Magnetorotational Core-Collapse Supernovae in Three Dimensions

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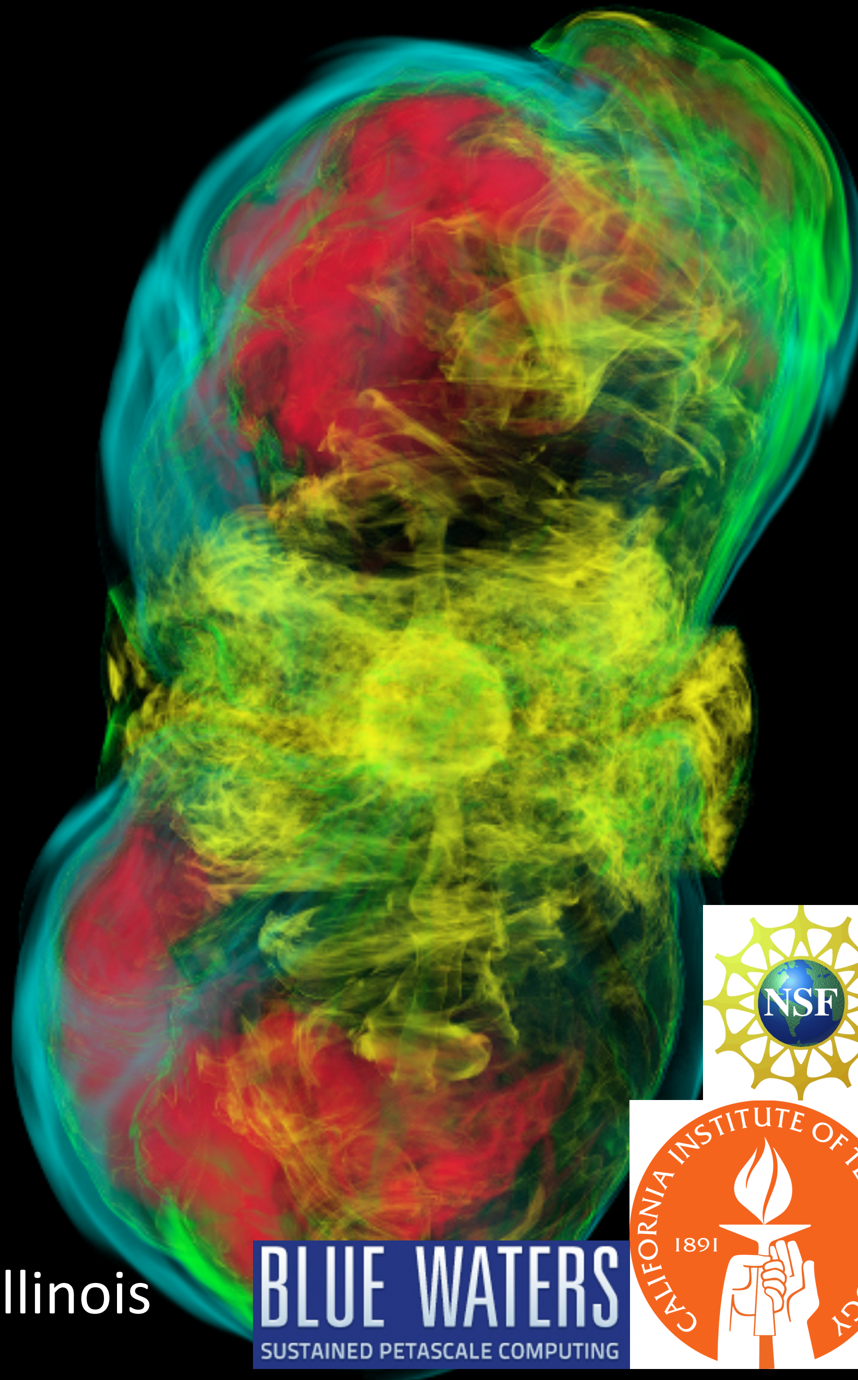
Astrophysical Journal, 785, L29

BlueWaters Symposium 2014, NCSA, Illinois

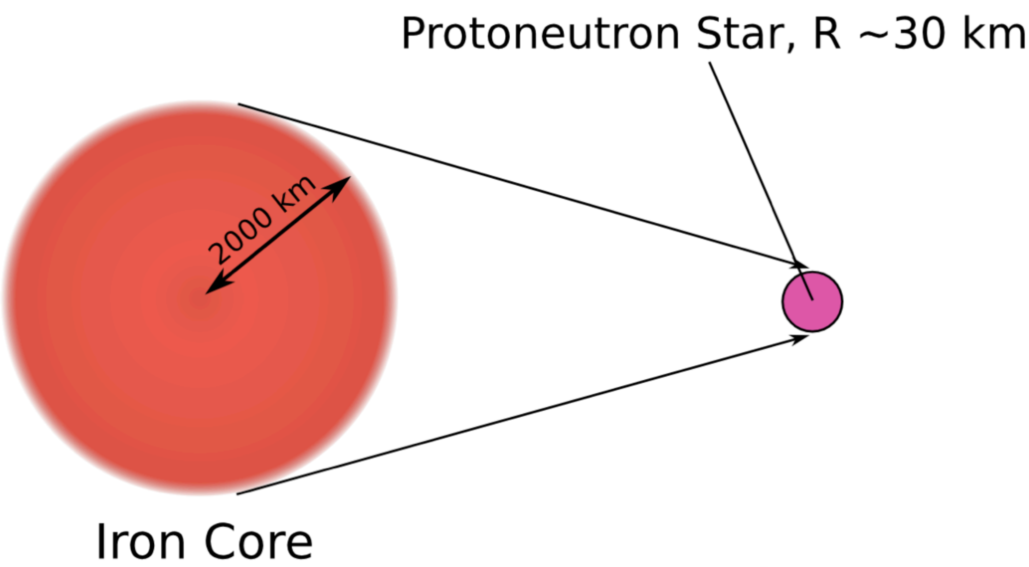


BLUE WATERS
SUSTAINED PETASCALE COMPUTING

NSF

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Core Collapse Basics



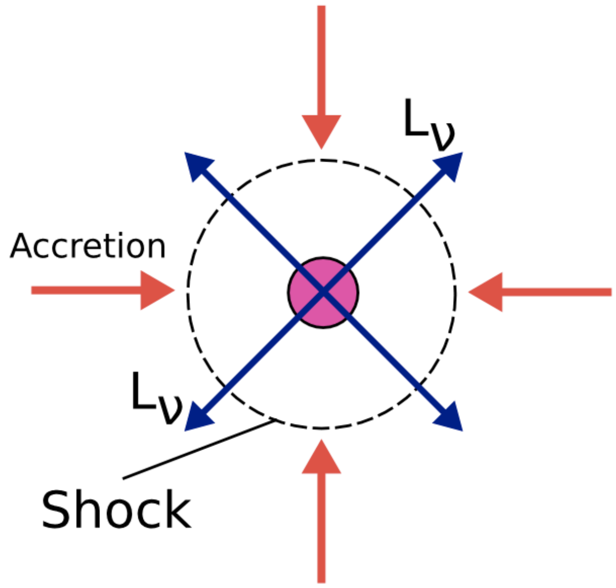
Nuclear equation of state (EOS) stiffens at nuclear density.

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

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

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

Reviews:
Bethe'90
Janka+'12



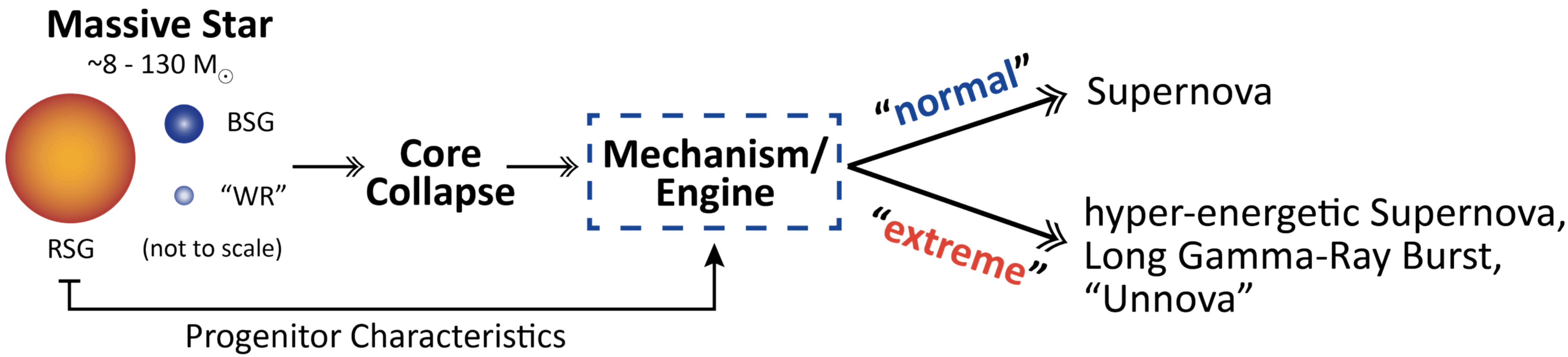
Hyperenergetic Supernovae

Small fraction (~0.1%) of CCSN:

- hyperenergetic
- doppler-broadened lines (Type Ic-bl)
- Relativistic outflows
- Some connected to long gamma-ray bursts

Supernova 1998bw
Image Credit: ESO

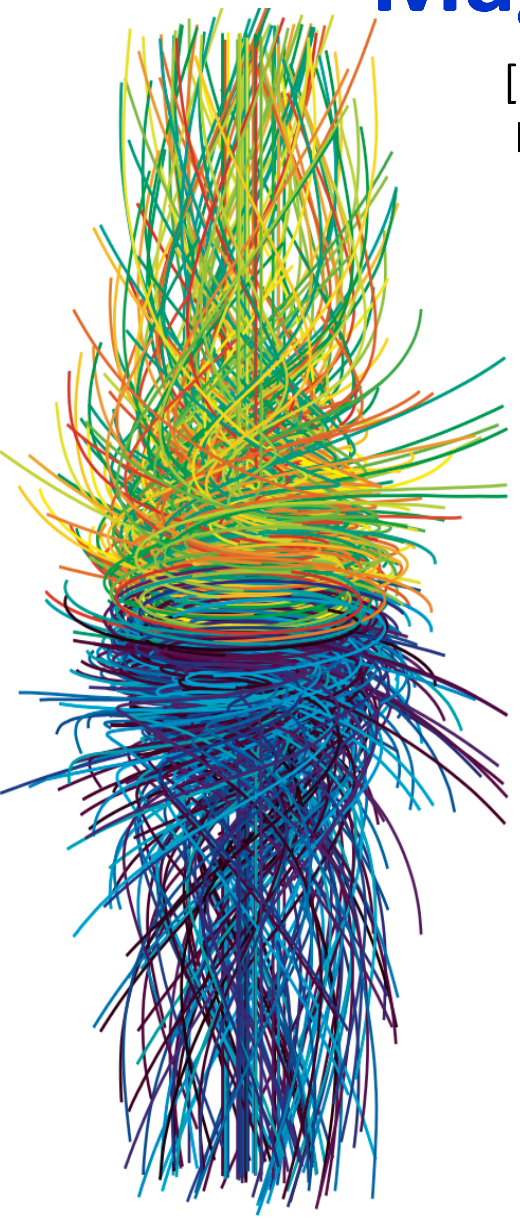
Hypernovae & GRBs



- 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).
- Neutrino mechanism is inefficient (η~10%);
  can't deliver a hypernova.
- What mechanism drives these extreme explosions?

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?

Computational challenge

Core-collapse supernovae pose a multi-scale, multi-dimensional, multi-physics problem:

- General Relativity, magnetohydrodynamics, nuclear equation of state, neutrino transport, neutrino/nuclear interactions
- turbulence (e.g. MRI) on scales 10^3 cm but radius of relevant stellar interior is 10^9 cm
- Courant-limited timestep is 10^{-6} s but cooling time of protoneutron star is 10 s
- 3 spatial, 3 momentum (neutrinos) space dimensions + 1 time dimension
- Need full 3D (turbulence, instabilities)

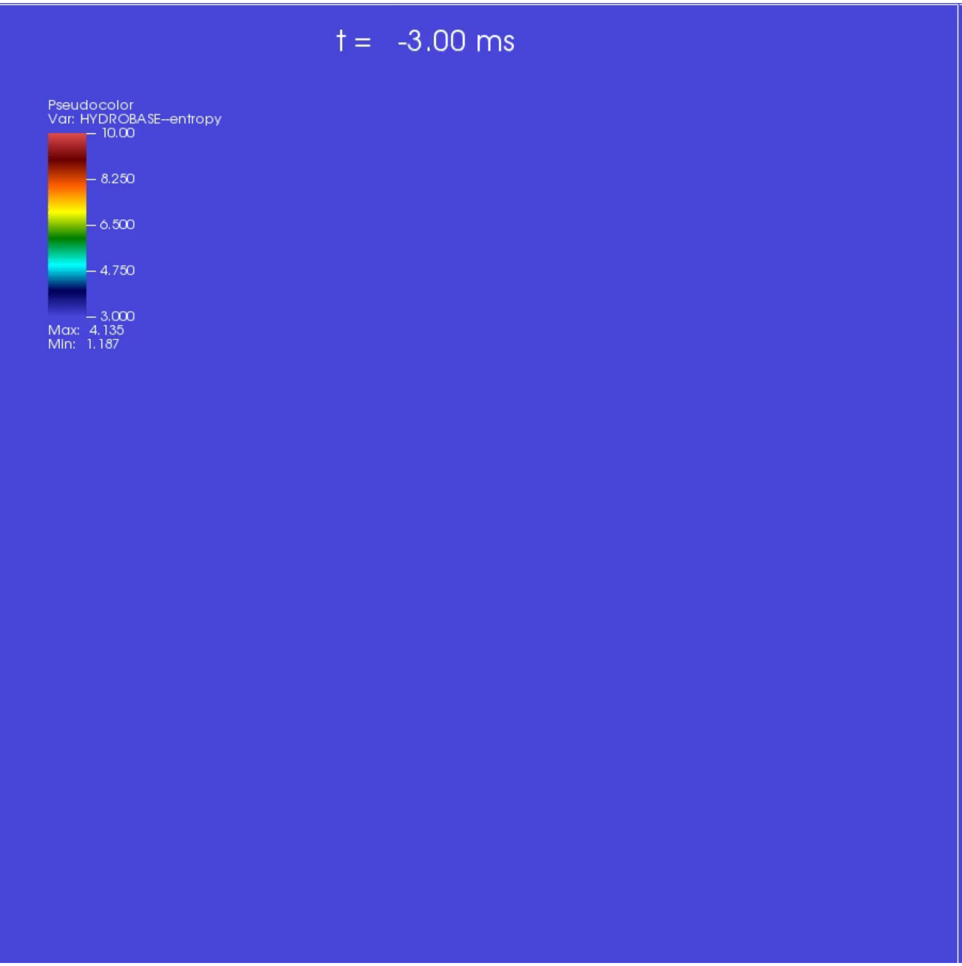
New 3D Simulations

- Open-source simulation code based on **Einstein Toolkit** (einsteintoolkit.org) [Moesta+'14].
- Full 3D general relativity (GR).
- Ideal GR magneto-hydrodynamics with detailed nuclear equation of state (LS220) and neutrino heating/cooling via Leakage scheme [O'Connor+'10, Ott+'12].
- div B = 0 via constrained transport.
- 9 levels of adaptive mesh refinement.
  6 TB runtime memory.
  500 TB simulation output.
- Simulation on ~20k compute cores on NSF Blue Waters at NCSA/Illinois.

3D Dynamics of Magnetorotational Explosions

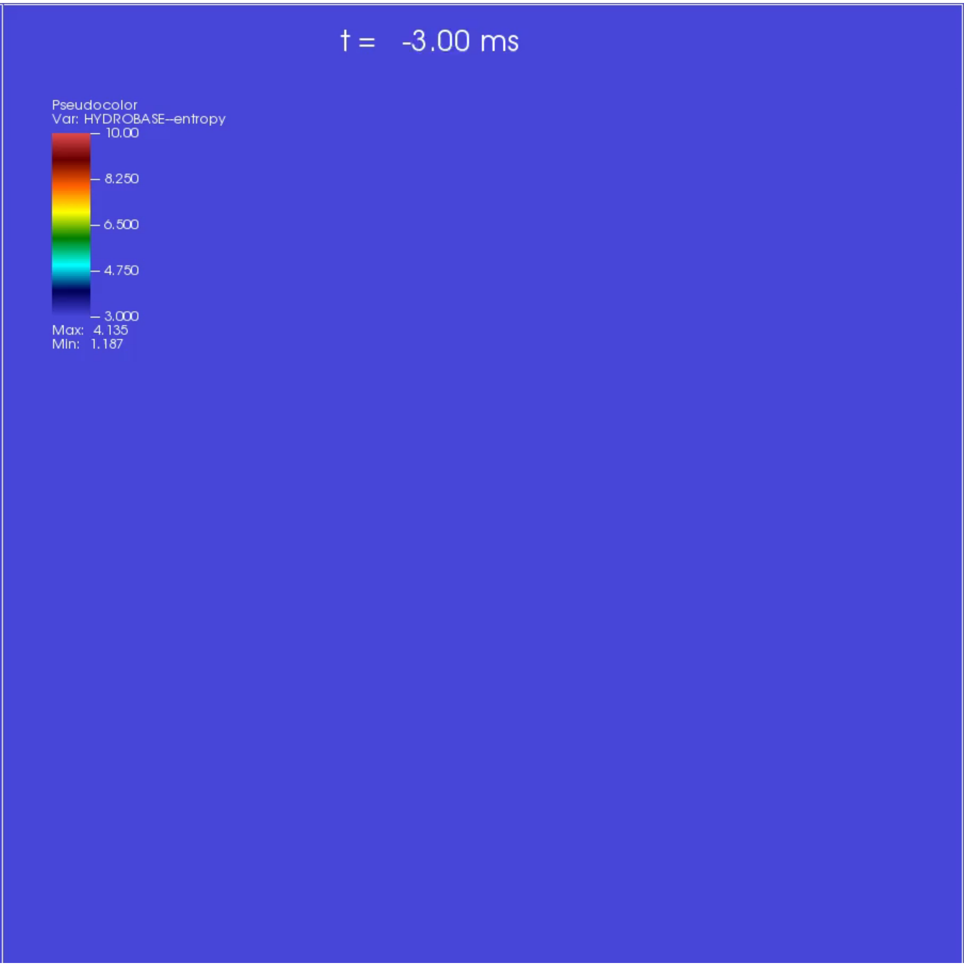
New, full 3D GR simulations. **Mösta+ 2014**, ApJ 759, L24
Initial configuration as in Takiwaki+11, 10^{12} G seed field.

← 2000 km →



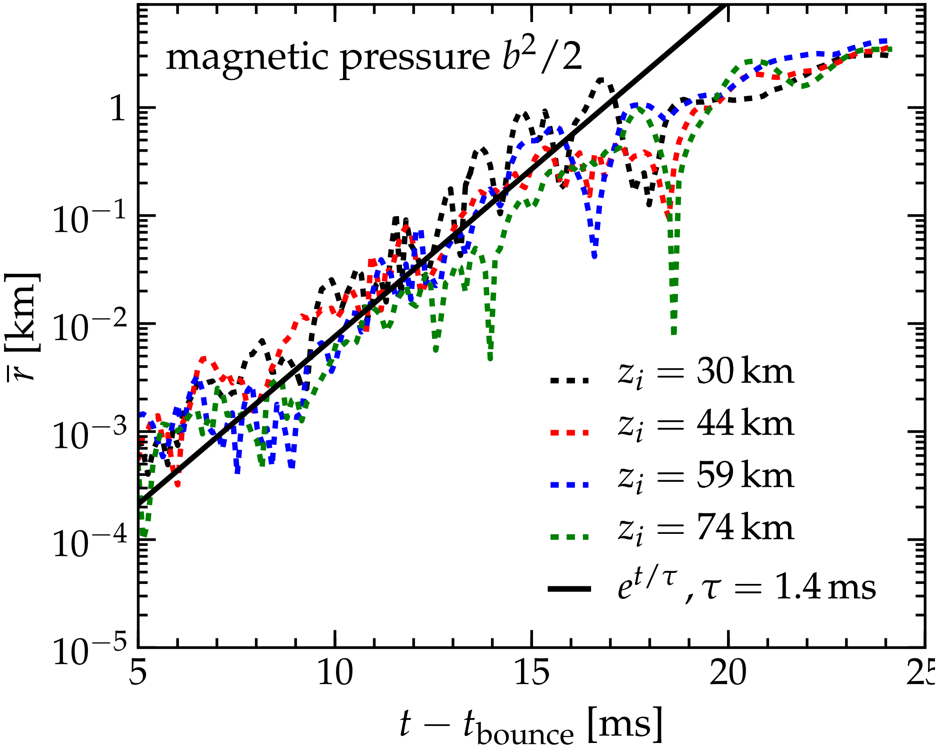
Octant Symmetry (no odd modes)

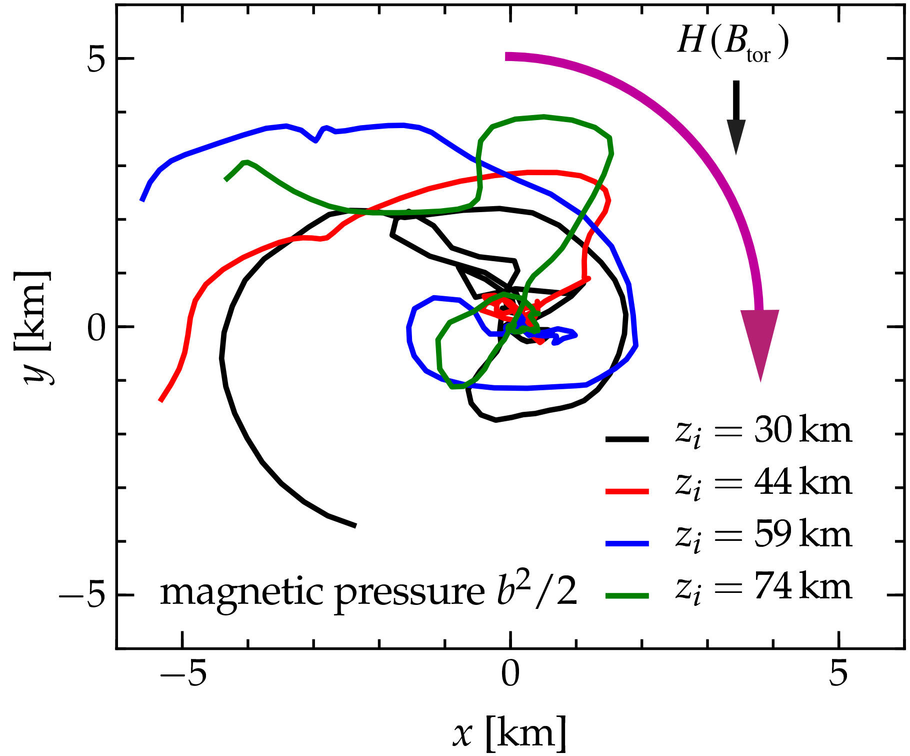
← 2000 km →



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

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

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

MHD Kink Instability

Braithwaite+’06

3D: Plasma flow unstable to
MHD “kink” instability
(as seen in laboratories in Tokamak fusion reactors!)

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

t = -3.00 ms

Entropy

Mösta et al. 2014

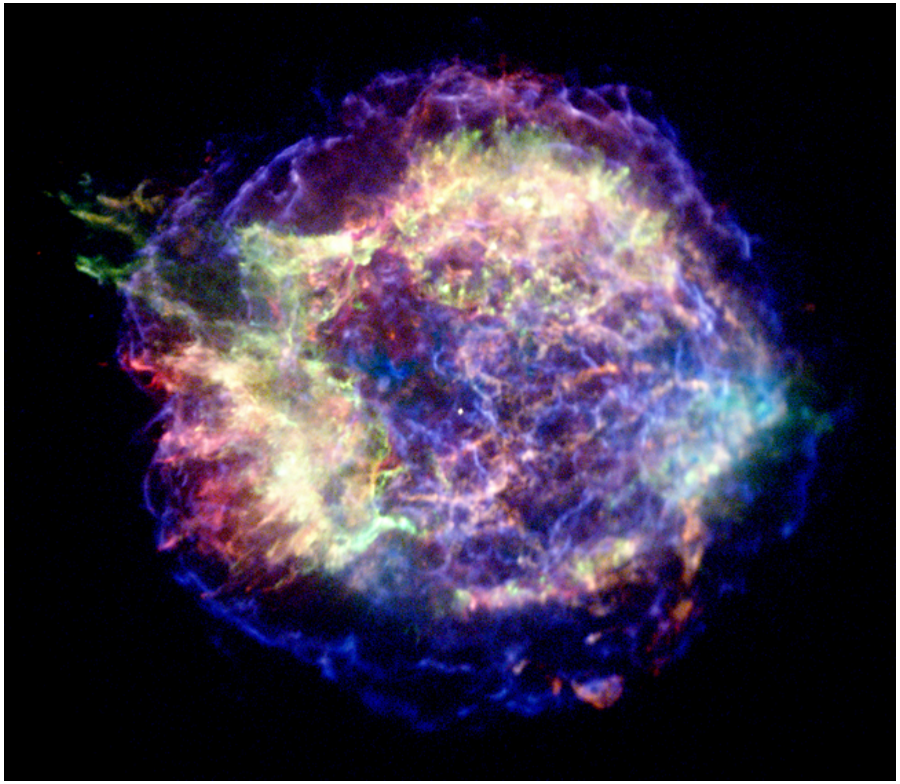
3D Volume Visualization of

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

Mösta et al. 2014

t = -4.95 ms

Connection to Observations



Cassiopeia A Supernova Remnant
Image Credit: NASA.

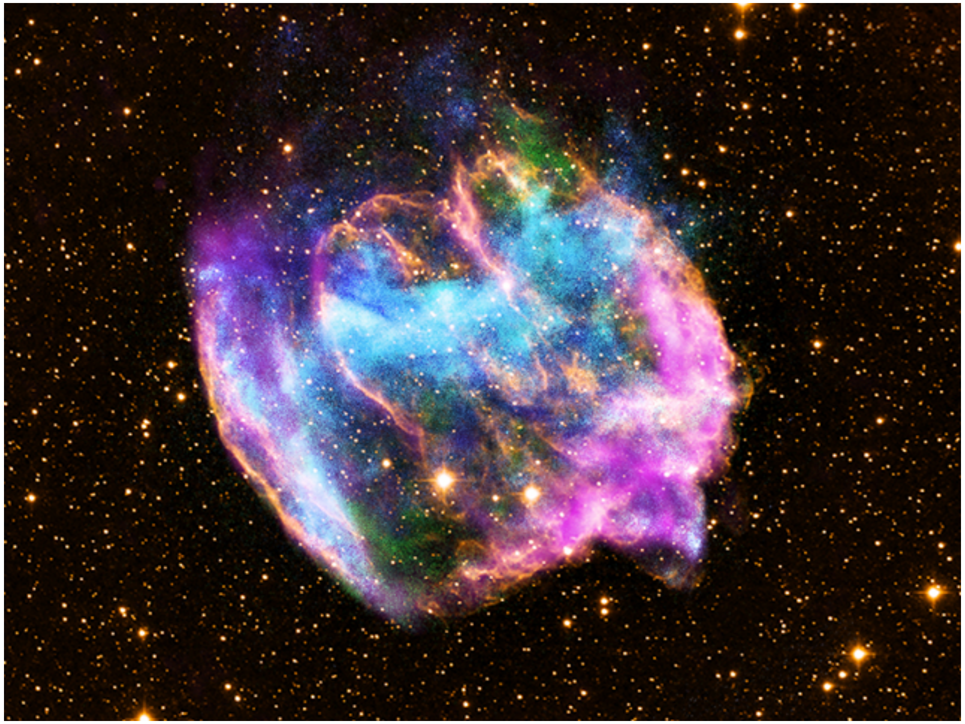
$Y_e \sim 0.1 - 0.2 \quad s \sim 10 - 15 \ \mathrm{k_b baryon^{-1}}$

$\beta \sim 0.01 - 0.1$ underdense

- Highly magnetized outflows show plausible conditions for creation of neutron-rich heavy elements, possibly r-process.
- May explain observed asymmetries in SNR also for rotating progenitors (recent NuStar observations).
- Explosion?

Implications for Gamma-Ray Bursts

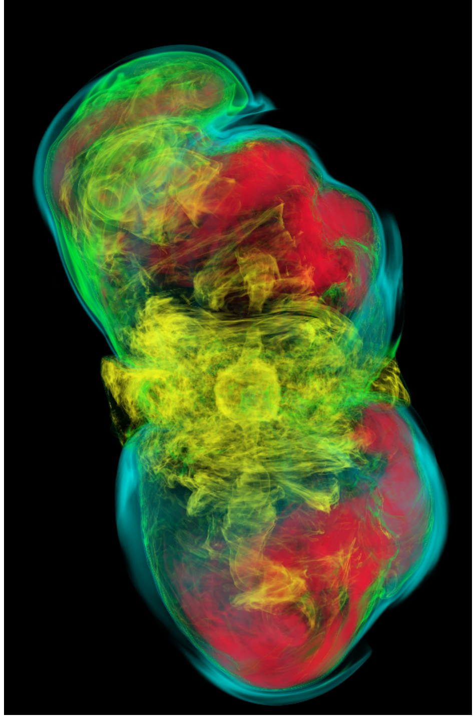
- Long gamma-ray bursts come with extreme supernovae.
- Central engine of GRB: black hole or neutron star?
- Simulations show: continued accretion on the equator in supernova phase.
- Favors formation of black-hole engine (collapsar).

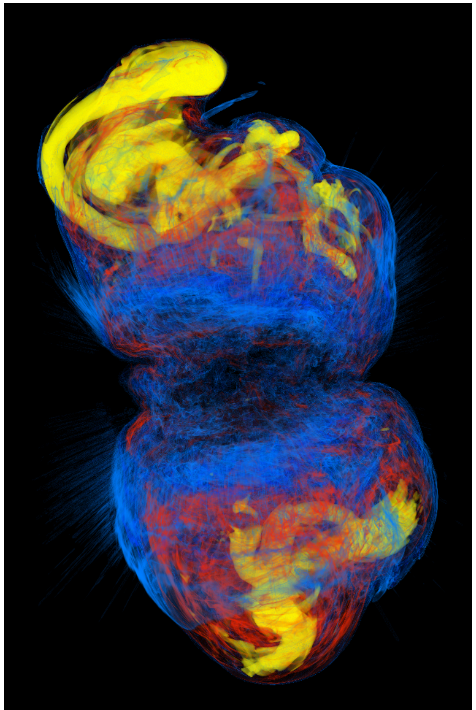


Supernova remnant W49B; harboring a black hole? (Lopez+2013)

Summary

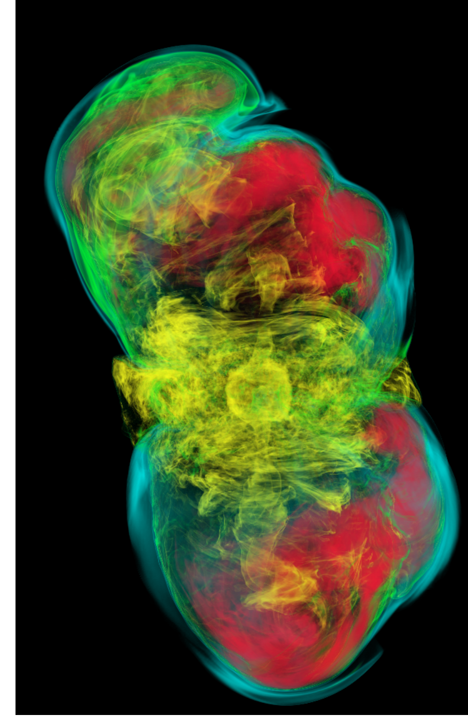
- We are using BlueWaters for full 3D core-collapse supernova simulations
- Developing jet becomes 'kink'-unstable and is disrupted
- Highly magnetized outflows drive shock into dual-lobe structure
- Accretion continues -> favors collapsar long gamma-ray burst engine
- Asymmetries may explain off-(jet-)axis ejecta elements for rapidly spinning progenitors (-> NuStar ^{44}Ti mapping in CasA)

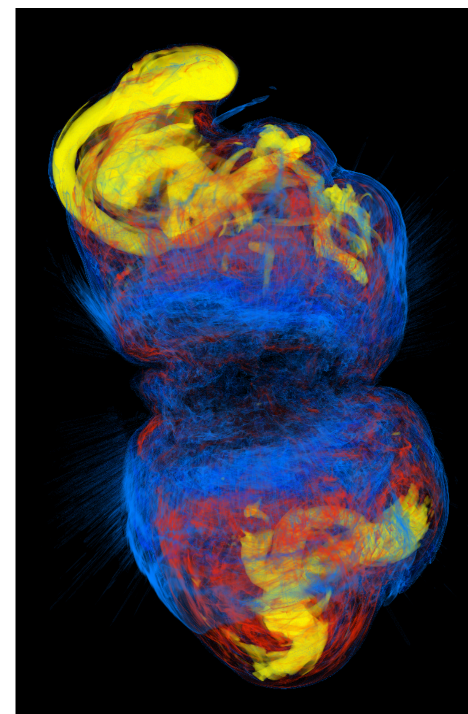




Future

- Longer simulations
- Tracer particles and nucleosynthesis
- Gravitational waves
- Progenitor parameter dependence
- Full star simulations -> True Petascale challenge

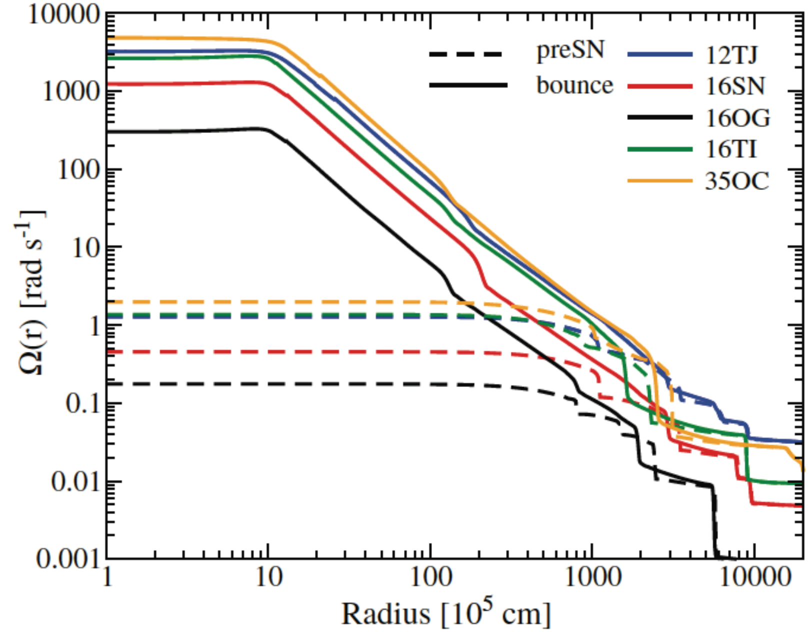




Initial Conditions

- E25 ($25M_{sun}$ ZAMS) progenitor (Heger+'00), stripped-envelope Wolf-Rayet type star
- Strong differential rotation; precollapse spin period 2.25s -> millisecond rotation of protoneutron star

$$\Omega(x,z) = \Omega_0 \frac{x_0^2}{x^2+x_0^2} \frac{z_0^4}{z^4+z_0^4}$$



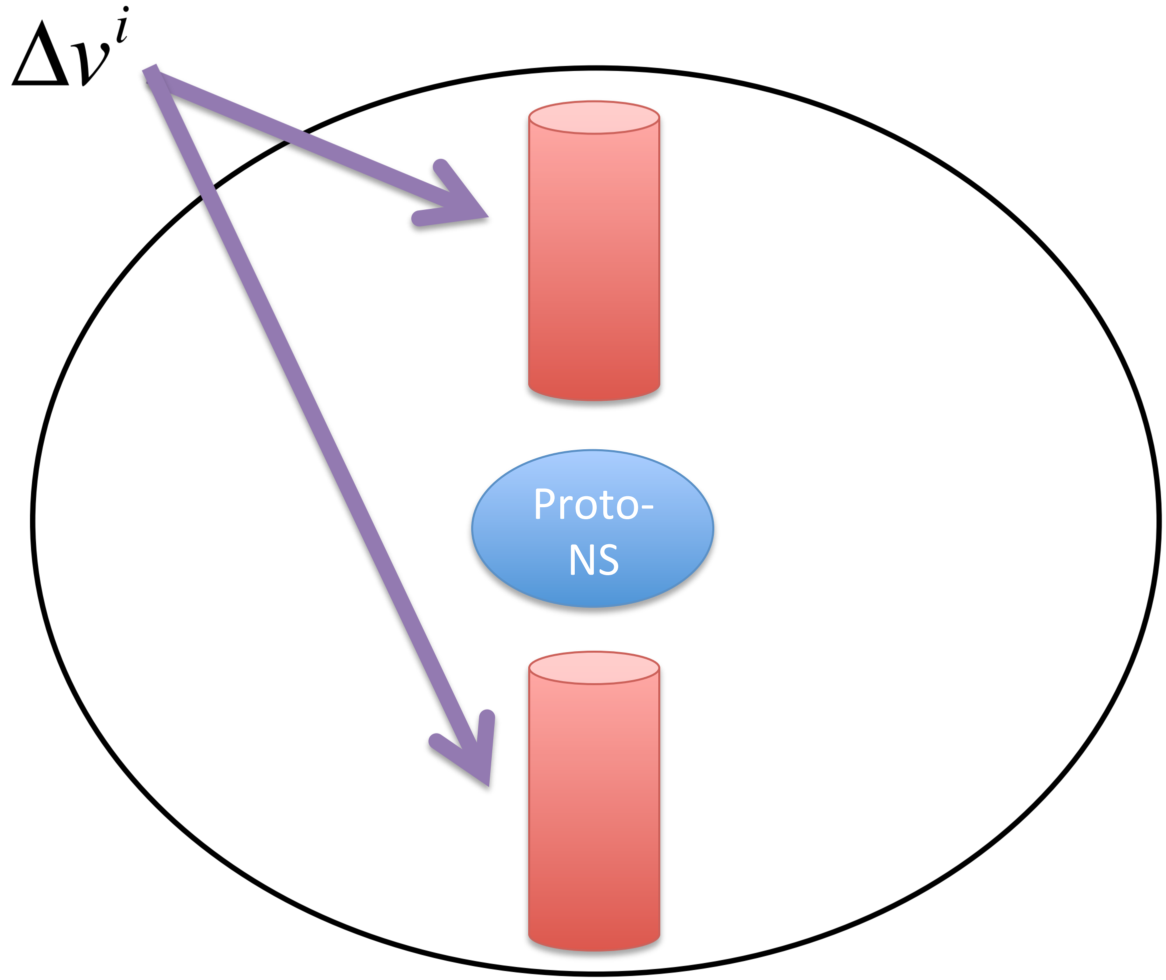
Dessart+'12

- Strong dipolar magnetic field ($B_0 = 10^{12}$ G)

Identical to Takiwaki+11 model B12X5β0.1

Perturbation Setup

- 1 % amplitude perturbations added 5ms after bounce.
- Perturbations outside protoneutron star-> disentagle multiple instabilities (e.g. low-T/|W|, SASI).
- Unperturbed run -> jet explosion



Standing accretion shock