Modeling MHD-driven Core-Collapse Supernovae in Three Dimensions

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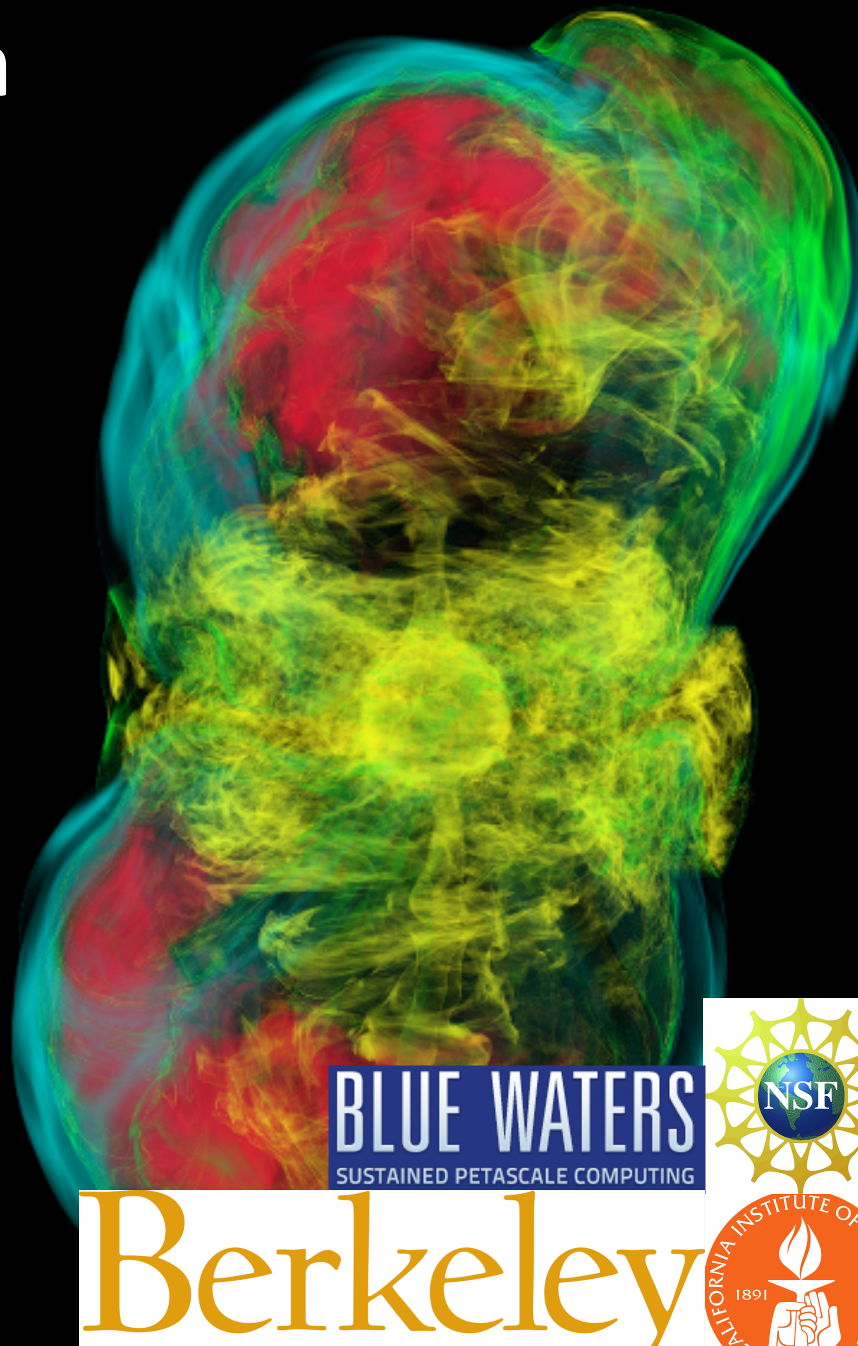
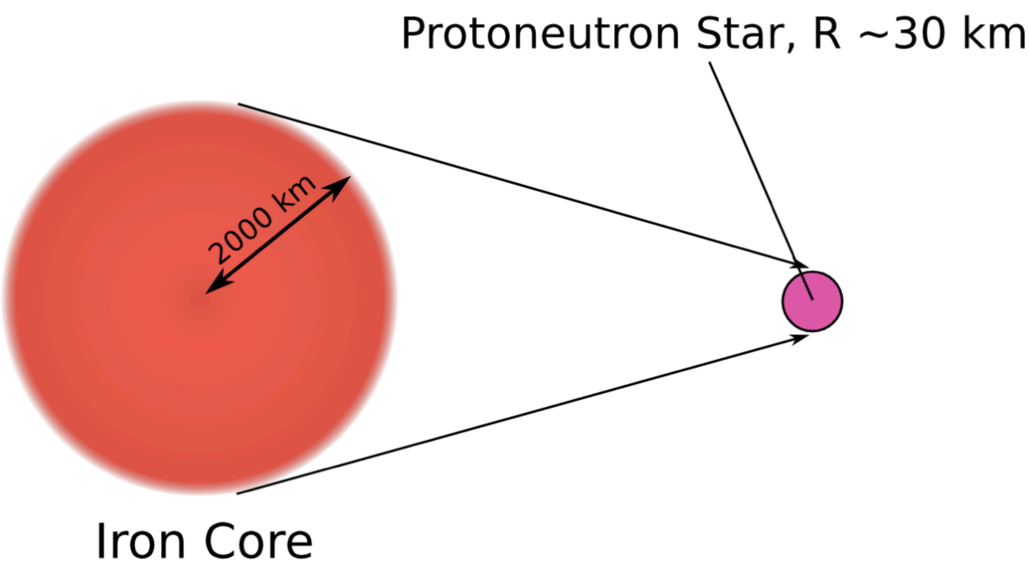


Core-Collapse Supernovae

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



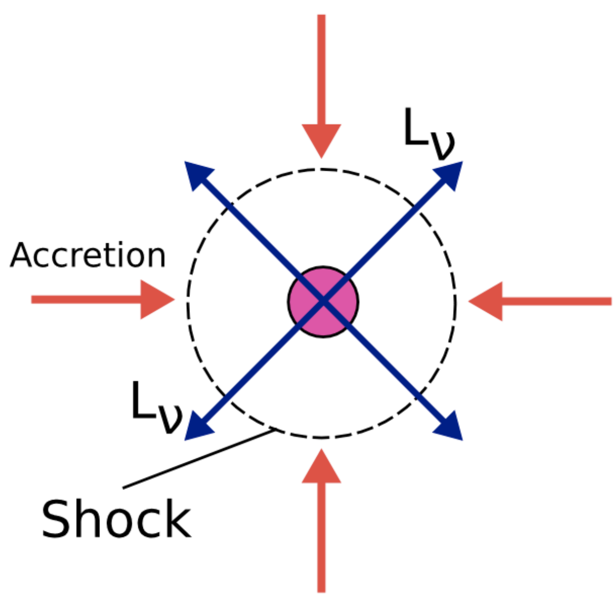
Nuclear equation of state (EOS) stiffens at nuclear density.

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

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



Core-Collapse Supernova Energetics

- Collapse to a neutron star:
  3×10^{53} erg = 300 [B]ethe
  gravitational energy ($\approx 0.15\ M_{Sun}c^2$) released.
  Initially stored in protoneutron star
  -> Any explosion mechanism must tap this reservoir

- Typical supernova: 10^{51} erg = 1 B kinetic and internal energy of the ejecta; Extreme cases: 10 B "hypernova"

- 99% of the energy is radiated in neutrinos over tens of seconds in protoneutron star cooling
  -> Strong evidence from SN 1987A neutrino observations

Hyperenergetic Supernovae

Small fraction (~1%) of CCSN:

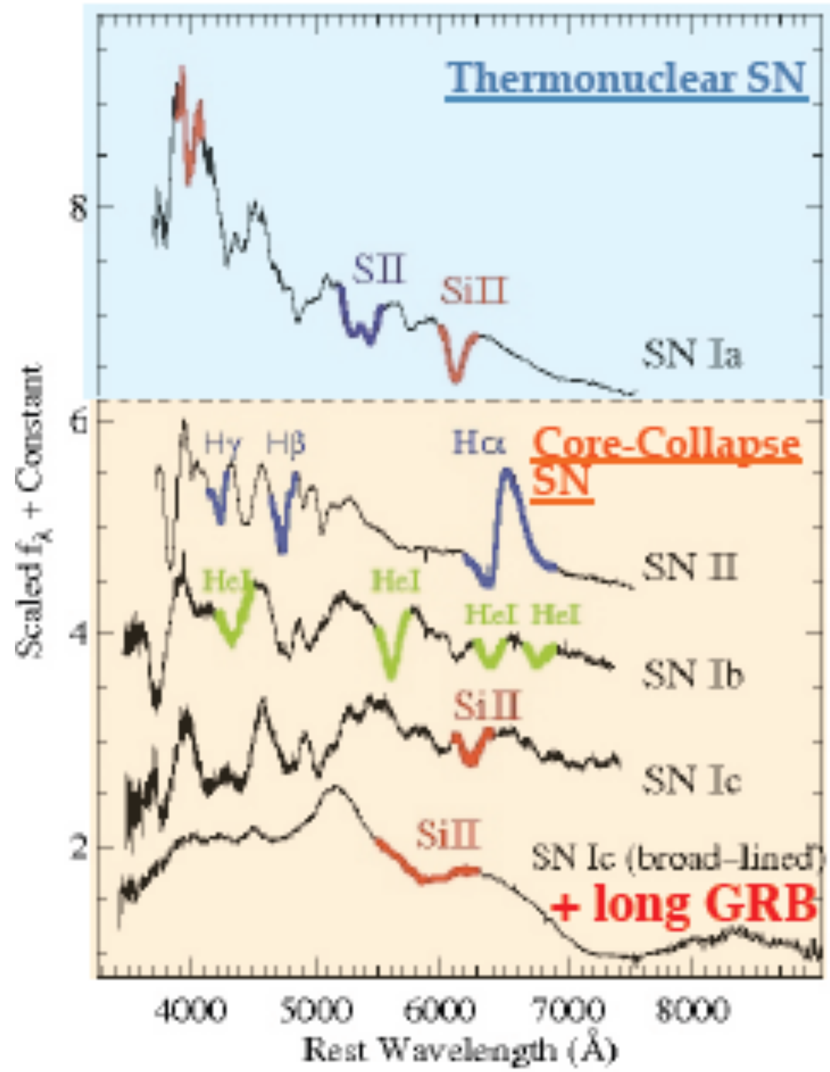
- Hyperenergetic and very luminous
- Some connected to long gamma-ray bursts

Supernova 1998bw
Image Credit: ESO

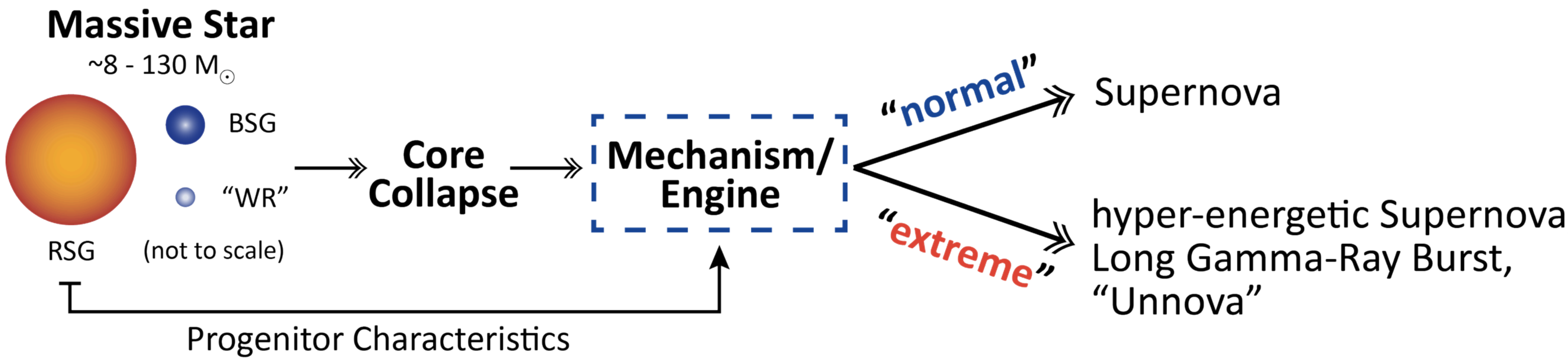
Hyperenergetic Supernovae

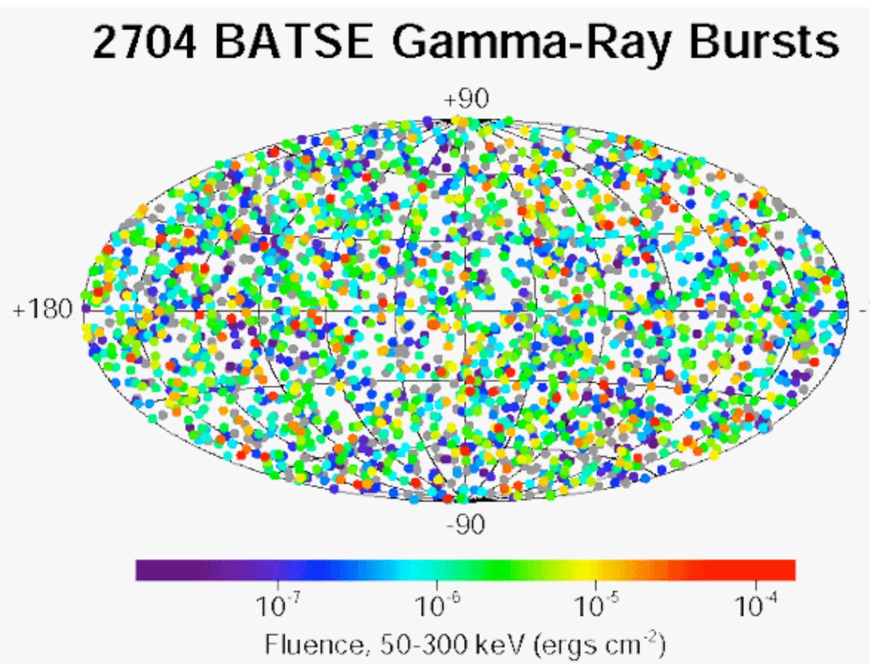
Small fraction (~1%) of CCSN:

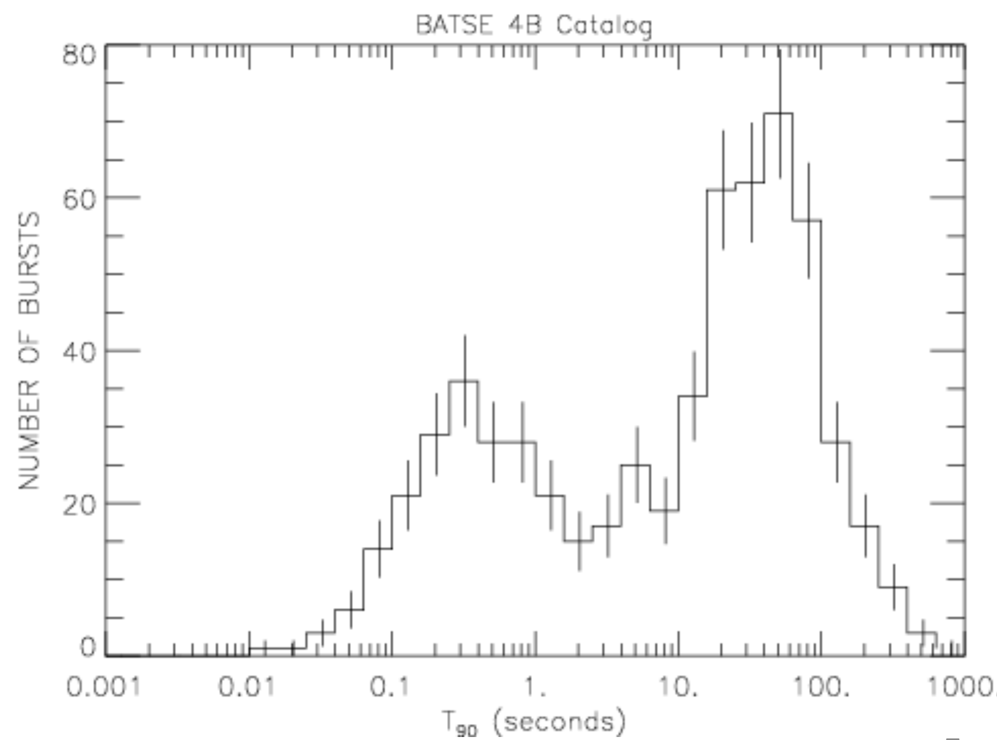
- doppler-broadened lines (Type Ic-bl) indicate relativistic outflows



Hypernovae & GRBs

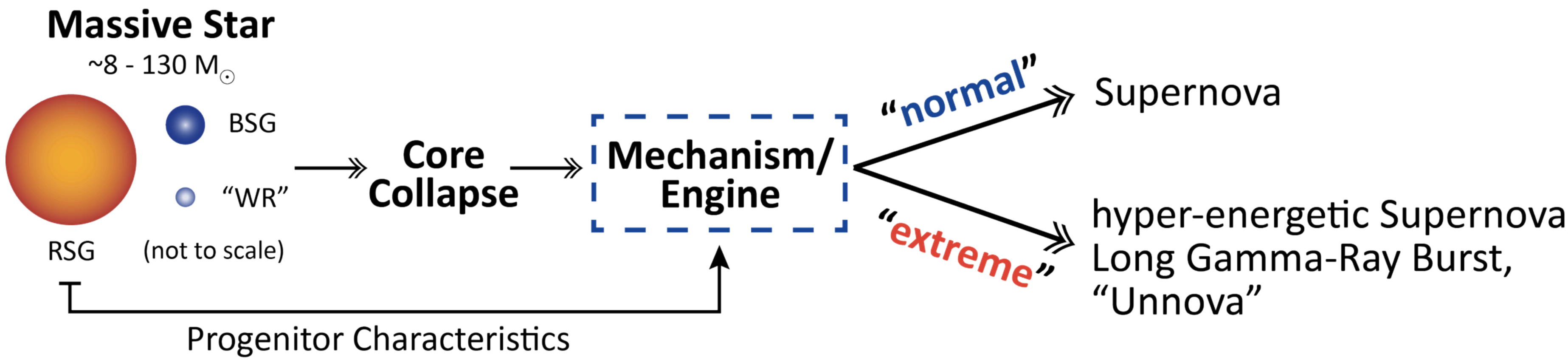






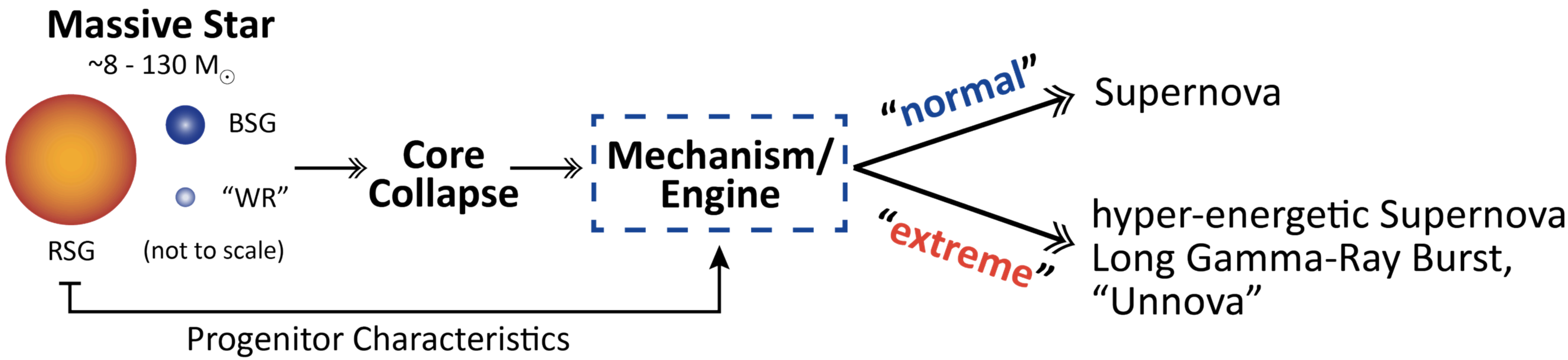
http://apod.nasa.gov/apod/ap000628.html

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 ($\sim 10^{52}$ erg).
- But not all type Ic-bl supernovae come with GRBs
- Trace low metallicity and low redshift
- Neutrino mechanism is inefficient ($\eta \sim 10\%$); can't deliver a hypernova.

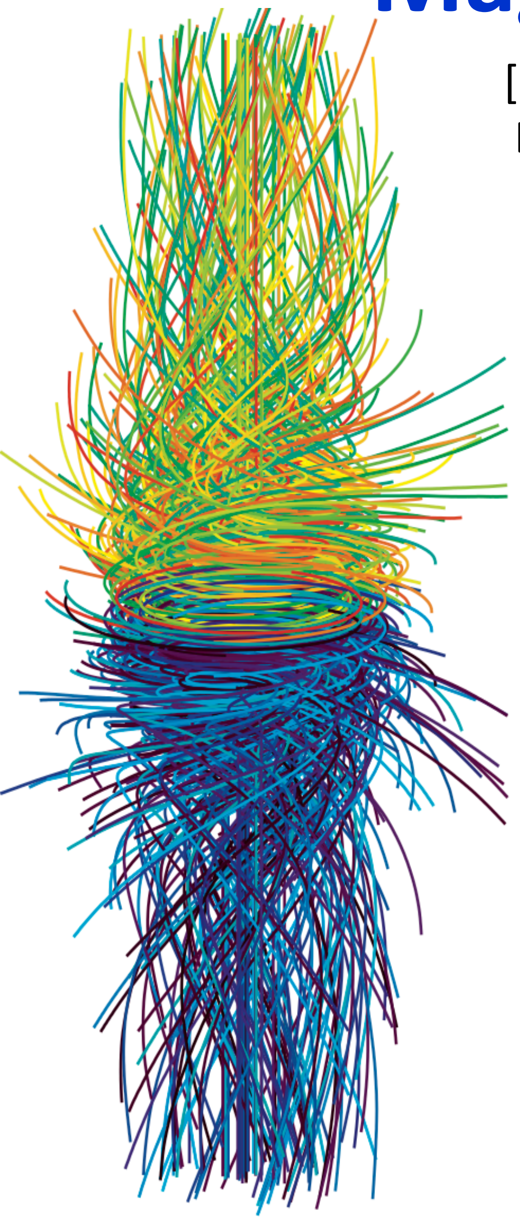
Hypernovae & GRBs



- 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 amplification?

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**.

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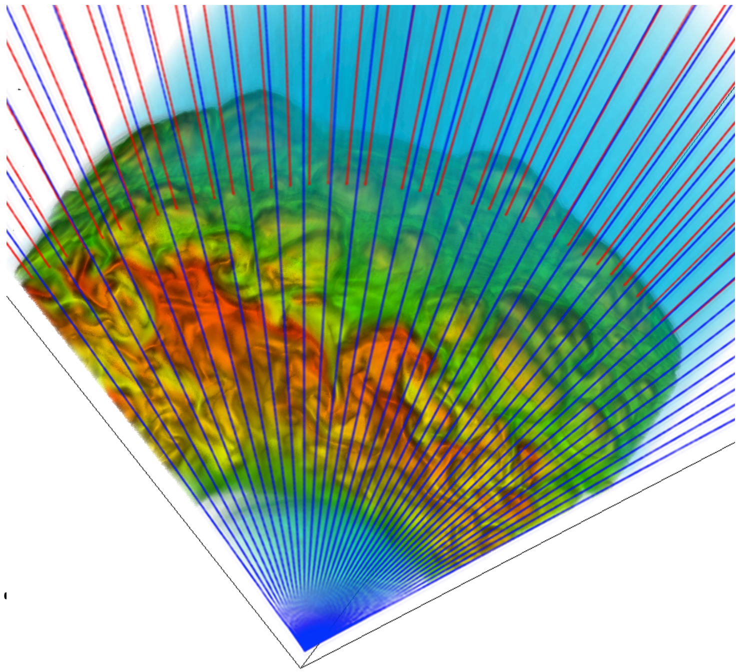
- Additional Complication: **Core-Collapse Supernovae are 3D**
  - Rotation, fluid instabilities (convection, turbulence, rotational), **MHD**, multi-D structure from convective burning -> **Need 3D treatment**
  - turbulence (e.g. MRI) on scales 10^3 cm but radius of relevant stellar interior is 10^9cm; Courant-limited timestep is 10^{-6} s but cooling time of protoneutron star is 10 s

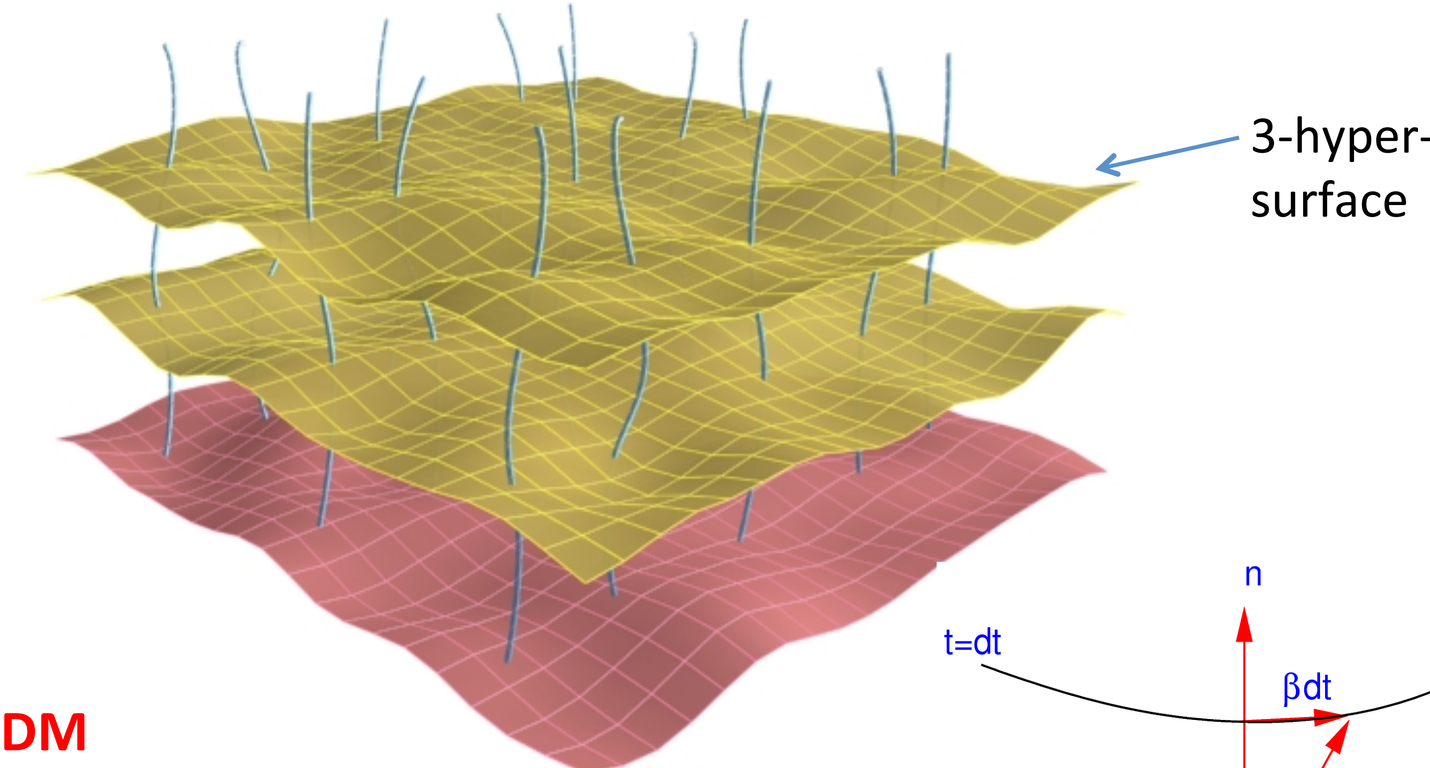
- Route of Attack: **Computational Modeling**

Supernova Modeling in 3D

- Open-source simulation code based on **Einstein Toolkit** (einsteintoolkit.org) [Moesta+'14].
- Full 3D general relativity (GR).
- Ideal GR magneto-hydrodynamics with 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.
- Simulations run on ~20k compute cores on NSF Blue Waters at NCSA/Illinois.



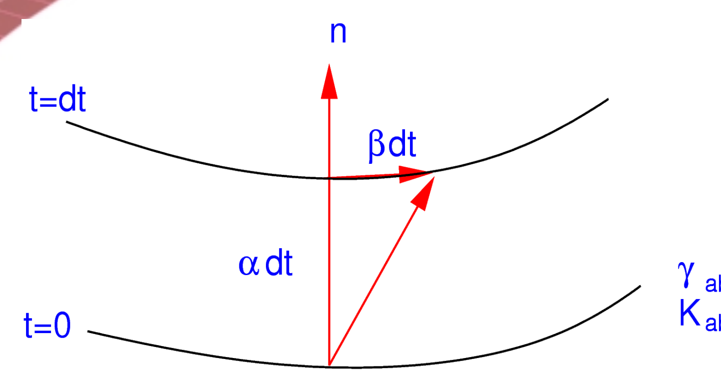
3D Supernova Modeling in Numerical Relativity



ADM

3+1 split of spacetime

Figure: C. Reisswig

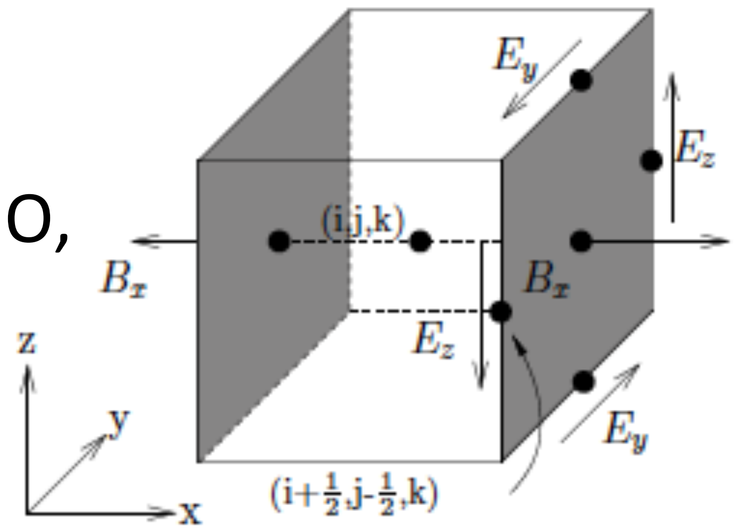


$$G^{\mu\nu} = \frac{8\pi G}{c^4} T^{\mu\nu}$$

- 12 first-order hyperbolic *evolution* equations.
- 4 elliptic *constraint* equations
- 4 coordinate gauge degrees of freedom: α, β^i.

MHD with the Einstein Toolkit

- Vertex or cell-centered AMR
- High-order reconstruction (WENO, MP5,…)
- Flexible EOS interface
- Can couple to different space-time evolution codes
- Divergence cleaning or constrained transport for divB = 0

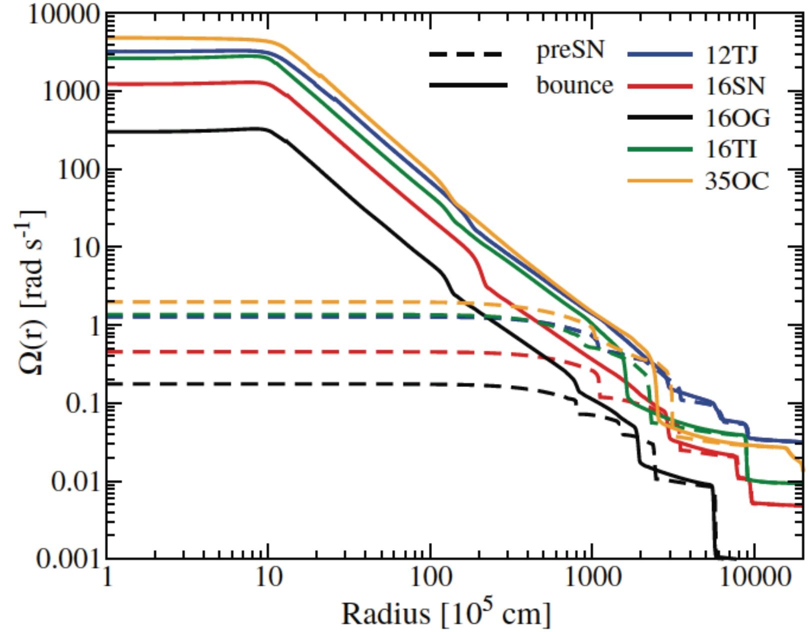


Moesta+14

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

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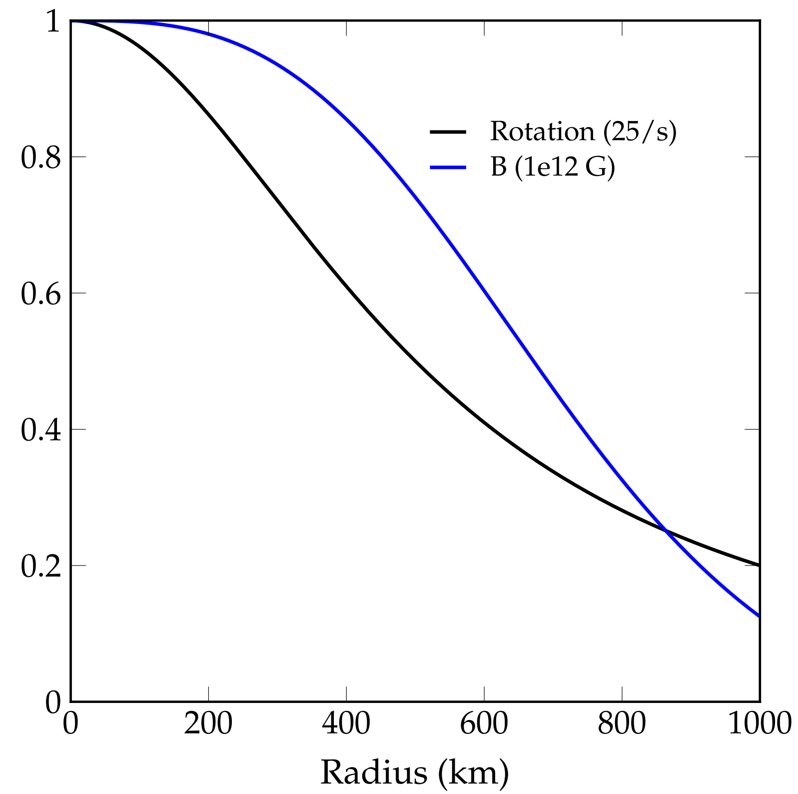

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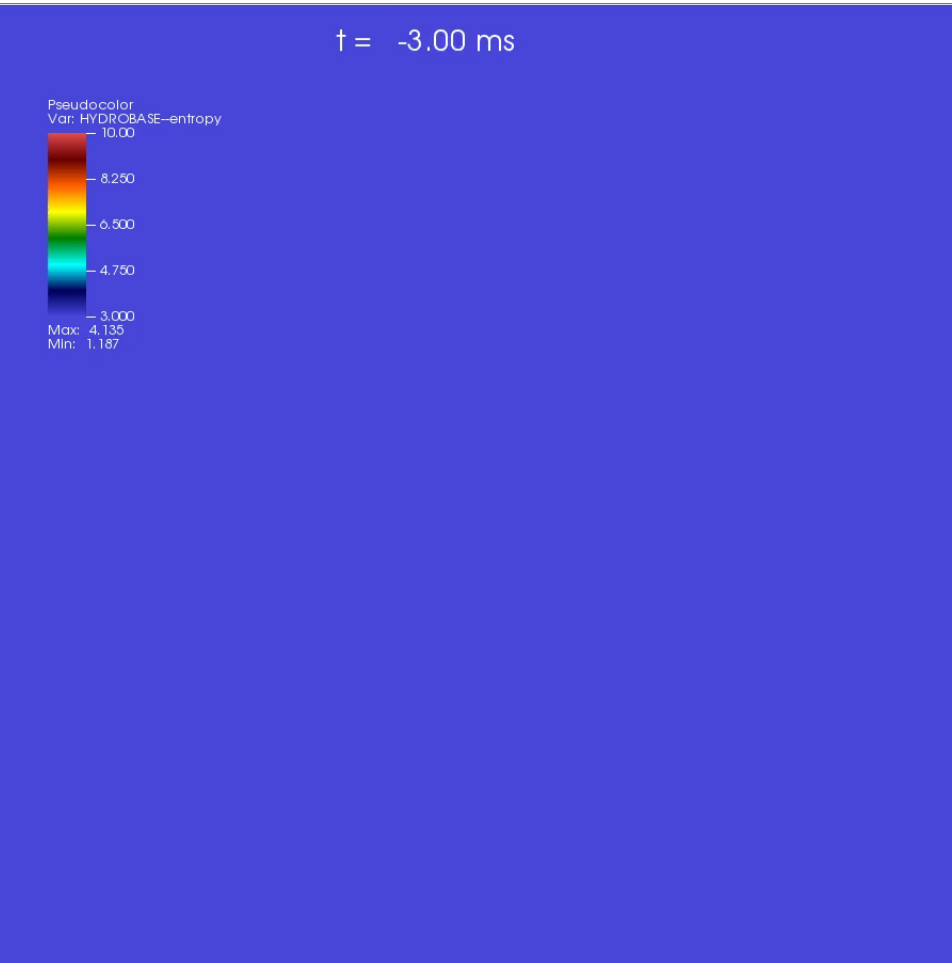
3D Dynamics of Magnetorotational Explosions

New, full 3D GR simulations. **Mösta+ 2014**, ApJ 759, L24

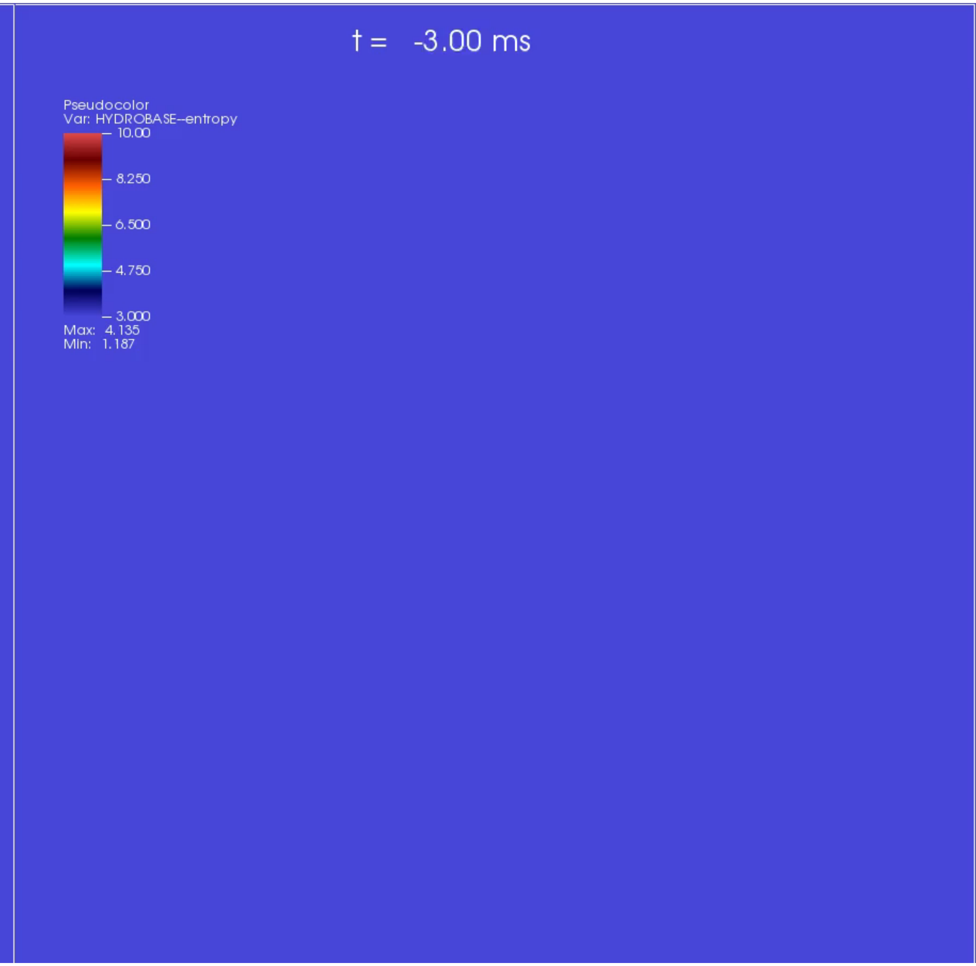
Initial configuration as in Takiwaki+11, 10^{12} G seed field.

← 2000 km →



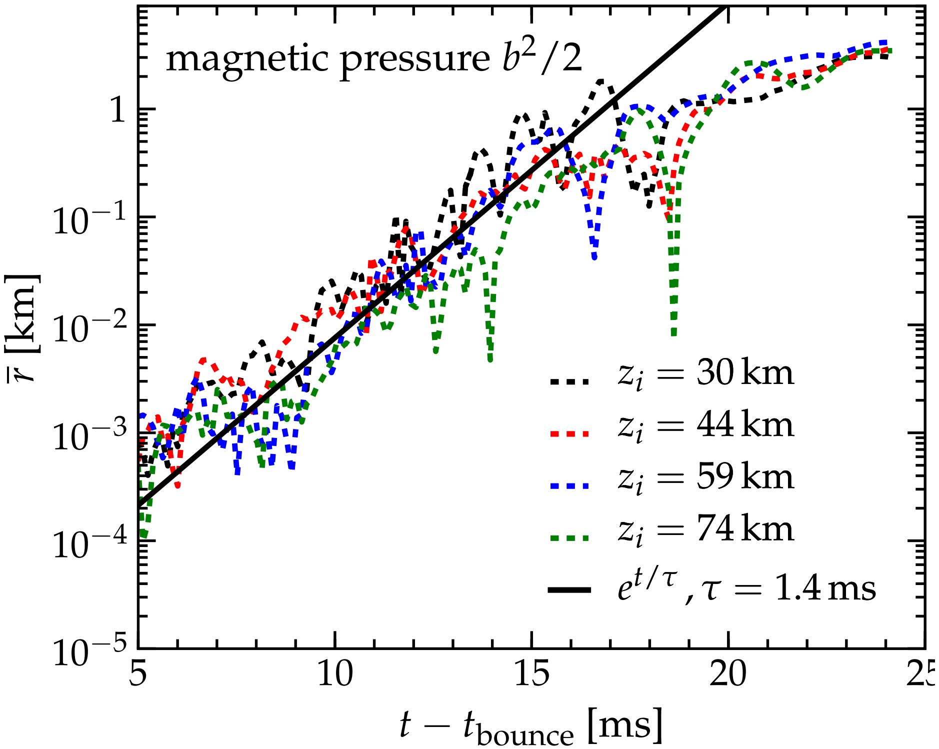
Octant Symmetry (no odd modes)

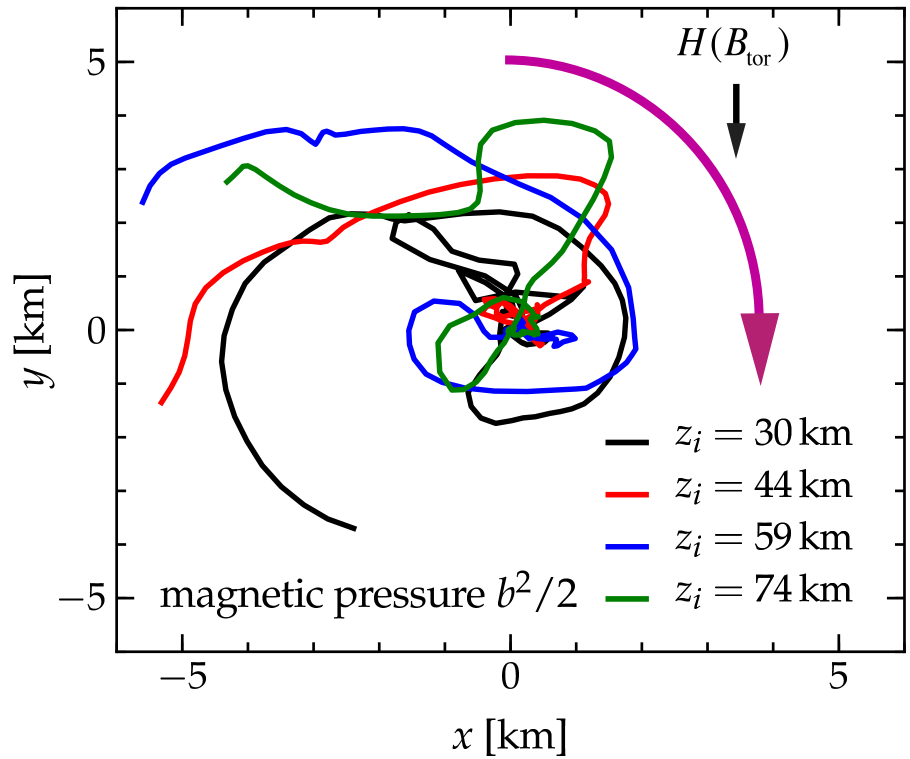
← 2000 km →



Full 3D

What's going on here?



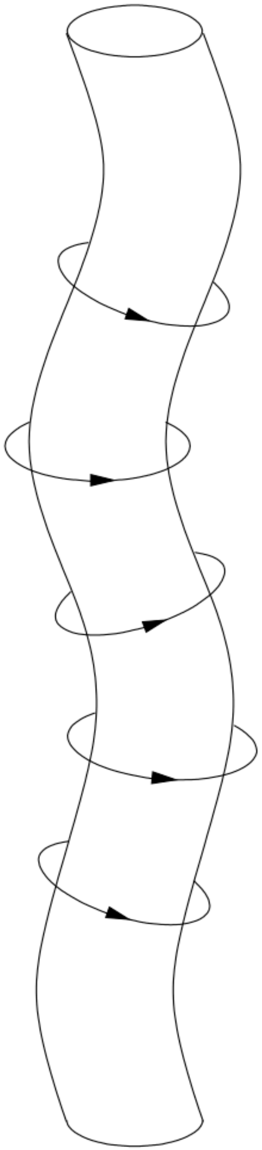


- m=1 spiral instability
- Growth rate, wavelength and helicity of fastest growing mode consistent with MHD kink instability; should hold independent of initial B-field strength

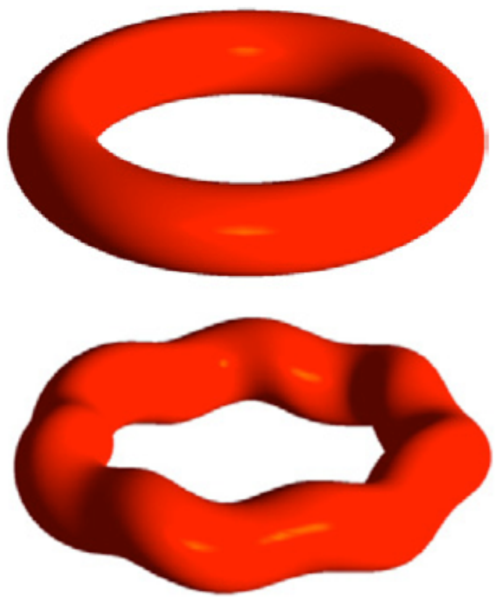
$$\tau_{\text{fgm}} \approx \frac{4a\sqrt{\pi\rho}}{B_{\text{tor}}} \approx 1\,\text{ms}$$

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

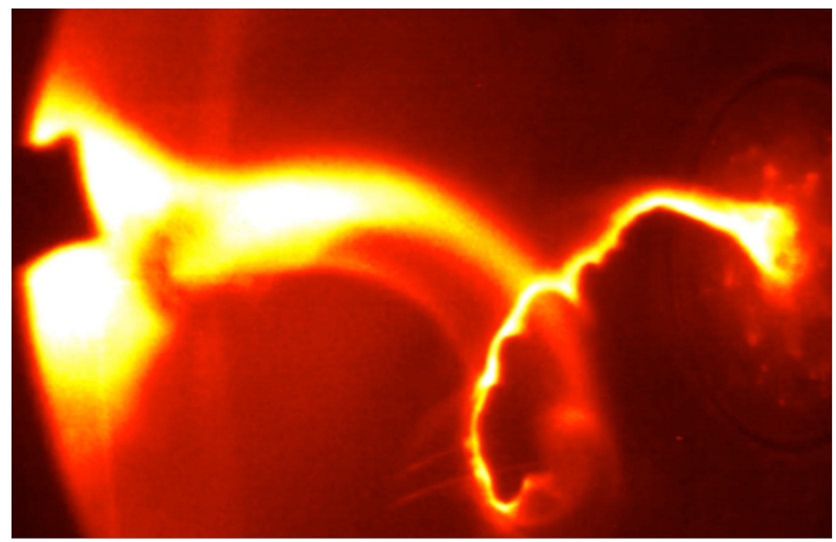
MHD Kink Instability



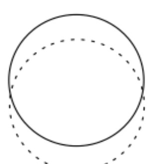
- B-field near proto-NS: $B_{tor} >> B_z$
- Unstable to MHD screw-pinch kink instability.
- Similar to situation in Tokamak fusion reactors!



Sarff+13



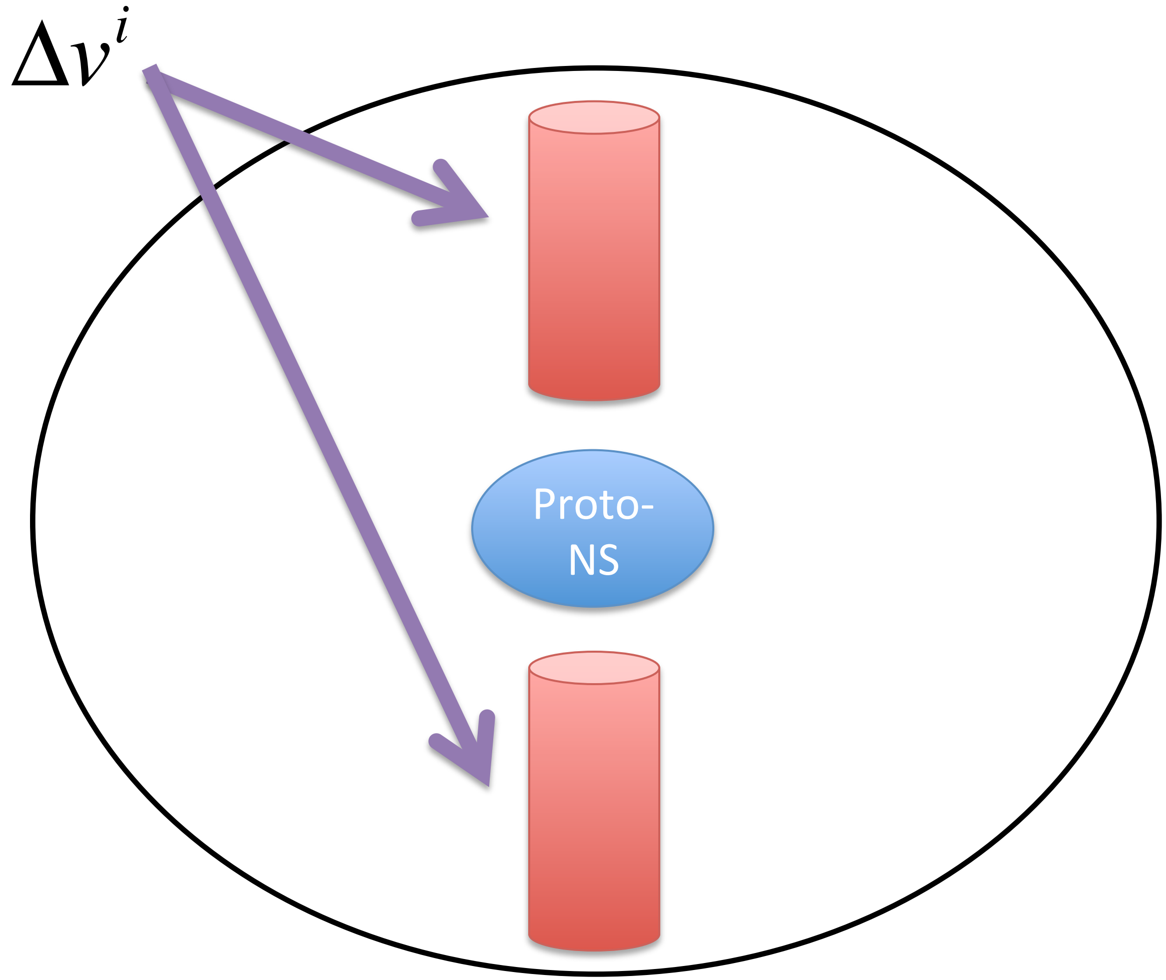
Credit: Moser & Bellan, Caltech



Braithwaite+ '06

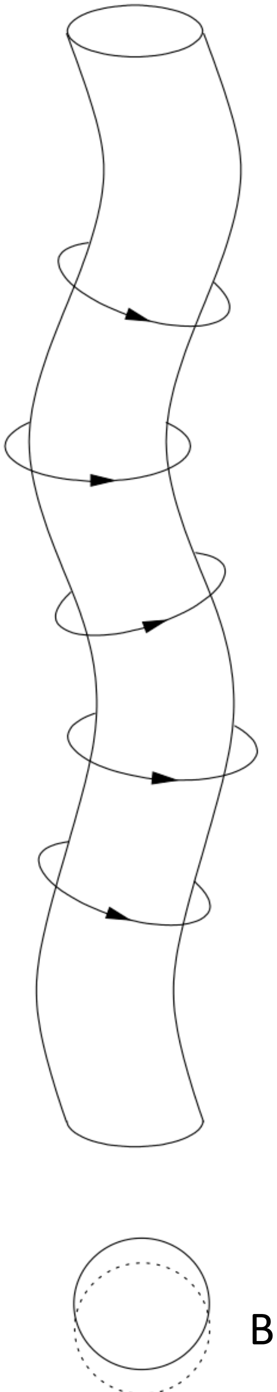
Perturbation Setup

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



Standing accretion shock

MHD Kink Instability



3D: Plasma flow unstable to MHD "kink" instability

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

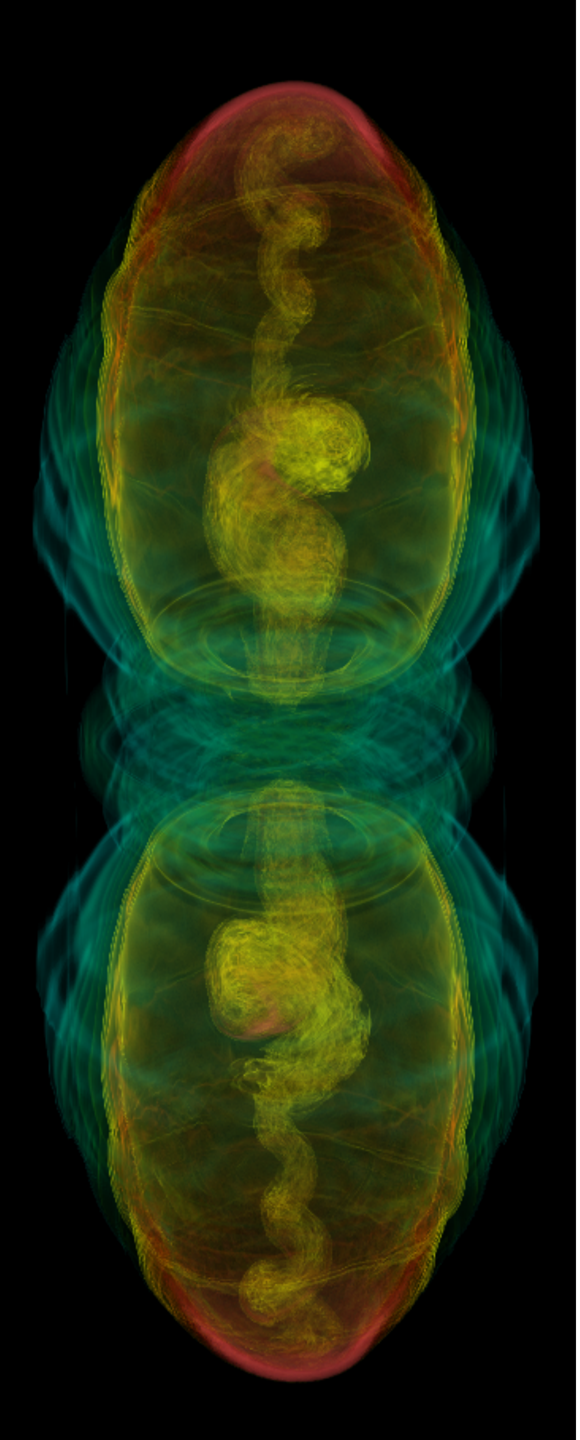
[Shafranov+'56, Kruskal+'58]

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

- Magnetic pressure driven
- cannot be countered by magnetic tension

Braithwaite+ '06

MHD Kink Instability



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3D Volume Visualization of

t = -3.00 ms

Entropy

Mösta et al. 2014

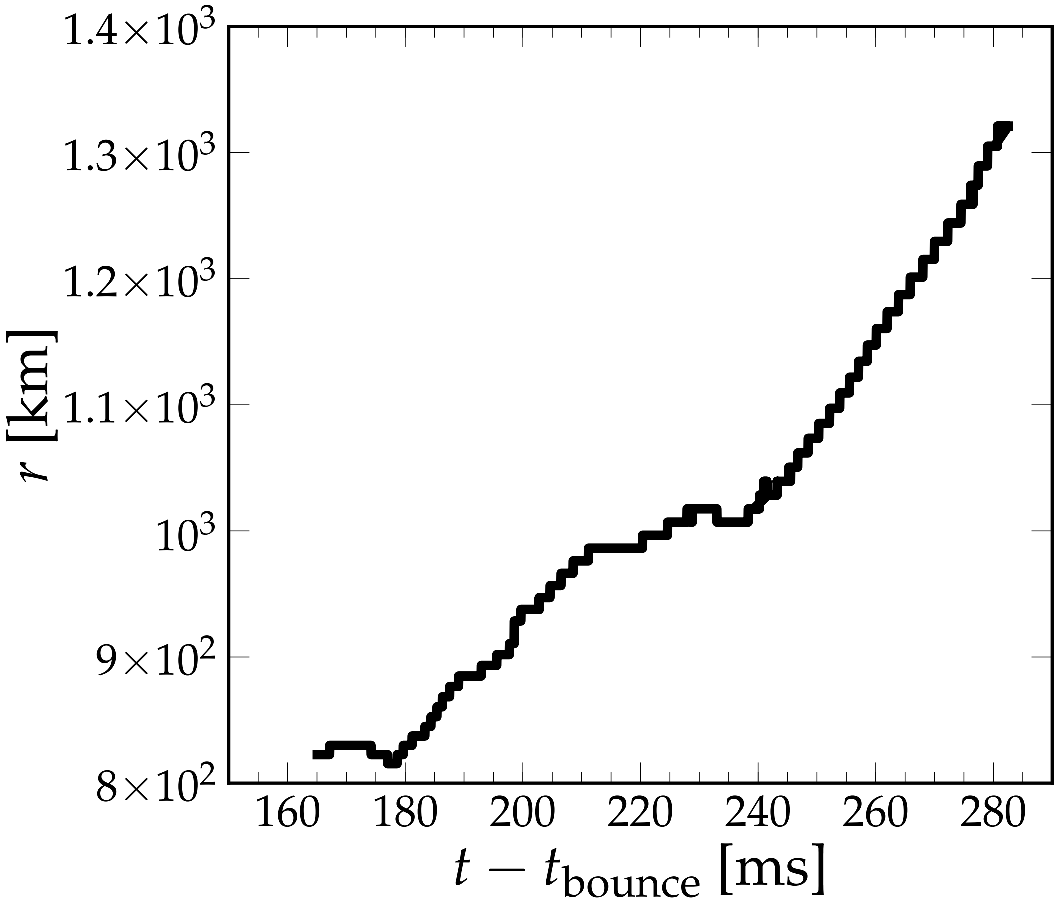
3D Volume Visualization of

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

Mösta et al. 2014

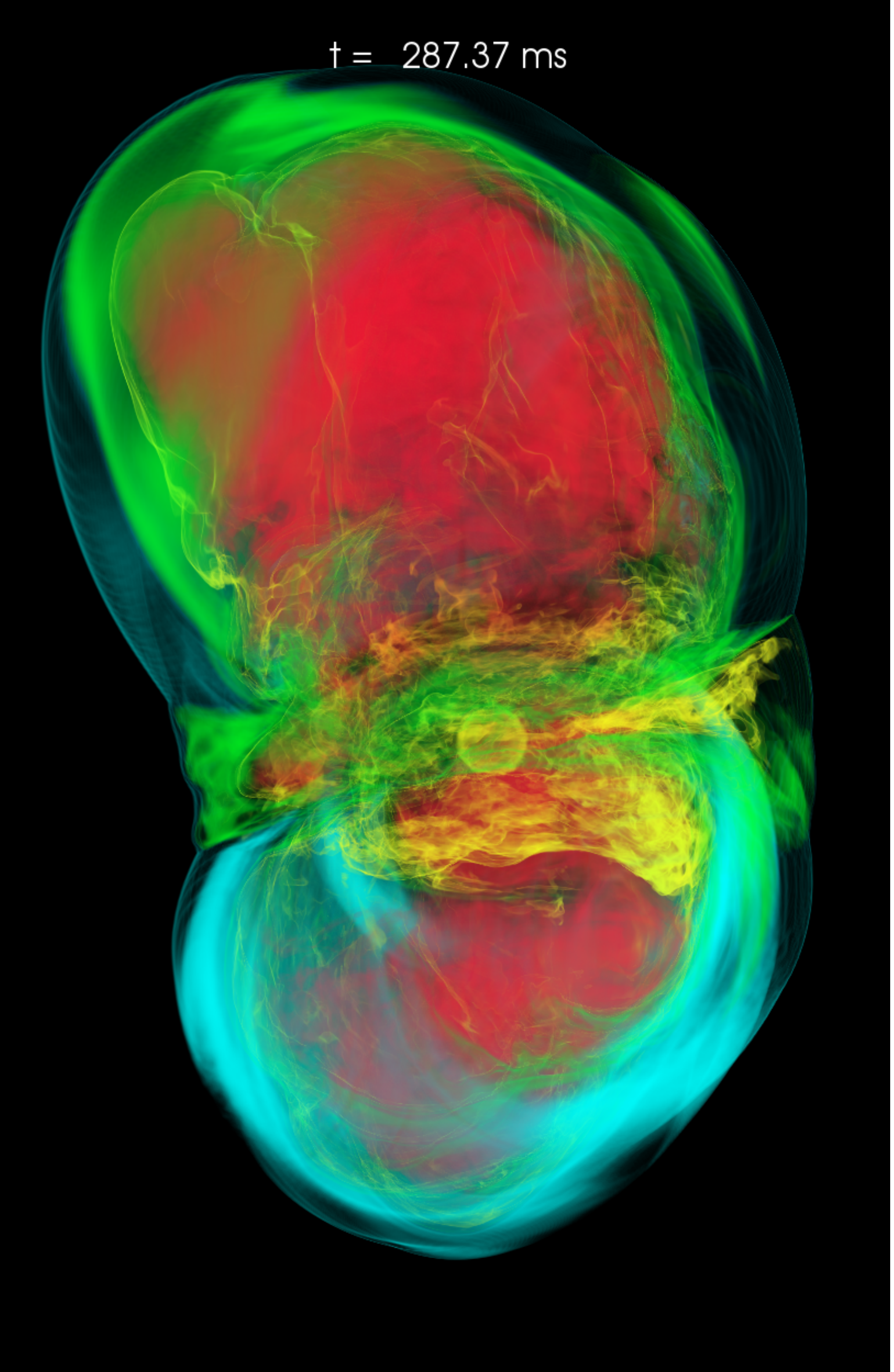
t = -4.95 ms

Ongoing Simulation



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

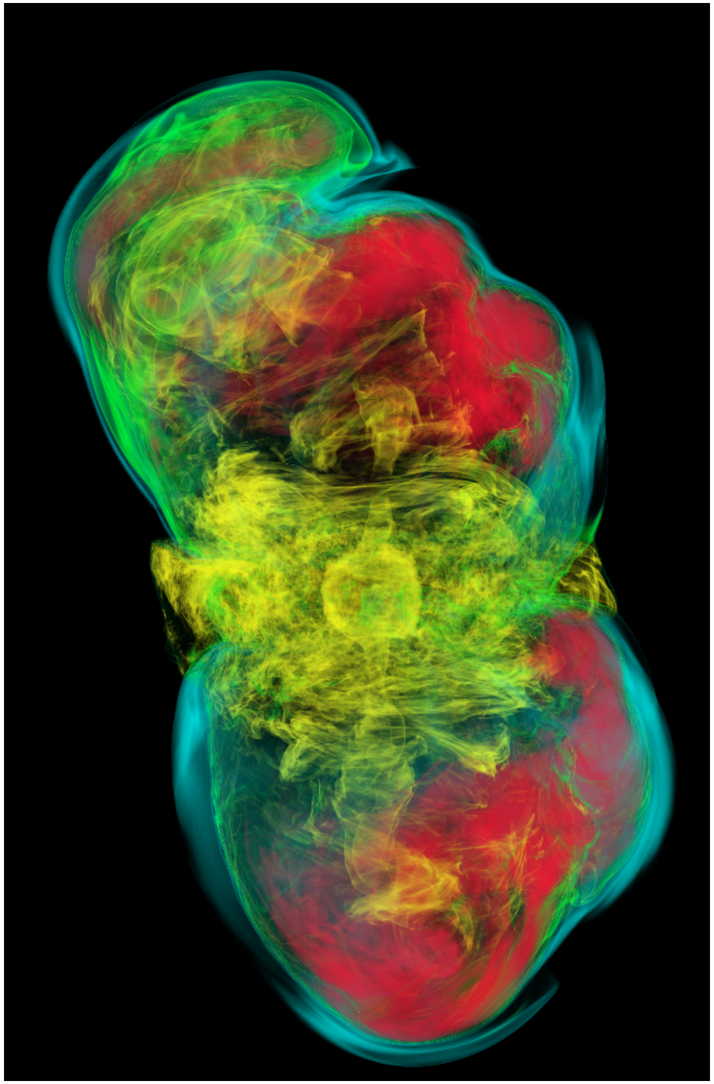
Explosion?



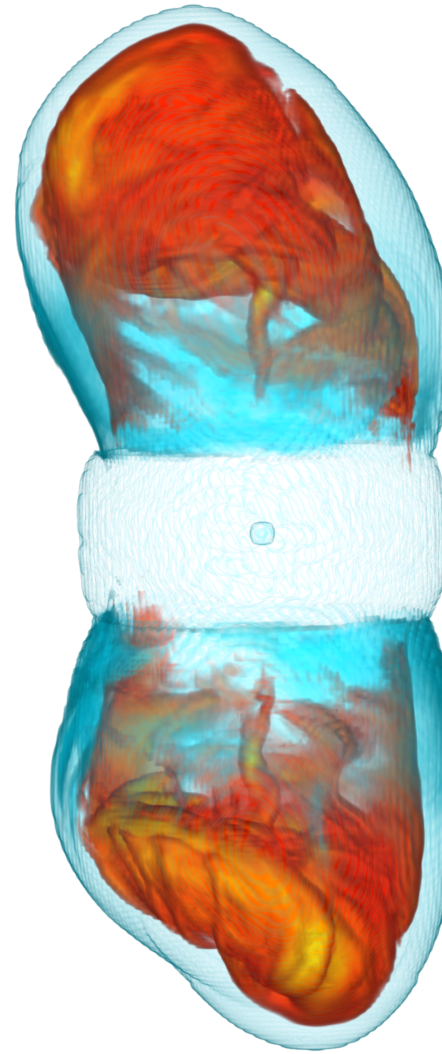
Ongoing Simulation

- 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

Cross-code comparison with FLASH simulations

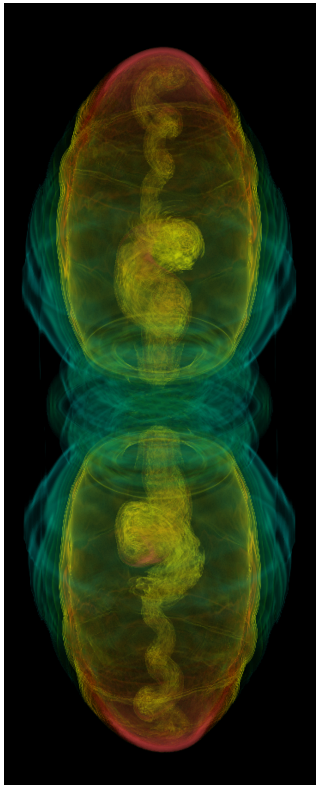


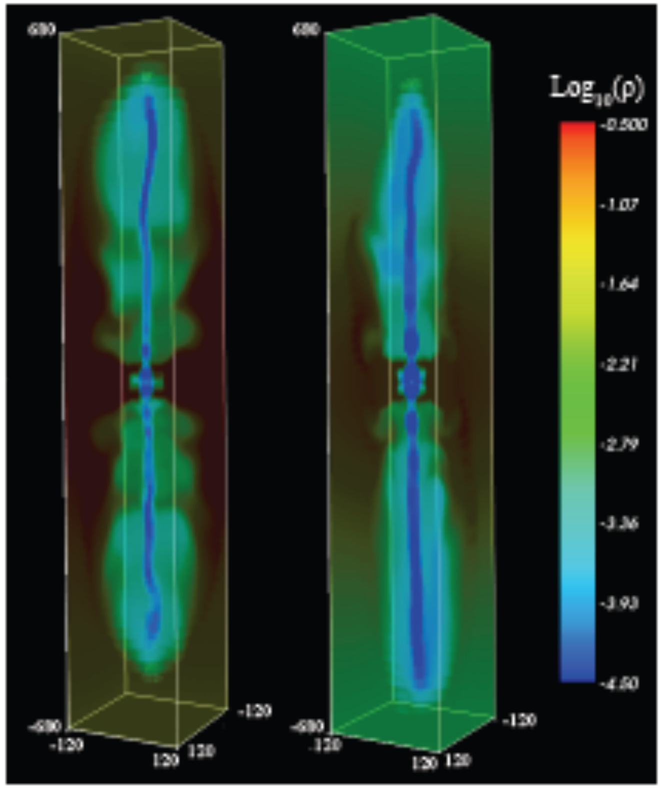
Mösta+ 14

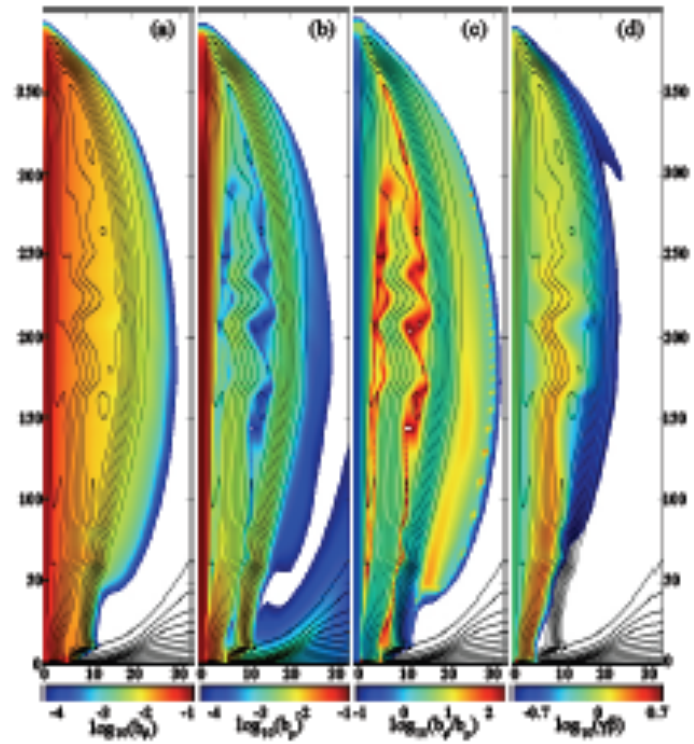


Couch+ 15 (in prep.)

Connection to ‘other’ Jets







Mösta+ 14

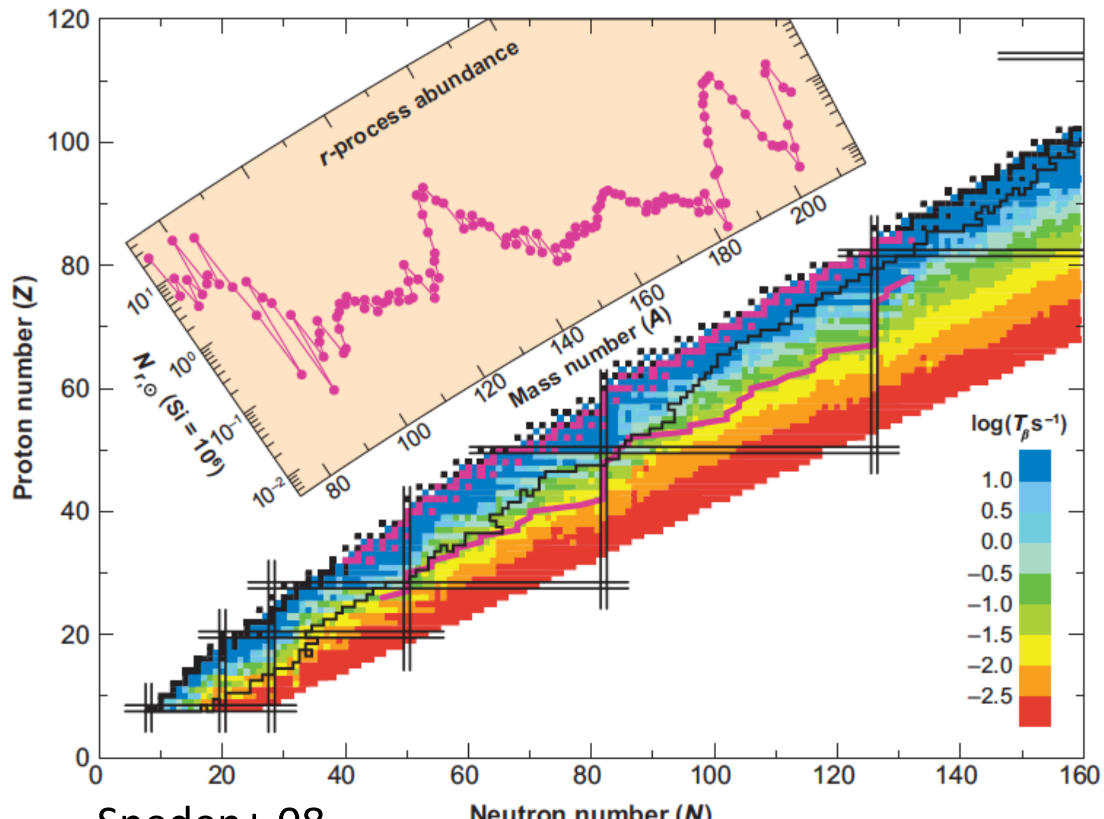
Bromberg & Tchekhovskoy 15

- Kink instabilities affect most jets (GRB/AGN); generally dissipate energy, lead to slower propagation speed, but also more mixing, better coupling to star!

R-process Nucleosynthesis in Hypernovae

Jet-driven explosions proposed as site for r-process: Material in the jet characterized by

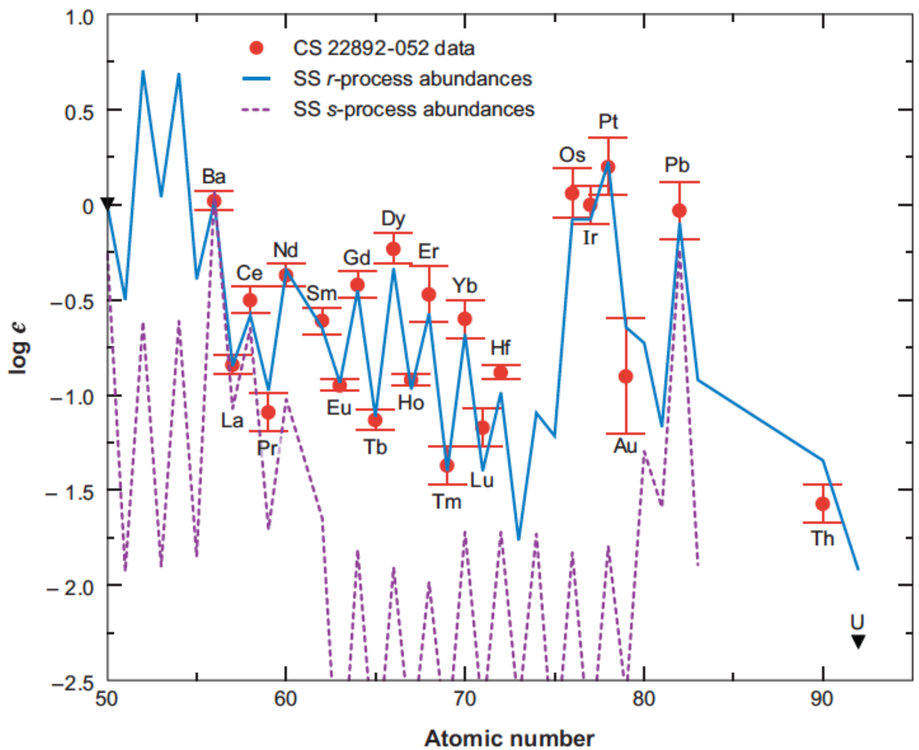
- Low electron fraction
- Medium entropy
- Low density
- High temperature



Sneden+ 08

R-process Observations

- Low-metallicity galactic halo stars show remarkable agreement with solar r-process abundance pattern (few exceptions, e.g. Honda+ 06)
- NS-NS / NS-BH binaries unlikely to contribute in early epochs



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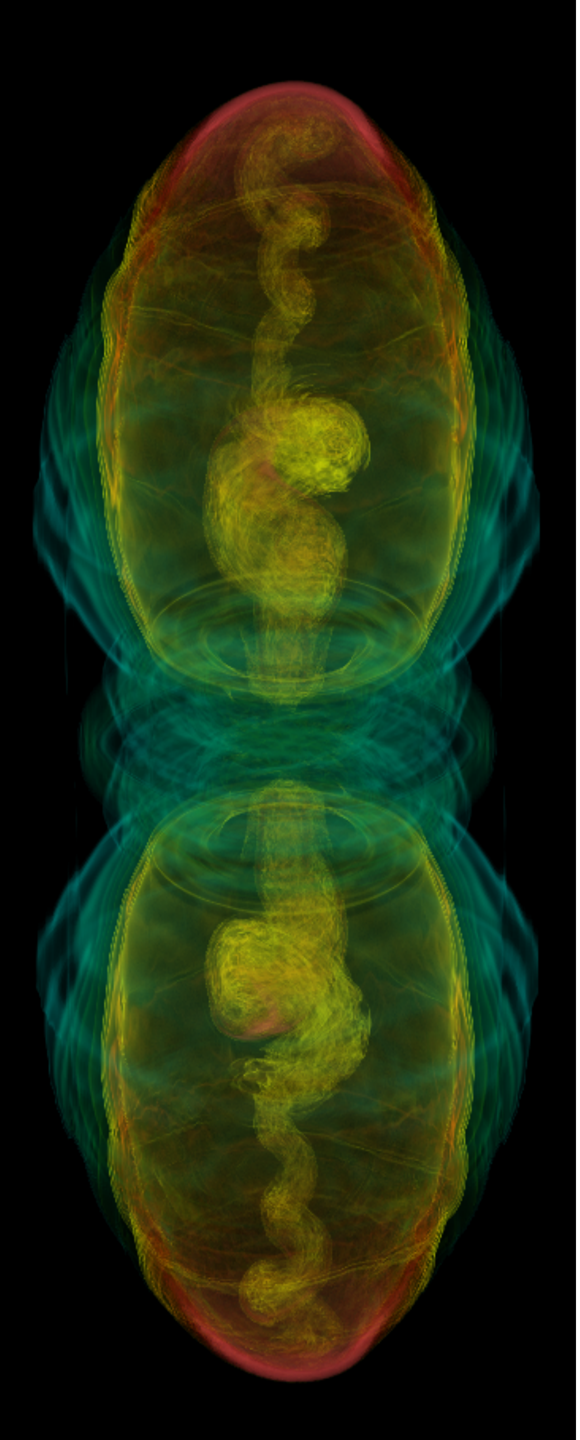
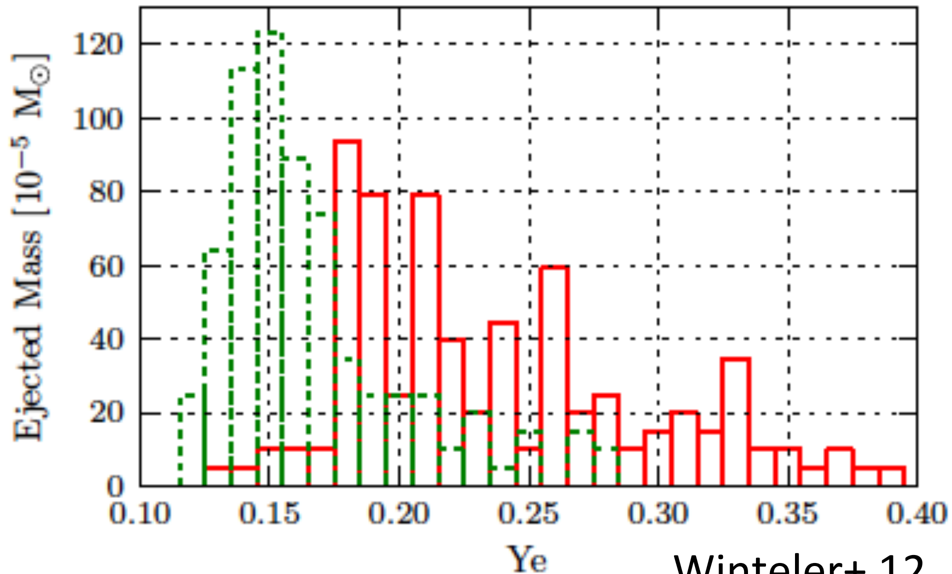
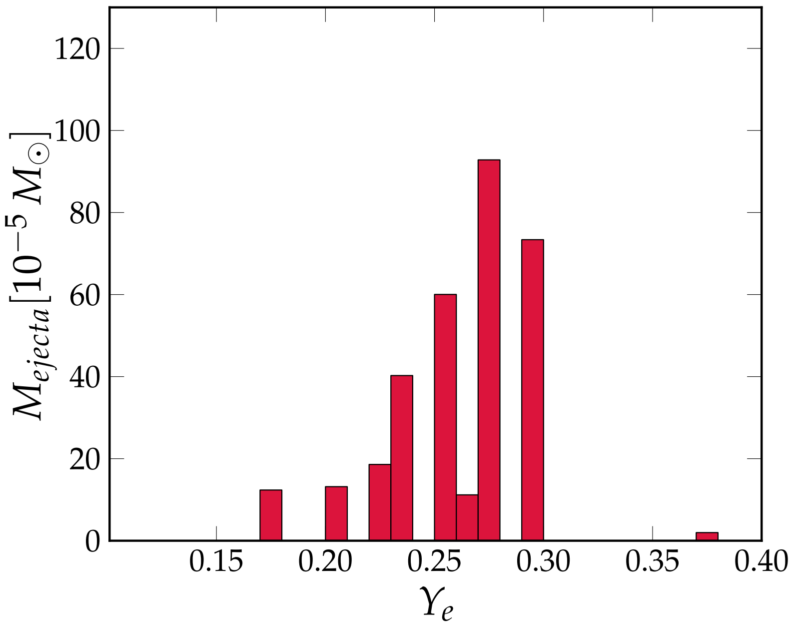


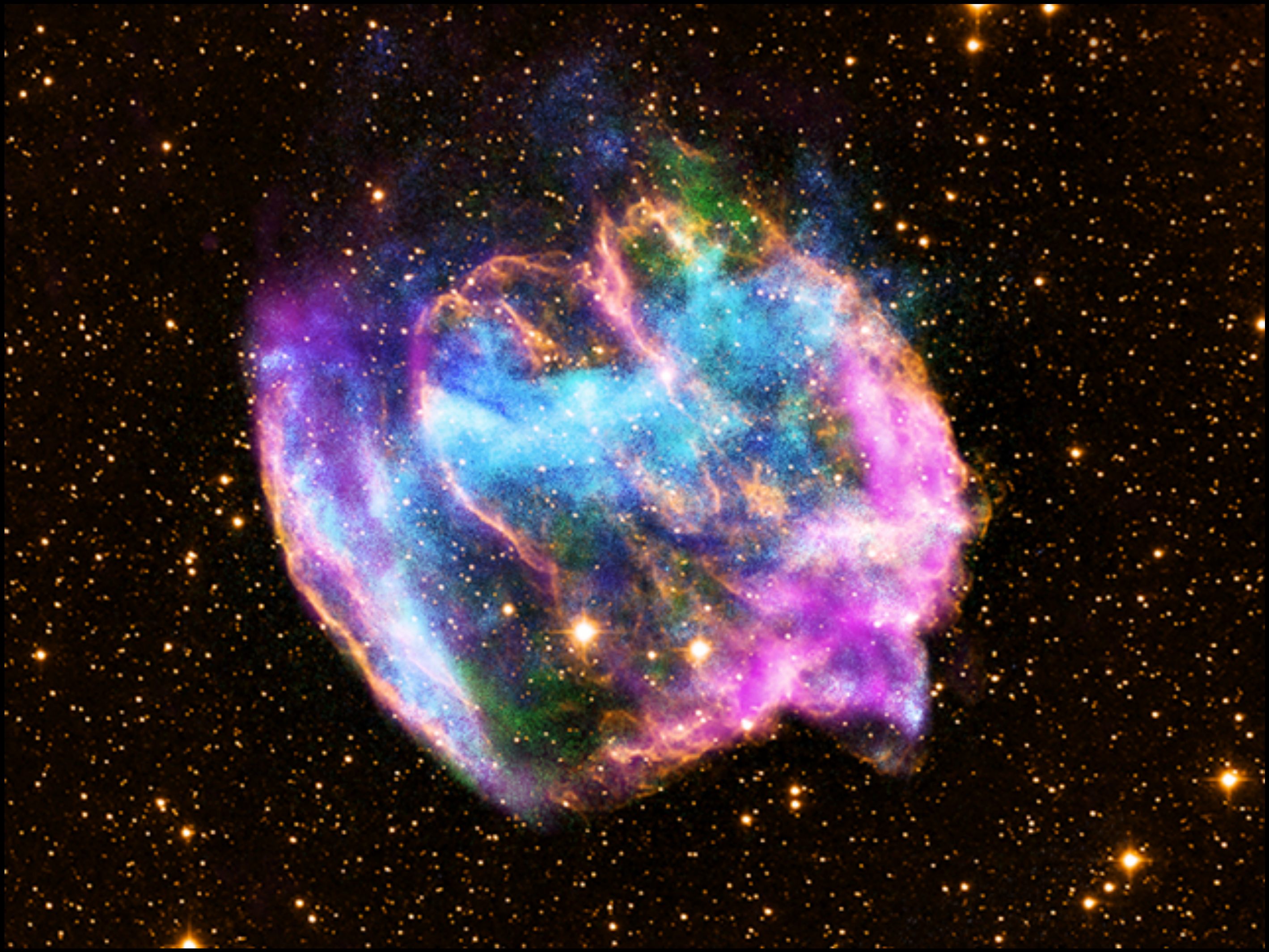
R-process: First Results



Winteler+ 12



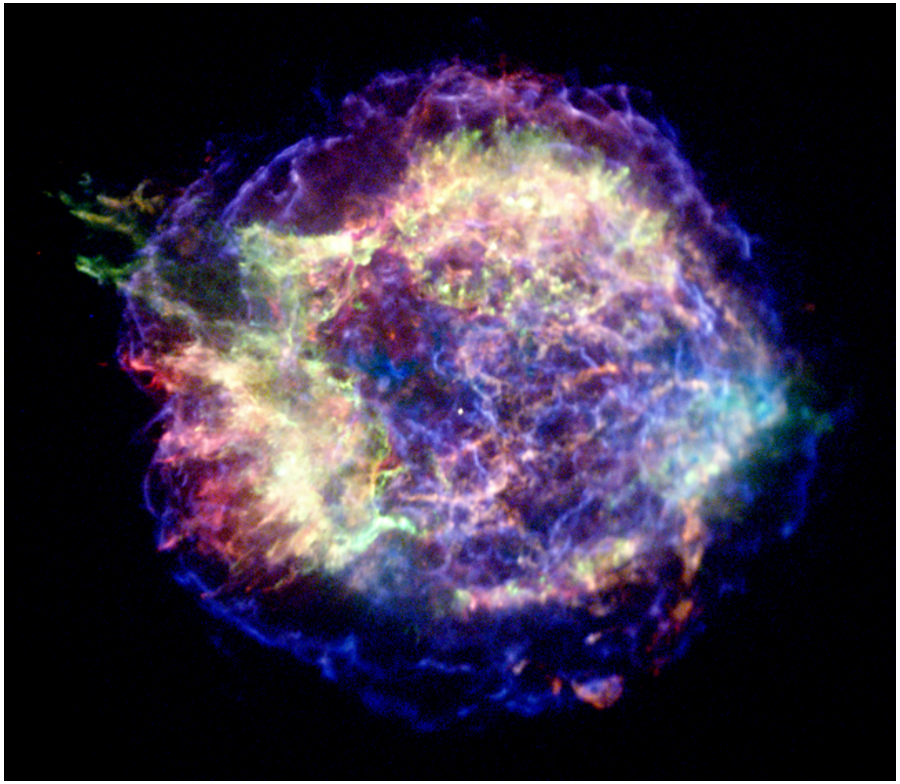
Implications?



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

Image credit: Composite X/IR/Radio image NASA/CXC/MIT/Lopez et al./
Palomar/SF/NRAO/VLA

Connection to Observations



Cassiopeia A Supernova Remnant
Image Credit: NASA.

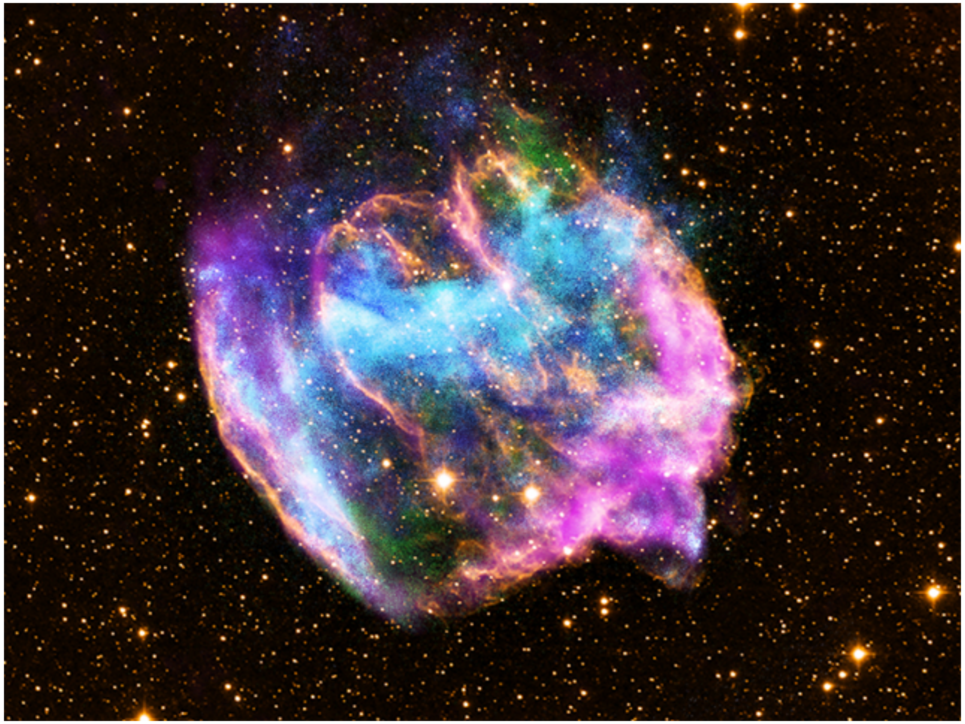
$$Y_e \sim 0.1 - 0.2 \quad s \sim 10 - 15 \ \mathrm{k_b baryon}^{-1}$$

$\beta \sim 0.01 - 0.1$ underdense

- Outflows show plausible conditions for creation of neutron-rich heavy elements, but electron fraction seems on the high end for r-process
- May explain observed asymmetries in SNR also for rotating progenitors (recent NuStar CasA observations)

Gamma-Ray Burst Connection

- Long gamma-ray bursts come with extreme supernovae
- Central engine of GRB: Black hole or magnetar?
- Simulations show continued accretion on the equator in supernova phase

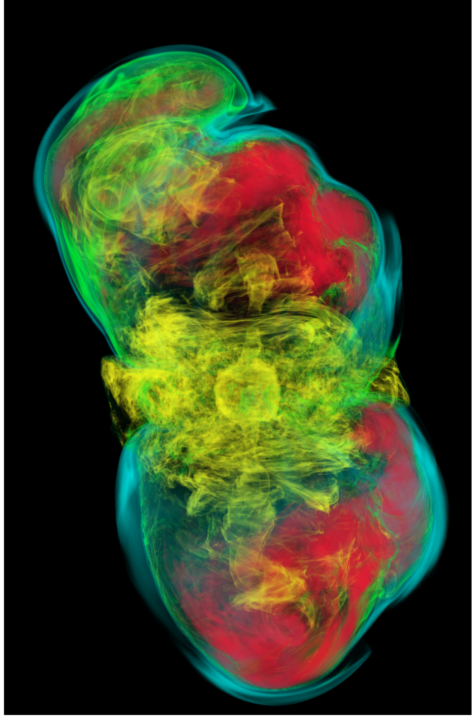


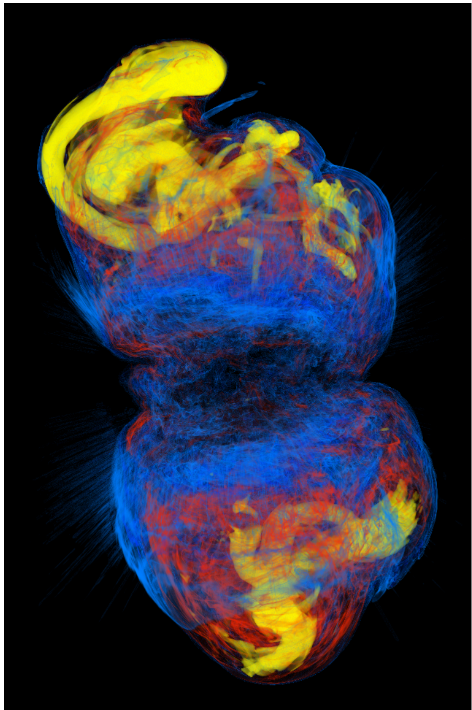
Supernova remnant W49B; harboring a black hole? (Lopez+2013)

Simulations allow for magnetar or collapsar scenario; progenitor dependence?

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
- Is the r-process robust for 3D MHD explosions?





Open Questions:

- How realistic are rapidly rotating progenitor stars?

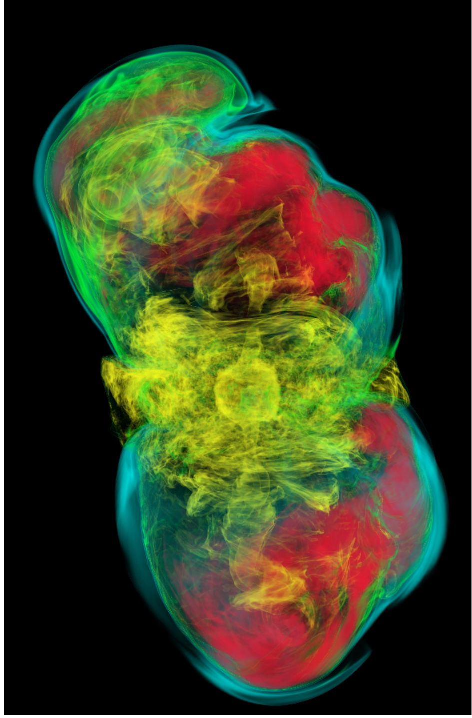
- Binary interaction, chemically homogenous evolution

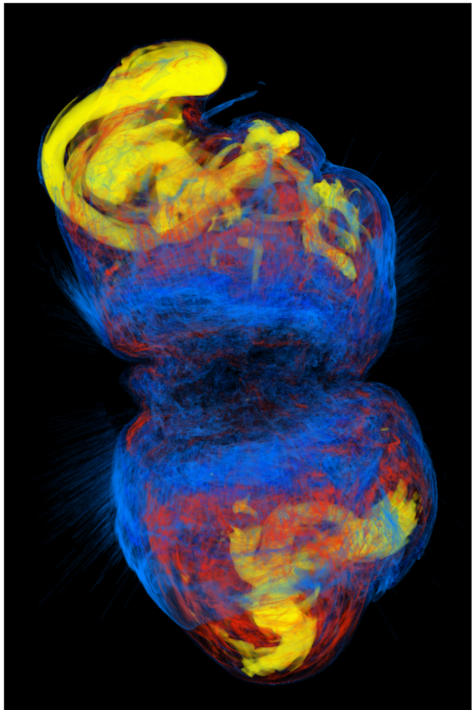
- But also magnetic braking and angular momentum redistribution

- What about progenitor magnetic fields?

- How can we get constraints for massive stars?

- Does the MRI work in delivering field?





Next steps in modeling

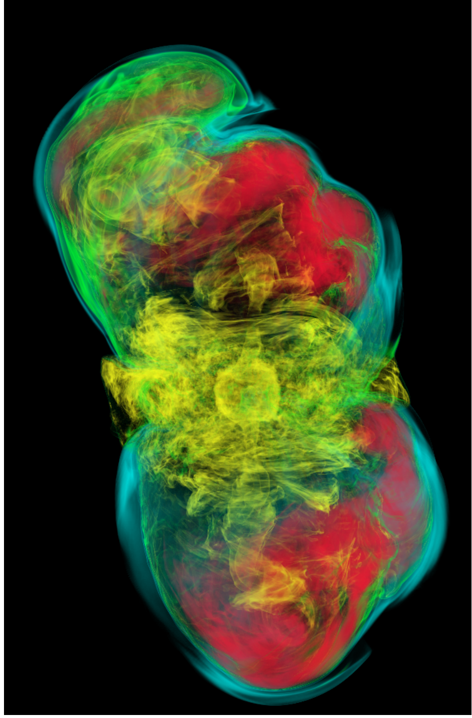
- Robust numerical algorithms for high magnetization needed: Con2Prim, reconstruction, Riemann solver! What is most important?

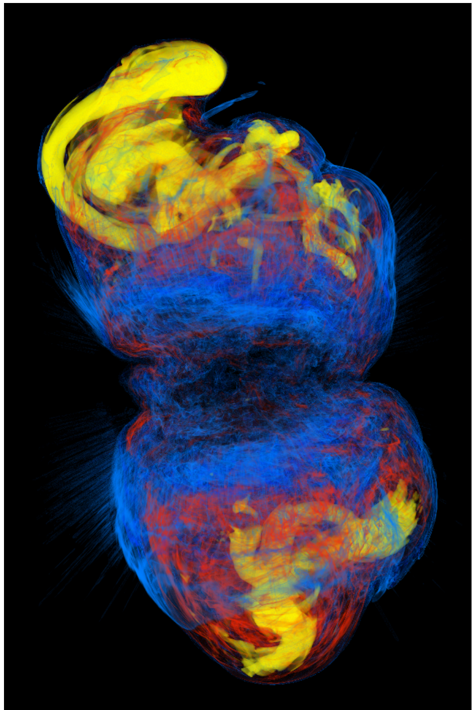
- Radiation MHD -> M1, especially important for detailed nucleosynthesis

- How much resolution do we need? Can we build a (reliable) subgrid model for MHD turbulence?

- What about weak magnetic fields and their impact on turbulence in CCSN?

- Beyond ideal MHD -> resistivity, … How important is this going to be in core-collapse?





Thank you!