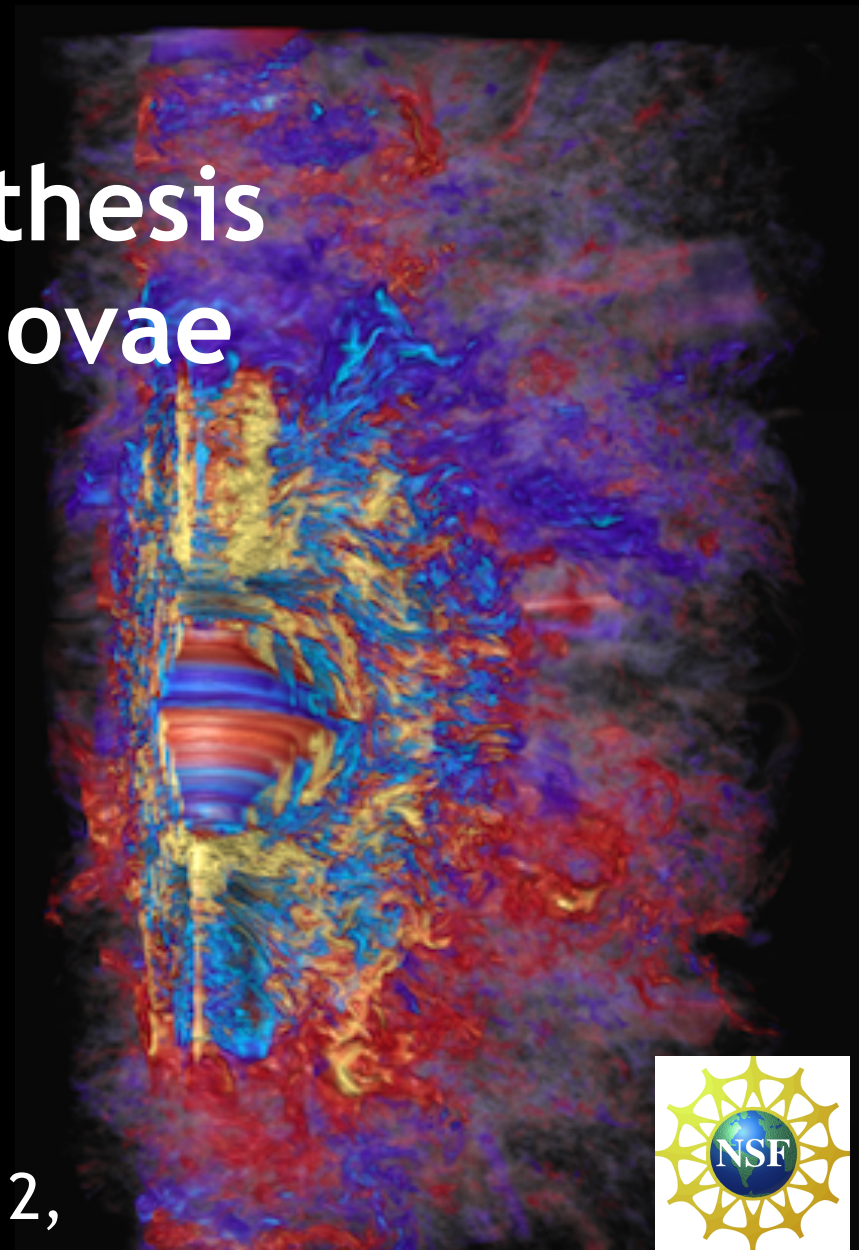


R-process nucleosynthesis in jet-driven supernovae

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Einstein fellow @ UC Berkeley
pmoesta@berkeley.edu

Einstein fellows symposium, Oct 12,
2017



New era of transient science

- Current (PTF, DeCAM, ASAS-SN) and upcoming wide-field time domain astronomy (ZTF, LSST, ...) -> wealth of data
- adv LIGO / gravitational waves detected
- Computational tools at dawn of new exascale era

Transformative years ahead for our understanding of these events



Image: PTF/ZTF/COO

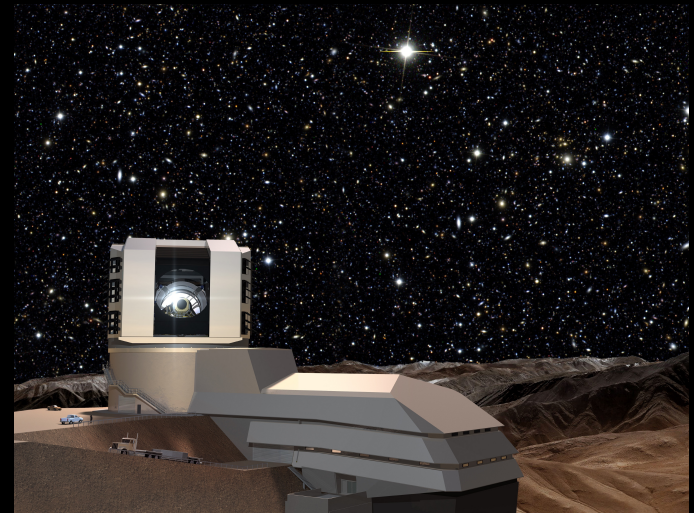


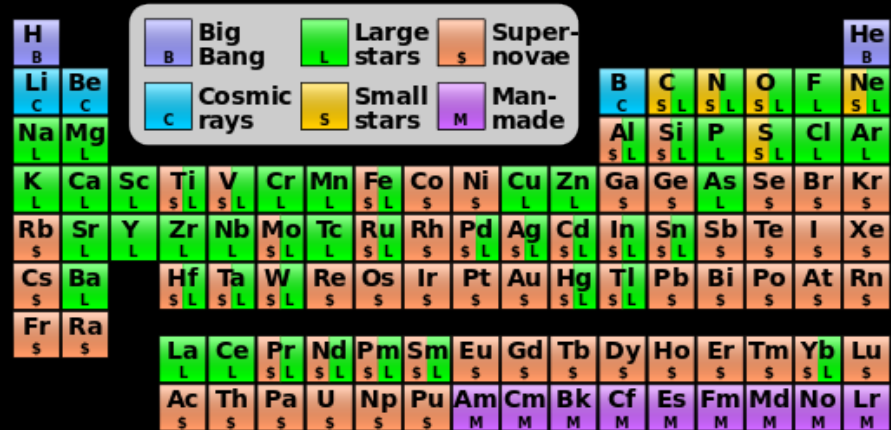
Image: LSST

Astrophysics of core-collapse supernovae

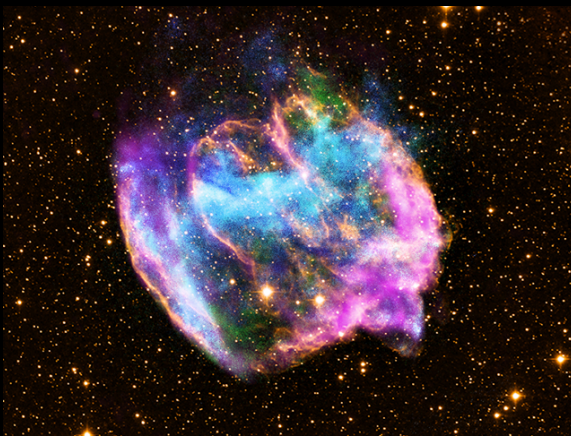


M82/Chandra/NASA

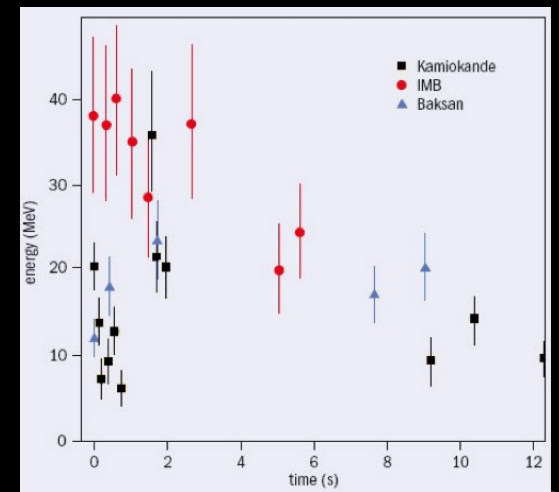
Galaxy evolution/feedback



Heavy element nucleosynthesis

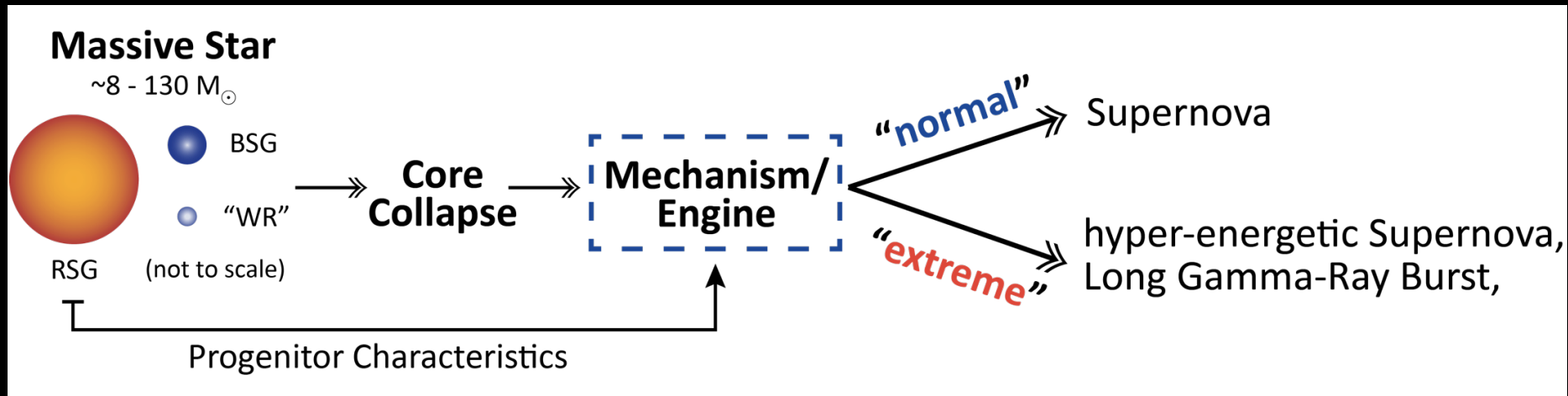


Birth sites of black holes / neutron stars



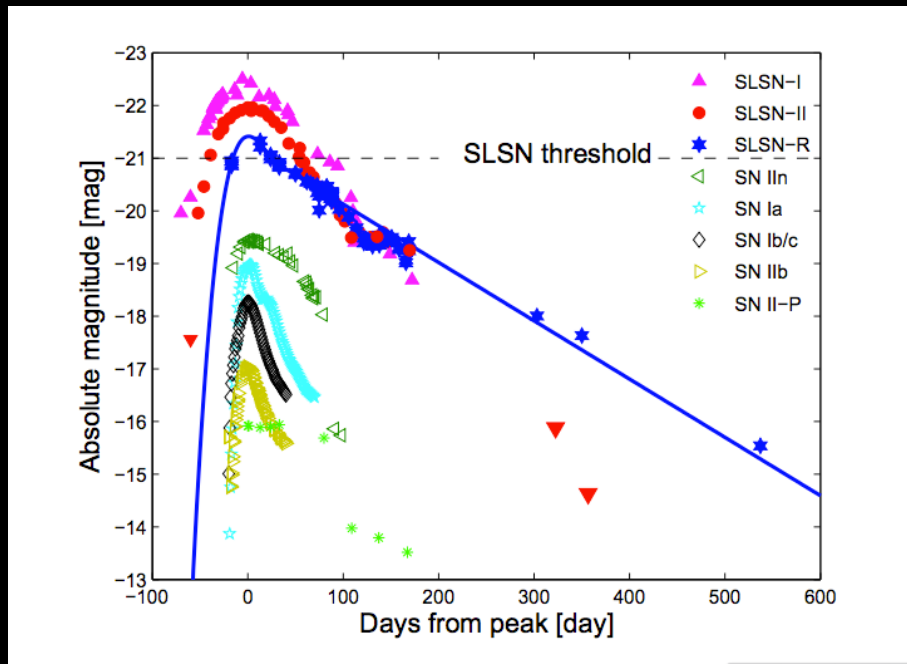
Neutrinos

Hypernovae & GRBs



- 11 long GRB - core-collapse supernova associations.
- All GRB-SNe are stripped envelope, show outflows $v \sim 0.1c$
- But not all stripped-envelope supernovae come with GRBs
- Trace low metallicity and low redshift

Superluminous supernovae



Gal-Yam+12

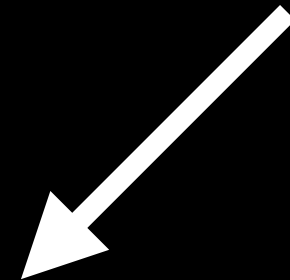
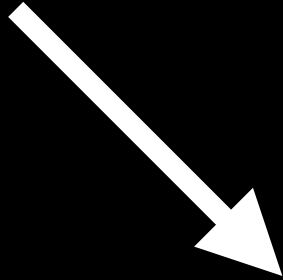
Some events:
stripped envelope
no interaction
 $E_{\text{lum}} \sim 10^{45}$ erg
 E_{rad} up to 10^{52} erg

Superluminous / hyperenergetic supernovae

SLSN Ic

SN Ic-bl

IGRBs



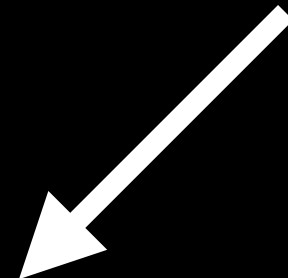
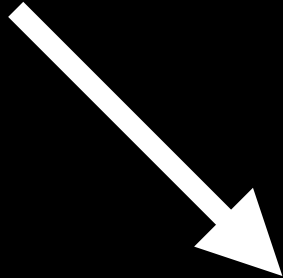
**Common engine?
Magnetar?**

Superluminous / hyperenergetic supernovae

SLSN Ic

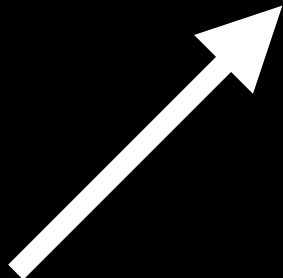
SN Ic-bl

IGRBs

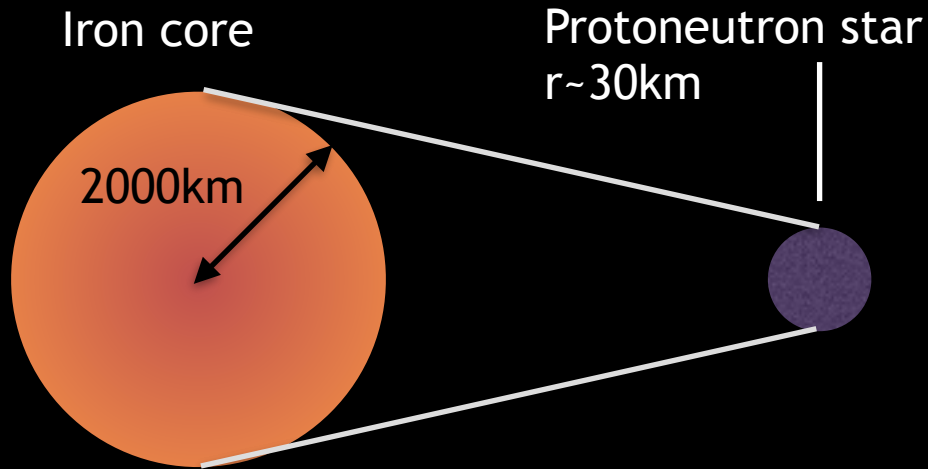


Common engine?
Magnetar?

FRBs?



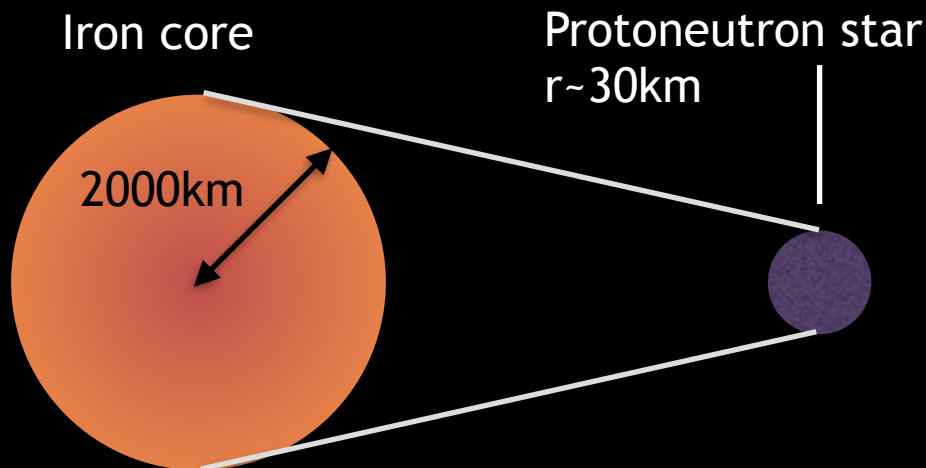
Core collapse basics



Nuclear equation of state stiffens at nuclear density

Inner core ($\sim 0.5 M_{\odot}$)
-> protoneutron star + shockwave

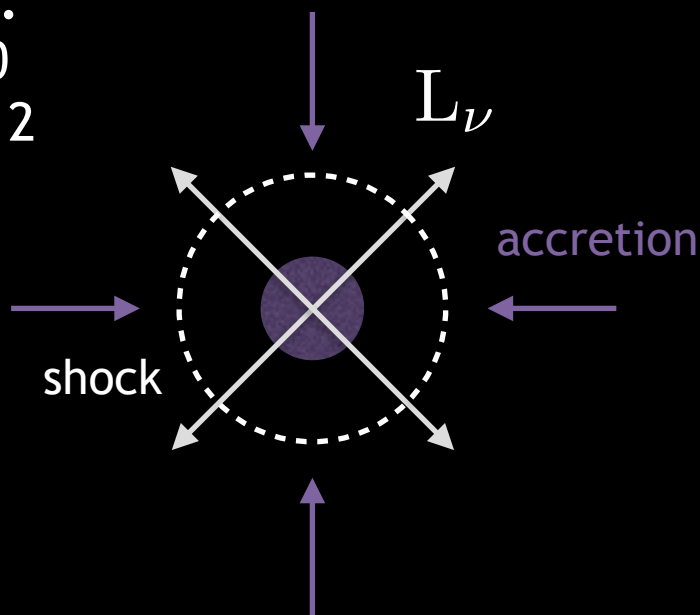
Core collapse basics



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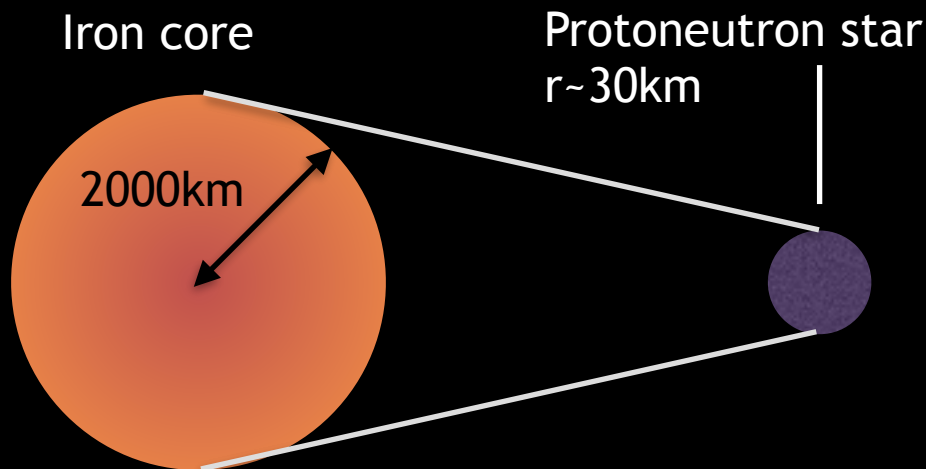
Reviews:
Bethe'90
Janka+'12



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

Shock stalls at $\sim 100\text{ km}$

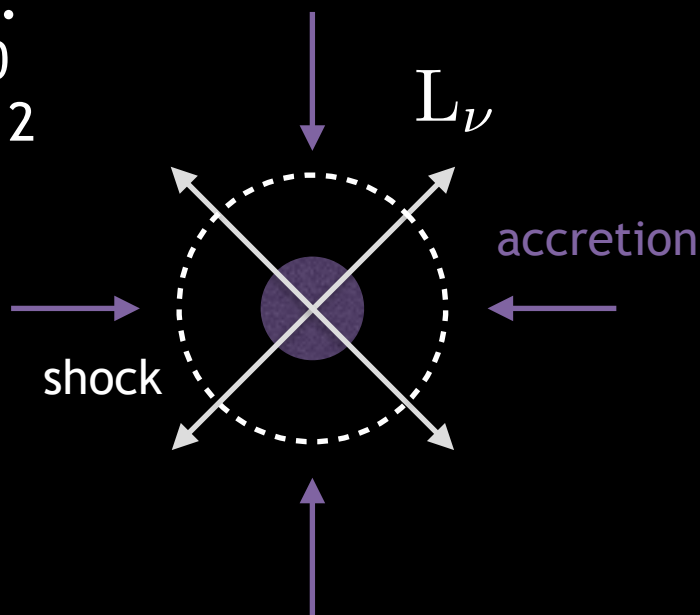
Core collapse basics



Nuclear equation of state stiffens at nuclear density

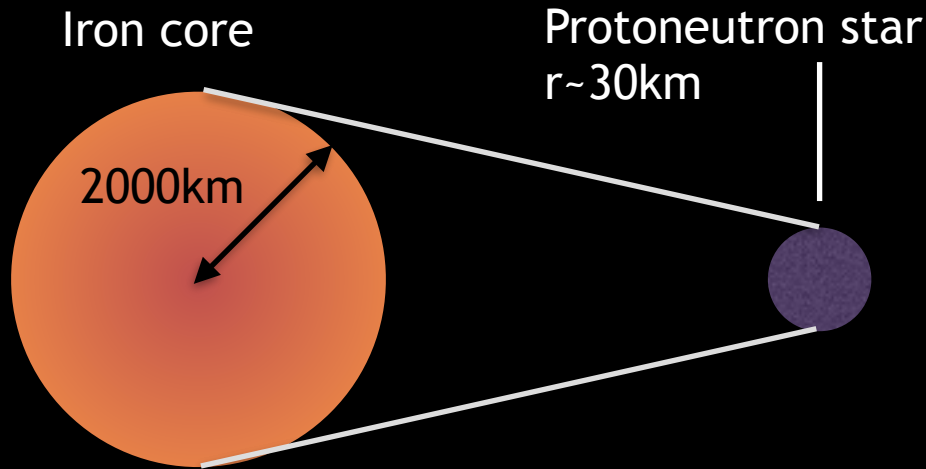
Inner core ($\sim 0.5 M_{\odot}$)
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Reviews:
Bethe'90
Janka+'12



Core-collapse
supernova problem:
How to revive the
shockwave?

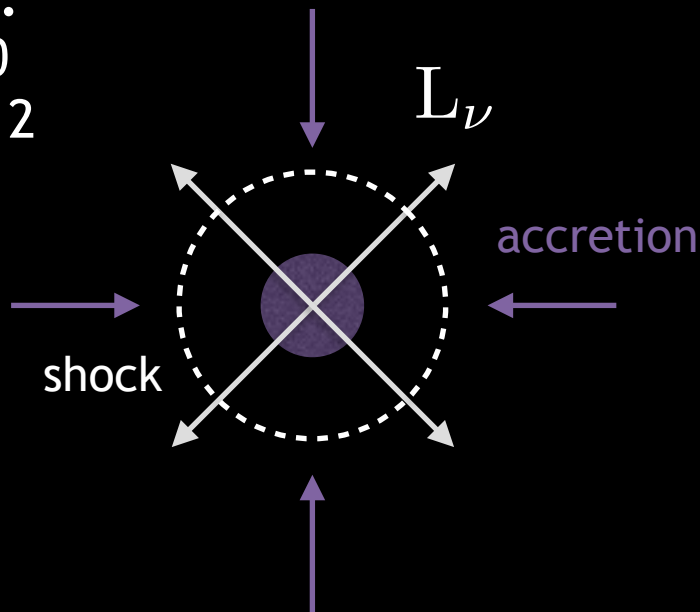
Core collapse basics



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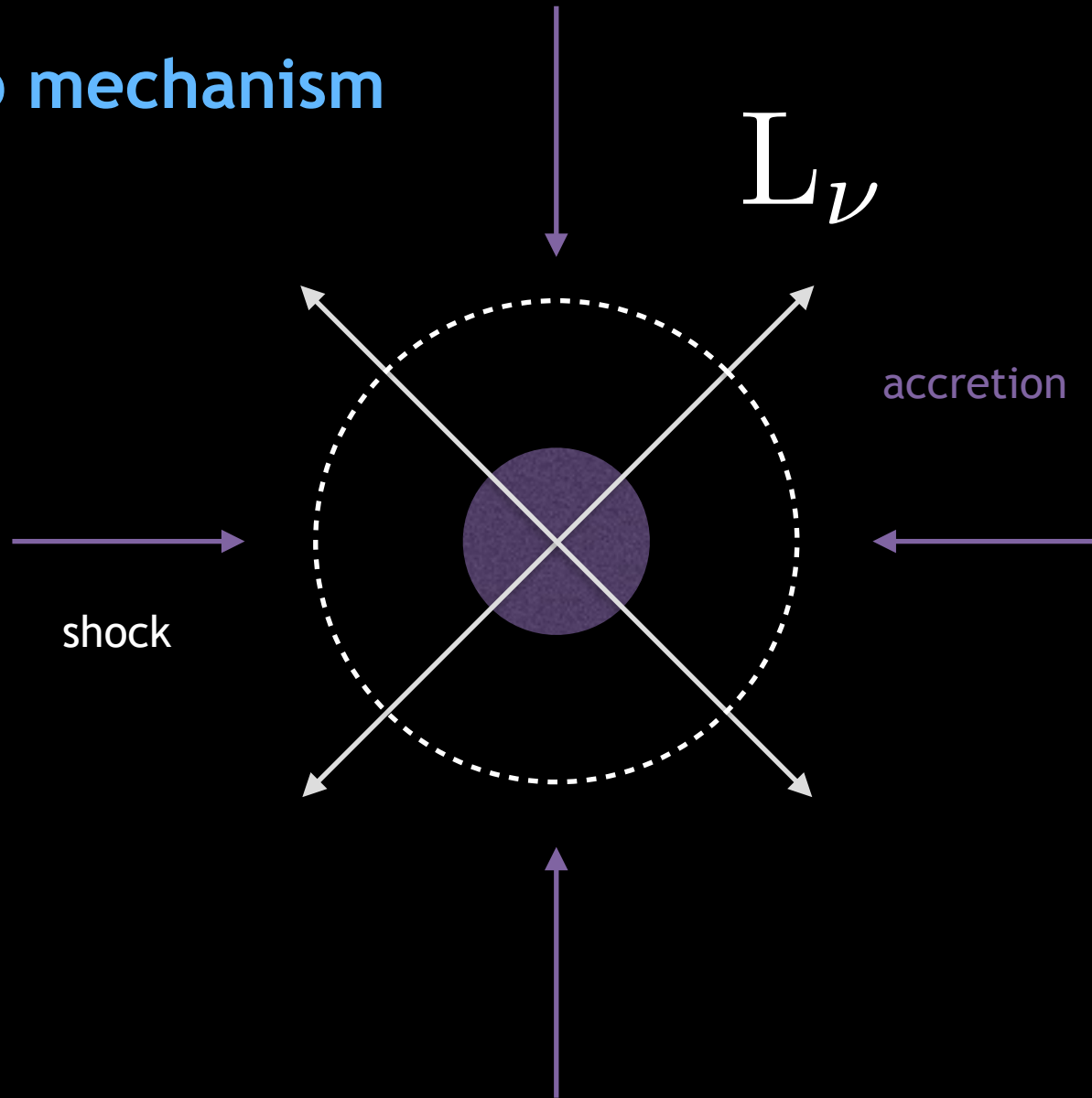
Reviews:
Bethe'90
Janka+'12



Engine formation?

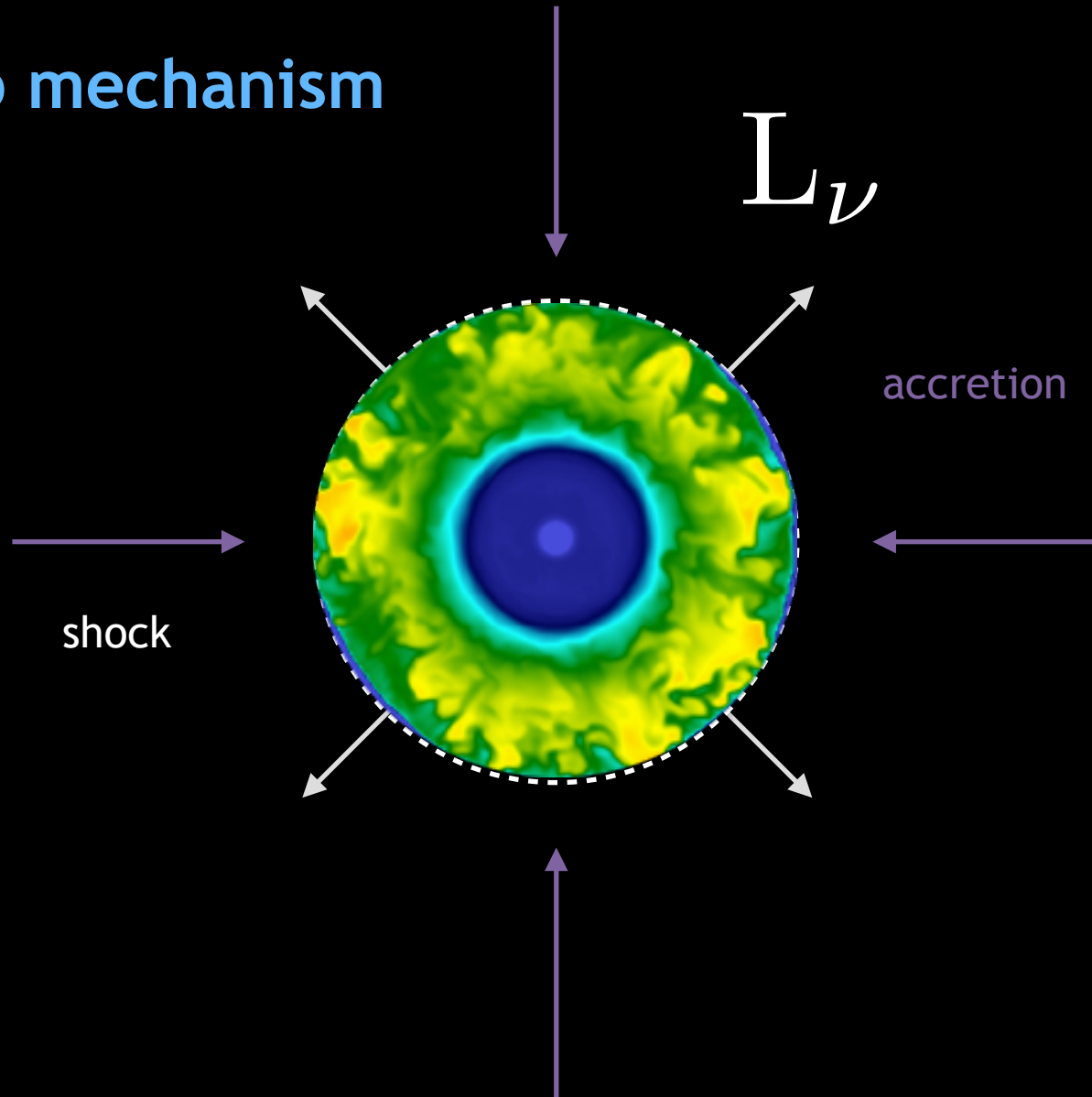
Core collapse basics

Neutrino mechanism



Core collapse basics

Neutrino mechanism



Core collapse basics

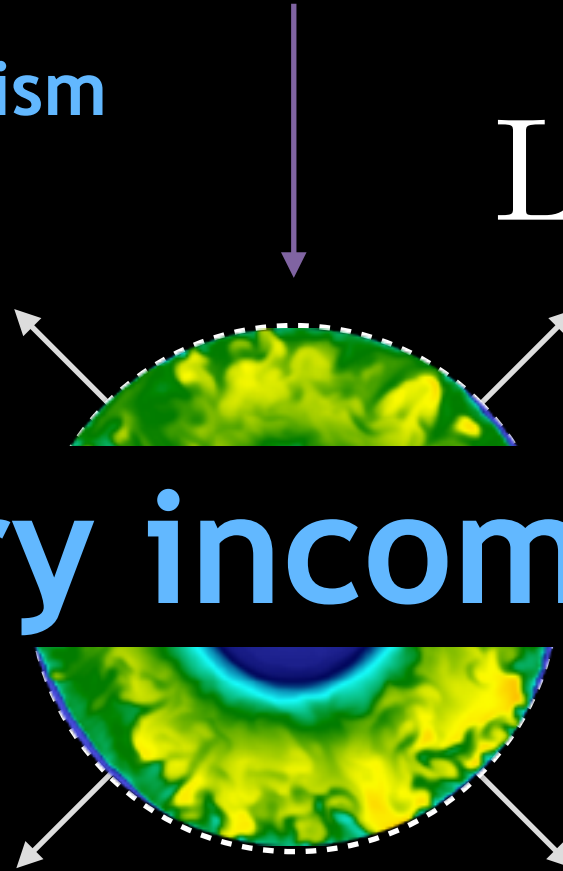
Neutrino mechanism

L_ν

Theory incomplete!

shock

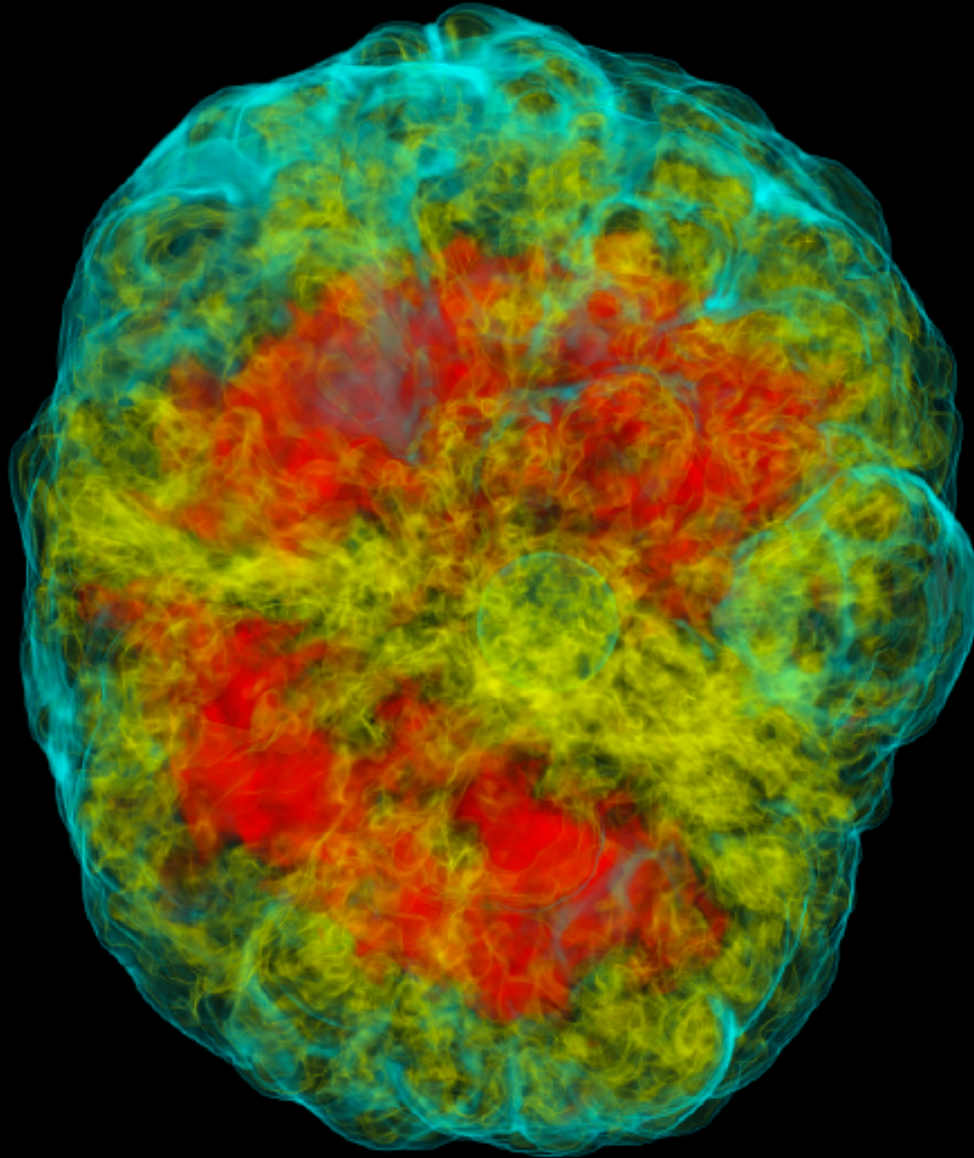
accretion



Core collapse basics

3D Volume
Visualization of

Entropy



Roberts+16

Protomagnetar powered explosions



Rapid Rotation + B-field amplification

Results in ms-period proto-magnetar

2D: Energetic bipolar explosions
Energy in rotation up to 10^{52} erg

A multiphysics challenge

Magneto-Hydrodynamics

→ Gas/plasma dynamics

A multiphysics challenge

Magneto-Hydrodynamics

→ Gas/plasma dynamics

General Relativity

→ Gravity

A multiphysics challenge

Magneto-Hydrodynamics

→ Gas/plasma dynamics

General Relativity

→ Gravity

Nuclear and Neutrino Physics

→ Nuclear EOS, nuclear reactions & ν interactions

A multiphysics challenge

Magneto-Hydrodynamics

→ Gas/plasma dynamics

General Relativity

→ Gravity

Nuclear and Neutrino Physics

→ Nuclear EOS, nuclear reactions & ν interactions

Boltzmann Transport Theory

→ Neutrino transport

A multiphysics challenge

Fully coupled!

Magneto-Hydrodynamics

→ Gas/plasma dynamics

General Relativity

→ Gravity

Nuclear and Neutrino Physics

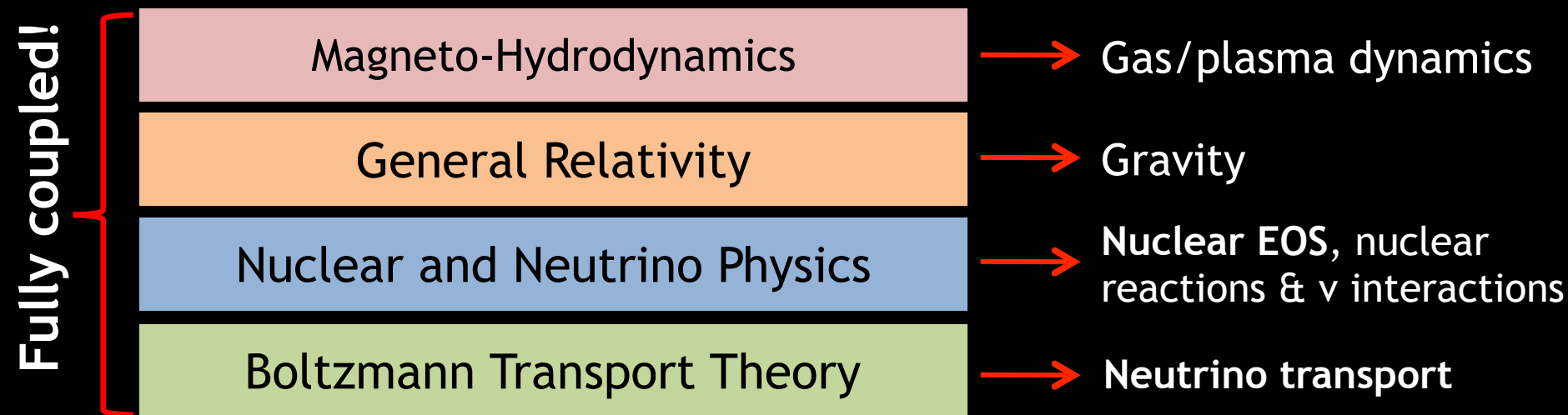
→ Nuclear EOS, nuclear reactions & ν interactions

Boltzmann Transport Theory

→ Neutrino transport

All four forces!

A multiphysics challenge



All four forces!

Additional Complication: Core-Collapse Supernovae are 3D

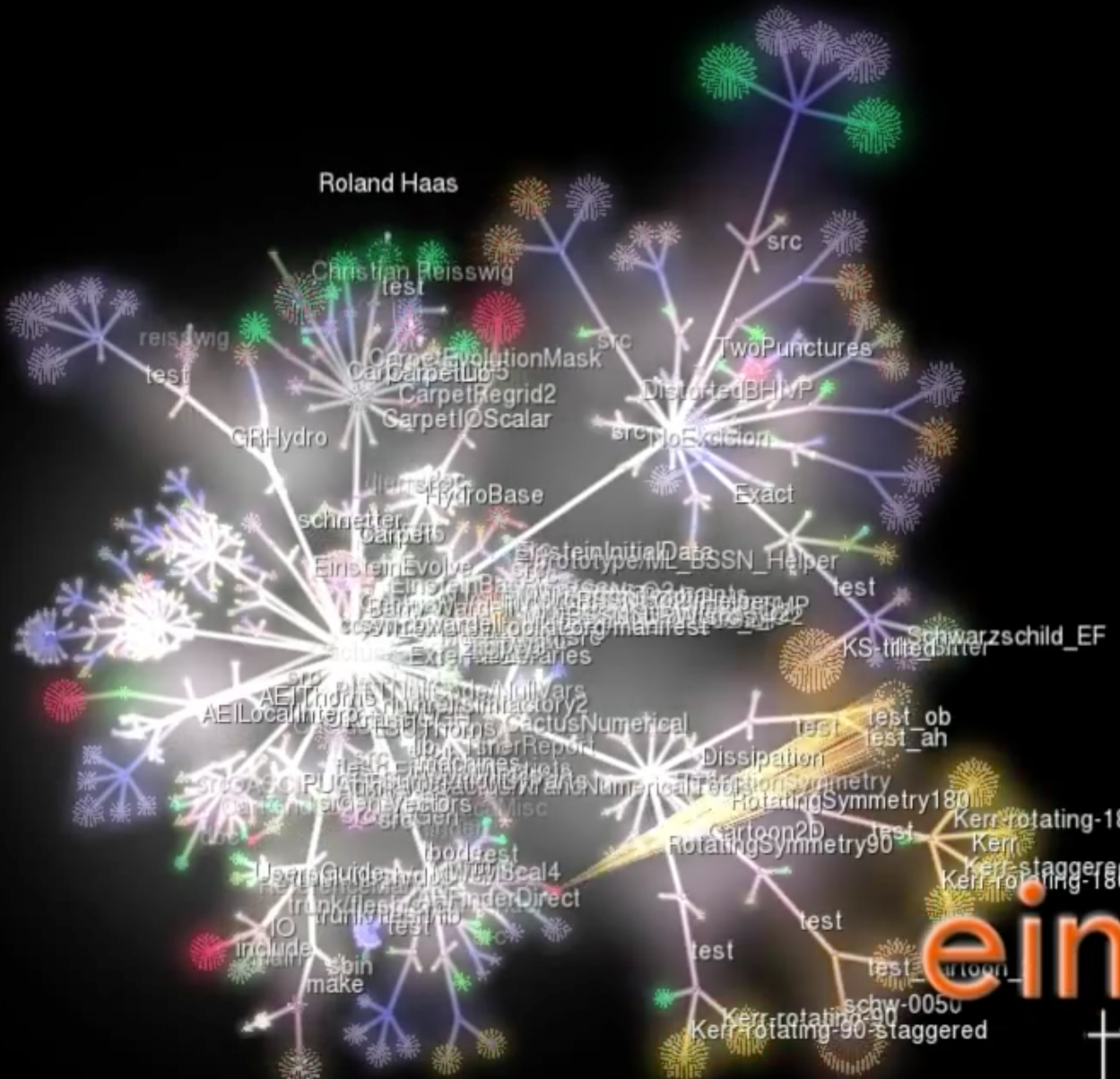
- rotation
- fluid and MHD instabilities, multi-D structure, spatial scales

Need 21st century tools:

- cutting edge numerical algorithms
- sophisticated open-source software infrastructure
- peta/exa scale computers



2012-05-17



einstein toolkit

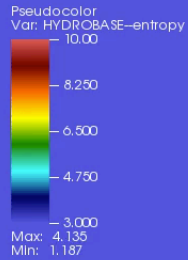
<http://einsteintoolkit.org>

3D explosions dynamics very different!

PM+ 14

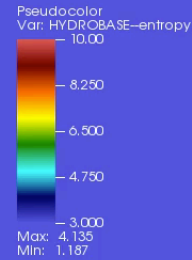
← 2000 km →

$t = -3.00$ ms



← 2000 km →

$t = -3.00$ ms

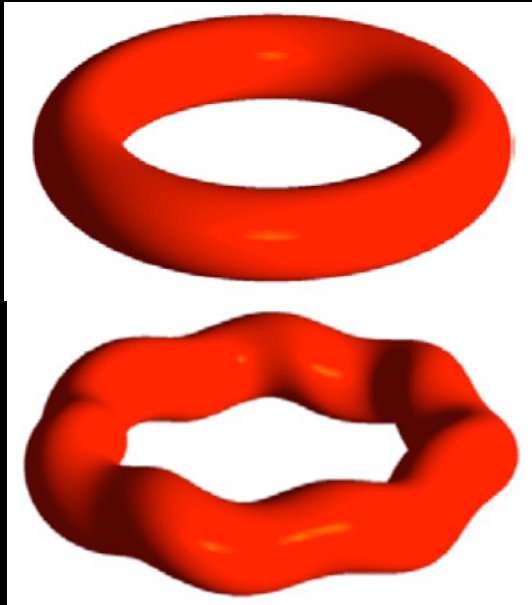
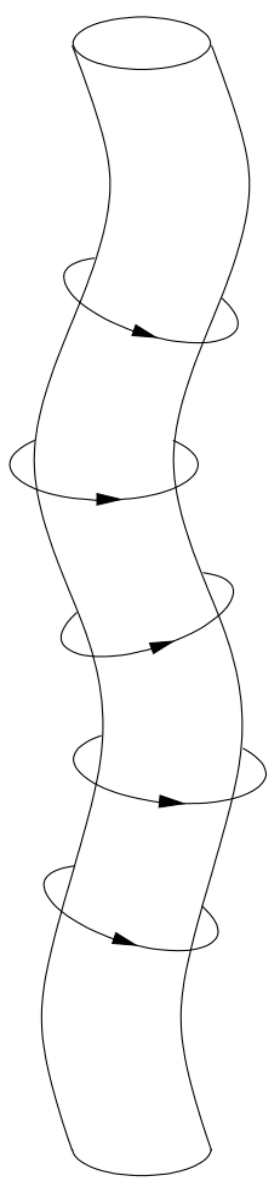


Octant Symmetry (no odd modes)
identical to 2D

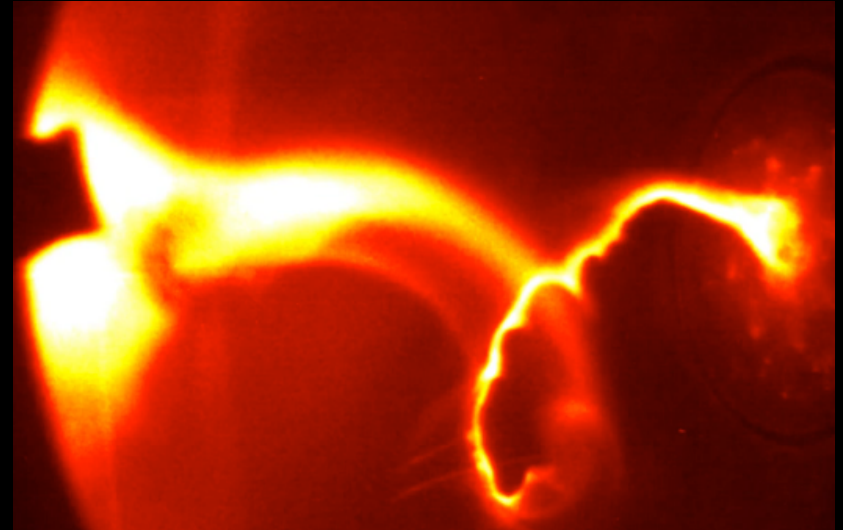
Full 3D

MHD Kink Instability

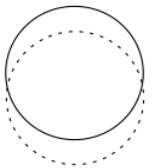
- B-field near proto-NS: $B_{\text{tor}} \gg B_z$
- Unstable to MHD screw-pinch kink instability.
- Similar to situation in Tokamak fusion reactors!



Sarff+13



Credit: Moser & Bellan, Caltech



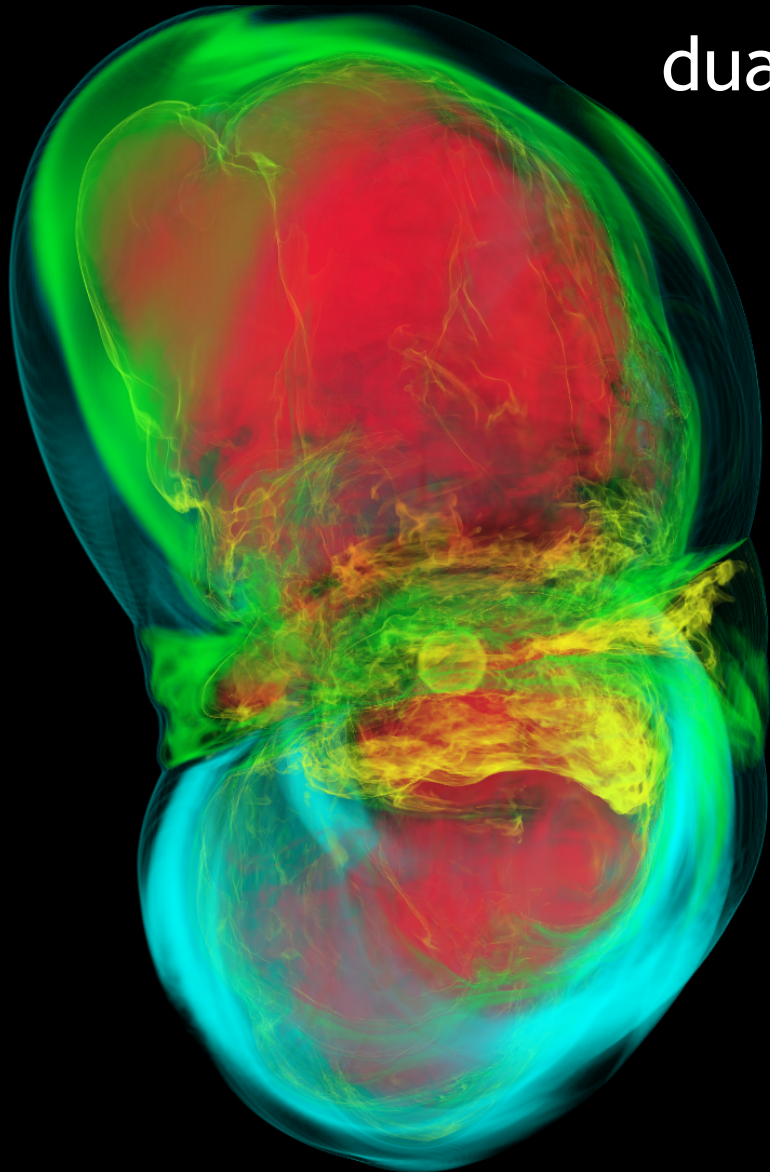
Braithwaite+ '06

Entropy

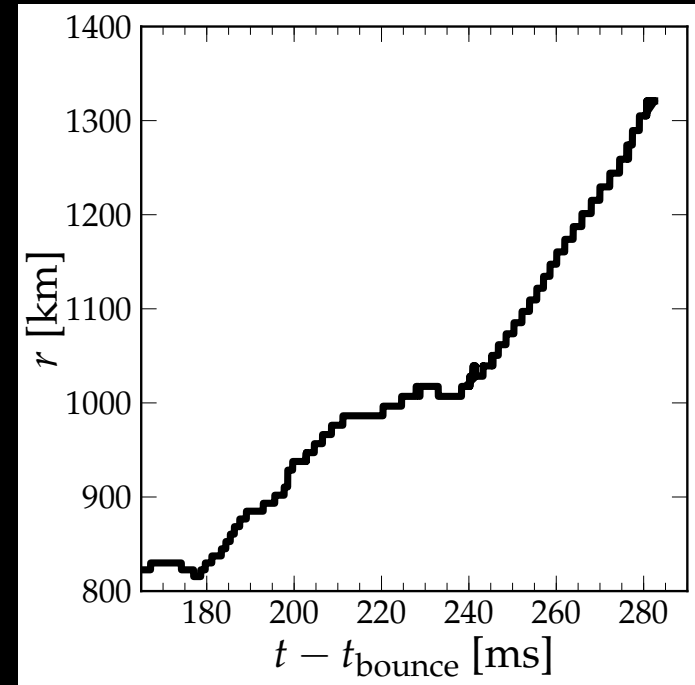
PM, Richers+ 14



Implications for long Gamma-Ray Bursts



dual-lobe ‘slow’
explosion



**Continued accretion ->
Black hole engine possible!**

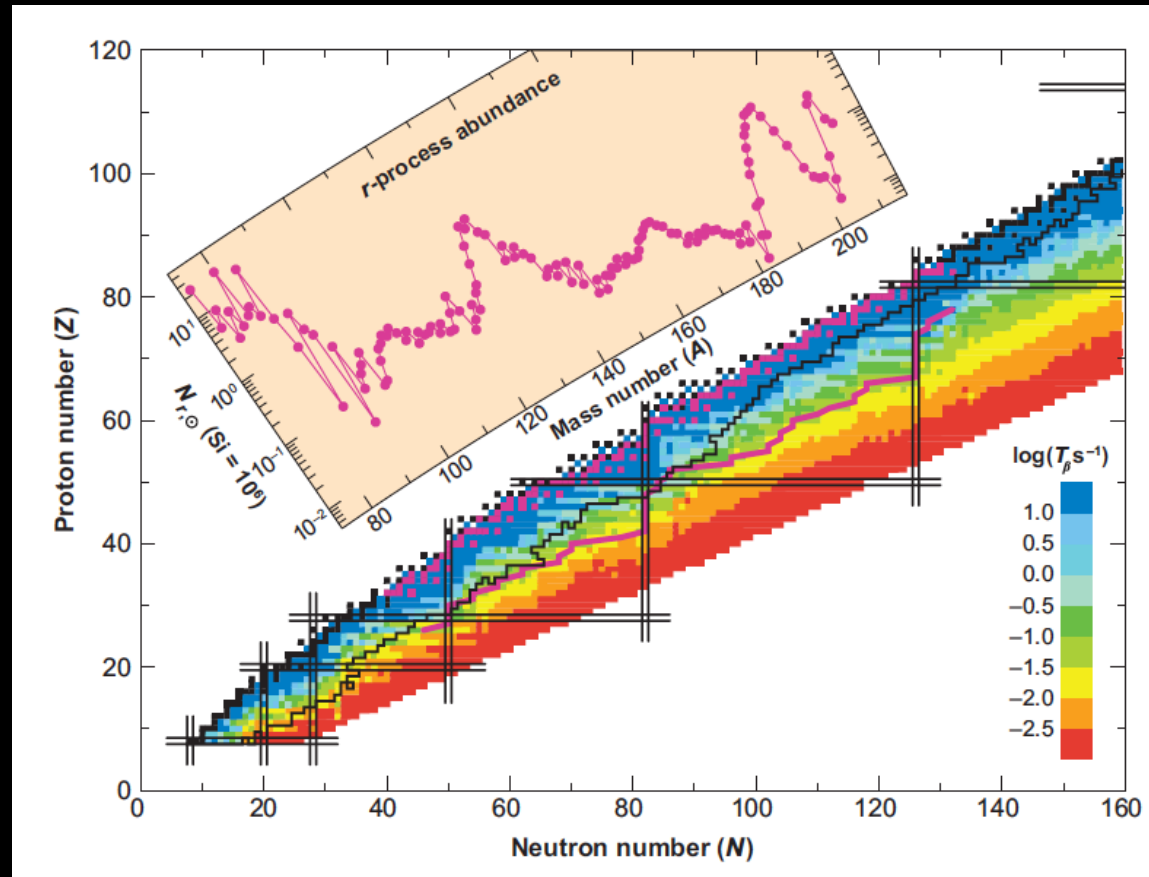
R-process nucleosynthesis in magnetar-driven explosions

Neutron-rich nucleosynthesis in supernovae

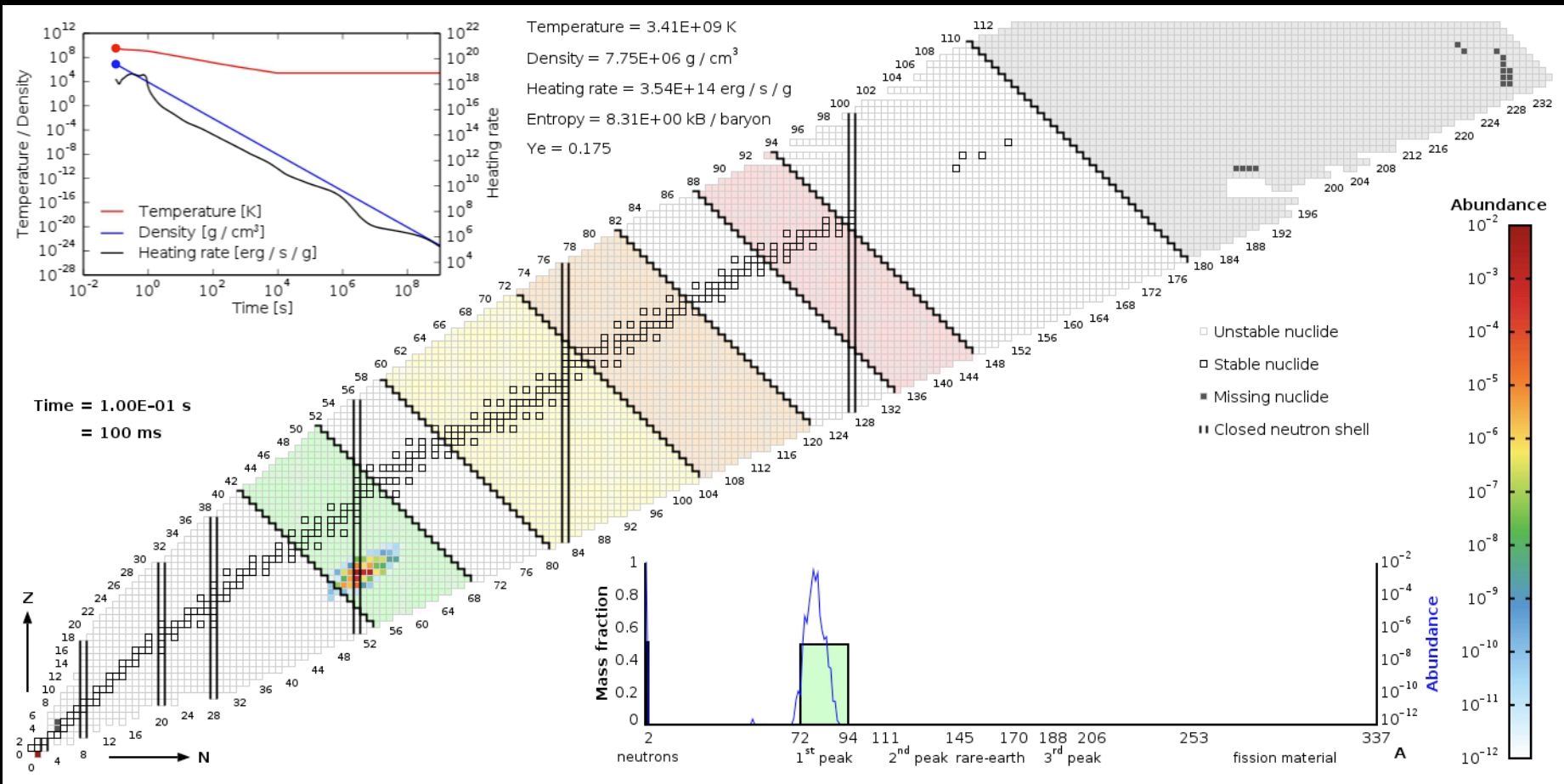
Creating the heaviest elements

Jet-driven explosions proposed as site for r-process

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



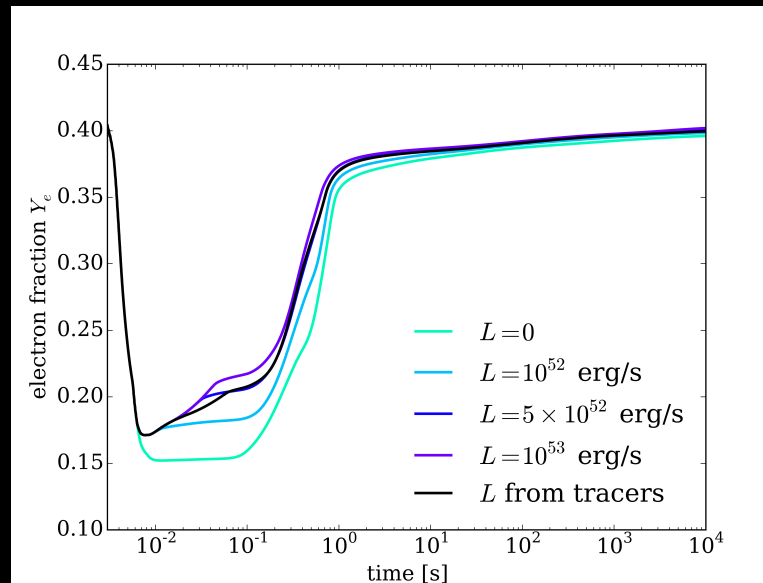
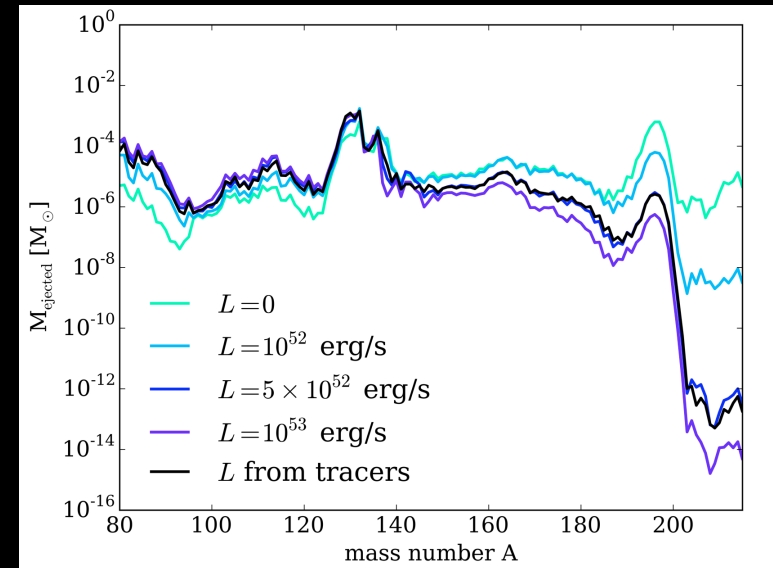
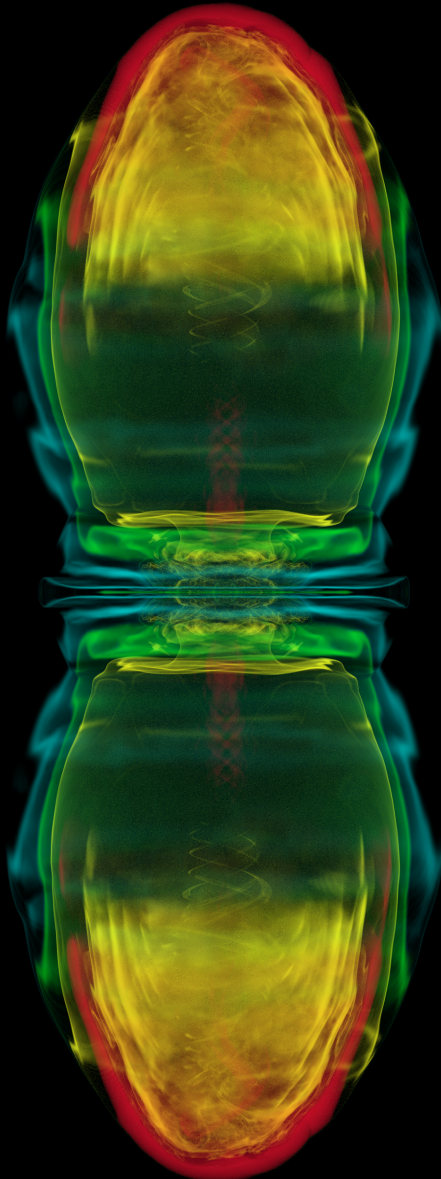
R-process - Basics



PM, Roberts, Halevi+ 17 (in prep)
 Halevi, PM+ 17 (in prep)

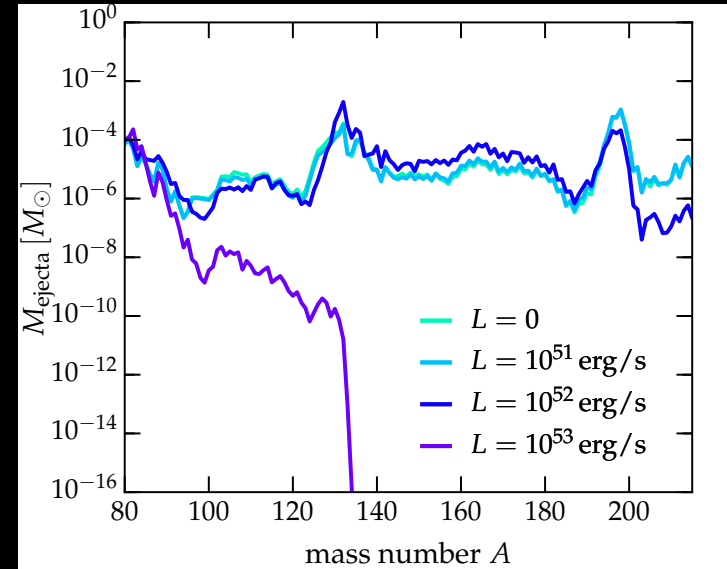
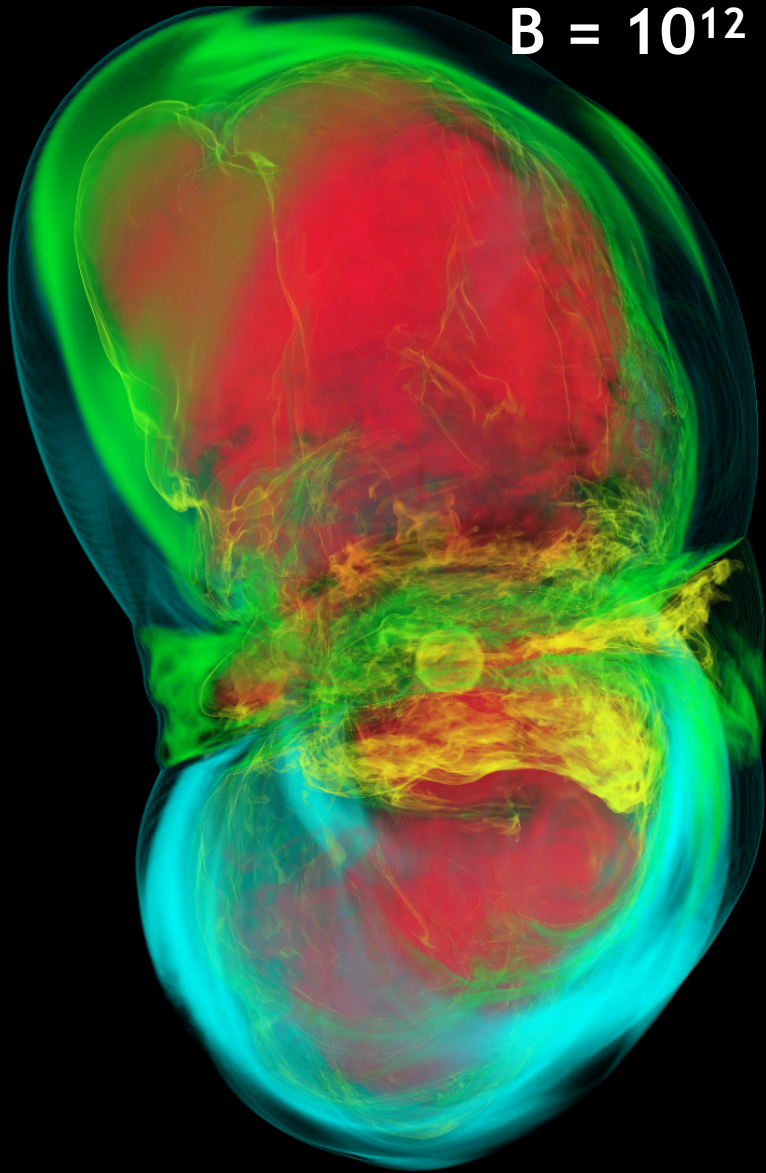
R-process in jet-driven supernovae

$B = 10^{13}$ G

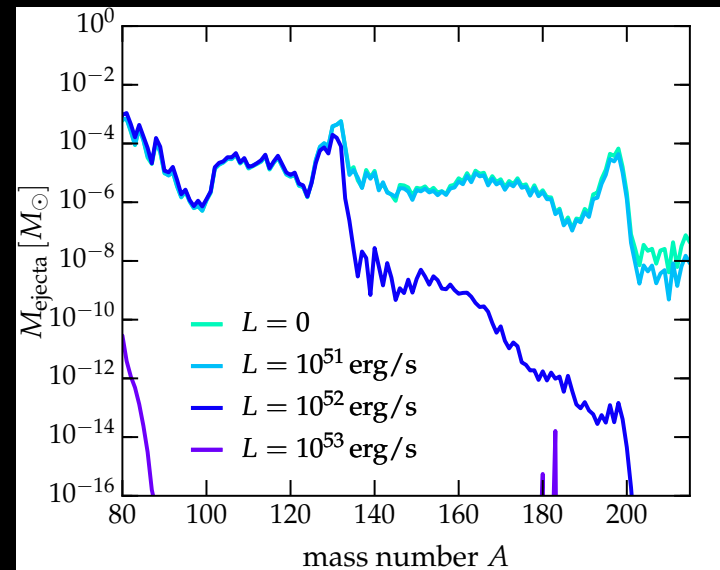


R-process in jet-driven supernovae

$B = 10^{12}$ G / octant



$B = 10^{12}$ G full 3D



Summary

New (hyperenergetic/superluminous) transients challenge our engine models

Need detailed massively parallel 3D GRMHD simulations to interpret observational data

Robust r-process elements only from iron cores that were magnetized strongly precollapse

High-performance computing key to solving these puzzles

Thank you!