Shock-Turbulence Interaction in Core-Collapse Supernovae

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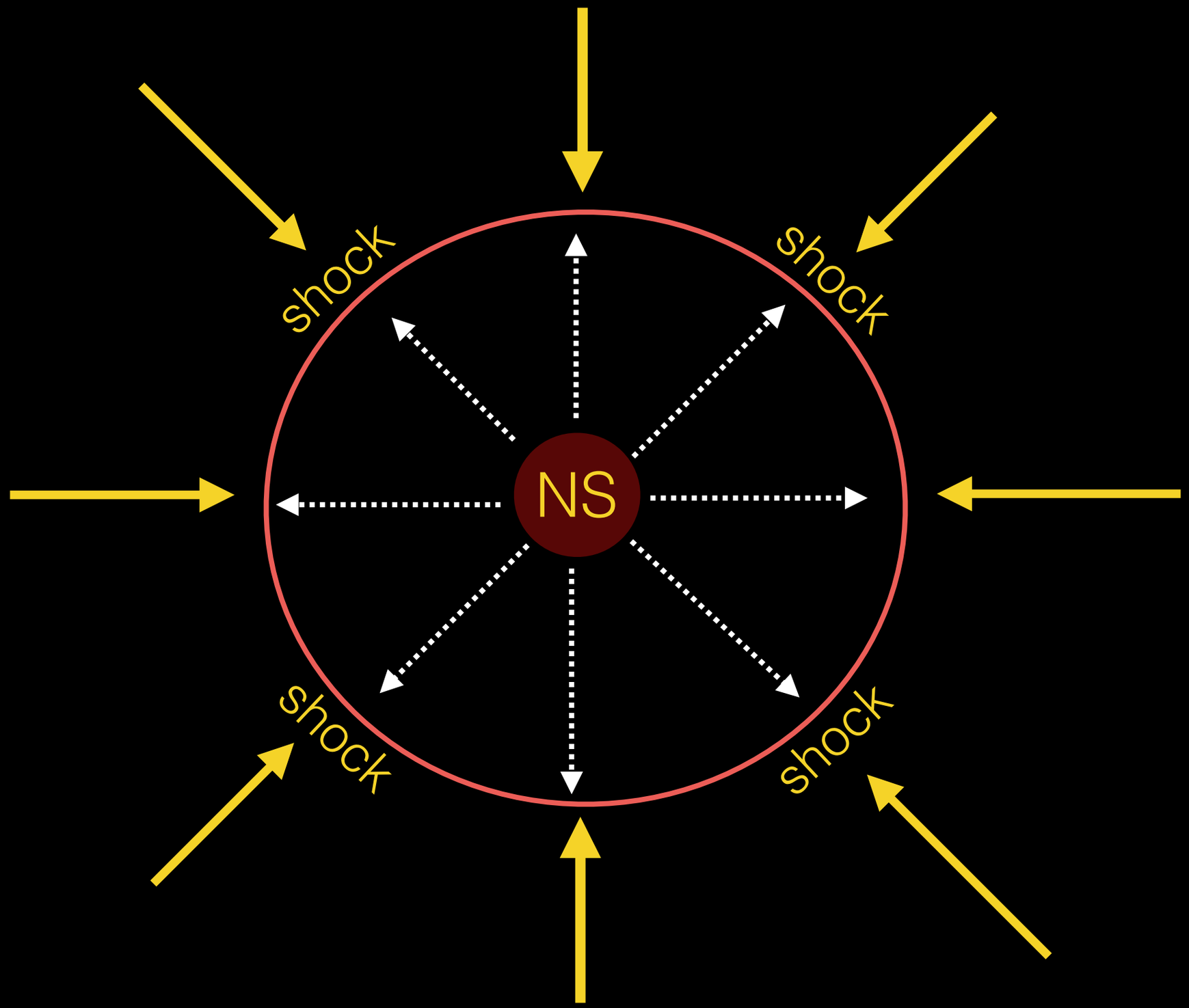
Neutrino Mechanism and non-radial dynamics



Presentations by H. Andresen, K. Kotake, B. Müller, E. Müller, M. Obergaulinger.

Progenitor asphericities

Couch & Ott 2013, 2015, Couch et al 2015,
Müller & Janka 2015, B. Müller et al 2016

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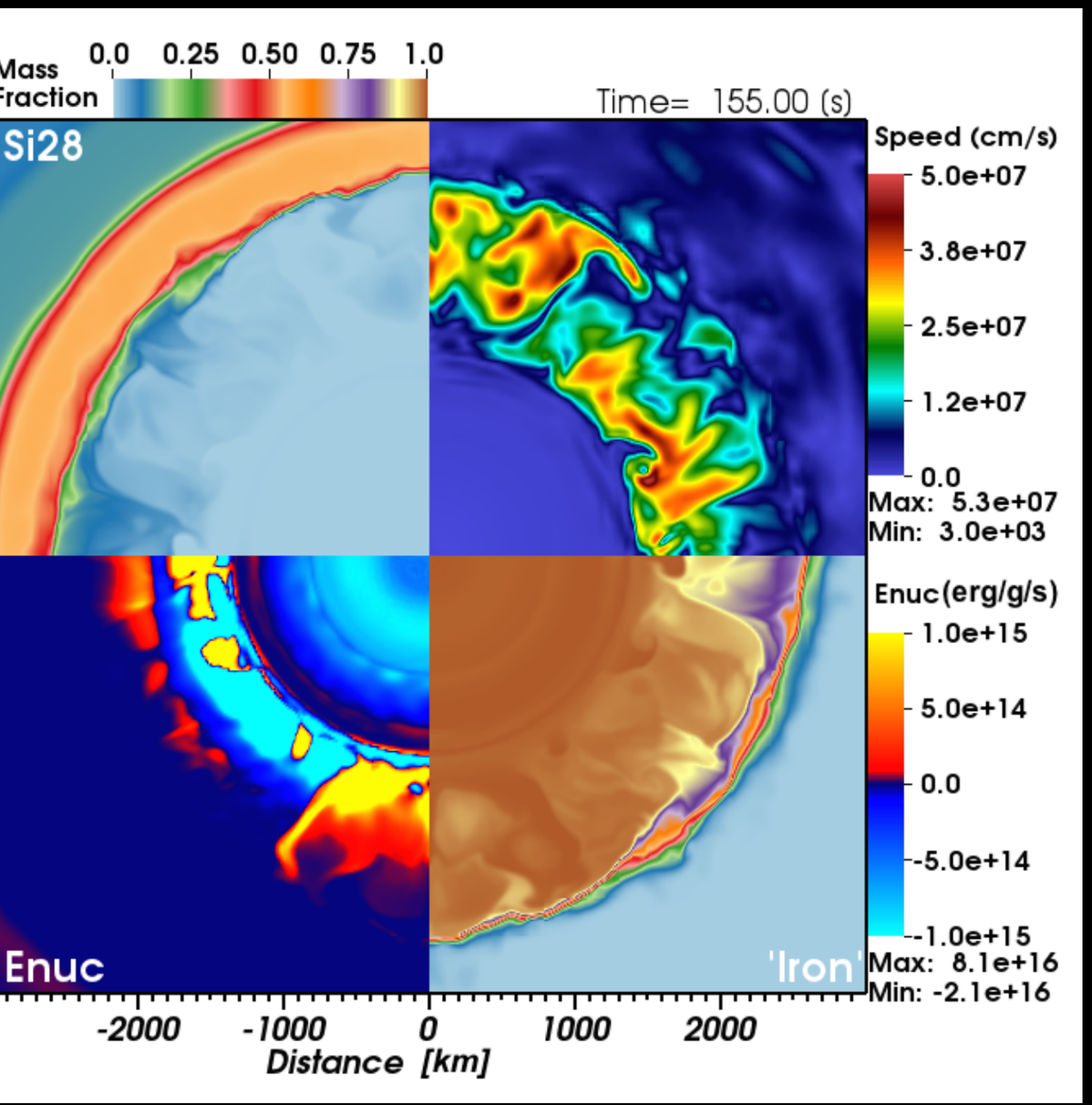
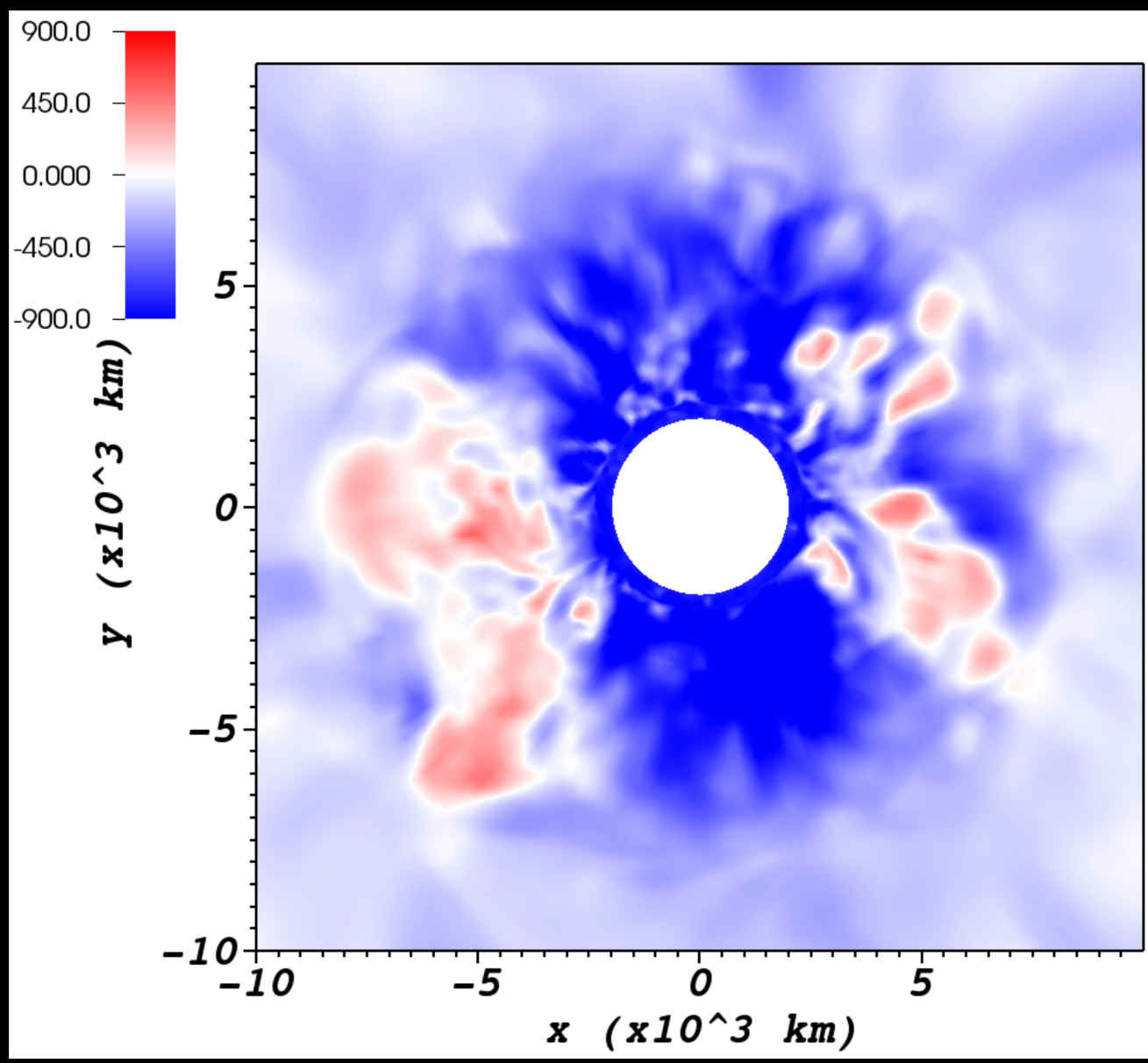


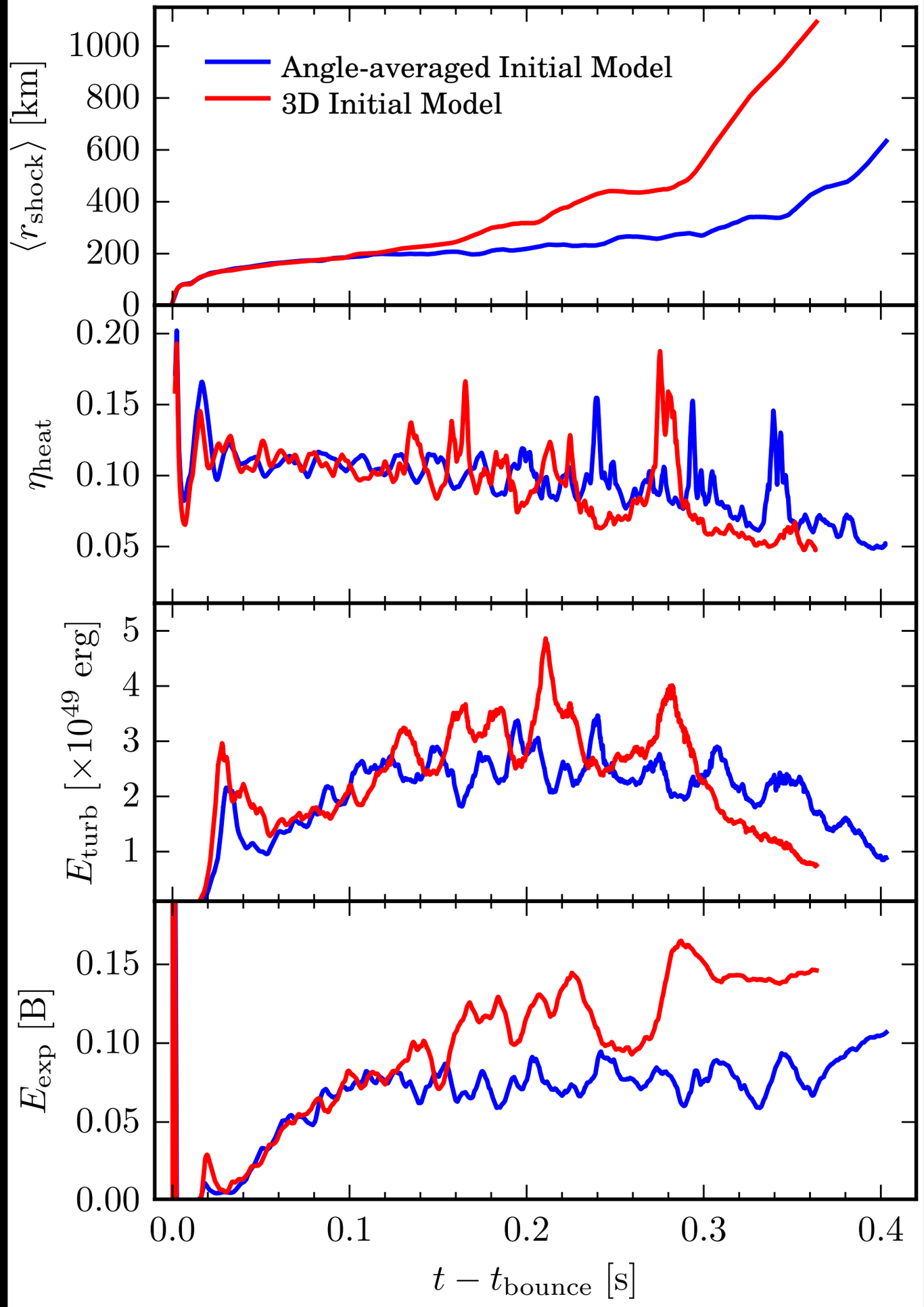
Couch+'15



B. Müller+'16

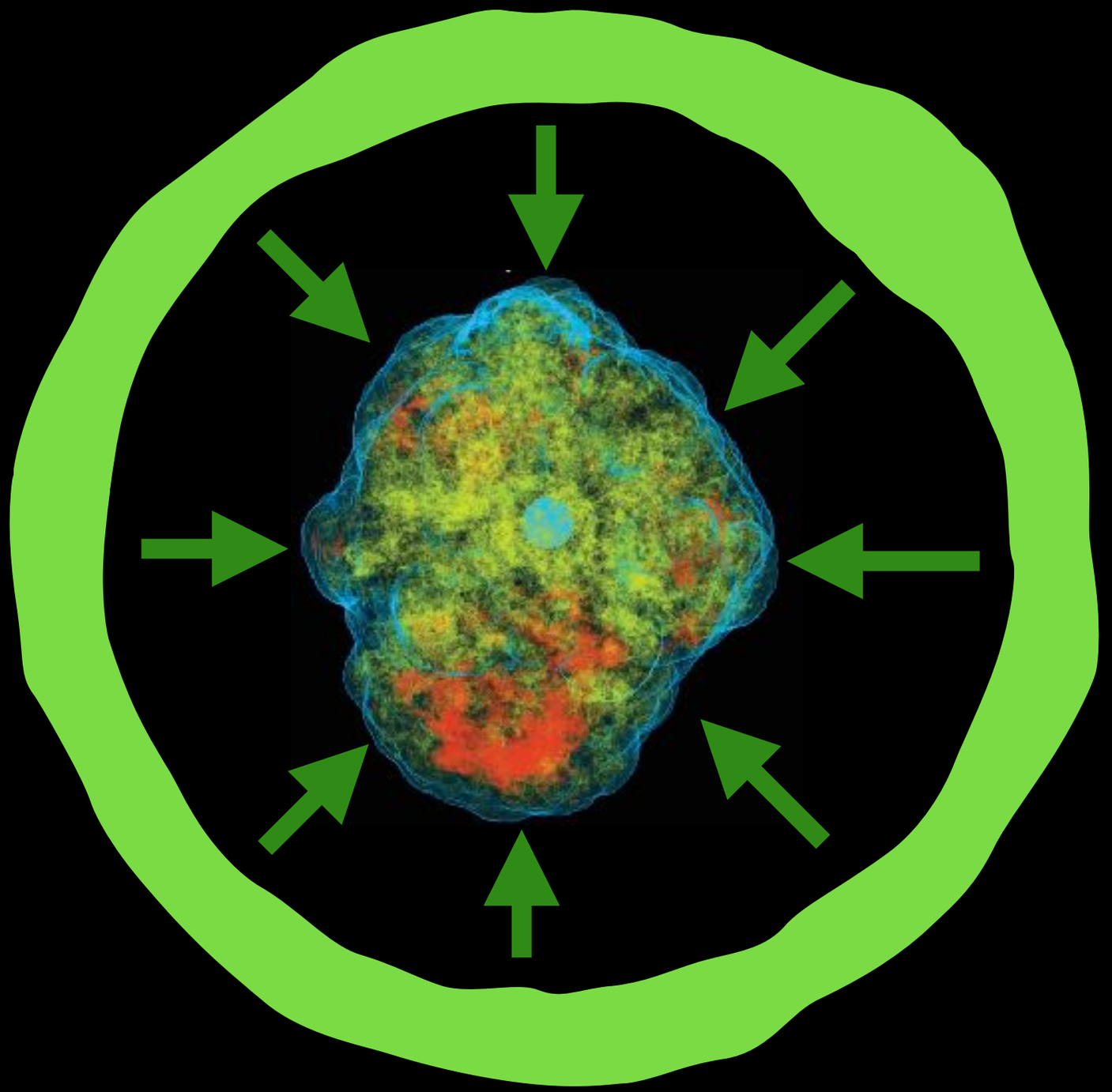
Other works: Arnett & Meakin '16, Chatzapoulos+'16

Couch et al 2015



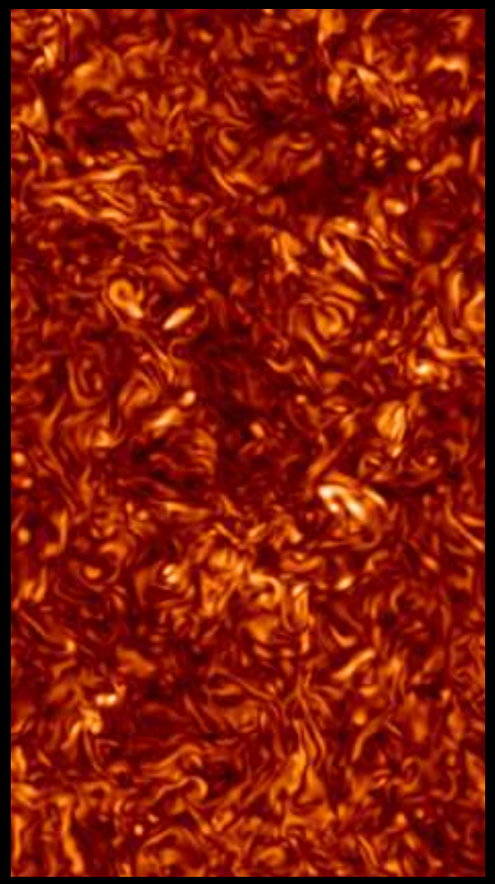
Goal: the (linear) physics of

- Infall
- Shock crossing
- Post-shock



Shock crossing

Radice+16



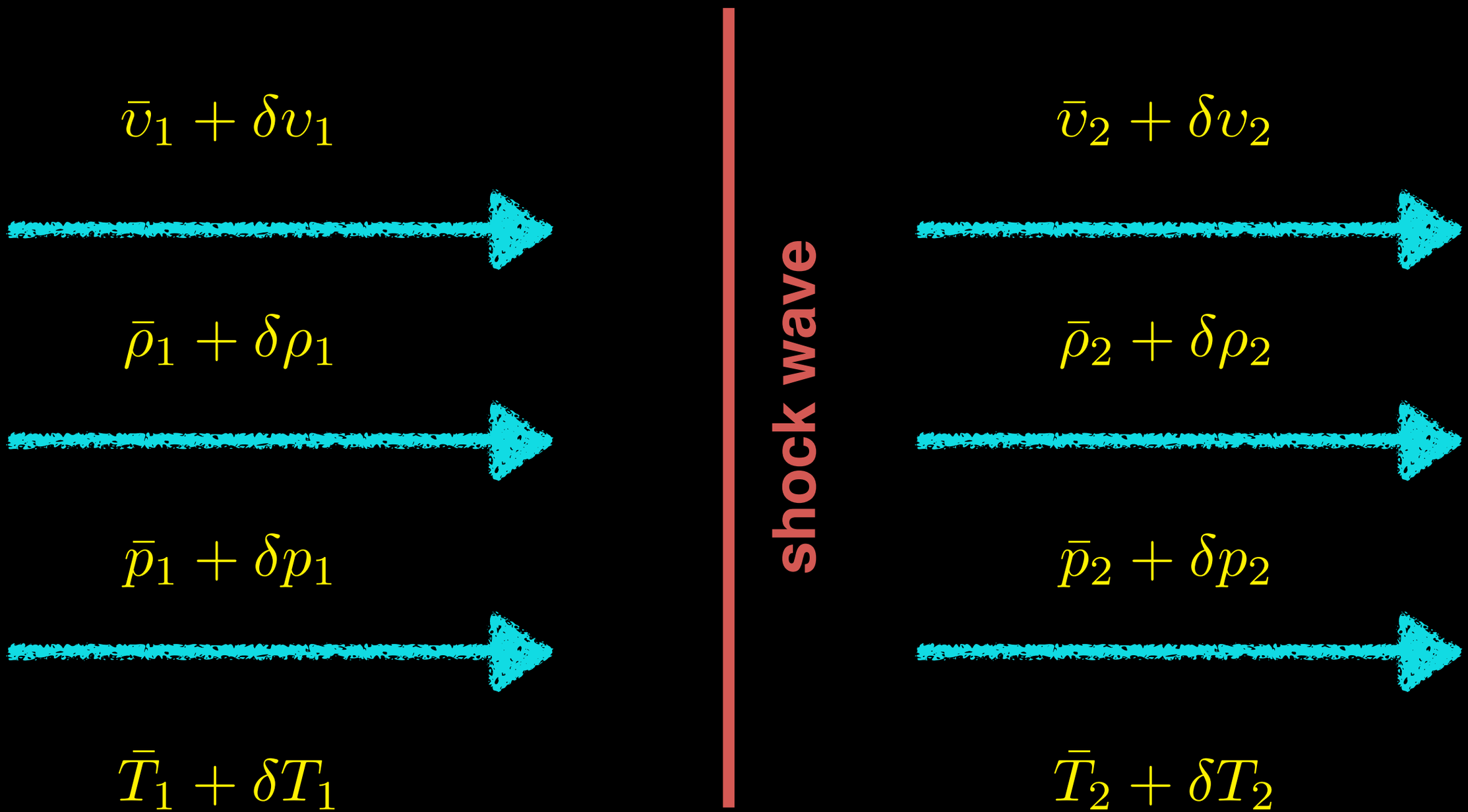
Turbulent flow

shock wave

?

Linear Interaction Analysis

Ribner (1953), Moore (1954), Chang (1957), …



Linear approximation: validity region

$$\langle \delta \mathrm{Ma}^2 \rangle \lesssim 0.1 (\mathrm{Ma}^2 - 1)$$

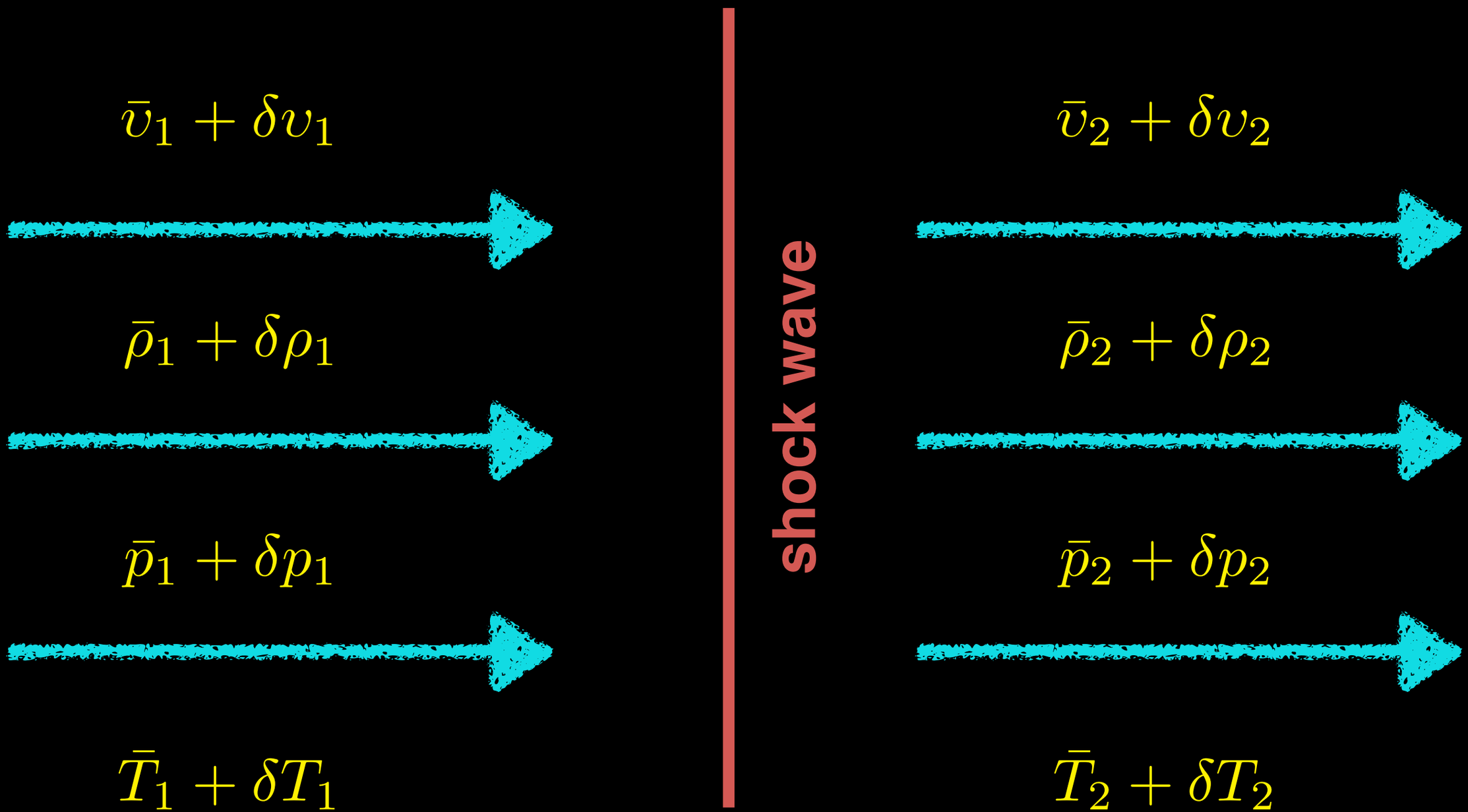
Lee et al (1993), Ryu & Livescu (2014)

In CCSN progenitors: $\delta \mathrm{Ma} \sim 0.1, \ \mathrm{Ma} \gtrsim 5$

e.g., Müller et al (2016)

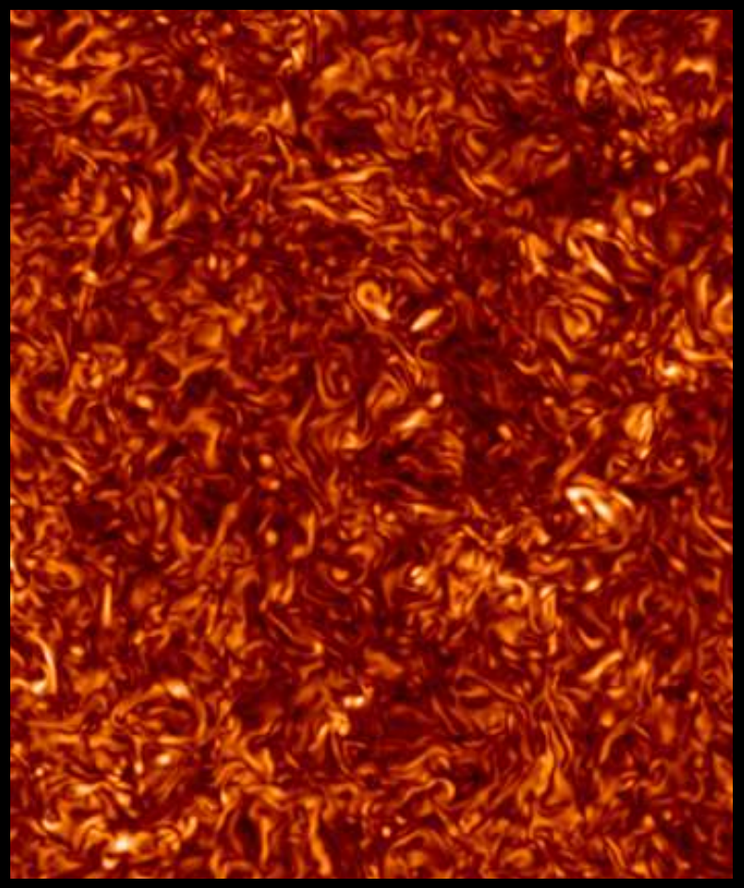
Linear Interaction Analysis

Ribner (1953), Moore (1954), Chang (1957), …



Turbulent Fluctuations: decomposition

Kovasznay (1953)



Radice+16

Entropy $(\delta\rho,\ \delta T)$

Vorticity $(\nabla \cdot \delta v = 0)$

Acoustic $(\delta\rho,\ \delta p,\ \nabla \times \delta v = 0)$

Turbulent Fluctuations: decomposition

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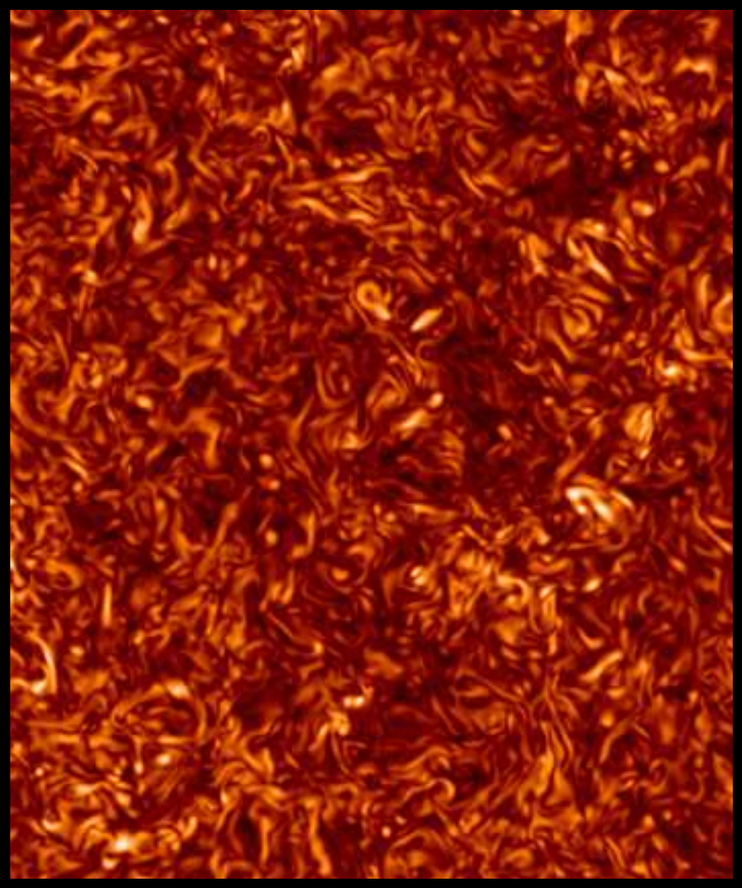
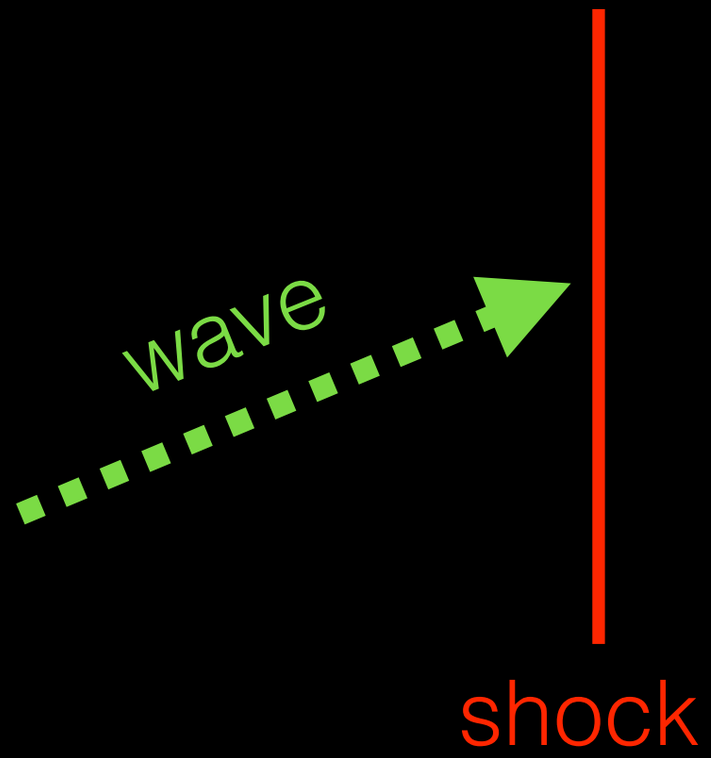


Radice+16

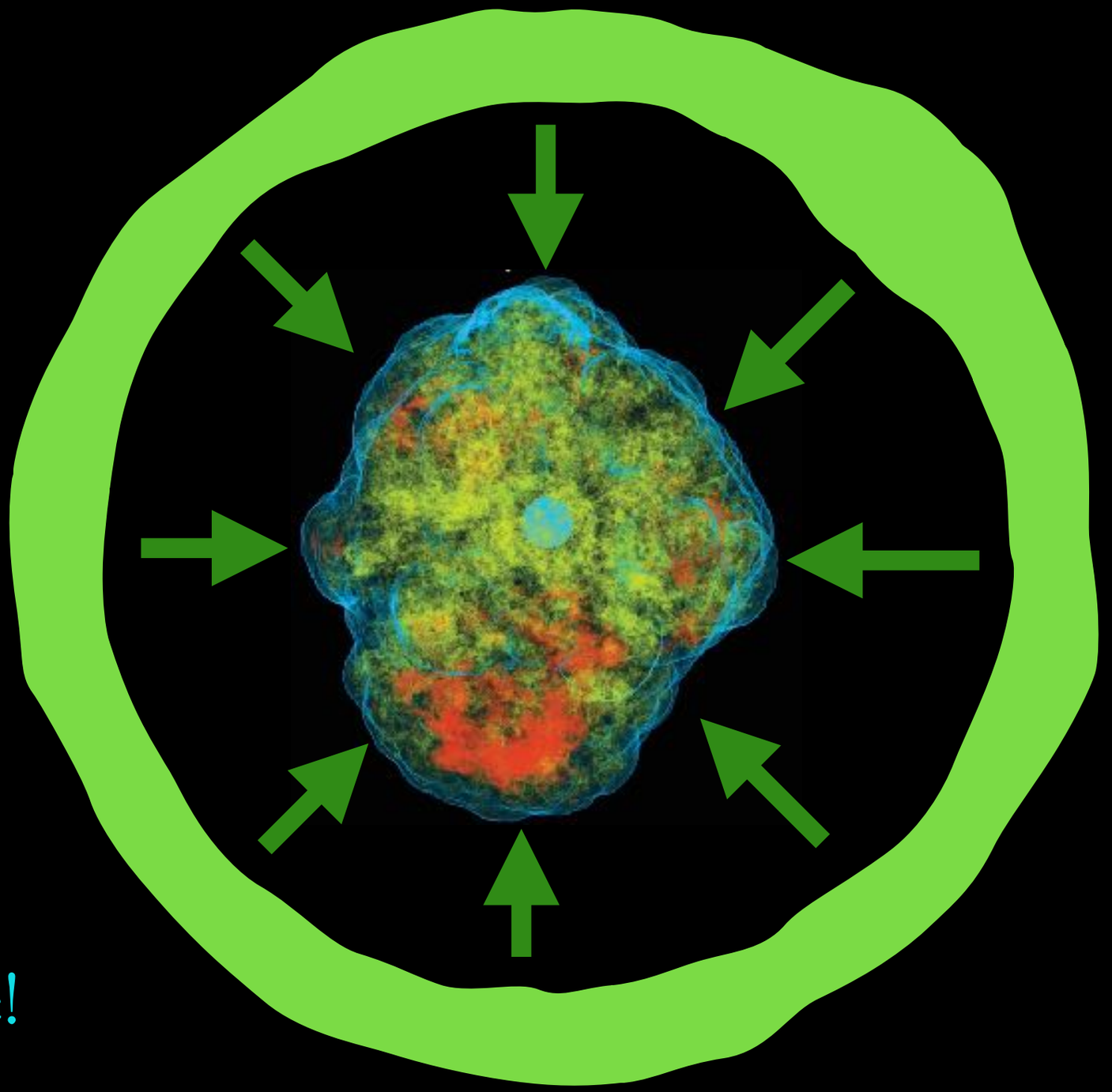
Modes decouple in the linear limit for uniform mean flow.



Emission of Sound by Turbulent Motion

$$\varepsilon \propto \delta \mathrm{Ma}^8$$

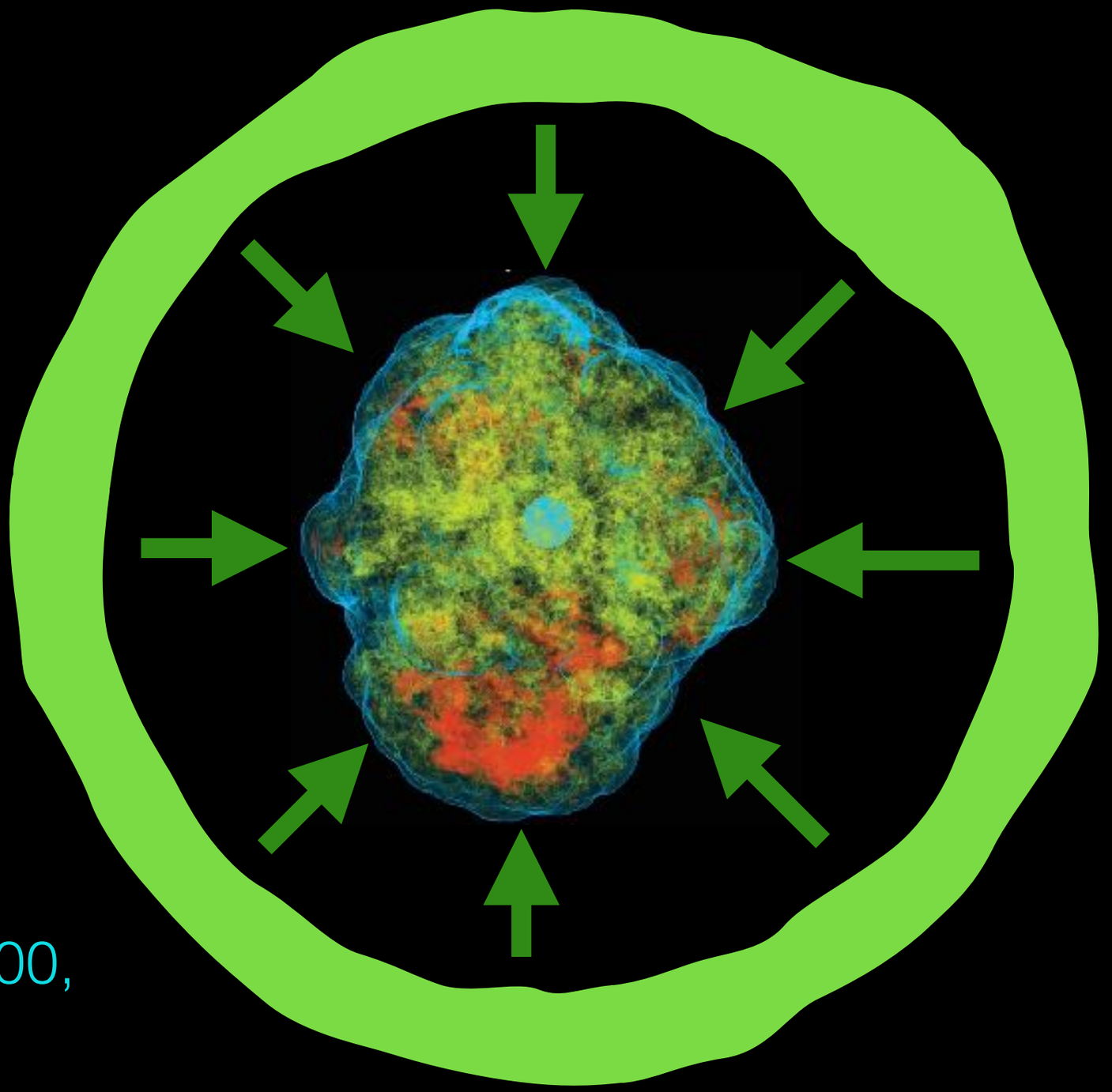
[Lighthill 1952, Landau & Lifshitz 1959]



For subsonic turbulence,
sound emission is negligible!

Emission of sound waves during infall

e.g., Kovalenko & Eremin 1998, Foglio & Tagger 2000, Foglizzo 2001, …



Other works: Lai & Goldreich 2000,
Takahashi & Yamada 2014

This talks:
incident vorticity and entropy waves

U_1

U_2

y

$\bar{\rho}_1, \bar{p}_1, \overline{T}_1$

entropy wave

vorticity wave

acoustic wave

entropy wave

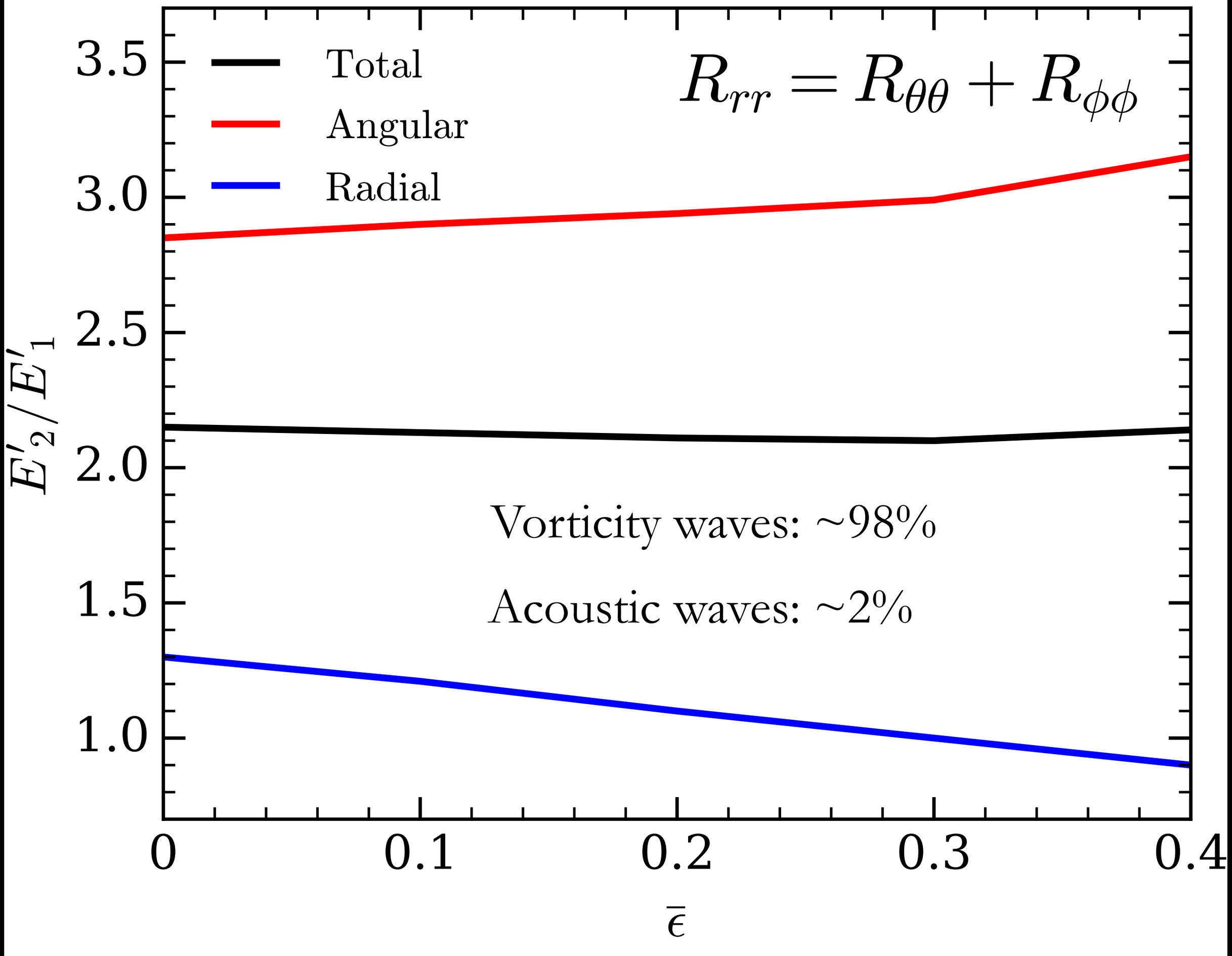
vorticity wave

$\xi(y,t)$

Ψ_1

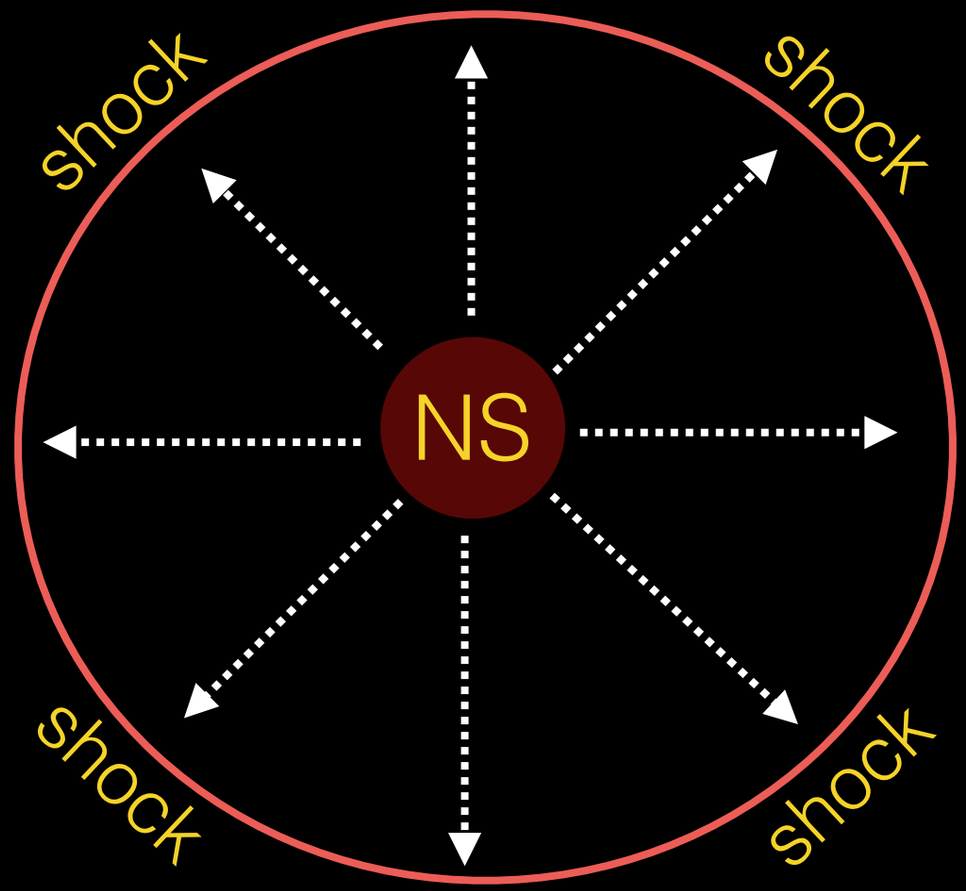
$\bar{\rho}_2, \bar{p}_2, \overline{T}_2$

x


Total
Angular
Radial
$R_{rr} = R_{\theta\theta} + R_{\phi\phi}$
Vorticity waves: ~98%
Acoustic waves: ~2%
E'_2/E'_1
$\bar{\epsilon}$
3.5
3.0
2.5
2.0
1.5
1.0
0
0.1
0.2
0.3
0.4

Role of Turbulence

$$P_{\rm turb} \sim \langle \delta v^2 \rangle \rho$$

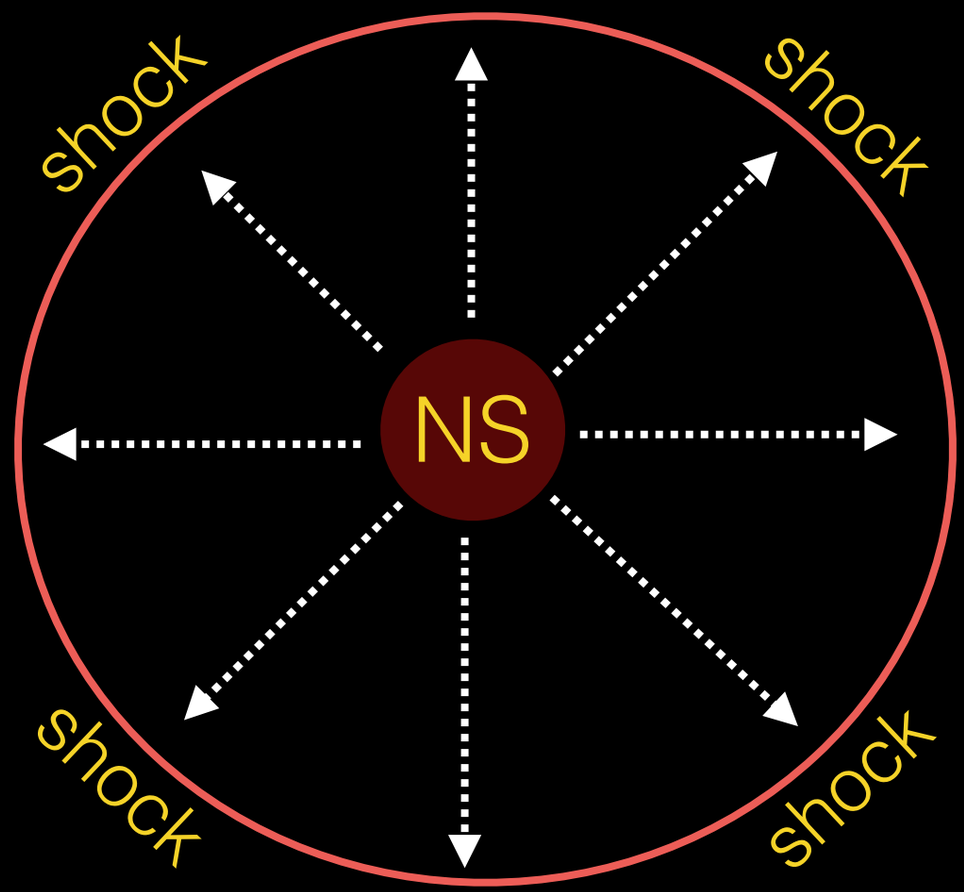


Role of Turbulence

$$P_{\rm turb} \sim \langle \delta v^2 \rangle \rho$$

$$L_{\rm crit} \propto \left(1 + \frac{4}{3}\langle {\rm Ma}_2^2 \rangle\right)^{-3/5}$$

Müller & Janka (2015)



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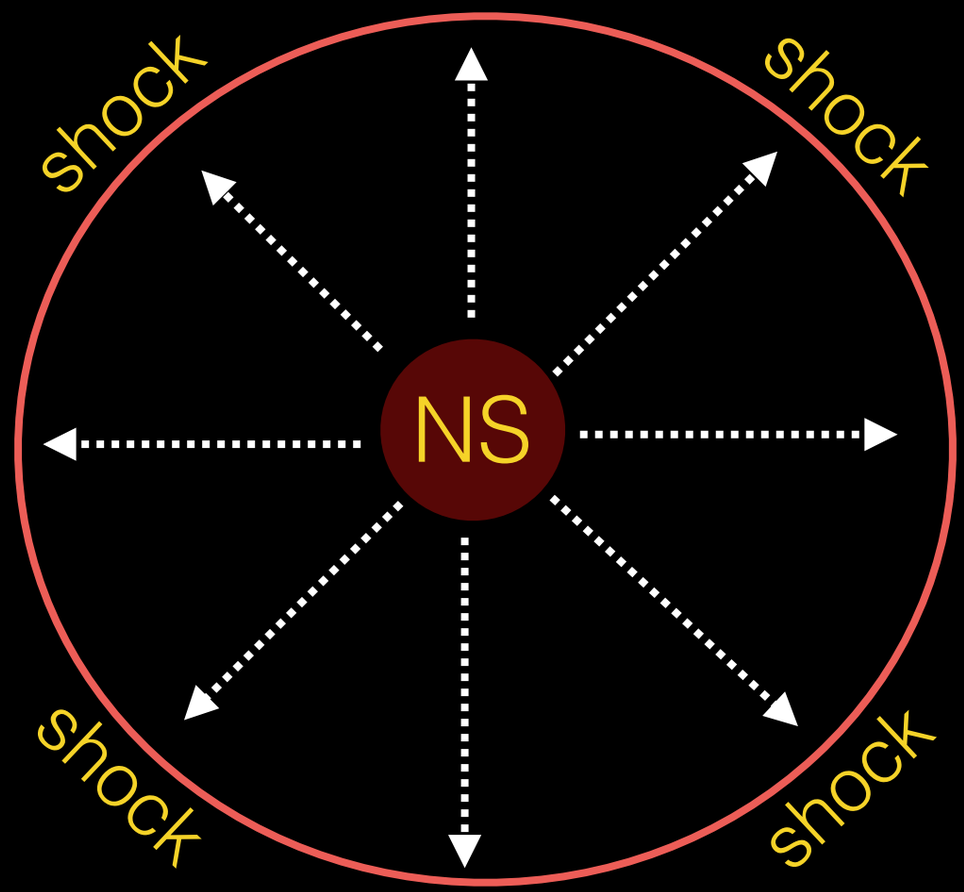


Order-of-magnitude estimate using LIA:

$$L_{\rm crit} \propto \frac{4}{5}\frac{E'_{\rm a,2}}{E'_{\rm a,1}}\frac{\langle c_{\rm s,1}^2 \rangle}{\langle c_{\rm s,2}^2 \rangle}\langle \mathcal{M}'^2_1 \rangle,$$

Explosion Condition

$$\mathrm{Ma} \sim 0.1$$

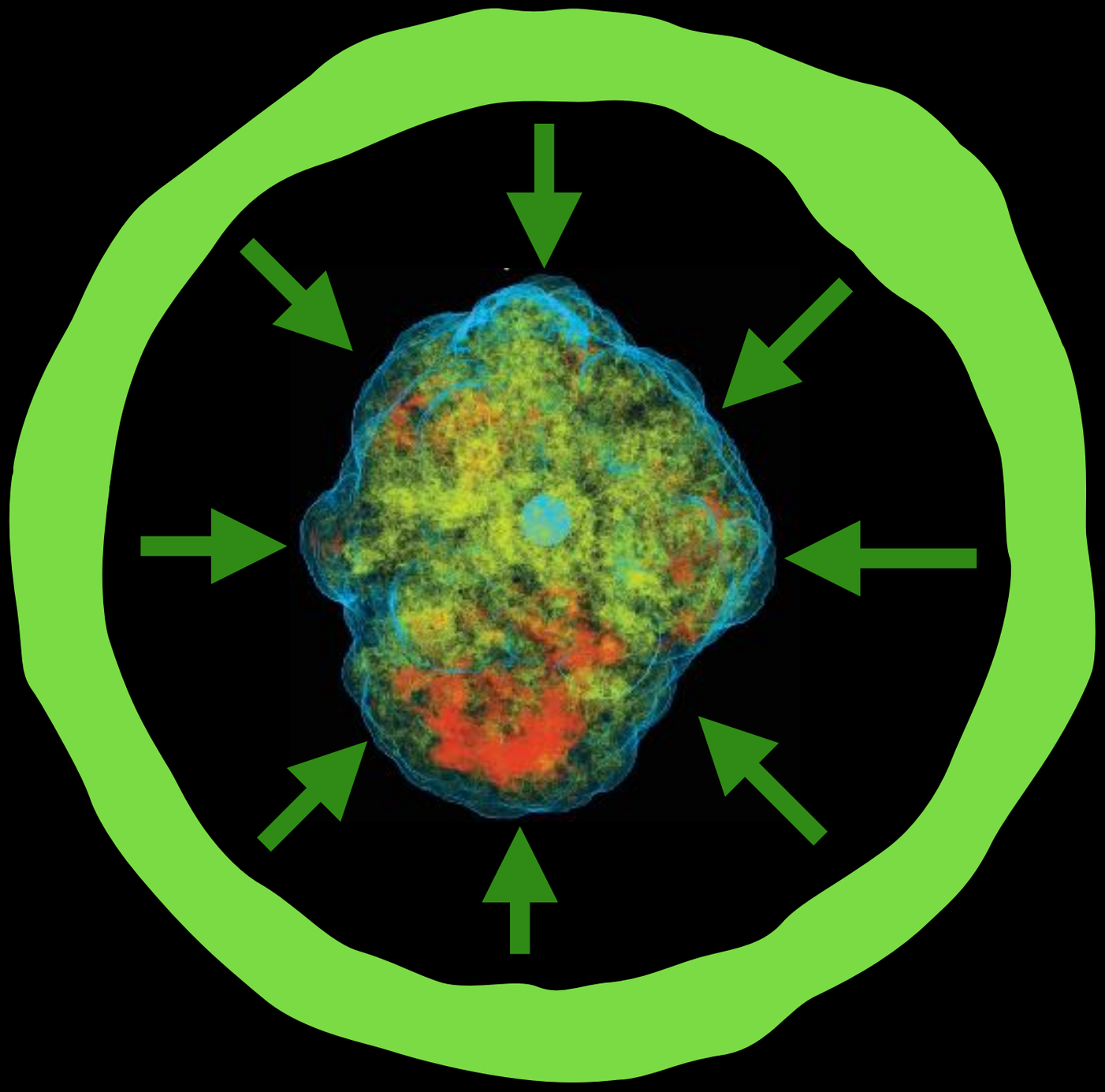
e.g., Müller et al (2016)

$$\mathrm{Ma} \propto r^{(3\gamma-7)/4}$$

Kovalenko & Eremin (1998)

$$\delta L_{\mathrm{crit}} \sim -12\%$$

Abdikamalov et al (2016)



Recent review: Müller 2016

What's next?

- Improved infall evolution
- Acoustic waves
- Post-shock evolution