The Role of Turbulence in Core-Collapse Supernova Explosions

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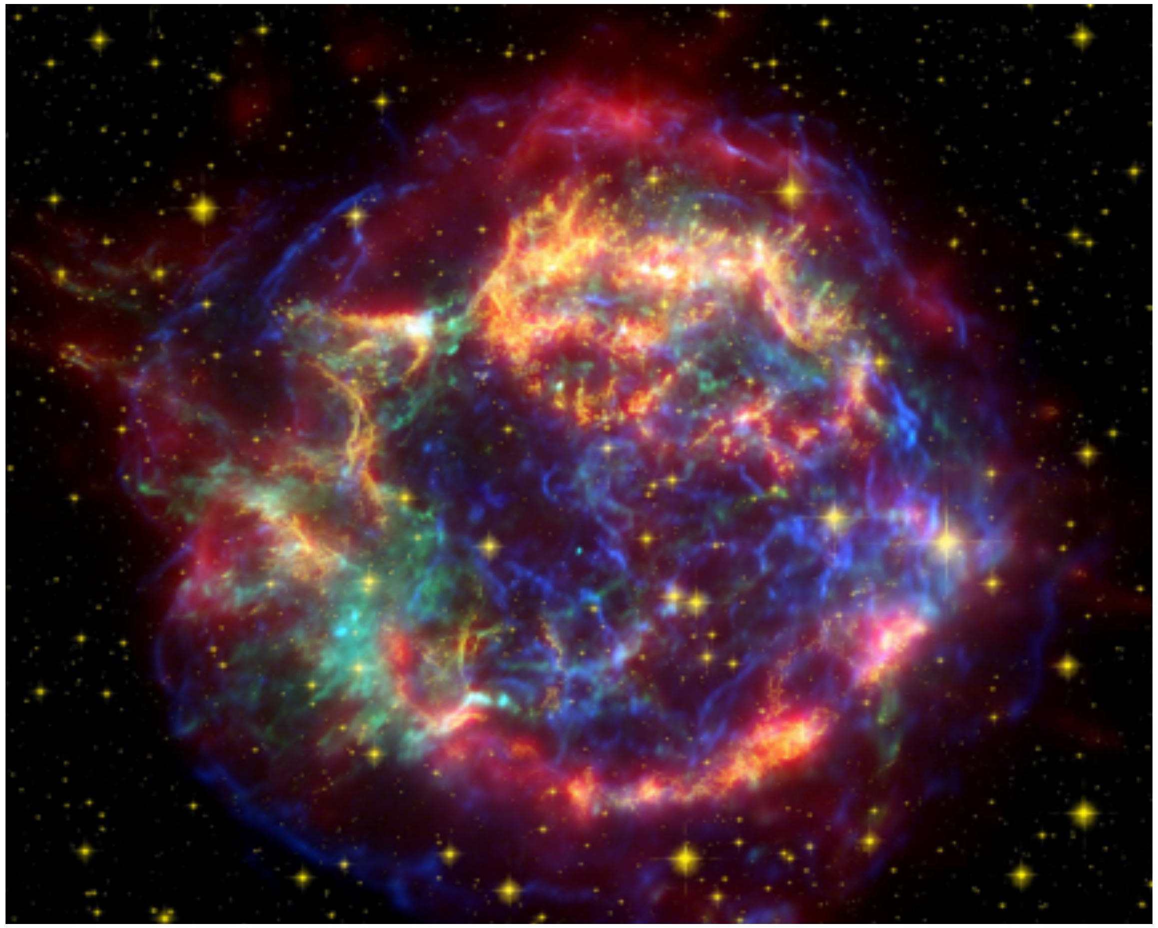
The Supernova Problem



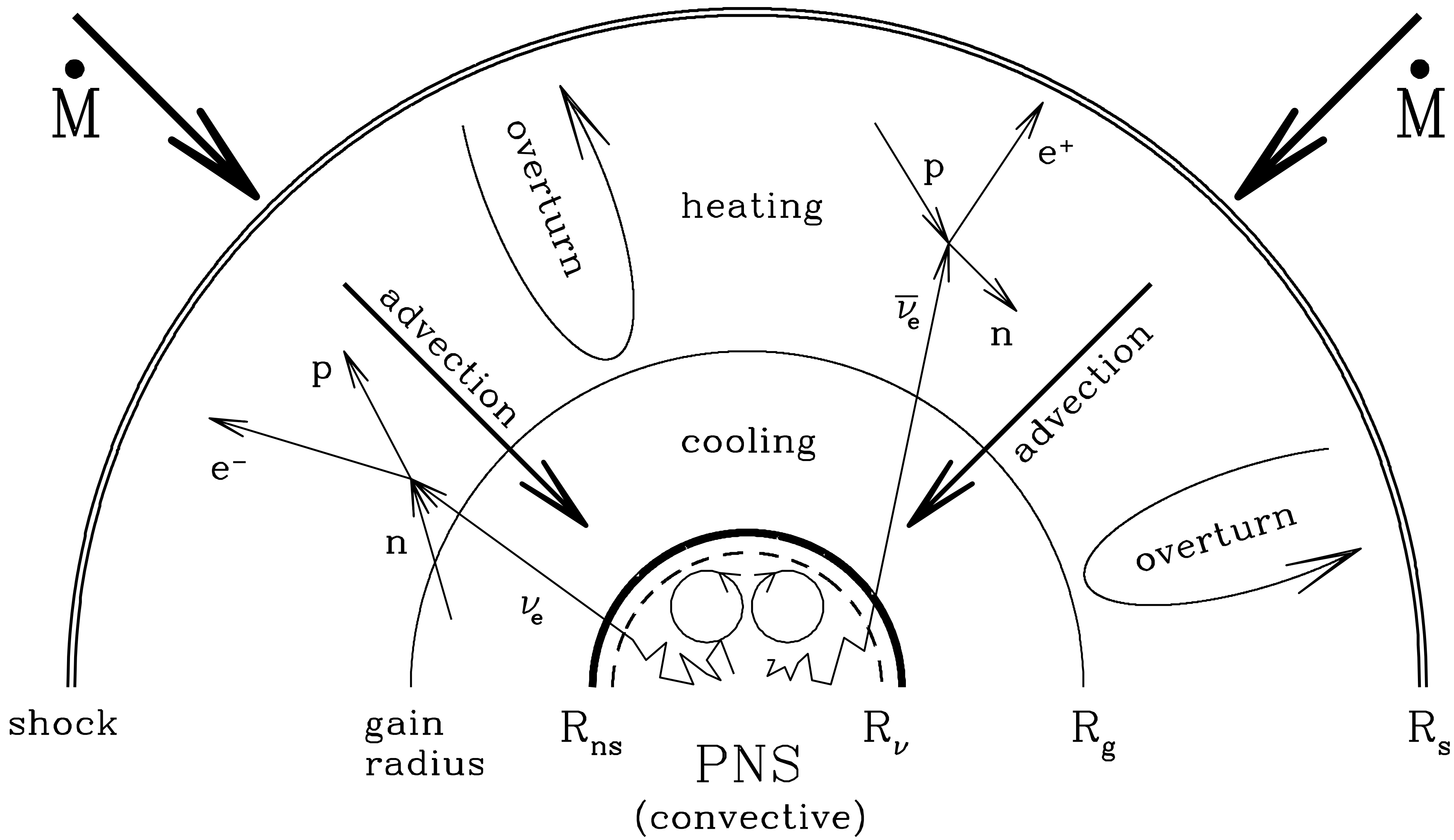
Cassiopeia-A

Core-Collapse Supernovae:

- End of massive stars
- Birthplace of heavy elements, pulsars, black holes …
- Particle acceleration
- …

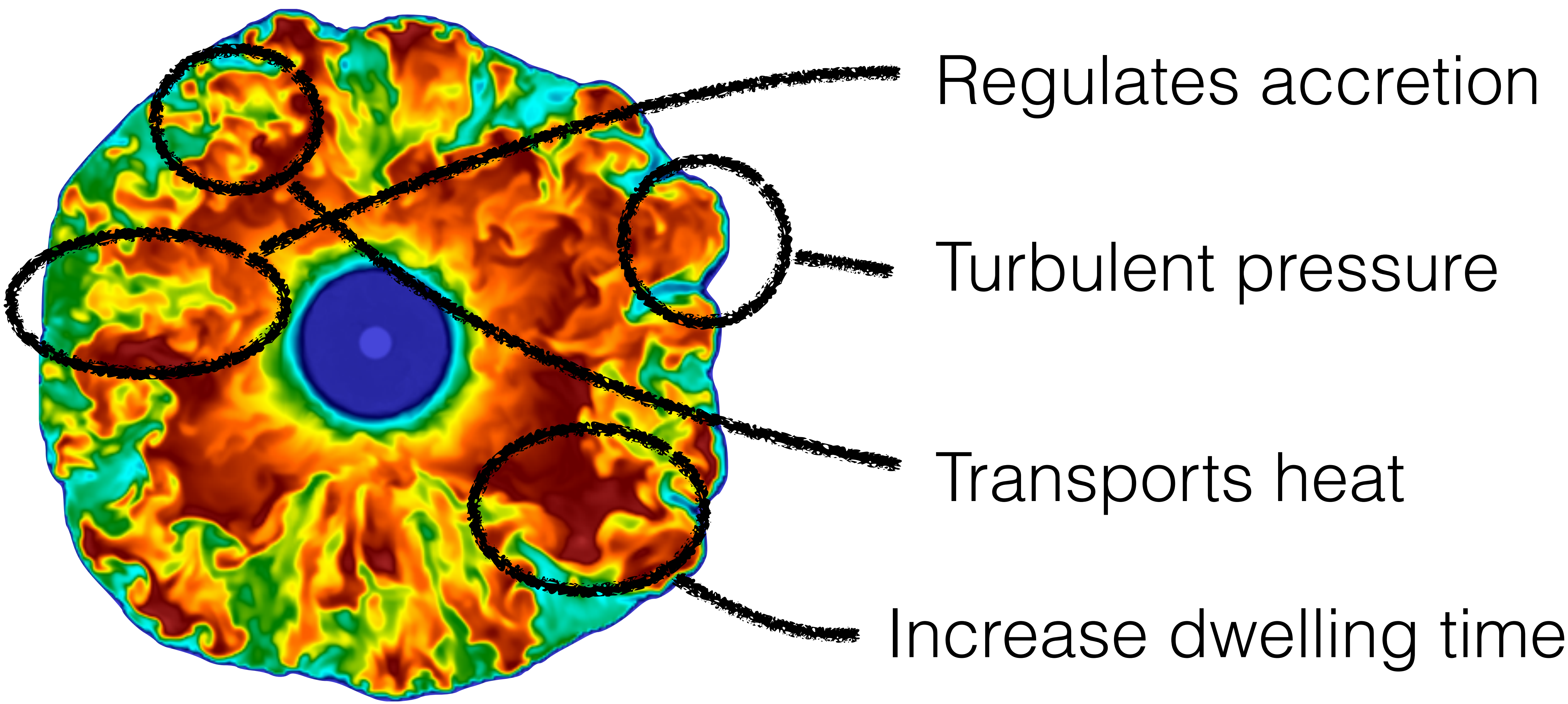
Problem: how do they explode?

Shock Revival by Neutrinos



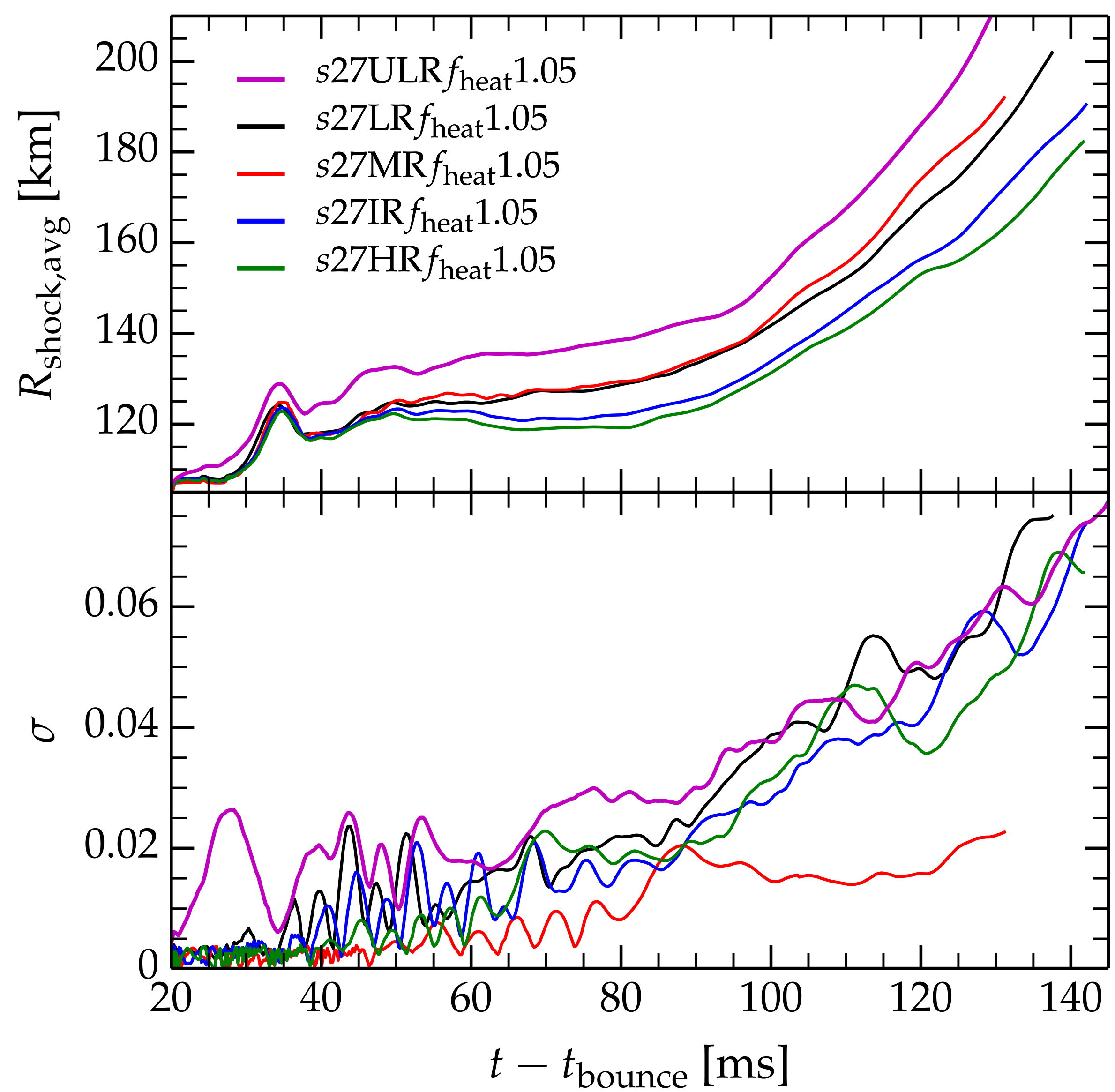
From Janka 2001

The Roles of Turbulence



Difficult to simulate!

Resolution Dependence



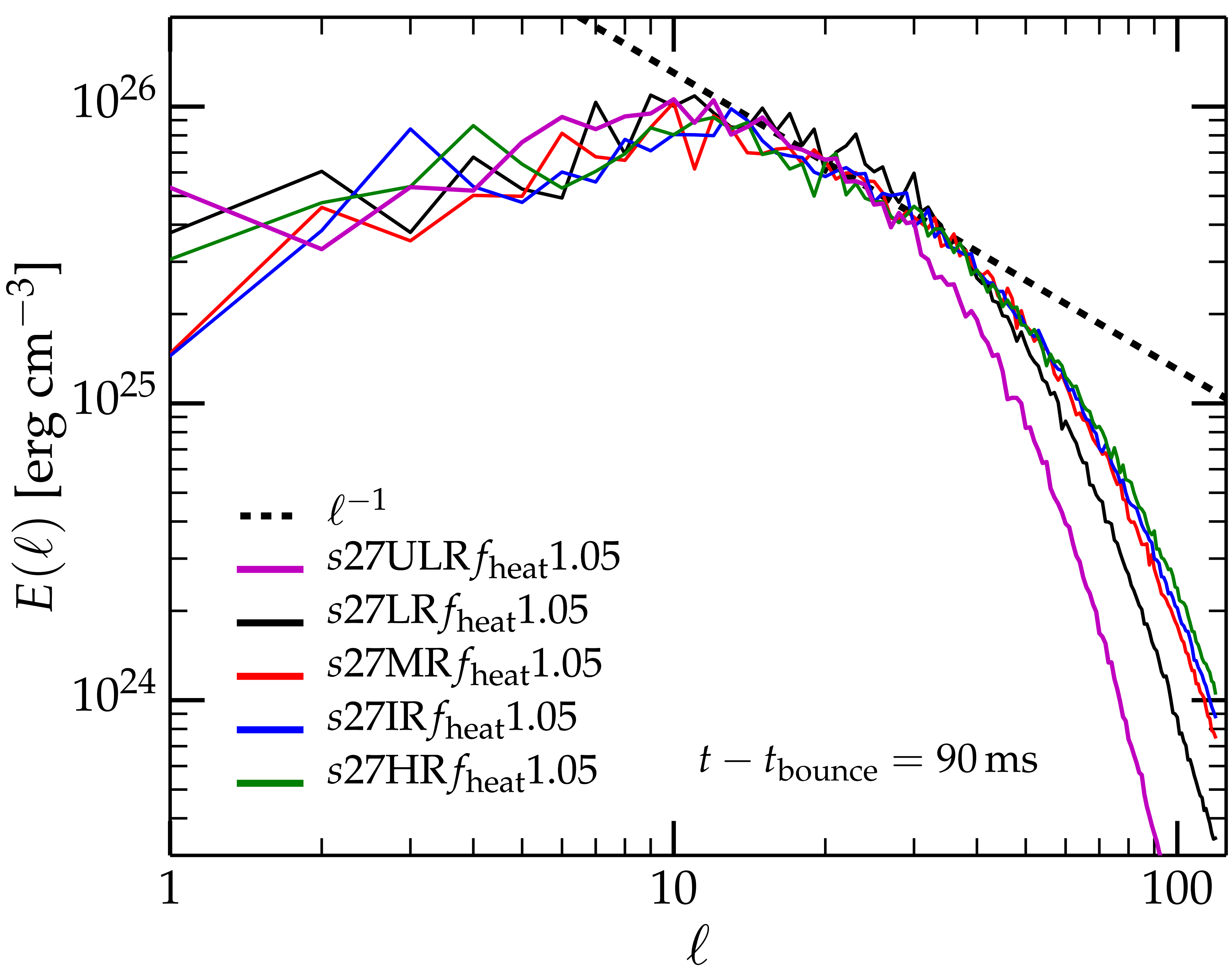
ULR	3.78 km
LR	1.89 km
MR	1.42 km
IR	1.24 km
HR	1.06 km

Resolutions

Explosion more difficult at higher resolution!

Abdikamalov, Ott, **DR**+ 2015

Turbulent Energy Spectrum



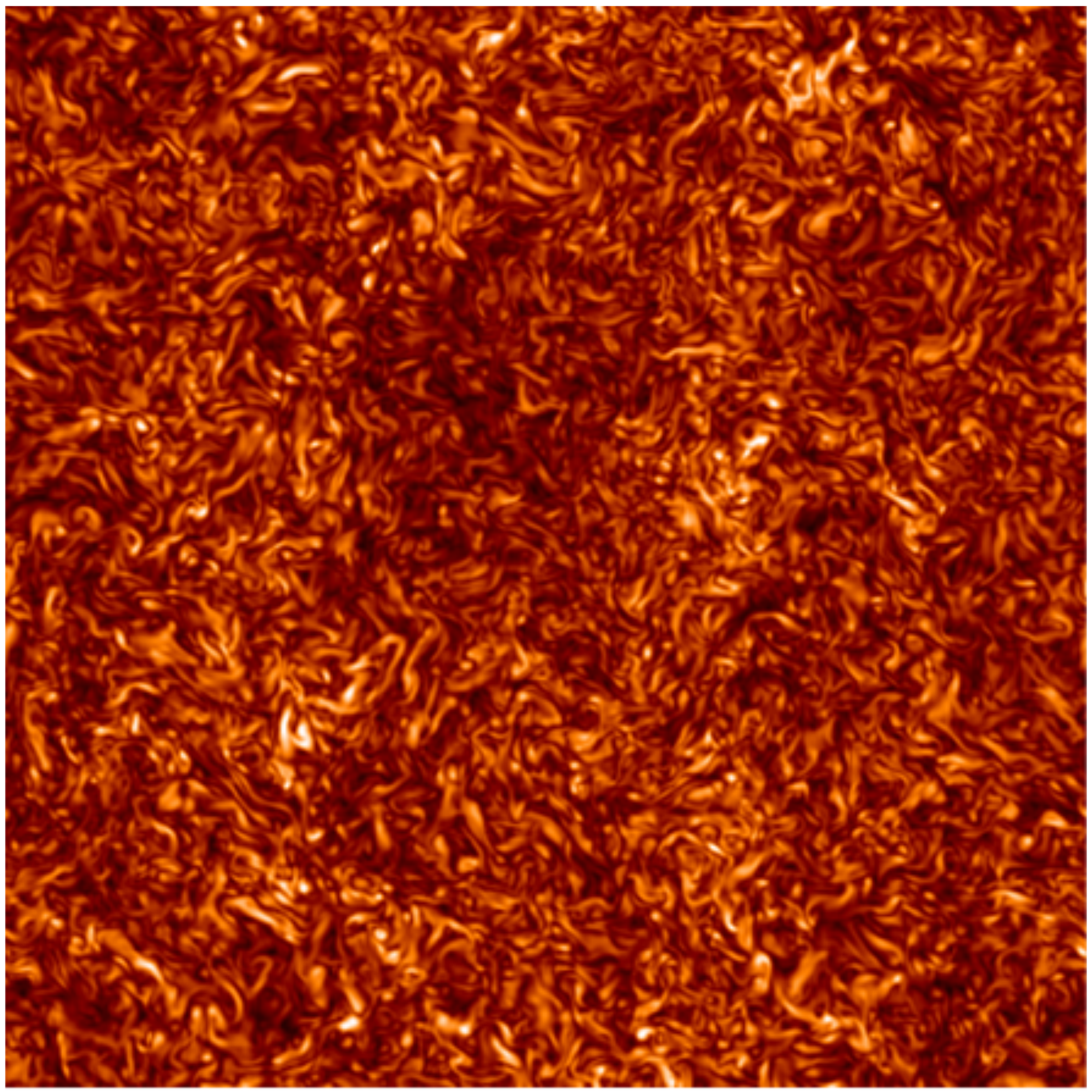
Abdikamalov, Ott, **DR**+ 2015

Open Questions

- When is the resolution good enough?
- How does neutrino-driven convection work?
- What is the main role of turbulence?

Our approach: local and semi-global simulations

Local Simulations

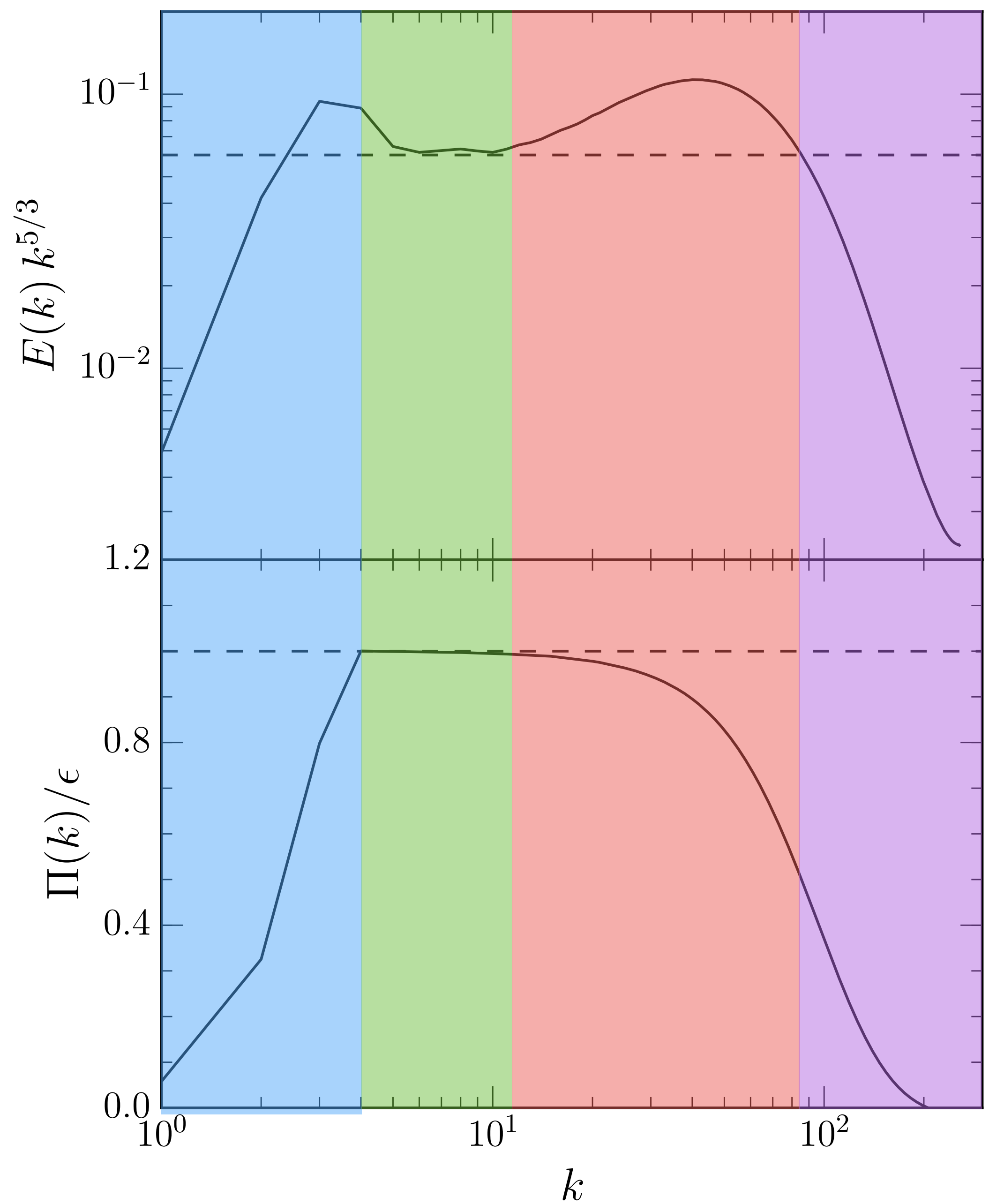


PPM+HLLC, N=512^3, Vorticity

- Periodic box
- Anisotropic
- Mildly compressible
- Study energy cascade

DR, Couch, Ott 2015

Energy Cascade (I)

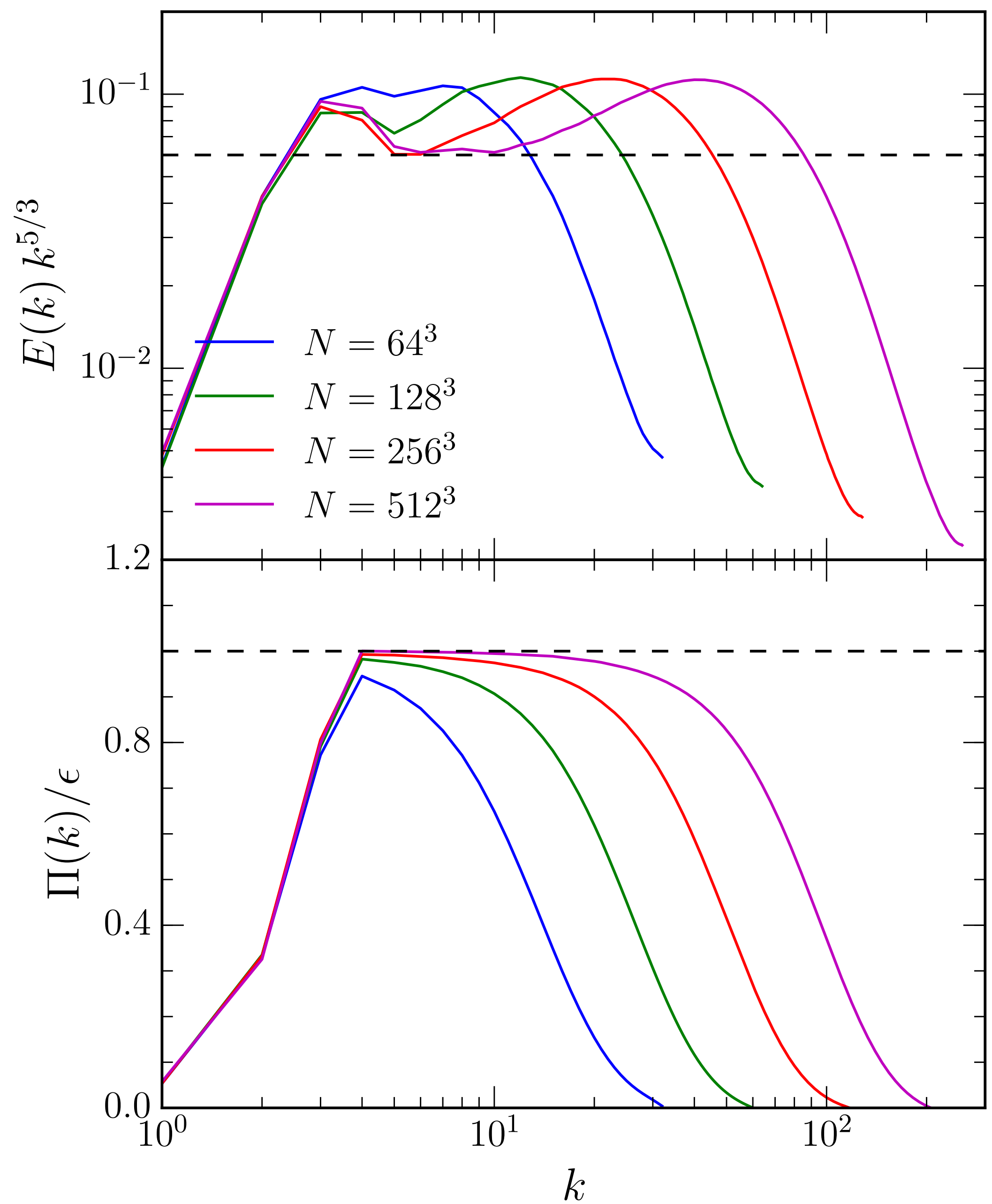


PPM+HLLC, N = 512^3

- Energy injection scale
- Inertial range
- Bottleneck
- Dissipation range

DR, Couch, Ott 2015

Energy Cascade (II)



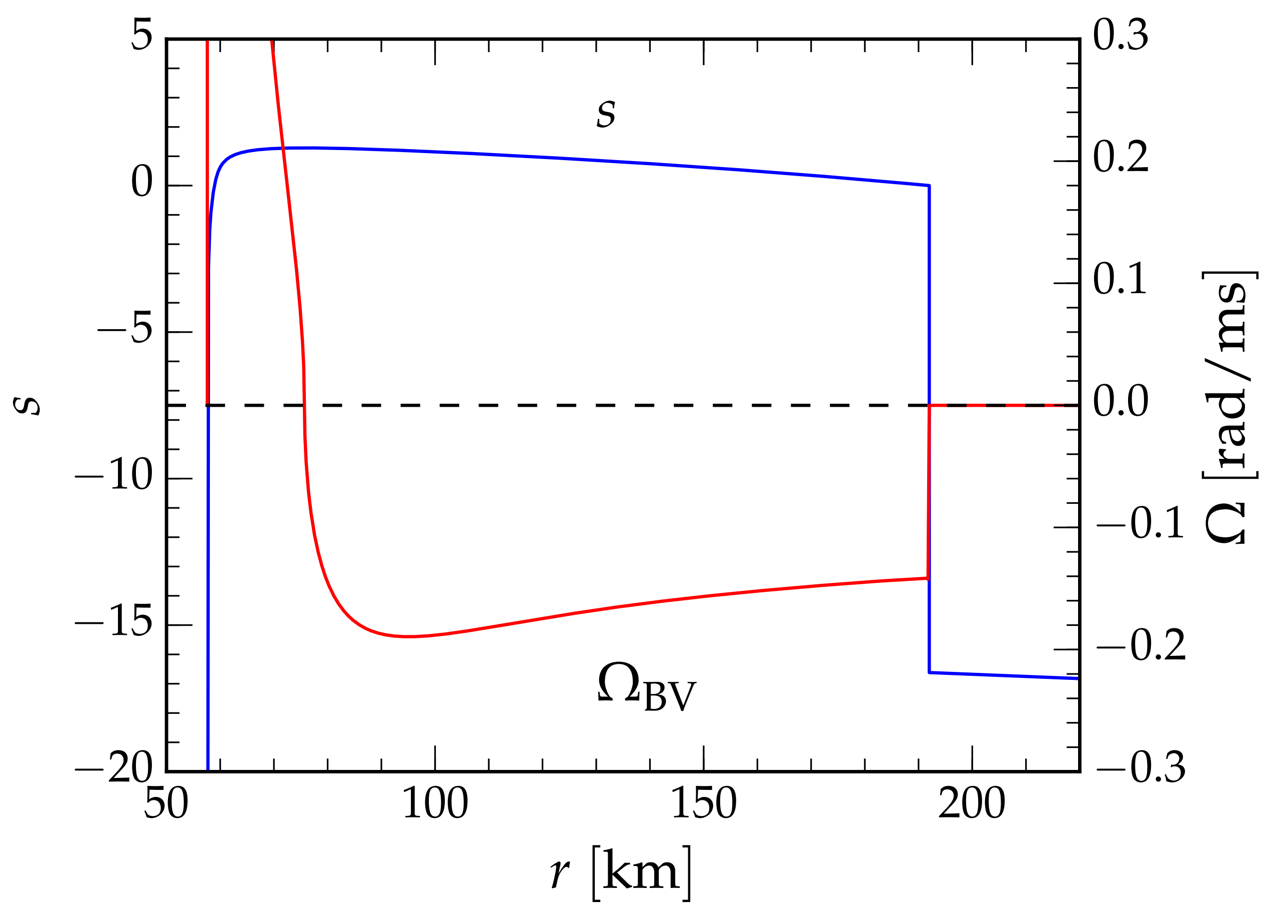
PPM+HLLC

- Global simulations ~ 64^3
  bottleneck dominated!
- 2x: start to converge
- 8x: inertial range

DR, Couch, Ott 2015

Semi-Global Simulations

- Local simulations: instructive, but very simplified
- Global simulations: expensive, more difficult to interpret

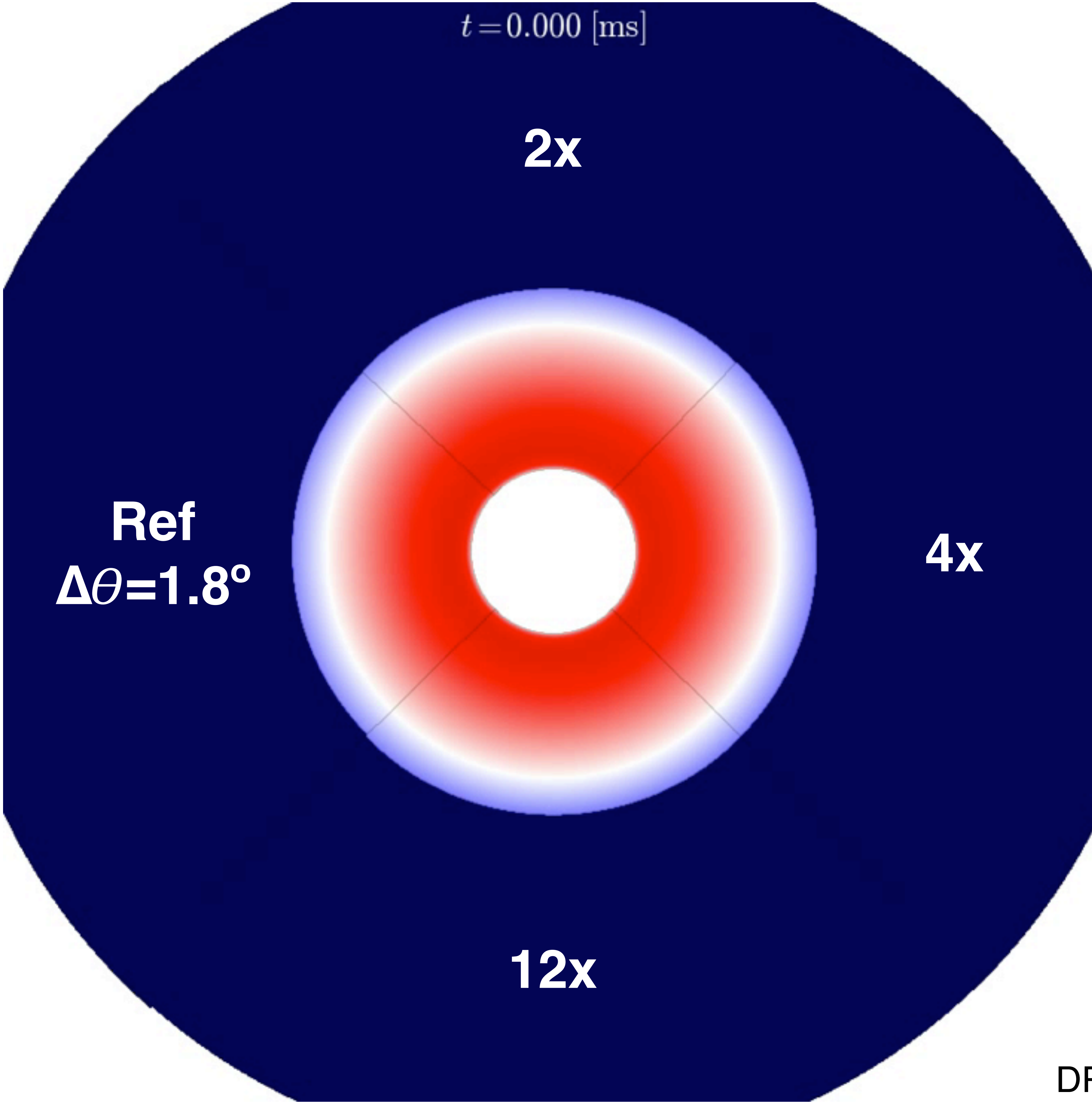


Semi-global simulations: initial data

Semi-global simulations

- Stationary initial conditions
- 90^o 3D wedge domain
- Simplified neutrino cooling/heating
- Simplified nuclear dissociation treatment

DR, Ott+ 2016



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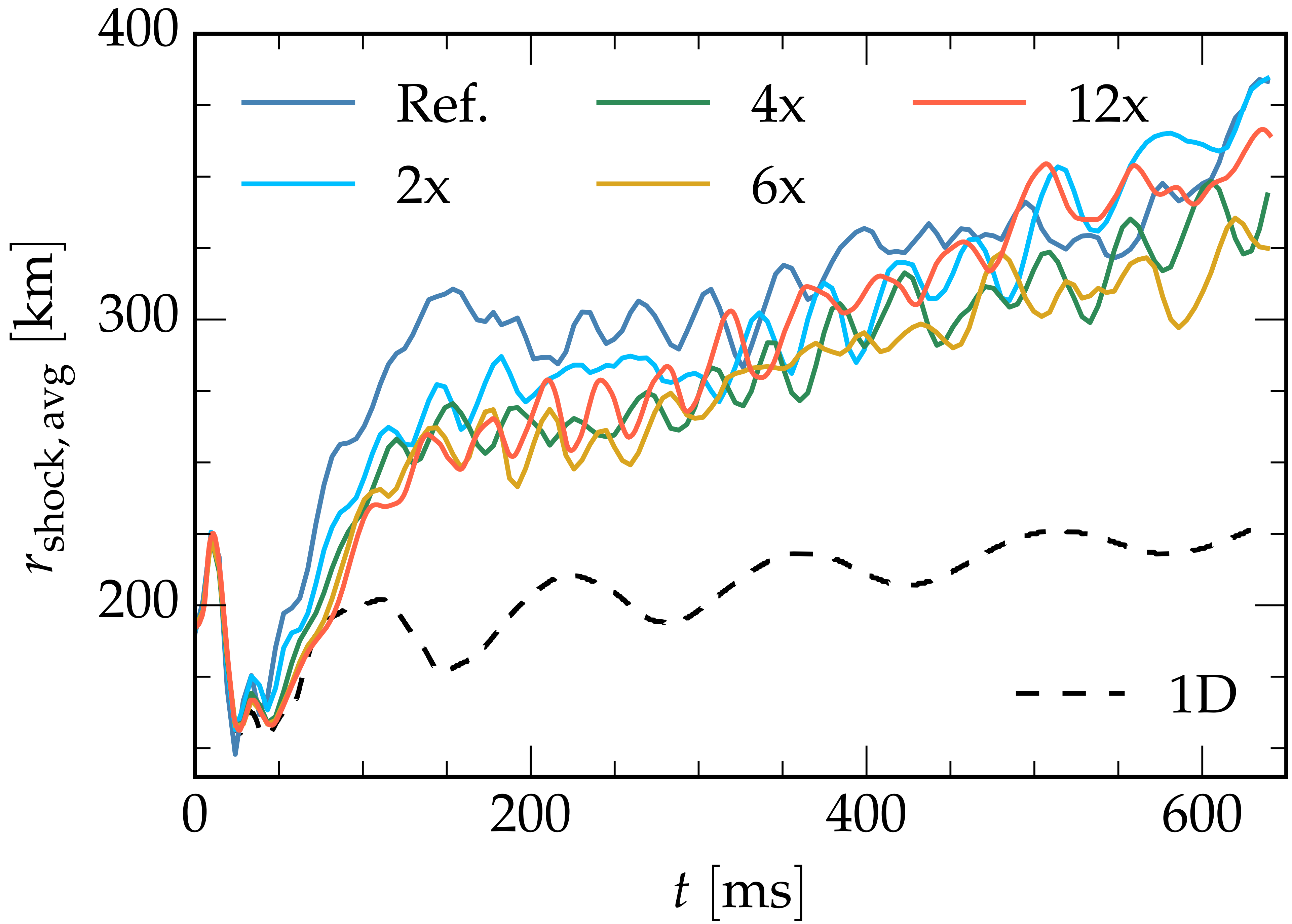
Global Dynamics



Shock radius

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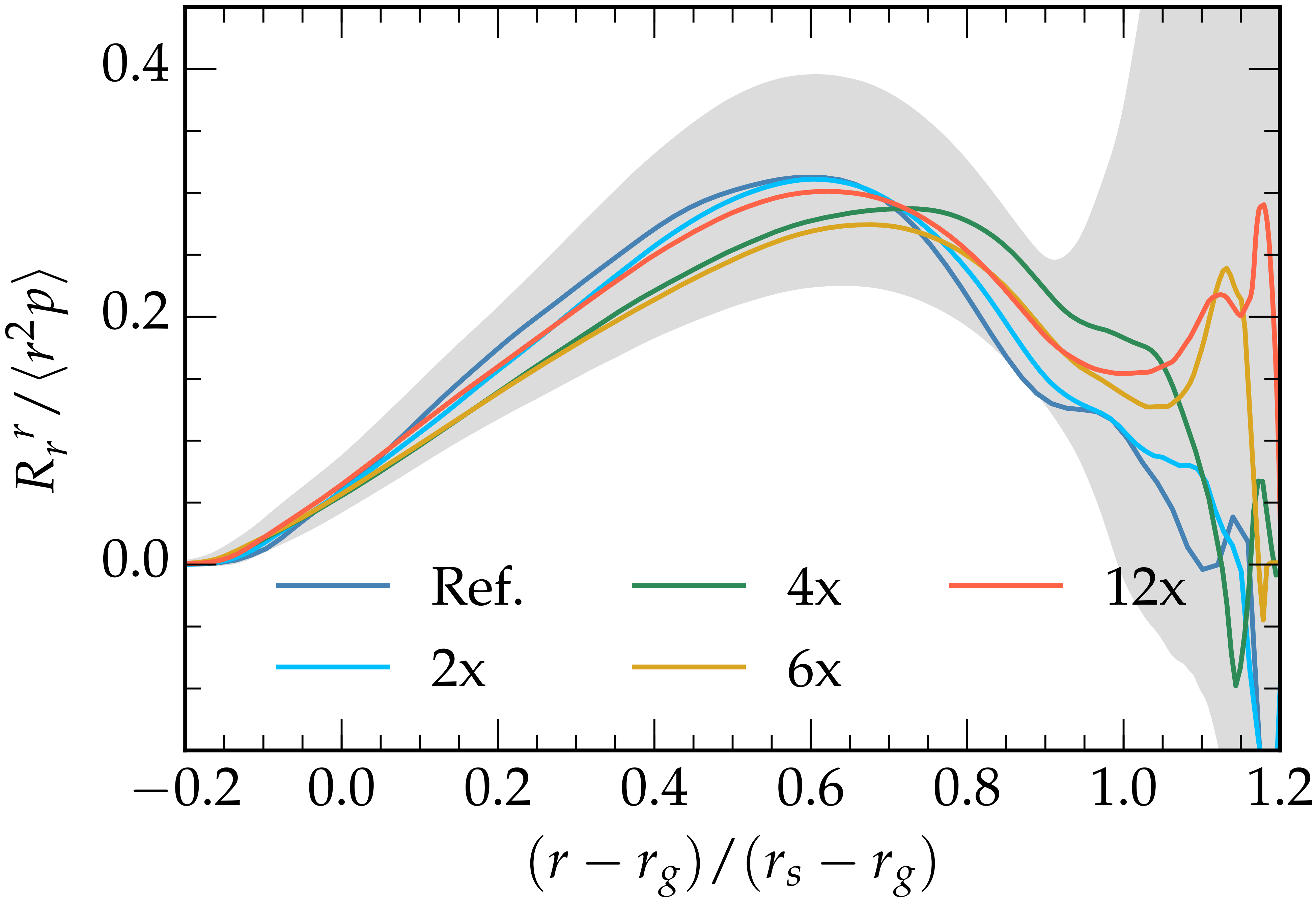
Turbulent Pressure



Turbulent pressure

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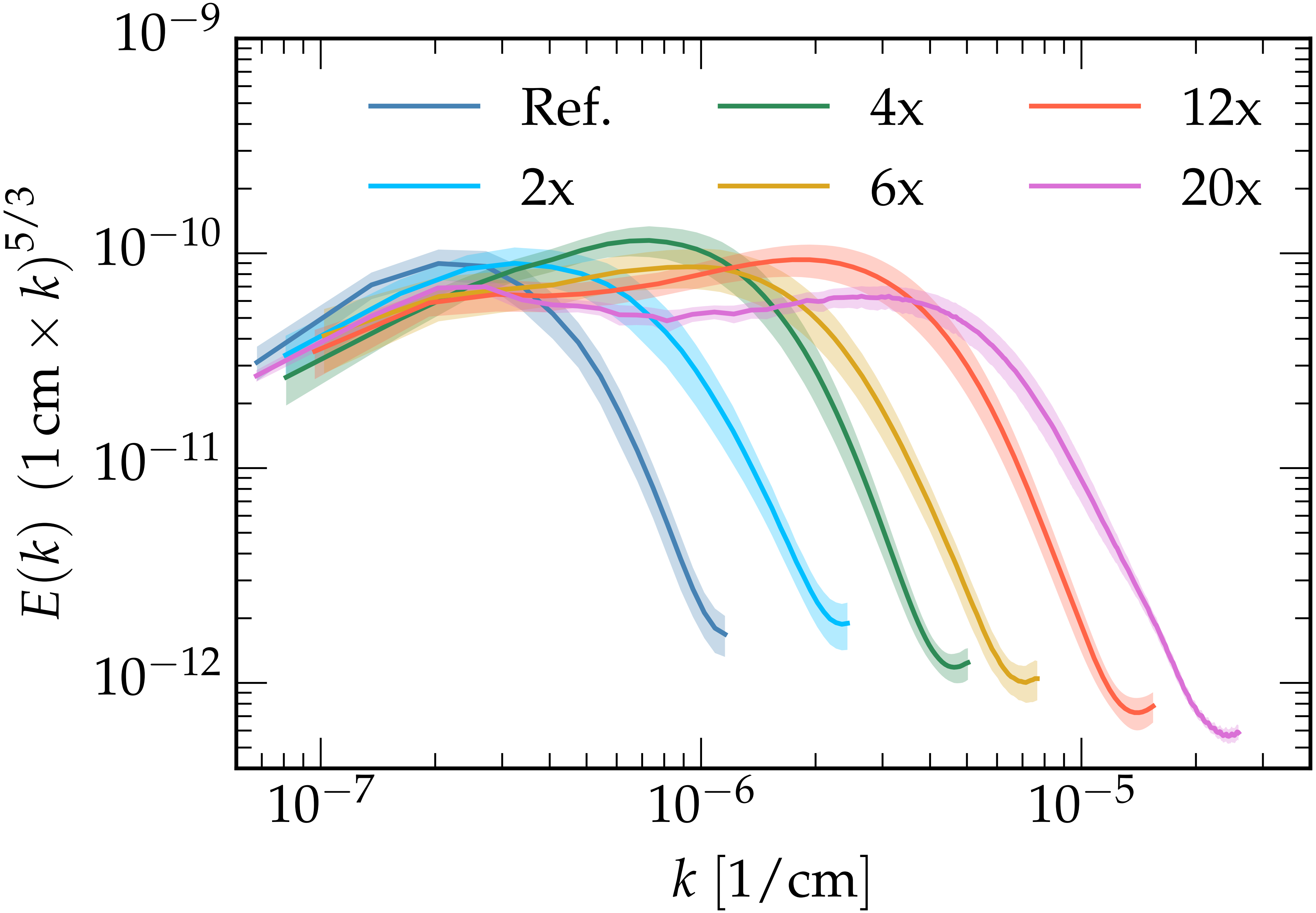
Turbulent Cascade



Turbulent energy spectra

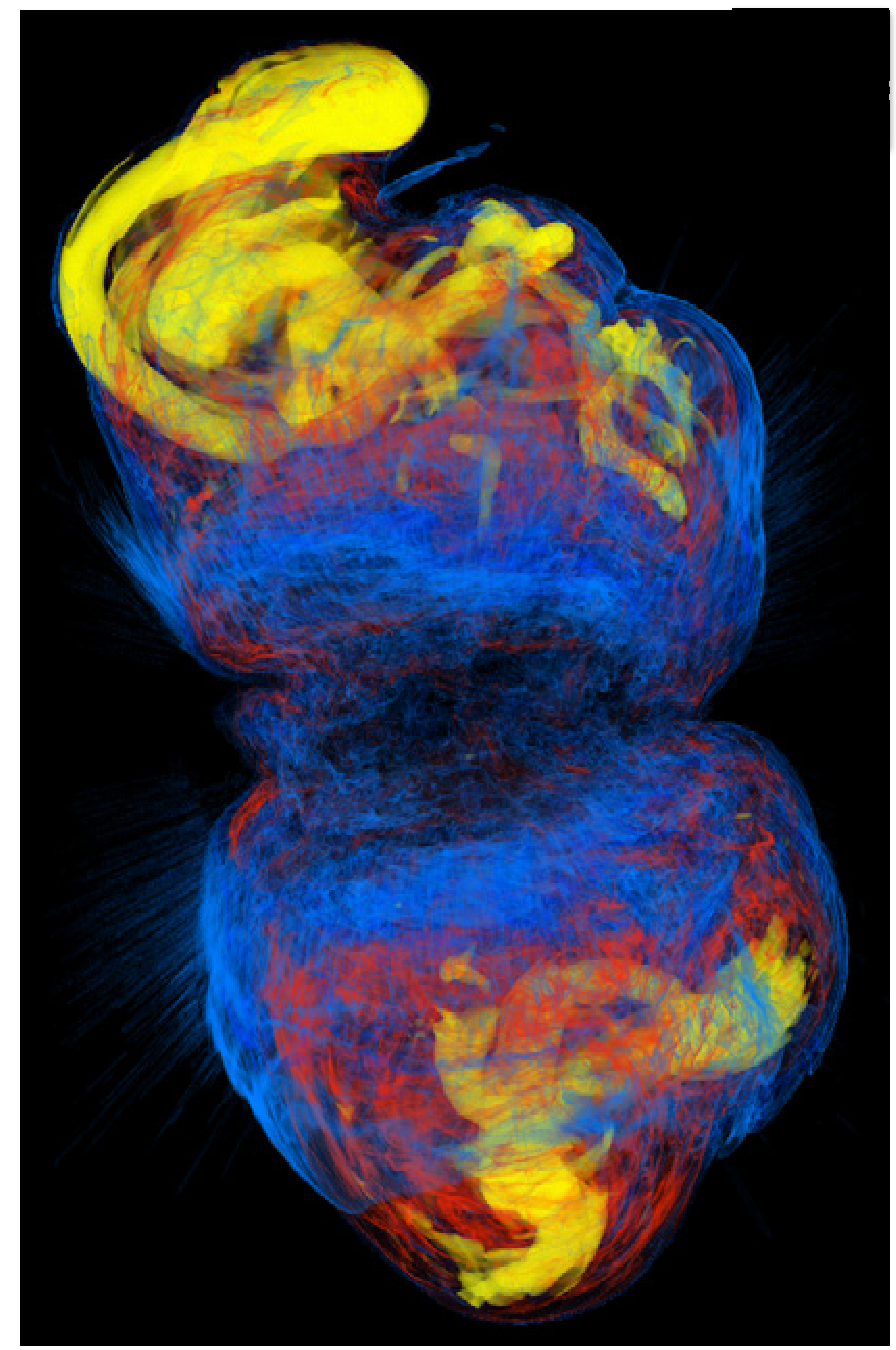
DR, Ott+ 2016

What about magnetic fields and rotation?

MHD-Powered Explosions

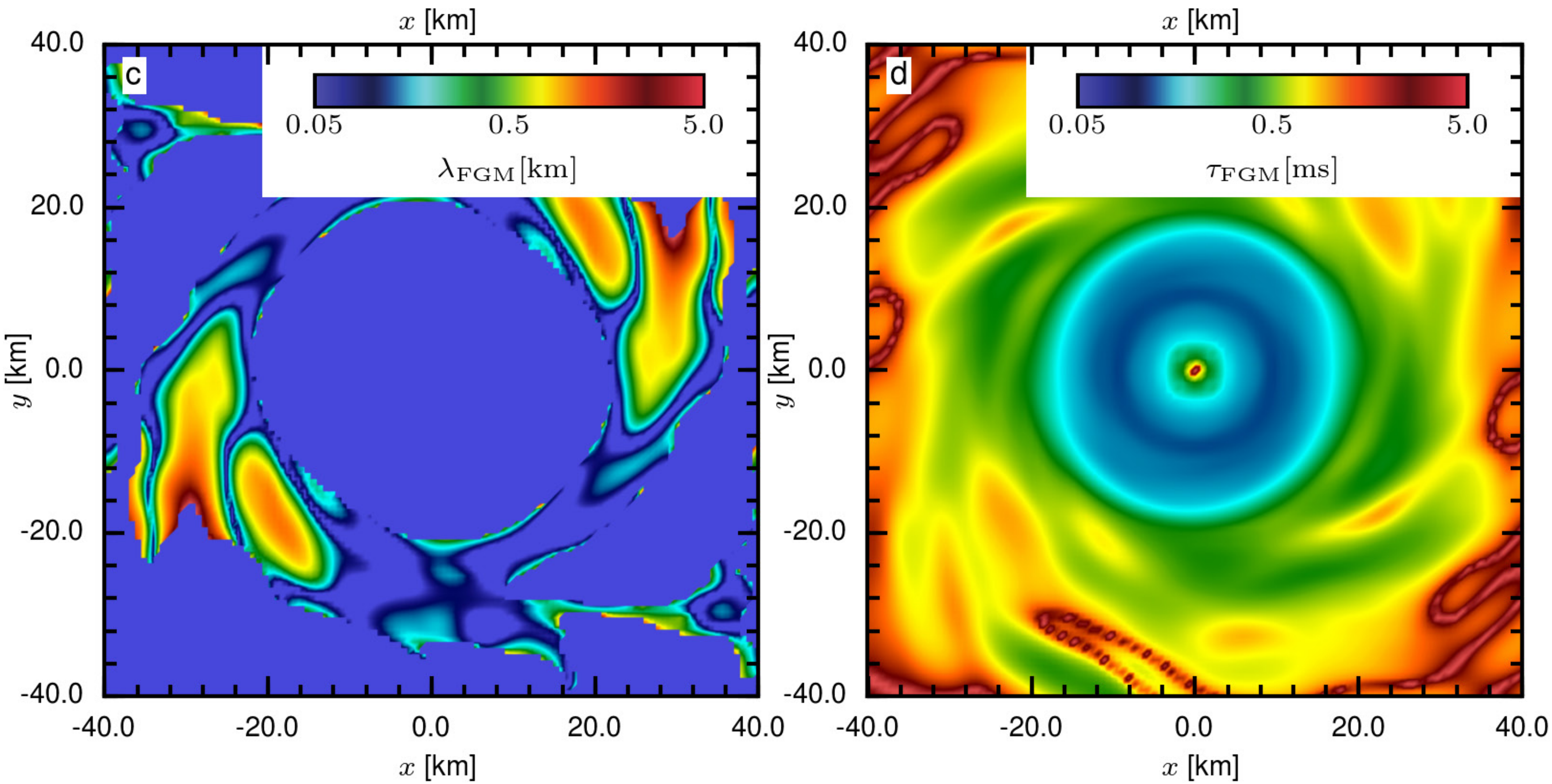
From Burrows+ 2007

- Fast rotation and strong magnetic fields can produce very powerful explosions
- Neutrinos cannot power hypernovae
- How to build up the magnetic field?



From Mösta+ 2014

The Magnetorotational Instability (I)

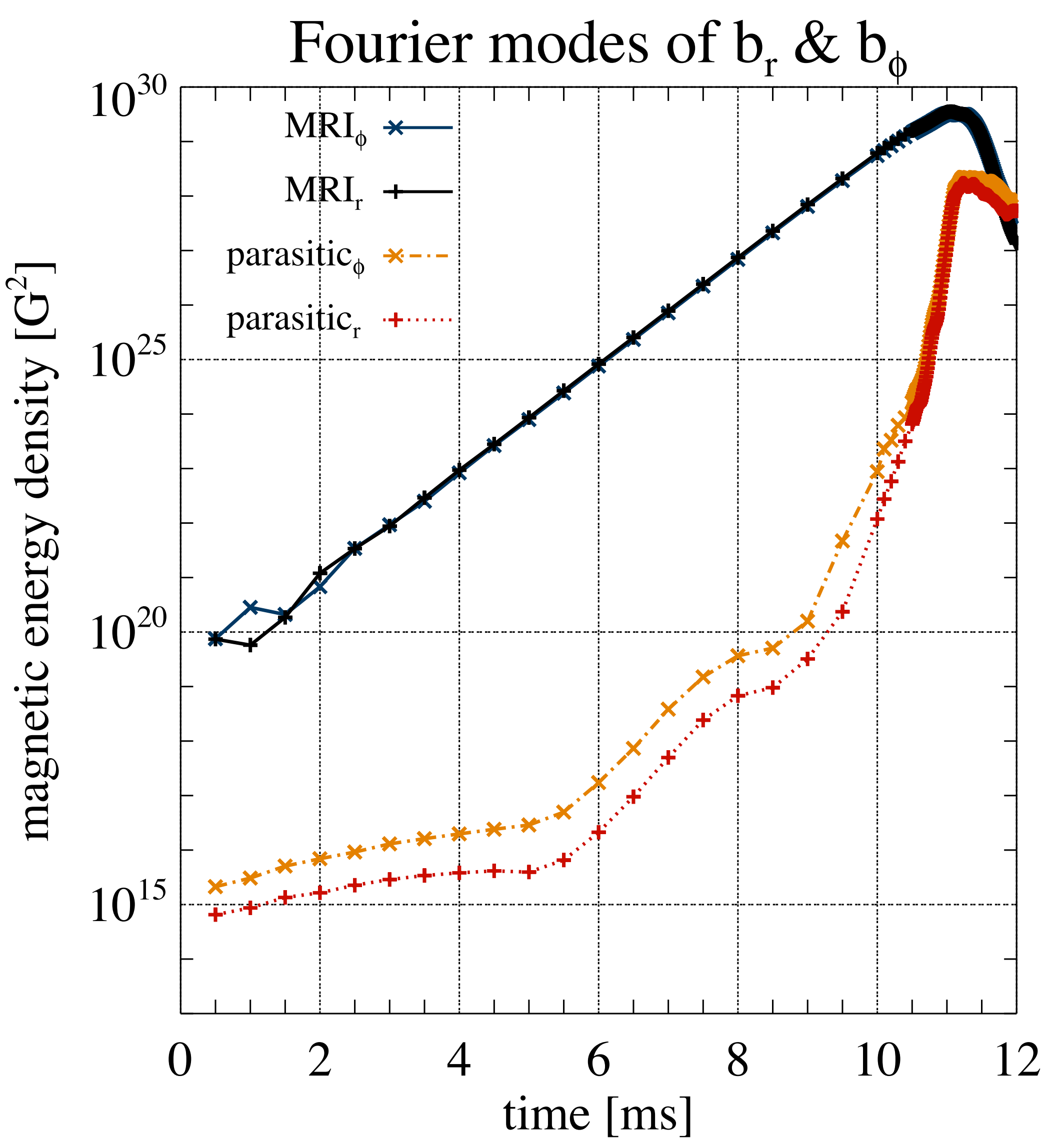


The MRI Must Be Operating

Mösta, Ott, **DR**+ 2015

The Magnetorotational Instability (II)

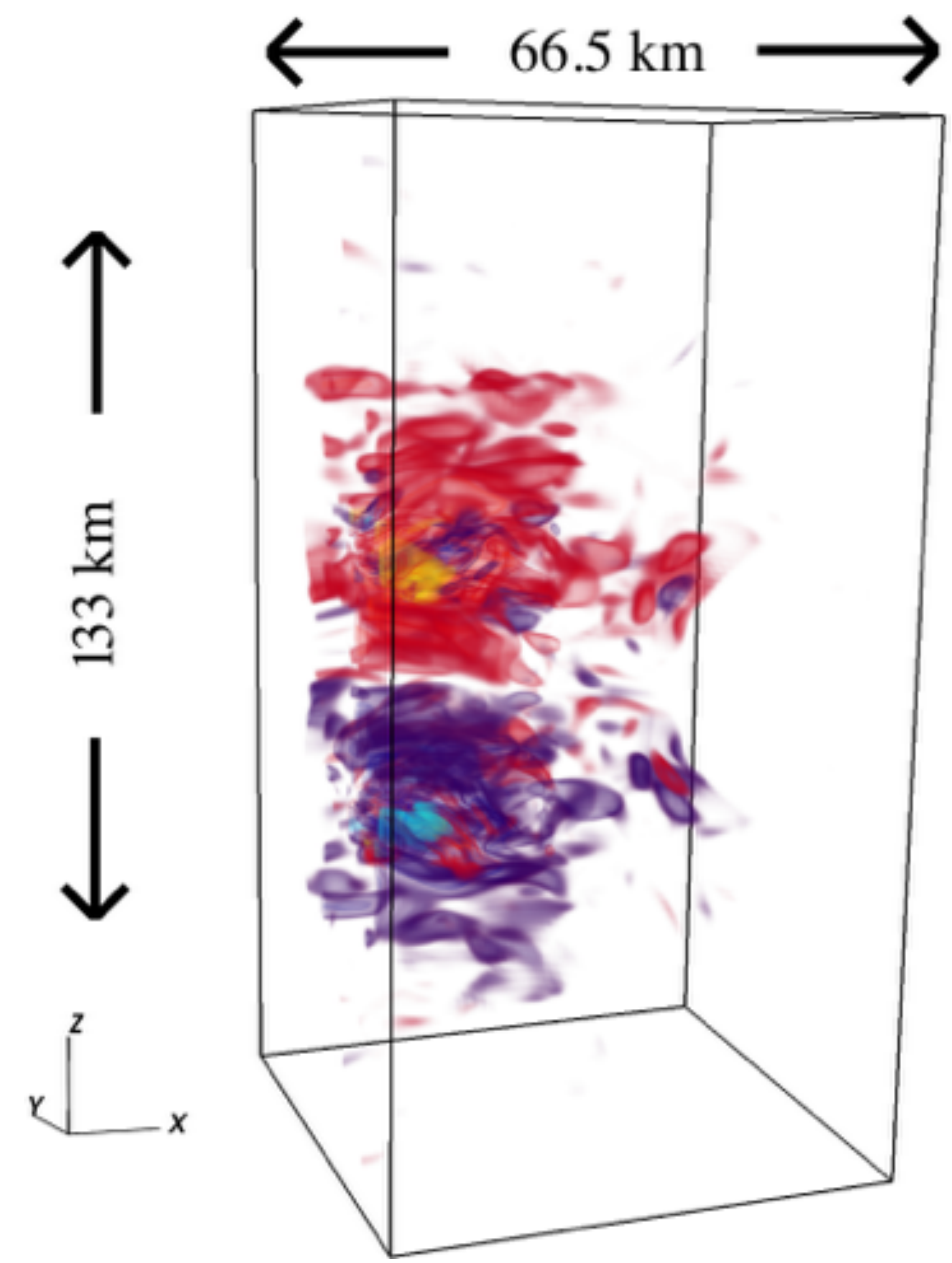
- Explosive growth of the magnetic field at small scales
- Global dynamics?
- Dynamo action?



From Rembiasz+ 2015

Global MHD Simulations

- 10 billion grid points
- 130 thousand cores on Blue Waters
- 2 weeks wall time
- 60 million compute hours



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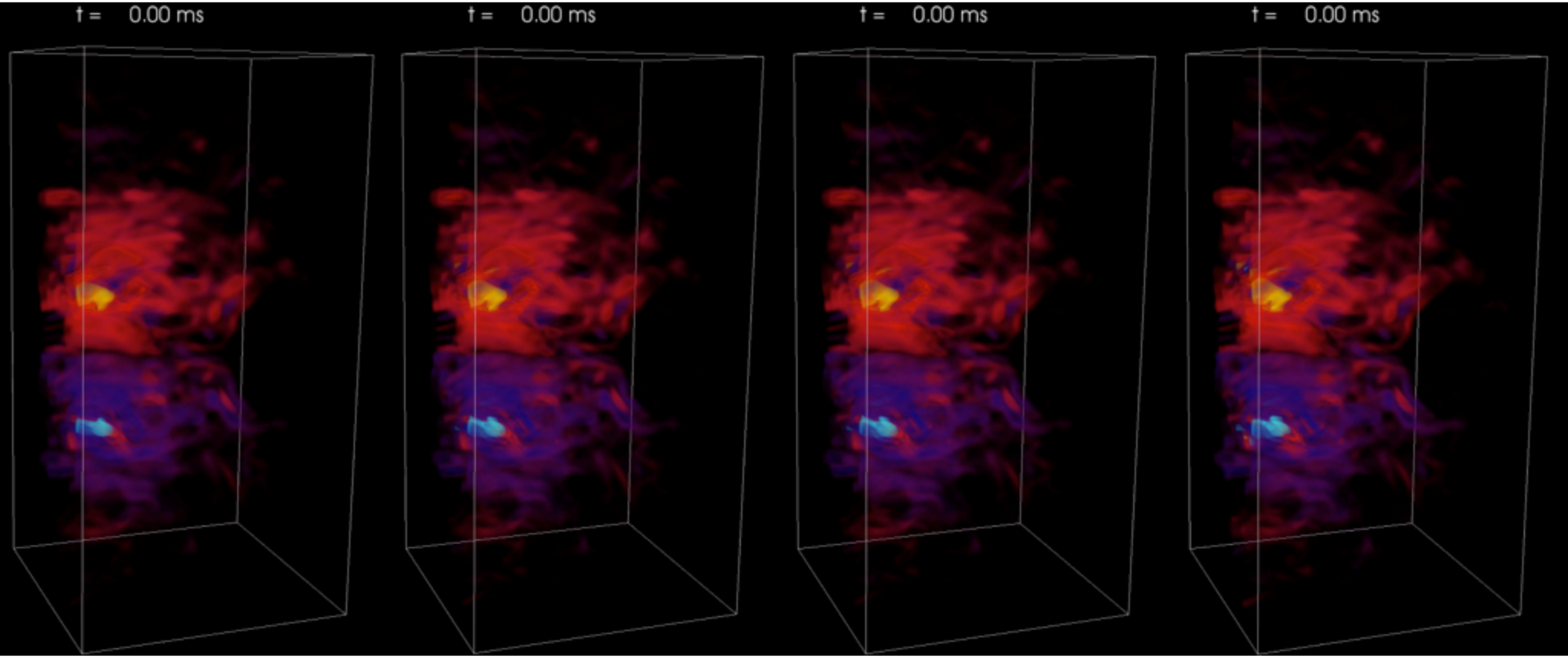
Magnetic Field Structure

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



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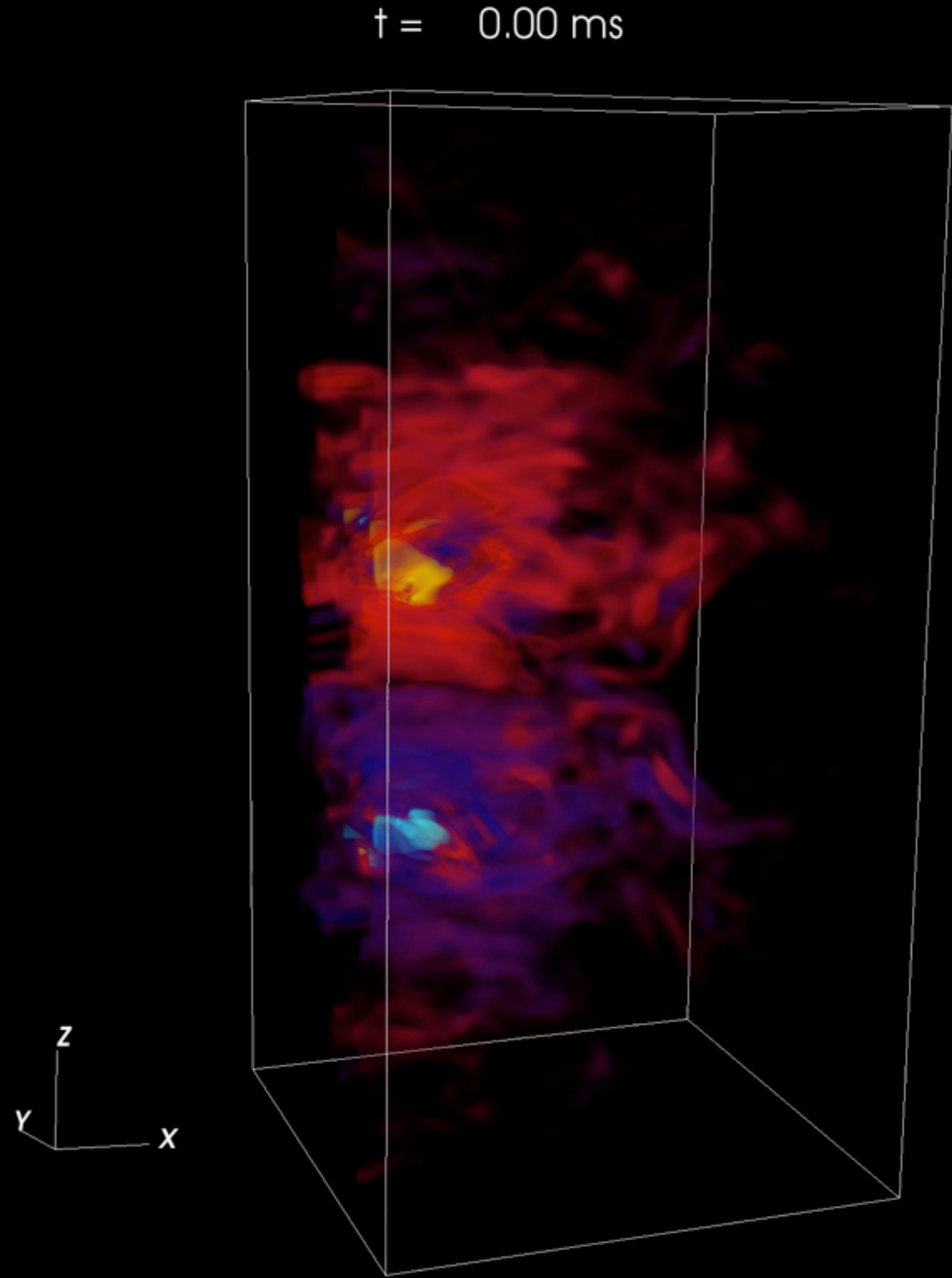
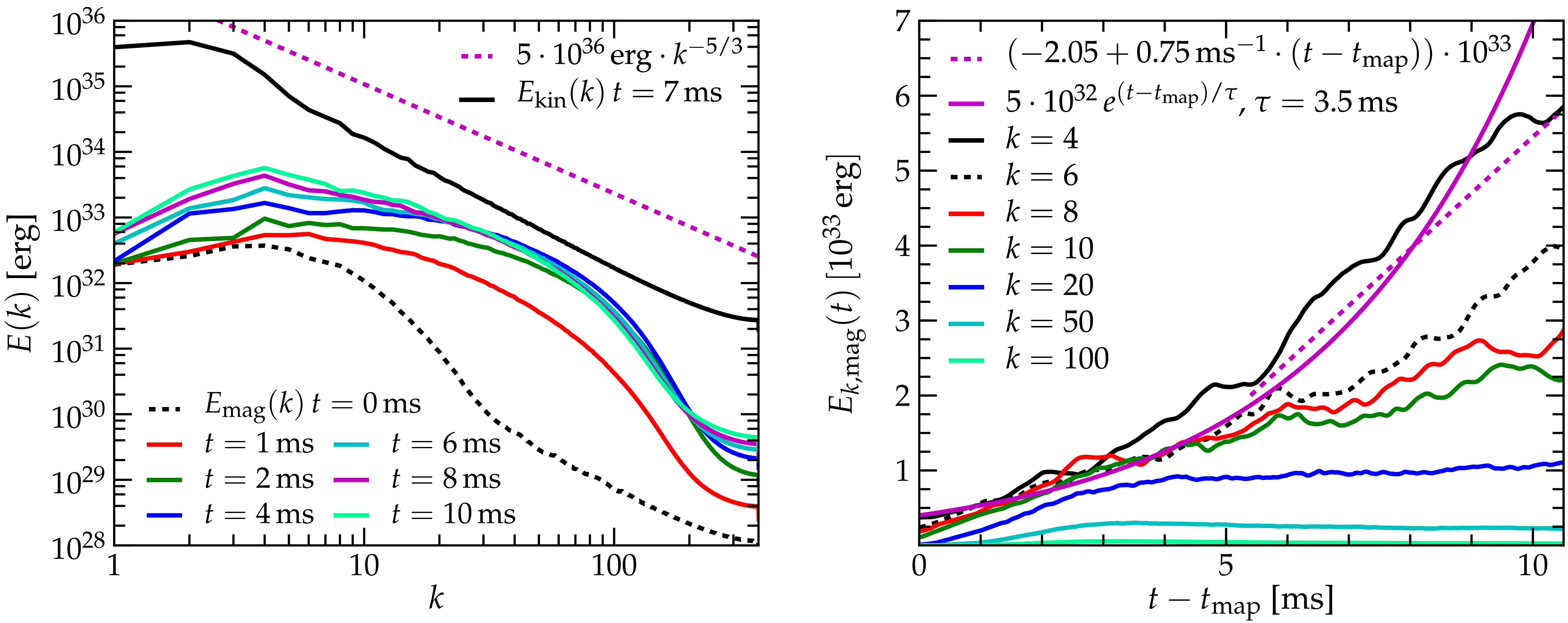

t = 0.00 ms
Z
Y
X

Dynamo Action



Fast growth at small scale and inverse cascade

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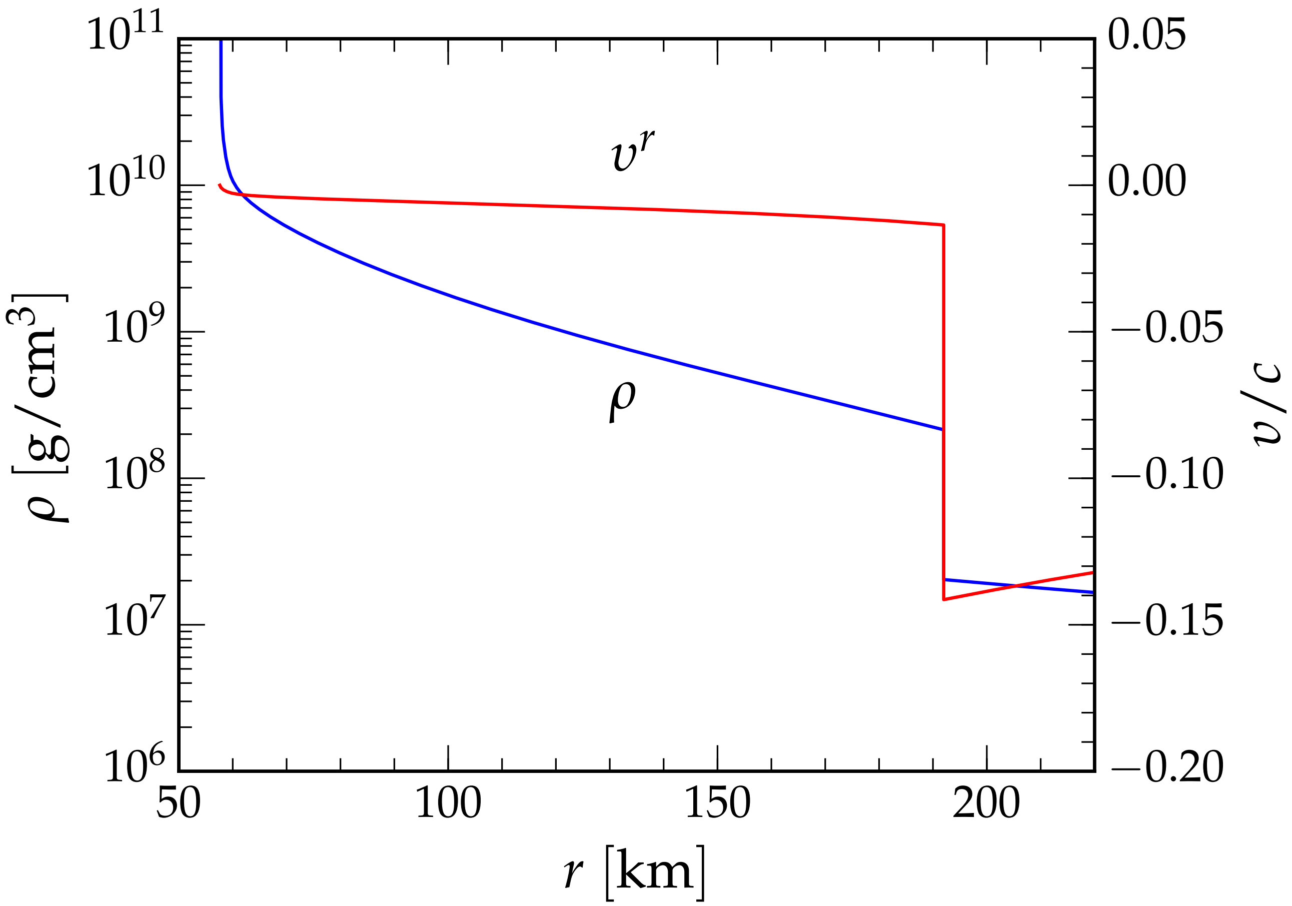
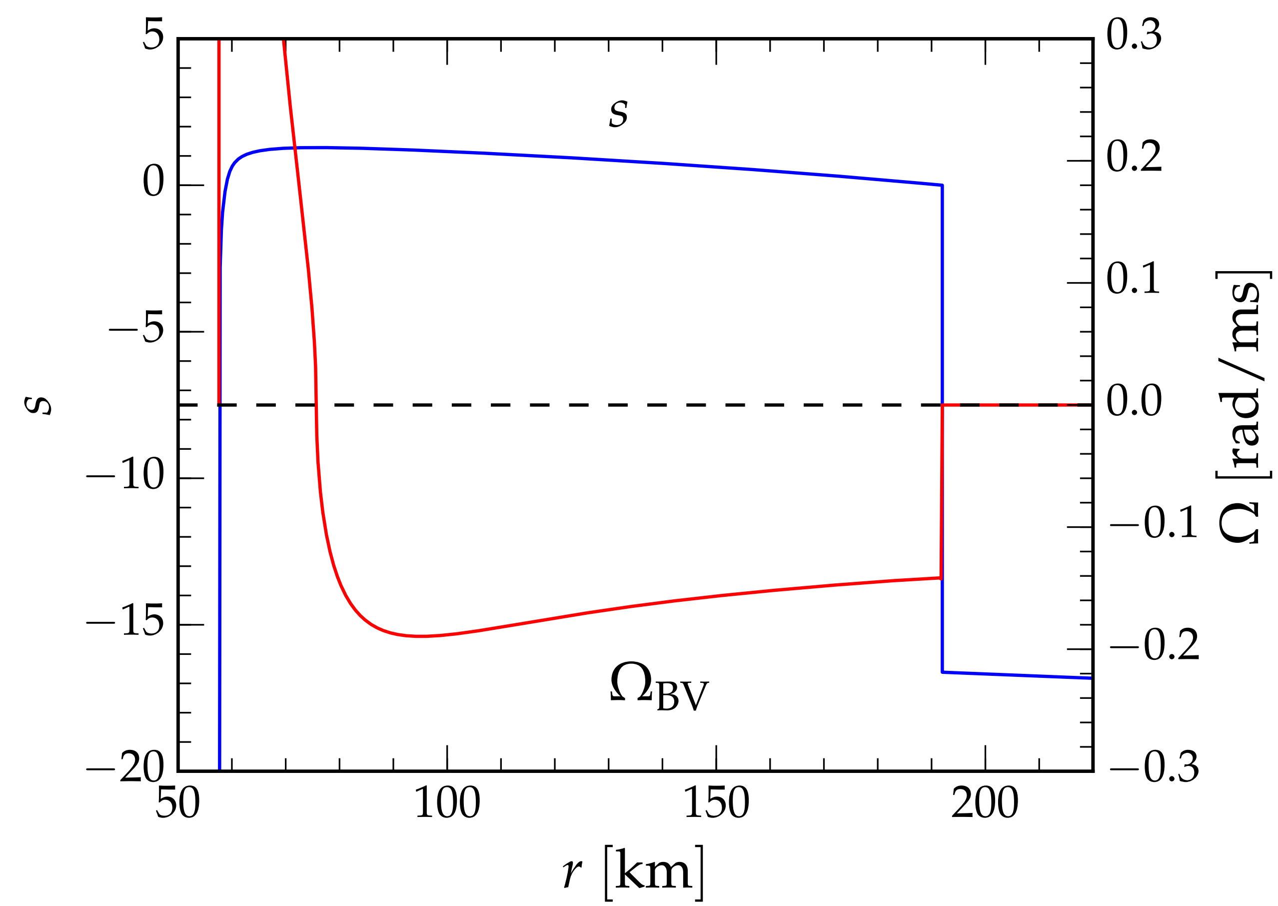
Conclusions

- Turbulence: need for very high resolutions
- Kolmogorov spectrum is recovered
- MHD: large-scale fields can be produced

Initial Data





Stationary initial data