Neutrino-Driven Turbulent Convection in Stalled Supernova Cores

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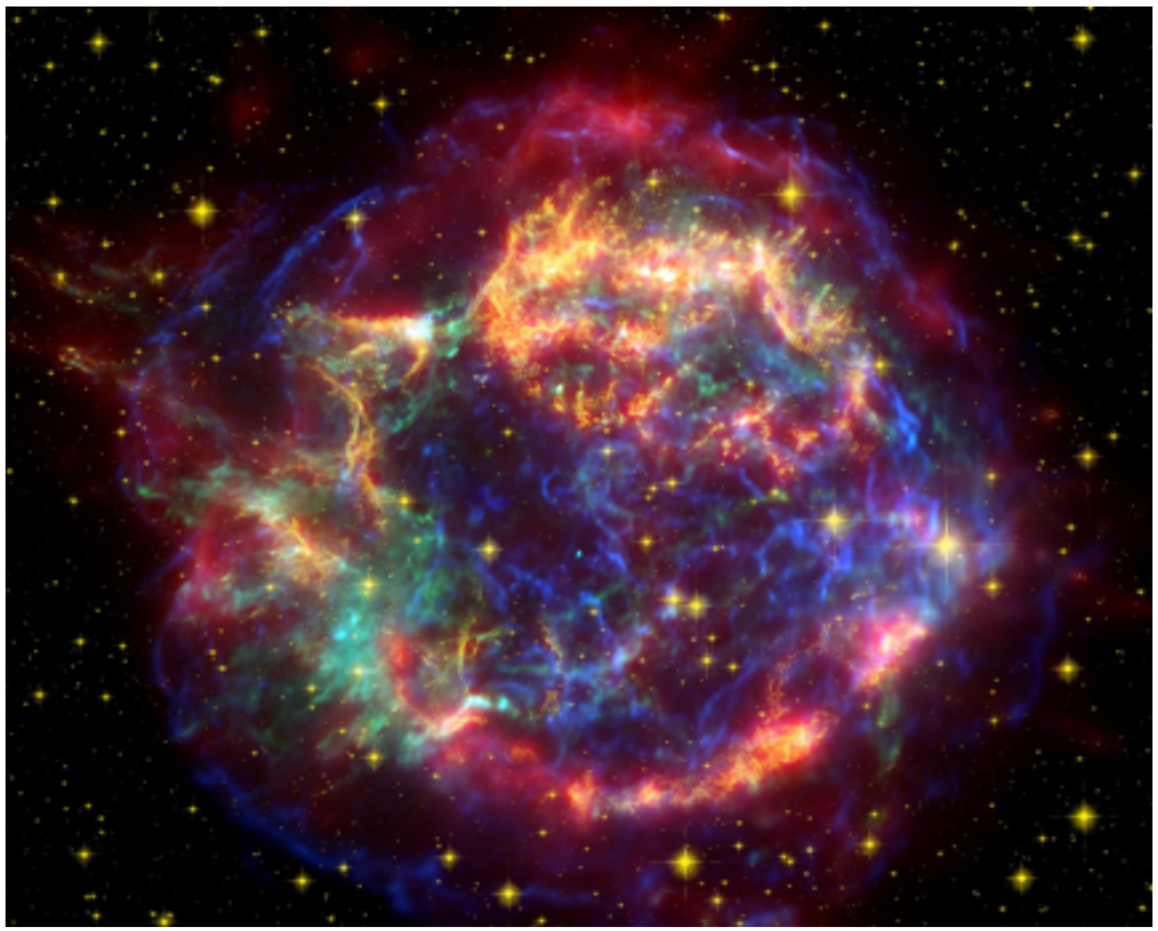
The Supernova Problem



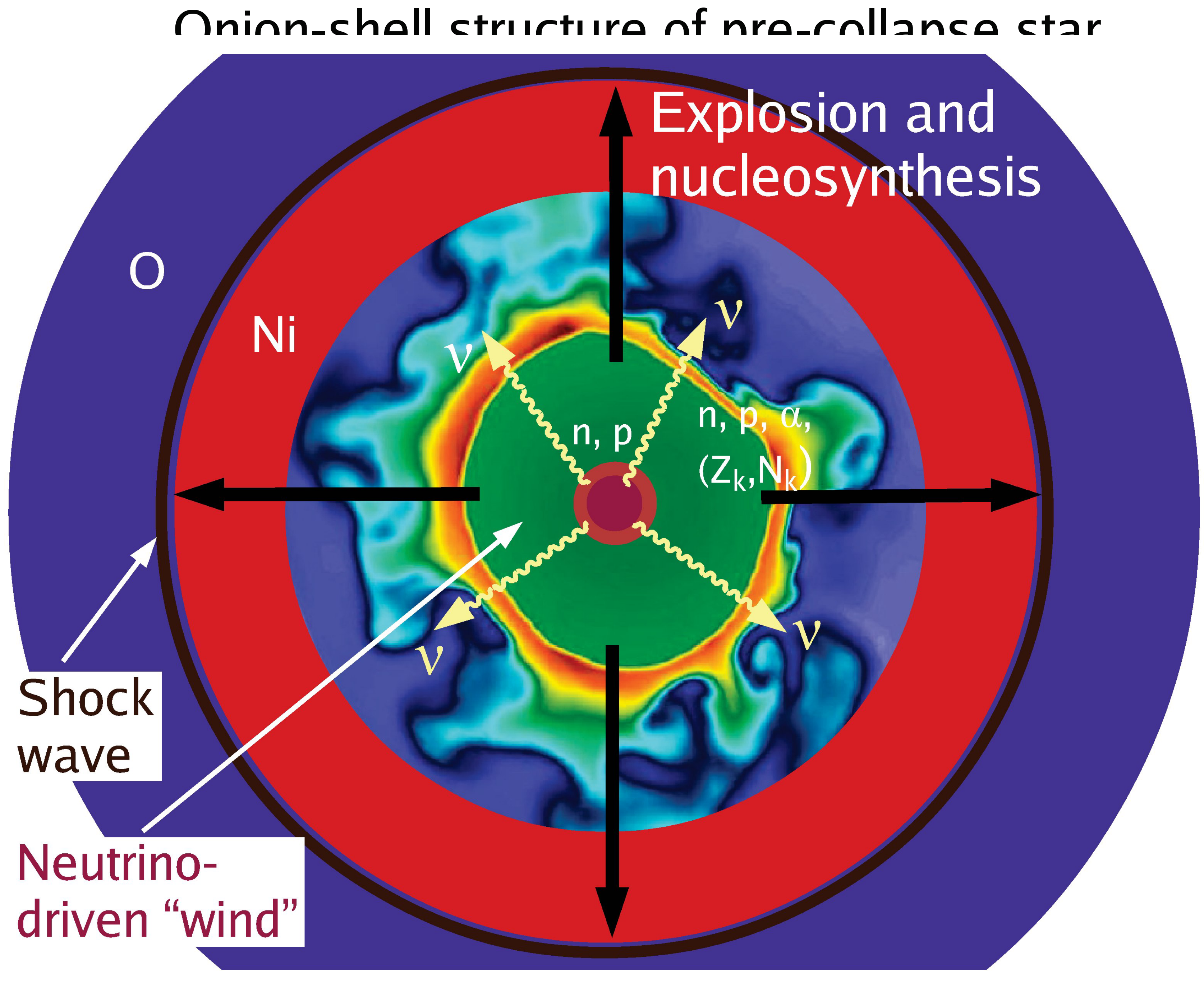
Cassiopeia-A

Core-Collapse Supernovae:

- End of massive stars
- Birthplace of heavy elements, neutron stars, black holes …
- Regulate star formation
- …

Problem: how do they explode?

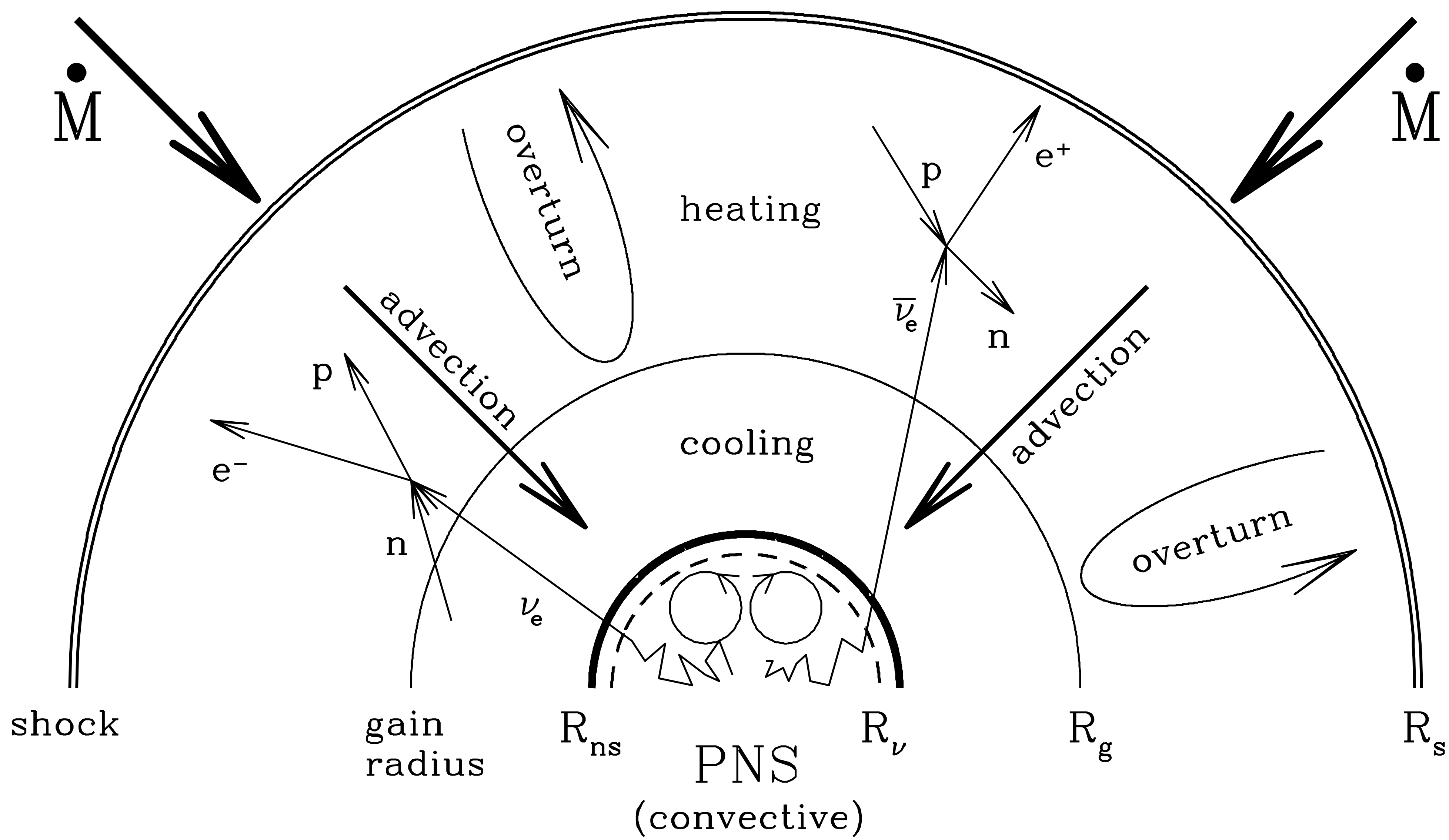
Core-Collapse Supernovae



(layers not drawn to scale)

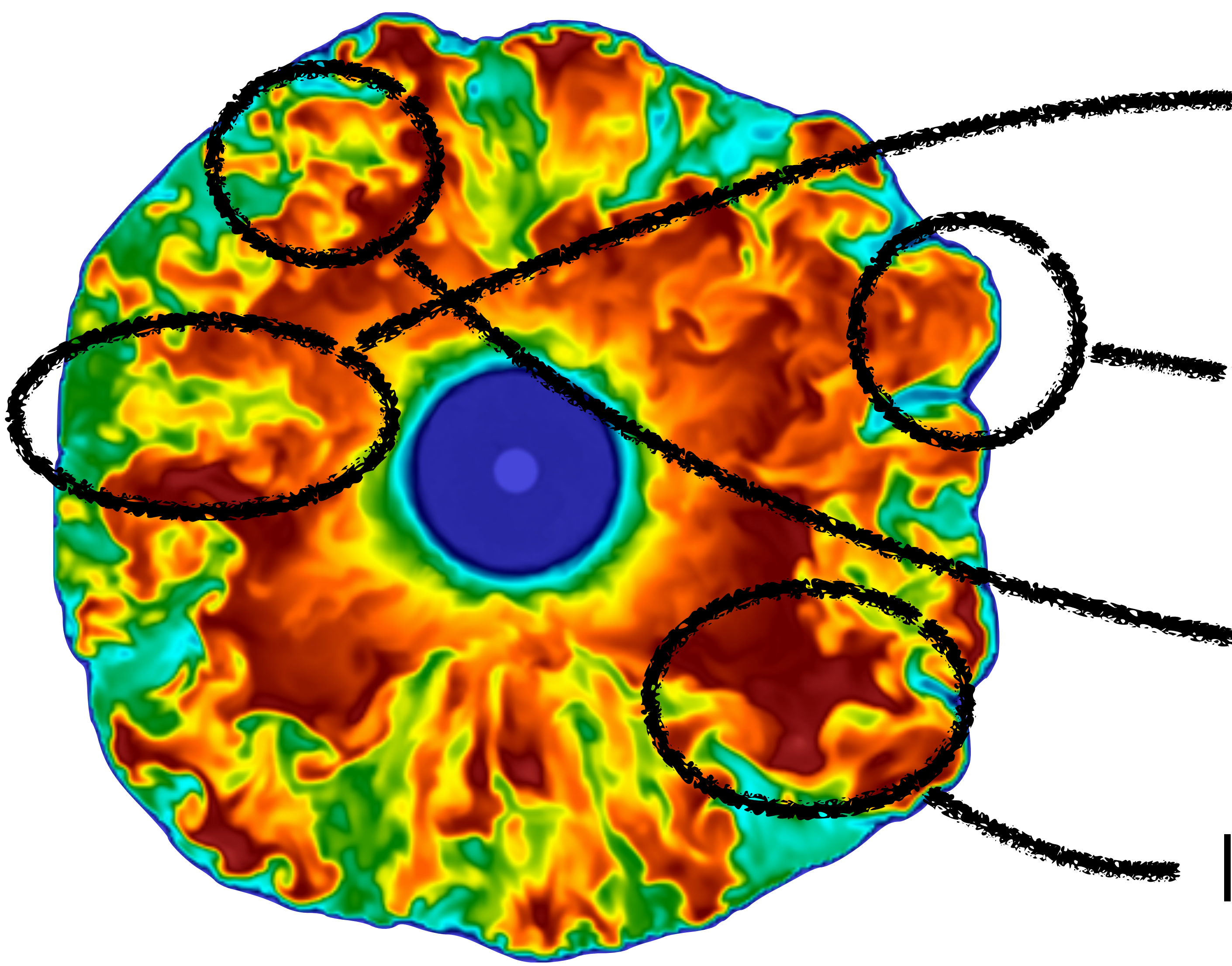
From Janka et al. 2012

Shock Revival by Neutrinos



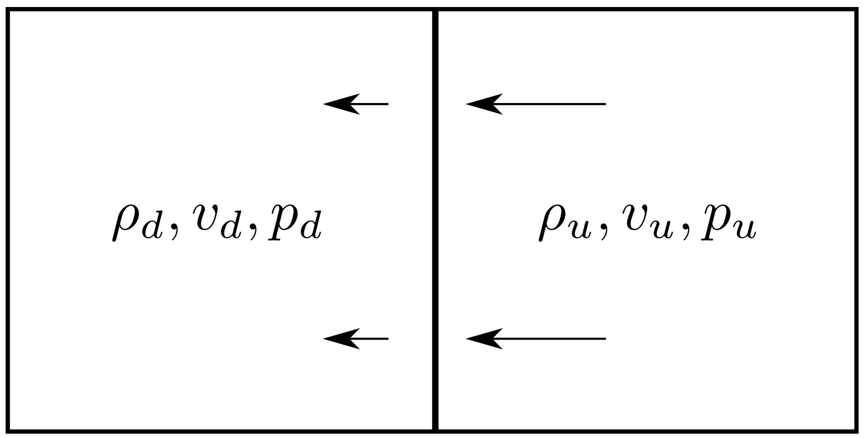
From Janka 2001

The Roles of Turbulence



Difficult to simulate!

Turbulent Pressure



Rankine-Hogoniot jump condition:

$$\rho_d v_d^2 + p_d = \rho_u v_u^2 + p_u$$

EOS:

$$p_d = (\gamma_{\rm th} - 1)\rho_d \epsilon_d \qquad \gamma_{\rm th} \simeq \frac{4}{3}$$

Effect of downstream turbulence (Murphy et al. 2013):

$$\rho_d v_d^2 + p_d \rightarrow \rho_d \bar{v}_d^2 + \rho_d (\delta v)_d^2 + p_d$$

$\gamma_{\rm turb} > \gamma_{\rm th}$!

Turbulence can be modeled with an effective EOS

$$\rho_d (\delta v)_d^2 \leftrightarrow (\gamma_{\rm turb} - 1)\rho_d \epsilon_{\rm turb} \qquad \gamma_{\rm turb} \simeq 2$$

Jump conditions for a shock with downstream turbulence:

$$\rho_d \bar{v}_d^2 + (\gamma_{\rm turb} - 1)\rho_d \epsilon_{\rm turb} + (\gamma_{\rm th} - 1)\rho_d \epsilon_d = \rho_u v_u^2 + p_u$$

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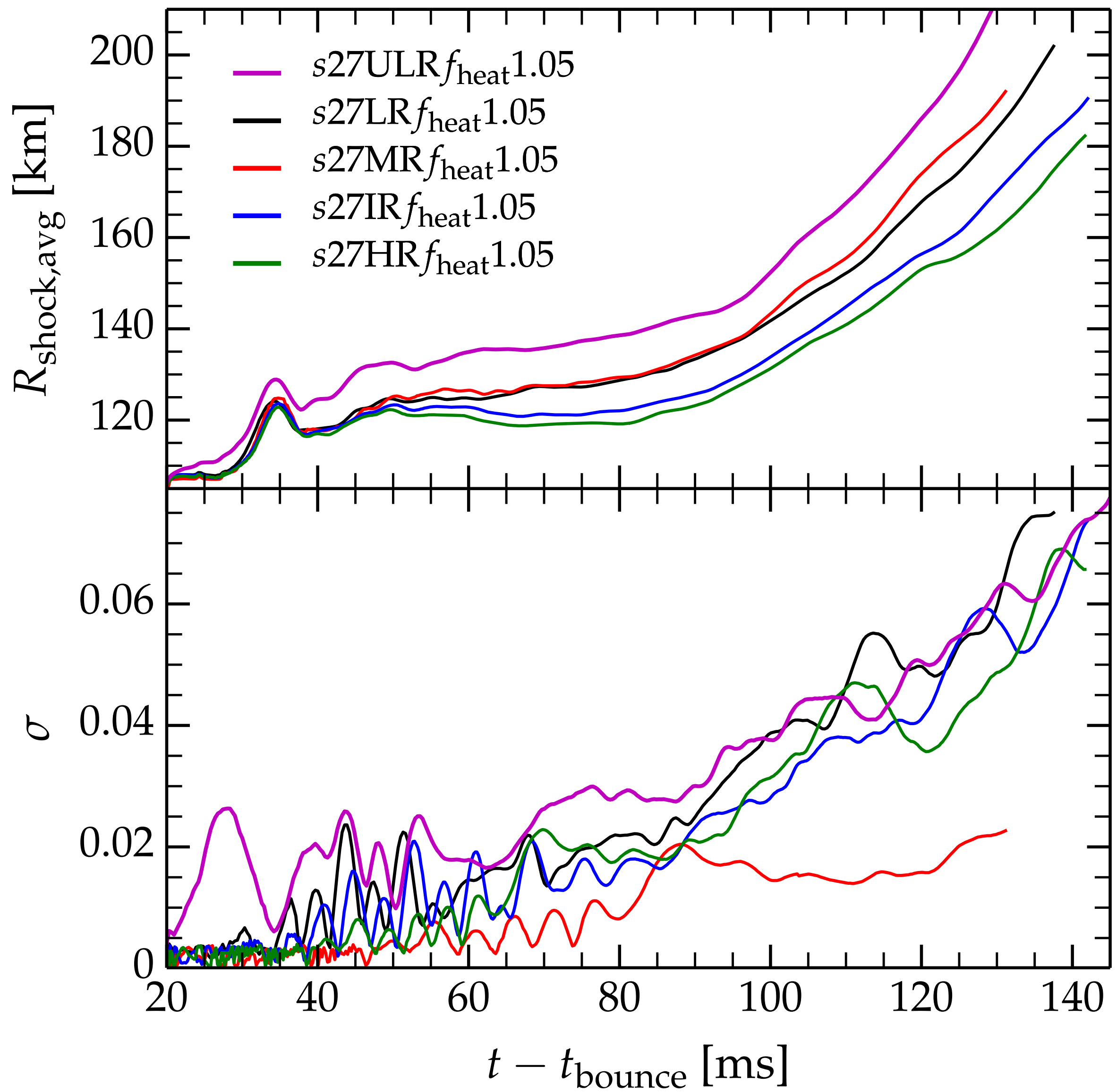
Resolution Dependance



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!

Why?

- Lower resolution favors the formation of larger, longer lived structures
- Secondary instabilities (Kelvin-Helmholtz) is suppressed by numerical viscosity
- When is the resolution good enough?

Turbulent Cascade I

Energy flux

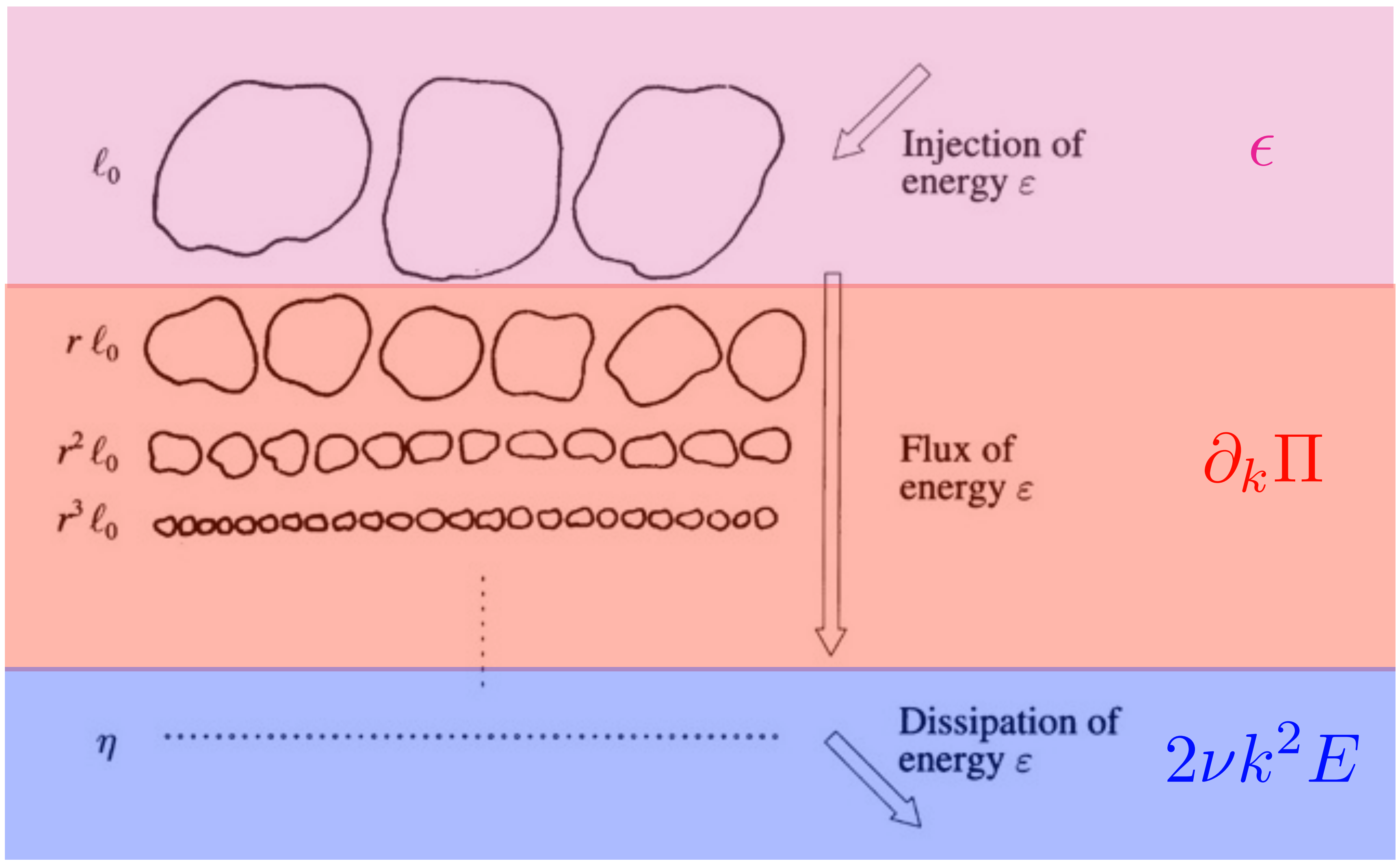
Energy injection

$$\partial_t E + \partial_k \Pi = -2\nu k^2 E + \epsilon$$

Specific kinetic energy

Energy dissipation

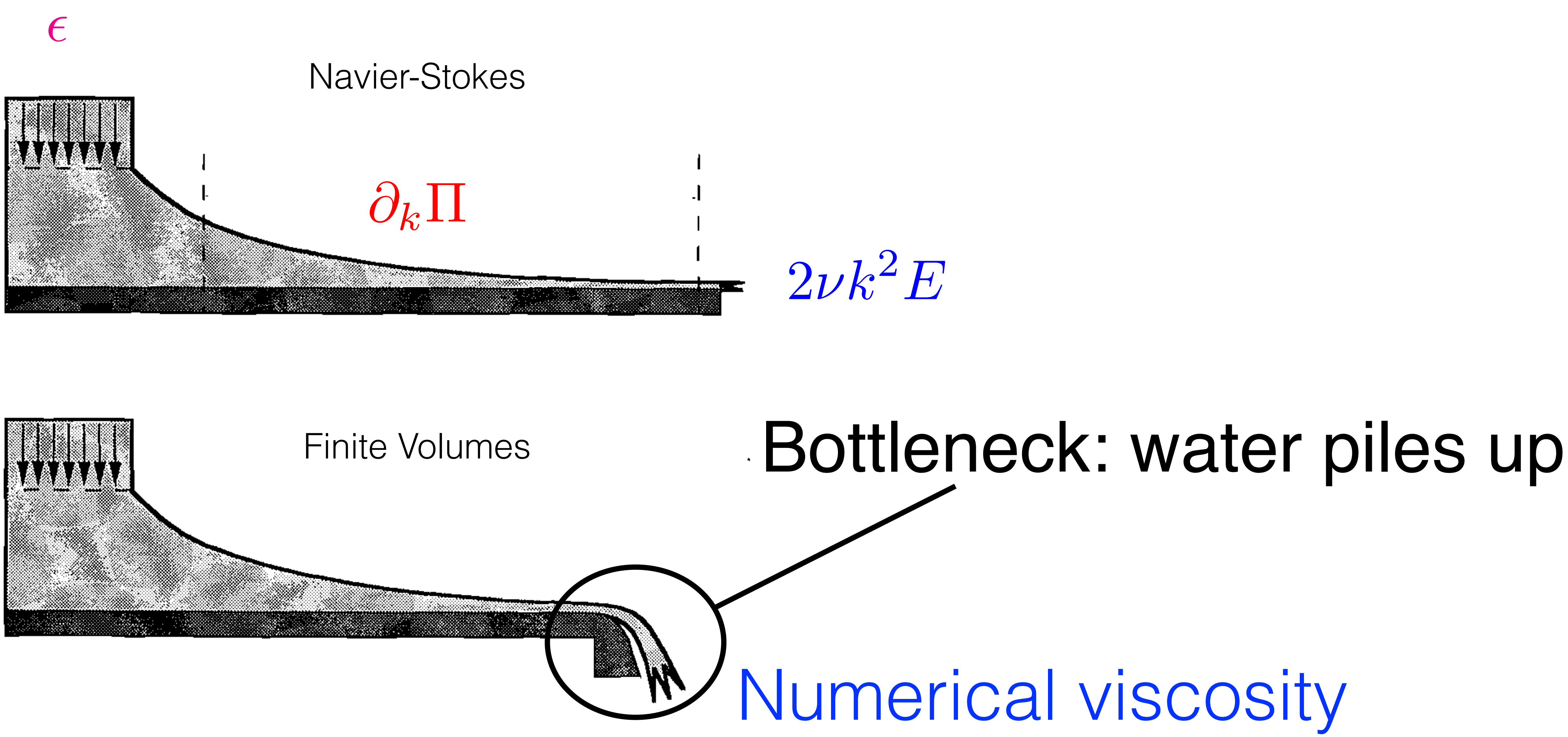
Turbulent Cascade II



Adapted from Frisch 1996

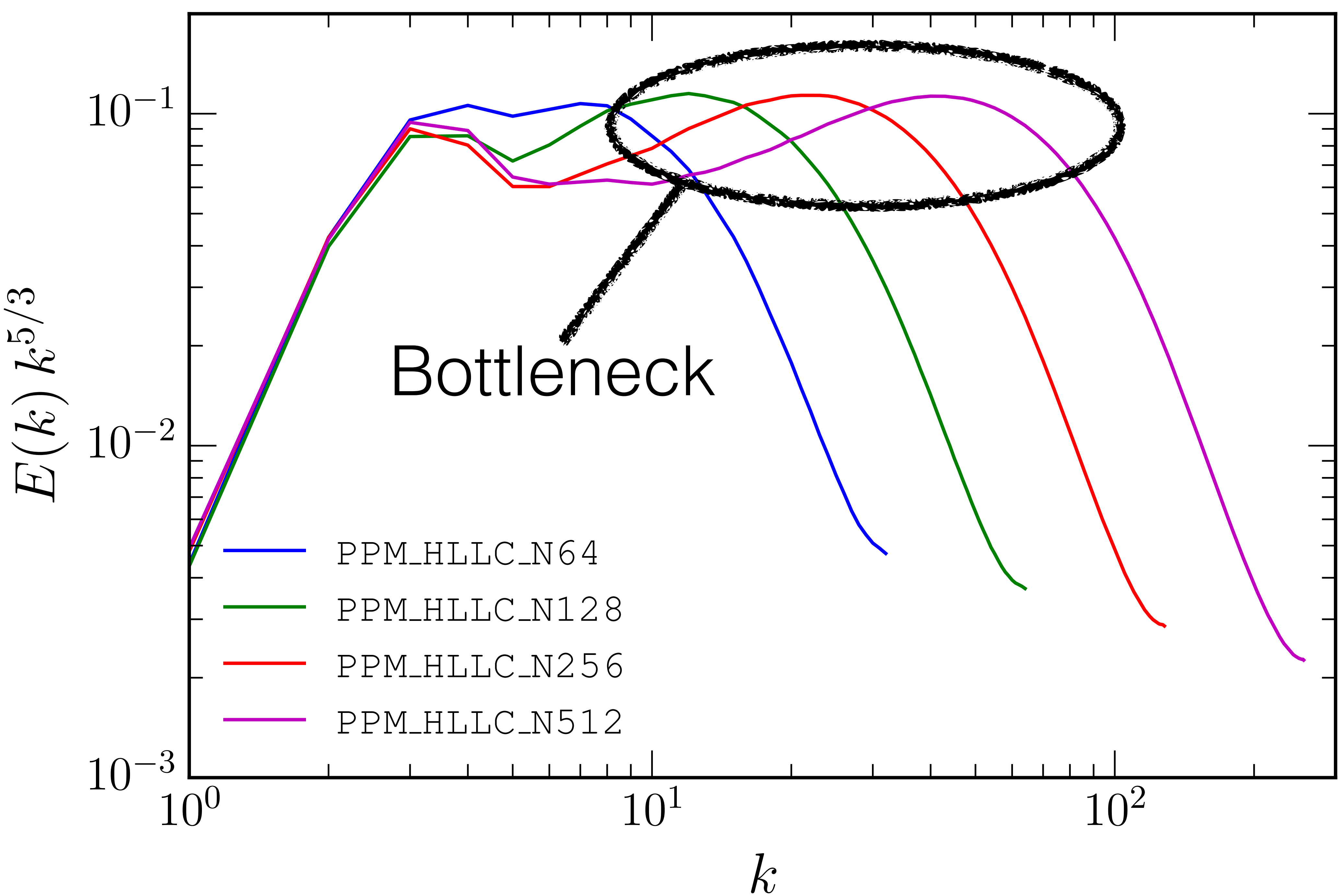
$$\text{Kolmogorov 1941:} \quad \Pi \simeq \text{const} \quad \Longrightarrow \quad E \sim k^{-5/3}$$

The Water-Spill Analogy

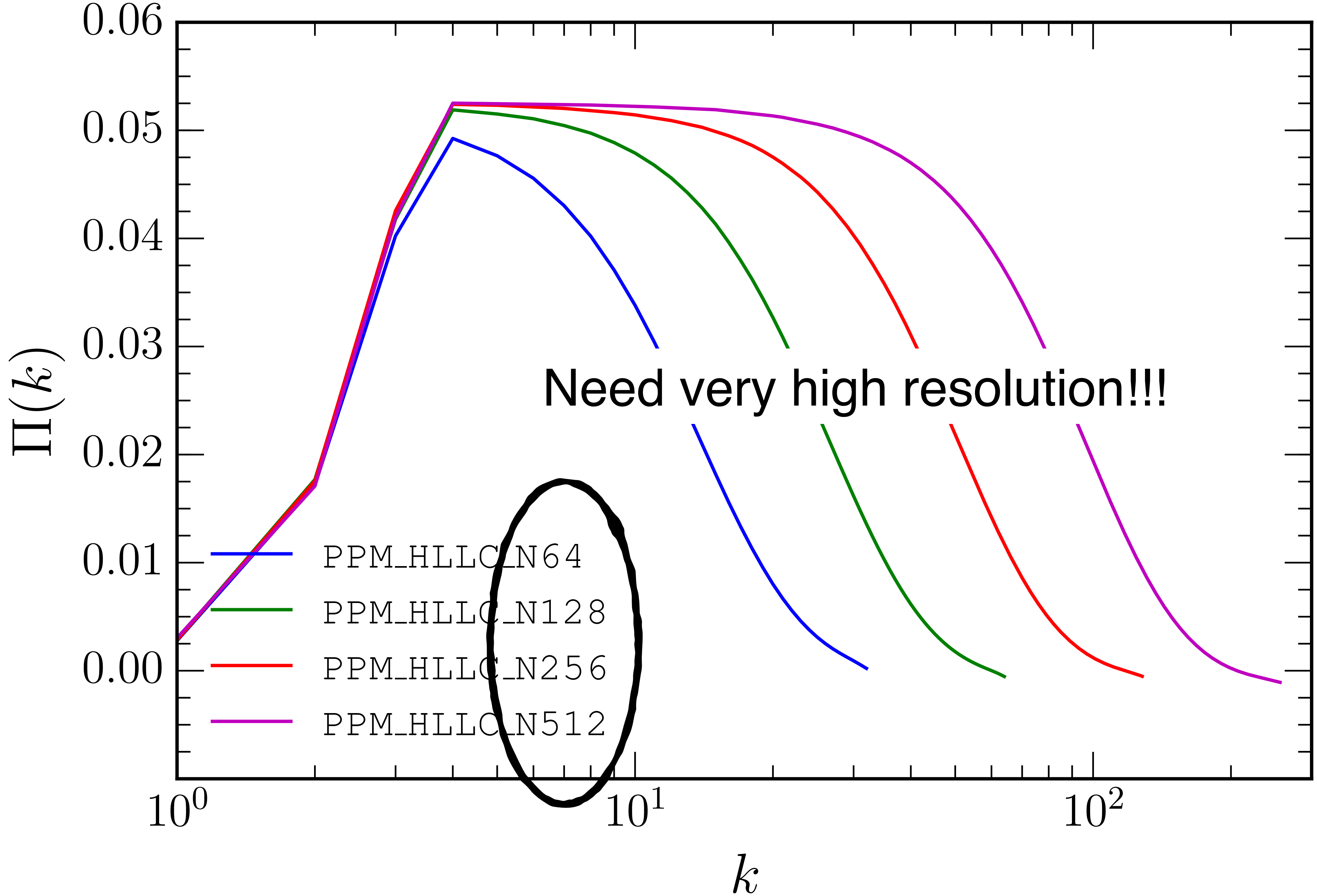


Adapted from Boris 1992

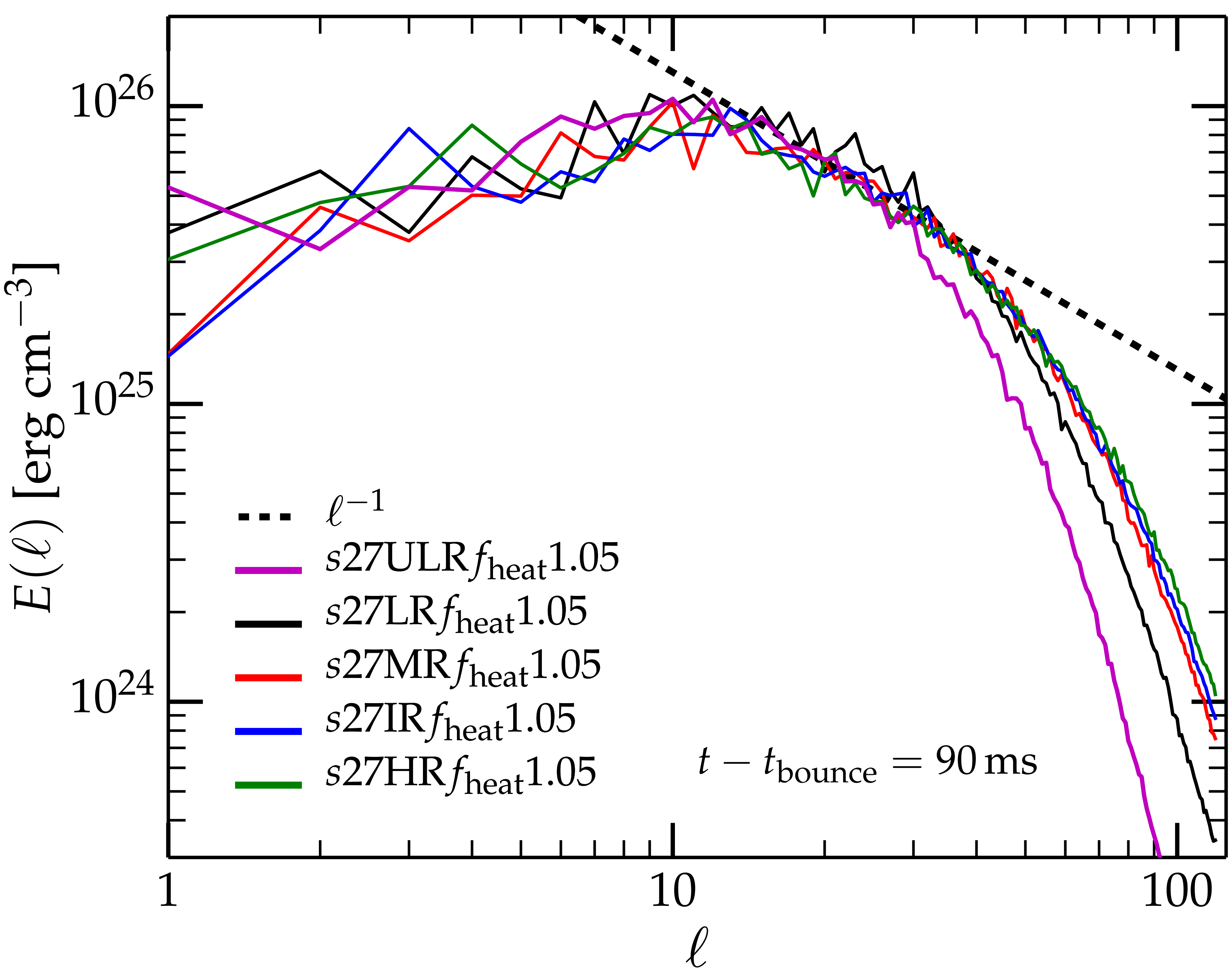
The Bottleneck Effect



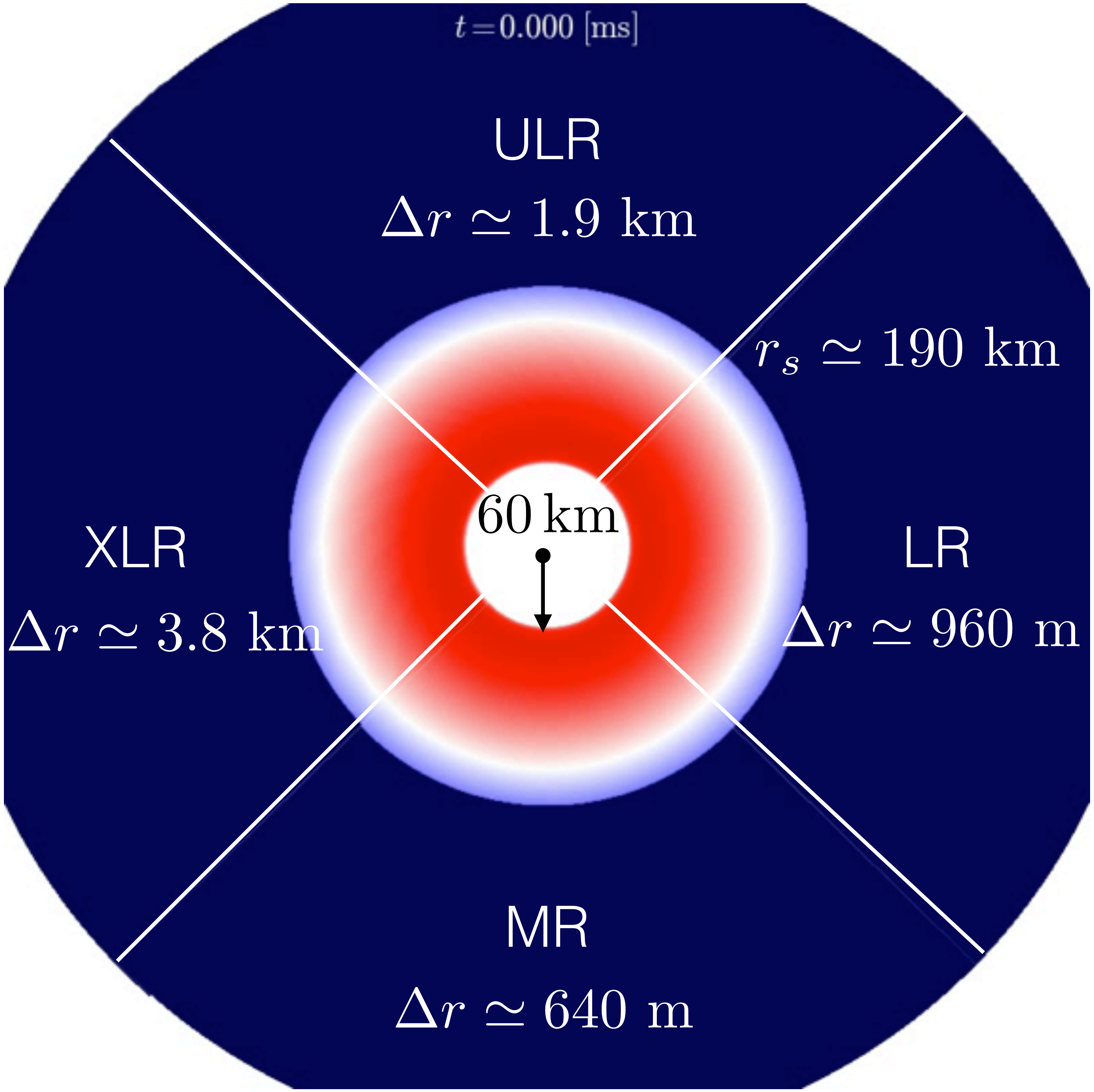
Energy Cascade: PPM

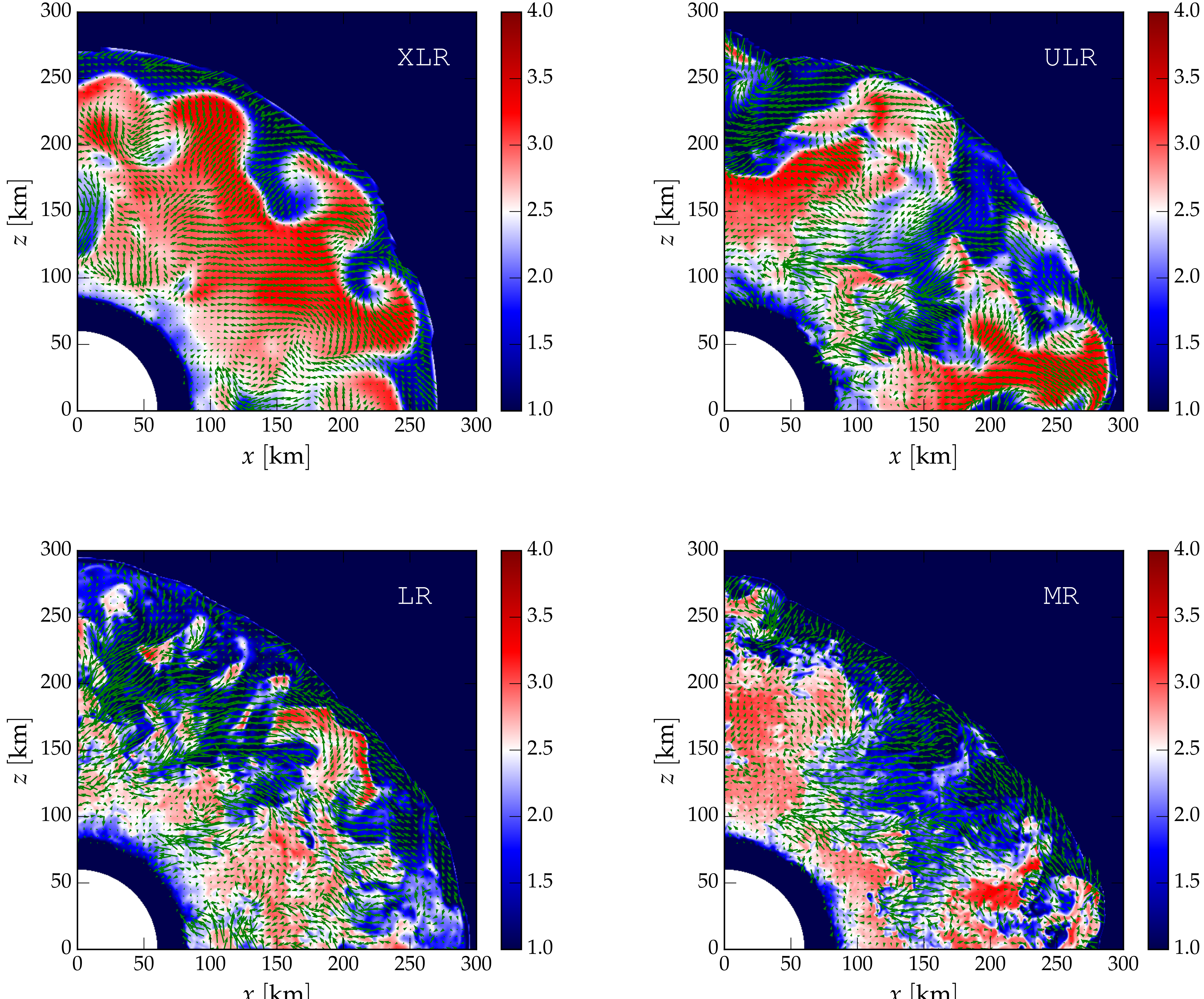


Turbulent Energy Spectrum

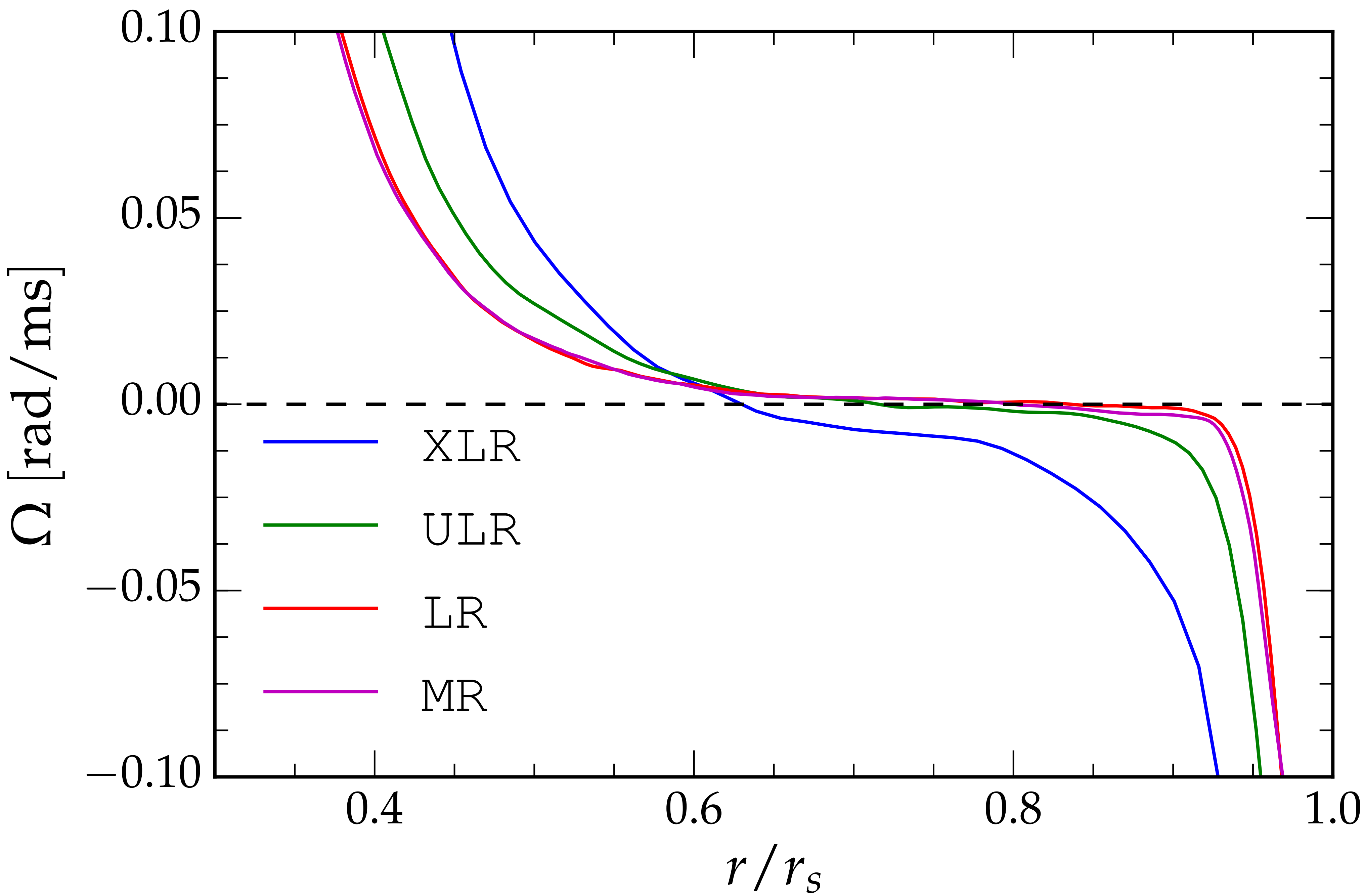


Semi-Global Convection Study

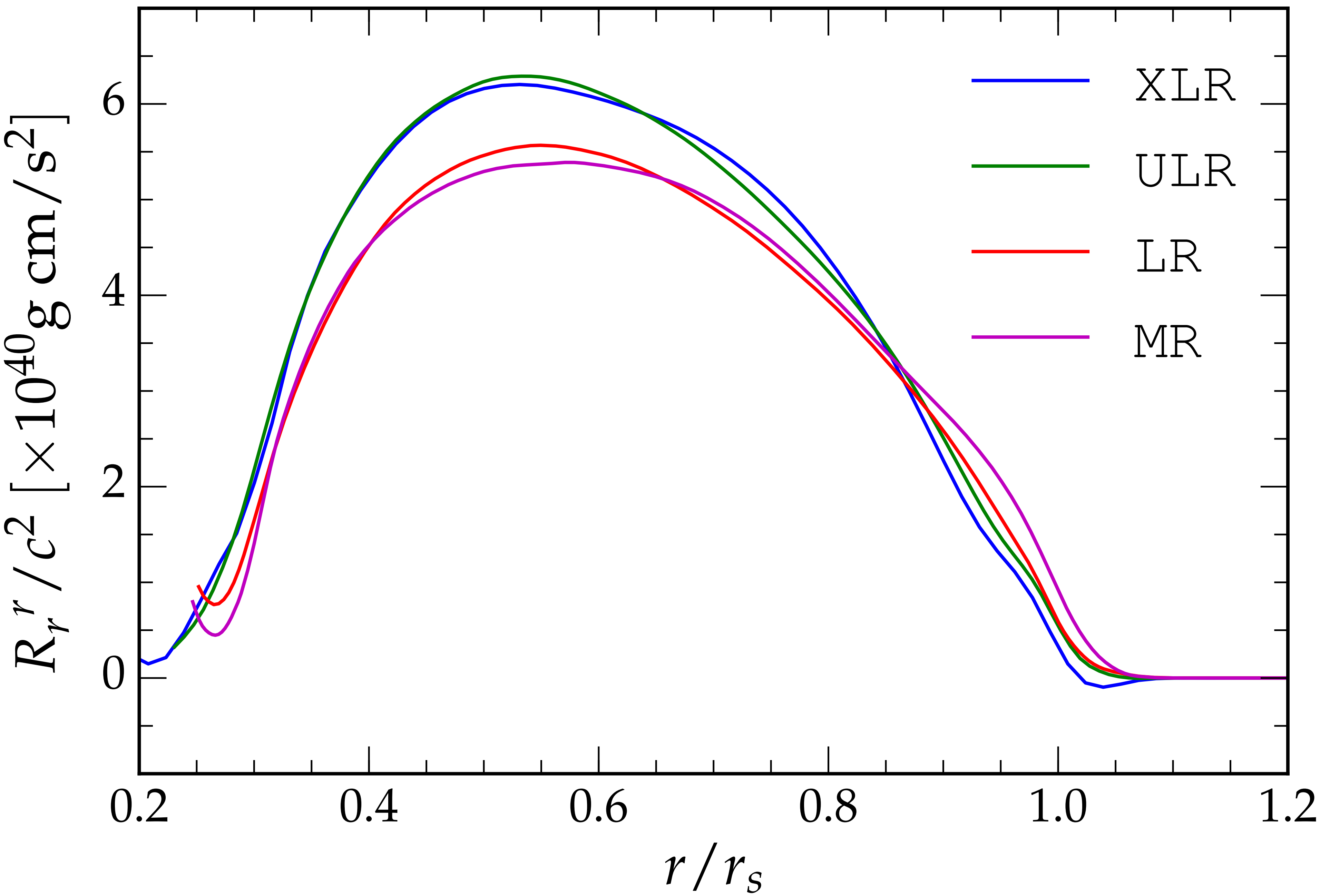



XLR
ULR
LR
MR
z [km]
x [km]
0
50
100
150
200
250
300
1.0
1.5
2.0
2.5
3.0
3.5
4.0

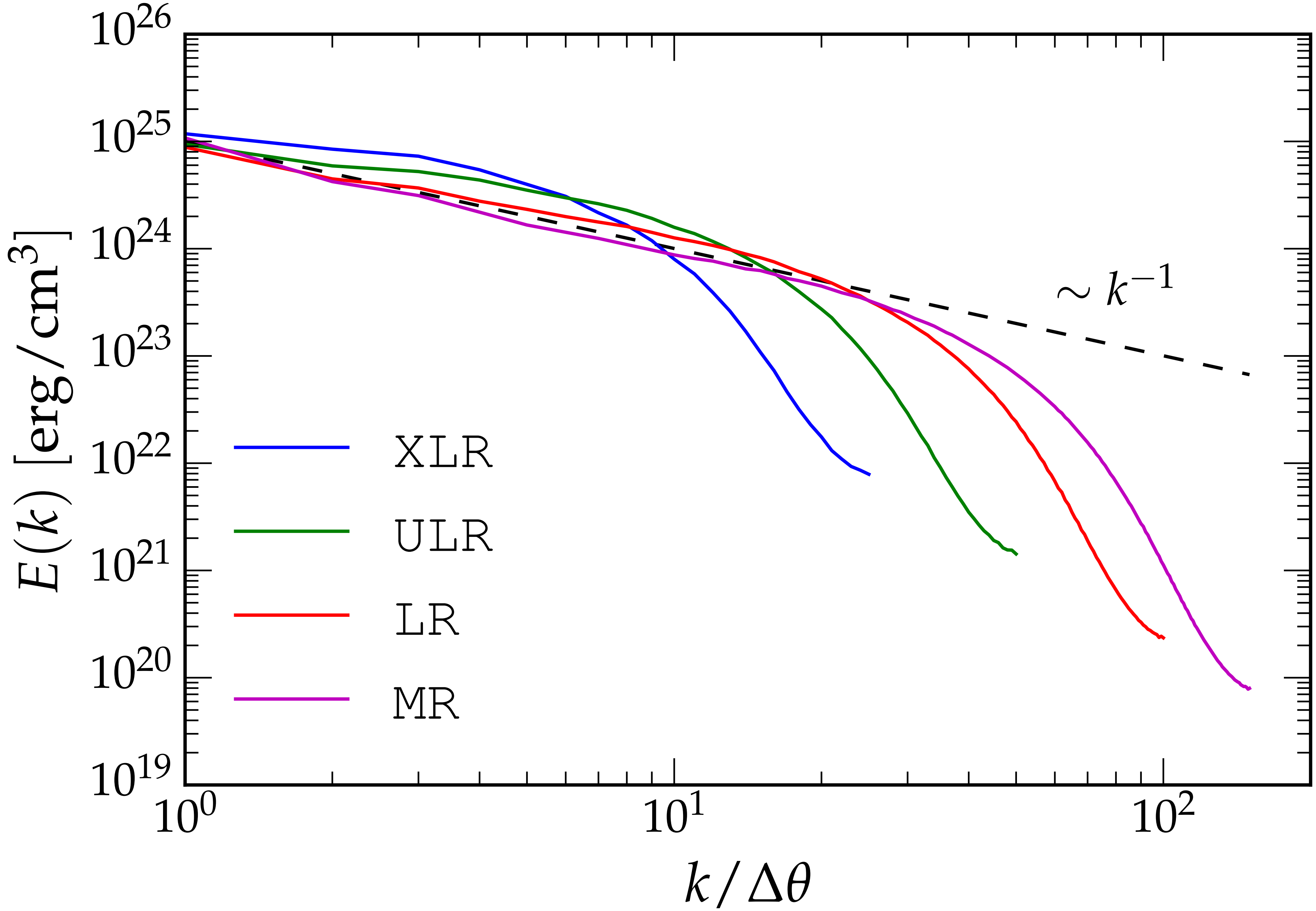
Convective Instability



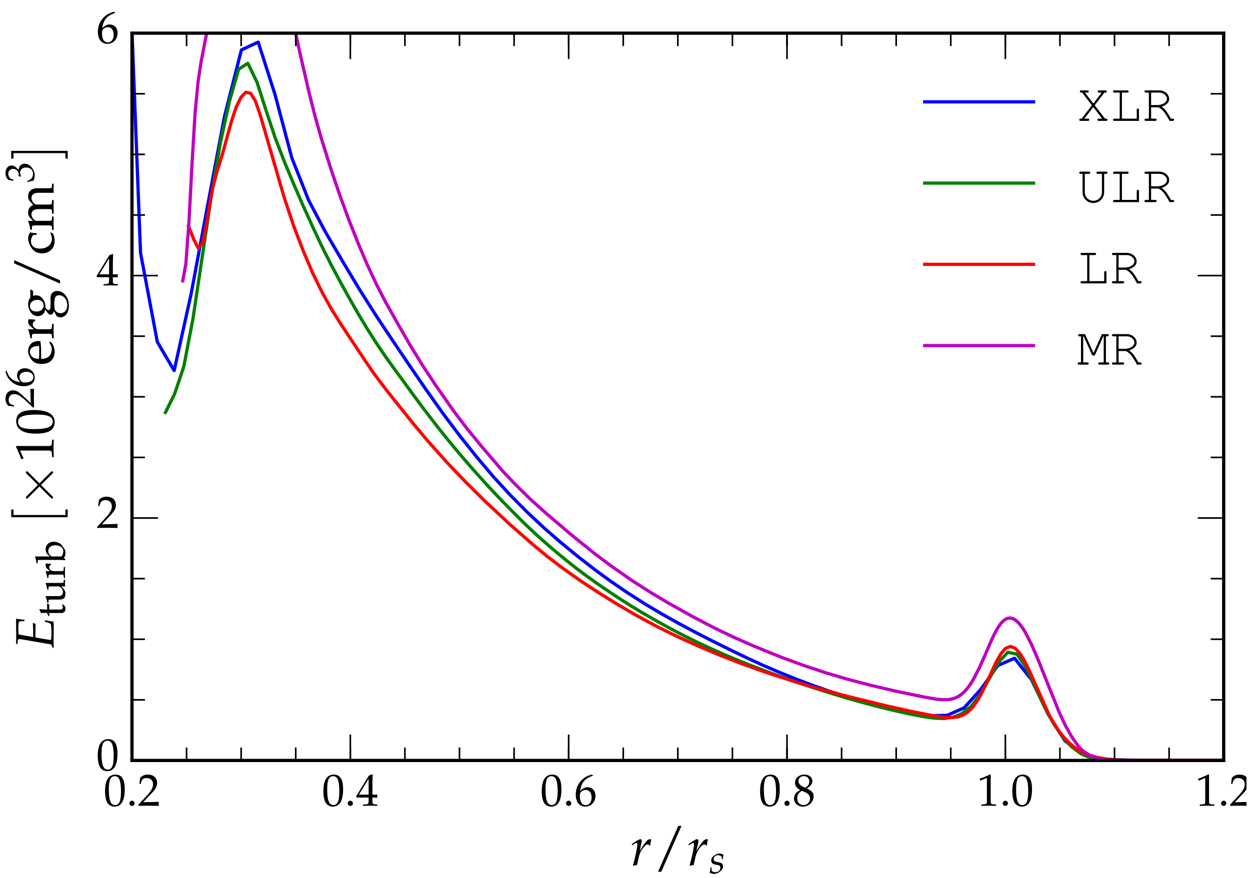
Radial Reynolds Stresses



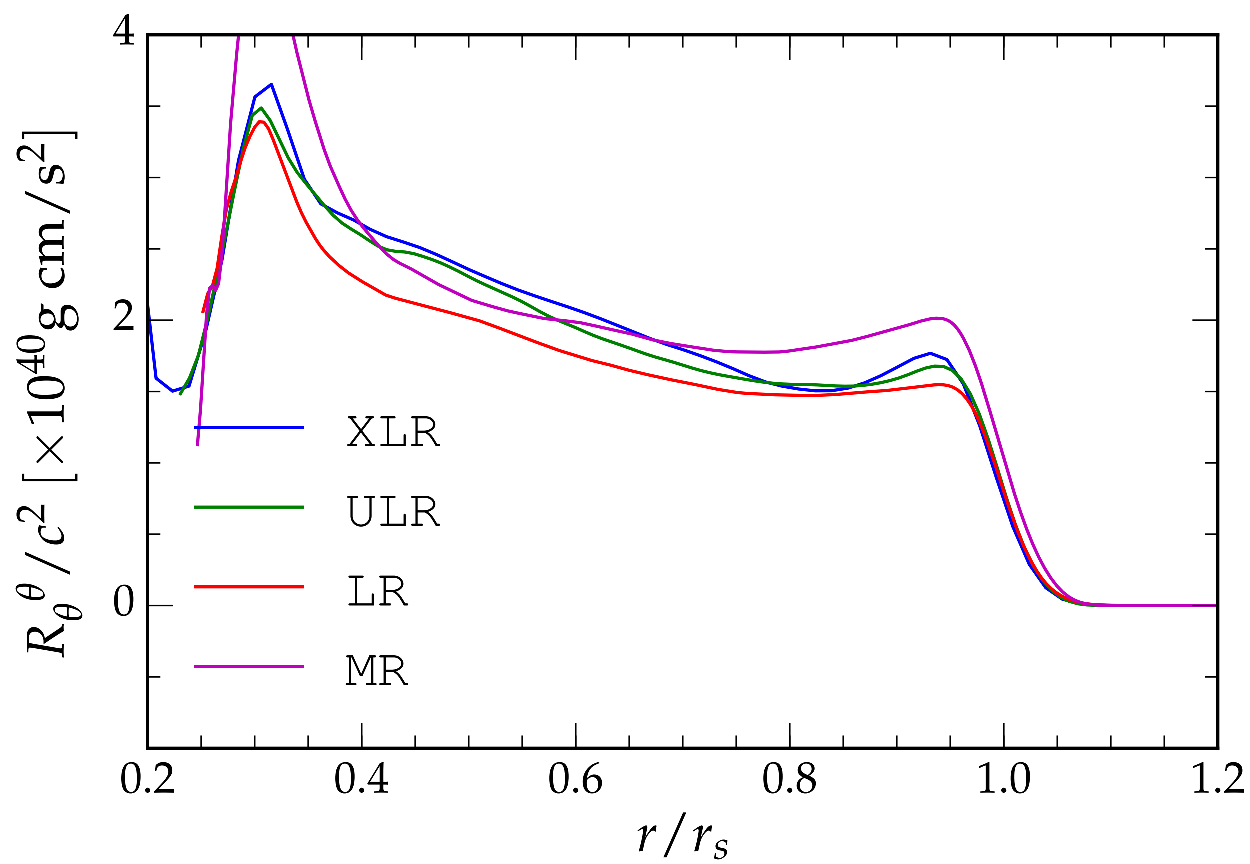
Not Quite There Yet



A New Ingredient: Intermittency I

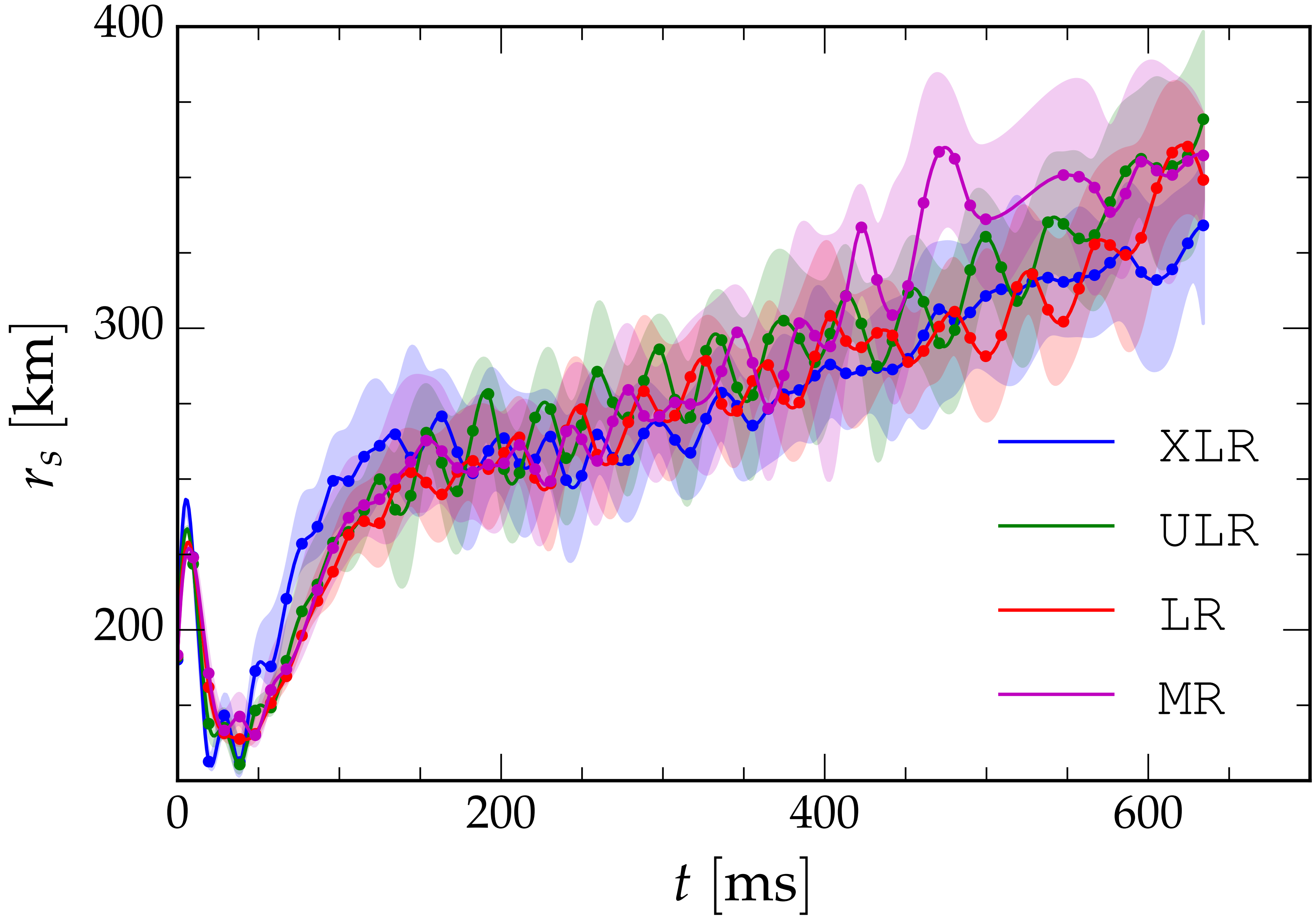


Turbulent energy density



Tangential Reynolds stress

A New Ingredient: Intermittency II



Shock radius evolution

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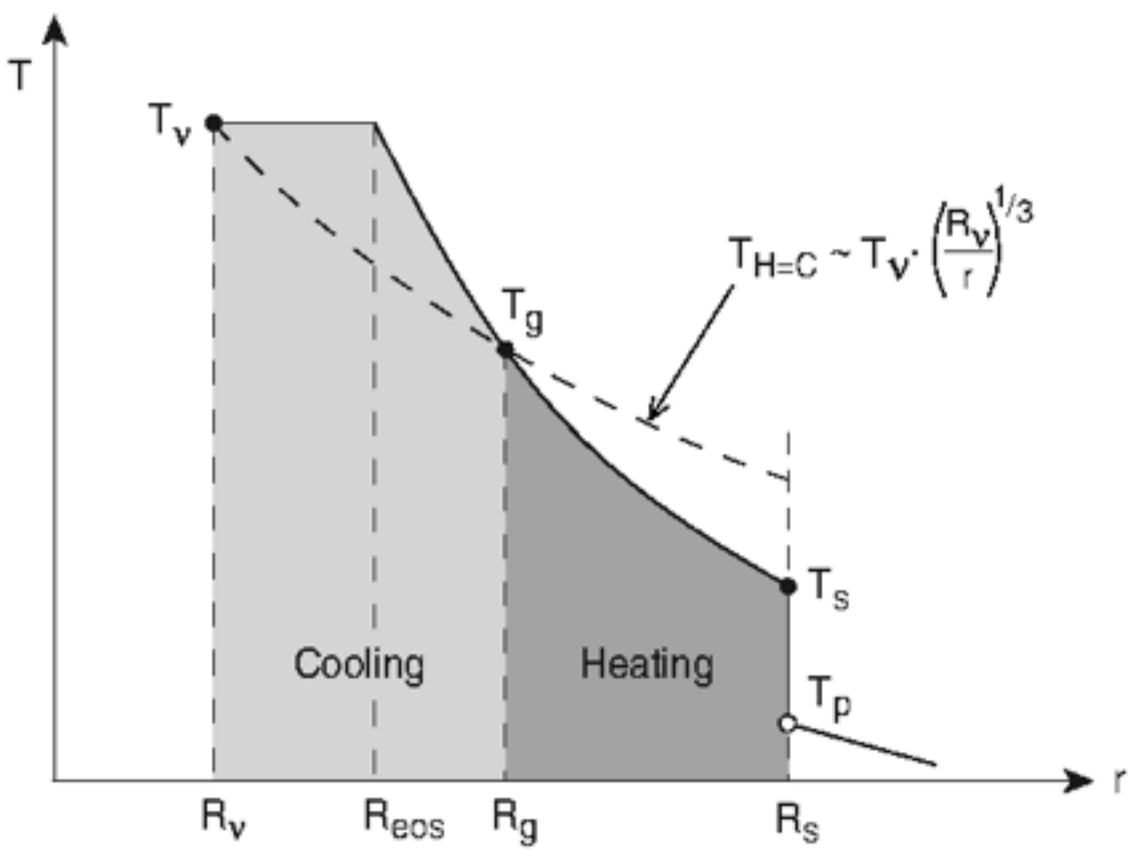
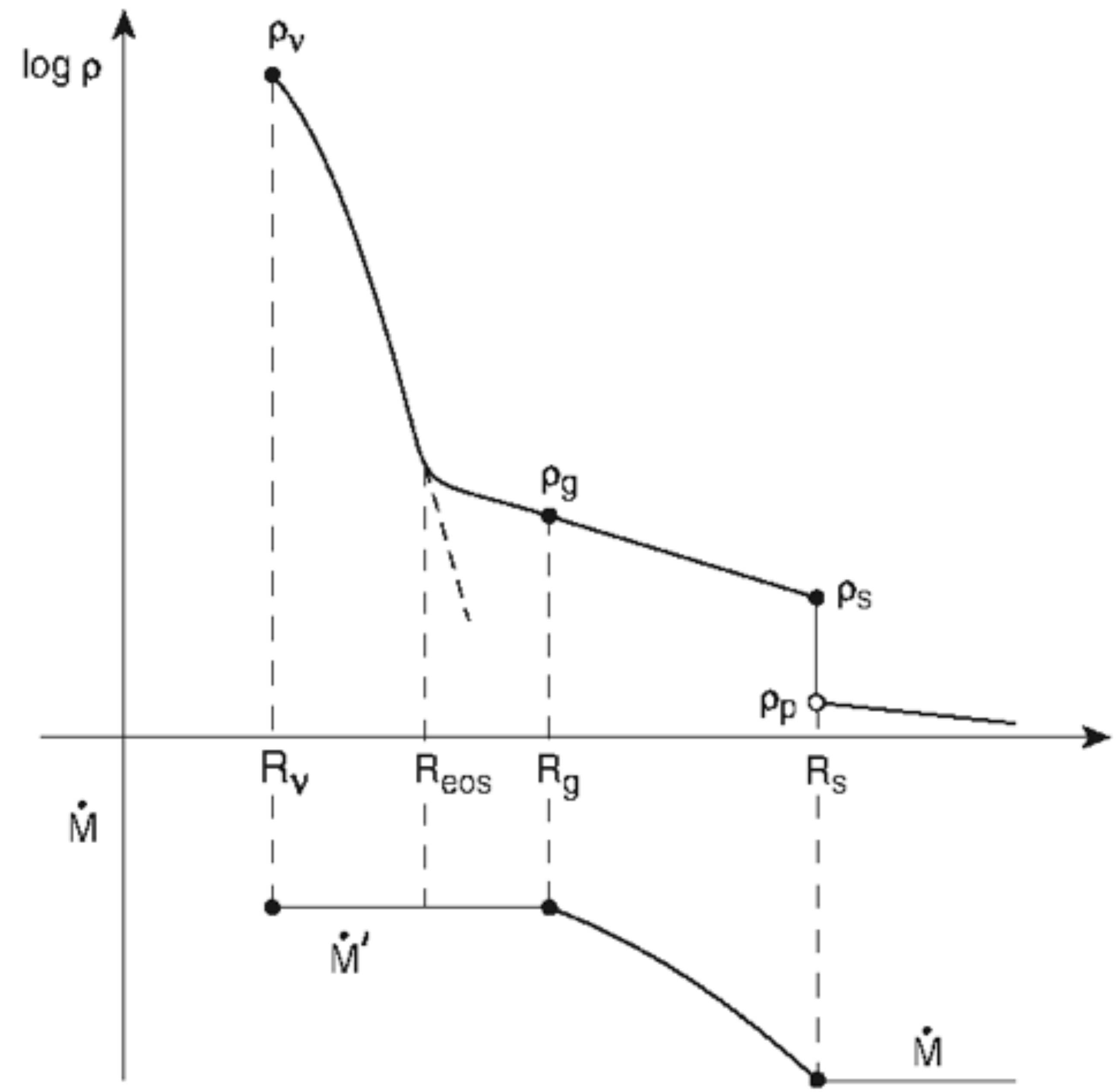
Conclusions

- Turbulence: crucial role for supernova explosions
- Local simulations: very high resolution is needed
- Idealized global simulations: rich dynamics of turbulent convection

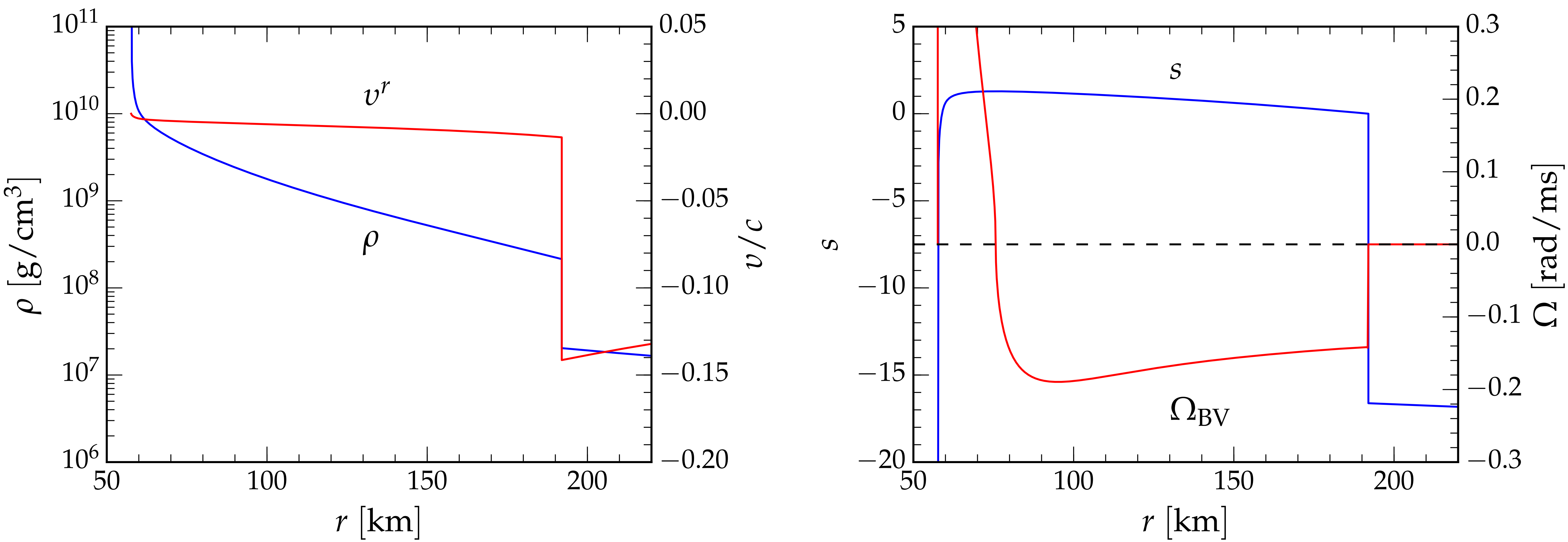
The Standing Shock Flow



From Janka 2001



Initial Data



Stationary initial data