Relativistic Explosions: AMR Hydrodynamics

1. RAM Code
2. Collapsars/GRB Central Engine
3. GRB Afterglow Blastwave

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astro-ph/0505481

GRB/SN dynamics

- Relativity (SR & GR)
- Range of length scales ↔ resolution
- Rotation
- 2D/3D
- Magnetic Fields
- Nuclear Physics
- Neutrinos
- EOS

RAM

- Special Relativistic
- Adaptive Mesh Refinement (AMR)
- Self Gravity w/ Pseudo GR potential
- Nuclear Reactions w/ photodisint.
- Neutrino Cooling (optically thin)
- EOS
- Based on ASCI/FLASH code

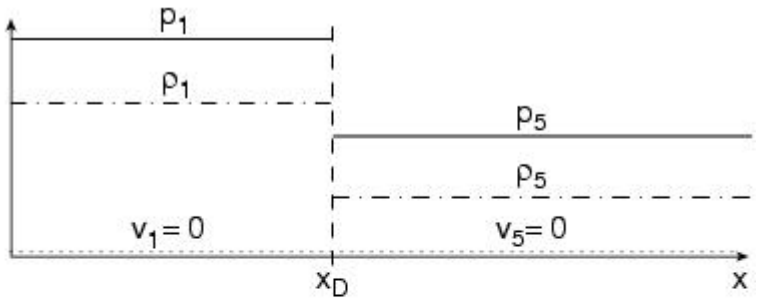
Zhang & MacFadyen (2005)

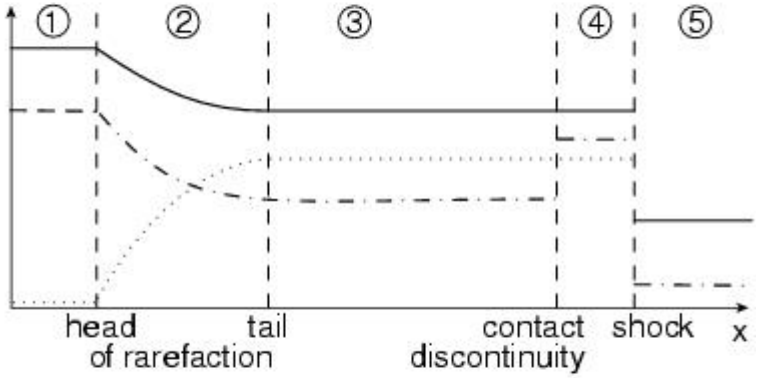
Method

- WENO 5th order (Jiang & Shu ,1996)
- SRHD characteristic stucture (Donat et al 1998)
- Runge-Kutta 3rd order (Shu & Osher 1988)
- Also PLM reconstruction w/ minmod (Kurganov & Tadmor, 2000)
- F-WENO, F-PLM, U-PPM, U-PLM
- AMR from PARAMESH/FLASH2.3

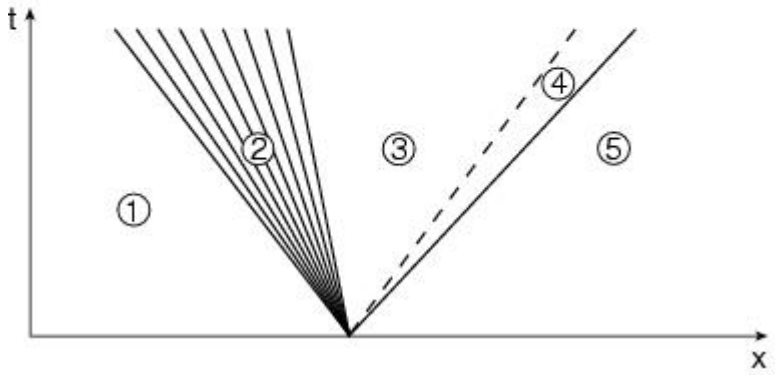
Riemann Problem

"Shock Tube"

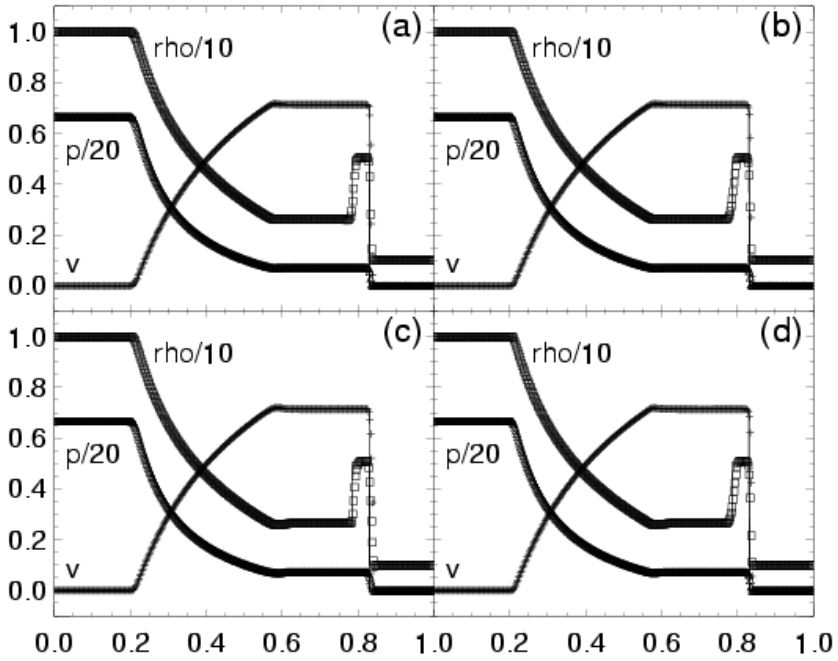


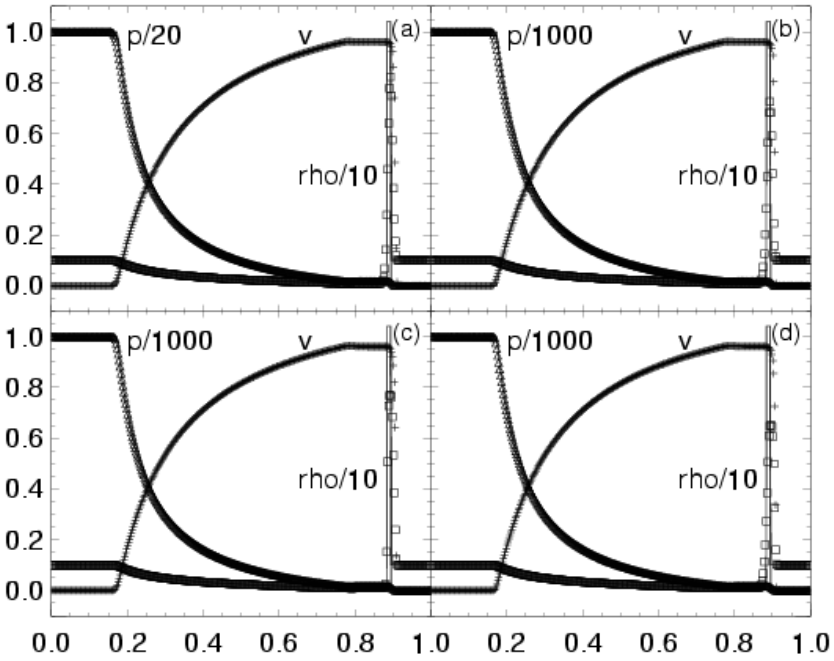


Breakup of two constant states when barrier is removed



Shock Tube Test





F-WENO	F-PLM
U-PPM	U-PLM

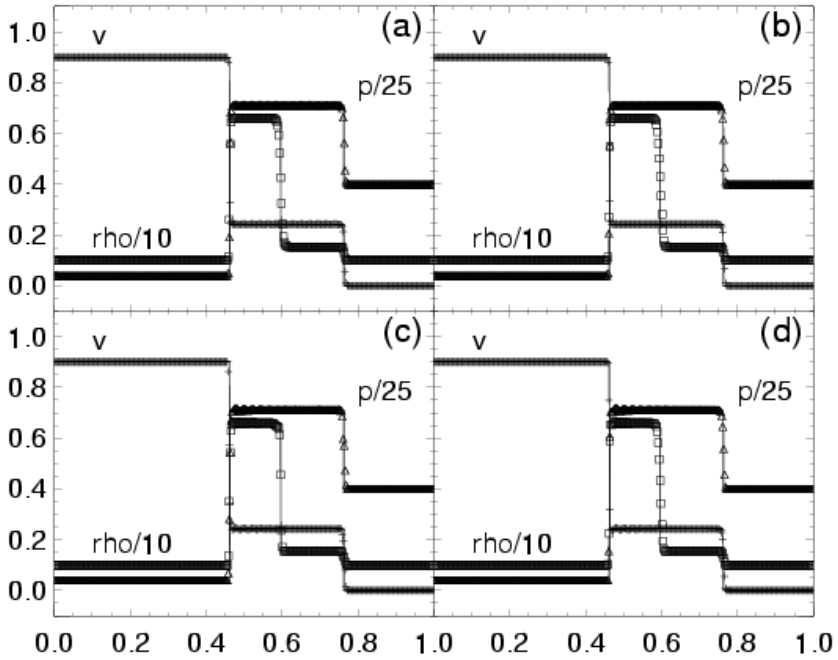
1D Tests

Compression =

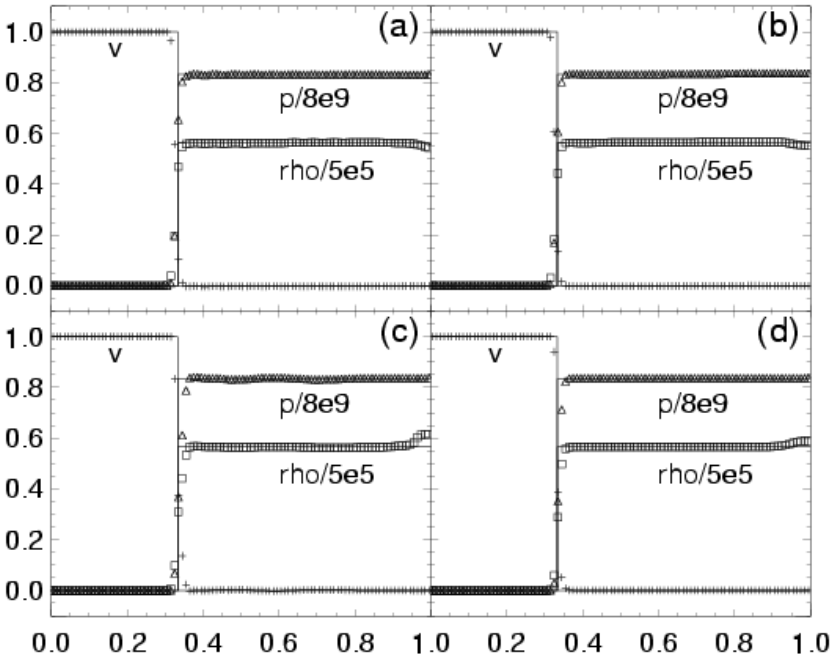
(Γ+1)/(Γ-1) + Γ/(Γ-1)e, e≈W-1

Density error:

a)3.9% b)2.4% c) 8.9% d) 4.3%



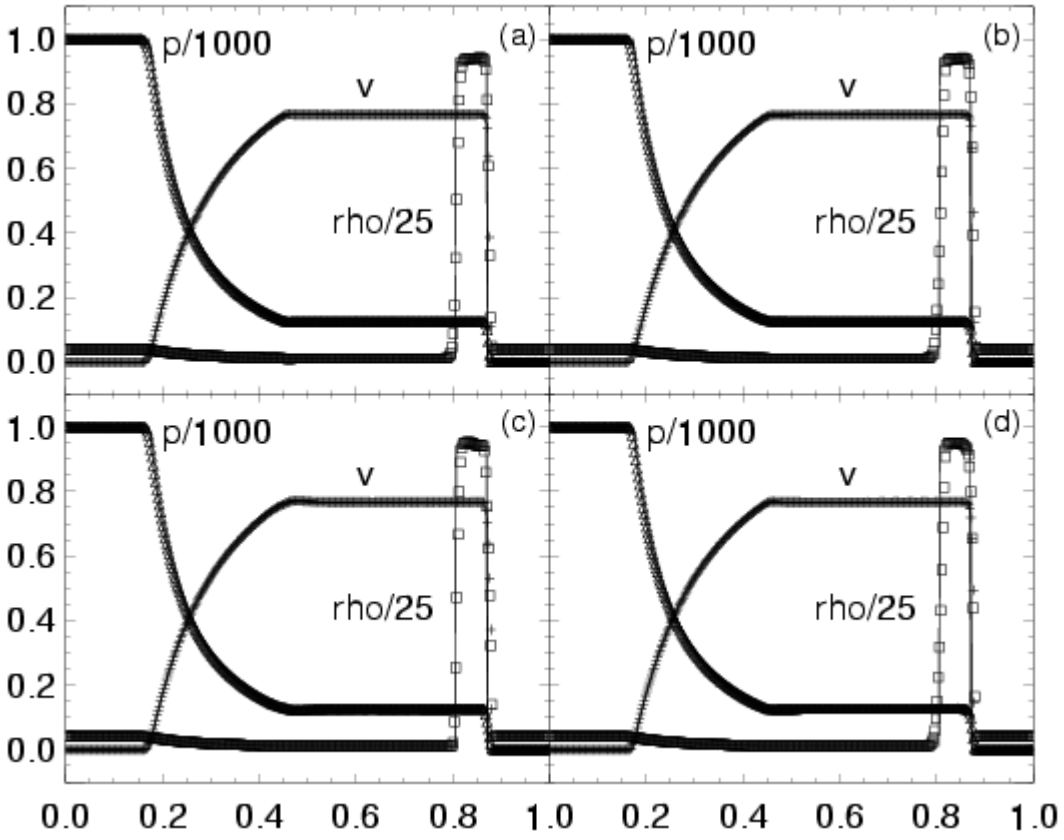
400 zones t=0.4



100 zones W=70,711
V=0.999999999c

Riemann w/ Transverse Velocity 1

Left State: Vy=0 Right State: Vy = 0.99c

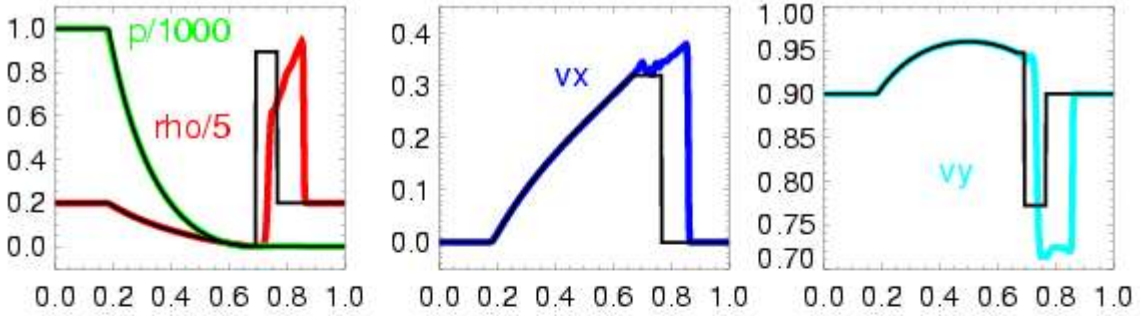


400 zones

Riemann w/ Transverse Velocity 2

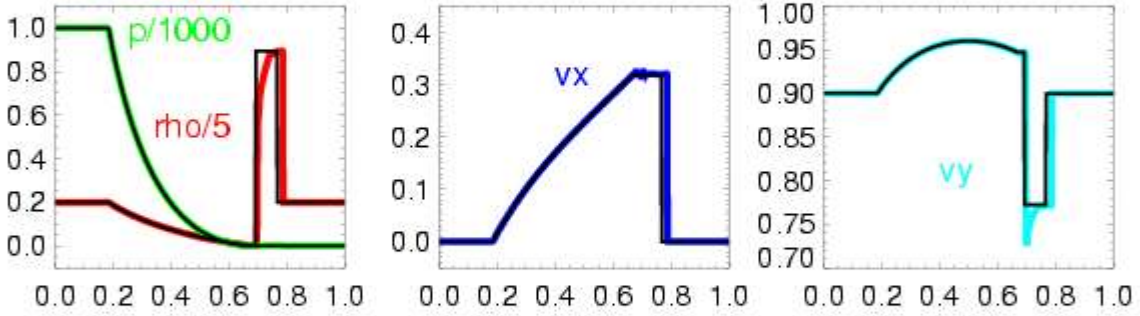
Left State: Vy=0.99c Right State: Vy = 0.99c

1 level



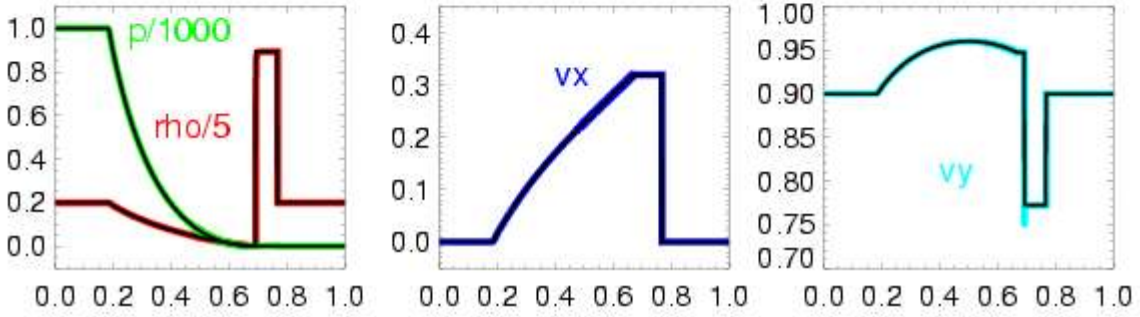
400 zones

4 levels



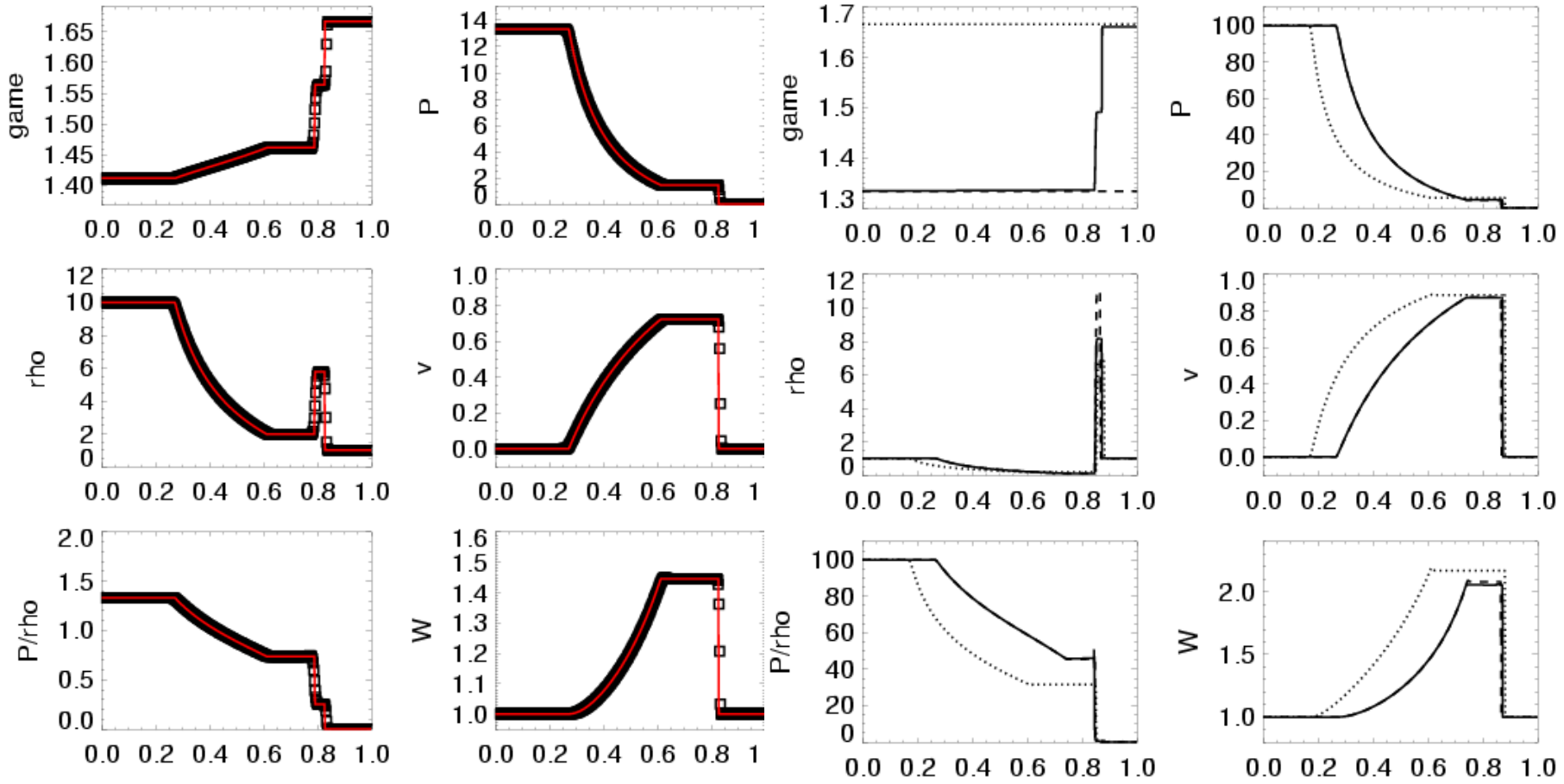
3200 zones

8 levels



51200 zones

TM EOS



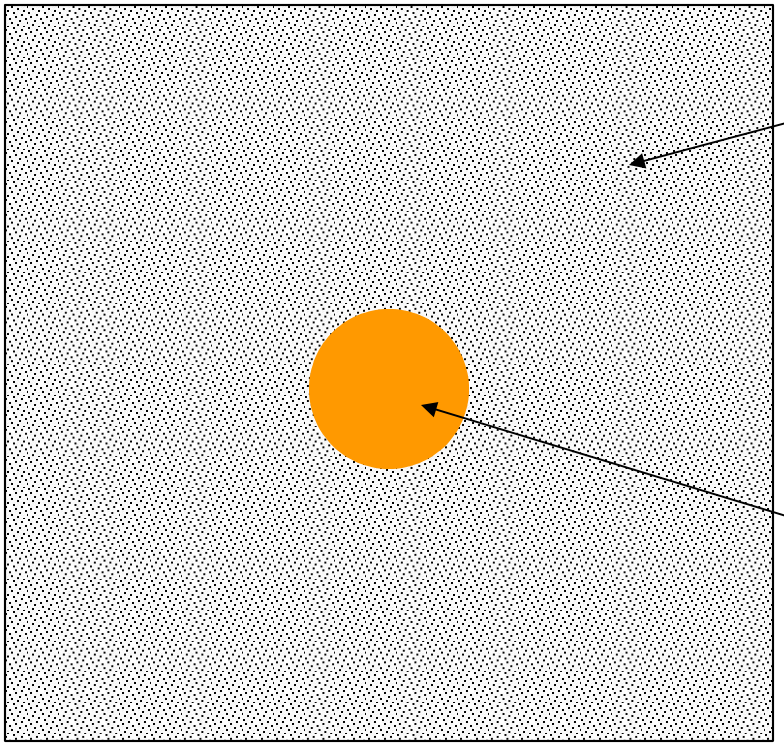
$e=0.5((9\theta^2+4)^{0.5}+3\theta-2)$

$\theta \equiv P/\rho$

Ultrarelativistic $\Gamma=4/3$ Newtonian $\Gamma=5/3$

$e=\theta/(\Gamma-1)$

Relativistic Blastwave



n = 1 cm^-3

10^52 erg

eta = E/m = 100

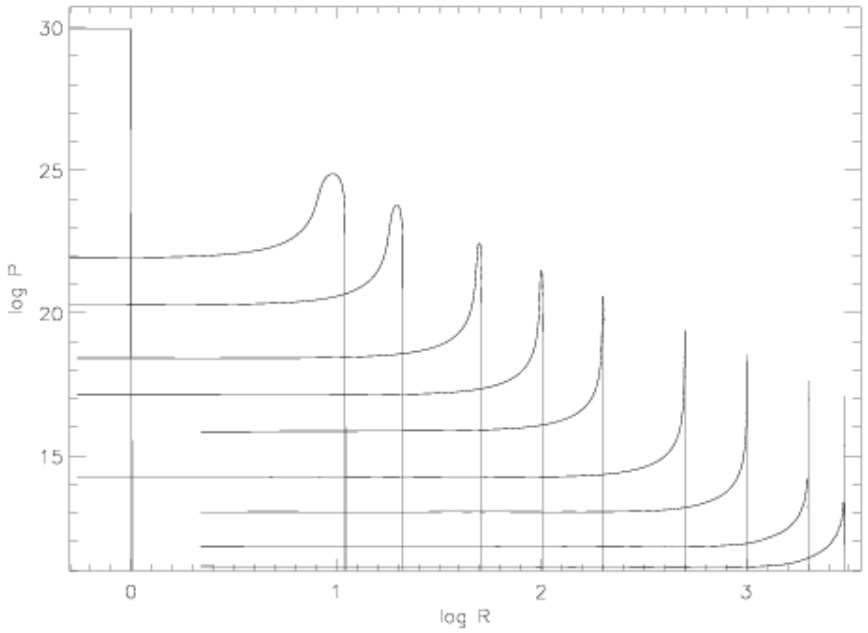
R = 1 = 3x10^10cm

$\Gamma >> 1$

Blandford & McKee (1976)

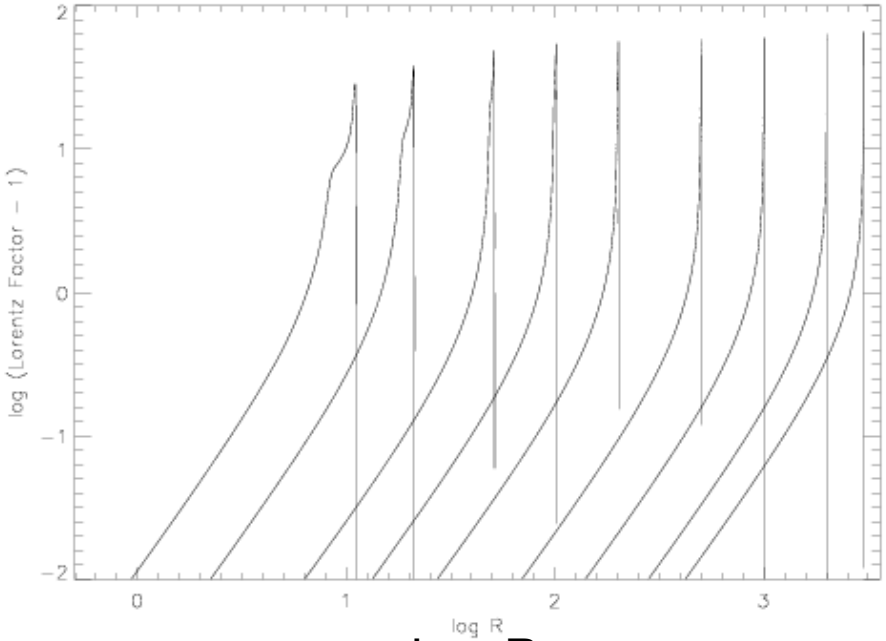
Fireball Acceleration

pressure



Log R

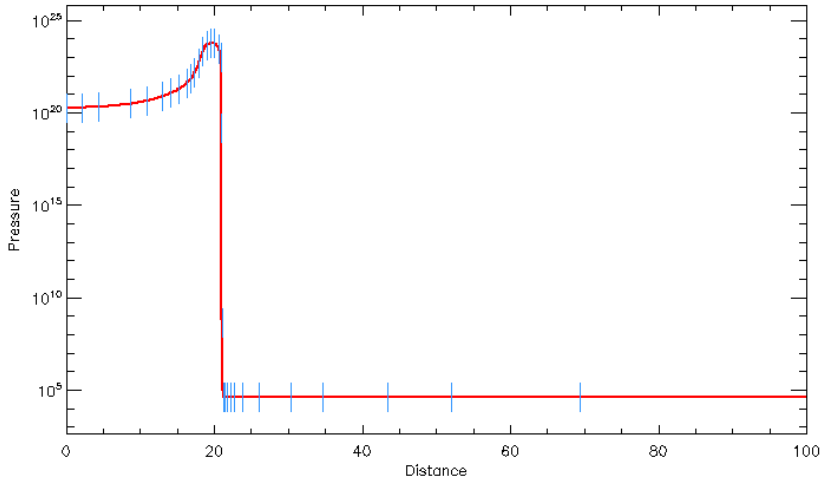
Γ-1



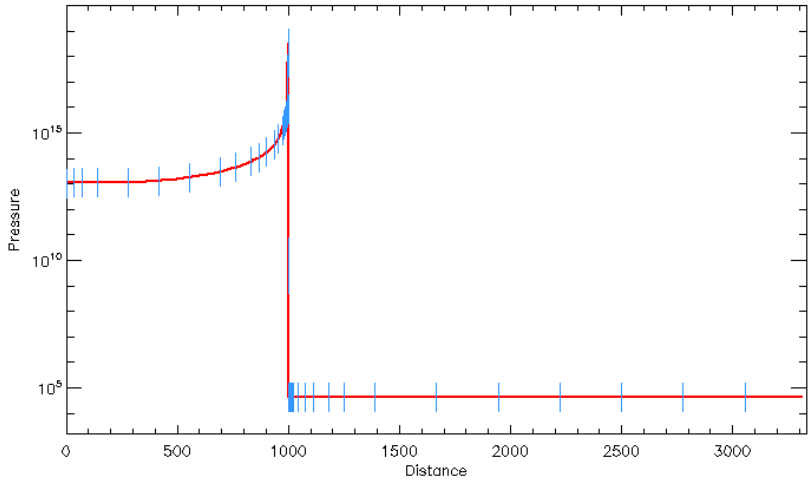
Log R

MacFadyen & Zhang (2005), Kobayashi, Piran & Sari (1999)

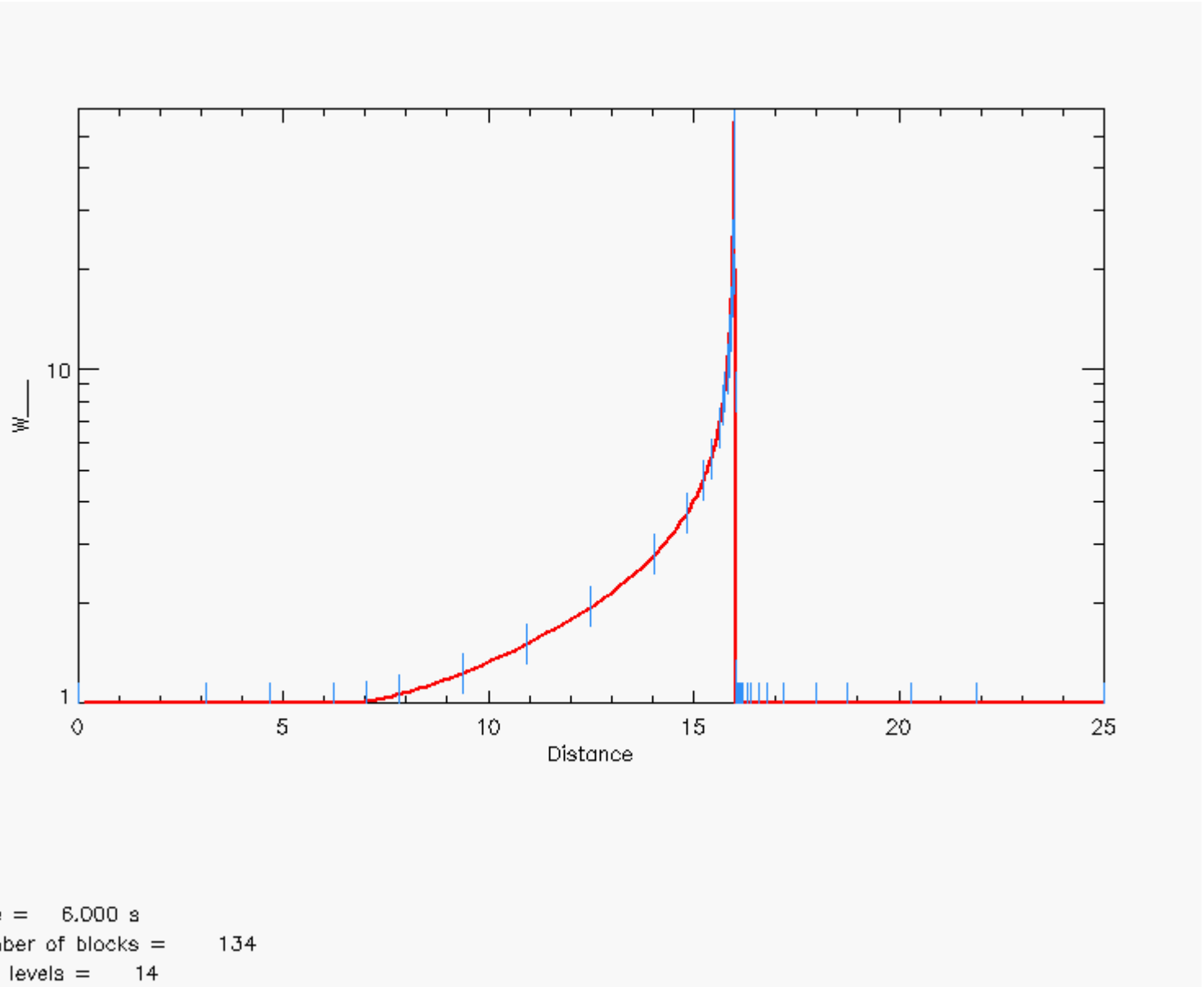
Required Resolution ~ $1/\Gamma^2$



time = 20.004 s
number of blocks = 82
AMR levels = 12



time = ******* s
number of blocks = 108
AMR levels = 12


10
1
W
0
5
10
15
20
25
Distance
time = 6.000 s
number of blocks = 134
AMR levels = 14

Deceleration

- Relativistic $E \sim \Gamma^2 \rho R^3$ $\underline{\Gamma \sim R^{-3/2}}$

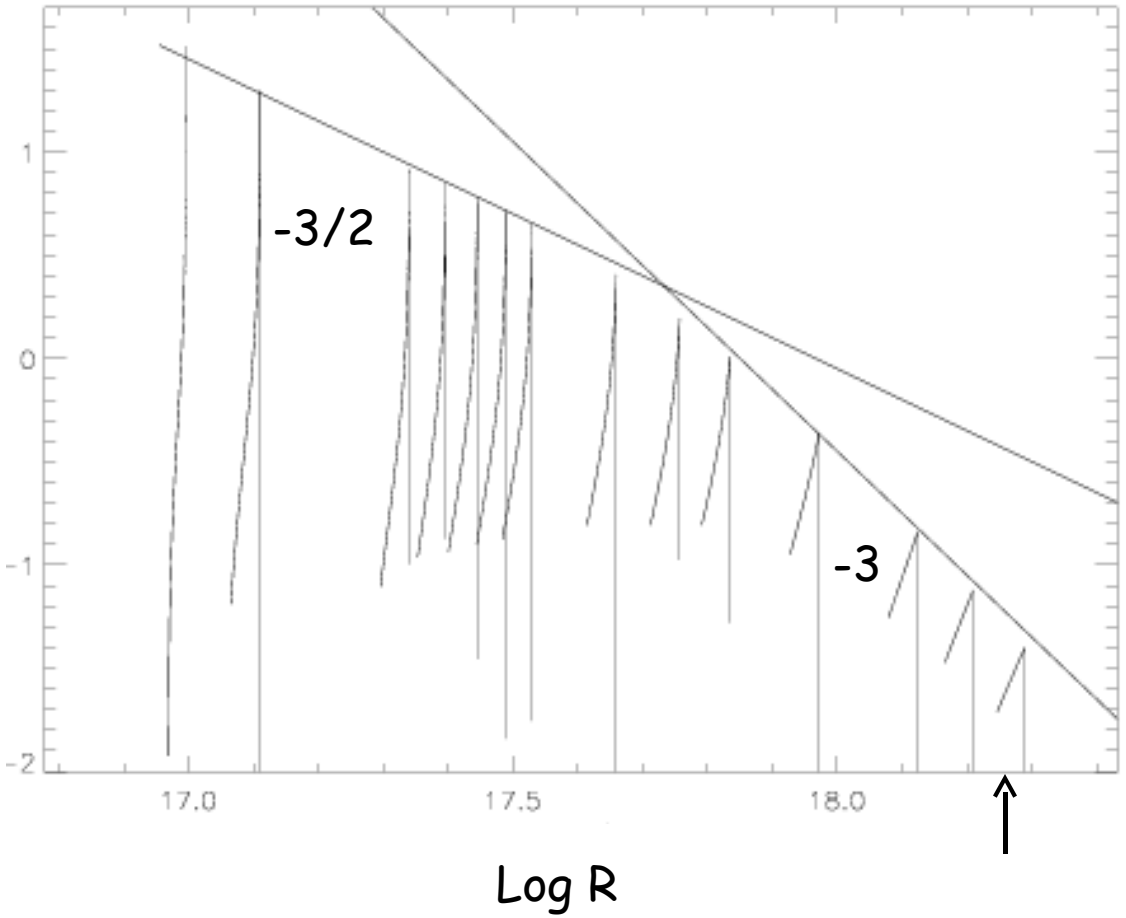
- Jet spreading $\Gamma \sim 1/\theta_{jet}$

- Newtonian $E \sim v^2 \rho R^3$ $v^2 \sim \underline{\Gamma^{-1} \sim R^{-3}}$

Transition to Non-relativistic

E = 10^52 erg

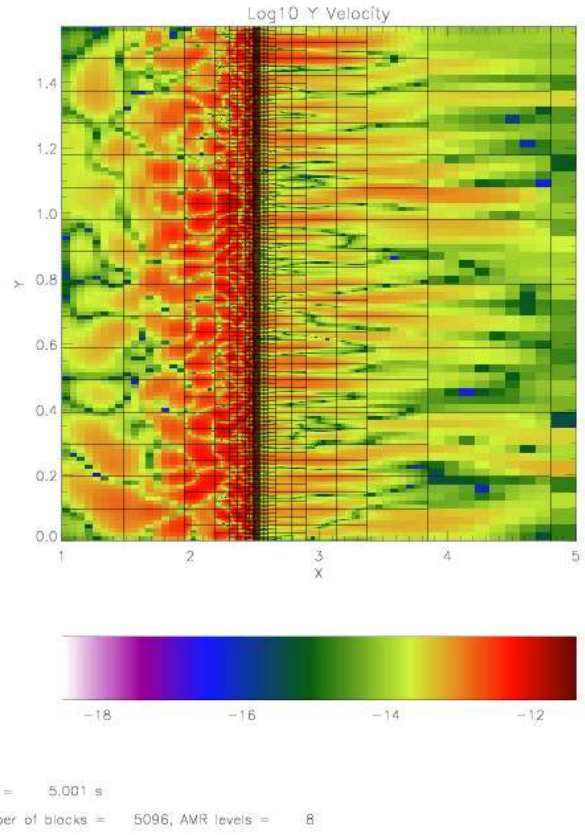
n = 1 cm^-3

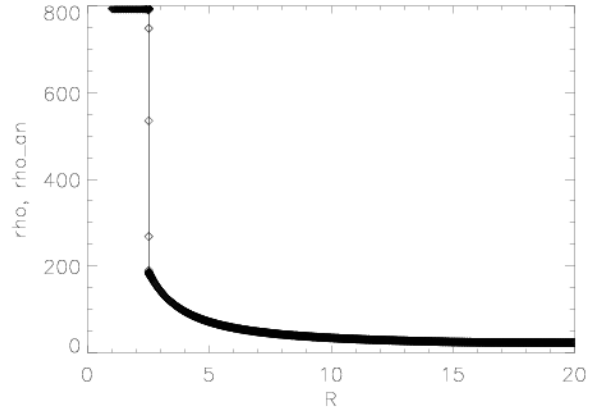


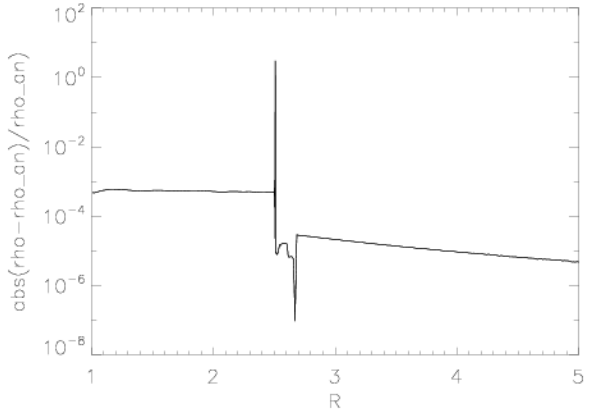
Relativistic Thin Shells

- Resolution required $\Delta R/R \sim 1/\Gamma^2$
- $R_0 \sim 5e16$ cm, $R_{max} \sim 5e18$ cm
- $\Gamma=20$, $\Delta R \approx R/25\Gamma^2 \sim 1e13$ cm
- $\Delta R/ R_{max} \sim 1e\text{-}6 \rightarrow (1e6)^n$ zones
- Need AMR ~15 levels or more
- For $\Gamma=50$ 18 levels
- Parallel supercomputing (days-weeks on 128 processors)

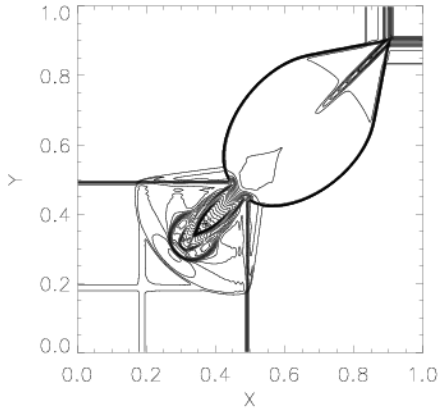
Spherical Implosion (Noh)

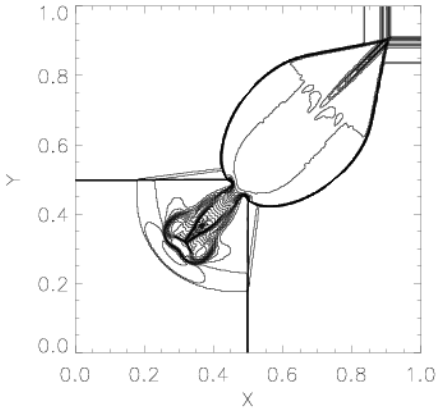


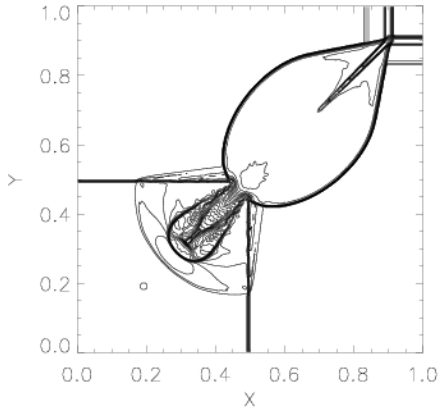


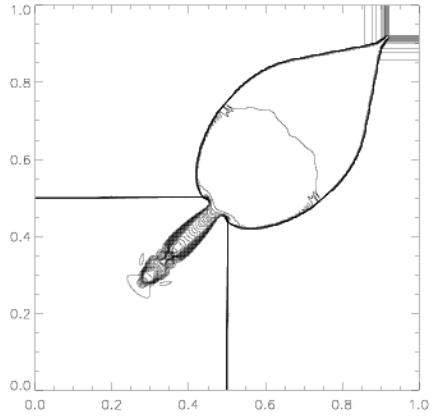


2D Riemann Problem

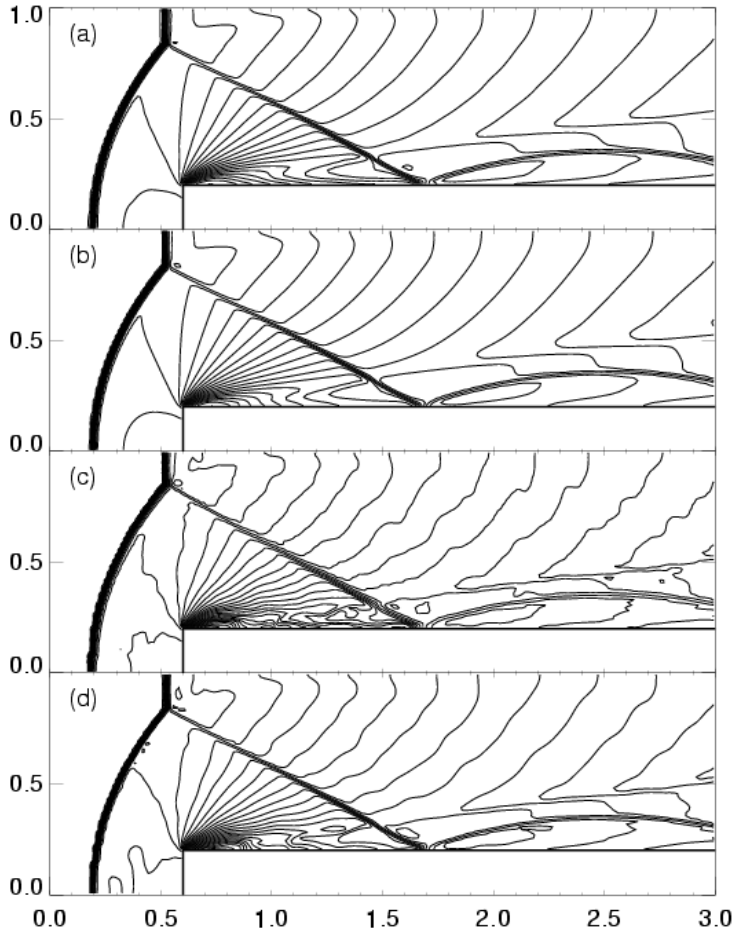


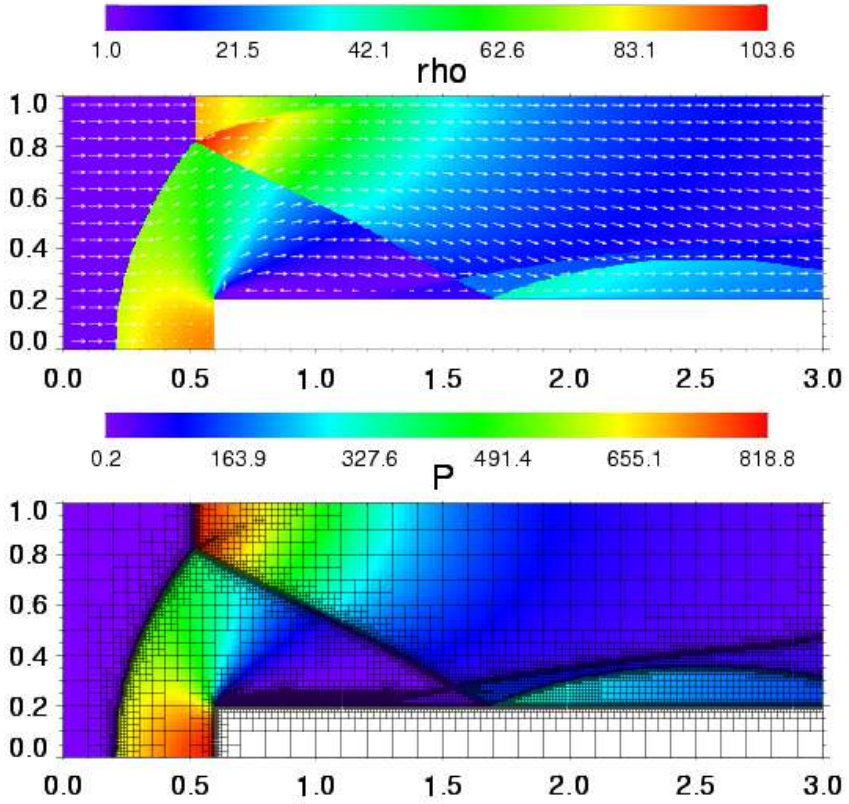




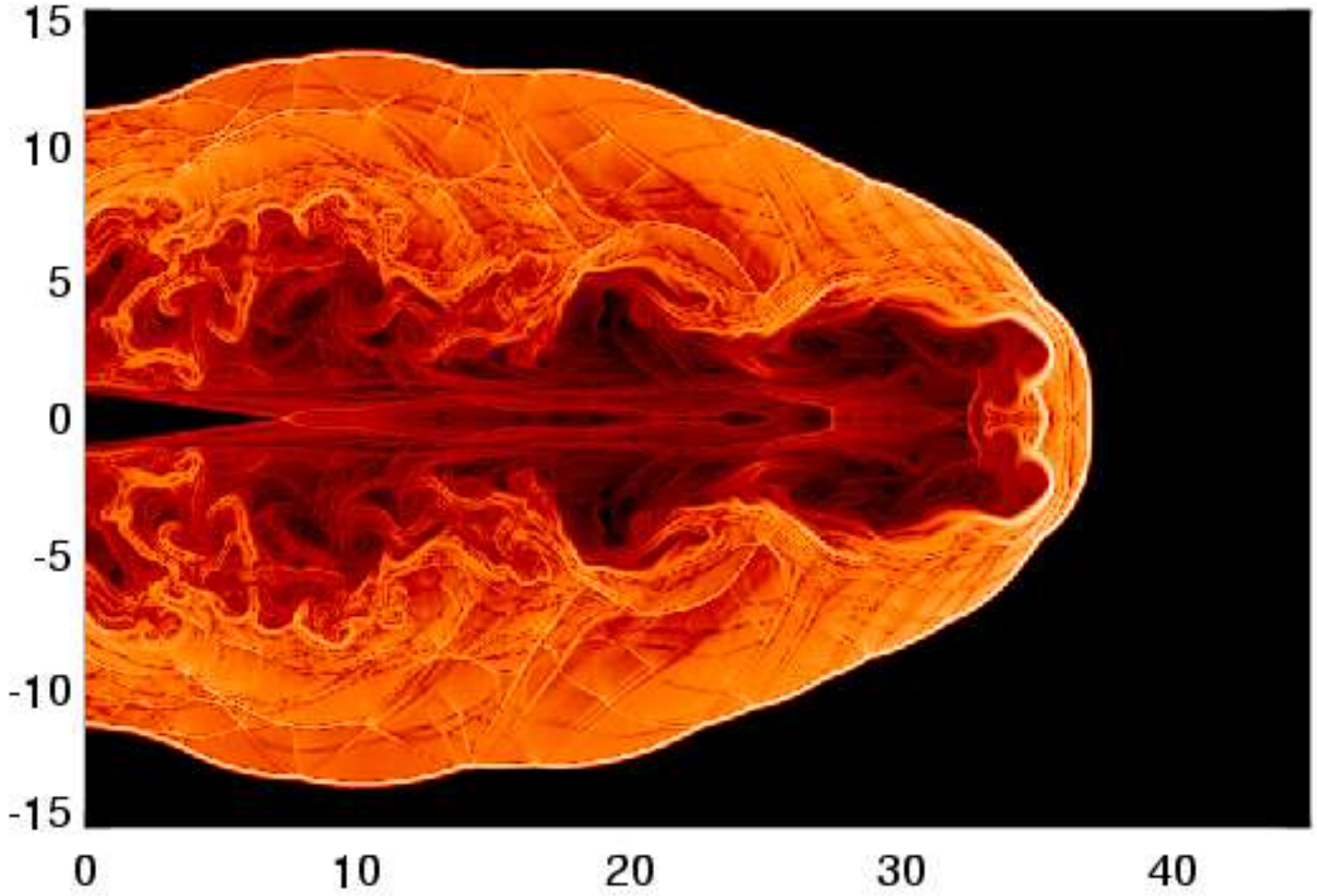


Emery Step


(a)
(b)
(c)
(d)
1.0
0.5
0.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0

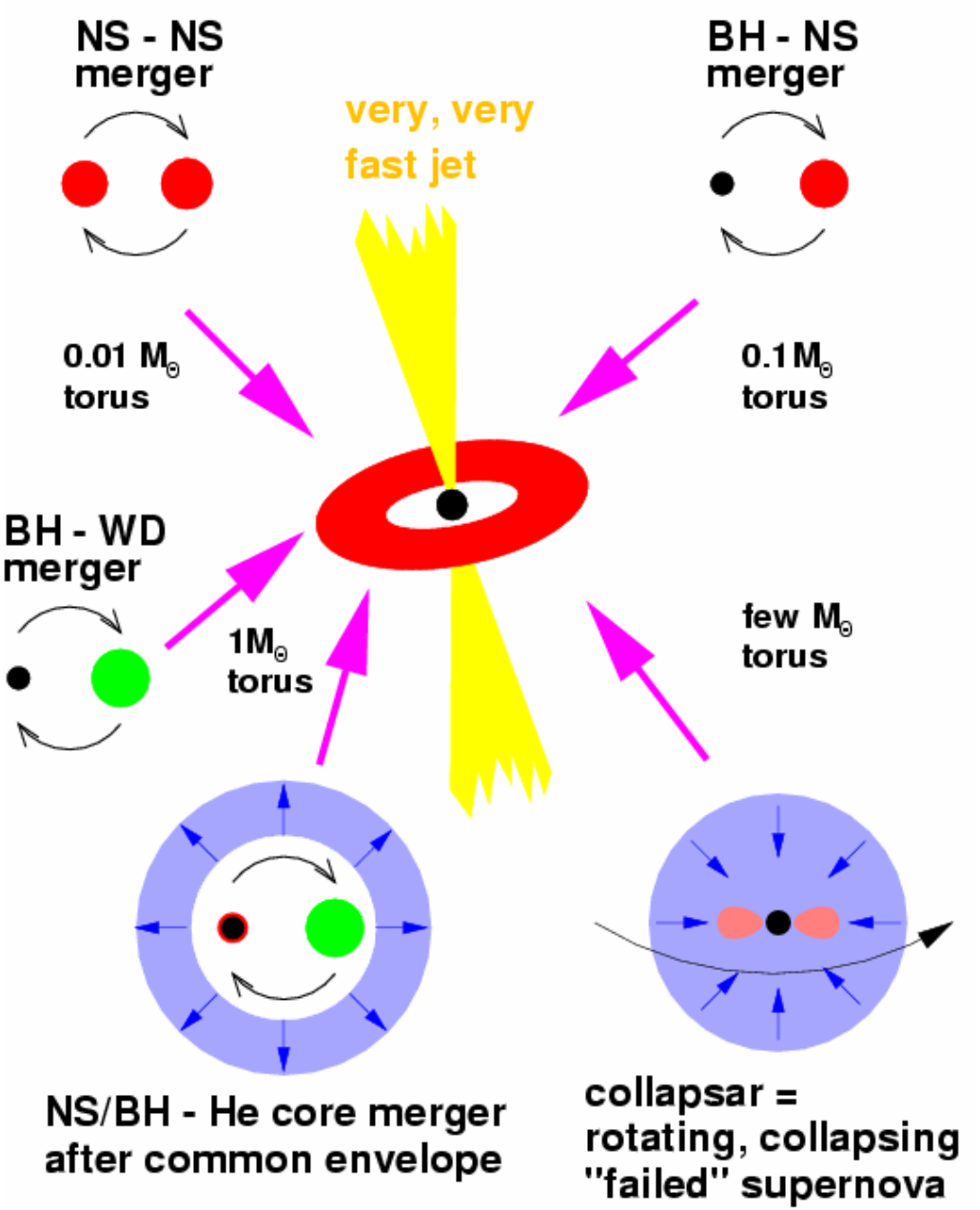

1.0
21.5
42.1
62.6
83.1
103.6
rho
0.2
163.9
327.6
491.4
655.1
818.8
P
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0

2D Jet



EOS in weak shocks

Hyper-accreting black hole or high field neutron star (rotating)

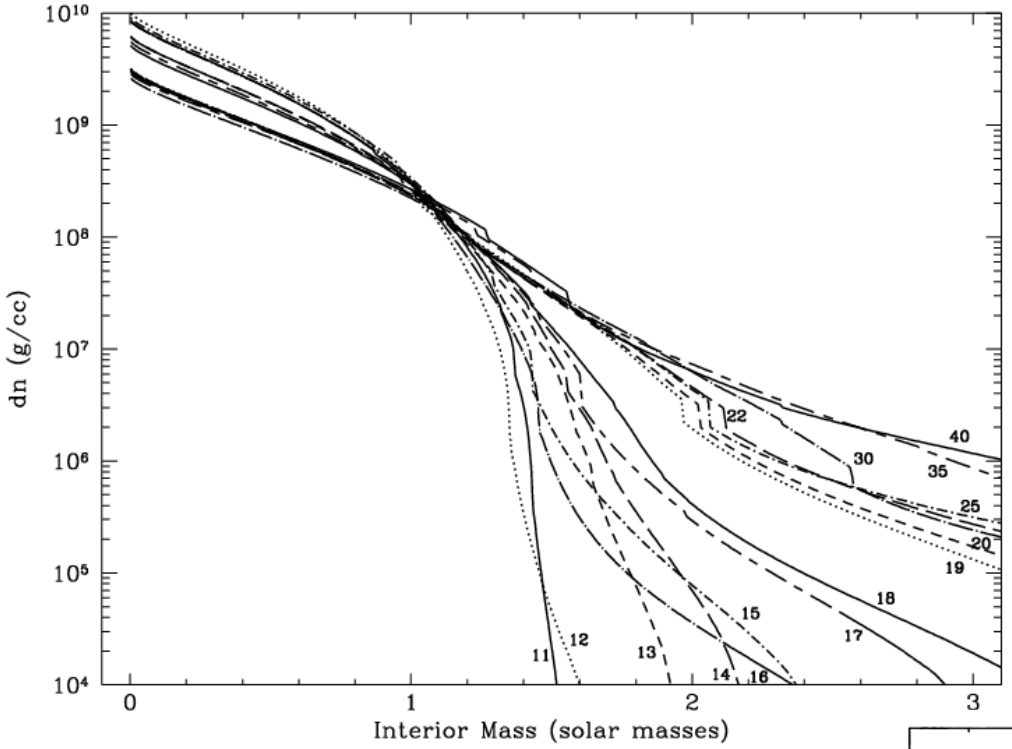


GRB photons are made far away from engine.

Can't observe engine directly with light. (neutrinos, gravitational waves?)

Electromagnetic process or neutrino annihilation to tap power of central compact object.

Pre-Supernova Density Structure



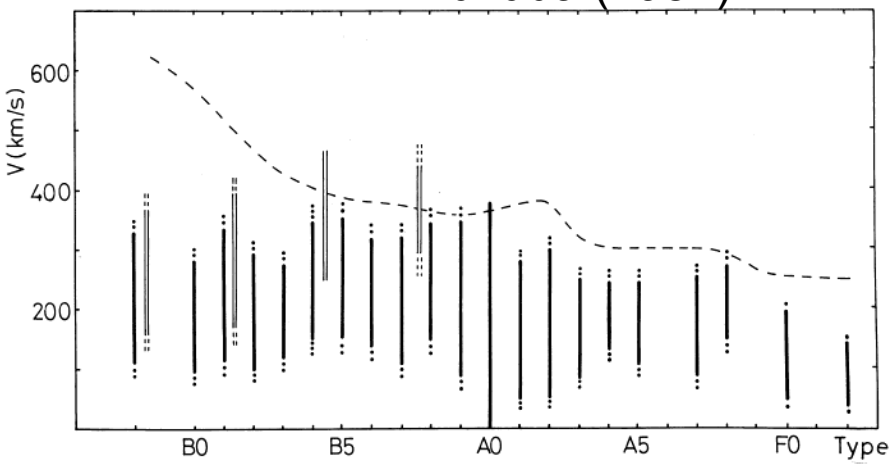
Woosley & Weaver (1995)

Bigger stars:

Higher entropy

Shallower density gradients

Fukuda (1982)



IF Two conditions occur (sometimes):

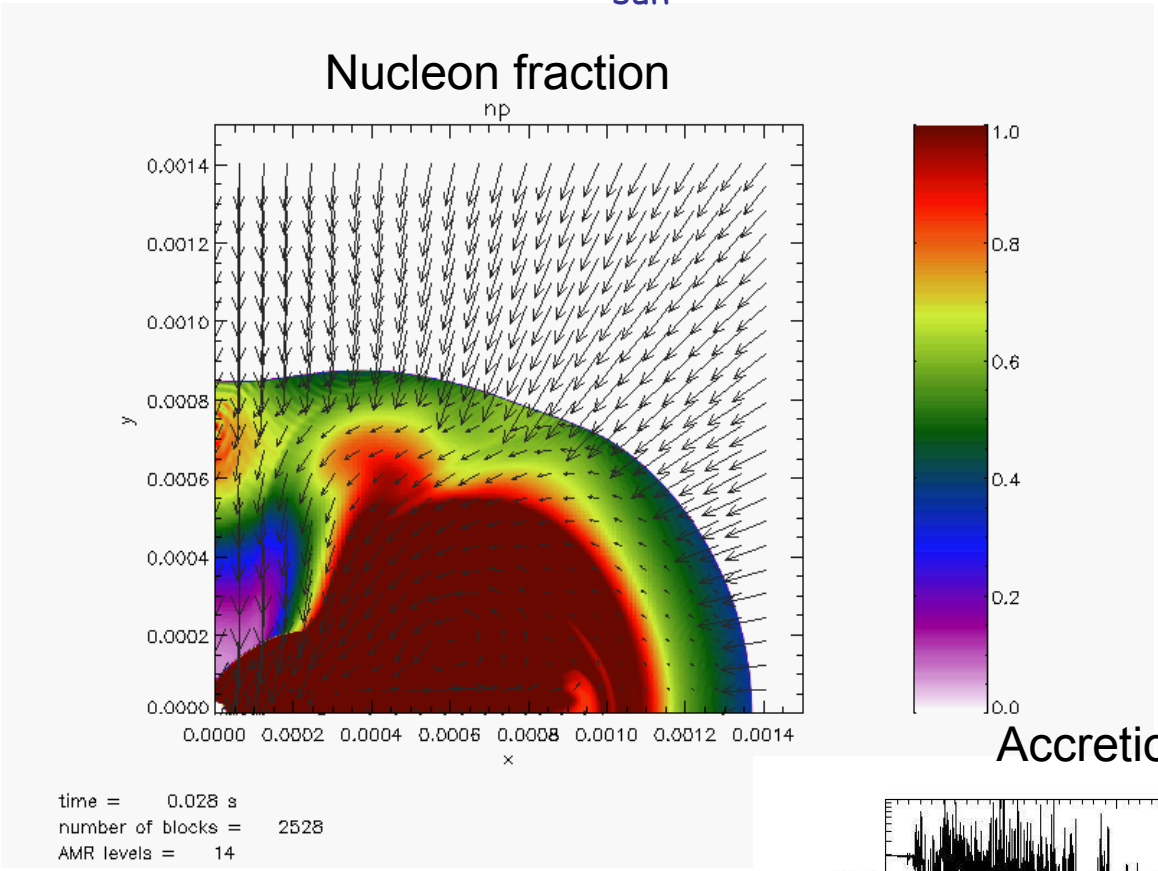
1. Failure of neutrino powered SN explosion
   a. complete
   b. partial (fallback)
2. Rotating stellar cores
   $j > 3 \times 10^{16}$ cm^2/s

THEN

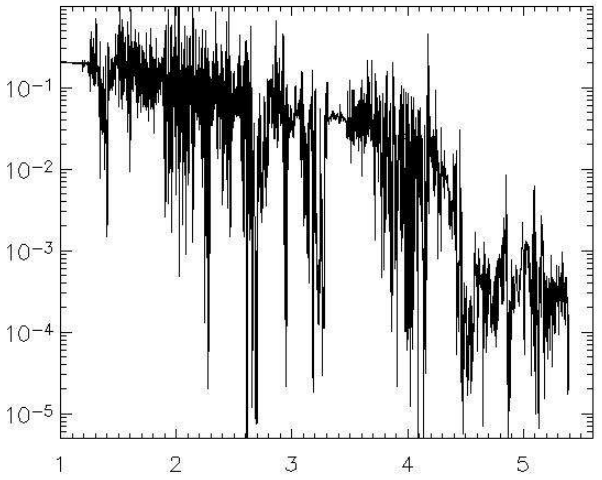
Rapidly accreting black hole, ($\dot{M} \sim 0.1\ M_\odot$/s)
fed by collapsing star ($t_{dyn} \sim 446$ s/ $\rho^{\frac{1}{2}} \sim 10$ s)
Disk formation

$\Rightarrow$ COLLAPSAR

$\alpha = 0.1 \quad \langle \dot{M} \rangle = 0.07\ M_{sun}\ /s = 1.3 \times 10^{53}\ erg/s$

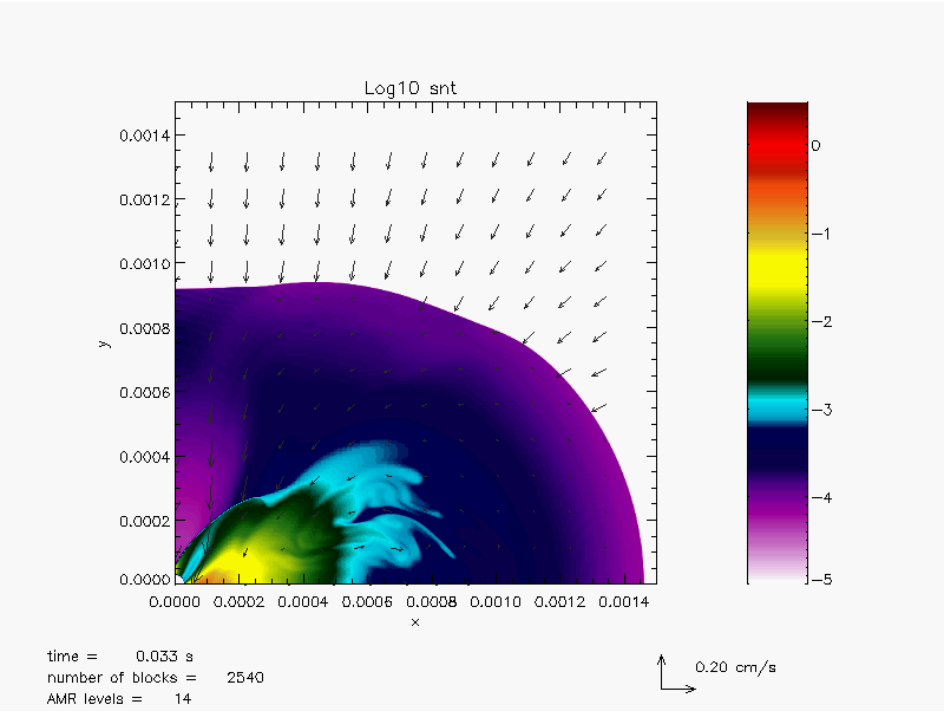


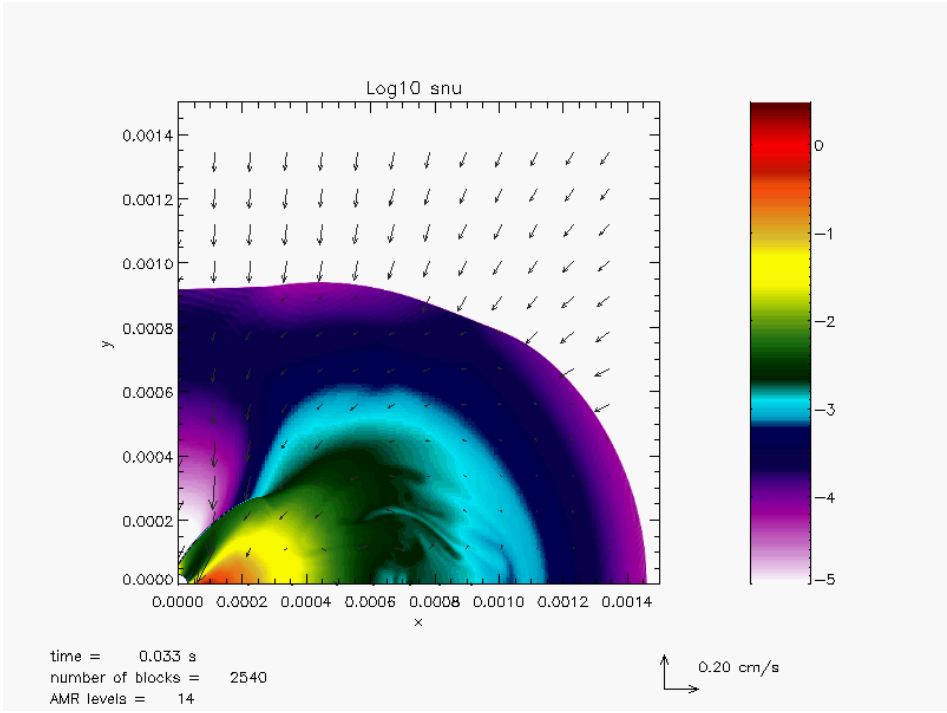
Accretion Rate



Msun/s

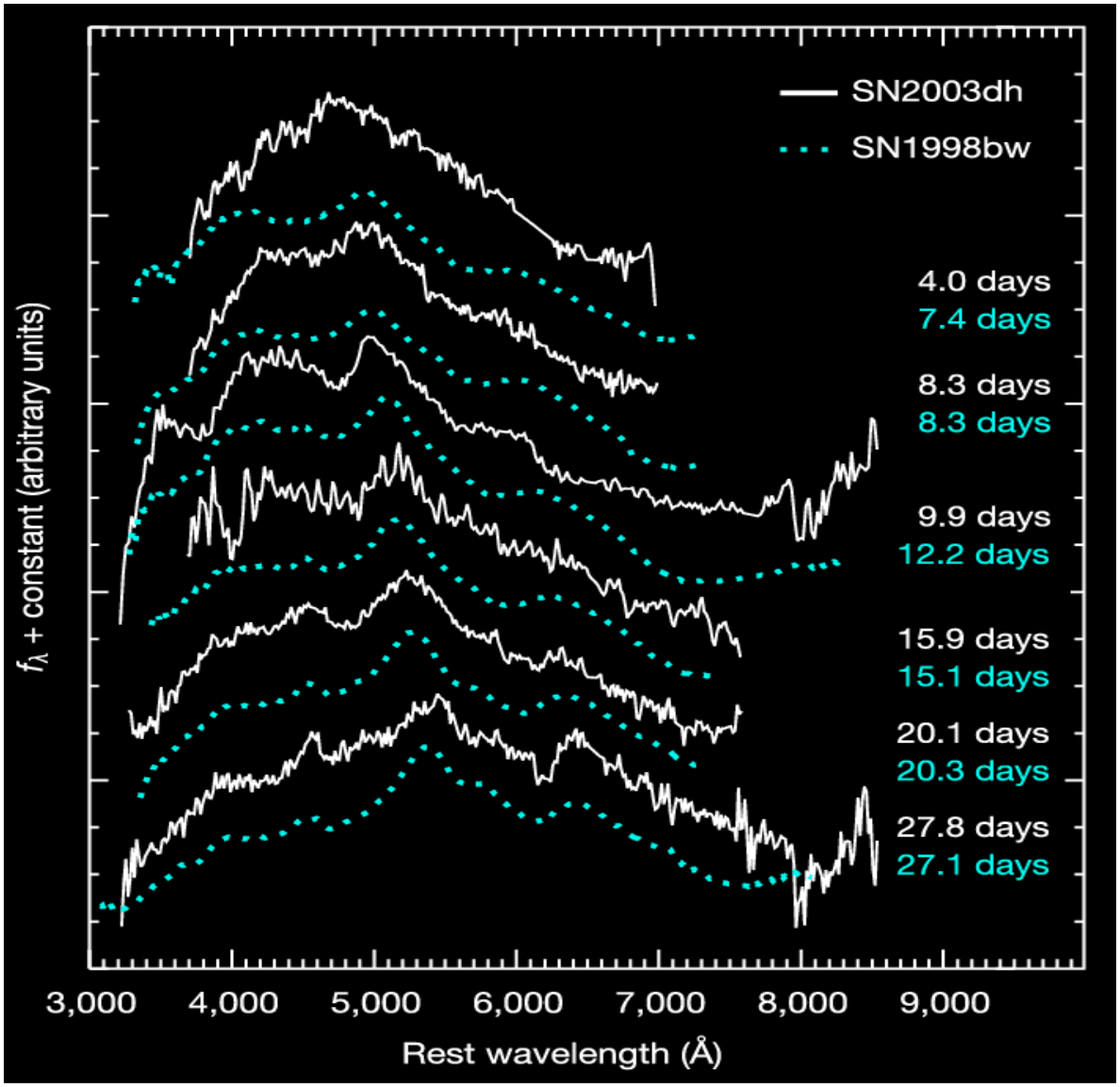
Thermal vs. URCA neutrinos
URCA 10 times more important





Smoking gun number 2

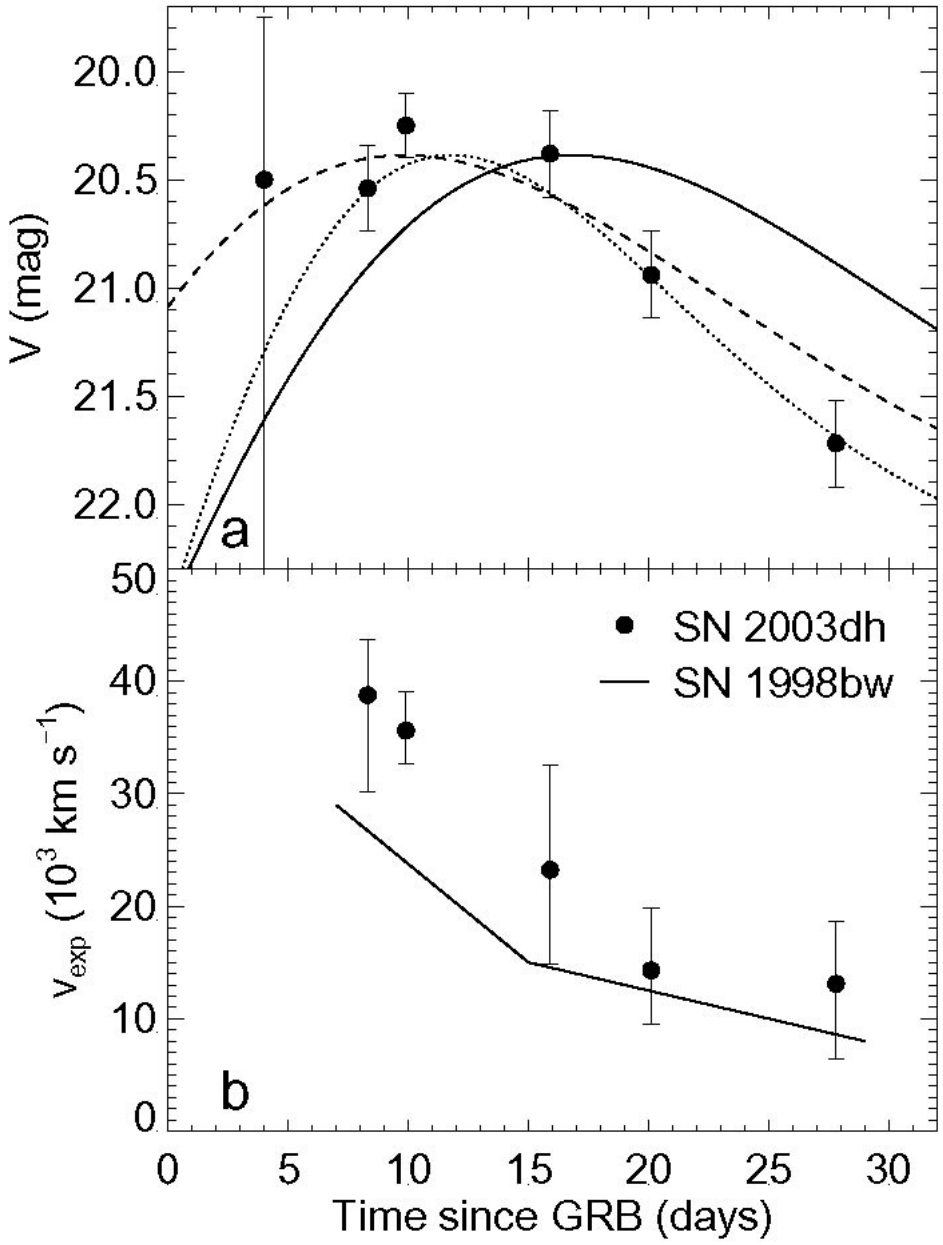
GRB030329/
SN2003dh



z = 0.1685

One of the brightest GRBs ever – HETE2

Stanek et al.,
Chornock et al.
Eracleous et al.,
Hjorth et al.,
Kawabata et al.



L_{peak} implies (again) ~0.5 solar masses of ^{56}Ni

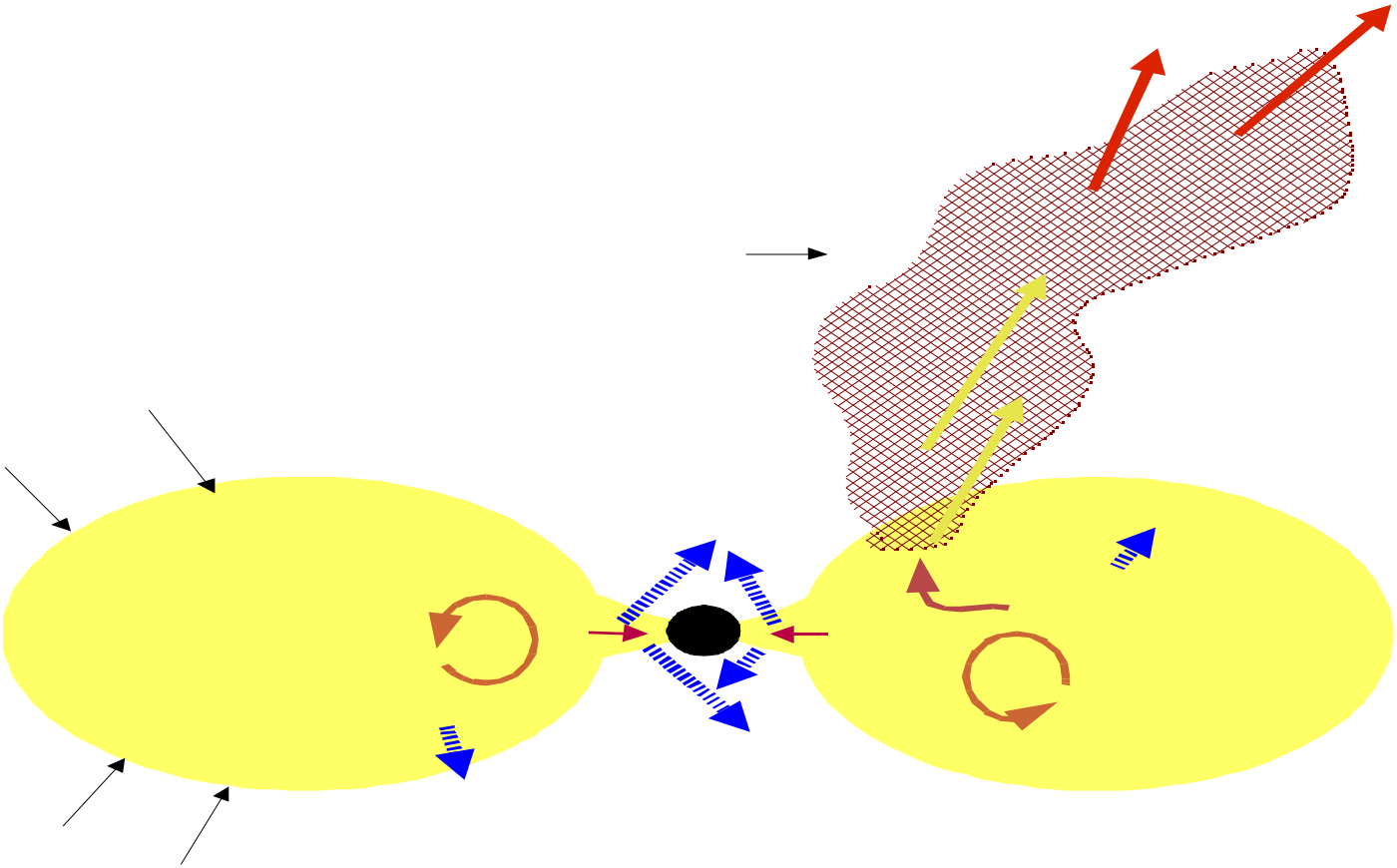
Exceptionally ---
- bright
- fast
- high velocity
- radio bright

Supernova simultaneous with the GRB (+- 2 days).

Exploding star

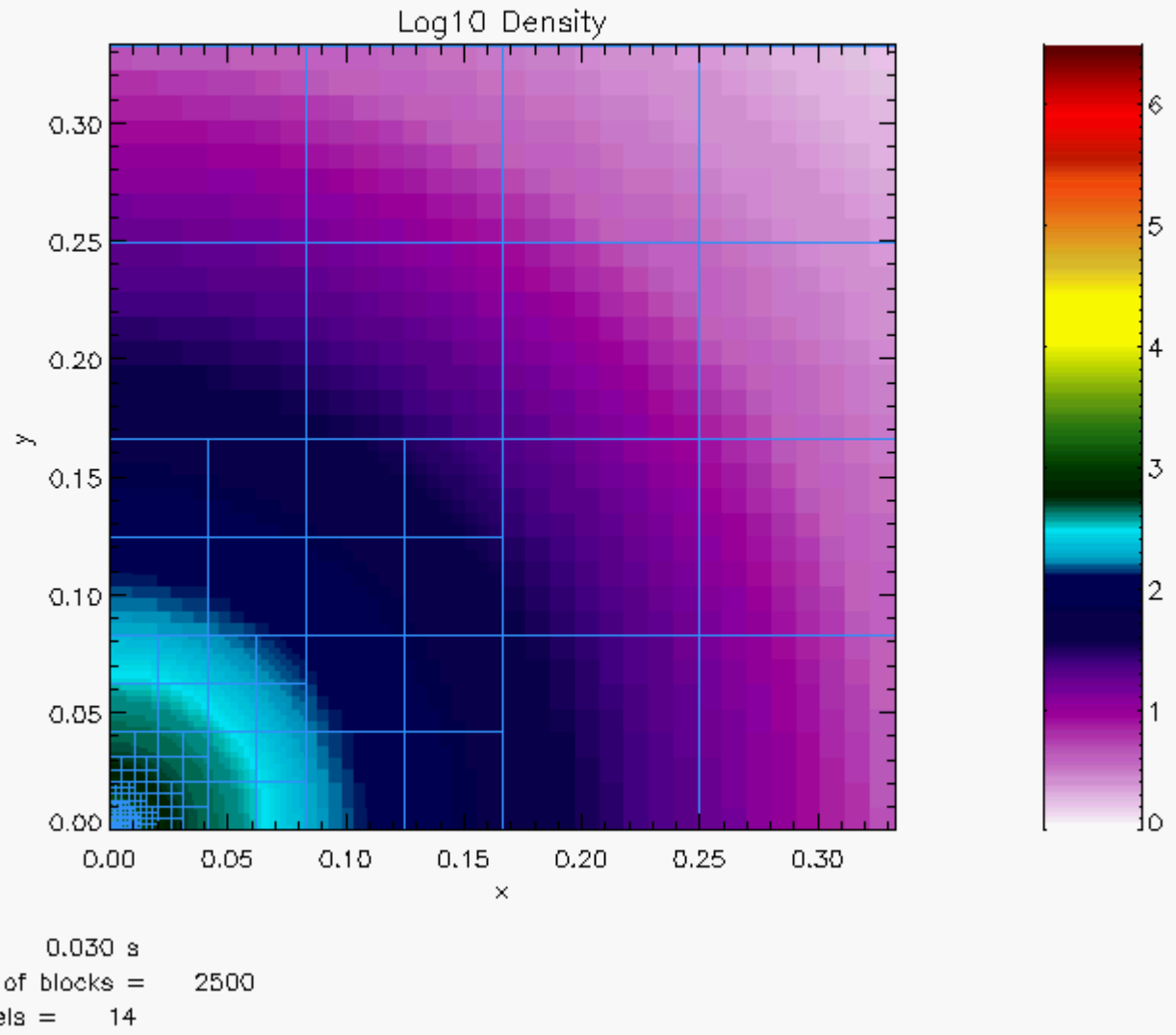
≠ Supernovae

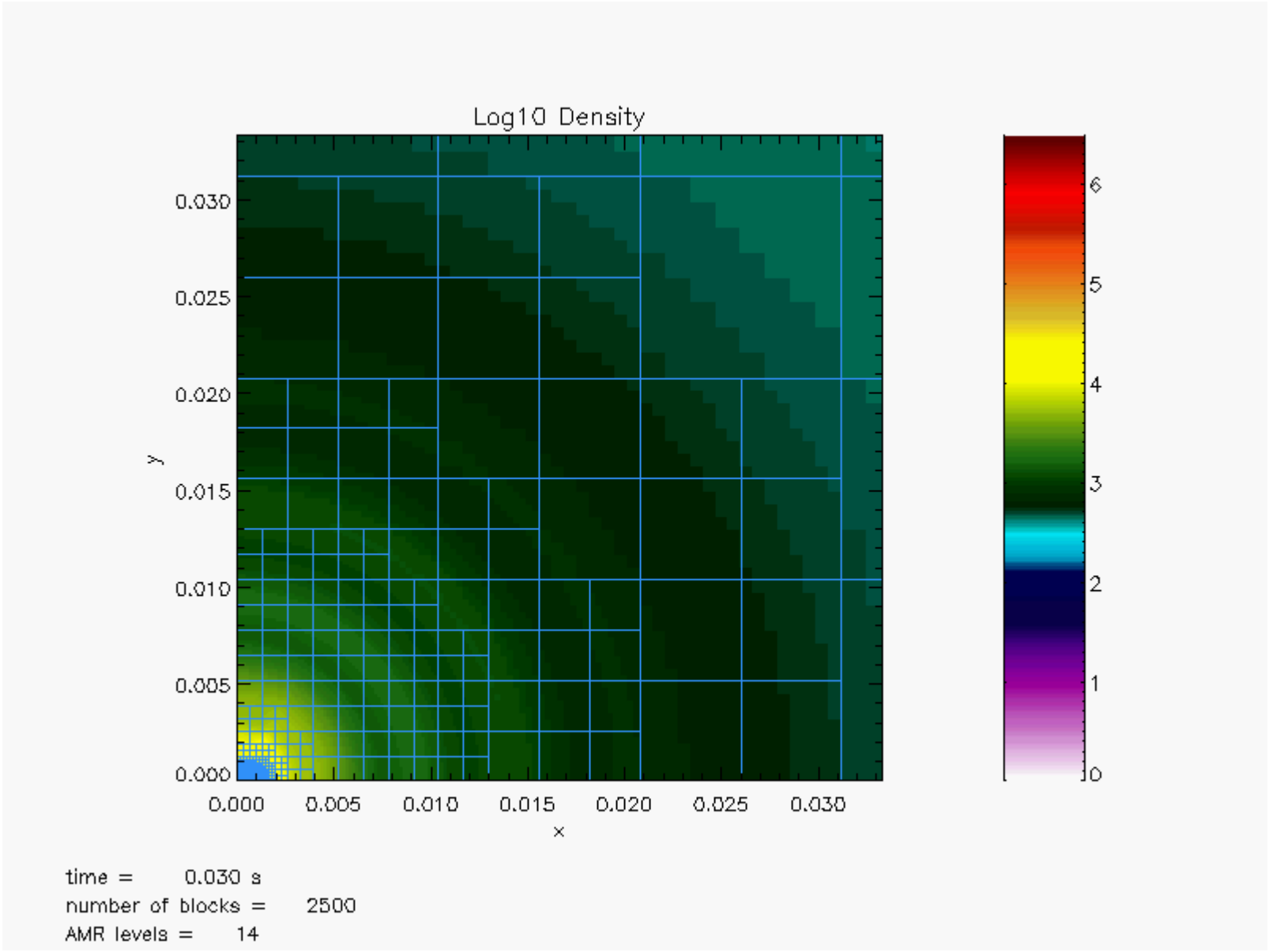
- Radioactive decay of Ni56
- tail of Type II, ALL of Type I
- Type I compact star WD or W-R
- E_{exp} -> adiabatic expansion not light
- no Ni56 -> no Supernova
- SN 1998bw & 2003dh need 0.5 M_{sun}

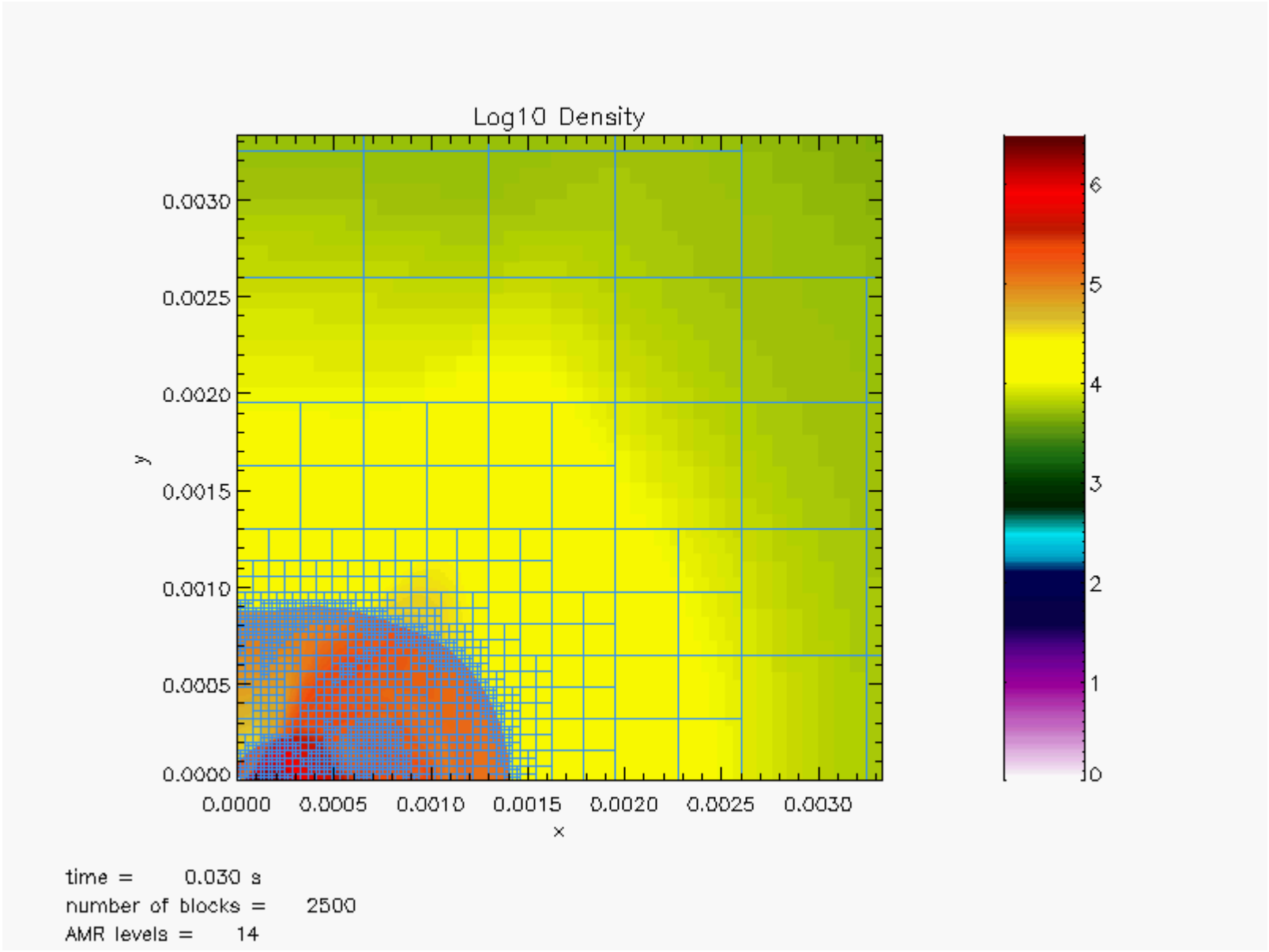


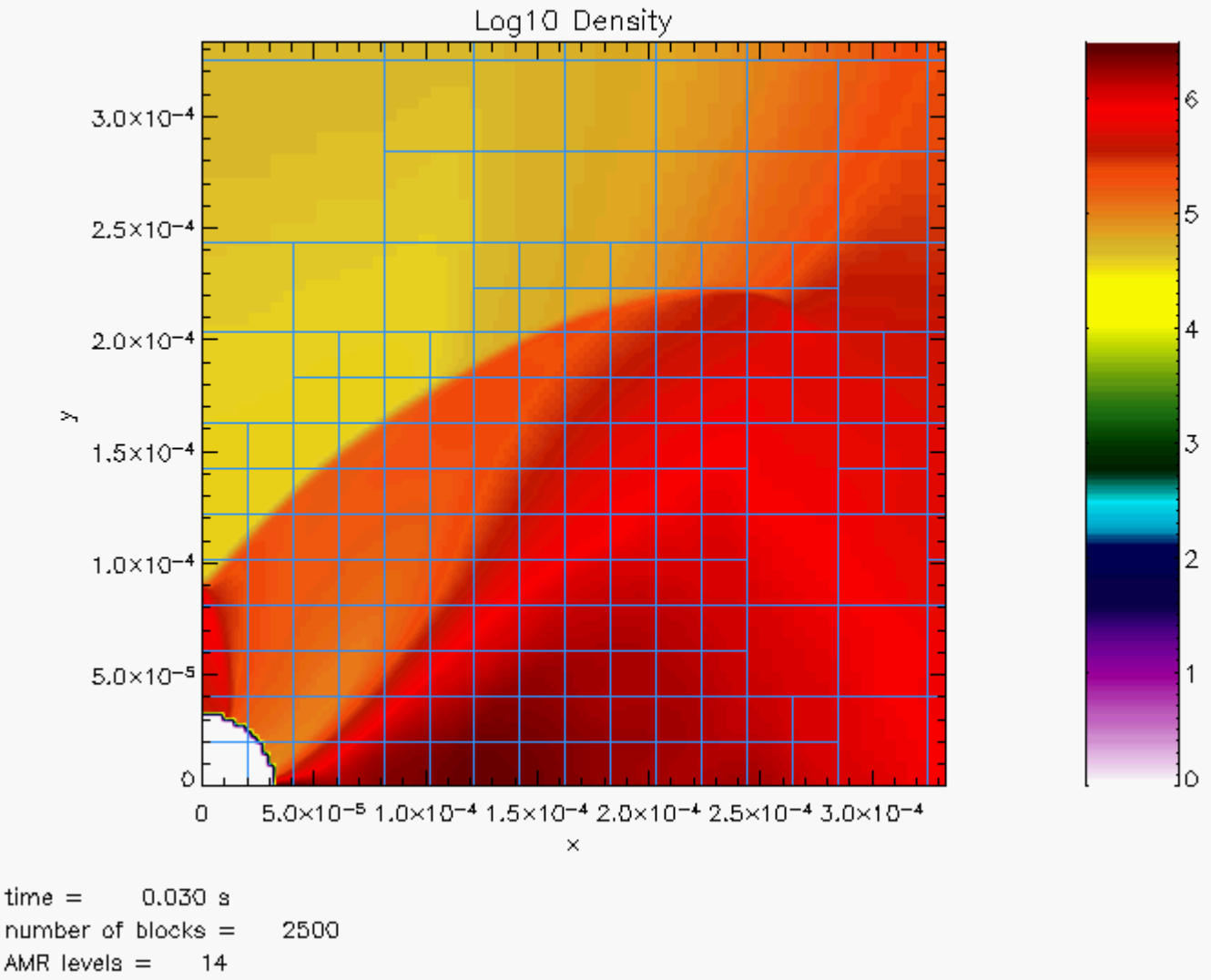
MacFadyen (2003)
Kohri, Narayan & Piran (2005)

R star ~ 10^{11} cm (3 lt-s) R hole ~ 10^{6} cm (3e-5 lt-s)



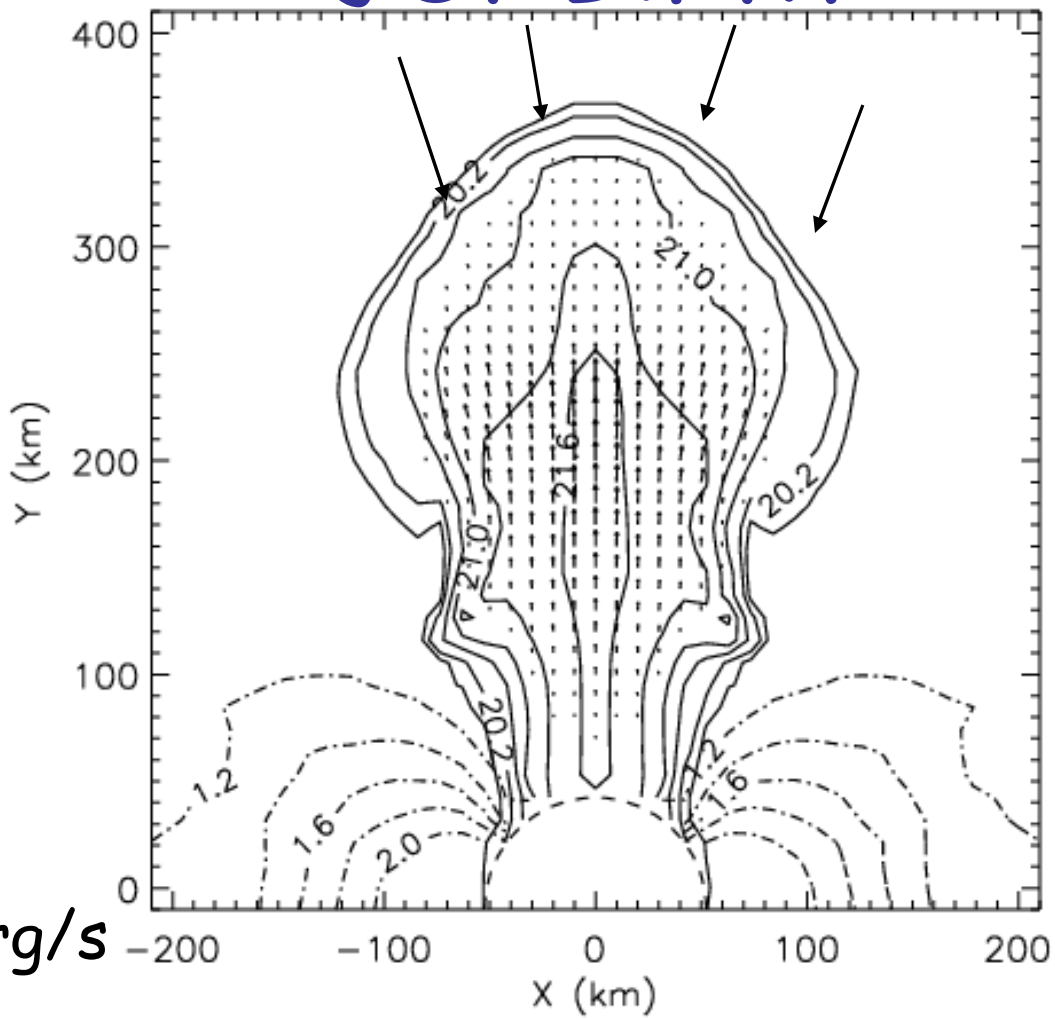

Log10 Density
0.030
0.025
0.020
0.015
0.010
0.005
0.000
y
0.000
0.005
0.010
0.015
0.020
0.025
0.030
x
6
5
4
3
2
1
0
time = 0.030 s
number of blocks = 2500
AMR levels = 14


Log10 Density
0.0030
0.0025
0.0020
0.0015
0.0010
0.0005
0.0000
y
0.0000
0.0005
0.0010
0.0015
0.0020
0.0025
0.0030
x
6
5
4
3
2
1
0
time = 0.030 s
number of blocks = 2500
AMR levels = 14


Log10 Density
3.0×10⁻⁴
2.5×10⁻⁴
2.0×10⁻⁴
1.5×10⁻⁴
1.0×10⁻⁴
5.0×10⁻⁵
0
y
0
5.0×10⁻⁵
1.0×10⁻⁴
1.5×10⁻⁴
2.0×10⁻⁴
2.5×10⁻⁴
3.0×10⁻⁴
x
6
5
4
3
2
1
0
time = 0.030 s
number of blocks = 2500
AMR levels = 14

Jet Birth

Thermal energy deposition focused by toroidal funnel structure



$\dot{E}_{jet} = f \dot{M}_{acc} c^2$

MHD

ν ν

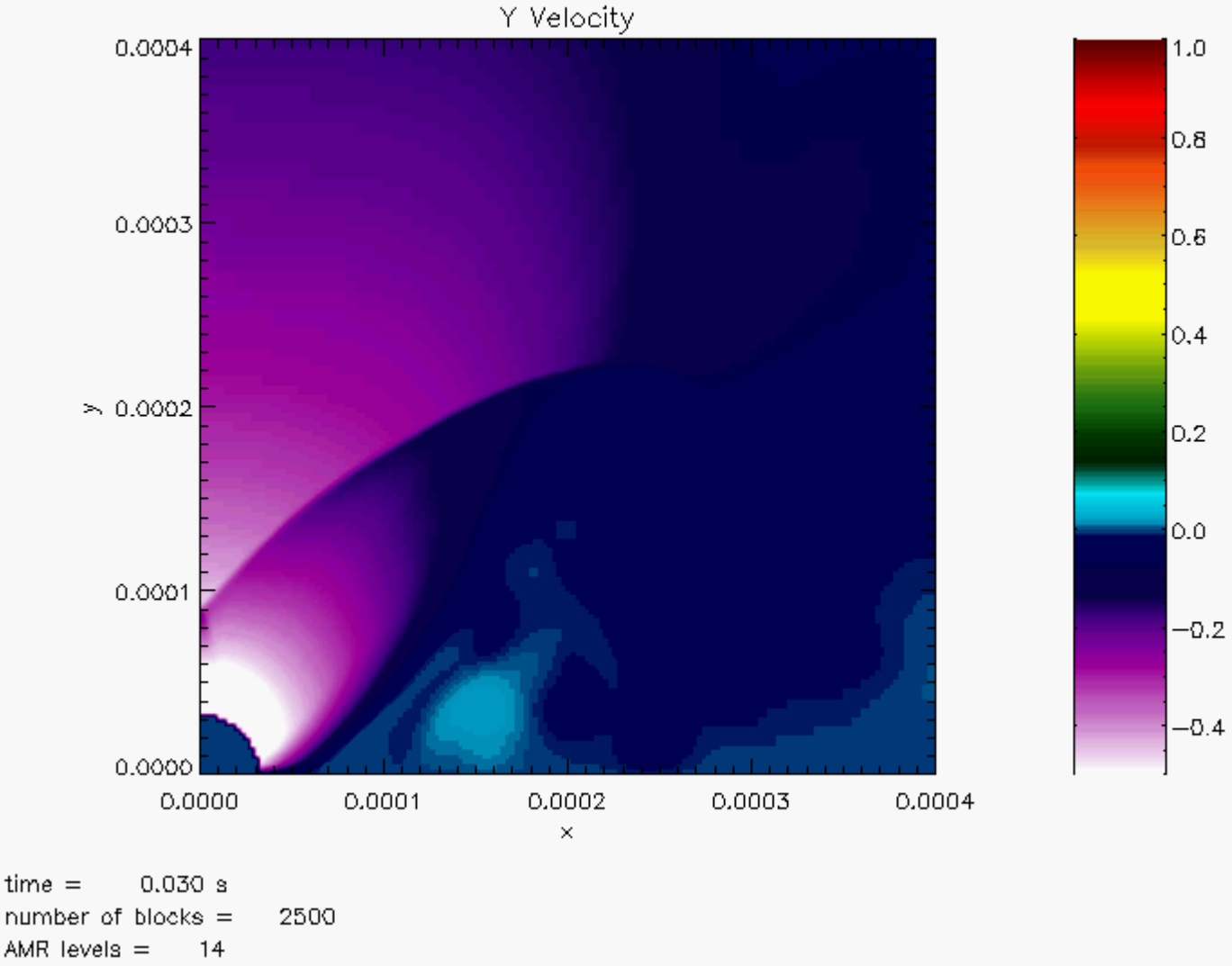
T = 5.7 ms

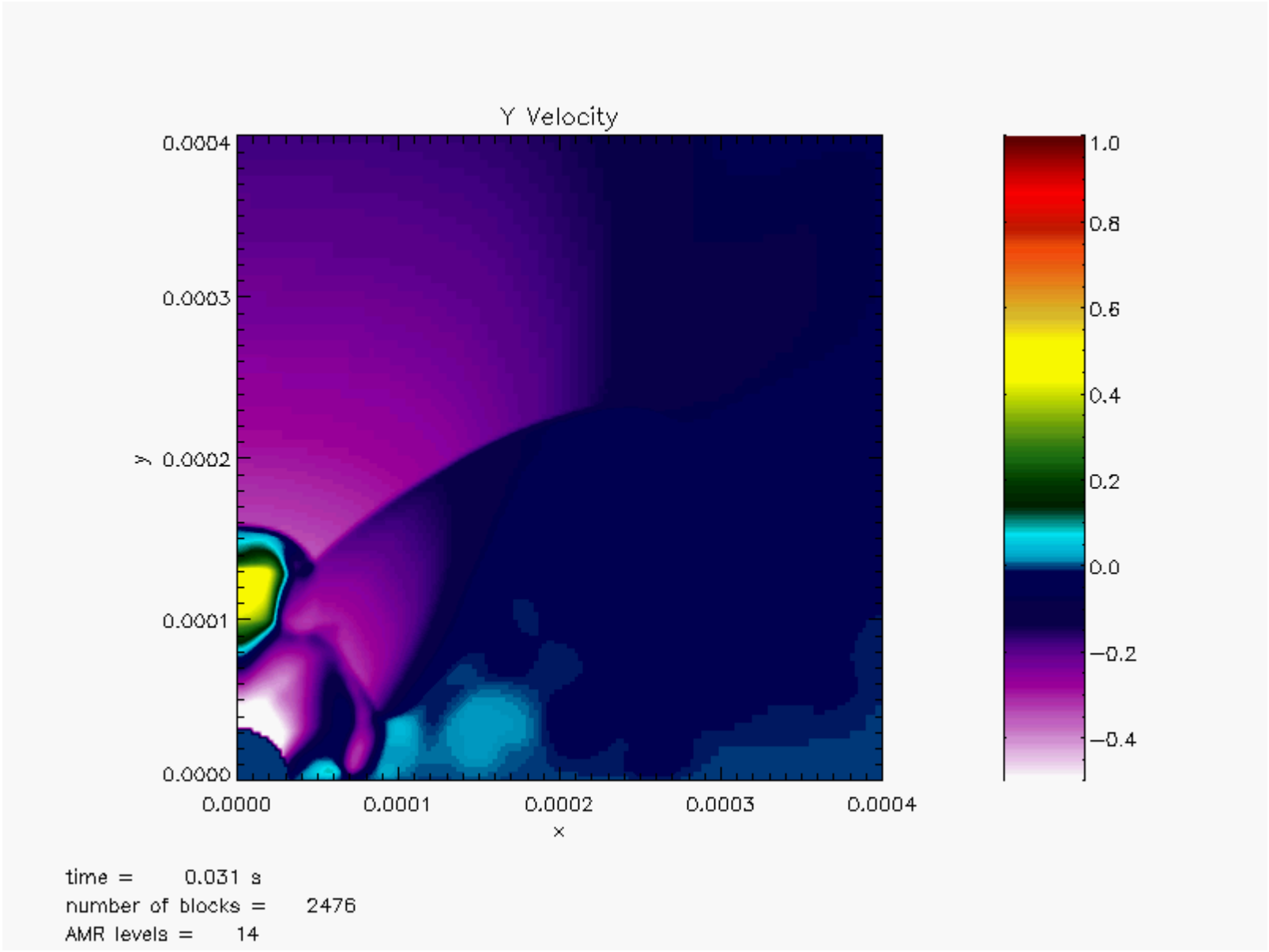
E = 5 x 10^{50} erg/s

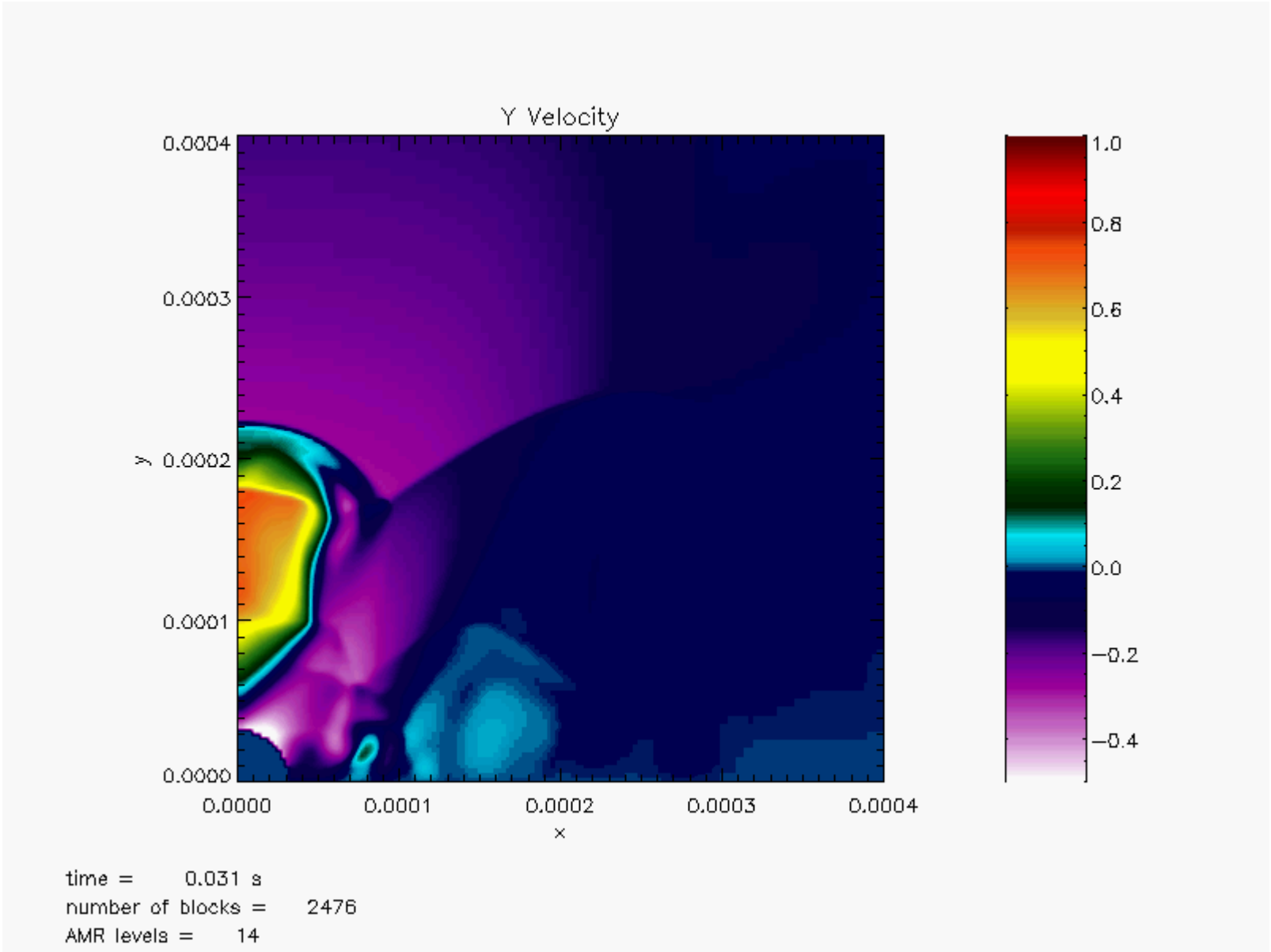
E_{dep} = 2.8 x 10^{48} erg

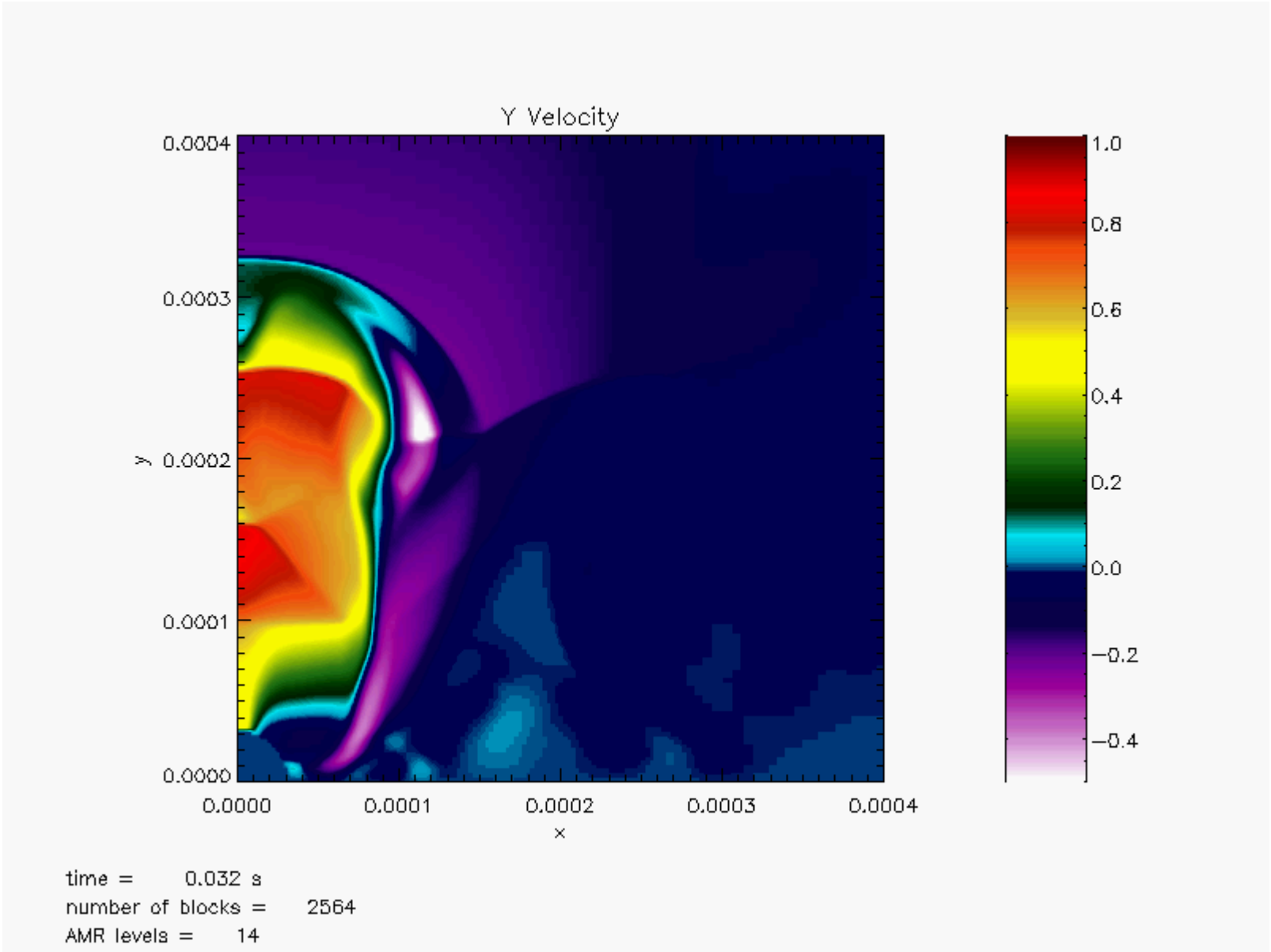
f_{max} ~ .06 - .4

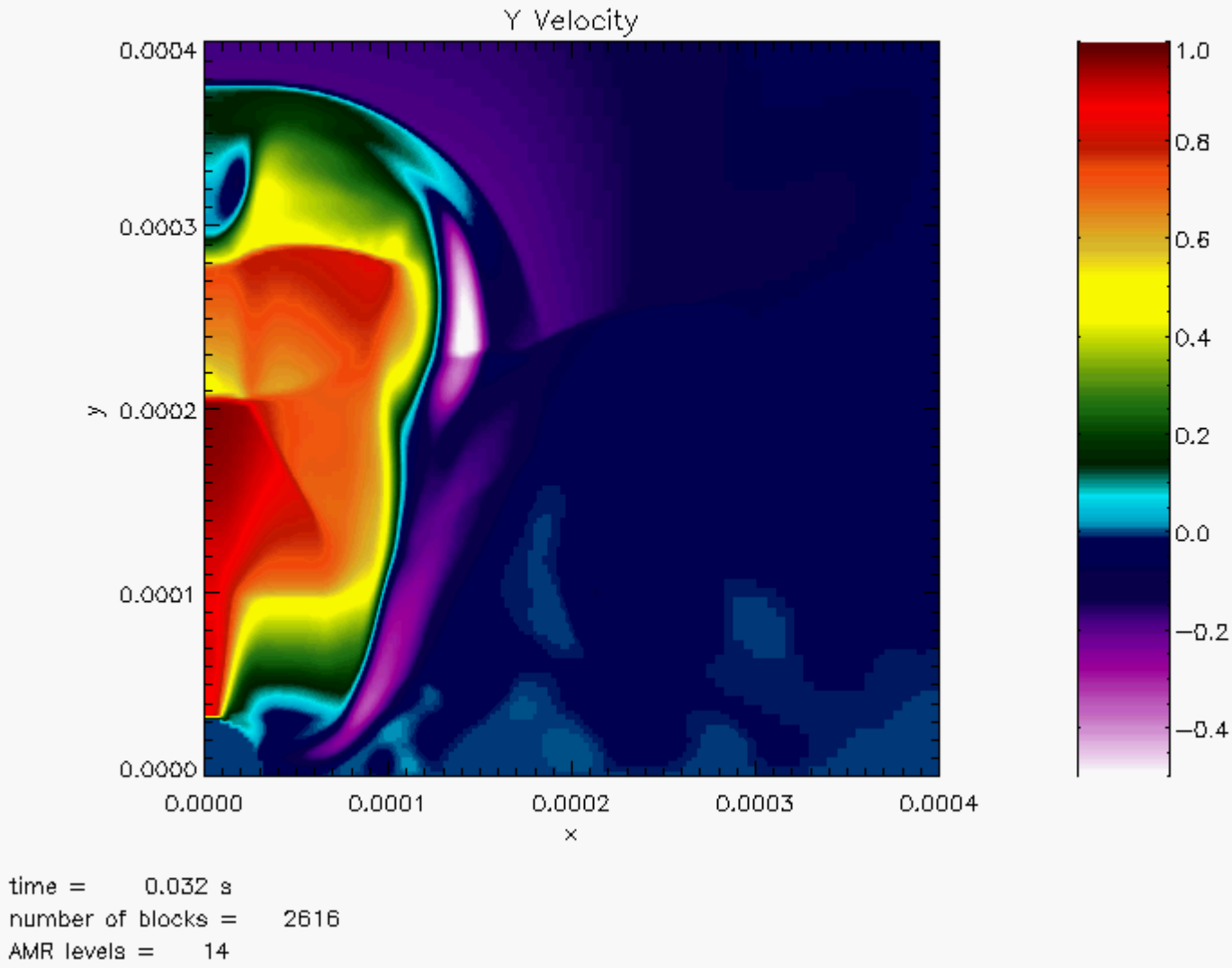
Early Jet Propogation



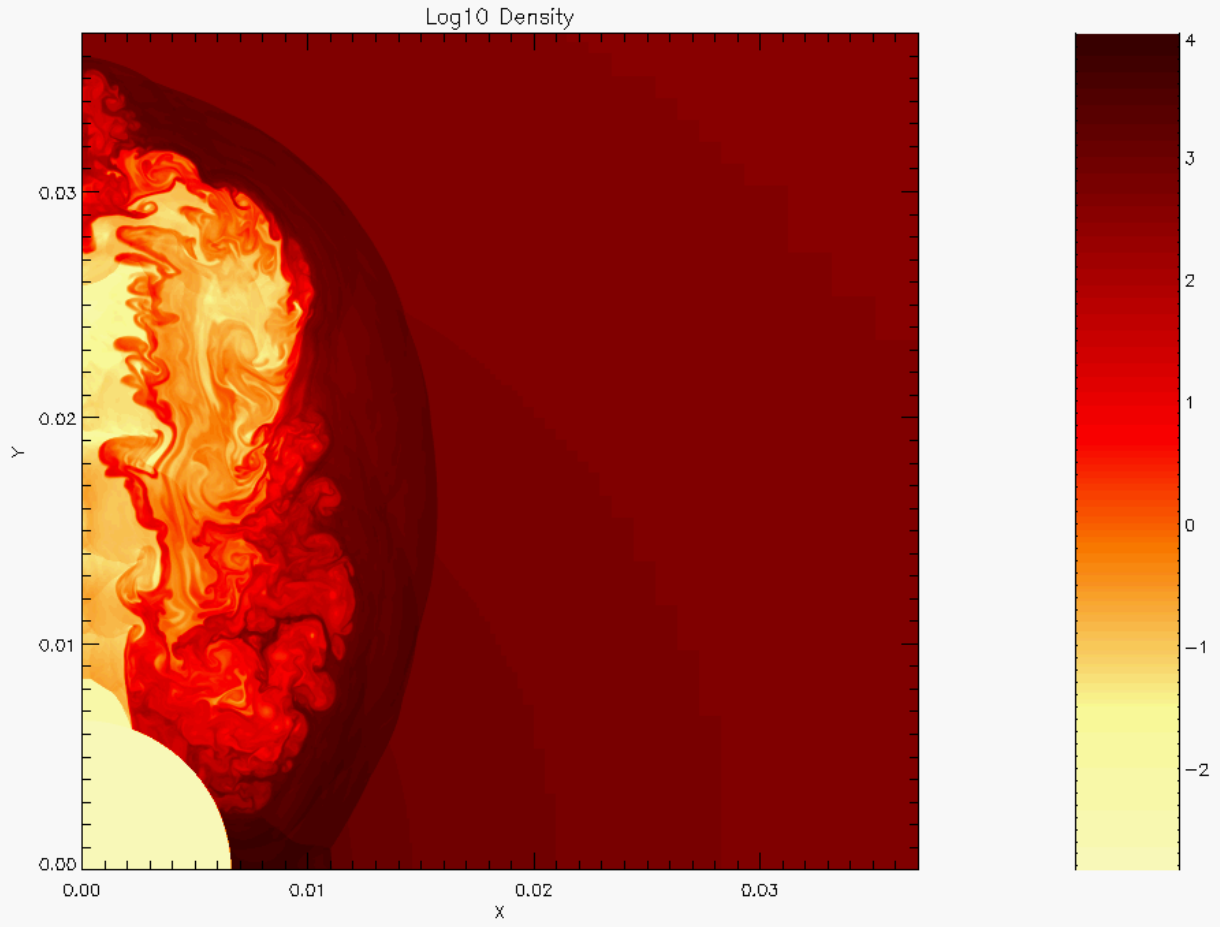

Y Velocity
0.0004
0.0003
0.0002
0.0001
0.0000
y
0.0000
0.0001
0.0002
0.0003
0.0004
x
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
time = 0.031 s
number of blocks = 2476
AMR levels = 14


Y Velocity
0.0004
0.0003
0.0002
0.0001
0.0000
y
0.0000
0.0001
0.0002
0.0003
0.0004
x
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
time = 0.031 s
number of blocks = 2476
AMR levels = 14

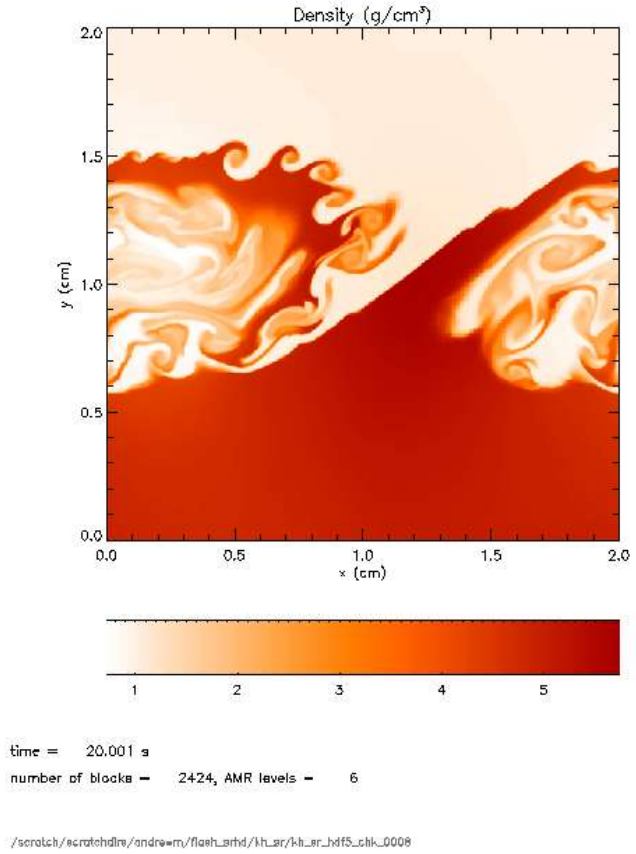

Y Velocity
0.0004
0.0003
0.0002
0.0001
0.0000
y
0.0000
0.0001
0.0002
0.0003
0.0004
x
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
time = 0.032 s
number of blocks = 2564
AMR levels = 14

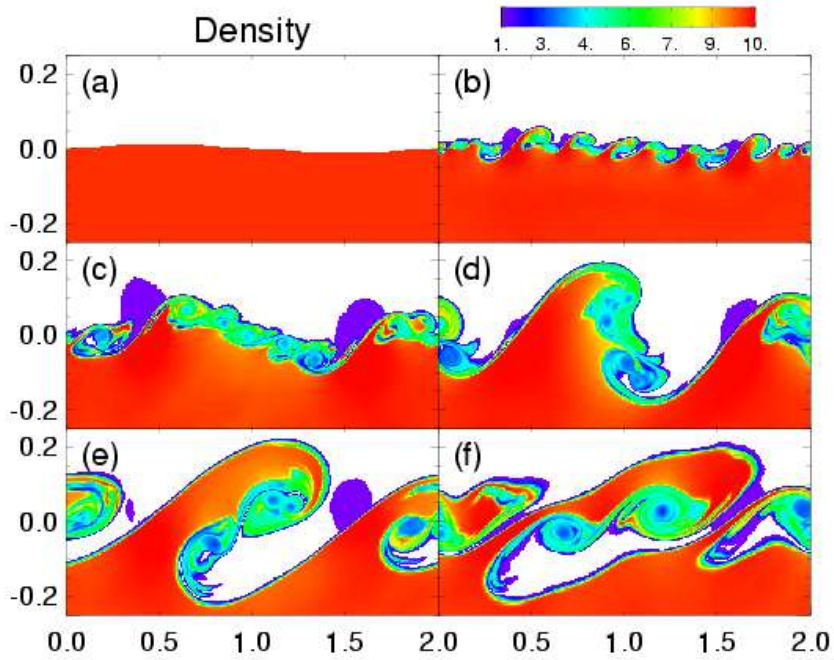

Y Velocity
0.0004
0.0003
0.0002
0.0001
0.0000
y
0.0000
0.0001
0.0002
0.0003
0.0004
x
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
time = 0.032 s
number of blocks = 2616
AMR levels = 14

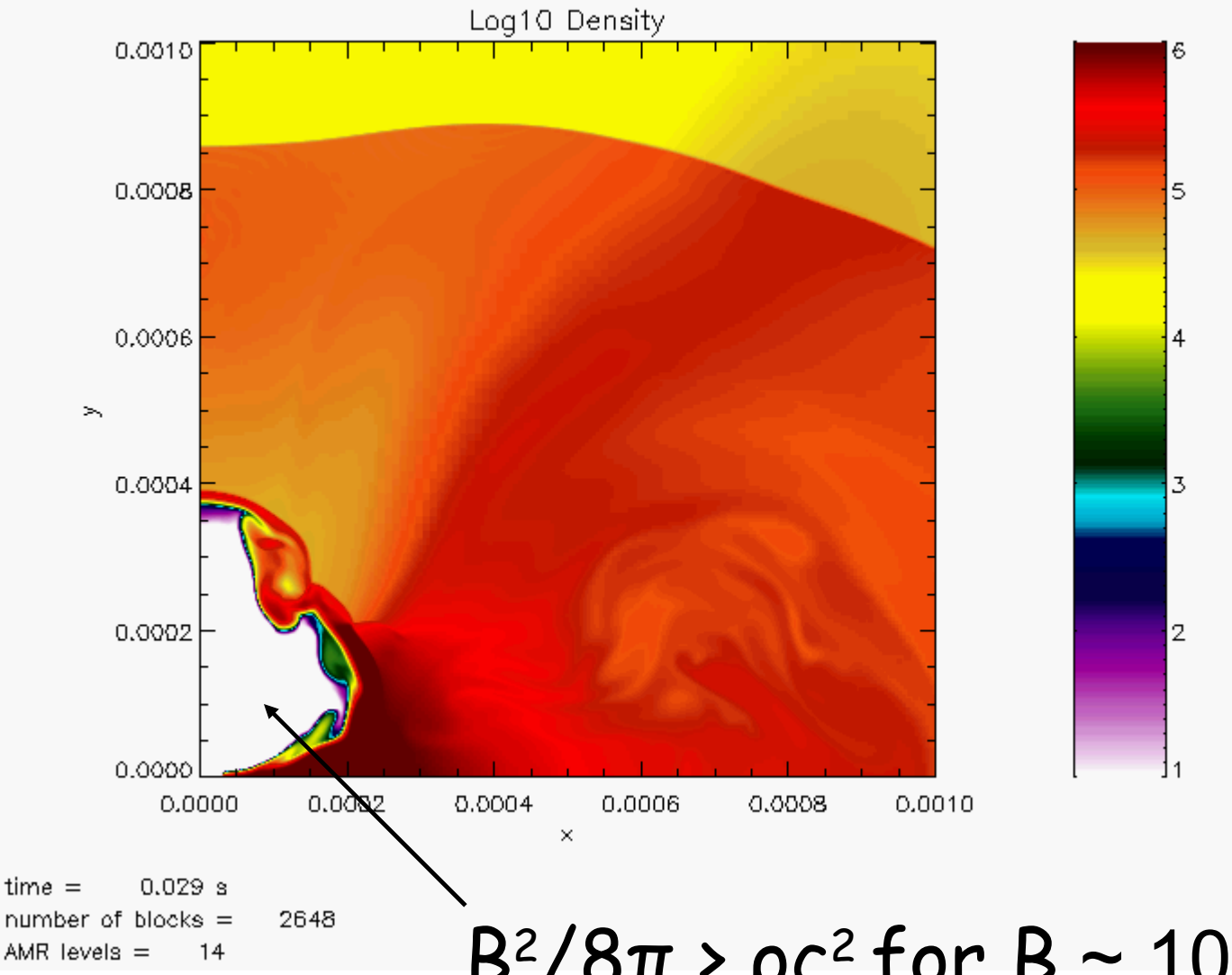
Relativistic Jet Simulations with RAM (2004)



Relativistic Mixing



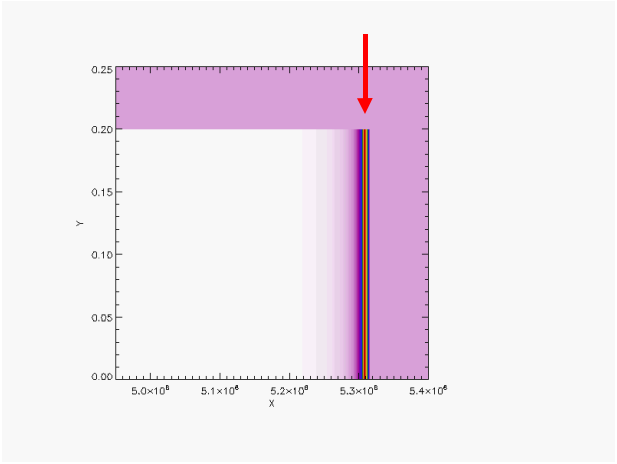


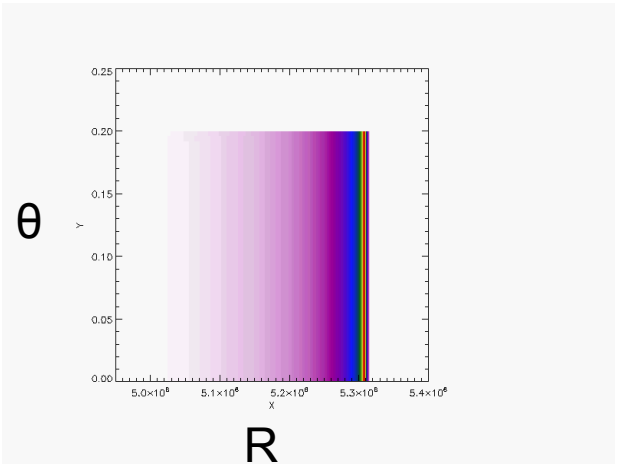


$B^2/8\pi > \rho c^2$ for $B \sim 10^{12}\,G$

AG Jet Initial Conditions

Γ = 23.1





- Blandford-McKee
- E_{iso} = 1e52 erg
- n_o = 1cm^{-3}
- Γ = 23.1
- Θ_{jet} = 0.2, 0.4

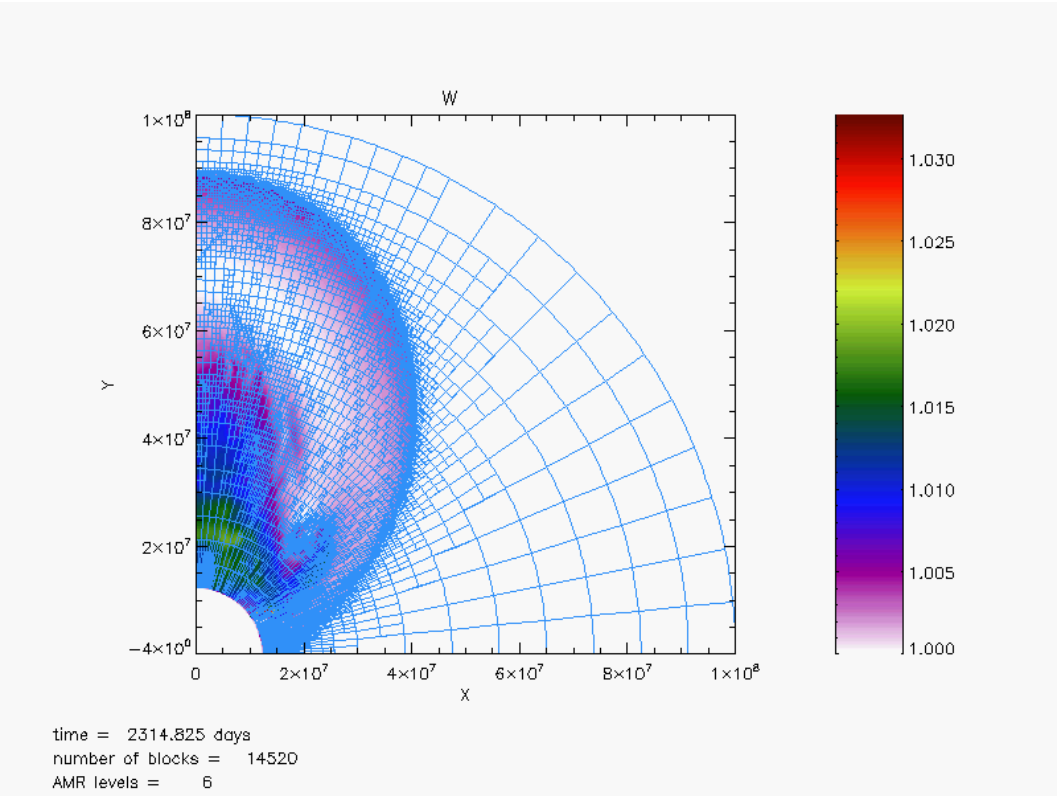
- Spherical
- R_o = 1.59e17 cm
- R/ΔR = 196608
- 4e10 zone equiv.

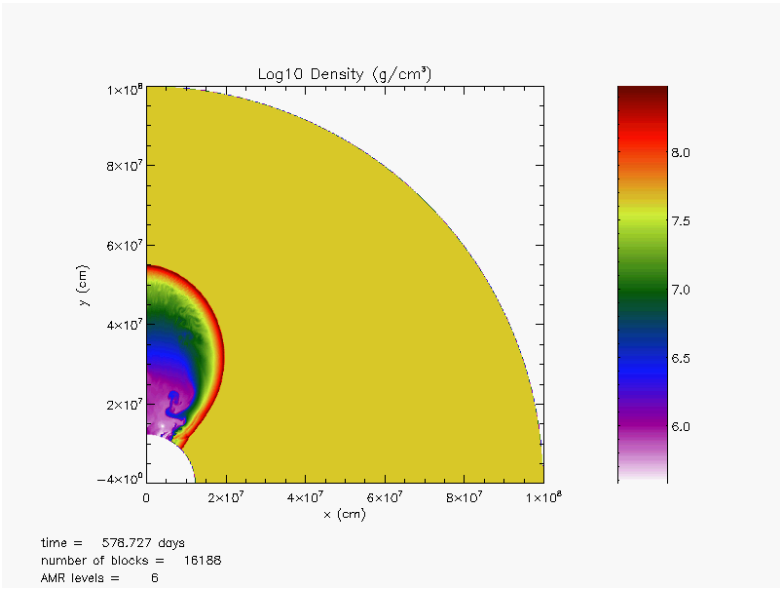
Granot et al (2001)

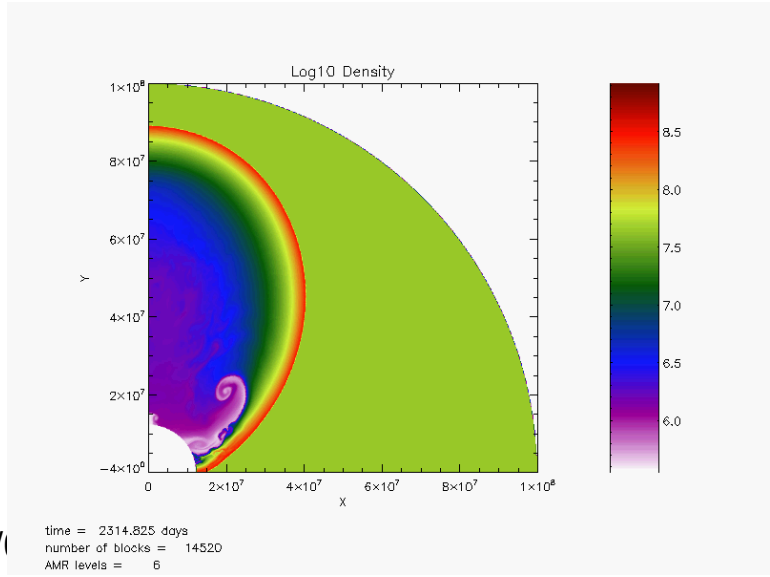
Blastwave Questions

- Lateral spreading: How fast? When?
- Afterglow Light curves
- Calorimetry
- Non-relativistic Transition: When? Spherical?
- Misaligned jets: When should we see them?
- Observations $\leftrightarrow$ relativistic hydro lab

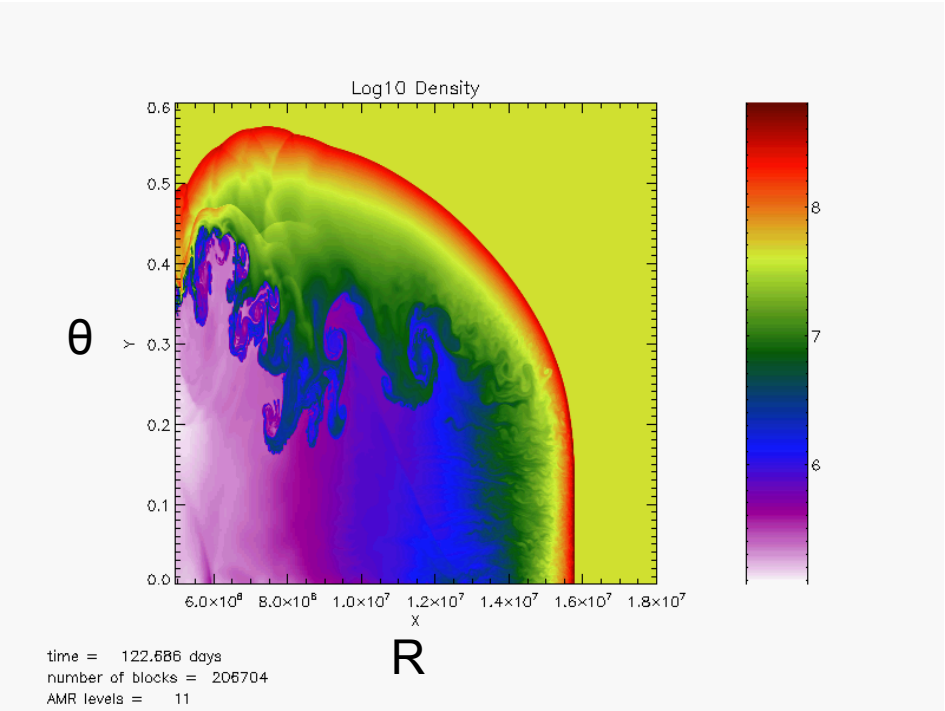
Jet Spreading

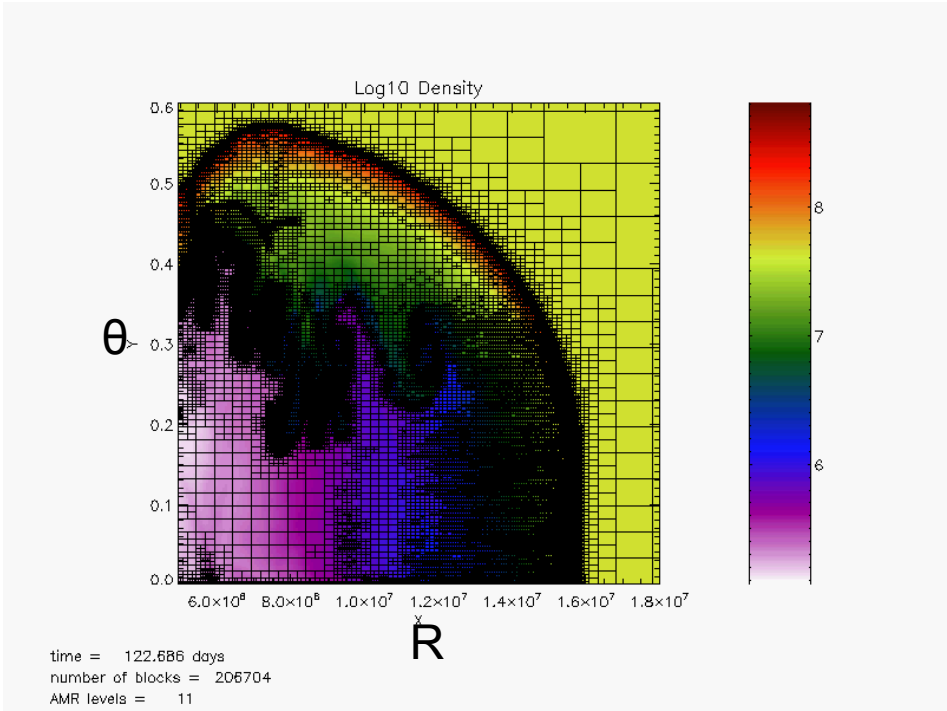


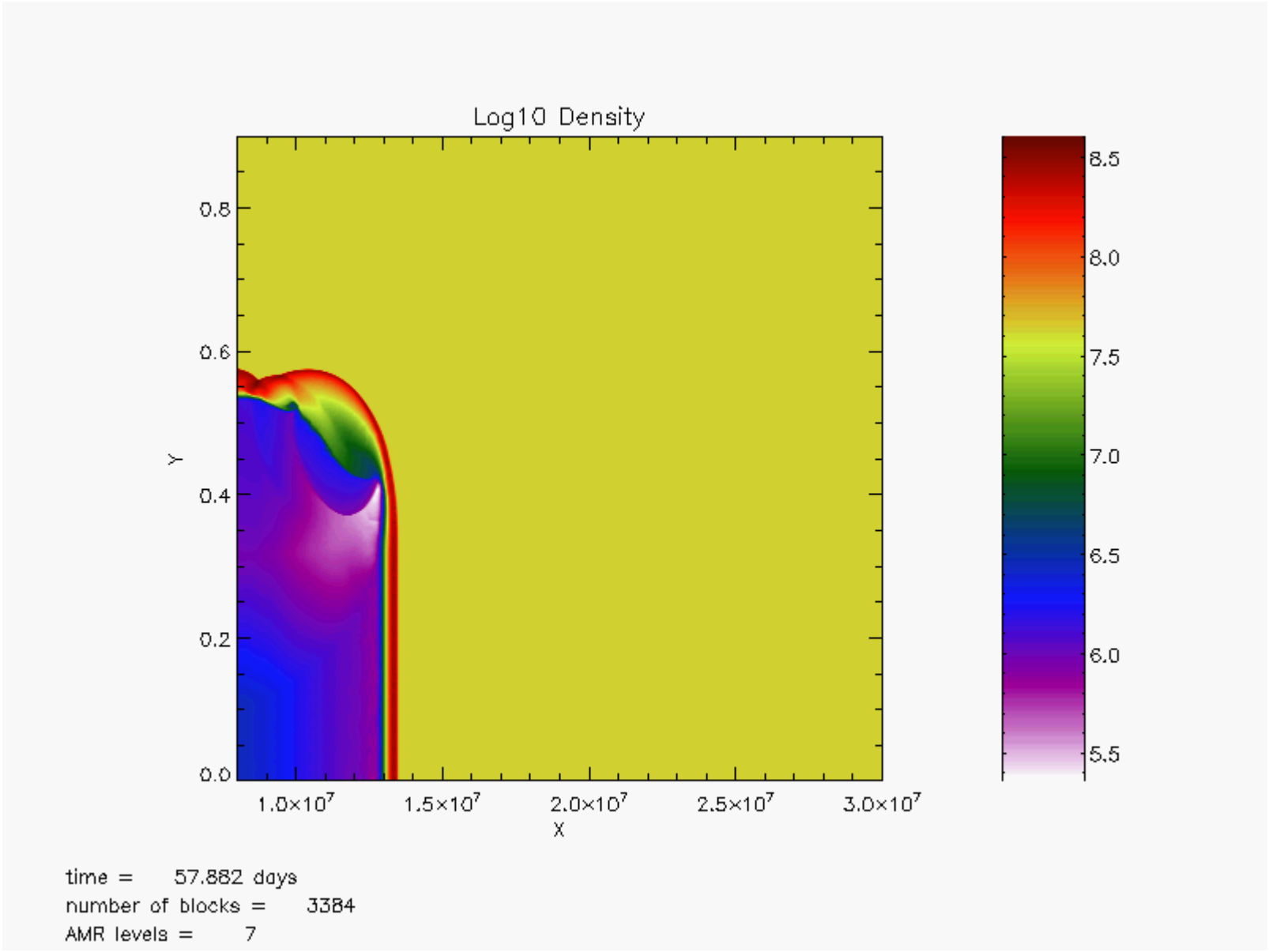


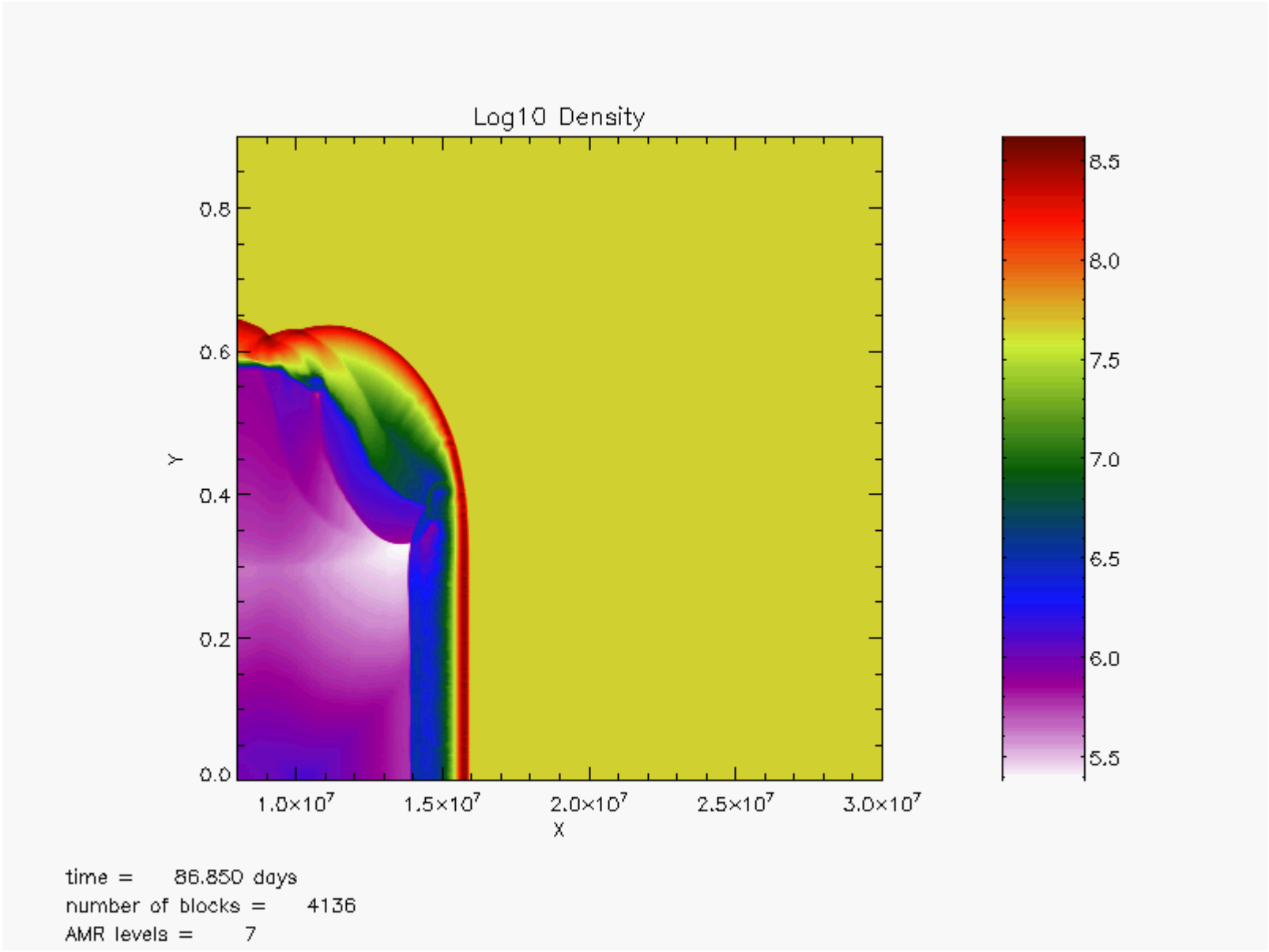


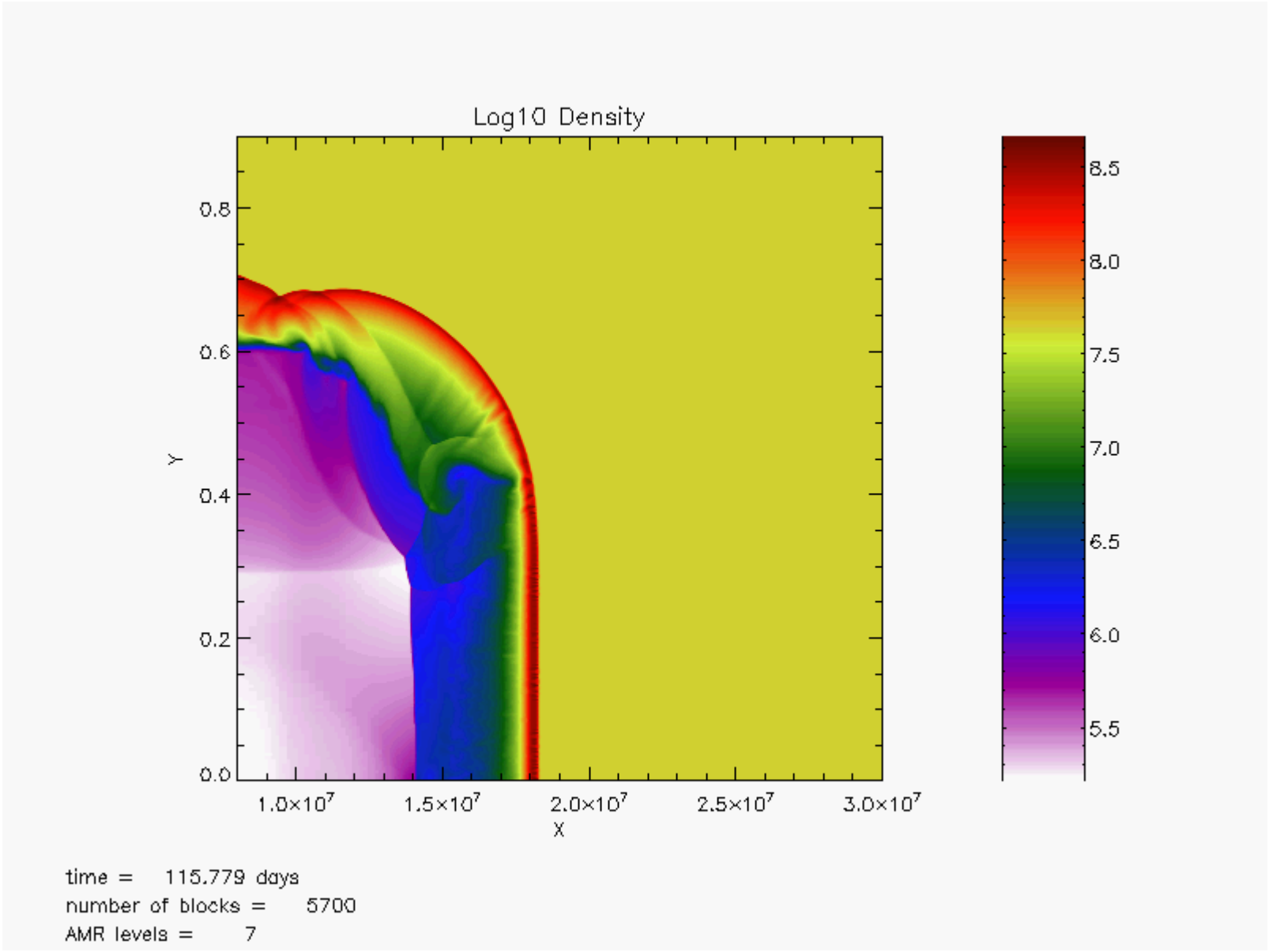
Decelerating Blastwave

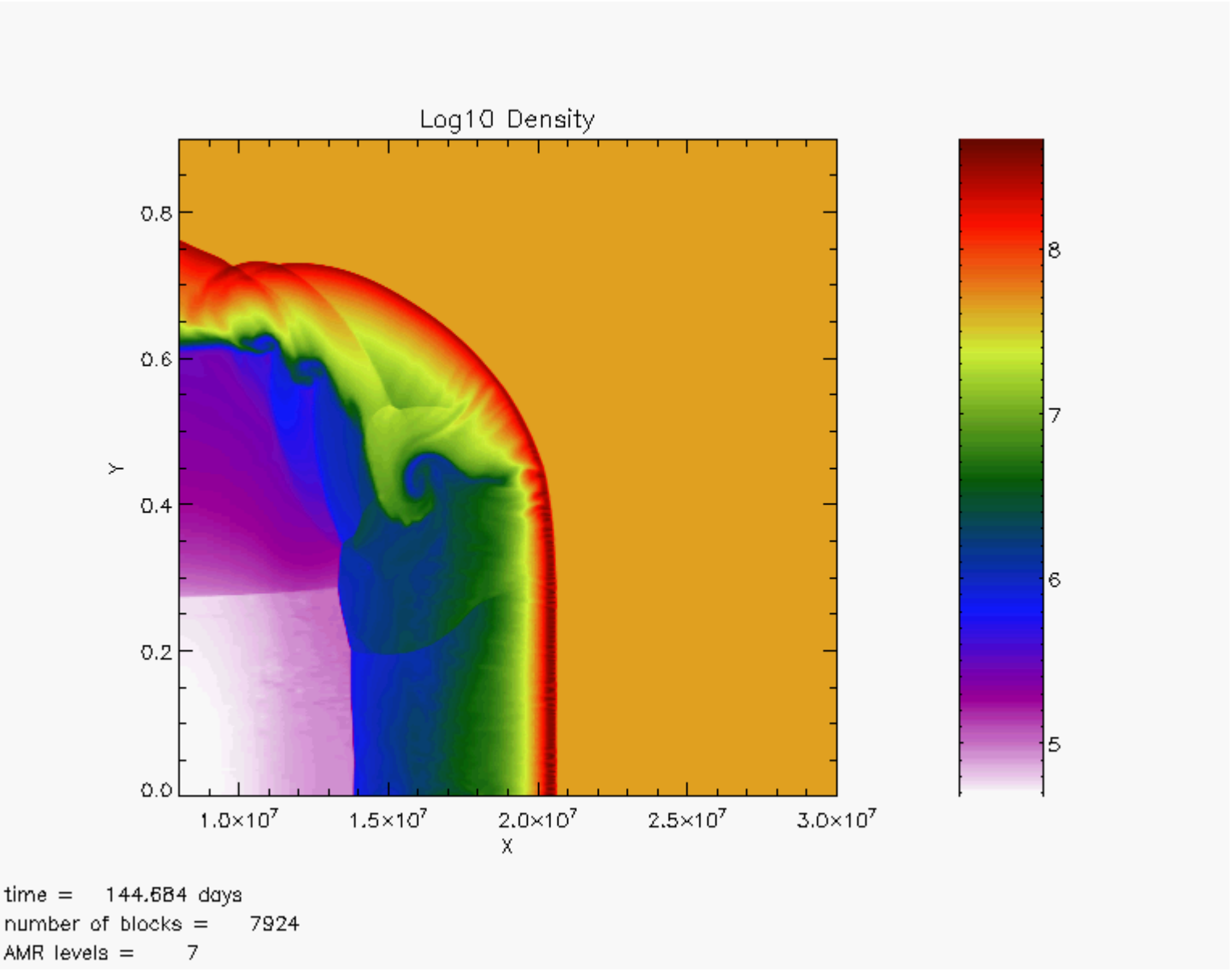


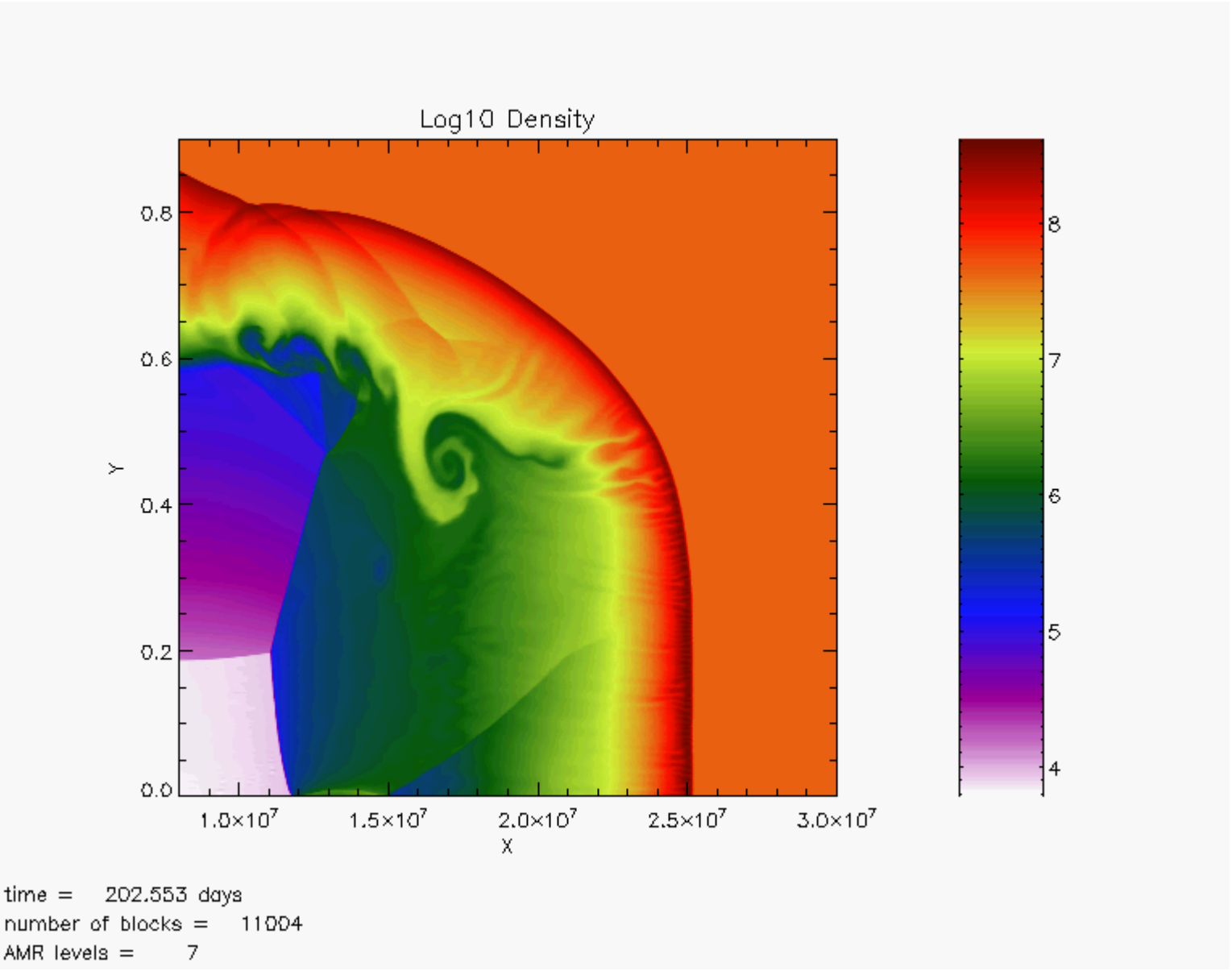


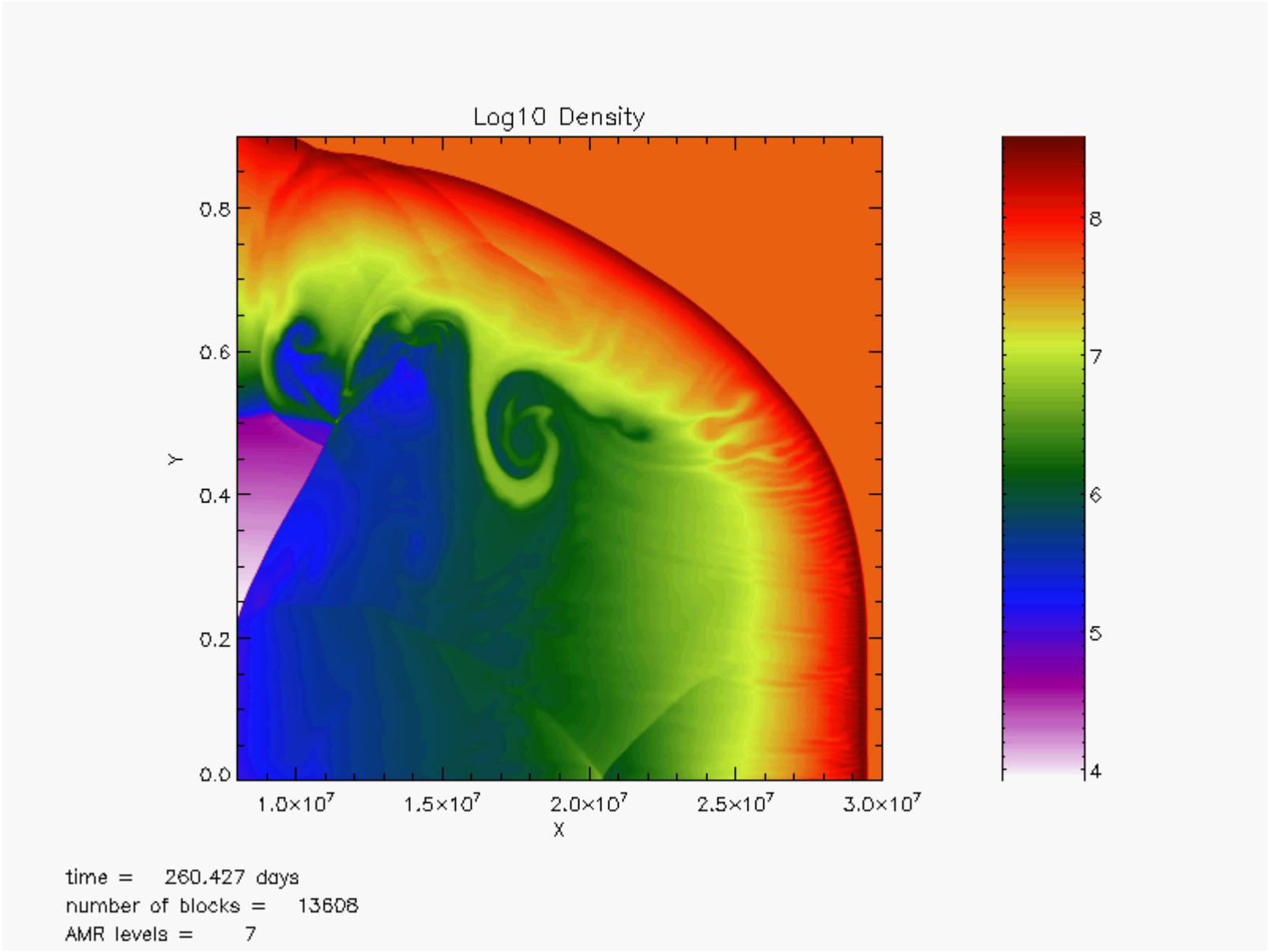

Log10 Density
0.8
0.6
0.4
0.2
0.0
Y
1.0×10^7
1.5×10^7
2.0×10^7
2.5×10^7
3.0×10^7
X
8.5
8.0
7.5
7.0
6.5
6.0
5.5
time = 57.882 days
number of blocks = 3384
AMR levels = 7

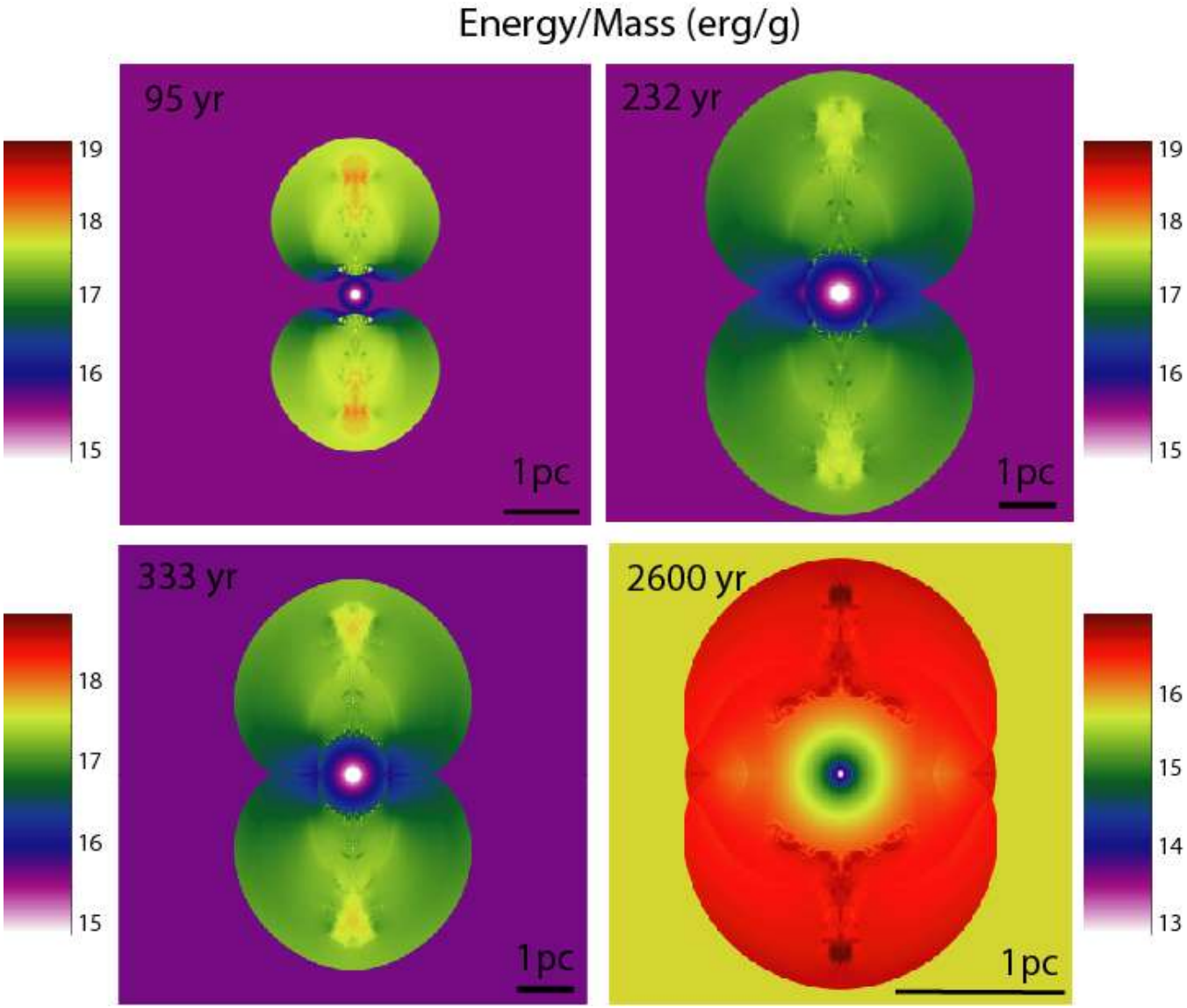

Log10 Density
0.8
0.6
0.4
0.2
0.0
Y
1.0×10^7
1.5×10^7
2.0×10^7
2.5×10^7
3.0×10^7
X
8.5
8.0
7.5
7.0
6.5
6.0
5.5
time = 86.850 days
number of blocks = 4136
AMR levels = 7


Log10 Density
0.8
0.6
0.4
0.2
0.0
Y
1.0×10^7
1.5×10^7
2.0×10^7
2.5×10^7
3.0×10^7
X
8.5
8.0
7.5
7.0
6.5
6.0
5.5
time = 115.779 days
number of blocks = 5700
AMR levels = 7


Log10 Density
0.8
0.6
0.4
0.2
0.0
Y
1.0×10^7
1.5×10^7
2.0×10^7
2.5×10^7
3.0×10^7
X
8
7
6
5
time = 144.684 days
number of blocks = 7924
AMR levels = 7

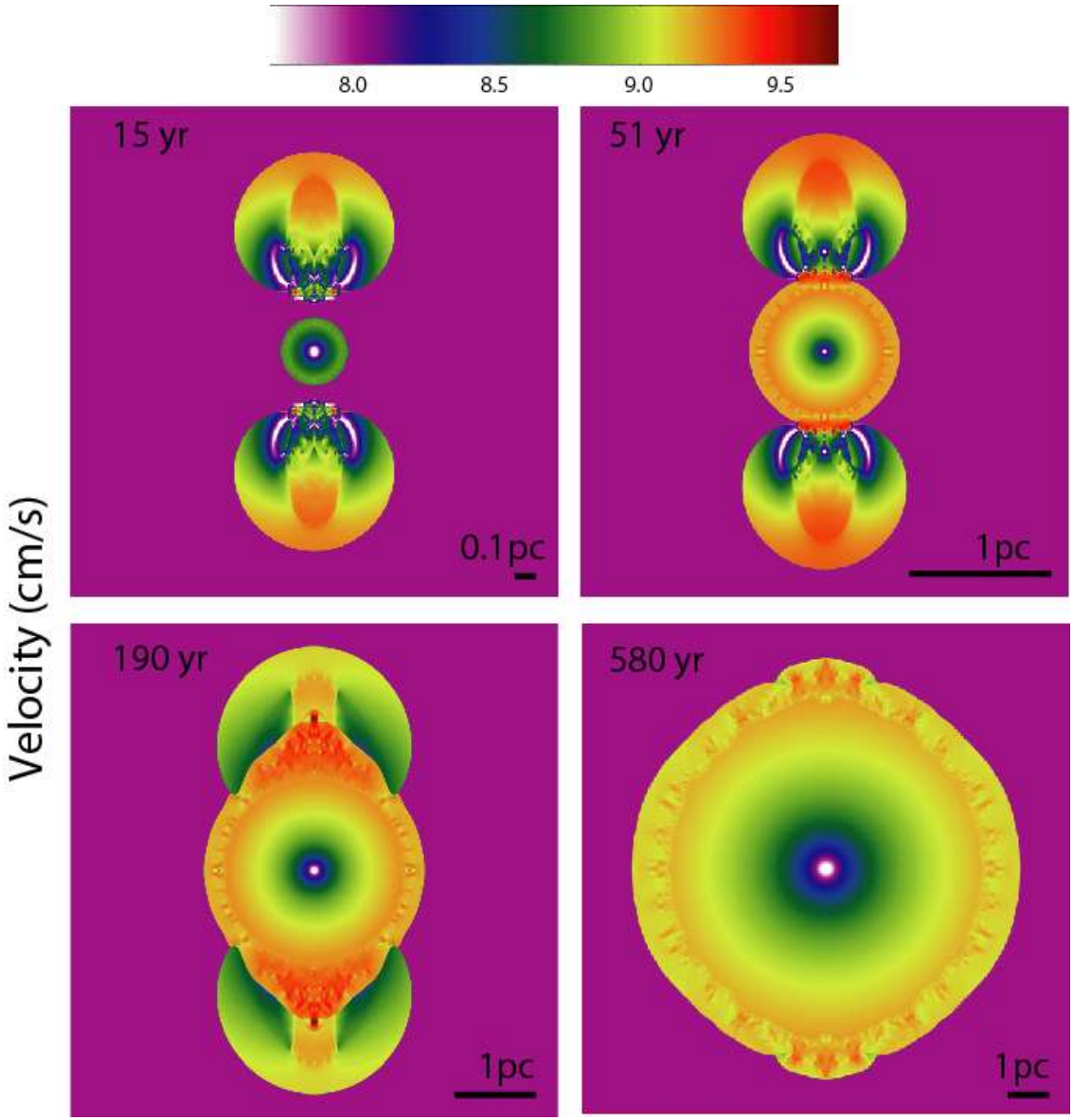

Log10 Density
0.8
0.6
0.4
0.2
0.0
Y
1.0×10^7
1.5×10^7
2.0×10^7
2.5×10^7
3.0×10^7
X
8
7
6
5
4
time = 202.553 days
number of blocks = 11004
AMR levels = 7

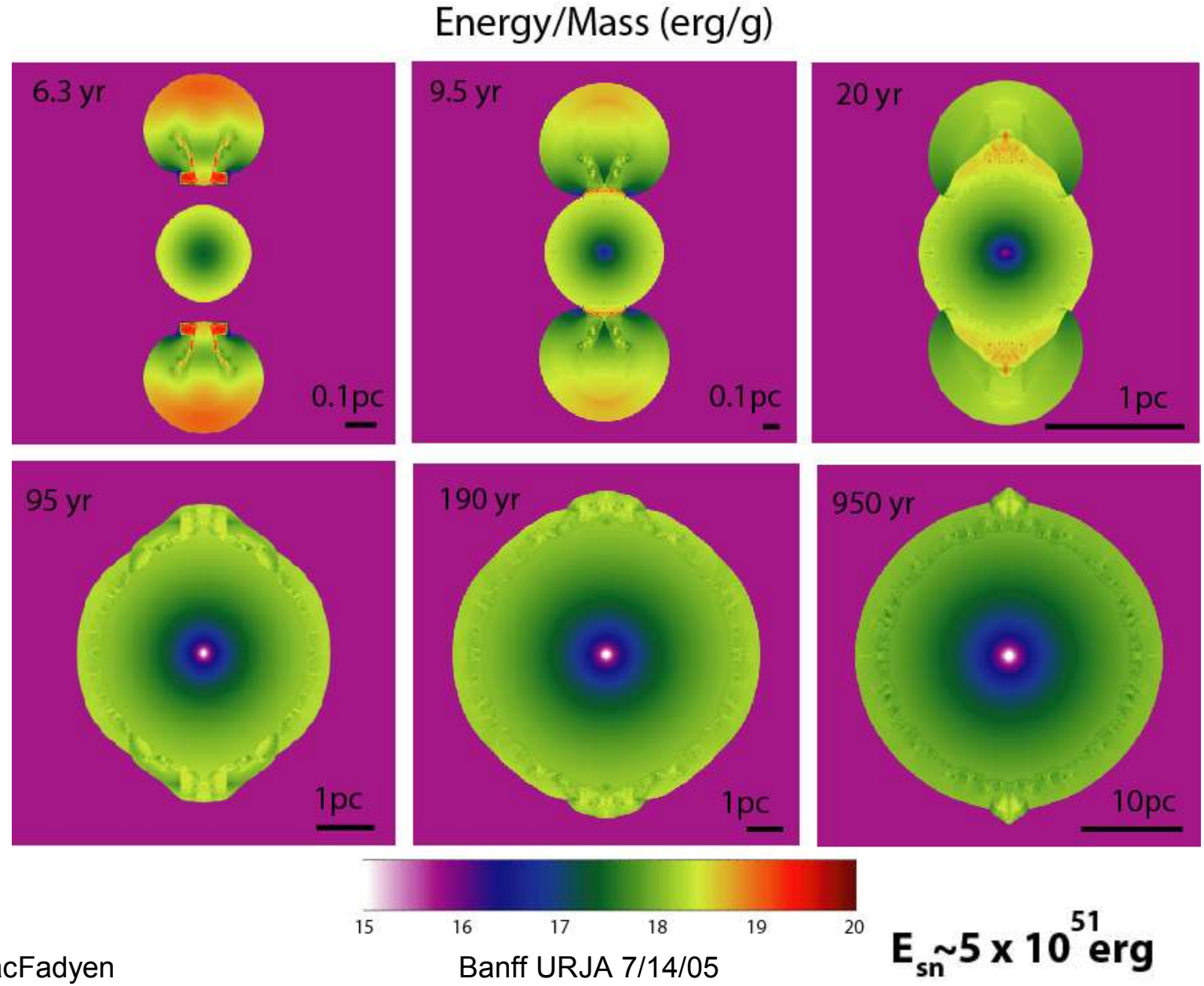

Log10 Density
0.8
0.6
0.4
0.2
0.0
Y
1.0×10^7
1.5×10^7
2.0×10^7
2.5×10^7
3.0×10^7
X
8
7
6
5
4
time = 260.427 days
number of blocks = 13608
AMR levels = 7



Ramirez-Ruiz & AM (2005)

Ayal & Piran (2001)


8.0
8.5
9.0
9.5
15 yr
0.1pc
51 yr
1pc
190 yr
1pc
580 yr
1pc
Velocity (cm/s)



A. MacFadyen

Banff URJA 7/14/05

Conclusions

- New SR AMR code RAM
- Microphysics:photodis., neutrinos, EOS
- 1D fireball acceleration
- Transition to Non-Relativistic BM
- Collapsar: BH + jet inside star
- Thin shells require high resolution
- 2D jet spreading