Collapsar Jets

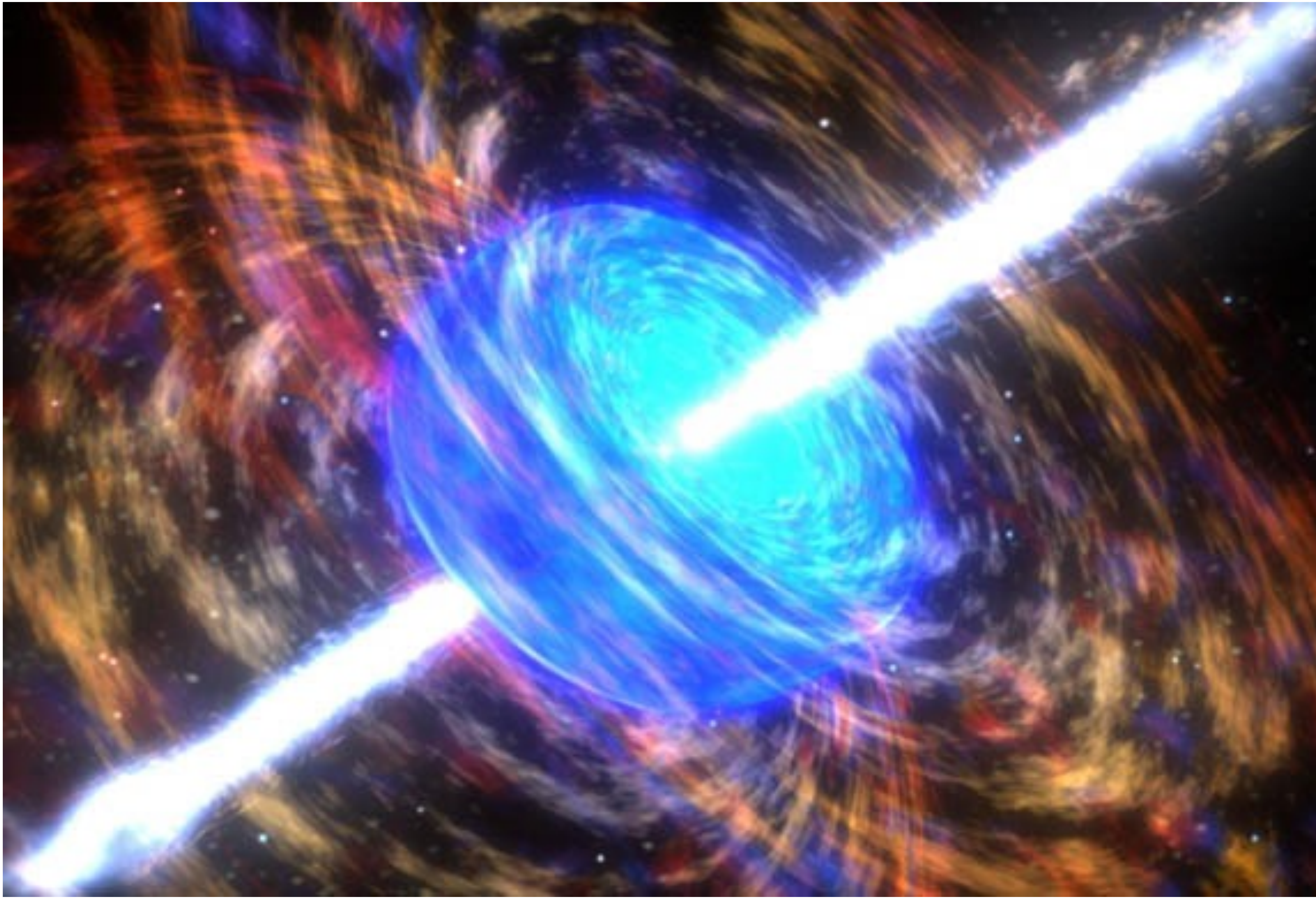
The Dynamics and Radiation of relativisitc jets using a **moving mesh**

Andrew MacFadyen (New York University)

Paul Duffell, Geoff Ryan, Hendrik van Eerten

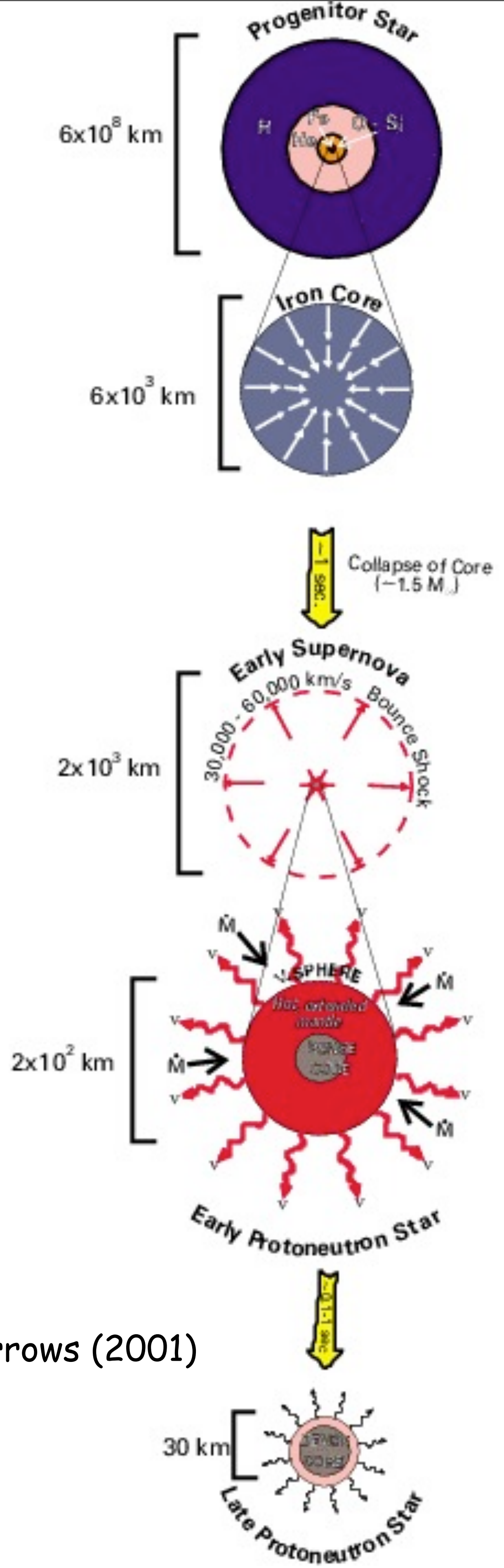
INT Workshop 14-56W, U.Wash. July 28, 2014

Duffell&AM (2011,2012,2014ab),
Ryan, van Eerten &AM (2014)

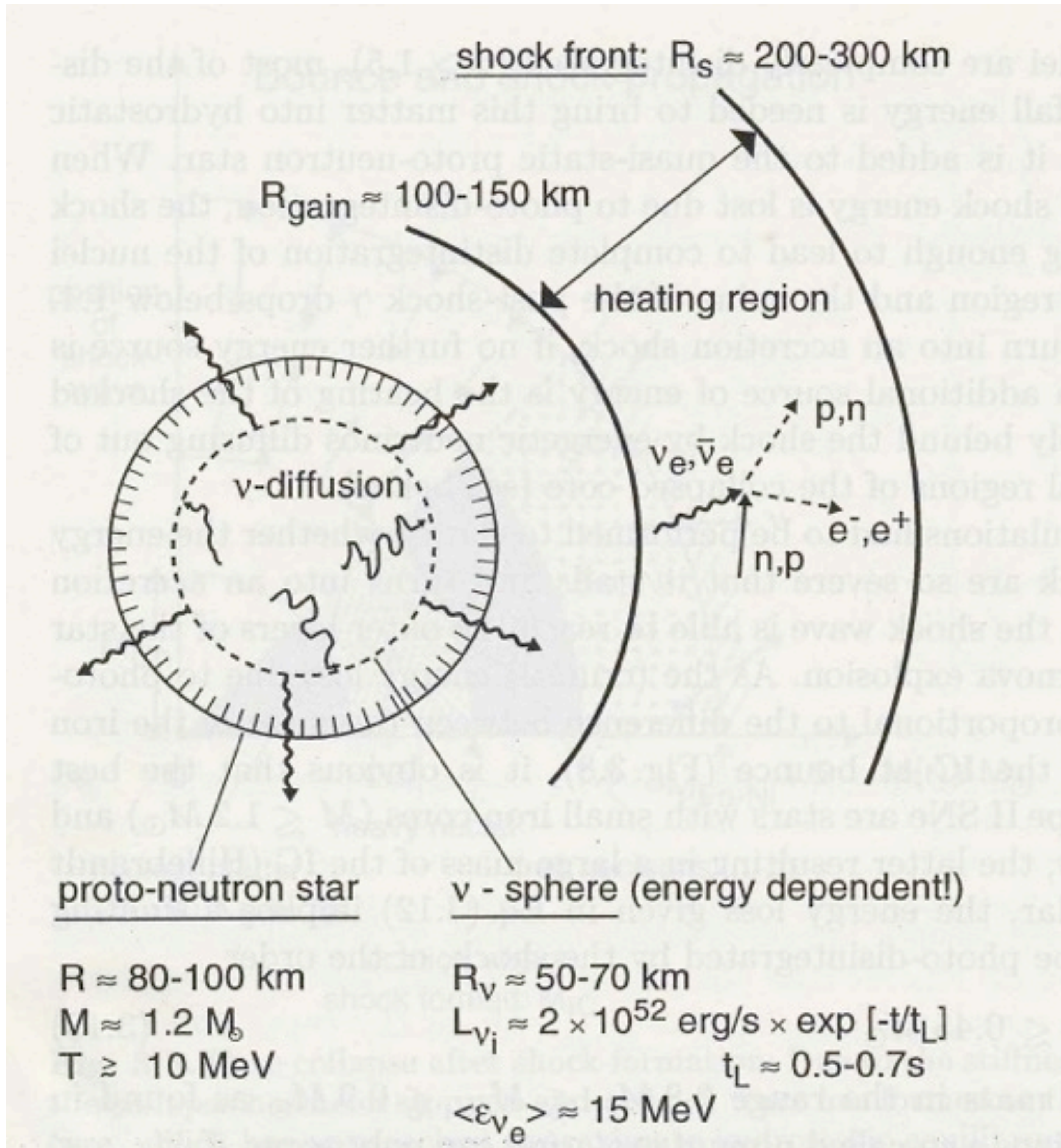


“Delayed” SN Explosion

Accretion vs. Neutrino heating

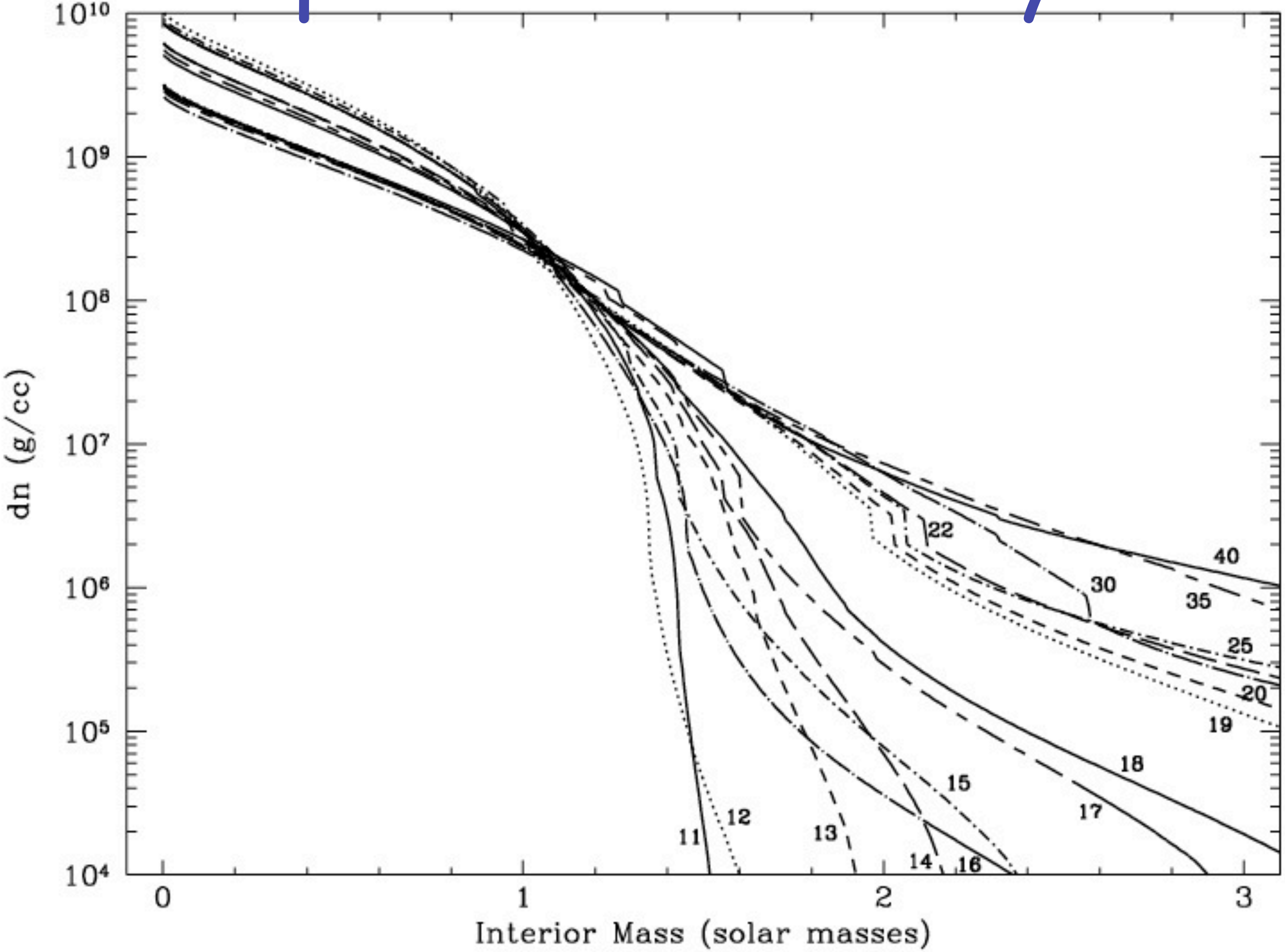


Burrows (2001)



Muller (1999)

Pre-Supernova Density Structure



Bigger stars:

Higher entropy

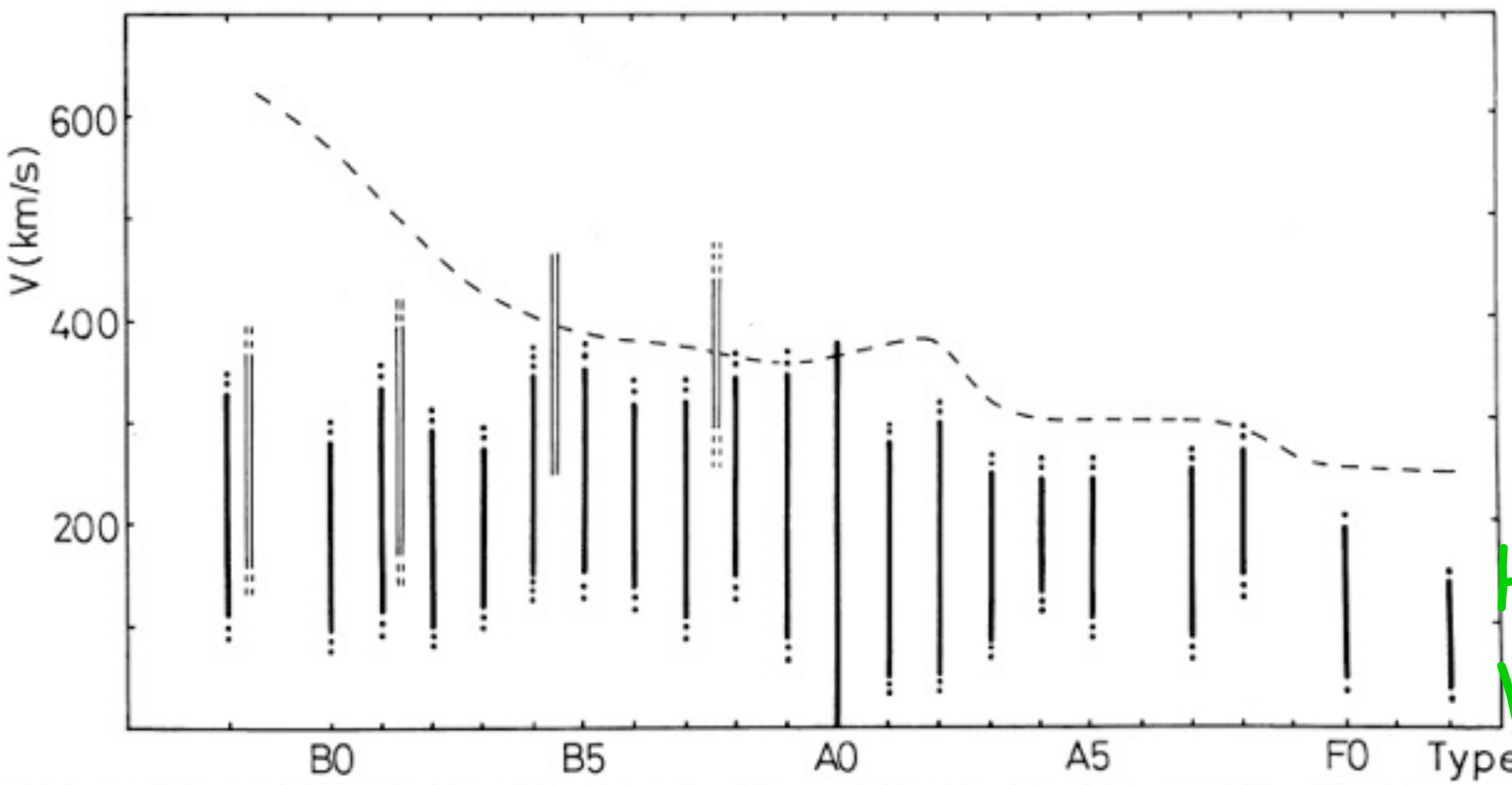
Shallower density gradients

Woosley & Weaver (1995)

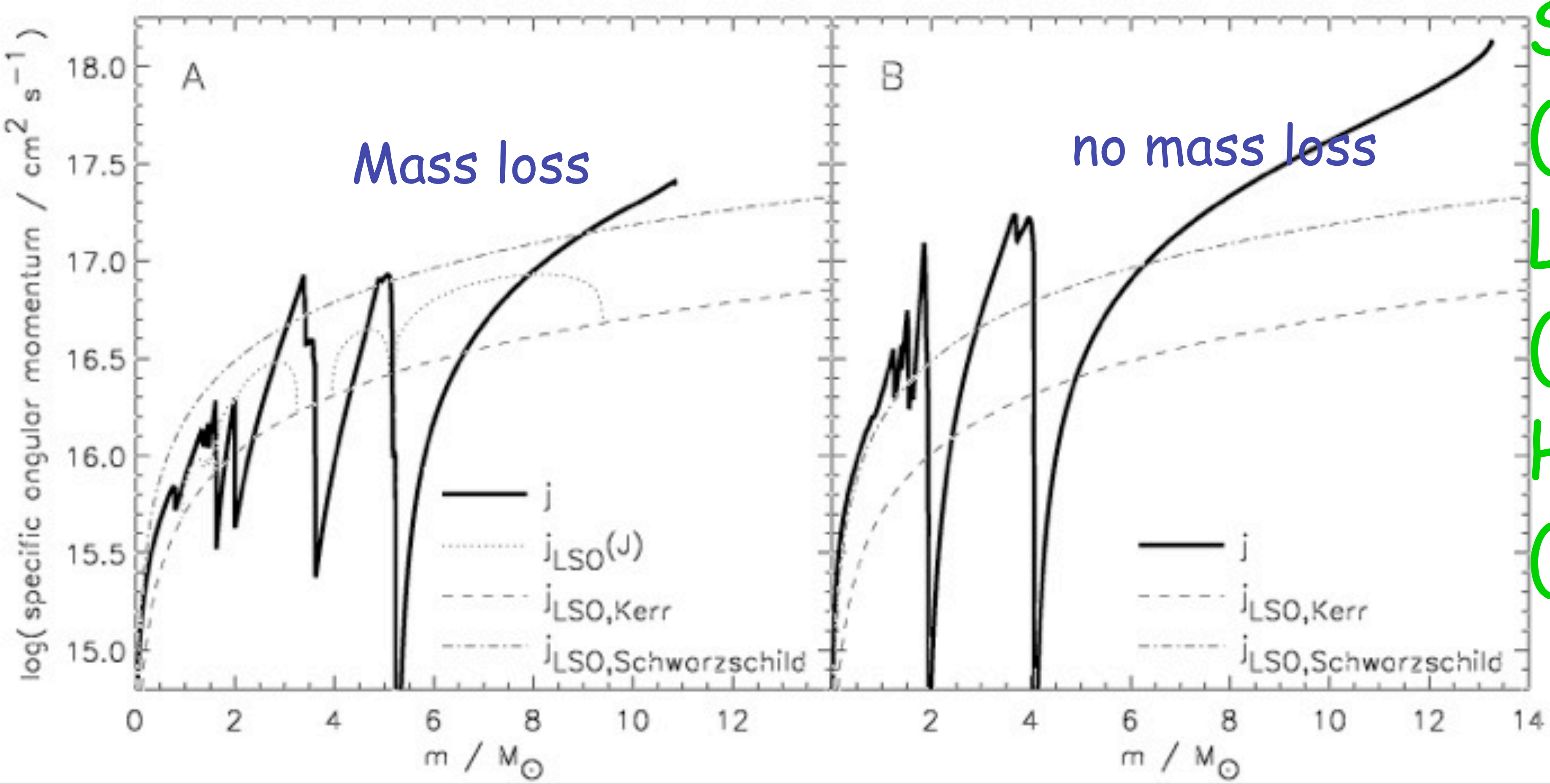
Stellar Rotation

Mass loss removes angular momentum

Low metallicity helps keep Ang. Mom.



Fukuda (1982)



Heger, Woosley & Spruit (2000,2005), Langer&Yoon (2006), Hirschi et al (2008)

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

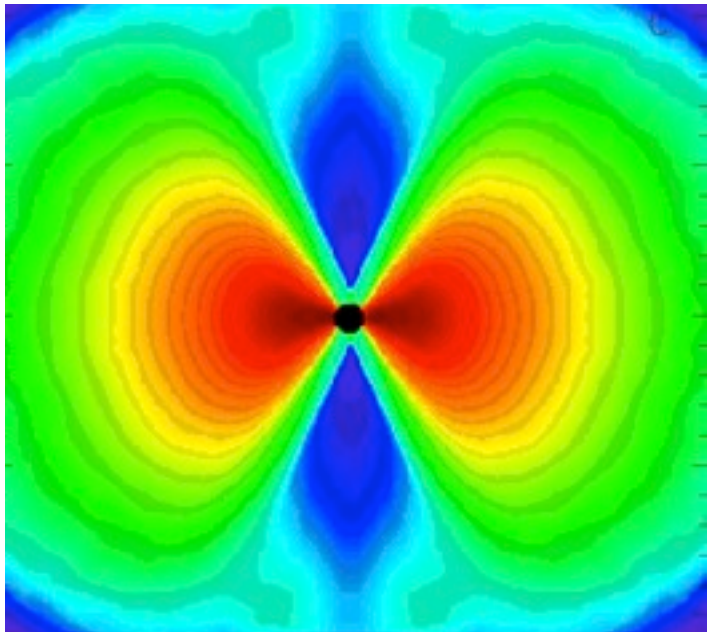
Rapidly accreting black hole, ($\dot{M} \sim 0.1\ M_\odot/s$)

fed by collapsing star ($t_{dyn} \sim 446\ s/\ \rho^{\frac{1}{2}} \sim 10\ s$)

Disk formation

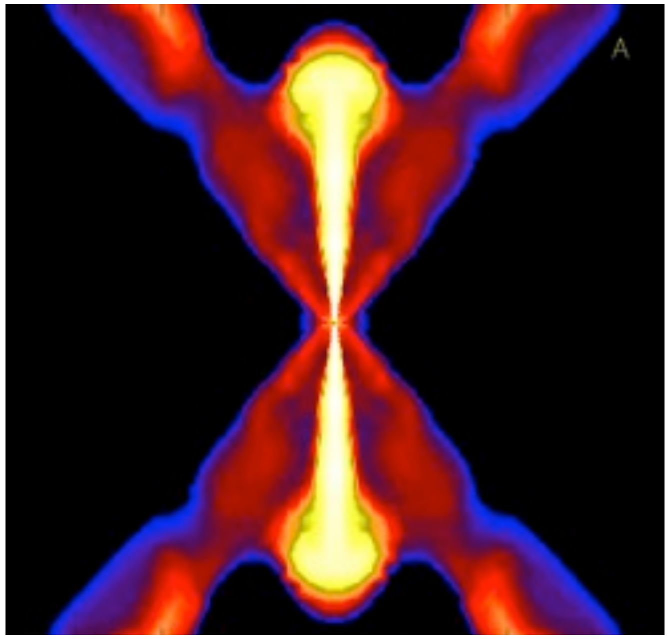
⇒ **COLLAPSAR**

Collapsar - Disk and Jet

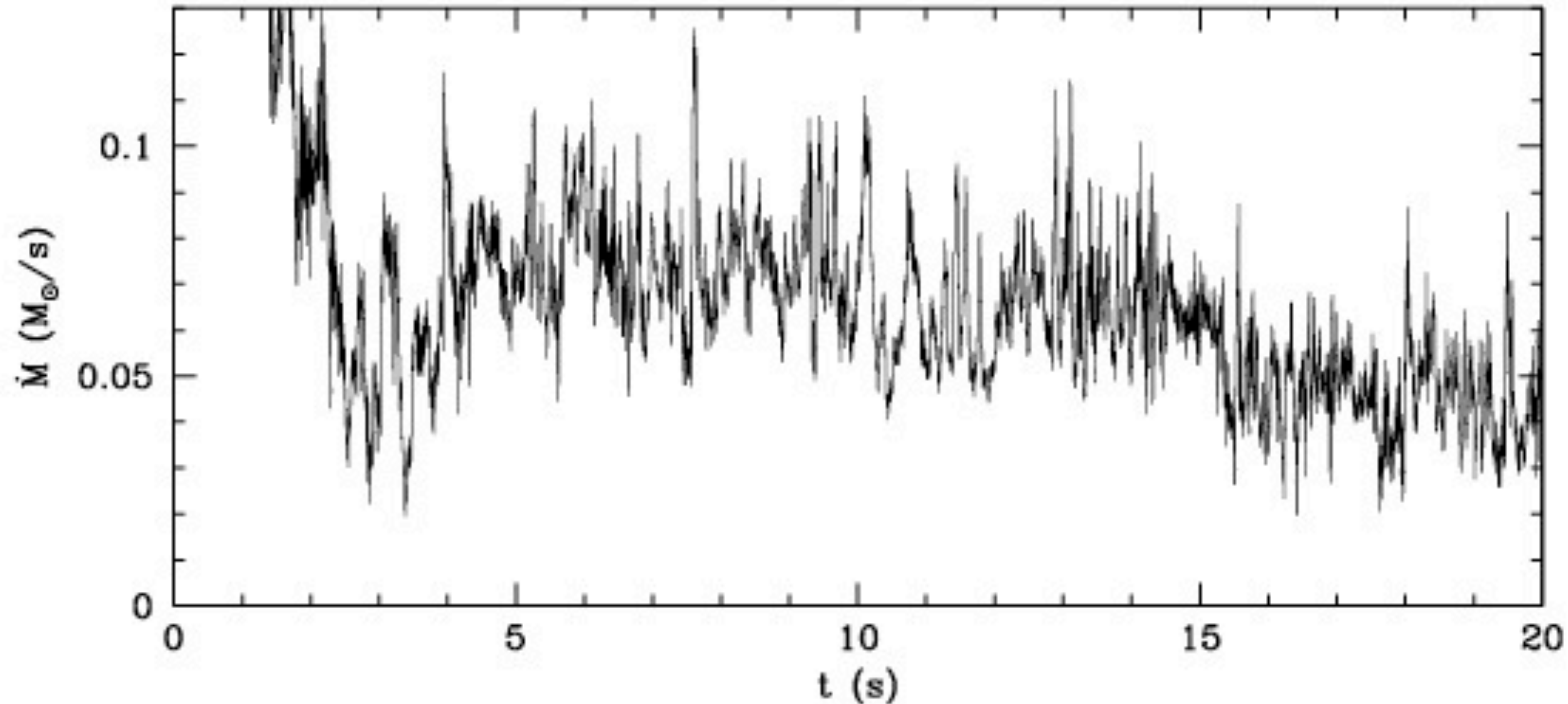


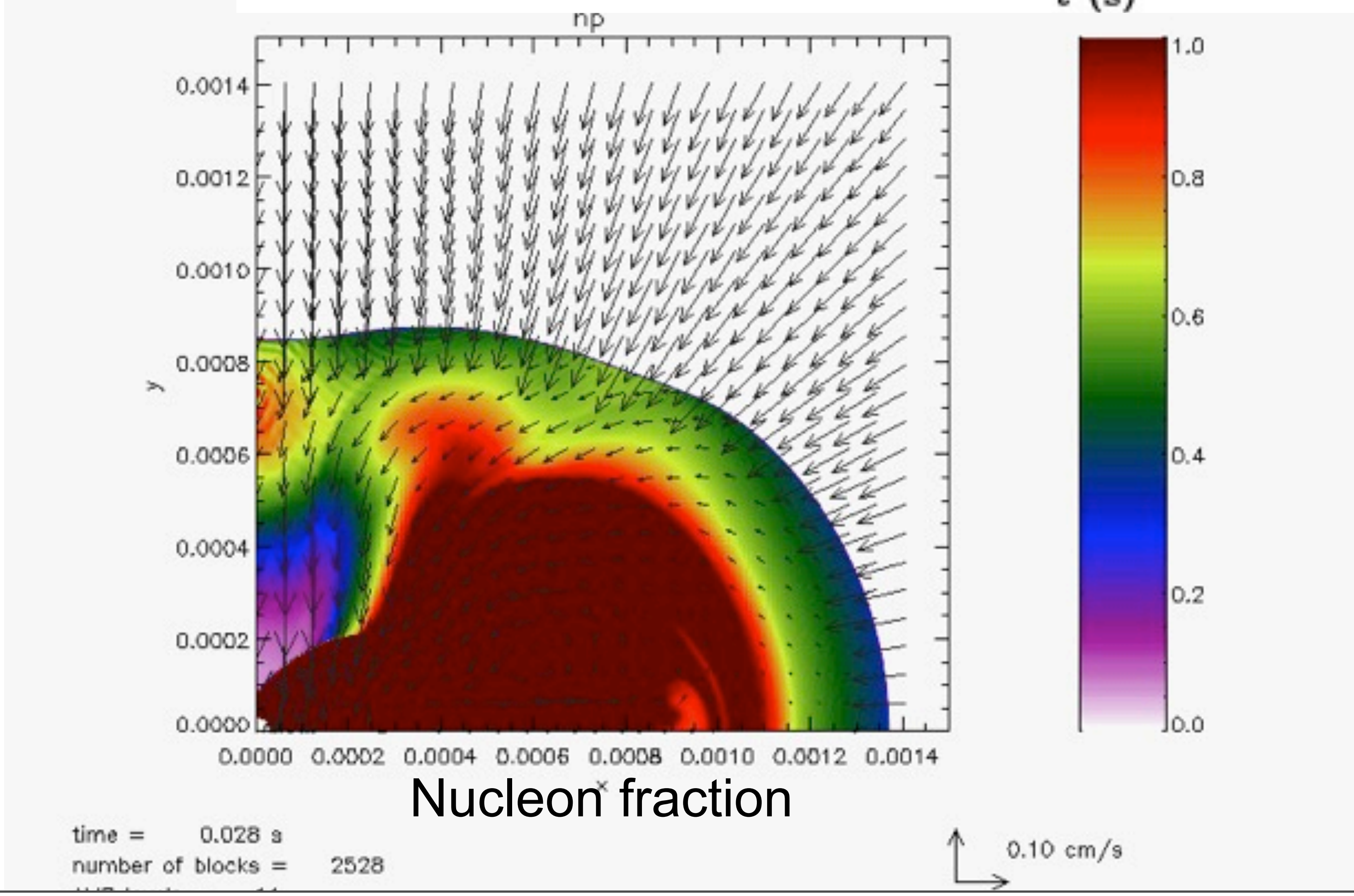
- pre-SN 15 Msun Helium star
- Newtonian Hydrodynamics (PPM)
- alpha viscosity
- rotation
- photodisintegration (NSE alpha, n, p)
- neutrino cooling, thermal + URCA optically thin
- Ideal nucleons, radiation, relativistic degenerate electrons, positions
- 2D axisymmetric, spherical grid
- self gravity
- R_{in} = 9 R_s R_{out} = 9000 R_s

See talks by Fryer and McLaughlin

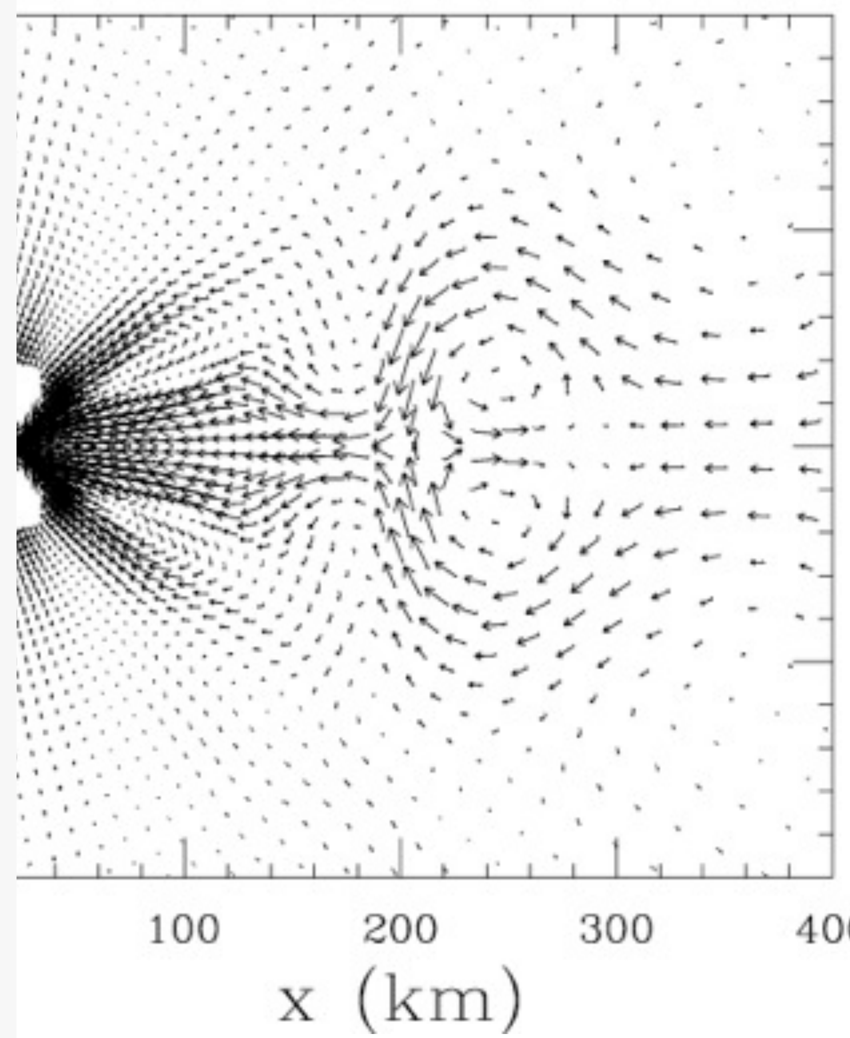


$\alpha = 0.1$ $\langle \dot{M} \rangle = 0.07\ M_{sun}/s = 1.3 \times 10^{53}$ erg/s





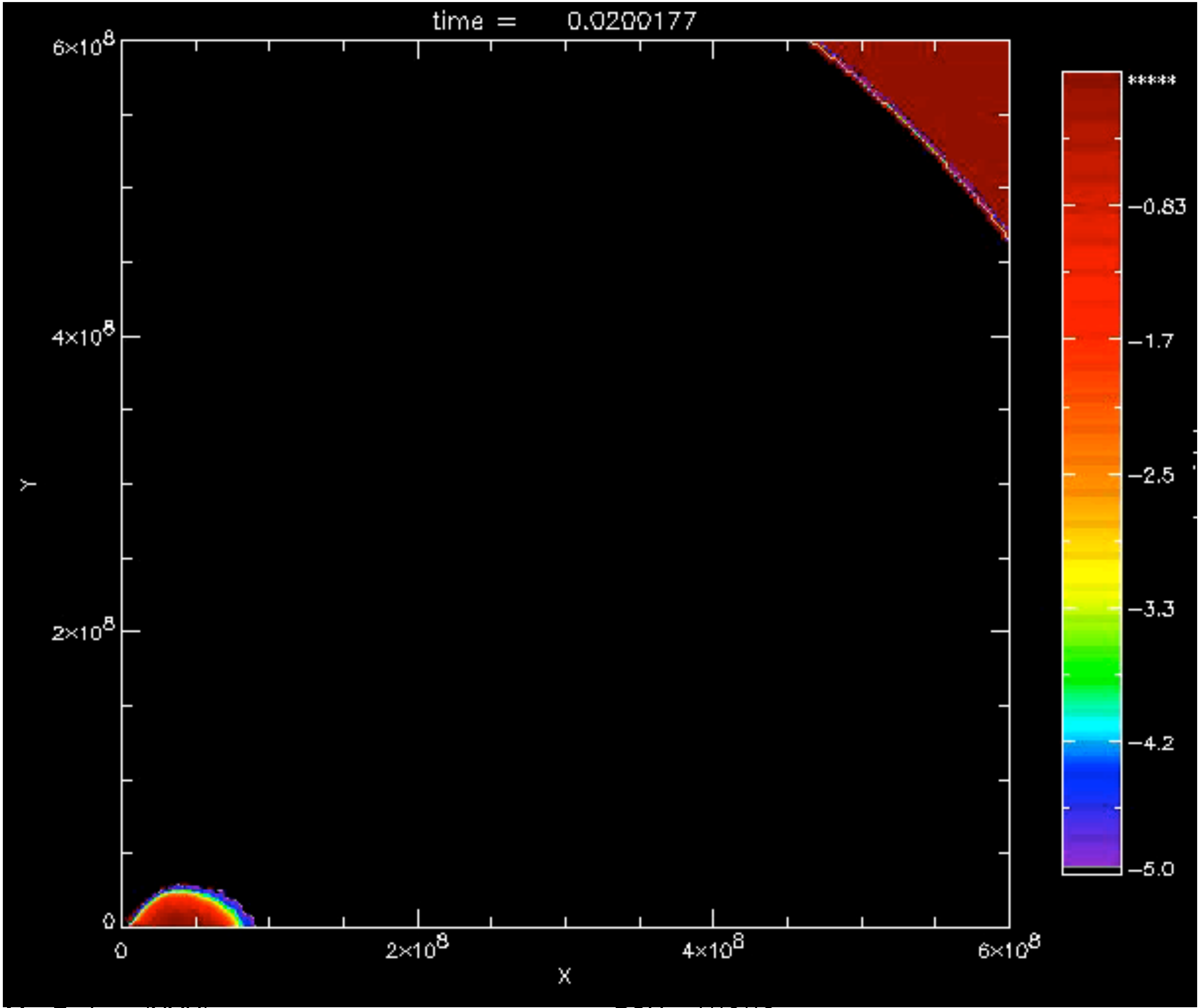
Nucleon fraction



"Nickel Wind"

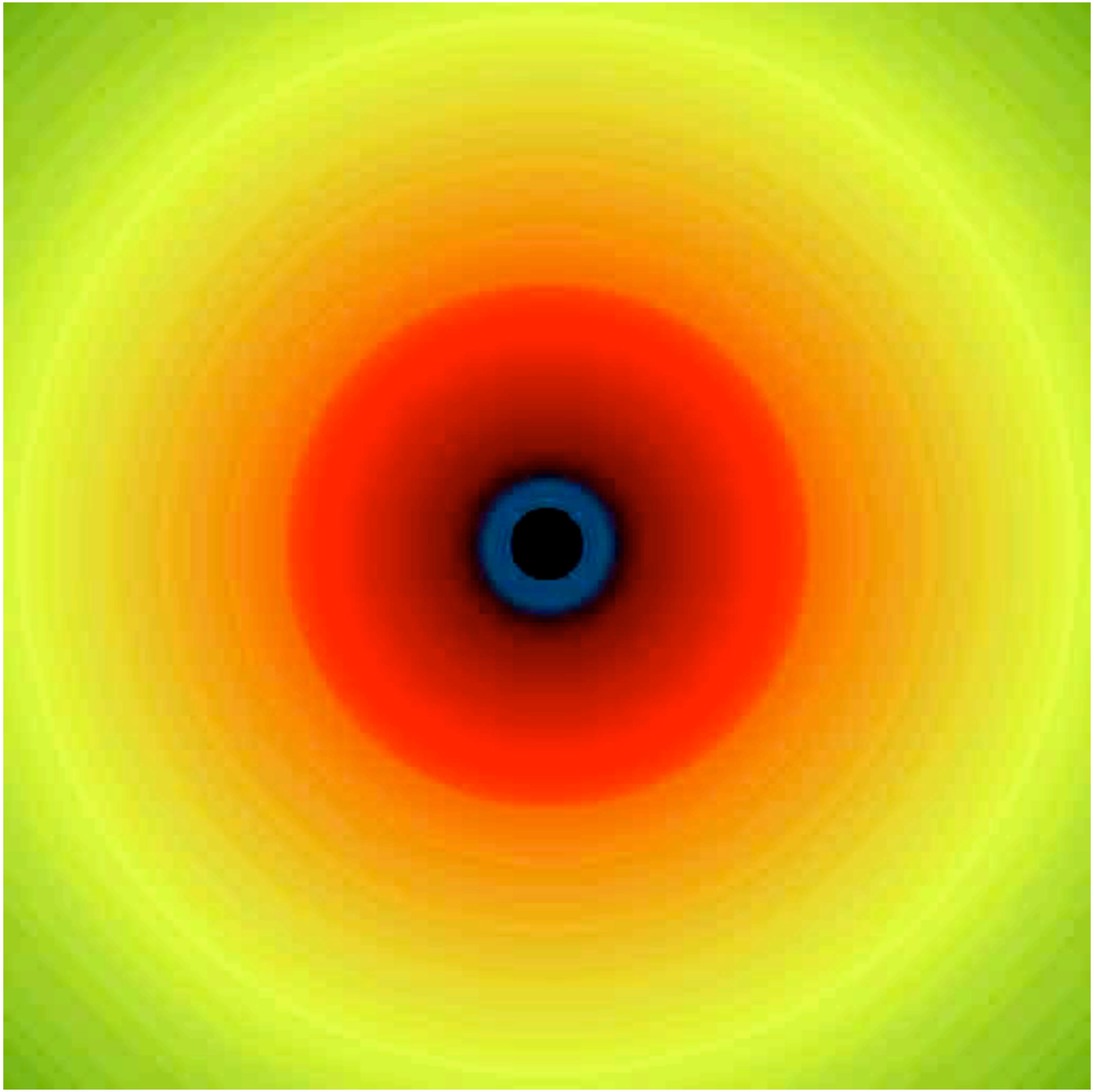
Nickel Wind Movie

$T > 5 \times 10^9$ K


time = 0.0200177
6×10^8
4×10^8
2×10^8
0
Y
X
*****
−0.83
−1.7
−2.5
−3.3
−4.2
−5.0

AMR
jet+wind

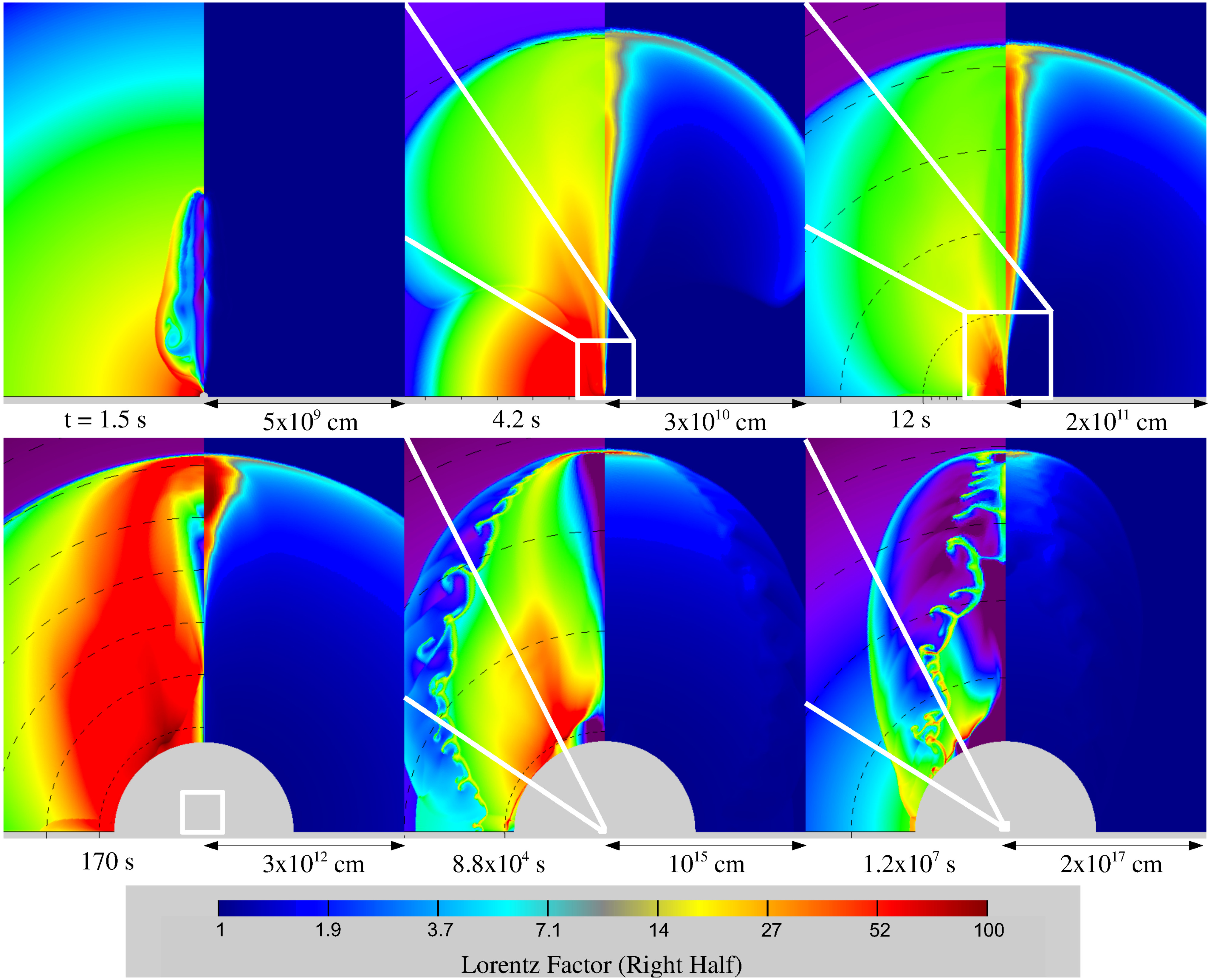
AM&Zhang
(2009)



AMR
jet+wind

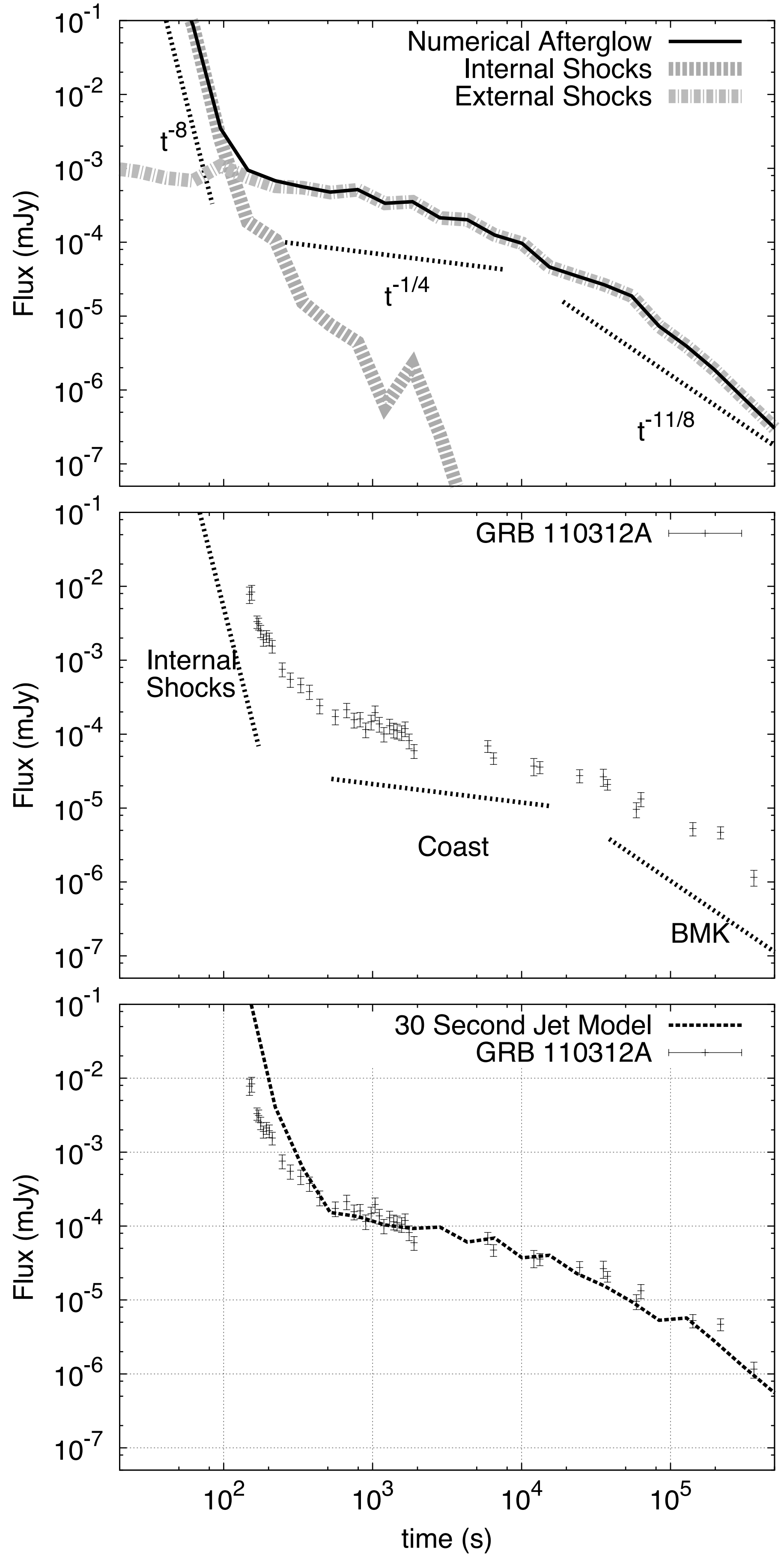
AM&Zhang
(2009)

Collapsars: From Engine to Afterglow



Duffell & AM, in prep

A. MacFadyen (NYU)



Duffell & AM, in prep

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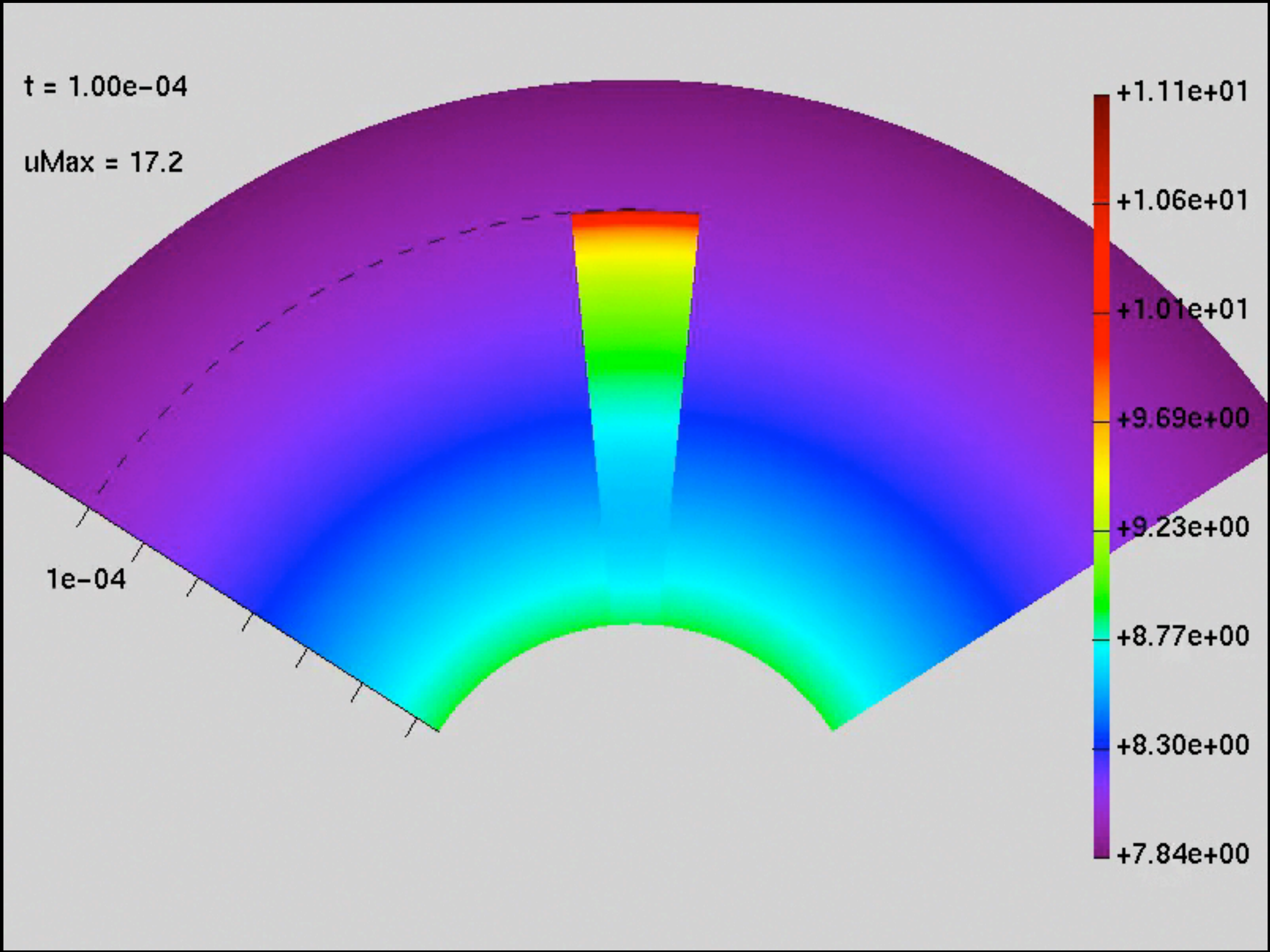
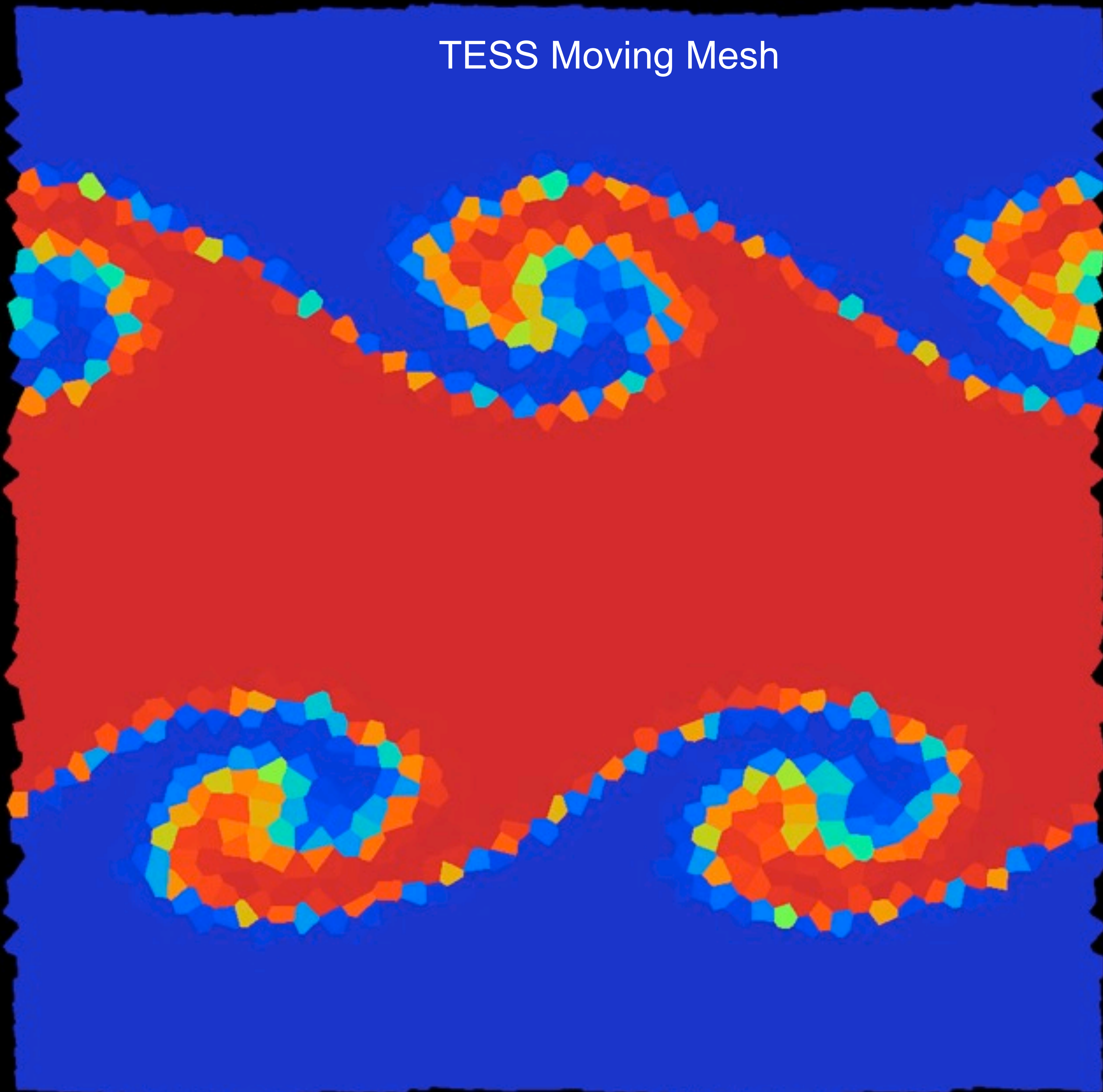
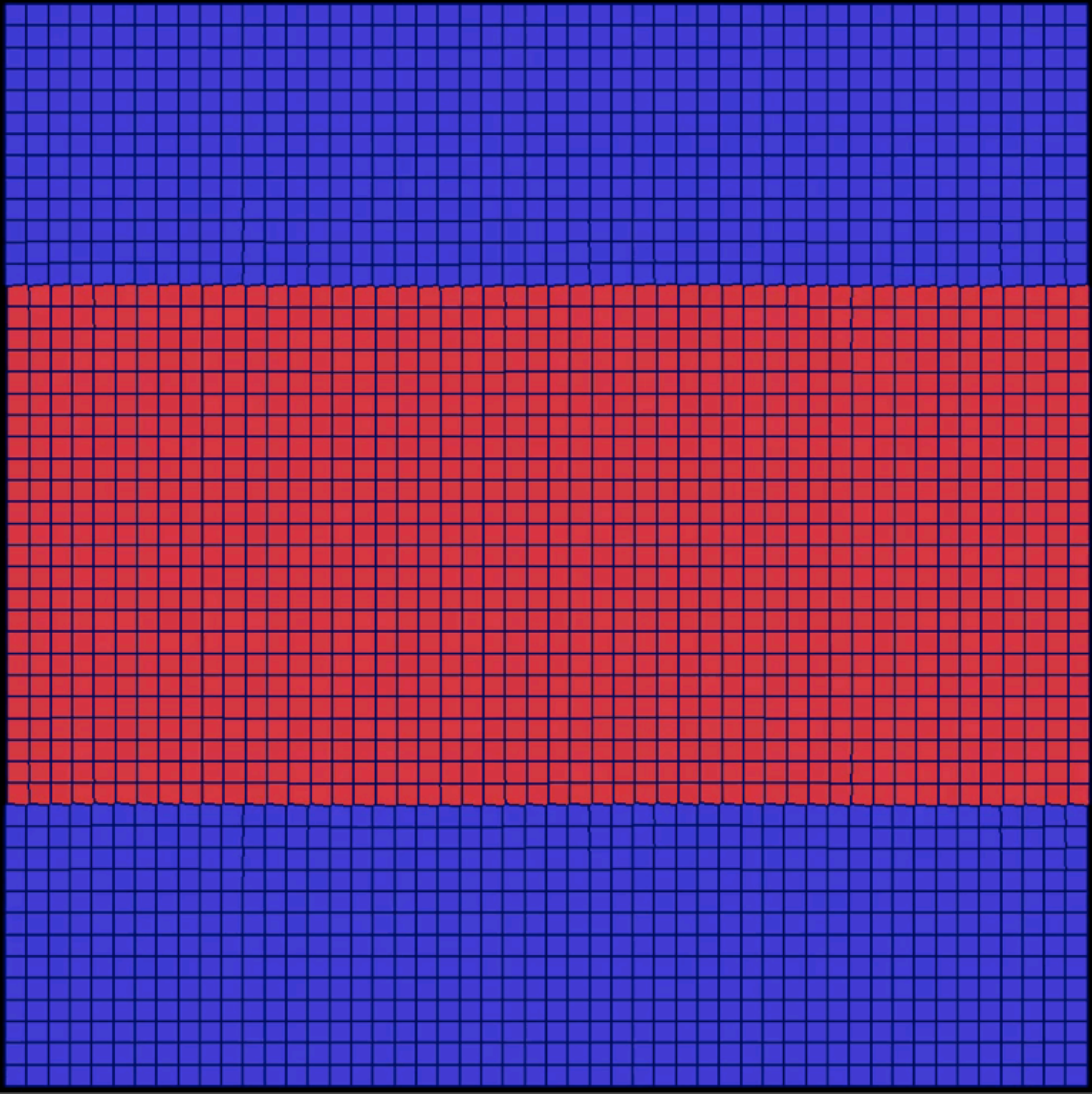

t = 1.00e-04
uMax = 17.2
1e-04
+1.11e+01
+1.06e+01
+1.01e+01
+9.69e+00
+9.23e+00
+8.77e+00
+8.30e+00
+7.84e+00

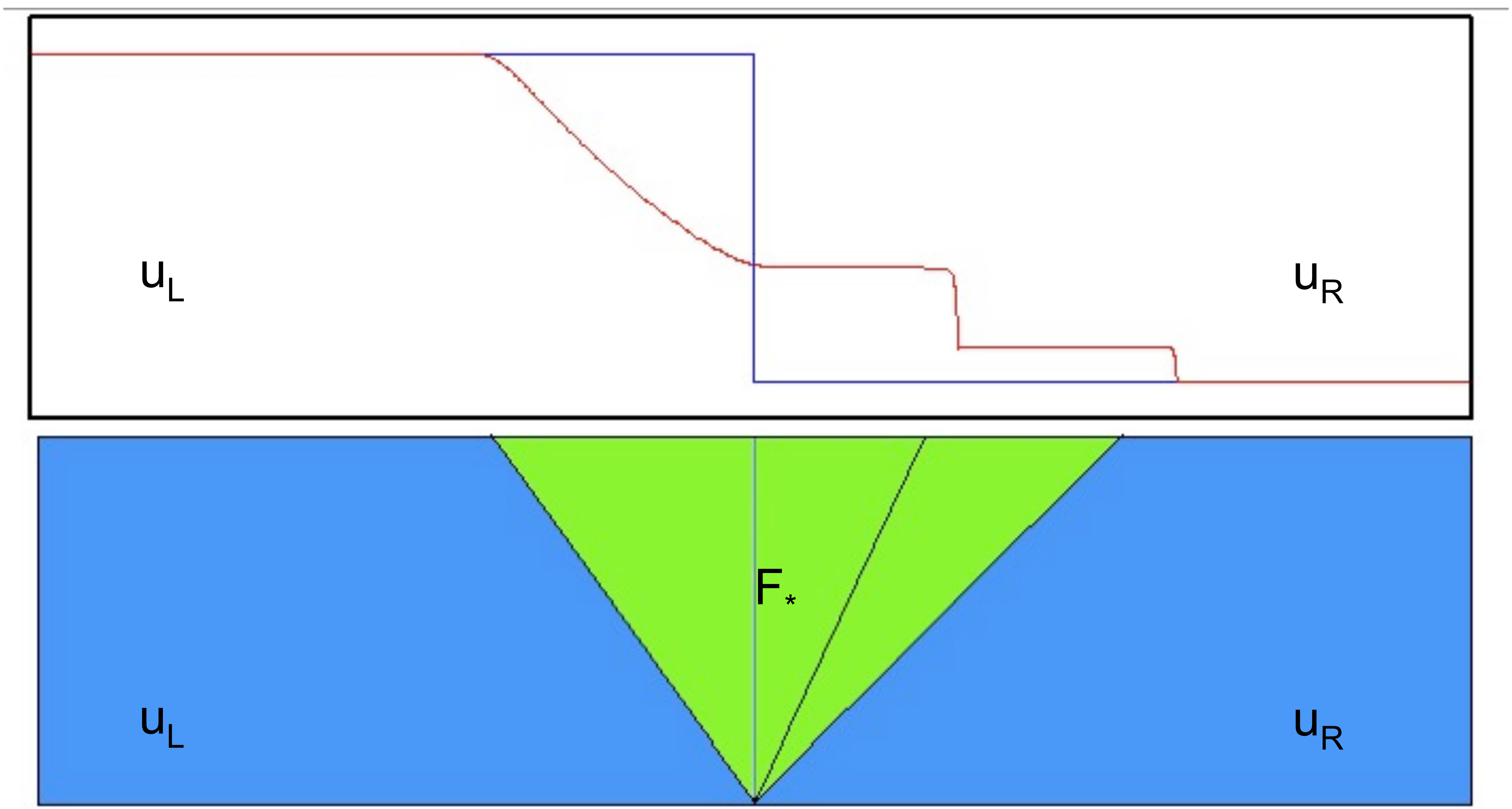
Hydrodynamics on a dynamic Voronoi Mesh

- Borgers & Peskin (JCP, 1987) - Incompressible Navier-Stokes - Physiology
- Springel (2010) - Compressible Euler - cosmology - “Arepo”
- Duffell & MacFadyen (2011) - Relativistic MHD - astrophysics - “Tess”

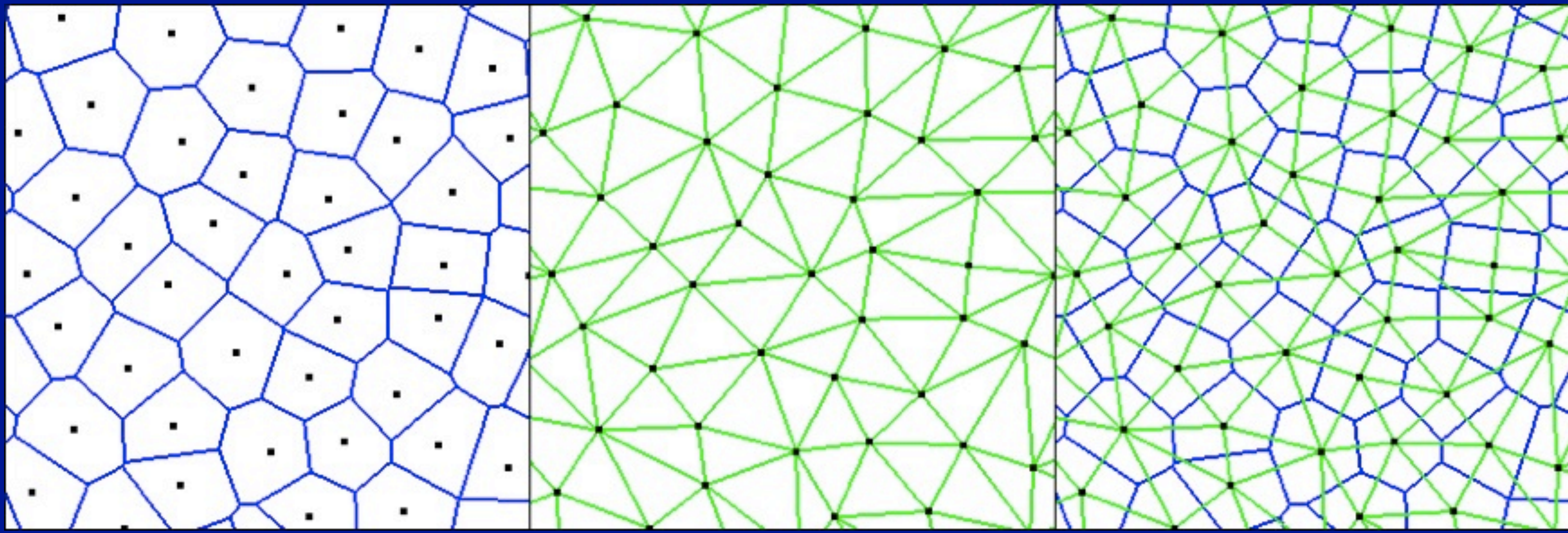

TESS Moving Mesh



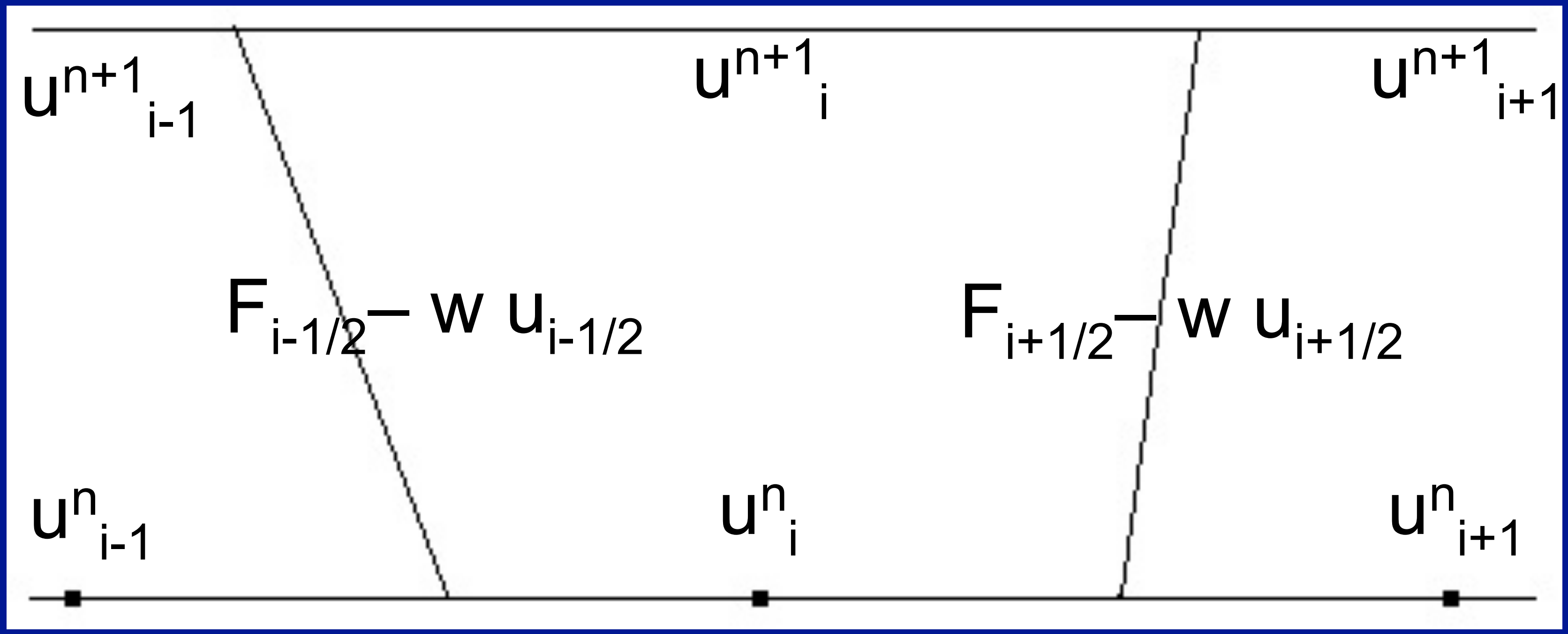
Numerical Methods for Solving Conservation Laws



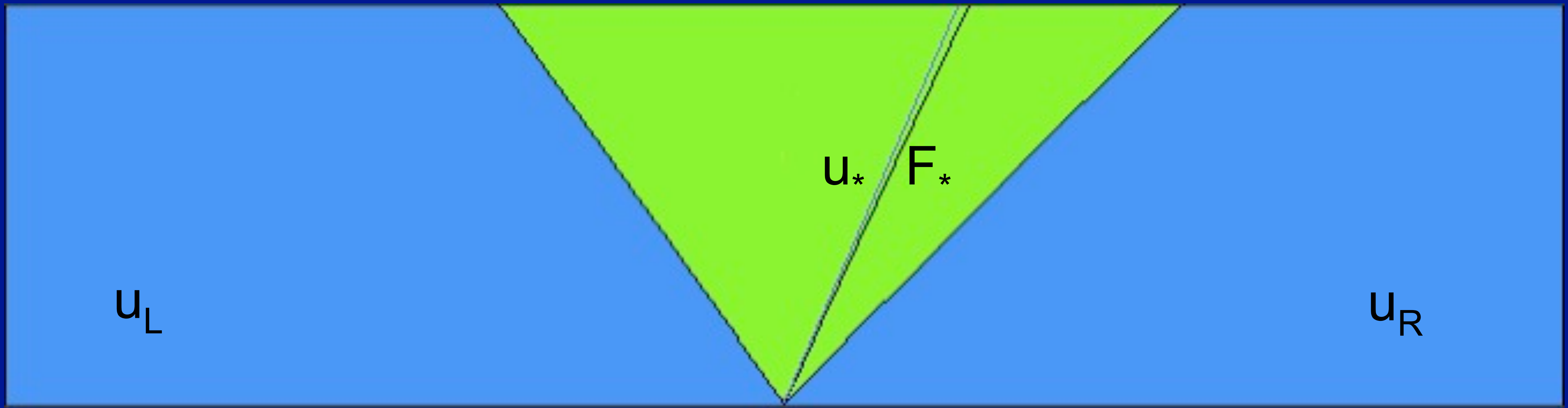
TESS: Lagrangian Hydrodynamics using a Dynamic Voronoi Mesh

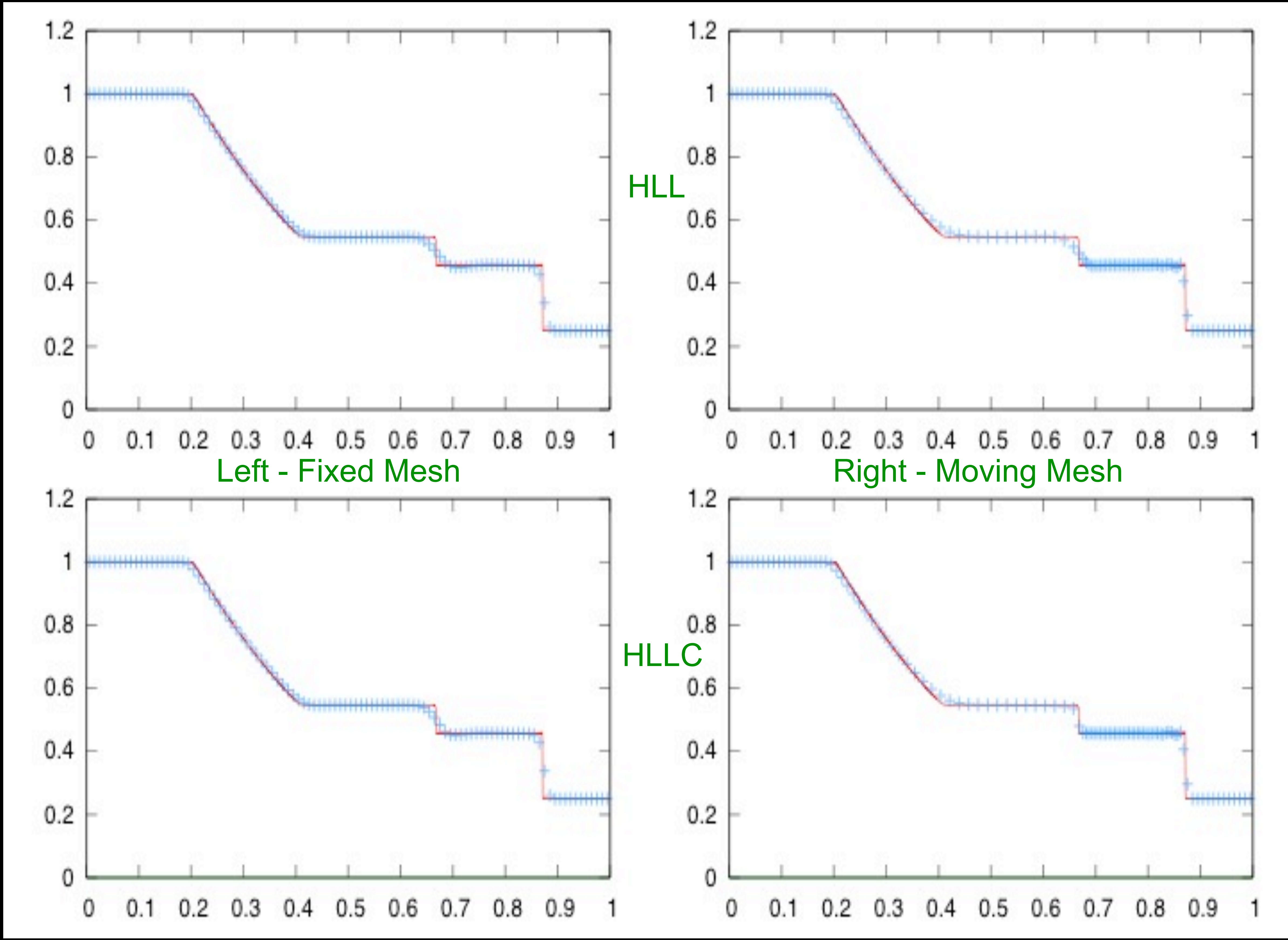


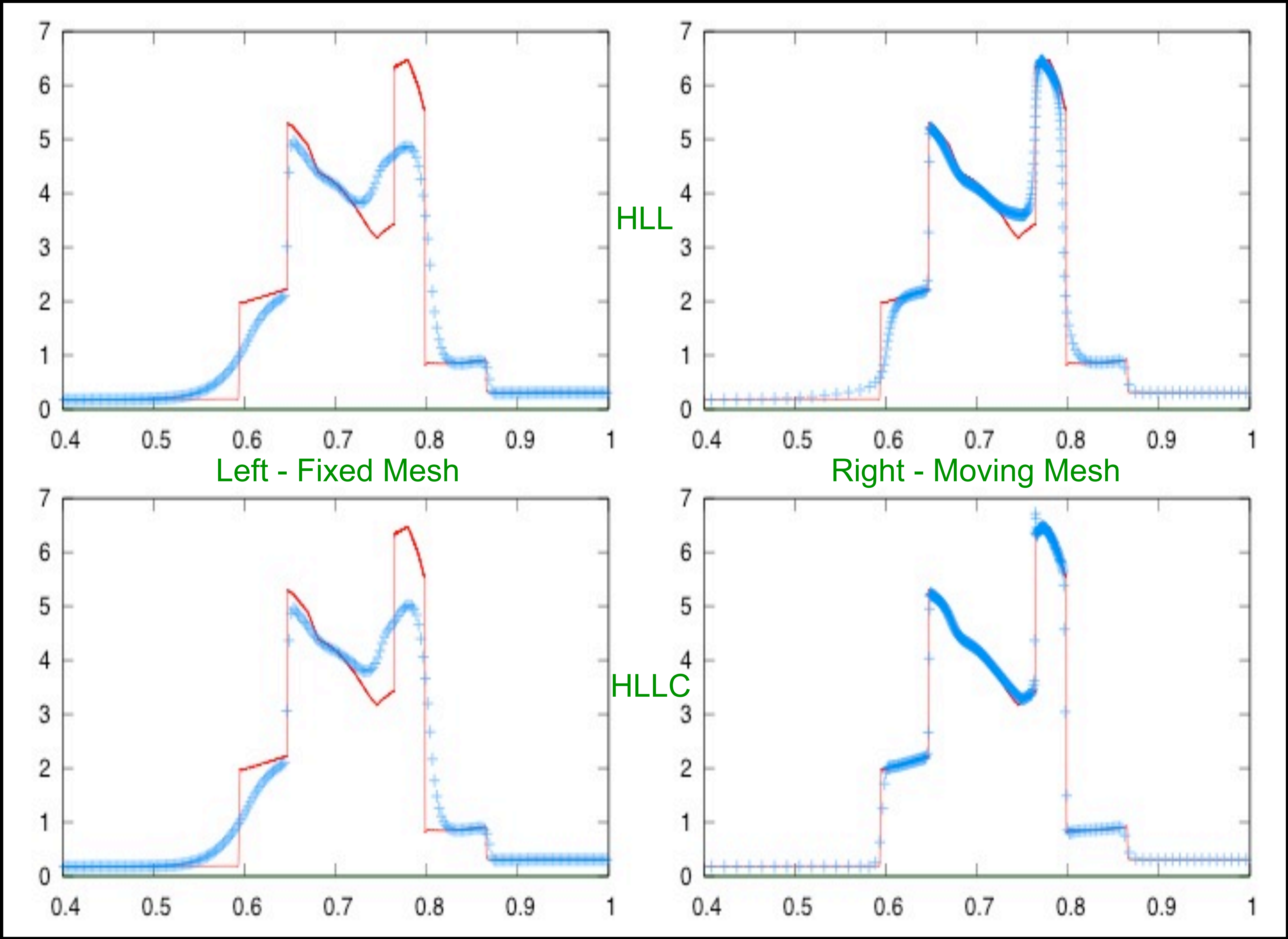
TESS: Lagrangian Hydrodynamics using a Dynamic Voronoi Mesh

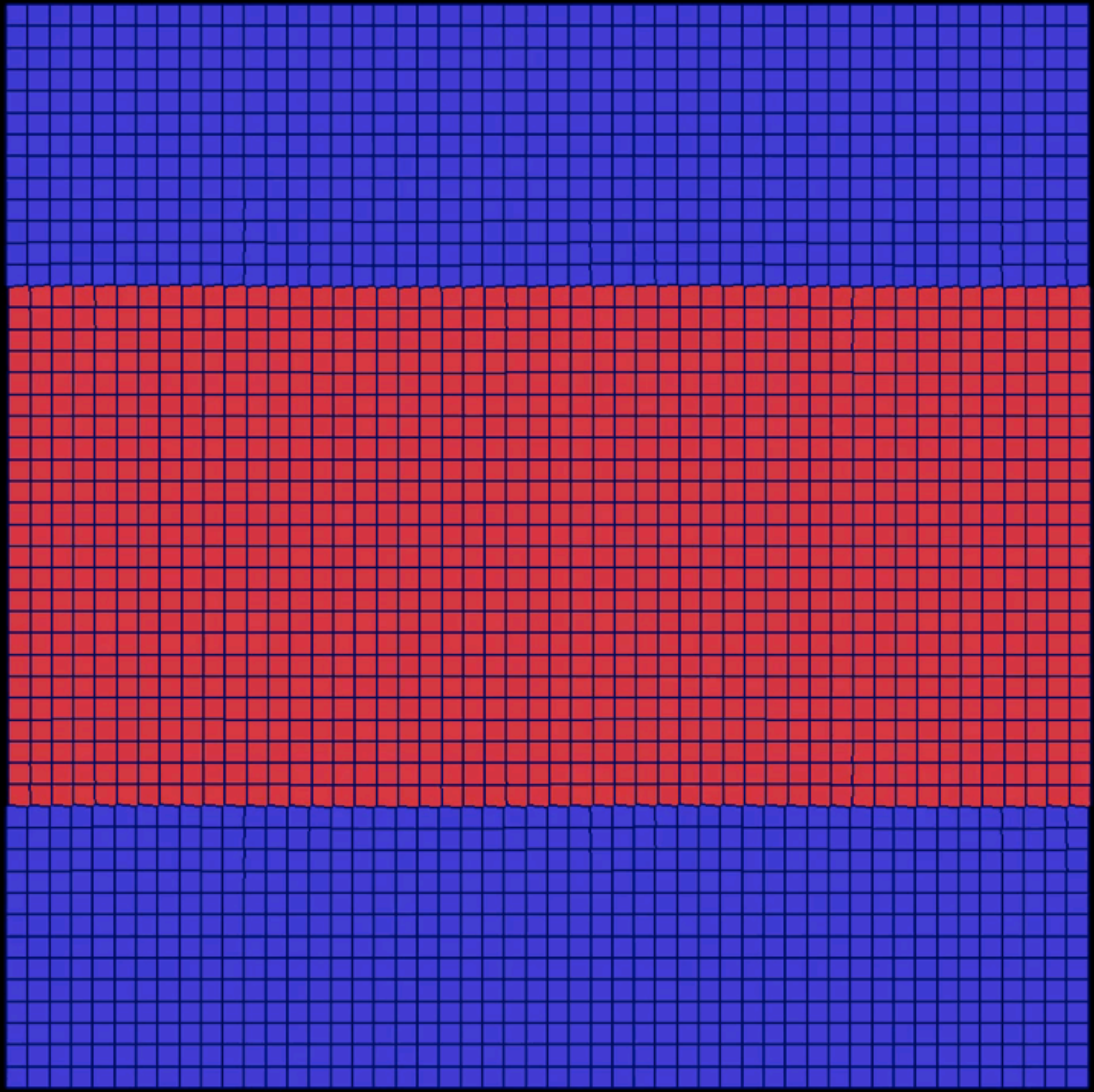


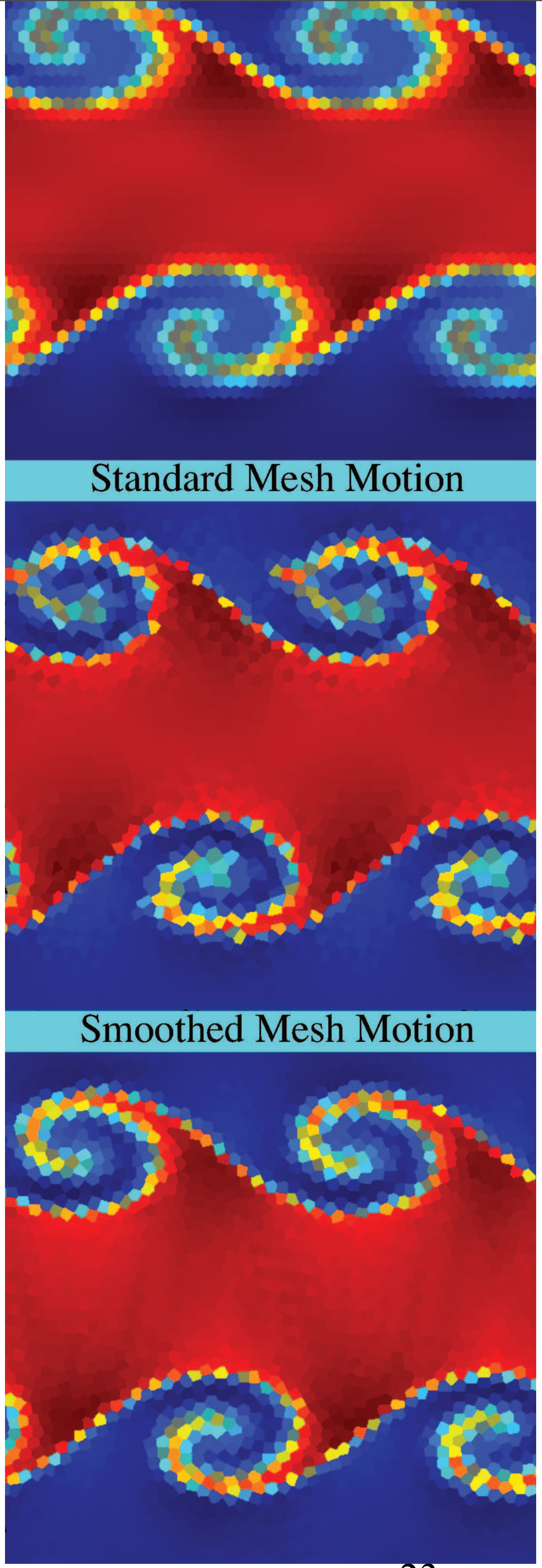
$$\vec{F}_* \rightarrow \vec{F}_* - \vec{w}\, u_*$$

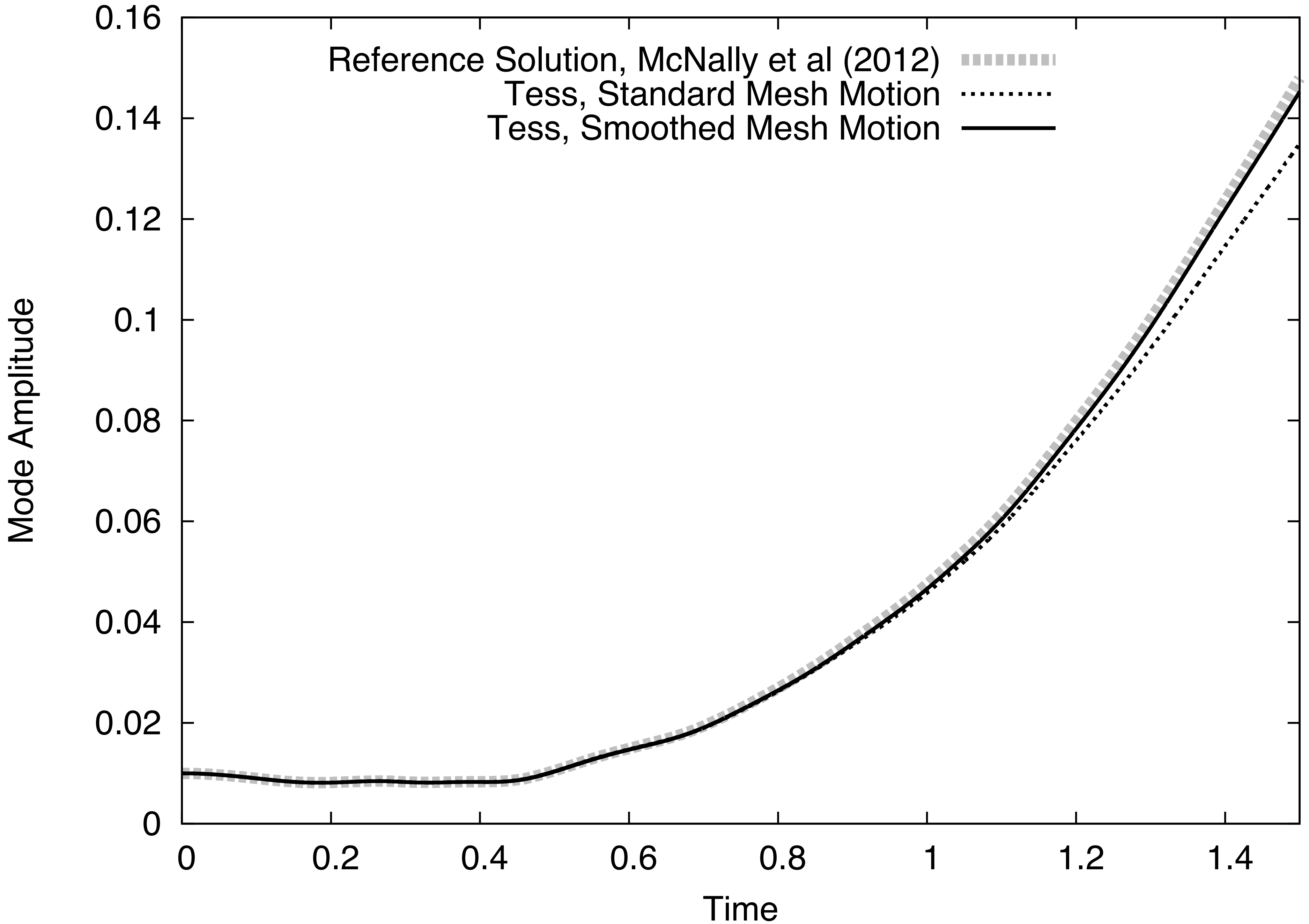



HLL
Left - Fixed Mesh
Right - Moving Mesh
HLLC
1.2
1
0.8
0.6
0.4
0.2
0
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1


HLL
HLLC
Left - Fixed Mesh
Right - Moving Mesh
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7

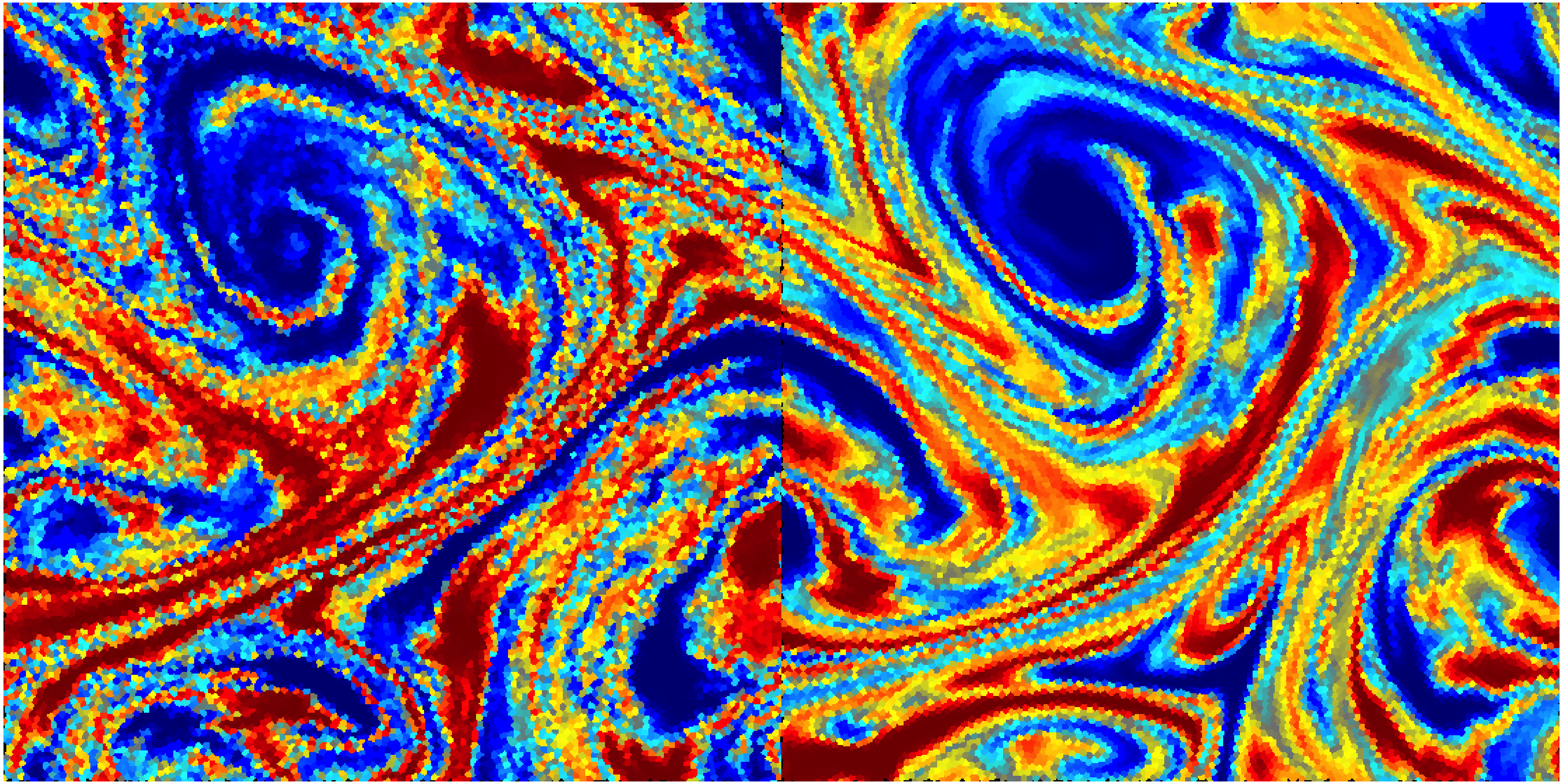


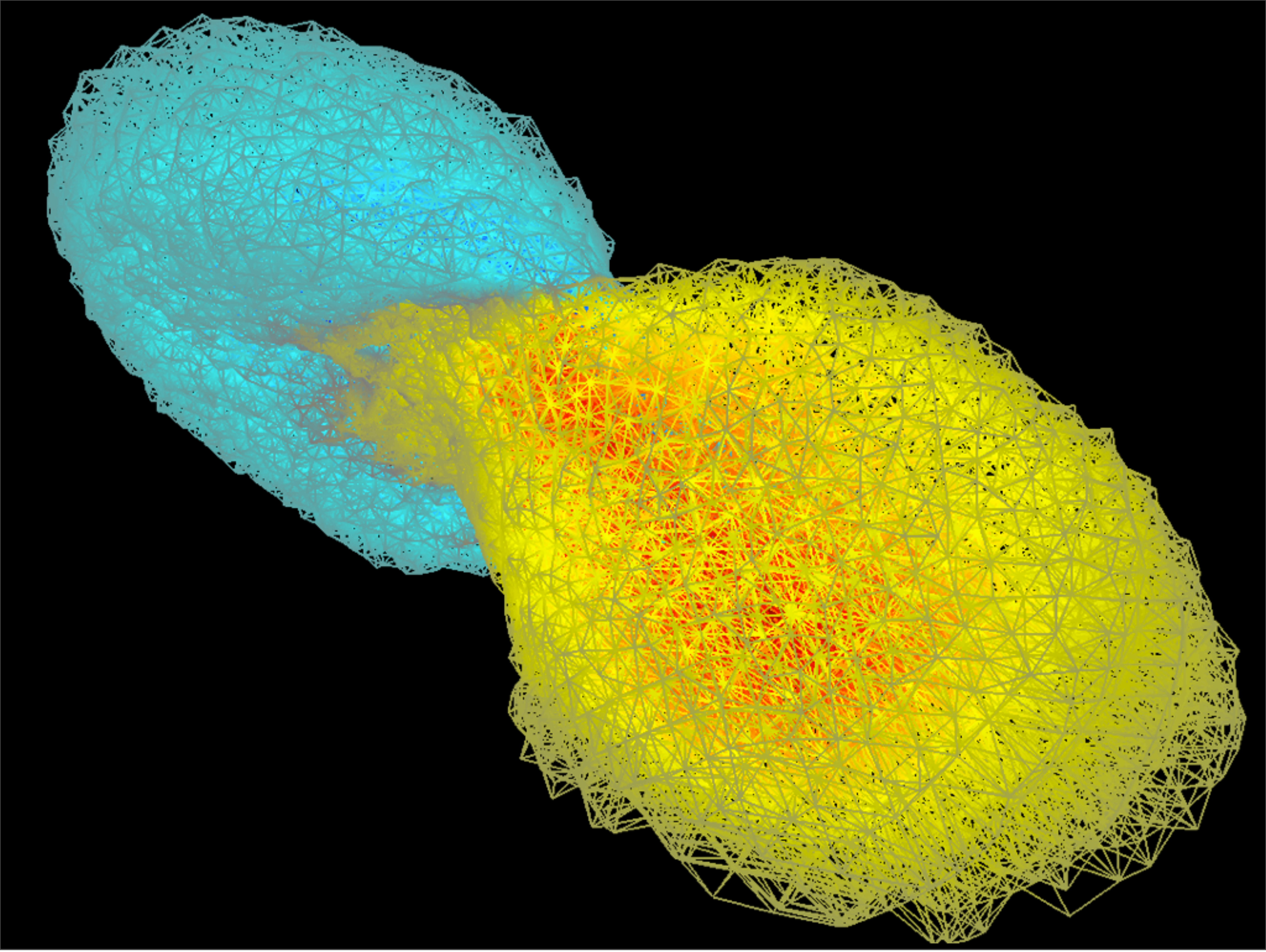

Standard Mesh Motion
Smoothed Mesh Motion

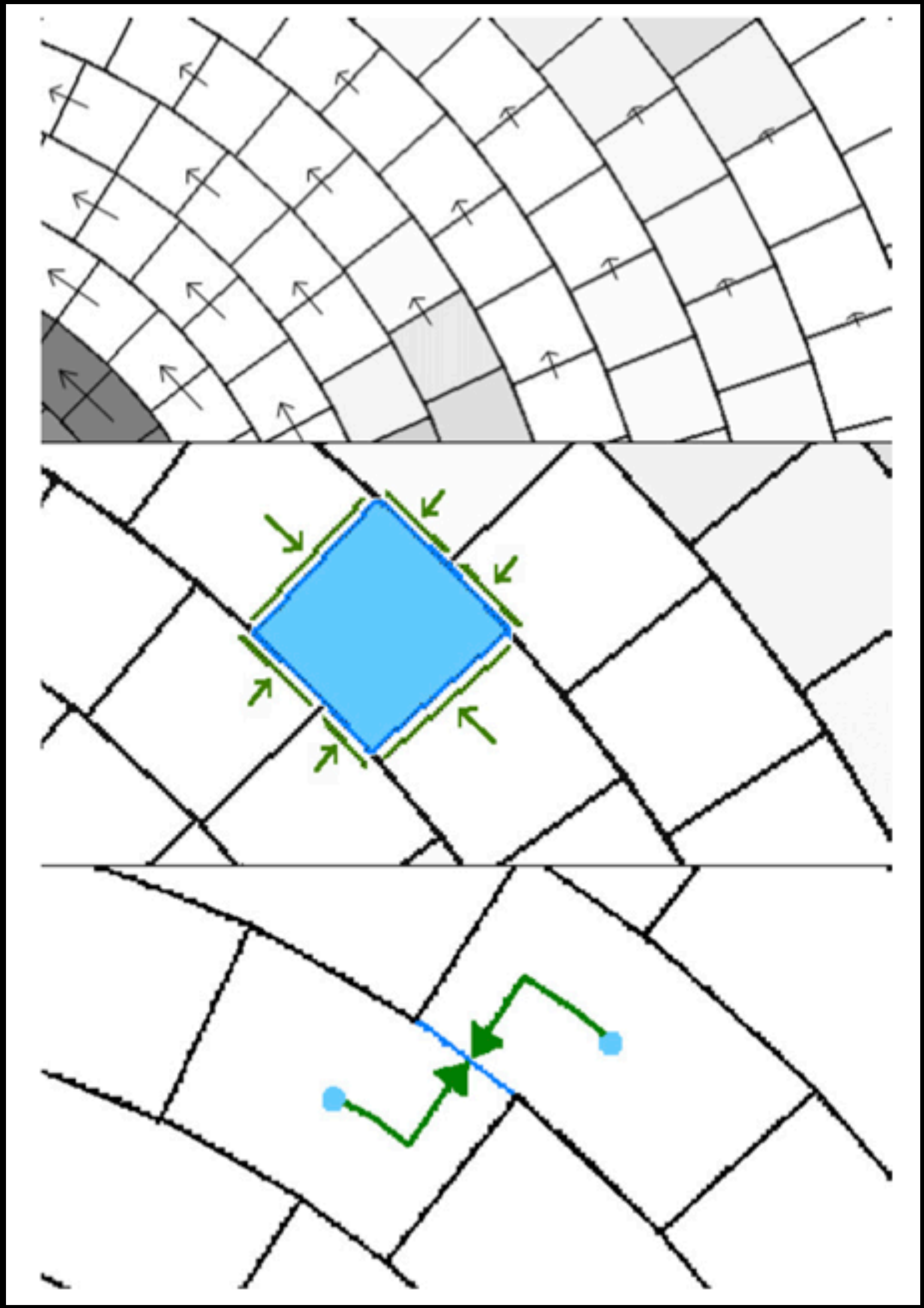


Reference Solution, McNally et al (2012)
Tess, Standard Mesh Motion
Tess, Smoothed Mesh Motion
Mode Amplitude
Time
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
0.2
0.4
0.6
0.8
1
1.2
1.4

Turbulence on Moving Mesh

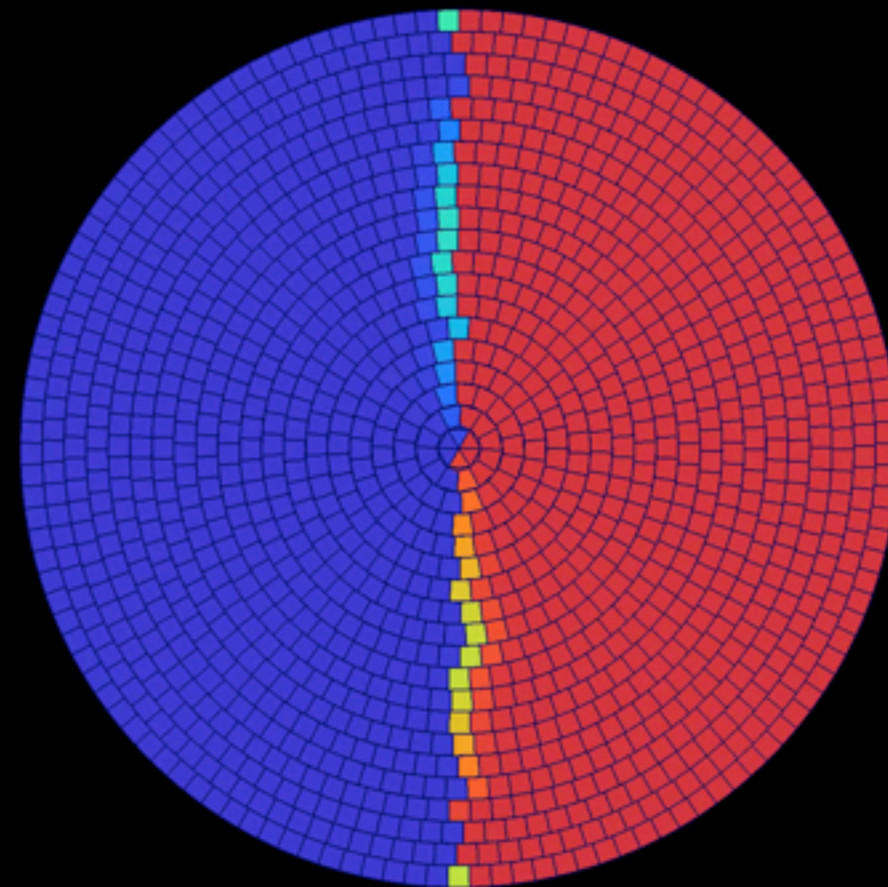




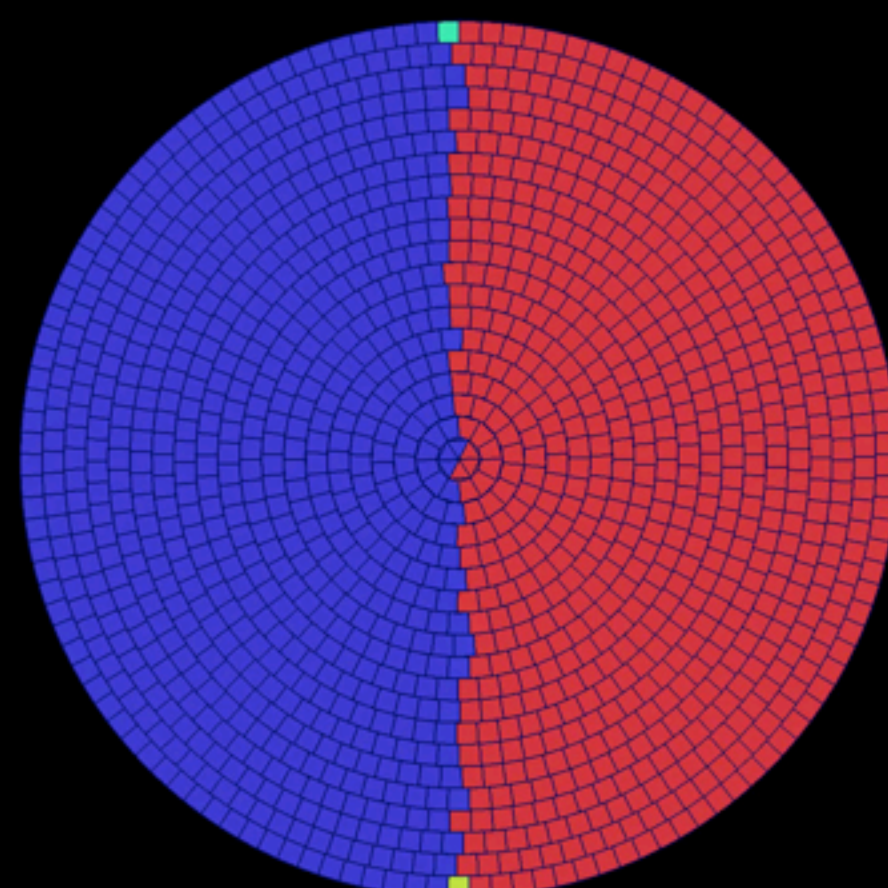


Fixed Mesh

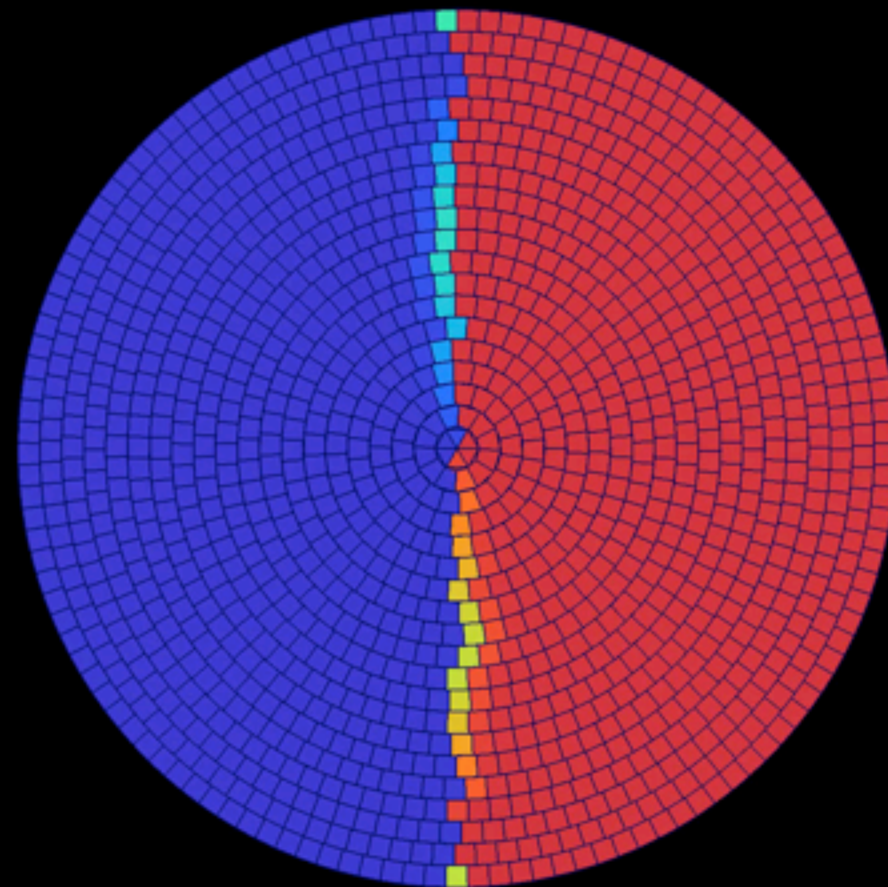
Moving Mesh



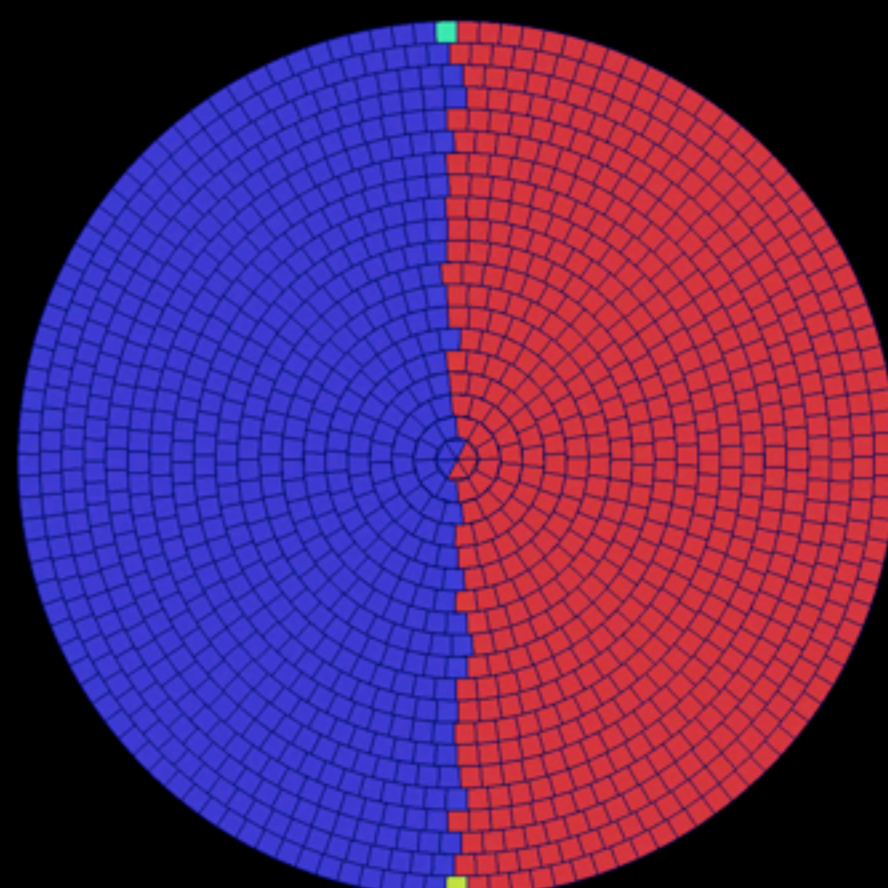
Fixed Mesh



Moving Mesh



Fixed Mesh



Moving Mesh

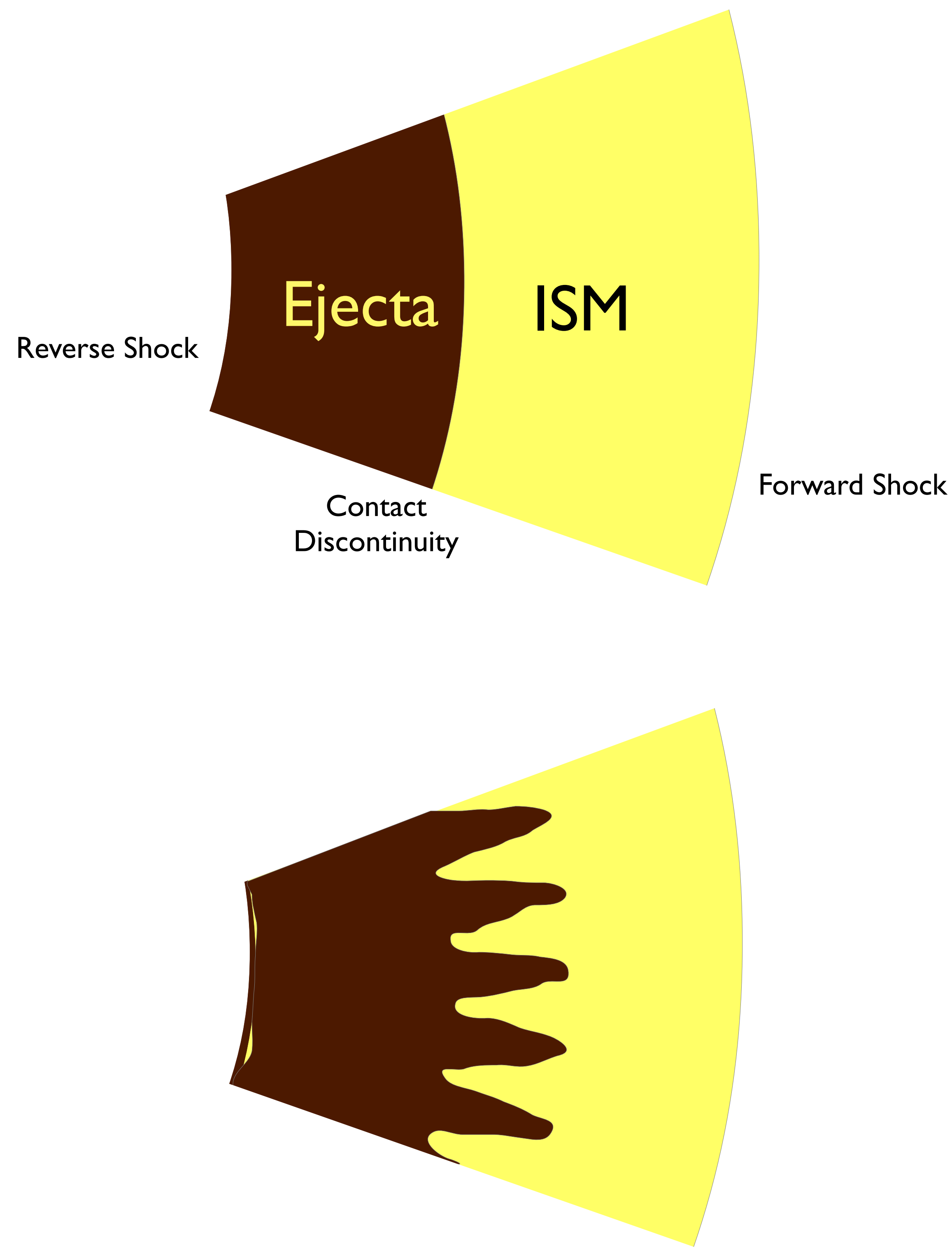
$\Gamma >> 1/\theta$

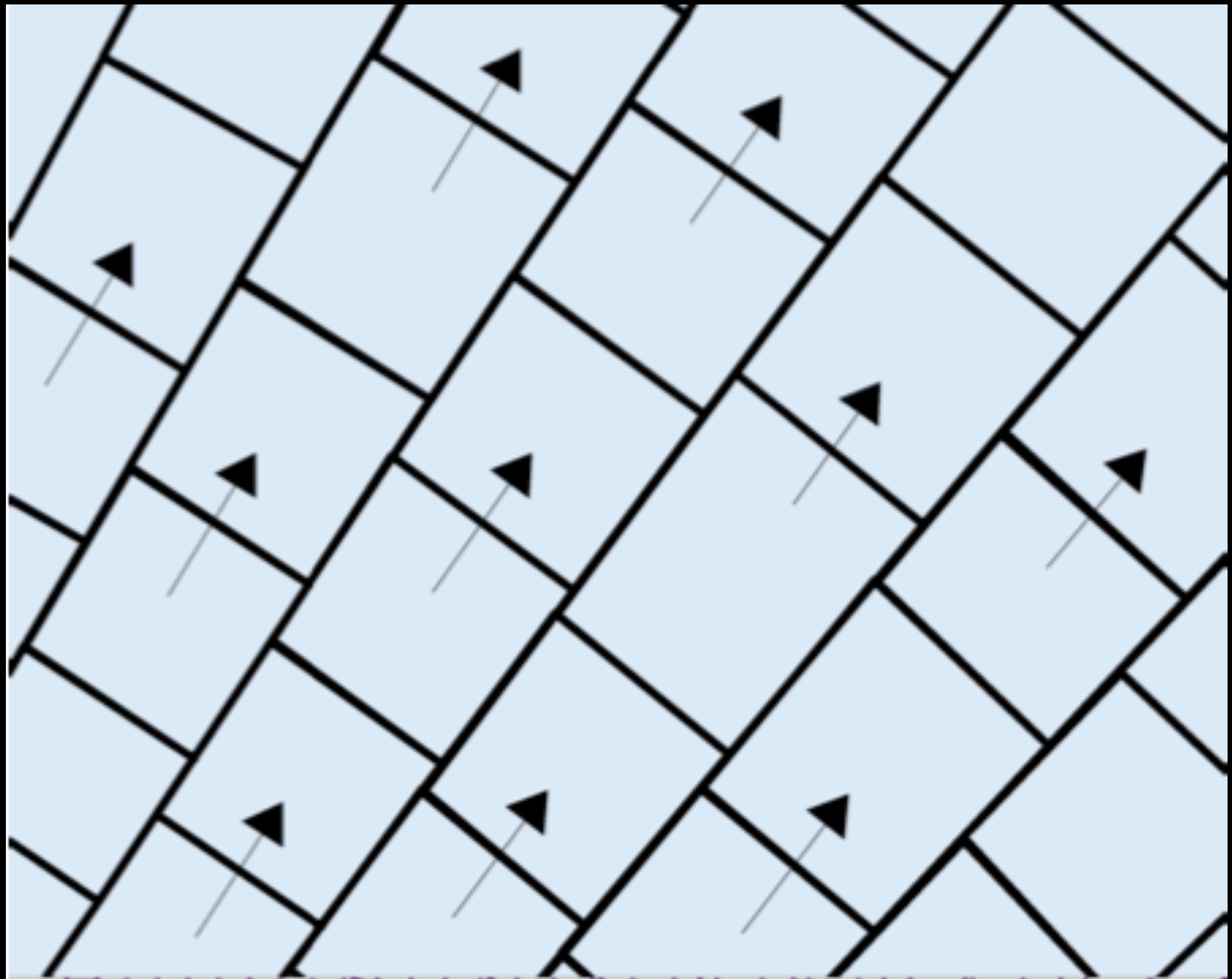
10^7 cm

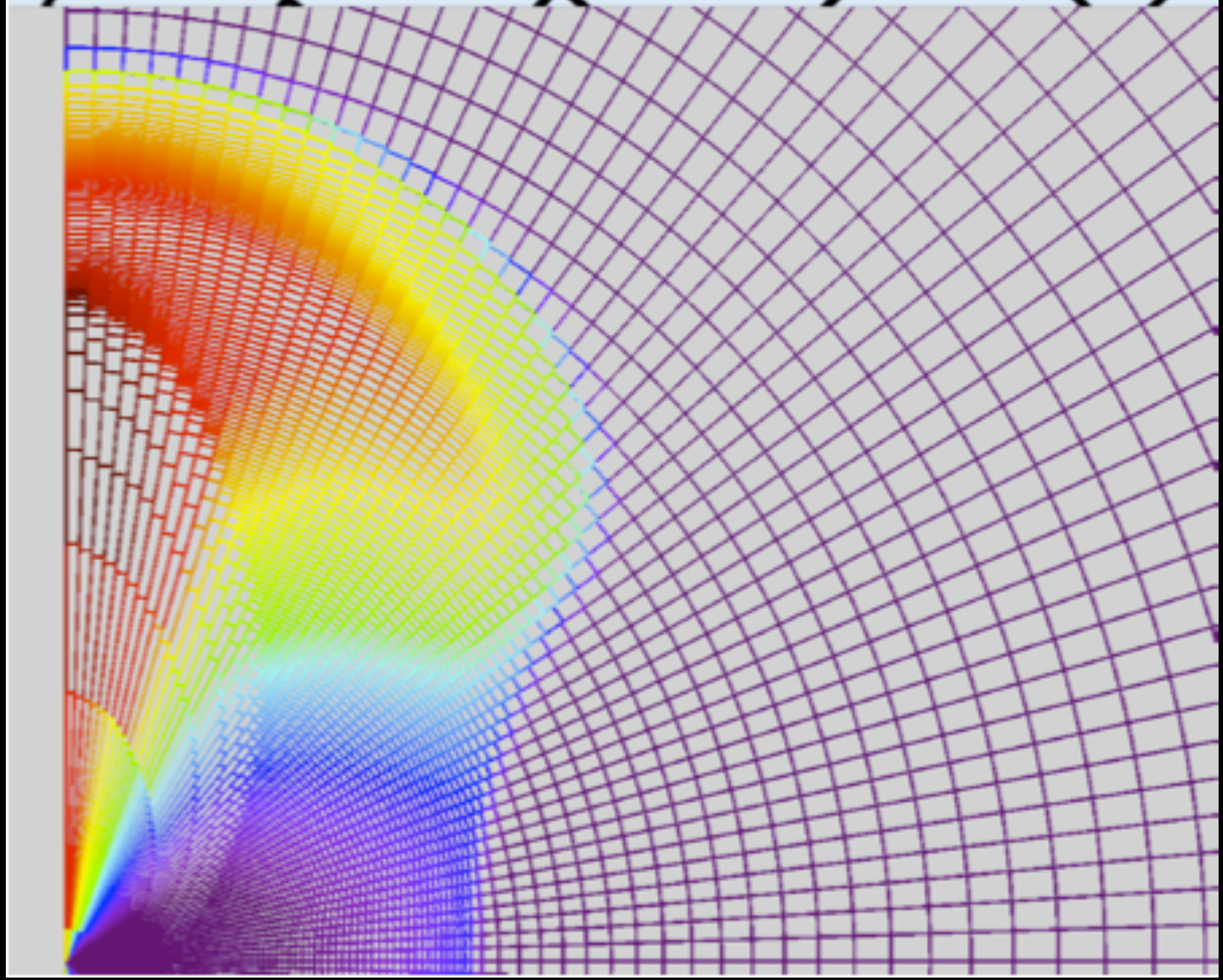
10^15 cm

10^18 cm

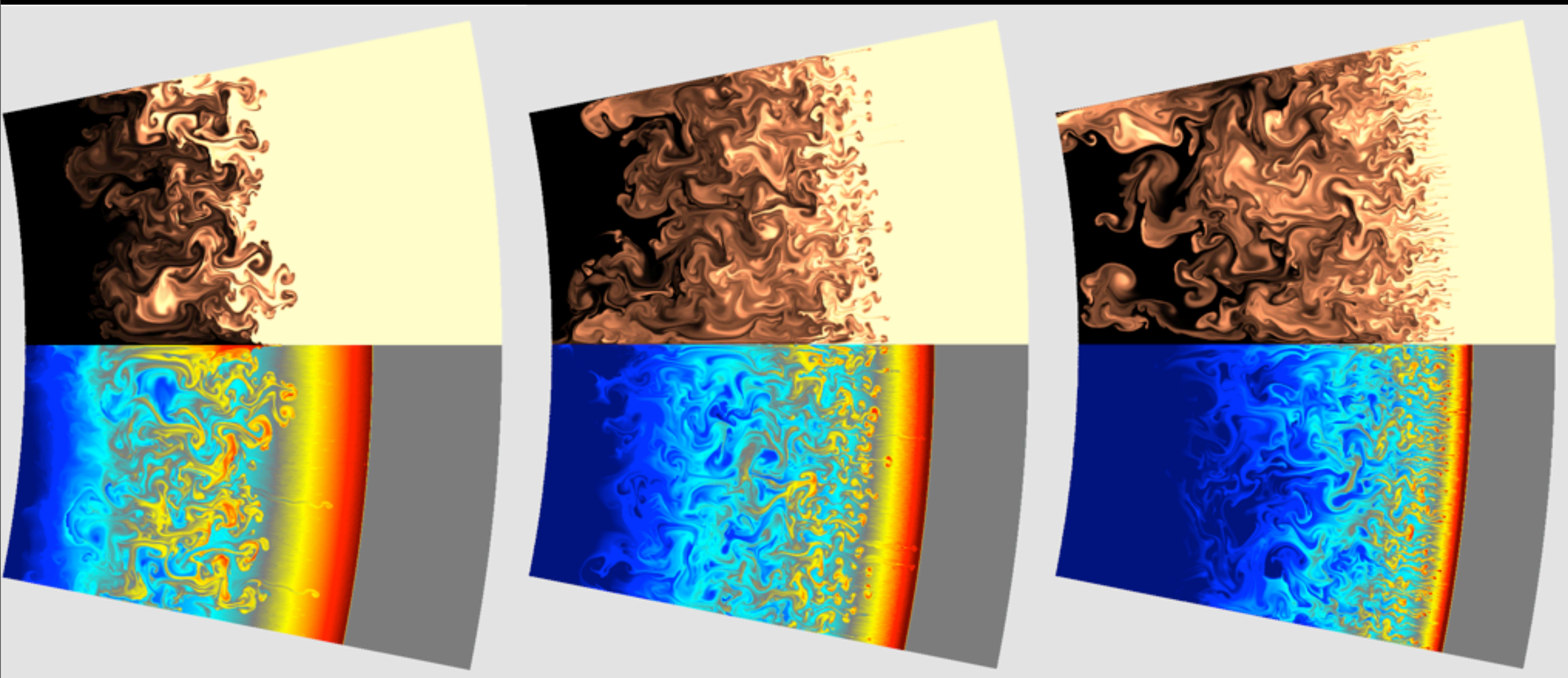
A. MacFadyen (NYU)


Ejecta
ISM
Reverse Shock
Contact
Discontinuity
Forward Shock

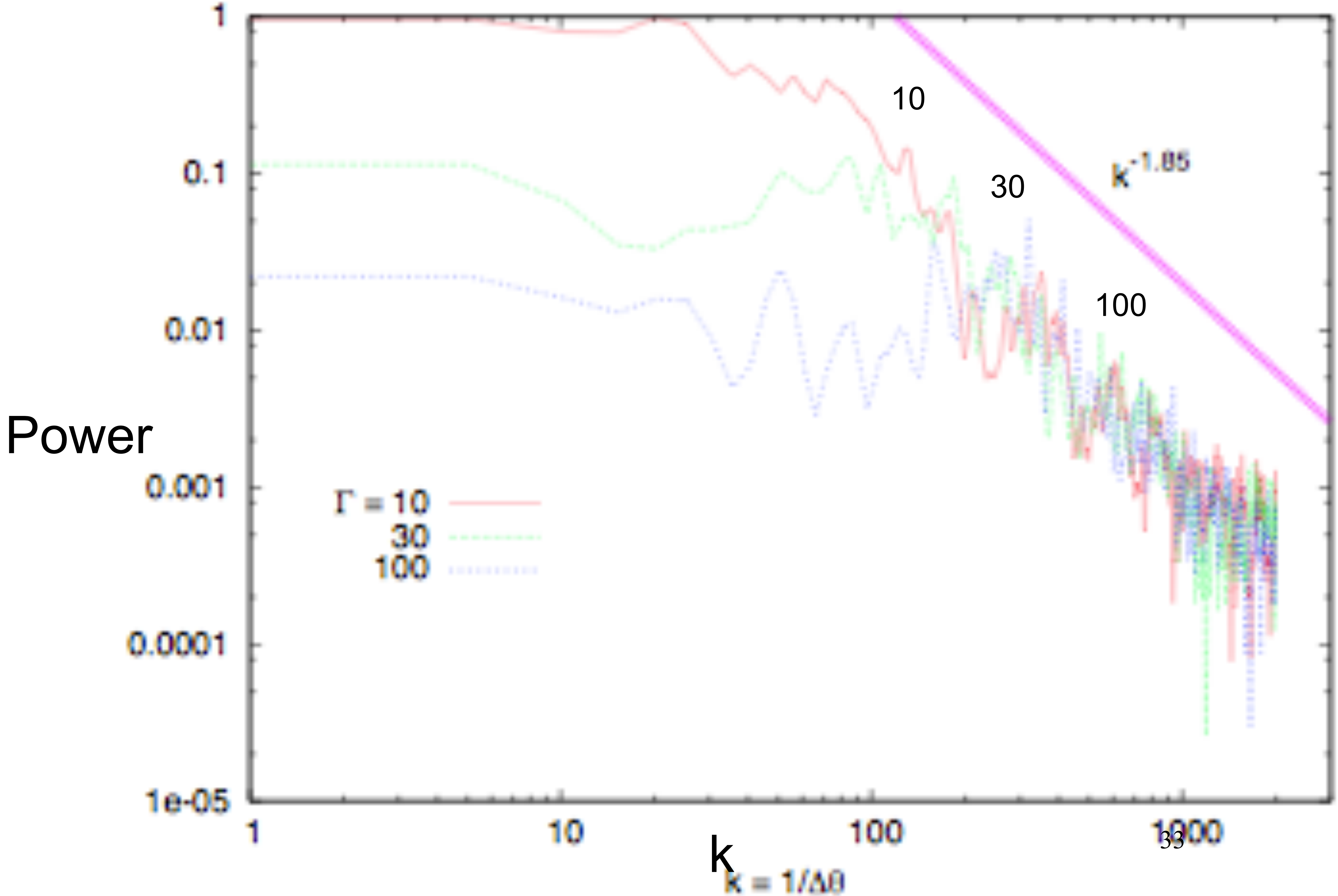


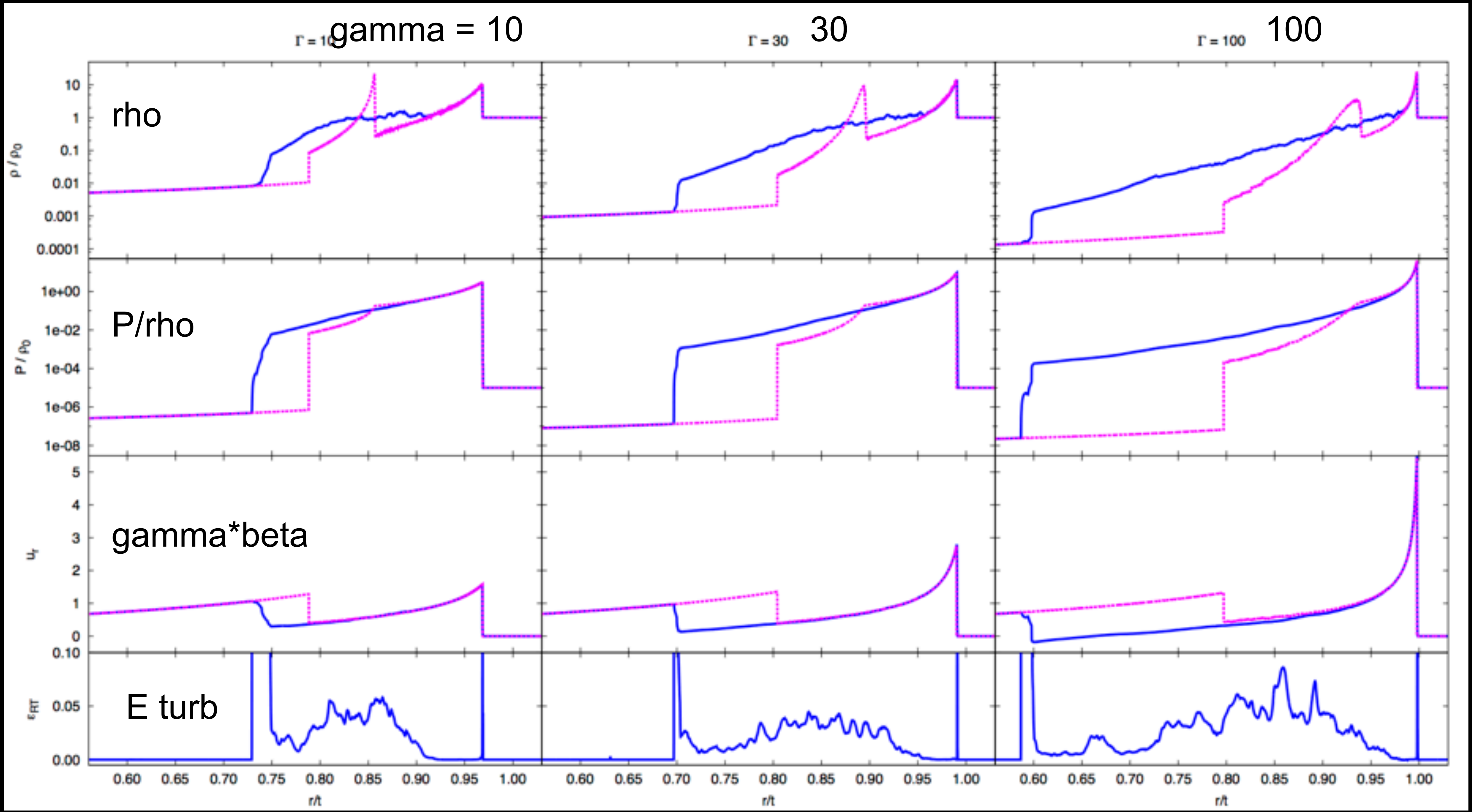


Lorentz Factor = 10 | 30 | 100



RT Turbulence Spectrum





gamma = 10
Γ = 10
30
Γ = 30
100
Γ = 100
rho
P/rho
gamma*beta
E turb
ρ / ρ0
P / ρ0
u_r
ε_RT
r/t