Vorticity Waves and Shock Dynamics in Core-Collapse Supernovae

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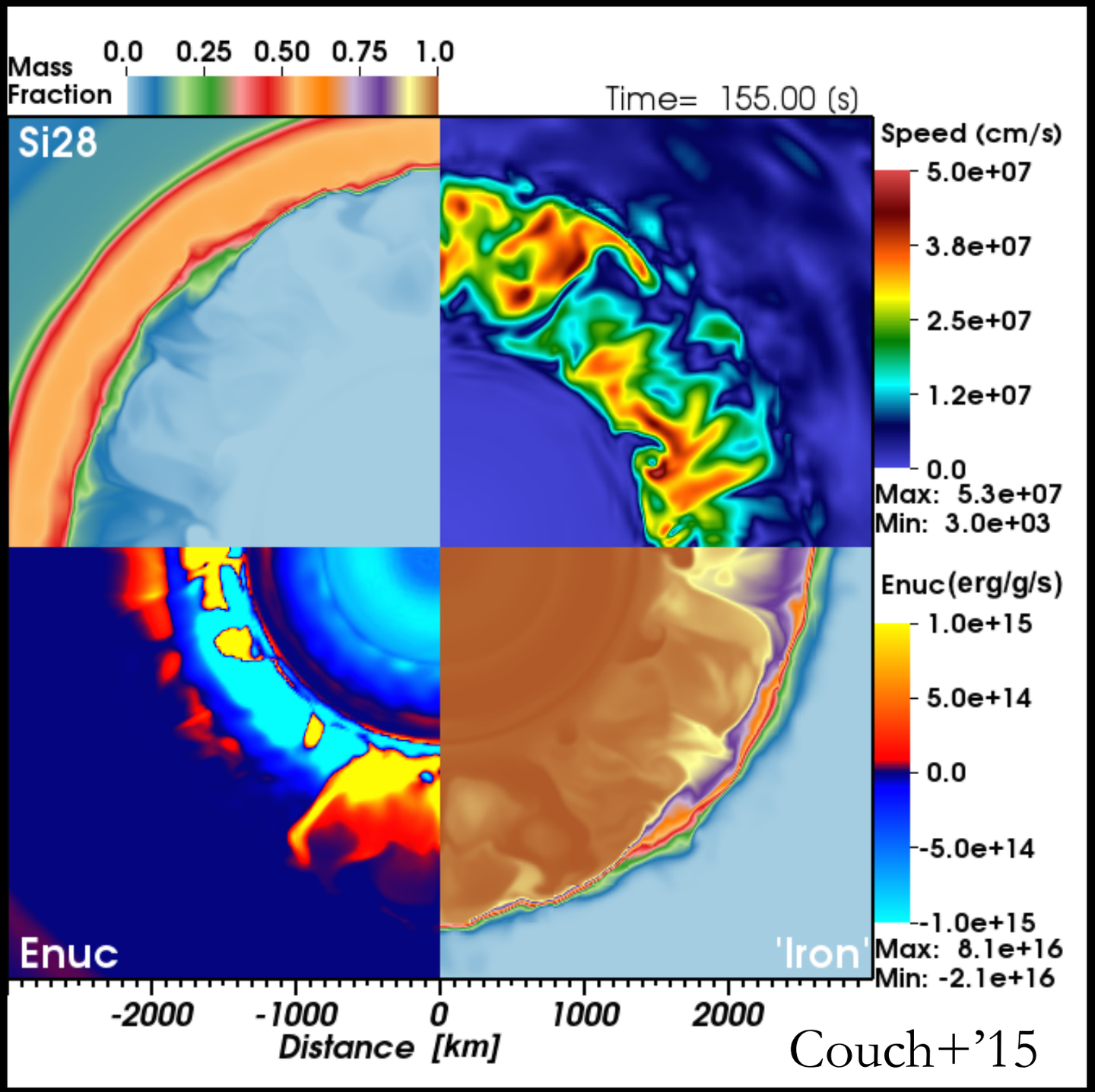
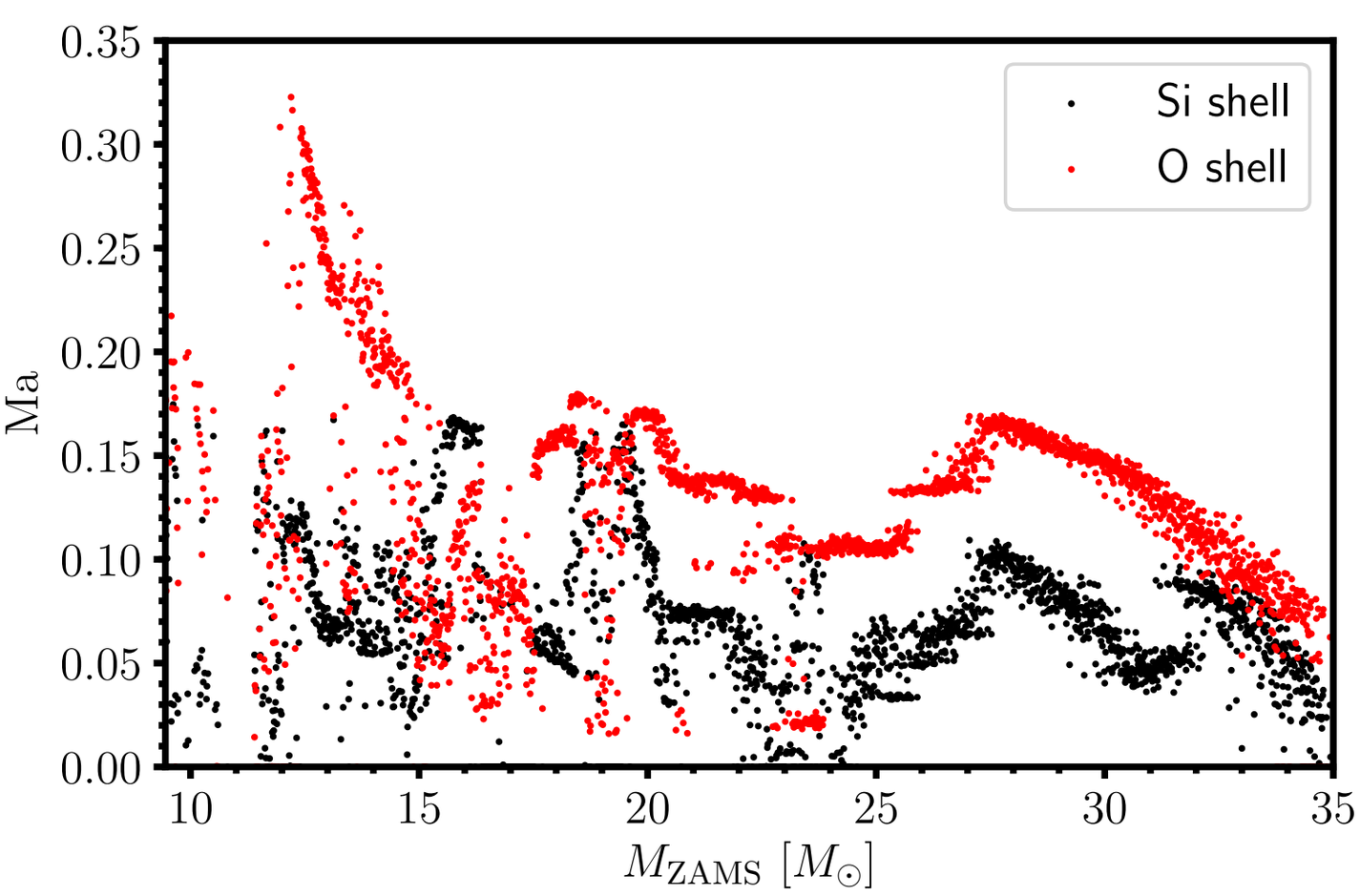
CoCoNuT 2017, Garching

Progenitor asphericities before core-collapse

Couch & Ott ’13, ’15, Couch+’15, Müller & Janka ’15, Müller+’16, ‘17

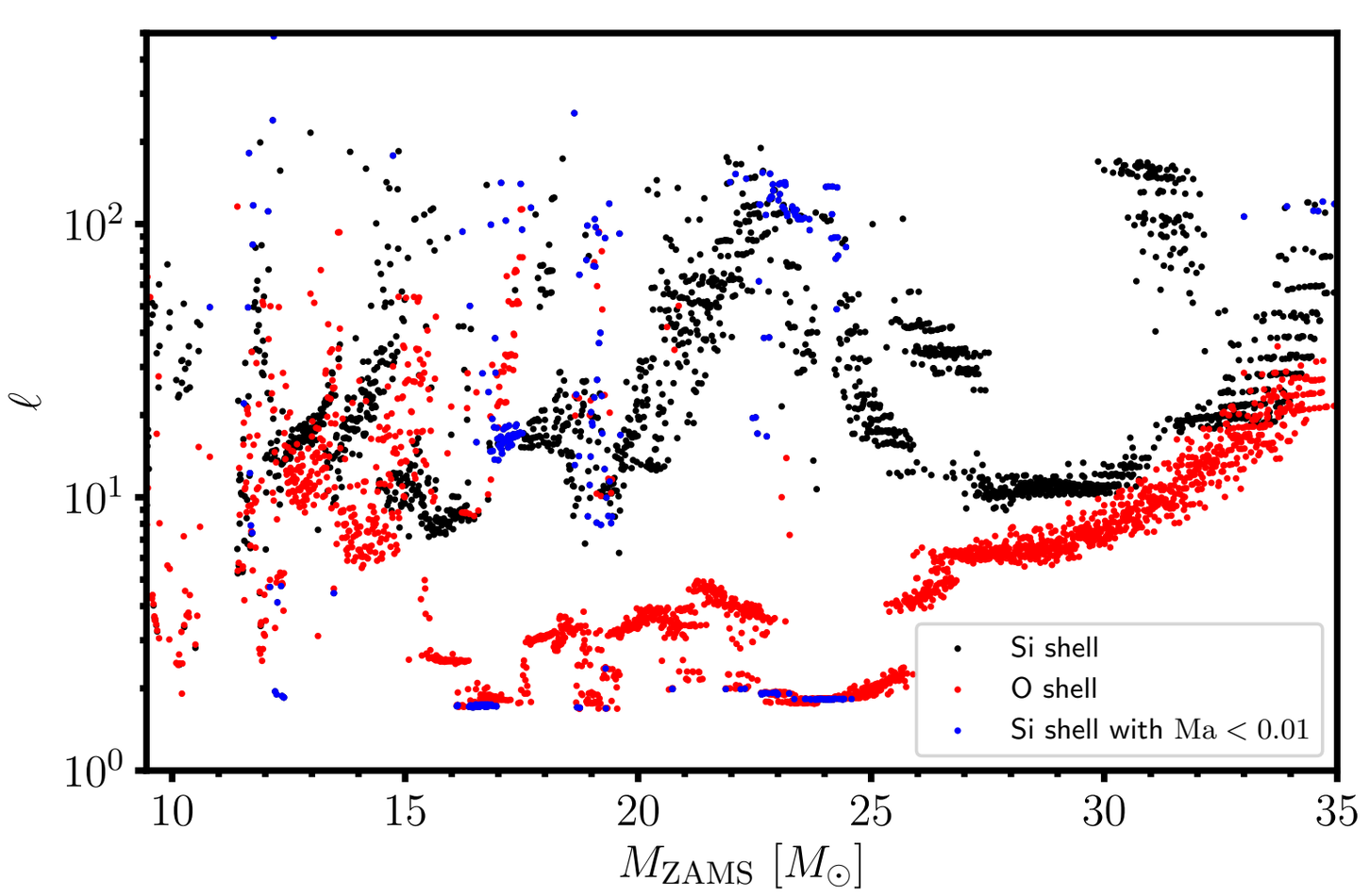


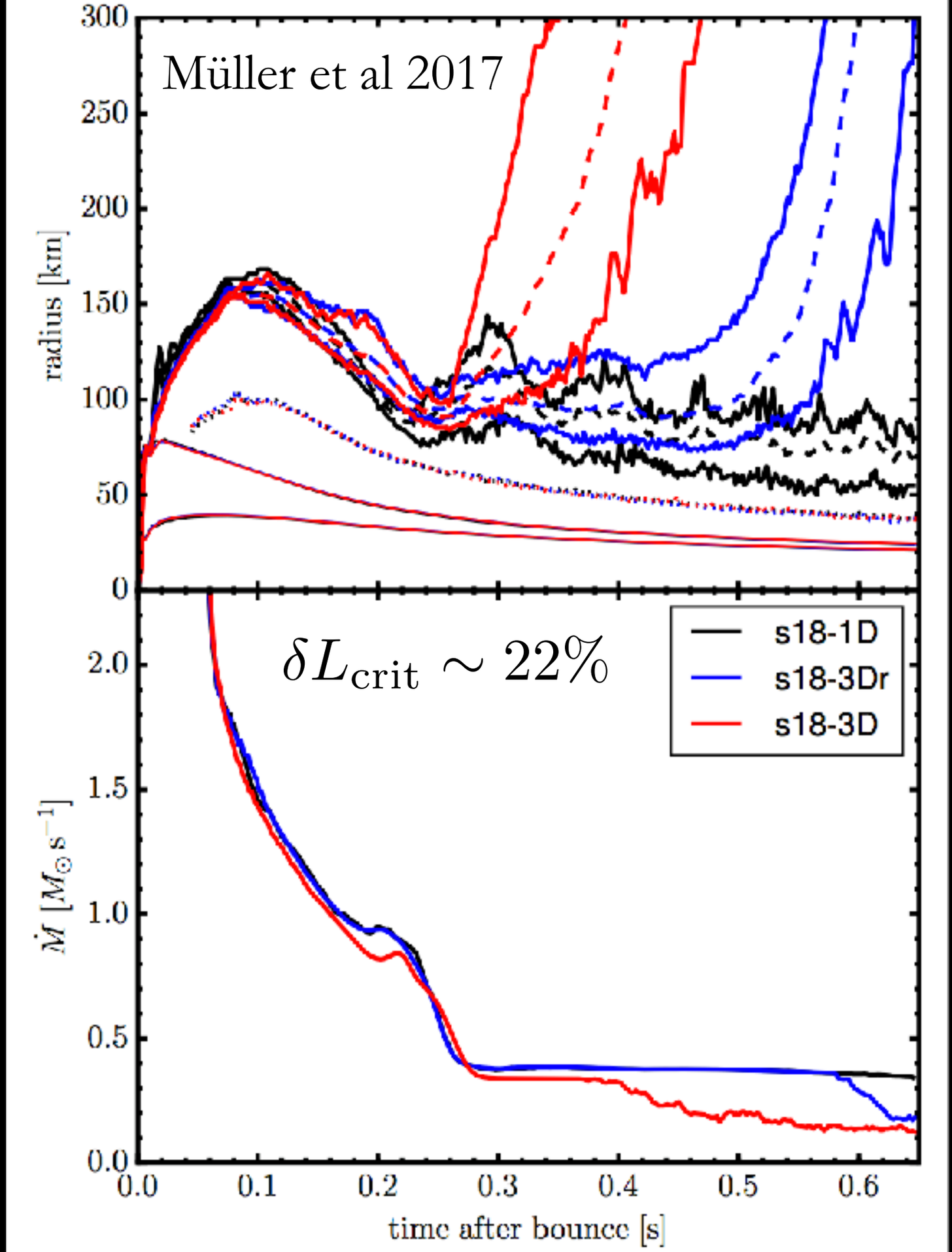
See also: Arnett & Meakin ‘16, Chatzapoulos+’16, Collins+’17, Fernandez ‘15



Large progenitor asphericities are common

Collins et al (2017)

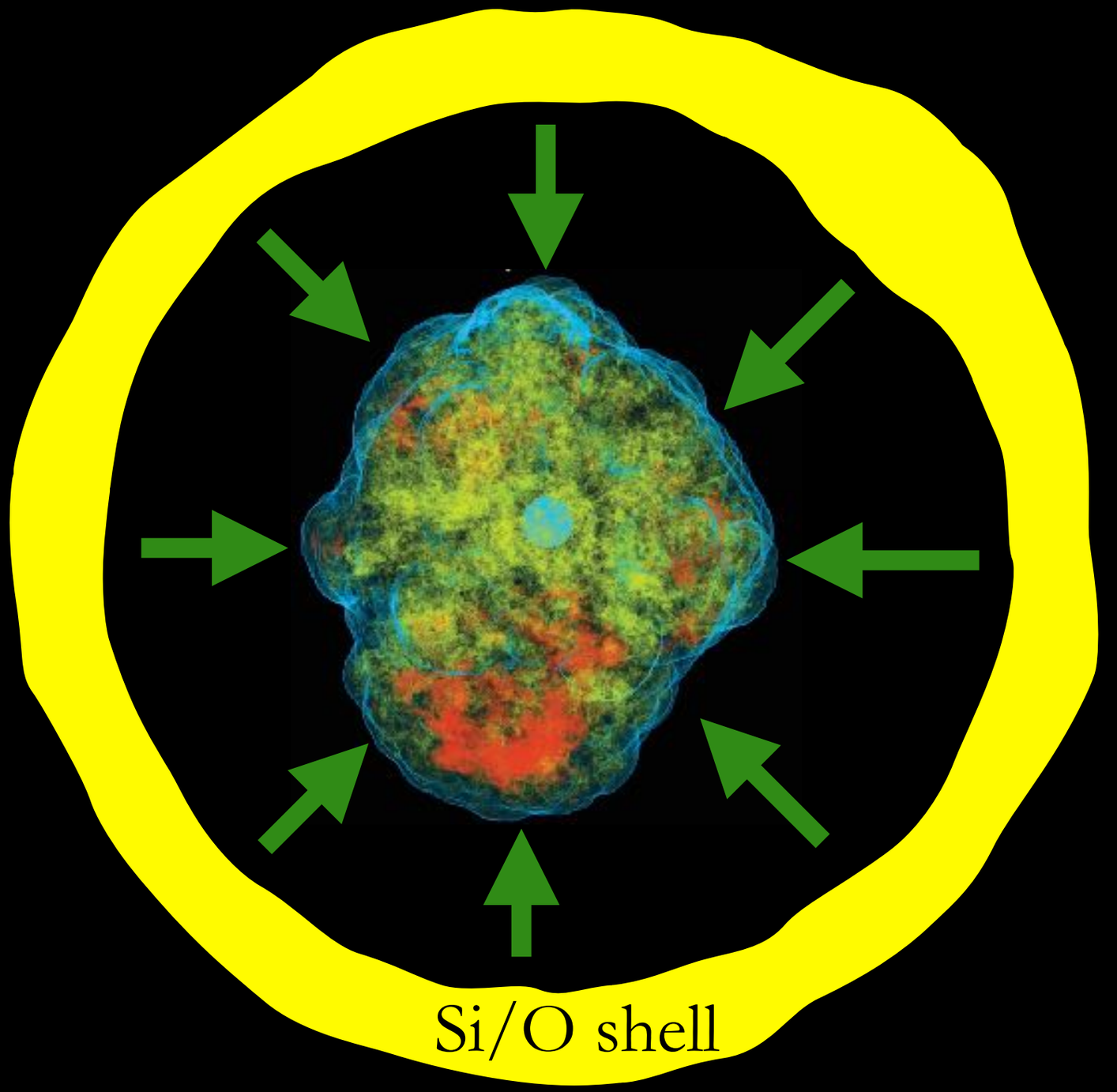



Müller et al 2017
$\delta L_{\rm crit} \sim 22\%$
s18-1D
s18-3Dr
s18-3D
radius [km]
$\dot{M}$ [$M_\odot$ s^{-1}]
time after bounce [s]
0
50
100
150
200
250
300
0.0
0.5
1.0
1.5
2.0
0.1
0.2
0.3
0.4
0.5
0.6

Qualitative Picture

Müller & Janka ’15, Müller+16, Couch & Ott ‘15

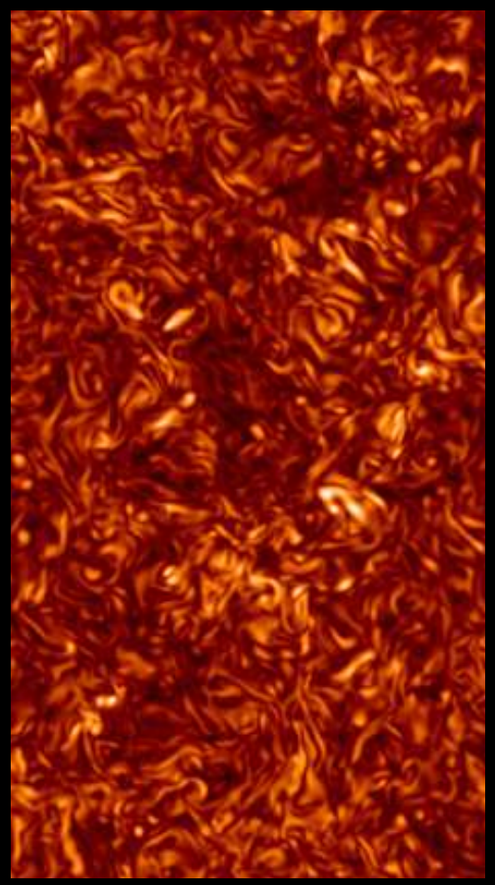
- **Accretion**
- **Shock crossing**
- **Post-shock**



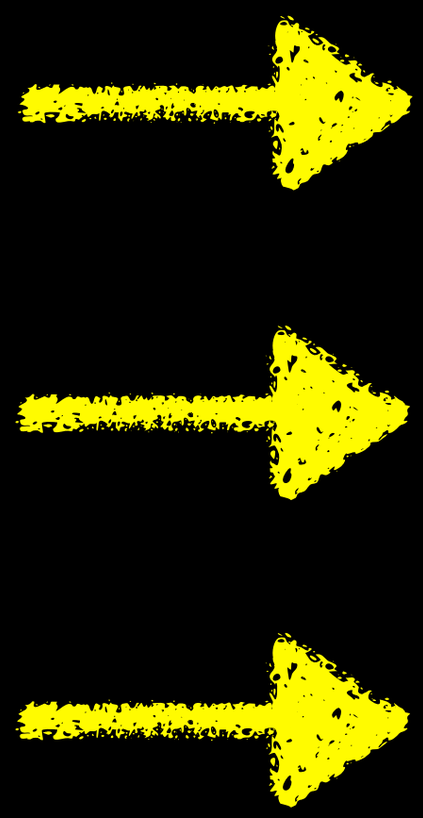
Shock crossing

Abdikamalov+2016 and Huete+2017

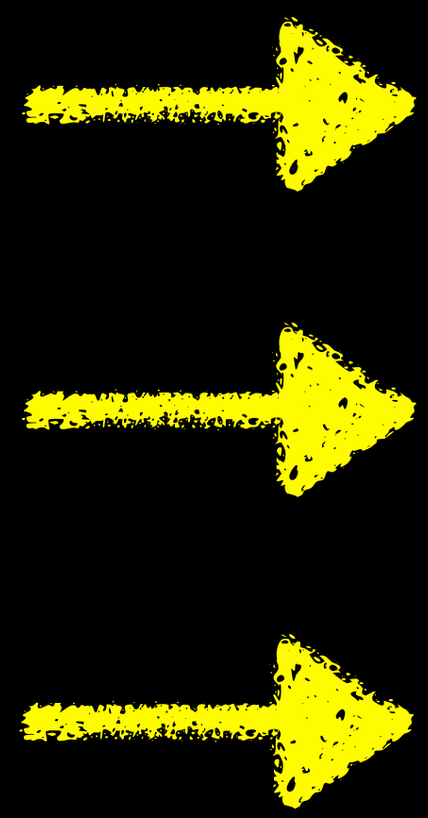
Turbulent flow



Radice+16

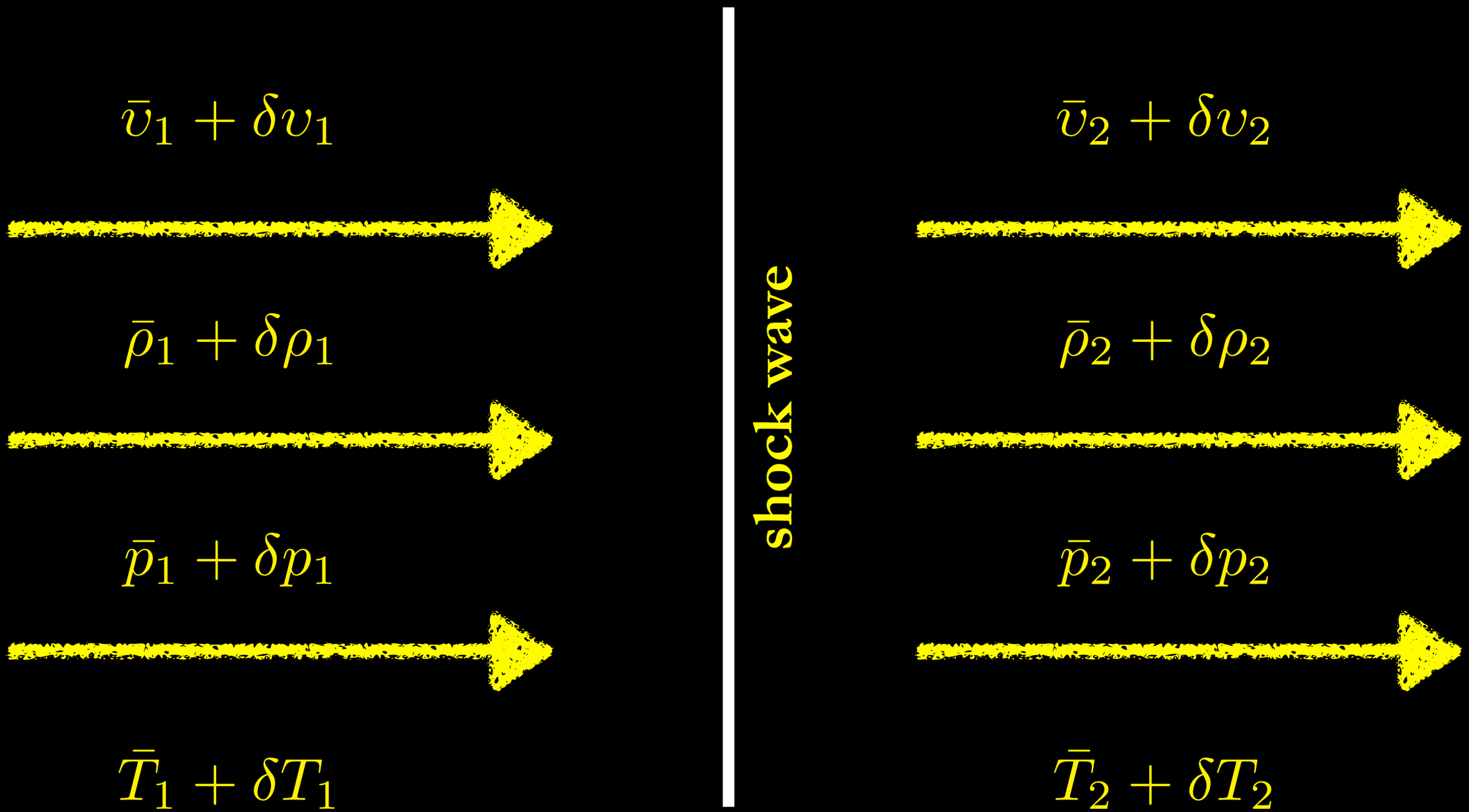


shock wave



Linear Interaction Analysis

Blokhintsev '40s, Ribner '53, Moore '54, Chang '57, …,
Wouchuk+'09, Huete+'17



Linear approximation: validity region

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

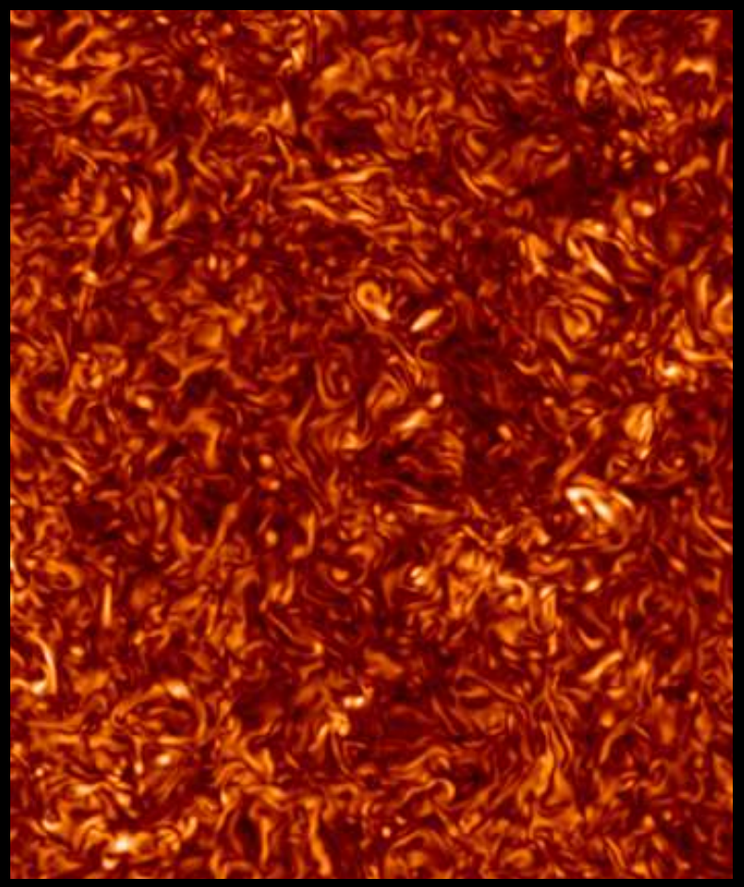
Lee et al (1993), Ryu & Livescu (2014)

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

e.g., Müller et al (2016)

Turbulent Fluctuations: decomposition

Kovasznay (1953)



Radice+16

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

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

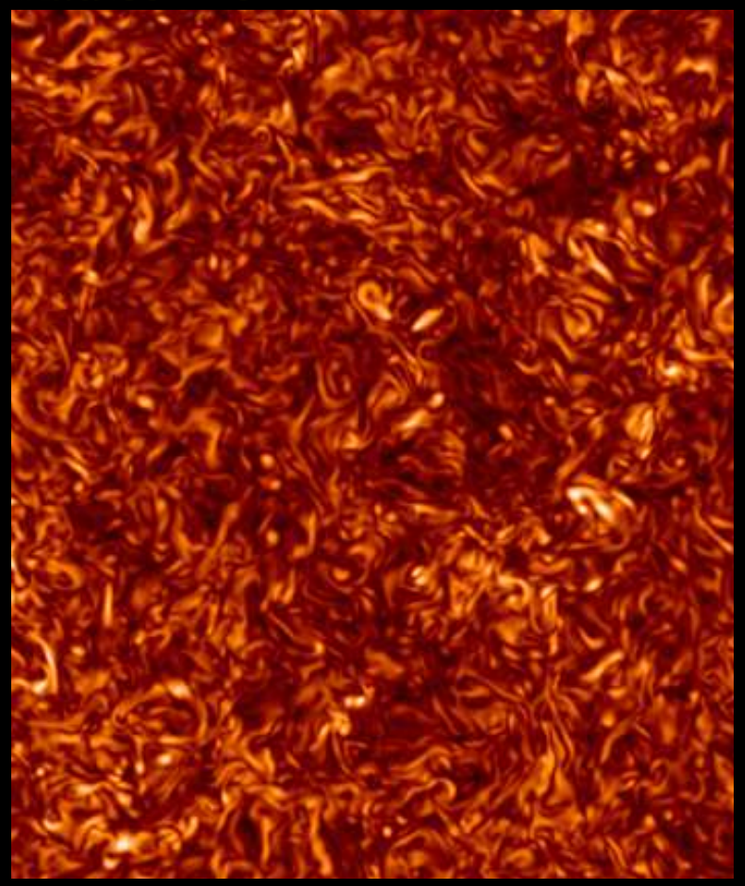
Acoustic $(\delta\rho,\ \delta p,\ \nabla \times \delta v = 0)$

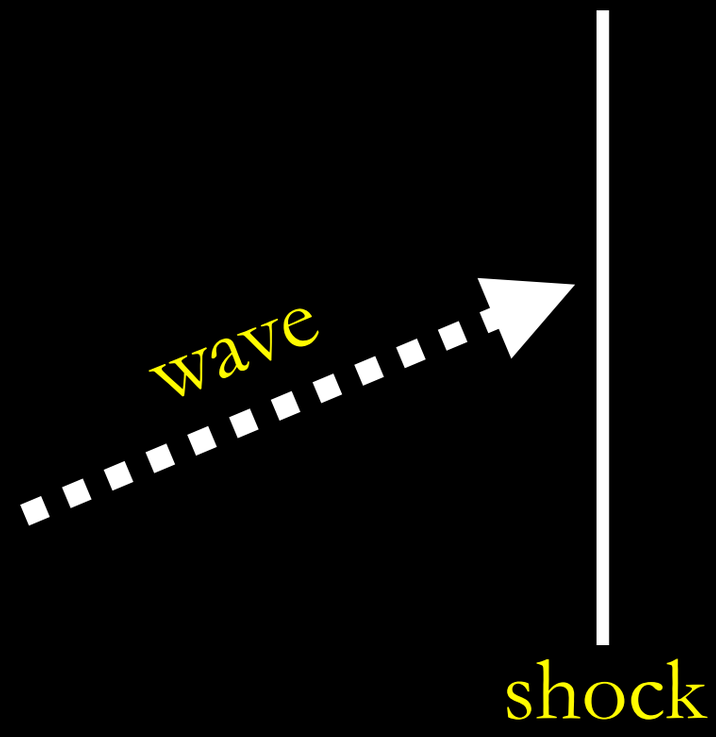
Modes evolve independently in the linear limit for uniform mean flow.

Turbulent Fluctuations: decomposition

Kovasznay (1953)

Radice+16

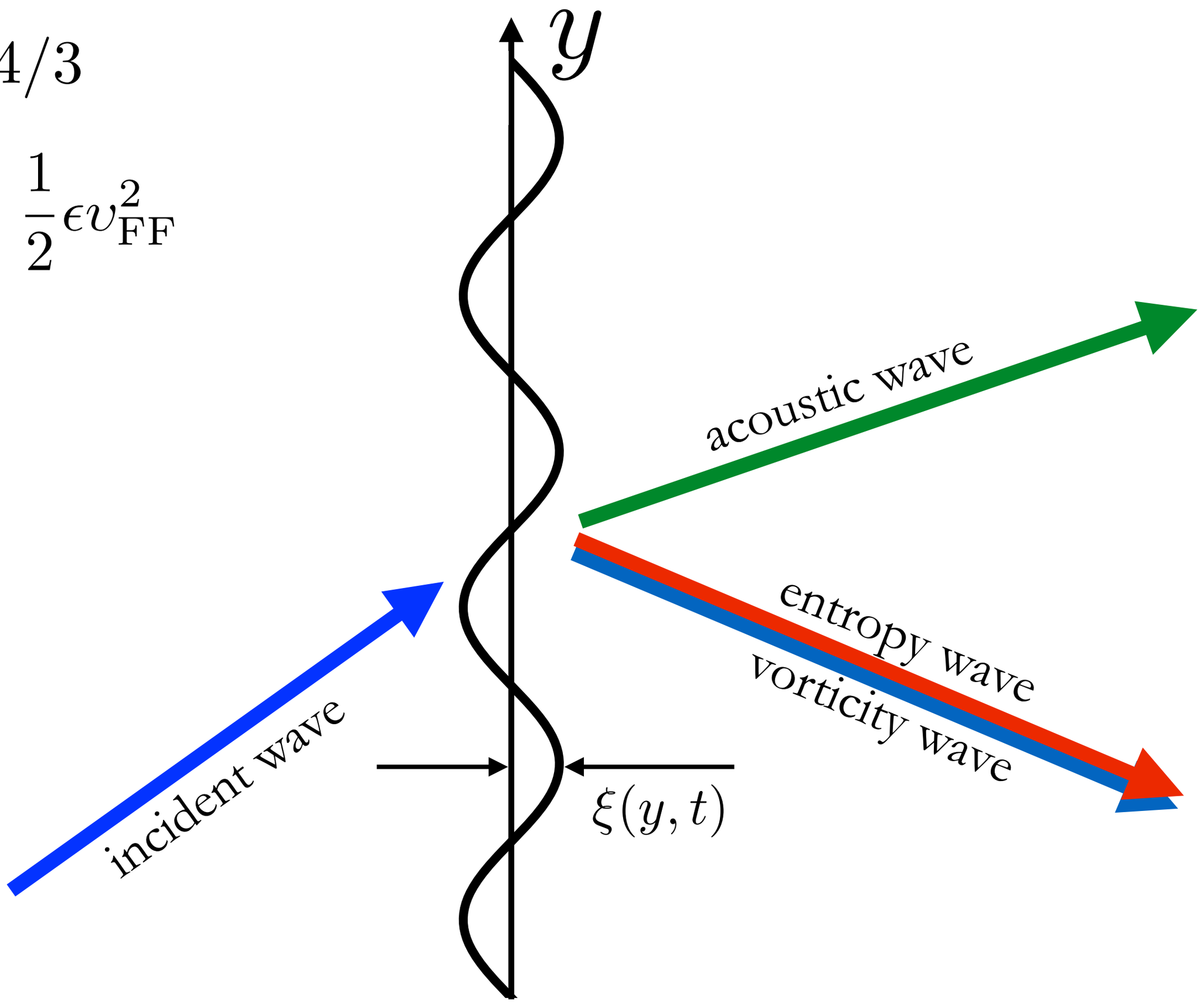




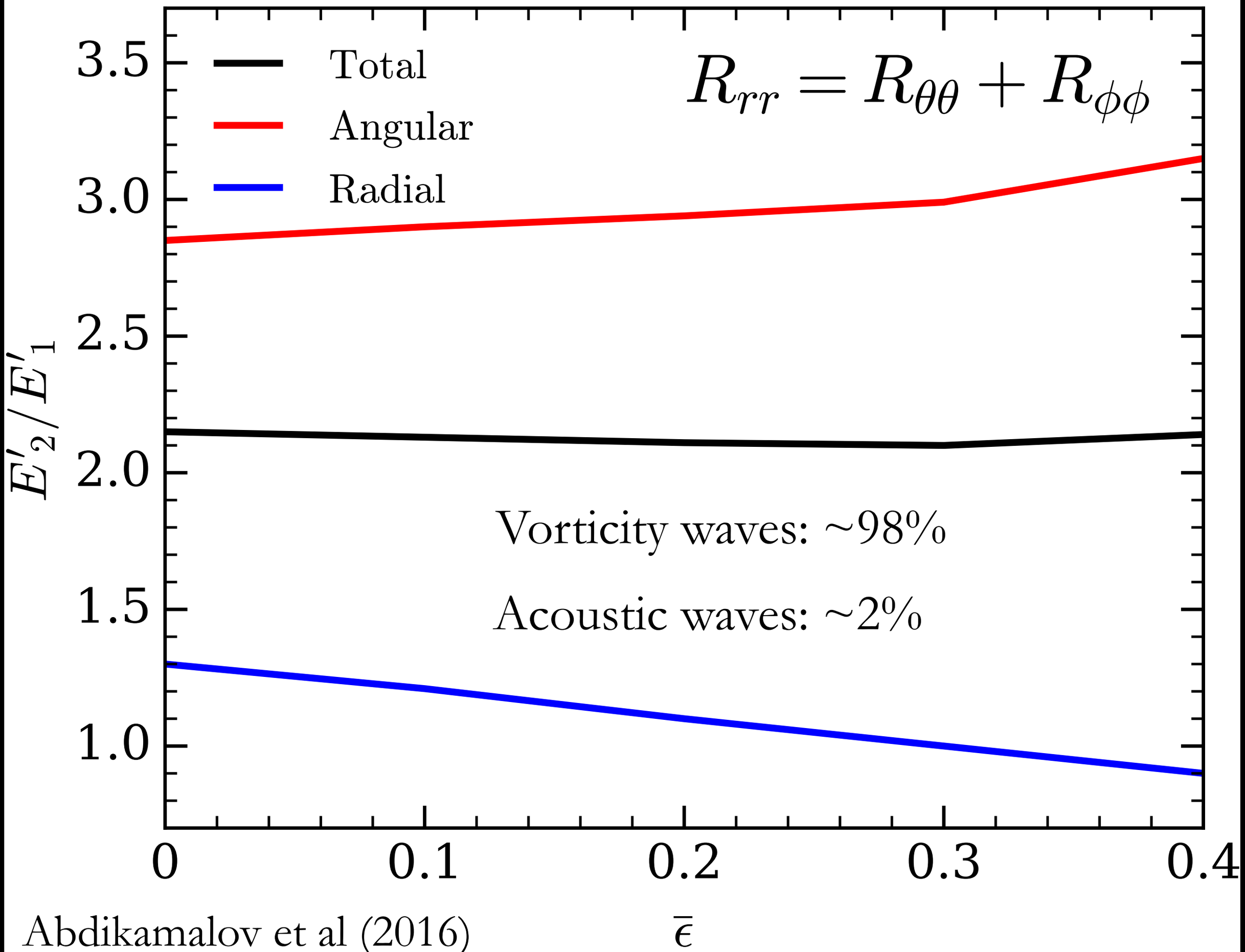
Method: decompose turbulence into waves, calculate interaction for each wave, and integrate the result over all waves

$$\gamma = 4/3$$

$$\Delta e = \frac{1}{2}\epsilon v_{\mathrm{FF}}^2$$



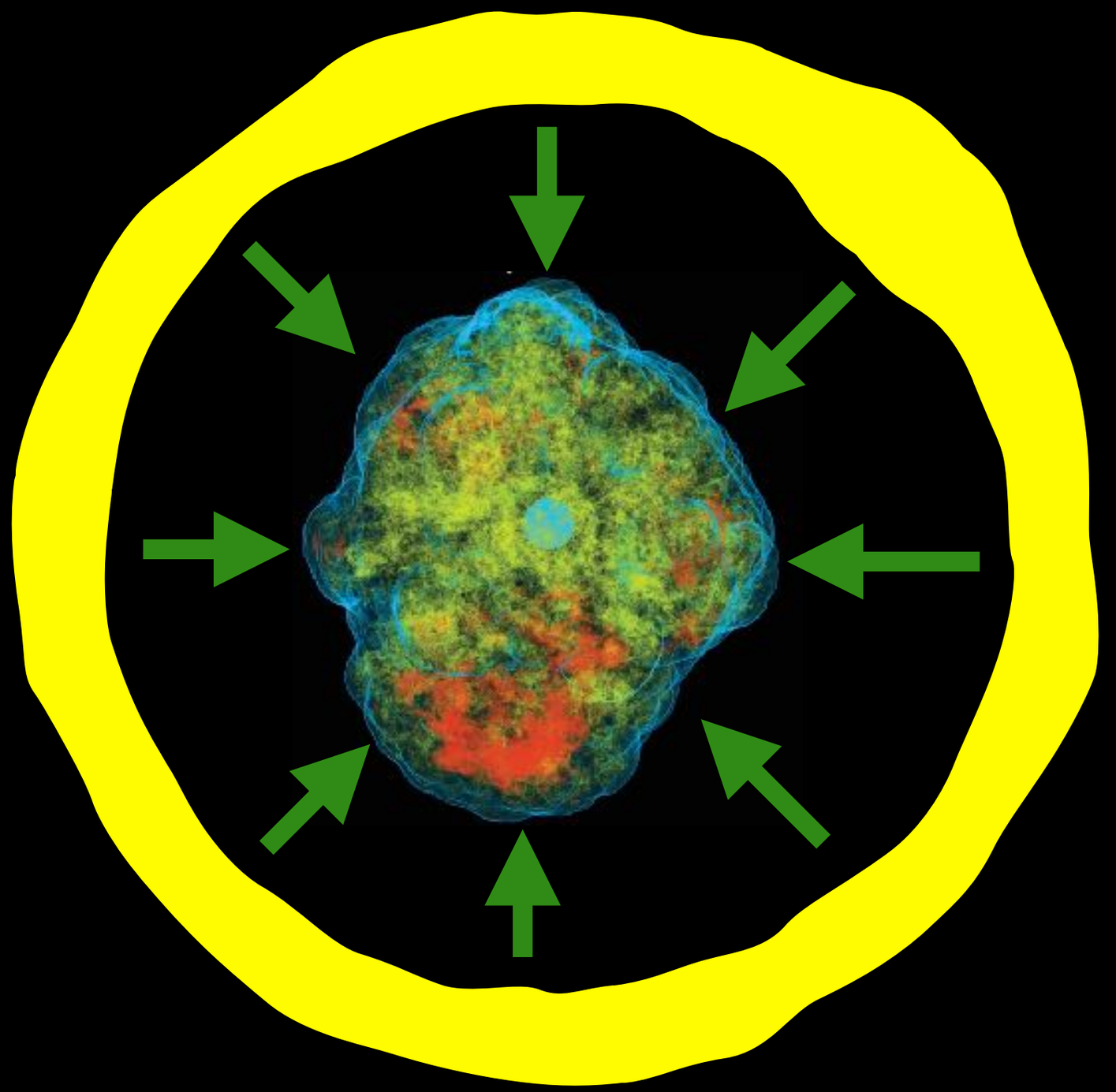
“Direct injection” of kinetic energy



Abdikamalov et al (2016)

Explosion Condition

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

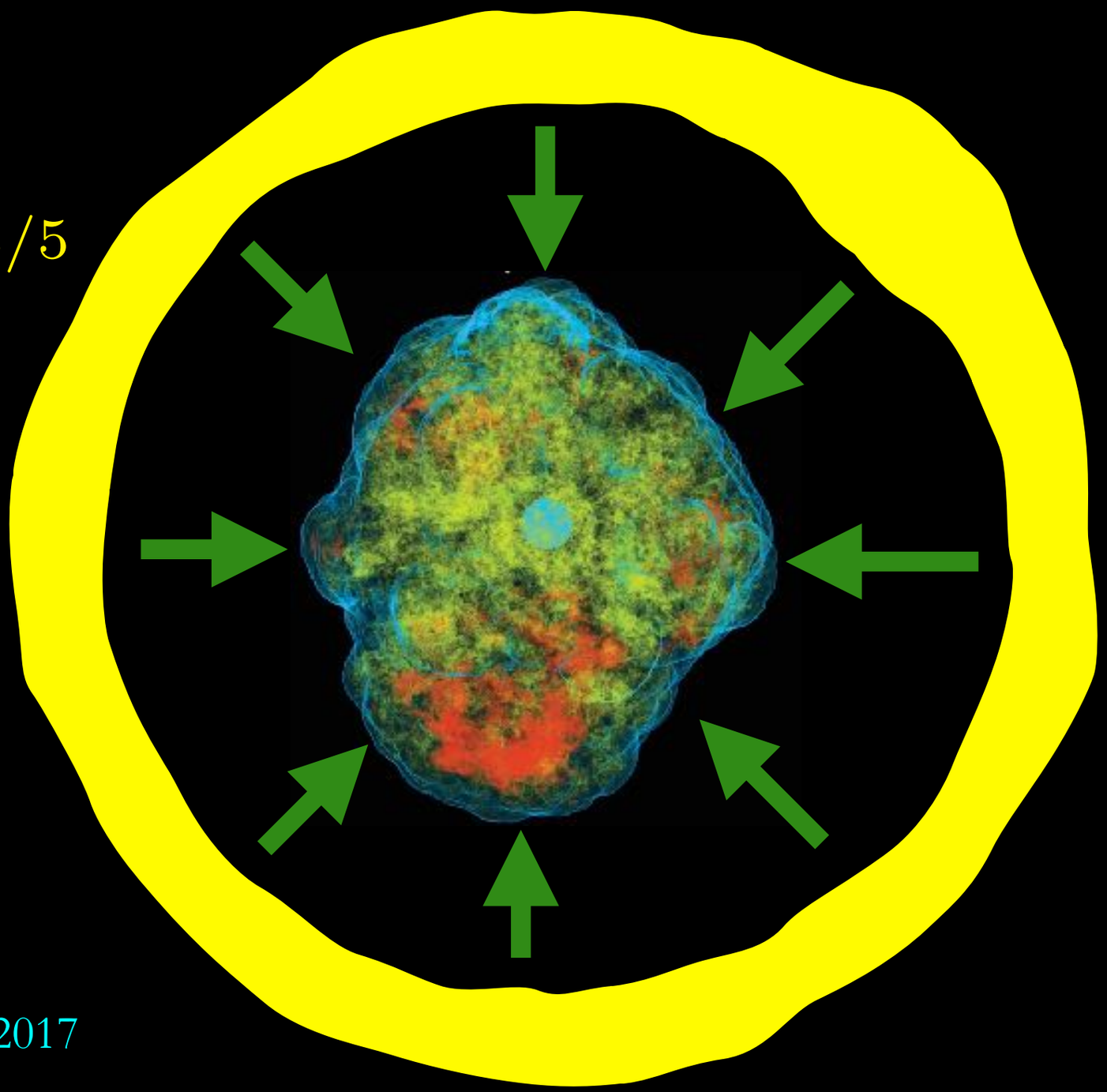


Explosion Condition

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

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

Müller & Janka (2015)



See also: Takahashi+2016, Mabanta & Murphy 2017

Explosion Condition

$\mathrm{Ma} \sim 0.1$ e.g., Müller et al (2016)

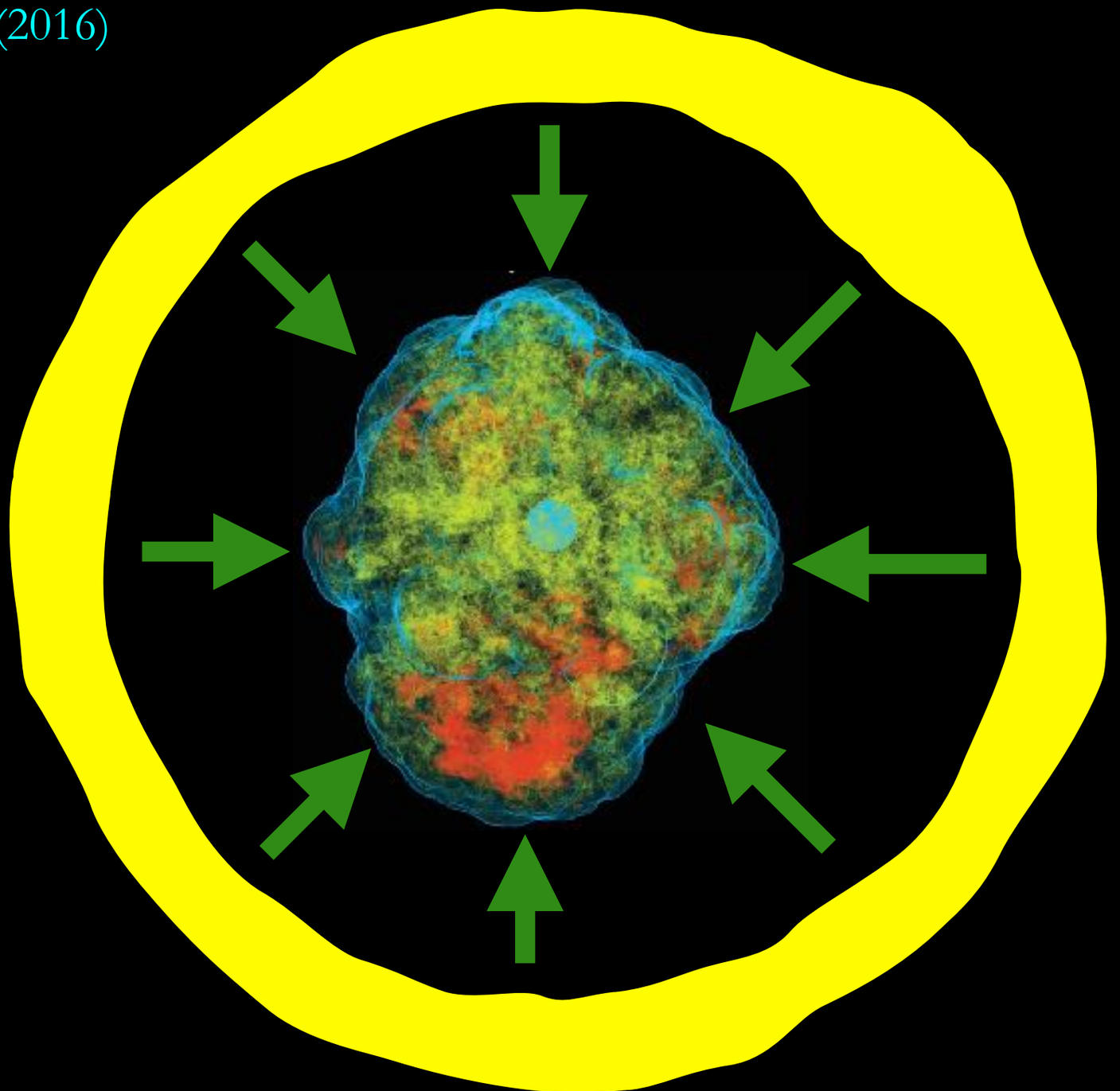
$\mathrm{Ma} \propto r^{(3\gamma-7)/4}$

Kovalenko & Eremin (1998)

Assuming "direct injection":

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

Abdikamalov et al (2016)



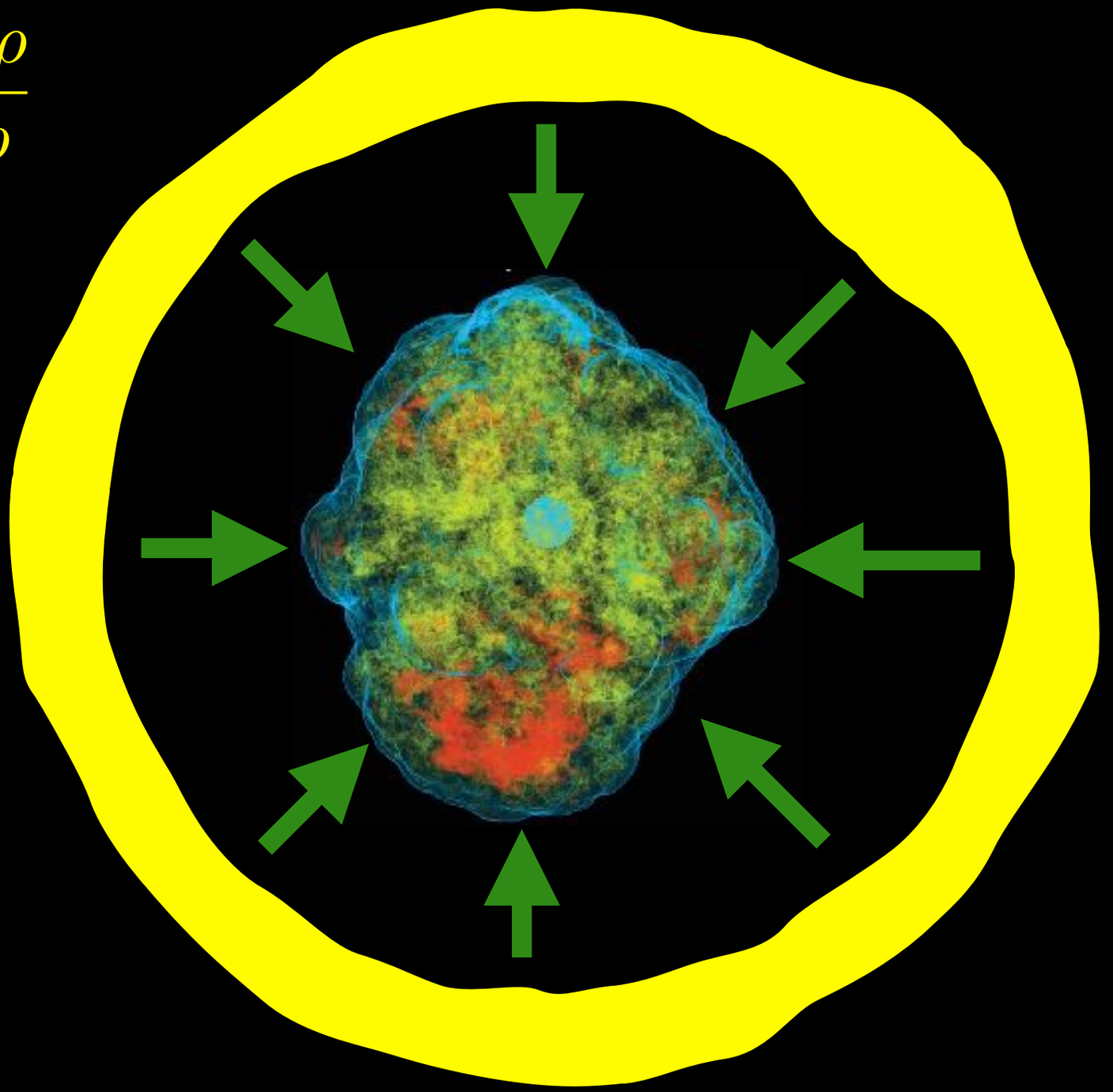
Turbulence driven by buoyancy

Müller et al (2016, 2017)

$$F_{\rm pot} \sim \dot{M} \left(\frac{GM}{R_{\rm sh}} - \frac{GM}{R_{\rm g}} \right) \frac{\delta\rho}{\rho}$$

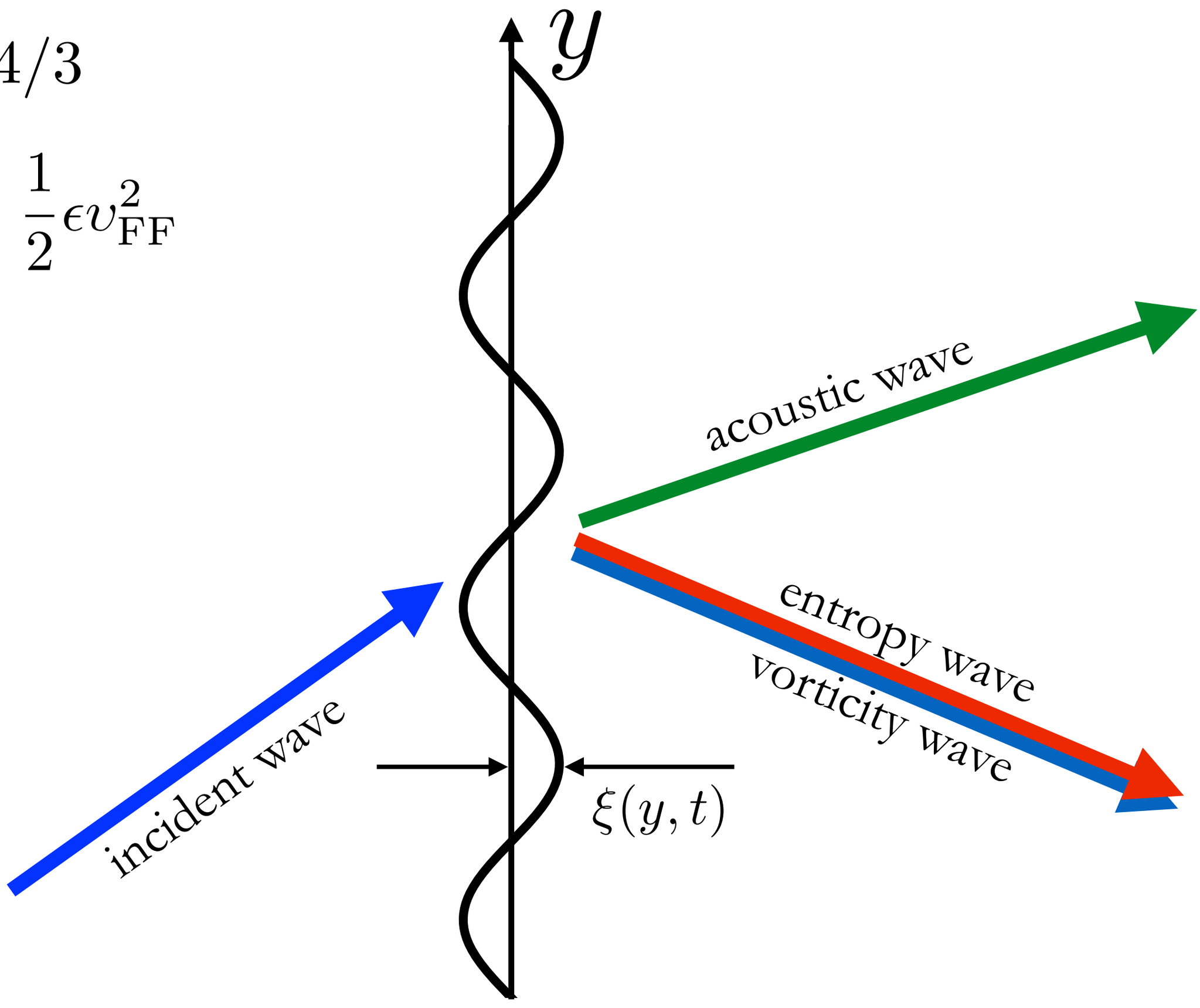
$$\delta L \sim -\frac{2.34}{\ell} \frac{\delta\rho}{\rho}$$

$$\frac{\delta\rho}{\rho} \sim \frac{\delta v_{\rm r}}{c_{\rm s}} \frac{\partial \ln \rho}{\partial \ln r}$$



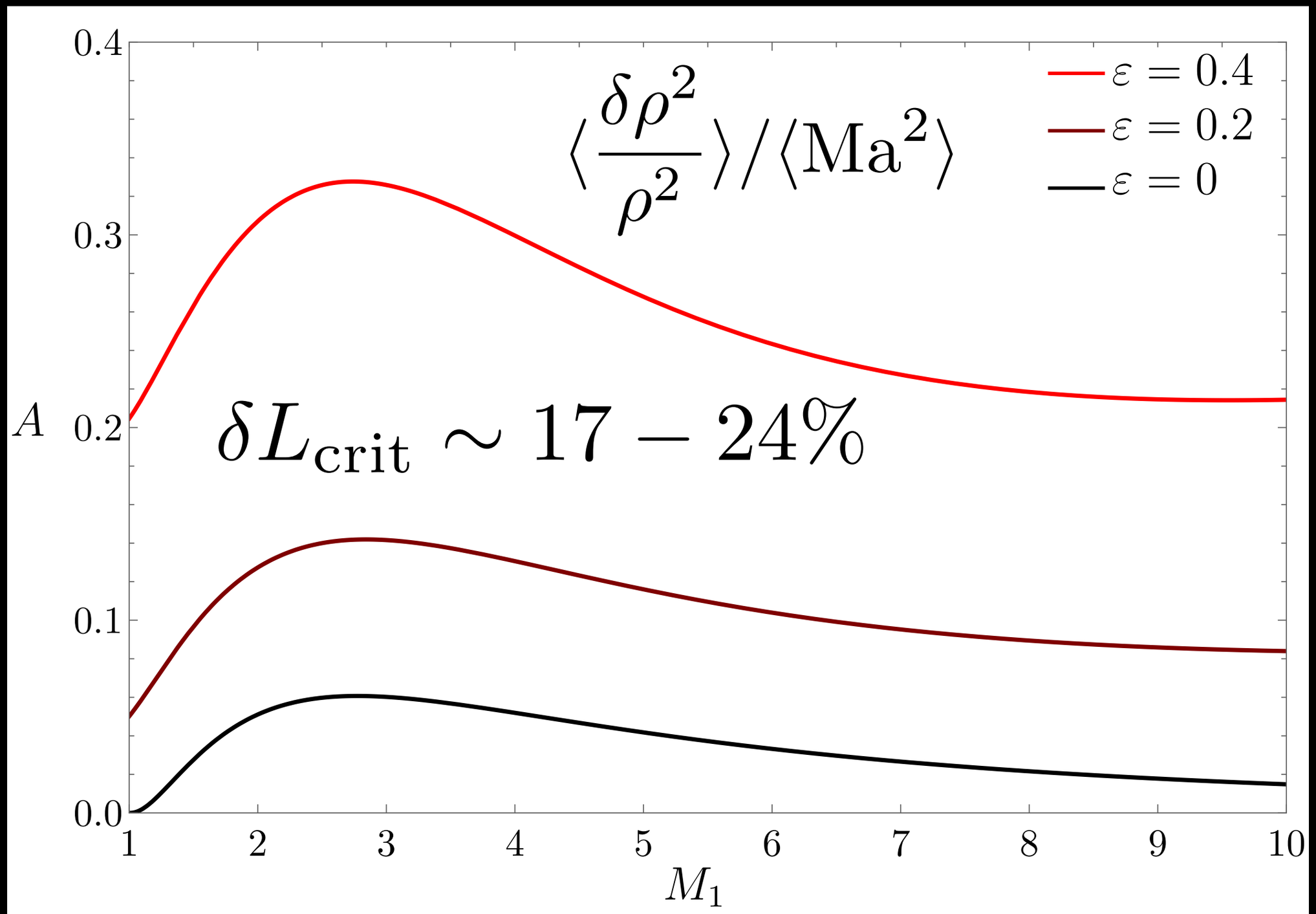
$$\gamma = 4/3$$

$$\Delta e = \frac{1}{2}\epsilon v_{\mathrm{FF}}^2$$

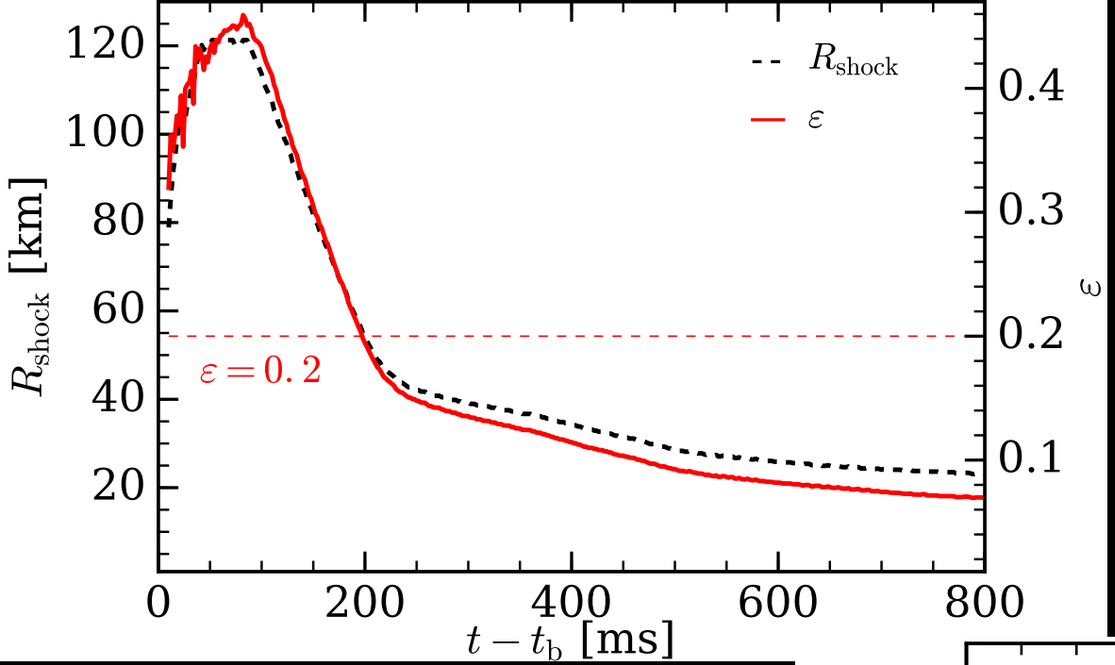


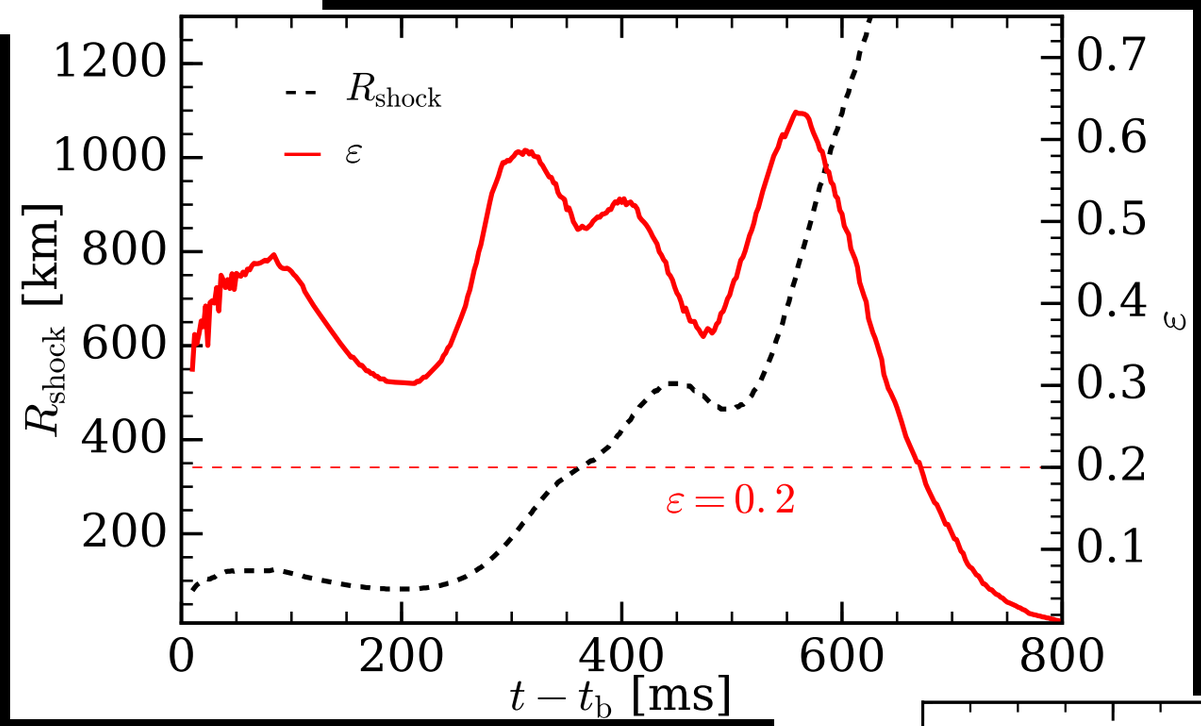
Entropy perturbations

Huete, Abdikamalov, Radice (2017)



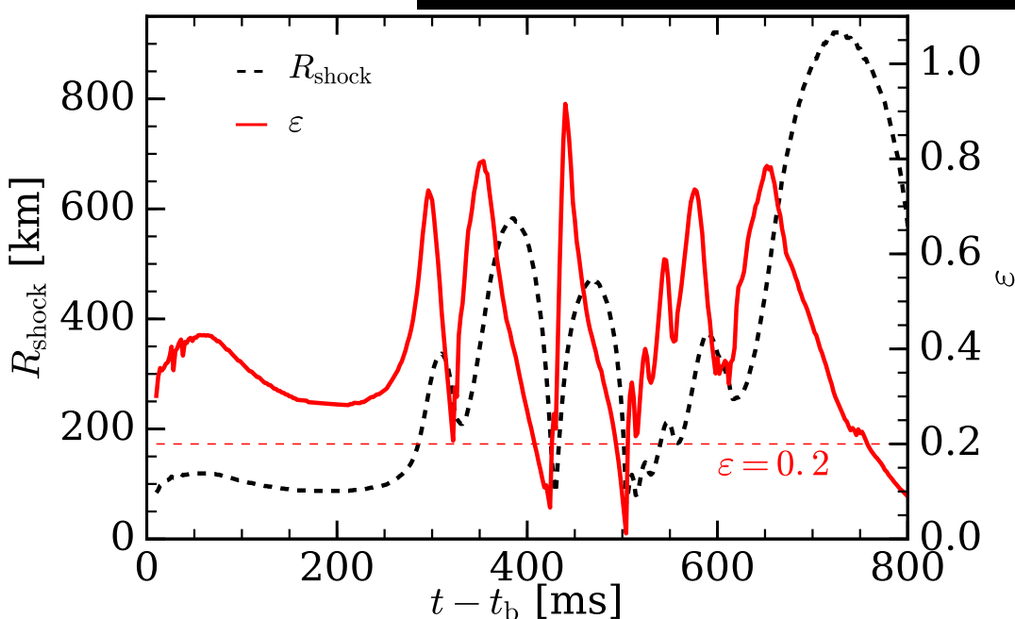
Nuclear dissociation parameter from 1D simulations

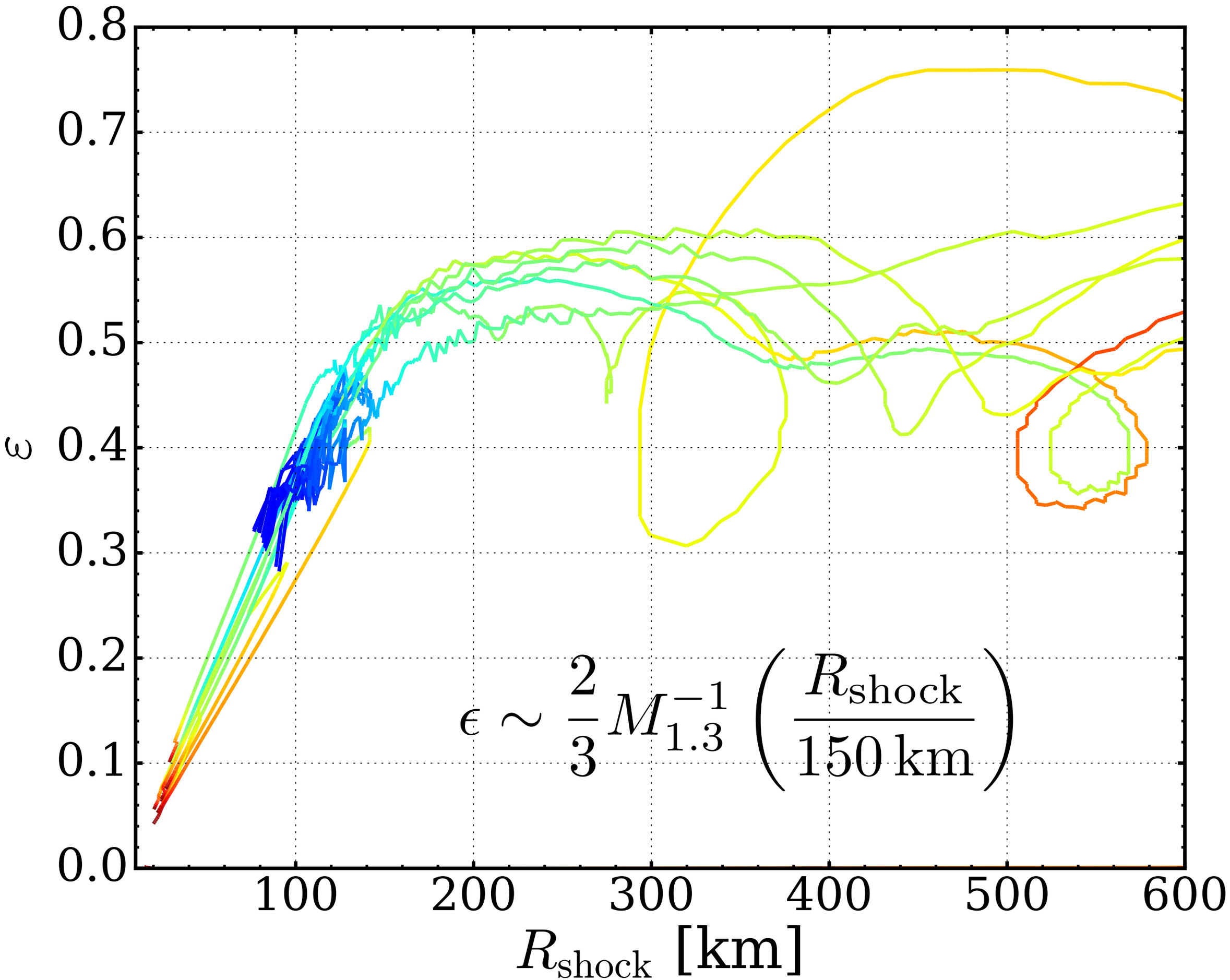




GR1D [O'Connor & Ott '11]

SFHo EOS [Steiner+'13]




0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
ω
100
200
300
400
500
600
$R_{\rm shock}$ [km]
$\epsilon \sim \frac{2}{3} M_{1.3}^{-1} \left(\frac{R_{\rm shock}}{150\,{\rm km}} \right)$

$$6.5 \times \left(\frac{150\ \mathrm{km}}{R_{\mathrm{shock}}}\right)^{0.37}$$

M_1

14
13
12
11
10
9
8
7
6
5
4
3

0
100
200
300
400
500
600

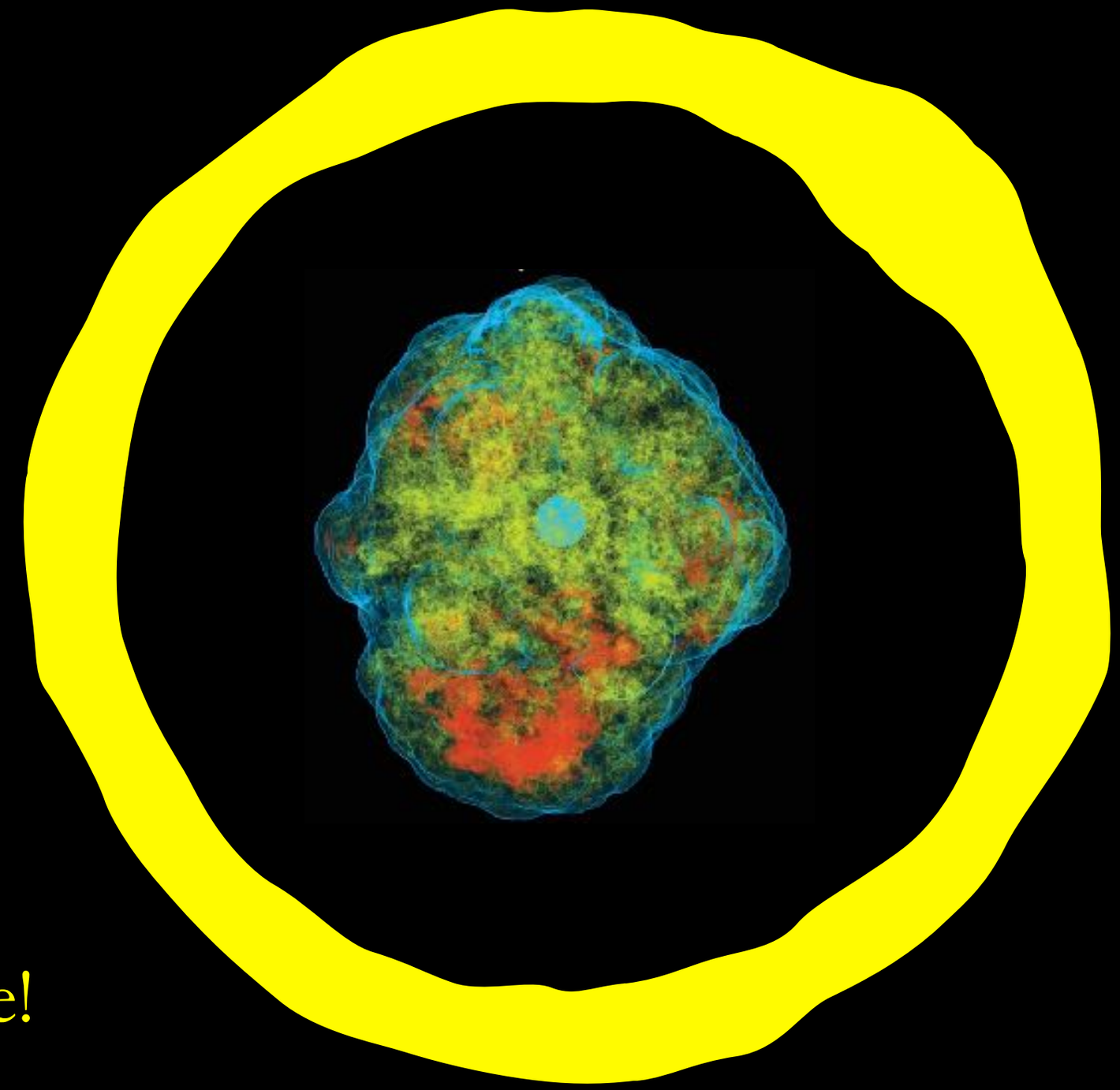
R_{shock} [km]

Other modes

Acoustic Waves in Turbulent Motion

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

[Lighthill 1952, Landau & Lifshitz 1959]



For subsonic turbulence,
sound emission is negligible!

Acoustic waves during accretion

Kovalenko & Eremin 1998, Foglizzo 2001, Müller & Janka 2015

1. Entropy perturbations:

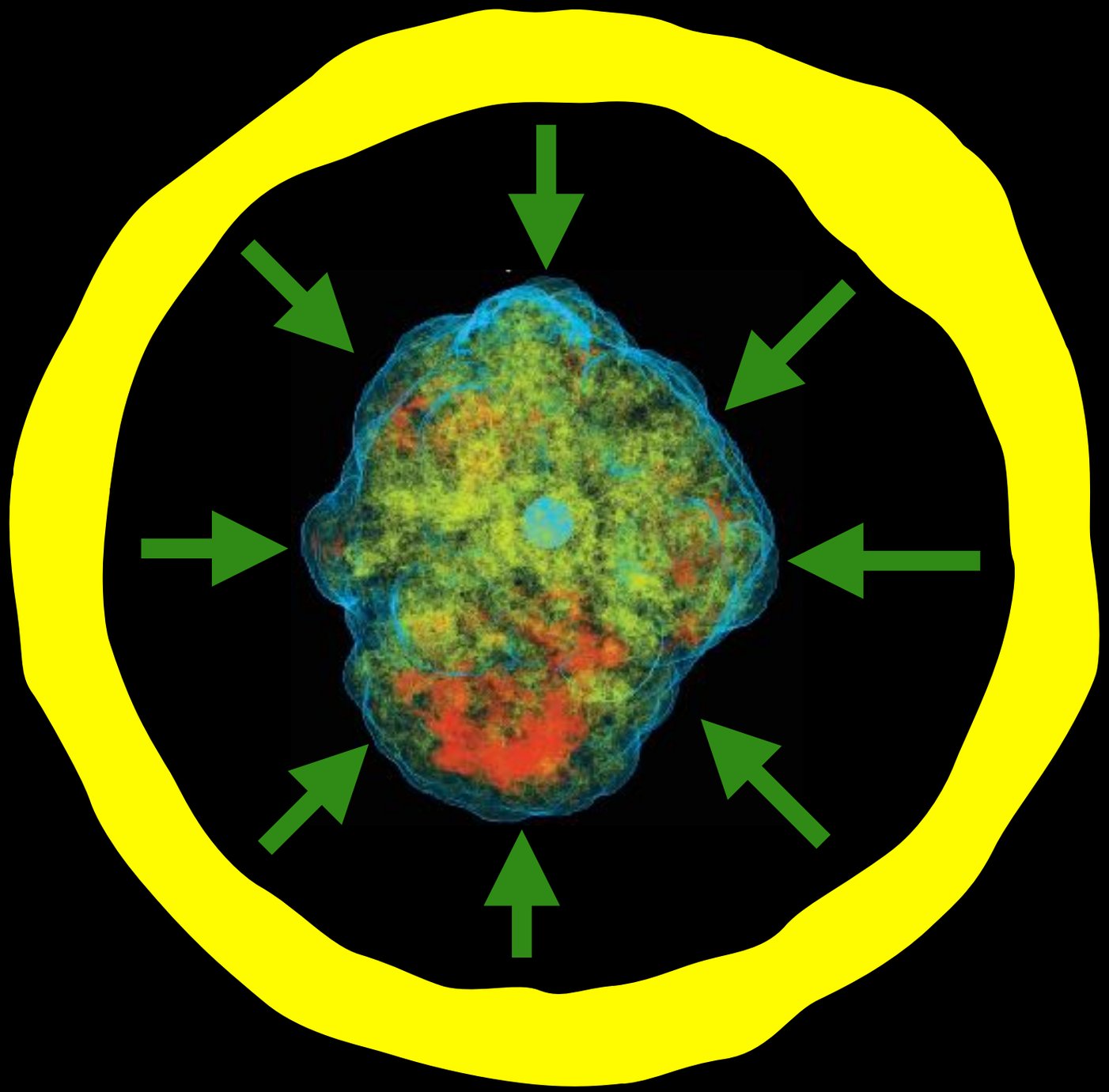
$$\delta E \sim (h_2 - h_1)\delta m$$

Foglizzo & Tagger 2000

2. Vorticity perturbations:

$$\frac{\delta\rho}{\rho} \sim \mathrm{Ma}$$

Müller et al (2016, 2017)



What's next?

- Improved infall evolution
- Acoustic waves
- Non-uniform flow
- Post-shock evolution