Simulating the Formation And Early Evolution Of Star Clusters

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MODEST Santorini 2018

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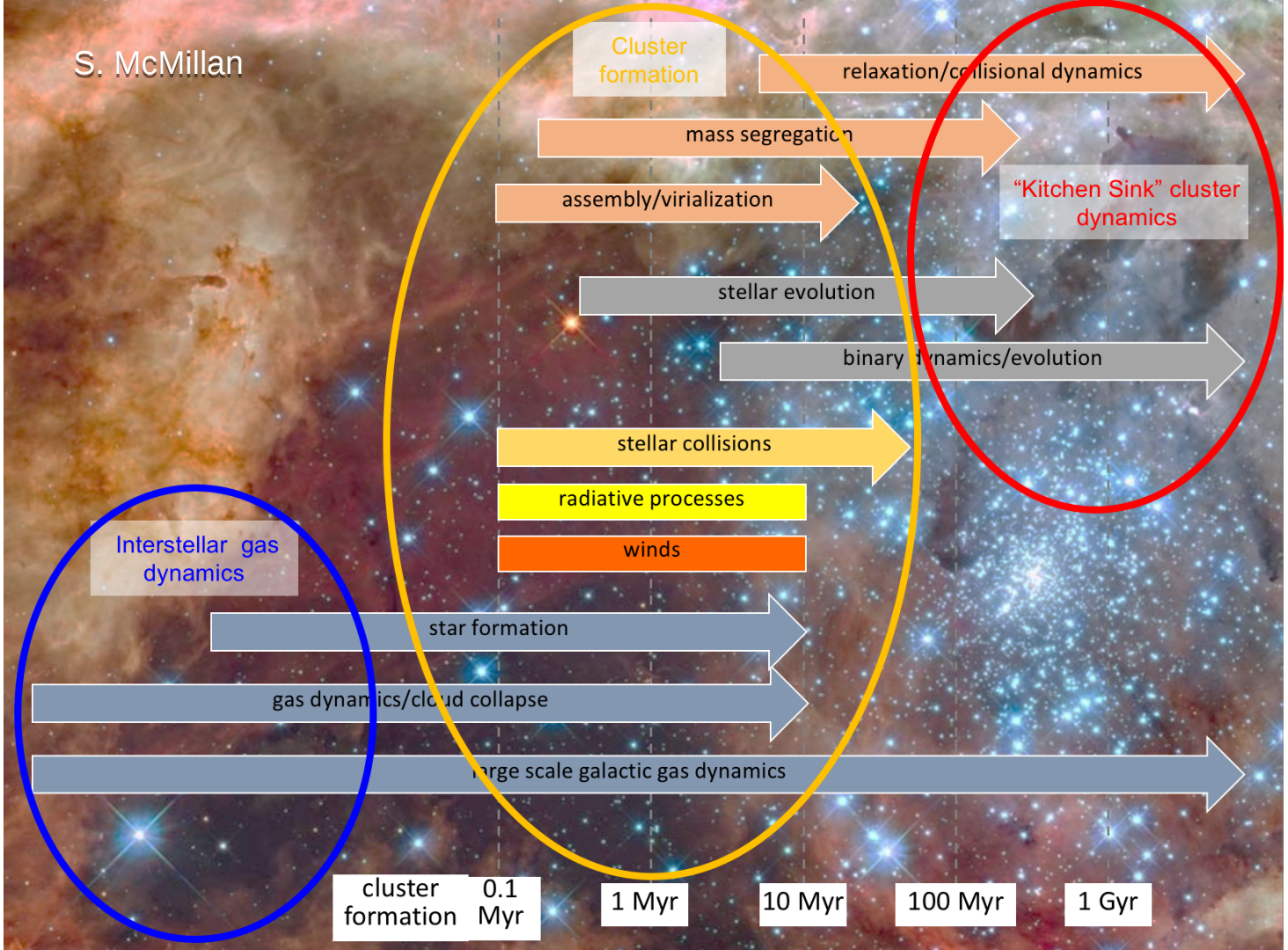
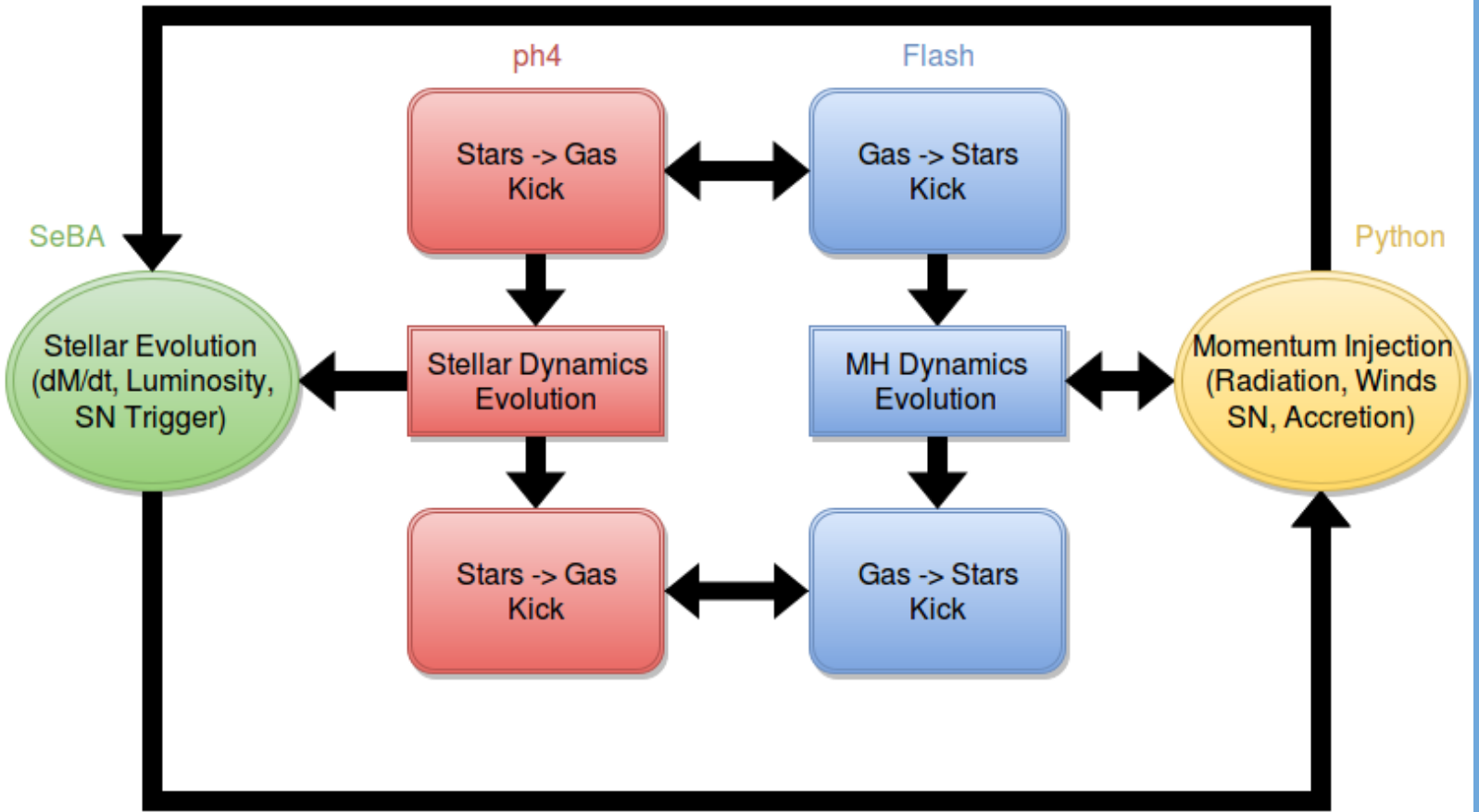

S. McMillan
Cluster formation
relaxation/collisional dynamics
mass segregation
assembly/virialization
"Kitchen Sink" cluster dynamics
stellar evolution
binary dynamics/evolution
stellar collisions
radiative processes
winds
Interstellar gas dynamics
star formation
gas dynamics/cloud collapse
large scale galactic gas dynamics
cluster formation
0.1 Myr
1 Myr
10 Myr
100 Myr
1 Gyr

Overview of Our Questions

- ❑ Which formation channels dominate in realistic molecular cloud environments (more monolithic or more hierarchical)?
- ❑ How effective is realistic feedback on ejecting gas from the stellar population? How effective is this ejection at cluster disruption?
- ❑ What are the effects of a realistic natal gas environment (whether simply embedded or being ejected) on the evolution of cluster properties such as mass segregation or fractal dimension?
- ❑ Many others can be explored (effects of primordial binaries, dynamical binaries, brown dwarf dynamics, feedback leakage, ionizing photon escape fraction, feedback effects on ISM and B fields, IMF choice on SFR, etc).

AMUSE


ph4
Flash
Stars -> Gas Kick
Gas -> Stars Kick
SeBA
Python
Stellar Evolution (dM/dt, Luminosity, SN Trigger)
Stellar Dynamics Evolution
MH Dynamics Evolution
Momentum Injection (Radiation, Winds SN, Accretion)
Stars -> Gas Kick
Gas -> Stars Kick

Gravity Bridge (Fujii+2007)

- Couples Flash MHD (Fryxel+2000) to N-body codes such as ph4 (McMillan in prep) through gravity interactions of the stars and gas.
- Kick / Drift / Kick symplectic integrator based on the method of Wisdom and Holman (1991).
- Conserves both energy and momentum of the system.

Flash (*AMUSE interface)		**ph4 / Multiples / SeBa**
MHD (Fryxell+2000)	Atomic cooling (Hill+2012)	N-body (McMillian)
*Rad Trans (Bacynzski+2015)	*Mol cool (Neufield+1996)	Binary formation (McMillan+)
*Winds (Markova+2008,Vink+2000, Kudritzski+2000)	*Dust<->Gas (Hollenbach+1989)	Binary dynamics (McMillan+)
*SN (Simpson+2016)	*Background FUV (Weingartner+2001)	Binary accretion (PZ+1996)
*Star formation (Sormani+2017)	*Cosmic rays (Galli+2015)	Stellar flux (Lanz+2003)
*Ionization fraction solver	*Local gas extinction (Banerjee+2006)	SE (PZ+1996)
Ionization heating (Bacynzski+2015)	*Radiation momentum	Stellar mass loss rate (other than OB winds) (PZ+1996)
*FUV local stellar heating (Weingartner+2001)	*EUV on dust (Draine 2011)	

* code I either fully developed or contributed to development

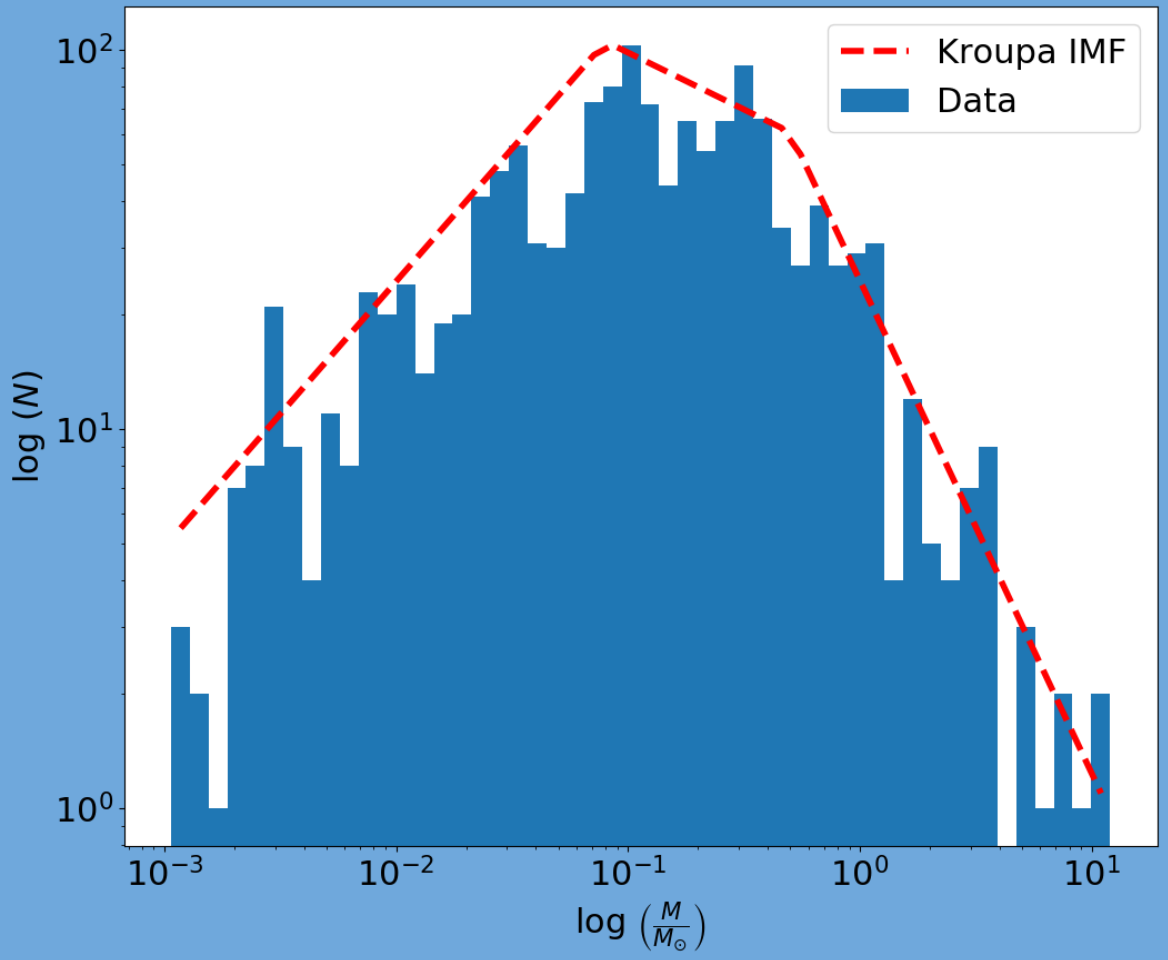
In development

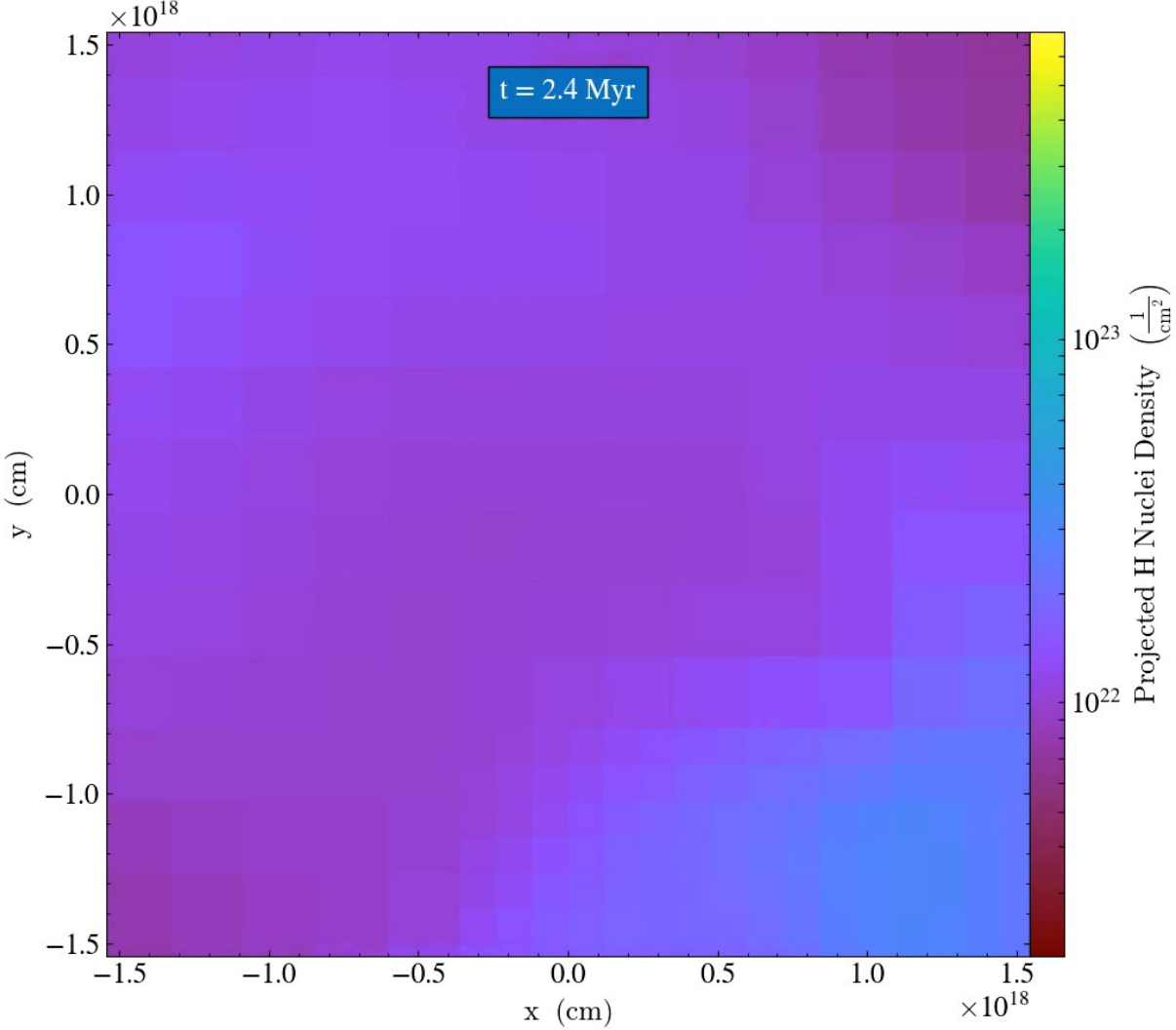
Fully implemented

Implemented, needs testing

Run	M	r (pc)	n_0	α	$\lvert B\rvert(\mu G)$
RunM3V07A	10^3	5	10^3	0.7	3.0
RunM4V07A	10^4	10	500	0.7	3.0
RunM5V07A	10^5	50	100	0.7	3.0
RunM3V04A	10^3	5	10^3	0.4	3.0
RunM4V04A	10^4	10	500	0.4	3.0
RunM5V04A	10^5	50	100	0.4	3.0
RunM3V02A	10^3	5	10^3	0.2	3.0
RunM4V02A	10^4	10	500	0.2	3.0
RunM5V02A	10^5	50	100	0.2	3.0

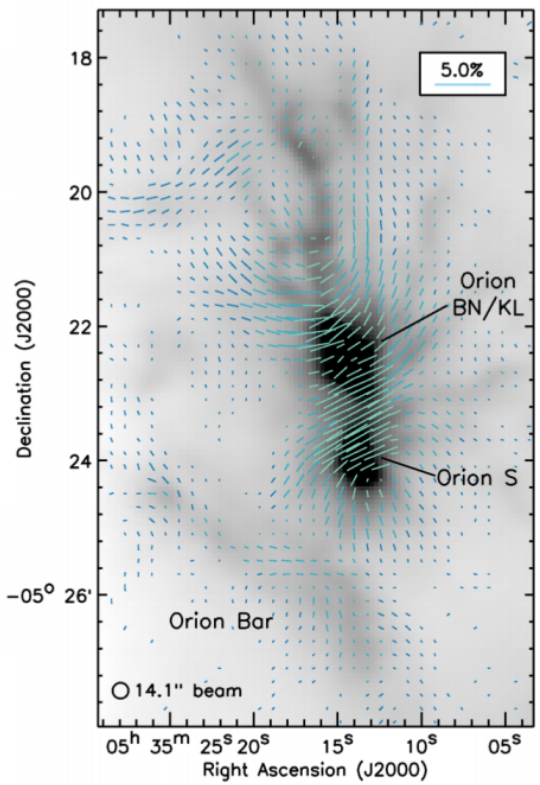
- *Input* is a Weidner+2013 IGIMF or Kroupa+2001 IMF (choice). Note that for star formation resolved at 1 solar mass requires resolution at 1 AU.
- Number of stars in each mass bin is calculated from a Poisson distribution as in Sormani+2017 (developed here independently).
- A list of candidate stars is pulled for each sink particle.
- Only if the sink can collect enough mass can the star form.
- This means feedback can halt star formation.
- Input IMF but output SFR and SFE.

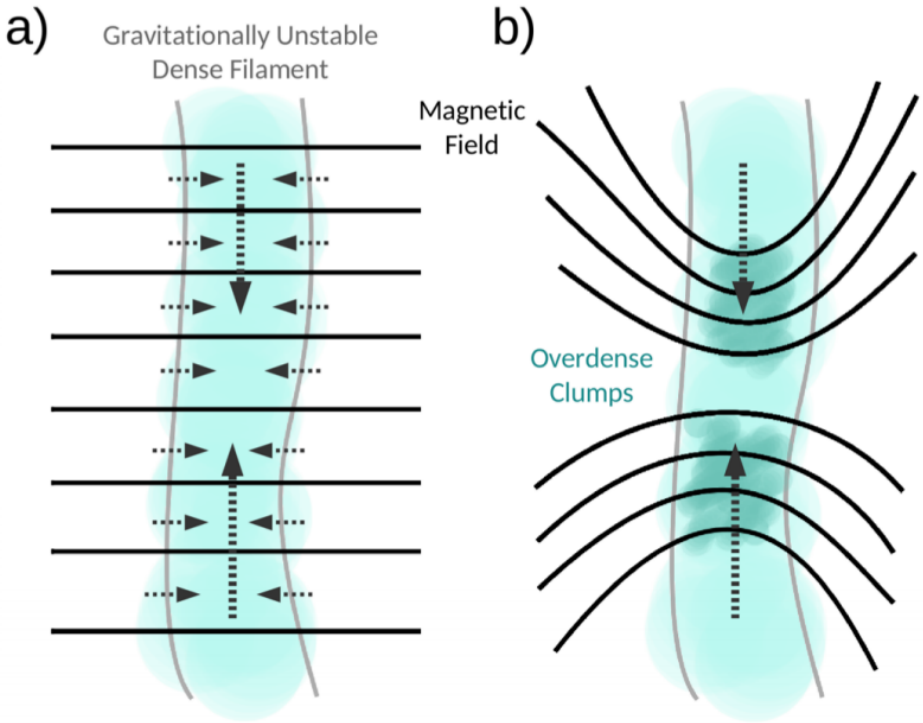



t = 2.4 Myr
×10^18
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
y (cm)
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
×10^18
x (cm)
10^23
10^22
Projected H Nuclei Density (1/cm^2)

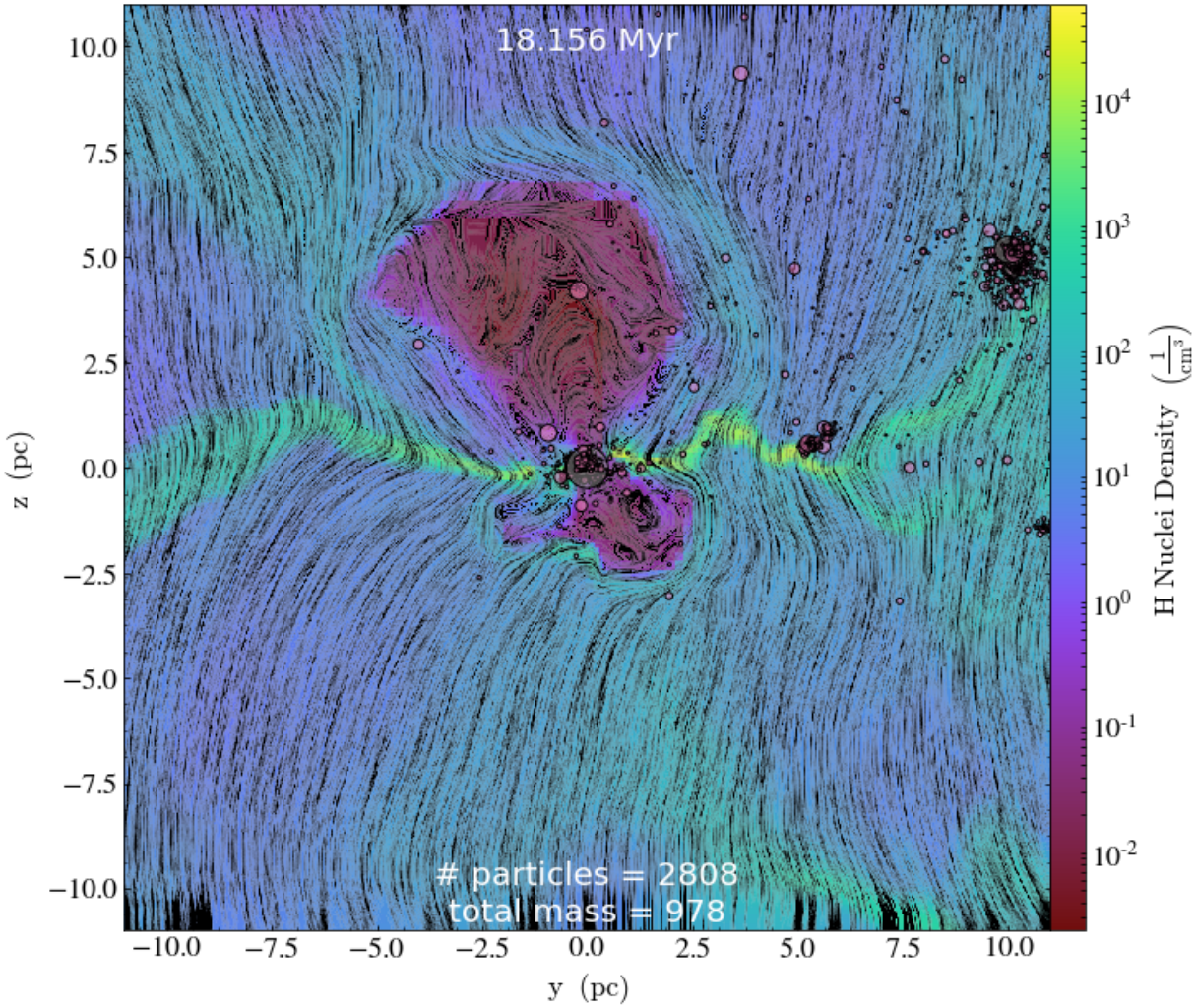
Borrowed from Stutz
MODEST17

The pinching instability: polarization "hour-glass" morphology in ONC

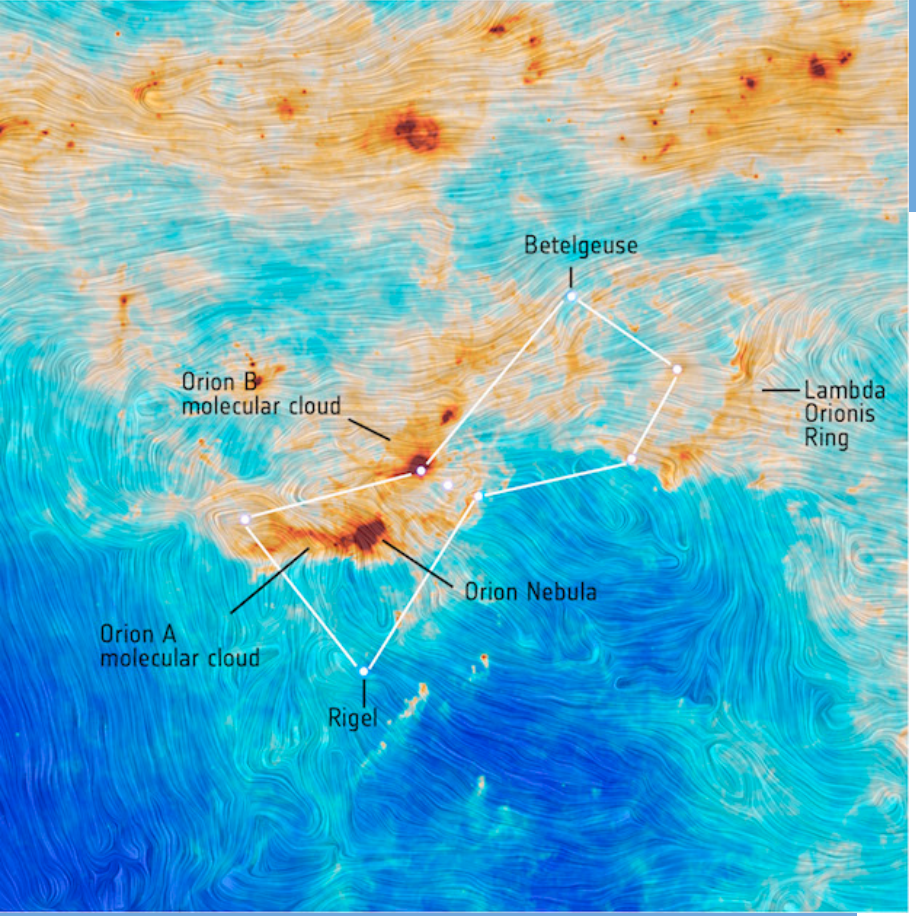




Pattle et al. (2017), arXiv:1707.05269


18.156 Myr
particles = 2808
total mass = 978
z (pc)
y (pc)
H Nuclei Density $\left(\frac{1}{cm^3}\right)$
10.0
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5
−10.0
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}

Magnetic fields are important for proper filament formation and by extension proper star formation. (10^4 run shown)



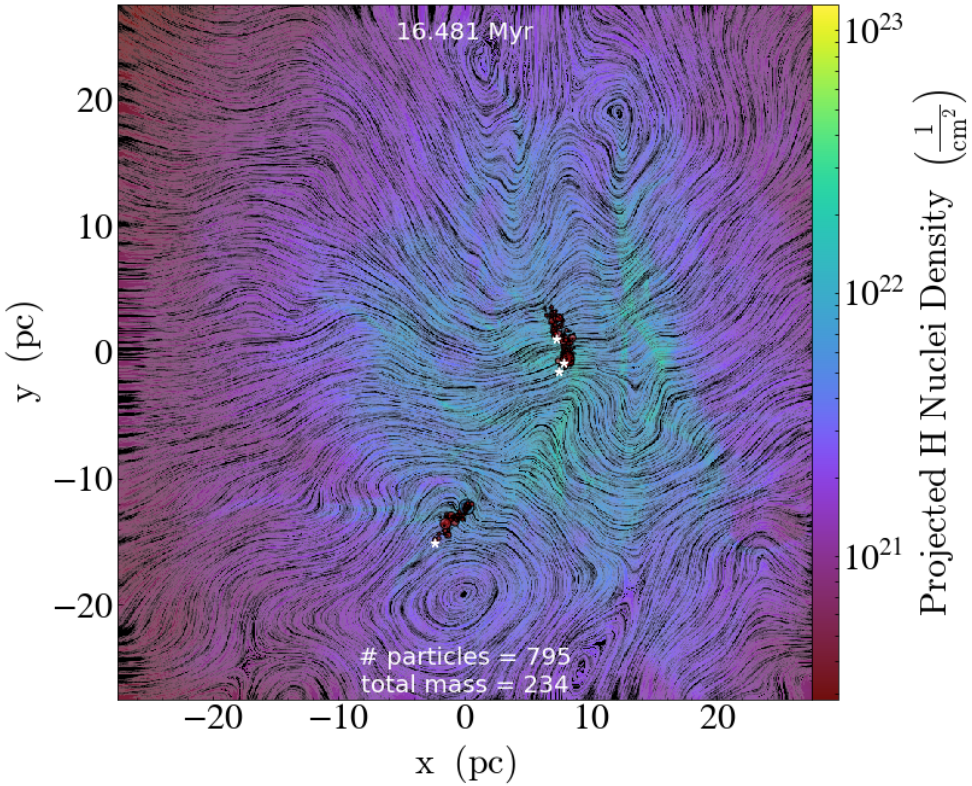
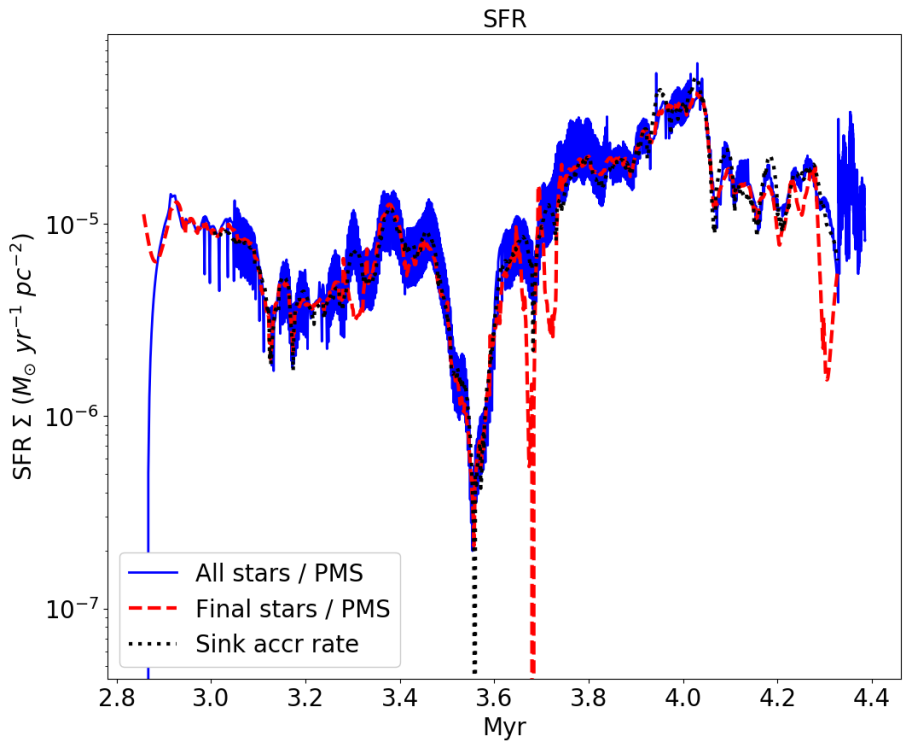
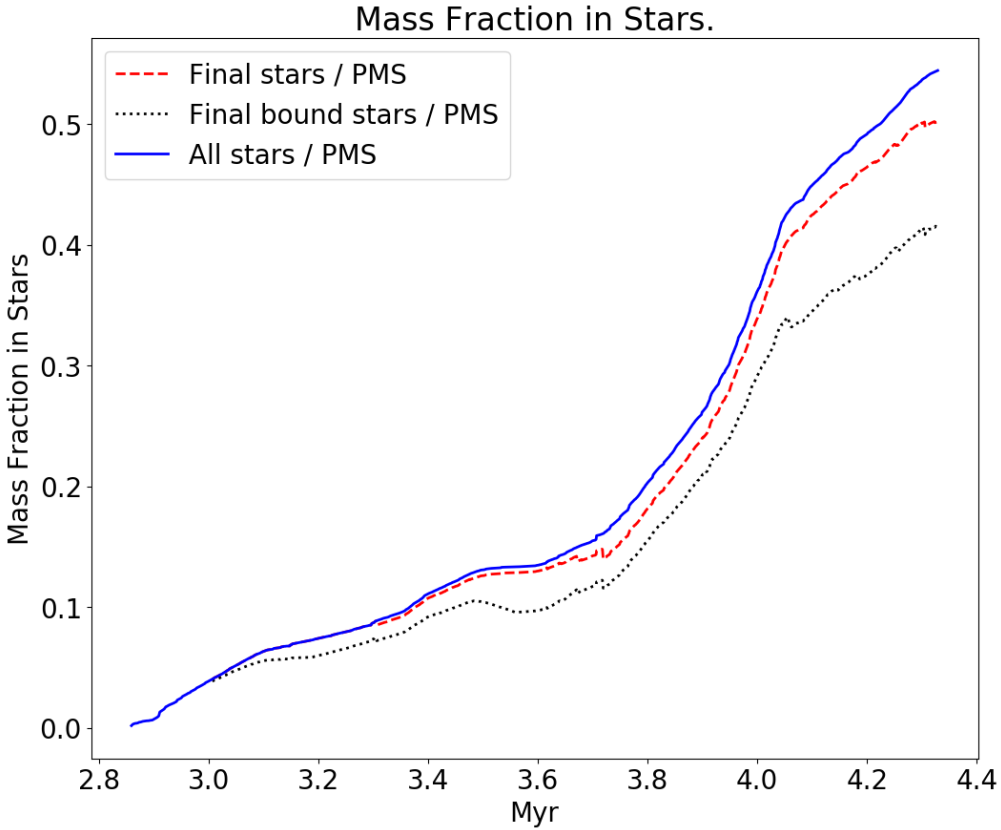
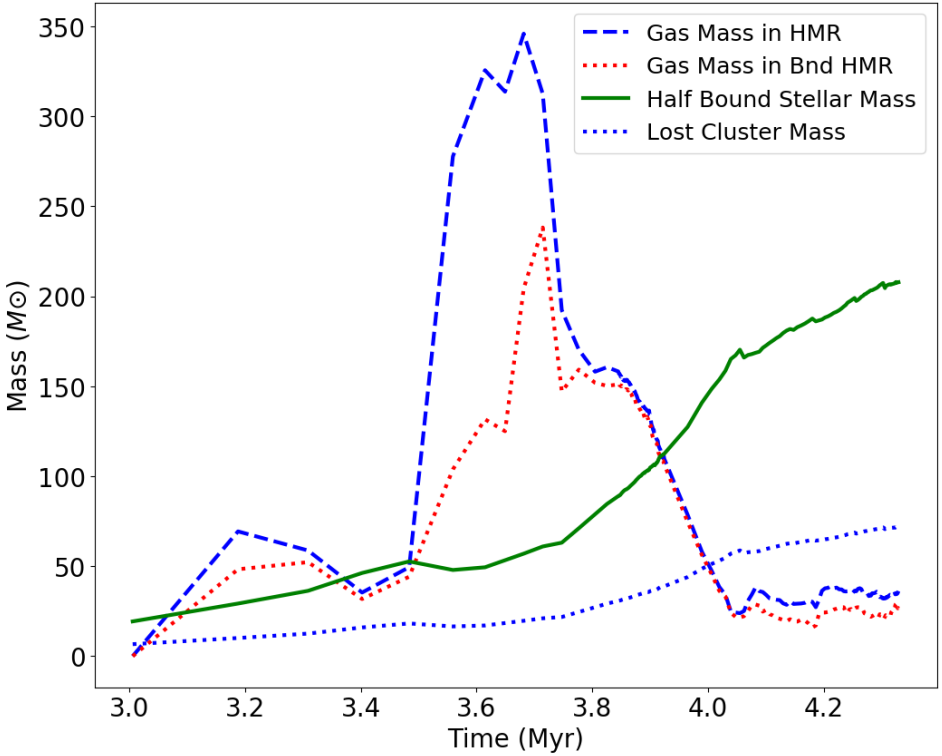


Image is 278 pc on a side
(ESA Planck Collaboration)



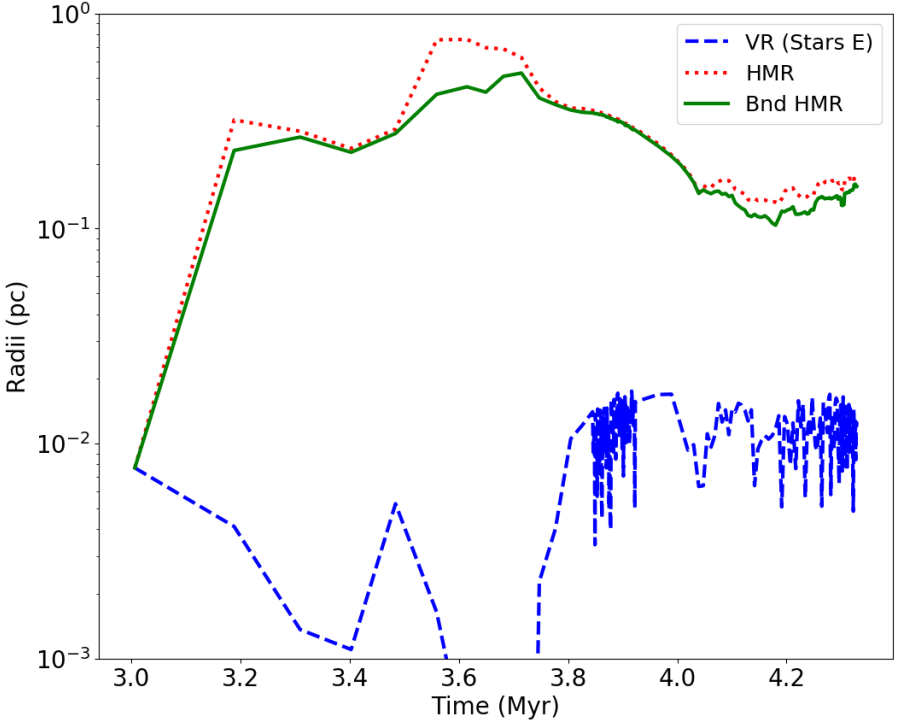
Note the SFE here is purely dynamically driven.

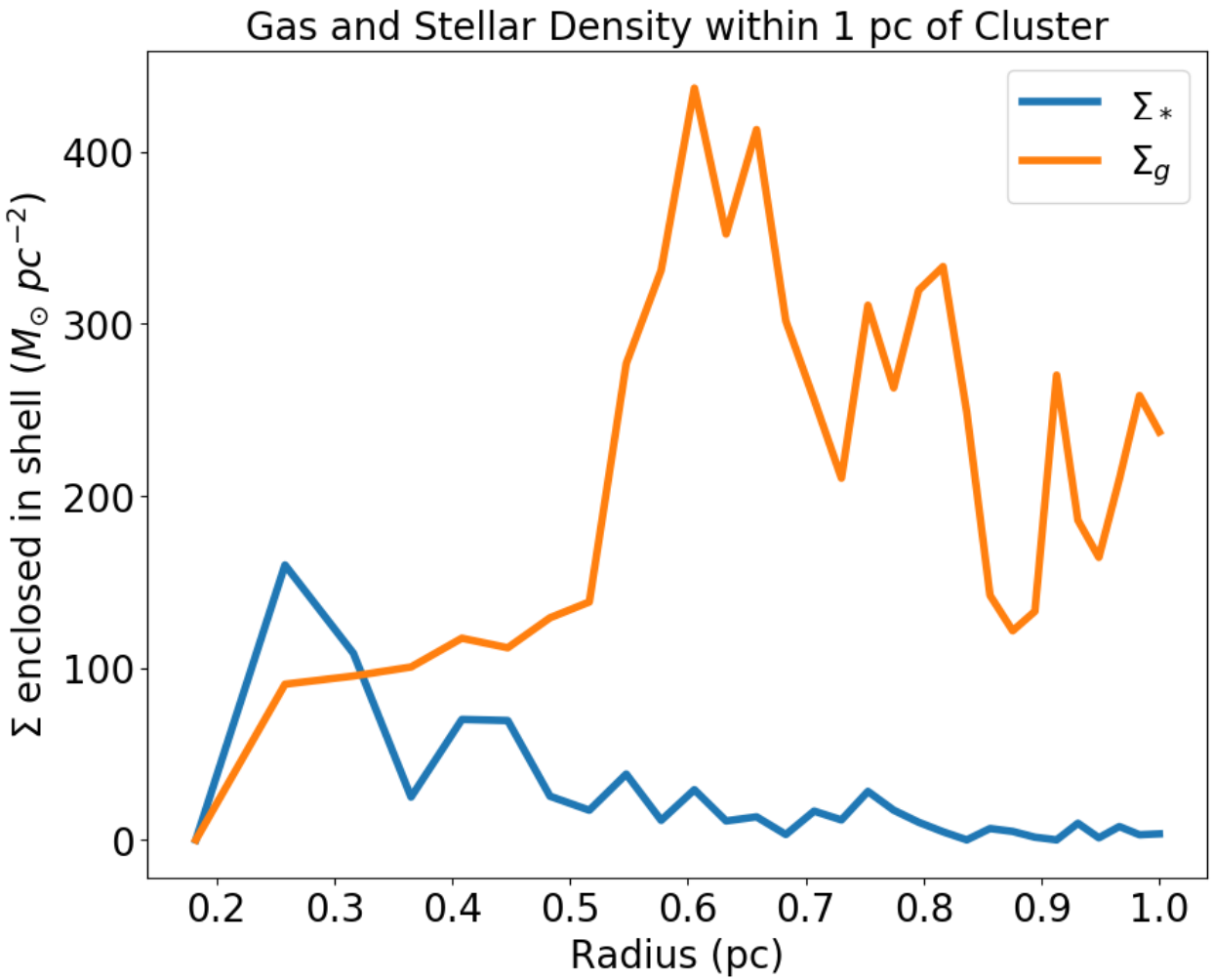


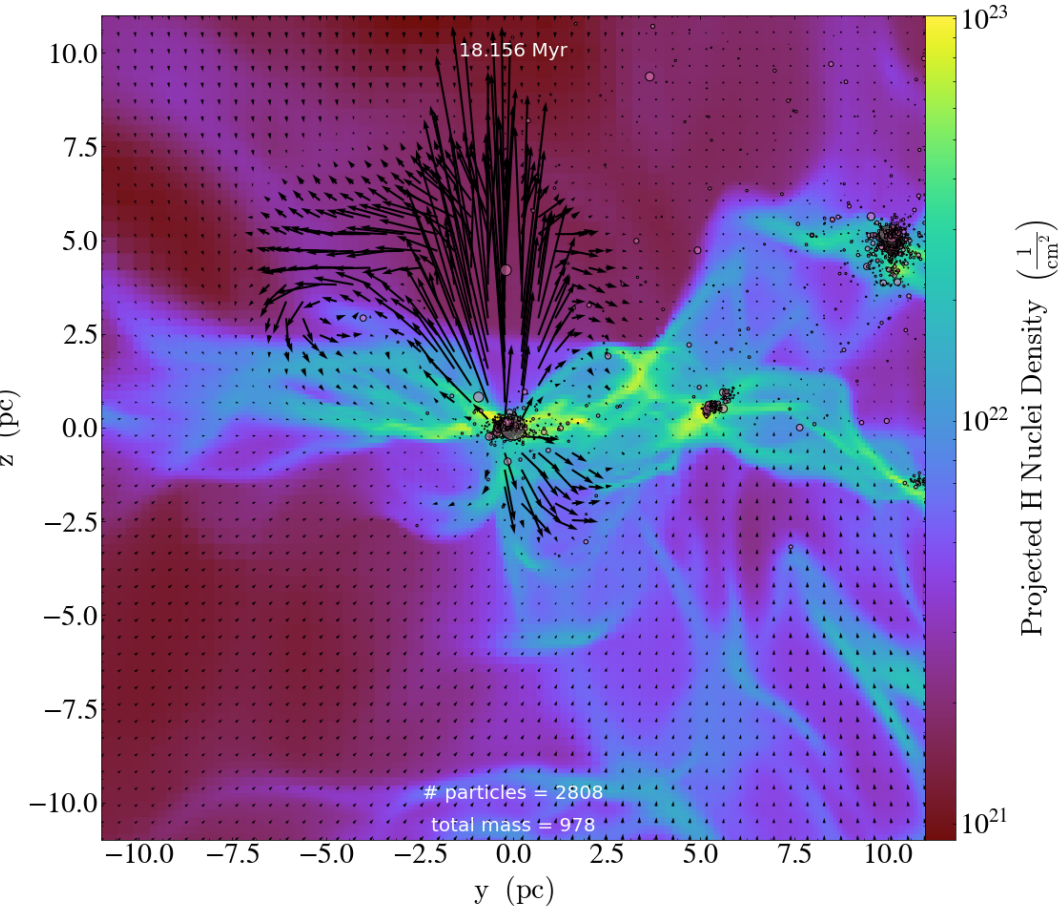


Mass in stellar half mass radius

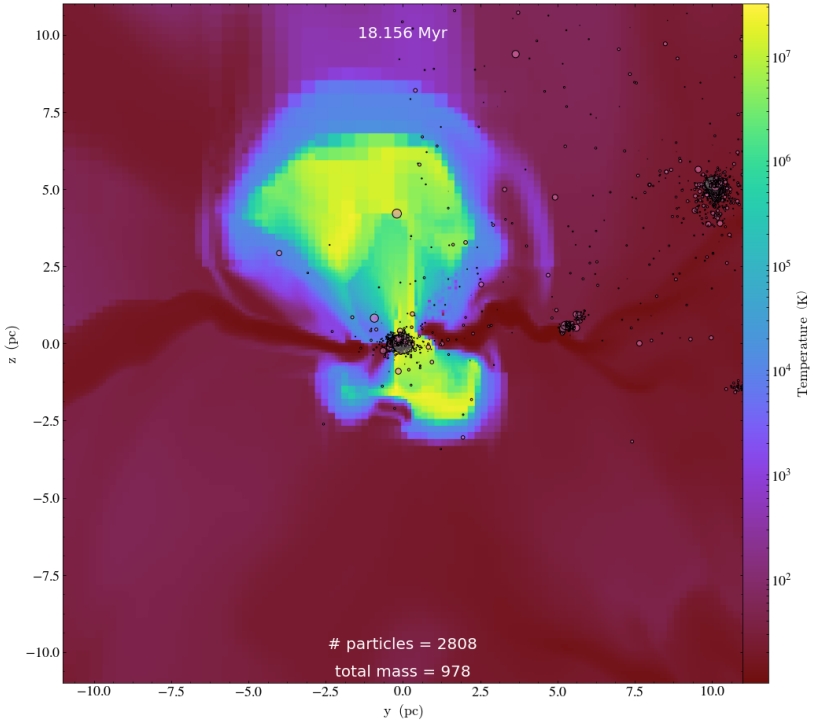
Stellar half mass radii.

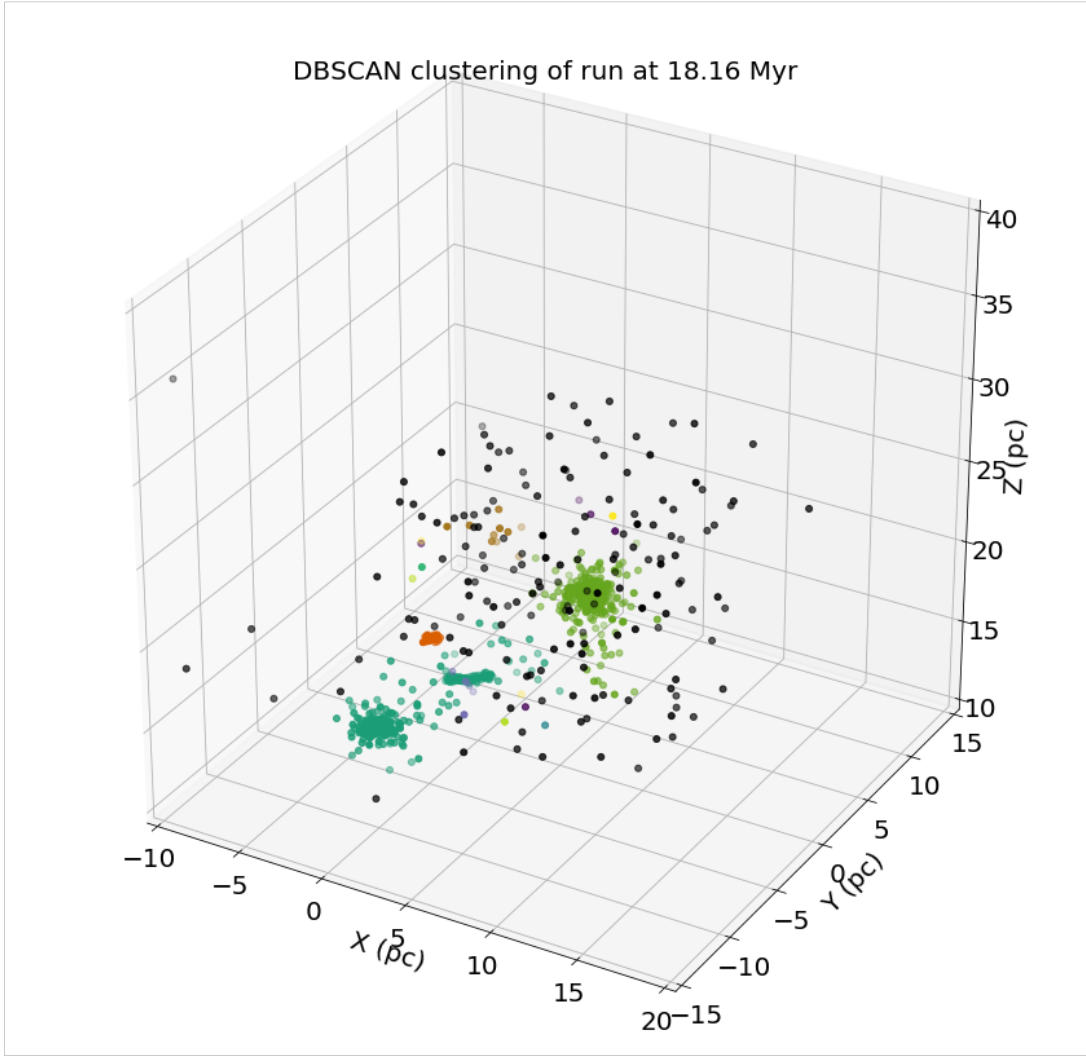



Gas and Stellar Density within 1 pc of Cluster
Σ_*
Σ_g
Σ enclosed in shell ($M_\odot\ pc^{-2}$)
0
100
200
300
400
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Radius (pc)



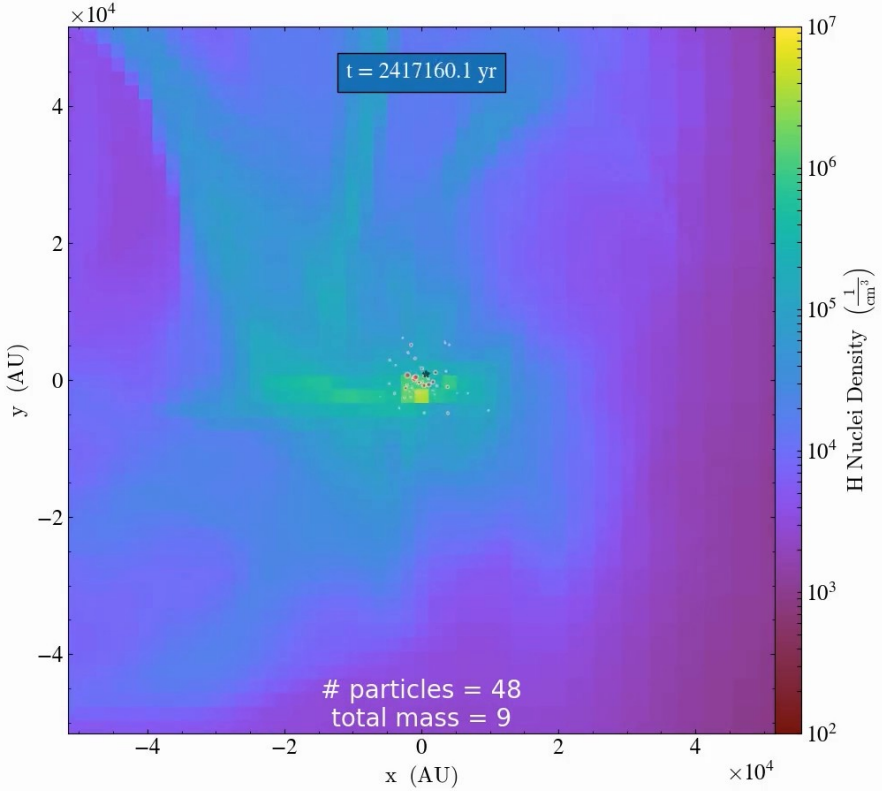
33 solar masses
10^4 solar mass initial cloud
Winds + UV + FUV + rad pressure
No mass loading

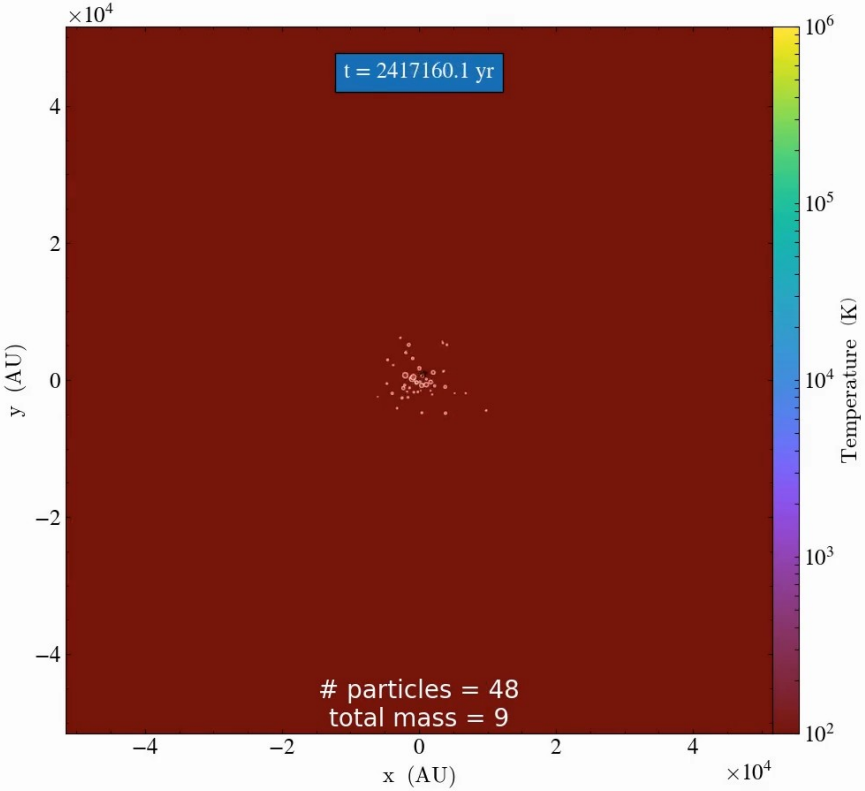



DBSCAN clustering of run at 18.16 Myr
X (pc)
Y (pc)
Z (pc)
−10
−5
0
5
10
15
20
−15
−10
−5
0
5
10
15
10
15
20
25
30
35
40

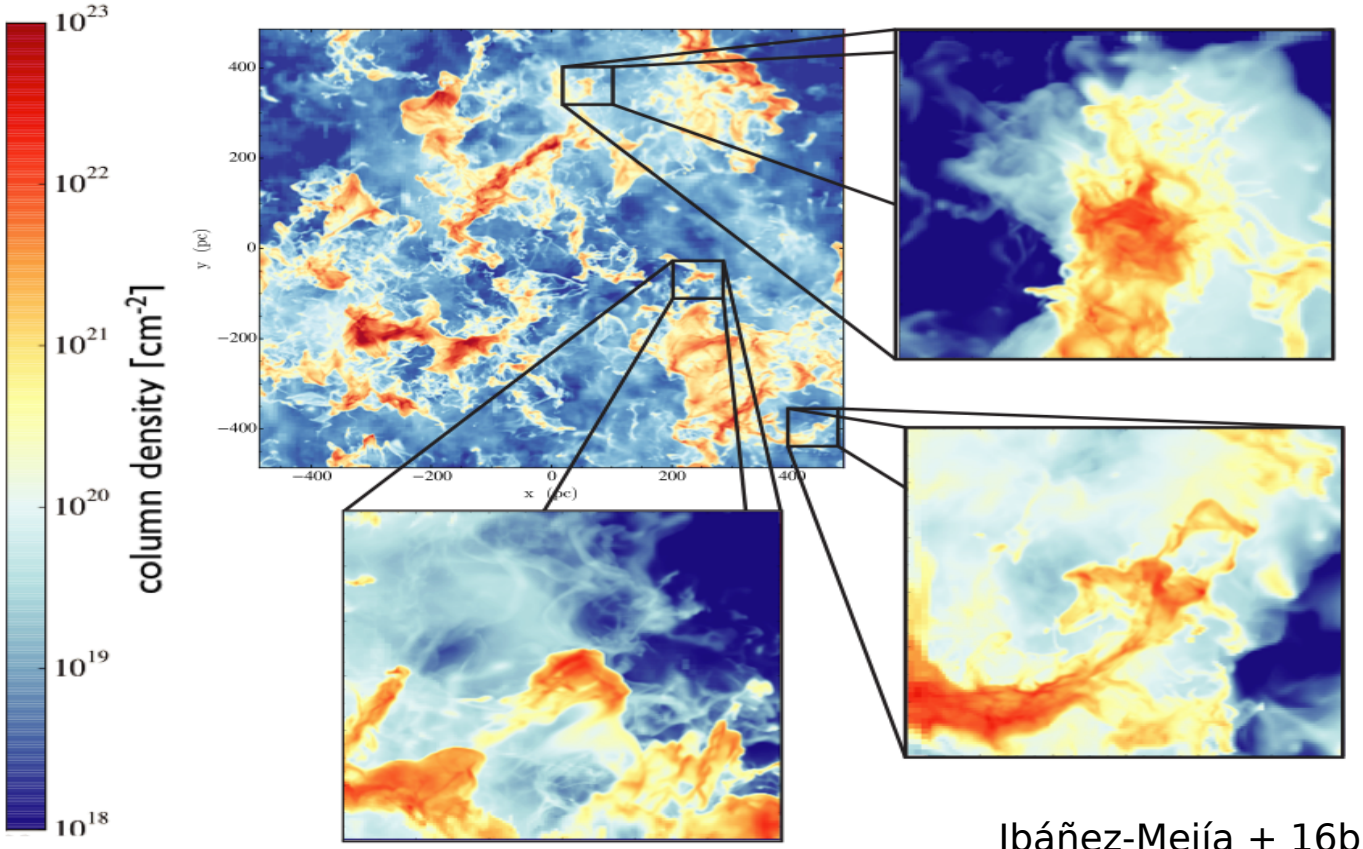
What's Cooking…

Note the inefficiency of the stellar feedback on the dense gas.
$\Gamma \sim n$ while $\Lambda \sim n^2$





Simulating individual clouds



Ibáñez-Mejía + 16b

Final thoughts

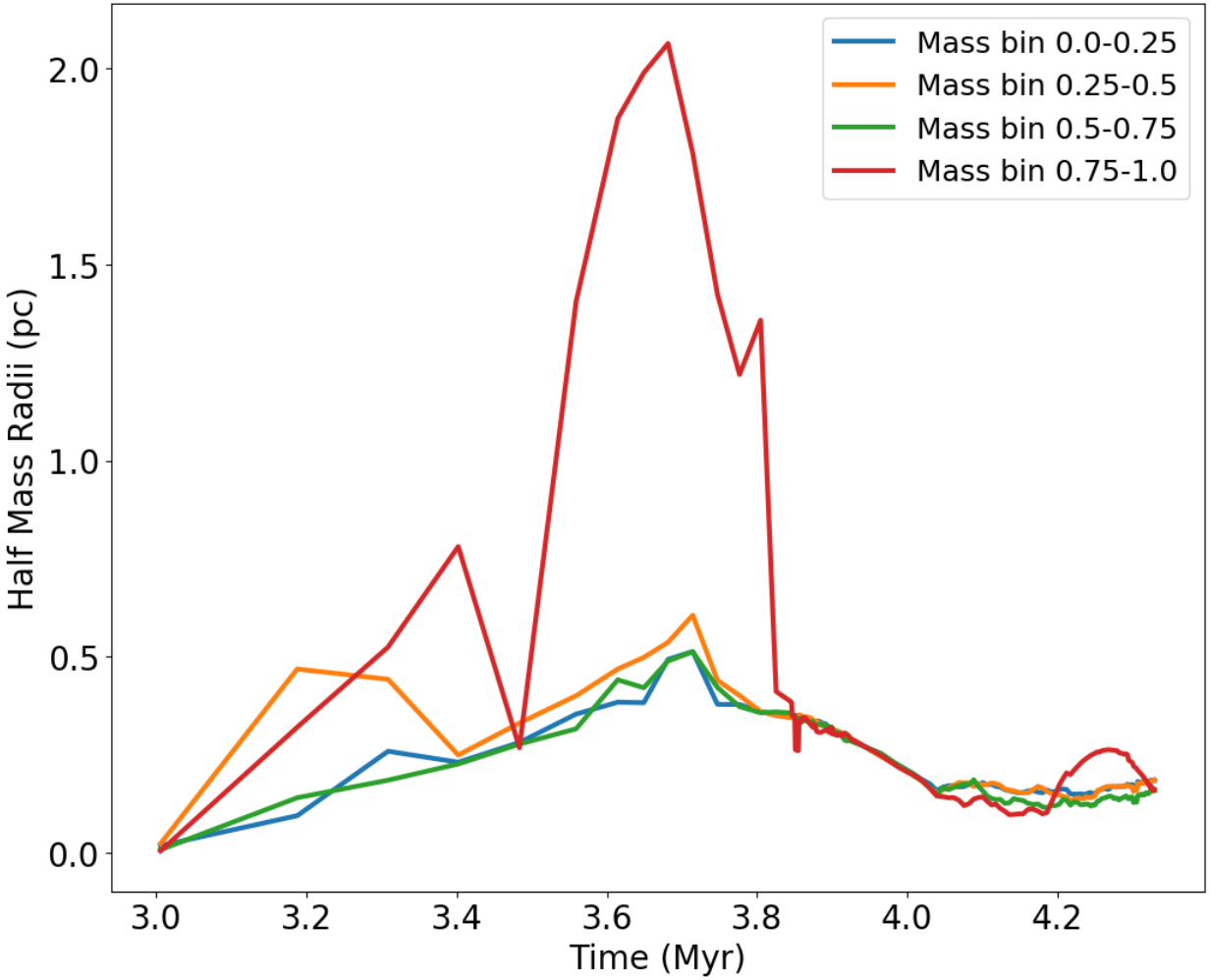
- ❑ Forming stars “the right way” is quite complicated.
- ❑ Feedback is often less effective than you might suspect.
- ❑ Feedback is a good place to attempt to test stochastic IMF vs. IGIMF (see Andrews+2013, 2014 and Guo+2016 for observational tests).

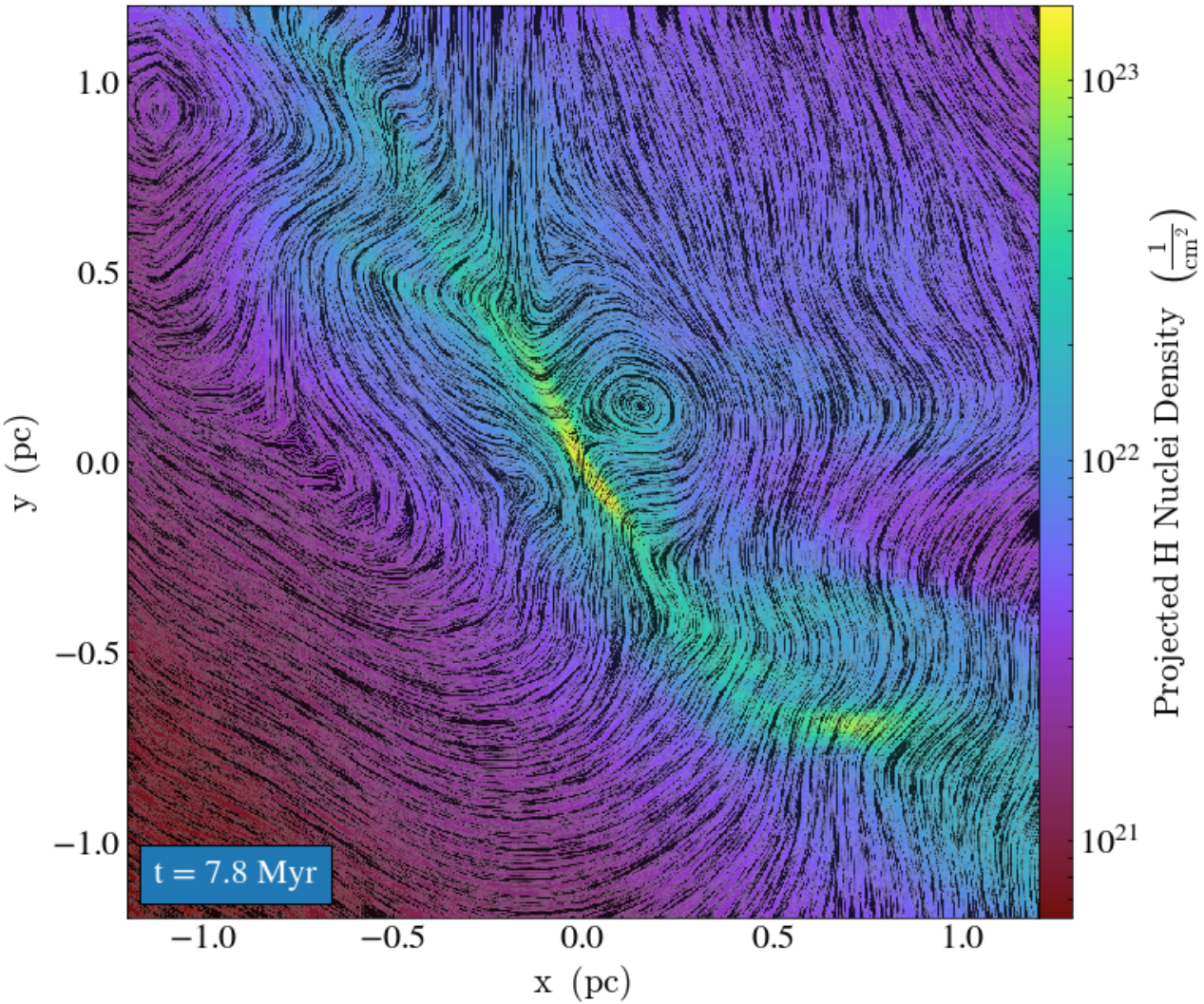
Next steps

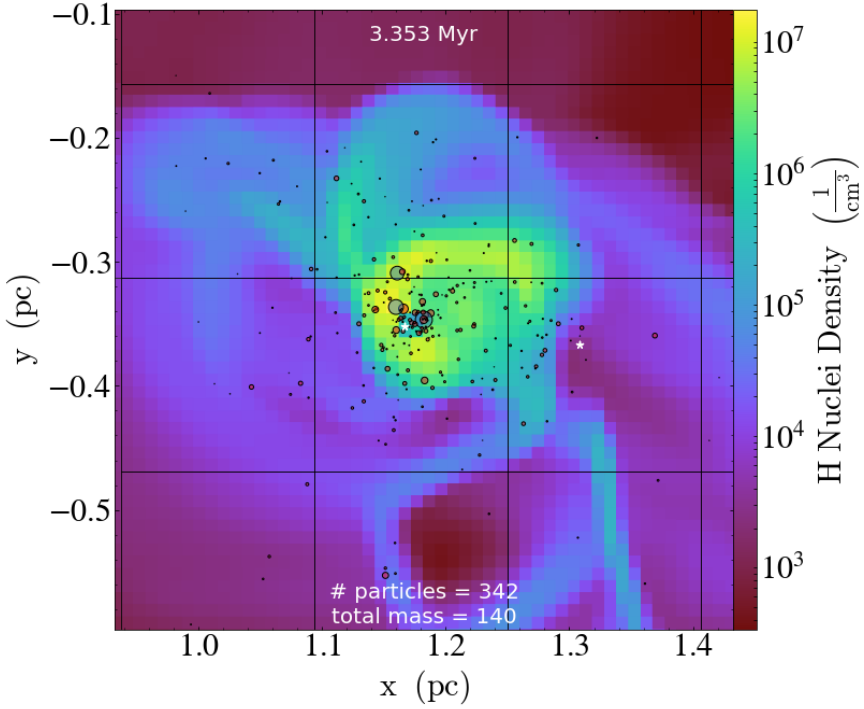
- ❑ More analysis (track subcluster structure in merged clusters, fractal dim, energetics of gas and stars, etc).
- ❑ Write papers (Methods to be submitted soon, 1st science paper starting up).
- ❑ Get awesome post doc position (applying this fall, will work for bar tab).

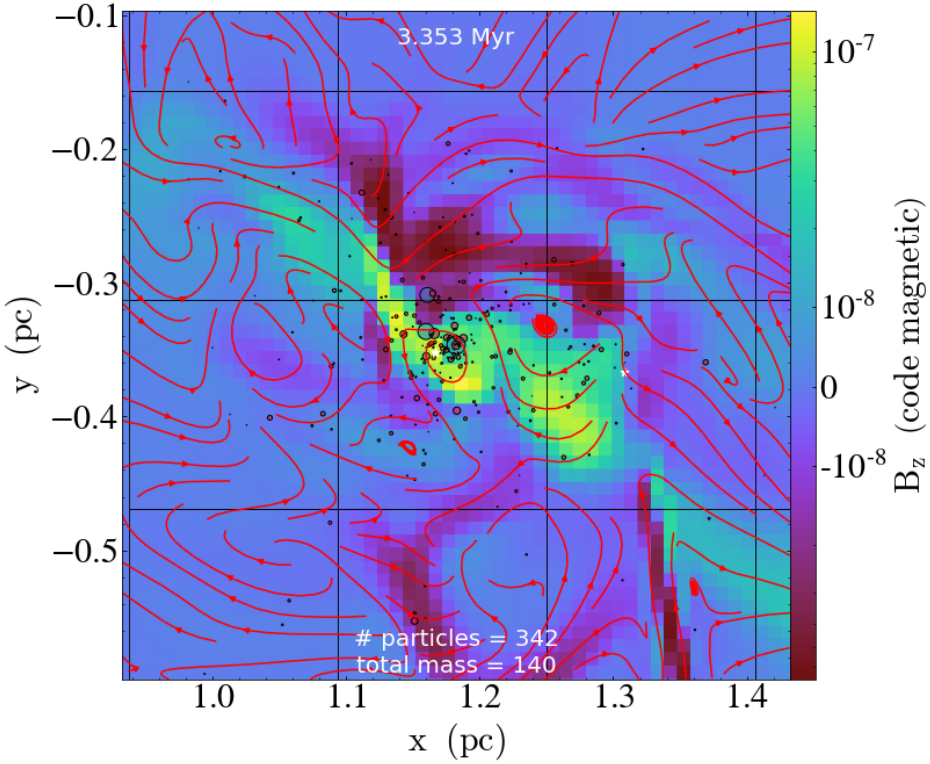
Questions?

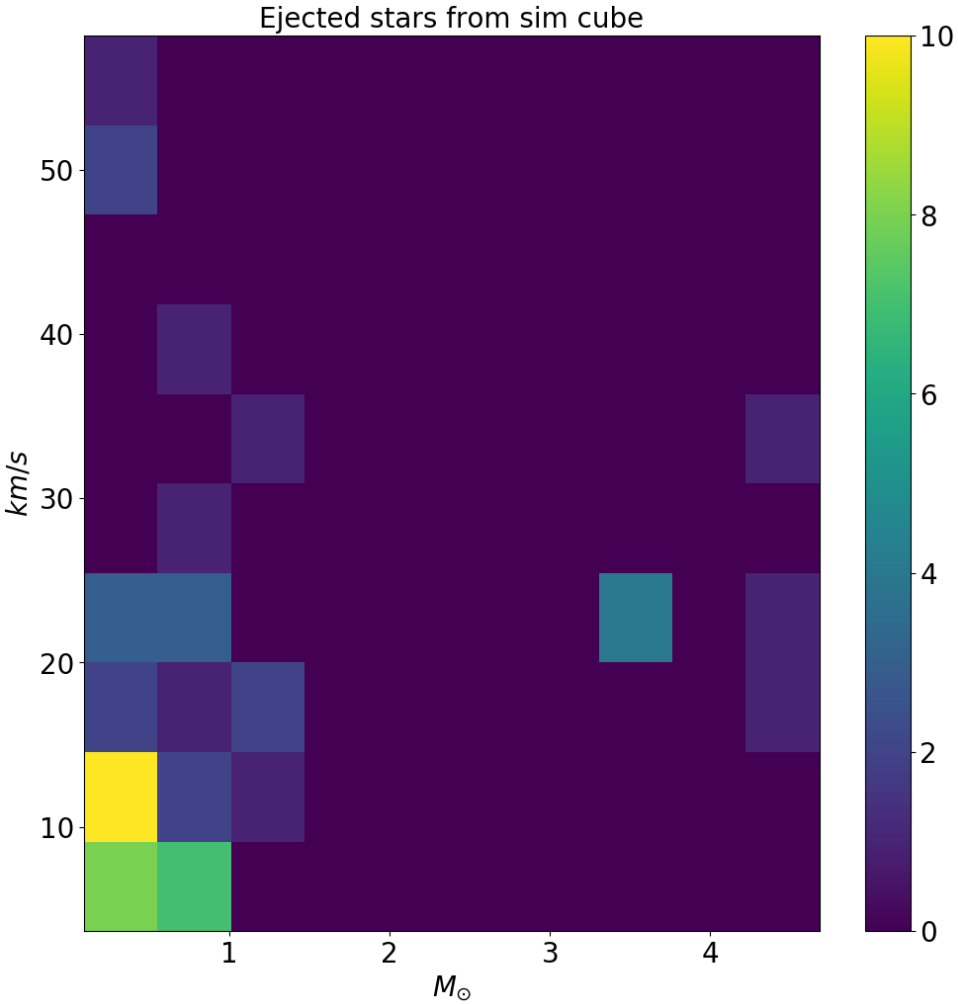
EC

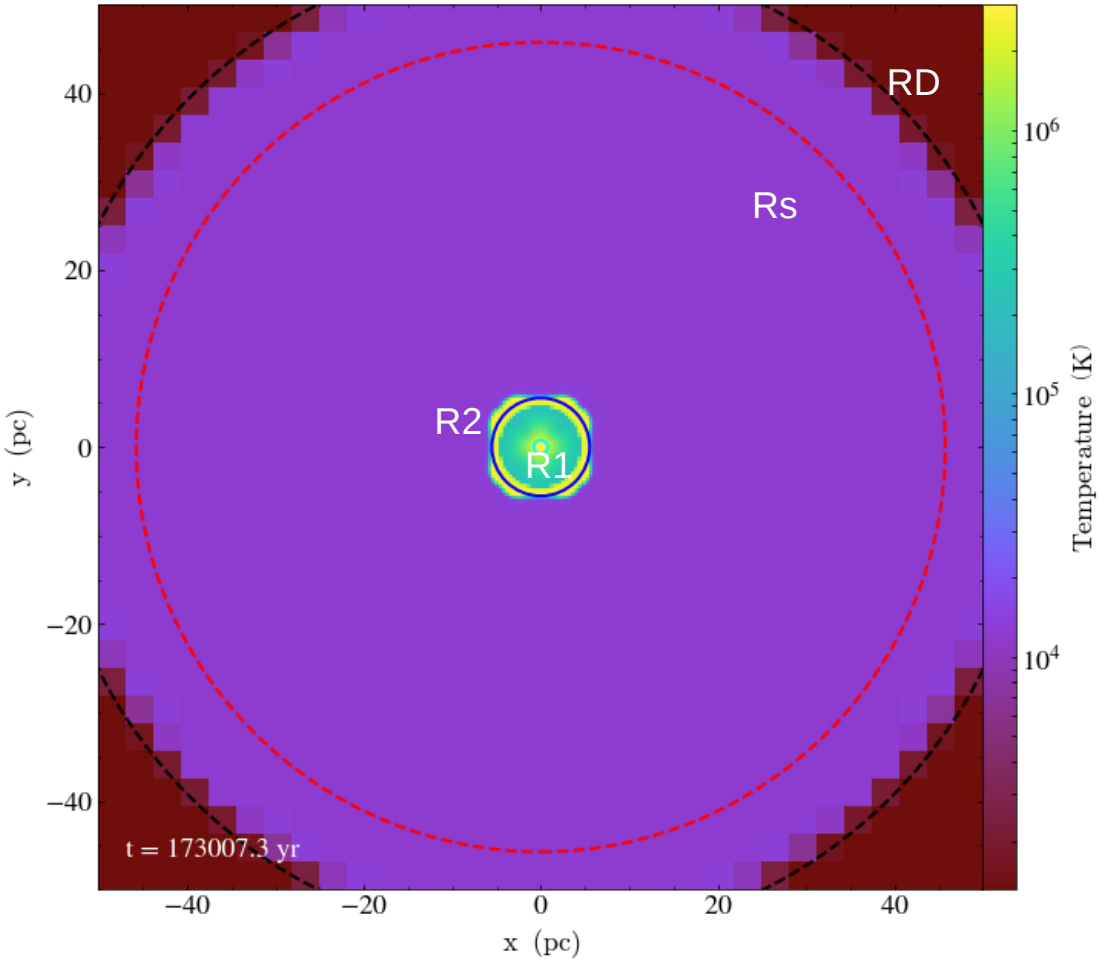

Mass bin 0.0-0.25
Mass bin 0.25-0.5
Mass bin 0.5-0.75
Mass bin 0.75-1.0
Half Mass Radii (pc)
0.0
0.5
1.0
1.5
2.0
3.0
3.2
3.4
3.6
3.8
4.0
4.2
Time (Myr)


t = 7.8 Myr
1.0
0.5
0.0
−0.5
−1.0
y (pc)
−1.0
−0.5
0.0
0.5
1.0
x (pc)
10^{23}
10^{22}
10^{21}
Projected H Nuclei Density $\left(\frac{1}{\mathrm{cm}^2}\right)$

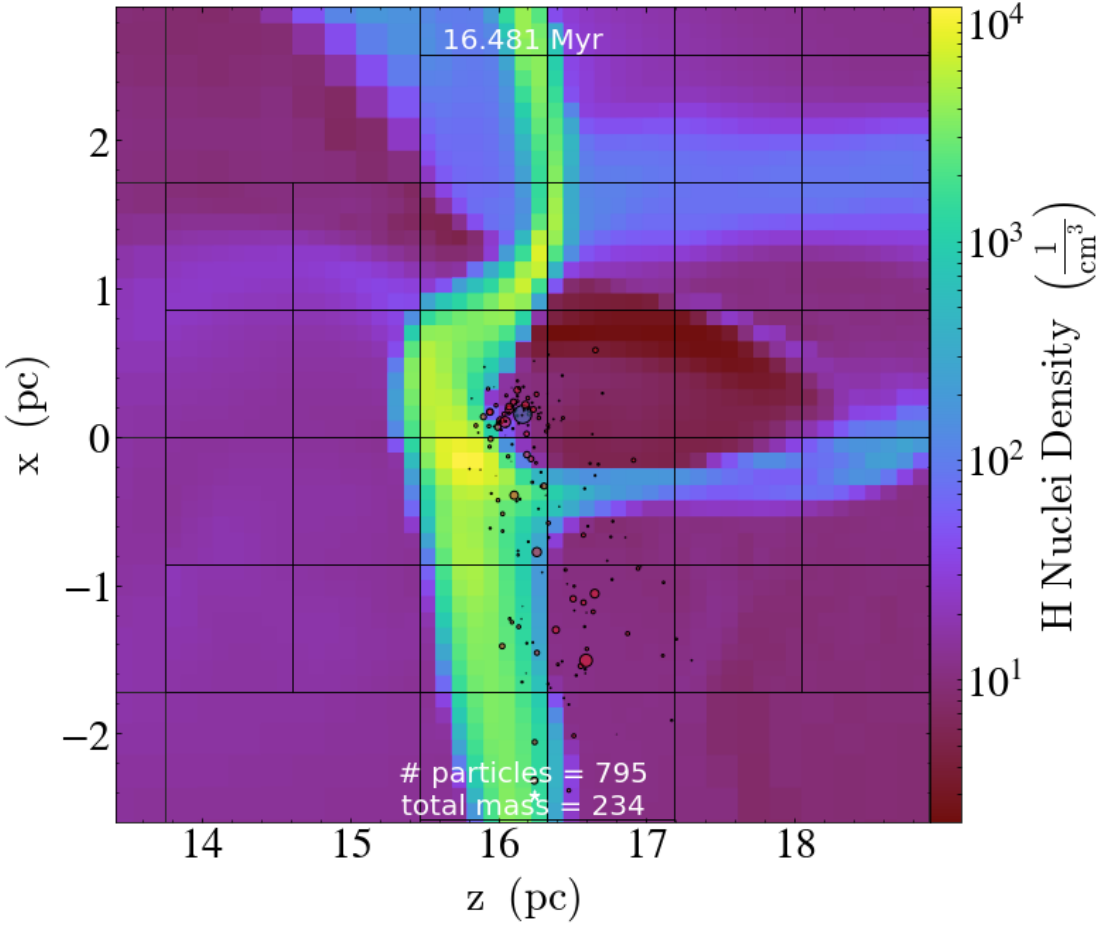

3.353 Myr
particles = 342
total mass = 140
y (pc)
x (pc)
H Nuclei Density $\left(\frac{1}{cm^3}\right)$

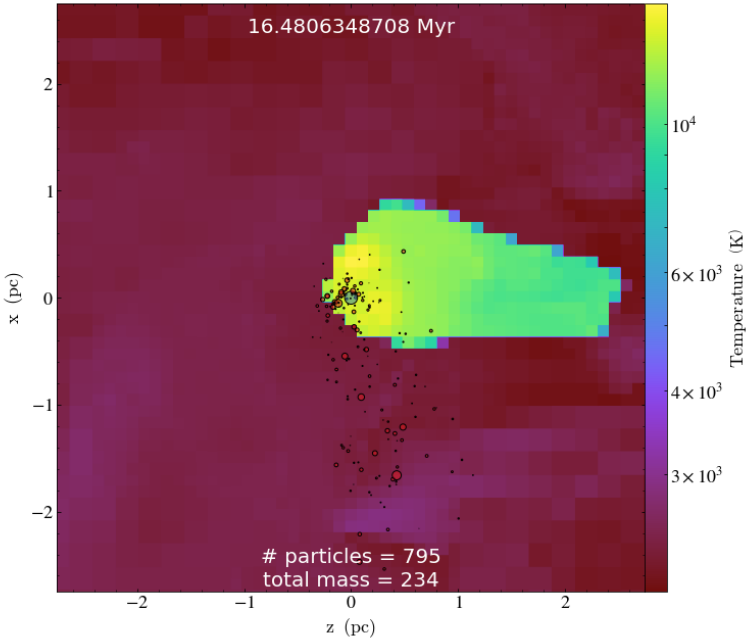

3.353 Myr
particles = 342
total mass = 140
y (pc)
x (pc)
B_z (code magnetic)

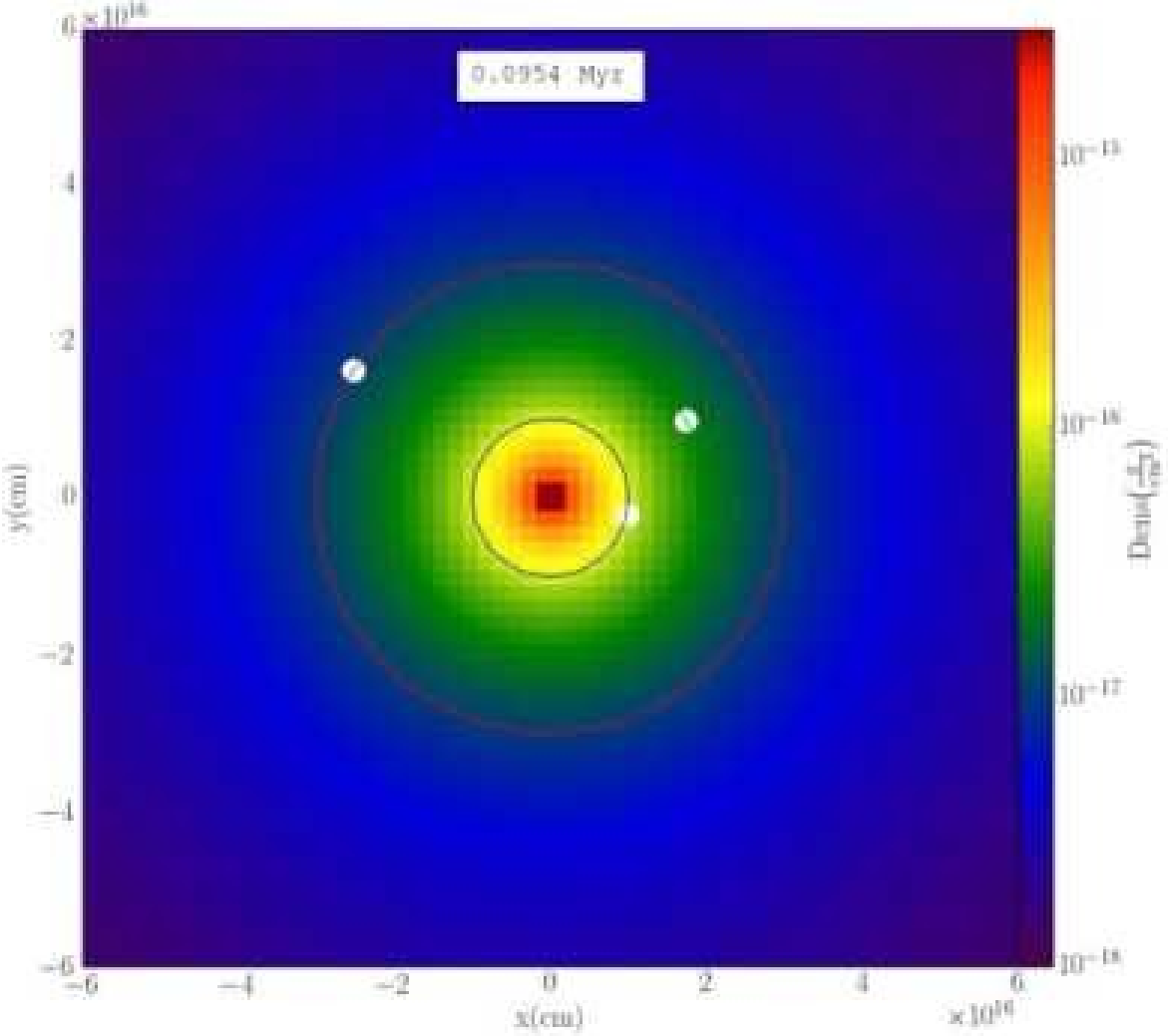

Ejected stars from sim cube
km/s
50
40
30
20
10
1
2
3
4
$M_\odot$
10
8
6
4
2
0

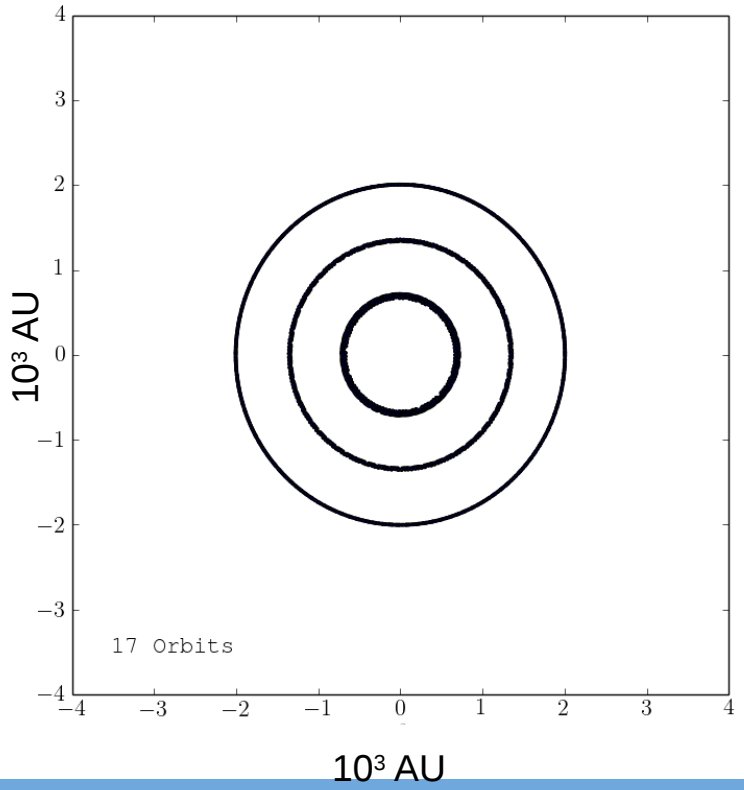


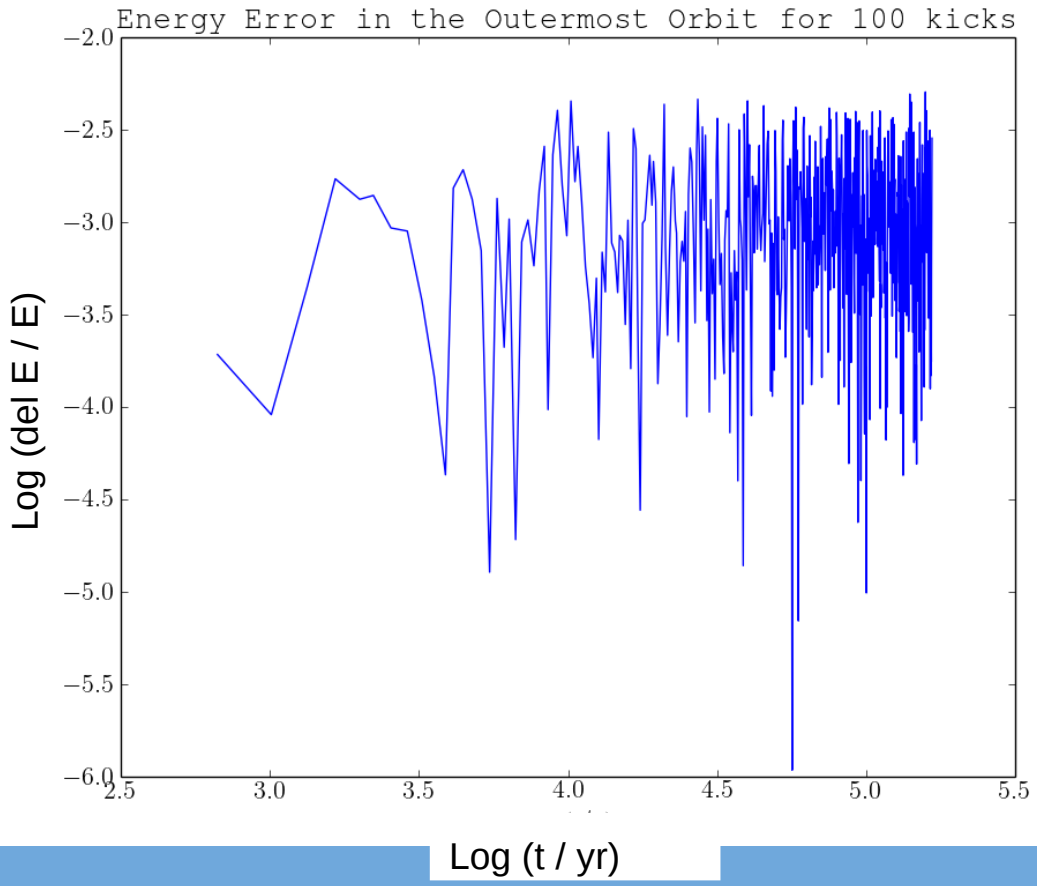
Weaver solutions

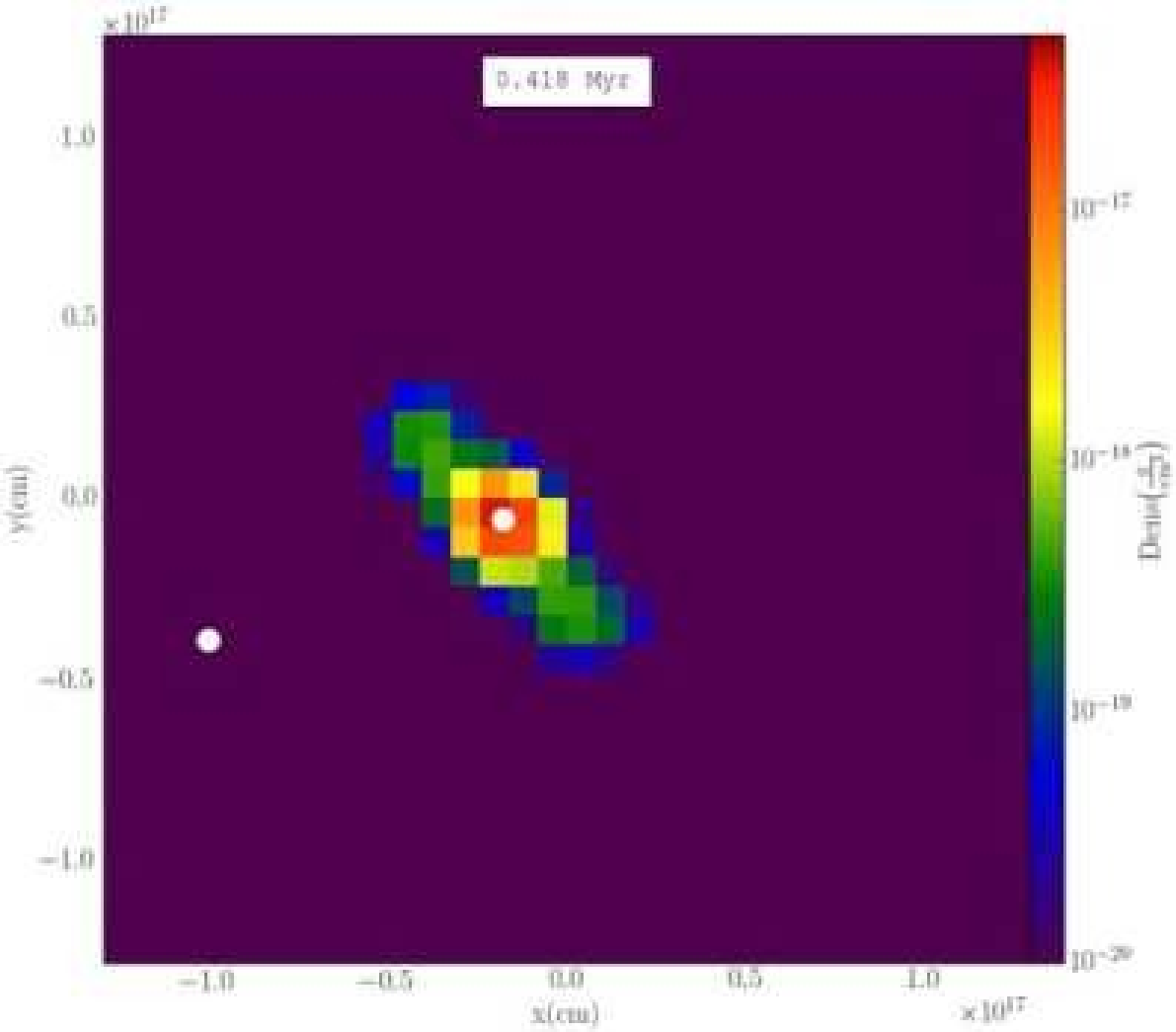

16.481 Myr
particles = 795
total mass = 234
x (pc)
z (pc)
H Nuclei Density $\left(\frac{1}{cm^3}\right)$
10^4
10^3
10^2
10^1
2
1
0
−1
−2
14
15
16
17
18

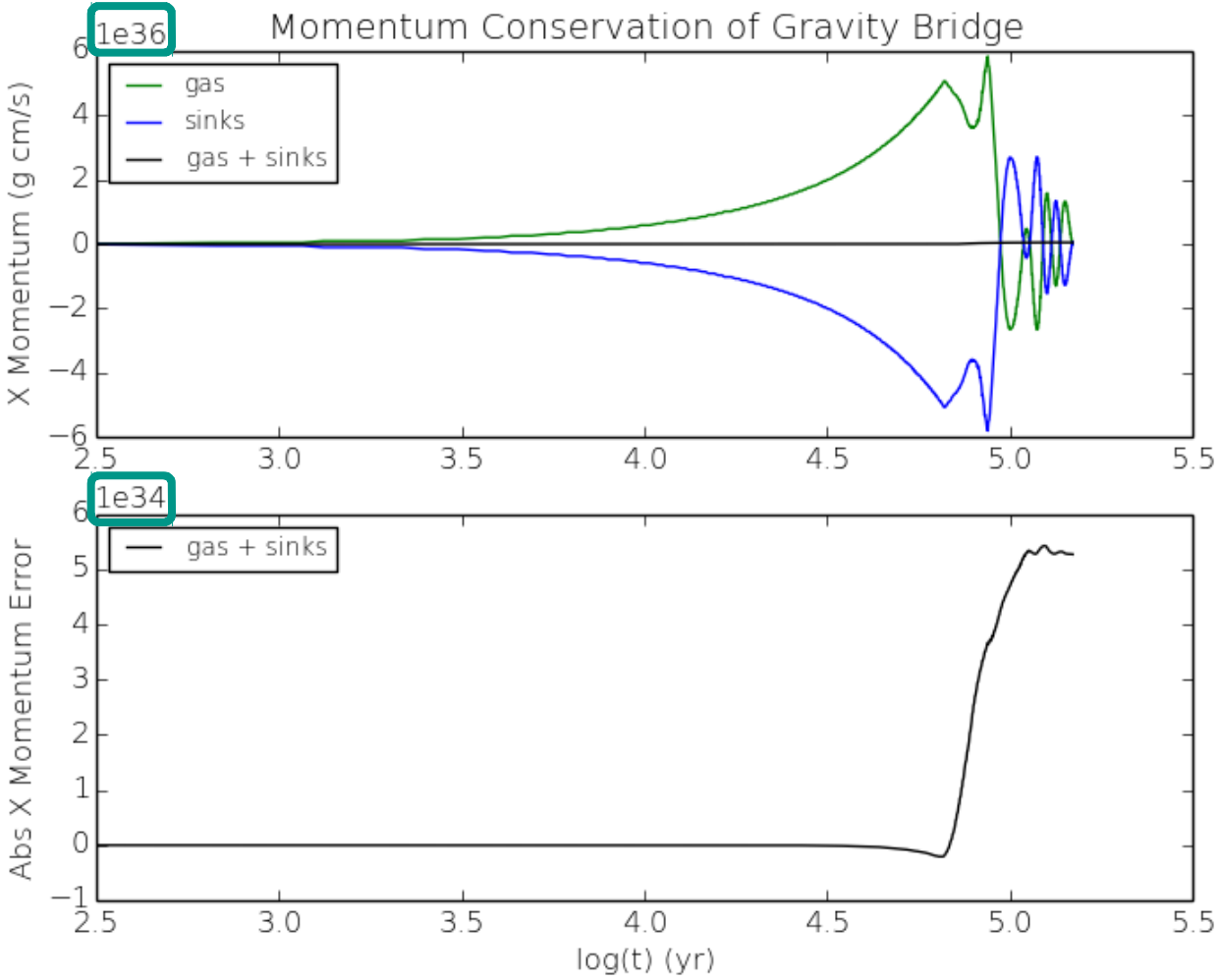

16.4806348708 Myr
particles = 795
total mass = 234
x (pc)
z (pc)
Temperature (K)
10^4
6×10^3
4×10^3
3×10^3
2
1
0
−1
−2


0.0954 Myr
6×10^{16}
4
2
0
−2
−4
−6
y(cm)
−6
−4
−2
0
2
4
6
$\times10^{16}$
x(cm)
10^{-15}
10^{-16}
10^{-17}
10^{-18}
Dens($\frac{g}{cm^3}$)


17 Orbits
10^3 AU
10^3 AU

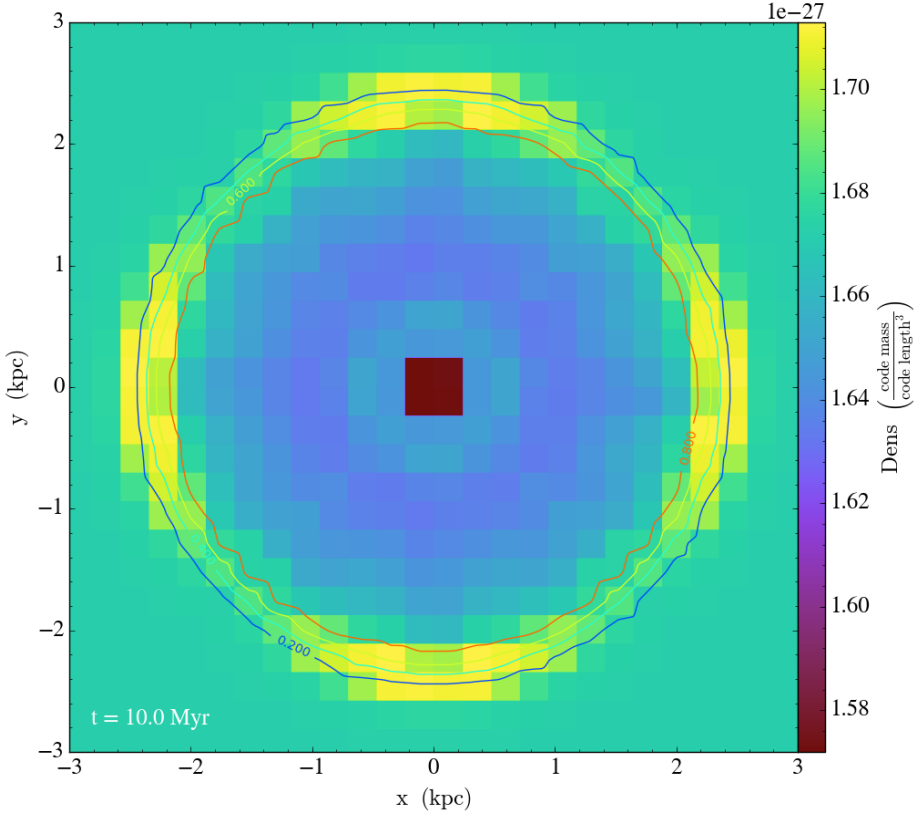

Energy Error in the Outermost Orbit for 100 kicks
Log (del E / E)
Log (t / yr)

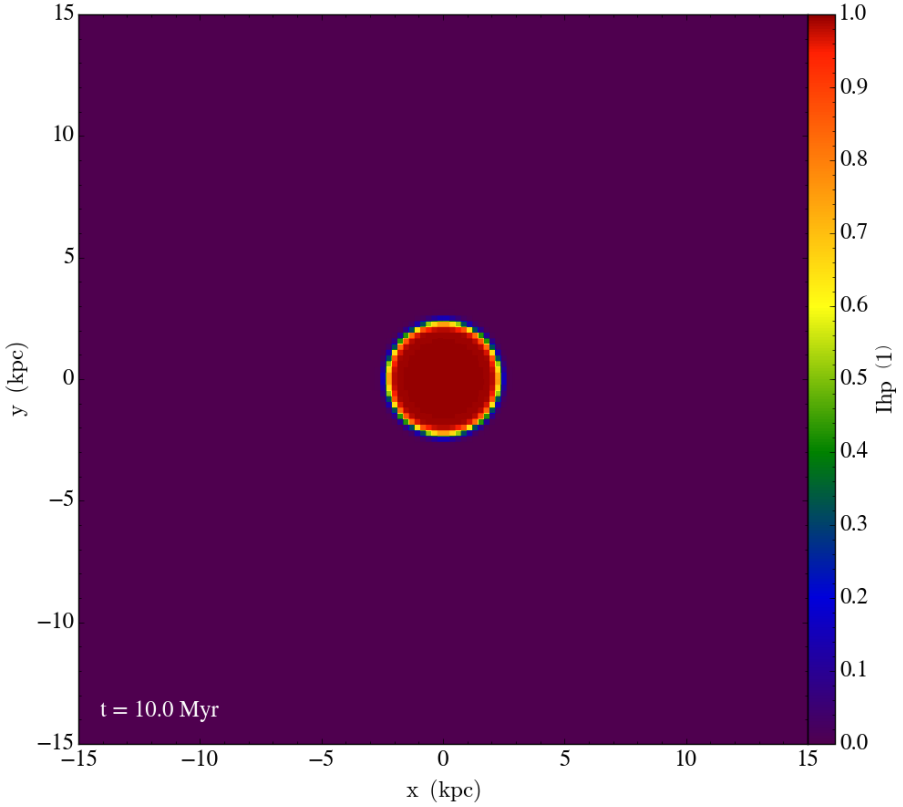

0.418 Myr
$\times 10^{17}$
1.0
0.5
0.0
−0.5
−1.0
y(cm)
−1.0
−0.5
0.0
0.5
1.0
x(cm)
$\times 10^{17}$
10^{-17}
10^{-18}
10^{-19}
10^{-20}
Density $\left(\frac{g}{cm^3}\right)$

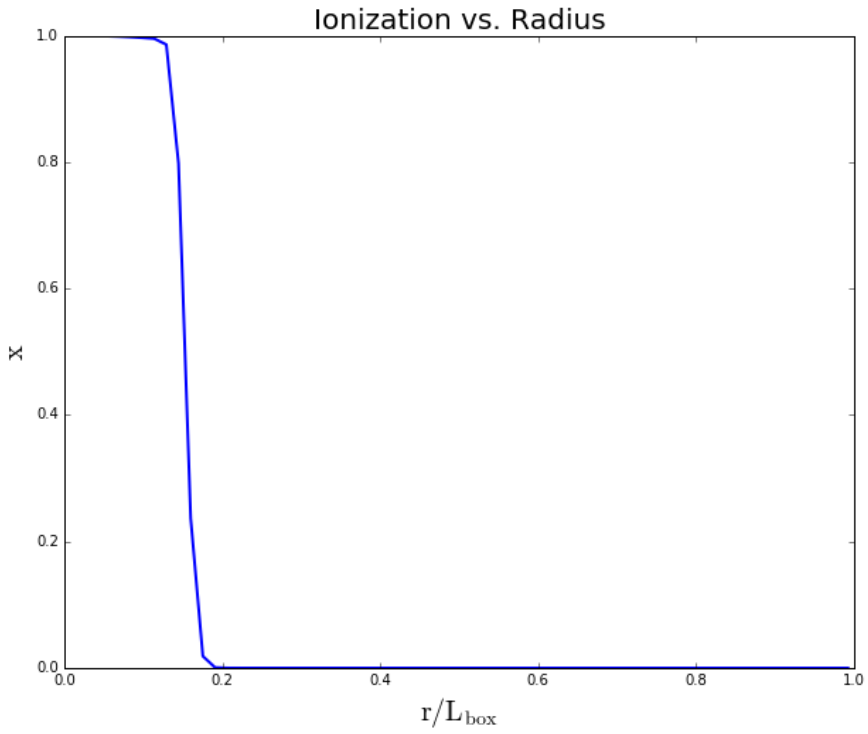

Momentum Conservation of Gravity Bridge
1e36
gas
sinks
gas + sinks
X Momentum (g cm/s)
6
4
2
0
−2
−4
−6
2.5
3.0
3.5
4.0
4.5
5.0
5.5
1e34
gas + sinks
Abs X Momentum Error
6
5
4
3
2
1
0
−1
2.5
3.0
3.5
4.0
4.5
5.0
5.5
log(t) (yr)

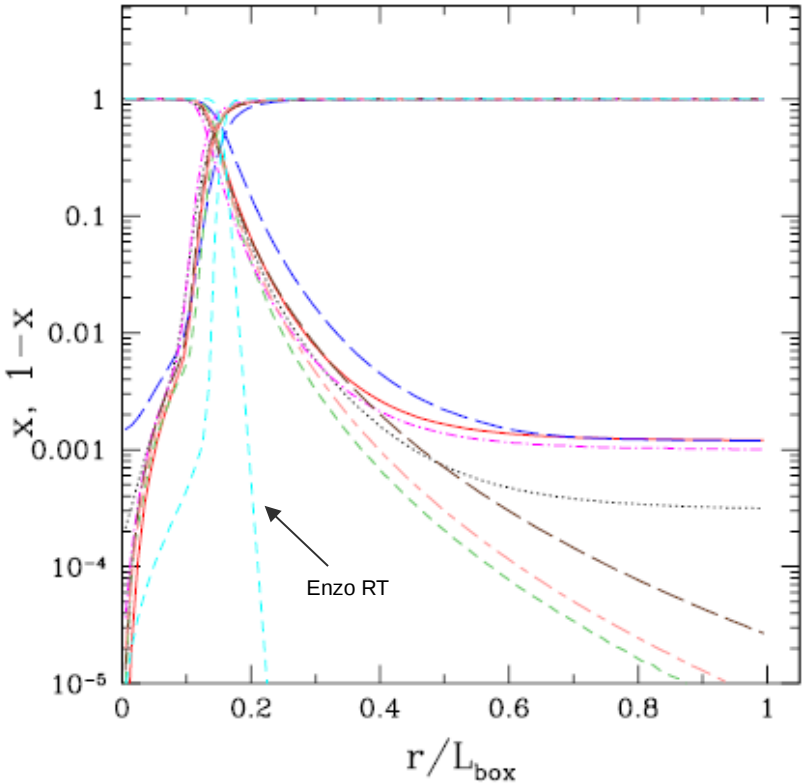
Numerical Methods for Stellar Feedback

- ❑ Implementation of the FERVENT ray tracing method for long characteristics (Baczynski et al 2015) coupled to the particles in Flash with a new ionization solver.
- ❑ Supernova kinetic and thermal energy injection using the method of Simpson et al (2015). This method adapts the kinetic energy injection fraction on the fly to the grid resolution.
- ❑ Winds kinetic energy injection modelled on the above SN method which conserves both momentum and energy of the wind.

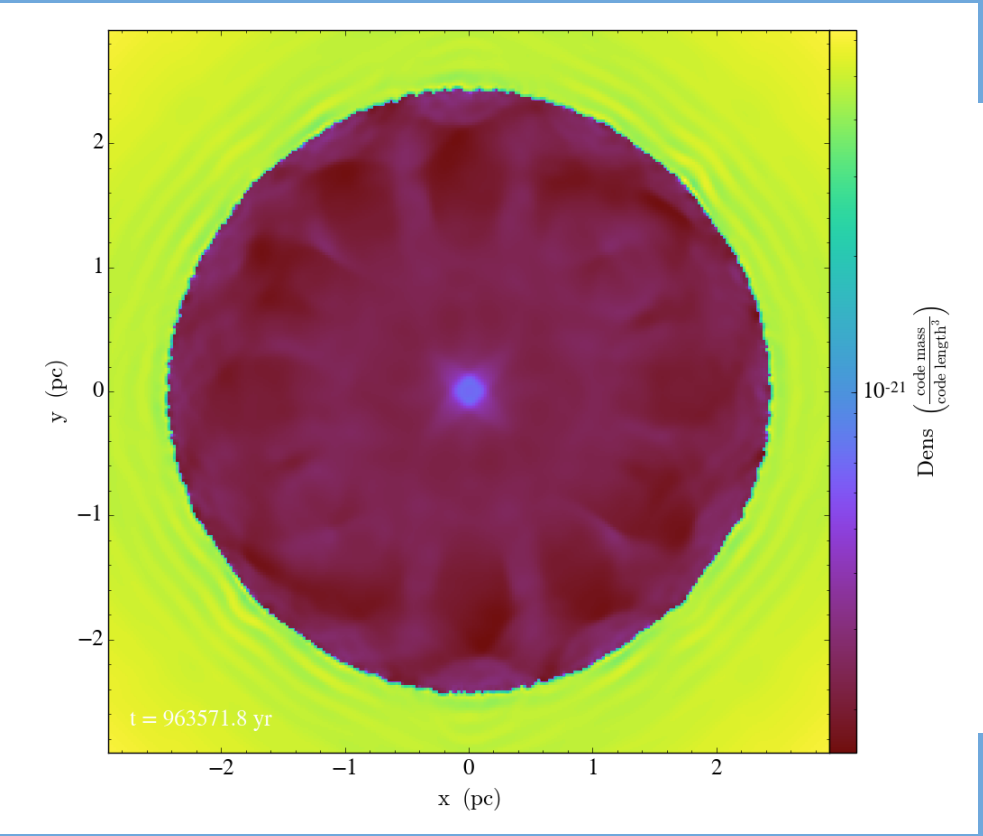

1e−27
1.70
1.68
1.66
1.64
1.62
1.60
1.58
Dens $\left(\frac{\text{code mass}}{\text{code length}^3}\right)$
0.600
0.200
t = 10.0 Myr
x (kpc)
y (kpc)

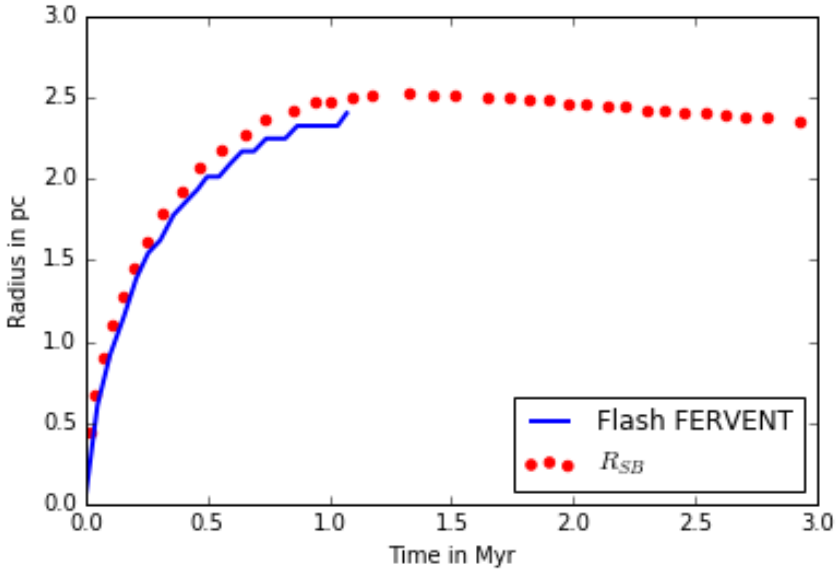

1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Inp (1)
t = 10.0 Myr
x (kpc)
y (kpc)



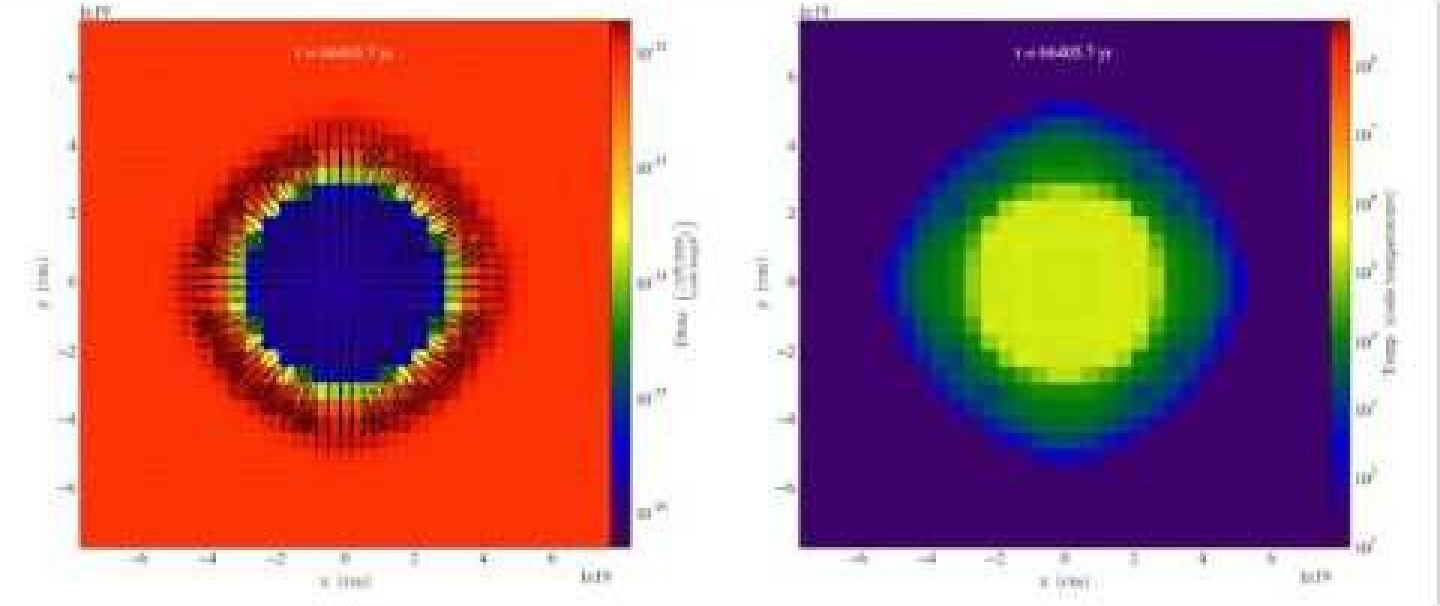


Iliev et al 2009, MNRAS 400, 3, 1283.

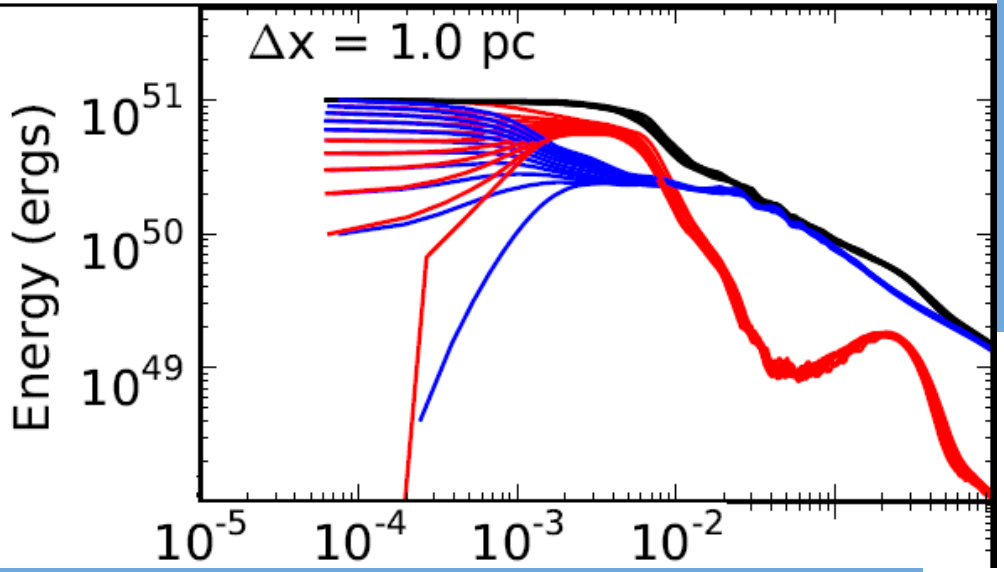


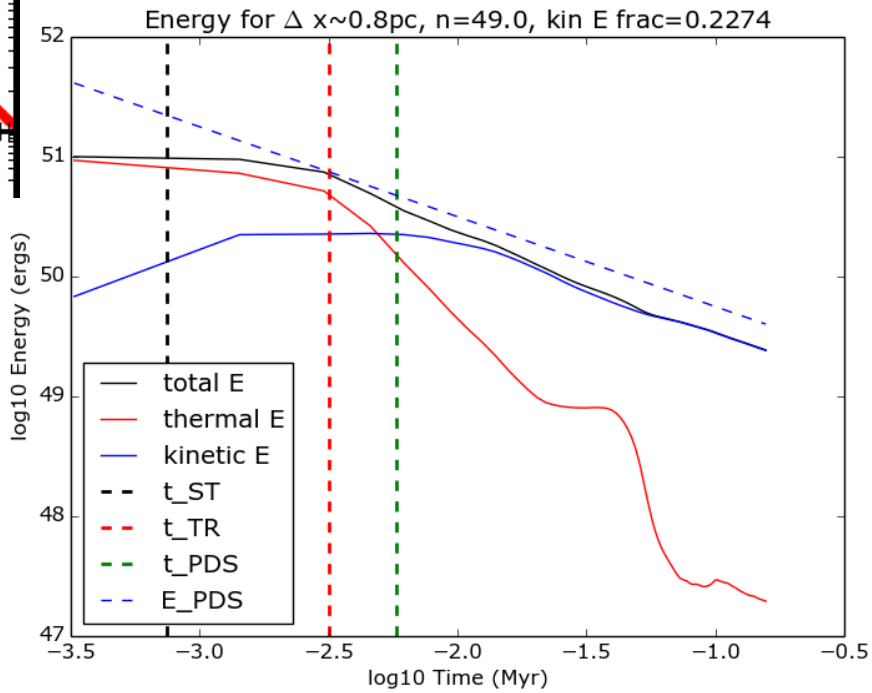


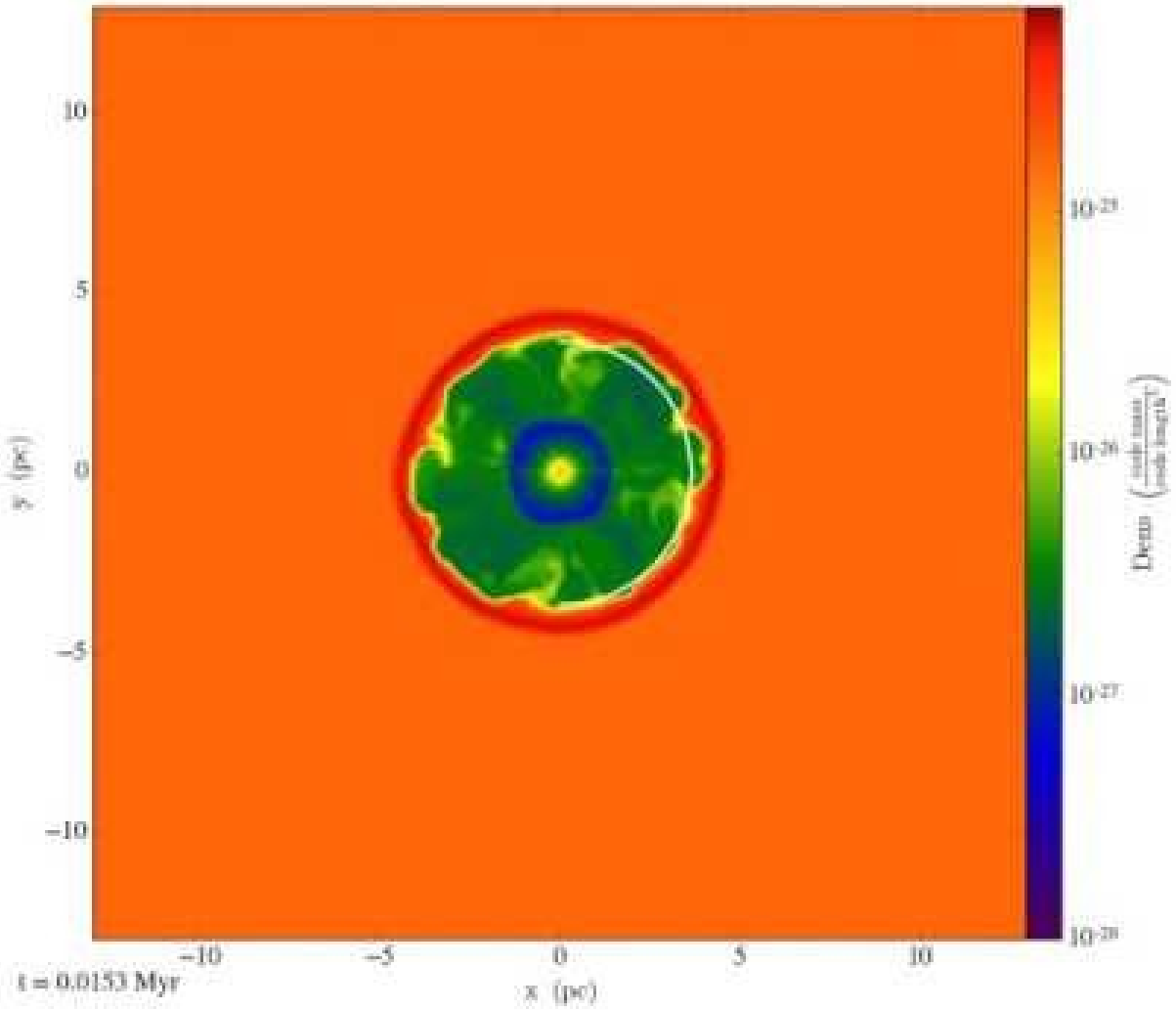
Bisbas et al 2015



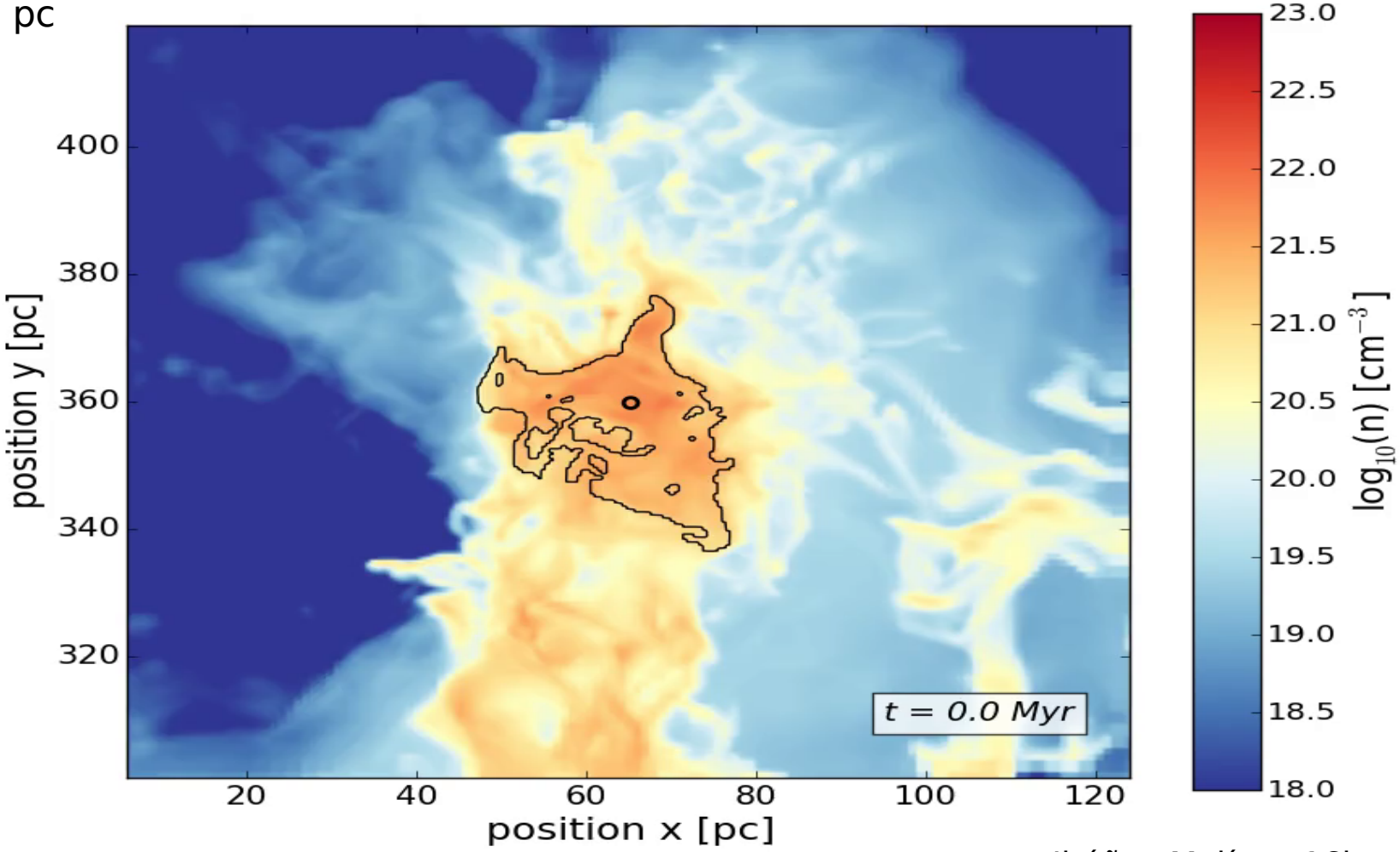
Simpson et al 2015, ApJ, 809, 69.



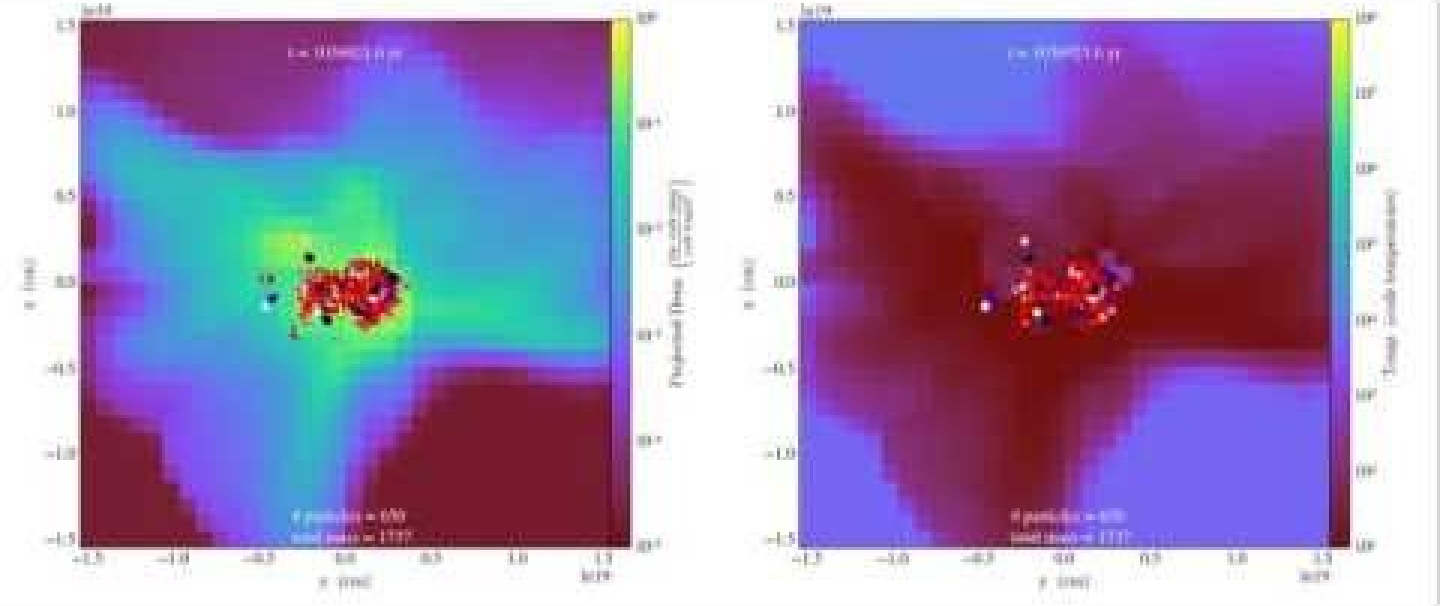



10
5
0
−5
−10
y (pc)
−10
−5
0
5
10
x (pc)
t = 0.0153 Myr
10^{-25}
10^{-26}
10^{-27}
10^{-28}

$\Delta x = 0.12$ pc



Ibáñez-Mejía + 16b



bridge_rad.py - /home/josh/amuse/src/amuse/community/flash - Geany

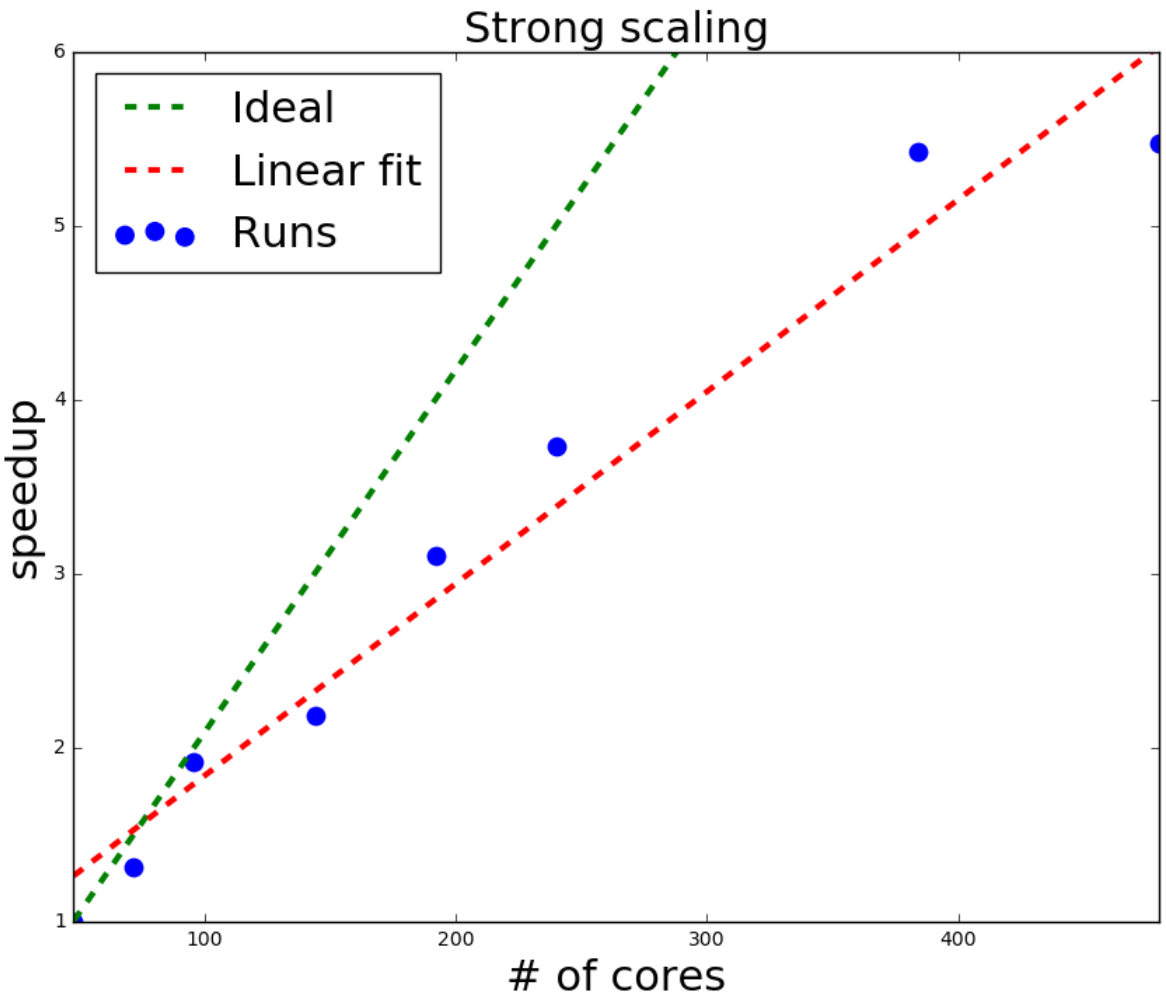
interface.F90 | interface.py | flash.par | paraplot.py | bridge_rad.py | Particles_sink...eateAccrete.F90 | dens_removal.F90 | RadHeat.F90 | bridge_rad_wSN.py | sampleIMF.F90

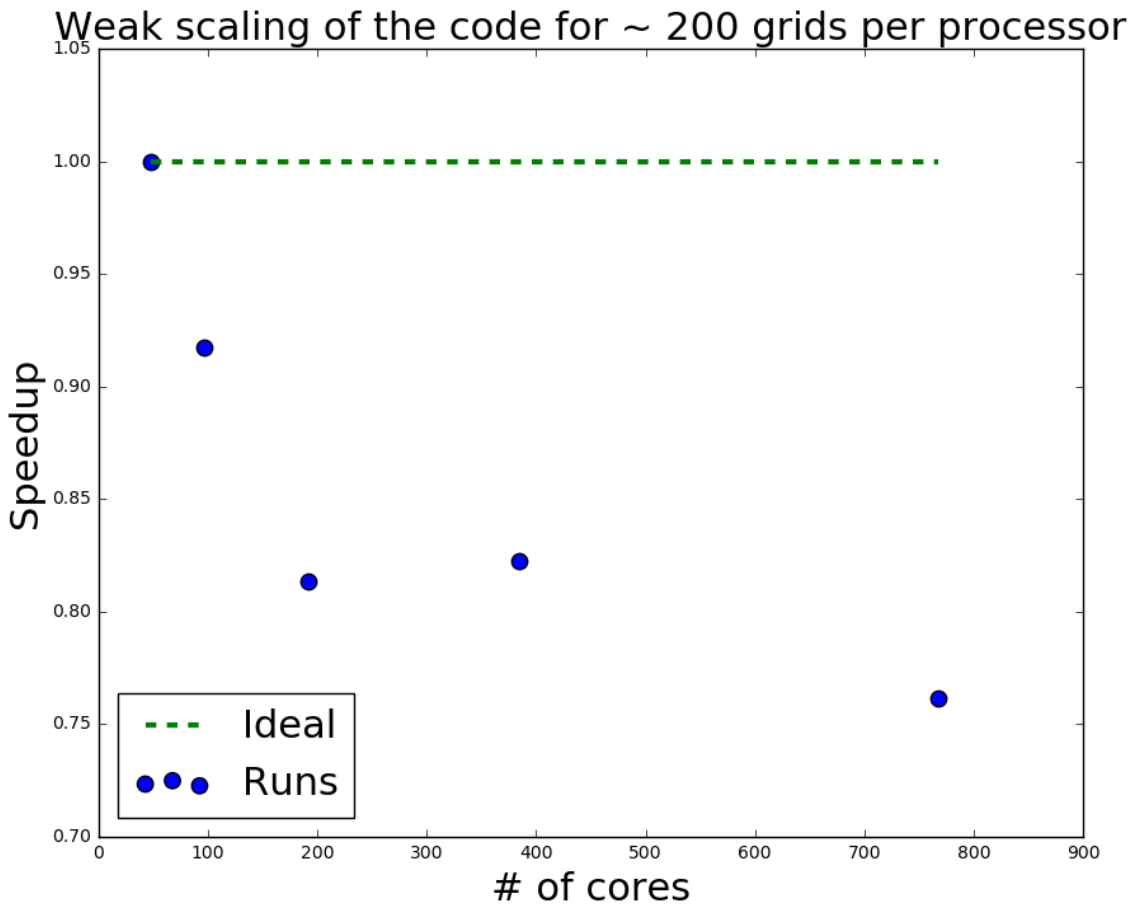
```
            # energy into the grid

                    if (with_sn):

                        if (do_sn_once):

                            sn=True
                            inj_x = -6.8130232380422451e+17 | units.cm
                            inj_y = -2.920997414750314e+18 | units.cm
                            inj_z = -5.8048724029988956e+18 | units.cm
                            tot_e = 1e51 | units.erg
                            fracKin = -1.0 #0.22734 #1.0
                            inj_mass = (25.*1.989e33) | units.g

                            if (sn):
                                #hydro.particles_sort()
                                dt = hydro.energy_injection(tot_e, fracKin, inj_mass, inj_x, inj_y, inj_z)
                                print "Timestep after SN is =", dt
                                t = t_old + dt
                                print "Now evolving until t =", t
                                do_sn_once = False
                                hydro.IO_out('pltpart')

                        else:

                            #for part in range(num_particles):

                            #print "Stellar type =", stars.stellar_type[part]

                            if (13 <= stars.stellar_type[part].value_in(units.stellar_type) <= 15):

                                print "Going supernova at", stars.x[part], stars.y[part], stars.z[part]

                                inj_x = stars.x[part]
                                inj_y = stars.y[part]
                                inj_z = stars.z[part]
                                tot_e = 1e51 | units.erg
```

Status | Compiler | Messages

08:56:56: Setting Spaces indentation mode for /home/josh/amuse/src/amuse/community/flash/src/flash4.2.2-stars_and_stuff/source/Particles/ParticlesMain/active/Sink/Couple_AMUSE/wind/inject_direct.F90.
08:56:56: File /home/josh/amuse/src/amuse/community/flash/src/fl...in/active/Sink/Couple_AMUSE/wind/inject_direct.F90 opened(11).
08:56:56: Setting Spaces indentation mode for /home/josh/amuse/src/amuse/community/flash/src/flash4.2.2-stars_and_stuff/source/Particles/ParticlesMain/active/Sink/Couple_AMUSE/wind/Particles_advance.F90.
08:56:56: File /home/josh/amuse/src/amuse/community/flash/src/fl...ctive/Sink/Couple_AMUSE/wind/Particles_advance.F90 opened(12).
08:56:56: Setting Spaces indentation mode for /home/josh/amuse/src/amuse/community/flash/src/flash4.2.2-stars_and_stuff/source/Particles/ParticlesMain/active/Sink/Couple_AMUSE/wind/Particles_sinkWind.F90.
08:56:56: File /home/josh/amuse/src/amuse/community/flash/src/fl...tive/Sink/Couple_AMUSE/wind/Particles_sinkWind.F90 opened(13).
08:58:00: File /home/josh/amuse/src/amuse/community/flash/paraplot.py saved.

line: 1073 / 1652 col: 67 sel: 0 INS SP mode: Unix (LF) encoding: UTF-8 filetype: Python scope: unknown

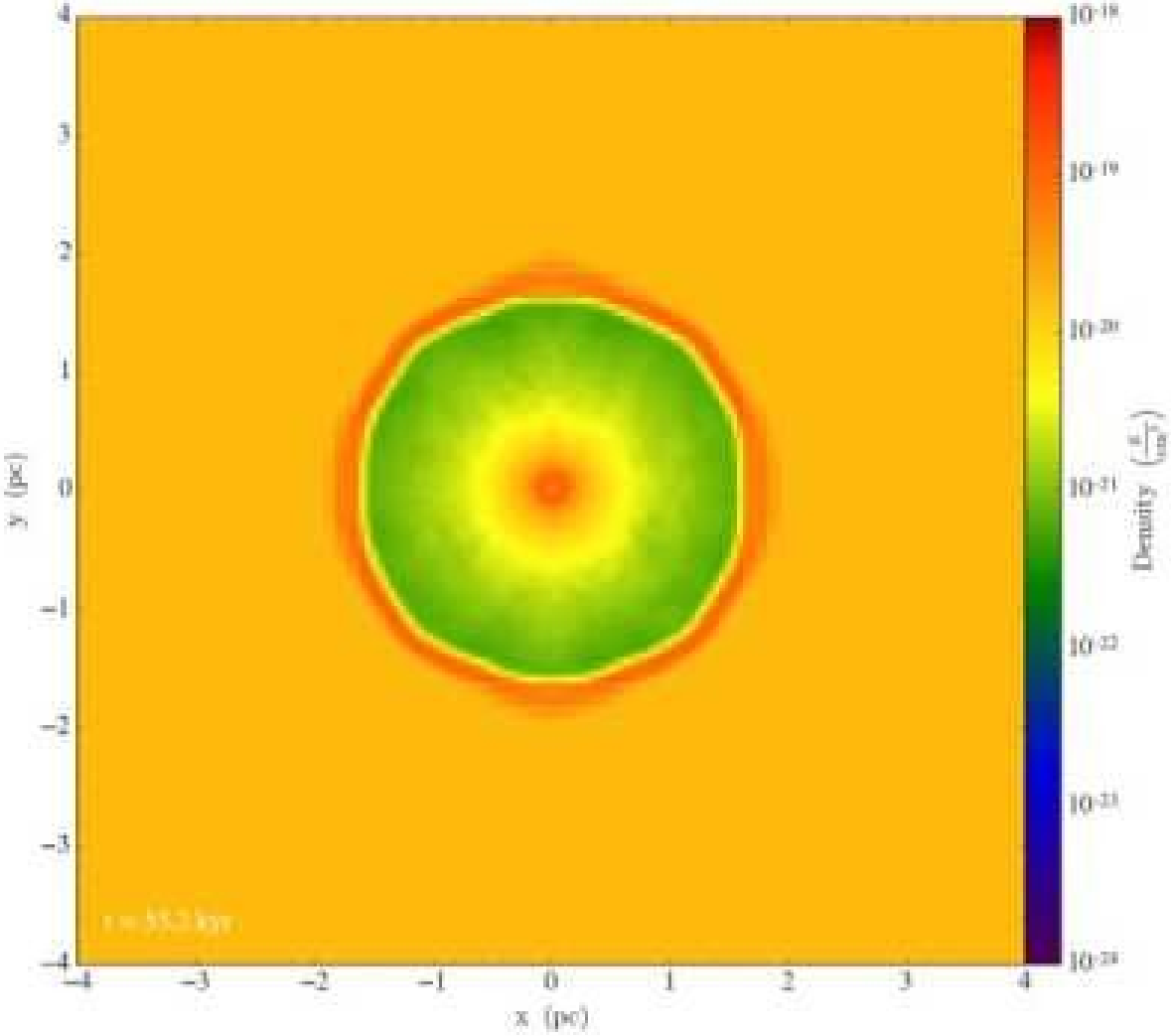

Strong scaling
Ideal
Linear fit
Runs
speedup
# of cores
1
2
3
4
5
6
100
200
300
400

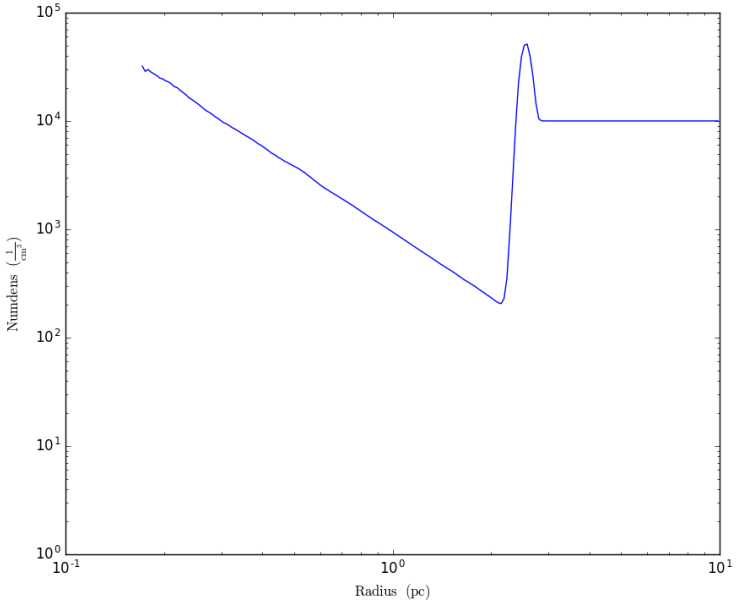

Weak scaling of the code for ~ 200 grids per processor
Speedup
# of cores
Ideal
Runs
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
0
100
200
300
400
500
600
700
800
900

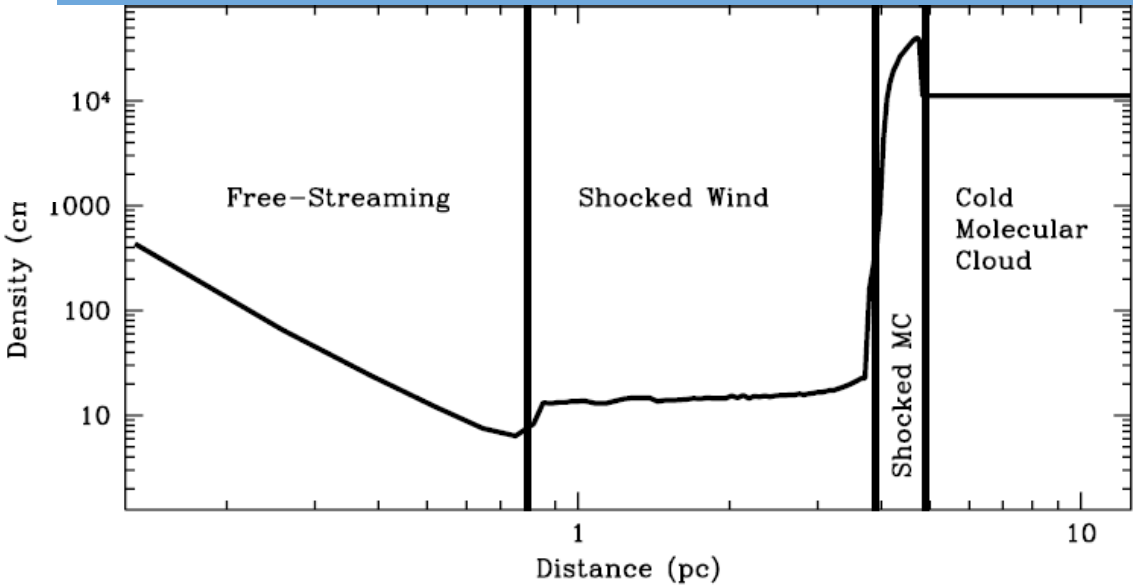
Physical Assumptions for RT Method

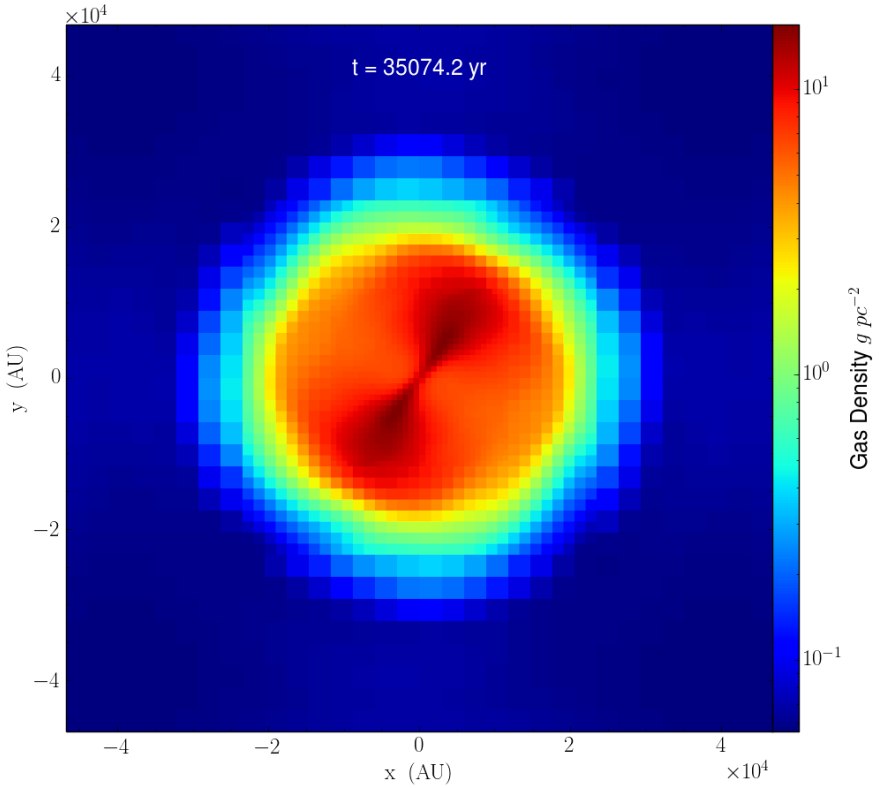
- Only the ionization of hydrogen is tracked, although radiation momentum pressure from photons is included.
- Dust pressure is not currently implemented, but is planned.
- IR pressure is ignored as we assume IR escapes immediately (single scatter approximation).
- Currently we use only one radiation bin (for the average ionizing photon energy). More could be used, but at increased cost (of extra rays).

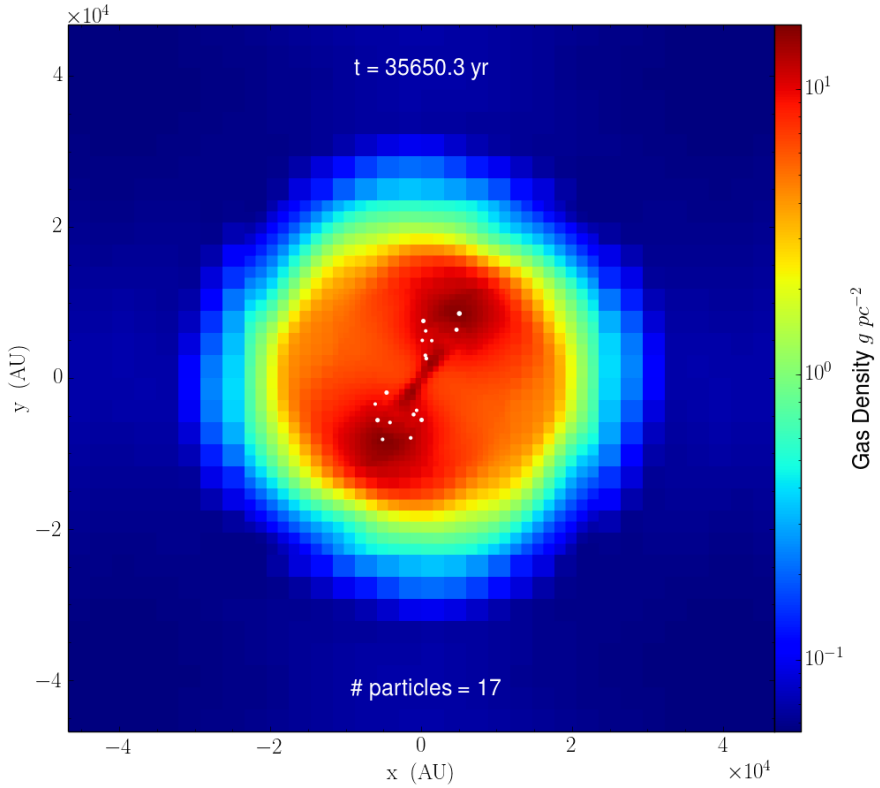
PE on dust	H2 dissociation	H ionization
<5.6 - 11.2 eV>	<11.2 - 13.6 eV>	<13.6+>

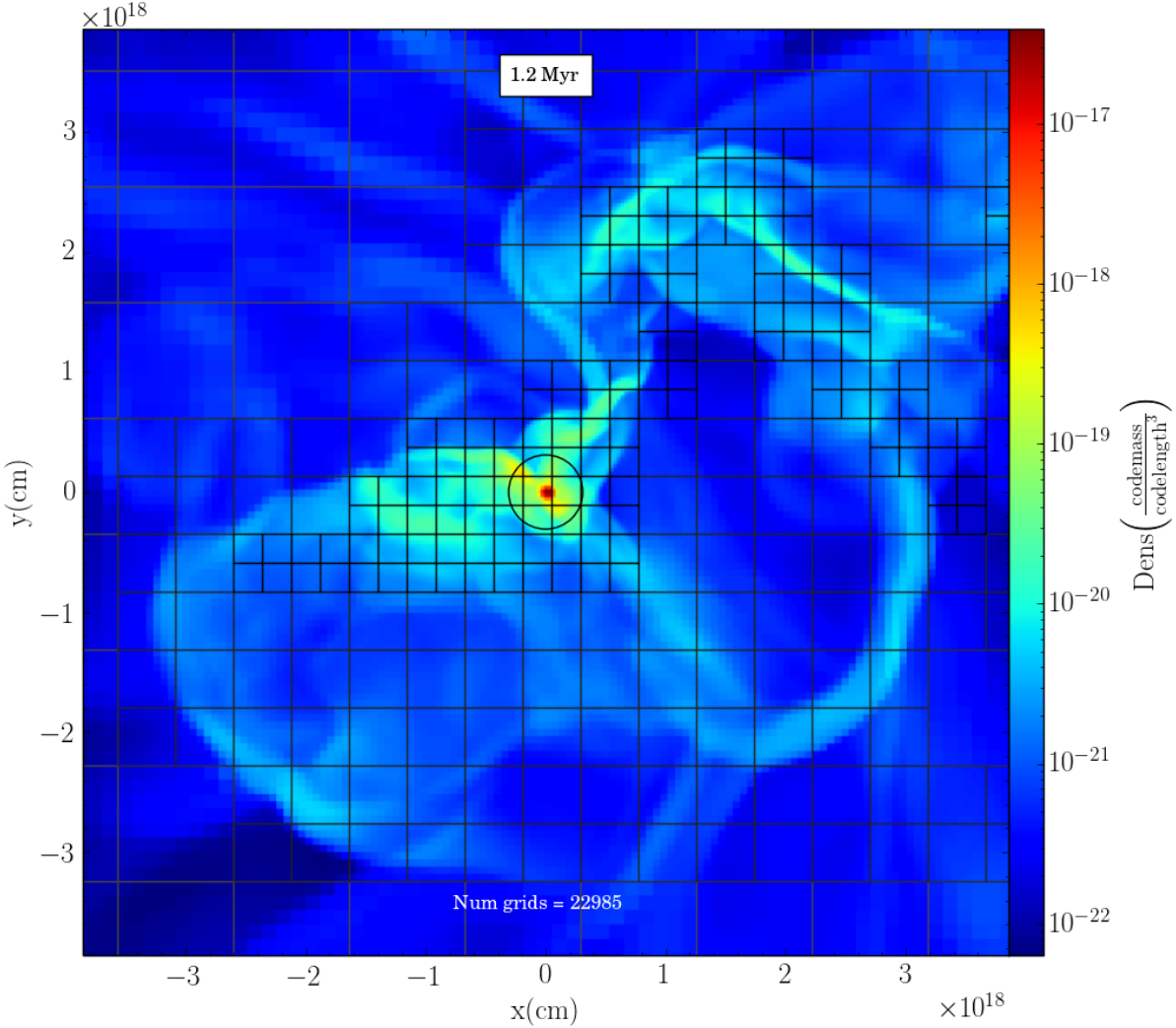

y (pc)
x (pc)
Density
4
3
2
1
0
−1
−2
−3
−4
−4
−3
−2
−1
0
1
2
3
4
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}


Numdens $(\frac{1}{cm^3})$
Radius (pc)


Free−Streaming
Shocked Wind
Shocked MC
Cold
Molecular
Cloud
Density (cm
Distance (pc)

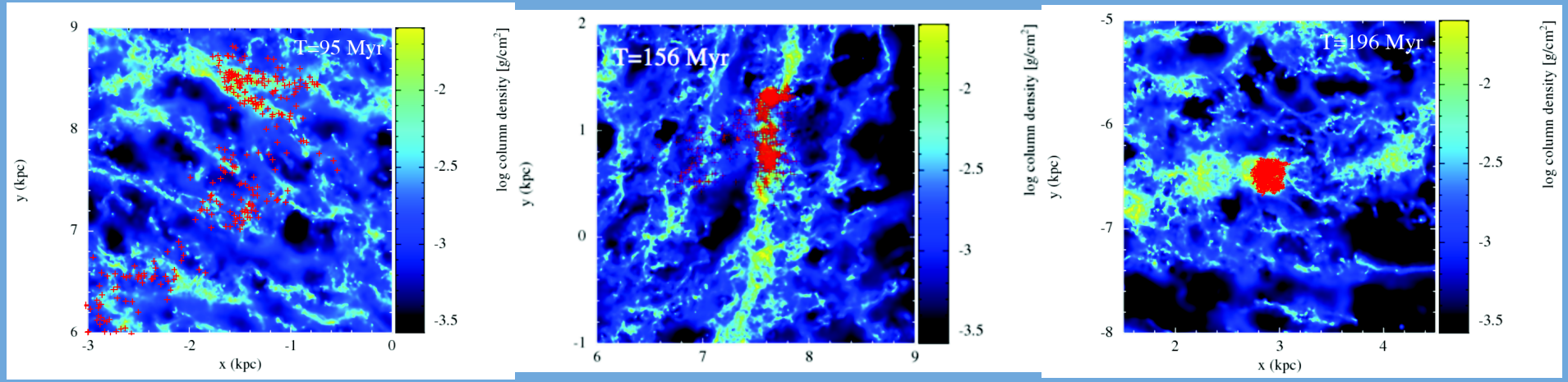

t = 35074.2 yr
×10^4
4
2
0
−2
−4
y (AU)
−4
−2
0
2
4
x (AU)
×10^4
10^1
10^0
10^−1
Gas Density g pc^−2


t = 35650.3 yr
# particles = 17
×10^4
4
2
0
−2
−4
y (AU)
−4
−2
0
2
4
x (AU)
×10^4
10^1
10^0
10^−1
Gas Density g pc^−2


1.2 Myr
Num grids = 22985
$\times 10^{18}$
3
2
1
0
−1
−2
−3
y(cm)
−3
−2
−1
0
1
2
3
x(cm)
$\times 10^{18}$
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
$\mathrm{Dens}\left(\frac{\mathrm{codemass}}{\mathrm{codelength}^3}\right)$

Science!

Hierarchical Cluster Formation



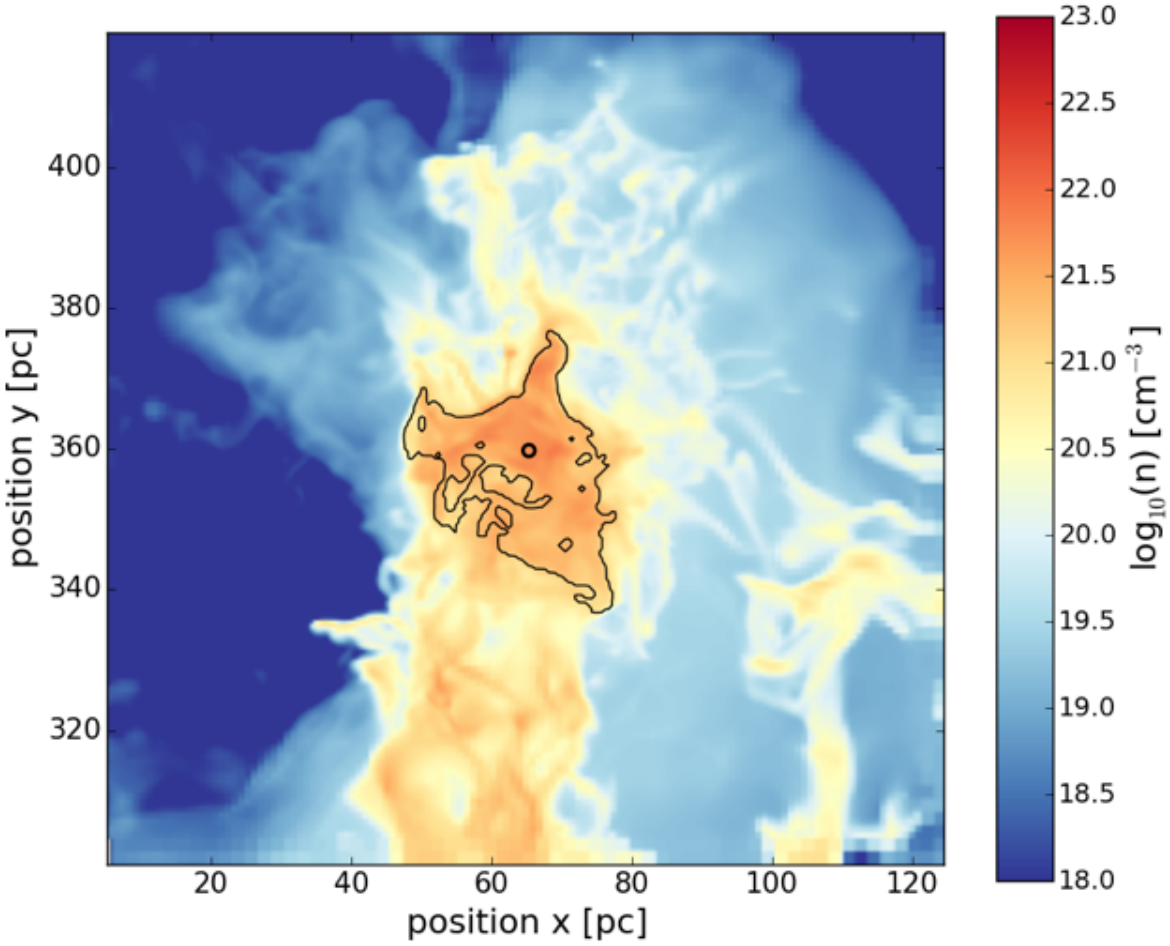
Dobbs et al 2016 , arXiv:1609.00209v1

Initial Conditions

10^3 - 10^6 solar masses

Formed from SN driven turbulence (which is still ongoing during our formation).

Magnetic fields present

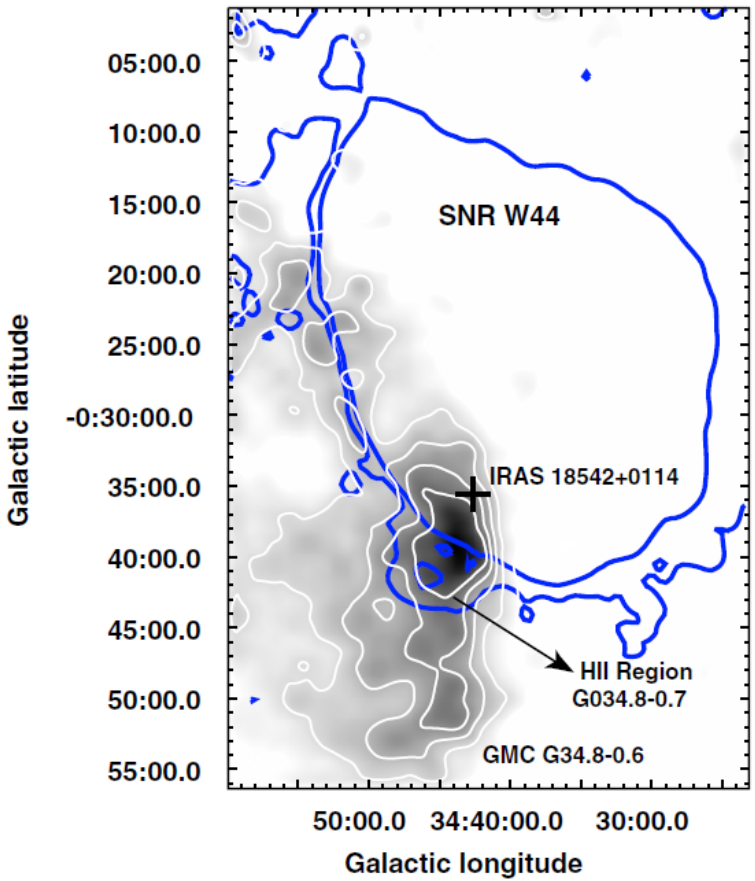


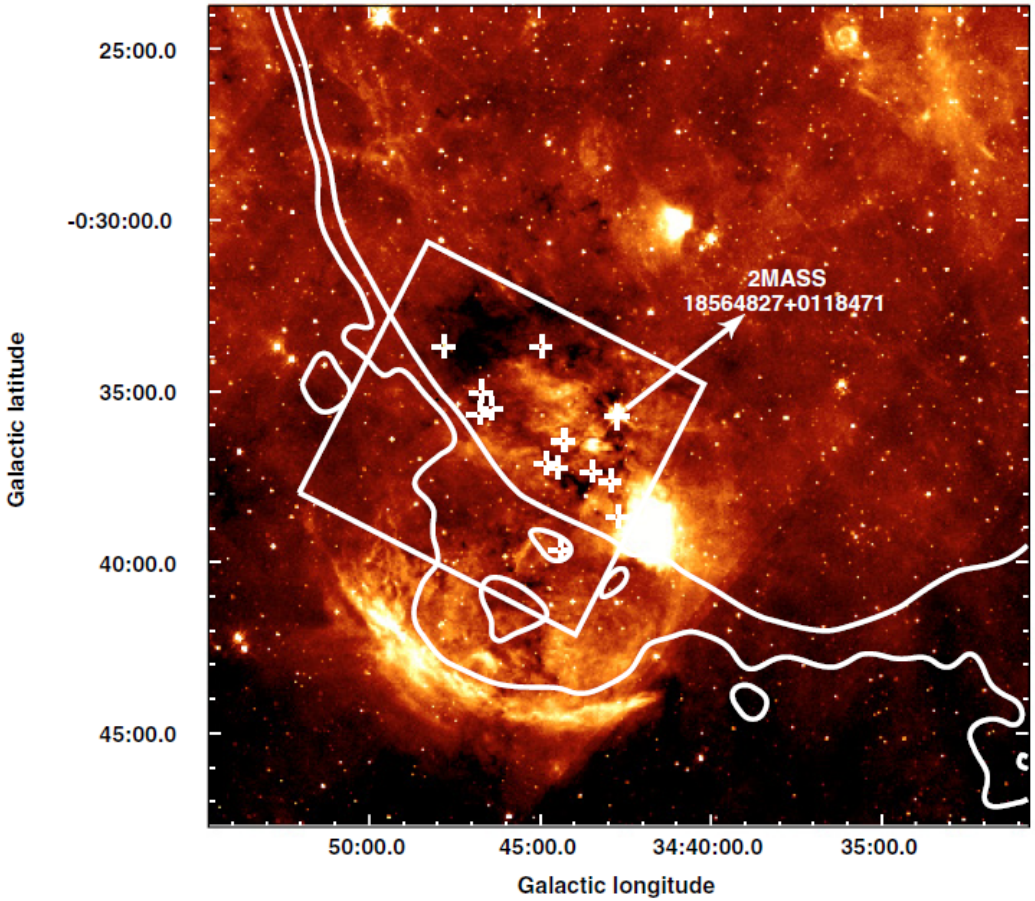
Science!

Feedback triggered star formation.
SNR44
18h 56m 48
+01 18’ 45”

ESA/PACS/SPIRE/Quang Nguyen Luong & Frederique Motte, HOBYS Key Program consortium (far-infrared).

ESA/XMM-Newton(x-ray).





Paron et al 2009, A&A, 498, 445.