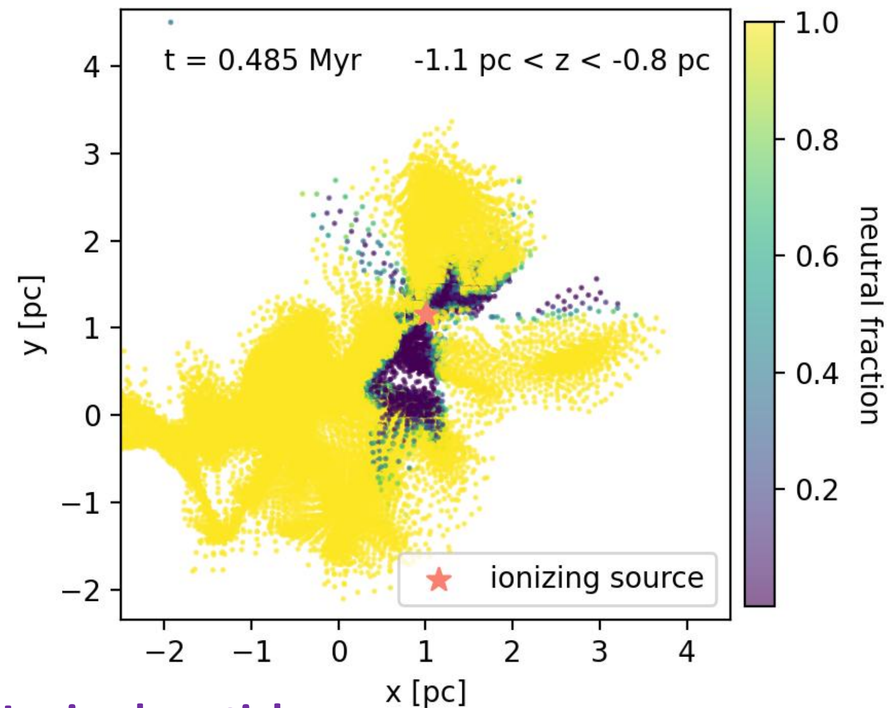
Before SN:
Ionized channels in GMC

A different slice

Internal energy



Ionic fractions



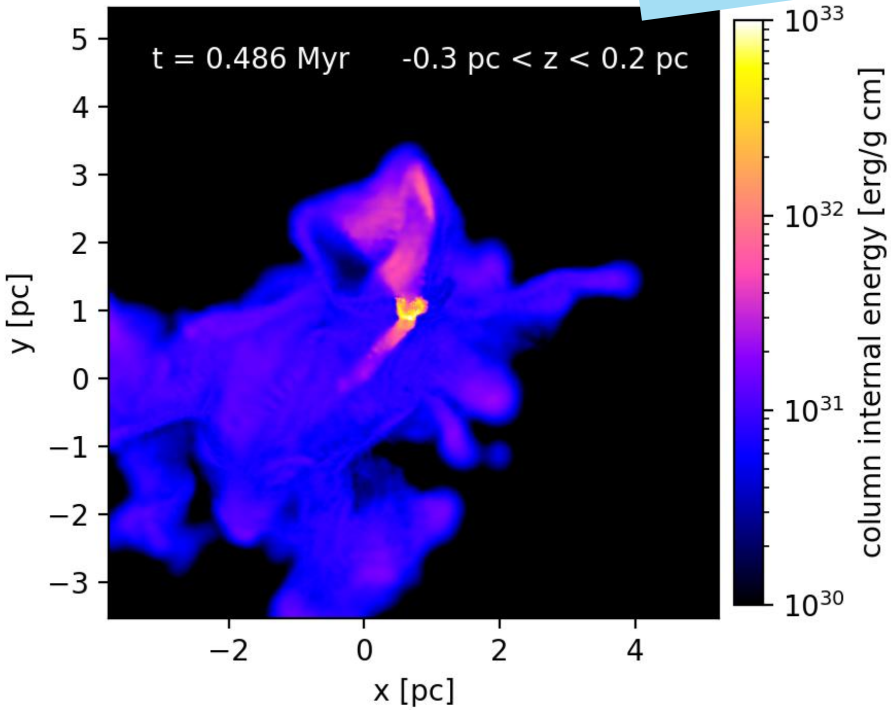
Ionized particles
Neutral particles

Lau, Bonnell & Lucas (2025) in prep.

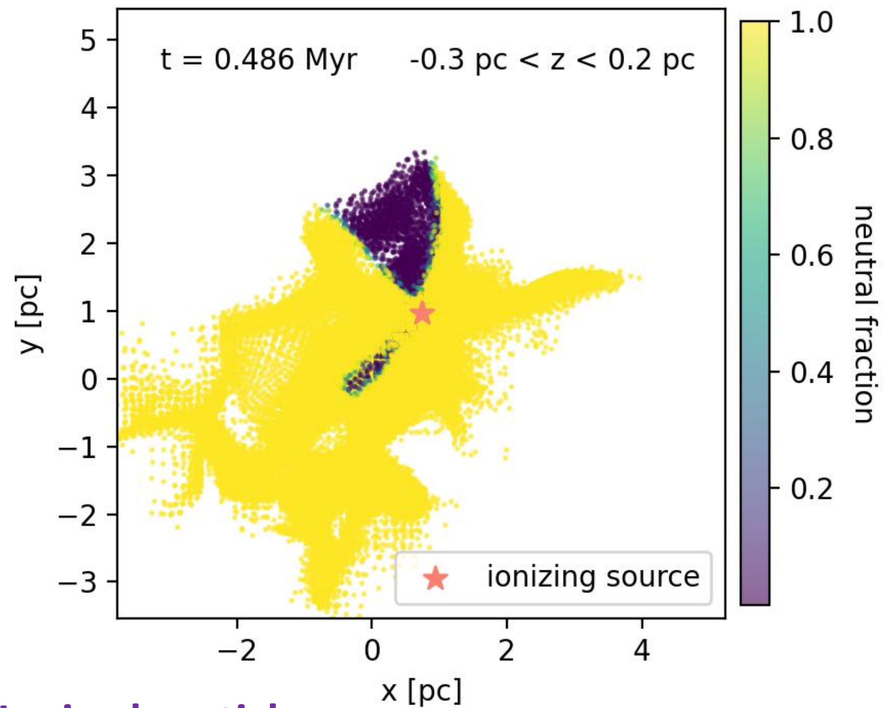
Before SN: Ionized channels in GMC

A different cloud

Internal energy



Ionic fractions

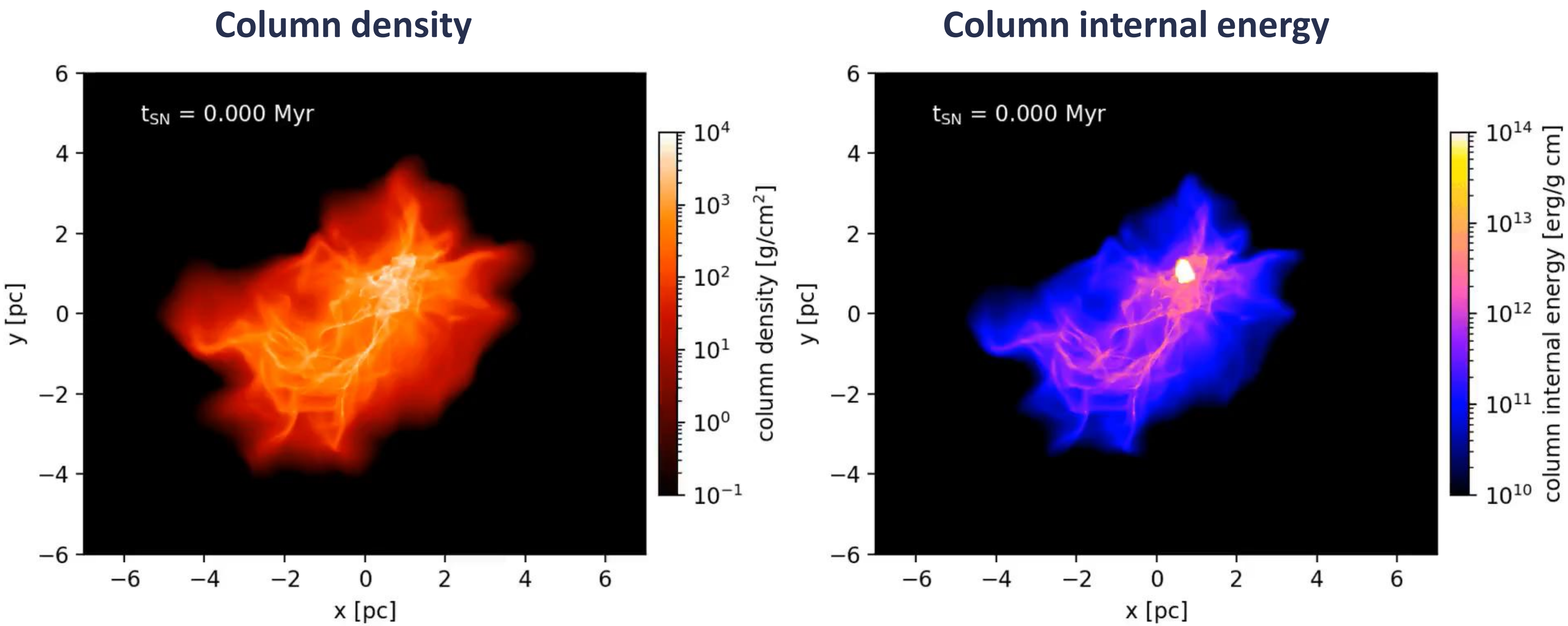


Ionized particles

Neutral particles

Lau, Bonnell & Lucas (2025) in prep.

Now with channels… Inject supernova

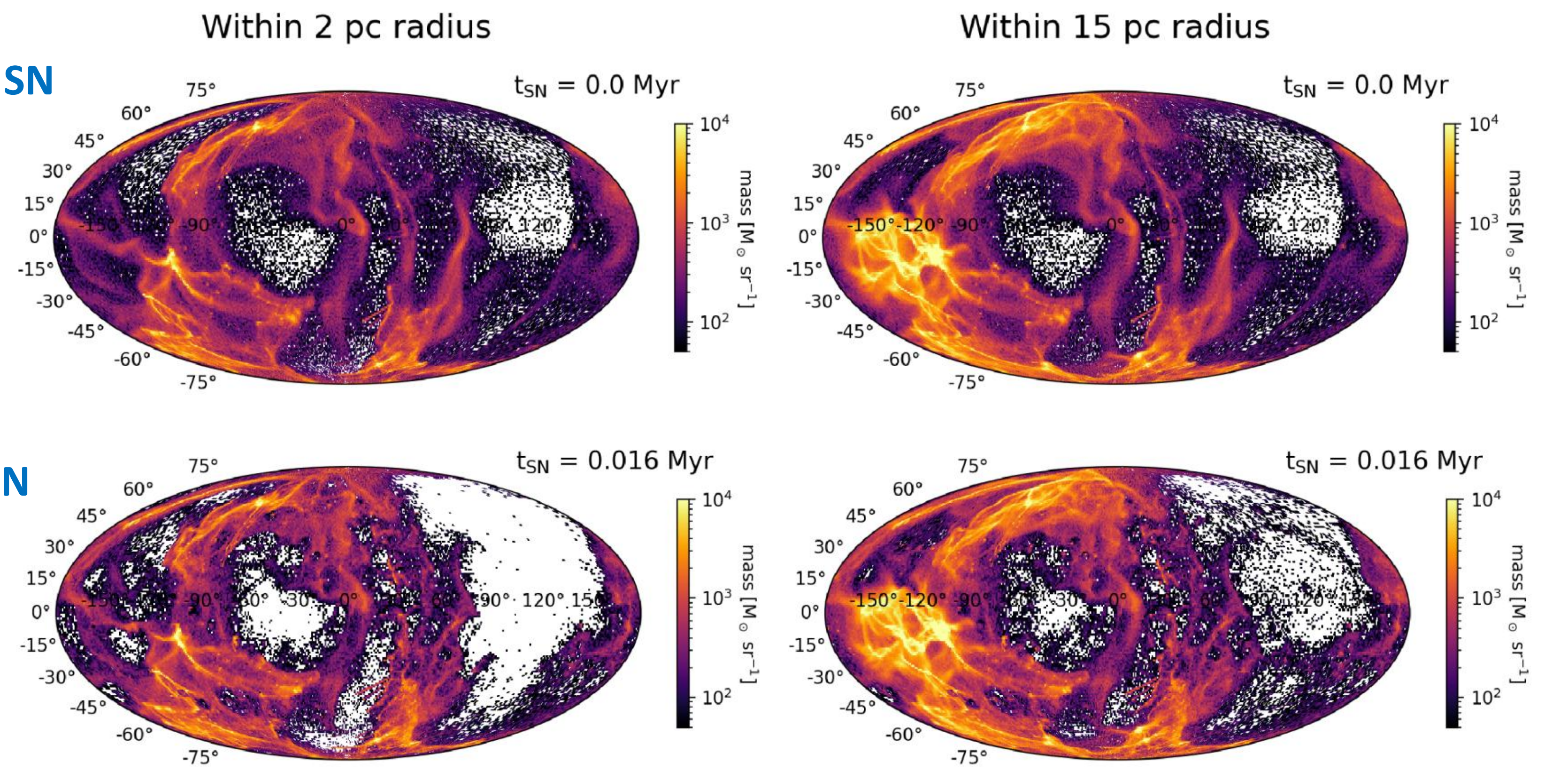


Lau, Bonnell & Lucas (2025) in prep.

Column densities seen from SN progenitor

Before SN

After SN

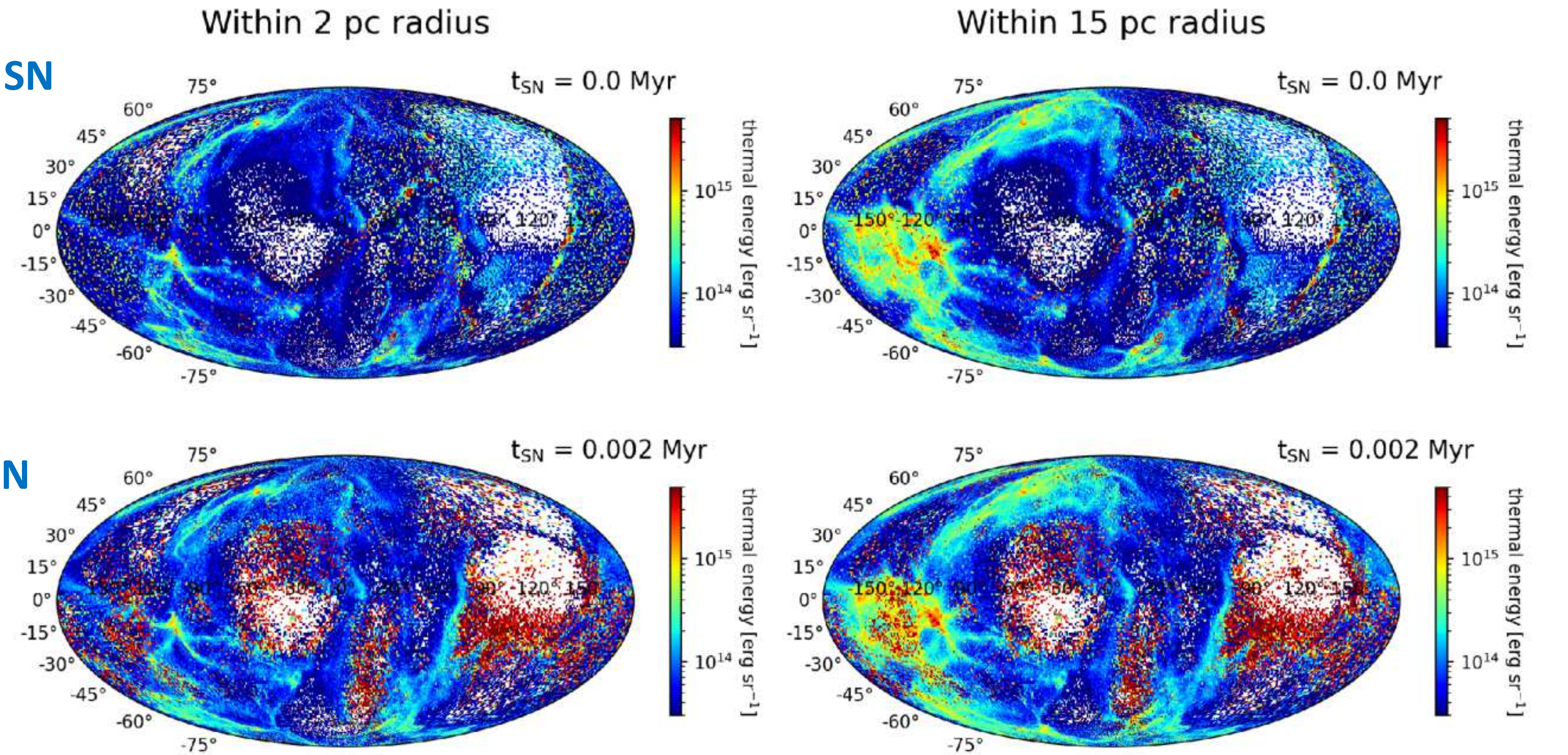


Lau, Bonnell & Lucas (2025) in prep.

Internal energies seen from SN progenitor

Before SN

After SN

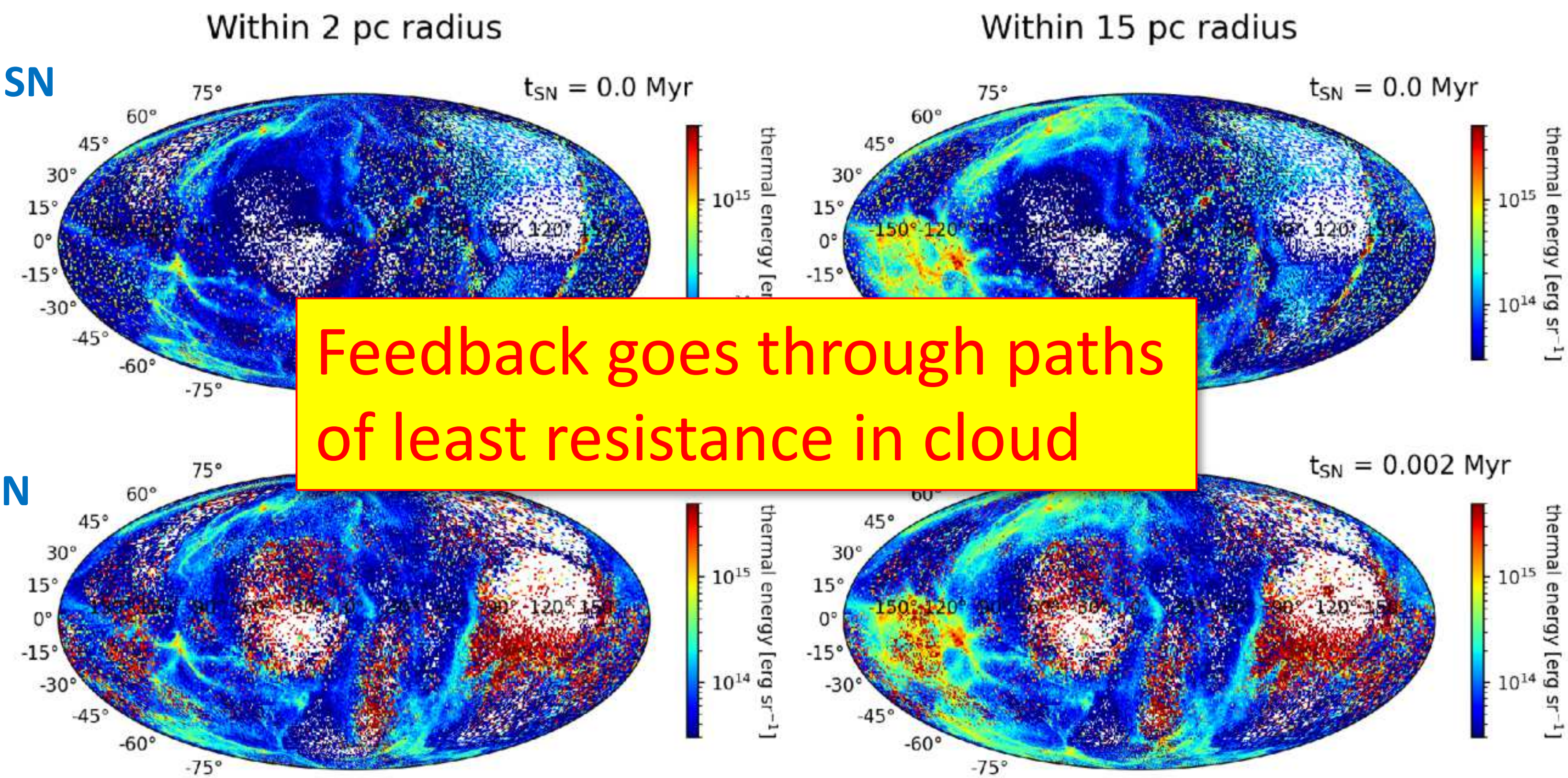


Lau, Bonnell & Lucas (2025) in prep.

Internal energies seen from SN progenitor

Before SN

After SN

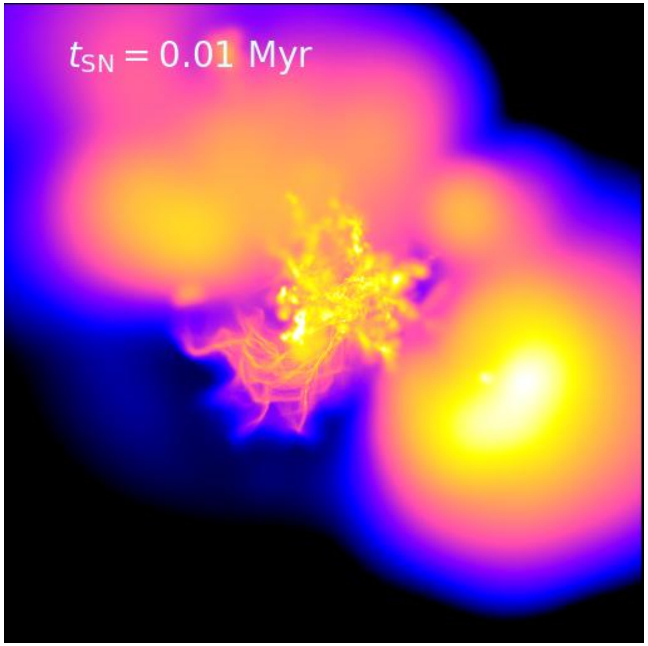


Feedback goes through paths of least resistance in cloud

Lau, Bonnell & Lucas (2025) in prep.

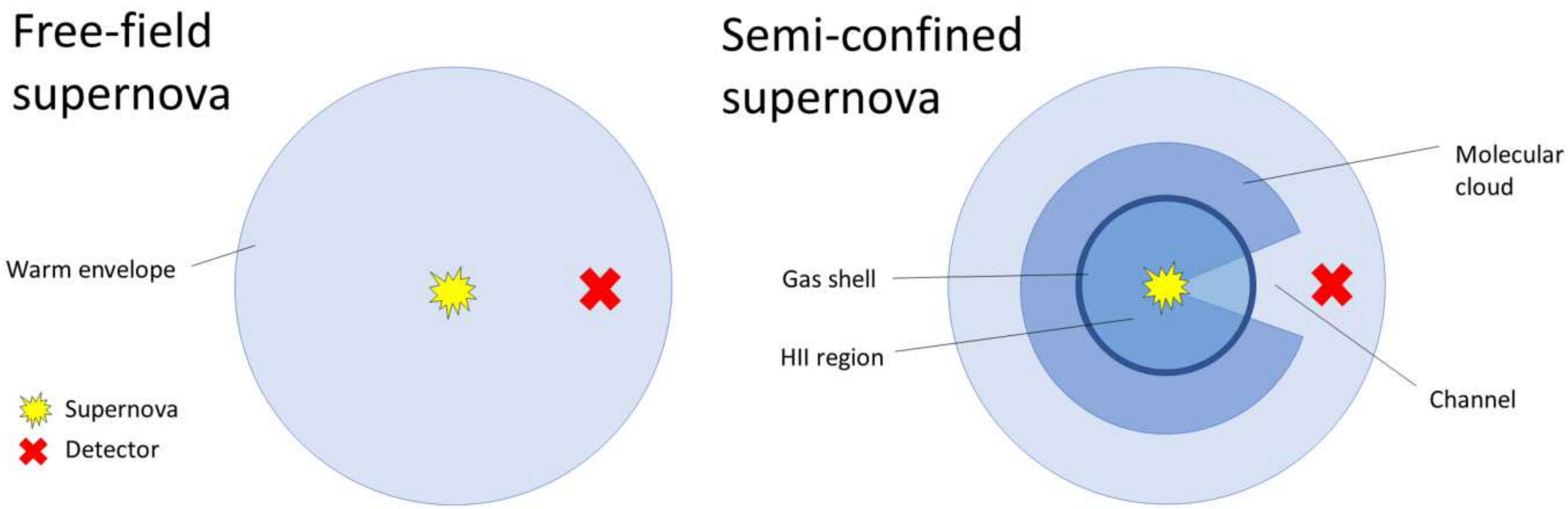
Breaking the symmetry

What is the difference in energy/momentum output between a typical 1-D spherical blast model and …



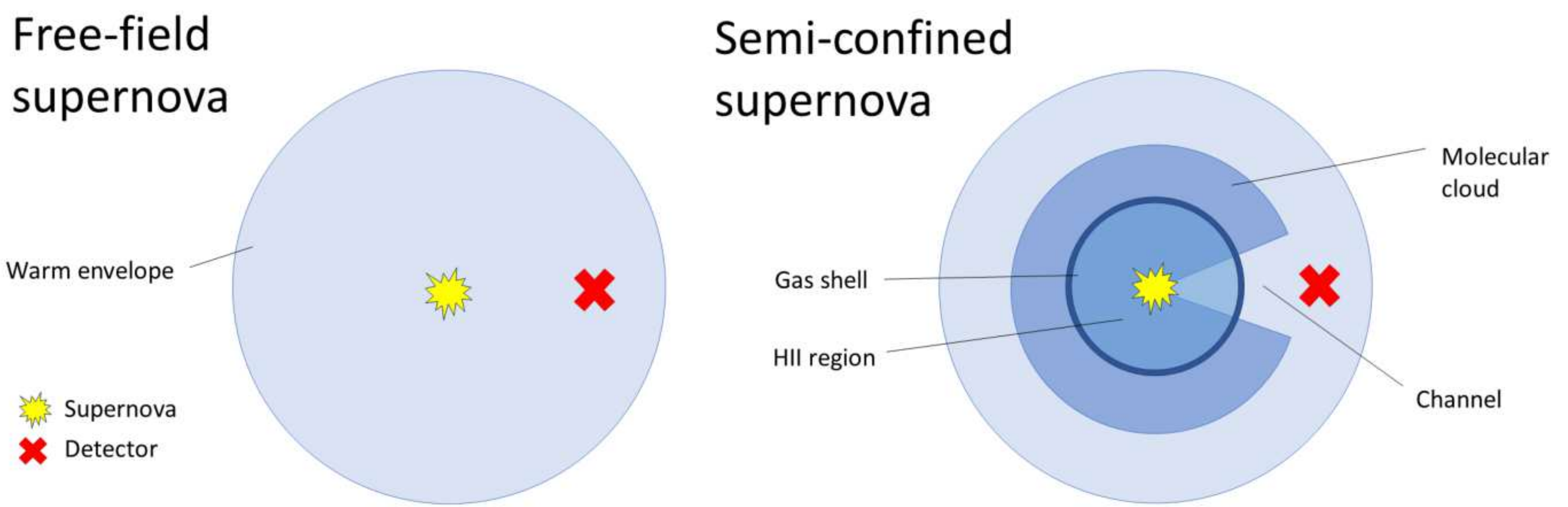
if we don't resolve it?

An idealized model



Lau & Bonnell (2025)

An idealized model



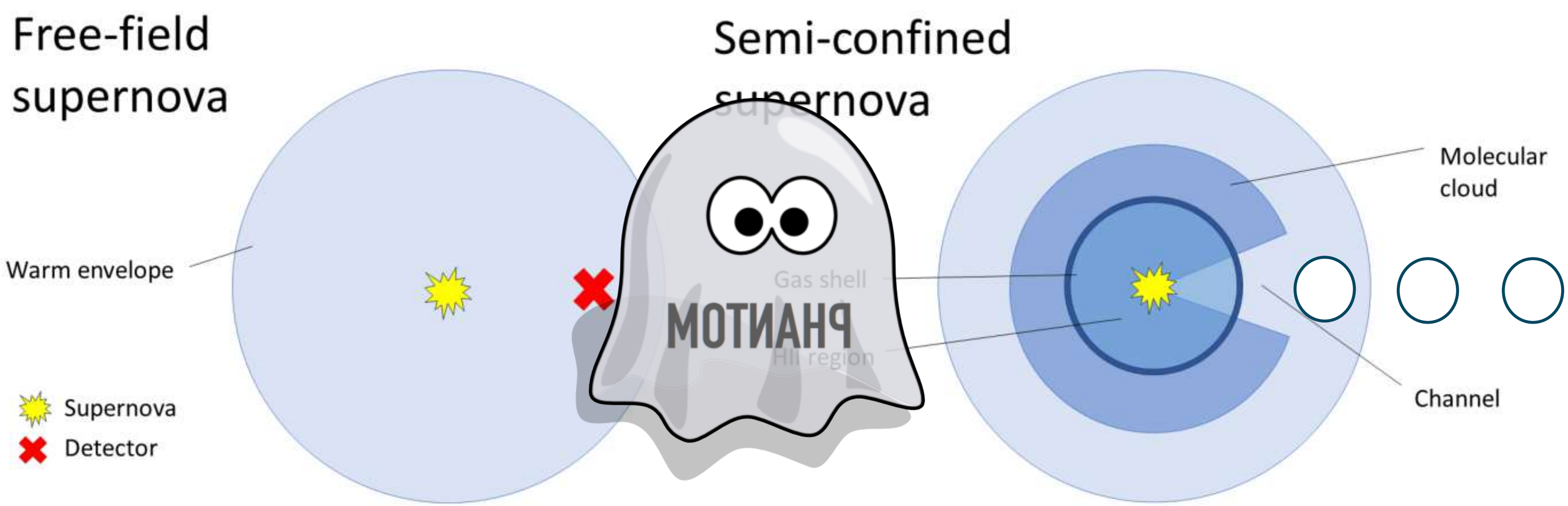
Compare:

1. Energy/momentum output
2. Strength of the outflow

How perturbed the gas is after the shock

Lau & Bonnell (2025)

An idealized model



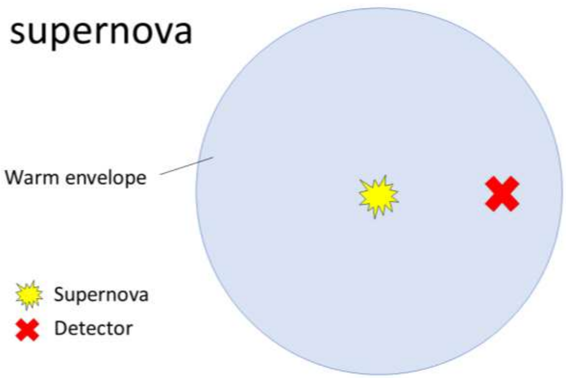
Compare:
1. Energy/momentum output
2. Strength of the outflow

How perturbed the gas is after the shock

Lau & Bonnell (2025)

Analytical model of free-field SNe

Free-field supernova



Sedov solution –
velocity $v_{\rm shock}$ as a function of $r_{\rm shock}$

$$v_{\rm shock} = \frac{2}{5}\xi_0^{5/2}\left(\frac{E_{\rm SN}}{\rho_{\rm env}}\right)^{1/2} r_{\rm shock}^{-3/2}$$

Assume it remains self-similar

Gas properties in post-shock region:

$$\frac{v'}{v_{\rm shock}} = \frac{\eta}{\gamma} + \left(\frac{\gamma-1}{\gamma^2+\gamma}\right)\eta^a$$

with Rankine-Hugoniot relations

$$\frac{\rho'}{\rho_{\rm env}} = \left(\frac{\gamma+1}{\gamma-1}\right)\frac{\eta^b}{\gamma^c}\left(\gamma+1-\eta^{a-1}\right)^c$$

where

$$\eta = \frac{r'}{r_{\rm shock}}$$

$$\frac{p'}{p_{\rm env}} = M_s^2\left(\frac{2\gamma^{1-d}}{\gamma+1}\right)\left(\gamma+1-\eta^{a-1}\right)^d$$

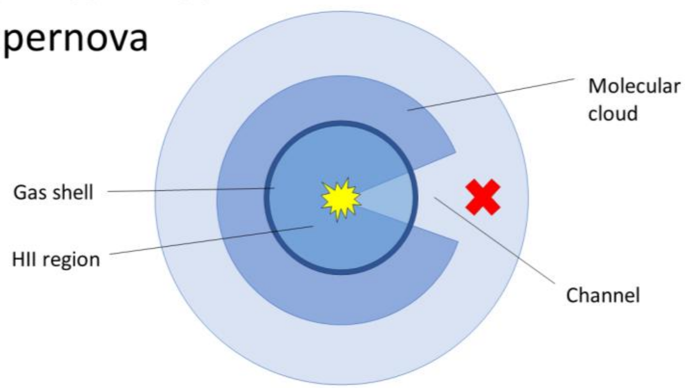
$$a = \frac{7\gamma-1}{\gamma^2-1},\quad b = \frac{3}{\gamma-1},\quad c = \frac{2\gamma+10}{\gamma-7},\quad d = \frac{2\gamma^2+7\gamma-3}{\gamma-7}$$

Gives:
Variation of v, ρ, P at detector location

Lau & Bonnell (2025)

Analytical model of semi-confined SNe

Semi-confined supernova



Two major considerations:

- Expansion of HII region shell after SN
- Venting of gas during pressure-relief phase

Few assumptions:

- SN energy completely thermalized upon colliding with shell
- Properties are uniform inside cavity
- Gas at detector is only affected by pressure gradient, i.e. not the direct impact from SN
- Gas remains adiabatic

$$p = p_{\rm env}\left(\frac{\rho}{\rho_{\rm env}}\right)^{\gamma}$$

Shell EOM $\frac{dv_{\rm shell}}{dt} = \frac{4\pi R^2}{M_{\rm shell}(R)}\left(p - \rho_{\rm cloud} v_{\rm shell}^2\right)$ $M_{\rm shell}(R) = M_{\rm shell,0} + 4\pi\rho_{\rm cloud}\int_{R_{\rm HII}}^{R} R^2\, dR$

Mass loss $\frac{dM}{dt} = \rho_{\rm env} v_{\rm out} s_{\rm out}$ Cavity pressure $p = \epsilon\,(\gamma - 1)\,\frac{M}{V}$

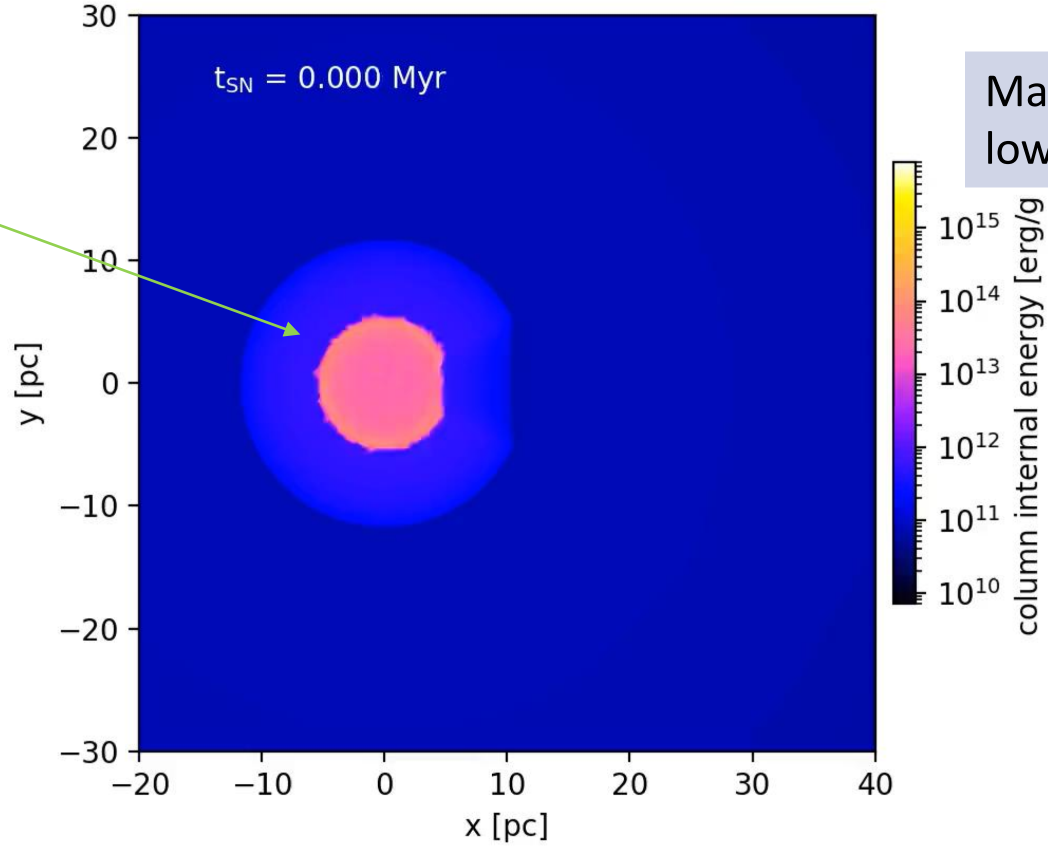
Outflow velocity $v_{\rm out} = \sqrt{2\frac{\gamma}{\gamma-1}\frac{p_{\rm env}}{\rho_{\rm env}}\left[\left(\frac{p}{p_{\rm env}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right]}$

Gives:
Variation of v, ρ, P at detector location

Lau & Bonnell (2025)

Idealized simulations adiabatic & cooling

Inject ionizing radiation

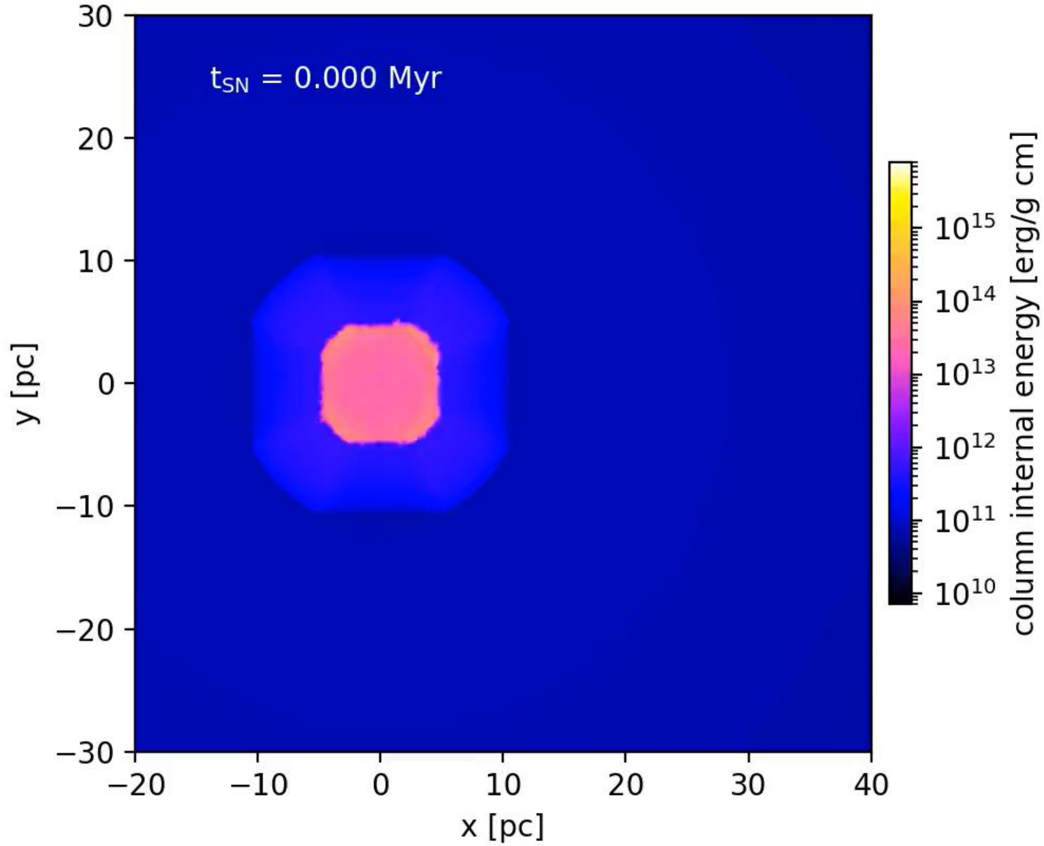


Manually carved a low-density channel

Lau & Bonnell (2025)

Idealized simulations adiabatic & cooling

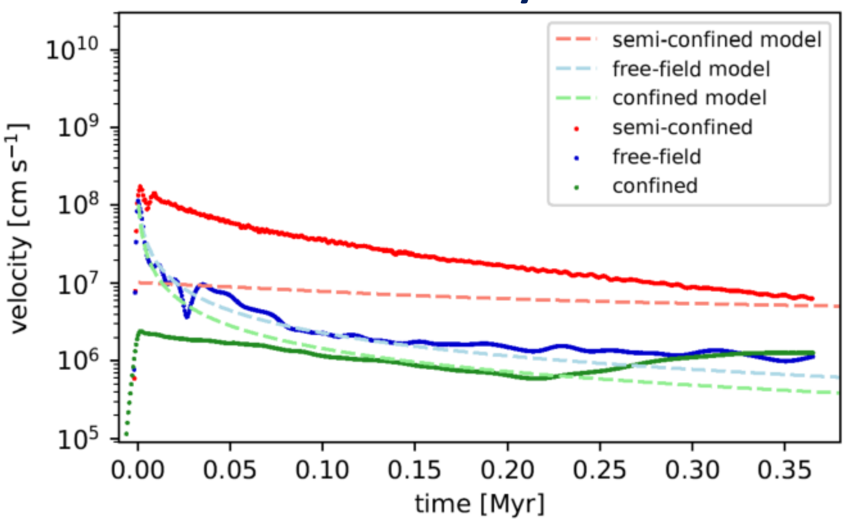
With 4 channels



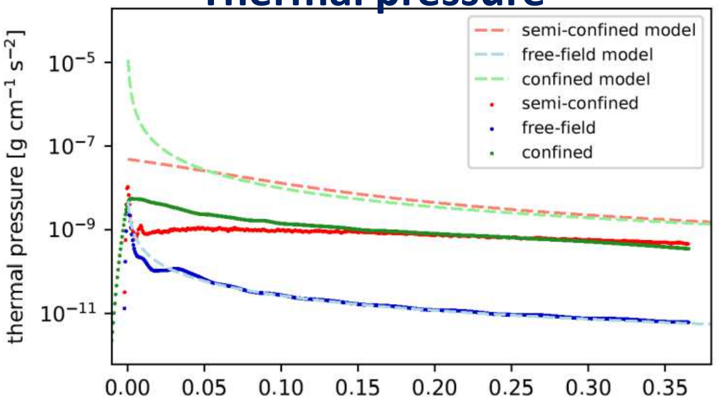
Lau & Bonnell (2025)

Gas properties at detector

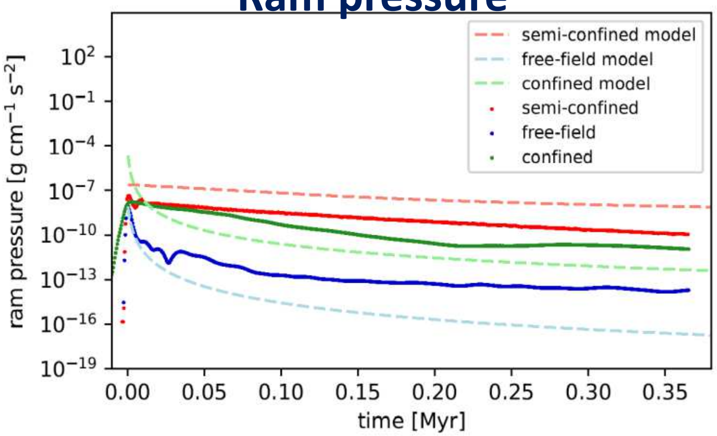
Velocity



Thermal pressure



Ram pressure



Semi-confined

Free-field

Fully-confined

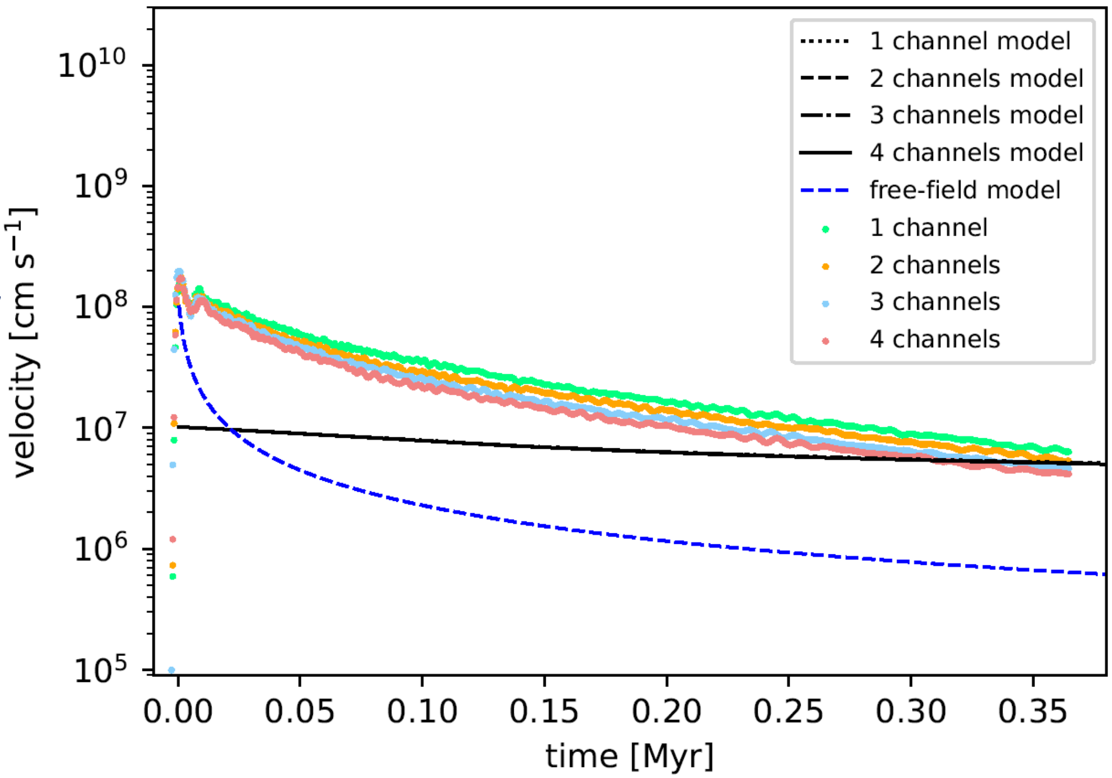
Dashed - model

Agrees with analytical model!

Lau & Bonnell (2025)

Flow velocities at detector with multiple channels

Outflow velocity

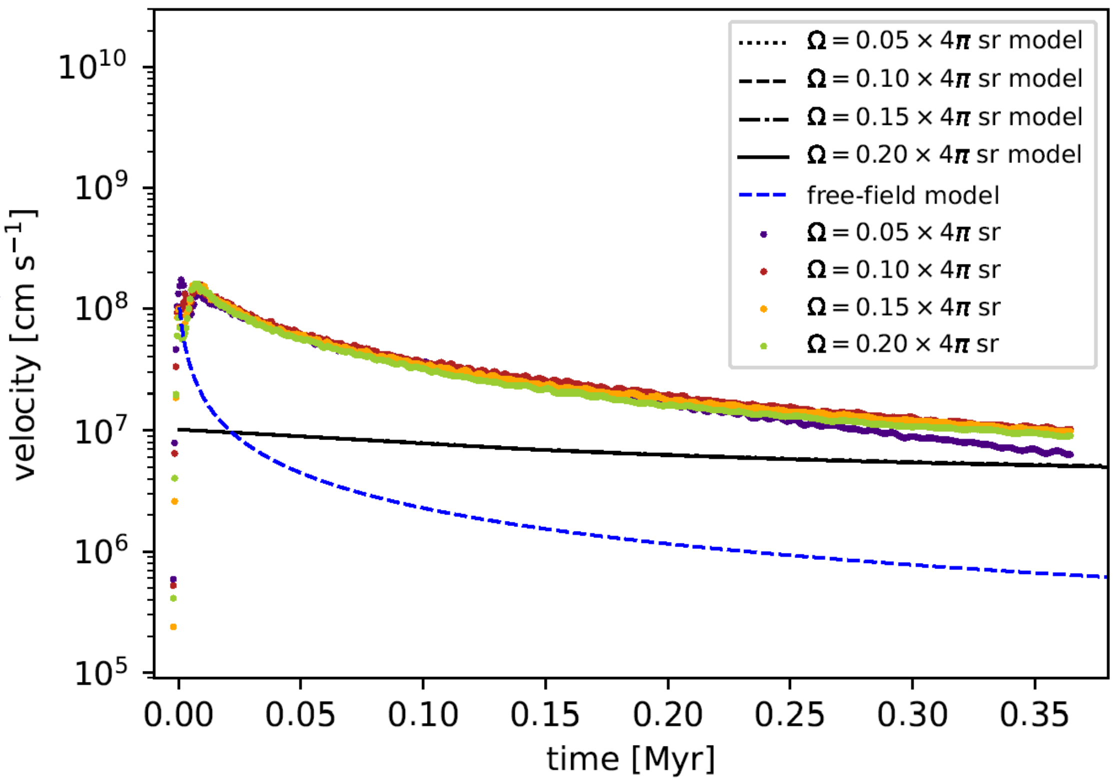


Surprisingly similar

Lau & Bonnell (2025)

Flow velocities at detector with bigger channels

Outflow velocity



Lau & Bonnell (2025)

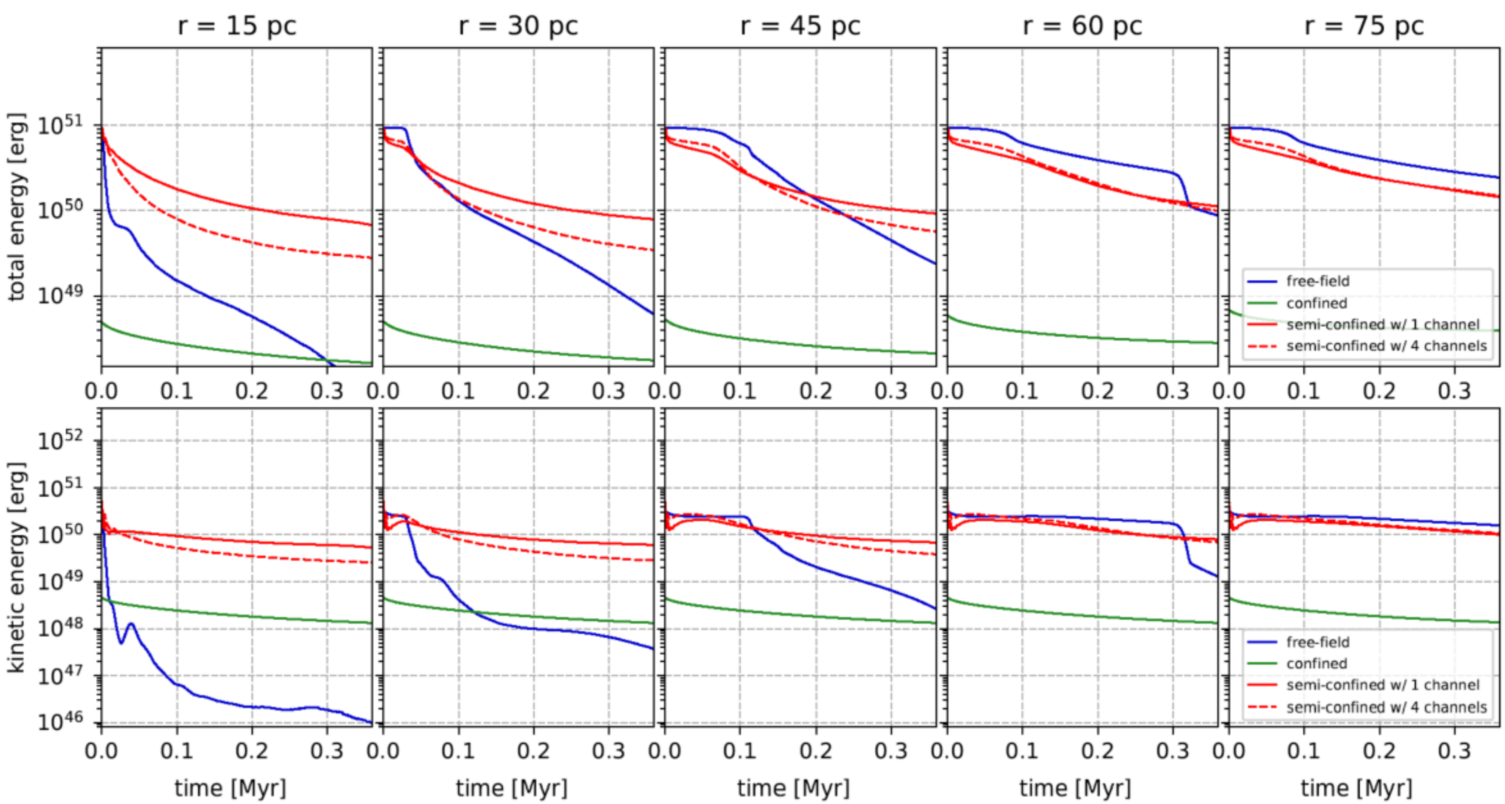
More energy deposited at closer radii

Semi-confined
Free-field
Fully-confined

radius

Total energy

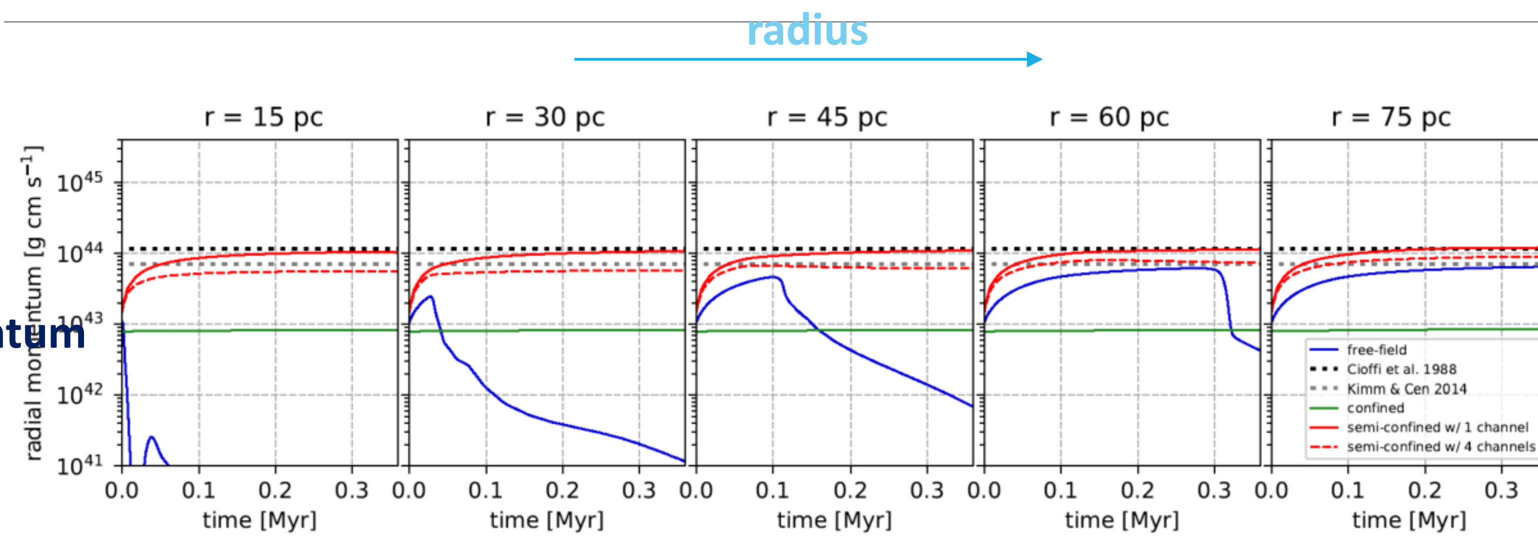
Kinetic energy



Lau & Bonnell (2025)

More momentum deposited at closer radii too

Radial momentum



Terminal radial momentum of SN:

$$\bar{\mu}_{\rm final} = 4.8 \times 10^5 \frac{E_{51}^{13/14}}{\zeta_m^{3/14} n_H^{1/7}} \qquad [{\rm M_\odot\ km\ s^{-1}}]$$

Cioffi et al. (1988)

$$\bar{\mu}_{\rm final} = 3.0 \times 10^5 \frac{E_{51}^{16/17}}{n_H^{2/17}} \max[\zeta_m, 0.01]^{-0.14} \qquad [{\rm M_\odot\ km\ s^{-1}}]$$

Kimm & Cen (2014)

Semi-confined
Free-field
Fully-confined

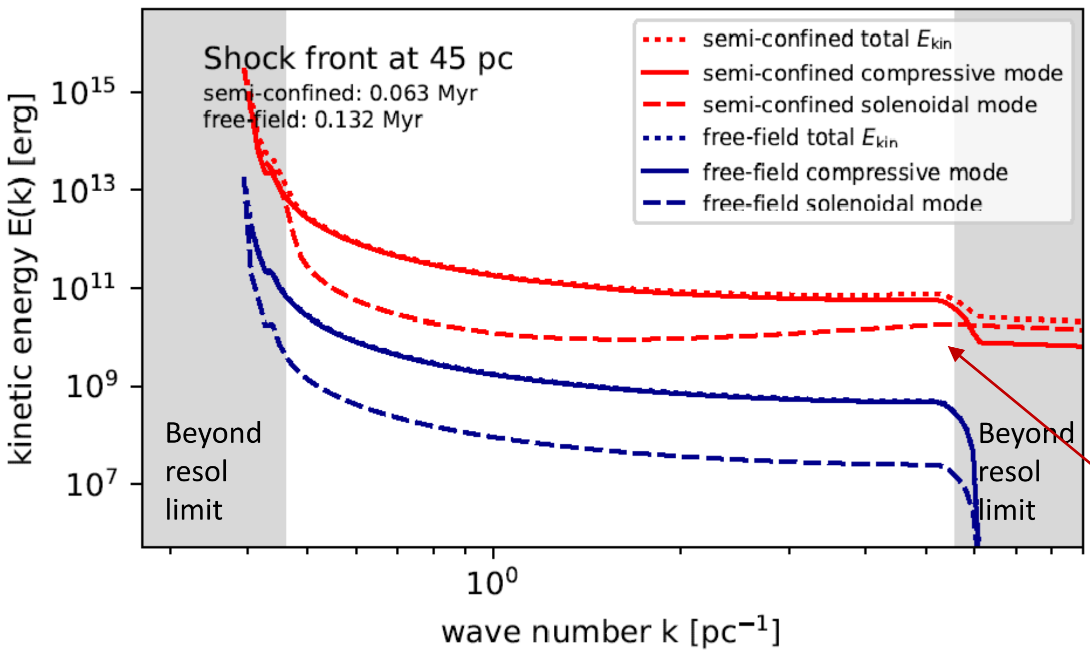
Lau & Bonnell (2025)

Turbulence in the outflow

Solid – compressive
Dashed – solenoidal

Semi-confined
Free-field

Kinetic energy spectrum



Post-shock region only

A little higher at small length-scales

Lau & Bonnell (2025)

Findings so far…

Semi-confined SNe:

- Sustain stronger perturbations – higher velocity and pressure
- Deposit more kinetic energy and momentum at small scales
- Sustain solenoidal turbulence behind the shock

Findings so far…

Semi-confined SNe:

- Sustain stronger perturbations – higher velocity and pressure
- Deposit more kinetic energy and momentum at small scales
- Sustain solenoidal turbulence behind the shock

Higher dynamical impact on **local** environment

Smaller supernova impact sizescale?

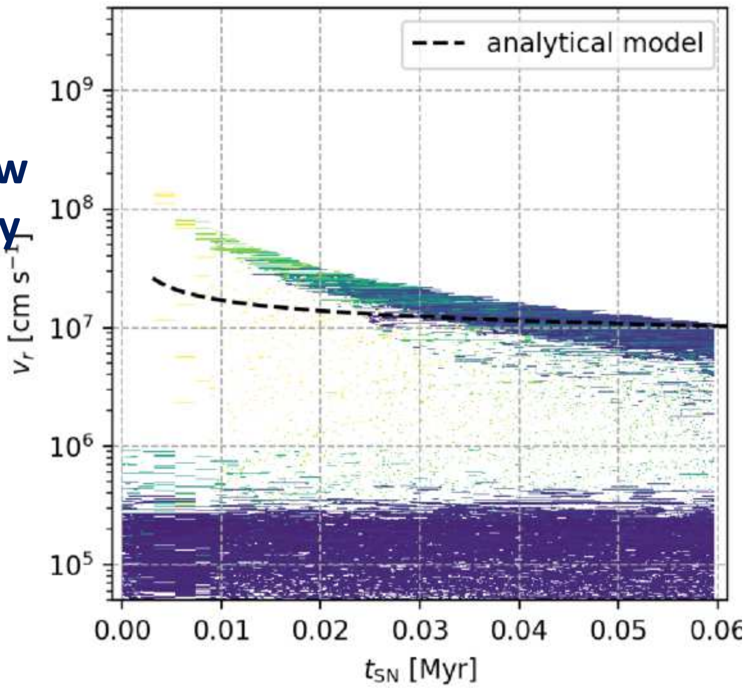
Possibly better for regulating SF

We probably should account for partial confinement in 1-D sub-grid models!

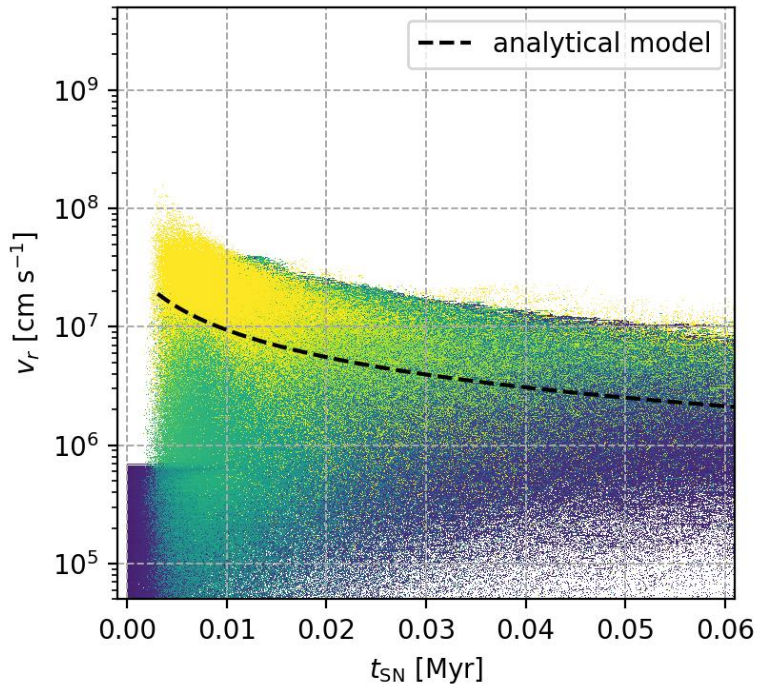
How can we turn this into a 1-D model?

Outflow velocity

SN in turbulent cloud



SN in homogenously turbulent medium

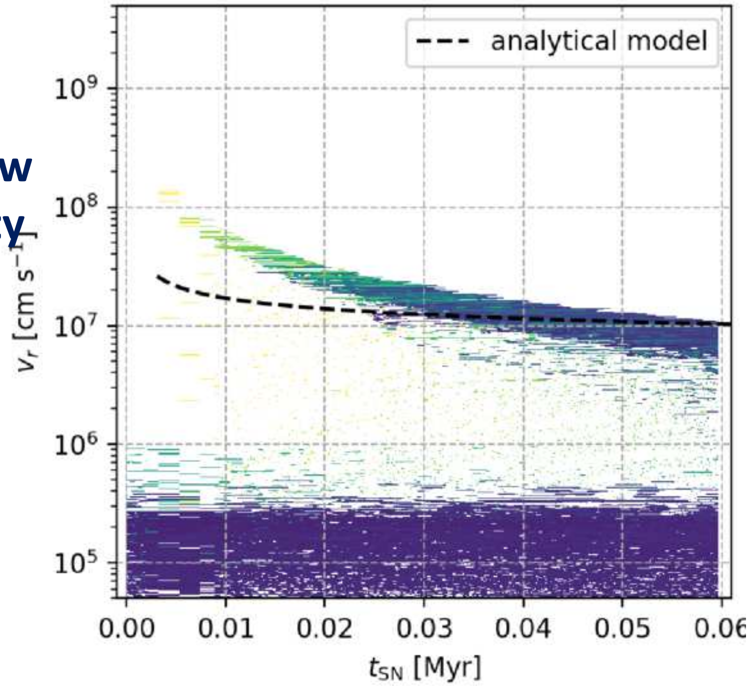


Mimic the local perturbation from cloud-confined SN

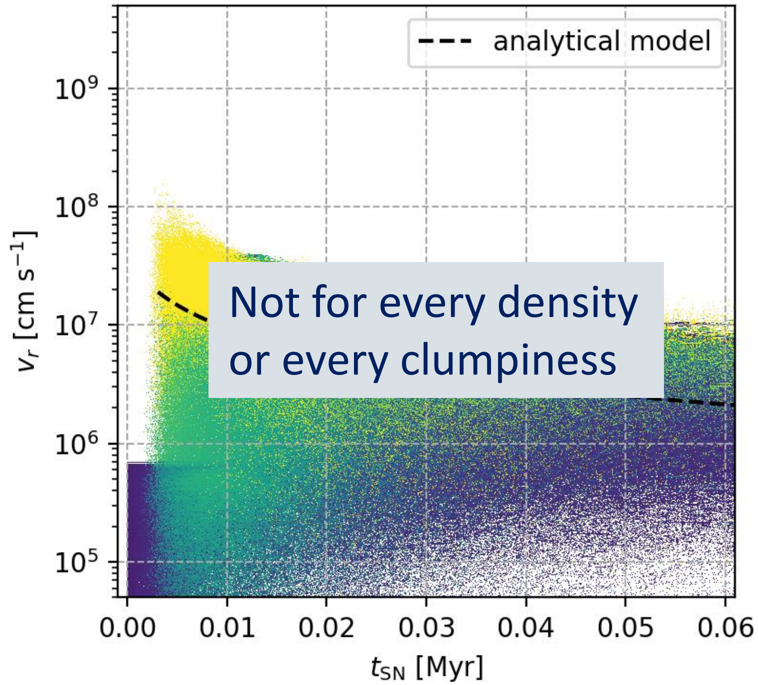
How can we turn this into a 1-D model?

Outflow velocity

SN in turbulent cloud



SN in homogenously turbulent medium



Mimic the local perturbation from cloud-confined SN

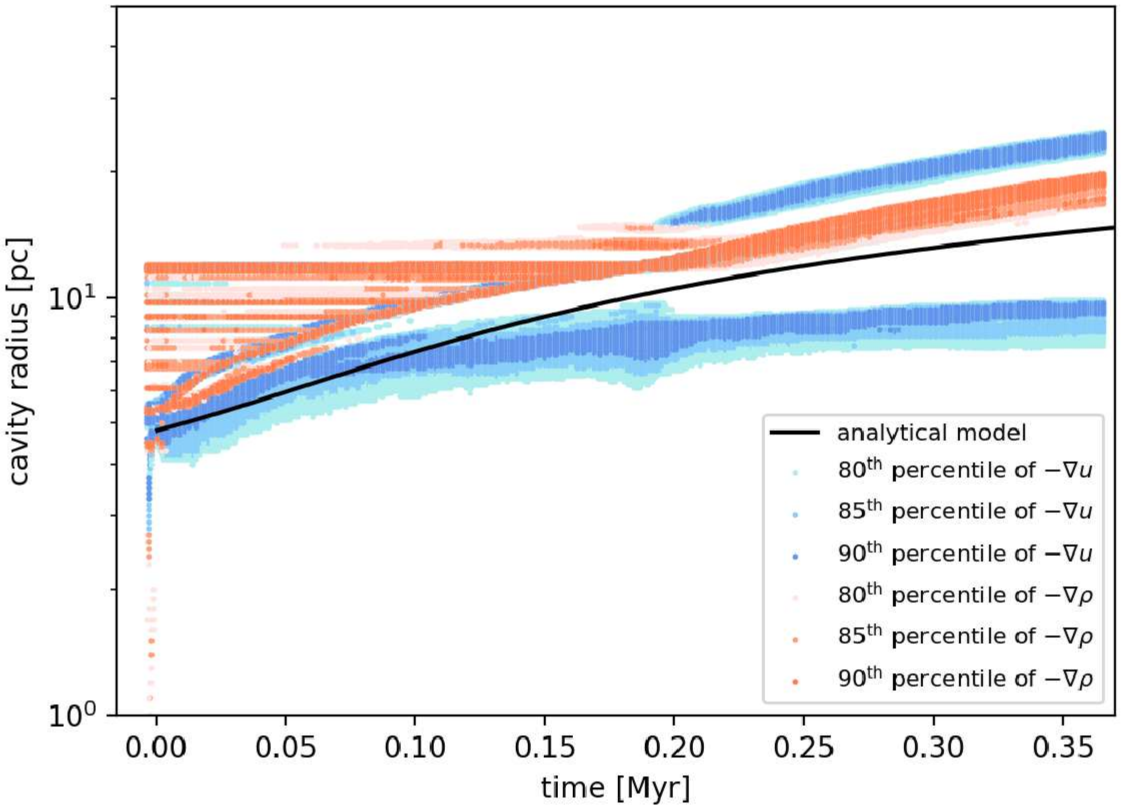
Conclusion

- SN energy from cloud usually leaves preferentially through the low-density channels, largely not a 1-D problem
- Analytical models for interior explosions can describe this scenario
- Semi-confined SNe produce higher outflow velocity from bubble
- Semi-confined SNe make stronger perturbation and larger energy/momentum deposition at small-scale environment
- Using clumpy medium for SN models may be the solution

Collision of SN on cavity shell

Cavity radius traced by density and IE gradients

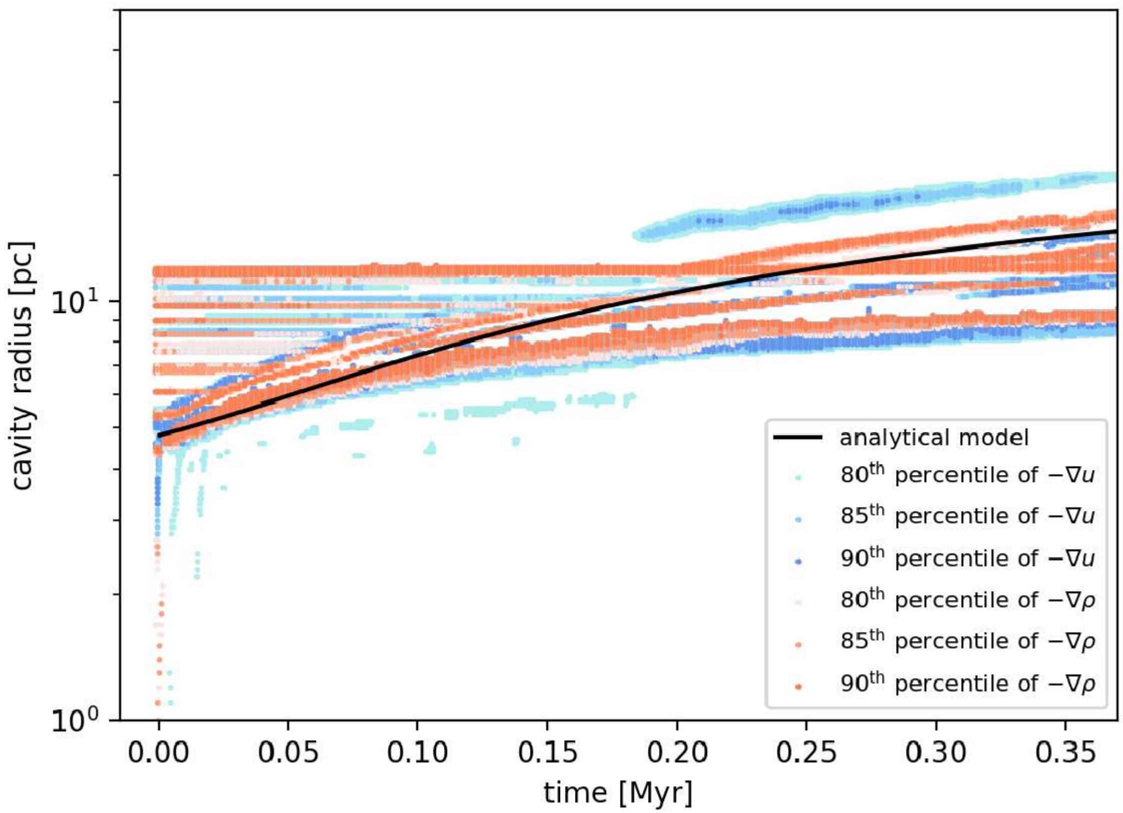
Adiabatic run



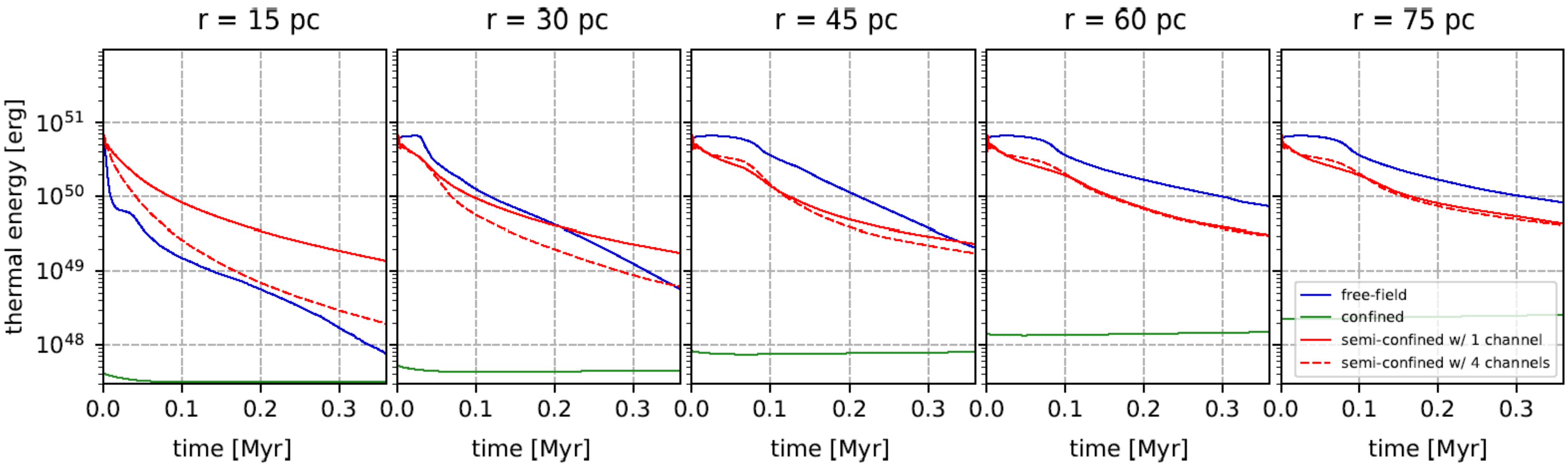
Collision of SN on cavity shell

Cavity radius traced by density and IE gradients

Cooling run



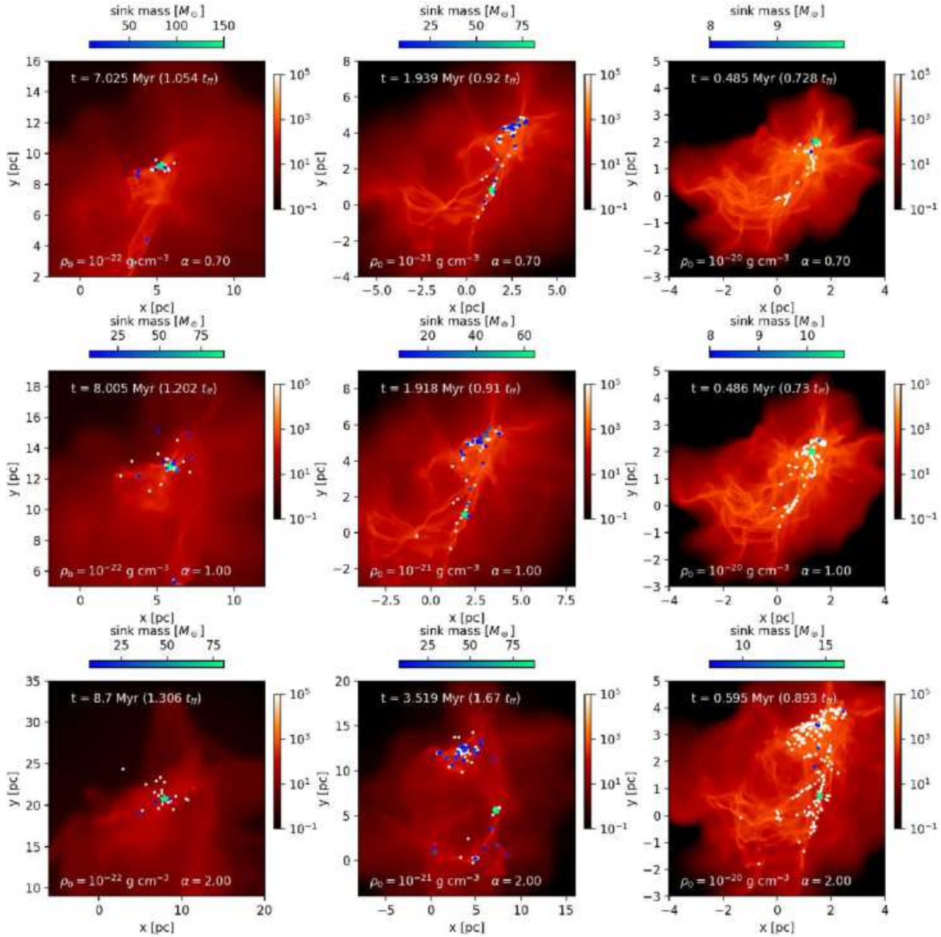
Cooling at a similar rate



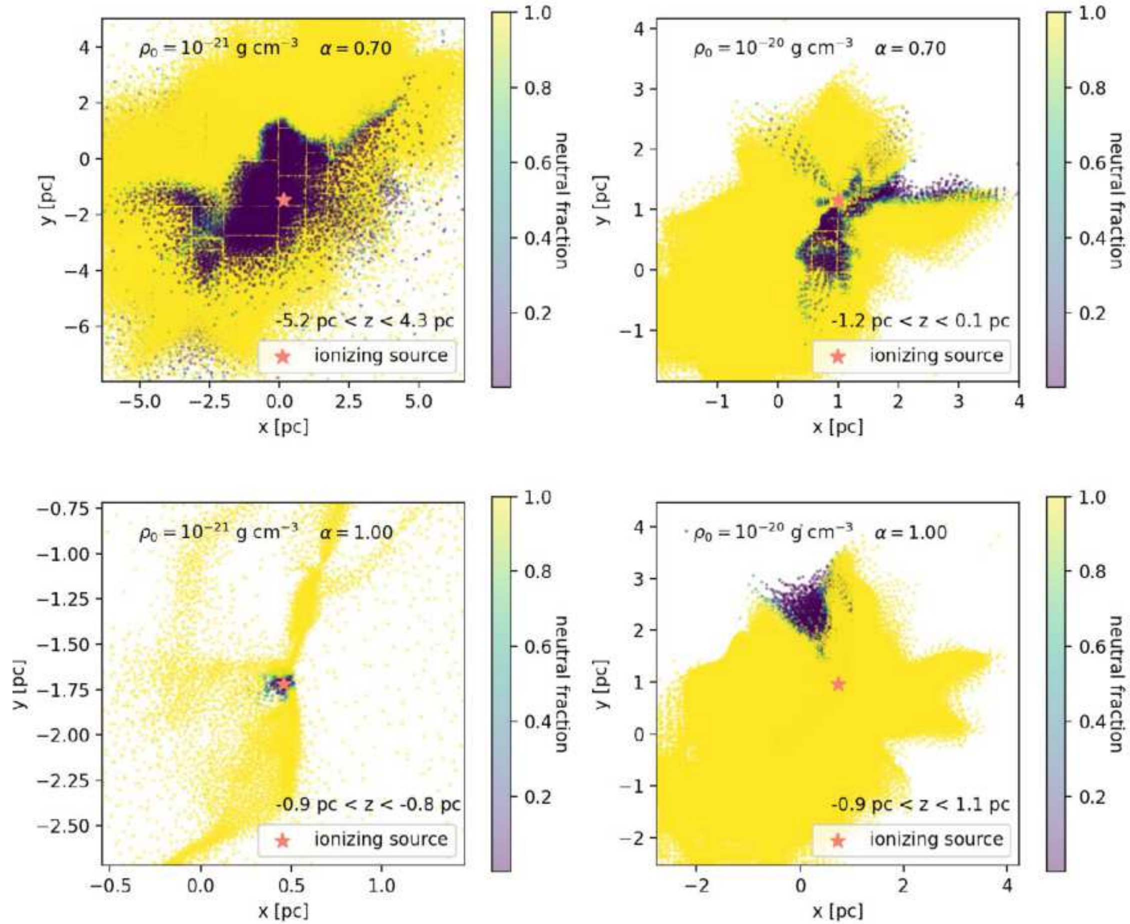
Molecular clouds

density

Virial ratio



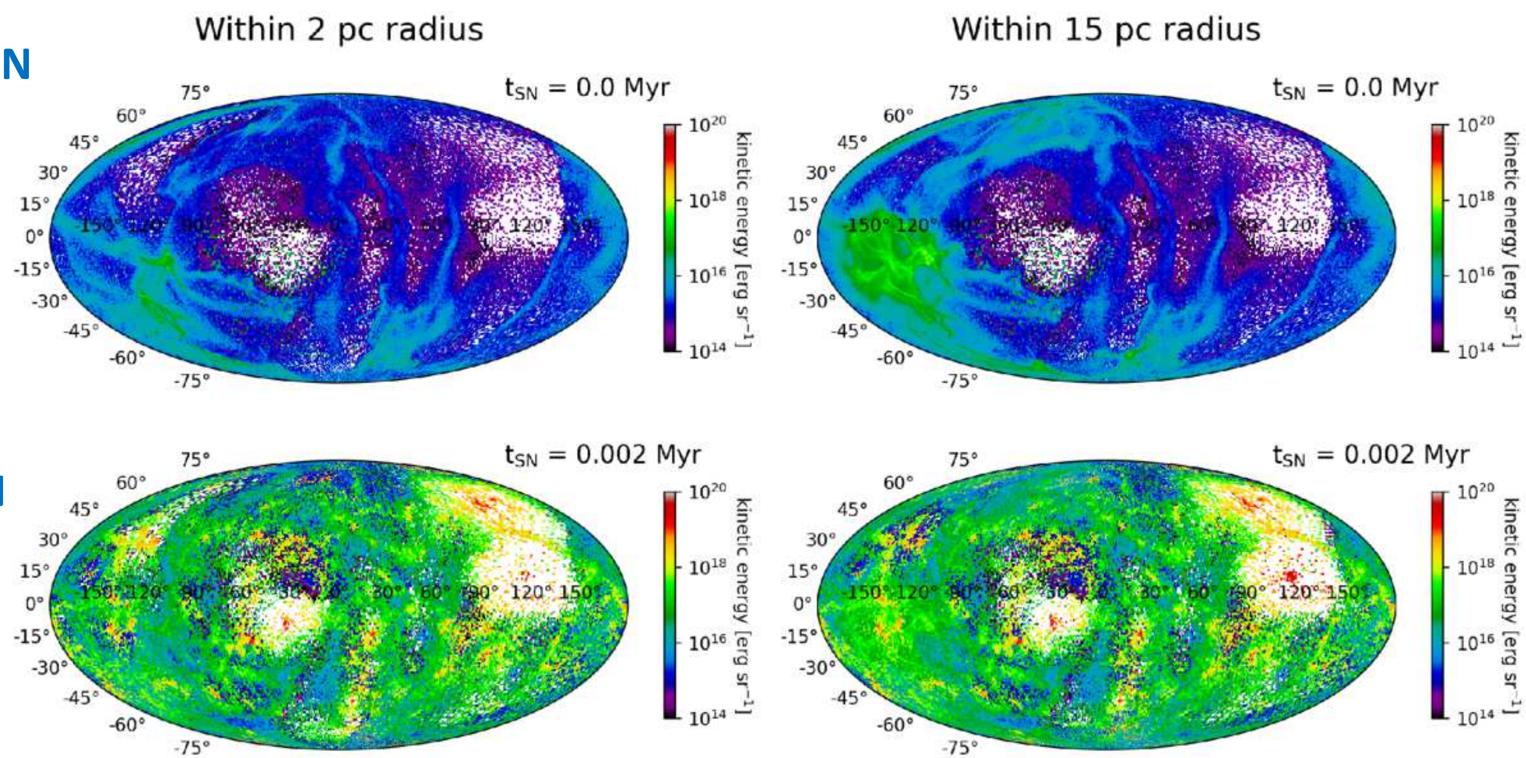
HII region in molecular clouds



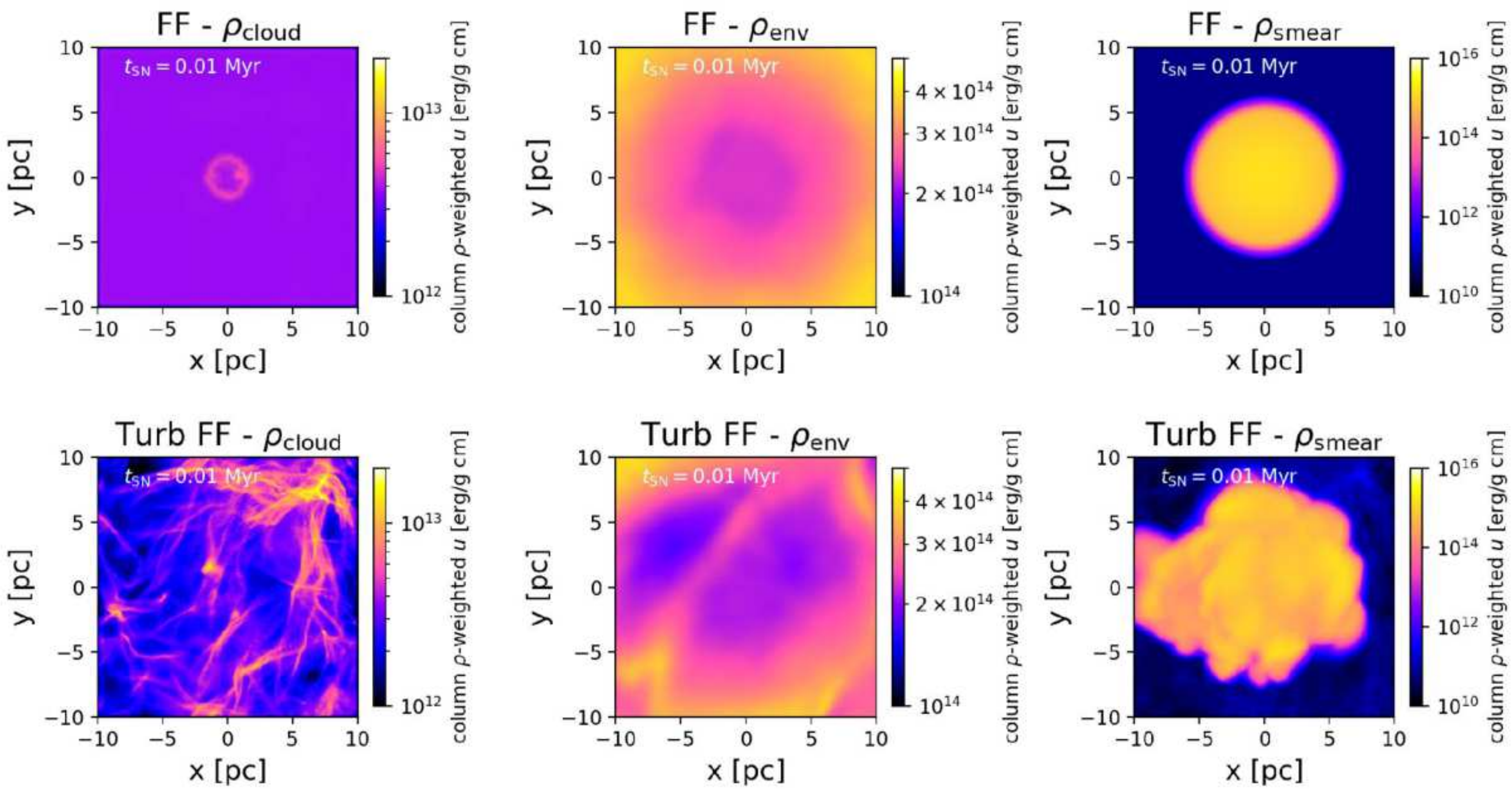
Kinetic energies seen from SN progenitor

Before SN

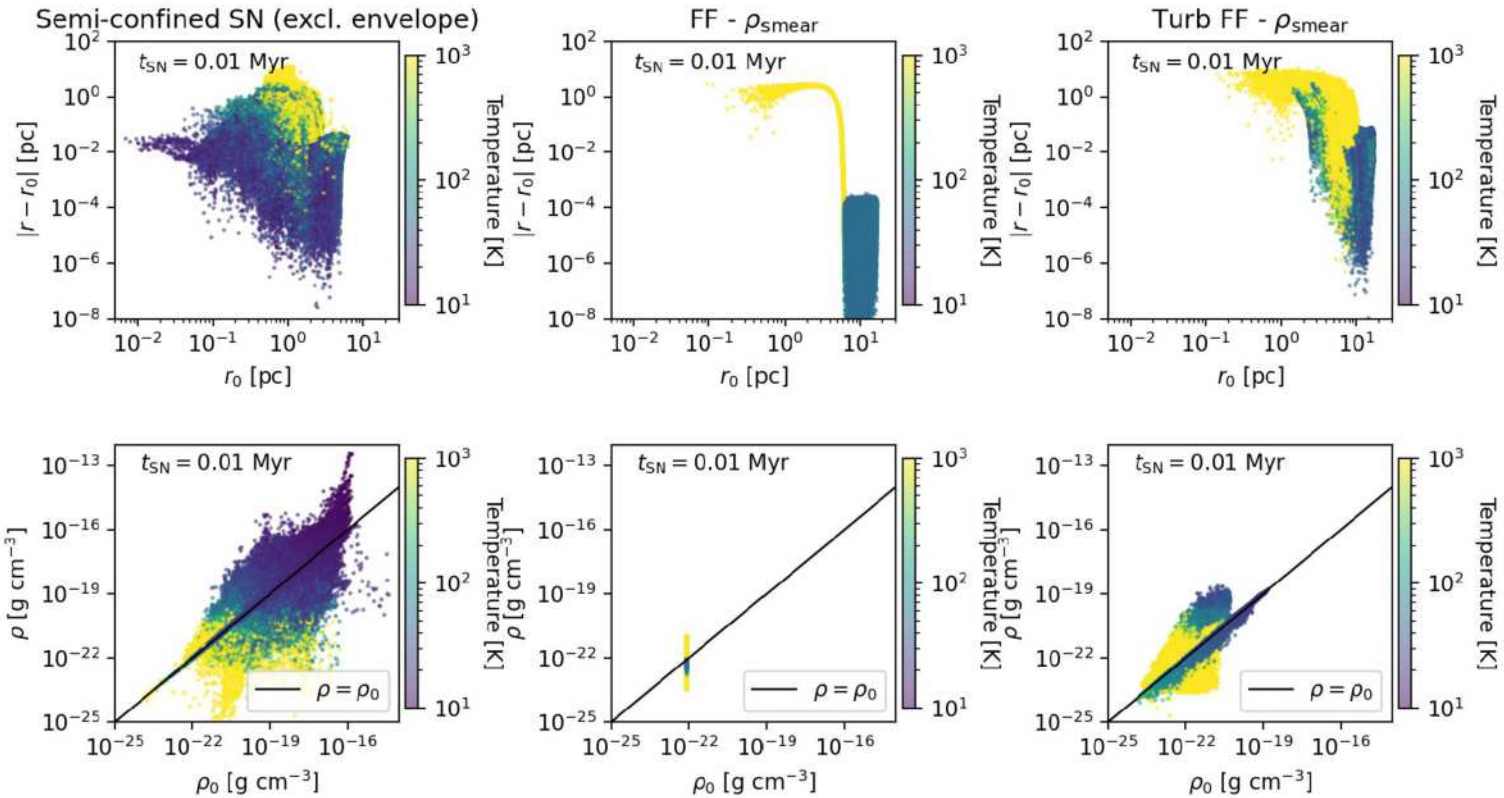
After SN



Turbulent free-field cases



Kicks by SNe in turbulent cloud vs turbulent free-field

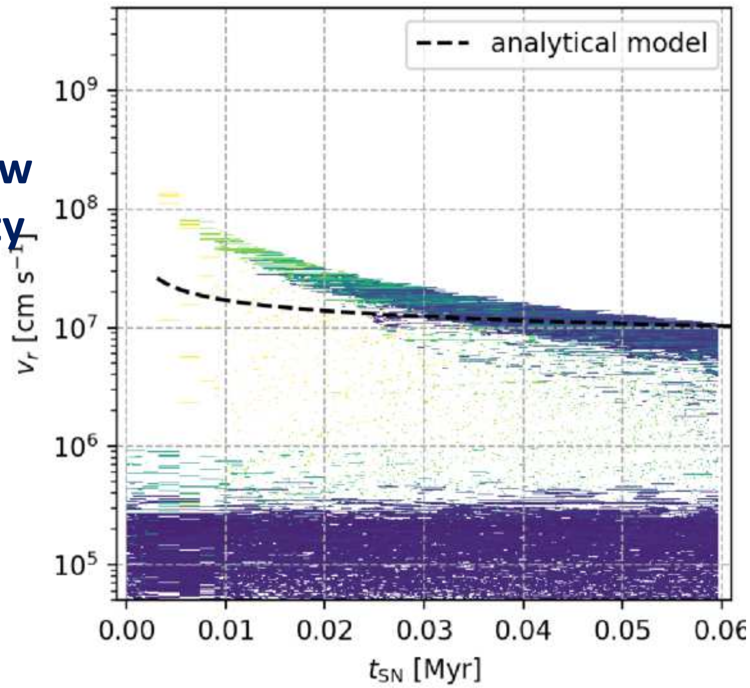


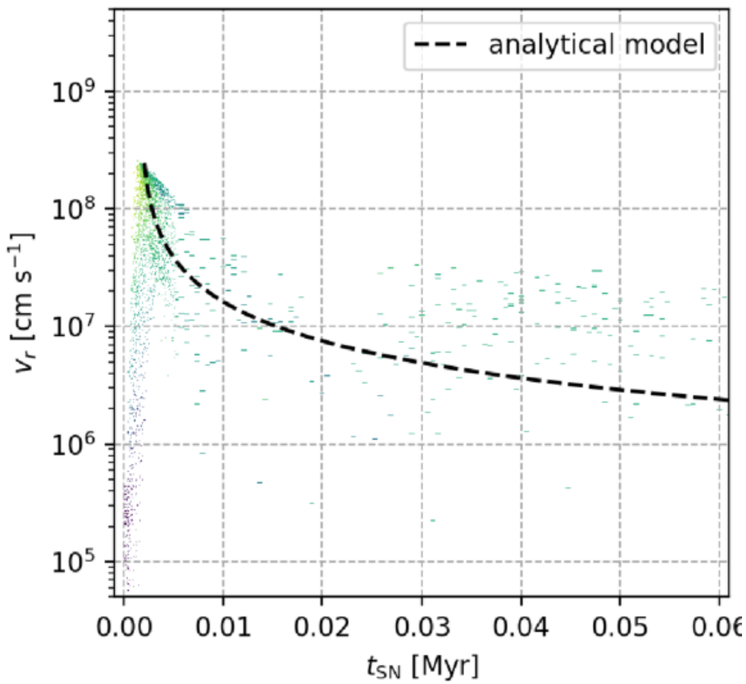
How can we turn this into a 1-D model?

SN in turbulent cloud

SN in homogenously turbulent medium

Outflow velocity



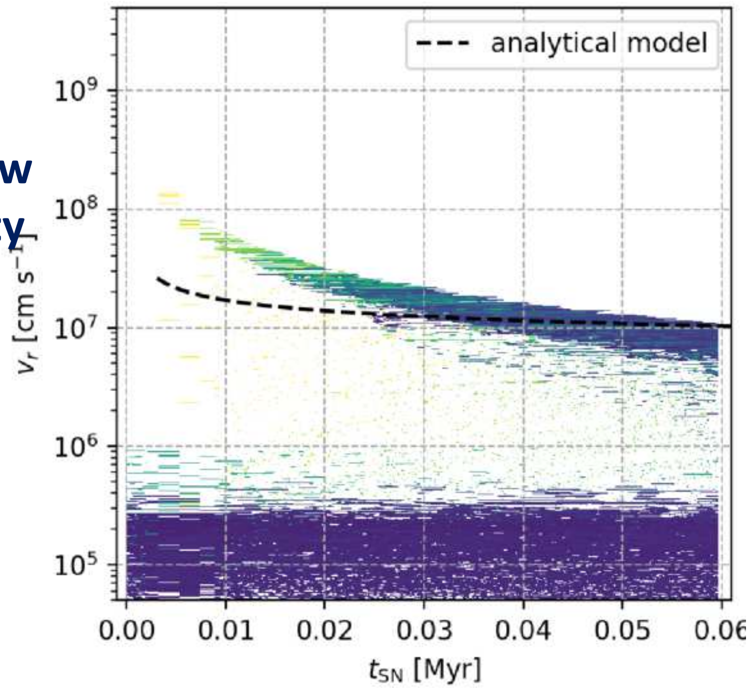


Velocities are too high

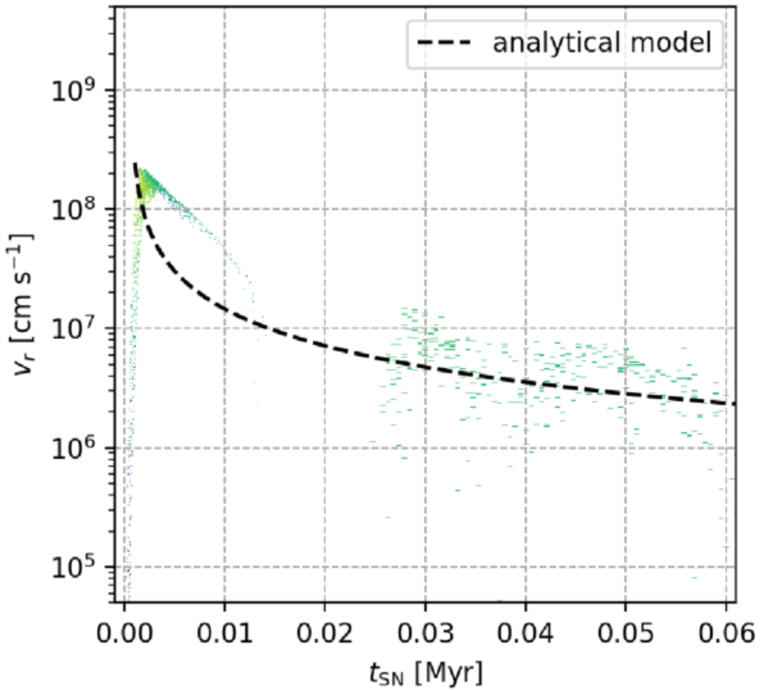
How can we turn this into a 1-D model?

SN in turbulent cloud

Outflow velocity



SN in homogenous uniform medium

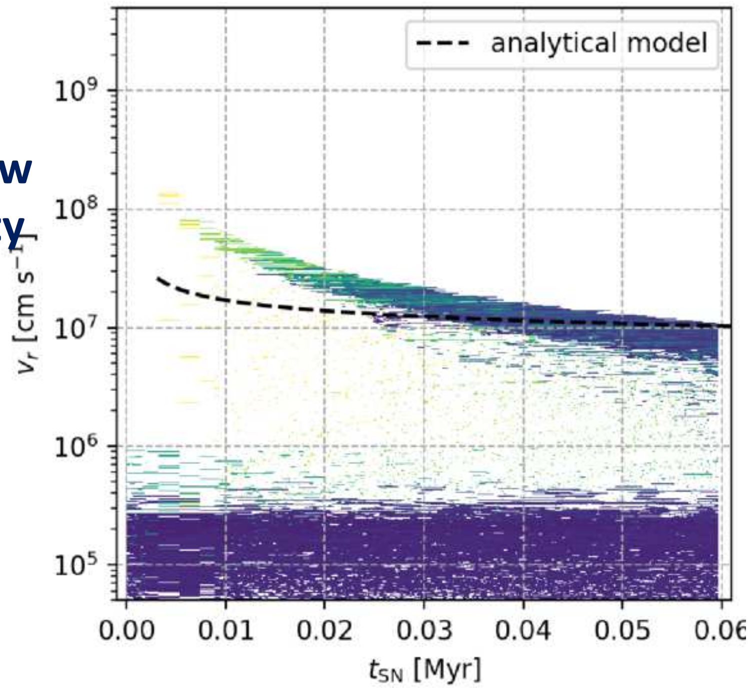


Velocities are too low

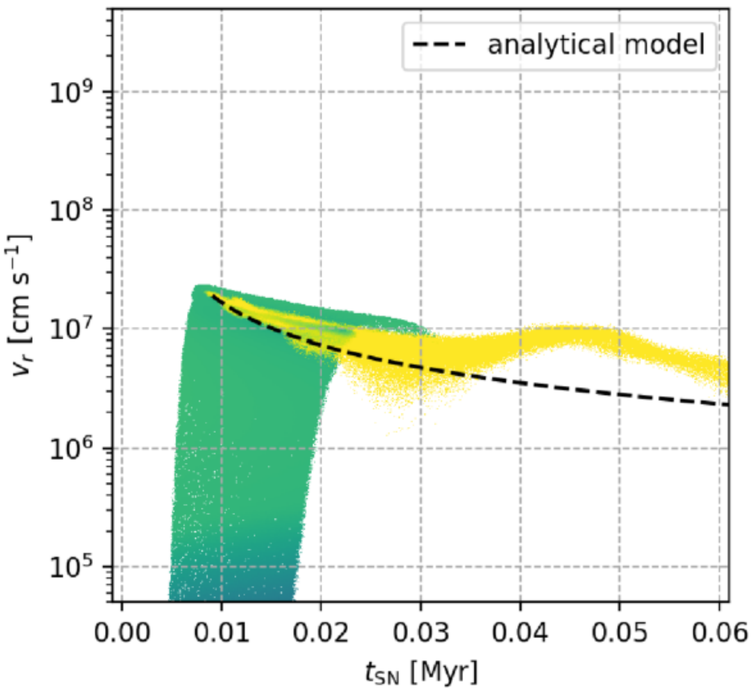
How can we turn this into a 1-D model?

SN in turbulent cloud

Outflow velocity



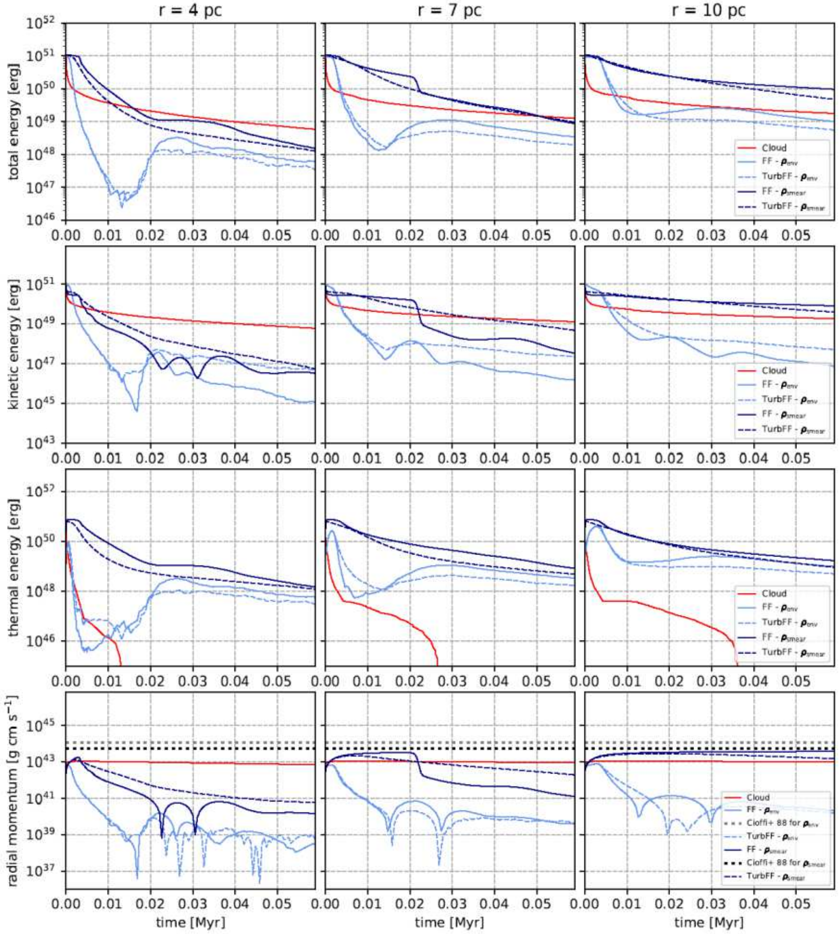
SN in homogenous uniform medium



Velocities are going down

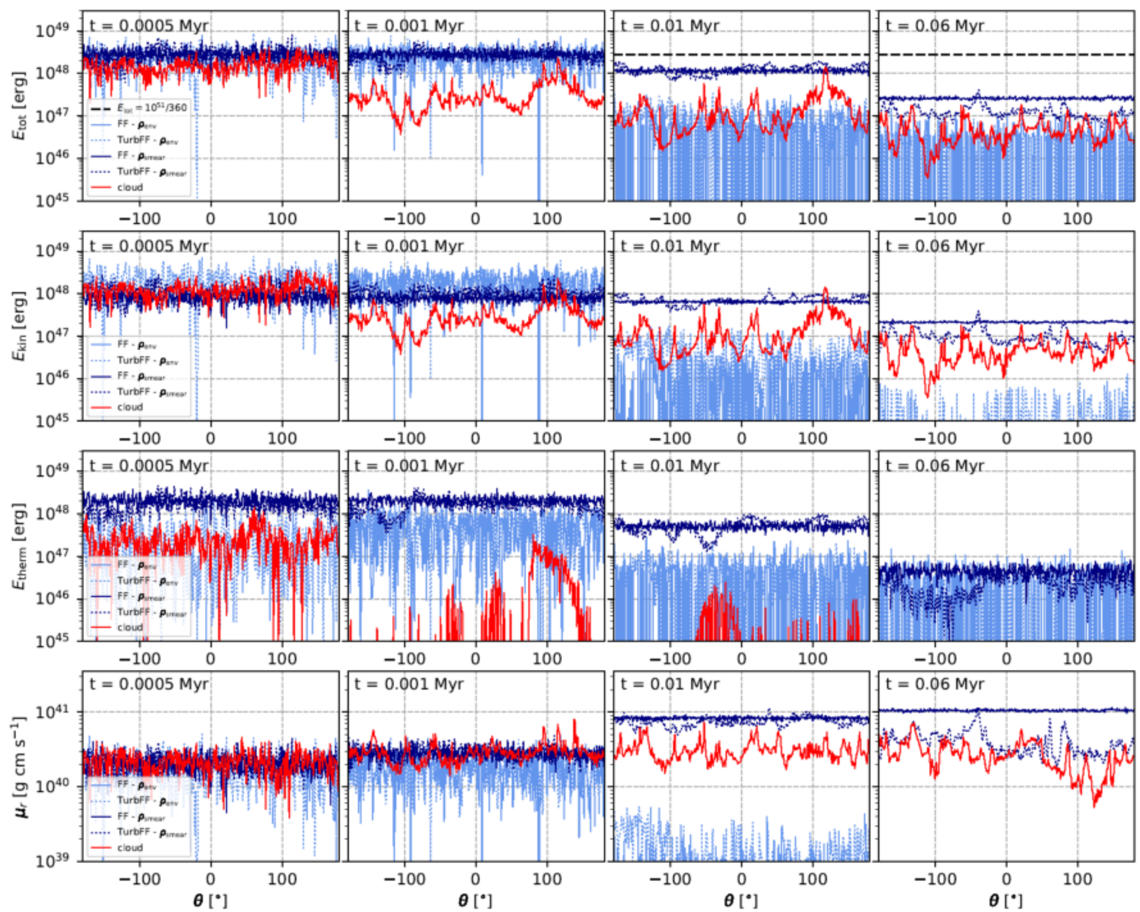
Energies of cloud vs turbulent free-fields

Total energy contained within each radius

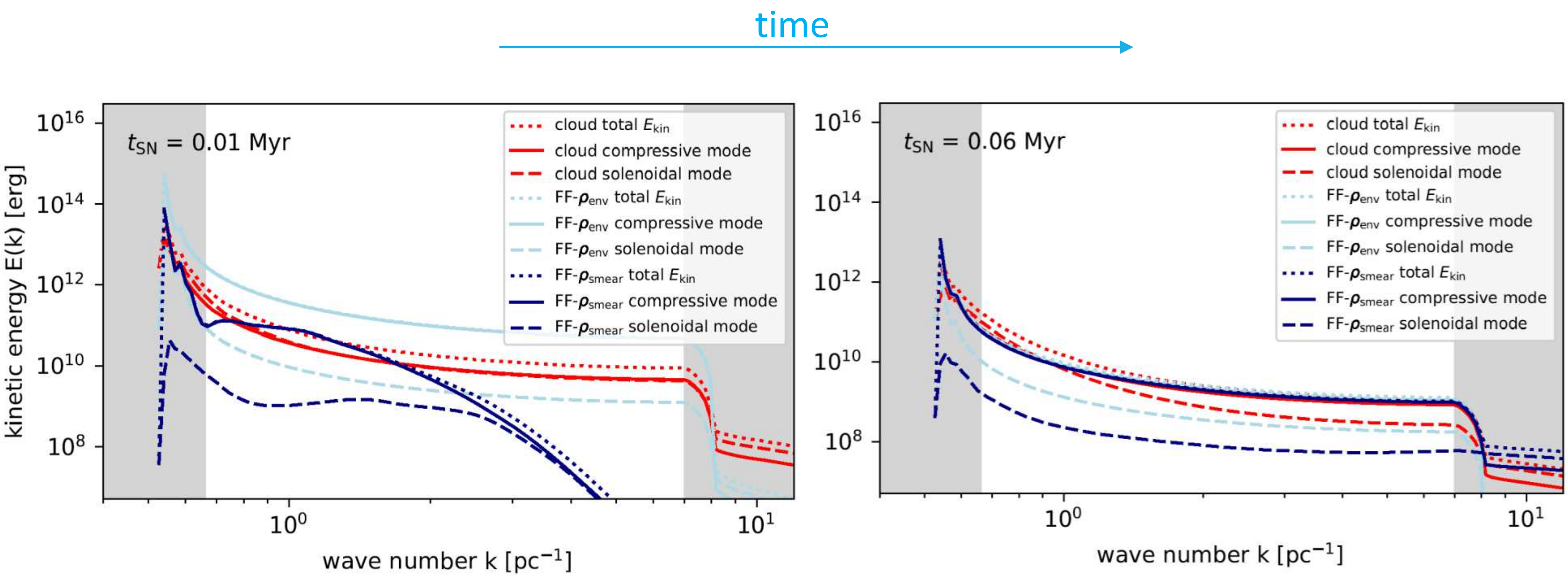


Energies of cloud vs turbulent free-fields

Energy binned by longitude contained within 10 pc



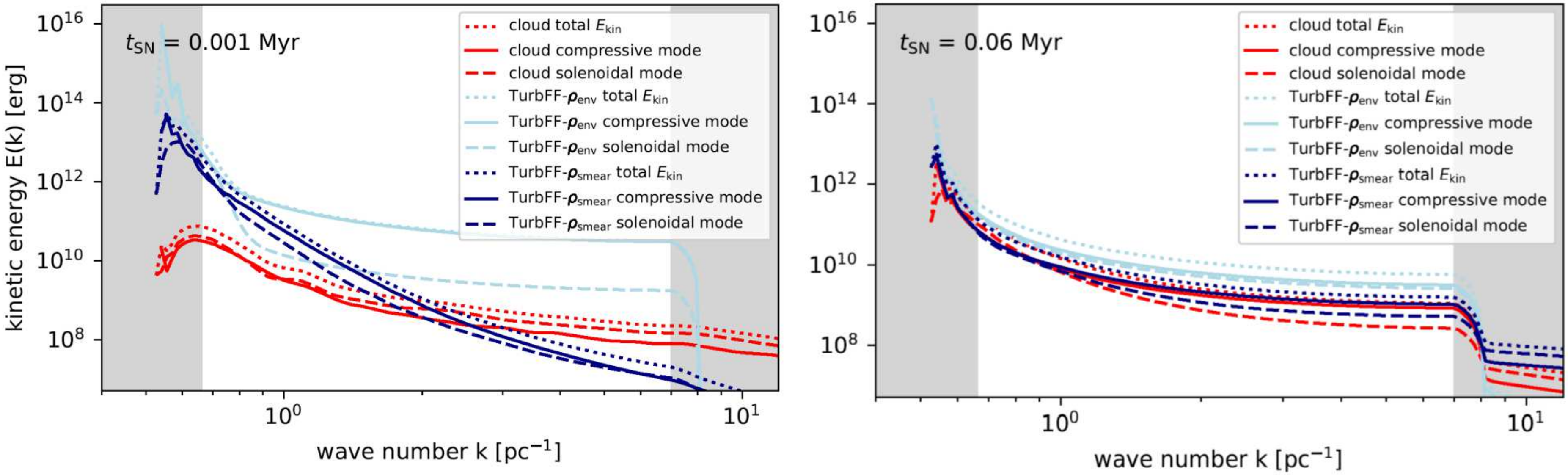
Turb spec –
cloud vs uniform free-field



Solenoidal component of uniform case is much lower

Turb spec –
cloud vs turbulent free-field

time



Solenoidal component becomes similar

Radiation Hydrodynamics
The SPH-MCRT scheme

Particle-based method

Smoothed Particle Hydrodynamics

Evolves the fluid

Grid-based method

Monte Carlo Radiative Transfer

Computes ionization

Hydro step

Particles positions, smoothing lengths, masses

Heat particles

Map particle densities onto Voronoi grids

MCRT simulation

Map ionic fractions of grid cells back onto particles

Exact mapping

Petkova, Vandenbroucke, Bonnell & Kruijssen (2021)
Lau, Petkova & Bonnell (2025)

Tree-based (fully adaptive)

Radiation Hydrodynamics

The SPH-MCRT scheme

Particle-based method

Smoothed Particle Hydrodynamics

Evolves the fluid

Grid-based method

Monte Carlo Radiative Transfer

Computes ionization

Hydro step

Particles positions, smoothing lengths, masses

Heat particles

Photoionization heating + radiative cooling (implicit) for multi-phase ISM

Map particle densities onto Voronoi grids

Exact mapping

MCRT simulation

Map ionic fractions of grid cells back onto particles

Petkova, Vandenbroucke, Bonnell & Kruijssen (2021)
Lau, Petkova & Bonnell (2025)