Jet-driven supernovae in the multi-messenger era

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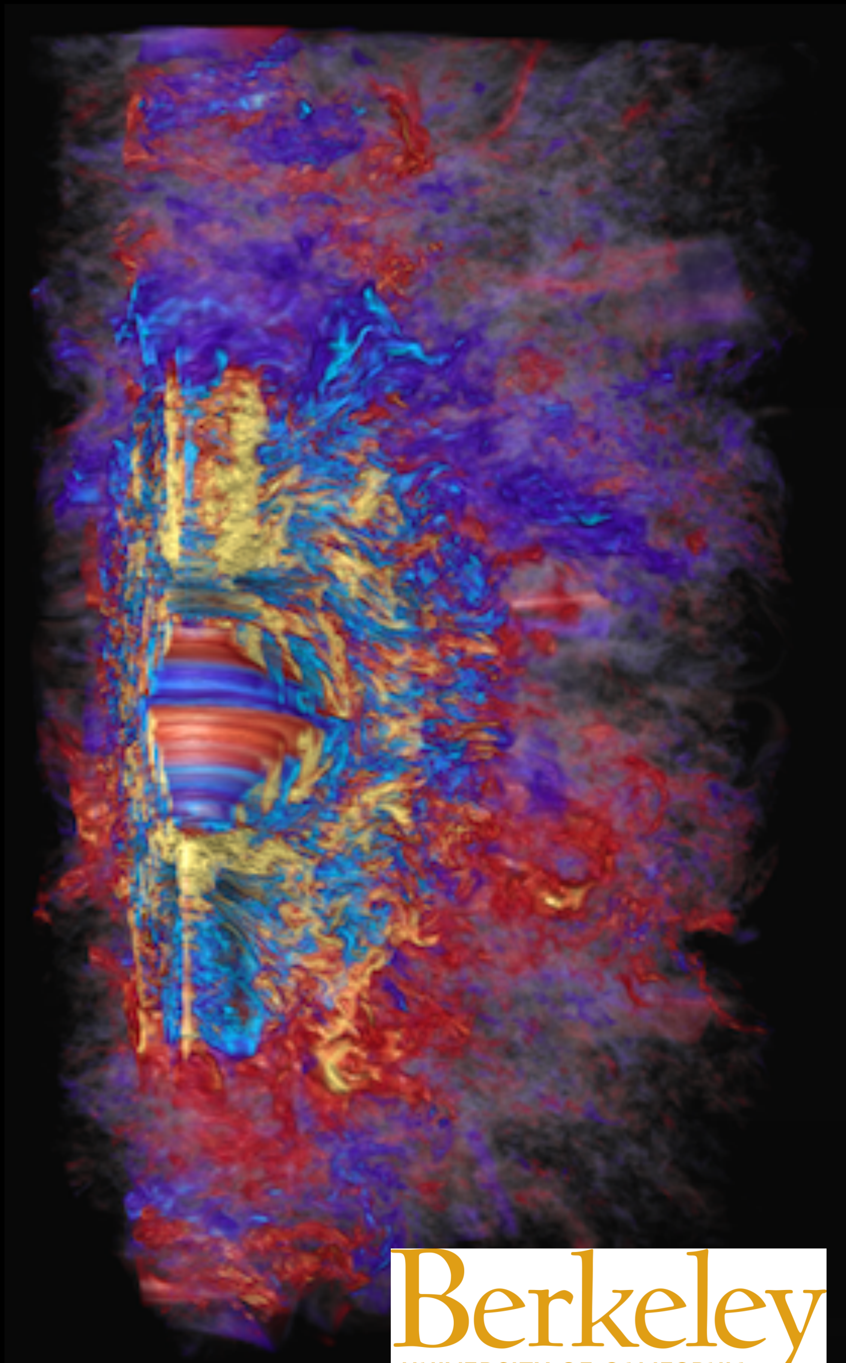
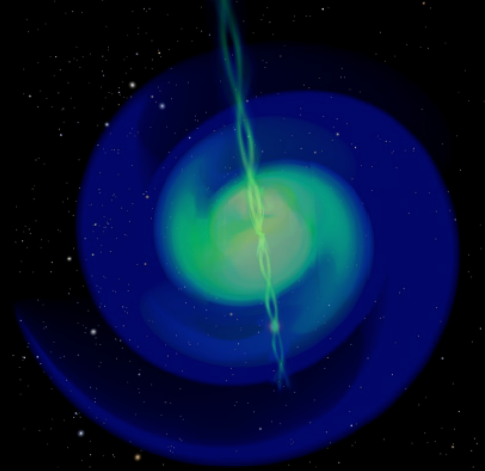
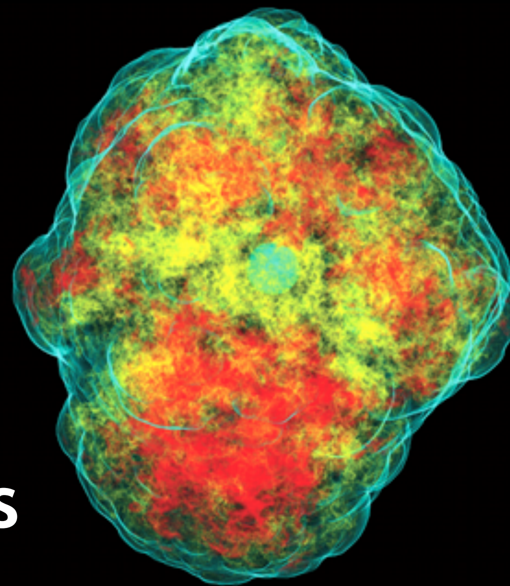
CEA Saclay, Jan 28, 2020



Berkeley
UNIVERSITY OF CALIFORNIA





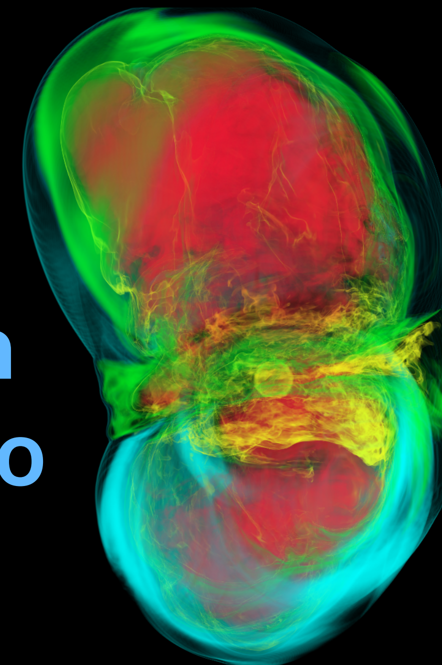
Core-collapse supernovae

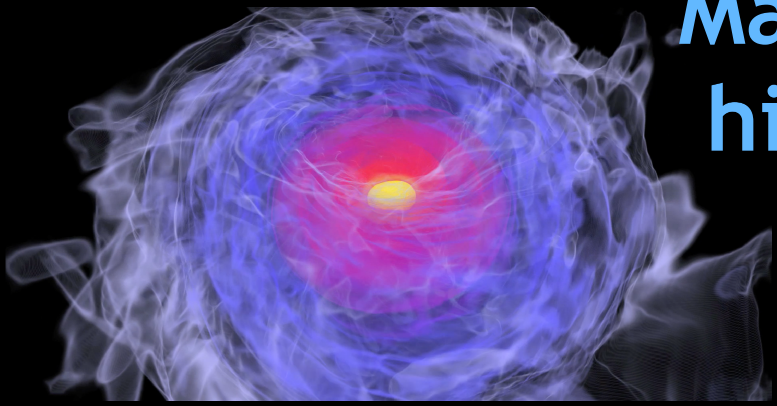
neutrinos
turbulence

(Binary) black holes

accretion disks
EM counterparts

Magnetic fields in high-energy astro





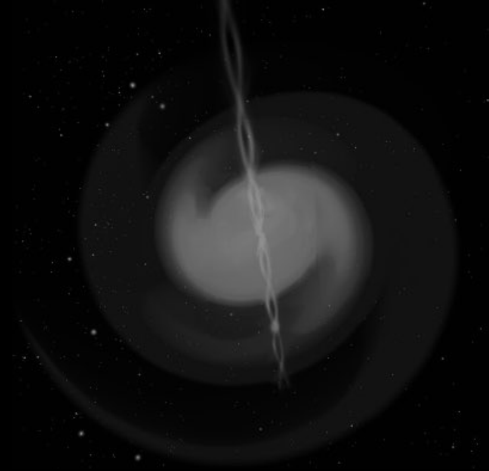
Binary neutron stars

gravitational waves
EM counterparts
sGRBs

Extreme core-collapse

hyperenergetic
superluminous
lGRBs

Magnetic fields in high-energy astro



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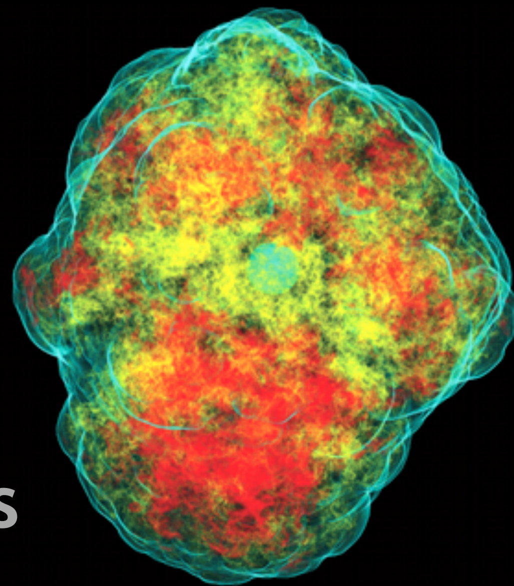

Core-collapse supernovae
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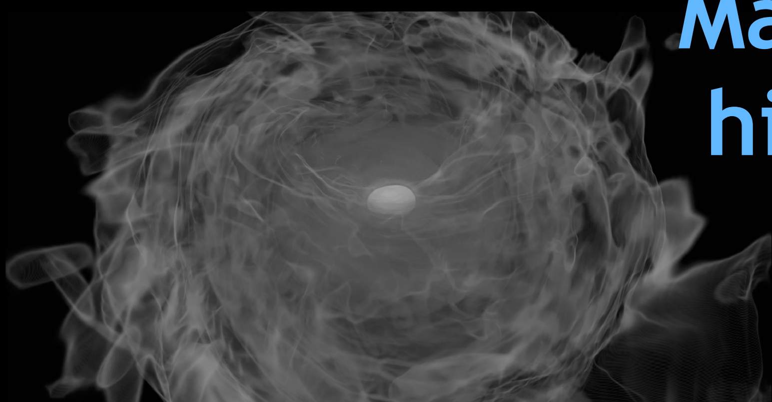

Binary neutron stars
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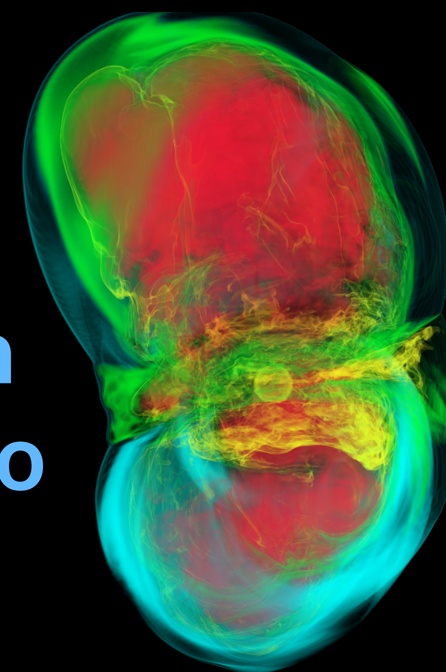

Extreme core-collapse
hyperenergetic
superluminous
lGRBs

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

Image: PTF/ZTF/COO

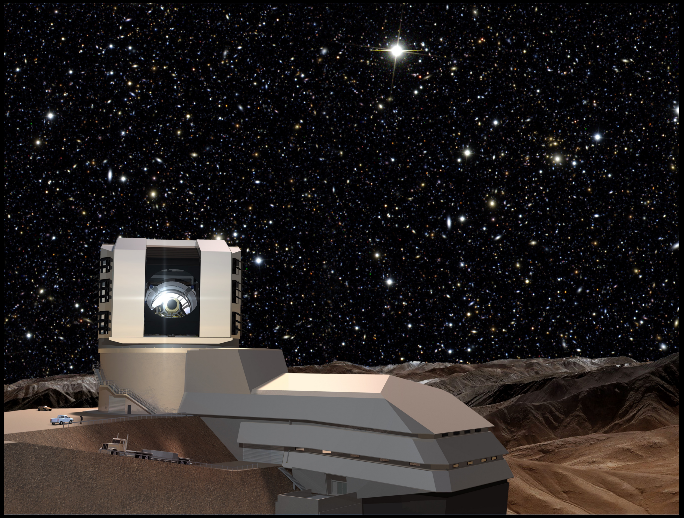

Image: LSST

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Transformative years ahead for our understanding of these events

Image: PTF/ZTF/COO

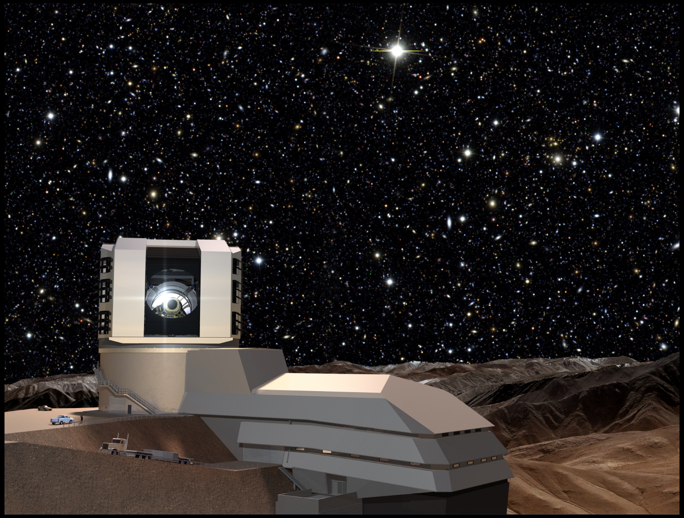


Image: LSST

Observational Facts

SN 1987A © Anglo-Australian Observatory

Progenitor BSG Sanduleak -69 220a, 18 M_{SUN}

~5 per second in universe

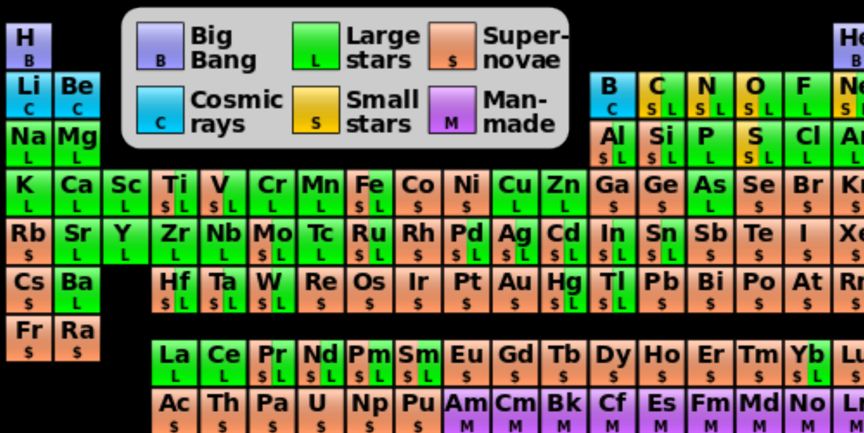
~1 per day observed

large kinetic energies ~10^{51} erg

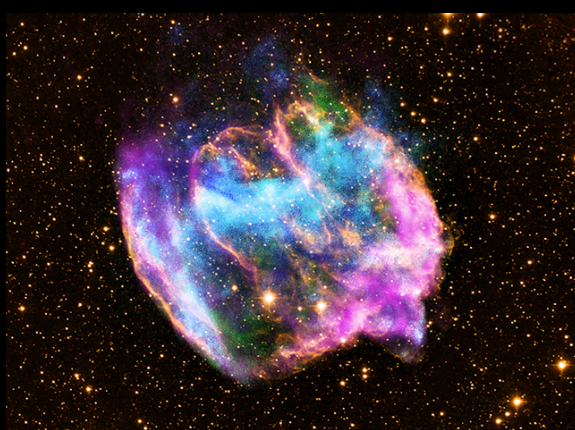
Astrophysics of core-collapse supernovae

M82/Chandra/NASA

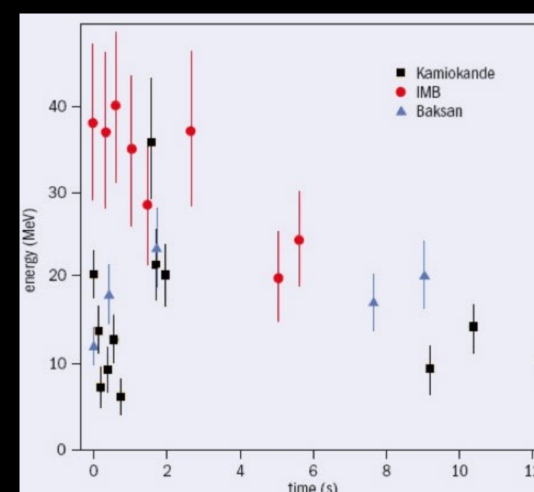
Galaxy evolution/feedback



Heavy element nucleosynthesis



Birth sites of black holes / neutron stars



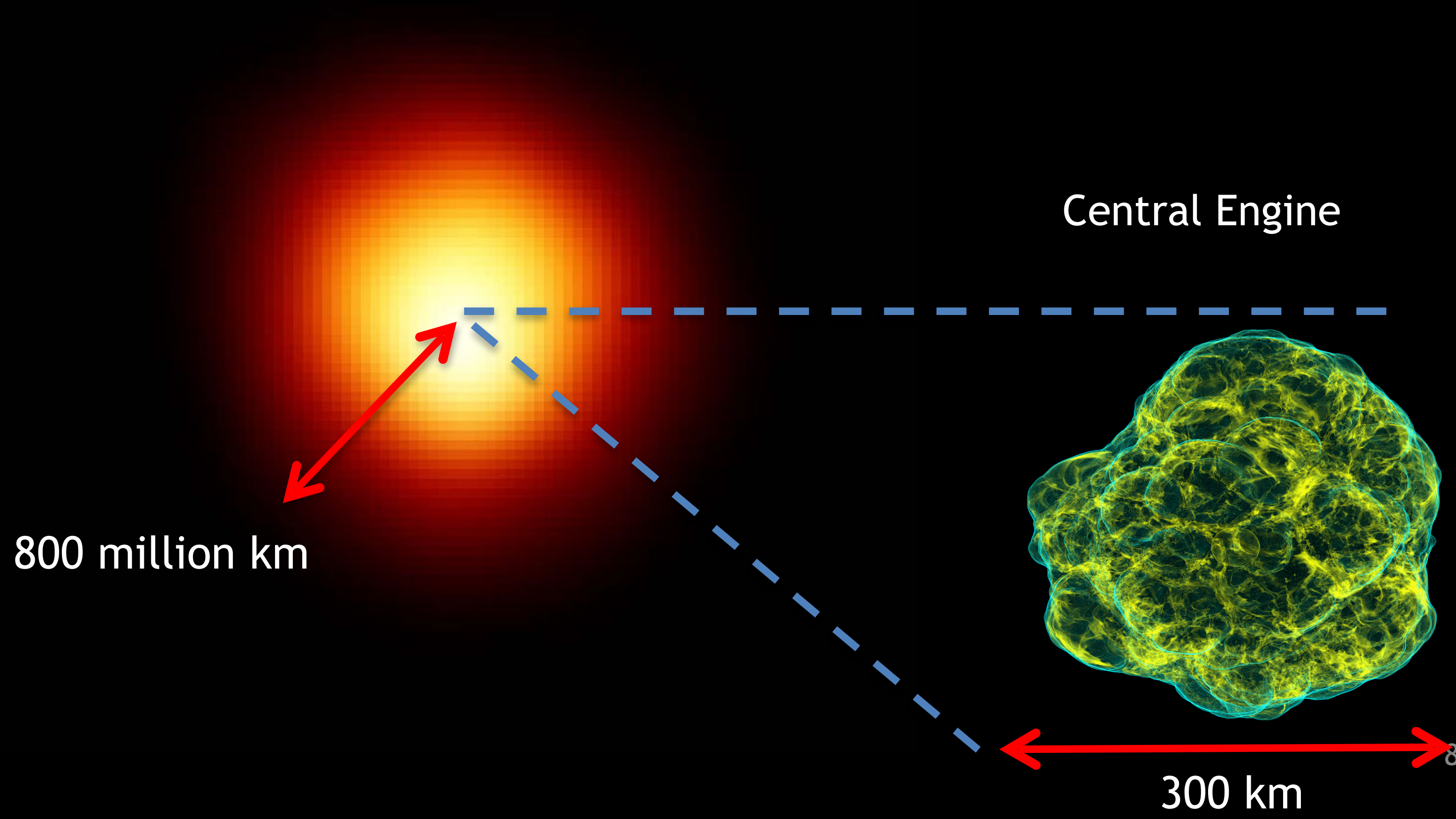
Neutrinos

Observing core-collapse supernovae

- **EM waves** **(optical/UV/X/Gamma):** secondary information, late-time probes of engine

Red Supergiant
Betelgeuse
D ~200 pc

HST



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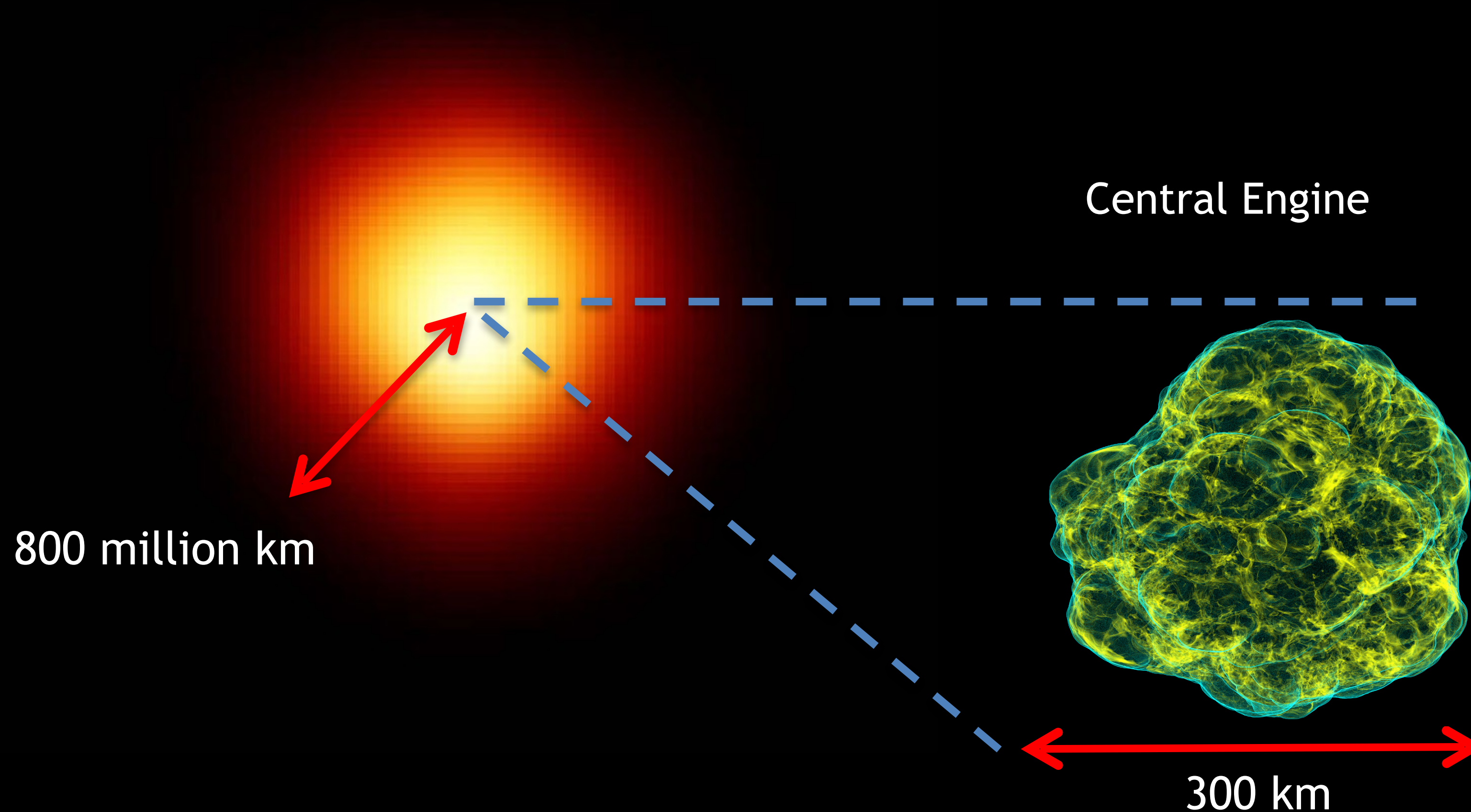

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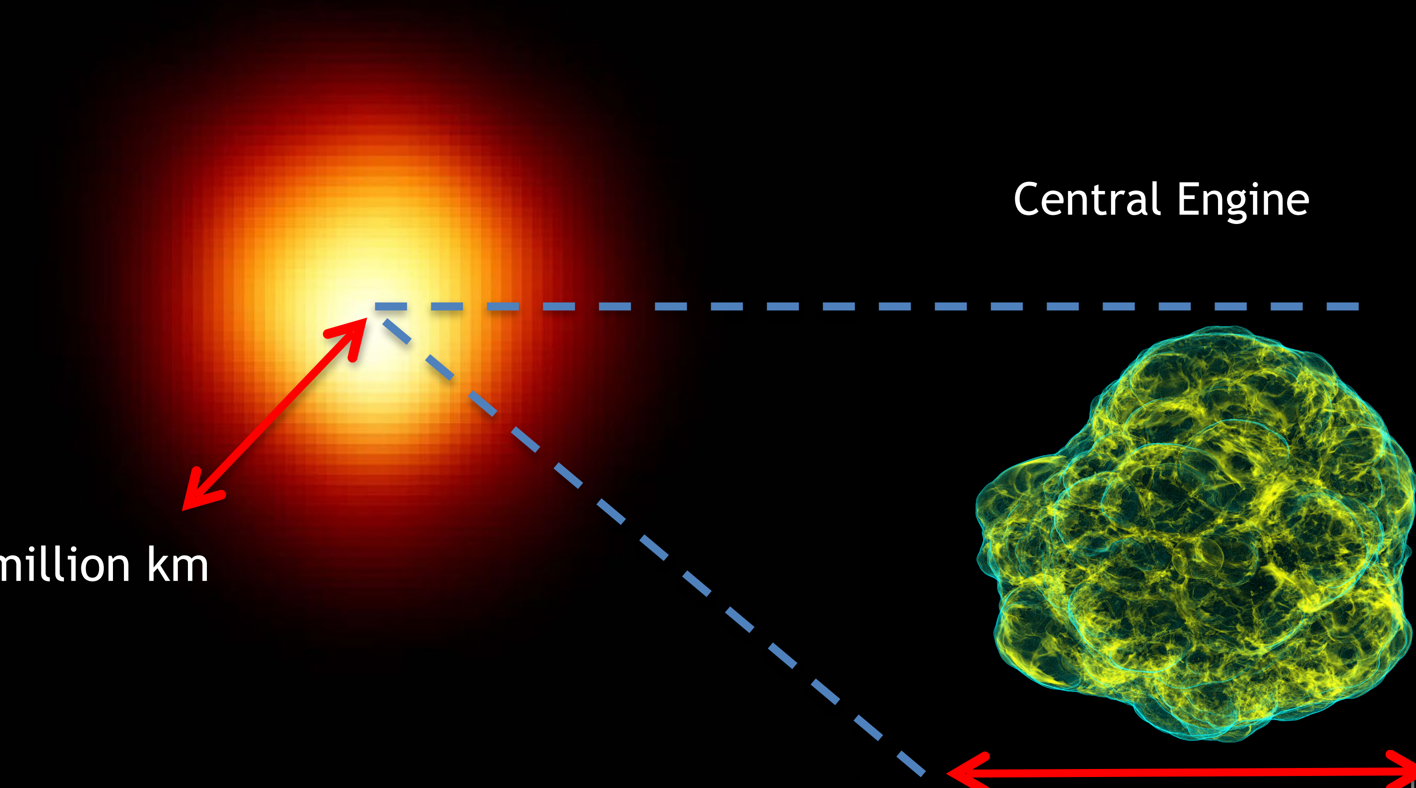
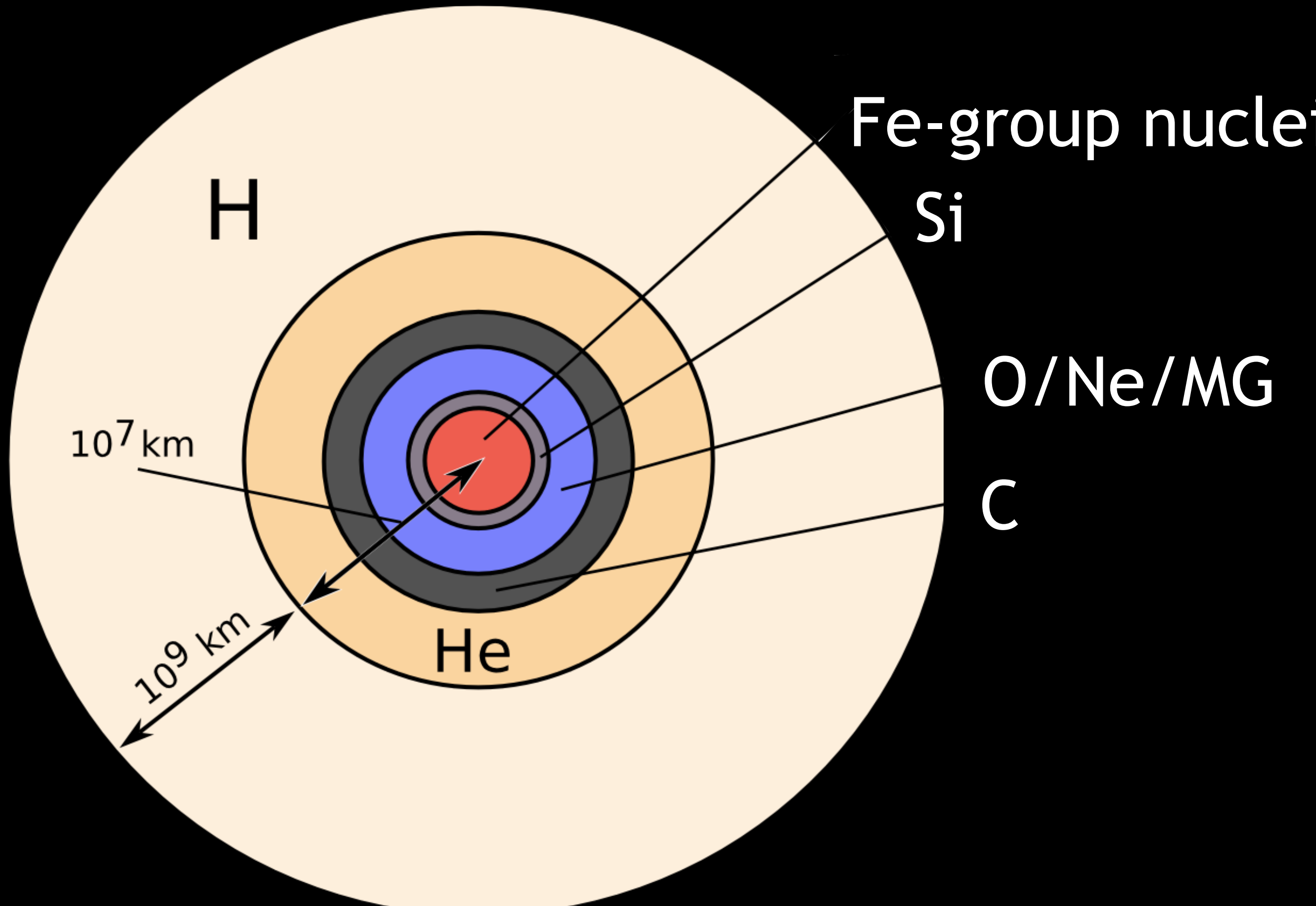


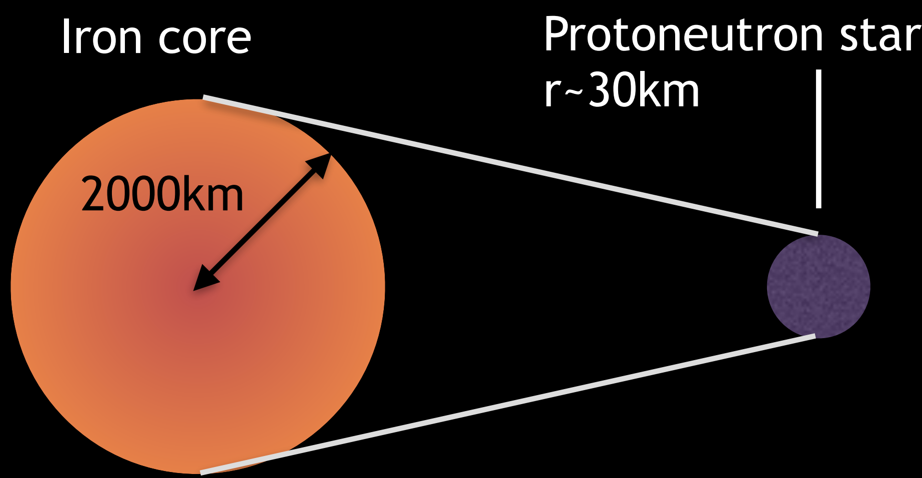
Core collapse basics

$$8M_\odot \lesssim M \lesssim 130M_\odot$$



[not drawn to scale]

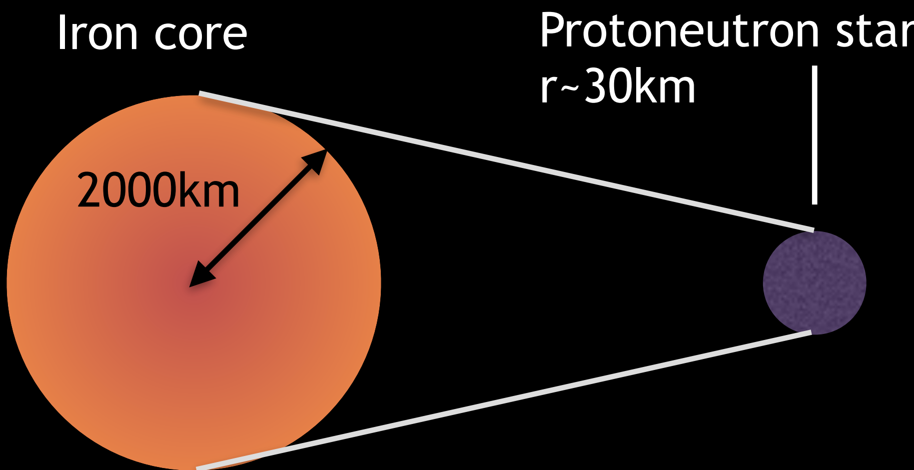
Core collapse basics



Nuclear equation of state stiffens at nuclear density

Inner core (~0.5 $M_\odot$)
-> protoneutron star + shockwave

Core collapse basics



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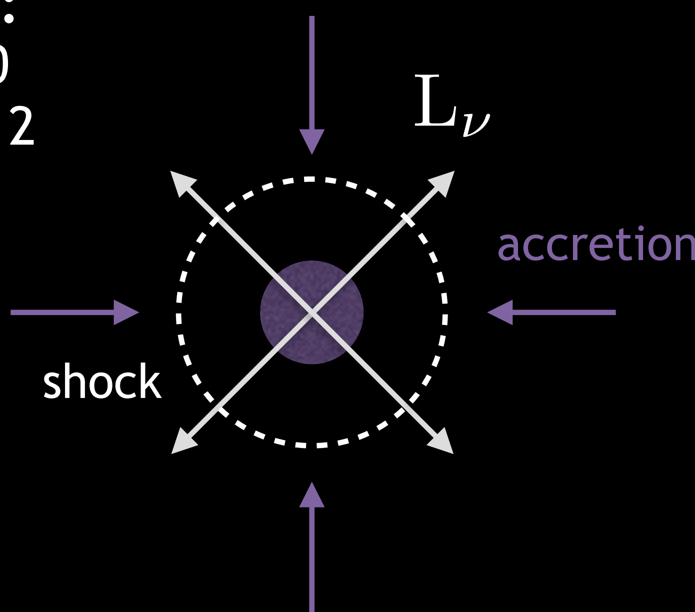
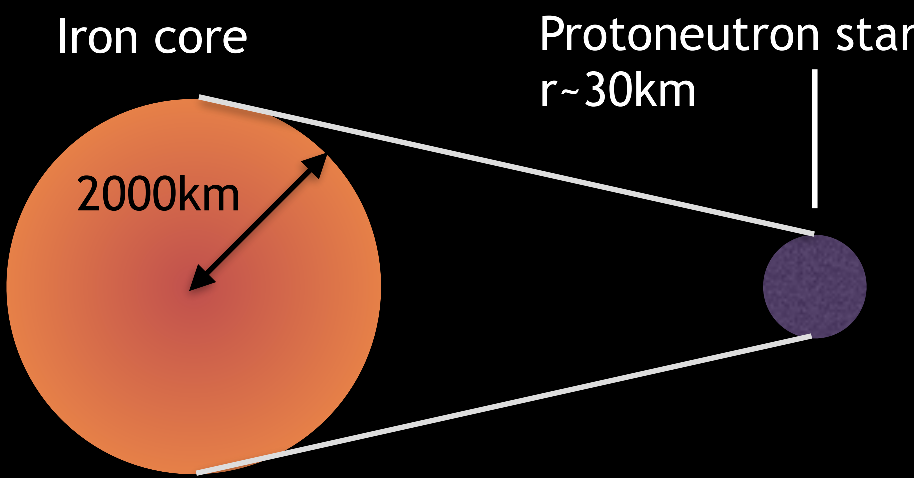
Reviews:
Bethe’90
Janka+‘12



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

Shock stalls at ~ 100 km

Core collapse basics



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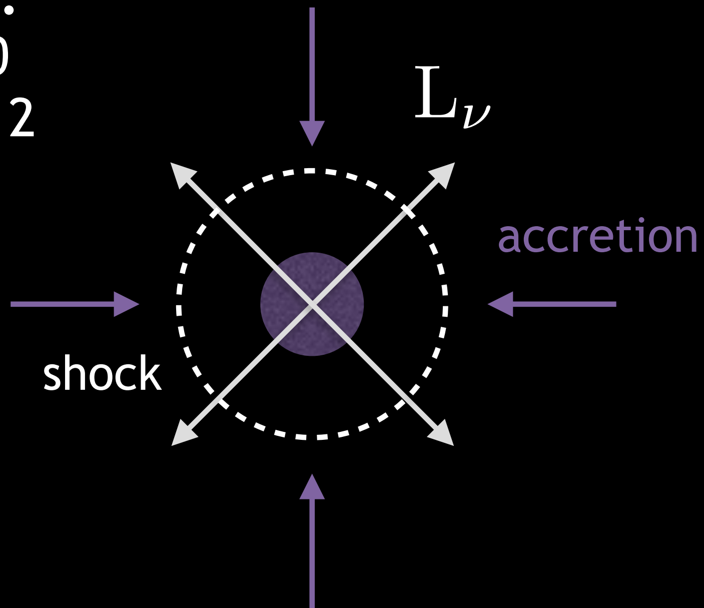
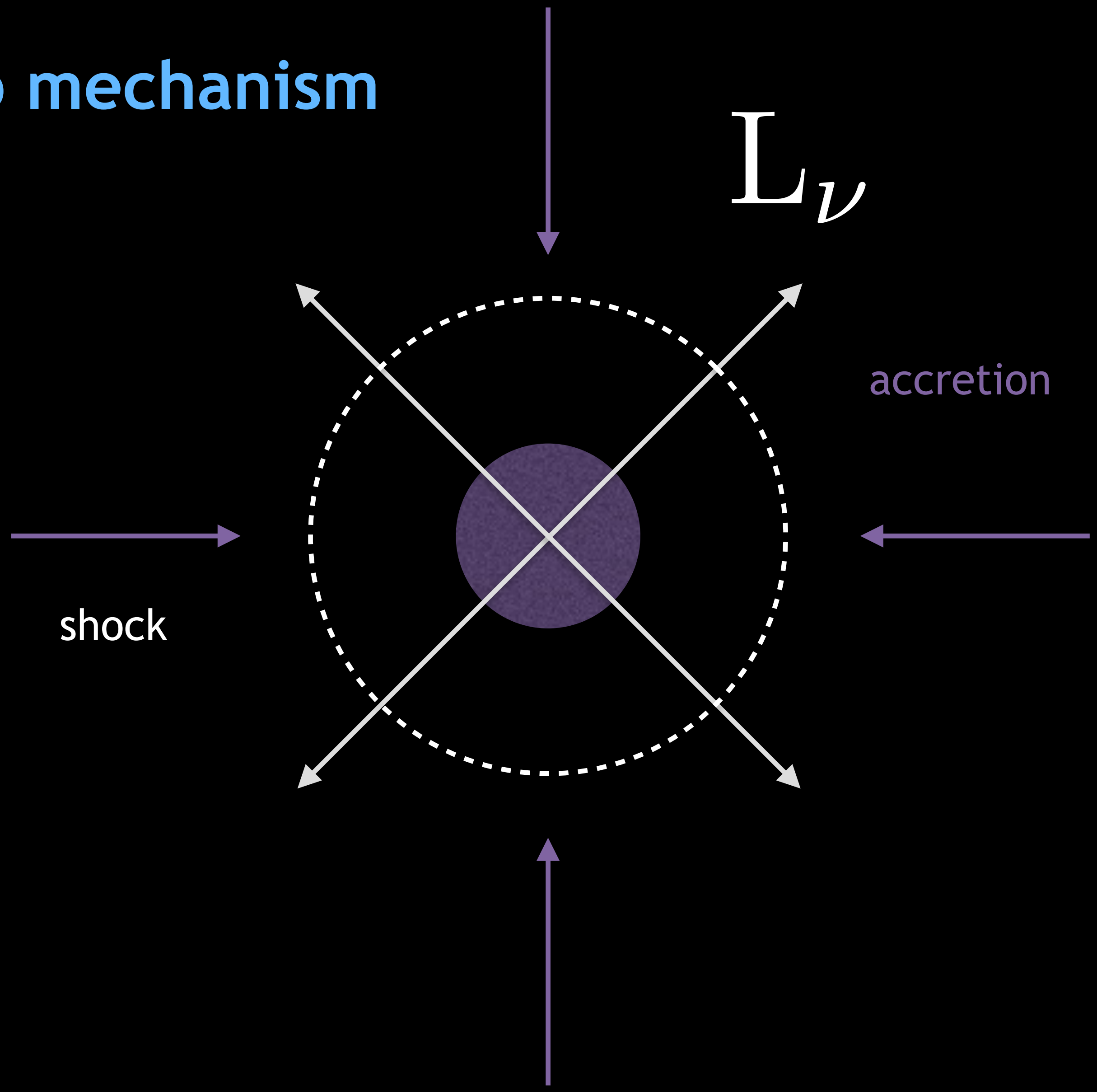


Core-collapse supernova problem:

How to revive the shockwave?

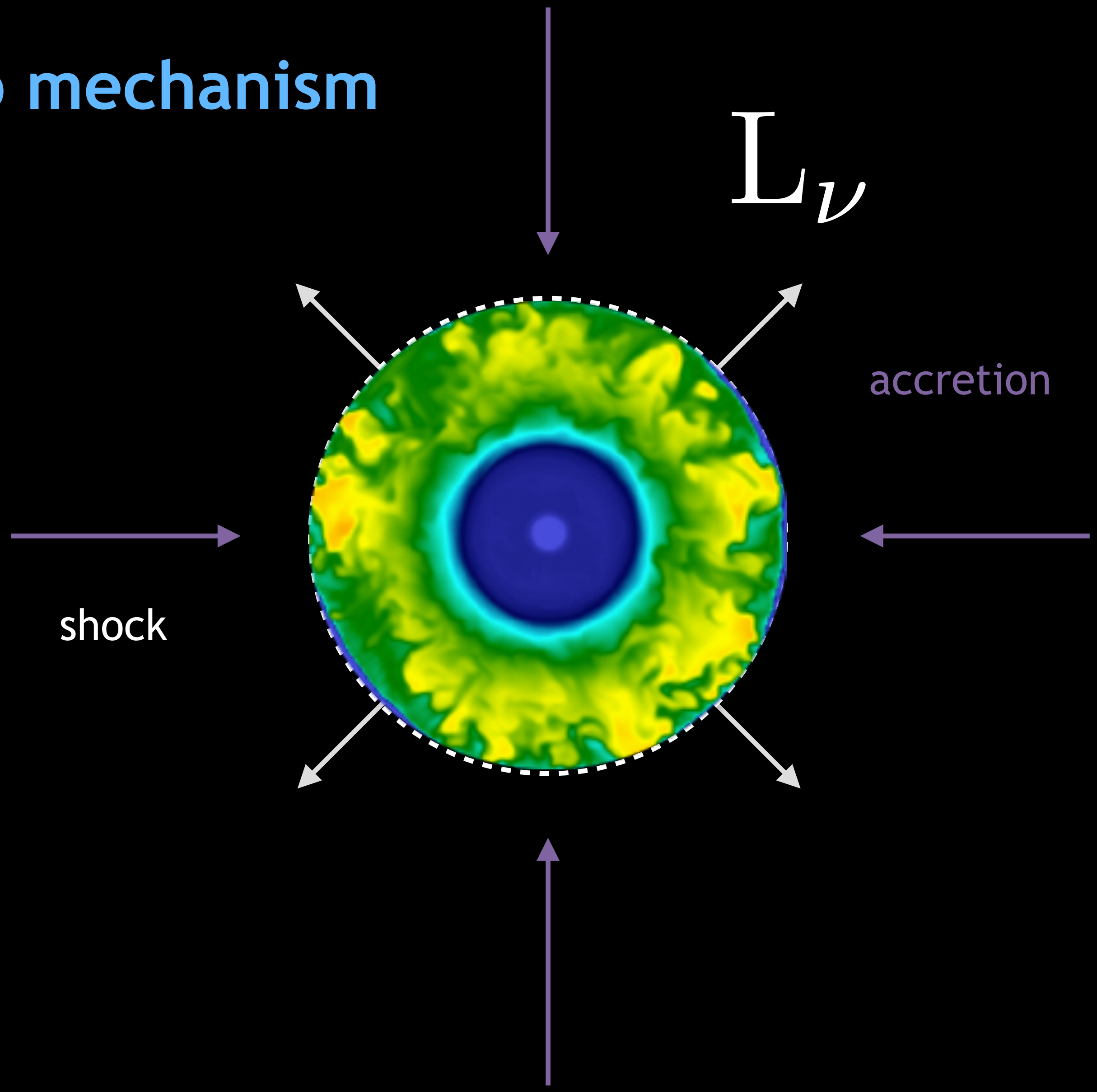
Core collapse basics

Neutrino mechanism



Core collapse basics

Neutrino mechanism



Core collapse basics

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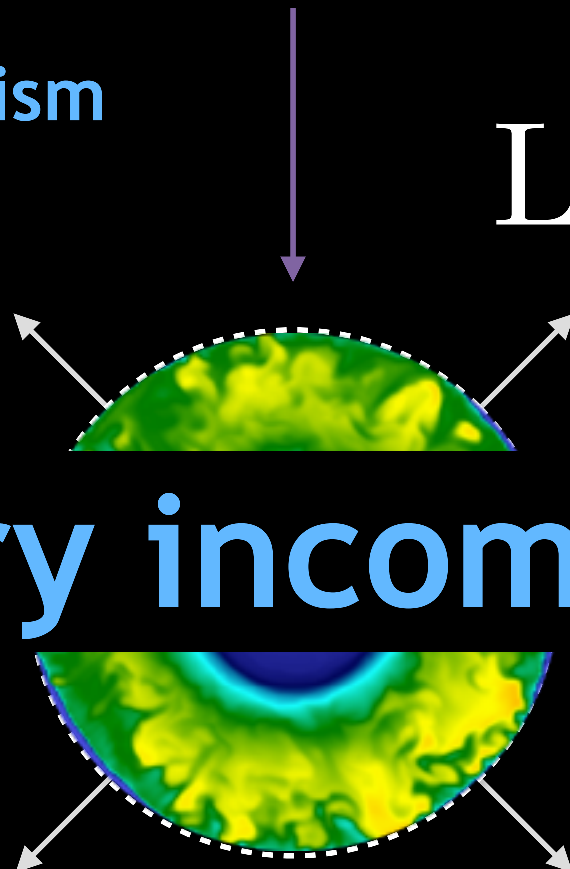
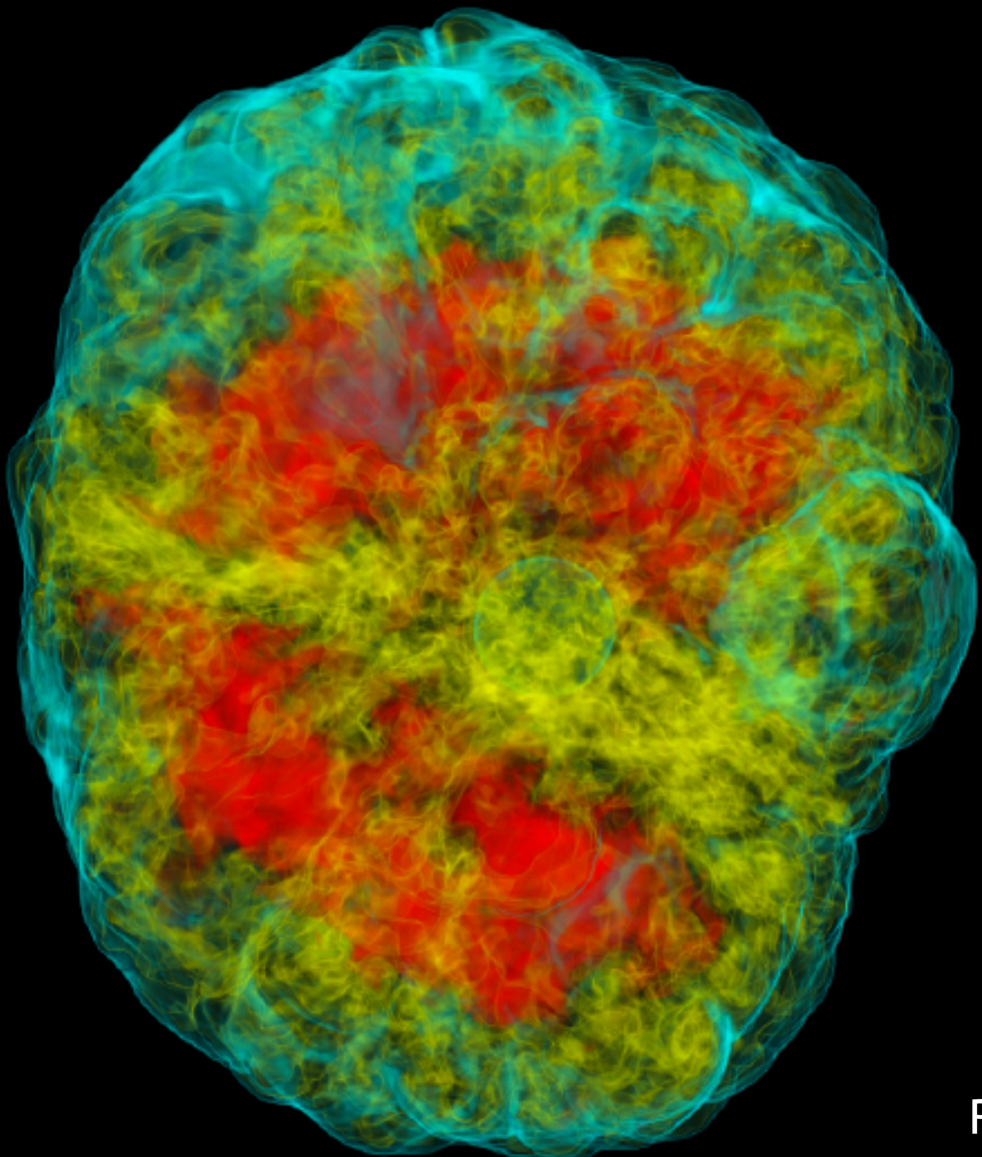


Theory incomplete!

Core collapse basics

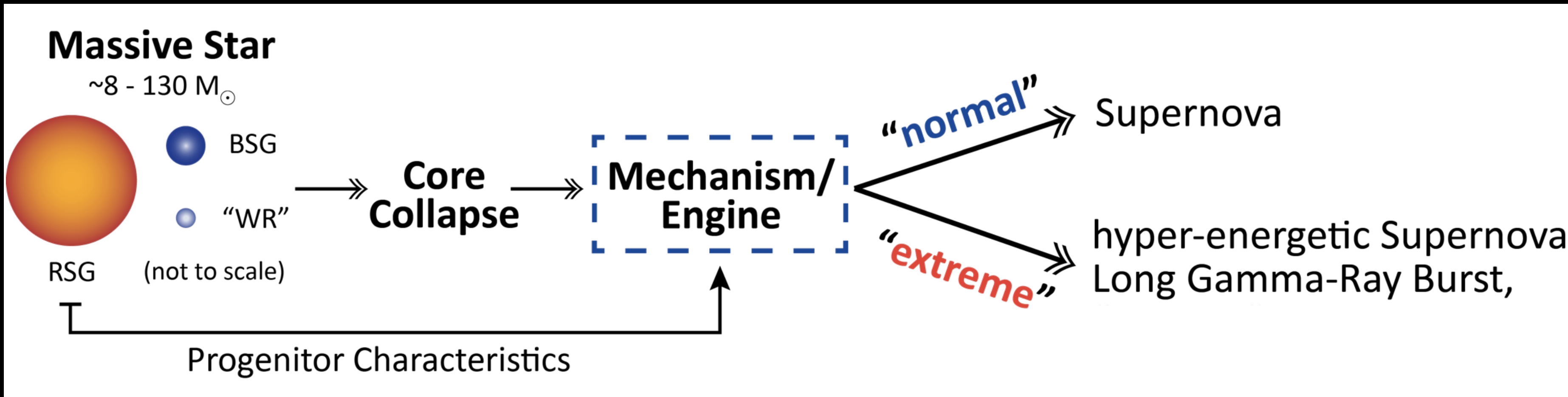


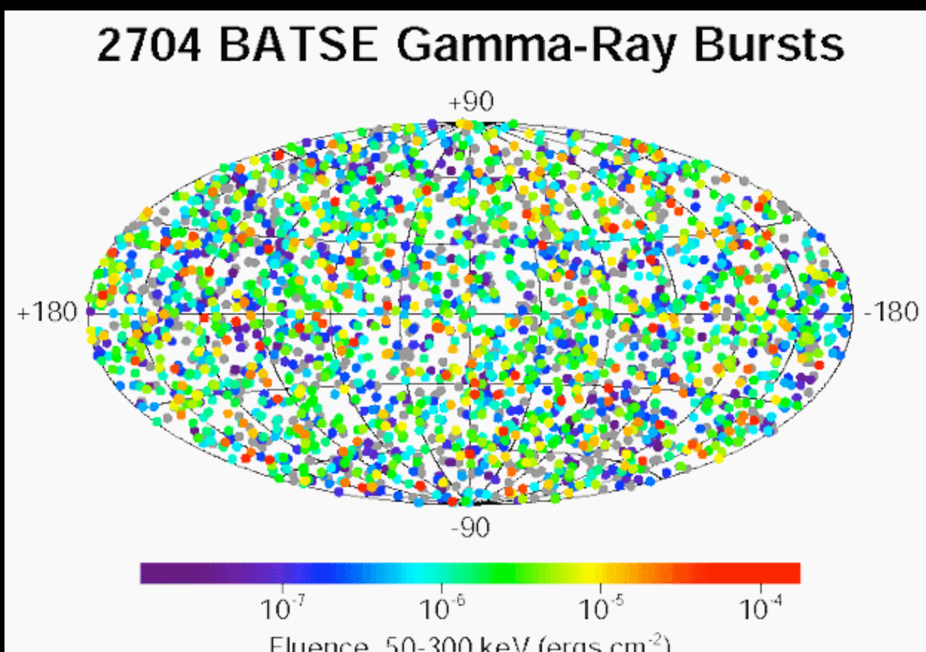
3D Volume
Visualization of

Entropy

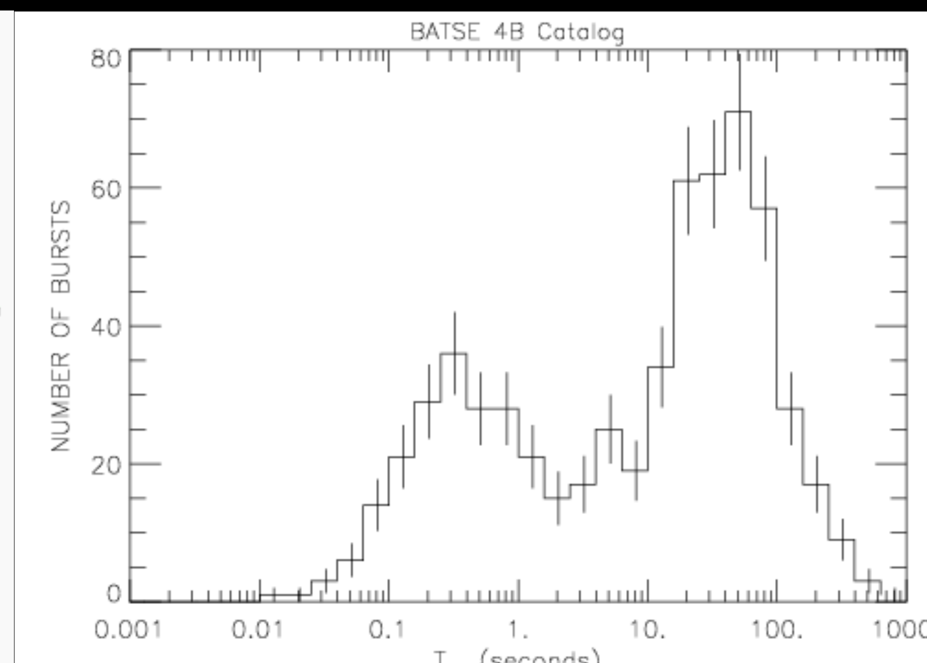
Roberts+16

Hypernovae & GRBs

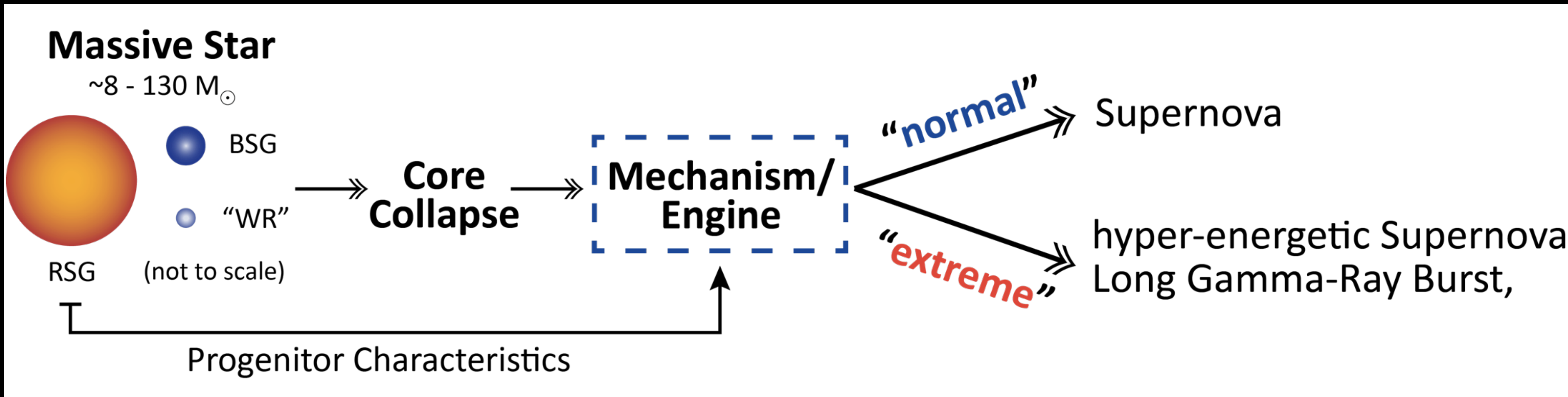




http://apod.nasa.gov/apod/ap000628.html

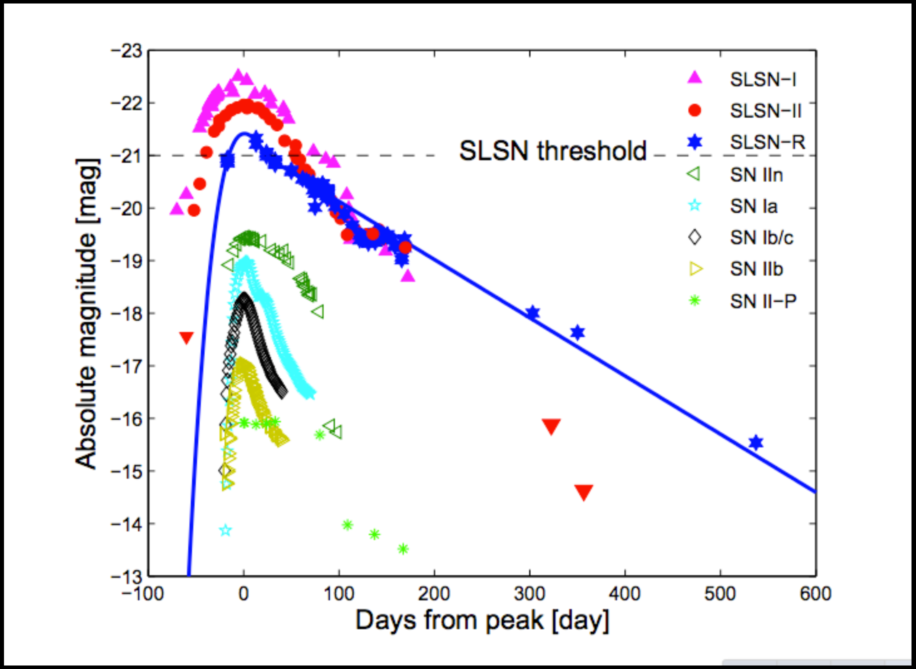


Extreme Supernovae and GRBs



- 11 long GRB – core-collapse supernova associations.
- **All GRB-SNe are stripped envelope, show outflows v~0.1c**
- But not all stripped-envelope supernovae come with GRBs
- Trace low metallicity environments
- Some SLSNe share same characteristics

Superluminous supernovae



Gal-Yam+12

Some events:

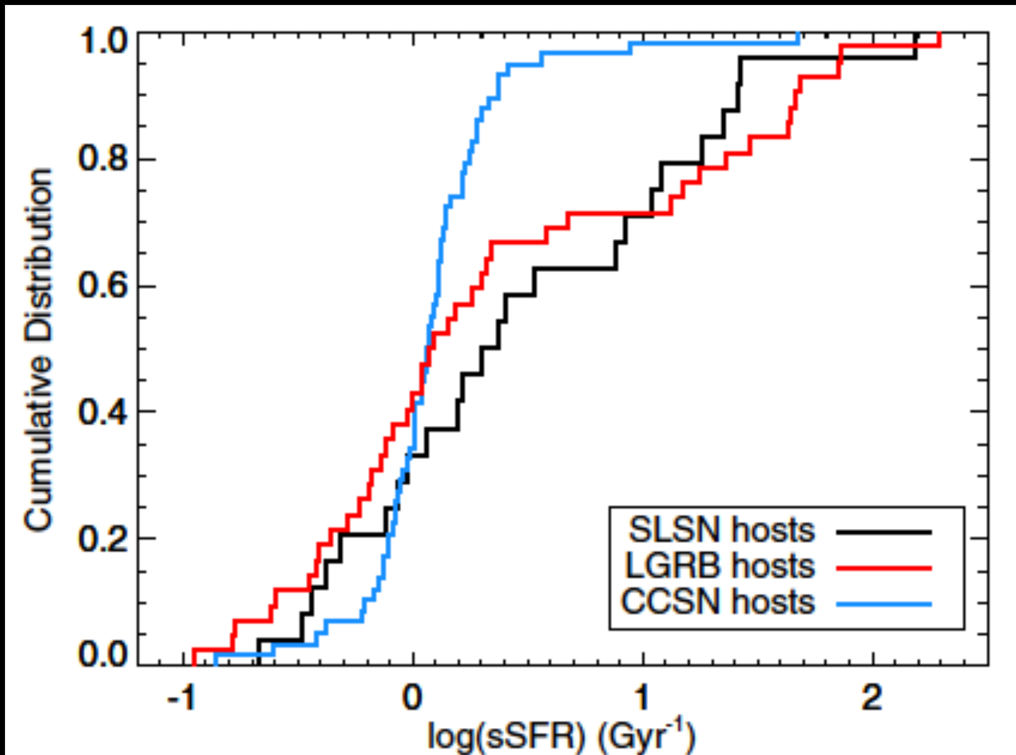
stripped envelope

no interaction

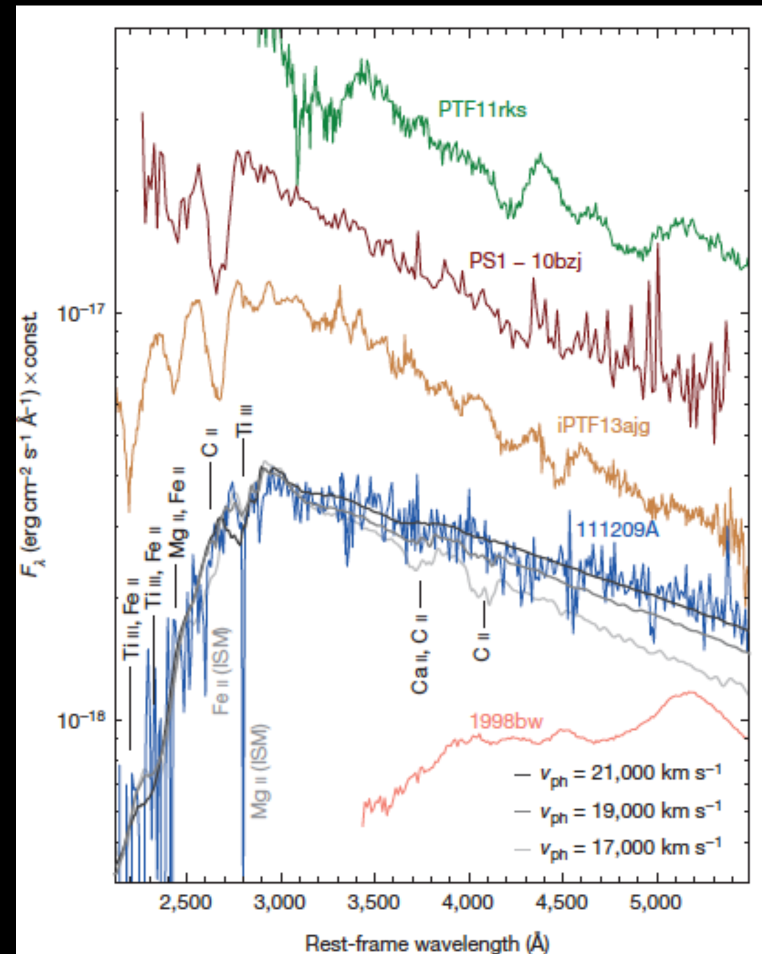
E_{lum} ~ 10^{45} erg

E_{rad} up to 10^{52} erg

Superluminous supernovae



Lunnan+14

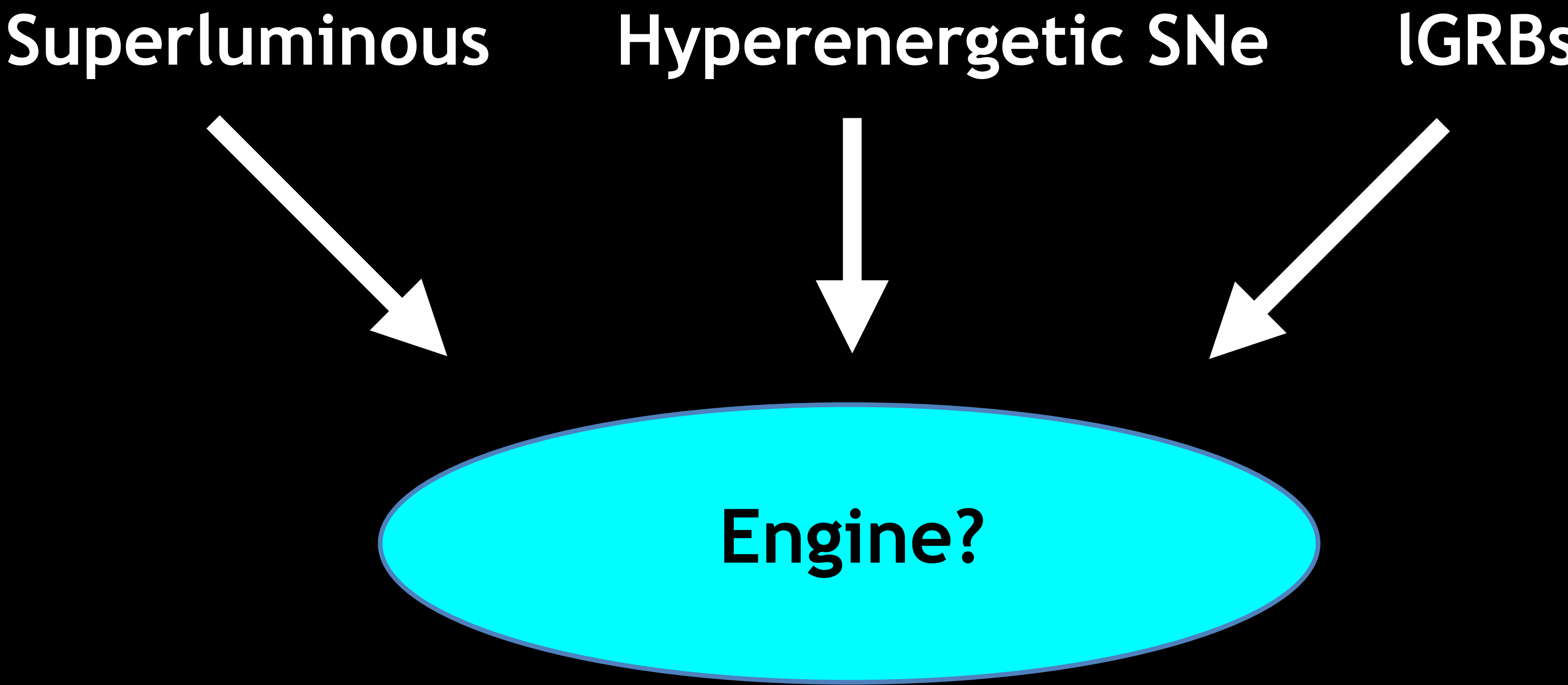


Greiner+15

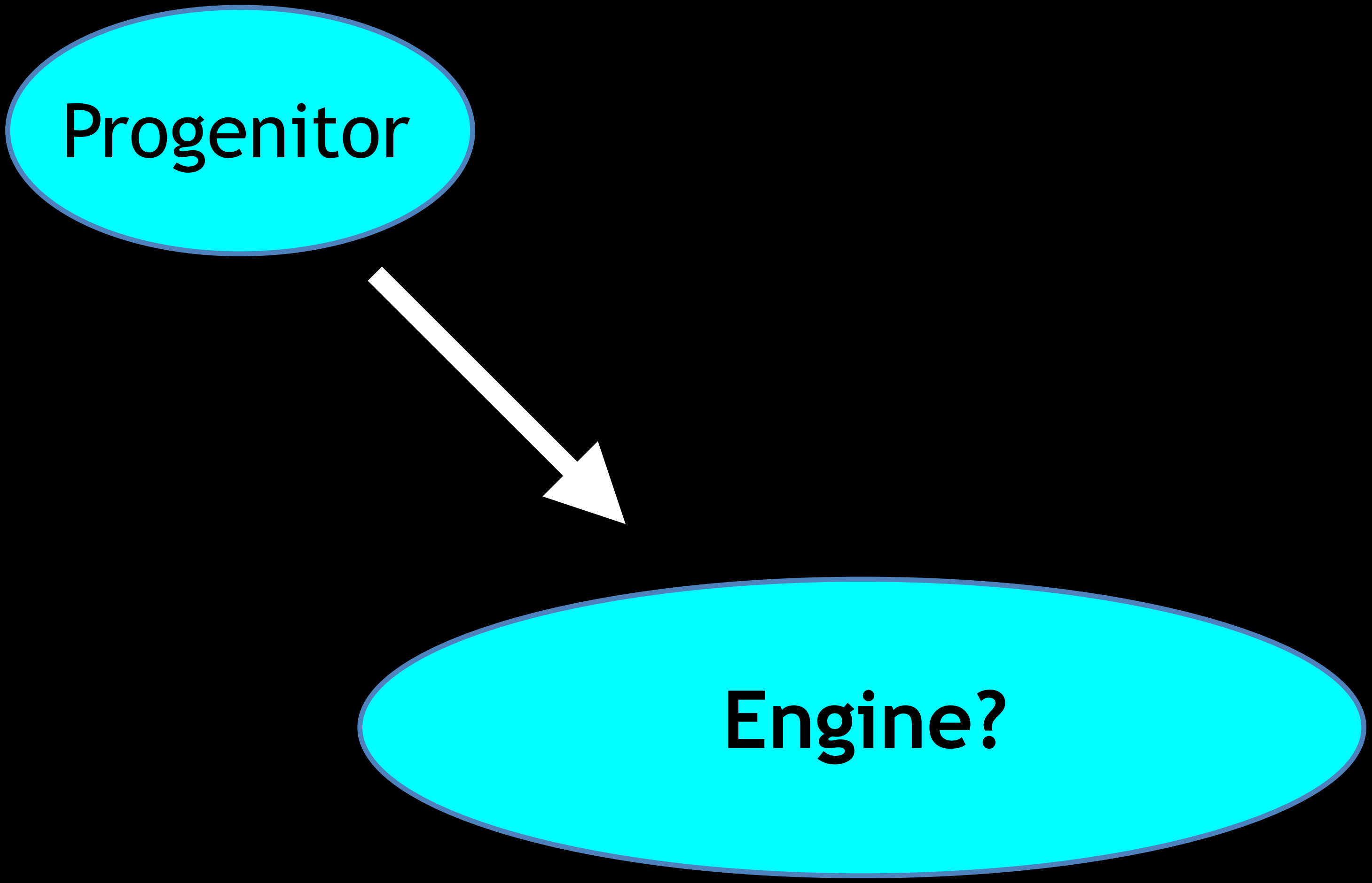
Connection between SLSN Ic and lGRBs

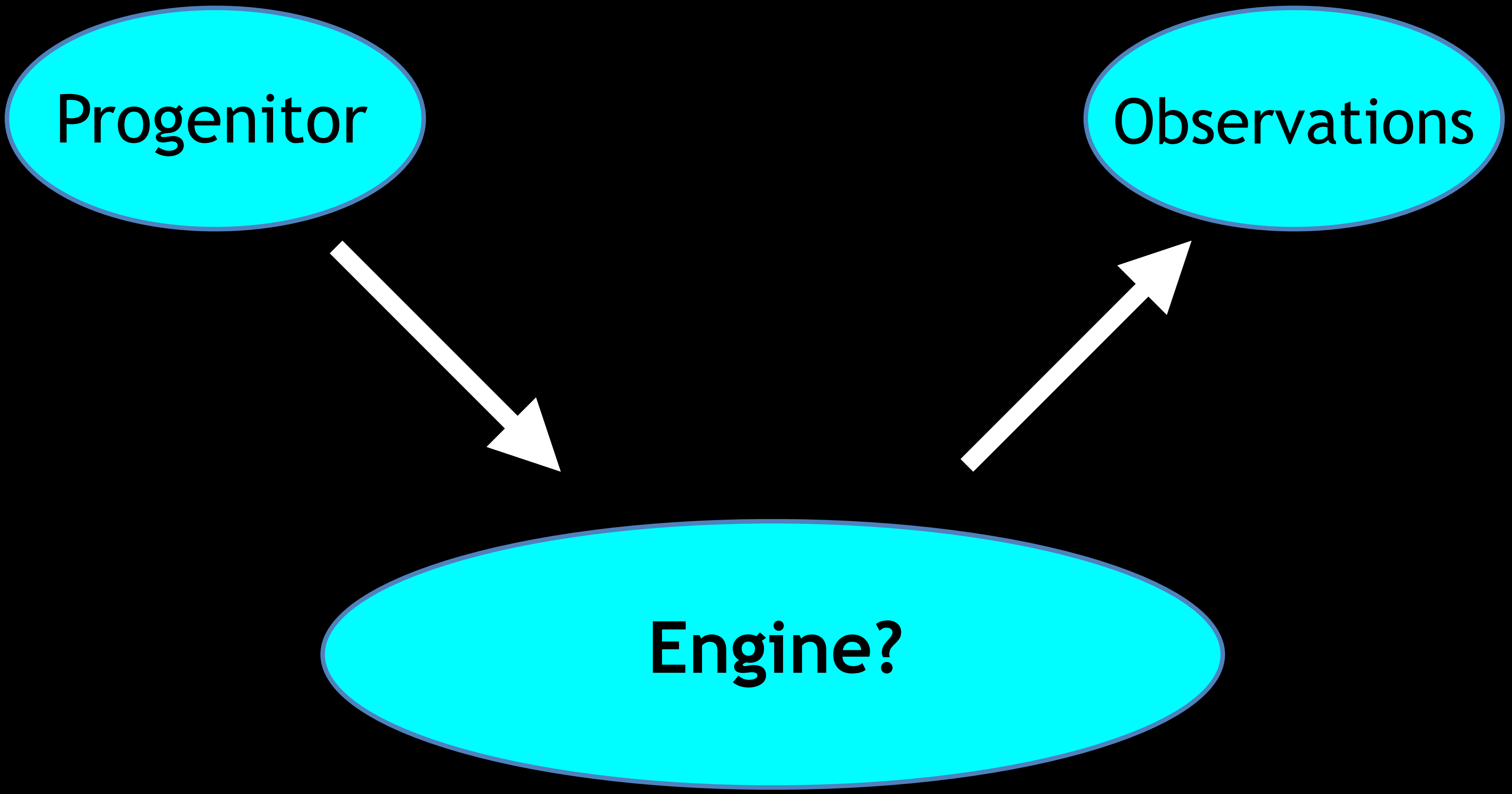
- prefer star-forming galaxies
- low metallicity
- large core angular momentum !?

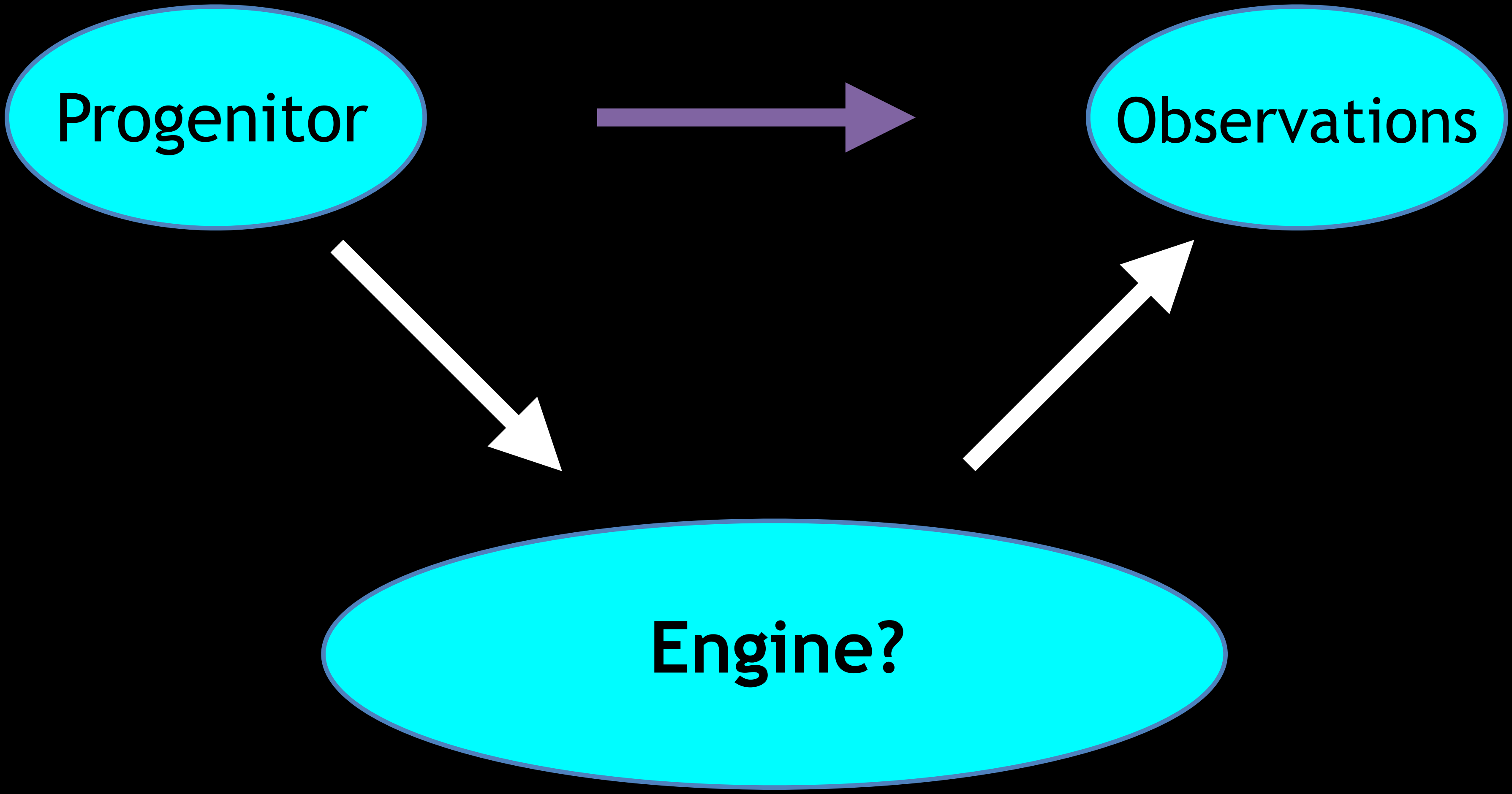
The engine(s) driving these transients



Engine?


Progenitor
Engine?


Progenitor
Observations
Engine?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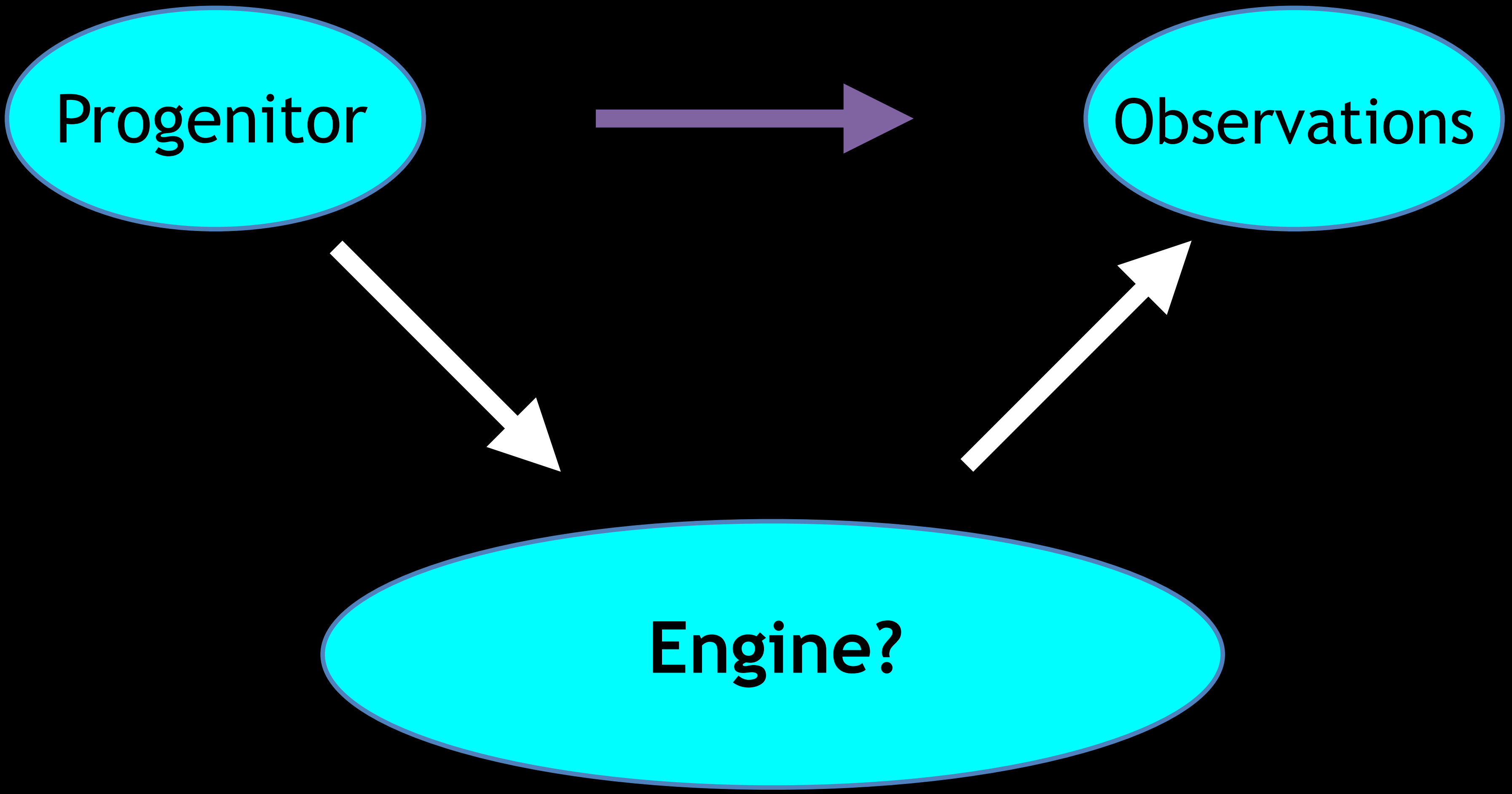
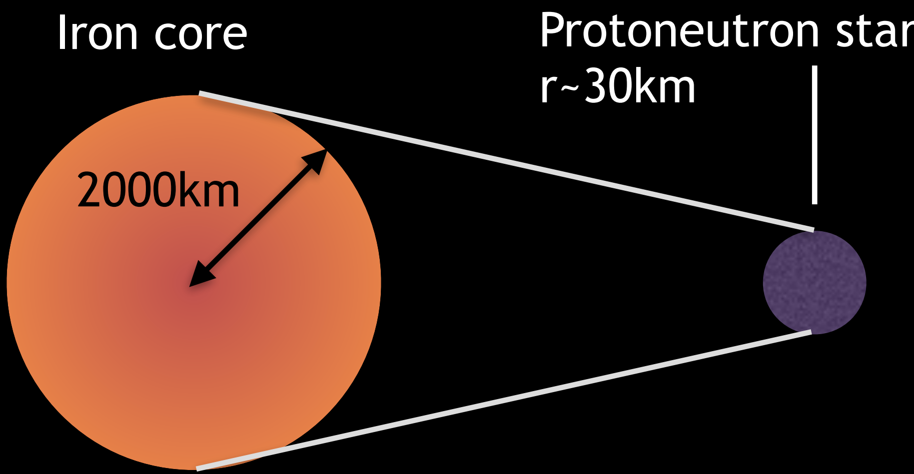


Establish mapping

progenitor -> engine -> observations

Core collapse basics



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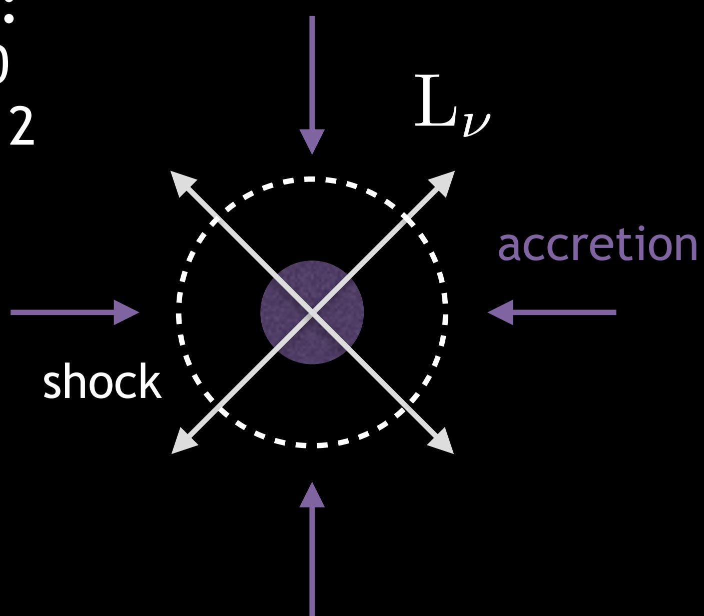

Engine formation?

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

MHD-supernova vs collapsar

MHD-supernova / magnetorotational supernova: outflows driven by protomagnetar

MHD-supernova vs collapsar

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Collapsar: Compact object (likely black hole) + accretion disk -> outflows driven by disk wind

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Two different engines with different signatures!

MHD-supernova vs collapsar

MHD-supernova / magnetorotational supernova: outflows driven by protomagnetar

Collapsar: Compact object (likely black hole) + accretion disk -> outflows driven by disk wind

Two different engines with different signatures!

Could be realized in same progenitor system but at different times

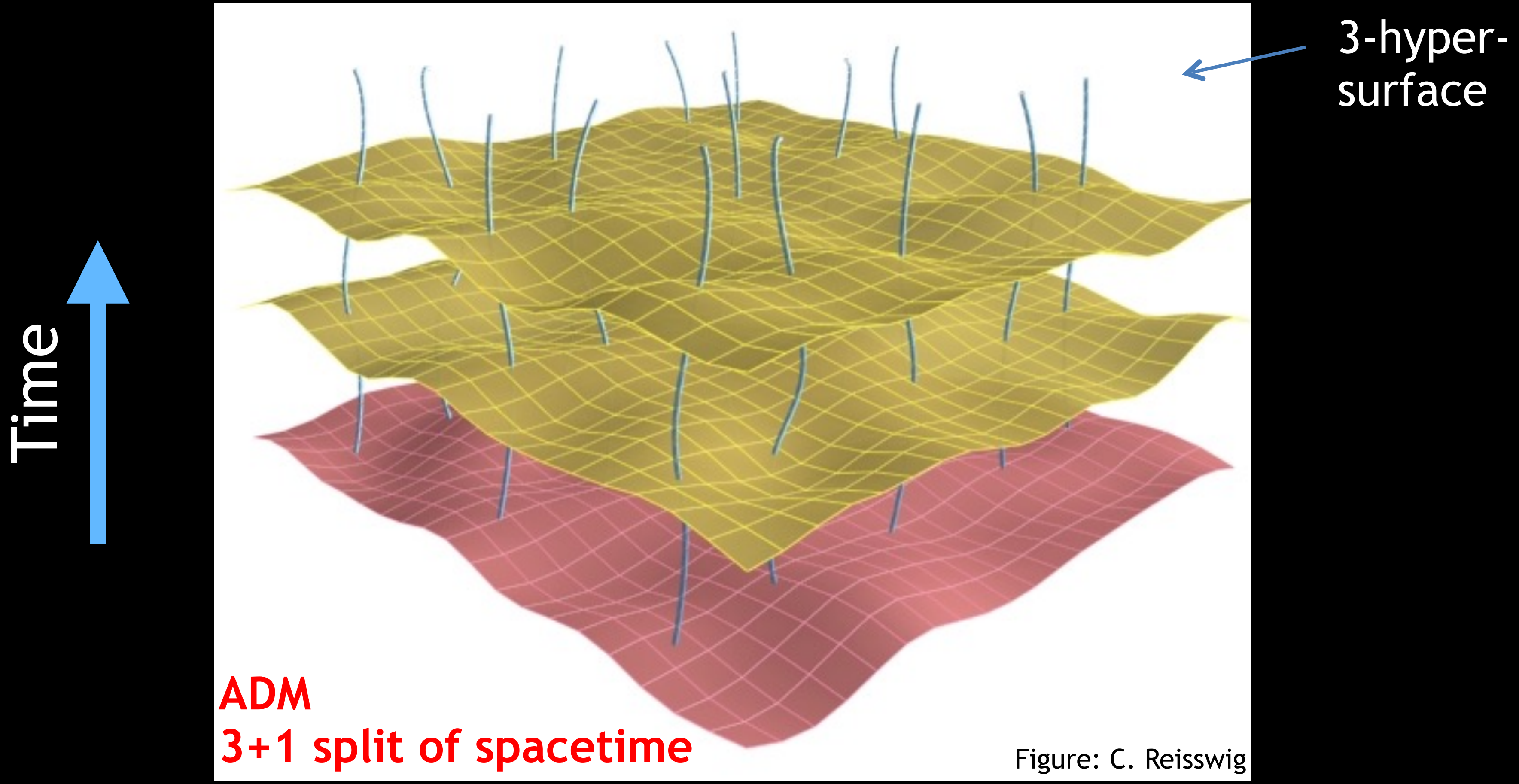
A multiphysics challenge

Magneto-Hydrodynamics → Gas/plasma dynamics

A multiphysics challenge

Magneto-Hydrodynamics	→	Gas/plasma dynamics
General Relativity	→	Gravity

Dynamical gravity / Numerical Relativity



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

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

A multiphysics challenge

Magneto-Hydrodynamics	→ Gas/plasma dynamics
General Relativity	→ Gravity
Nuclear and Neutrino Physics	→ **Nuclear EOS**, nuclear reactions & ν interactions

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A multiphysics challenge

Fully coupled!

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All four forces!

A multiphysics challenge

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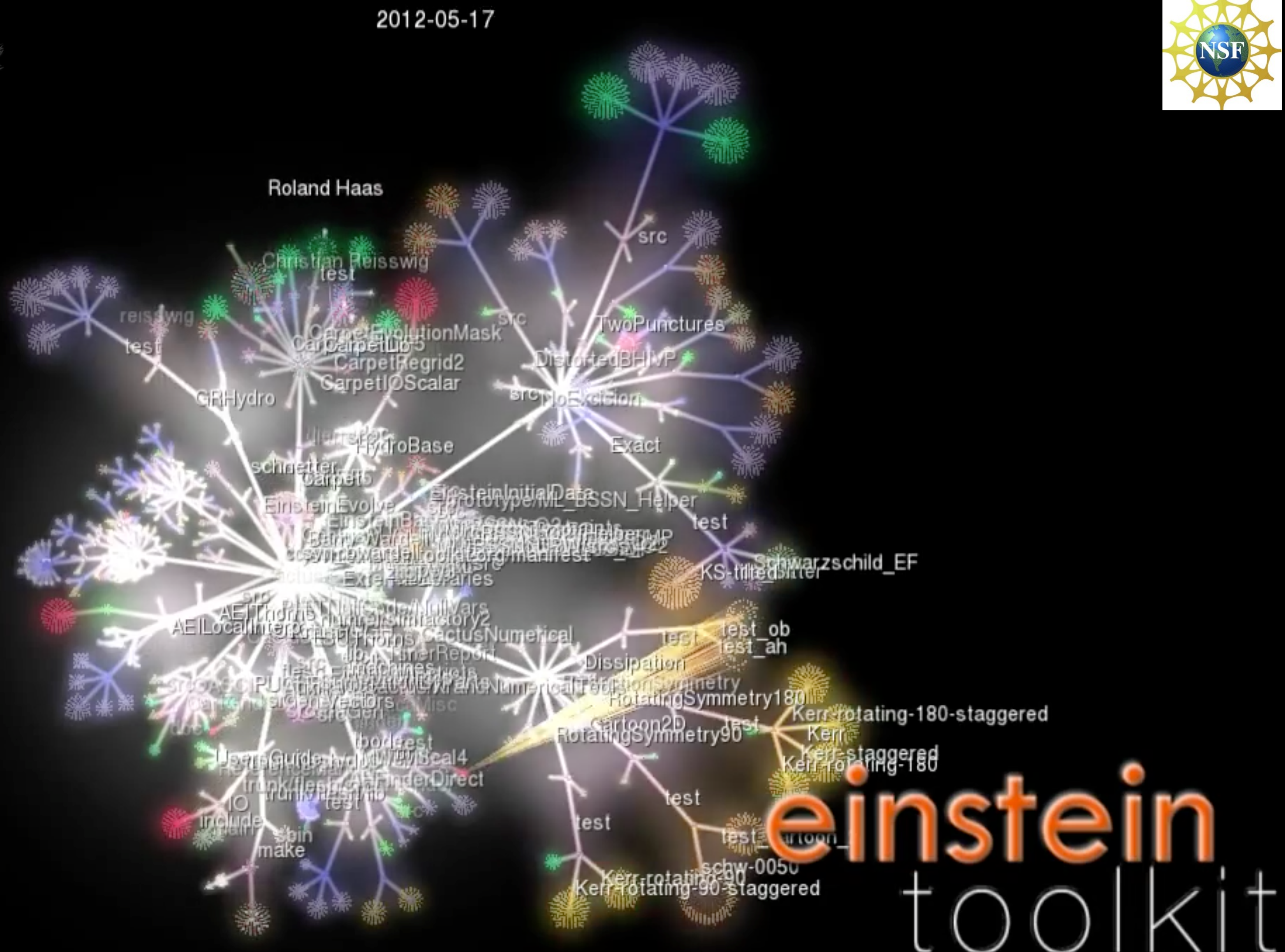
All four forces!

Additional Complication: Core-Collapse Supernovae are 3D

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

Need 21st century tools:

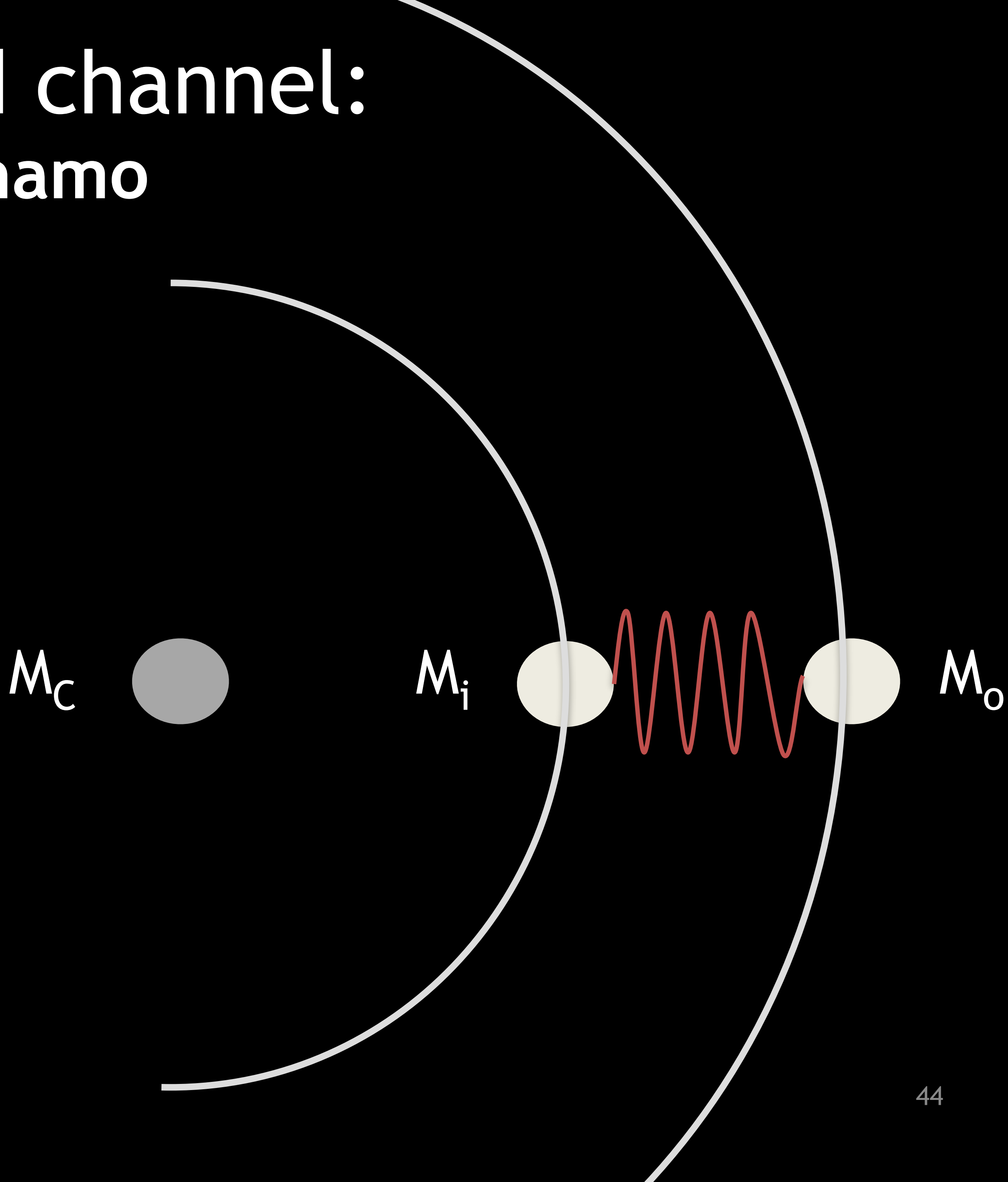
- cutting edge numerical algorithms
- sophisticated **open-source** software infrastructure
- peta/exa scale computers



http://einsteintoolkit.org

How do we form magnetars?

One proposed channel:
MRI + dynamo



MRI Basics

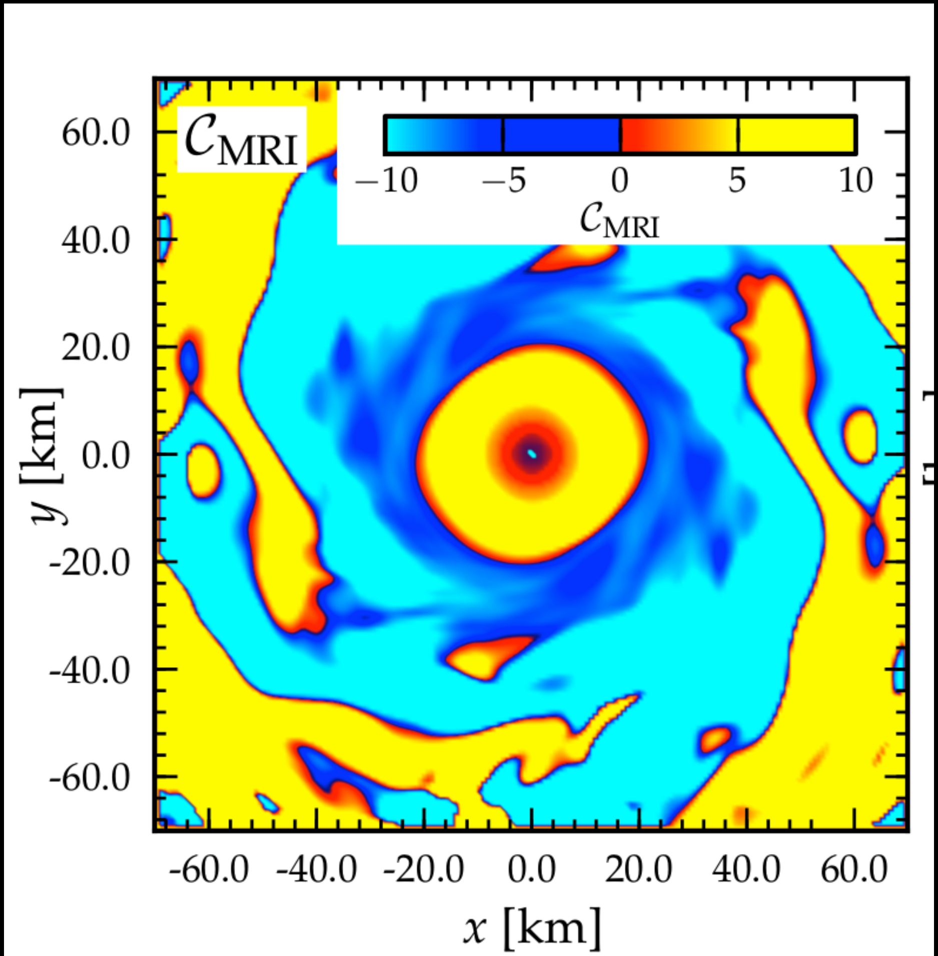
- Weak field instability
- Requires negative angular velocity gradient
- Can build up magnetic field exponentially fast
- Extensively researched in accretion disks: ability to modulate angular momentum transport and grow large scale field

What's the situation in core-collapse?

Stability criterion:

$$-8\Omega^2 < \omega_{\rm BV}^2 + r\frac{d\Omega^2}{dr} < 0$$

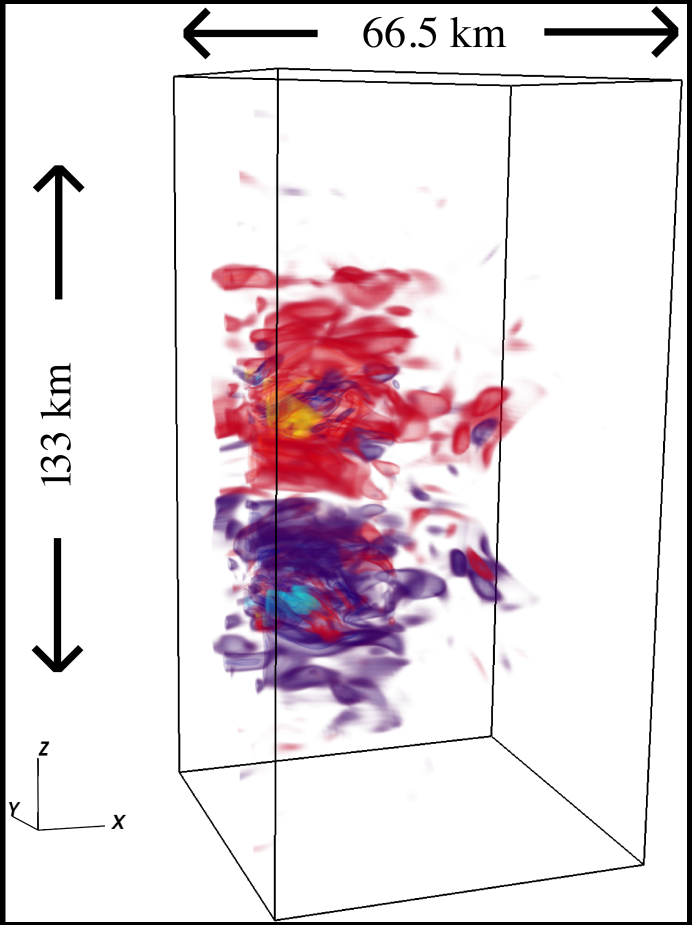
[Balbus&Hawley 91,98, Akiyama+03, Obergaulinger+09]



Global 3D MHD turbulence simulations

- 10 billion grid points (Millenium simulation used 10 billion particles)
- 130 thousand cores on Blue Waters
- 2 weeks wall time
- 60 million compute hours
- 10000 more expensive than any previous simulations

Do MRI and dynamo build up dynamically relevant global field?



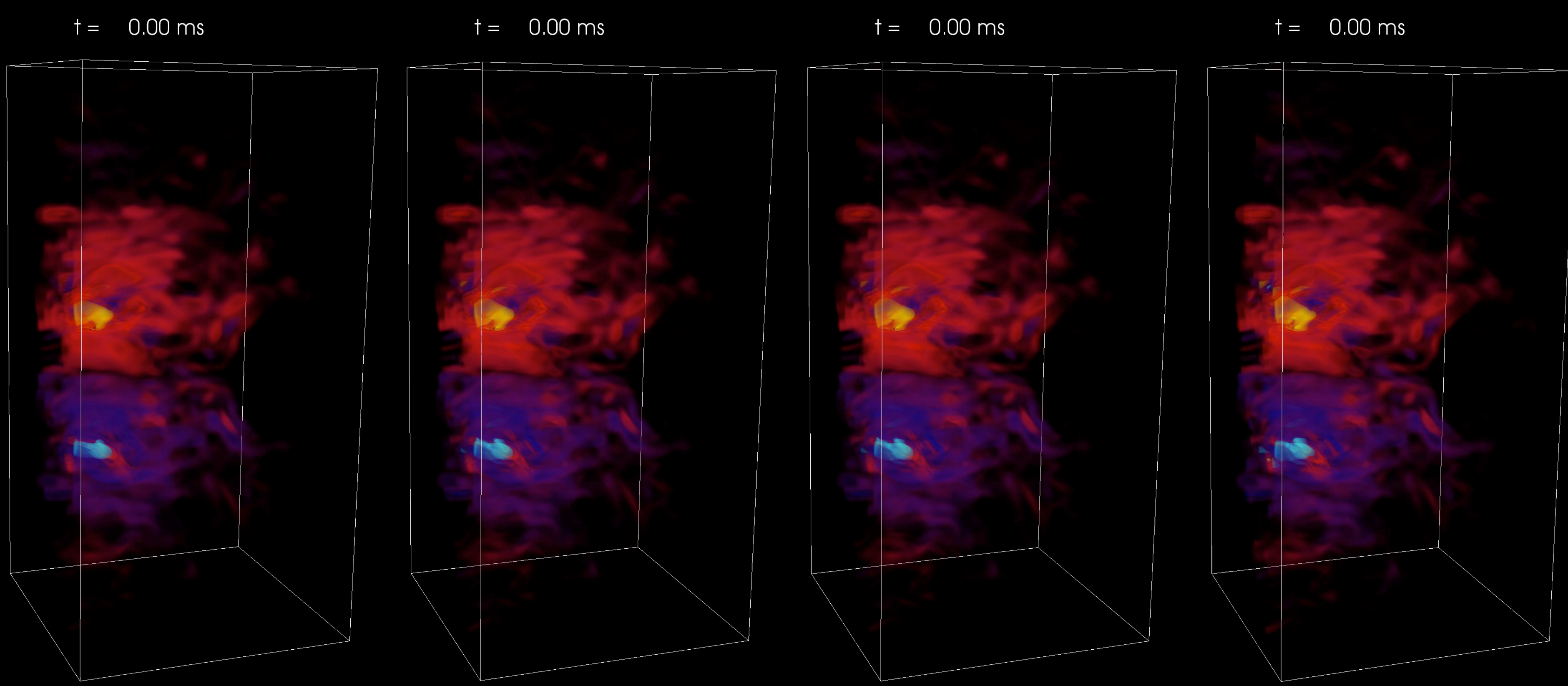
PM+ 15 Nature

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

NSF

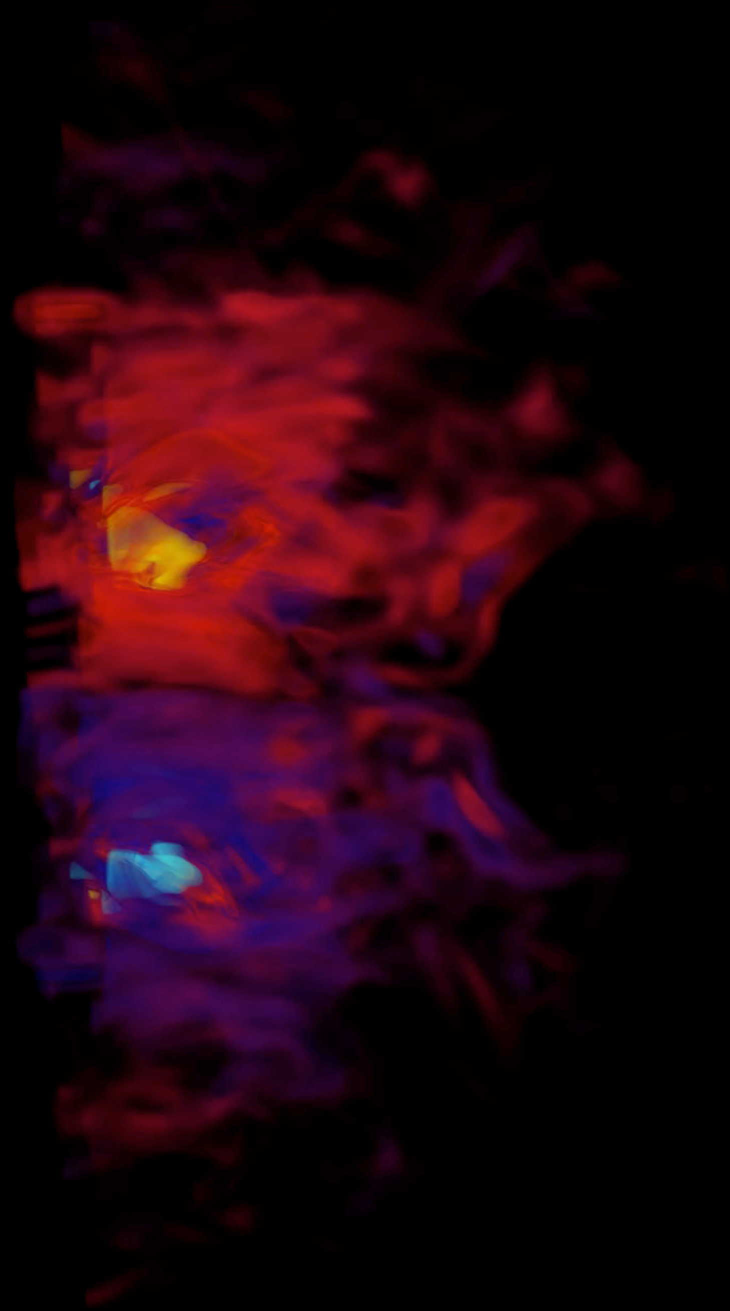
3D magnetic field structure

dx=500m dx=200m dx=100m dx=50m



PM+ 15 Nature

BLUE WATERS
SUSTAINED PETASCALE COMPUTING
NSF



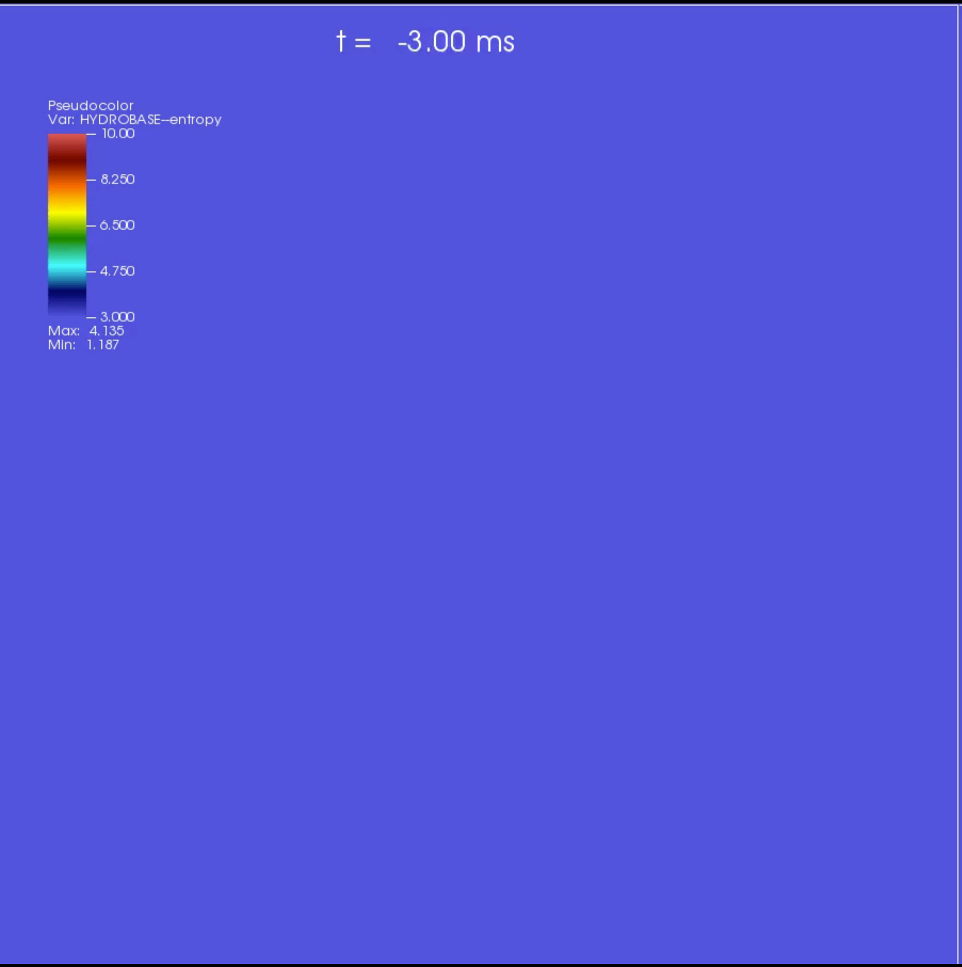
PM+15 Nature

R-process nucleosynthesis in magnetar-driven explosions

3D explosions dynamics very different!

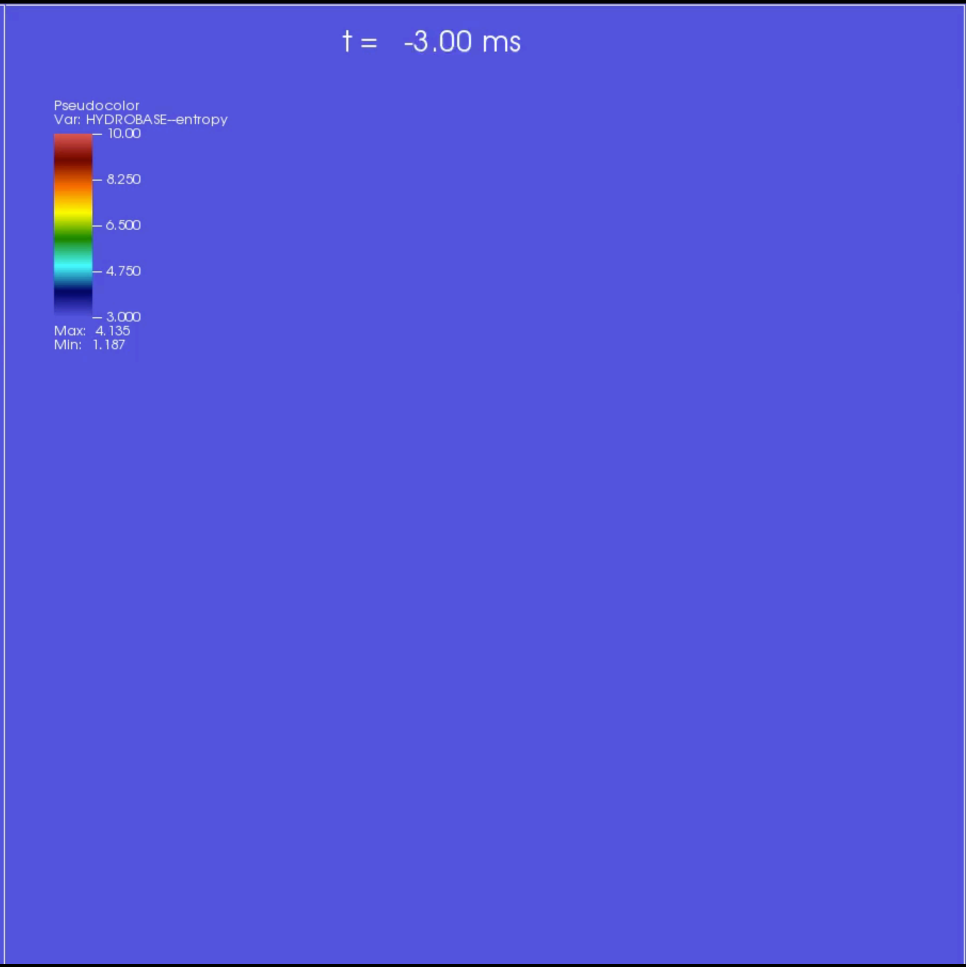
PM+ 14

← 2000 km →



Octant Symmetry (no odd modes) identical to 2D

← 2000 km →

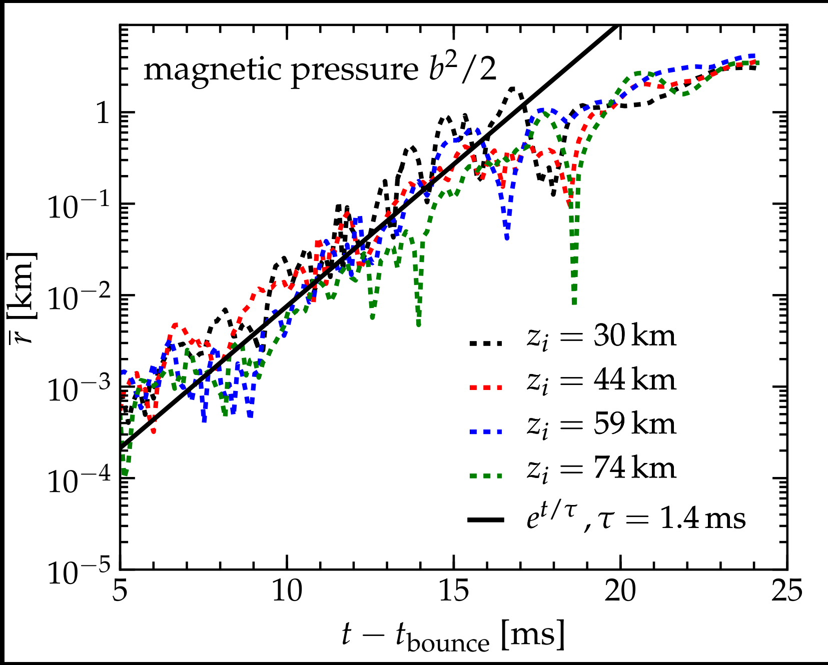


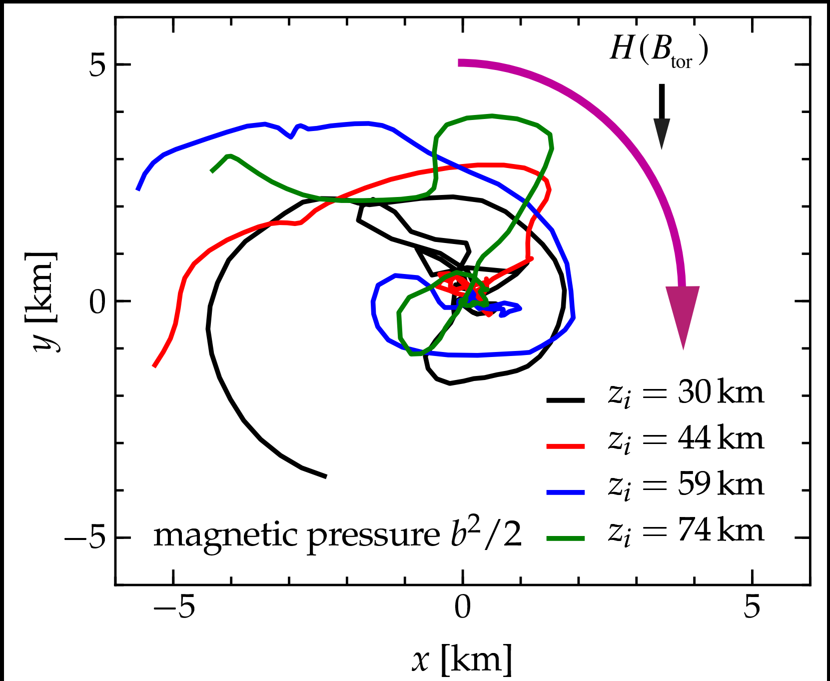
Full 3D

What's going on here?

PM, Richers+ 14

with Sherwood Richers (Caltech)





- m=1 spiral instability
- consistent with MHD kink instability; should hold independent of initial B-field strength

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

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

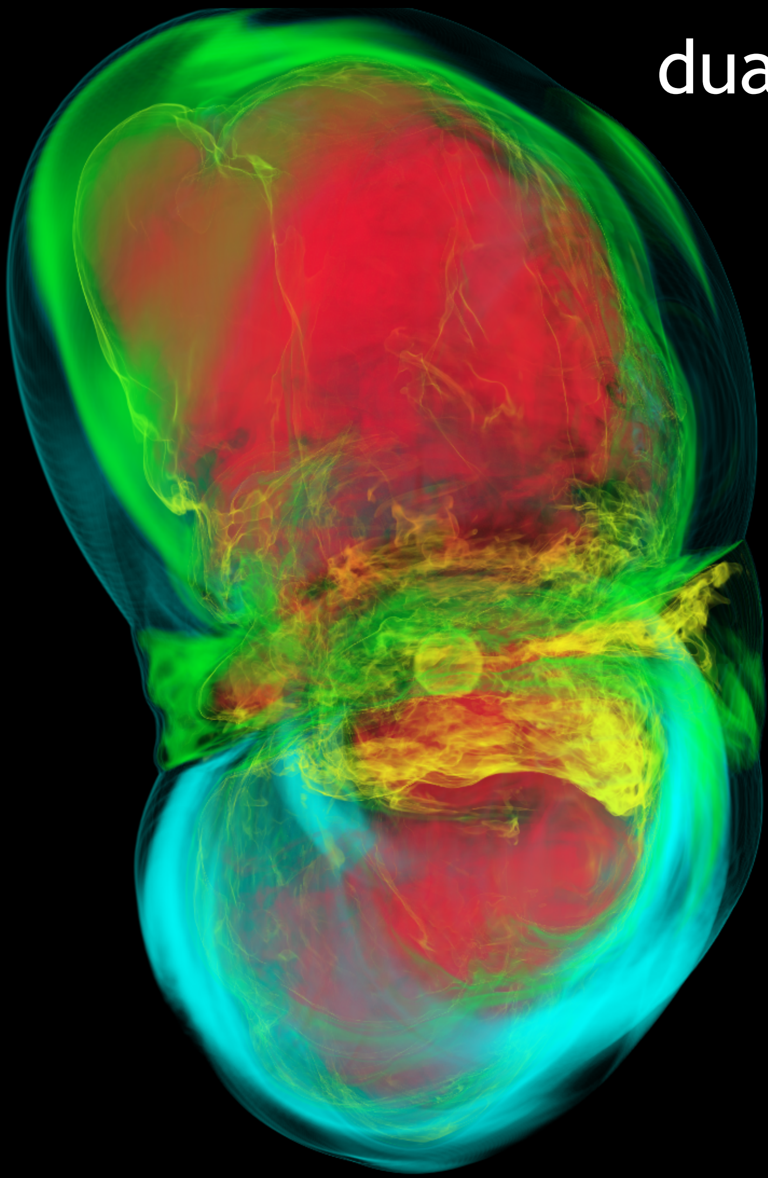
3D Volume Visualization of

Entropy

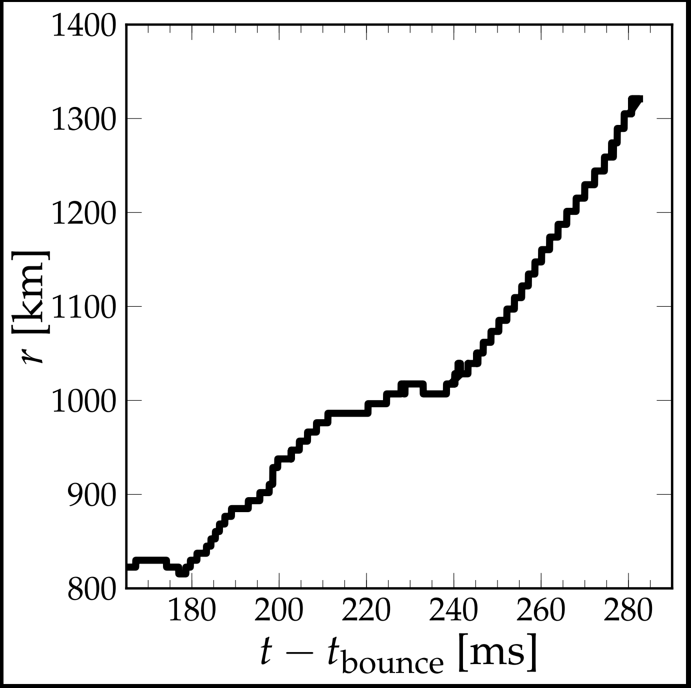
PM+ 14

t = -3.00 ms

Implications for long Gamma-Ray Bursts



dual-lobe 'slow' explosion



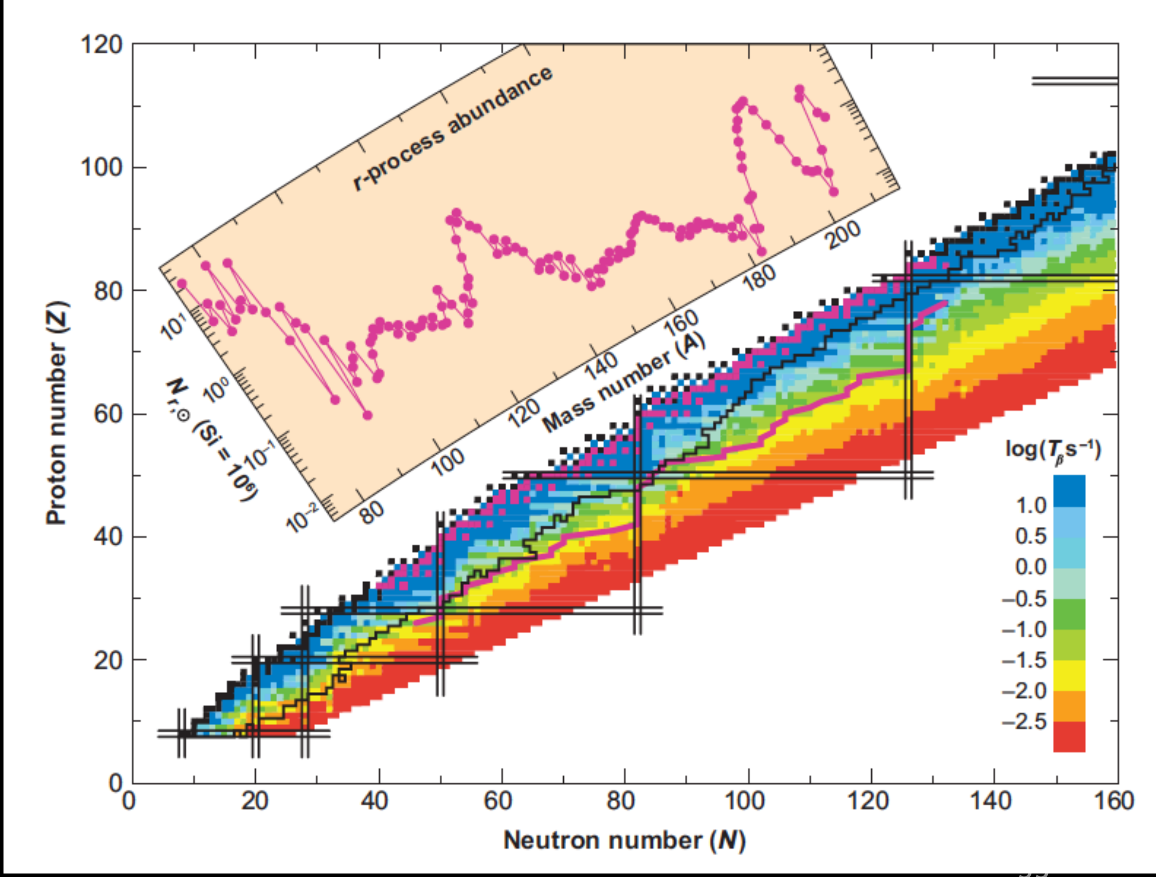
Continued accretion -> Black hole engine possible!

PM+ 18

Neutron-rich nucleosynthesis in supernovae
Creating the heaviest elements

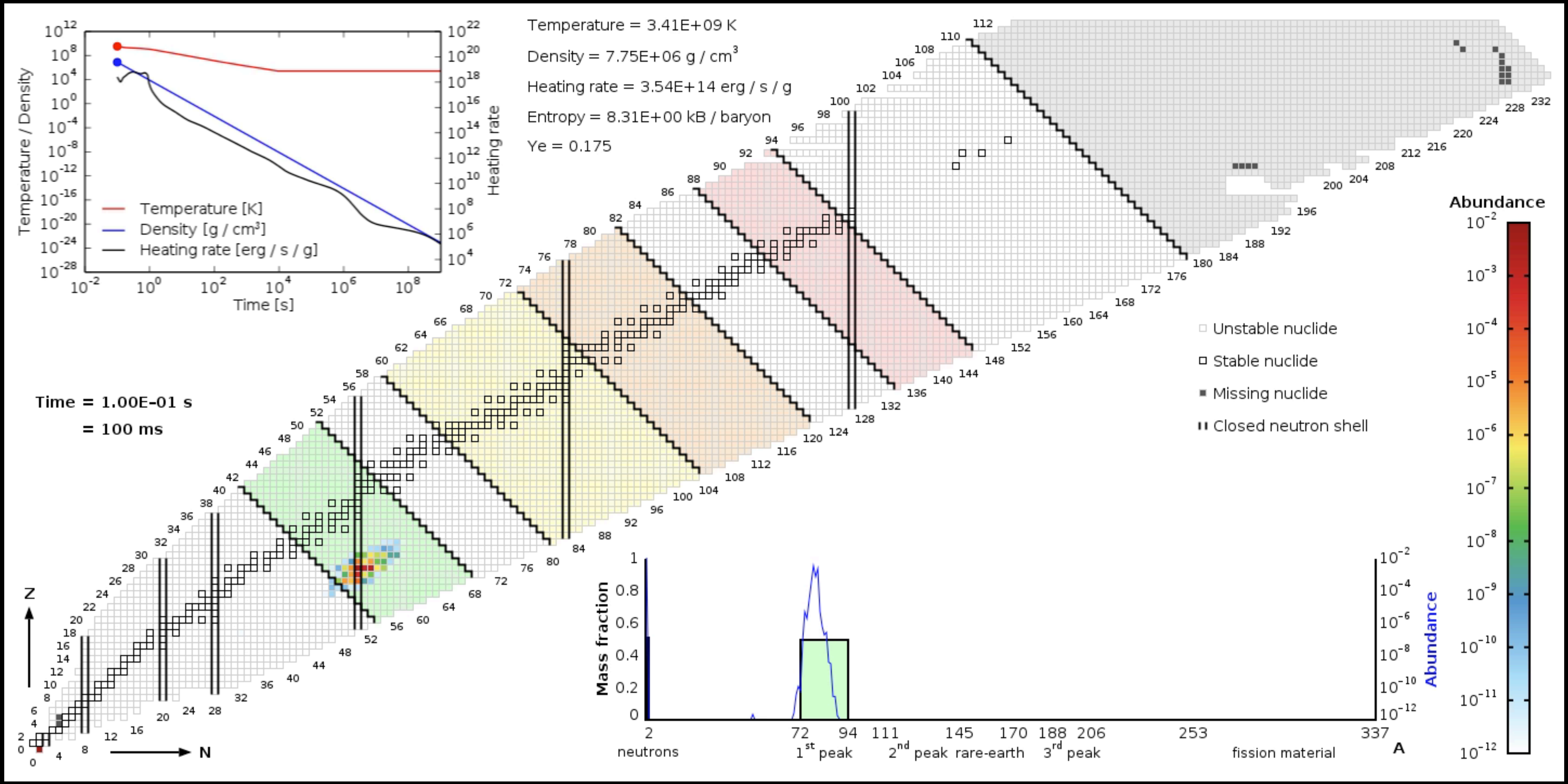
Jet-driven explosions proposed as site for r-process

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



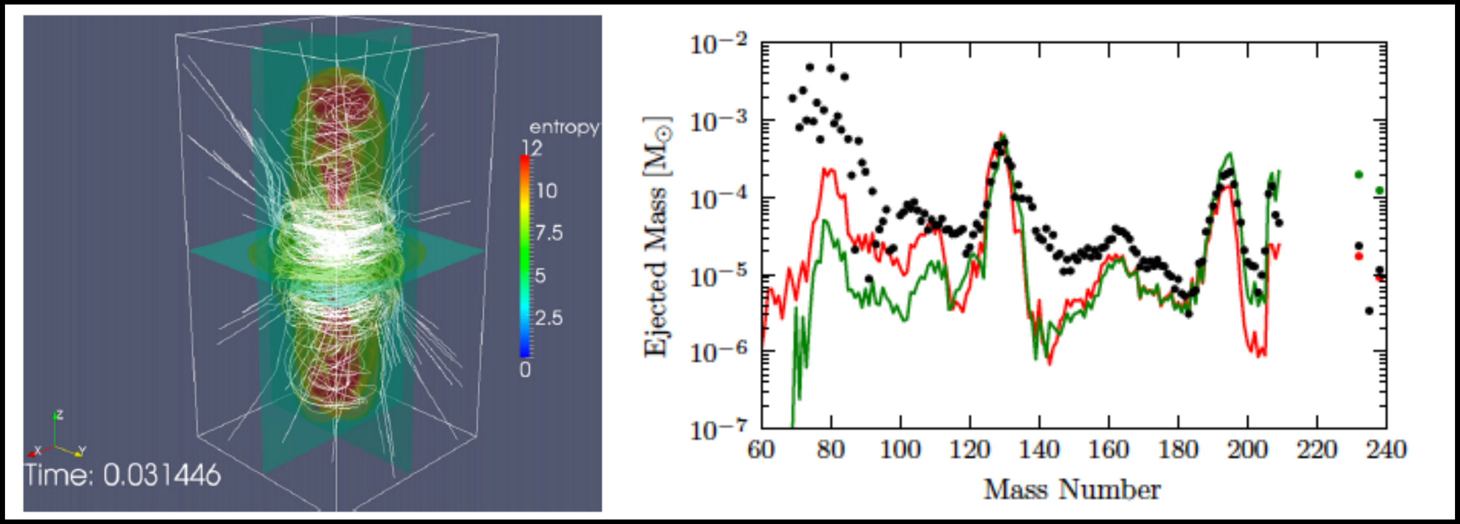
Sneden+ 08

Making the heaviest elements

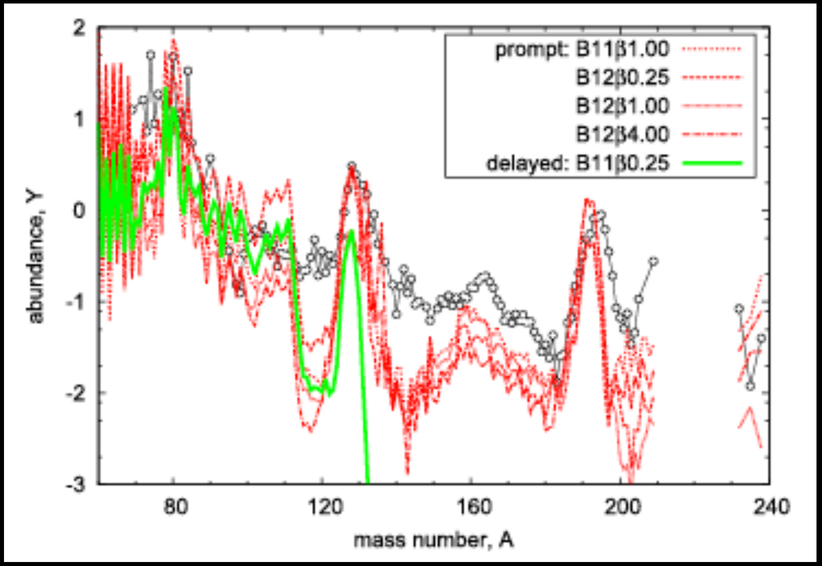


PM+ 18
Halevi, PM+ 18

R-process in jet-driven supernovae



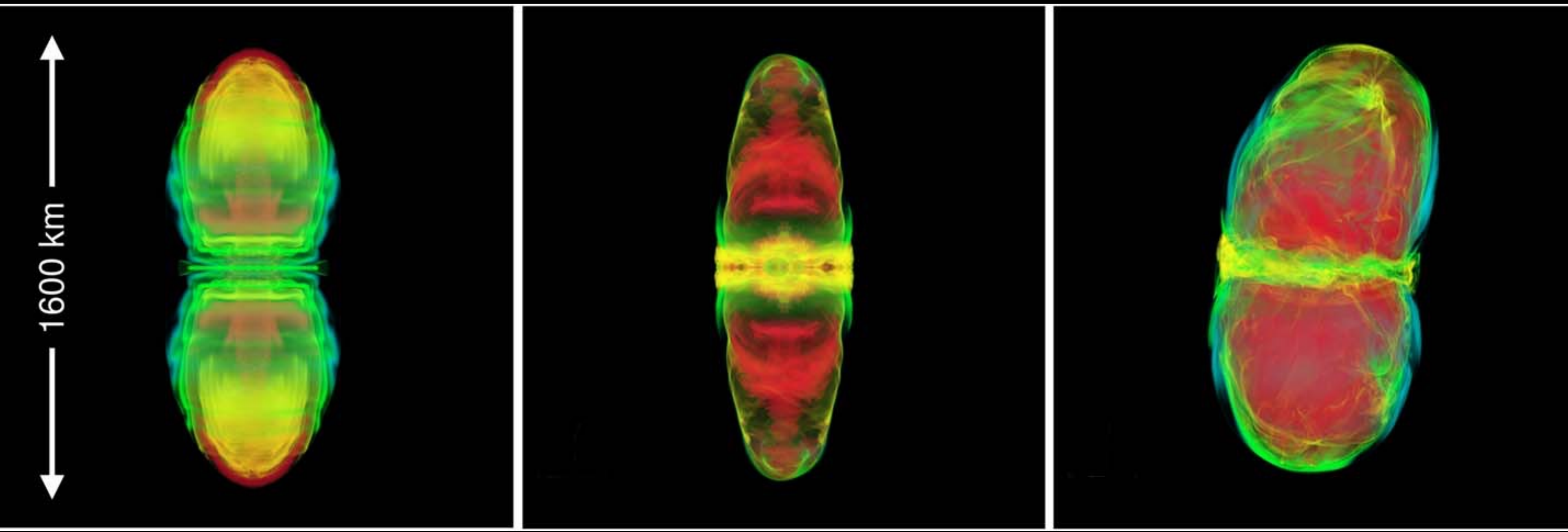
Winteler+12



Nobuya's talk yesterday!

Nishimura+15

R-process in jet-driven supernovae

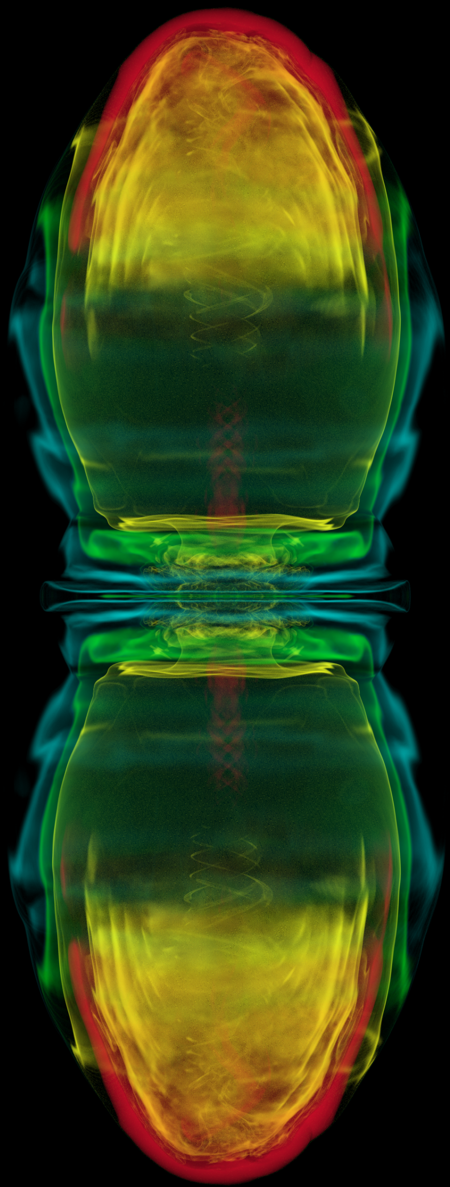


B = 10^{13} G full 3D   B = 10^{12} G octant   B = 10^{12} G full 3D

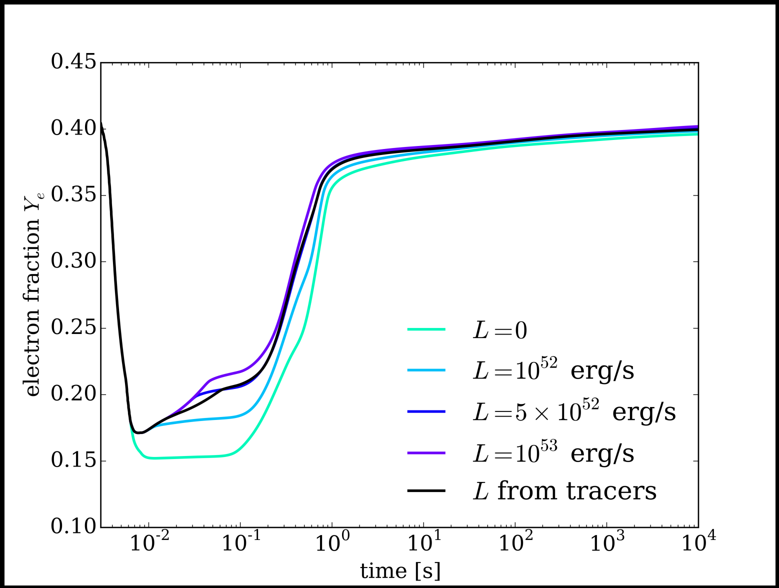
PM+ 18

R-process nucleosynthesis in supernovae

B = 10^{13} G

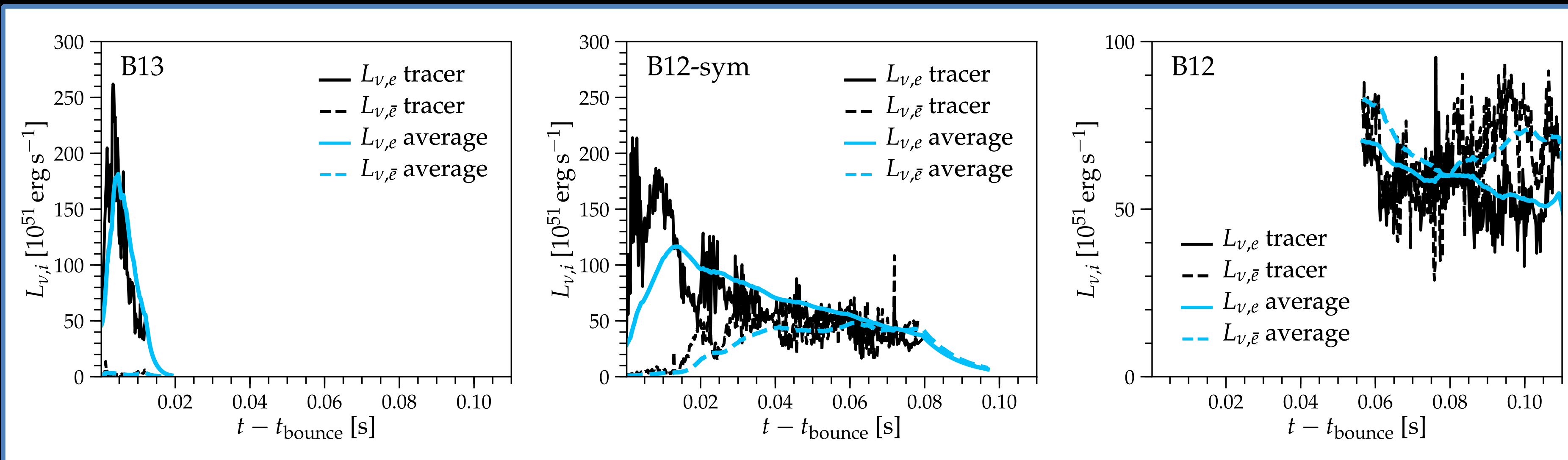


See Goni’s talk on Thursday morning!



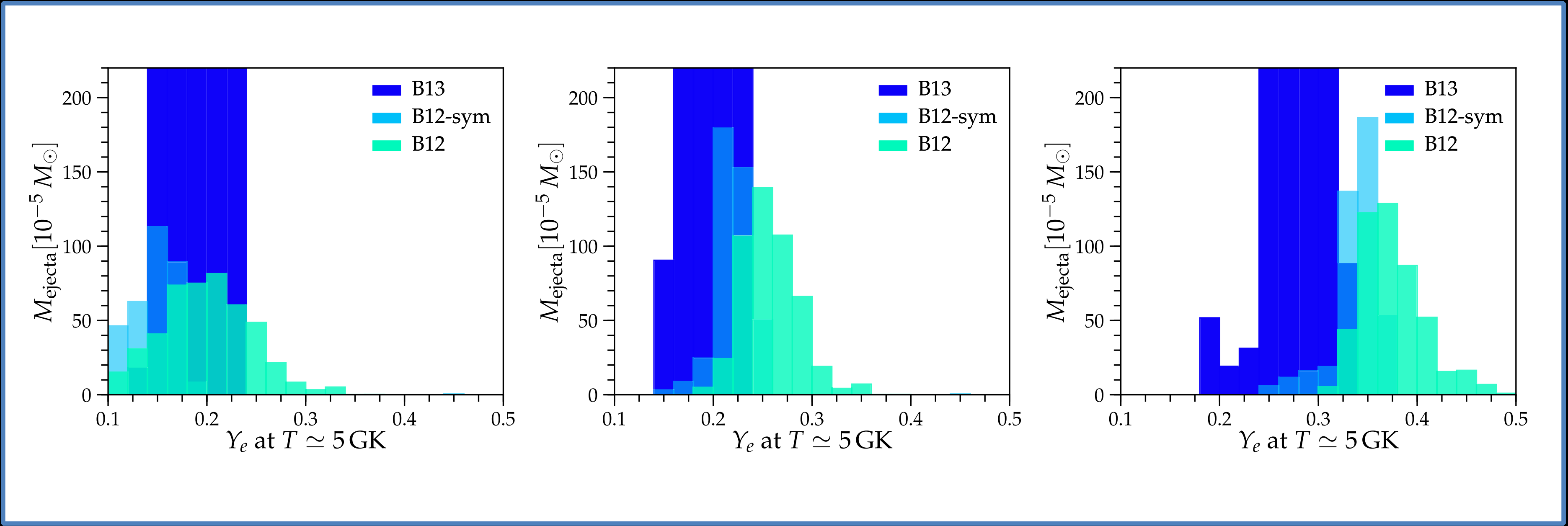
Halevi, PM 18

R-process in jet-driven supernovae



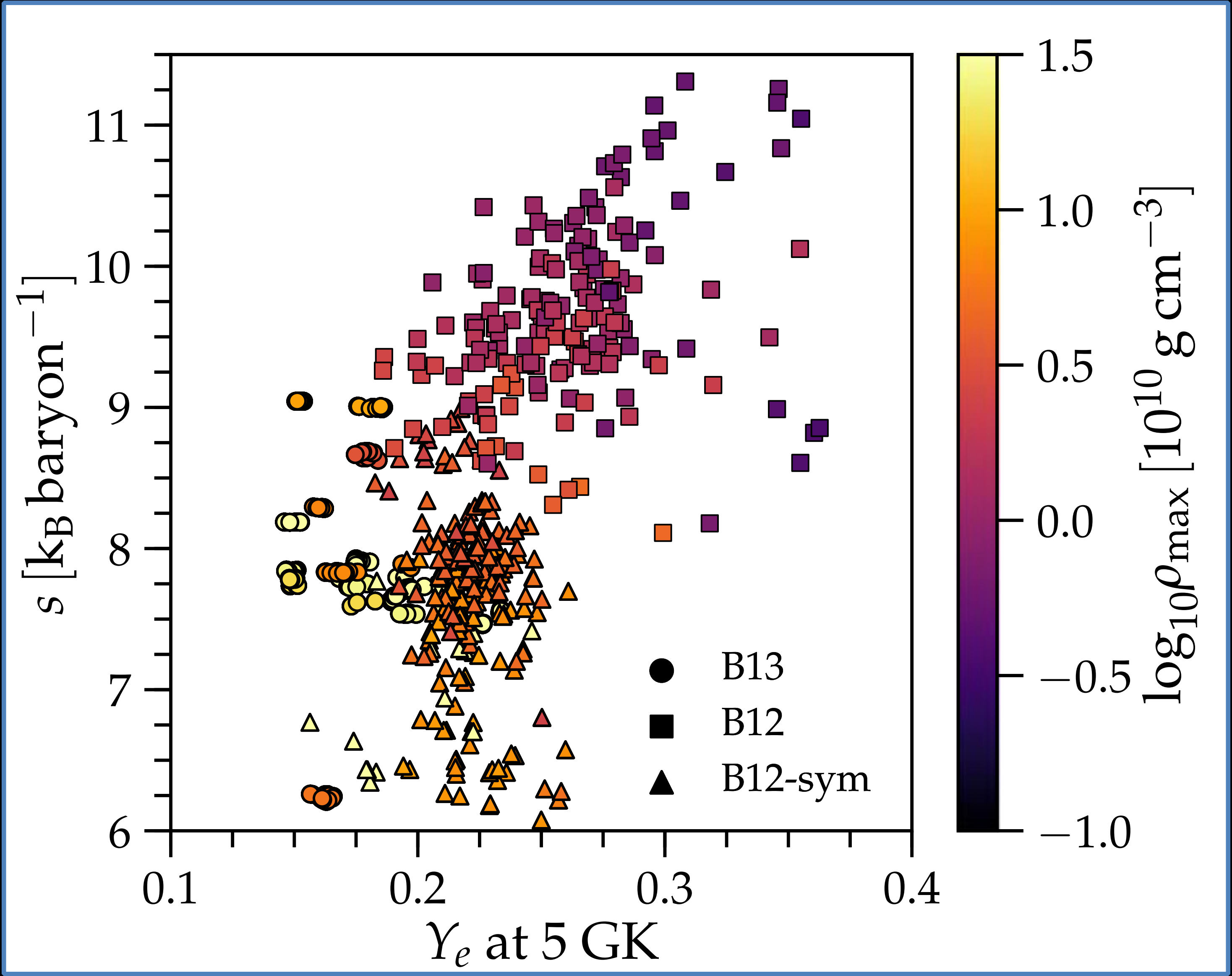
PM+ 18

R-process in jet-driven supernovae



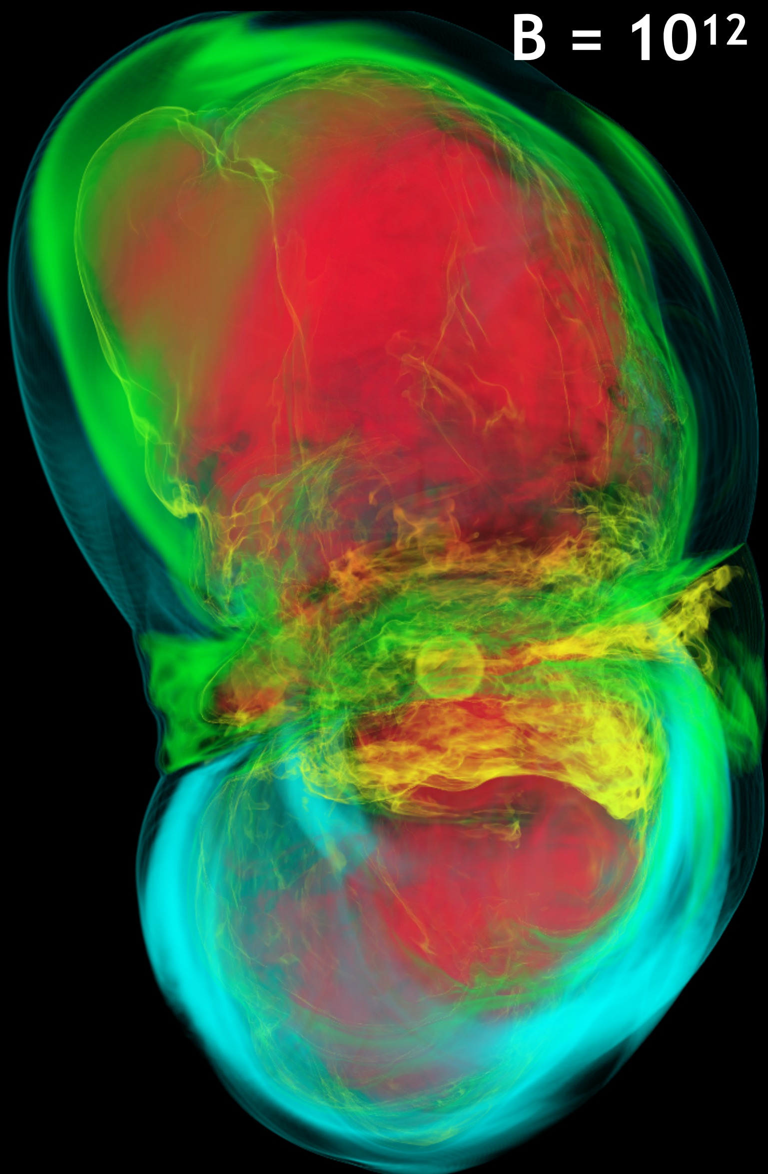
PM, Roberts, Halevi+ 18

R-process in jet-driven supernovae

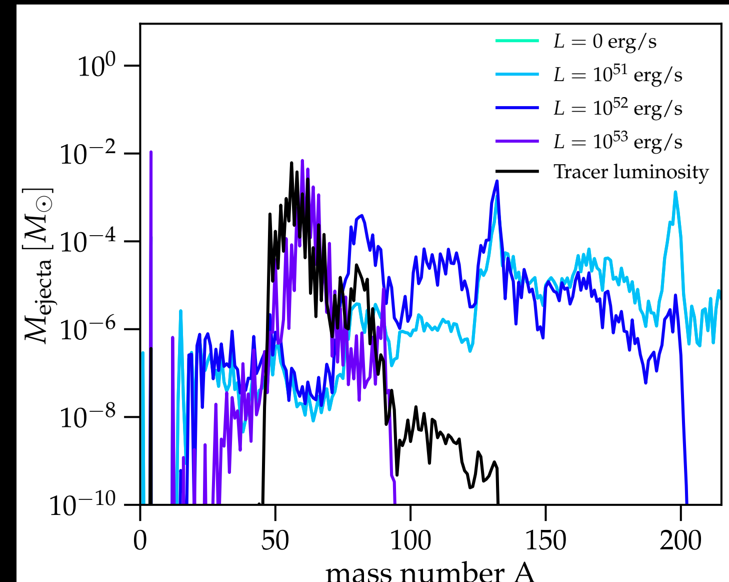


PM, Roberts, Halevi+ 18

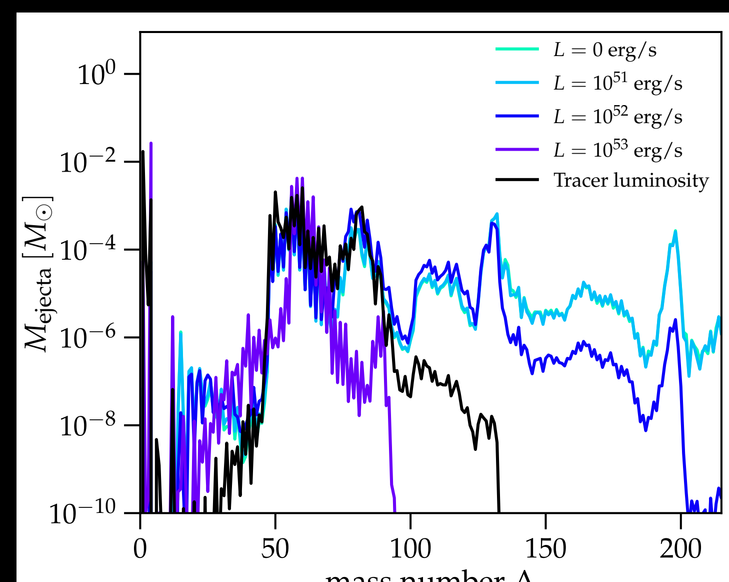
R-process nucleosynthesis in supernovae



B = 10^{12} G / octant

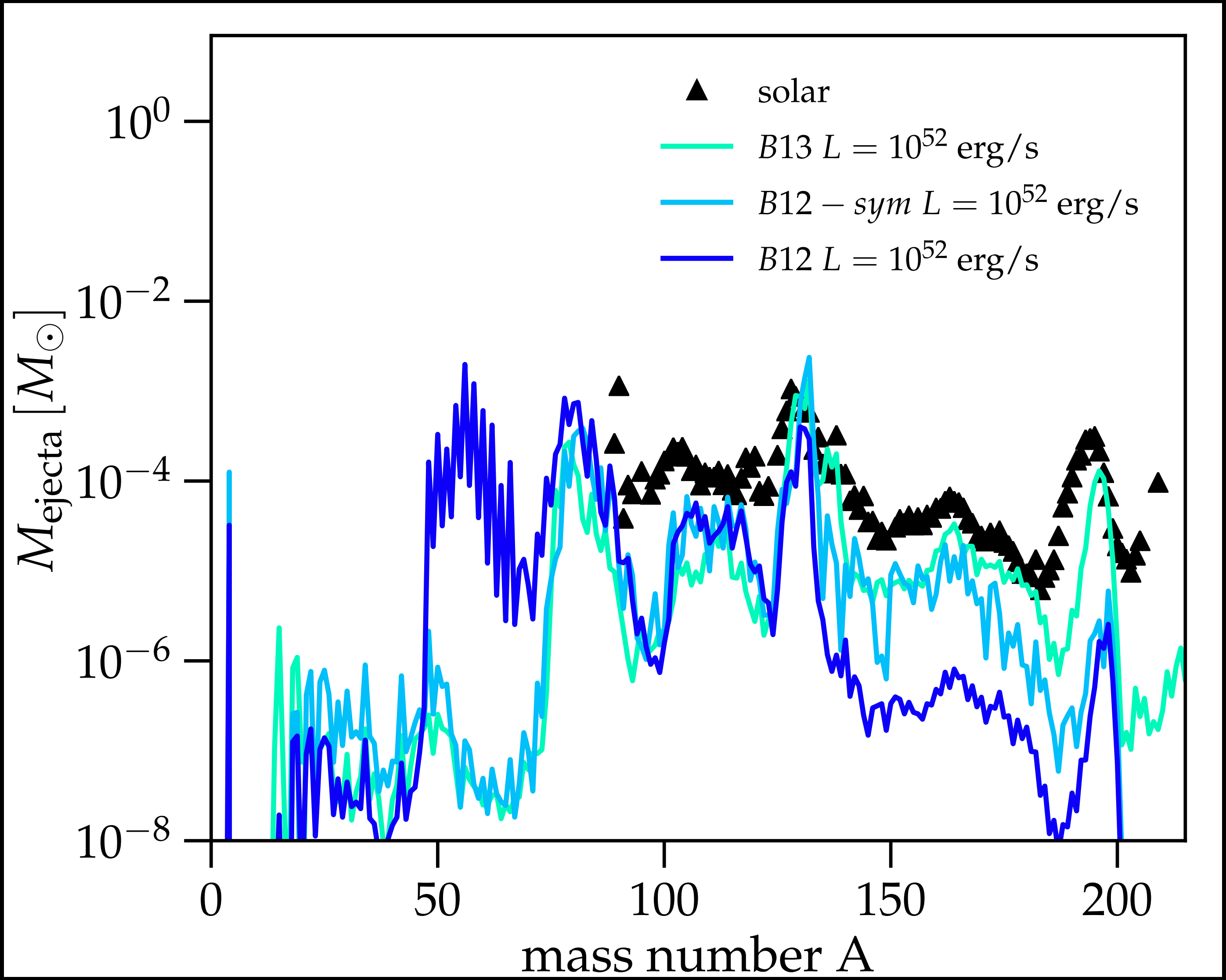


B = 10^{12} G full 3D



PM, Roberts, Halevi+ 18

R-process nucleosynthesis in supernovae



PM, Roberts, Halevi+ 18

From simulations to observations

Observations:

- new transients classes and subclasses
- need detailed predictions to constrain engines

Simulations

- initial 3D simulations open up diverse outcomes
- magnetic fields crucial component for signatures

Need mapping:

progenitor -> engine -> observations

From simulations to observations

State of the art now:

Detailed simulations
full physics
0.1-1s
~10000km

engine formation/dynamics
gravitational waves
nucleosynthesis

From simulations to observations

State of the art now:

Detailed simulations
full physics
0.1-1s
~10000km

From simulations to observations

State of the art now:

Detailed simulations
full physics
0.1-1s
~10000km

Current frontier:

1) engine model from full-physics simulations
2) simplified simulations with engine model to shock breakout

explosion geometry
explosion energy
nucleosynthesis
basic engine model

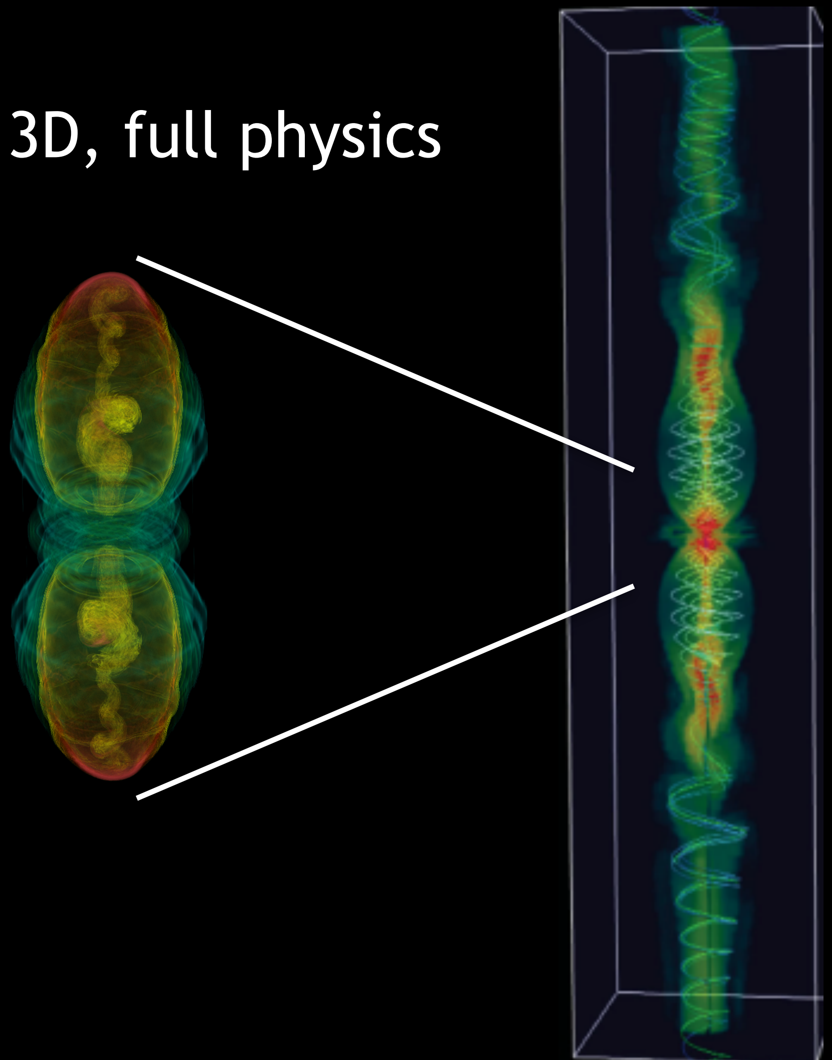
From simulations to observations

Full star

State of the art now:

Detailed simulations
full physics
0.1-1s
~10000km

Full 3D, full physics



Current frontier:

1) Engine model from full-physics simulations
2) Simplified simulations with engine model to shock breakout

From simulations to observations

State of the art now:

Detailed simulations
full physics
0.1-1s
~10000km

Current frontier:

1) Engine model from full-physics simulations
2) Simplified simulations with engine model to shock breakout

Next five years:

full-scale simulations
full physics
shock breakout

detailed light curves
detailed spectra
connect observations and engines
map progenitor params

Summary

New (hyperenergetic/superluminous) transients challenge our engine models

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

3D GRMHD simulations also key to hypermassive neutron star lifetime, EM counterparts and sGRB engines in neutron star mergers

High-performance computing key to solving these puzzles