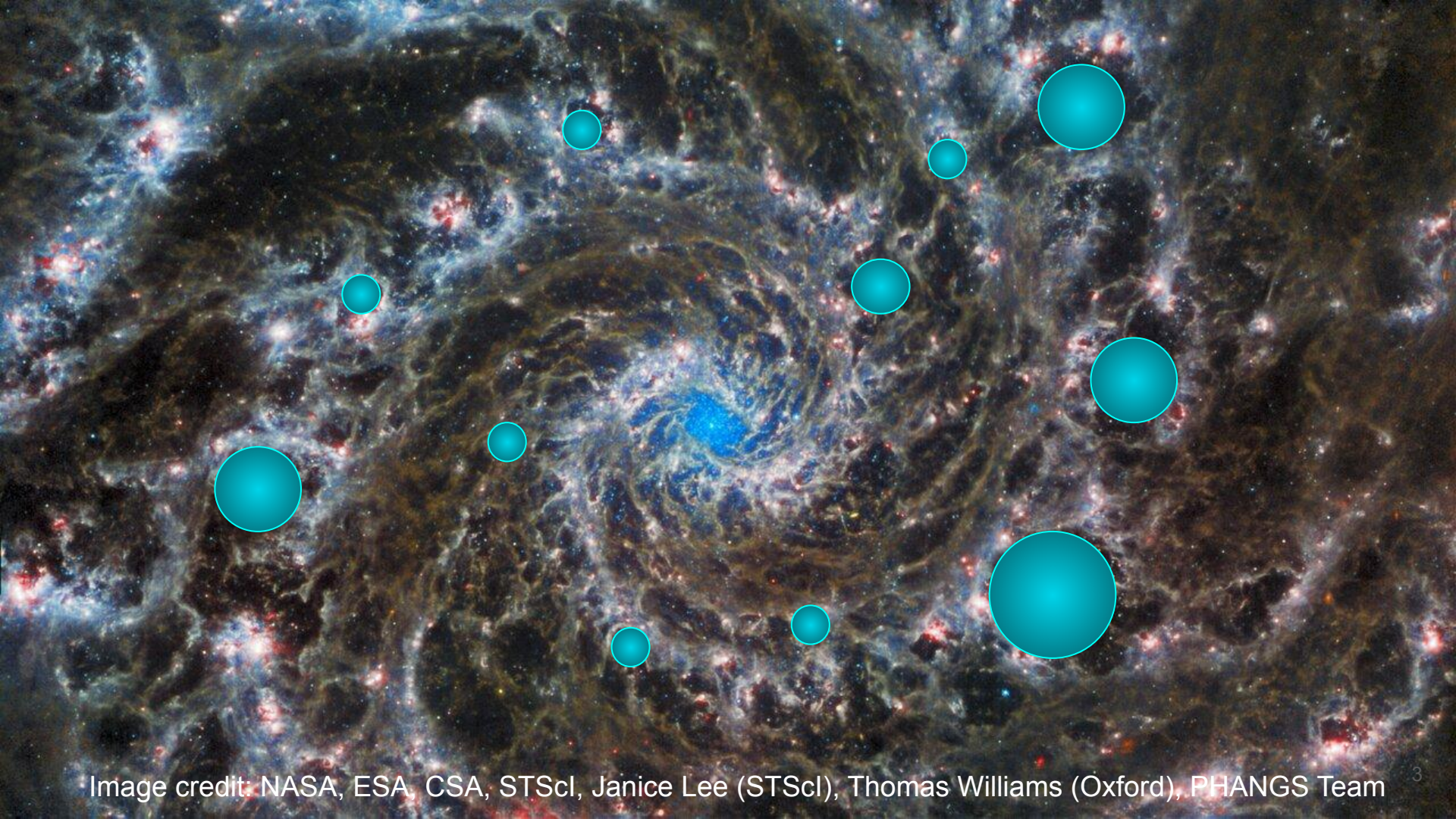
Project 9: Numerical Simulations Using the RAMSES and AREPO Codes

Vasanth Kashyap, Aurelien Piluso, Hans-Christian Poosch, Lori Porter, Laurin Soding
Supervisors: Simon Glover and Eva Ntormousi

Image credit: NASA, ESA, CSA, STScI, Janice Lee (STScI), Thomas Williams (Oxford), PHANGS Team



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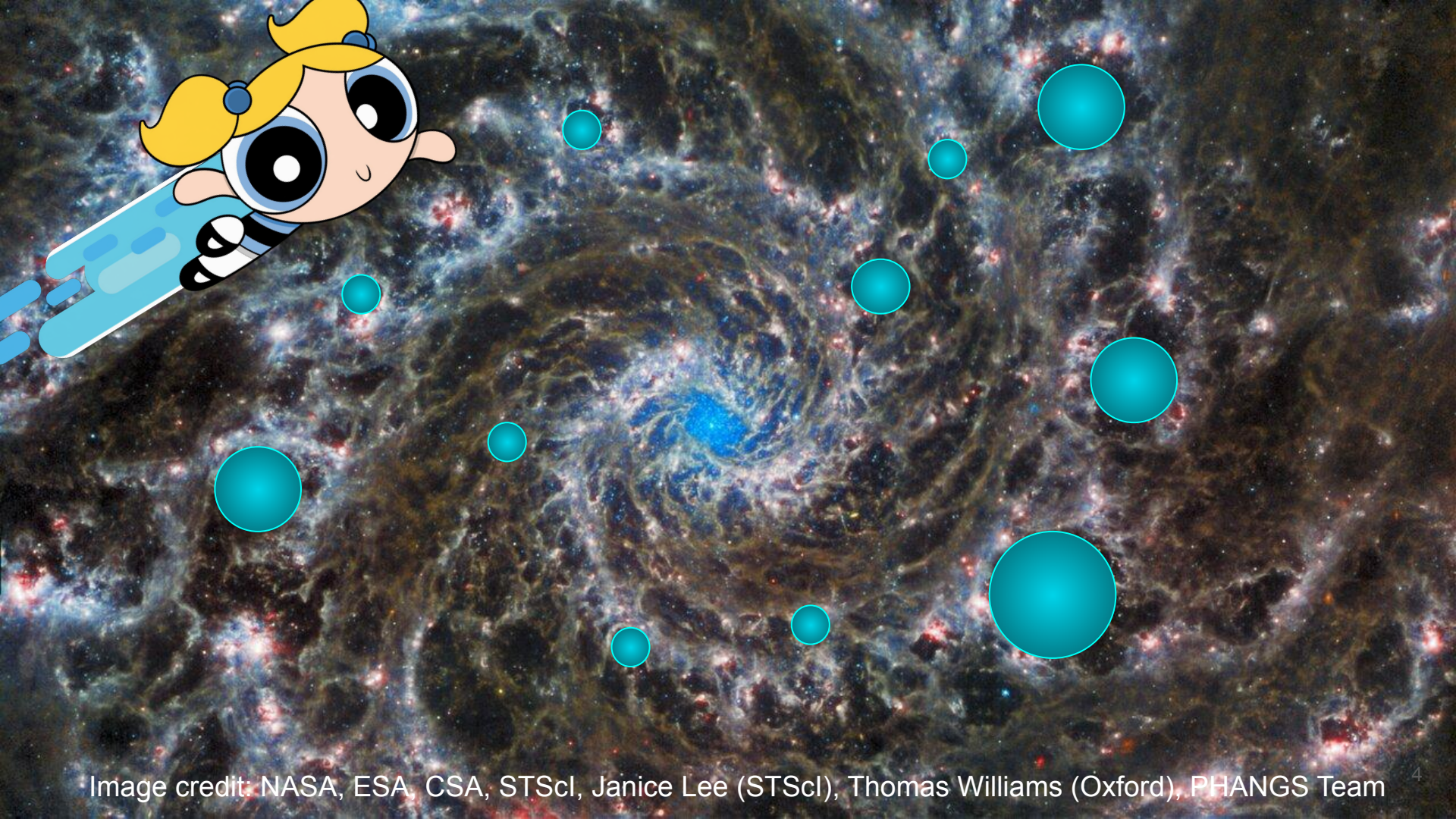

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What We've Done:

- ★ Simulation :
  - Deep dive into MHD equations and solvers
  - Simple simulations using RAMSES (1D, 3D)
  - Creation of own simulation in RAMSES 3D Sedov explosion

- ★ Data processing :
  - General data analysis of AREPO simulations of galaxy
  - Precise data extraction of relevant parameters :
    - Selection of SN bubbles
    - Extraction

Supernova shock evolution

1. Sudden injection of pressure
2. Accelerating material outwards

   → First ballistic, then supersonic velocities (**Sedov-Taylor-Phase**)

3. In spherically symmetric setting: No smooth transition possible between super- and sub-sonic solutions of hydrodynamical equations
4. Conservation of mass at the shock front: $\rho_{\mathrm{pre}} v_{\mathrm{pre}} = \rho_{\mathrm{post}} v_{\mathrm{post}}$

   If $\rho_{\mathrm{post}} > \rho_{\mathrm{pre}}$, then $v_{\mathrm{post}} = v_{\mathrm{pre}} \frac{\rho_{\mathrm{pre}}}{\rho_{\mathrm{post}}} < v_{\mathrm{pre}}$

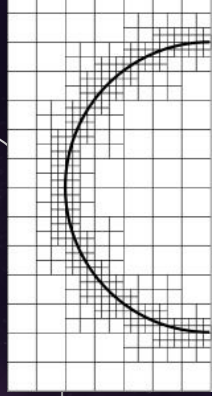
→ The flow is compressed and slowed down (in shock rest-frame)!

→ The shock converts bulk kinetic energy into heat!

$$R(t) = 2\,\mathrm{pc} \cdot \left(\frac{E_{\mathrm{SN}}}{1E51\ \mathrm{ergs}}\right)^{1/5} \cdot \left(\frac{n_{\mathrm{ISM}}}{100\ \mathrm{cm}^{-3}}\right)^{1/5} \cdot \left(\frac{t}{1\ \mathrm{kyr}}\right)^{2/5}$$

Kim, C.-G. & Ostriker, E. C. 2015, ApJ, 802, 99

RAMSES code



MHD simulation code : Eulerian approach (static volume element)

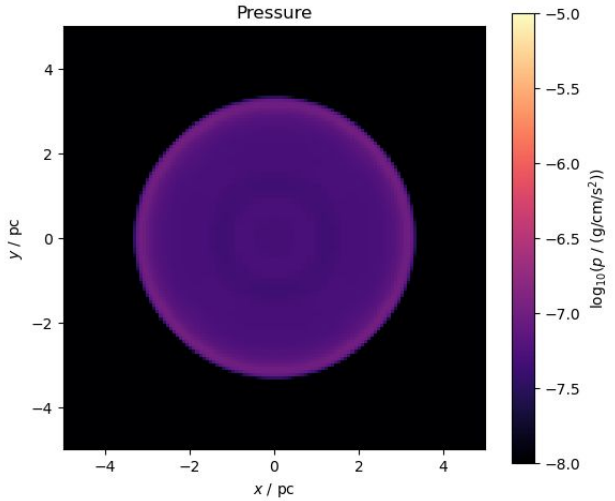
- **AMR** (*Adaptive Mesh Refinement*)**:** efficient **multi-scale resolution**
- **Finite-Volume :** Conservation of mass, momentum, energy.
- **Multi-Physics :** Hydrodynamics, MHD, Self-Gravity, Radiative Transfer.

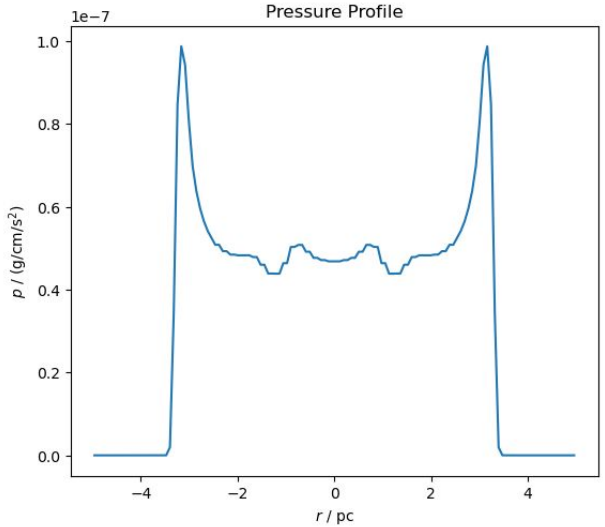
- **Numerical Strengths :** High-order schemes, Hierarchical time-stepping, Massively Parallel.
- **Hypotheses :** Fluid approximation, Reliance on sub-grid physics, Ideal MHD (*often*), RT simplifications.

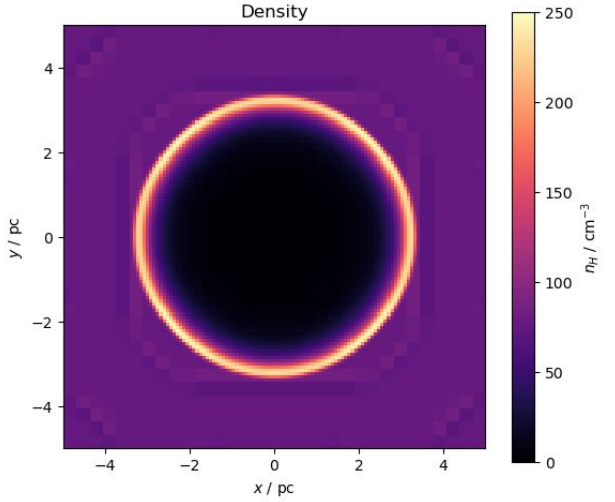
For detailed information, please refer to Simon Glover's lecture

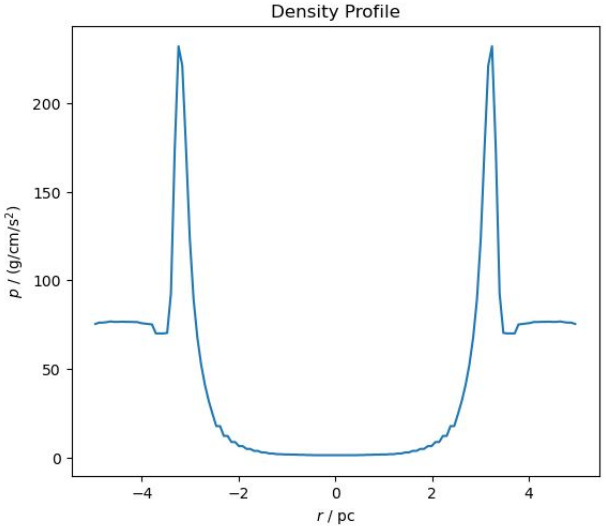
Hands-on project (part) : Use of RAMSES in simple cases in 1D and 3D

https://github.com/ramses-organisation/ramses





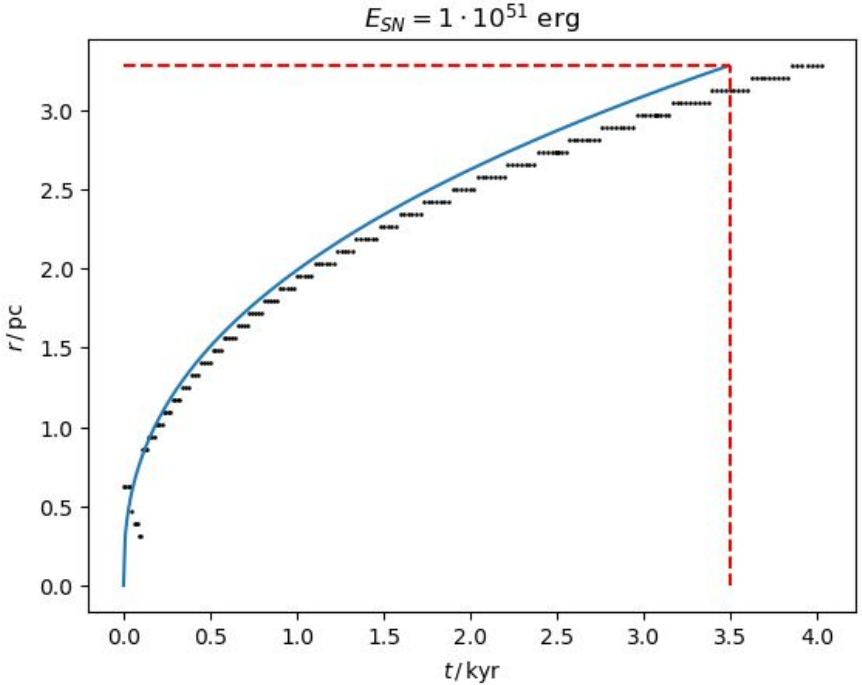


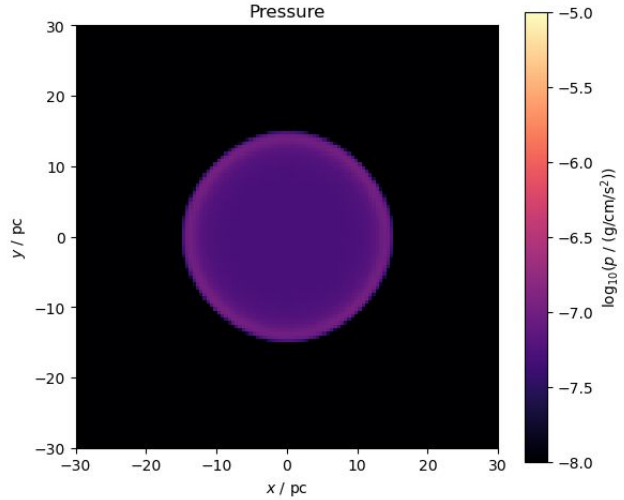


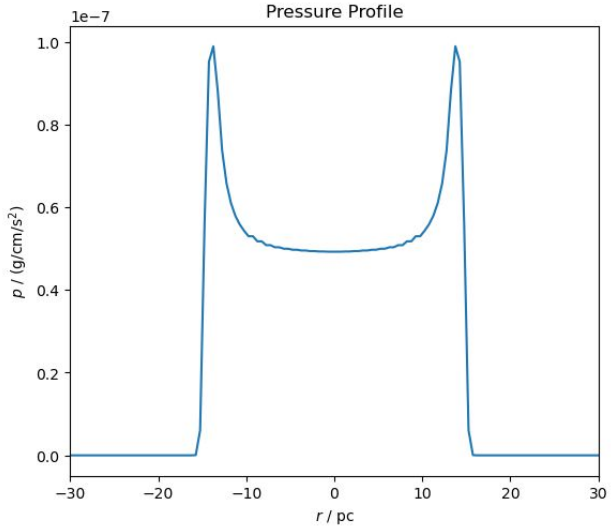
Supernova with an energy of 1e51 ergs

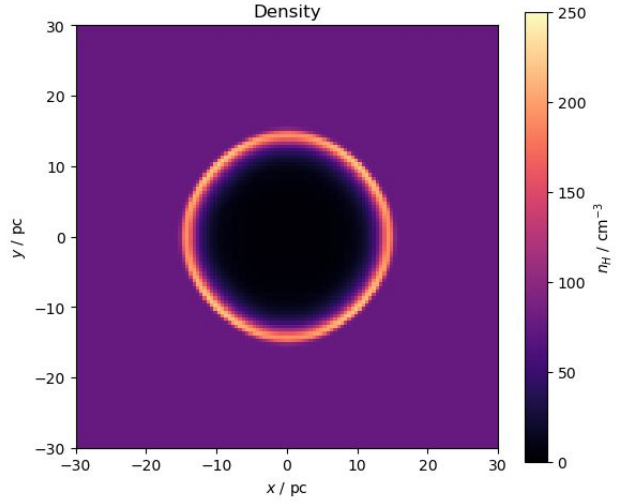
Density of surrounding ISM: 100 H/cm³

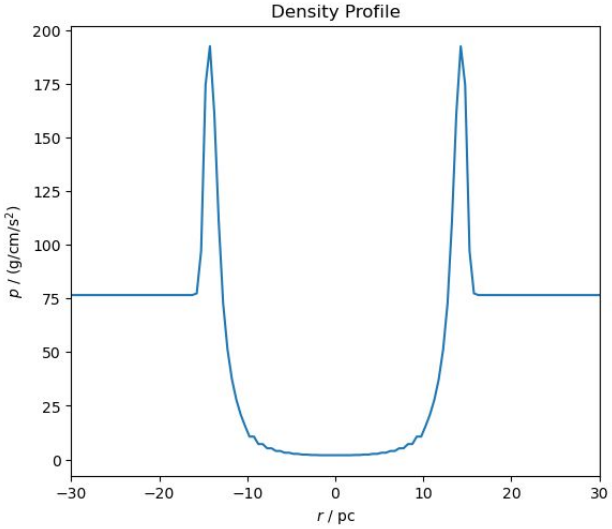
Initial size of pressurized region: 0.55pc


$E_{SN} = 1 \cdot 10^{51}$ erg
3.0
2.5
2.0
1.5
1.0
0.5
0.0
r / pc
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
t / kyr

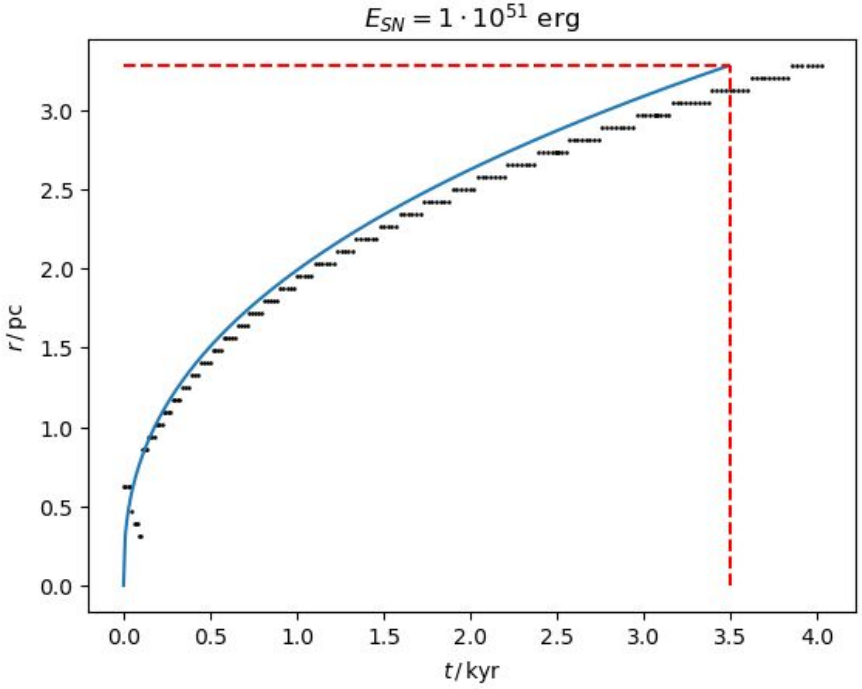


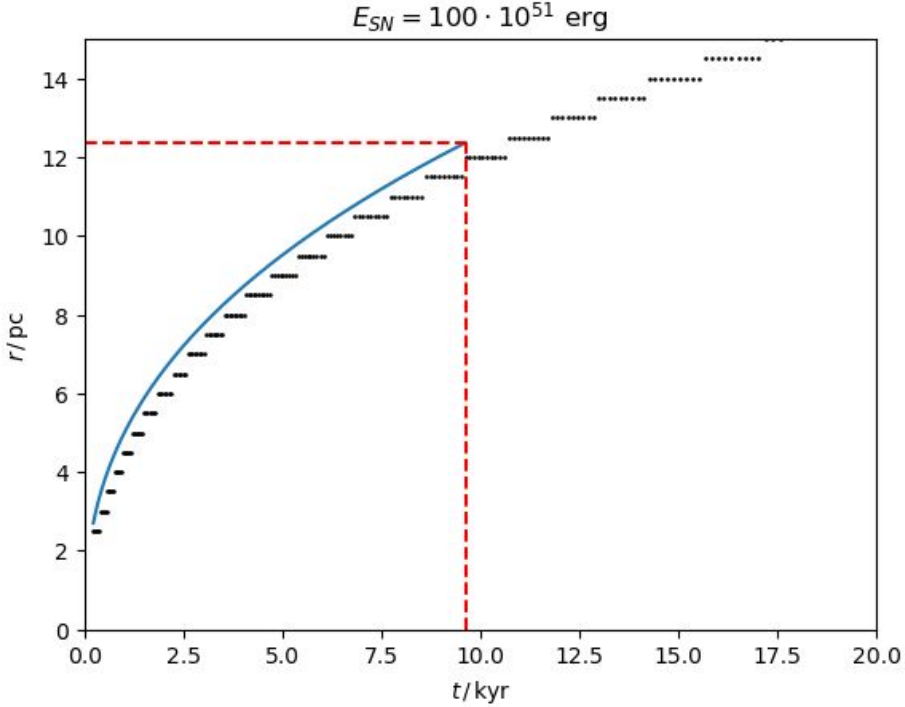




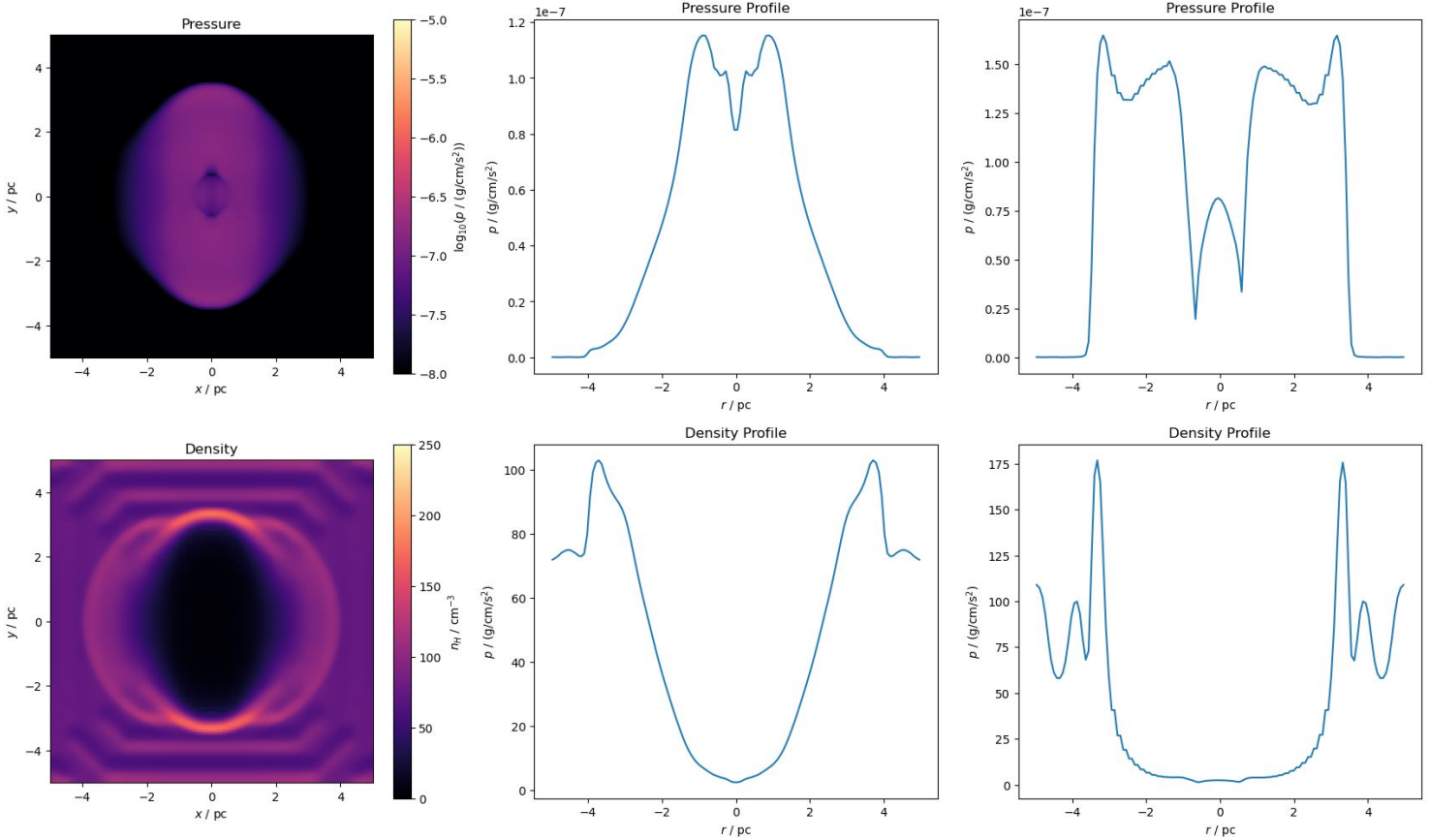


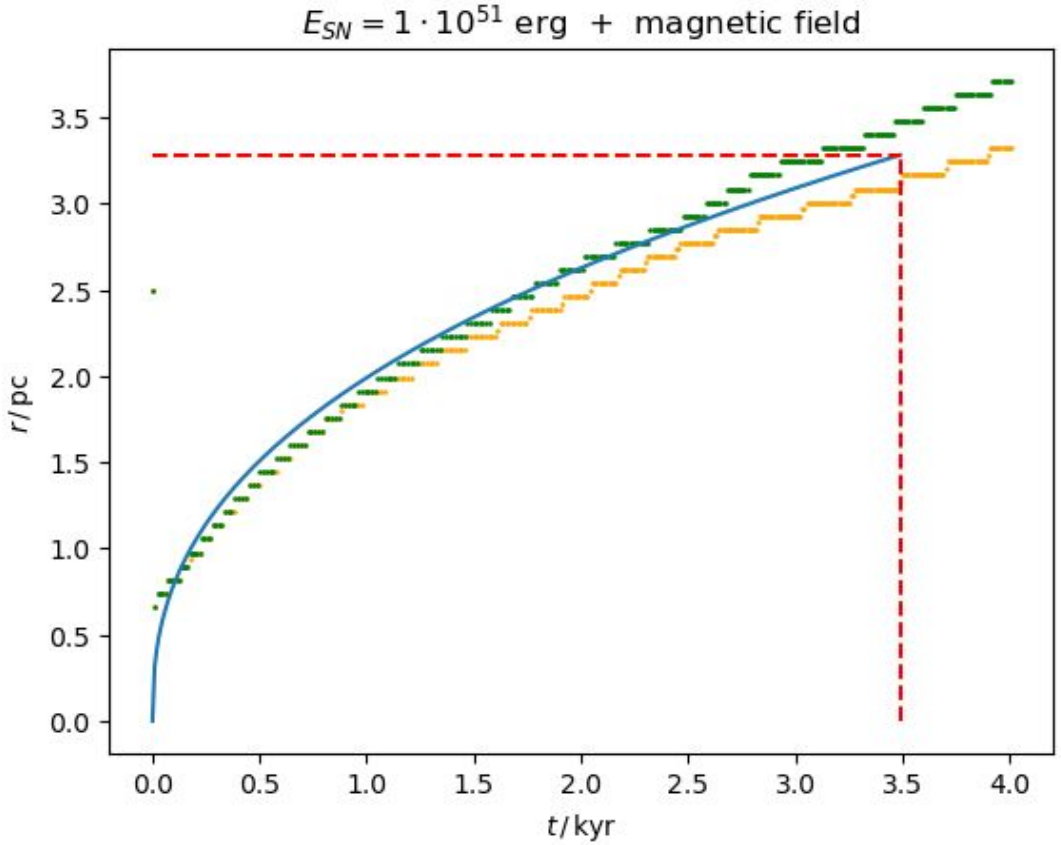
Supernova with an energy of 100*1e51 ergs


$E_{SN} = 1 \cdot 10^{51}$ erg
r / pc
t / kyr
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


$E_{SN} = 100 \cdot 10^{51}$ erg
r / pc
t / kyr
0
2
4
6
8
10
12
14
0.0
2.5
5.0
7.5
10.0
12.5
15.0
17.5
20.0

Supernova with an energy of 1e51 ergs and a magnetic field

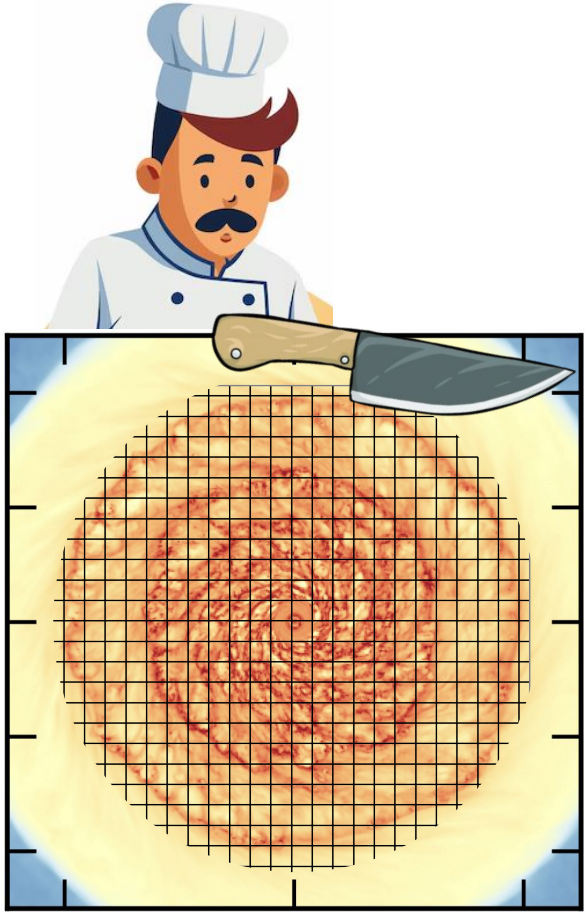




SN bubble no longer spherical -> ellipsoid

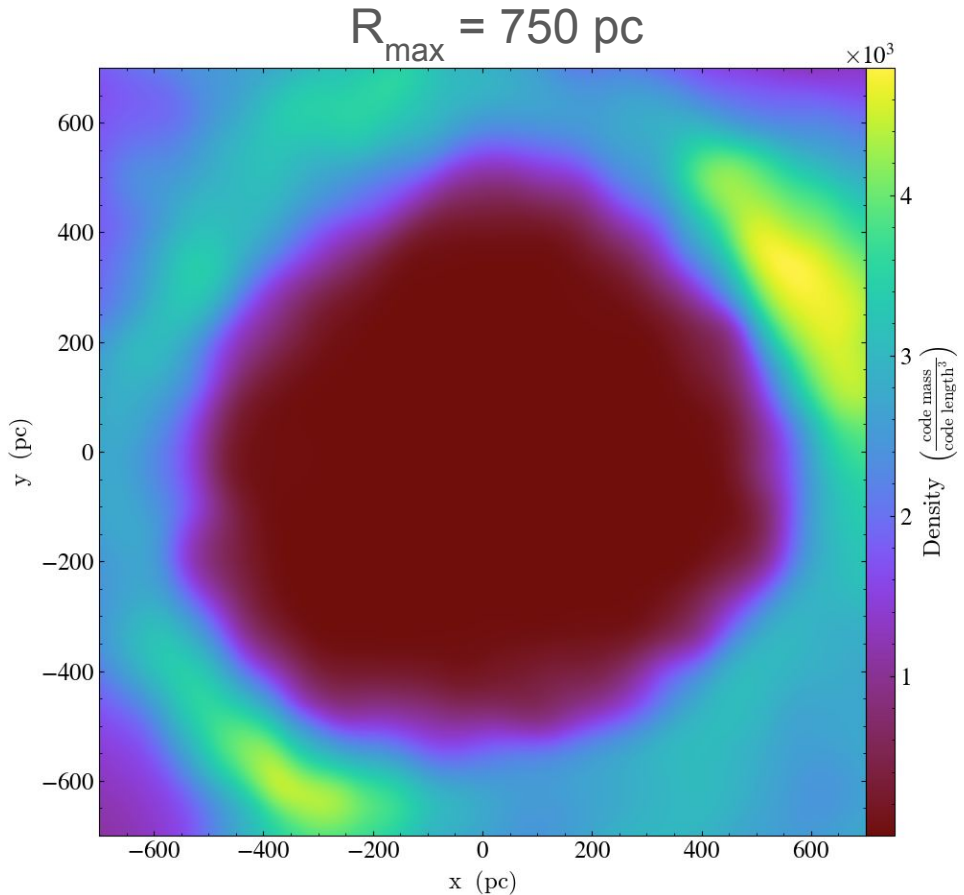
Minimum Density Finder

1. Use some of your chefs skills to slice the galaxy into cubes of 2 kpc
2. Get the particles with the least density
    a. Bottom 5% of the density distribution for stability
3. Calculate the mean coordinates of these points
    a. Weighted by $(\text{density})^{-1}$
4. Use this as center for the Bubble Finder

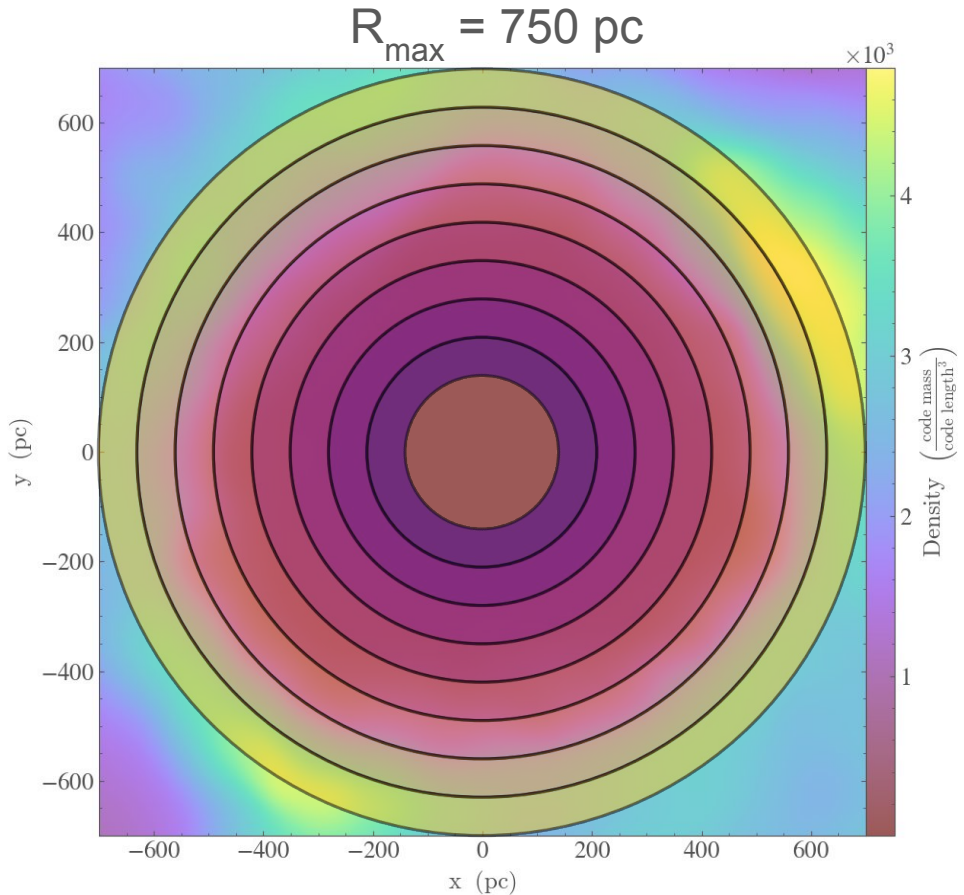


RHEA AREPO Simulations: See *Kjellgren et. al. 2025, Göller et. al. 2025*

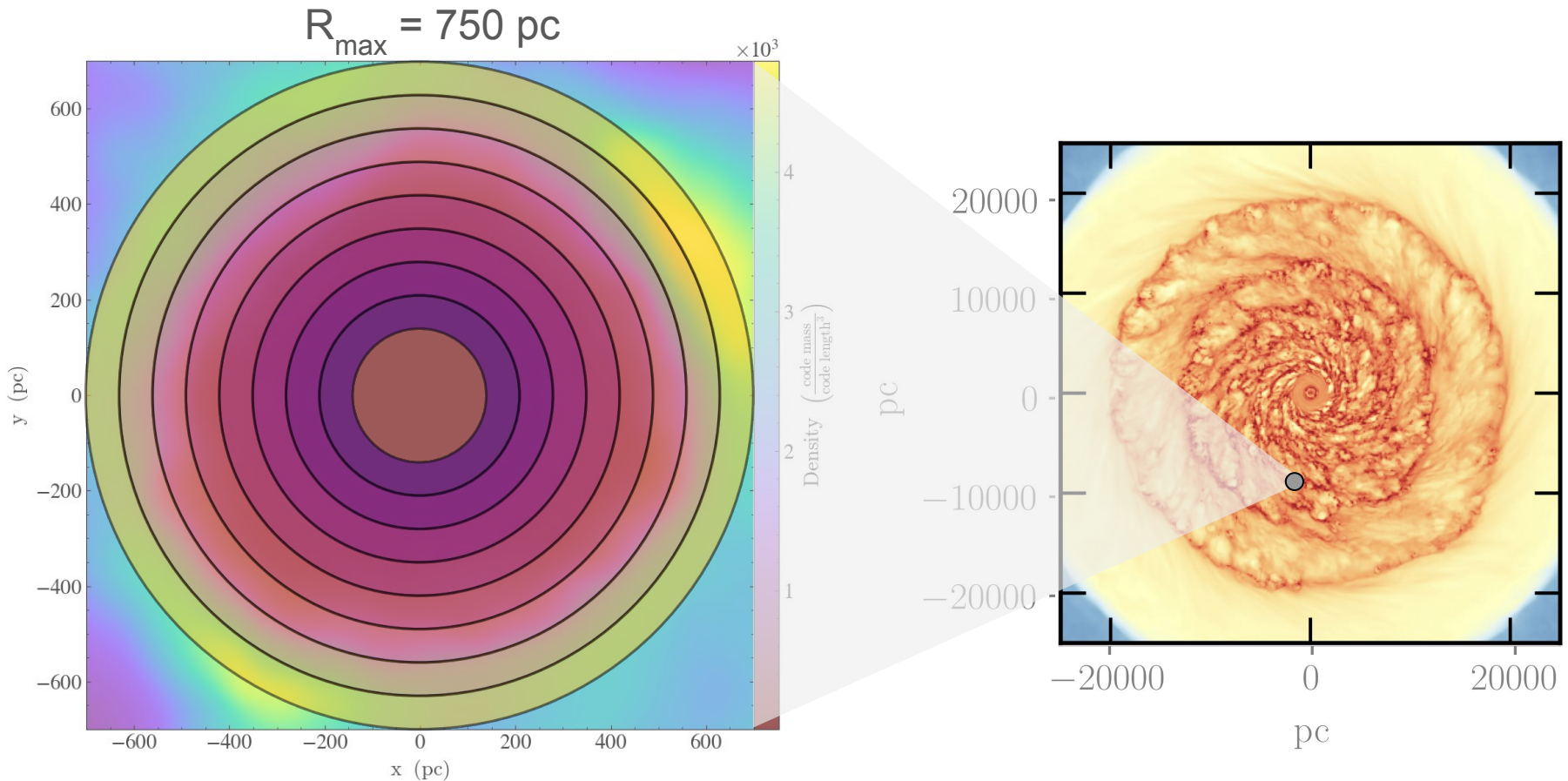
Finding Bubbles in AREPO Simulations



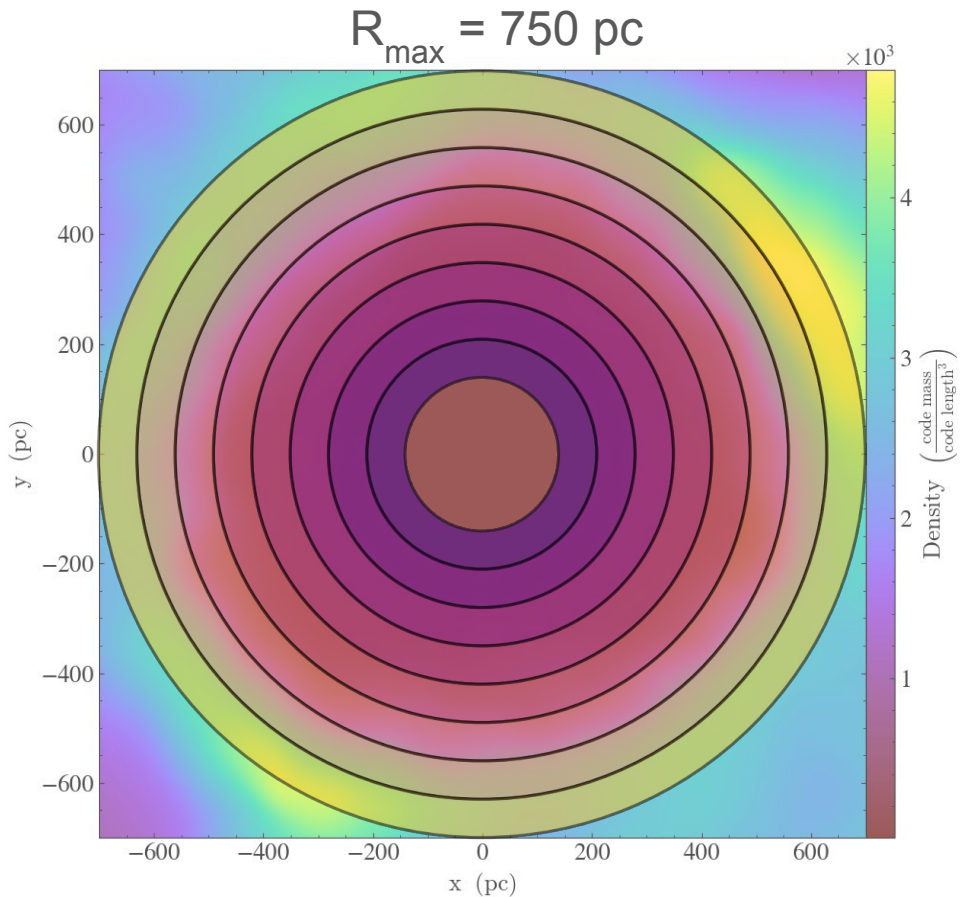
Finding Bubbles in AREPO Simulations

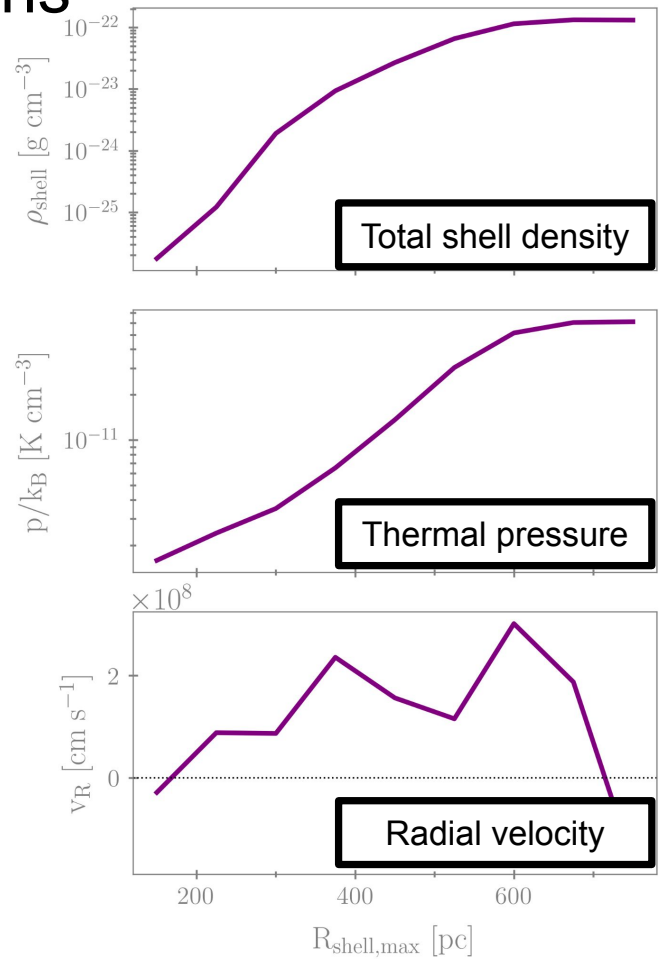


Finding Bubbles in AREPO Simulations



Finding Bubbles in AREPO Simulations





Bubble Finder - Selection Criteria

- Strong gradient in the Radial Velocity as we move from inside to the outside of the bubble
    - Require a steep radial velocity gradient and density profile

Caveats

- Resolution limited to Bubbles of size > 150 pc
- Number of bubbles we find is subject to the chefs chopping

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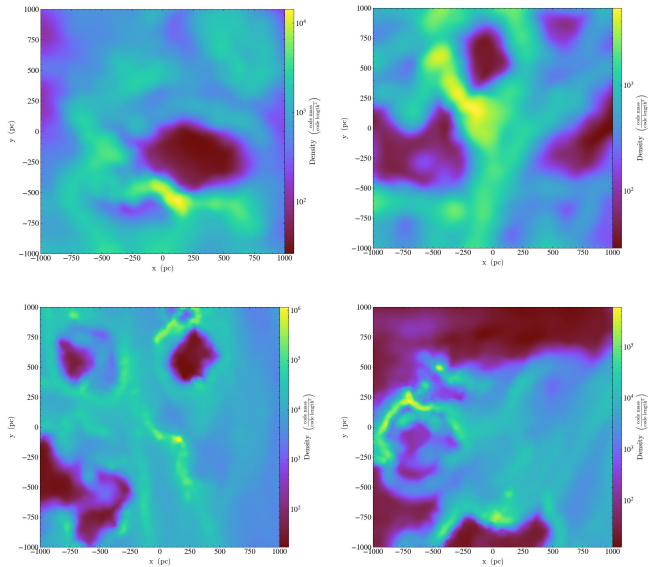
Total number of bubble candidates found (so far) in 1 snapshot:

15… *ish*



Bubble Finder - Selection Criteria

Caveats

- Spherical geometry holds for an isolated explosion
- Supernovae in ISM are far from isolated
- There is only so much we can do using just derivatives of one quantity.
- Wrong detections are usual