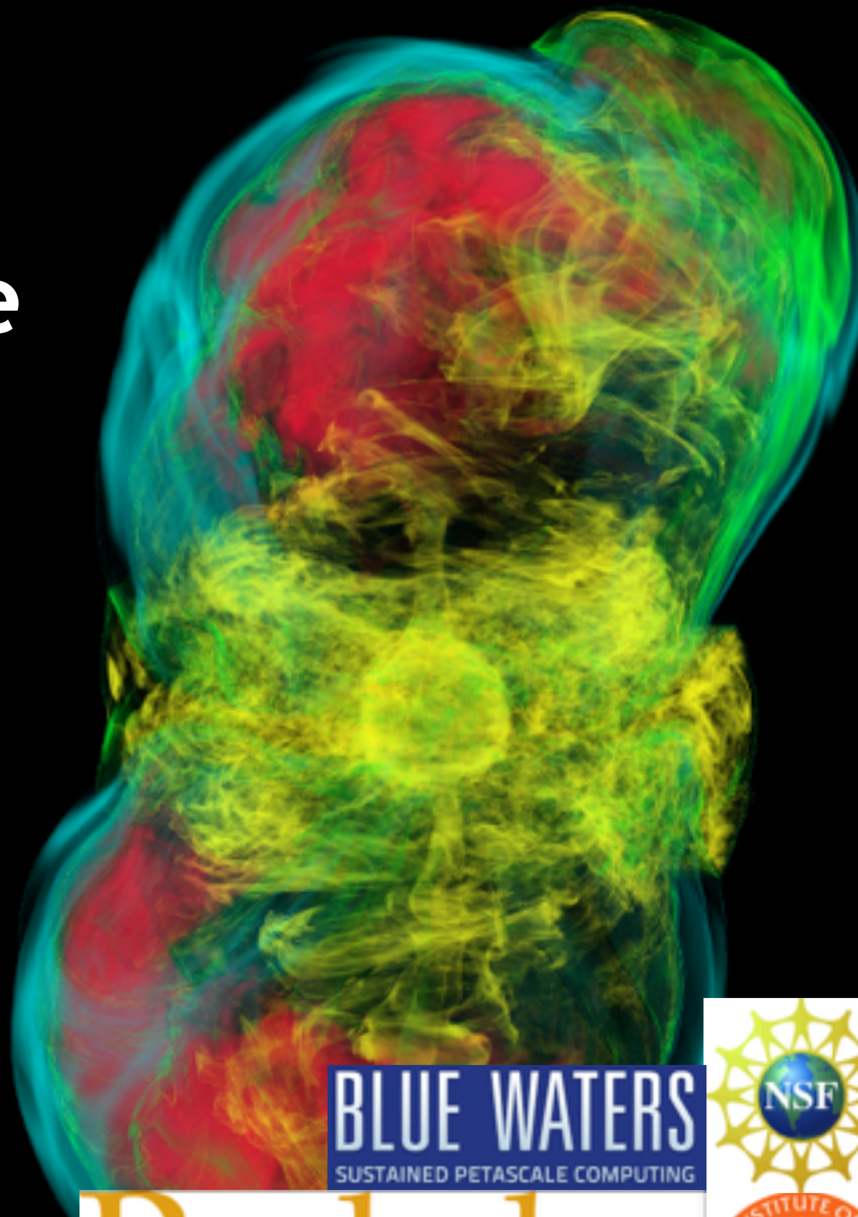
MHD-driven Core-Collapse Supernovae in Three Dimensions

Philipp Mösta

UC Berkeley

pmoesta@berkeley.edu

Christian Ott, Sherwood Richers, Luke Roberts,
David Radice, Roland Haas, Anthony L. Piro,
Ernazar Abdikamalov, Christian Reisswig,
Jonas Lippuner and Erik Schnetter



Einstein Fellowship symposium @ CFA
Oct 28, 2015

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

NSF

Berkeley
UNIVERSITY OF CALIFORNIA

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Core-Collapse Supernovae:

Explosions of Massive Stars $8M_\odot \lesssim M \lesssim 130M_\odot$

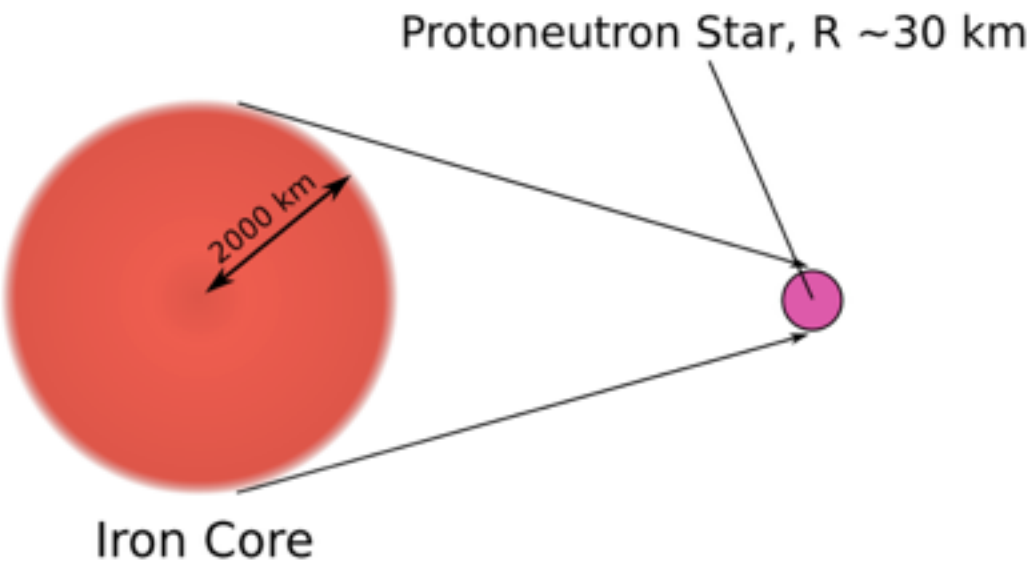
© Anglo-Australian Observatory

Core-Collapse Supernovae:

Explosions of Massive Stars $8M_\odot \lesssim M \lesssim 130M_\odot$

Supernova 1987A
Large Magellanic Cloud
Progenitor:
BSG Sanduleak -69 220a, 18 M_{SUN}

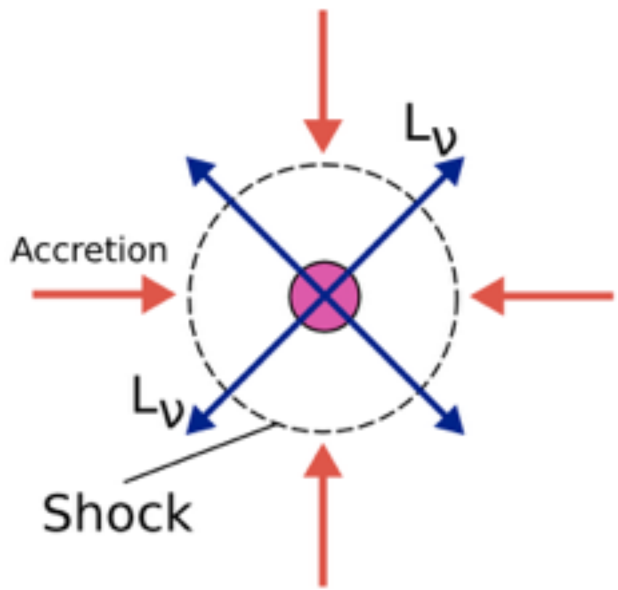
Core Collapse Basics



Nuclear equation of state (EOS) stiffens at nuclear density.

Inner core (~0.5 M_{Sun})
-> protoneutron star core.
Shock wave formed.

Reviews:
Bethe'90
Janka+'12



Outer core accretes onto shock & protoneutron star
with O(1) $M_\odot$/s.

-> Shock stalls at ~100 km, must be "revived" to drive explosion

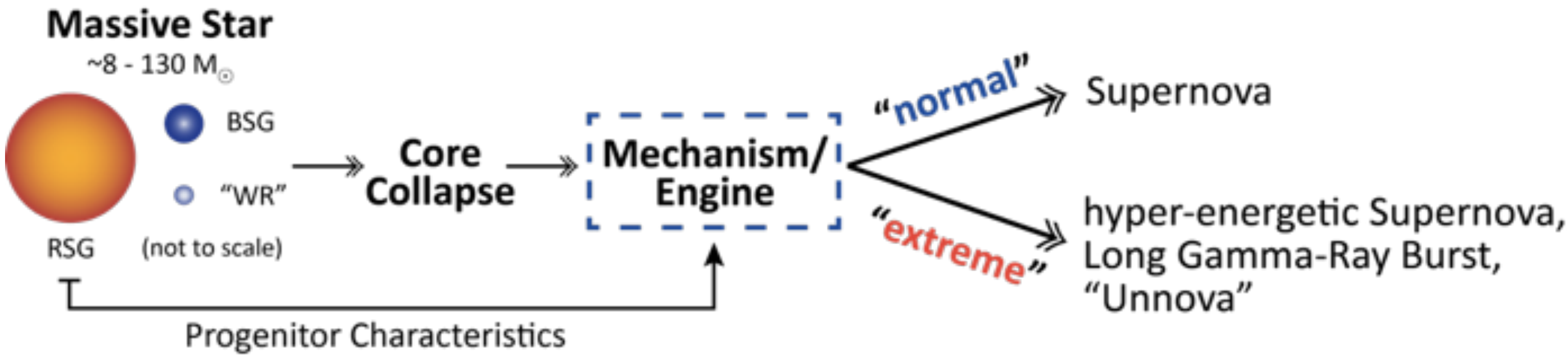
Hyperenergetic Supernovae

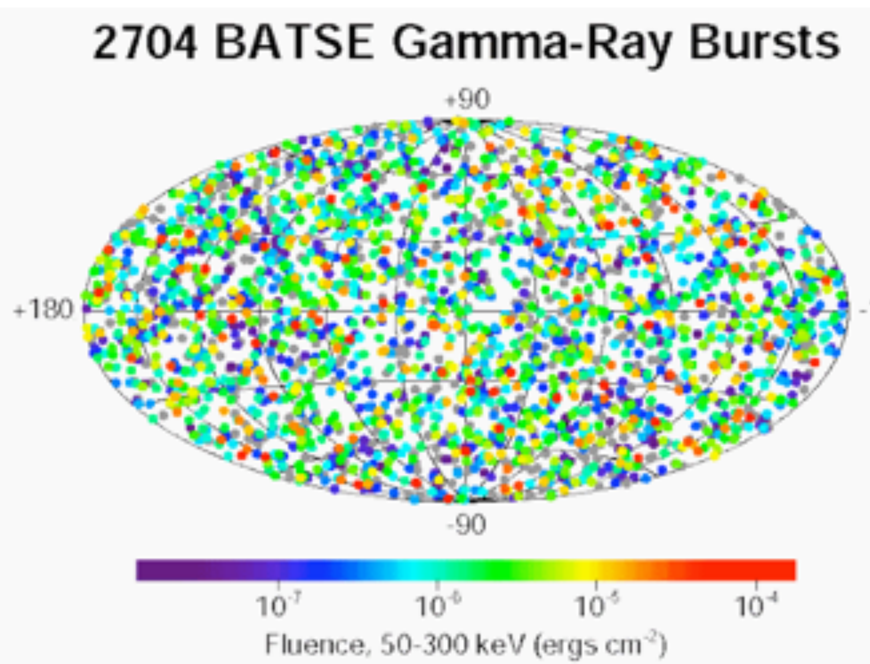
Small fraction (0.1-1%) of CCSN:

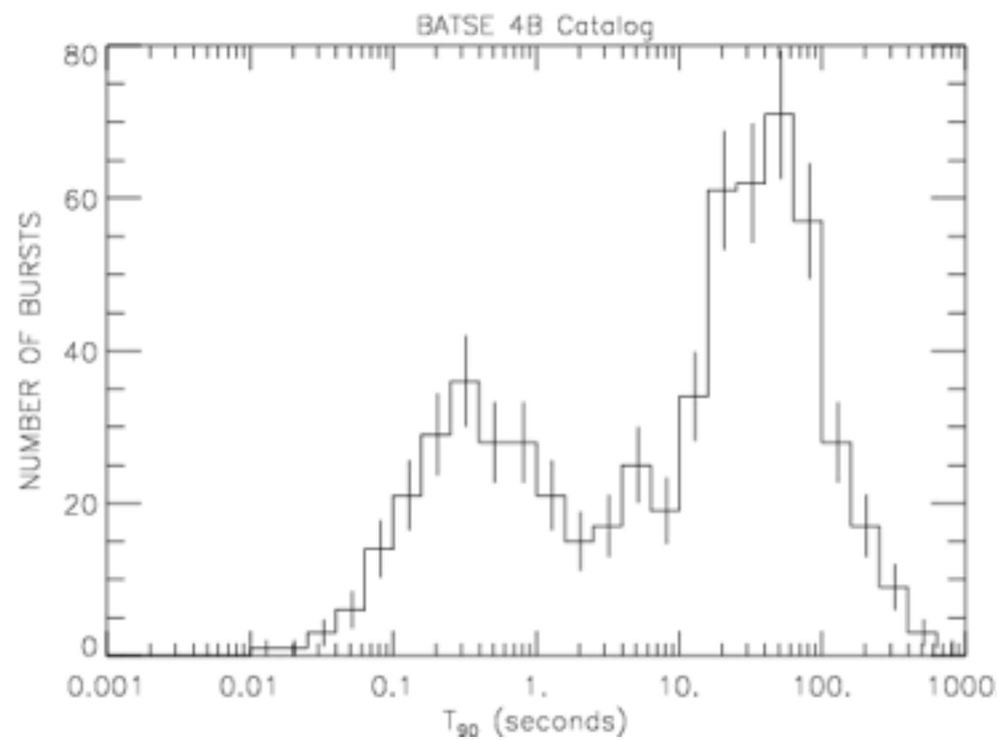
- Hyperenergetic (10 - 100 B)
- doppler-broadened lines (Type Ic-bl)
- Relativistic outflows
- Some connected to long gamma-ray bursts

Supernova 1998bw
Image Credit: ESO

Hypernovae & GRBs

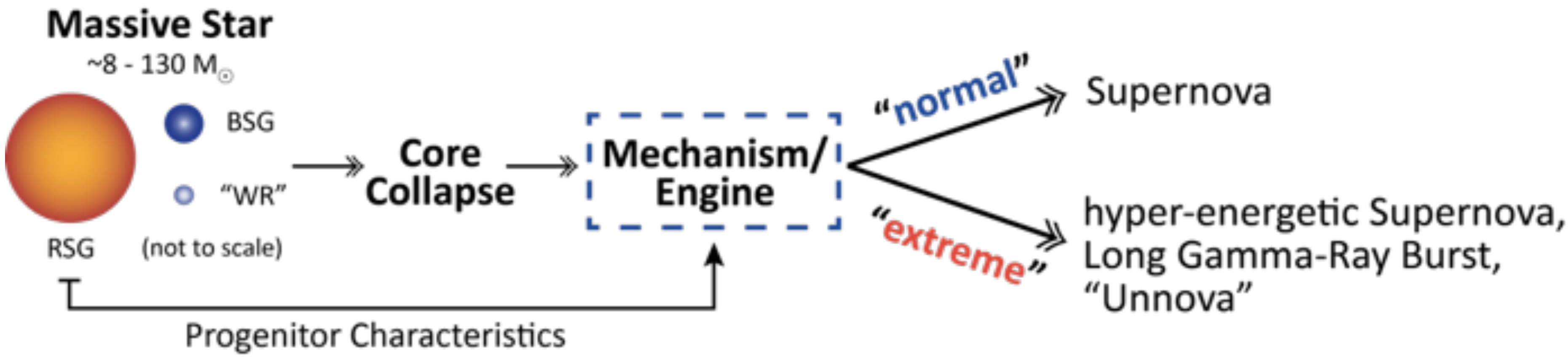






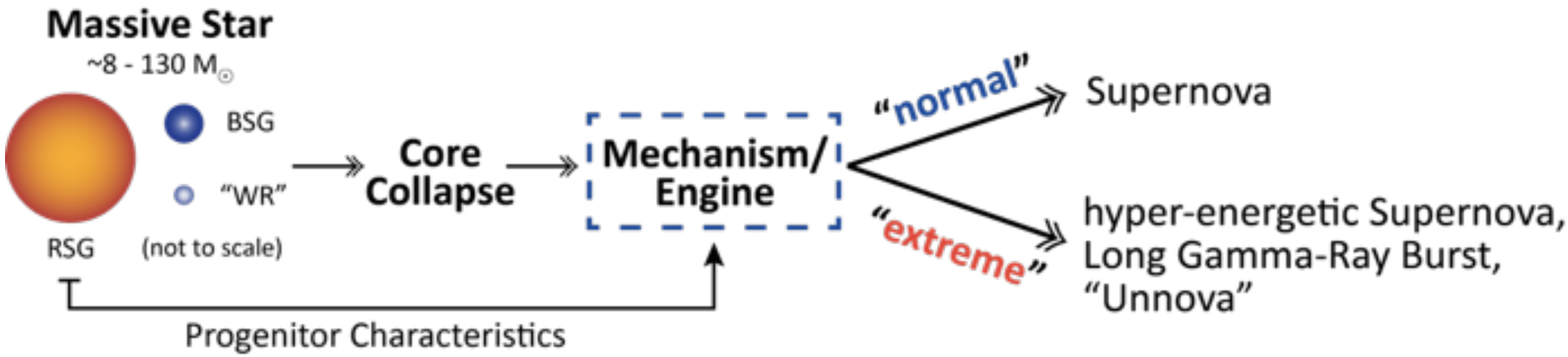
http://apod.nasa.gov/apod/ap000628.html

Hypernovae & GRBs



- 11 long GRB – core-collapse supernova associations.
- **All GRB-SNe are of type "Ic-bl"**: no H, He in spectra, relativistic velocities (bl: "broad lines"), hypernova energies (~10^{52} erg).
- But not all type Ic-bl supernovae come with GRBs
- Trace low metallicity and low redshift
- Neutrino mechanism is inefficient (η~10%); can't deliver a hypernova.

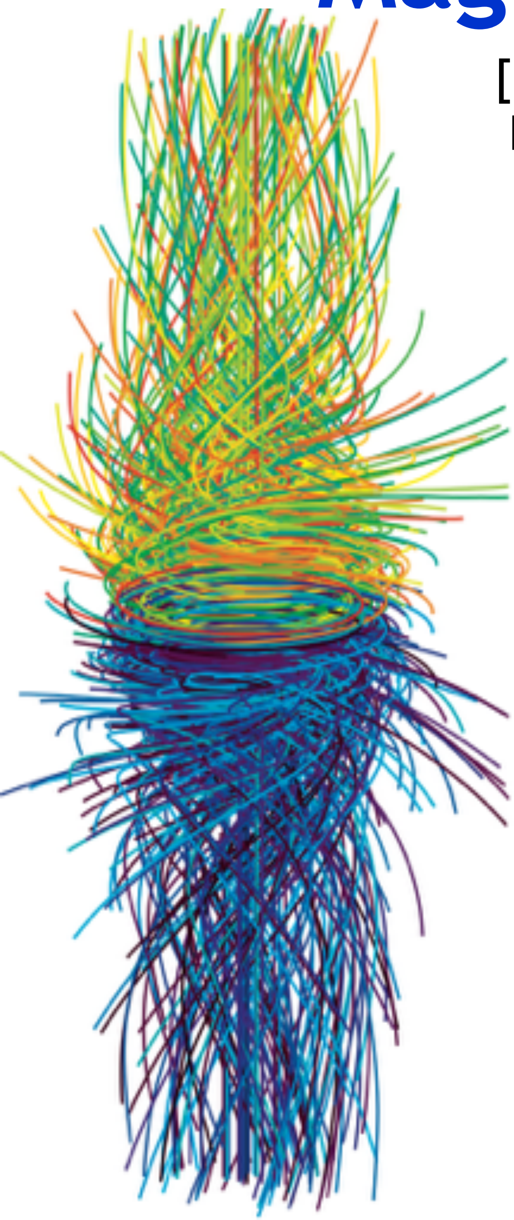
Hypernovae & GRBs



- What mechanism/engine drives these extreme explosions?
- What determines additional XRF/GRB launch?

Magnetorotational Mechanism

[LeBlanc & Wilson '70, Bisnovatyi-Kogan '70, Obergaulinger+'06, Burrows+ '07, Takiwaki & Kotake '11, Winteler+ 12]



Burrows+'07

Rapid Rotation + B-field amplification
(need magnetorotational instability [MRI]; difficult to resolve, but see, e.g, Obergaulinger+'09)

2D: Energetic bipolar explosions.
Energy in rotation up to 10B.

Results in ms-period proto-magnetar.
GRB connection?

Caveats: Need high core spin; only in very few progenitor stars? Magnetic field amplifaction?

Detailed Models: Ingredients

Fully coupled!

Magneto-Hydrodynamics	→ Dynamics of the stellar fluid.
General Relativity	→ Gravity
Nuclear and Neutrino Physics	→ **Nuclear EOS**, nuclear reactions & ν interactions.
Boltzmann Transport Theory	→ **Neutrino transport.**

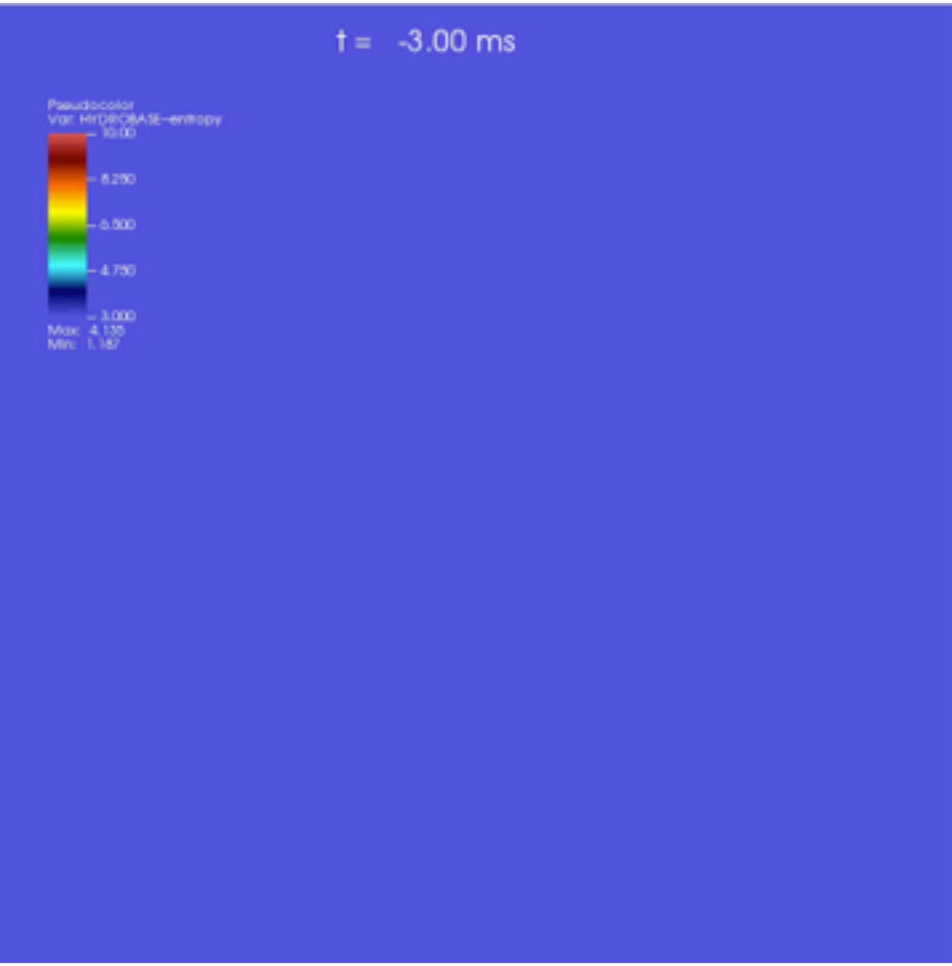
- **Additional Complication: Core-Collapse Supernovae are 3D**
  - Rotation, **fluid instabilities** (convection, turbulence, advective-acoustic, rotational), **MHD**, multi-D structure from convective burning -> **Need 3D treatment.**

- **Route of Attack: Computational Modeling**
  - turbulence on scales 10 m but relevant radius of star is at least 10^7 m; simulation timestep is 10^{-6} s but cooling time of protoneutron star is 10 s

3D Dynamics of Magnetorotational Explosions

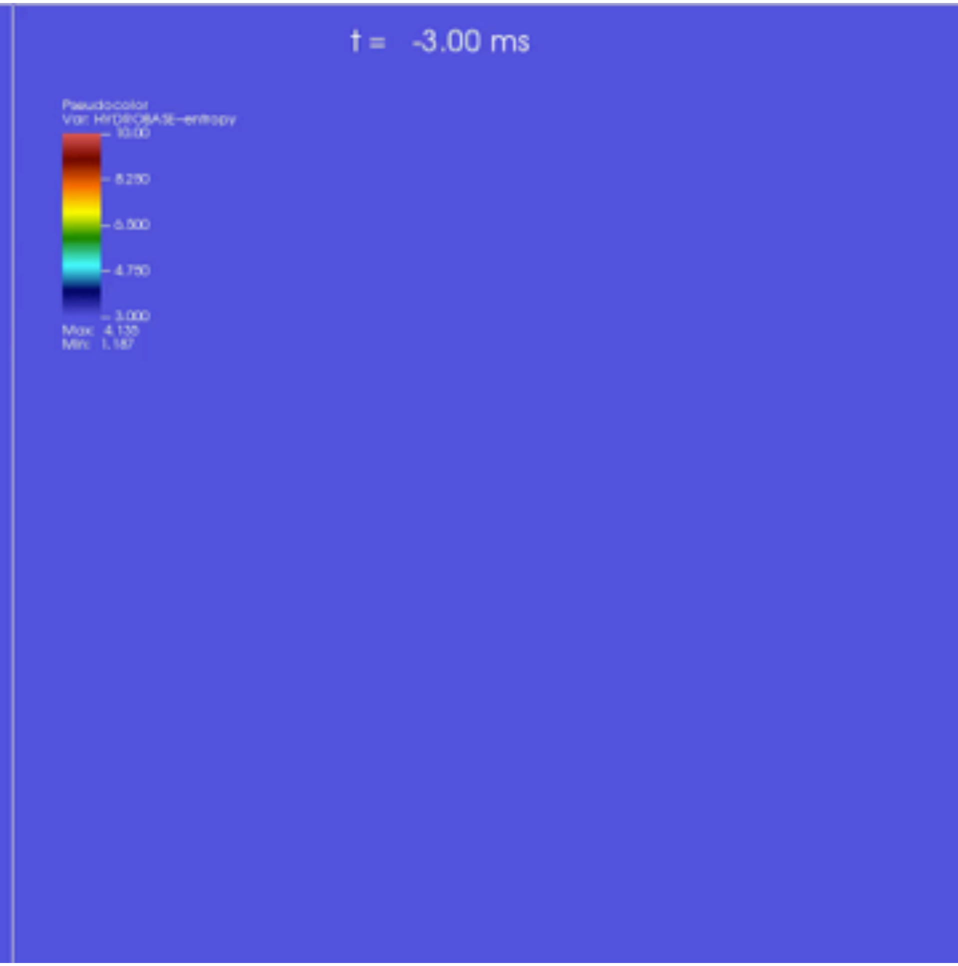
New, full 3D GR simulations. **Mösta+ 2014**, ApJ 759, L24
Initial configuration as in Takiwaki+11, 10^{12} G seed field.

← 2000 km →



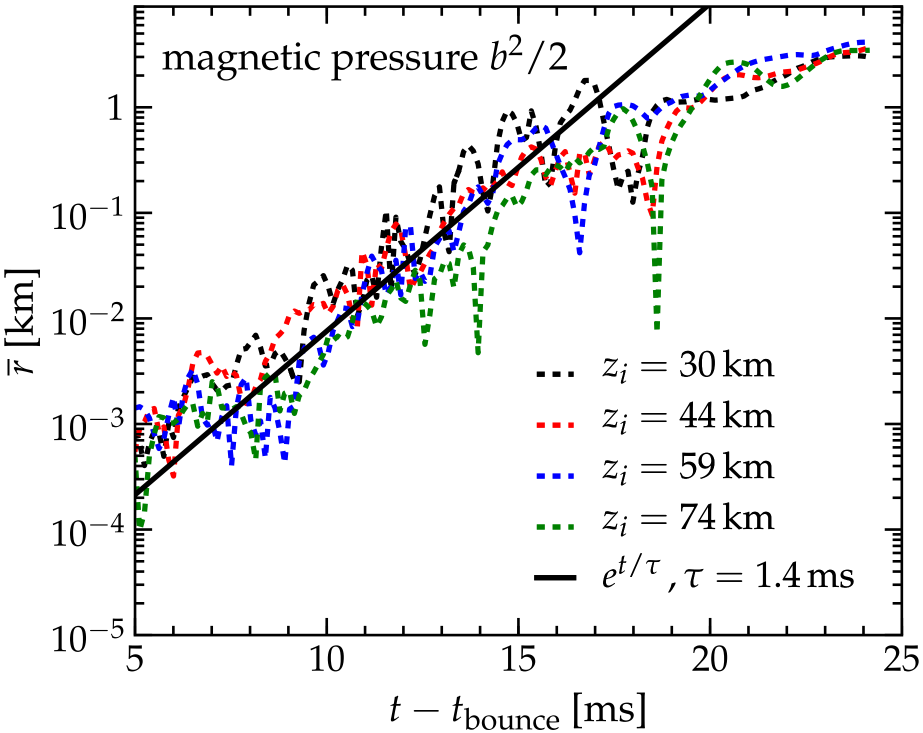
Octant Symmetry (no odd modes)

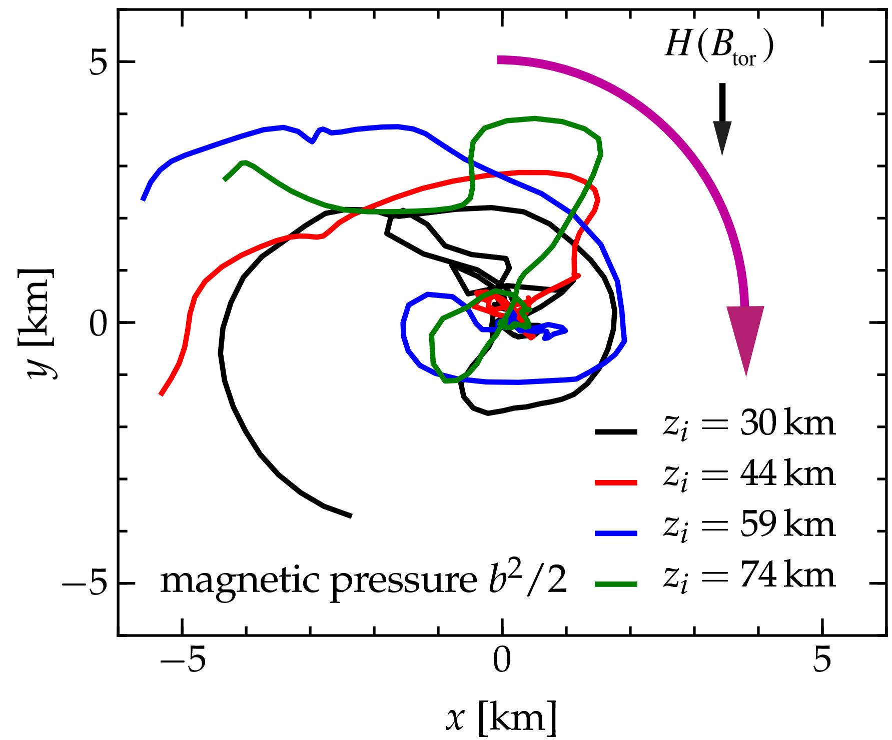
← 2000 km →



Full 3D

What's going on here?





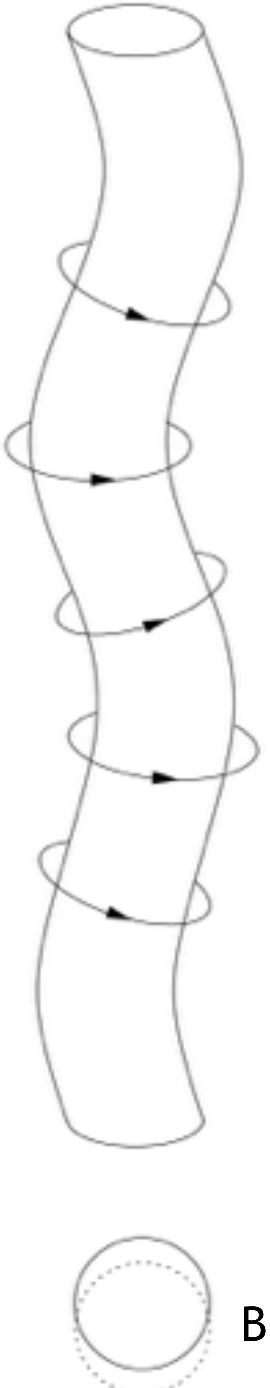
- m=1 spiral instability
- Growth rate, wavelength and helicity of fastest growing mode consistent with MHD kink instability; should hold independent of initial B-field strength

$$\tau_{\text{fgm}} \approx \frac{4a\sqrt{\pi\rho}}{B_{\text{tor}}} \approx 1\,\text{ms}$$

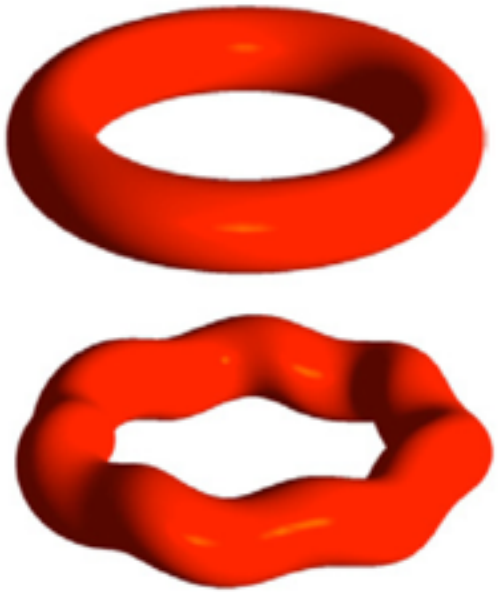
$$\lambda_{\text{fgm}} \approx \frac{4\pi a B_z}{B_{\text{tor}}} \approx 5\,\text{km}$$

MHD Kink Instability

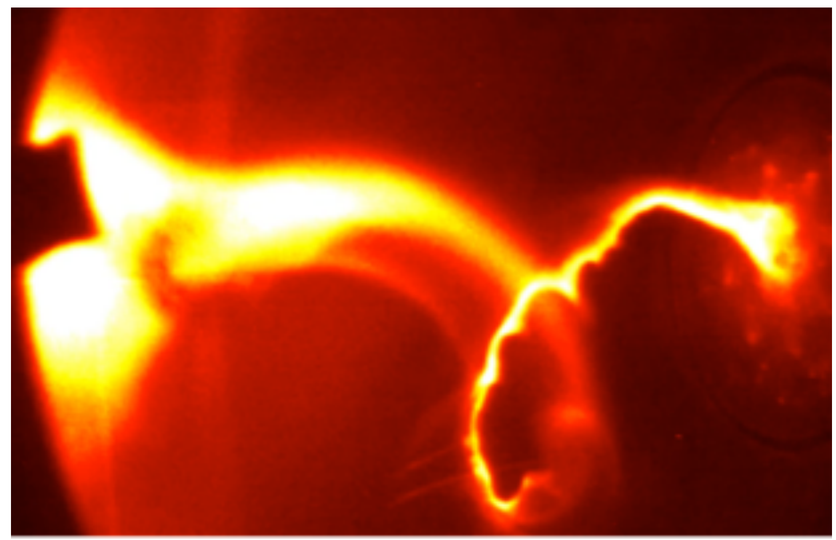
- B-field near proto-NS: $B_{tor} >> B_z$
- Unstable to MHD screw-pinch kink instability.
- Similar to situation in Tokamak fusion reactors!



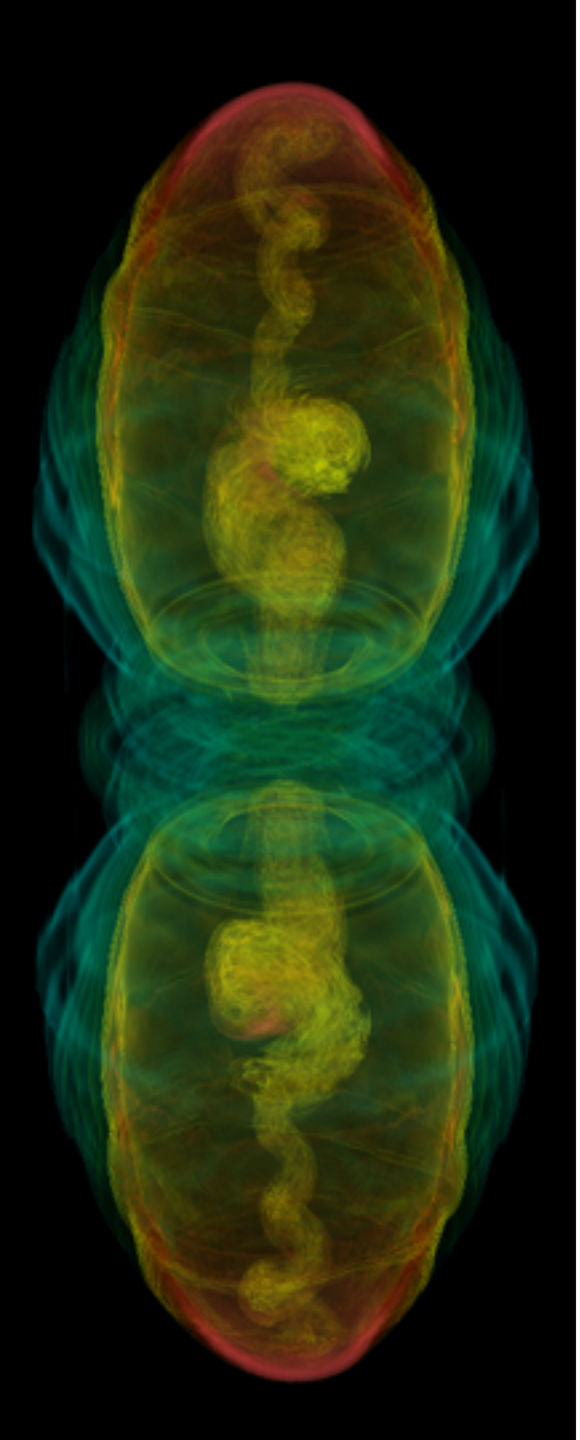
Braithwaite+ '06



Sarff+13



Credit: Moser & Bellan, Caltech



MHD Kink Instability

3D: Plasma flow unstable to MHD “kink” instability

Key for instability: $B_{tor}/B_z > 2\pi a/L$

[Shafranov+’56, Kruskal+’58]

$$\nabla\left(p+\frac{B^2}{8\pi}\right)=\frac{1}{4\pi}(B\cdot\nabla)B$$

- Magnetic pressure driven
- cannot be countered by magnetic tension

3D Volume Visualization of

Entropy

t = -3.00 ms

Mösta et al. 2014

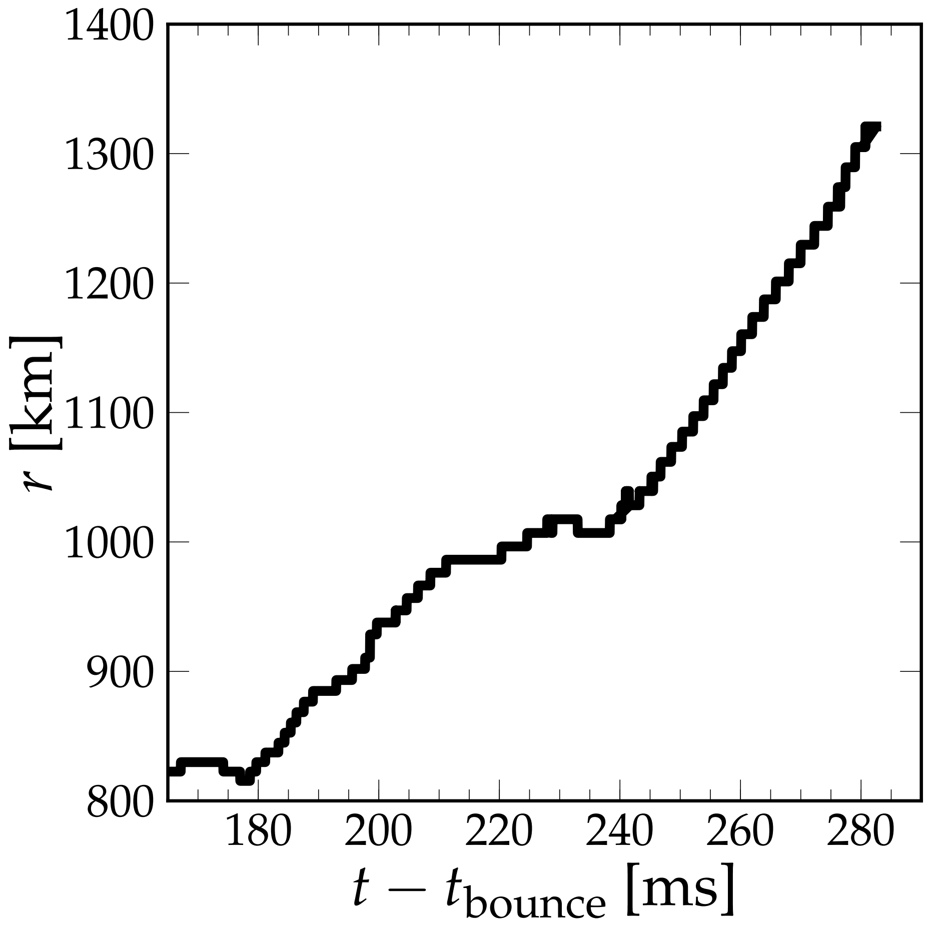
3D Volume Visualization of

$$\beta = \frac{P_{\rm gas}}{P_{\rm mag}}$$

Mösta et al. 2014

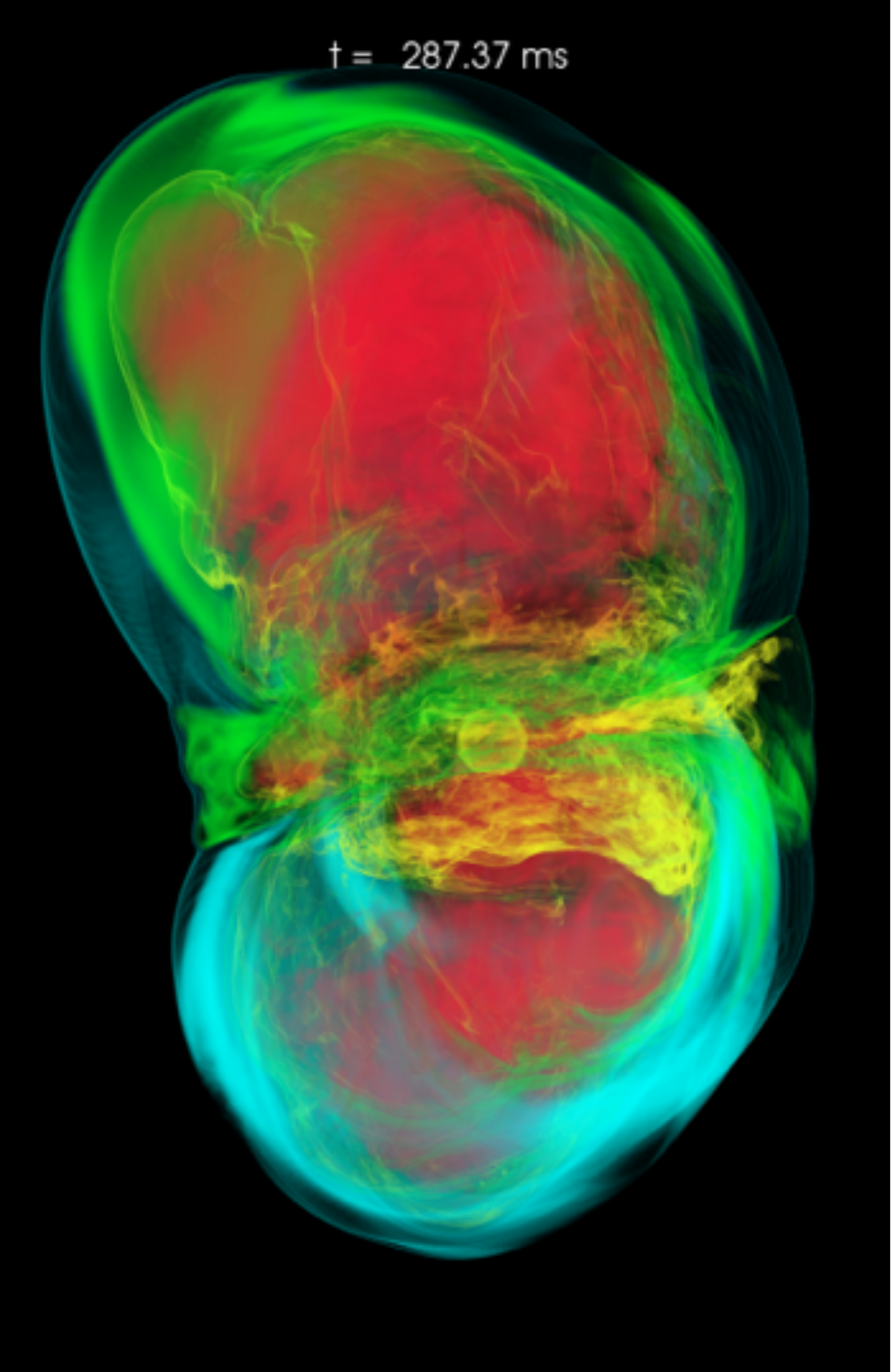
t = -4.95 ms

Ongoing Simulation



Explosion?

- Tracking shock with lower resolution as scales become larger and larger
- Follow evolution with tracer particles to extract nucleosynthetic yields



Ongoing Simulation

- Geometry becomes even more tilted, but general wide-lobe trend continues
- Expansion speed few percent of the speed of light; very different from 2D jet explosion

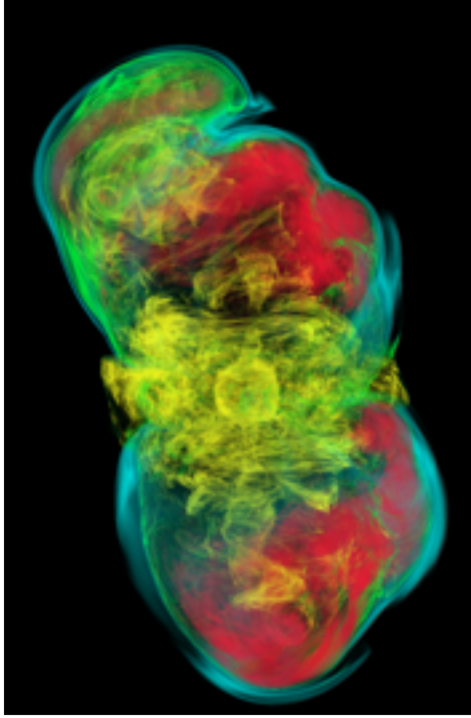
Implications for Gamma-Ray Bursts

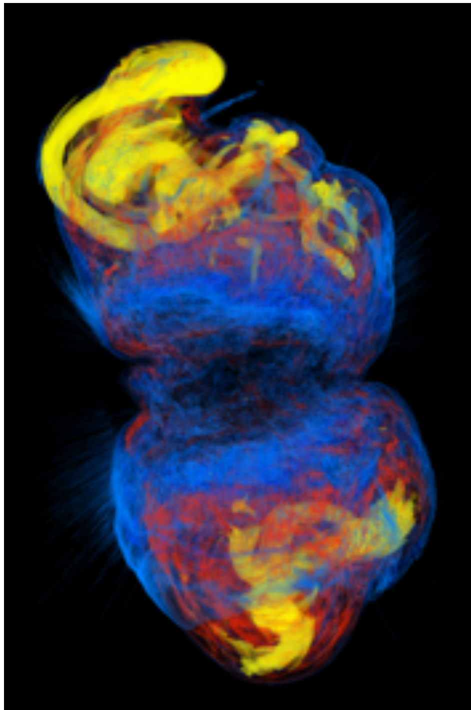
- Long gamma-ray bursts come with extreme supernovae.
- Central engine of GRB: black hole or neutron star?
- Simulations show: continued accretion on the equator in supernova phase.
- Favors formation of black-hole engine (collapsar).

Supernova remnant W49B; harboring a black hole? (Lopez+2013)

Summary

- MHD supernovae (and other high-energy astro systems) need to be modeled in 3D
- Developing jets become 'kink'-unstable, but highly magnetized outflows drive shock into dual-lobe structure that transitions into explosion
- Accretion continues and mass of the proto-NS increases -> Allows for magnetar and collapsar LGRB models
- Implications for r-process in jet-driven outflows





Thank you!