MHD Core Collapse Simulation with Cosmos++

-- MRI in core collapse --

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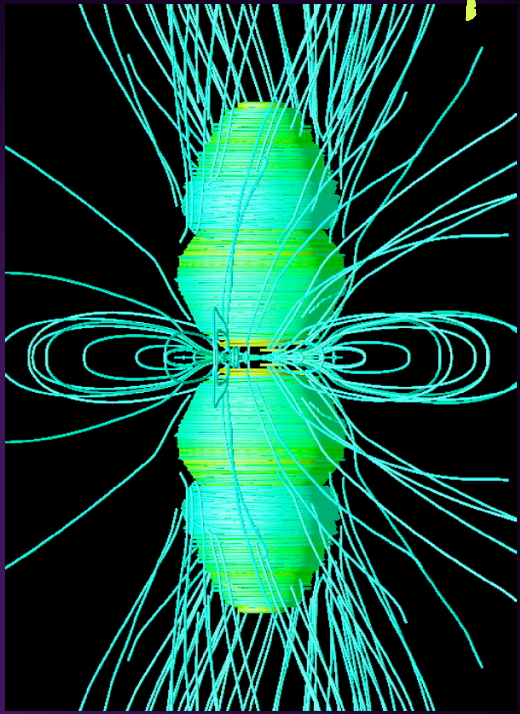
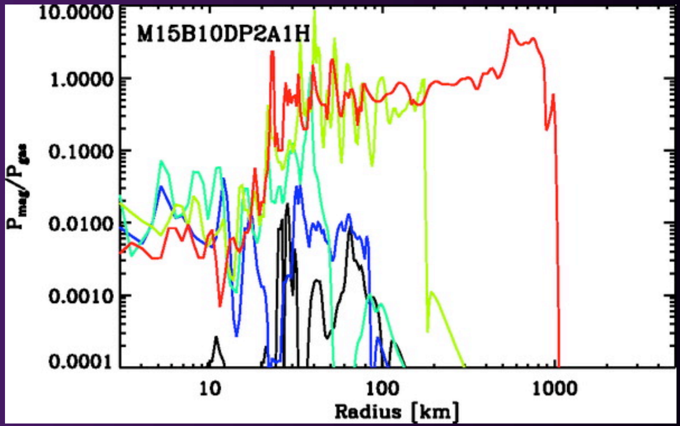
Outline

- Motivation for MHD core collapse
- Physics and Importance of the MRI
- Numerical Method (Cosmos++)
- Movies
- On going…
- Summary

Motivation for MHD core collapse

- Pulsars/magnetars = neutron stars with rotation and magnetic field
  - Clearly, rotation and magnetic field are present
  - Aspherical explosion (long lived bi-polar axis)
  - SN-GRB connection
  - Magnetar formation
- Rotation + magnetic fields => MHD jets
- Jet induced explosion
  - LeBlanc & Wilson (1970)
    - First MHD core collapse simulation
    - Bi-polar magnetic outflow
  - Burrows et al. (2007)
    - First 2D rotating, multi-group RMHD simulation





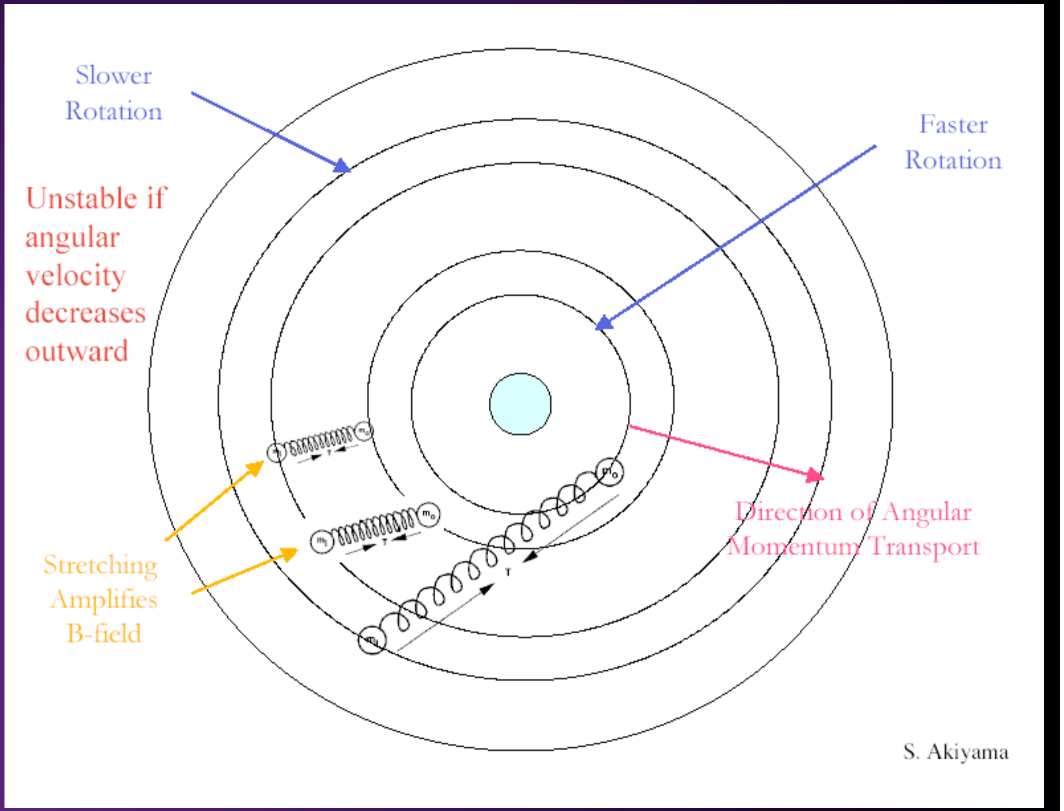
Burrows et al. (2007)

Why Rotation & Magnetic Field?

- Uncertainty in initial iron core
  - Requires initial moderate to rapid rotation
  - Requires initial strong magnetic field?
- Questions
  - MHD explosion typical or special?
  - Dynamical or non-dynamical MHD effects?
  - If typical, B-field amplification mechanism?
    - Poloidal field => compression (proportional to density ratio)
    - Toroidal field => wrapping of field line (linear in time)
  - MRI (magnetorotational instability) in core collapse?
    - Linear regime => exponential growth!
    - Small scale B

Magnetorotational Instability

- Disk
  - L grad +, Ω grad -
  - Rayleigh stable
- MRI is unstable when
  - Angular velocity has negative gradient
  - Weak seed magnetic field is present
  - Stability criteria independent of B
  - Dynamical instability
- MRI in disk and star
  - Gradient in variables
  - Convection



MRI in core collapse (1D)

Akiyama et al. (2003)

- 1D model calculation
- COLLAPSE code (Myra et al. 1987)
- Rotation profiles

$$\Omega_0(r) = \Omega_0 \frac{R^2}{r^2 + R^2}$$

- MRI criteria

$$N^2 + \frac{d\Omega^2}{d\ln r} < 0$$

- Exponential growth

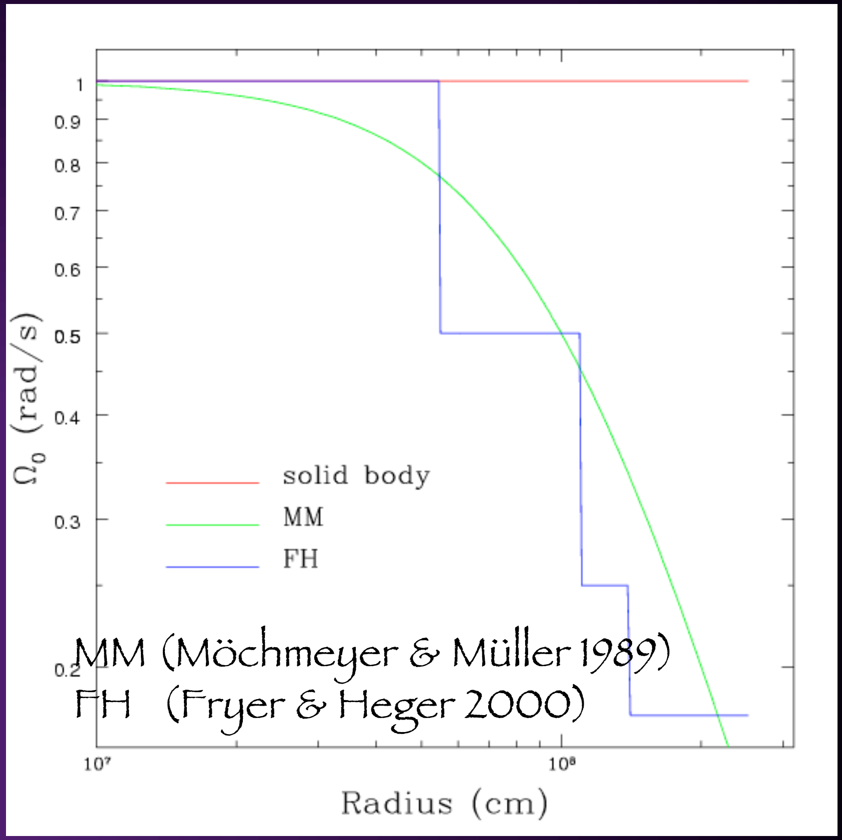
$$\tau_{\max,\mathrm{en}} = 4\pi \left| \frac{N^2}{2\Omega} + \frac{d\Omega}{d\ln r} \right|^{-1}$$

- Saturation strength

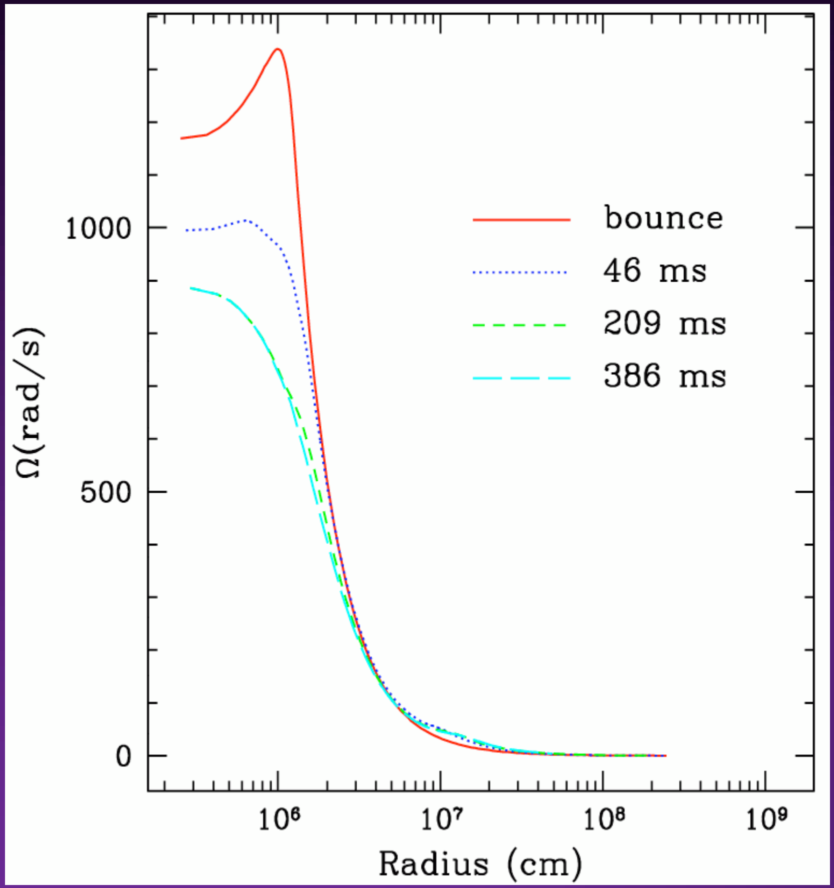
$$B^2_{\mathrm{sat}} \sim 4\pi\rho r^2 \Omega^2$$

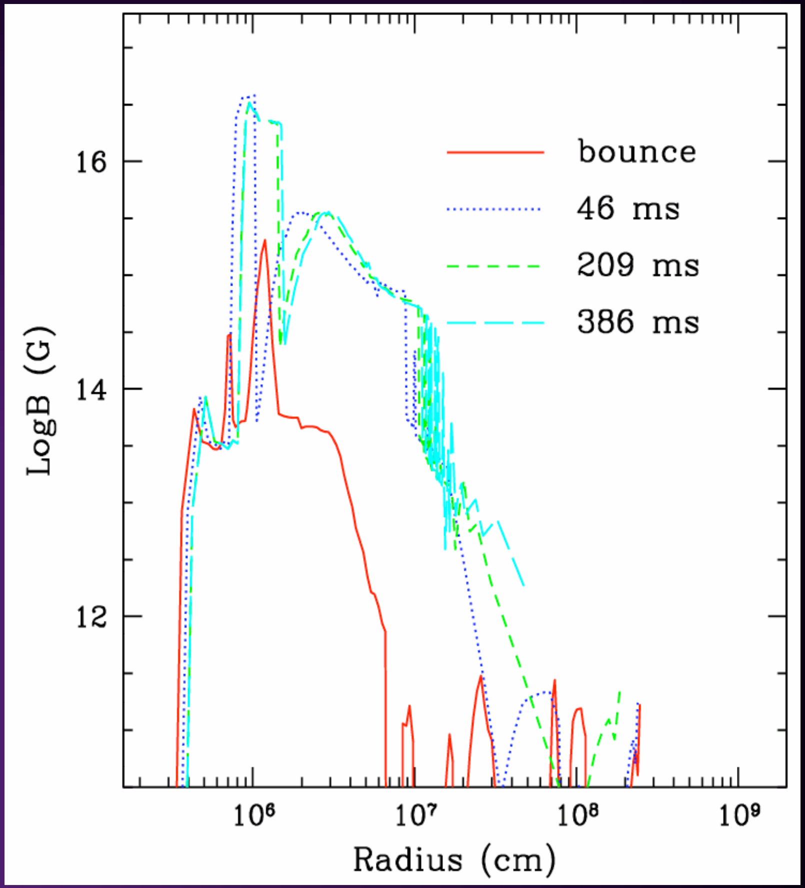
$$B^2_{\max,\mathrm{en}} = -B^2_{\mathrm{sat}} \cdot \left[\frac{1}{8\pi^2} \left(1 + \frac{1}{8} \left(\frac{N^2}{\Omega^2} + \frac{d\ln\Omega^2}{d\ln r} \right) \right) \left(\frac{N^2}{\Omega^2} + \frac{d\ln\Omega^2}{d\ln r} \right) \right]$$

- No rotational & magnetic feedback



Amplified Field





Akiyama et al. (2003)

- Generic shearing environment
- Peak B ~ 10^{15-16} G within few tens of msec

Simulating MRI growth

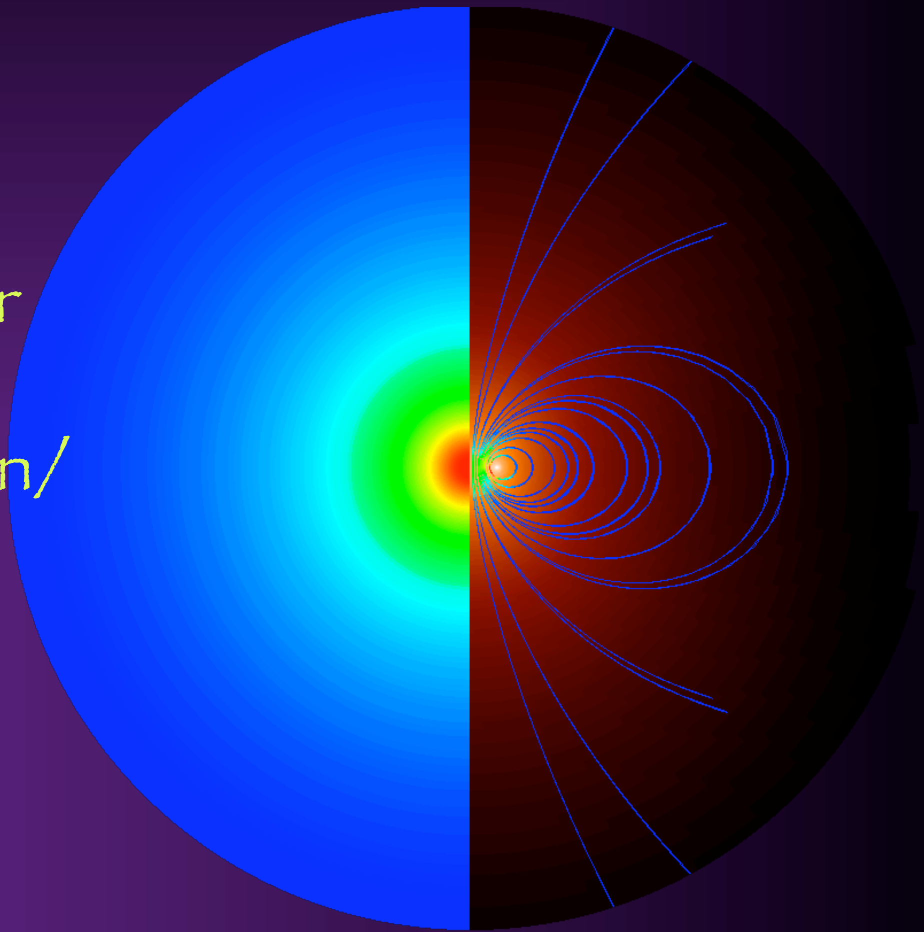
- Core collapse is messy place
- Multi-dimensional numerical study is required
- Length scale requirement
  - $\lambda \sim 1.8$ km × (B/10^{13}[G]) × (1000 [rad/s]/ Ω) × (10^{13}[g/cm^3]/ρ)$^{0.5}$
  - Few - 10 grid/wavelength required (Obergaulinger et al. 2009, Shibata et al. 2006)
  - 0.2 - 0.6 km/grid resolution for resolving the MRI growth!
- Local (or semi-global) simulation (Obergaulinger et al. (2009))
  - 15.5 km +/- 1 (or 2) km shearing box
  - Saturation at ~ 10^{15}G, confirming Akiyama et al. (2003)
- Quasi-global simulation!

Numerical Method: Cosmos++

- Anninos, Fragile, & Salmonson (2005)
- Shen/parametric EOS
- polytrope/s15b7s2 (15 Msolar, Woosley & Weaver 1995)
- Parametric deleptonization/ entropy evolution (Liebendorfer 2005)
- Rotational profile

$$\Omega_0(r) = \Omega_0 \frac{R^2}{r^2 + R^2}$$

- Magnetic profile
  - Poloidal field with current loop

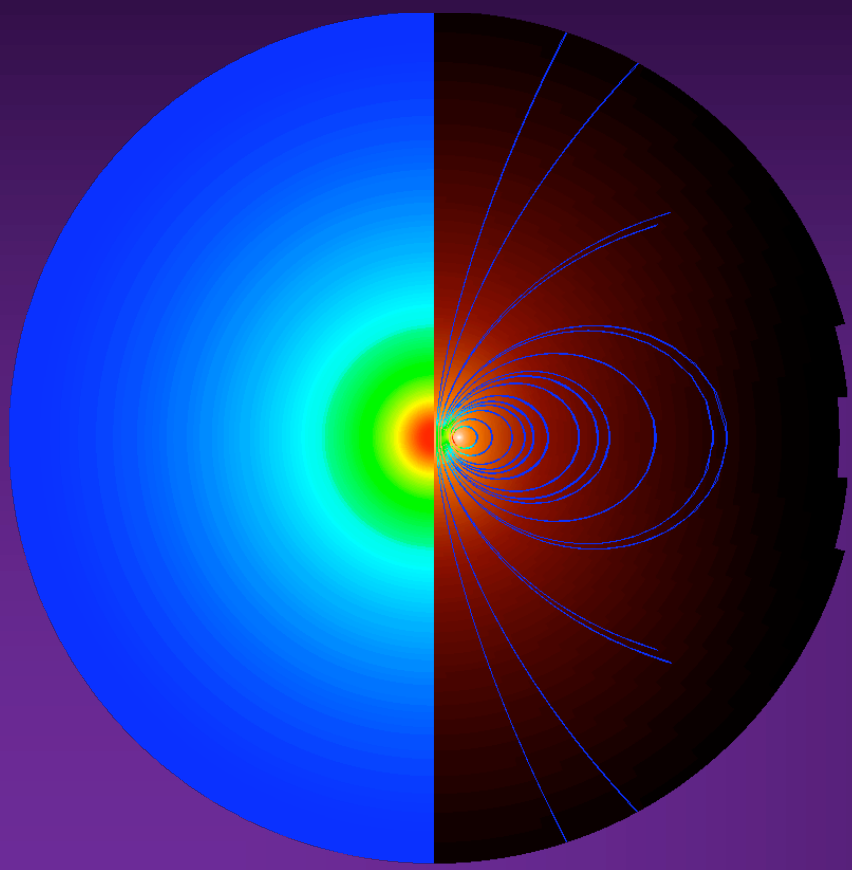


Models

- 2D core collapse (base sim.)
  - $R = 0.9e8$ cm, $\Omega_0 = 2.0$ rad/s, $B_0 = 1.0e12$ G
  - $nx = 256$, $ny = 64$, $\Delta r \sim 255$ m (@ 12 km)
- Remap sim. (~35 msec after bounce)
  - Radius: 12 - 68 km
  - Density: 6.0e13 ~ 1.5e11 g/cm^3
  - Magnetic field: ~1.0e15
  - Std: $nx = ny = 1024$, $\Delta r_{min} = 11$ m , $\Theta = 120$
  - Stdx2: $nx = ny = 2048$, $\Delta r_{min} = 5.5$ m, $\Theta = 120$
  - Stdx2_150: $nx = ny = 2048$, $\Delta r_{min} = 5.5$m, $\Theta = 150$

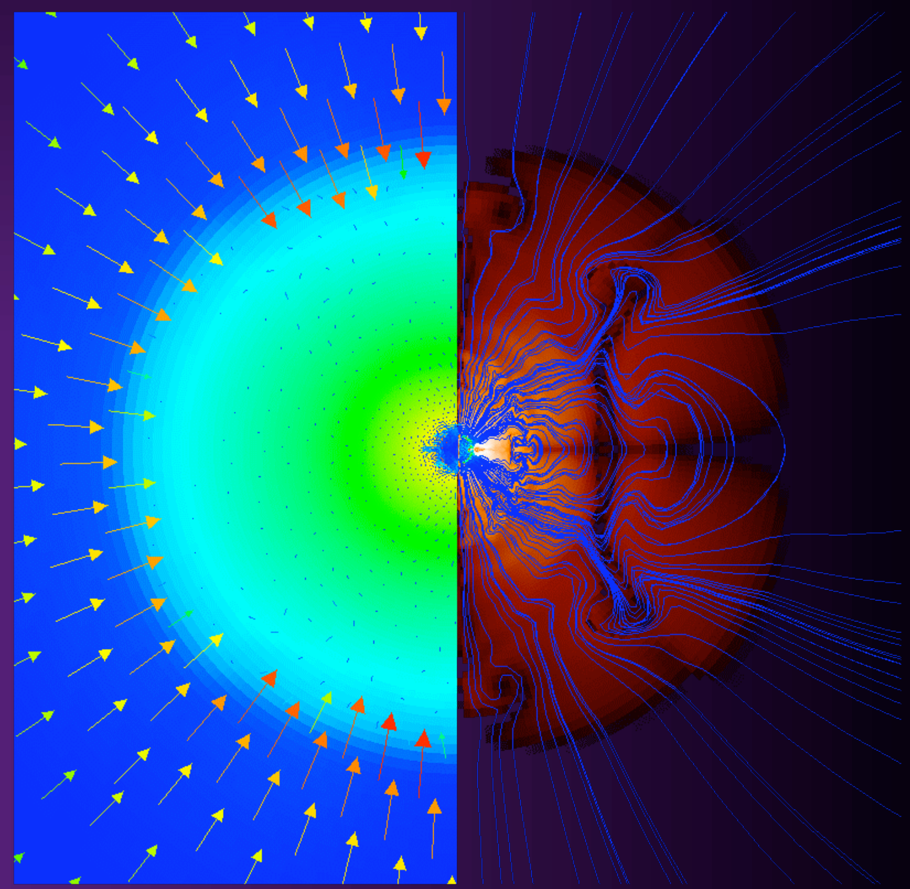
Base Sim.

Density (color) & velocity (vector)



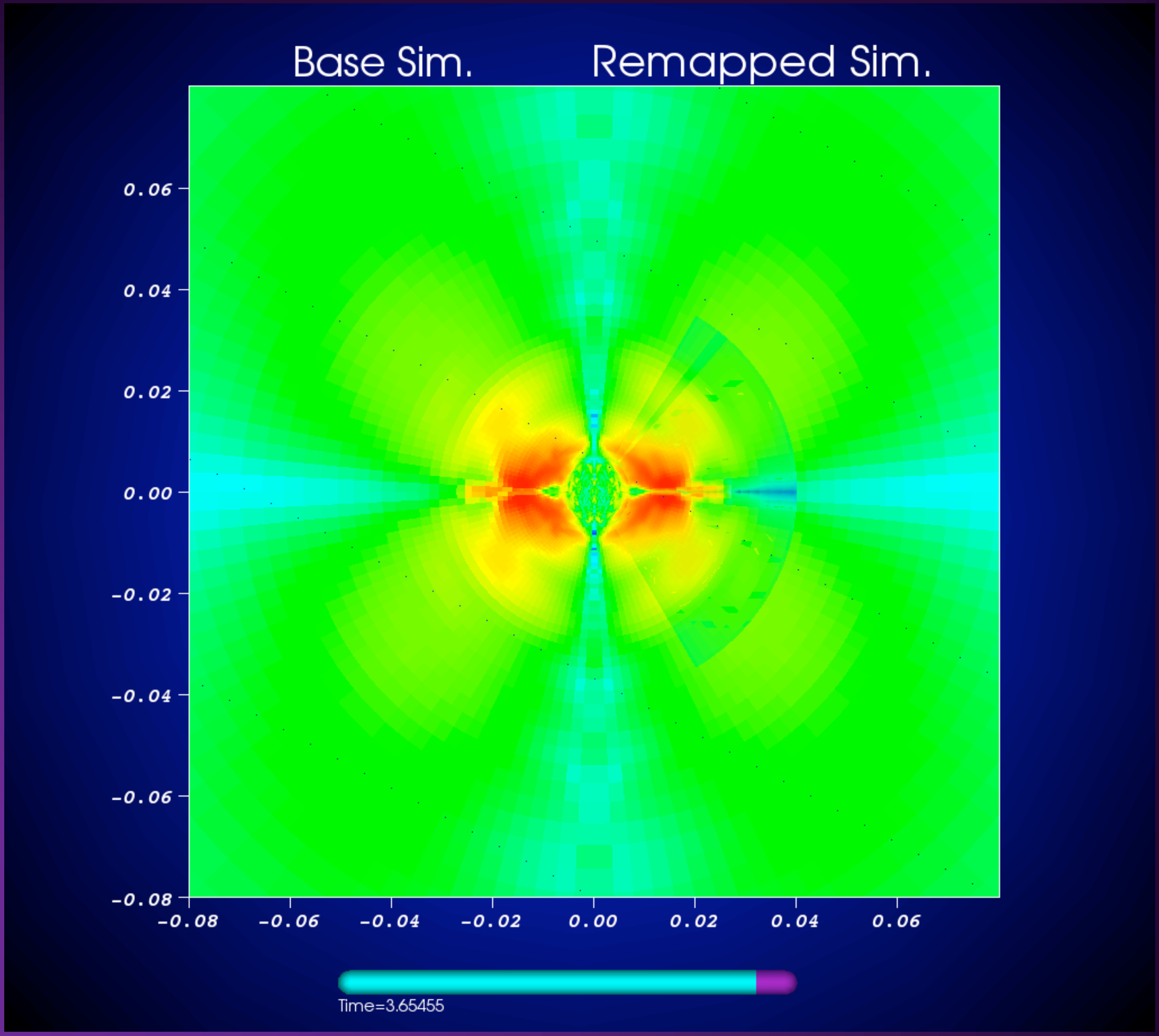
6,800 km

B_ϕ (color) & $B_{poloidal}$ (streamline)



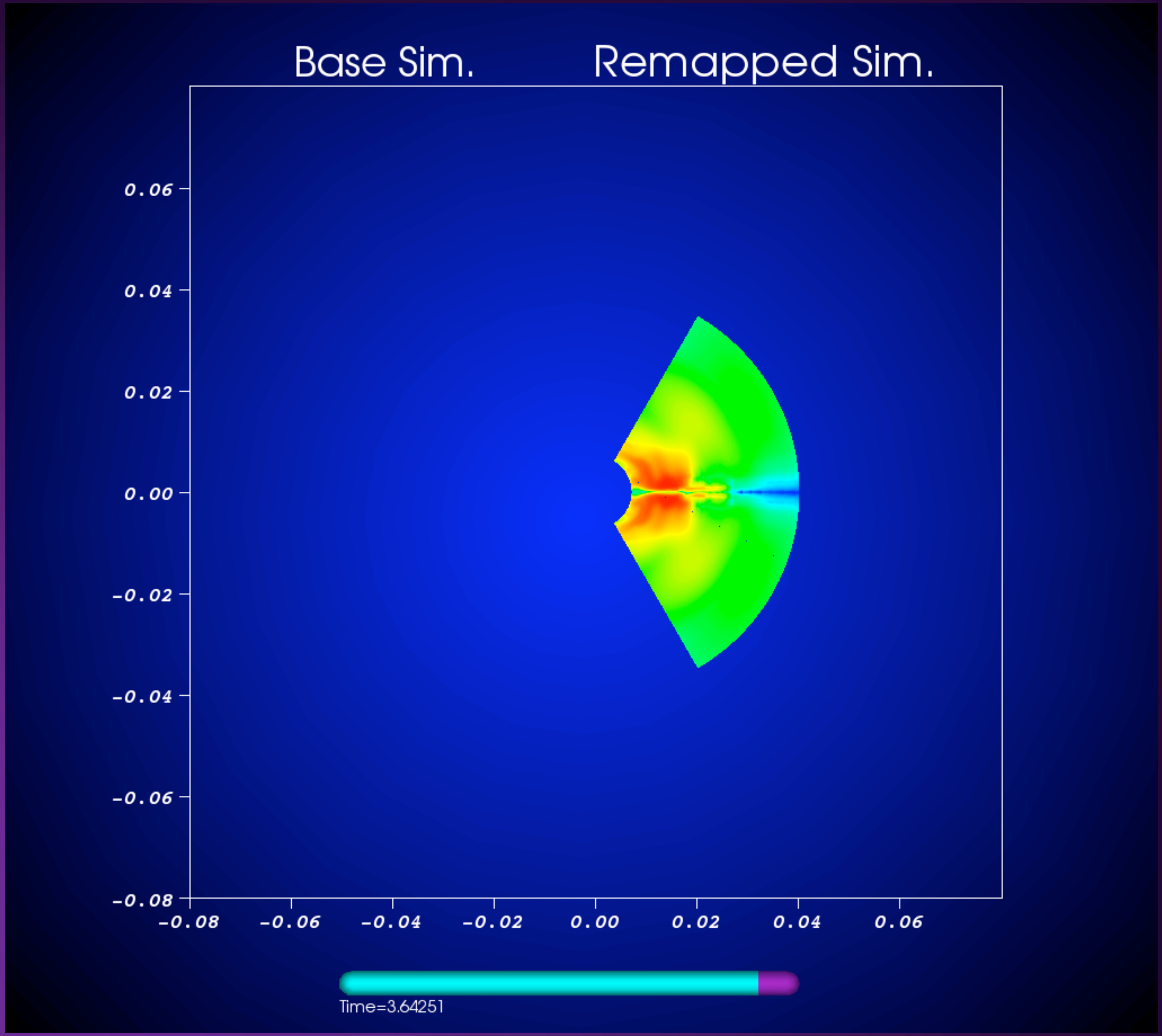
300 km

Remapping

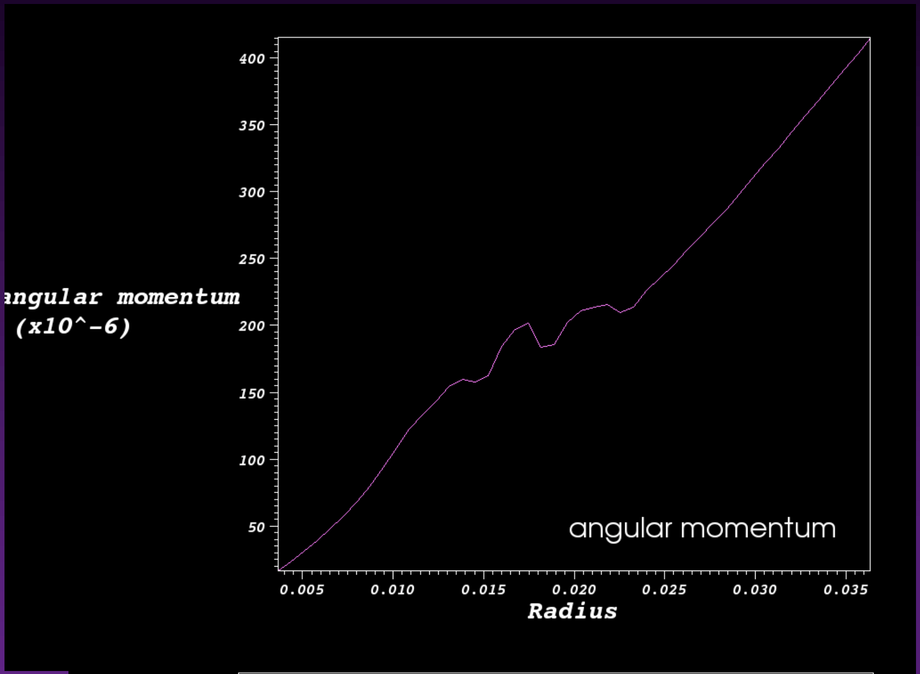


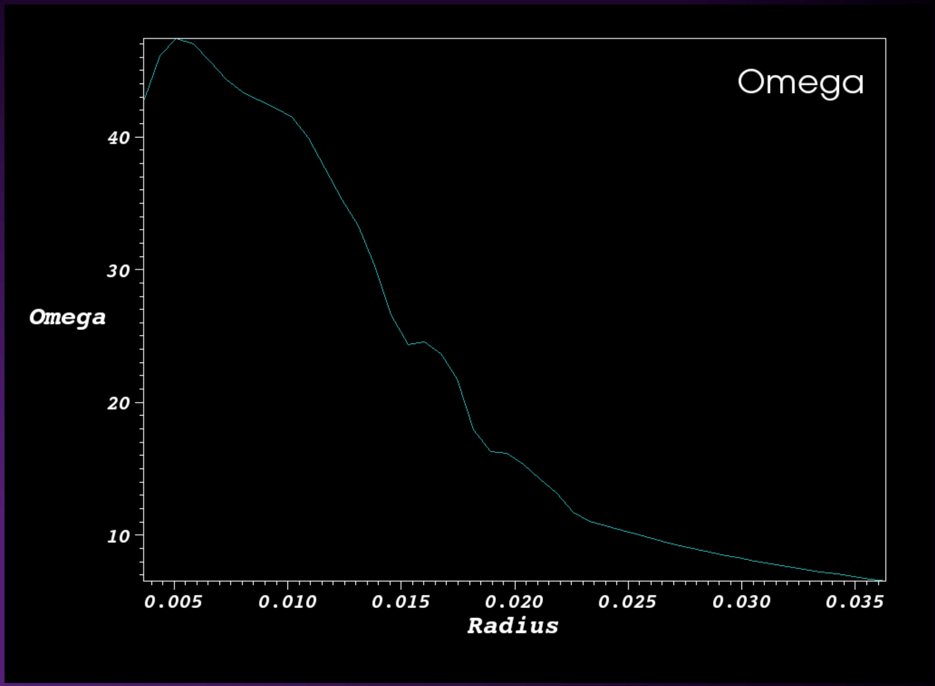
Base Sim.
Remapped Sim.
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.08
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
Time=3.65455

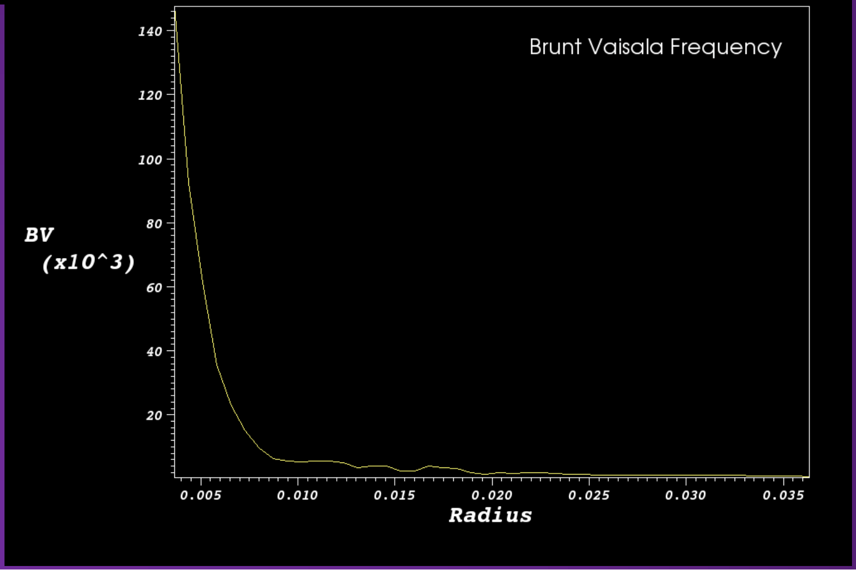
Remapping


Base Sim.
Remapped Sim.
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
−0.08
−0.08
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06
Time=3.64251

Stability



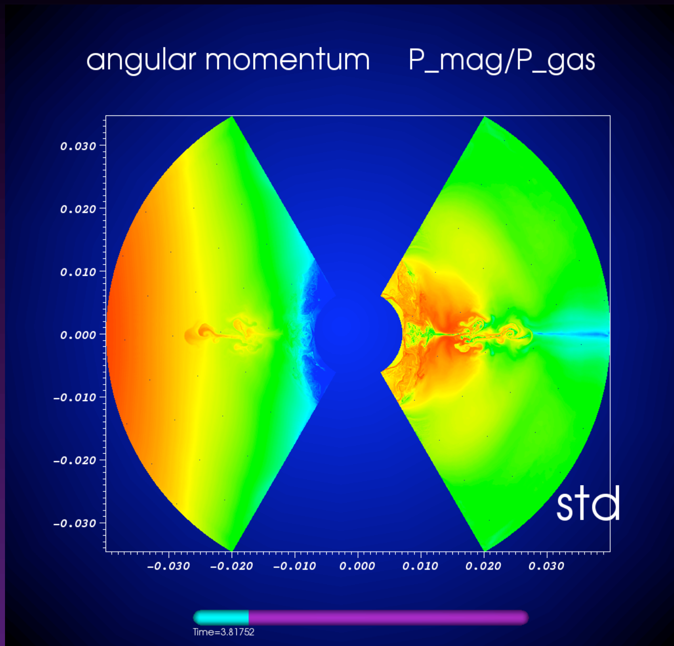


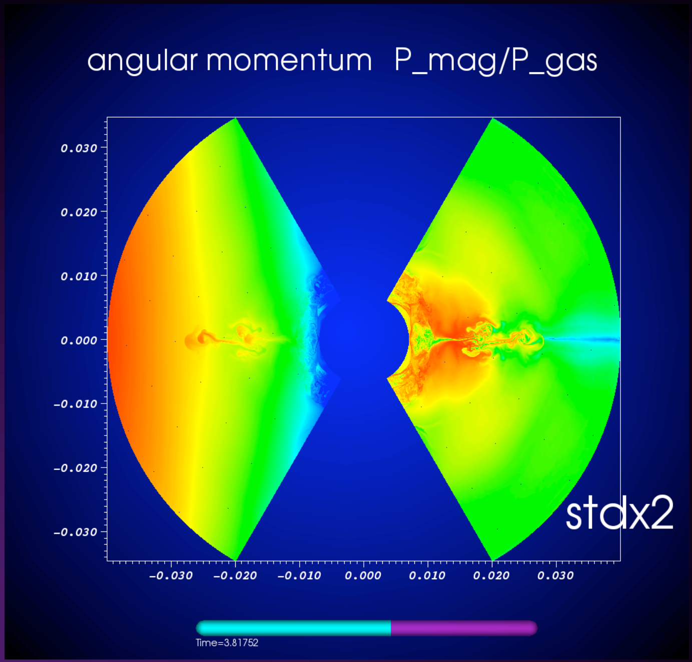


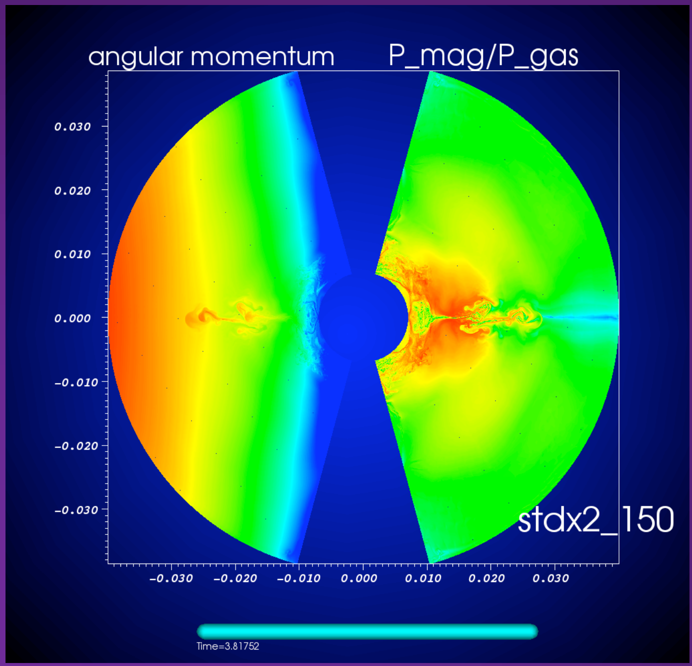
- Reighleigh stable
- Convectively stable
- MRI <u>unstable?</u>

Movies

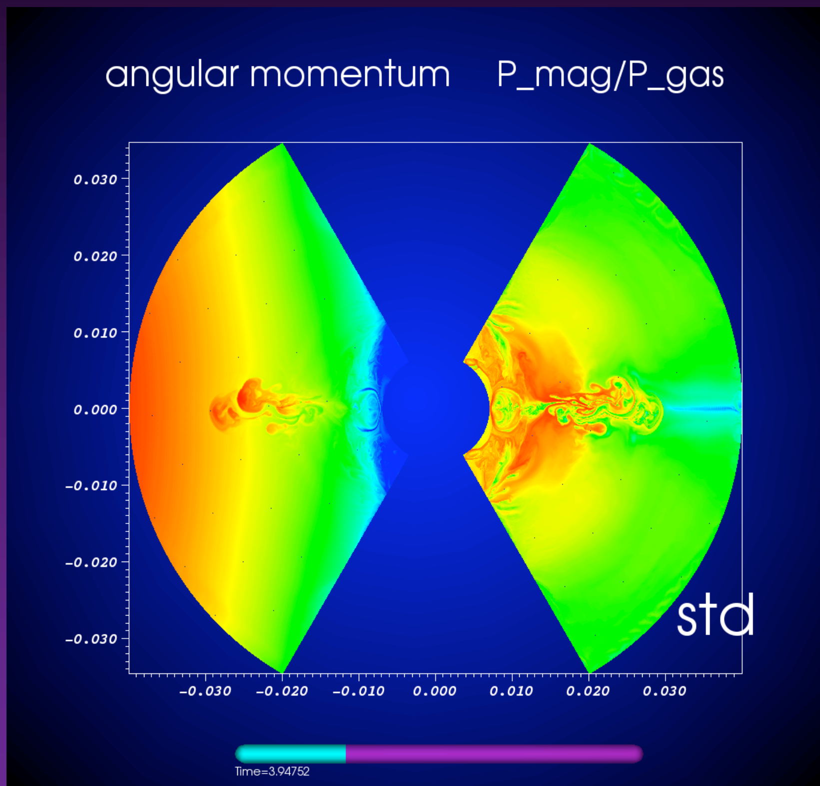
- Std
  - MRI crit & ratio (shear/BV)
  - Angular momentum & P_mag/P_gas
  - Entropy & mass density
- Stdx2
  - Angular momentum & P_mag/P_gas
  - Entropy & mass density
- Stdx2_150
  - Angular momentum & P_mag/P_gas
  - Entropy & mass density

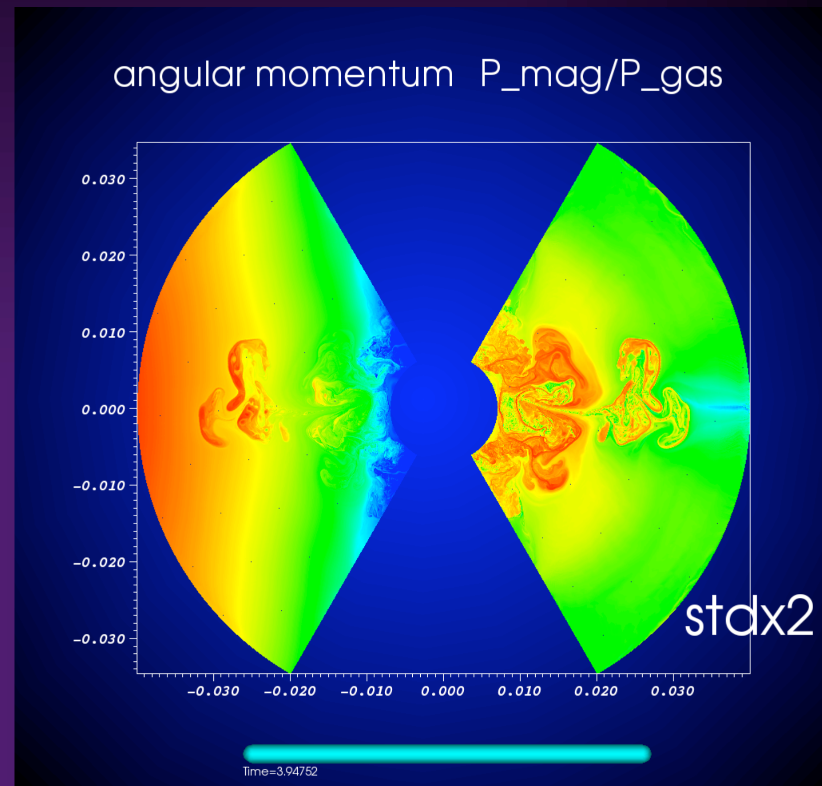




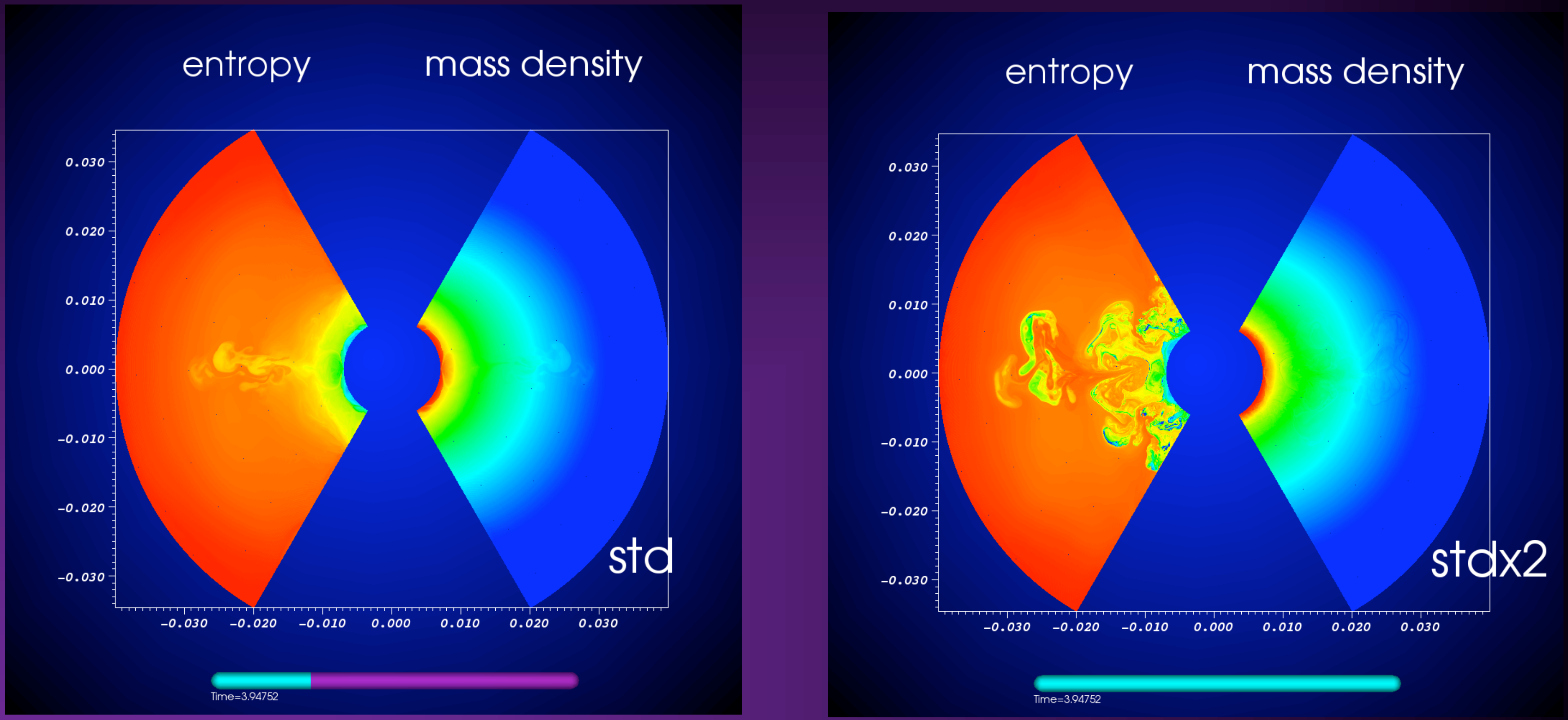


- 44 msec after bounce (~9 msec after remap)
- Very similar evolution

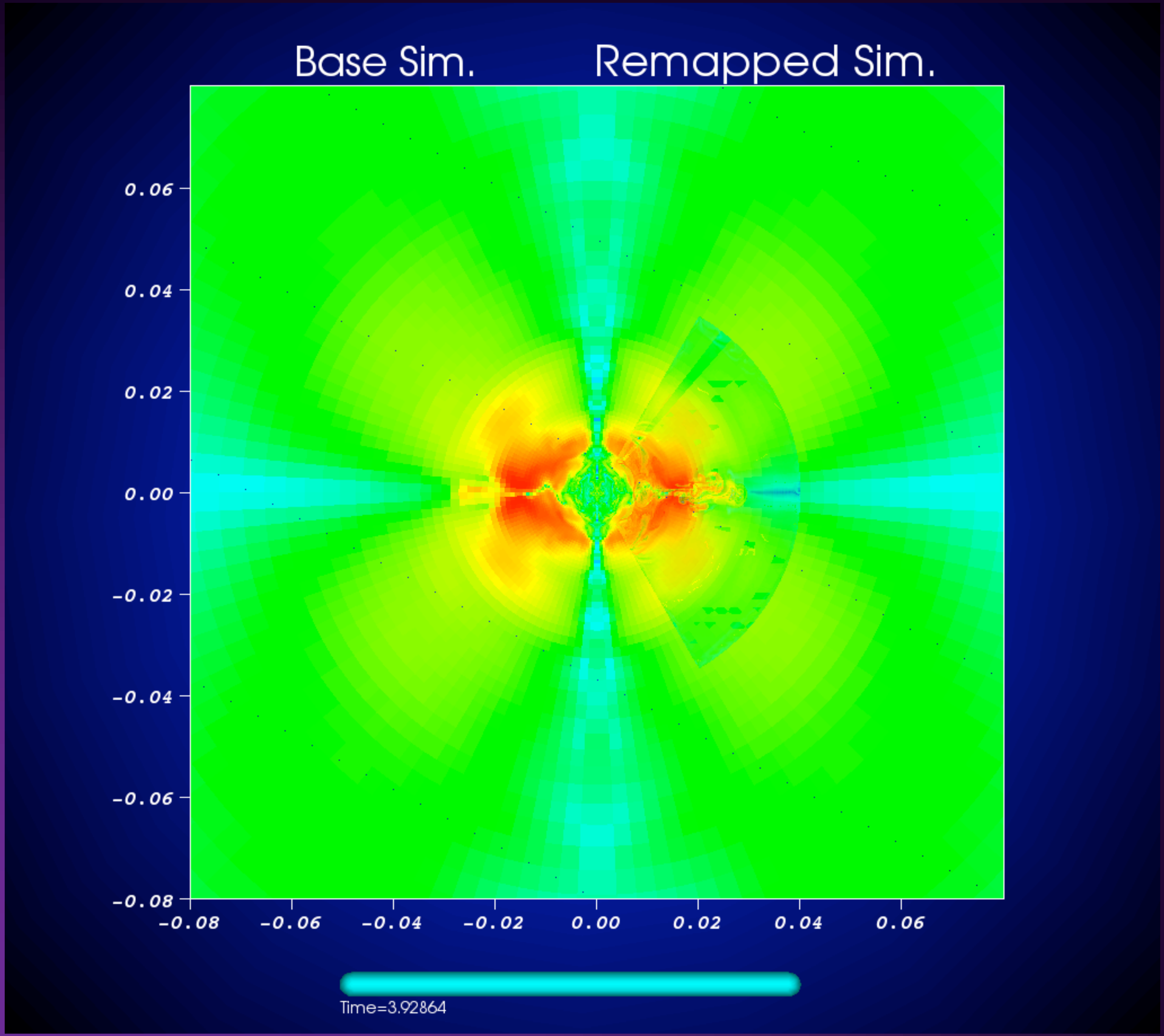




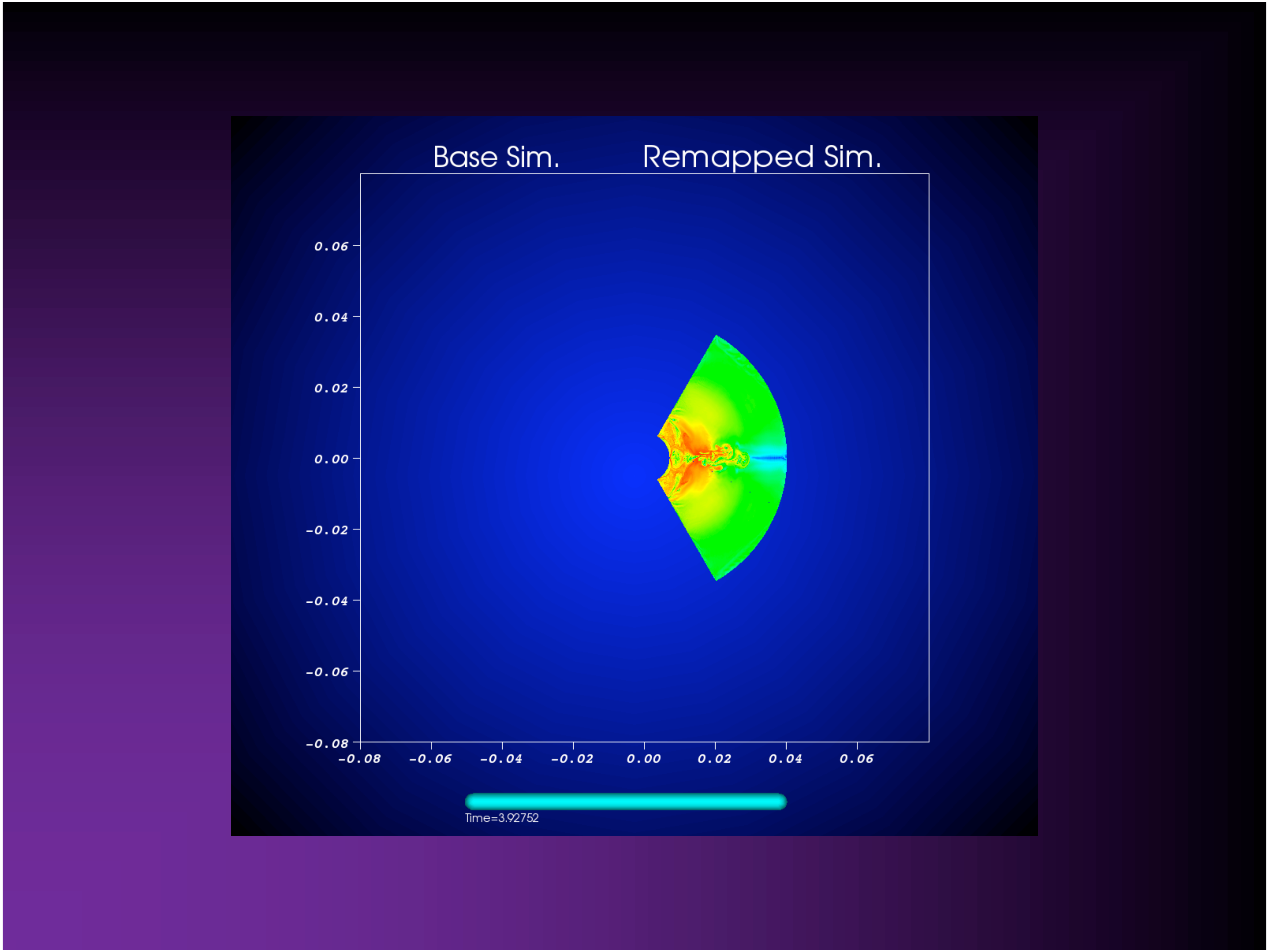
15 msec after remapping
Transport of angular momentum due to the MRI!



Entropy mixing due to the MRI!

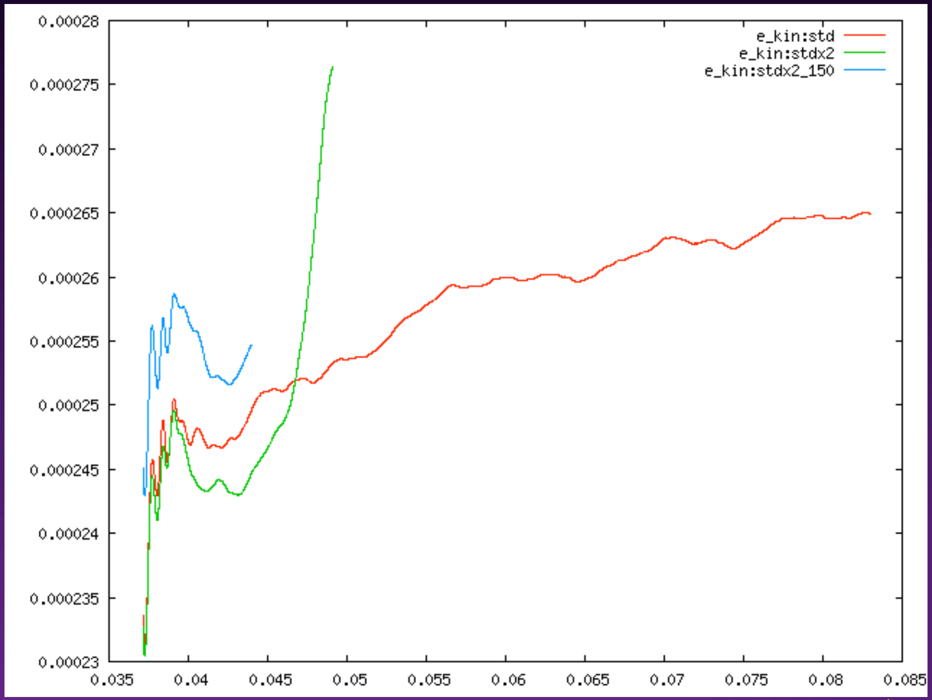


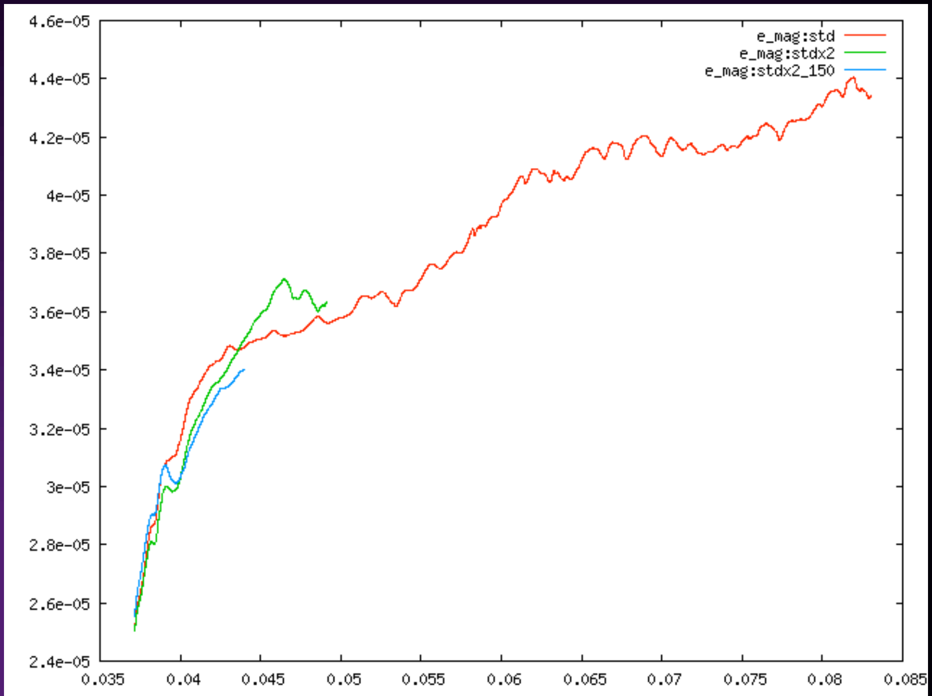
Base Sim.
Remapped Sim.
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.08
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
Time=3.92864



Base Sim.
Remapped Sim.
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
-0.08
-0.06
-0.04
-0.02
0.00
0.02
0.04
0.06
Time=3.92752

E_kin & E_mag





- e_mag/e_kin ~ 0.1
- e_mag continues to rise
- Higher resolution models
  - rapid rise in e_kin
  - Larger e_mag?
- Exponential growth?

On going…

- Explore more parameters
  - Smaller B_0
  - loop radius
  - field geometry
  - R & Ω_0
  - Base sims.
  - Remap timing
- Higher res 2D remap
  - Convergence?
- 3D remap
  - Saturation?

Summary

- 2D core collapse
  - Hydrodynamically stable
  - Adding magnetic field makes unstable!
- Realistic quasi-global simulation
  - 12 - 68 km with Drmin = 5.5 m
  - Background velocity field
  - Unstable region spreads and fills the volume
    - How big will the unstable region become?
  - Angular momentum, entropy mixing
    - Effects on neutrino cooling/heating?
  - Higher resolution => more development
  - Resistive heating due to turbulence? (Thompson et al. 2005)
  - MRI can affect non-dynamical processes!
  - Effects on explosion dynamics requires true global sim. In 3D
- No exponential growth (yet??)
- Interaction with SASI?