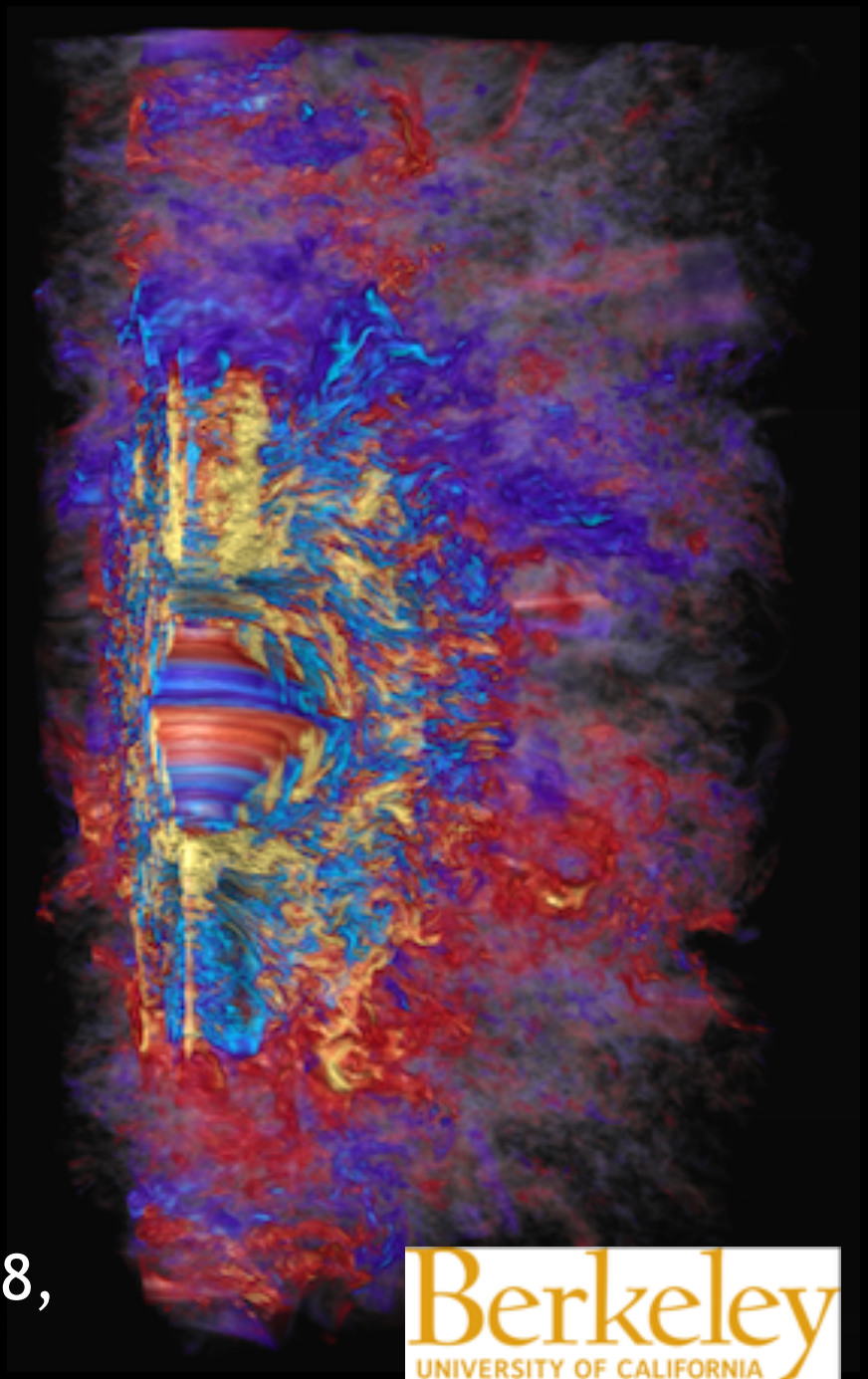
Turbulent Engines of Extreme Core-collapse Supernovae



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Einstein fellow @ UC Berkeley

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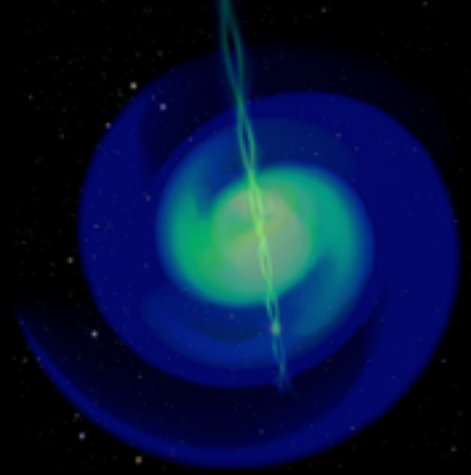
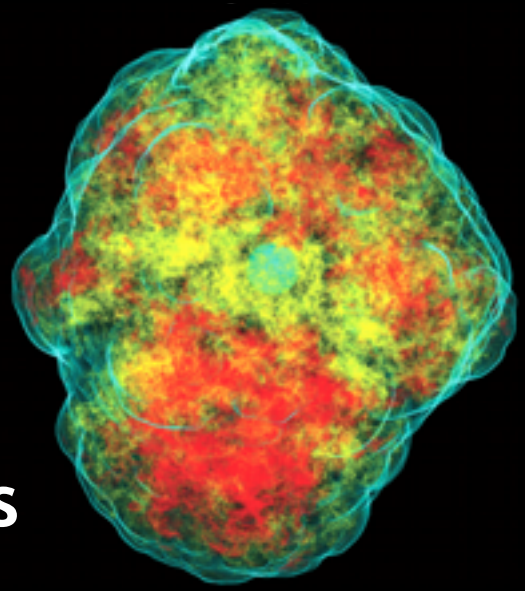
Einstein fellows symposium, Oct 18, 2016

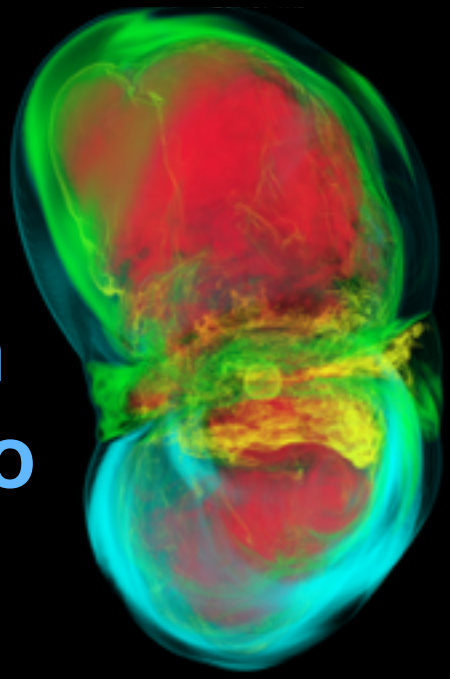
Berkeley
UNIVERSITY OF CALIFORNIA



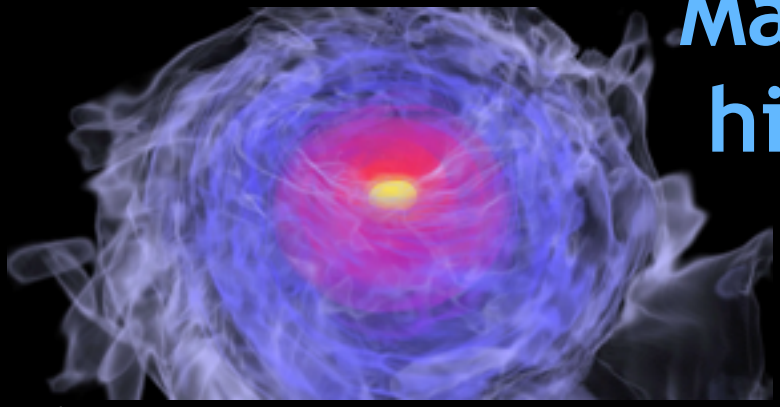


Core-collapse supernovae
neutrinos
turbulence

(Binary) black holes
accretion disks
EM counterparts

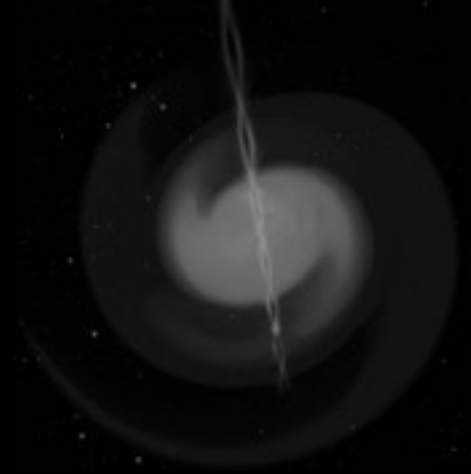


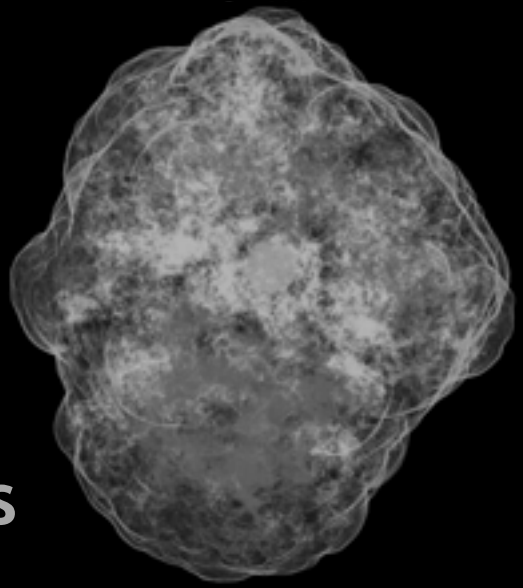
Magnetic fields in high-energy astro



Binary neutron stars
gravitational waves
EM counterparts
sGRBs

Extreme core-collapse
hyperenergetic
superluminous
lGRBs





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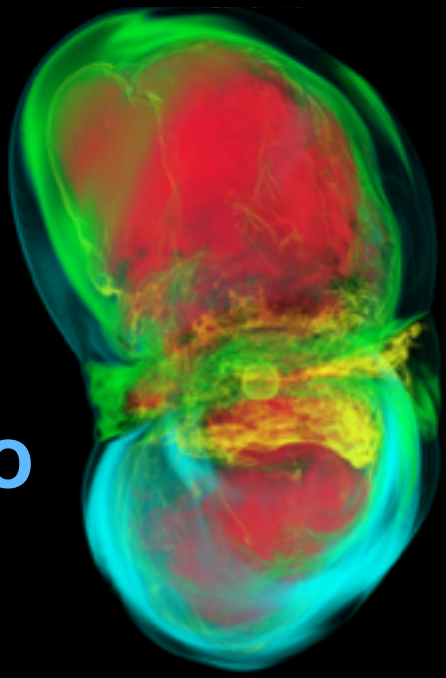

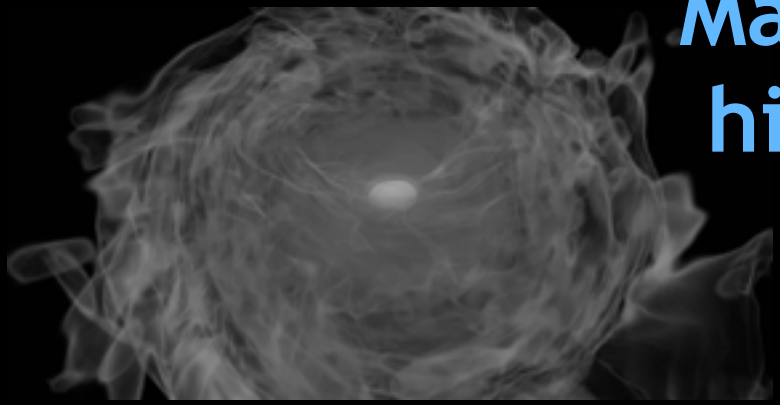

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gravitational waves
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Extreme core-collapse
hyperenergetic
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New era of transient science

- 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

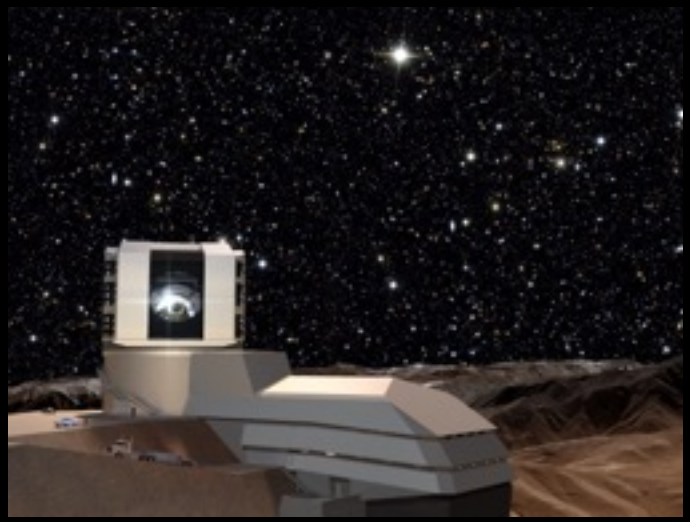

Image: LSST

New era of transient science

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Transformative years ahead for our understanding of these events

Image: PTF/ZTF/COO

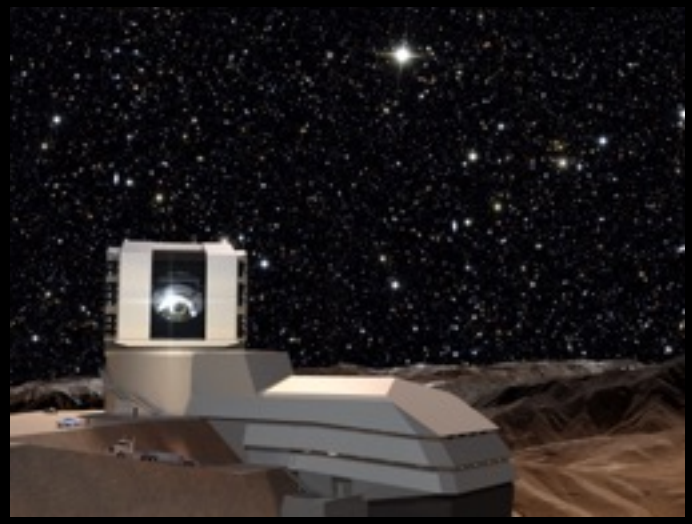
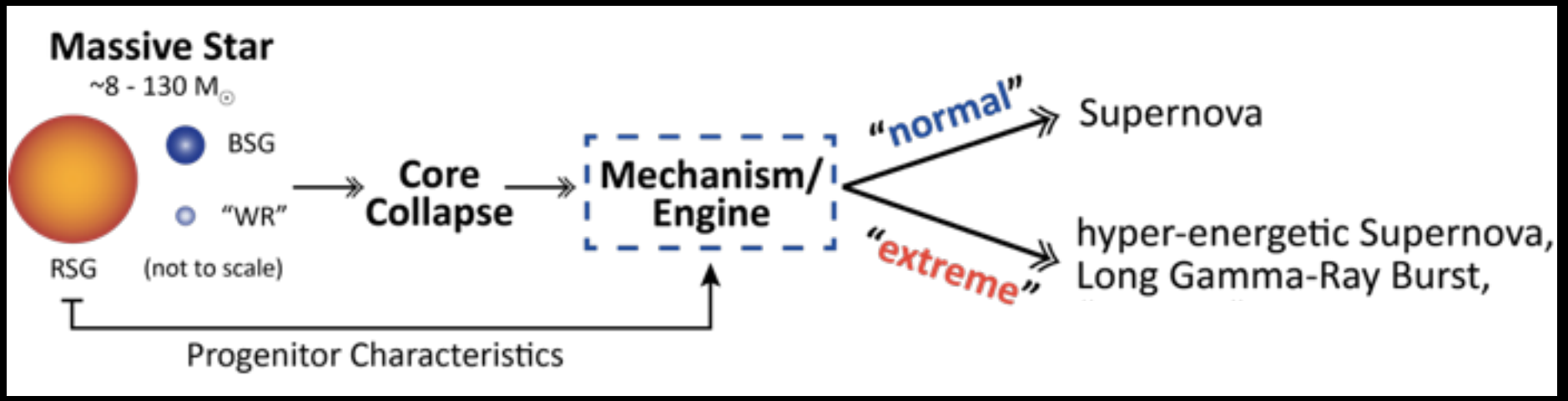


Image: LSST

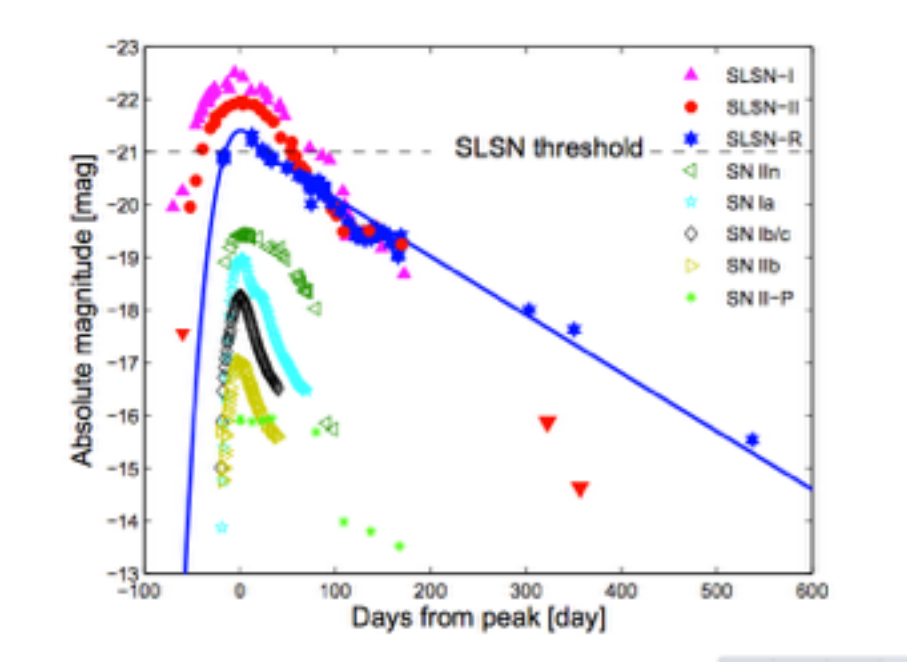
Hypernovae & GRBs



- 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 and low redshift

Neutrino mechanism is inefficient;
can't deliver a hypernova

Superluminous supernovae



Gal-Yam+12

Some events:

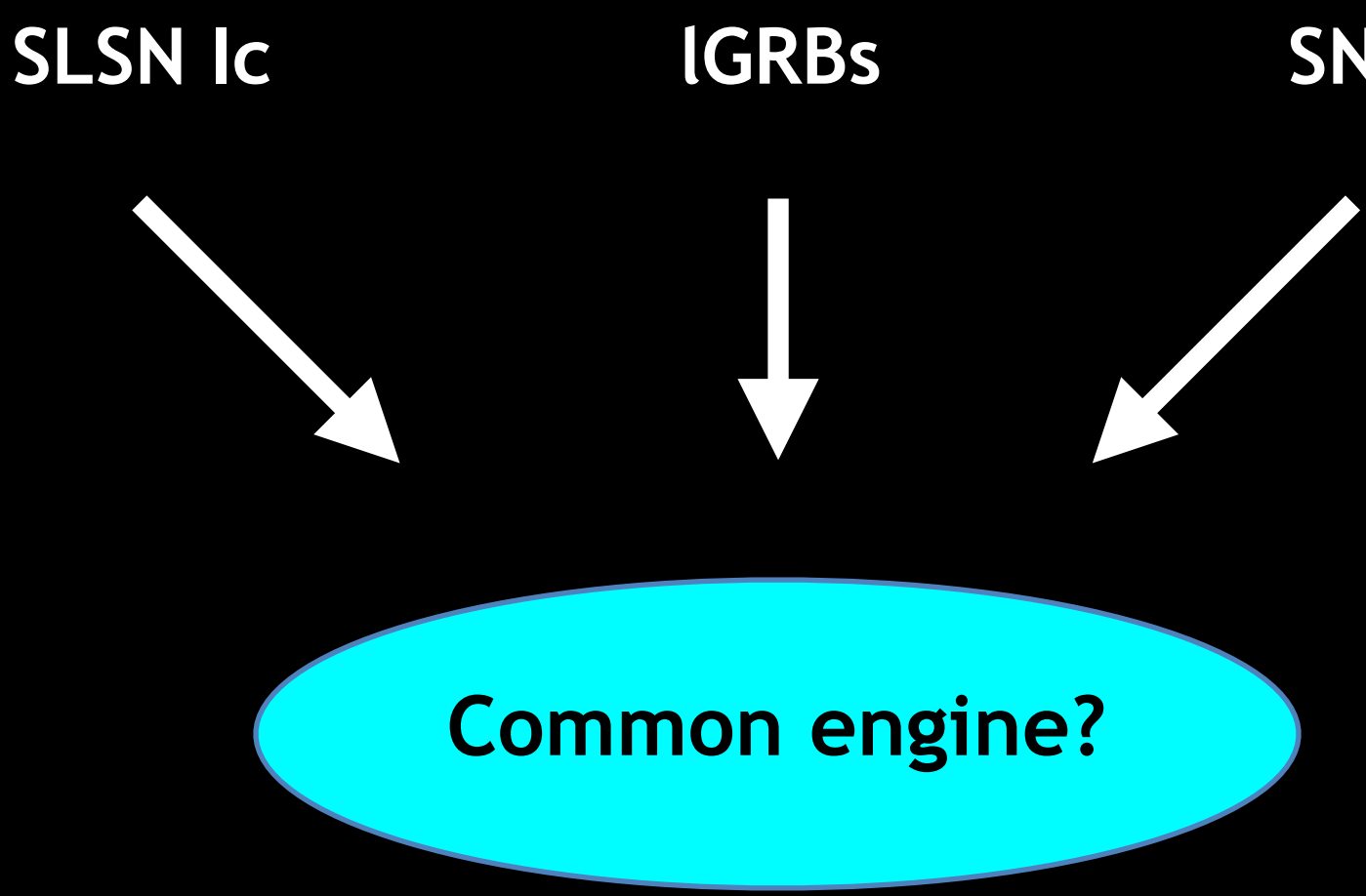
stripped envelope

no interaction

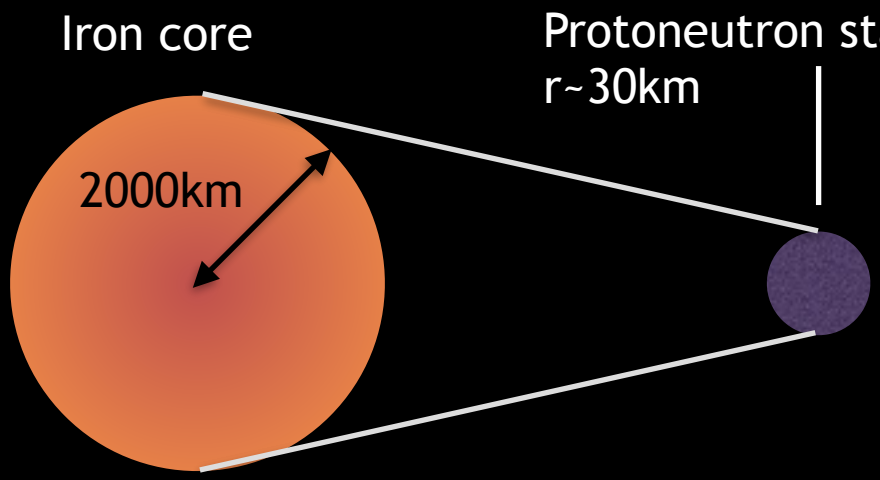
$E_{lum} \sim 10^{45}$ erg

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

Superluminous / hyperenergetic supernovae



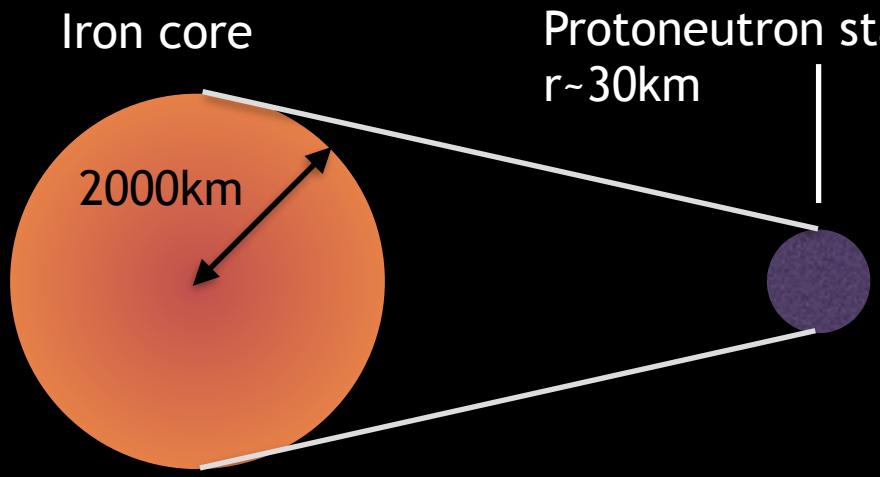
Core collapse basics



Nuclear equation of state stiffens at nuclear density

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

Core collapse basics



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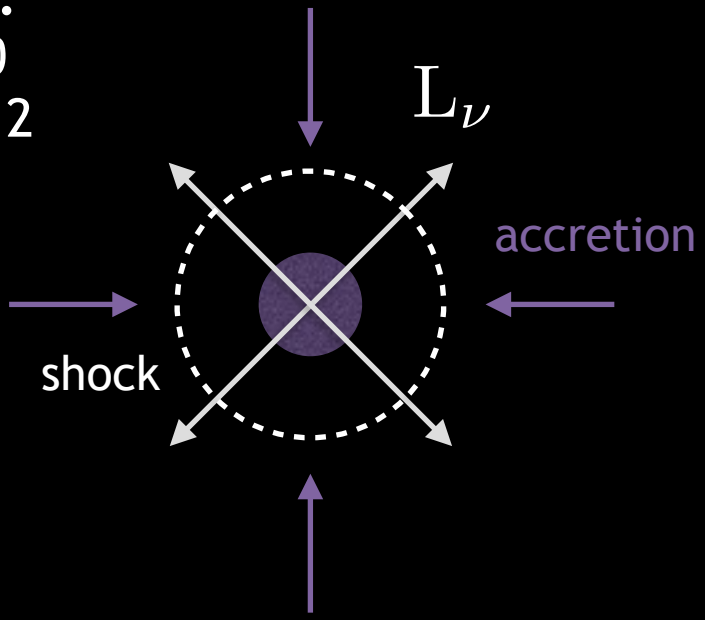
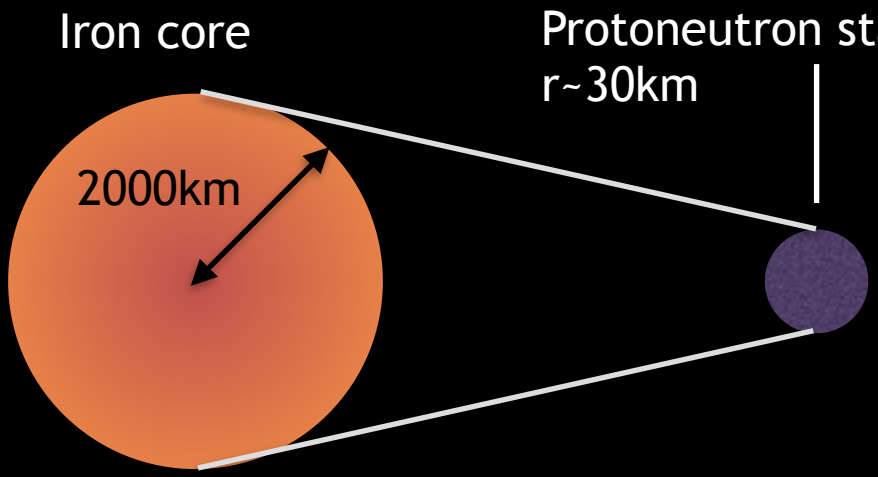
Reviews:
Bethe'90
Janka+'12



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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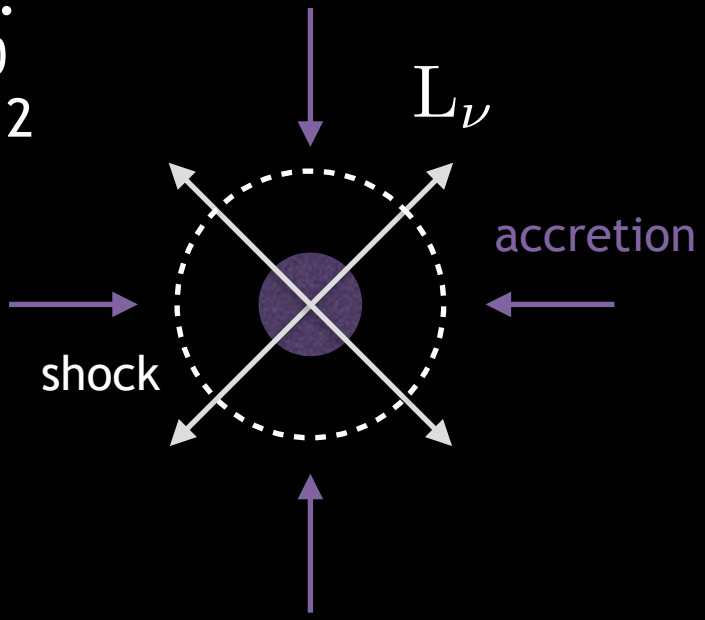


Core-collapse supernova problem:

How to revive the shockwave?

Magnetorotational mechanism

Burrows+'07

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

Rapid Rotation + B-field amplification
(need magnetorotational instability [MRI]; difficult to resolve, but see, e.g, Obergaulinger+'09, **PM**+15)

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

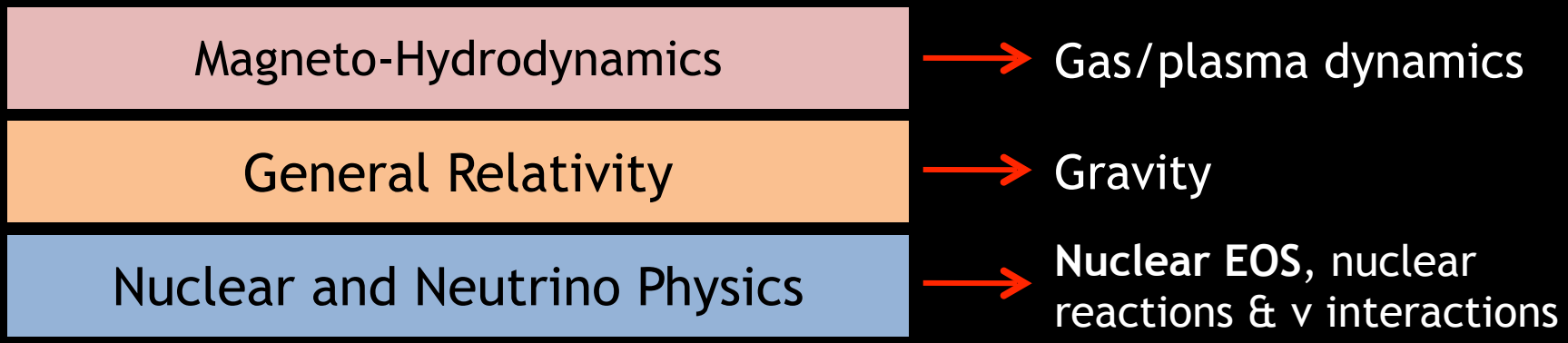
Results in ms-period proto-magnetar

A multiphysics challenge

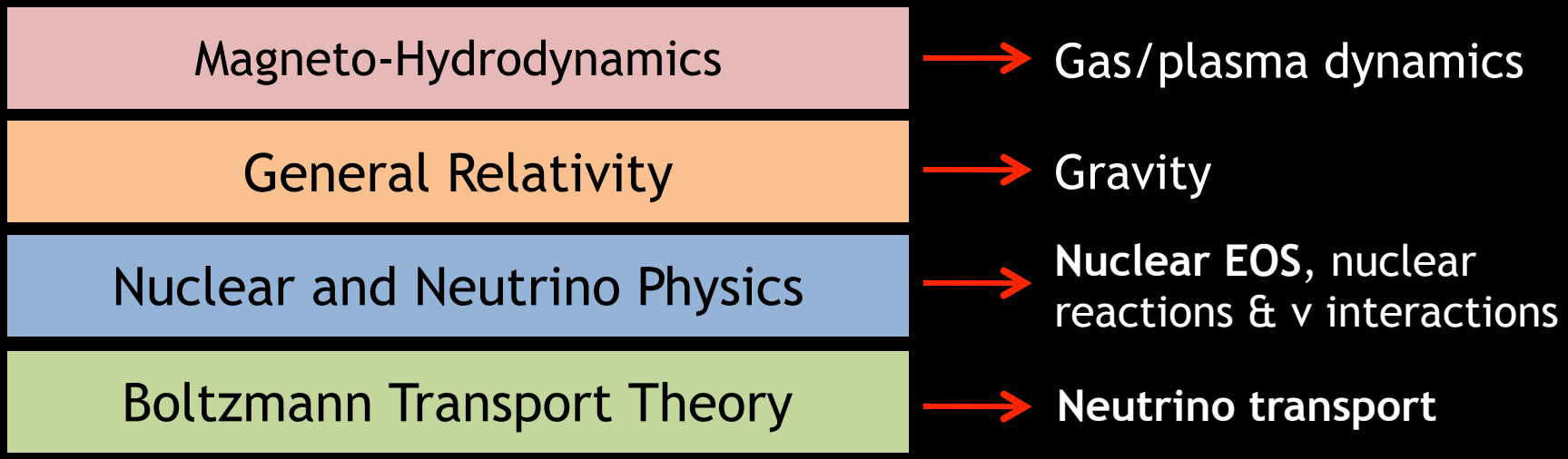
Magneto-Hydrodynamics → Gas/plasma dynamics

A multiphysics challenge

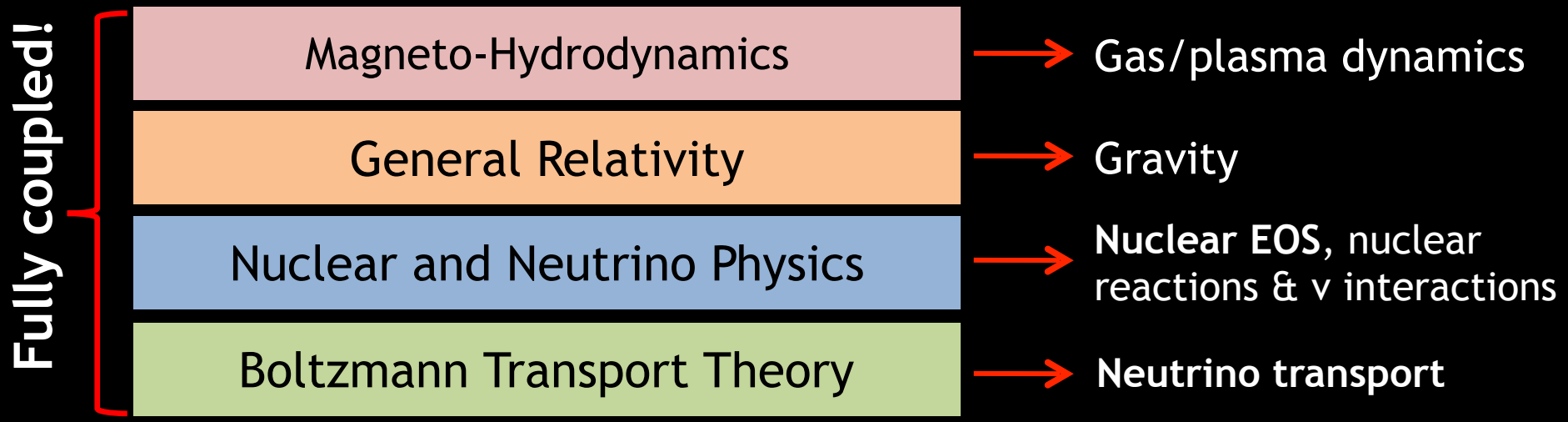
A multiphysics challenge



A multiphysics challenge

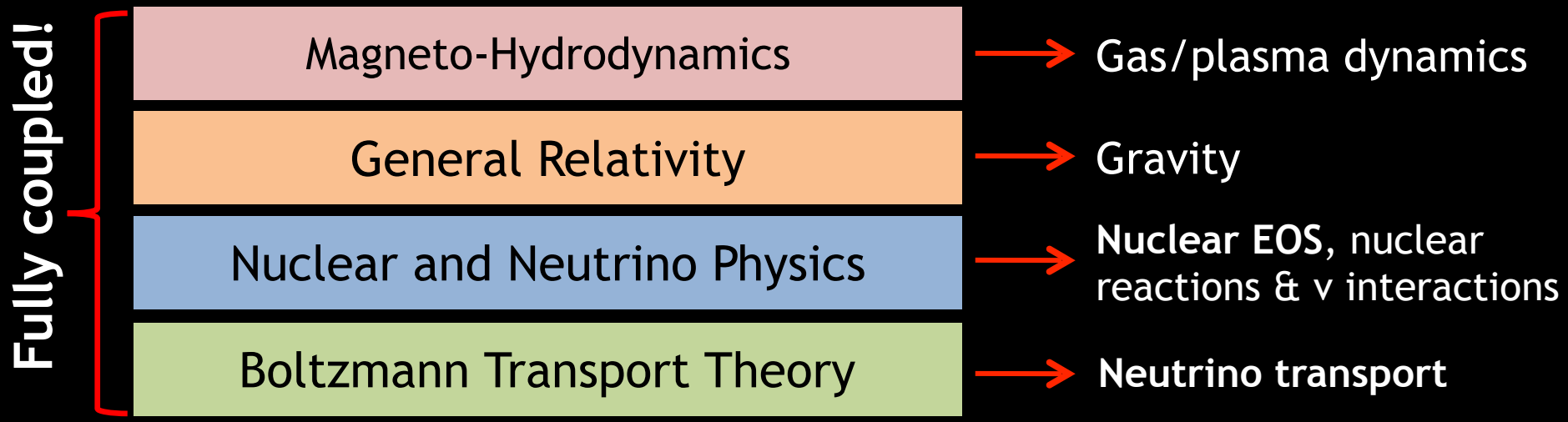


A multiphysics challenge



All four forces!

A multiphysics challenge



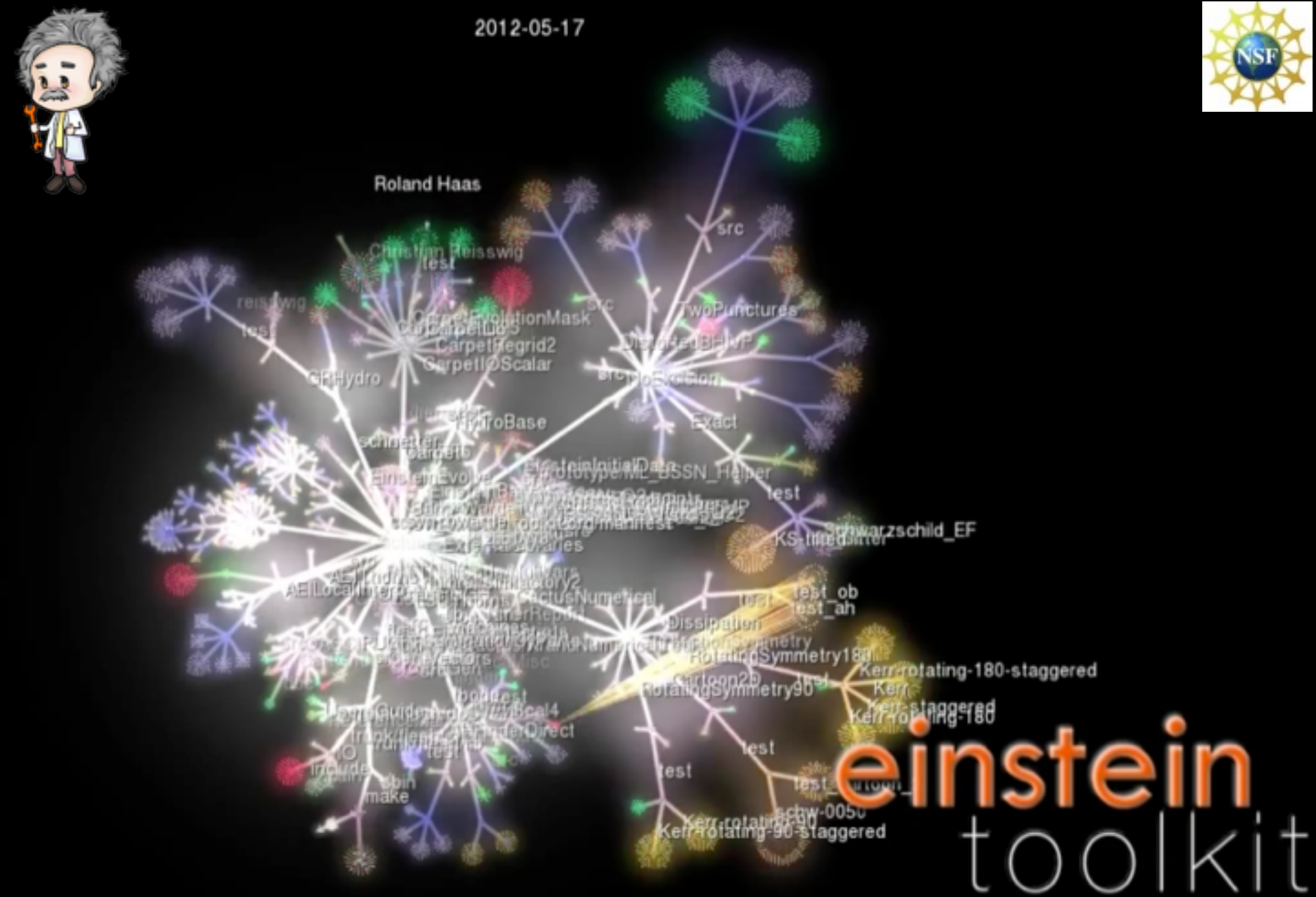
All four forces!

Additional Complication: Core-Collapse Supernovae are 3D

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

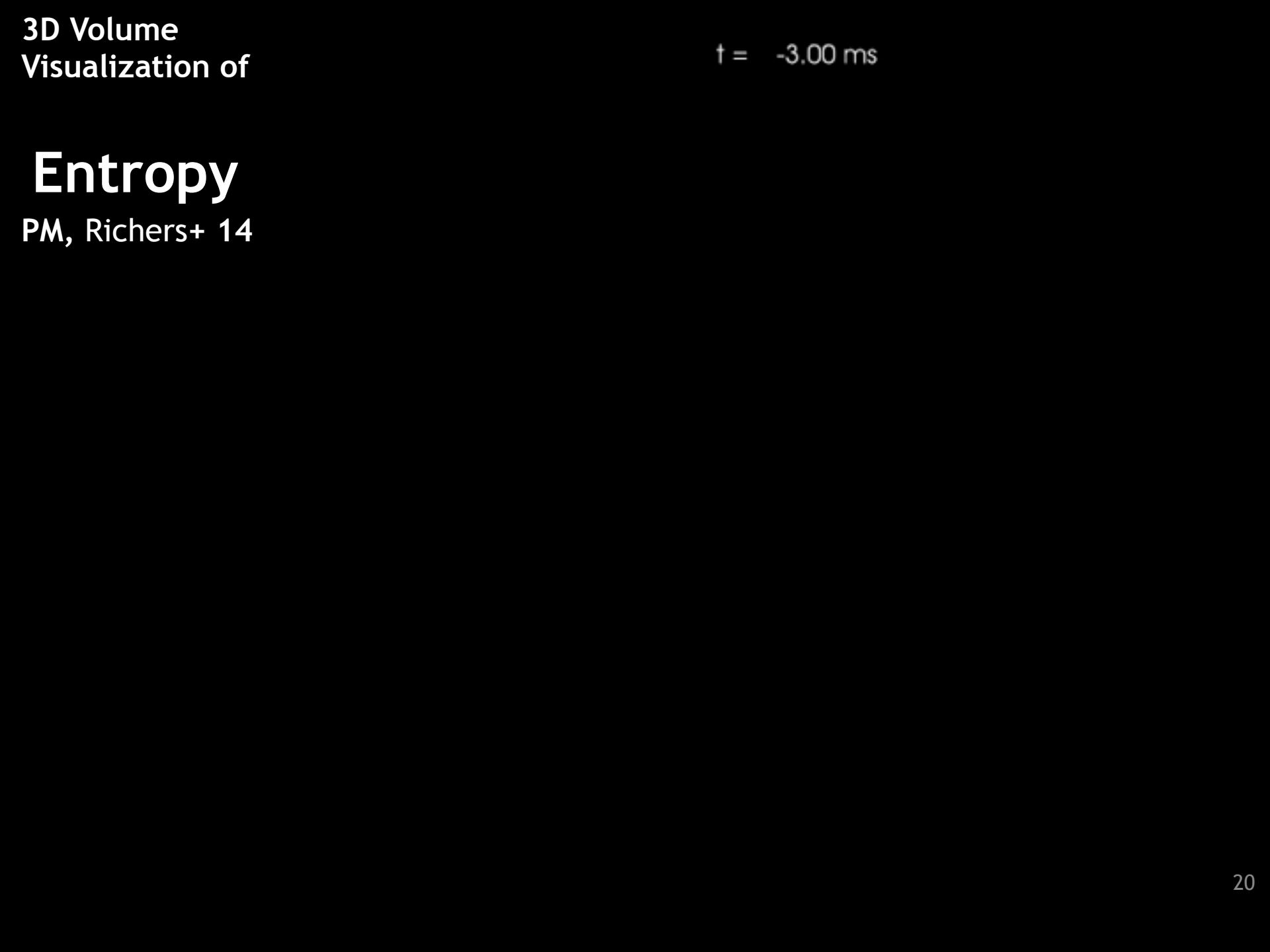
Need 21st century tools:

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



http://einsteintoolkit.org

3D Volume Visualization of



Entropy

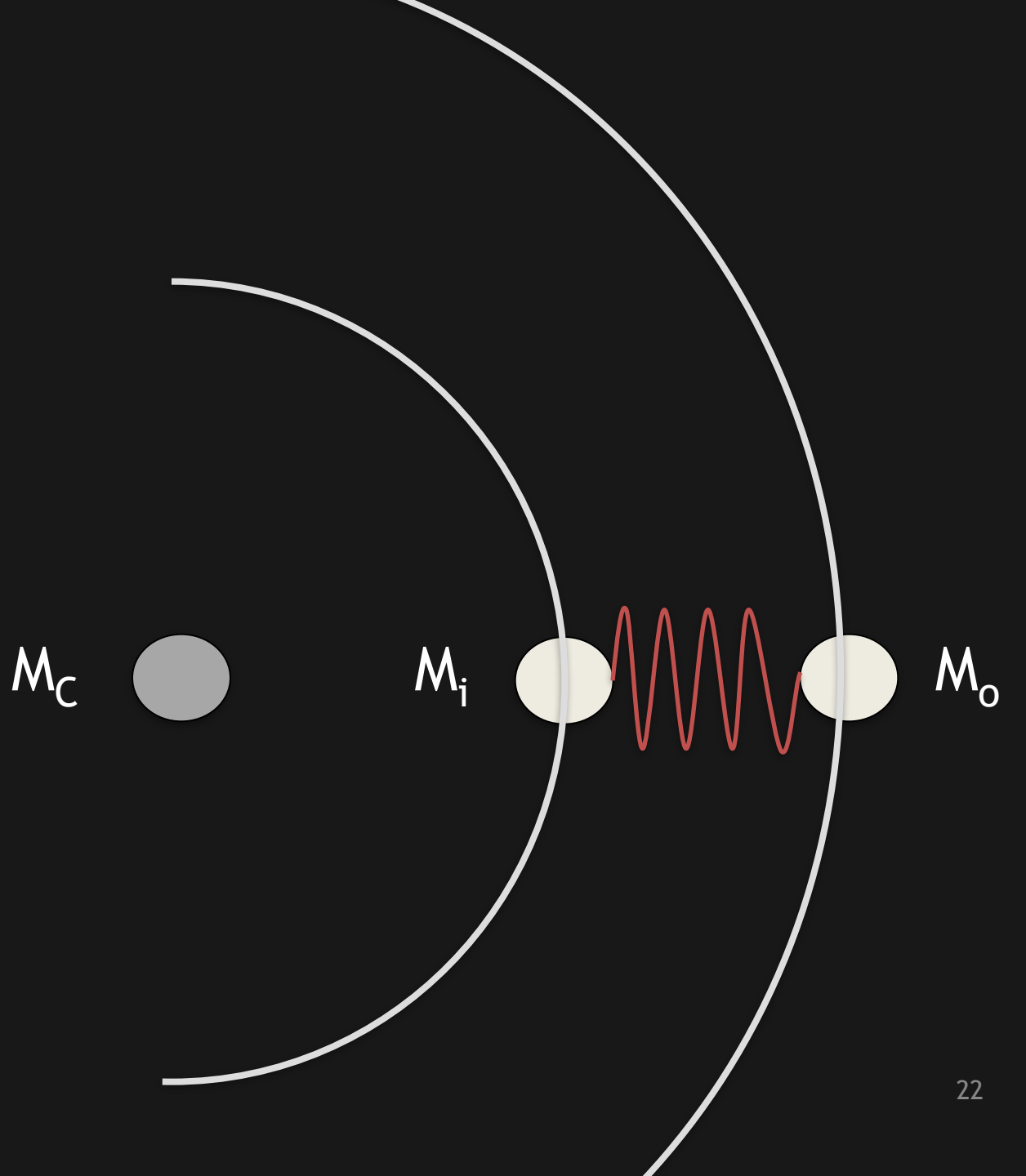
PM, Richers+ 14

Magnetorotational Mechanism

Burrows+'07

Big uncertainty so far:
How do we get the magnetic field amplification?

MRI Basics



MRI Basics

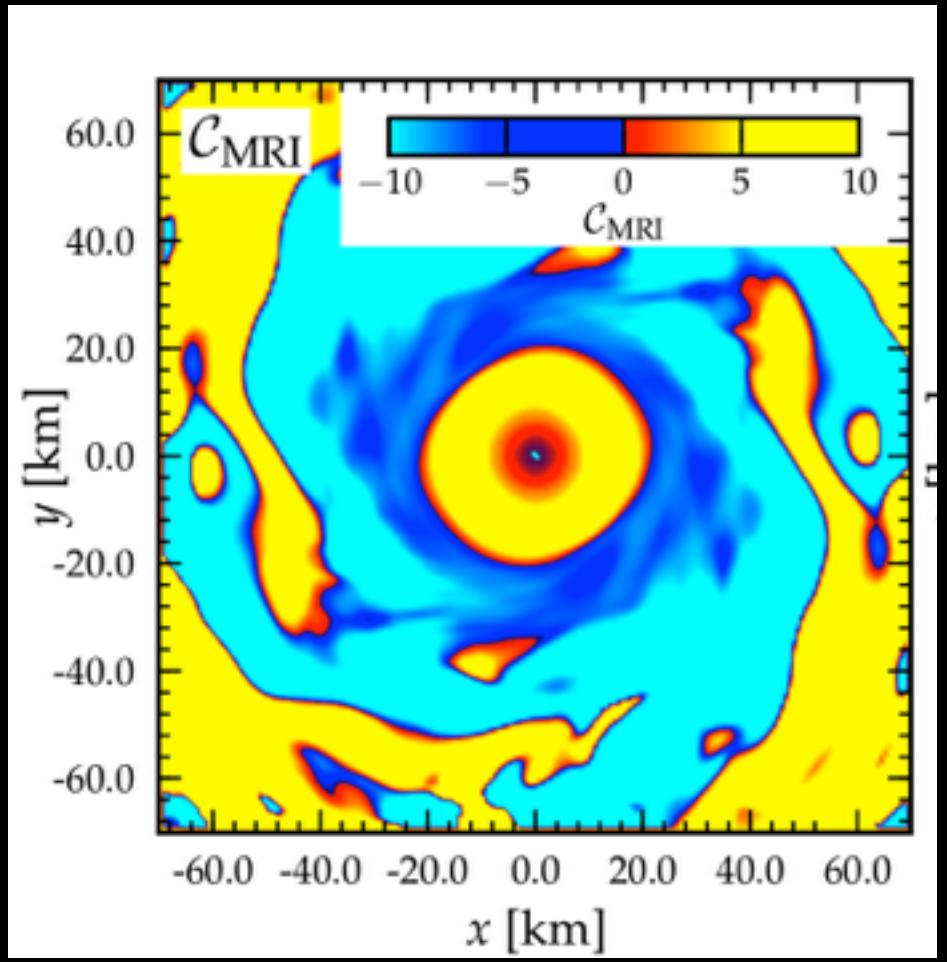
- Weak field instability
- Requires negative angular velocity gradient
- Can build up magnetic field exponentially fast
- Extensively researched in accretion disks: ability to modulate angular momentum transport and grow large scale field

What's the situation in core-collapse?

Stability criterion:

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

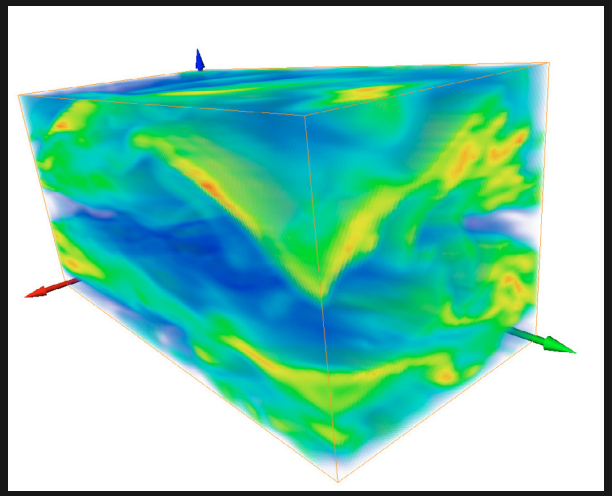
[Balbus&Hawley 91,98, Akiyama+03, Obergaulinger+09]



Magnetorotational Mechanism

Burrows+'07

- MRI works locally Akiyama+03, Shibata+06
- shearing box simulations



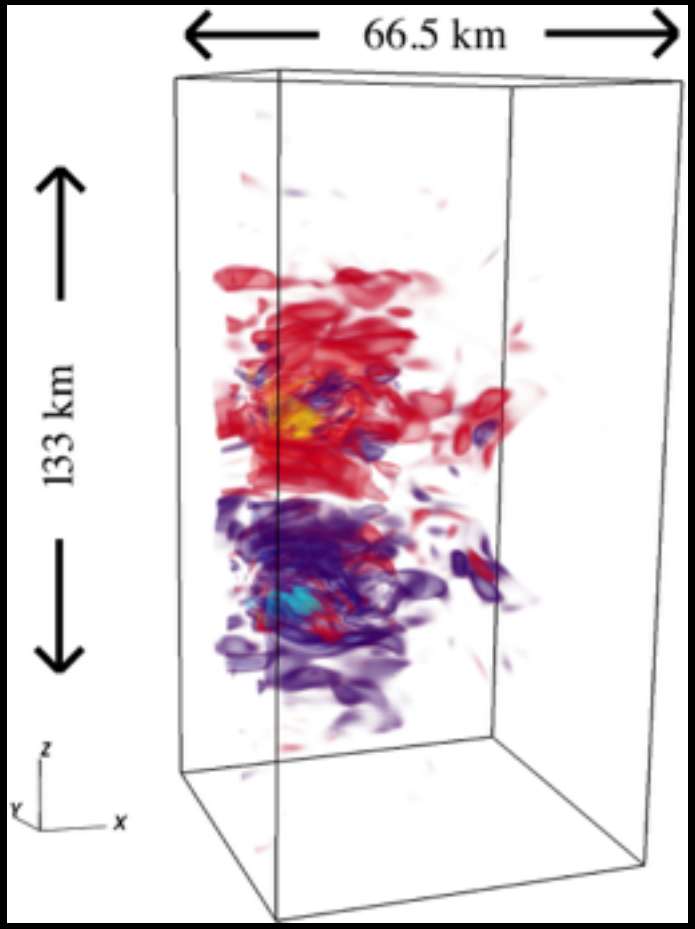
Obergaulinger+09

But what about global field?

First 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

Does the MRI efficiently build up dynamically relevant global field?



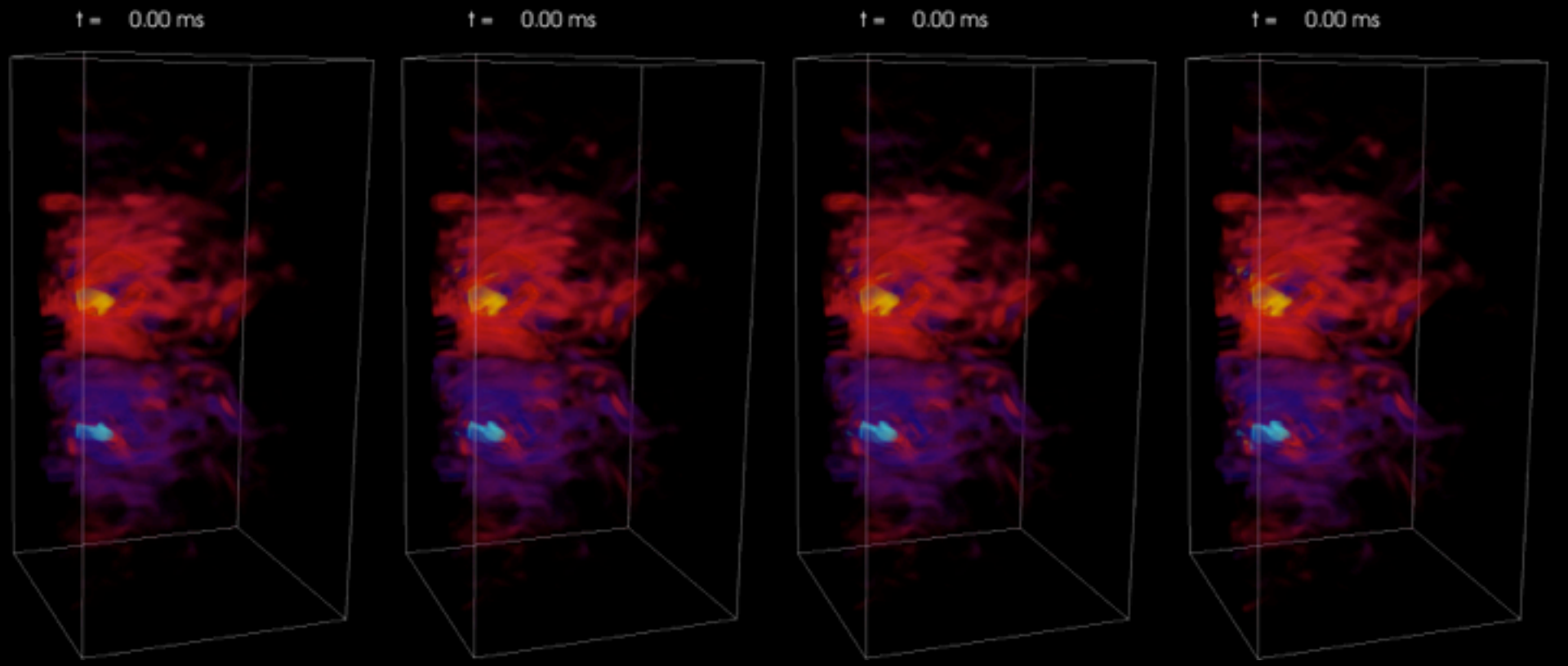
PM+ 15 Nature

BLUE WATERS
SUSTAINED PETASCALE COMPUTING

NSF

3D magnetic field structure

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



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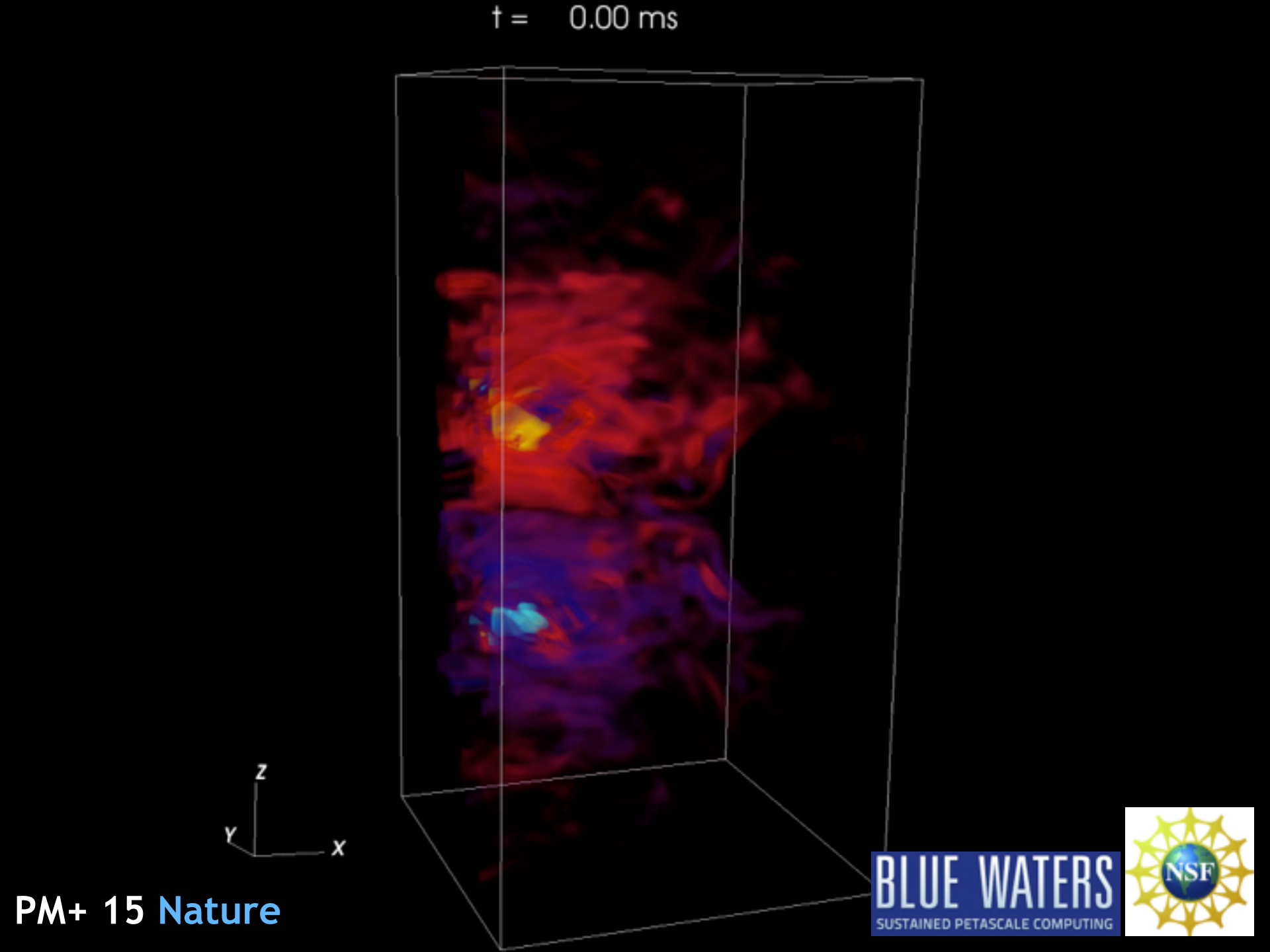
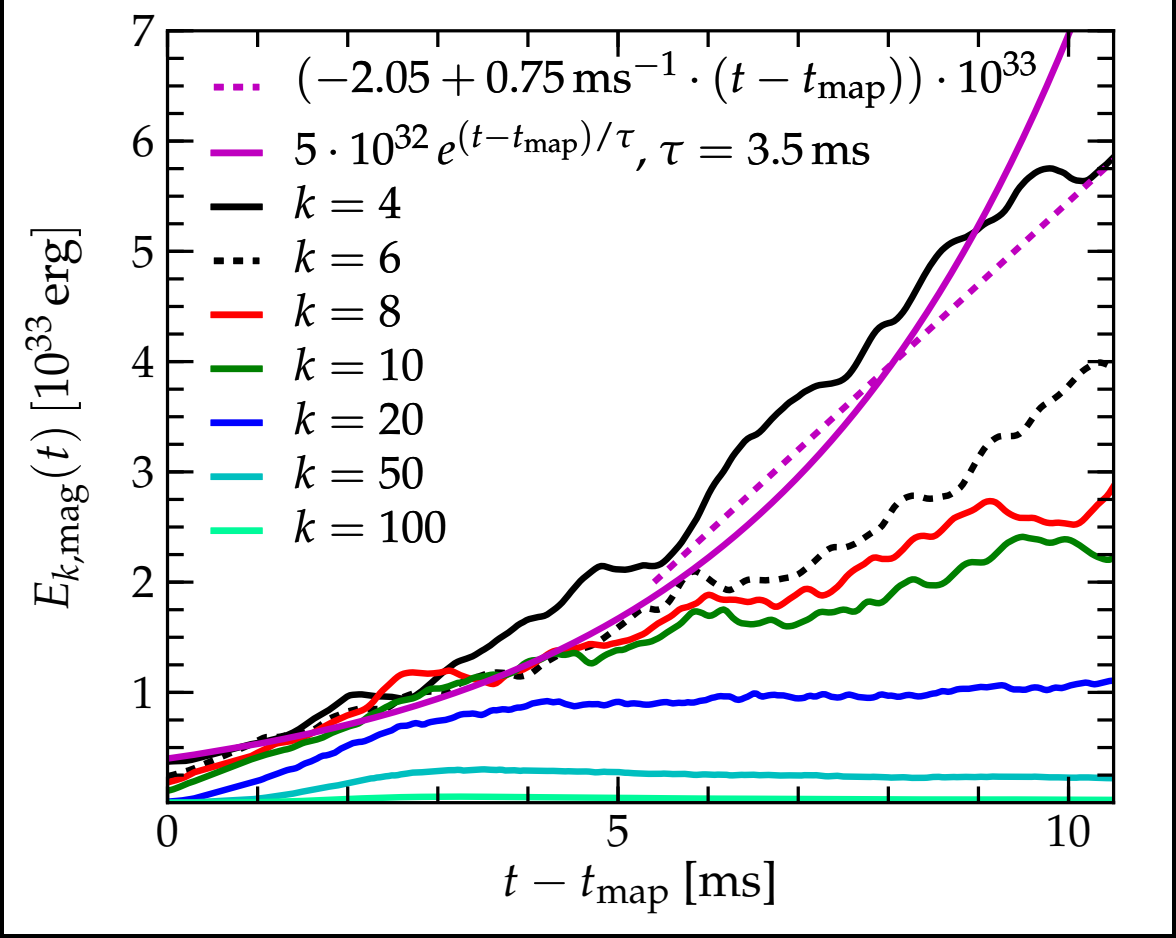


PM+ 15 Nature

Growth at Large Scales



saturation within 60ms

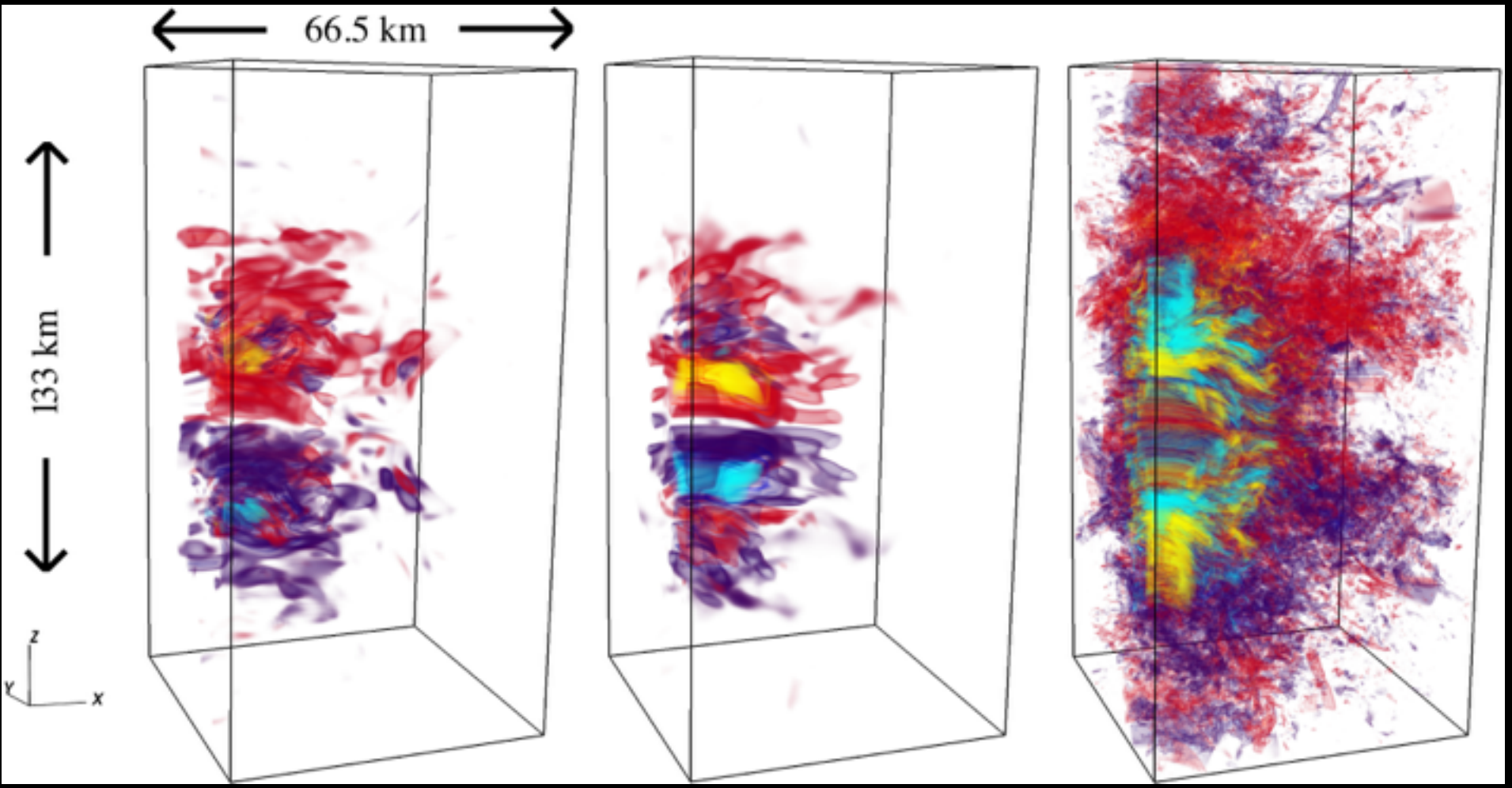
PM+ 15 Nature

Global Field Structure

PM+ 15 Nature

dx=500m

dx=50m



t=0ms

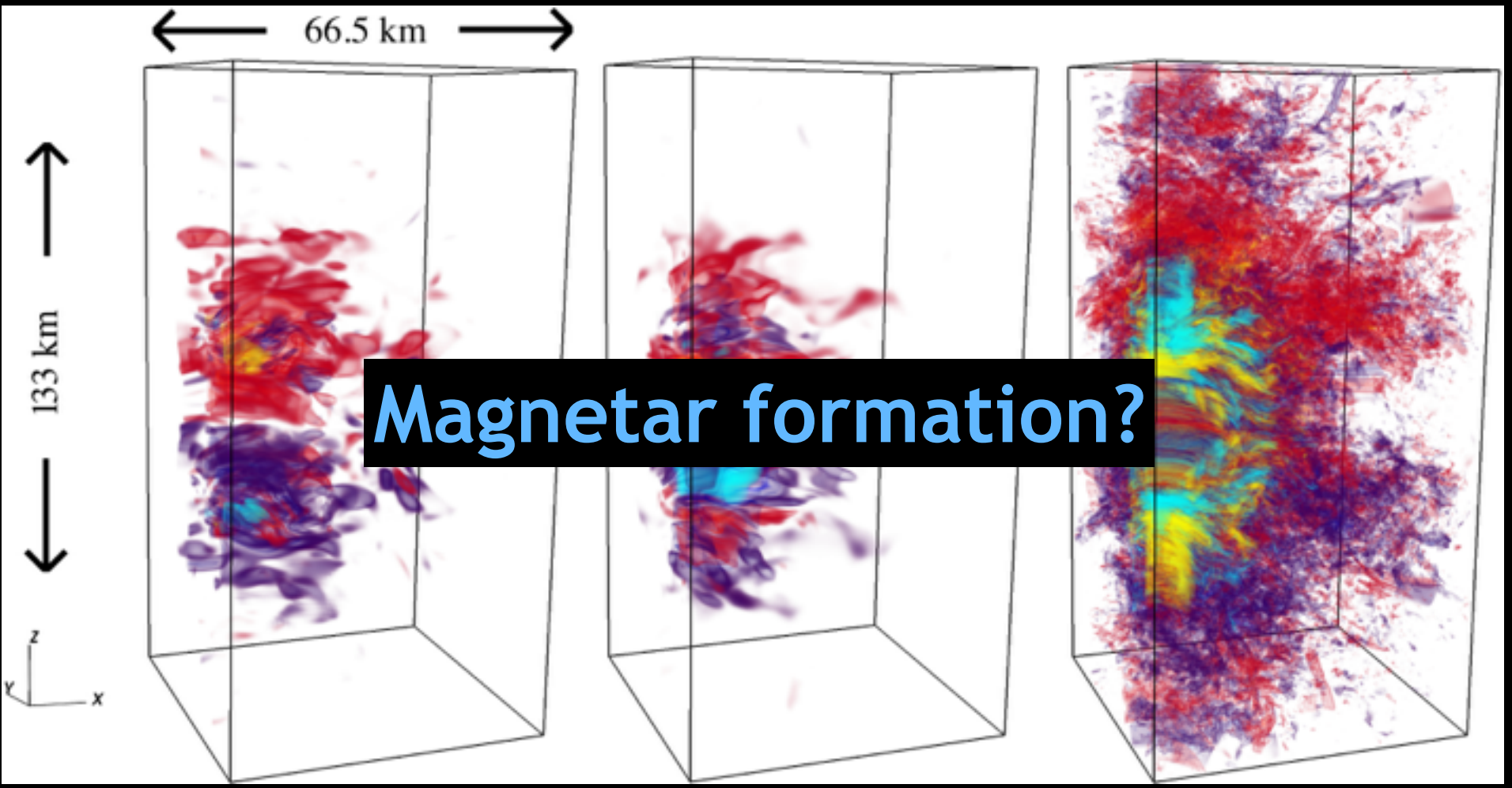
t=10ms

t=10ms

PM+ 15 Nature

Global Field Structure

PM+ 15 Nature



PM+ 15 Nature

Summary

New (hyperenergetic/superluminous) transients challenge our engine models

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

Magnetoturbulence and large-scale dynamo action create conditions for magnetar engine

High-performance computing key to solving these puzzles

Thank you!