Turbulence in Core-Collapse Supernovae

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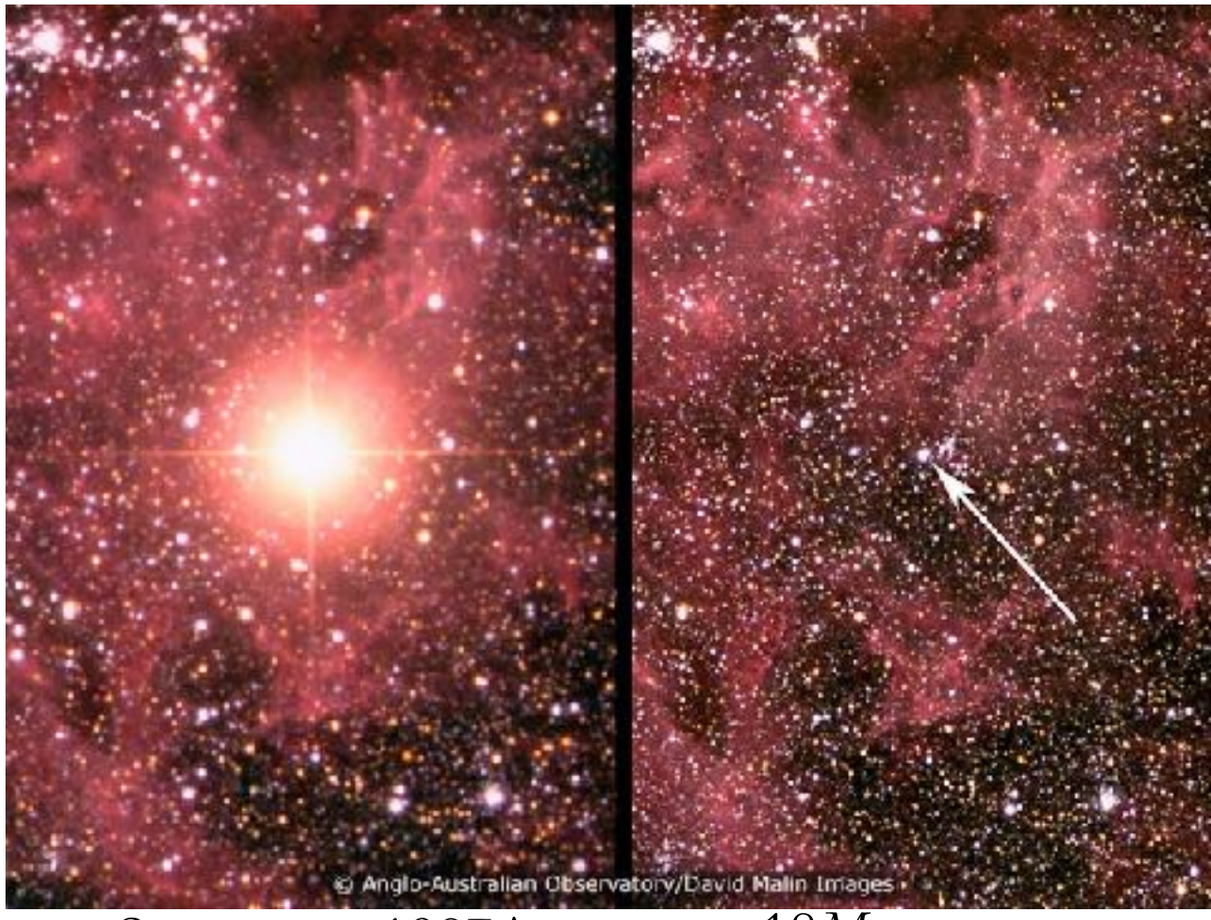
MPCS 2017, Yerevan

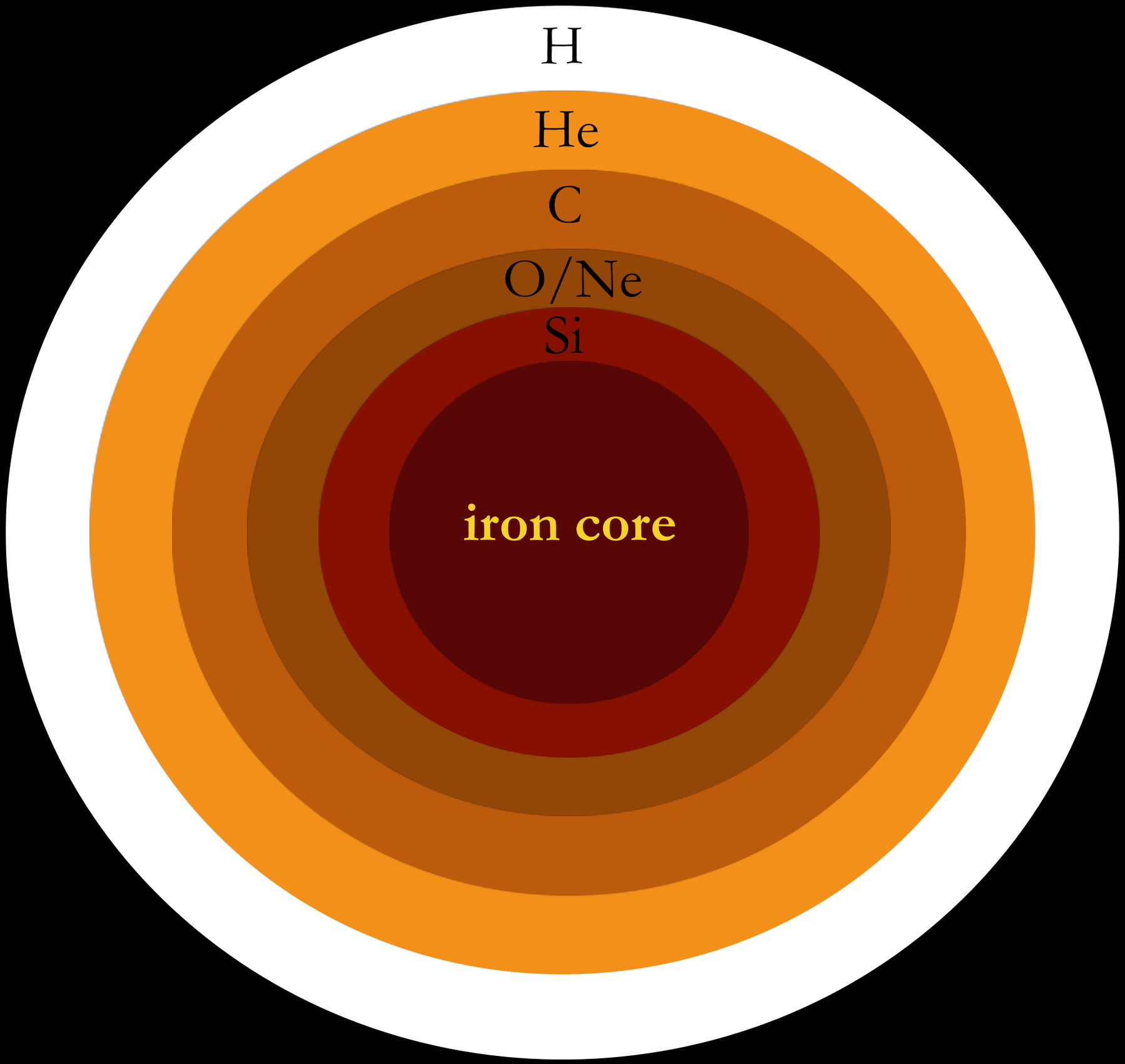
Core-Collapse Supernovae

- Stellar explosion that outshines entire galaxy
- Lasts for weeks-months
- Emits as much energy as Sun emits over its entire life

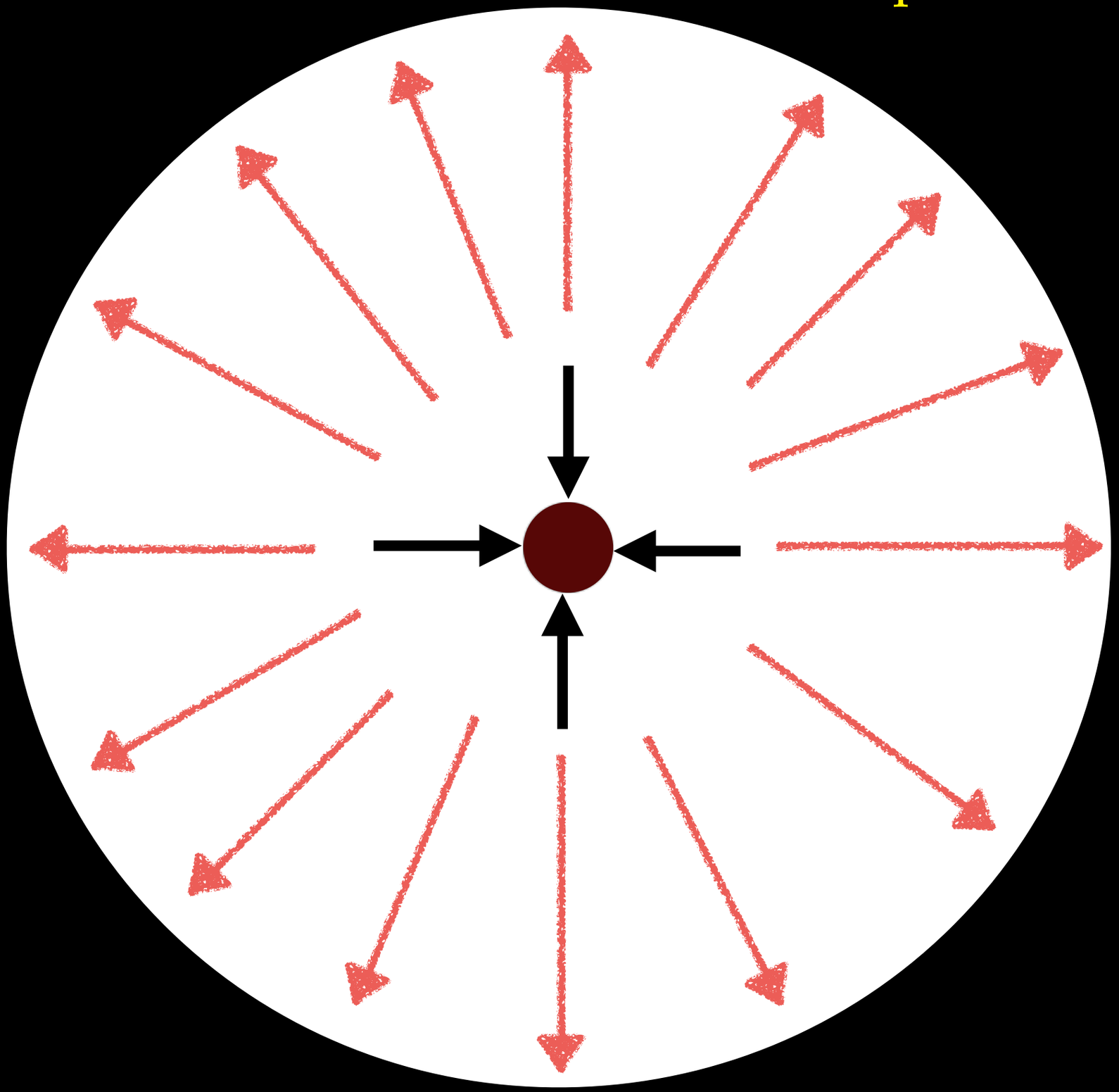


Supernova 1987A

$18M_{SUN}$ star


H
He
C
O/Ne
Si
iron core

$E_{\rm exp} \sim 10^{51}$ ergs



Explosion mechanisms

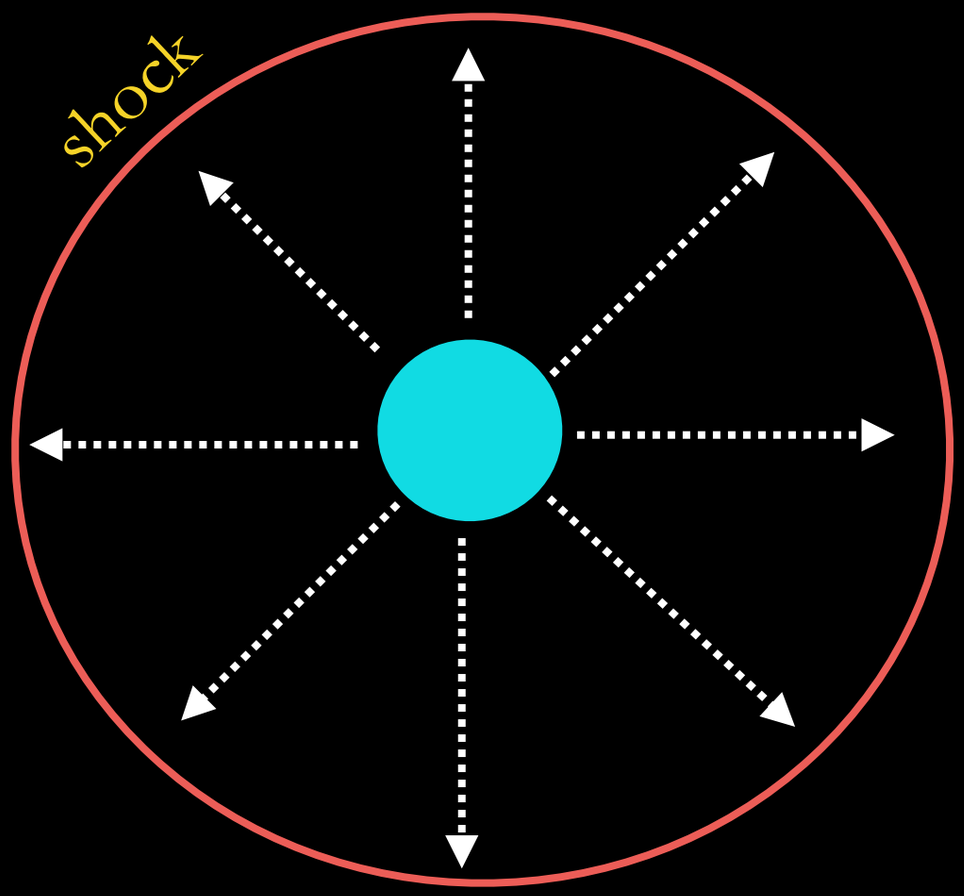
Slow rotation

Rapid rotation

Explosion mechanisms

Slow rotation

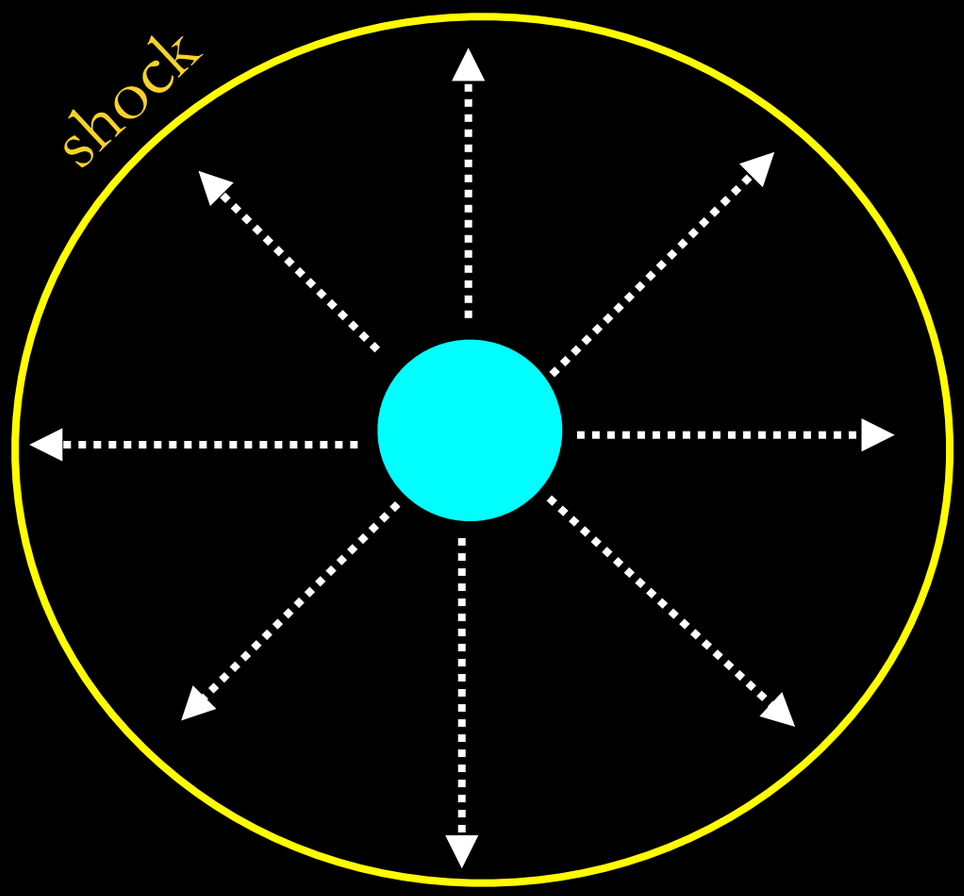
Rapid rotation



Neutrino mechanism

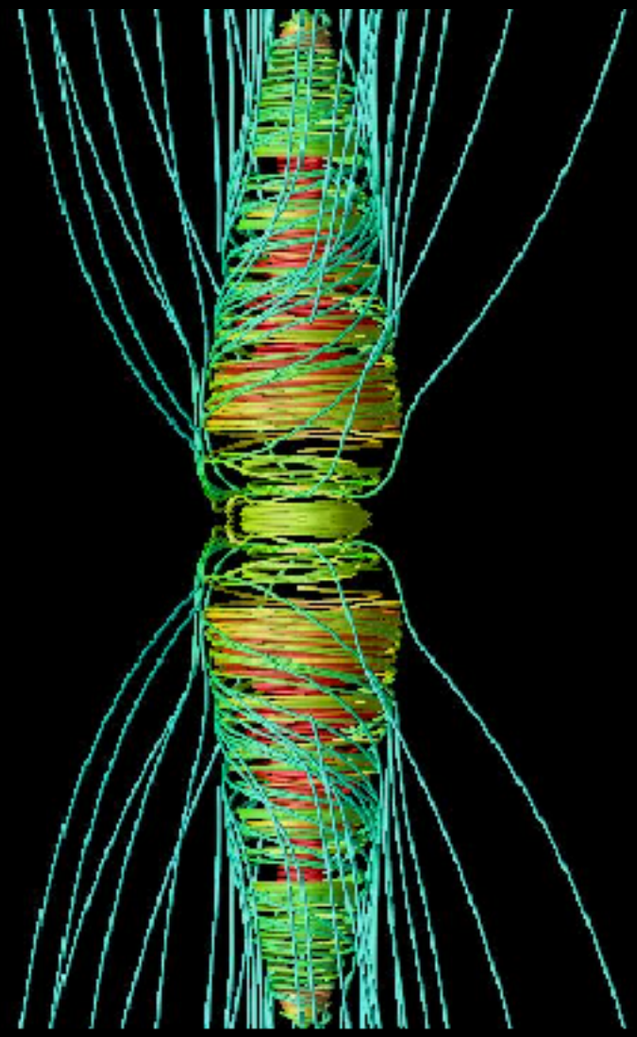
Explosion mechanisms

Slow rotation



Neutrino mechanism

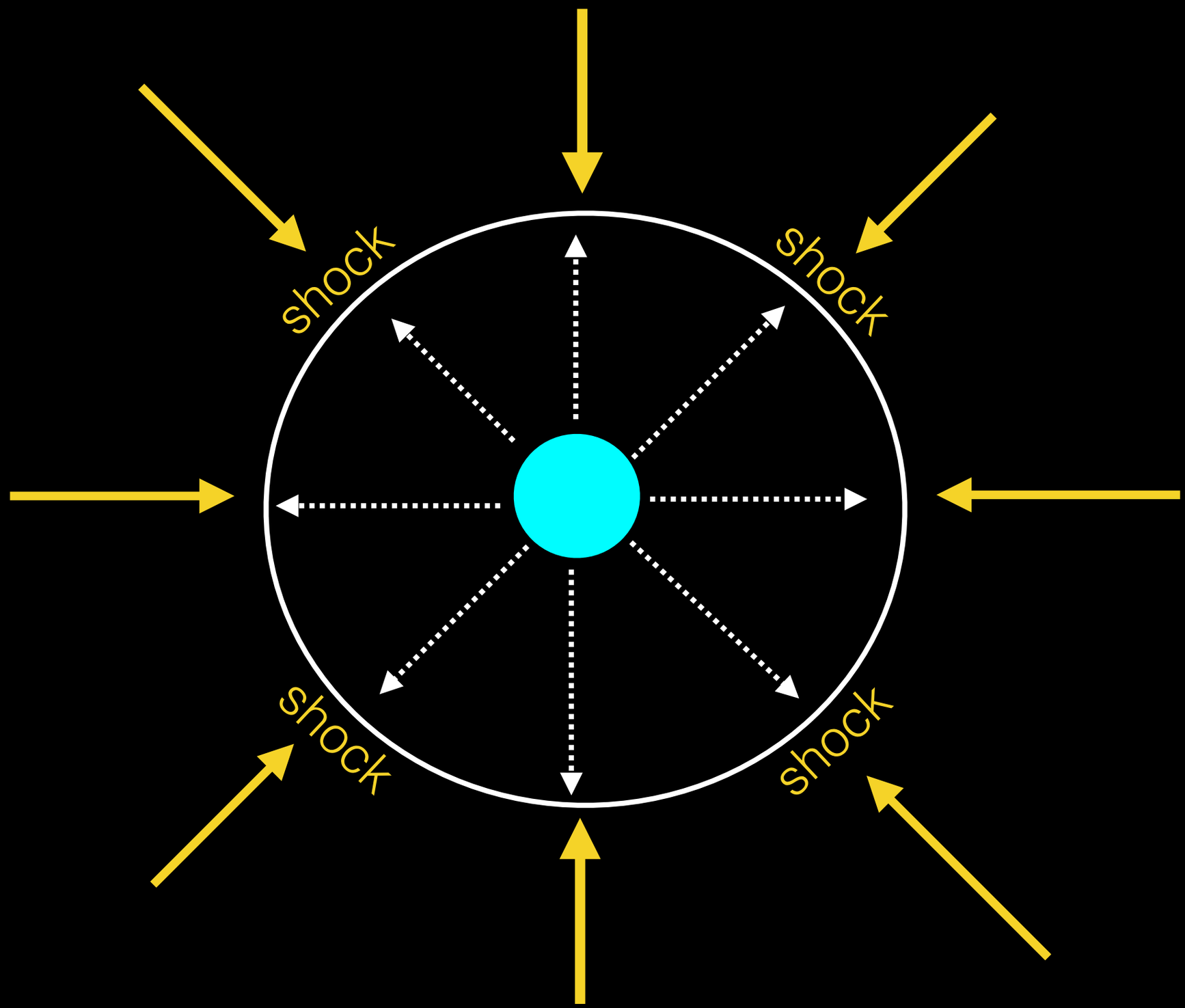
Rapid rotation



Burrows+07

Magnetorotational mechanism

Neutrino Mechanism



Recent reviews: Janka+”16, Müller+’17, Burrows ’13, Foglizzo+’15

Radice+'17

11.0: Sukhbold et al. (2016)

10.0: Sukhbold et al. (2016)

9.0: Sukhbold et al. (2016)

z9.6: Müller et al. (2013); $Z = 0$

u8.1: Müller et al. (2012); $Z = 10^{-4}$

n8.8: Nomoto (1984, 1987)

Density, ρ [g cm^{-3}]

Radius [km]

Radice+'17

z9.6 1D Baseline

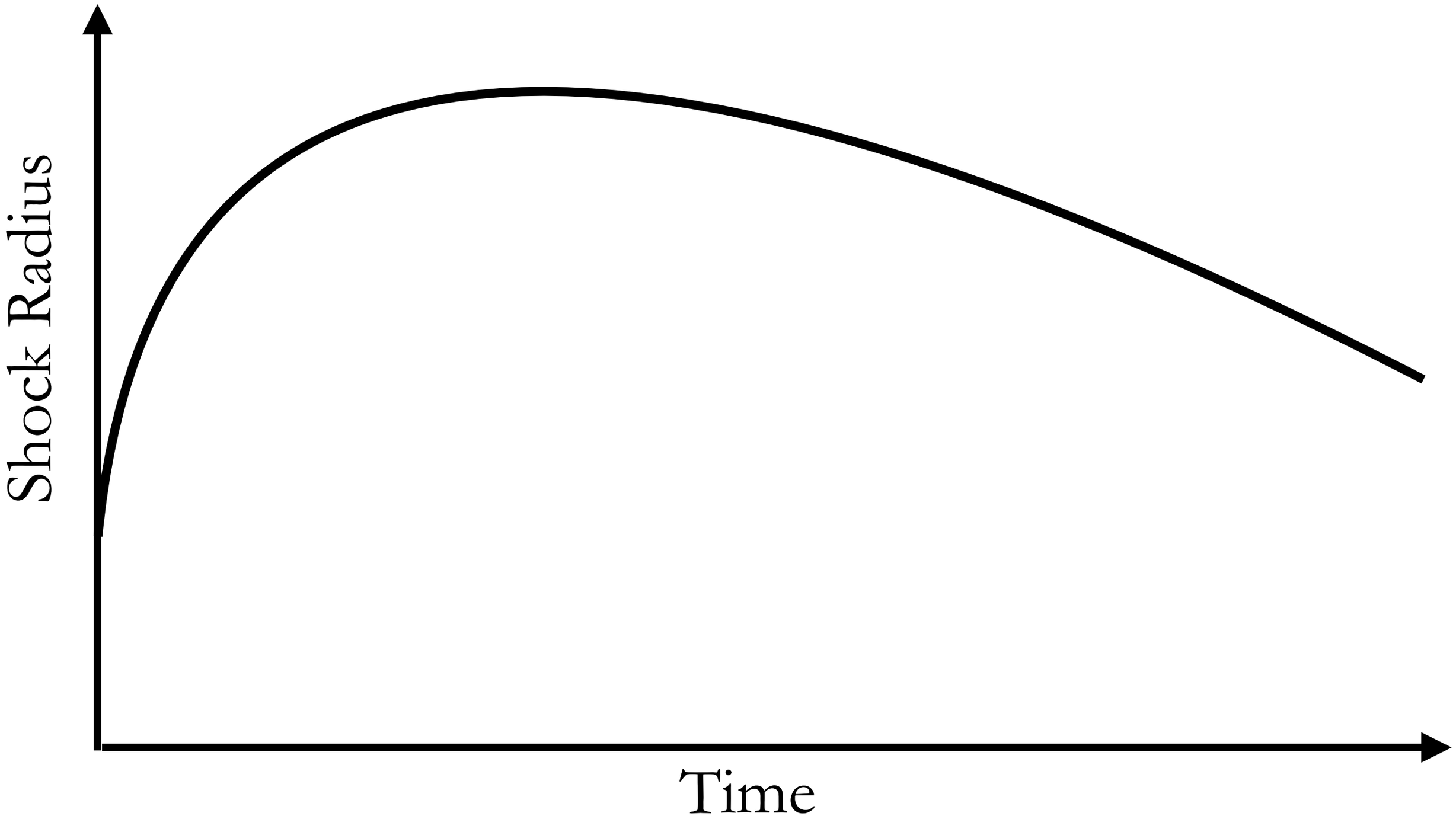
Density-averaged velocity [10^9 cm s^{-1}]

Radius [km]

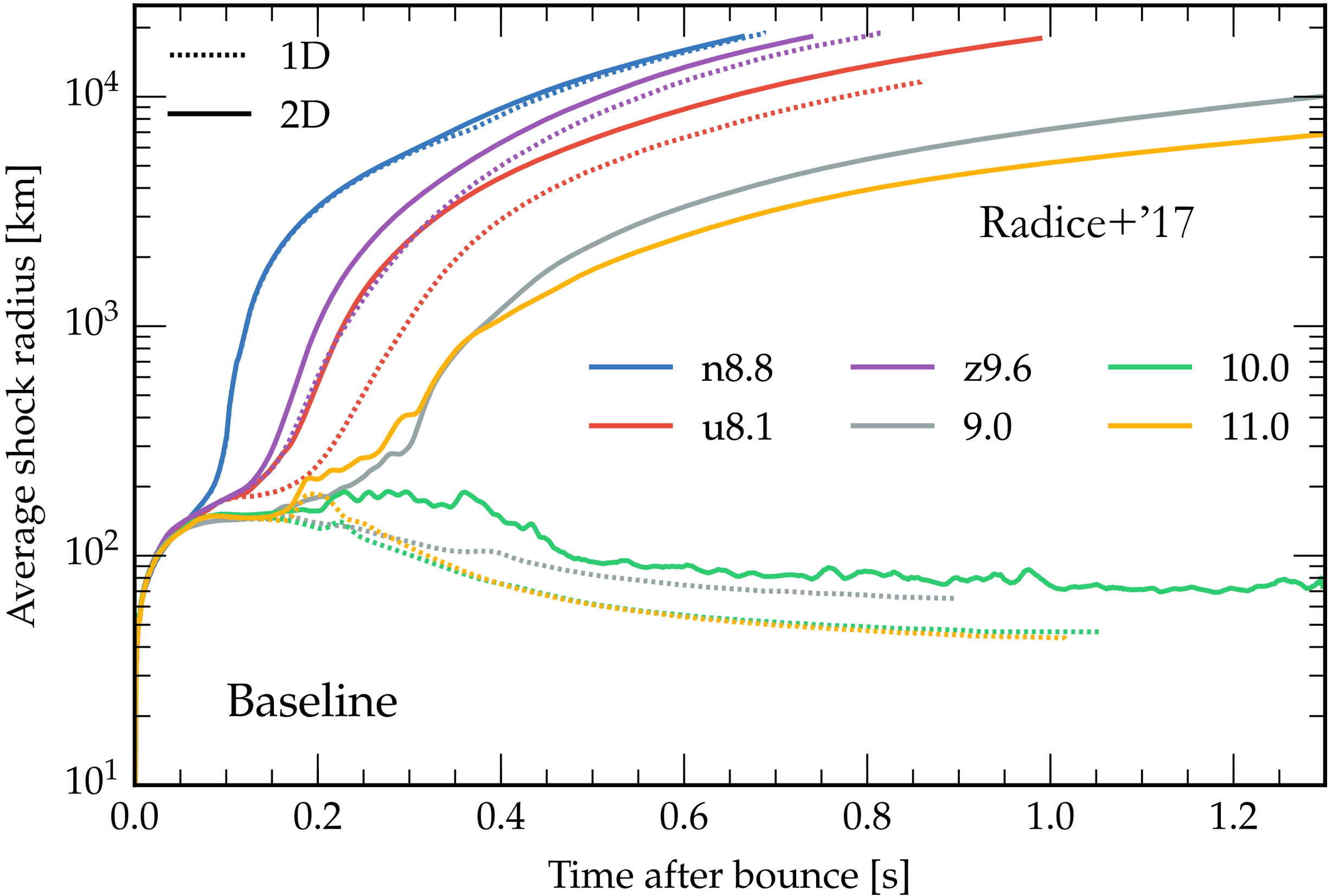
Time after bounce [s]

See also: Liebendorfer+01, Kitaura+'06, Burrows+'07, Sumiyoshi+'05

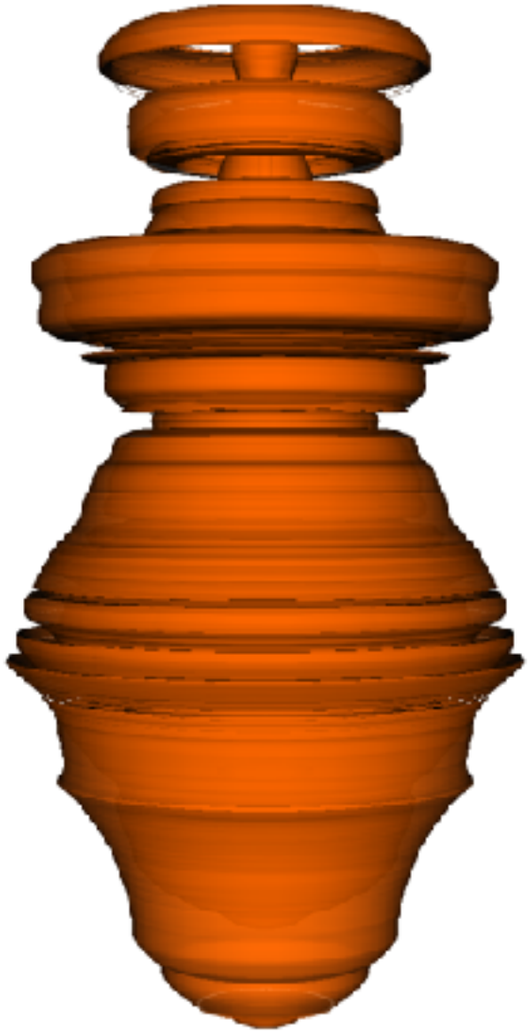
No explosion in higher mass models in 1D



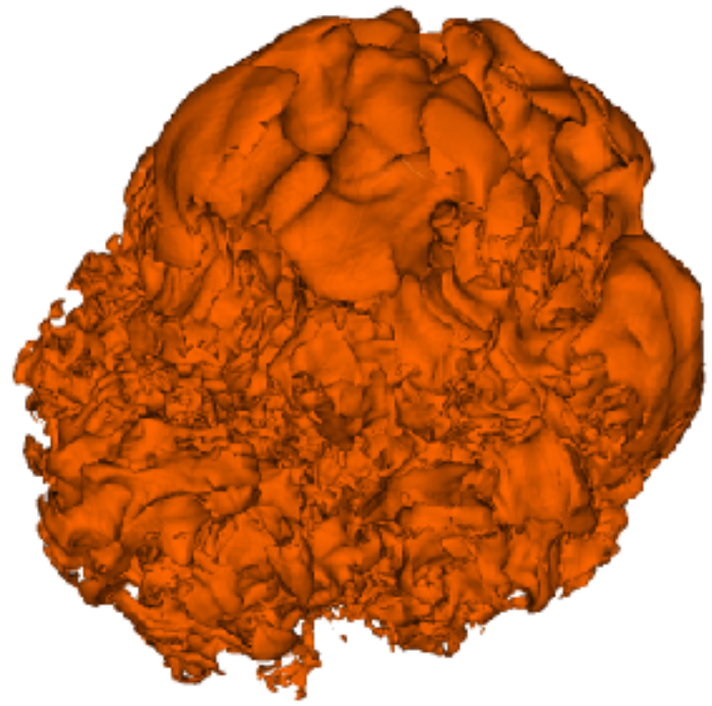
2D simulations



2D *vs.* 3D simulations



Couch (2013)



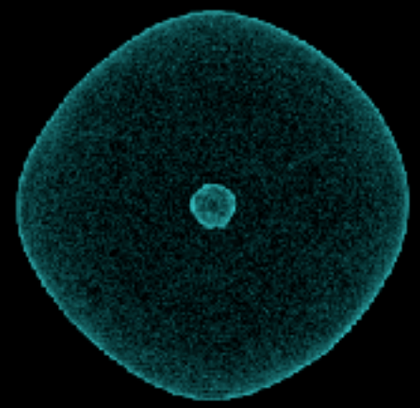
2D **3D**

See also: Nordhaus'+12, Hanke+'12, Dolence+'13, Muller+'15

3D simulations

[Ott, Abdikamalov+'13]

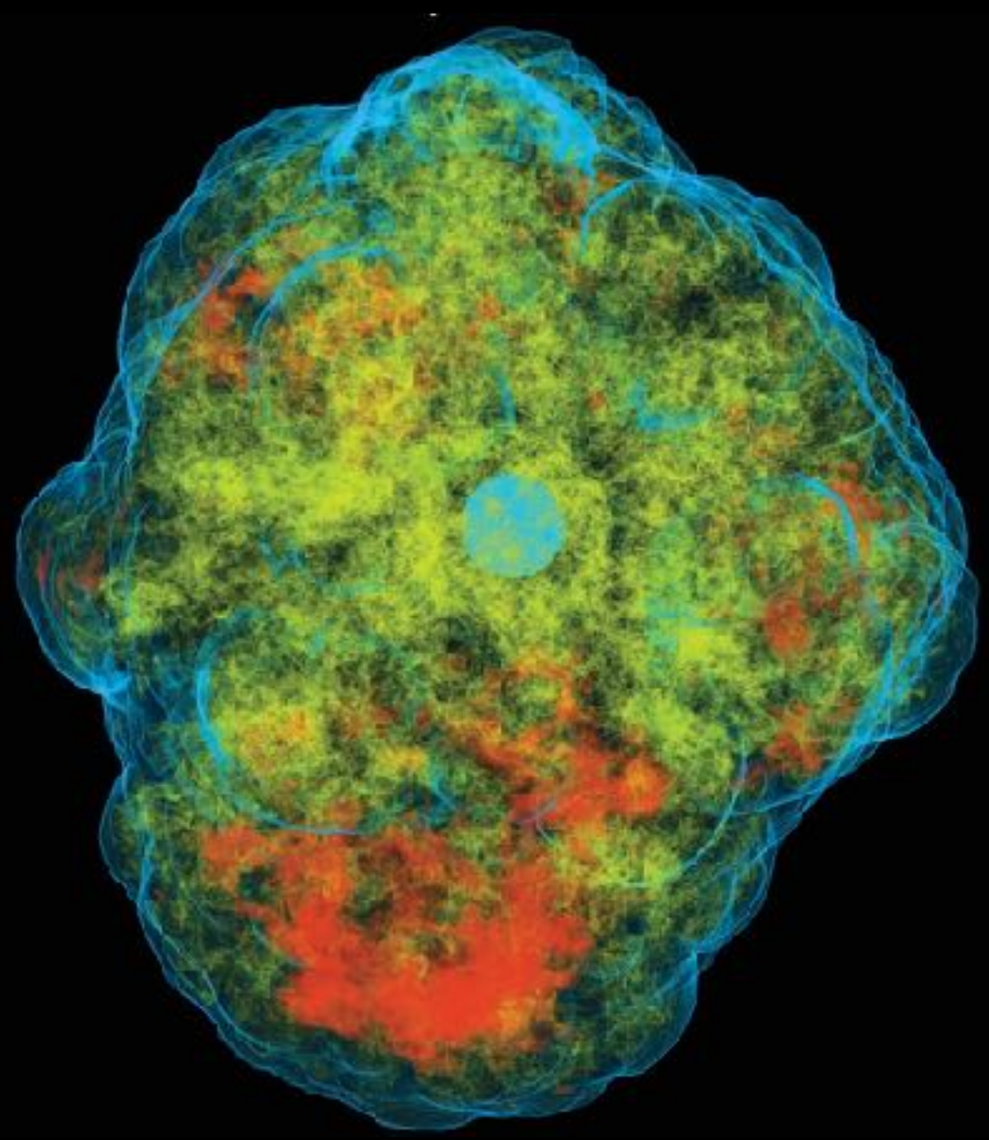
13.50 ms



See also: Hanke+'13, Abdikamalov+'15, Fernandez '15, Lentz+'15, Melson+'15, Roberts+'16

Role of Turbulence

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

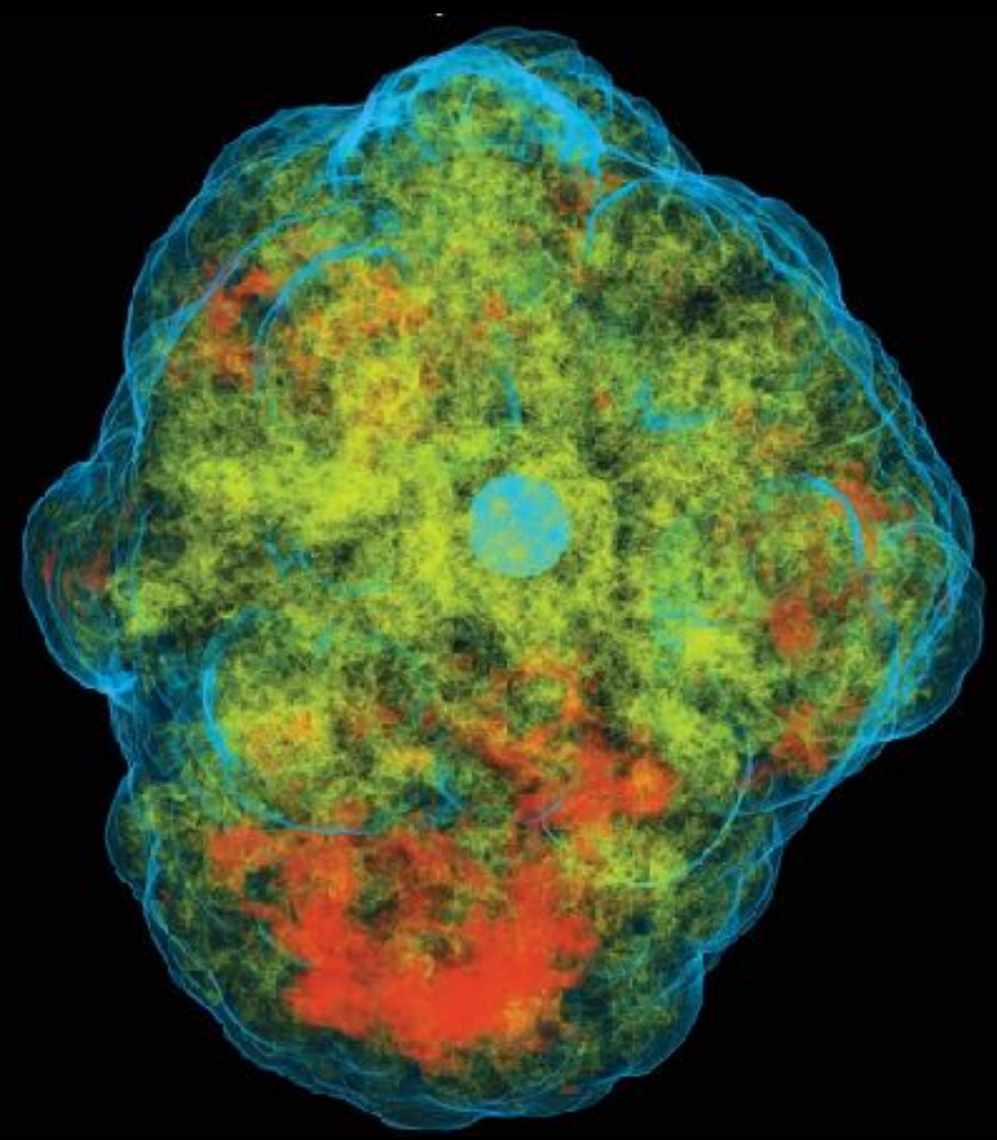


Role of Turbulence

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

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

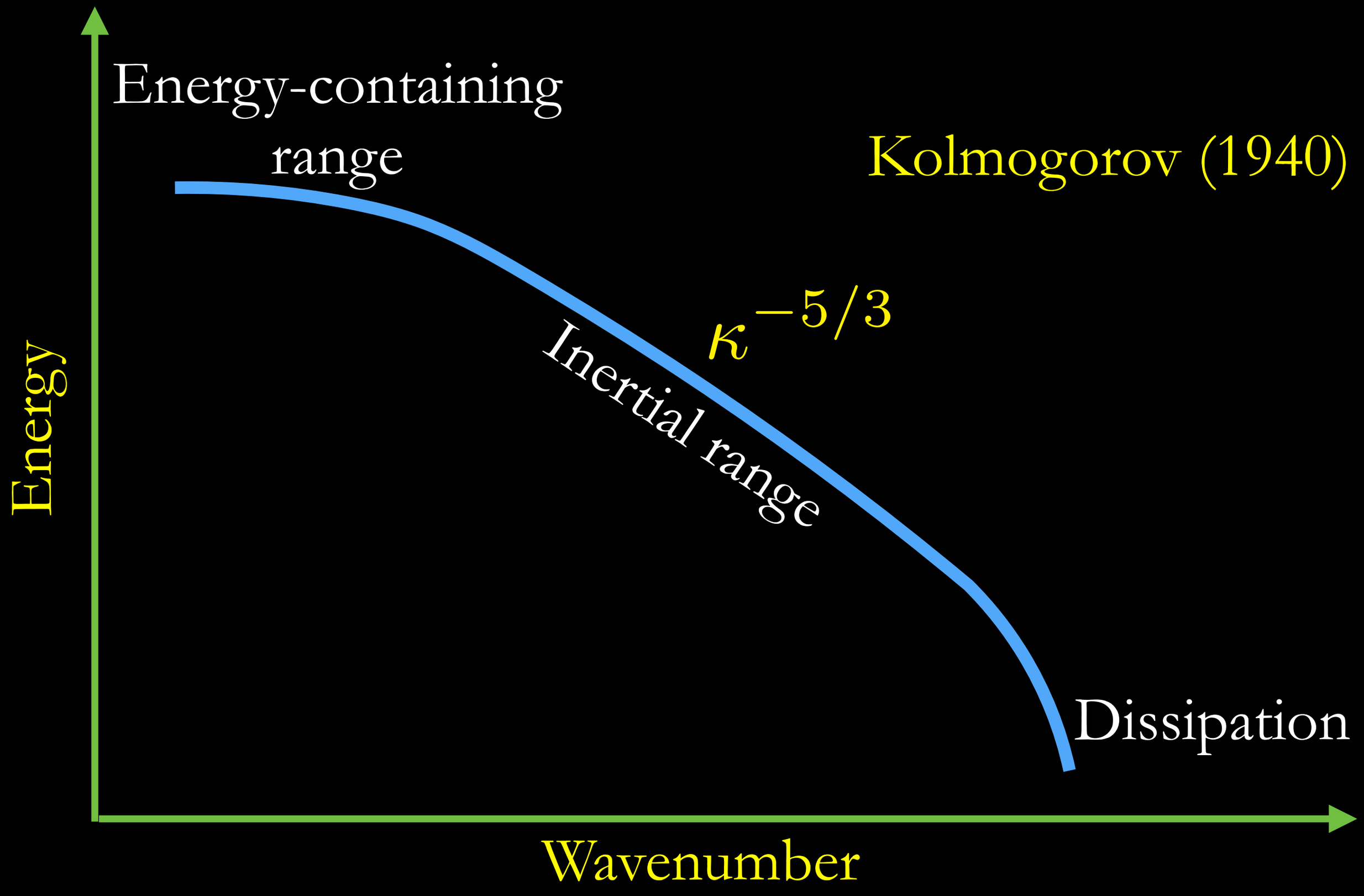
Müller & Janka (2015)



See also: Mabanta & Murphy (2017)

LR
MR
IR
HR
200
180
160
140
120
$R_{\rm shock}$ [km]
40
60
80
100
120
140
$t - t_{\rm bounce}$ [ms]
Abdikamalov+'15

Turbulence spectrum



10^{26}

10^{25}

10^{24}

$E(\ell)$ [erg cm^{-3}]

Bottleneck!

ℓ^{-1}

$s27\mathrm{ULR}f_{\mathrm{heat}}1.05$

$s27\mathrm{LR}f_{\mathrm{heat}}1.05$

$s27\mathrm{MR}f_{\mathrm{heat}}1.05$

$s27\mathrm{IR}f_{\mathrm{heat}}1.05$

$s27\mathrm{HR}f_{\mathrm{heat}}1.05$

$t - t_{\mathrm{bounce}} = 90\,\mathrm{ms}$

1 10 100

ℓ

Abdikamalov+'15

$t = 0.000$ [ms]

2x

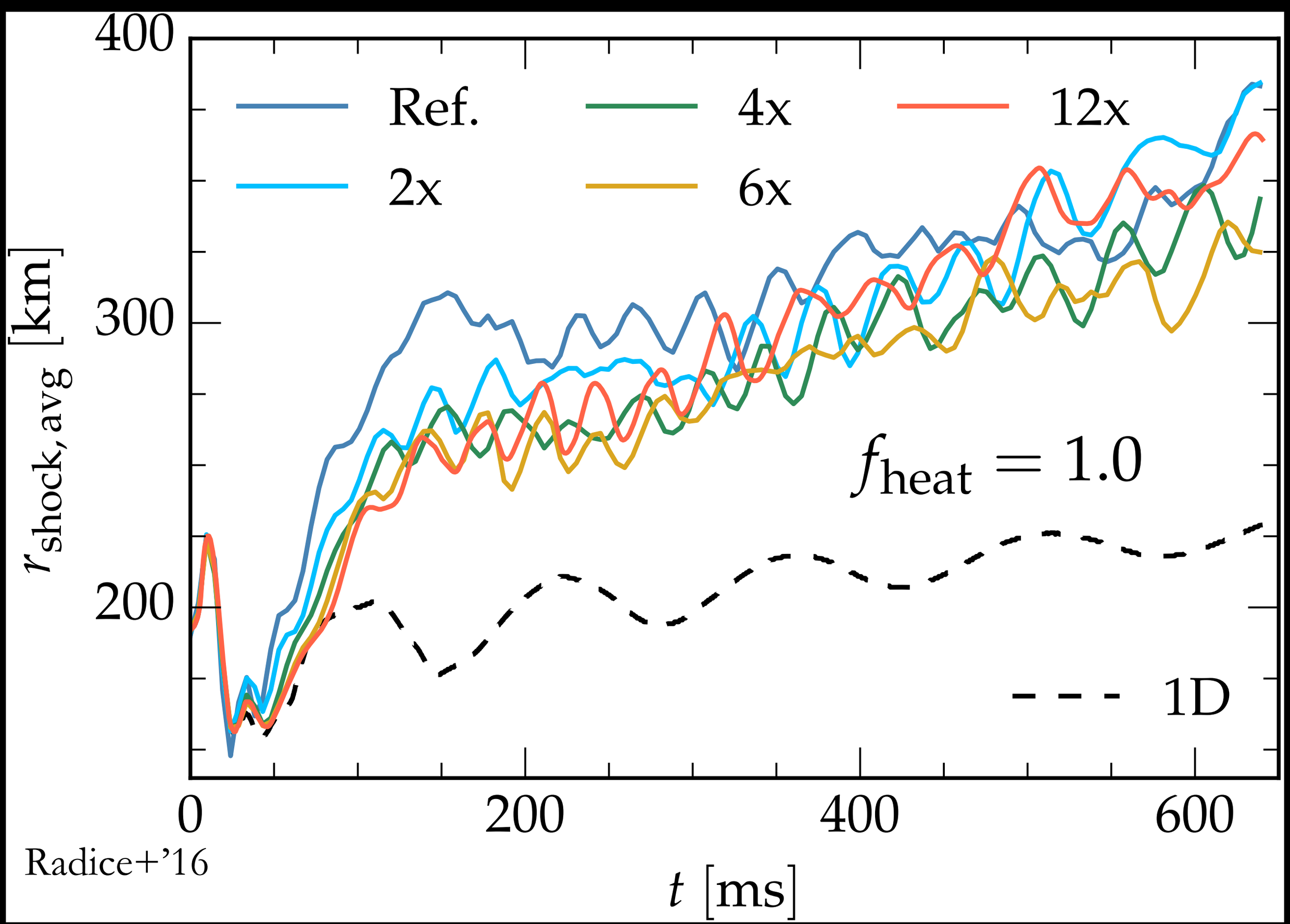
Ref.

4x

12x

Radice+'16

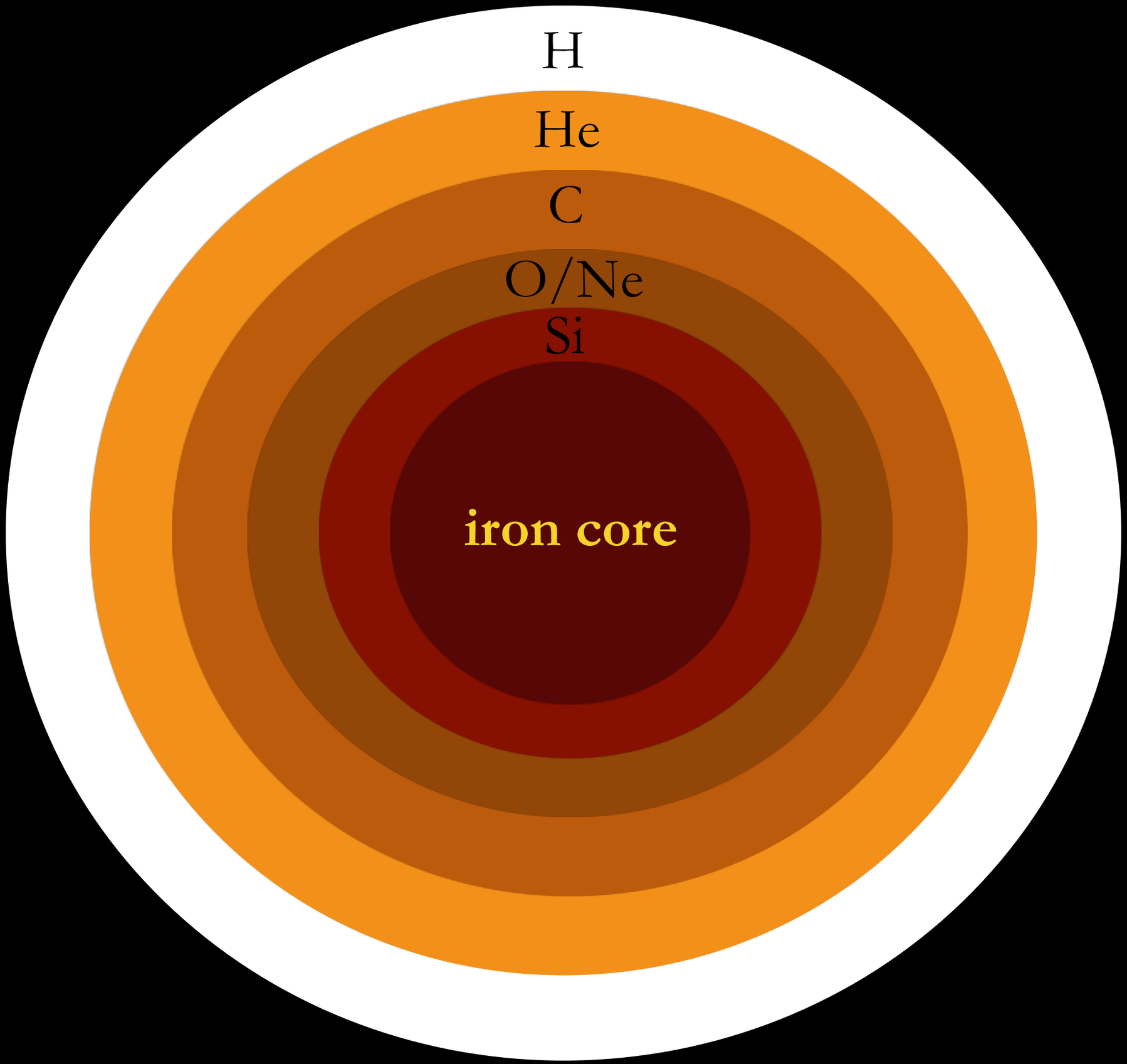
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$E(k)$
$k^{-5/3}$
6x
12x
20x
Ref.
2x
4x
10^{-7}
10^{-6}
10^{-5}
k [cm^{-1}]
Radice+'16



See also: B. Müller (2016)

But no reliable explosion in 3D.

What is missing?


H
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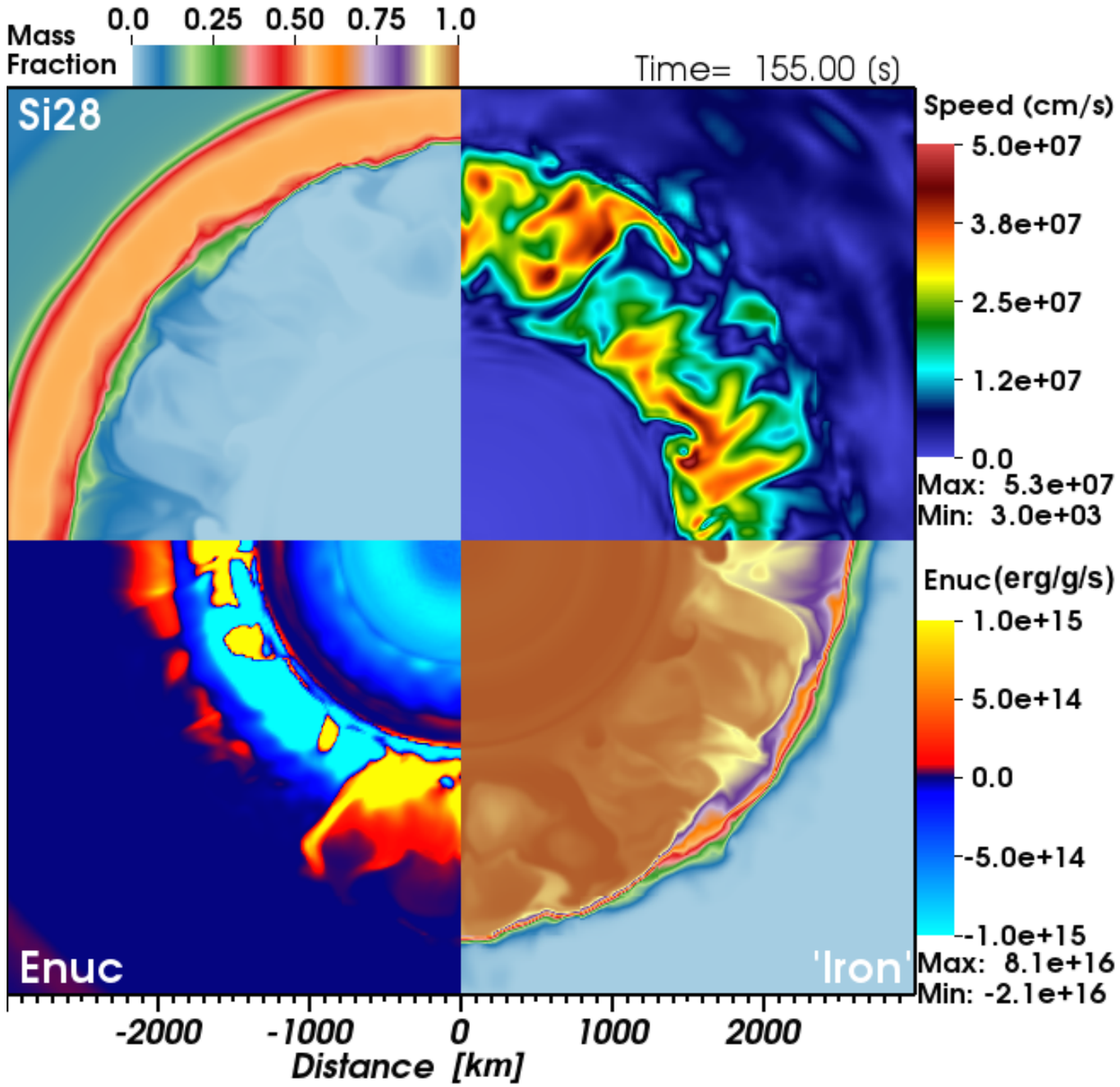
iron core

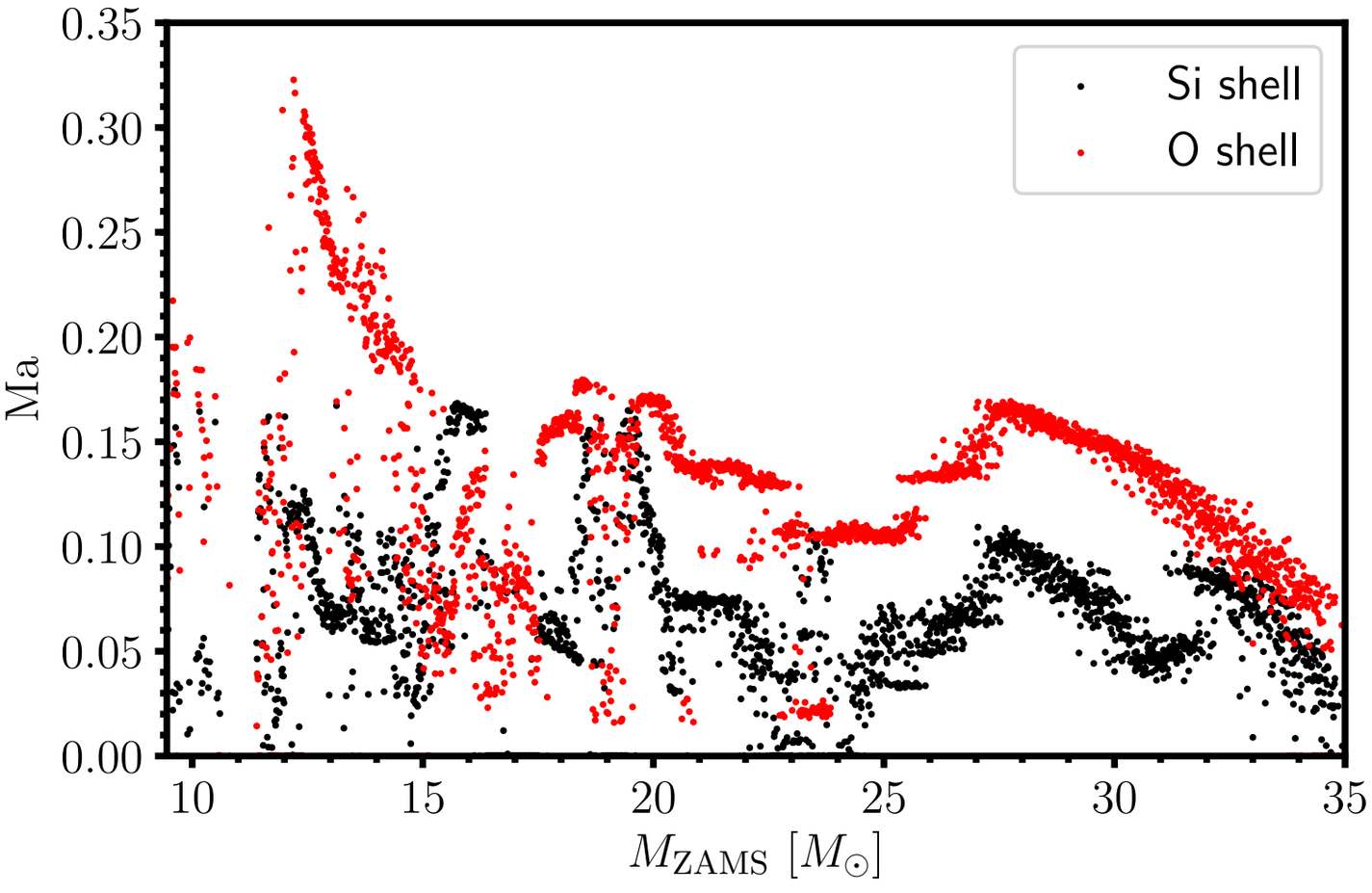
Progenitor asphericities

Couch & Ott 2013, 2015, Couch et al 2015,
Müller & Janka 2015, B. Müller et al 2016, 2017



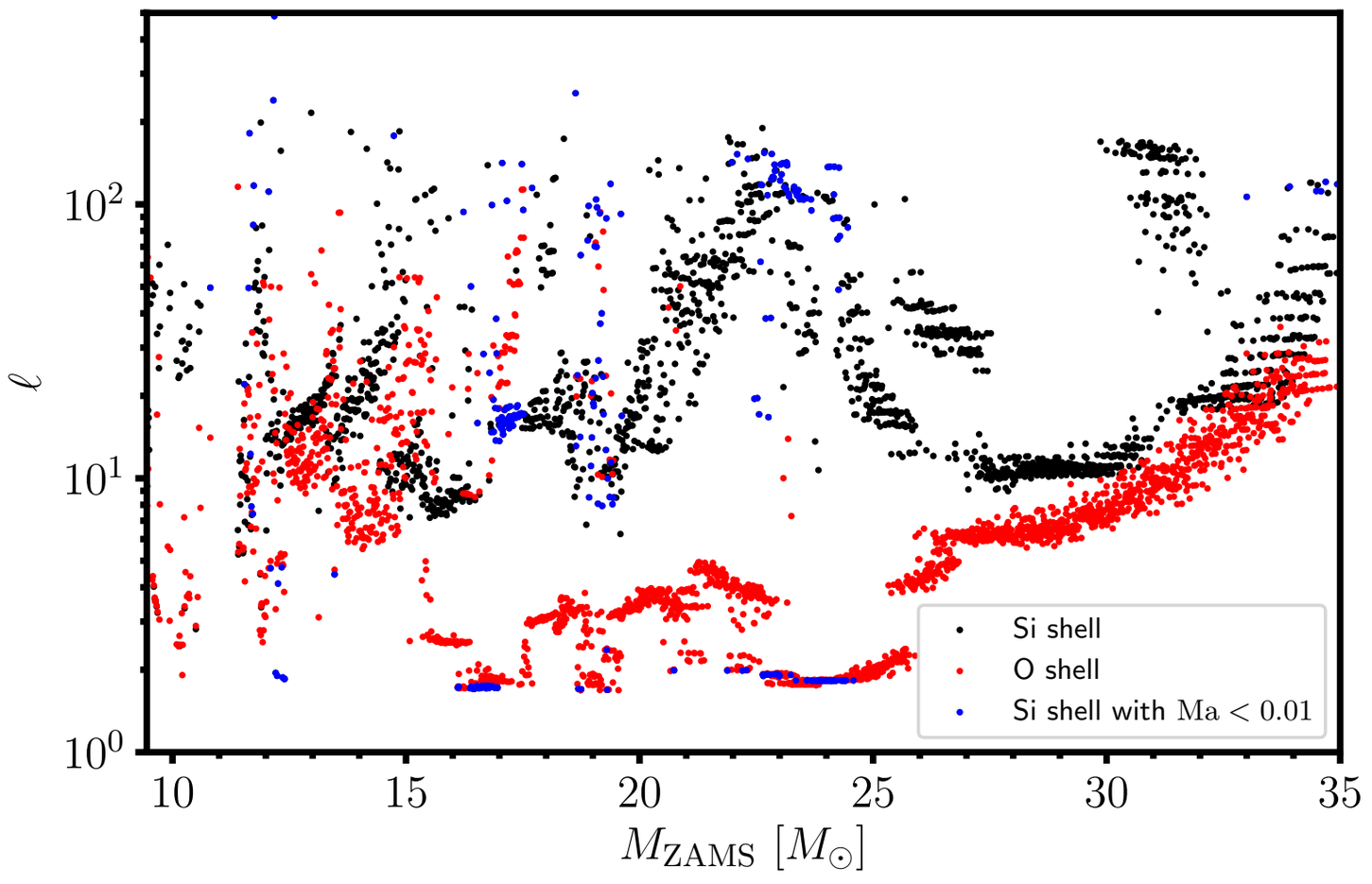
Couch+'15

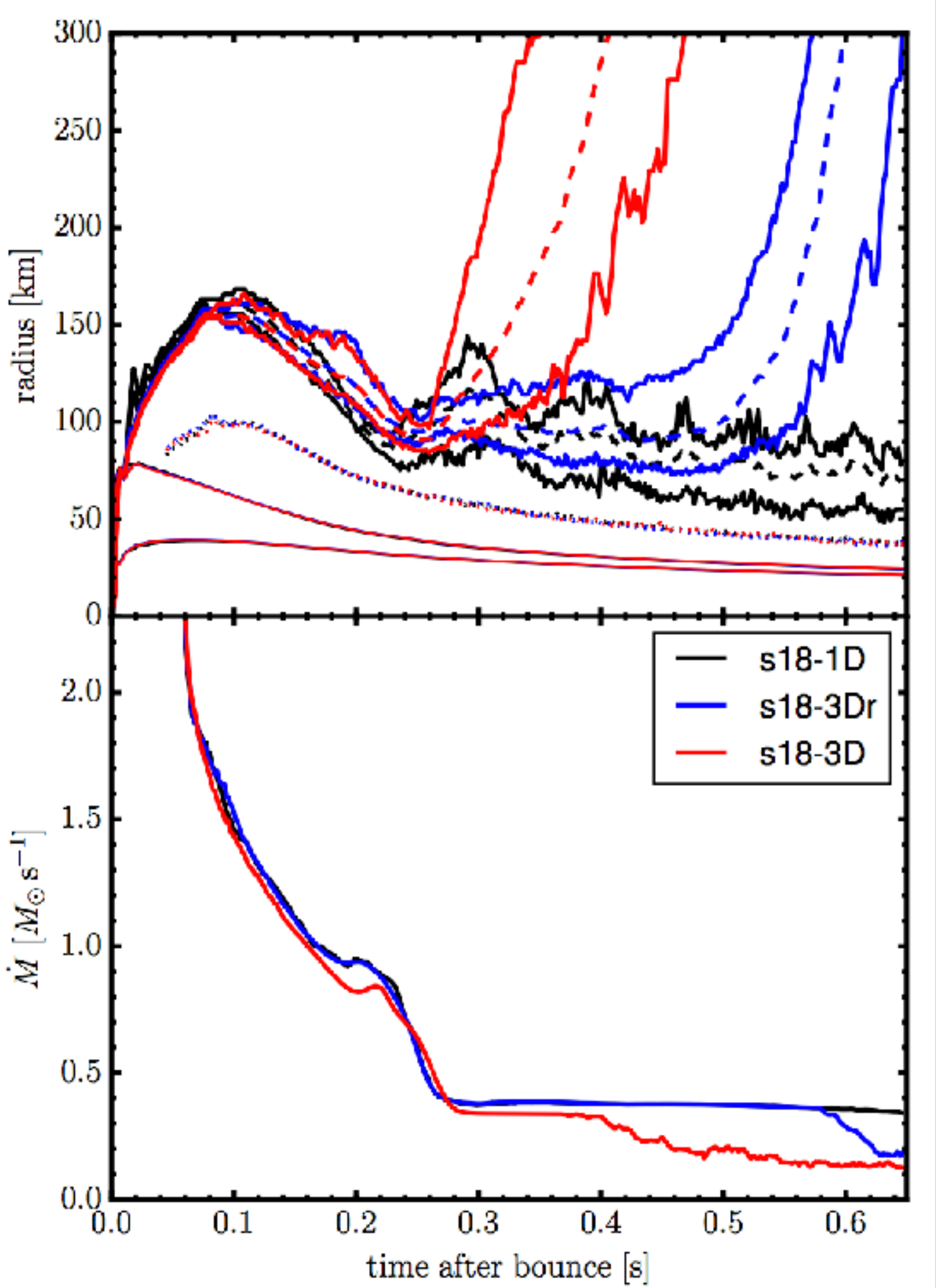
See also: Arnett & Meakin '16, Chatzapoulos+'16, Collins+'17



Large progenitor asphericities are common

Collins et al (2017)

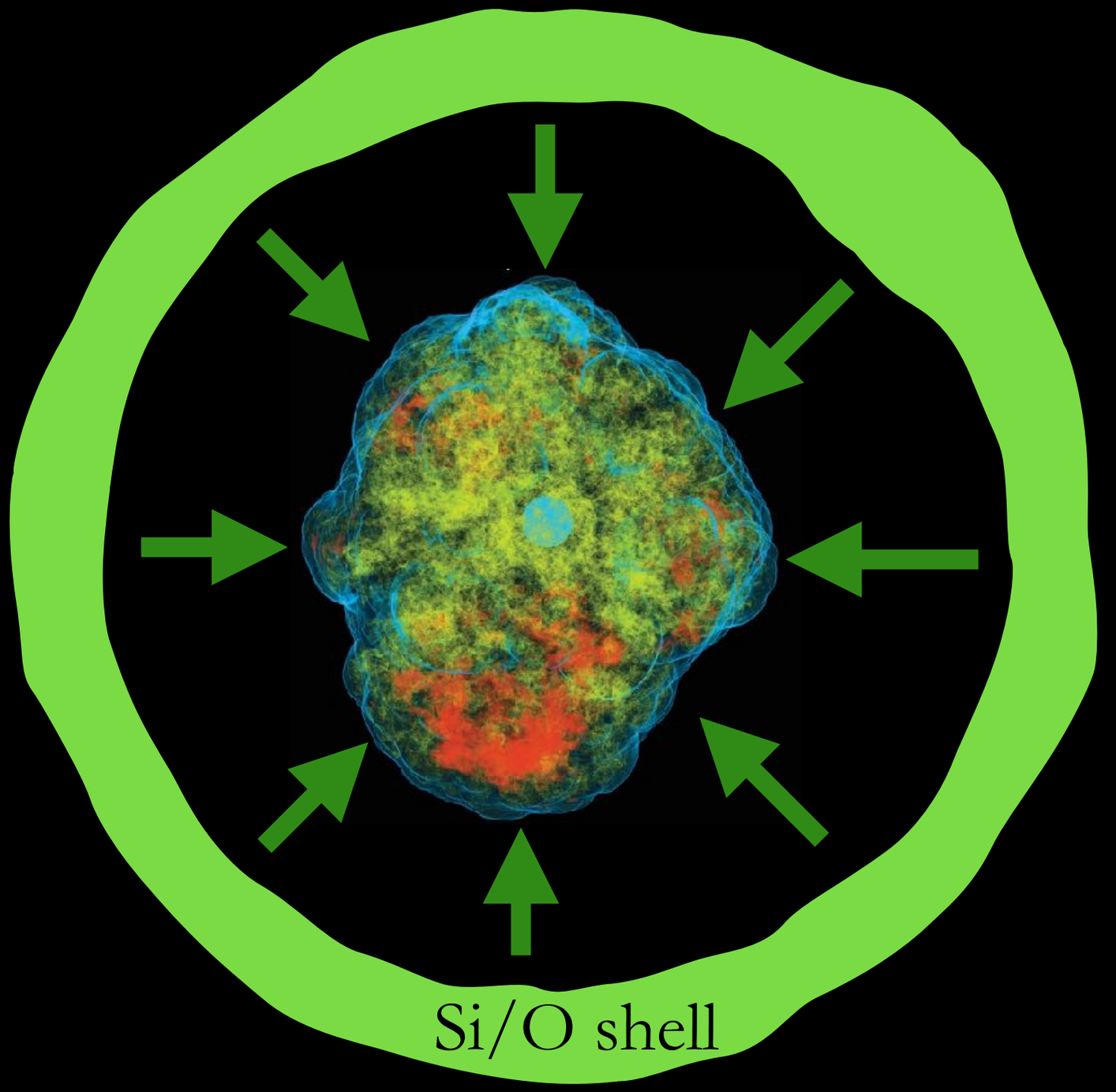




Müller et al 2017

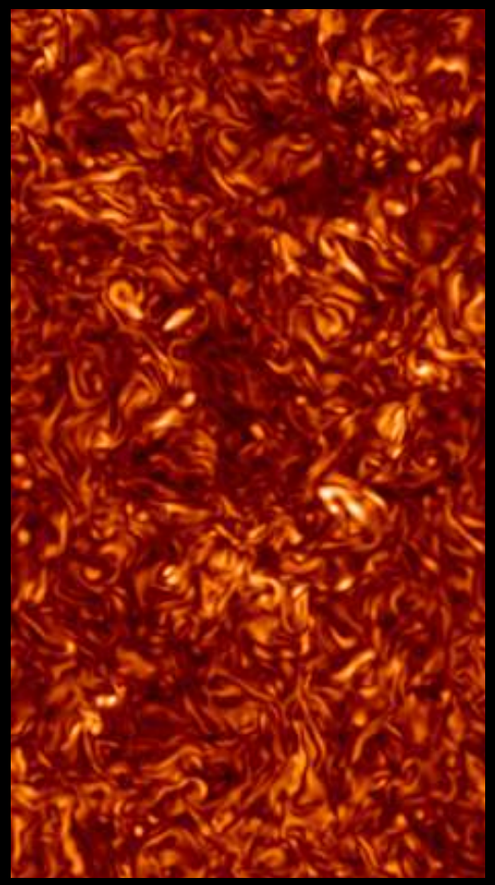
Our work:
simple/linear physics of

- Accretion
- Shock crossing
- Post-shock



Shock crossing

Turbulent flow



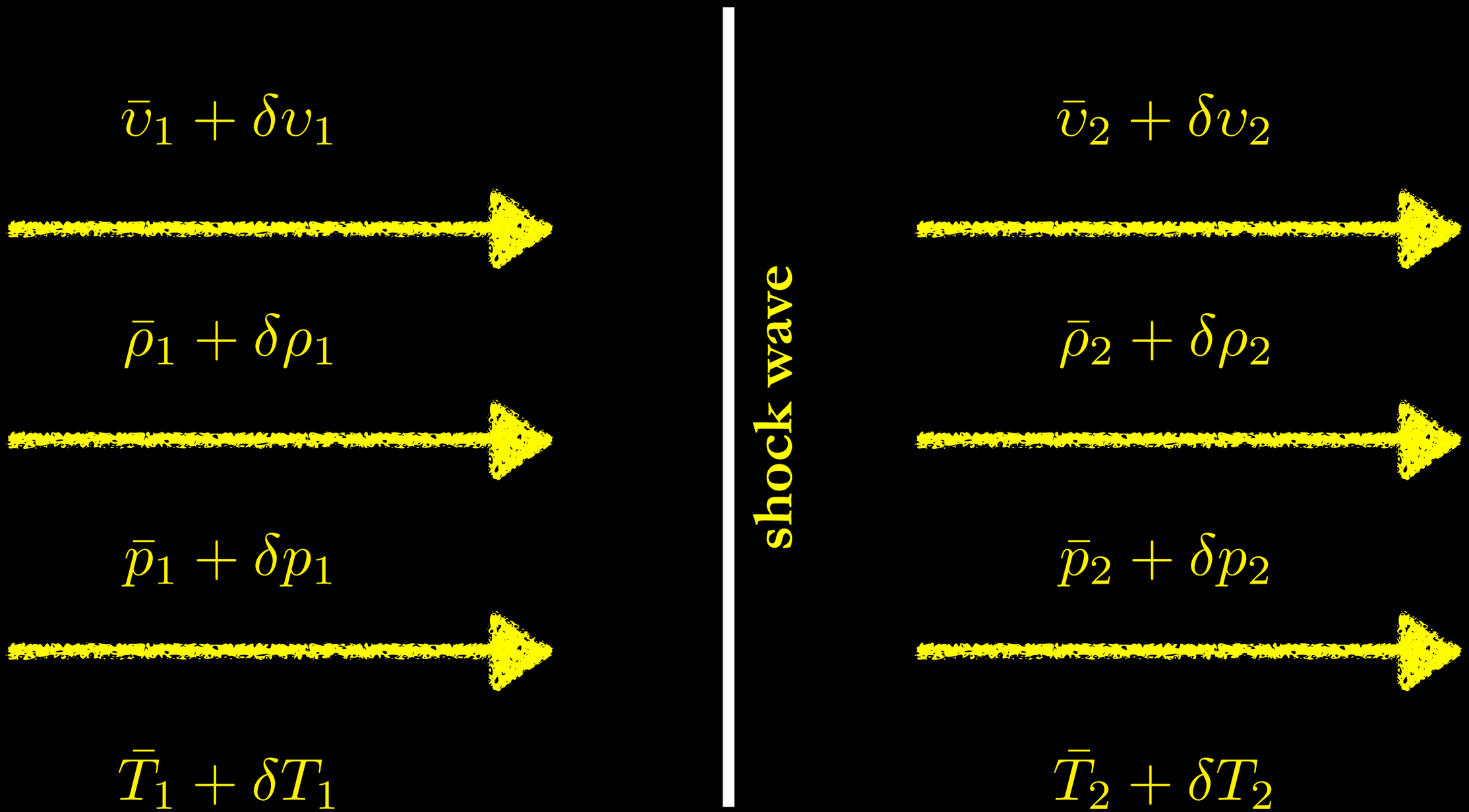
Radice+16

shock wave

?

Linear Interaction Analysis

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



Linear approximation: validity region

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

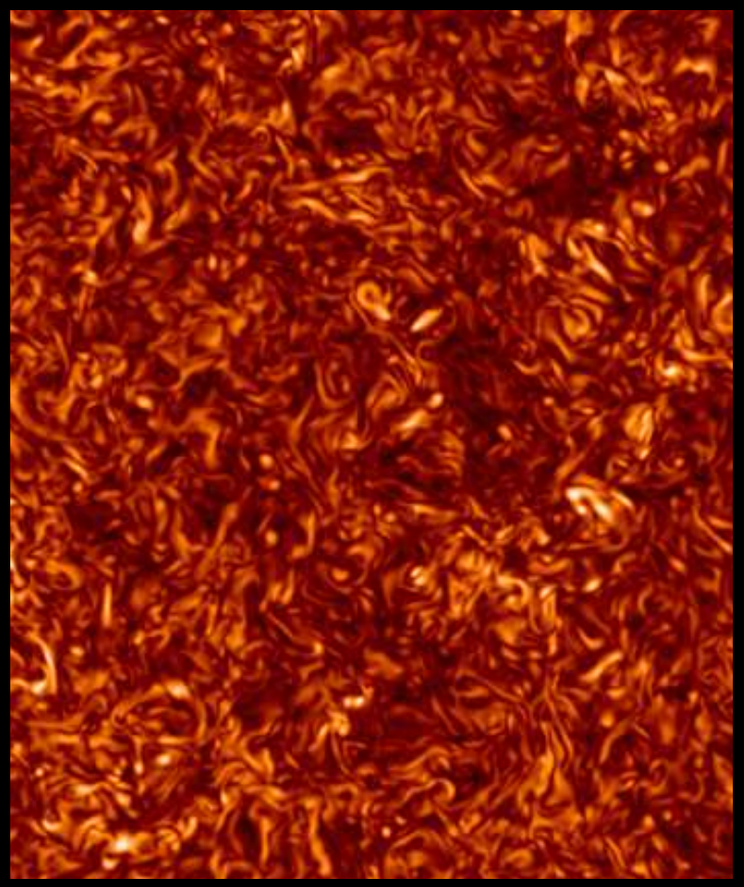
Lee et al (1993), Ryu & Livescu (2014)

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

e.g., Müller et al (2016)

Turbulent Fluctuations: decomposition

Kovasznay (1953)



Radice+16

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

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

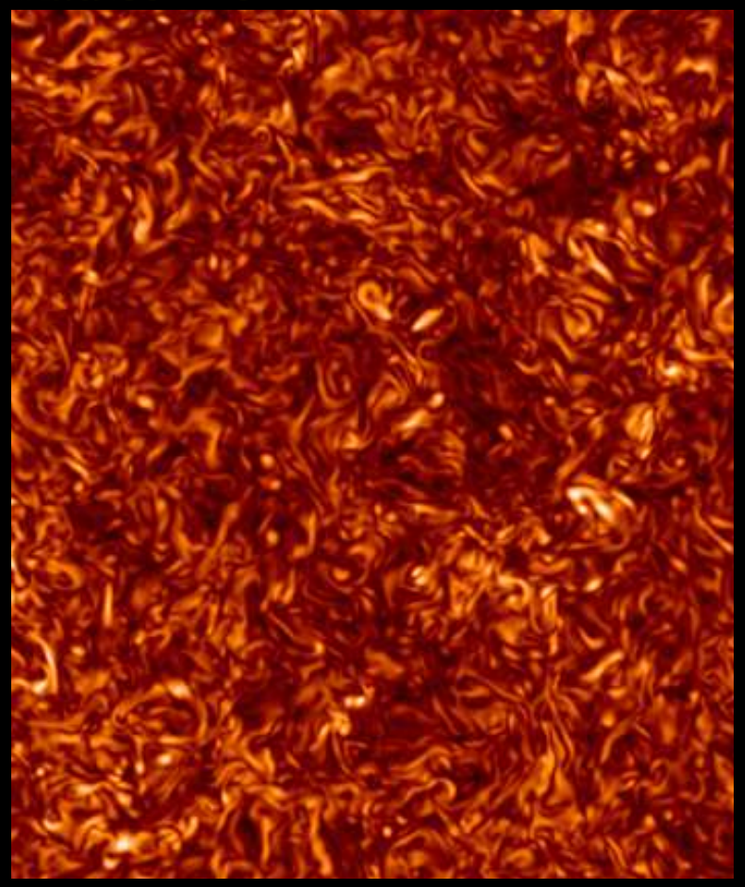
Acoustic $(\delta\rho,\ \delta p,\ \nabla \times \delta v = 0)$

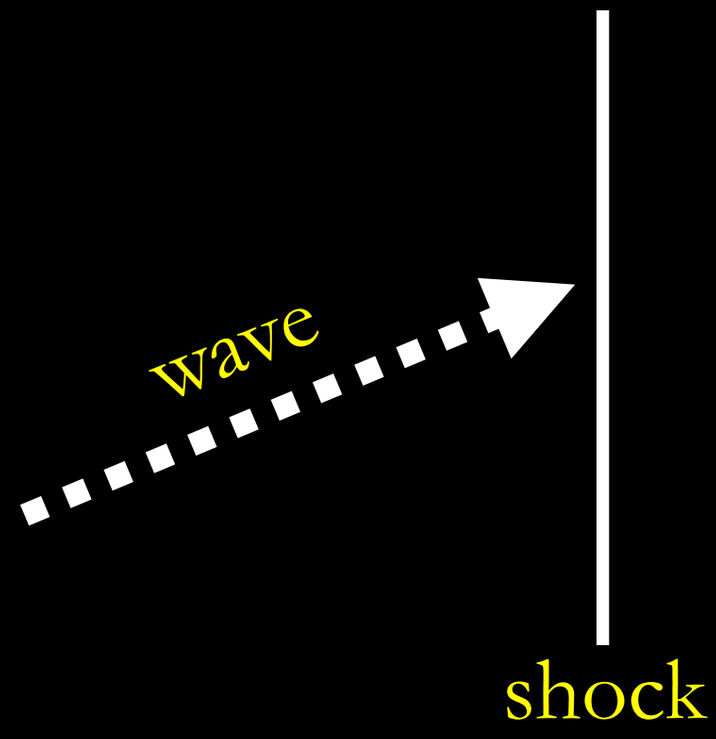
Modes evolve independently in the linear limit for uniform mean flow.

Turbulence decomposition

Kovasznay (1953)

Radice+16



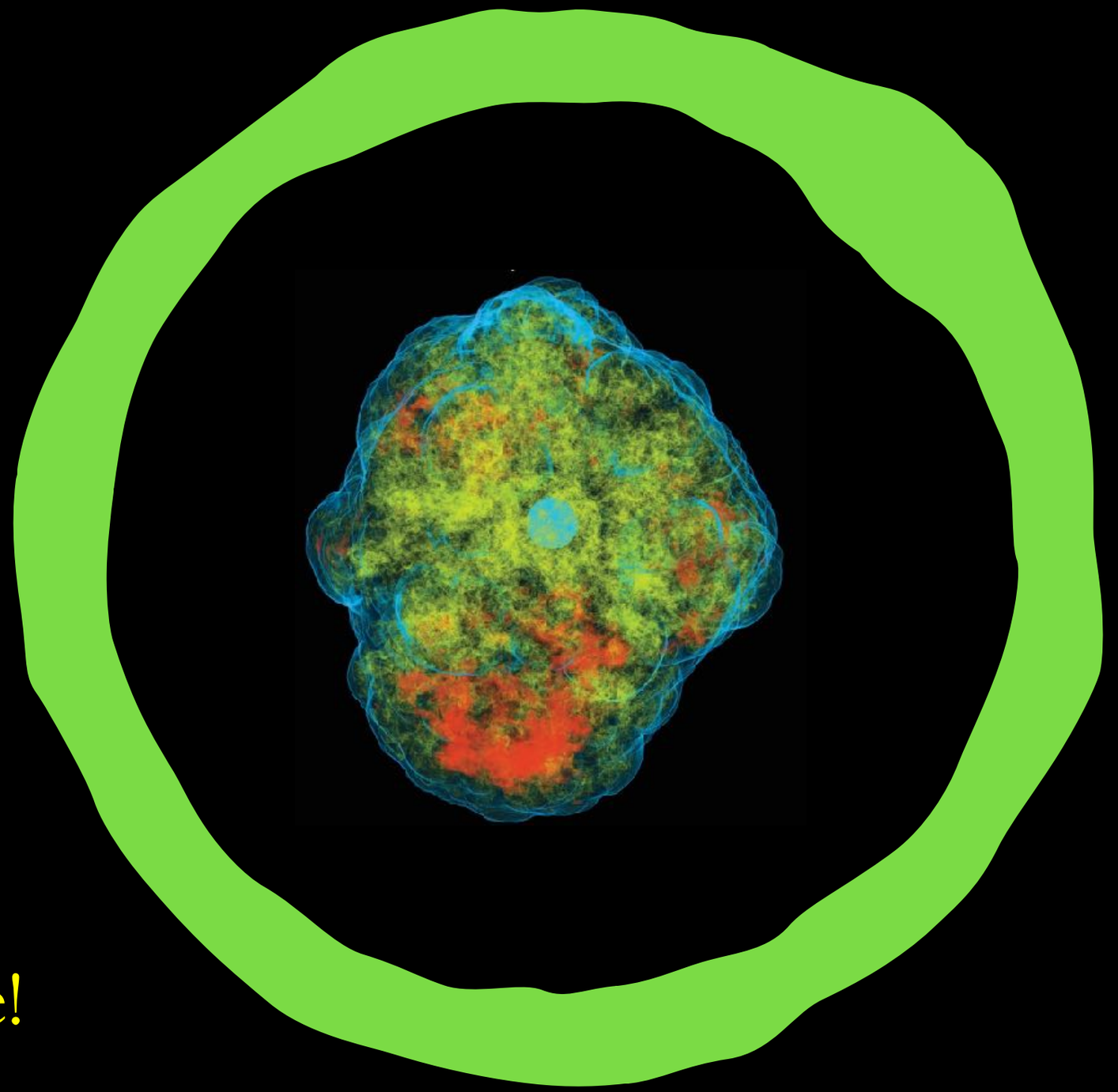


Method: decompose turbulence into waves, calculate interaction for each wave, and integrate the result over all waves

Emission of Sound by Turbulent Motion

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

[Lighthill 1952, Landau & Lifshitz 1959]



For subsonic turbulence,
sound emission is negligible!

U_1

U_2

y

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

entropy wave

vorticity wave

acoustic wave

entropy wave

vorticity wave

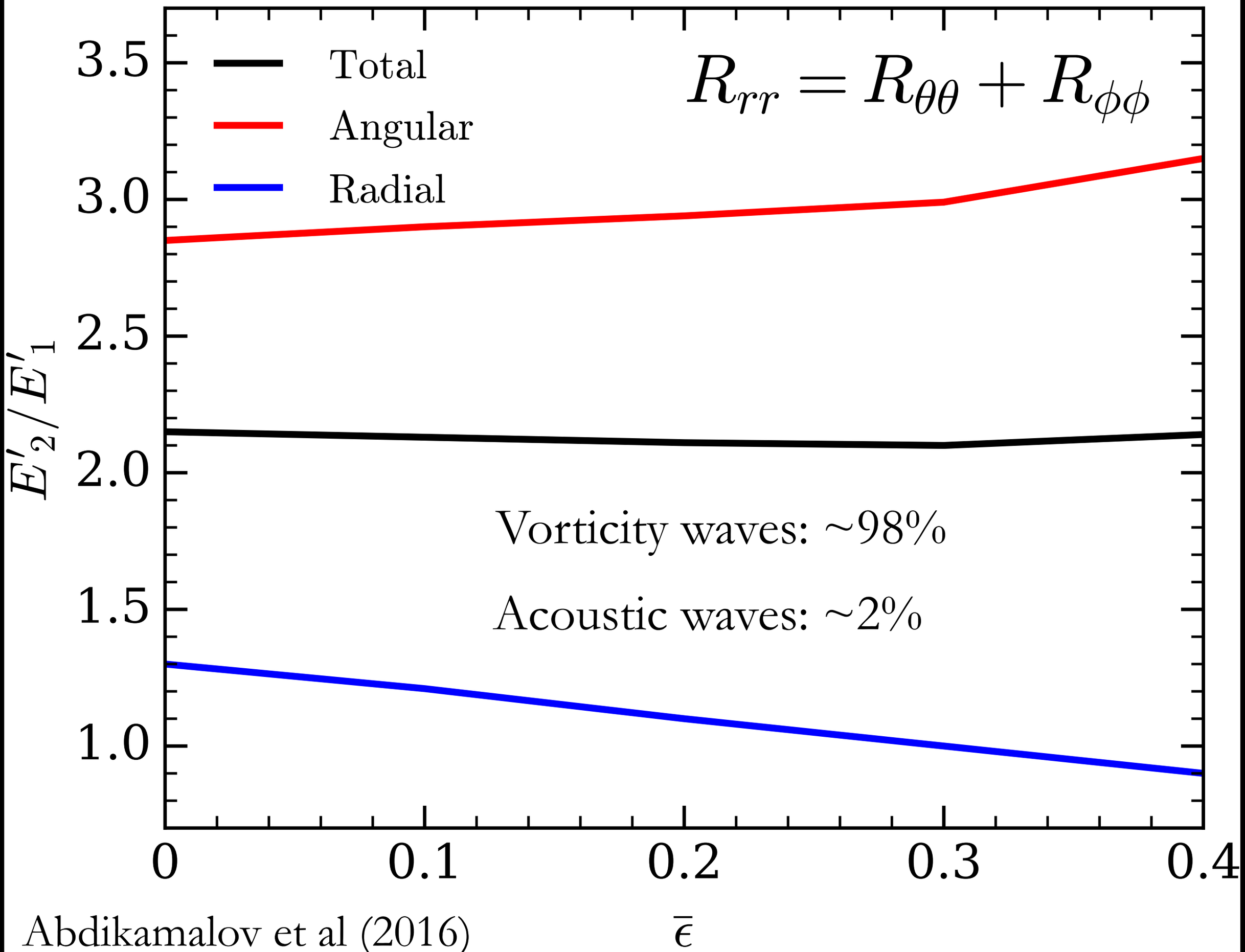
$\xi(y,t)$

Ψ_1

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

x

Abdikamalov et al (2016)



Abdikamalov et al (2016)

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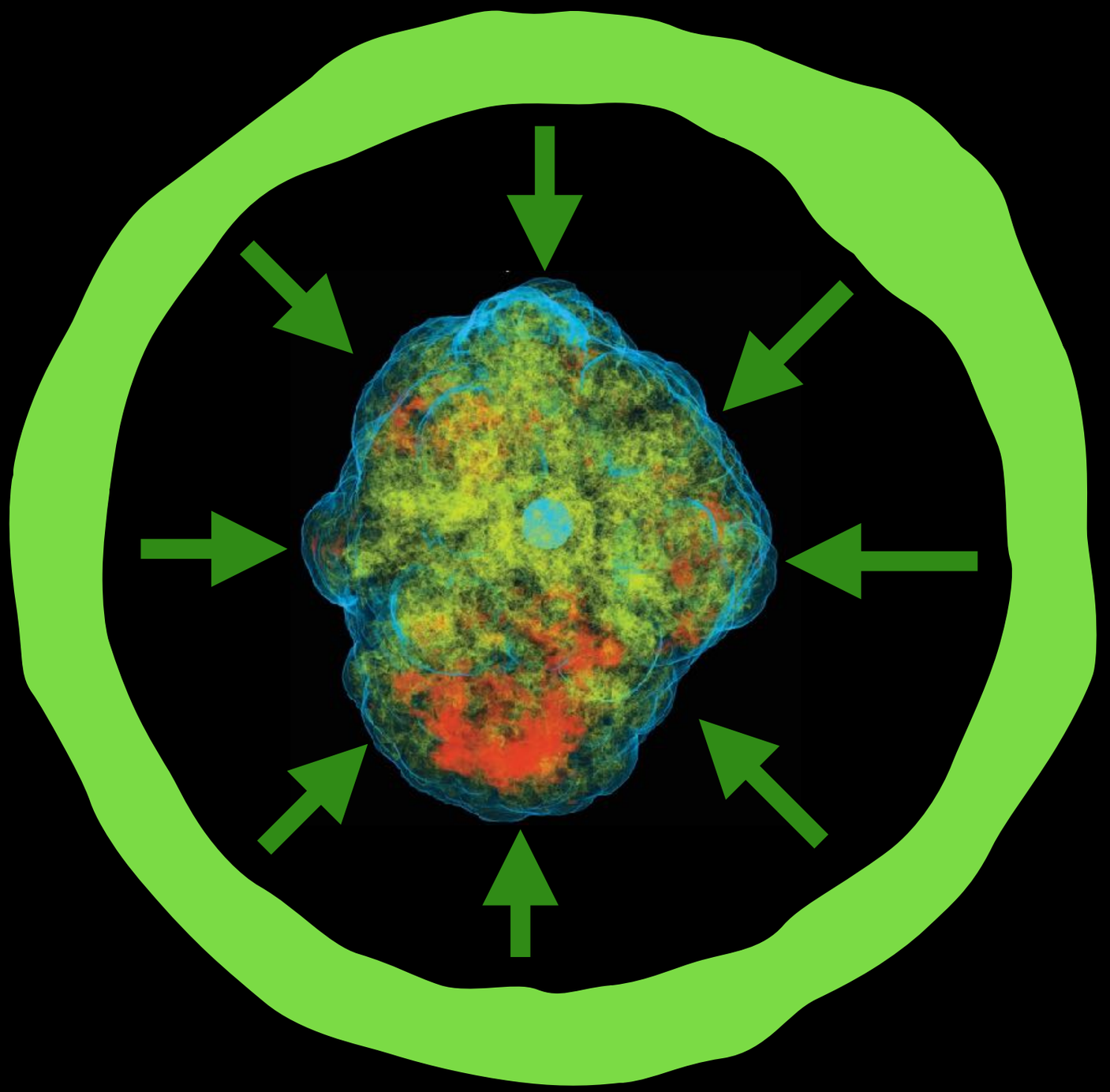

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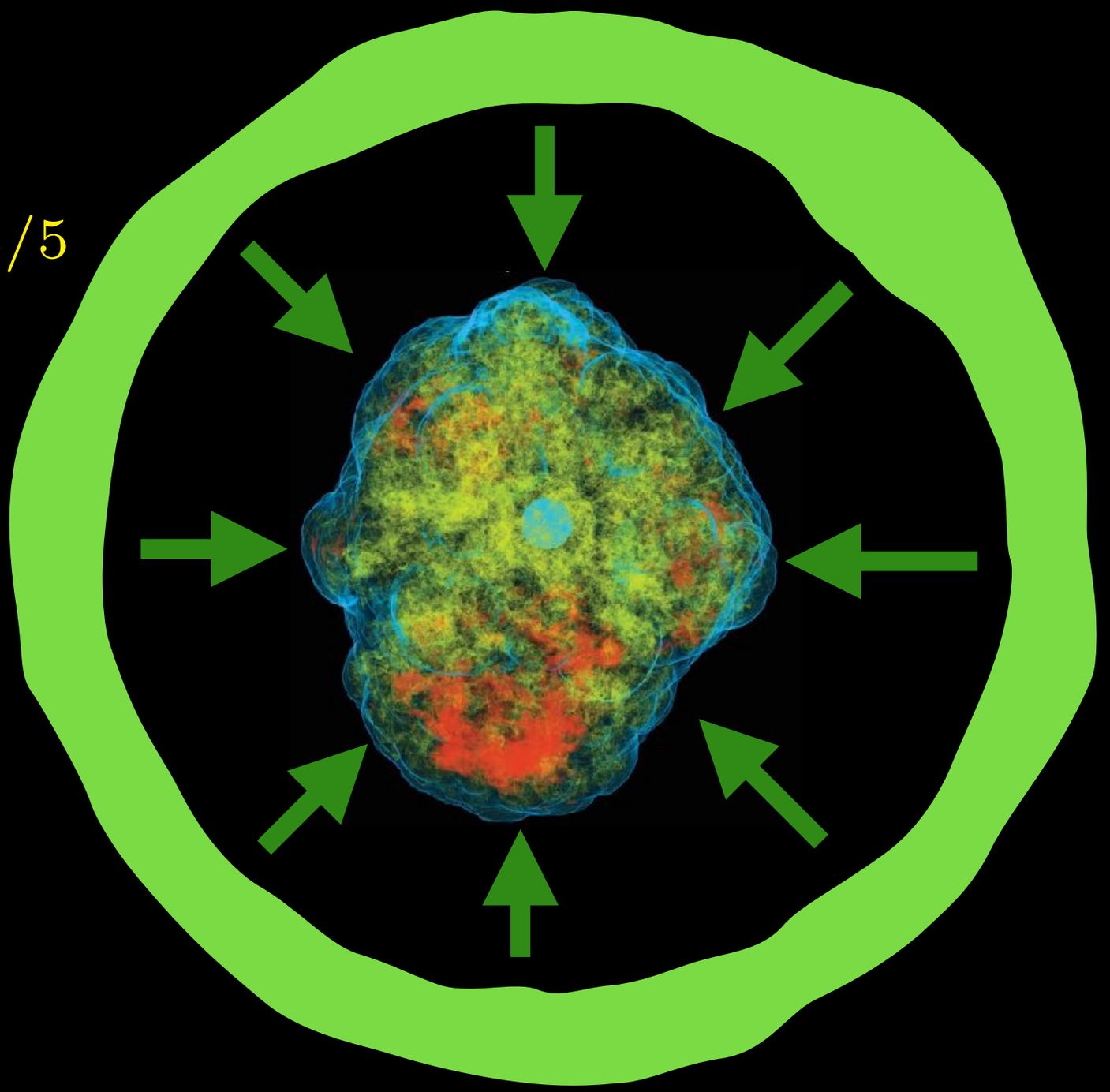
Müller & Janka (2015)



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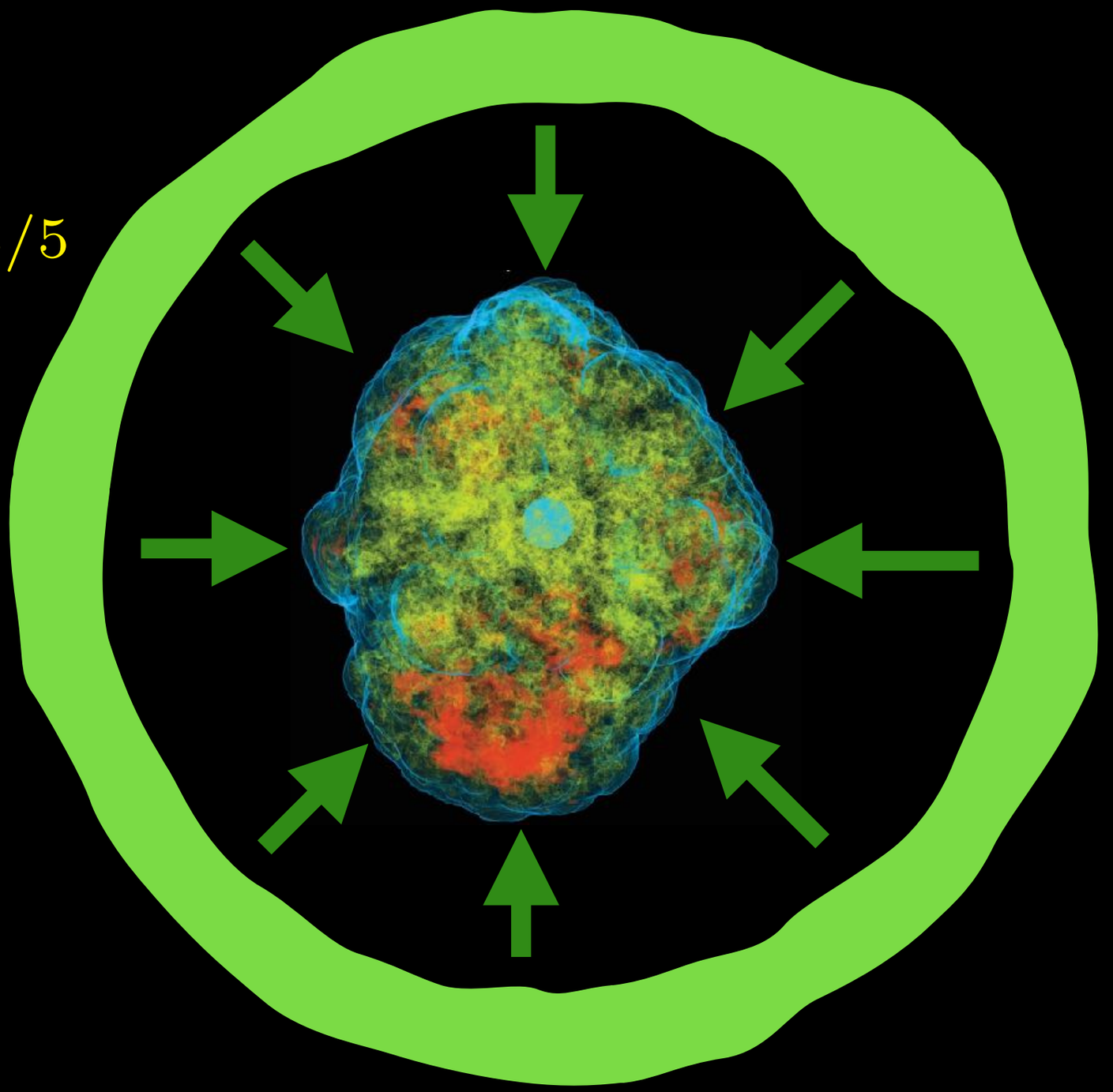
Müller & Janka (2015)

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

Abdikamalov et al (2016)



Sound waves

e.g., Kovalenko & Eremin 1998, Foglizzo 2001, …

1. Entropy perturbations:

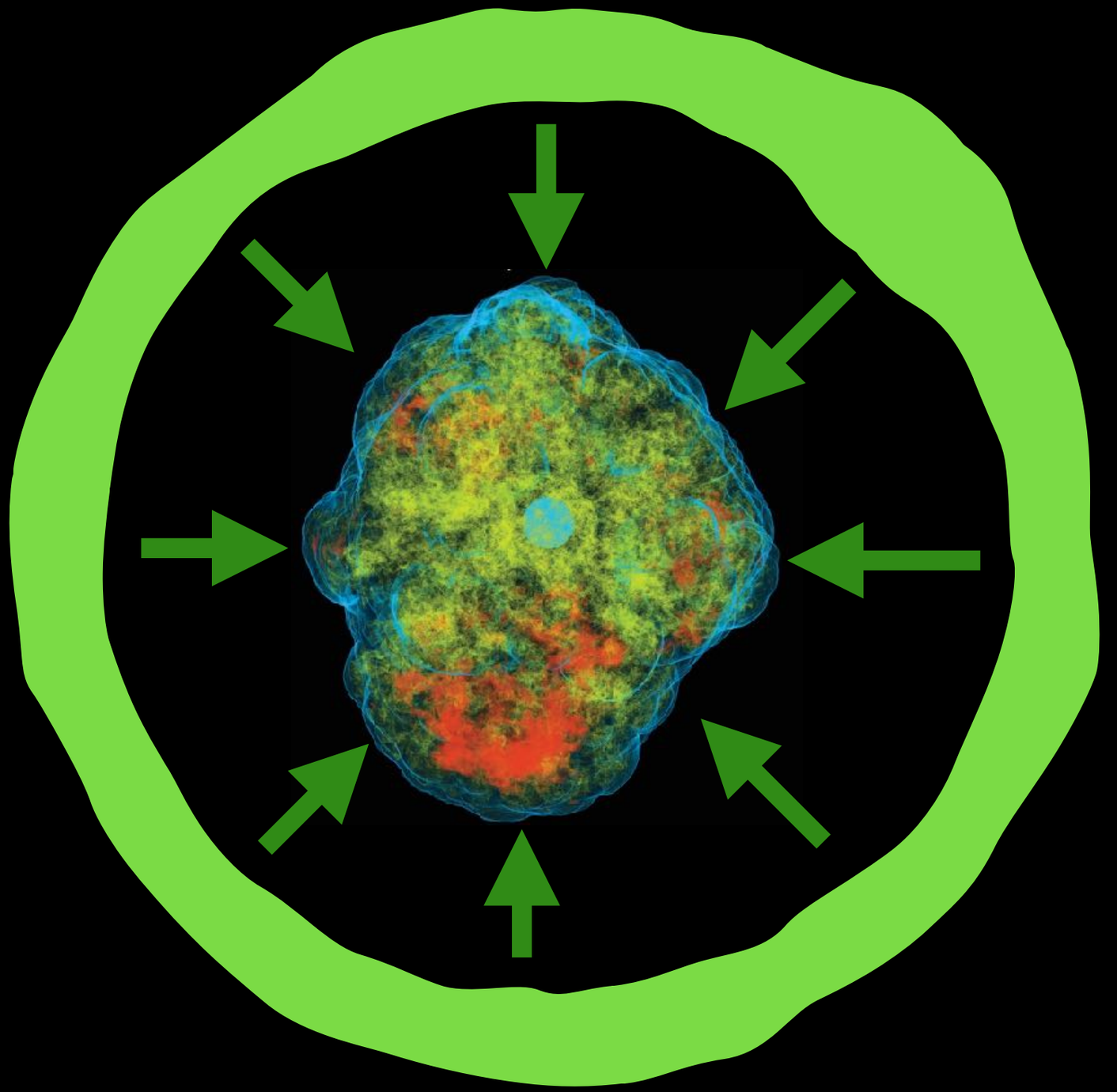
$$\delta E \sim (h_2 - h_1)\delta m$$

Foglizzo & Tagger 2000

2. Vorticity perturbations:

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

Müller et al (2016, 2017)

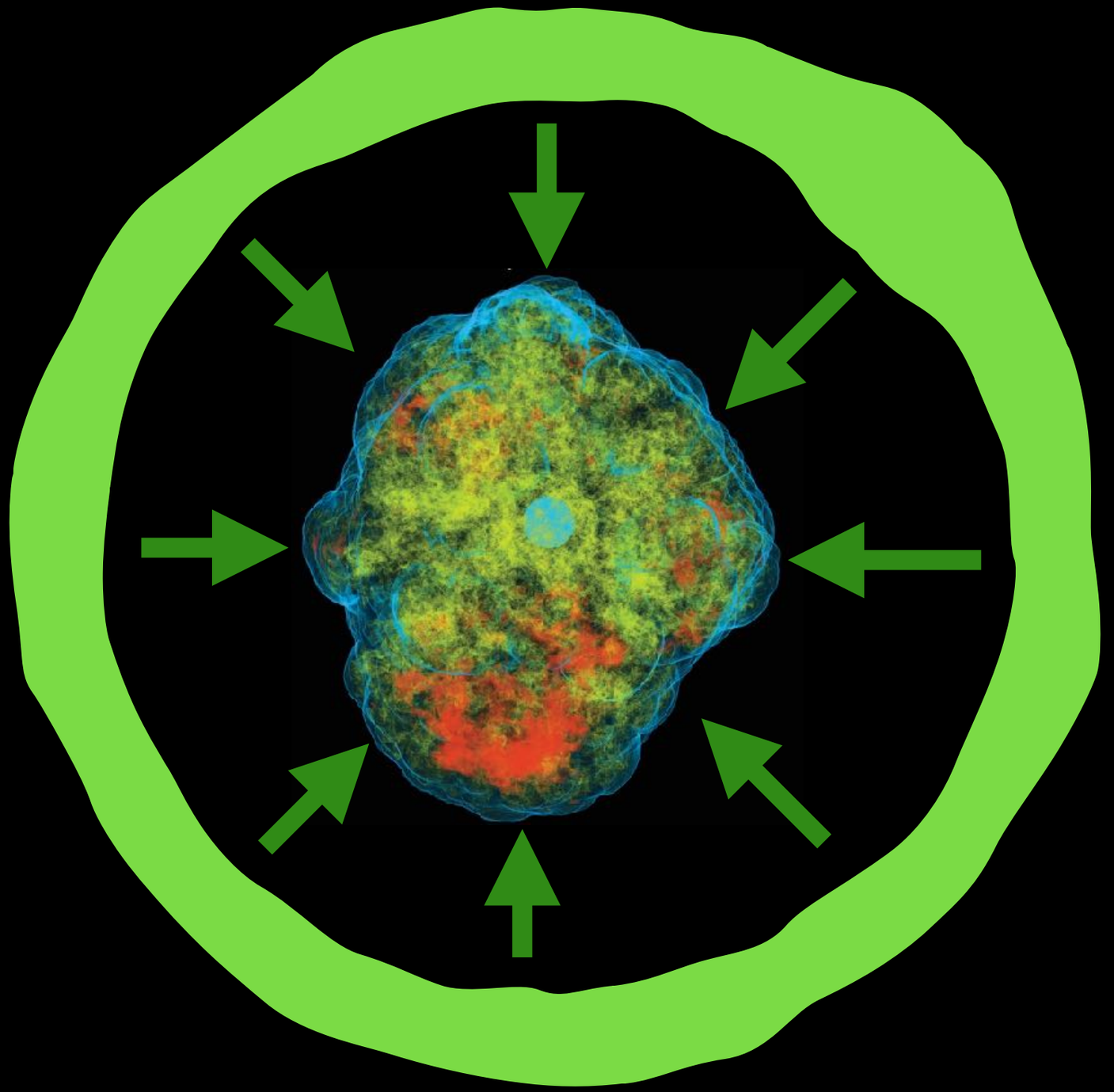


Turbulence driven by buoyancy

Müller et al (2016 2017)

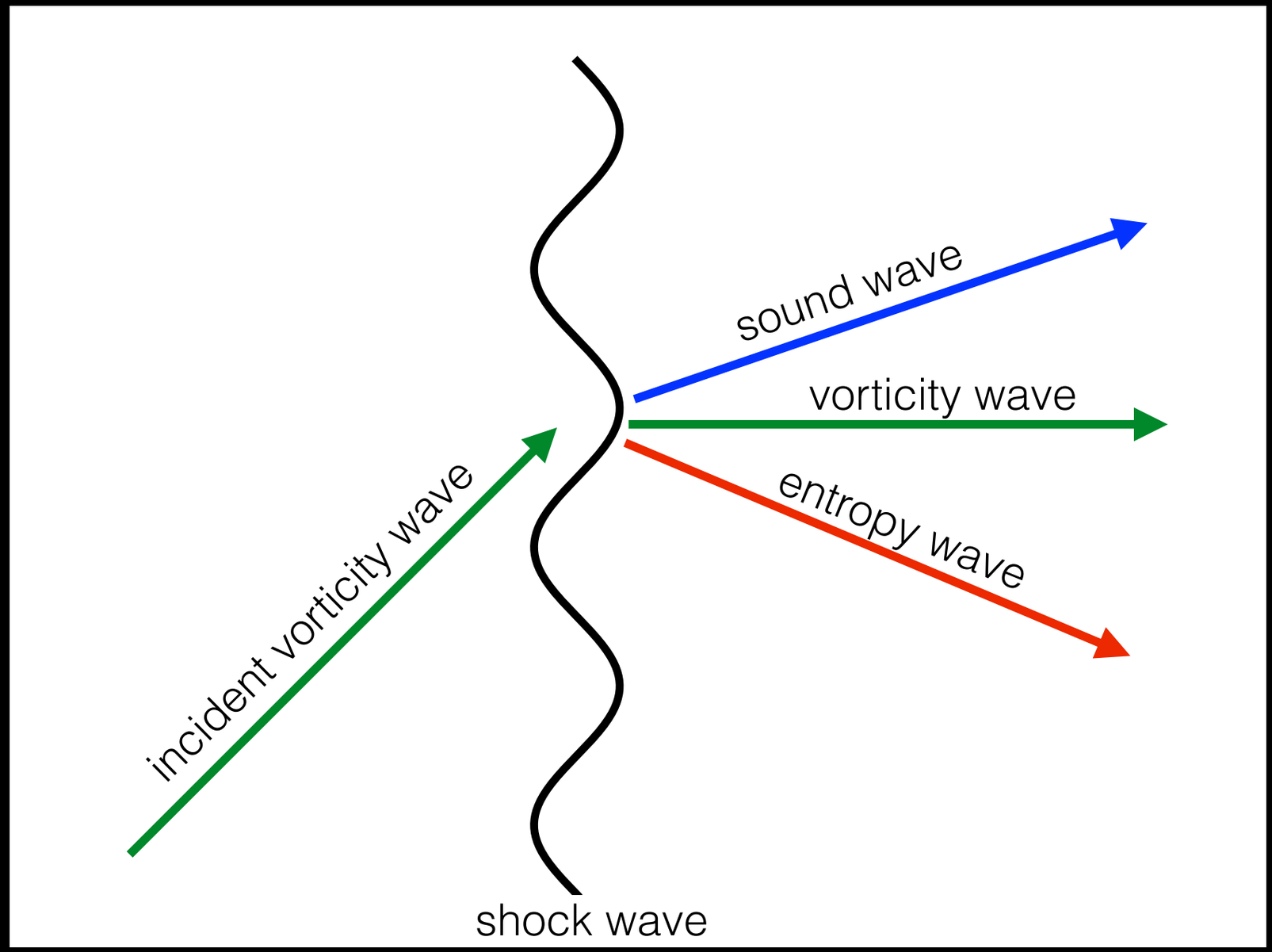
$$\frac{\delta\rho}{\rho} \sim \mathrm{Ma}$$

$$\frac{\Delta L_{\mathrm{crib}}}{L_{\mathrm{crib}}} \sim -2.34\frac{\mathrm{Ma}}{\ell}$$



Entropy perturbations

Huete, Abdikamalov, Radice (2017), *in prep*



$$\frac{\Delta L_{\rm crib}}{L_{\rm crib}} \sim -(1.5-2) \times 2.34 \frac{\rm Ma}{\ell}$$

What's next?

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