# The explosions of massive stars and formation of neutron stars

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# Supernovae

- Explosions that outshine galaxies ($E$~$10^{51}$ erg)
- Lasts for weeks-months


Supernova 1987A

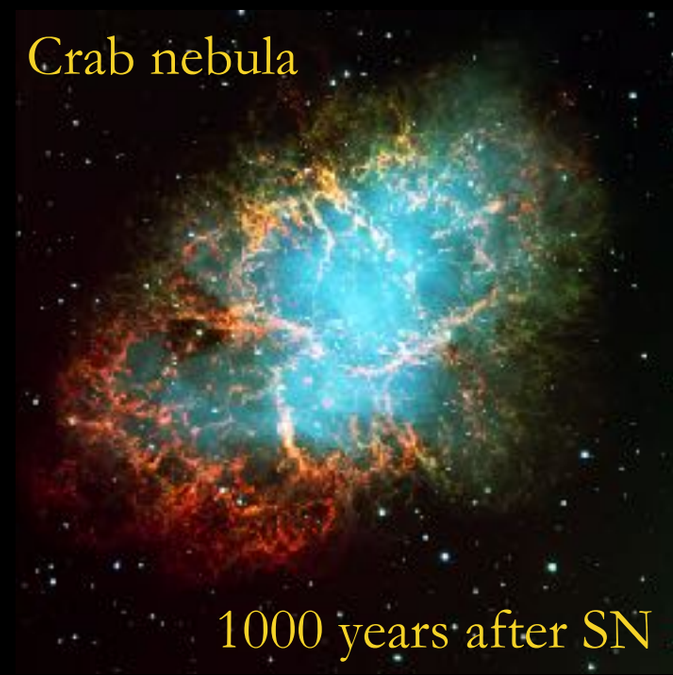
18 $M_{SUN}$ BSG

## Supernova types

**Thermonuclear**
(white dwarfs, pair-instability)

**Core-Collapse**
(massive stars -
neutron star, black hole)

Crab nebula



1000 years after SN

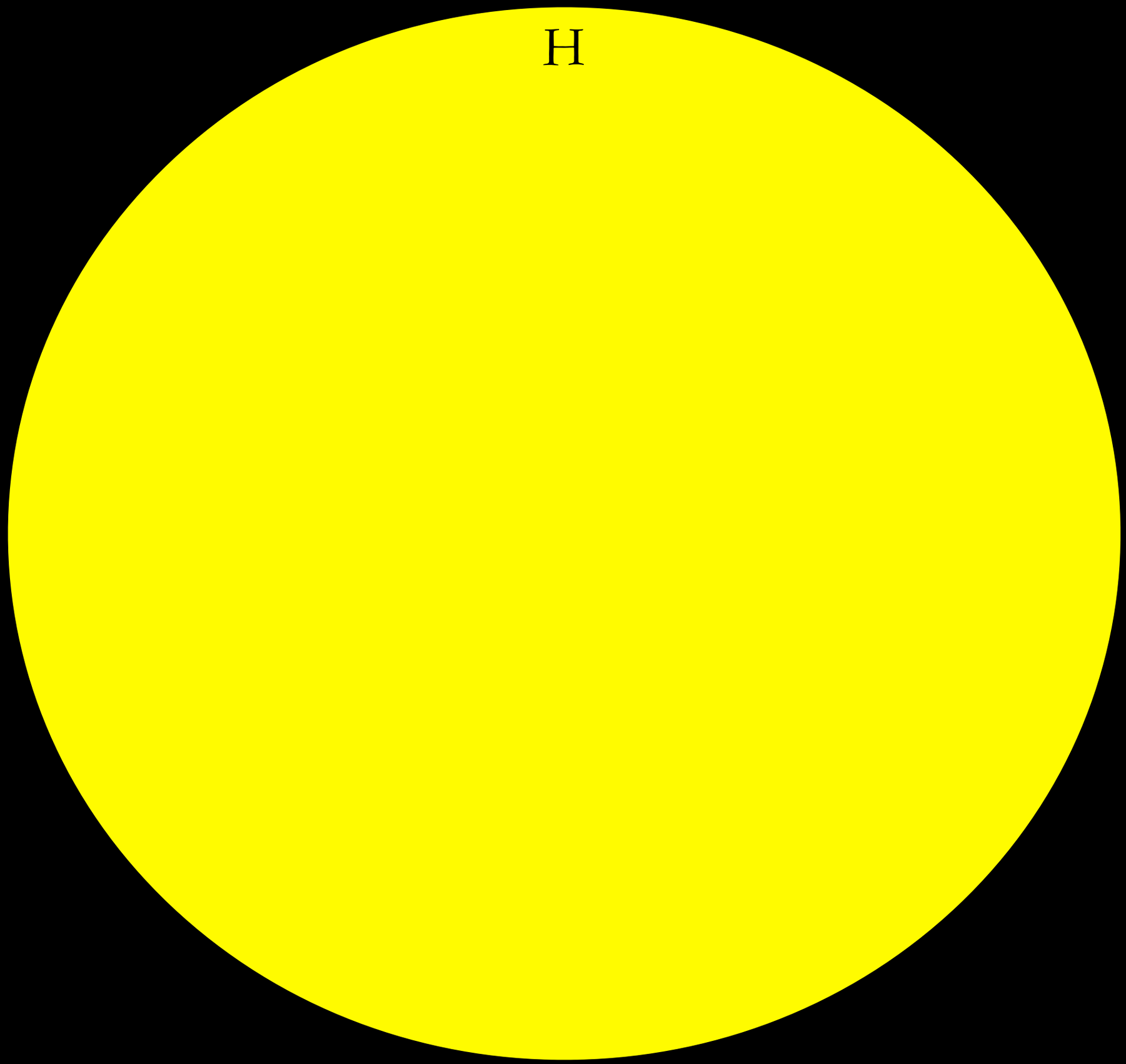
# Why study supernovae?

- Heavy elements
- Neutron stars and black holes
- Gravitational waves and neutrinos
- Learn about their progenitors and stellar evolution
- Long Gamma-Ray Bursts, Fast Radio Bursts(?)
- Learn about the early Universe

# How core-collapse supernovae are powered?

# Progenitor

$9M_\odot \lesssim M \lesssim 100M_\odot$



# Progenitor

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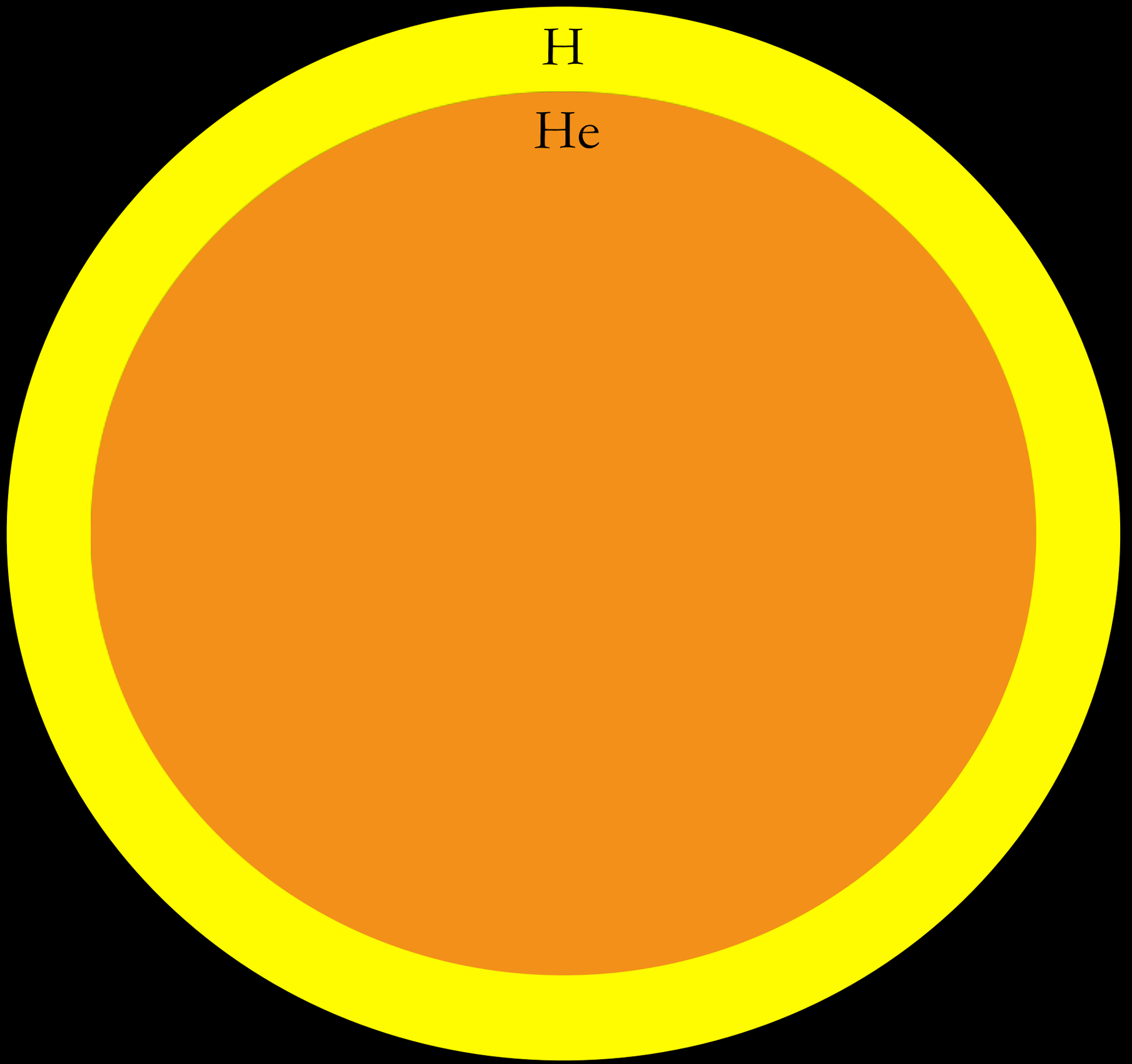

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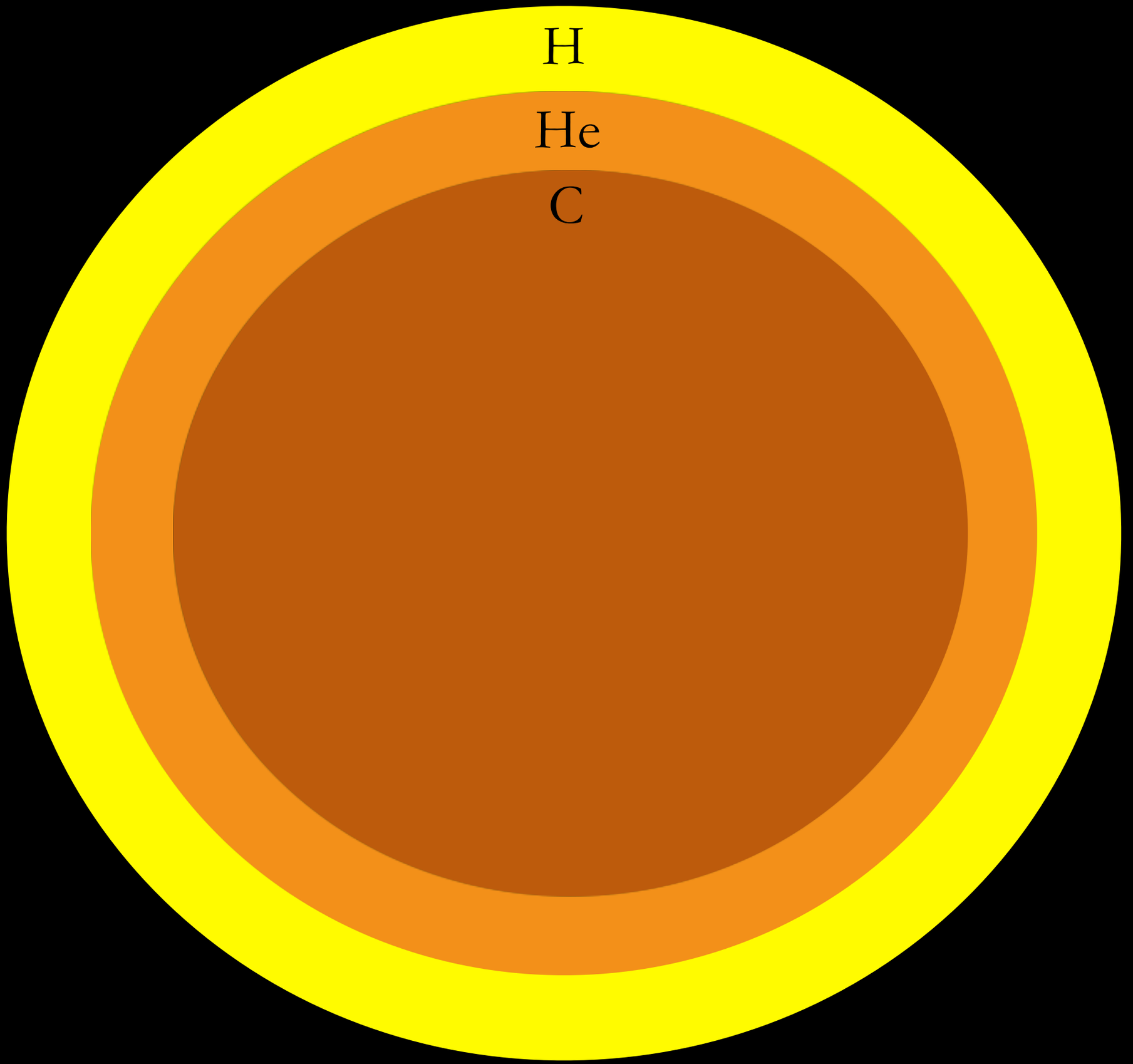

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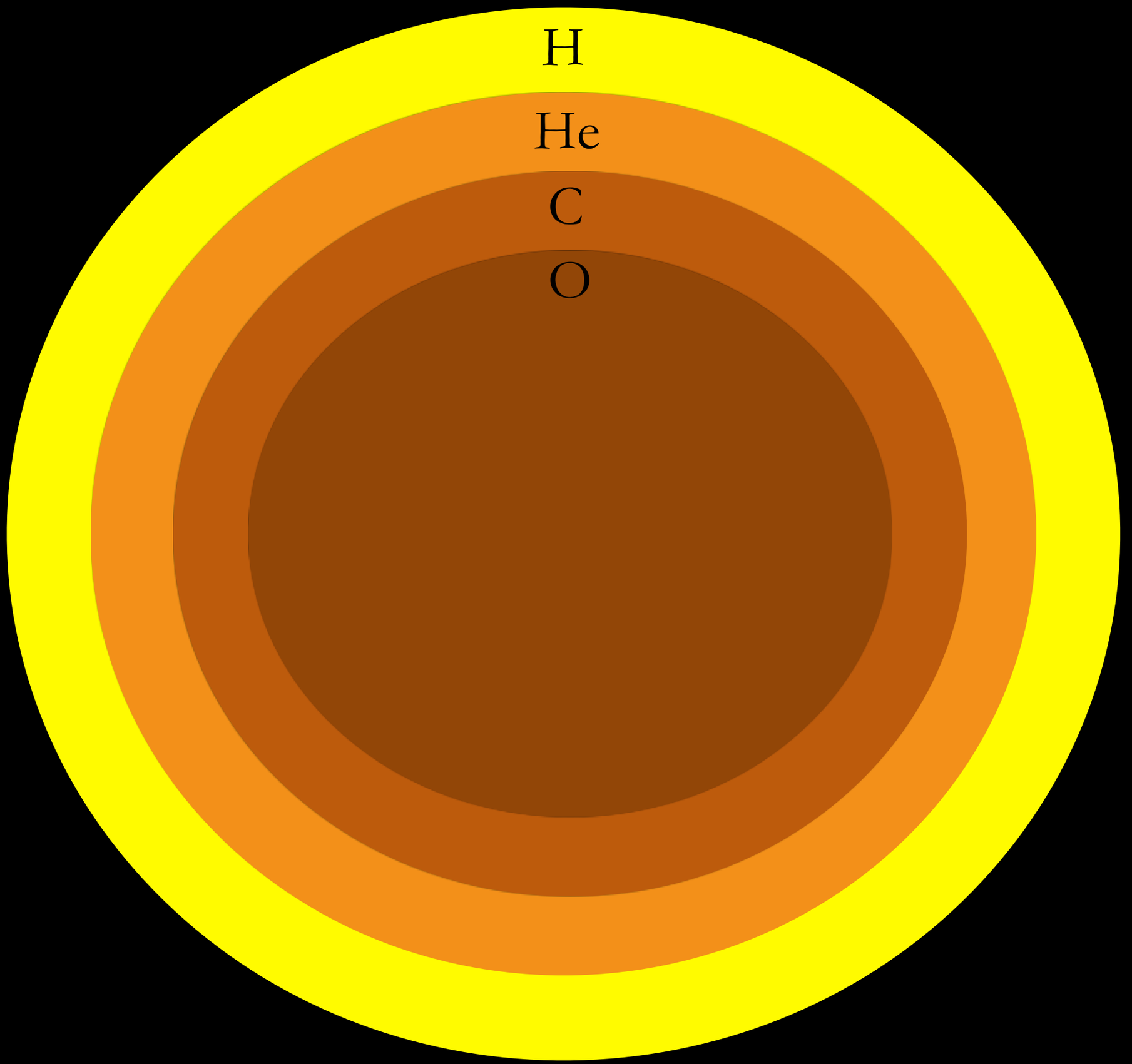

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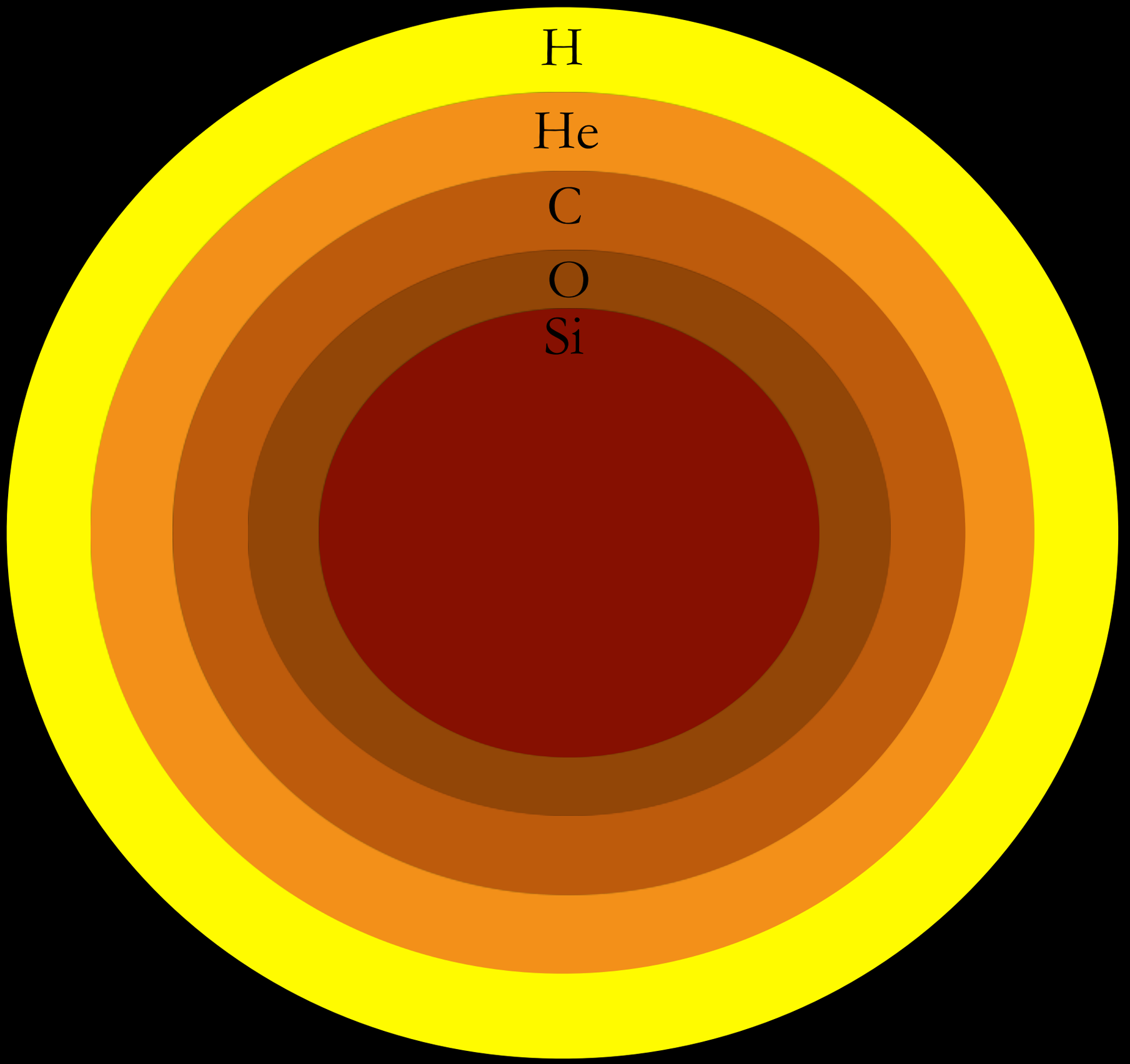

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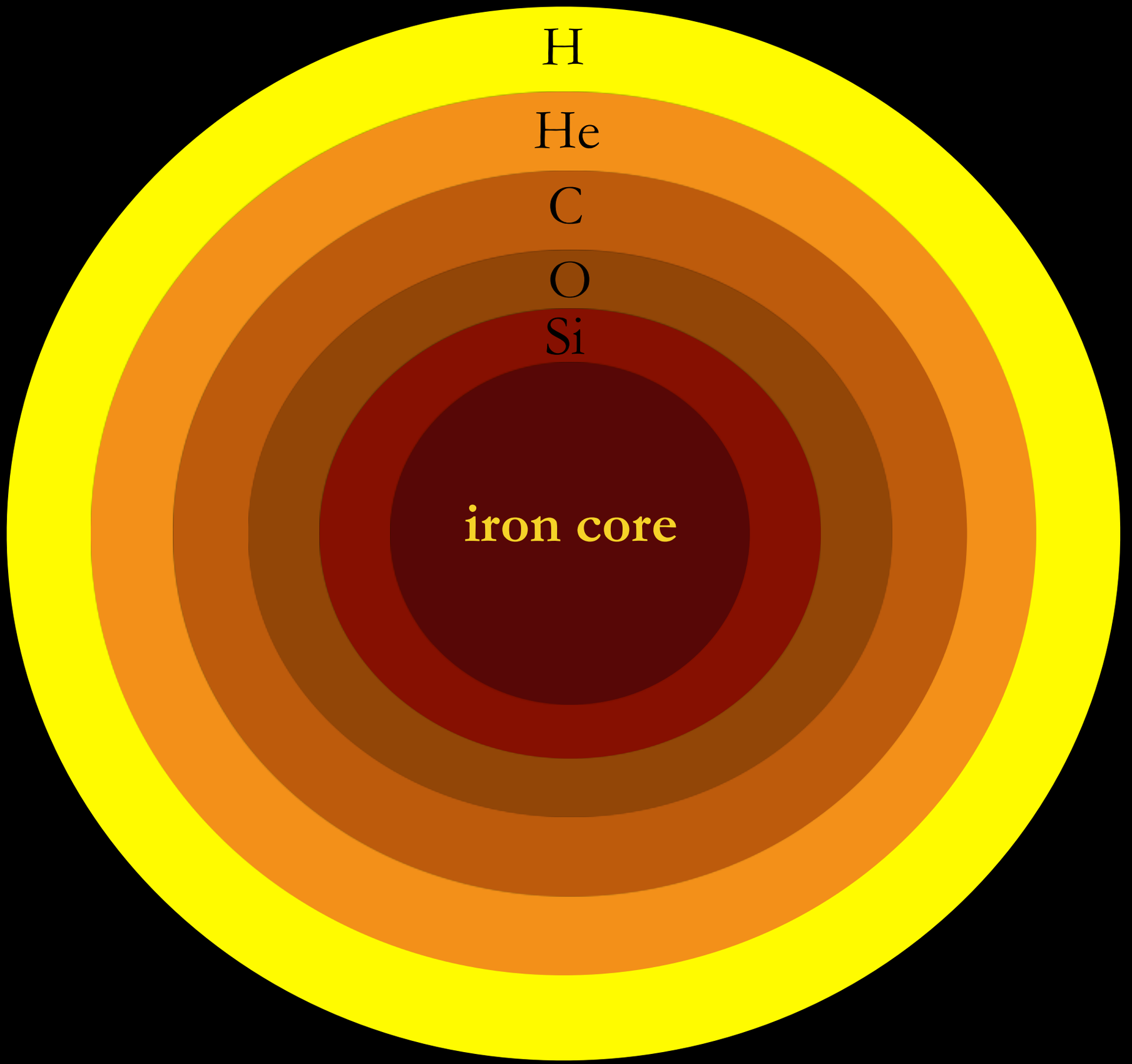
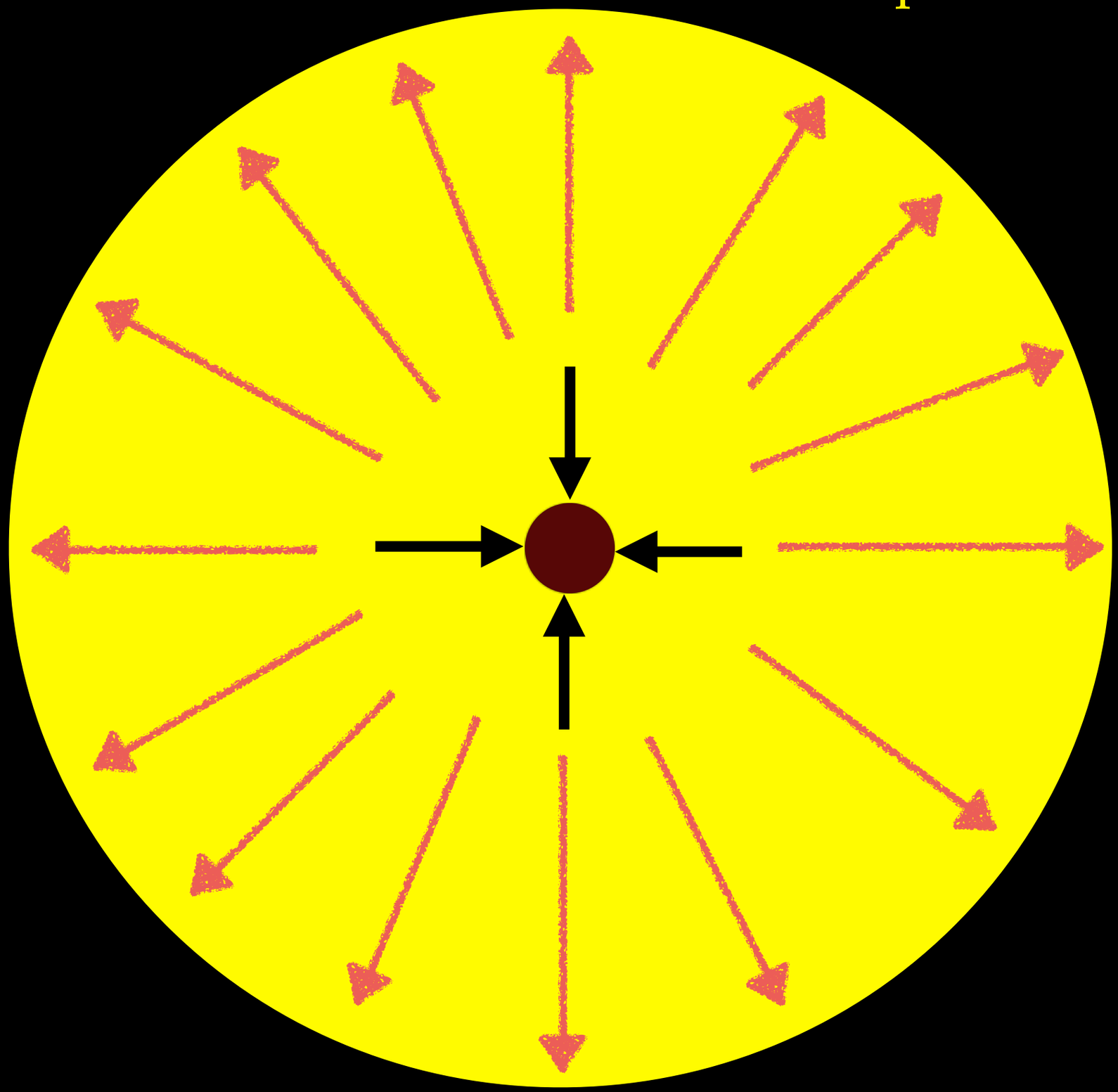
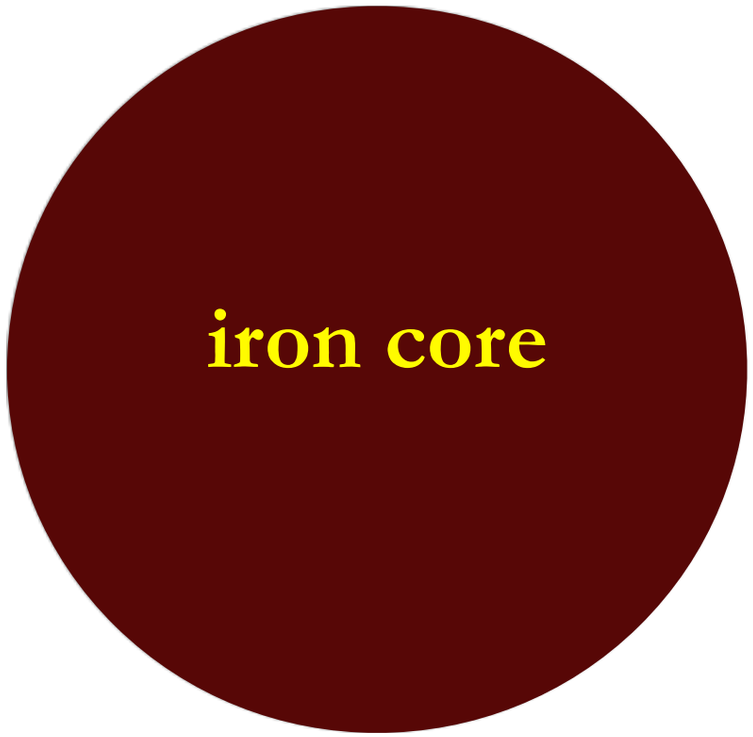


$E_{\rm exp} \sim 10^{51}$ ergs

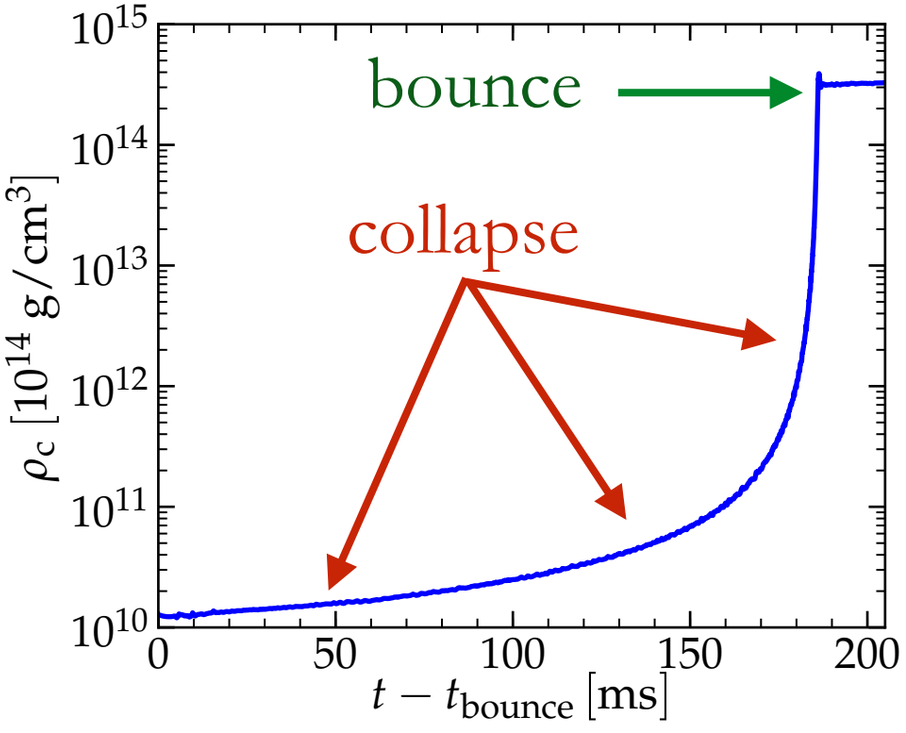


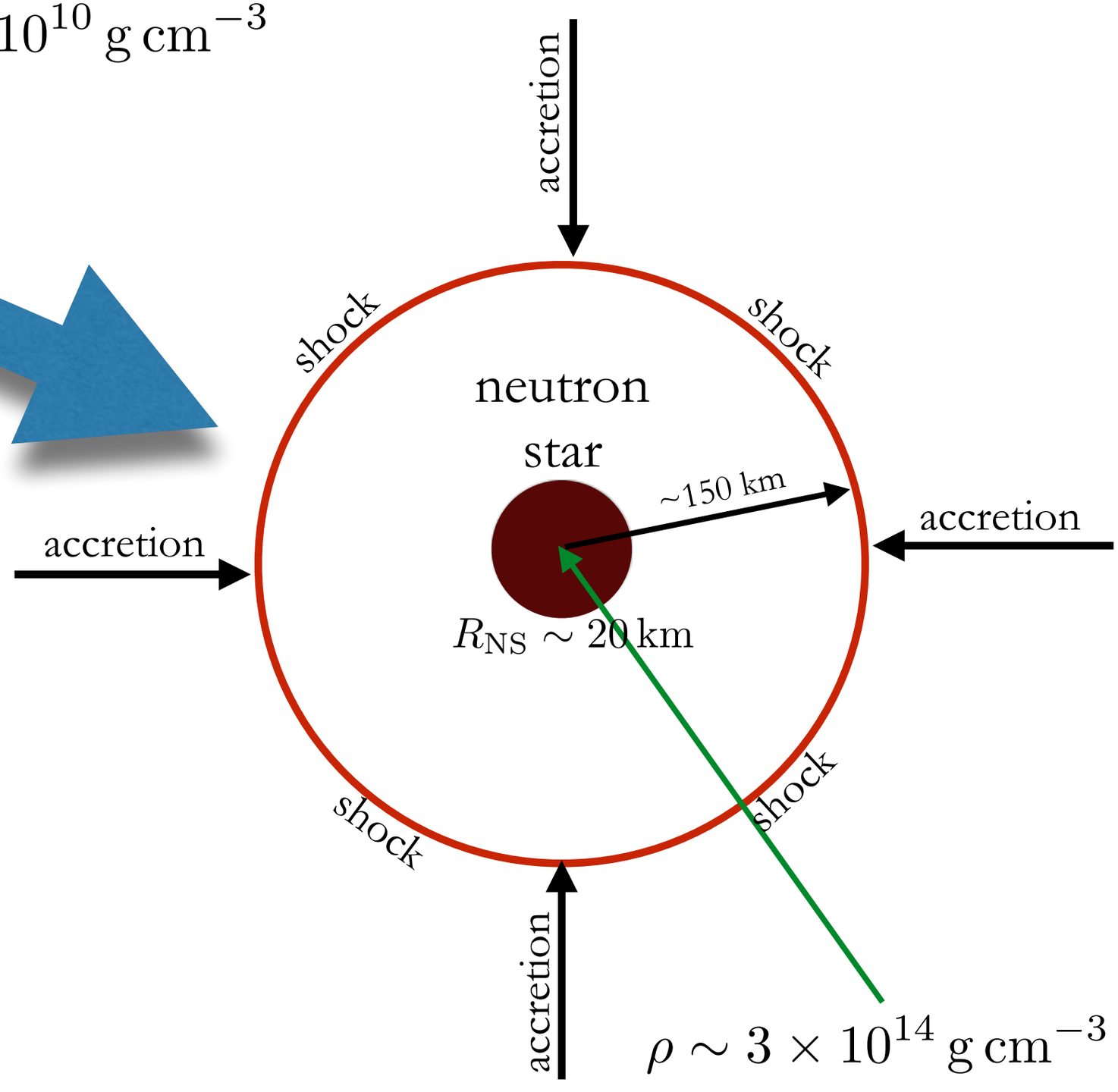
# Core collapse and shock stalling




$$R_{\rm IC} \sim 1500\,{\rm km}$$

$$\rho_{\rm IC} \sim 10^{10}\,{\rm g\,cm^{-3}}$$



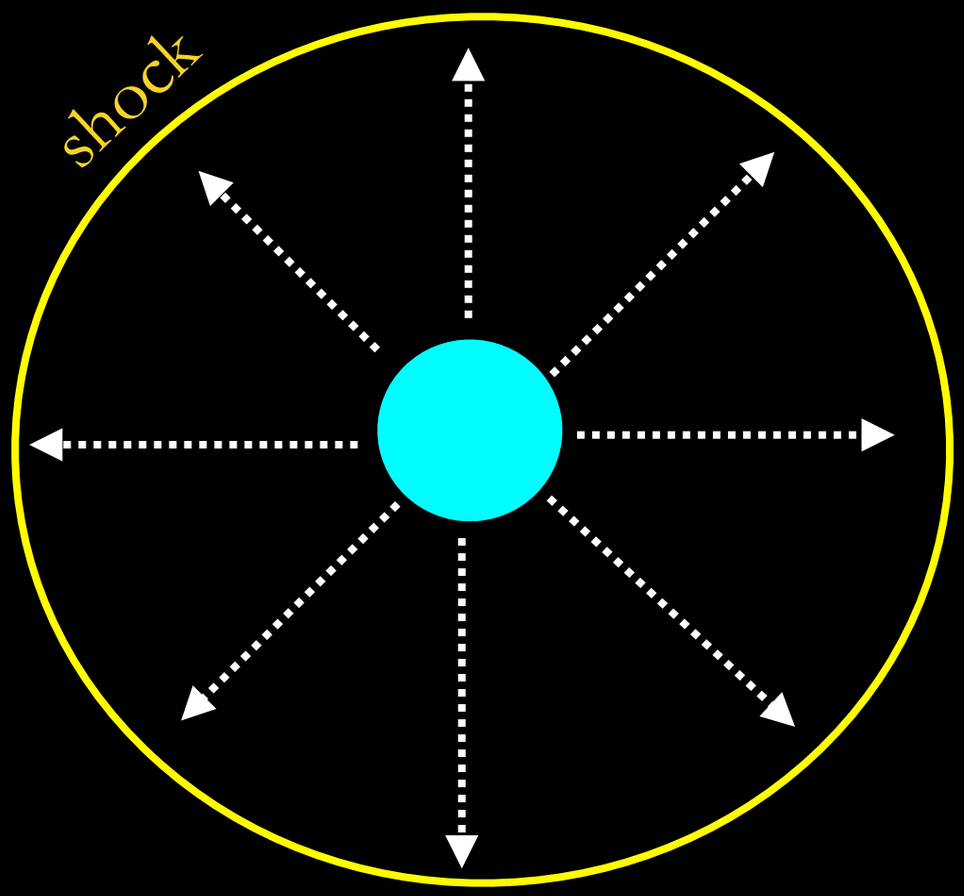



# Explosion mechanisms

**Slow rotation** **Rapid rotation**

# Explosion mechanisms

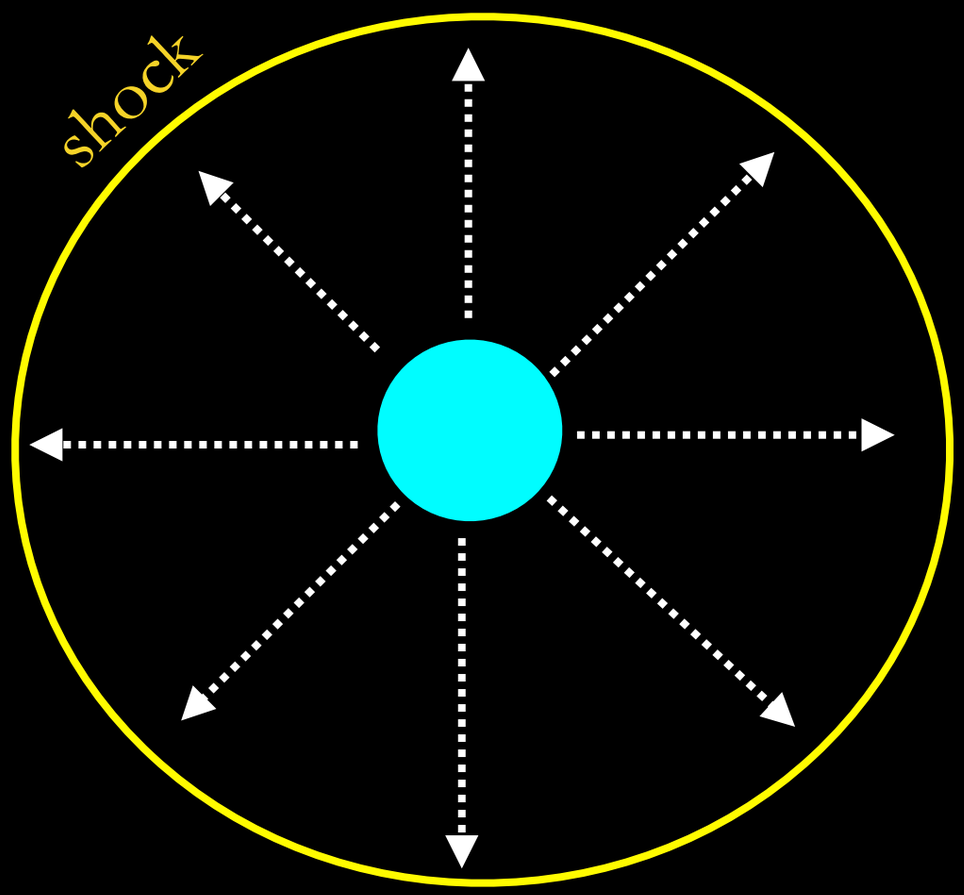
**Slow rotation** **Rapid rotation**




**Neutrino mechanism**

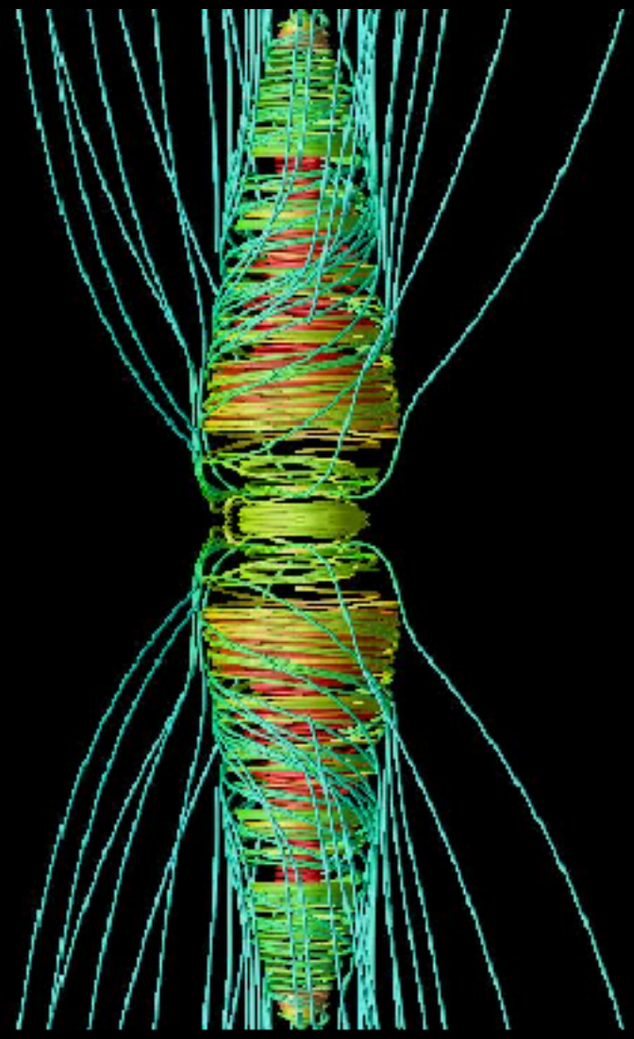
# Explosion mechanisms

## Slow rotation




## Neutrino mechanism

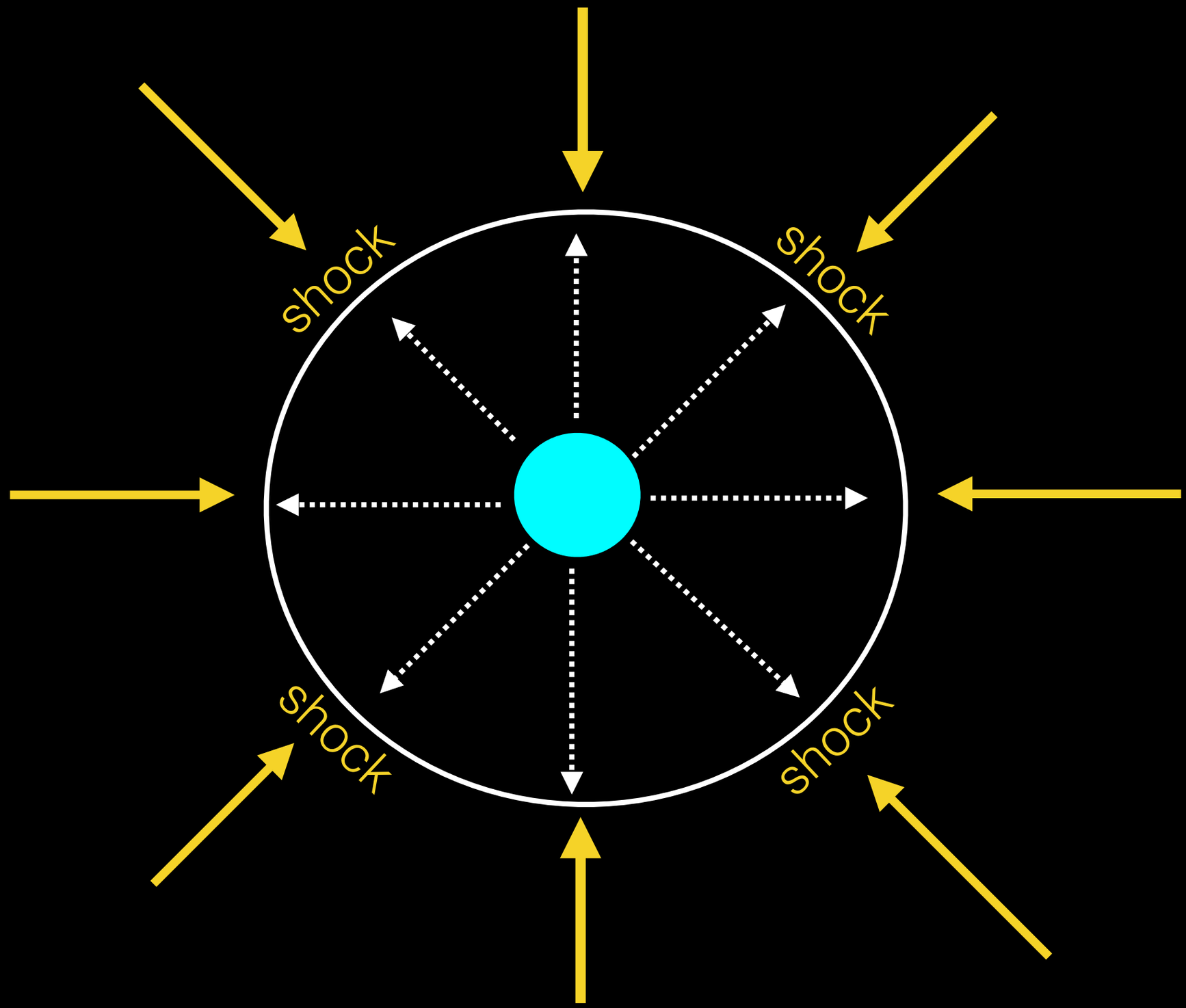
## Rapid rotation



Burrows+07

## Magnetorotational mechanism

# Neutrino mechanism in spherical symmetry




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

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

Radius [km]

$10^4$

$10^3$

$10^2$

$10^1$

$10^0$

$M = 1.3\ M_\odot$

n8.8 Baseline 1D

0.0

0.2

0.4

0.6

Time after bounce [s]

Density-averaged entropy [$k_B$]

40

35

30

25

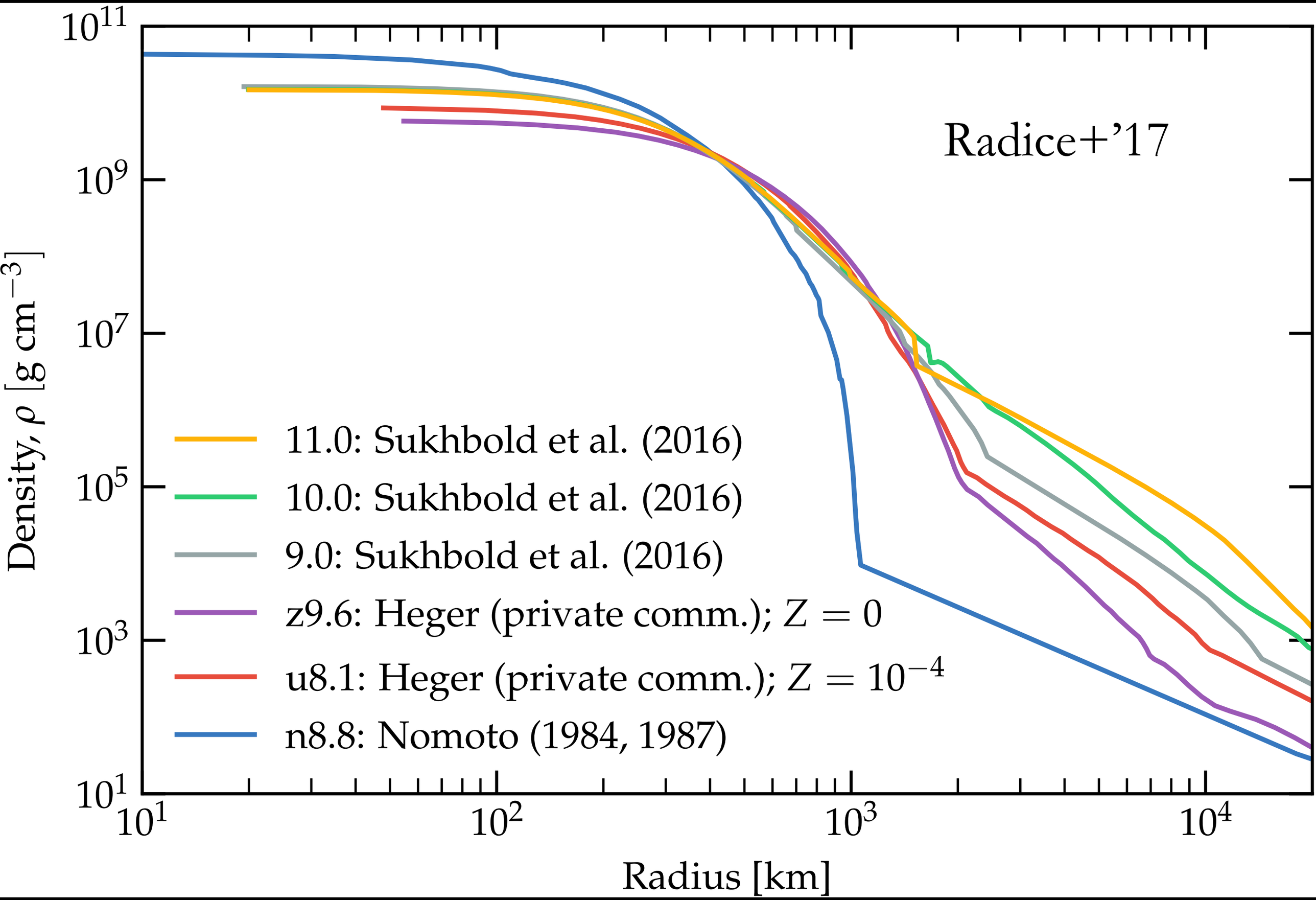
20

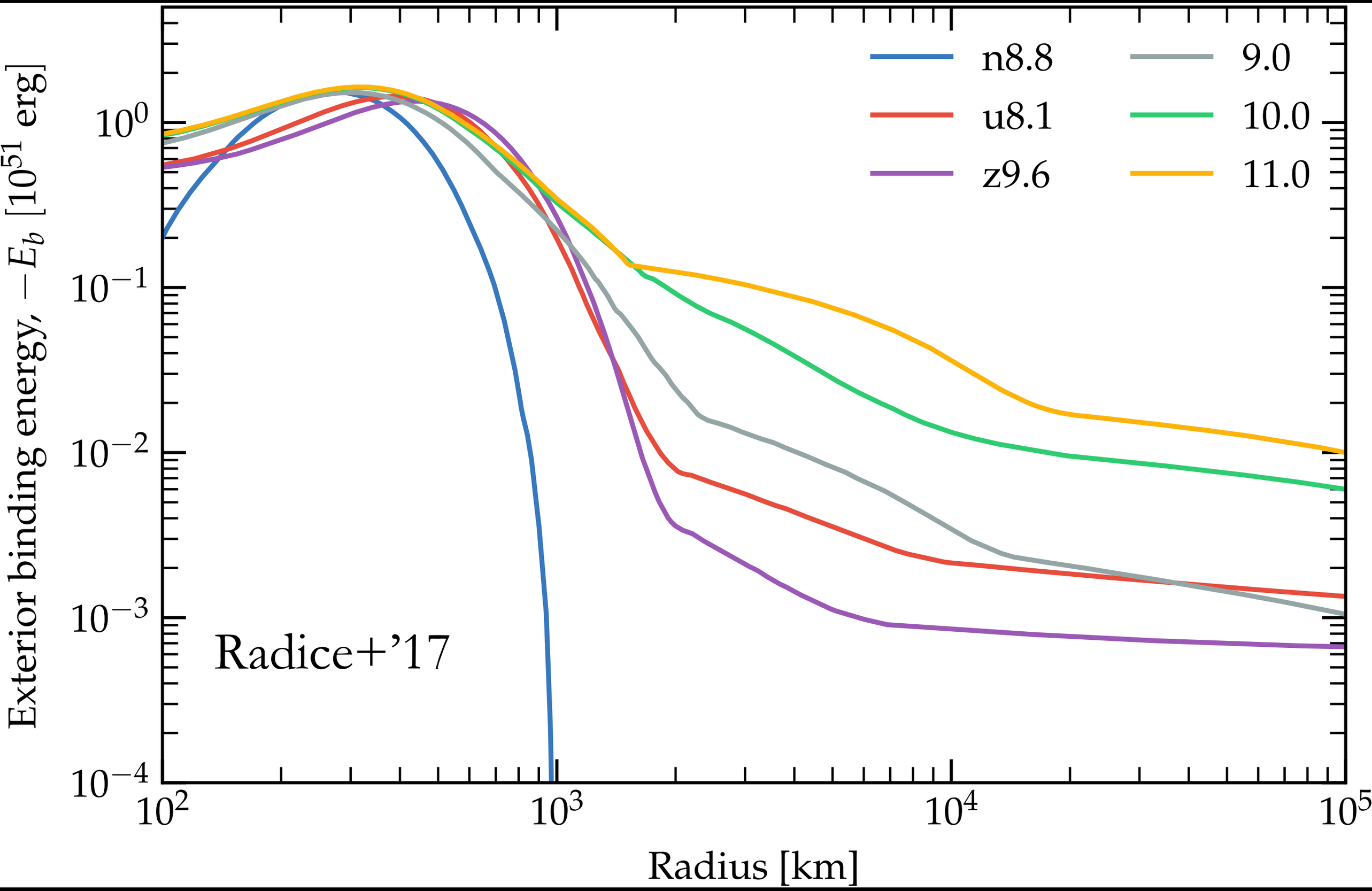
15

10

5

Radice+'17

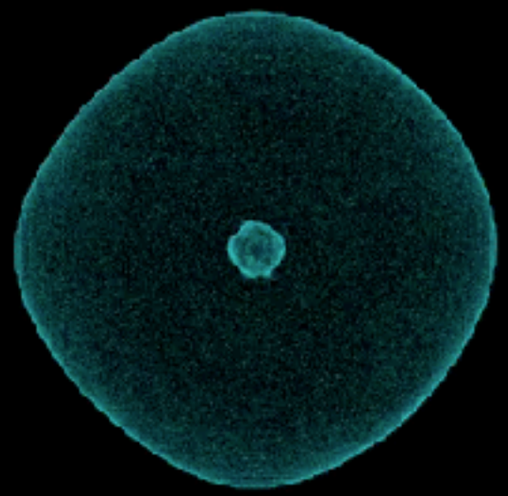

Radice+'17
11.0: Sukhbold et al. (2016)
10.0: Sukhbold et al. (2016)
9.0: Sukhbold et al. (2016)
z9.6: Heger (private comm.); $Z = 0$
u8.1: Heger (private comm.); $Z = 10^{-4}$
n8.8: Nomoto (1984, 1987)
Density, $\rho$ [g cm$^{-3}$]
Radius [km]
$10^{11}$
$10^{9}$
$10^{7}$
$10^{5}$
$10^{3}$
$10^{1}$
$10^{1}$
$10^{2}$
$10^{3}$
$10^{4}$


n8.8
u8.1
z9.6
9.0
10.0
11.0
Radice+'17
Exterior binding energy, $-E_b$ [$10^{51}$ erg]
Radius [km]
$10^0$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^2$
$10^3$
$10^4$
$10^5$

# What is missing in spherical symmetry?

# Multi-dimensional hydrodynamic instabilities

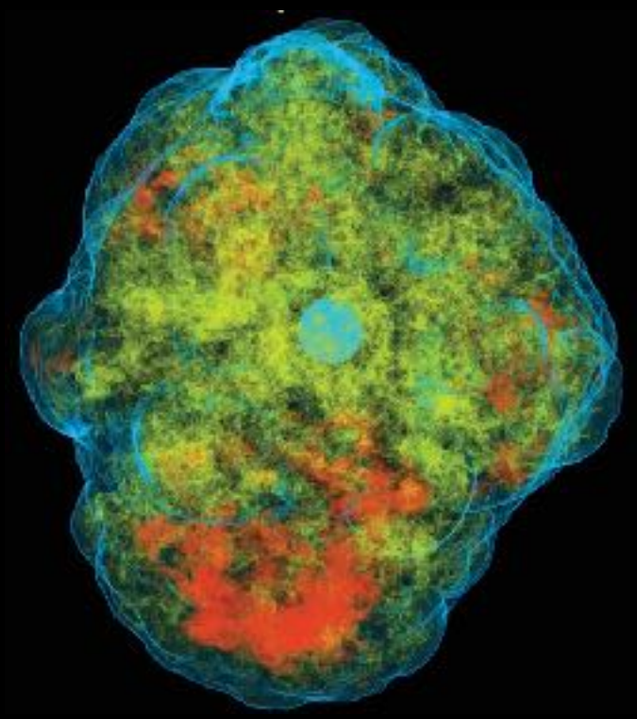
13.50 ms

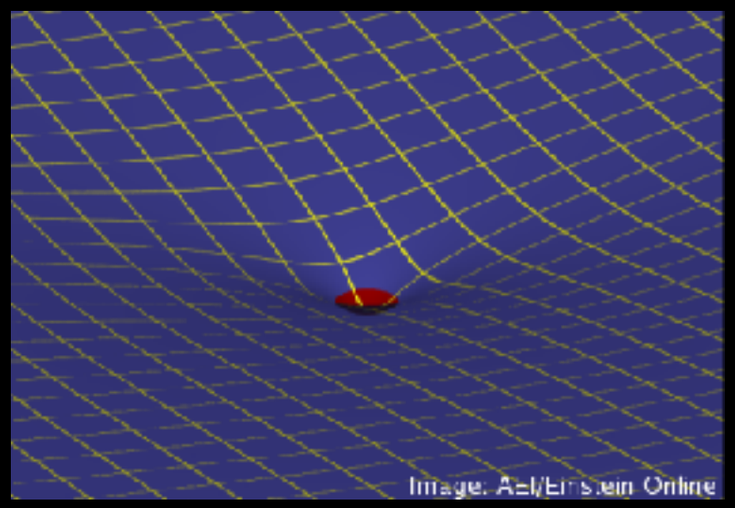


Ott, Abdikamalov et al ‘13

# Model Ingredients

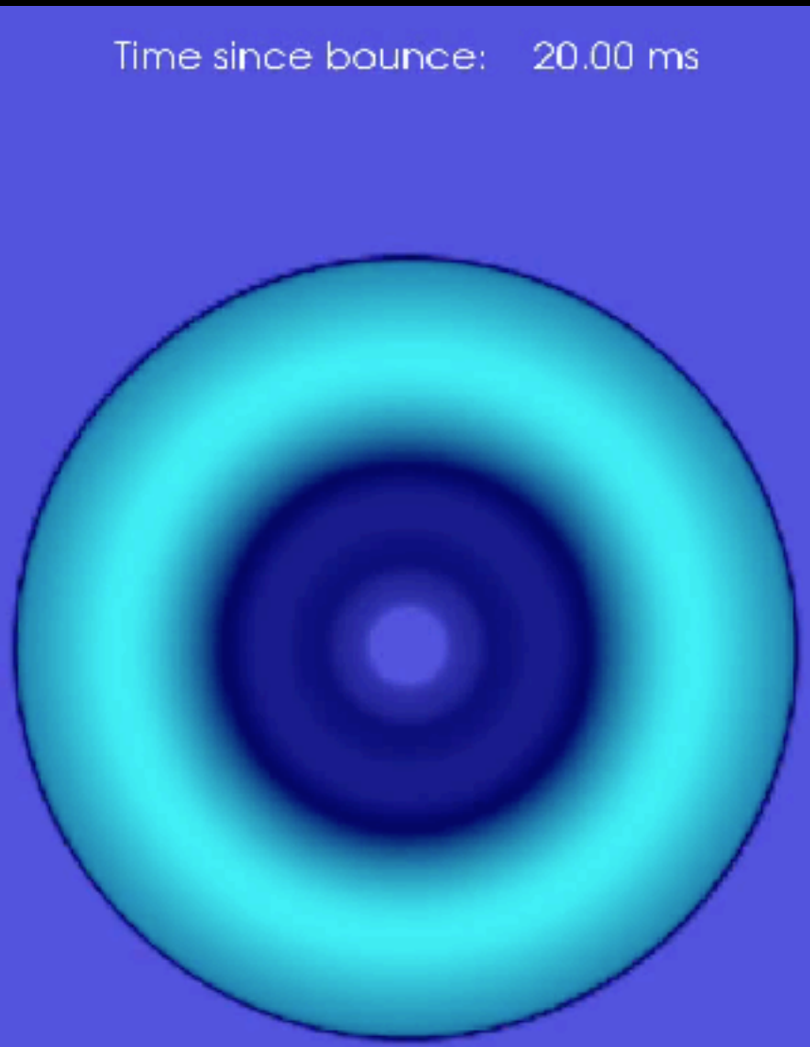
- Spatial scales: from ~10,000 km to ~0.1 km (or less?)
- Timescales: ~1 ms - ~1 s
- General relativity
- 3D (magneto)hydrodynamics
- 3D neutrino transport
- Nuclear and neutrino physics





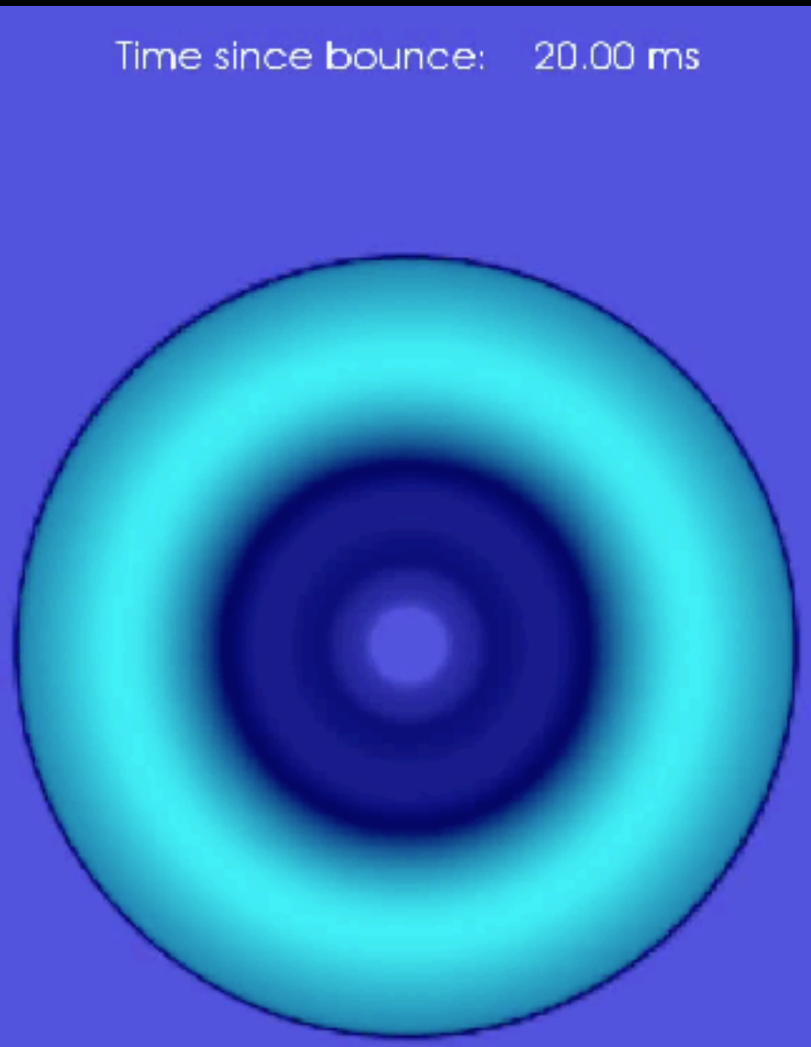
# Turbulence & SASI

# Turbulence




Abdikamalov+’15

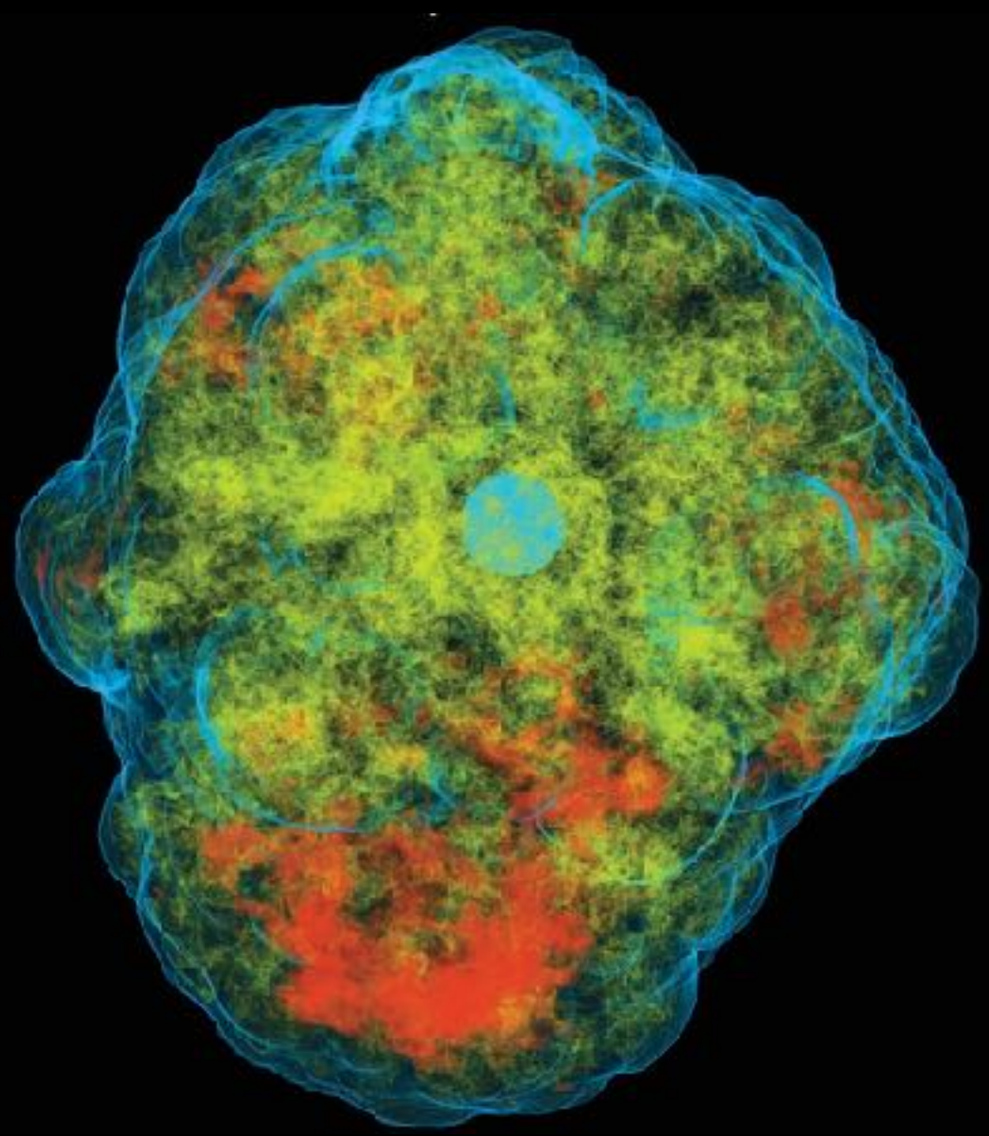
# SASI




See also: Hanke+’13, Fernandez ’15

# Role of Turbulence

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

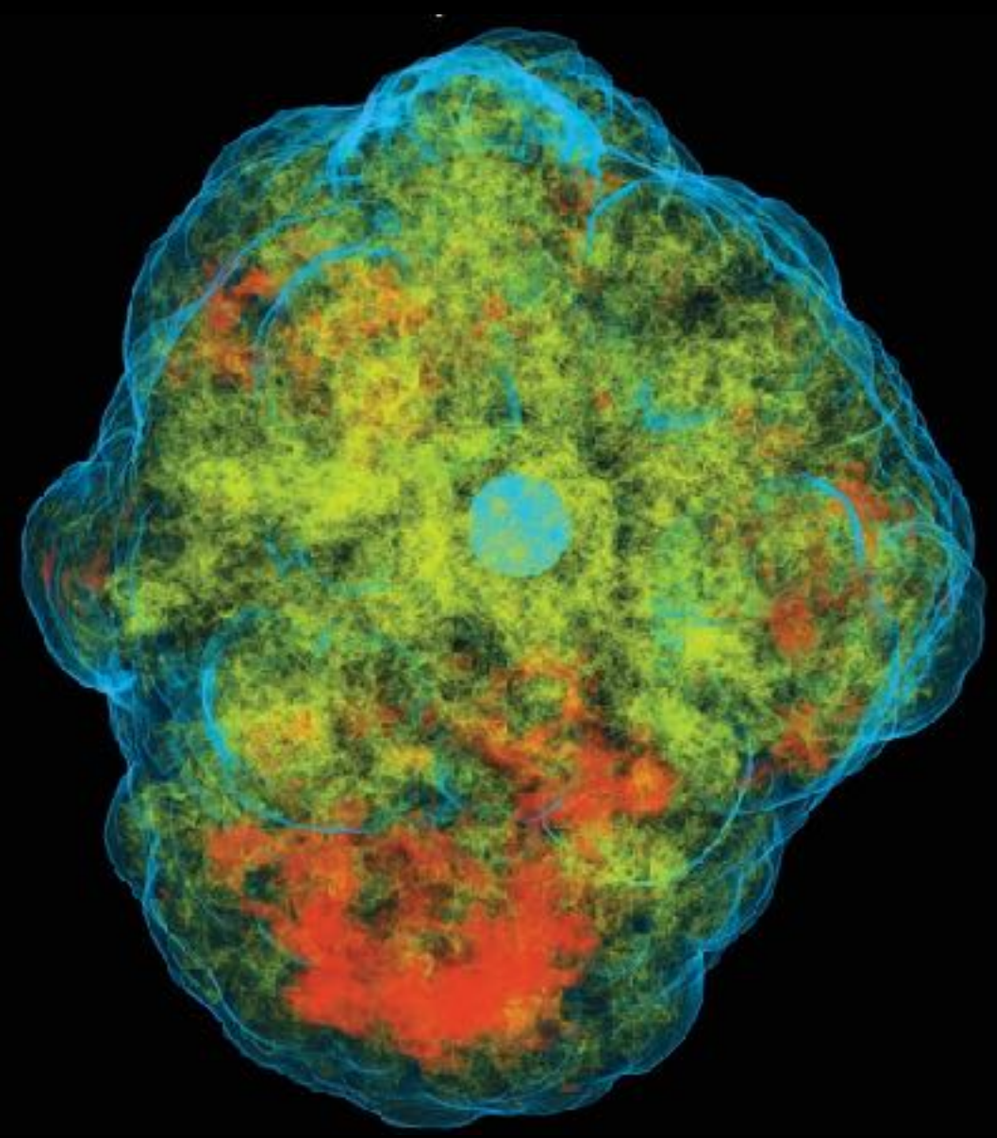


# Role of Turbulence

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

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

Müller & Janka (2015)

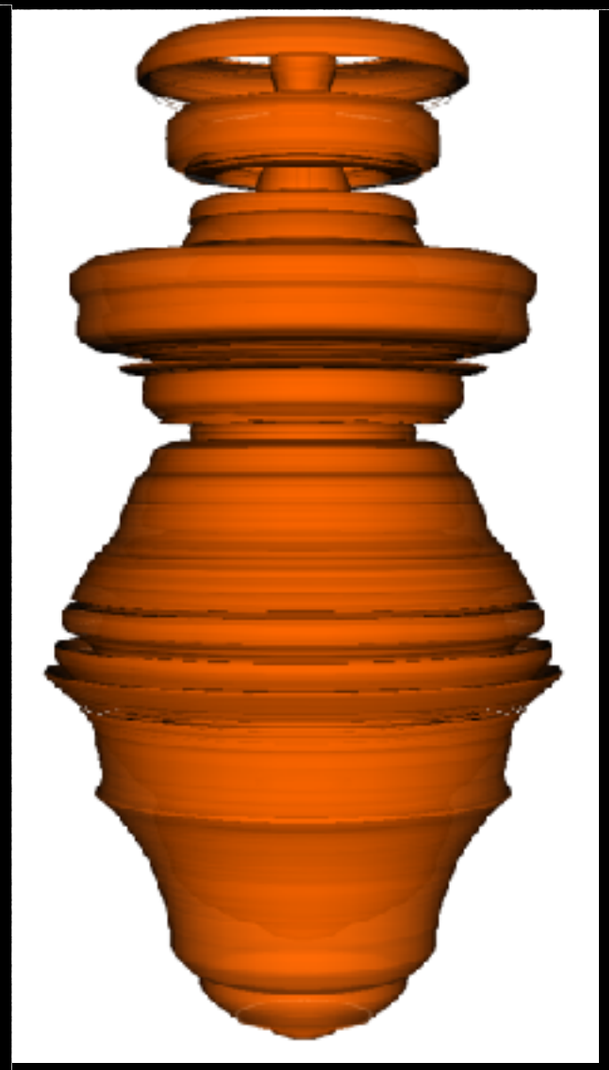


See also: Radice, Abdikamalov+'18 and Müller' 16 for recent reviews.

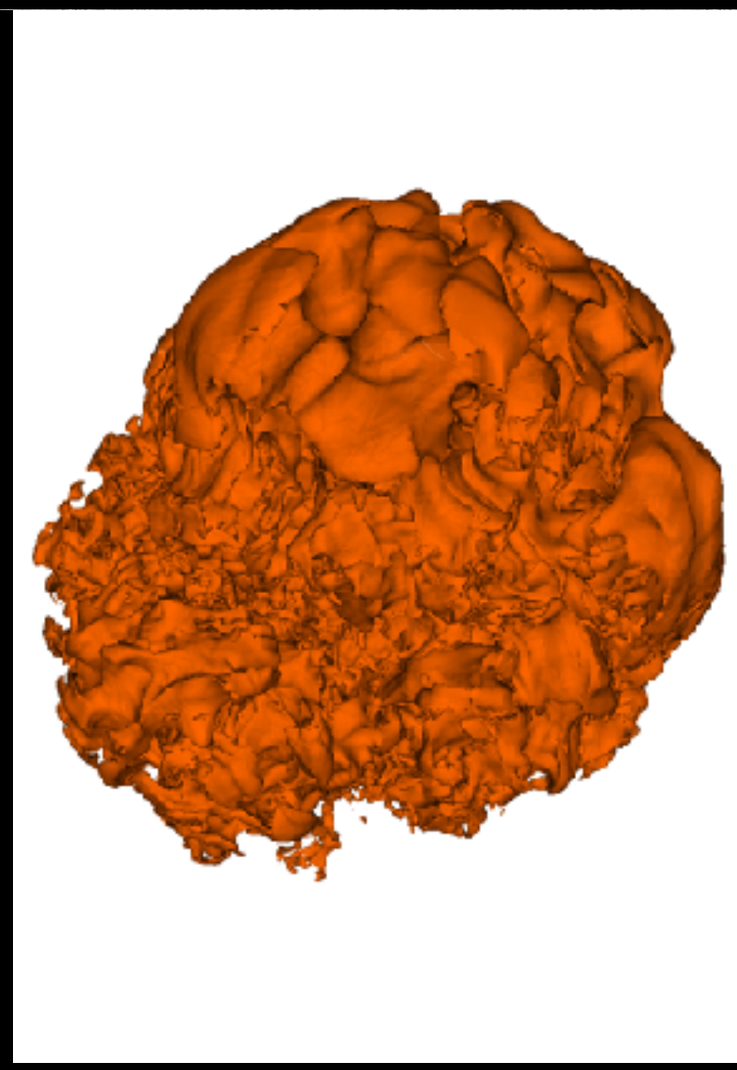
# 2D axisymmetry *vs.* 3D simulations

# 2D *vs.* 3D simulations

Couch (2013)



**2D**



**3D**

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

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

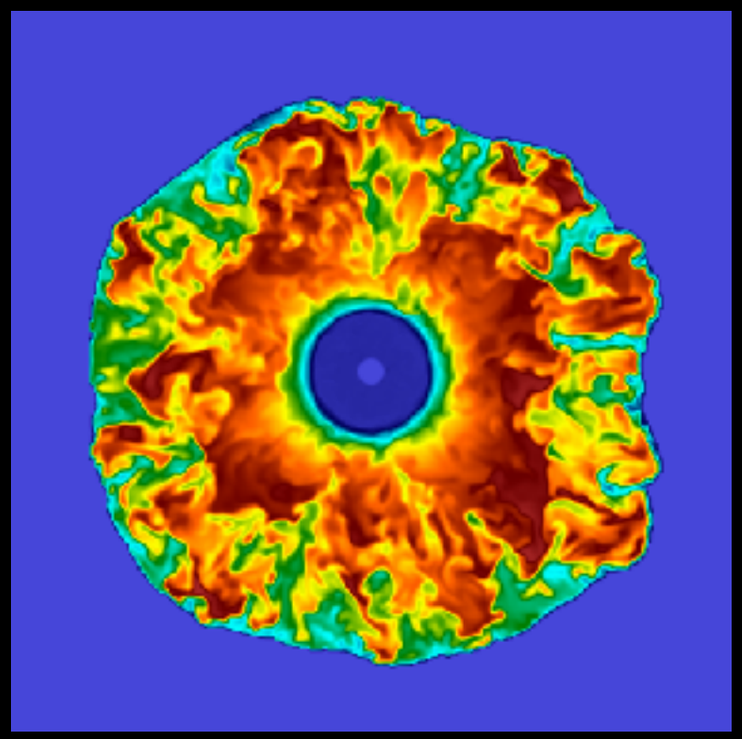
Energy-containing range

Kolmogorov (1940)

$\kappa^{-5/3}$

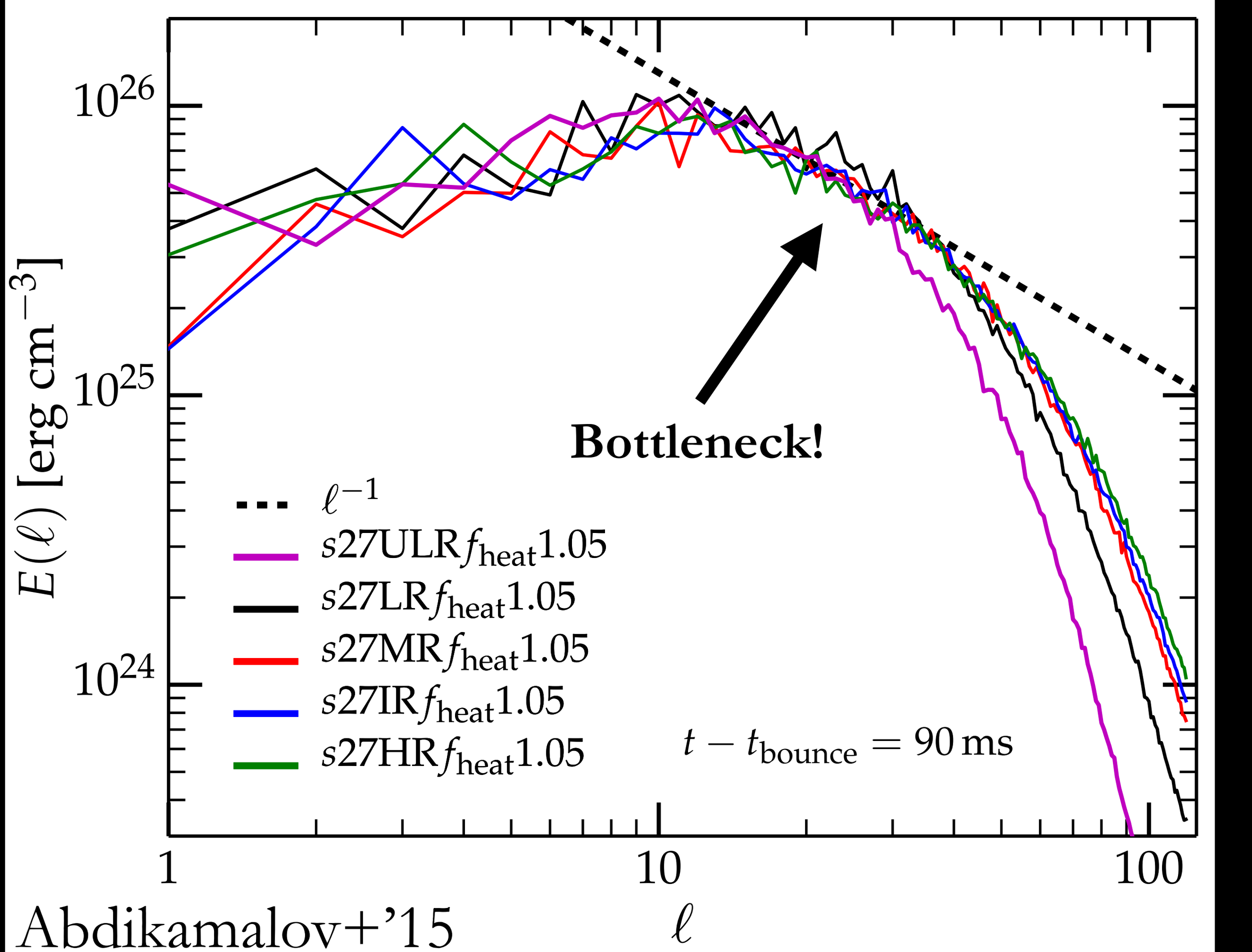
Inertial range

Dissipation

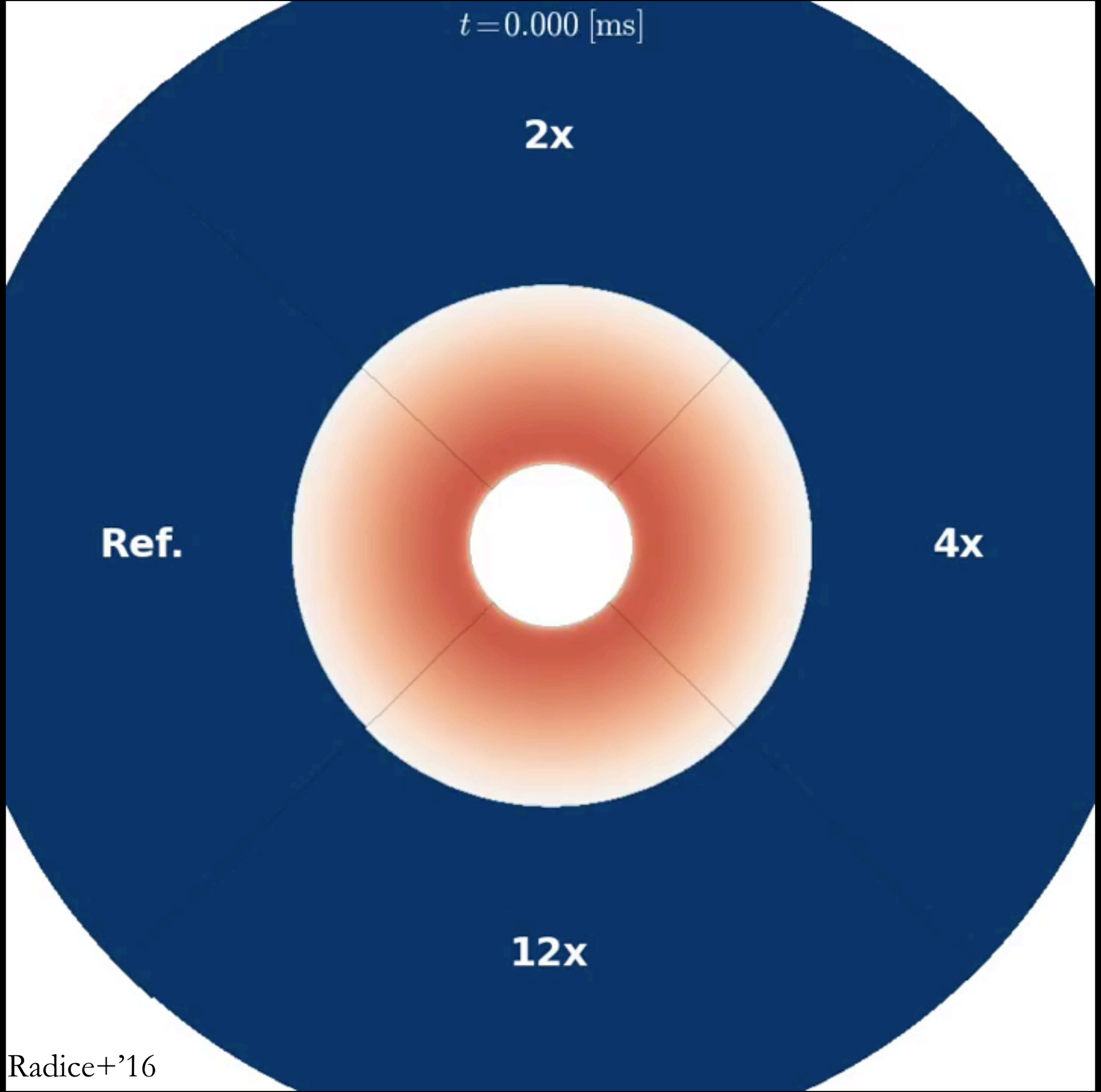


Energy

Wavenumber

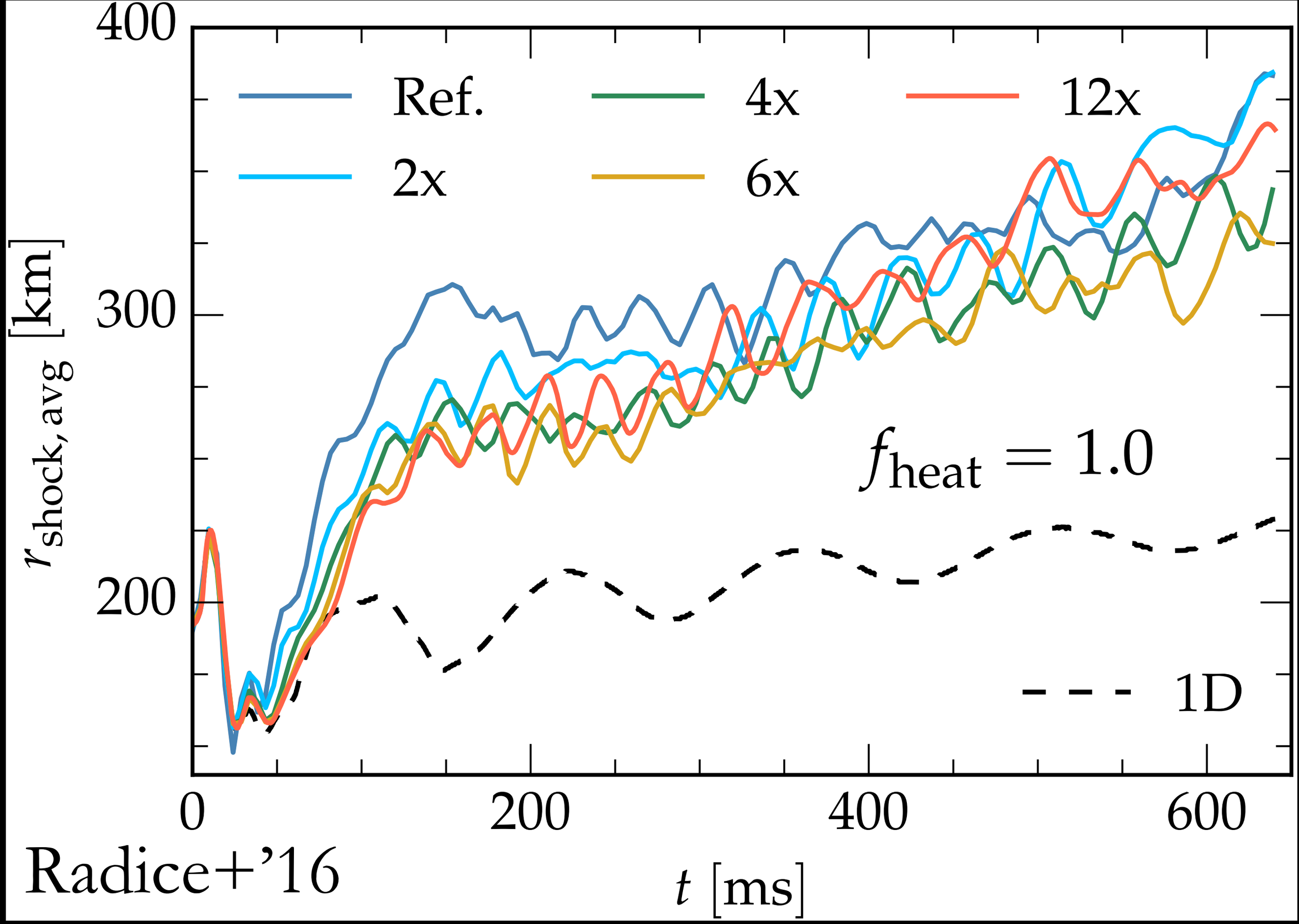



Abdikamalov+'15

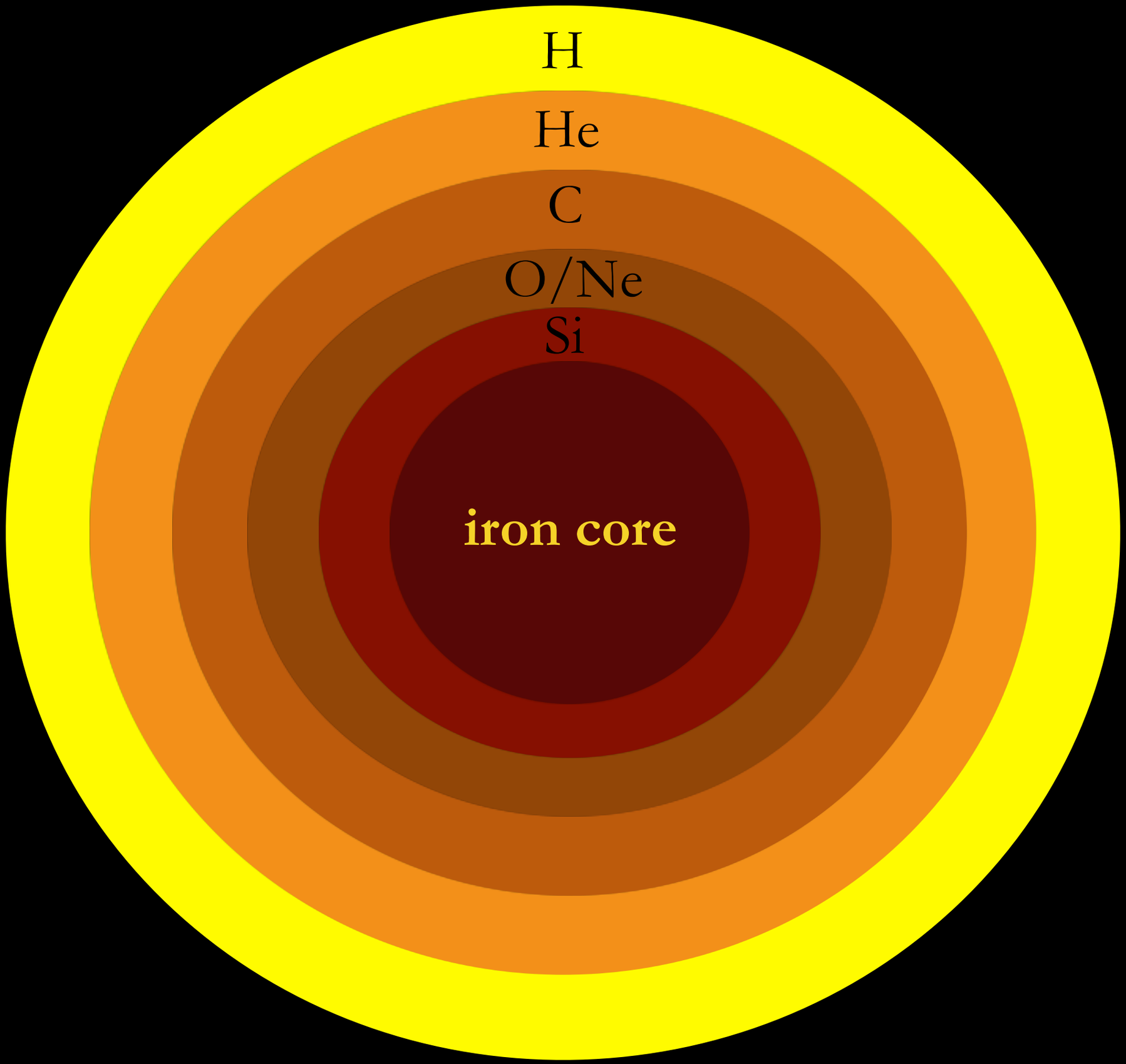



Radice+'16

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

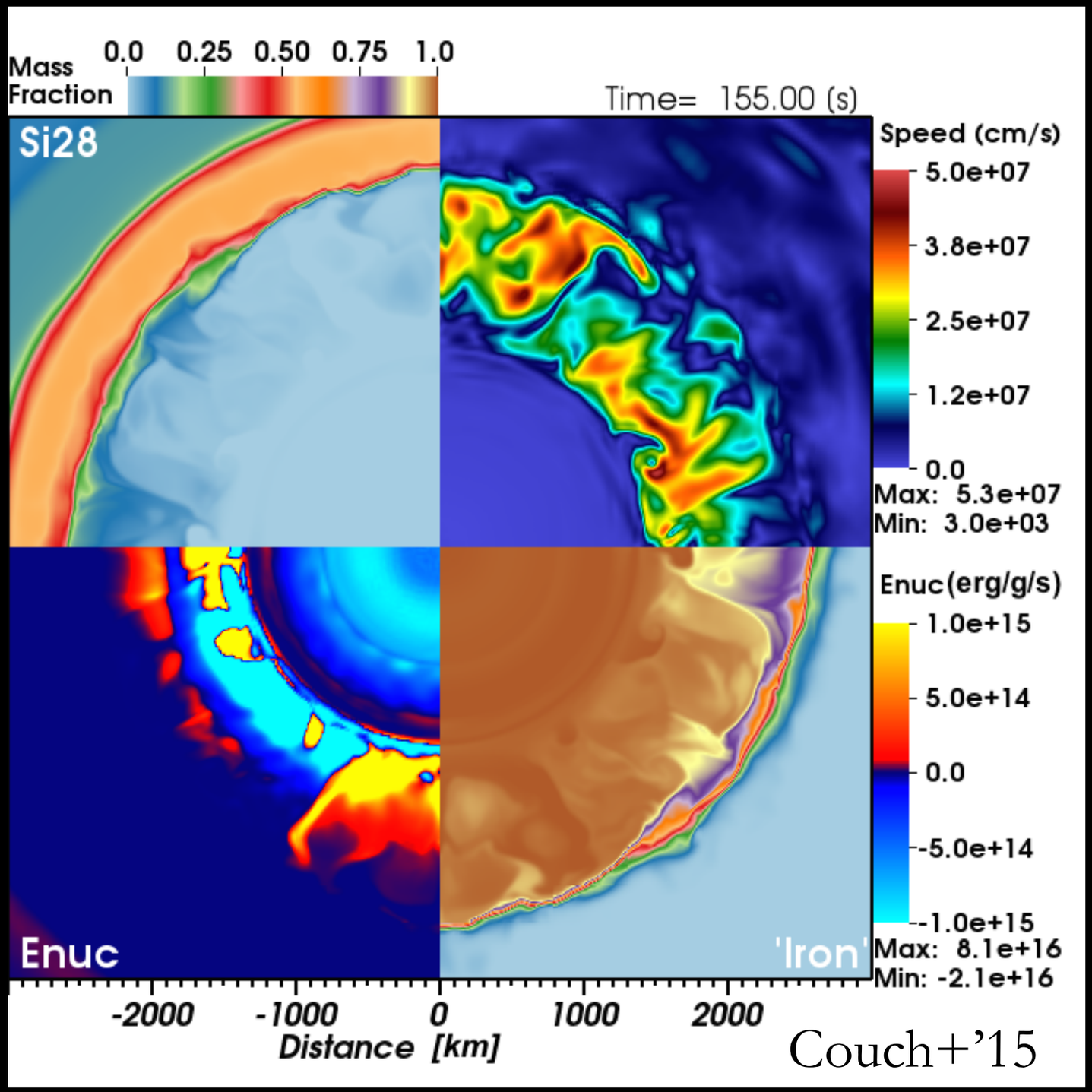



See Radice, Abdikamalov et al (2018) for recent review


H
He
C
O/Ne
Si
iron core

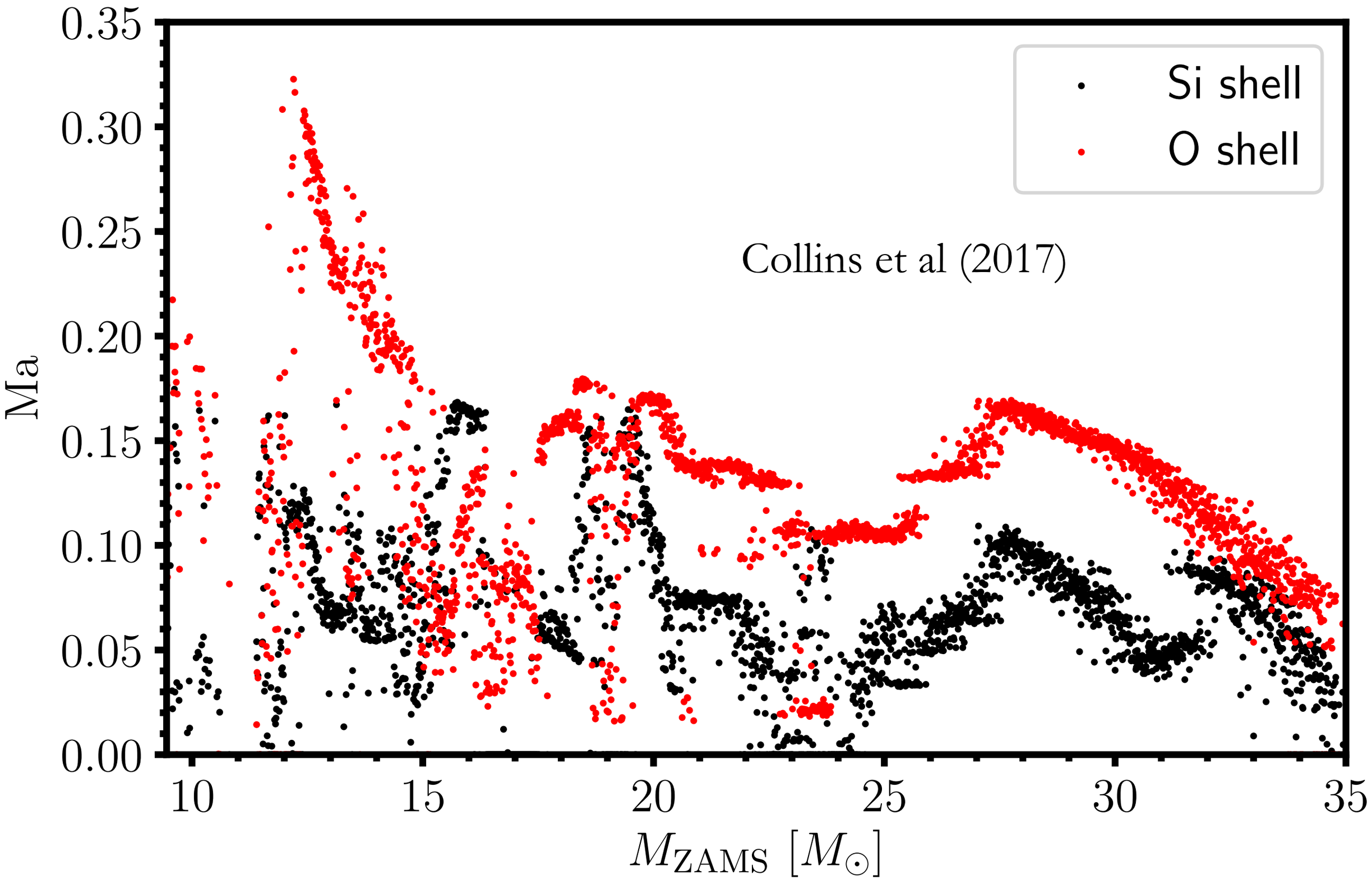
# Progenitor asphericities before core-collapse

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

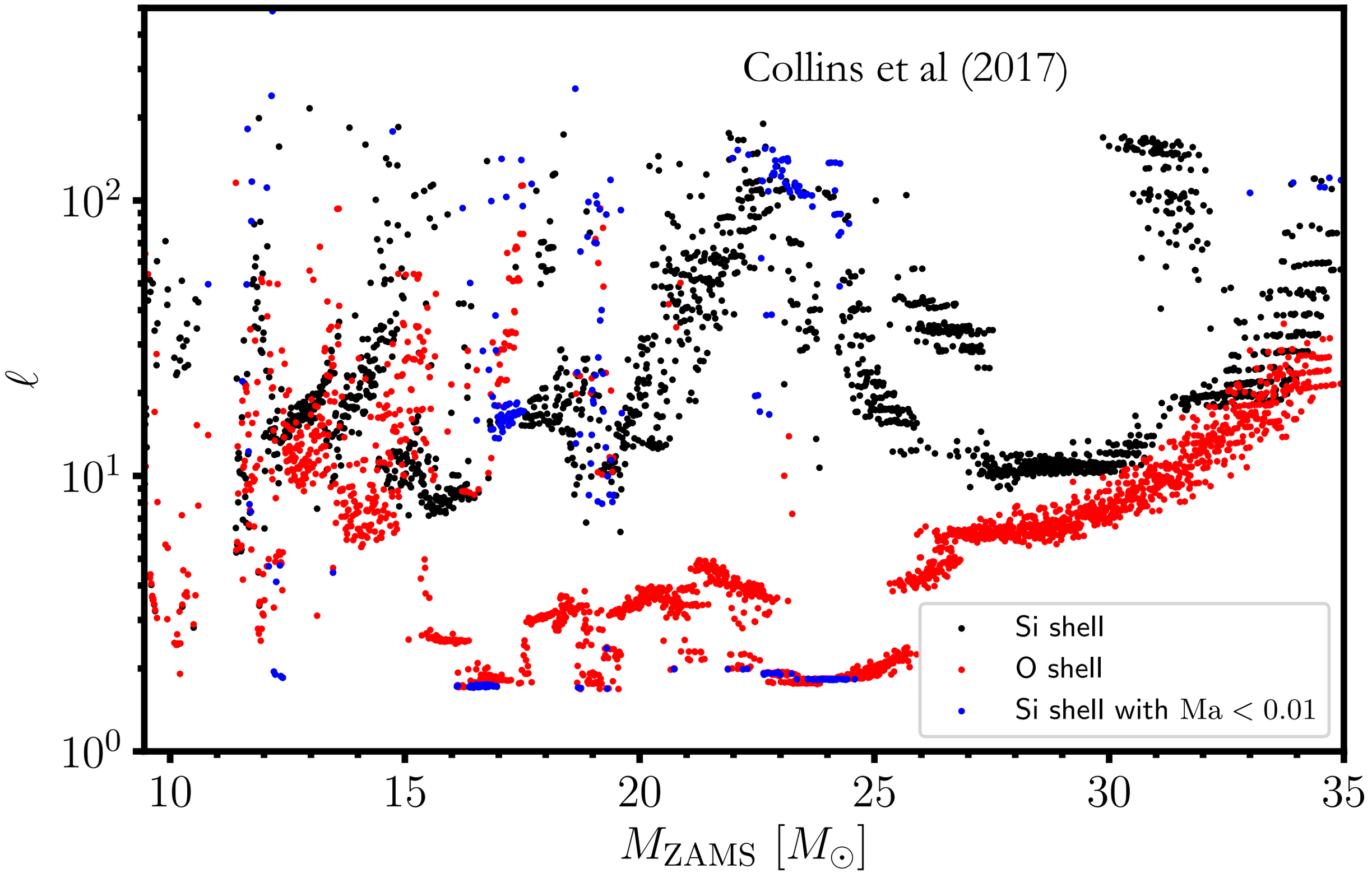


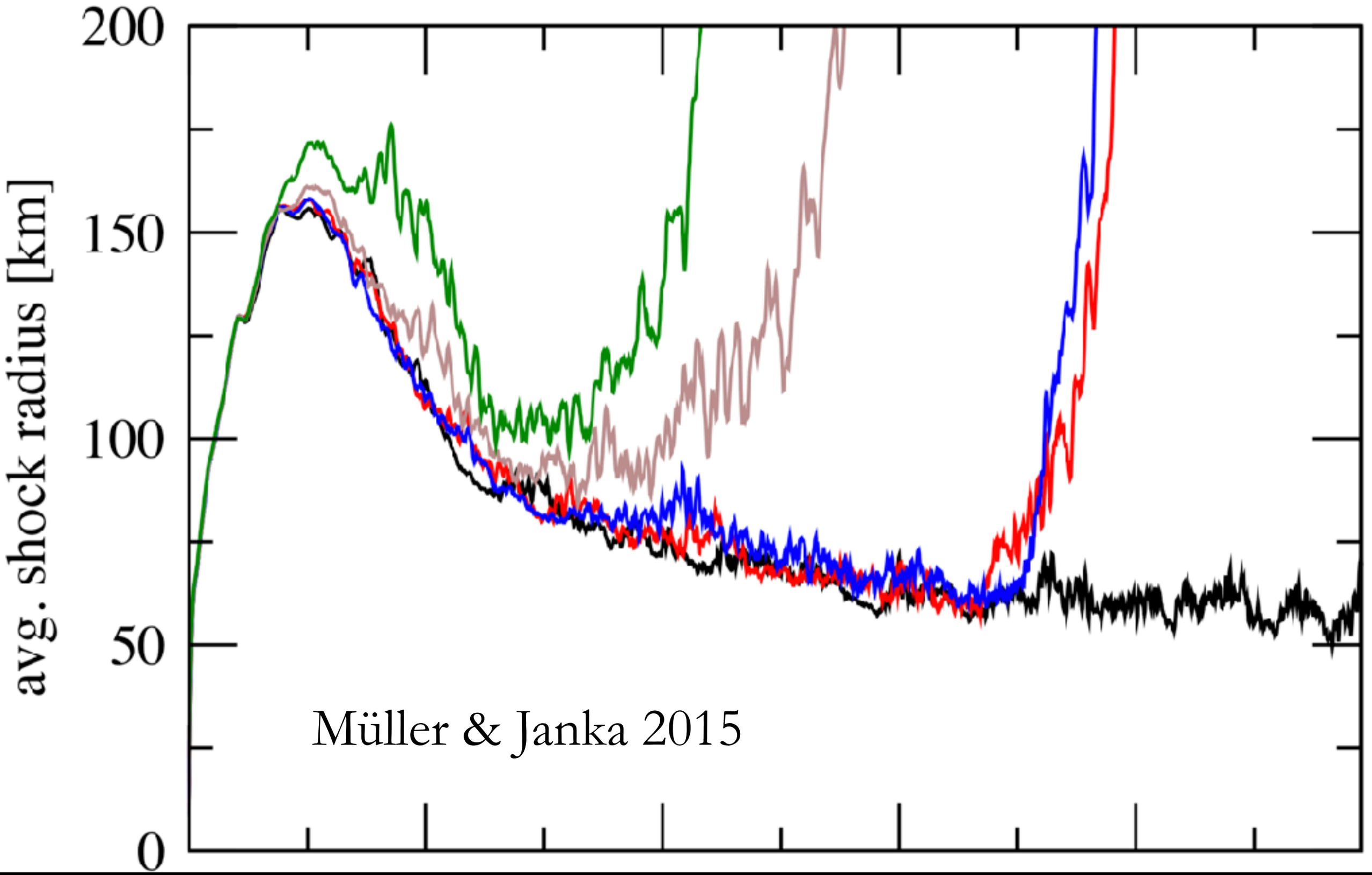

See also: Arnett & Meakin ‘16, Chatzapoulos+’16, Collins+’17, Fernandez ‘15

# Large progenitor aspherisities are common.



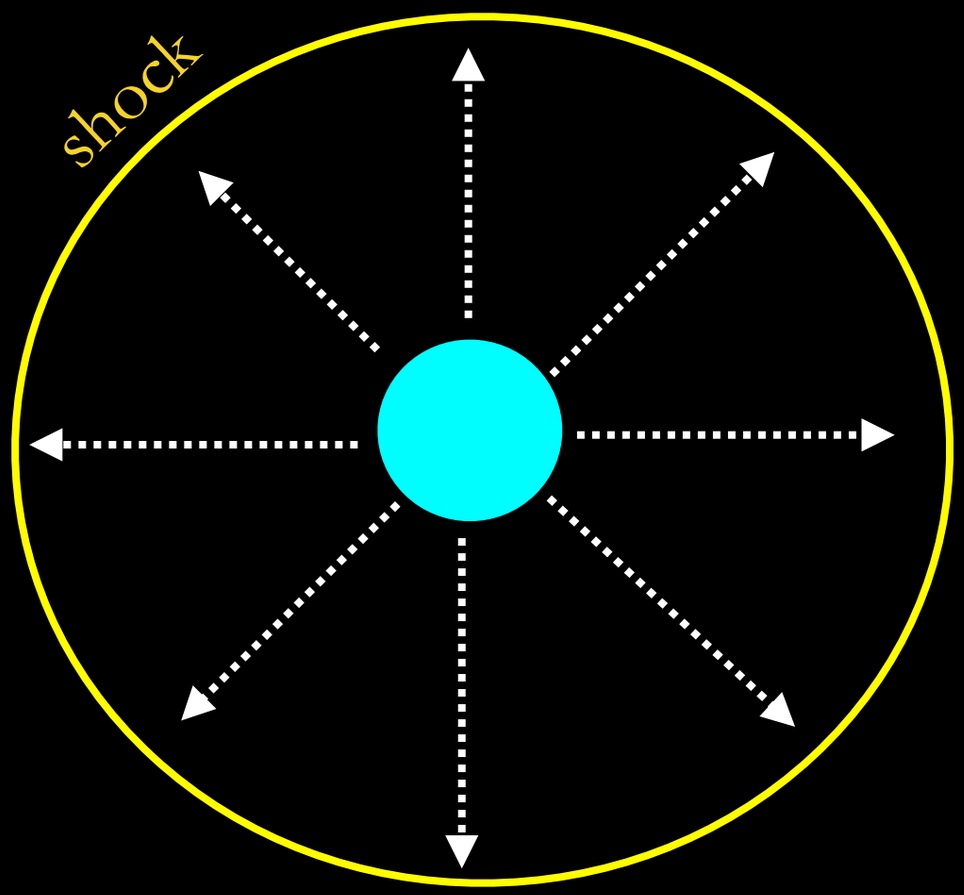
# Large progenitor asphericities are common.




200
150
100
50
0
avg. shock radius [km]
Müller & Janka 2015

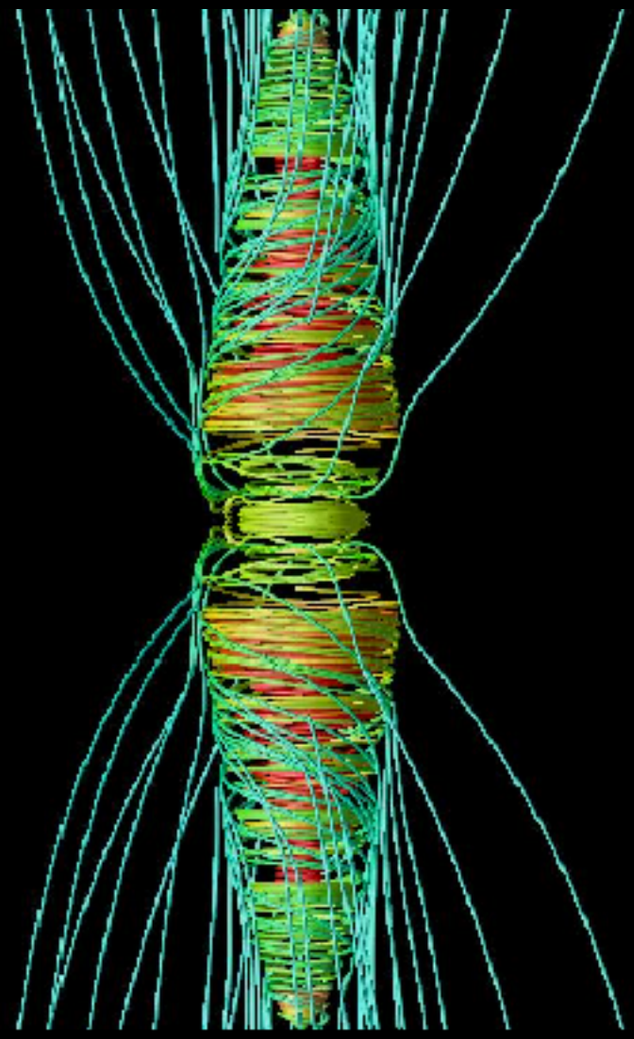
# Explosion mechanisms

## Slow rotation




## Neutrino mechanism

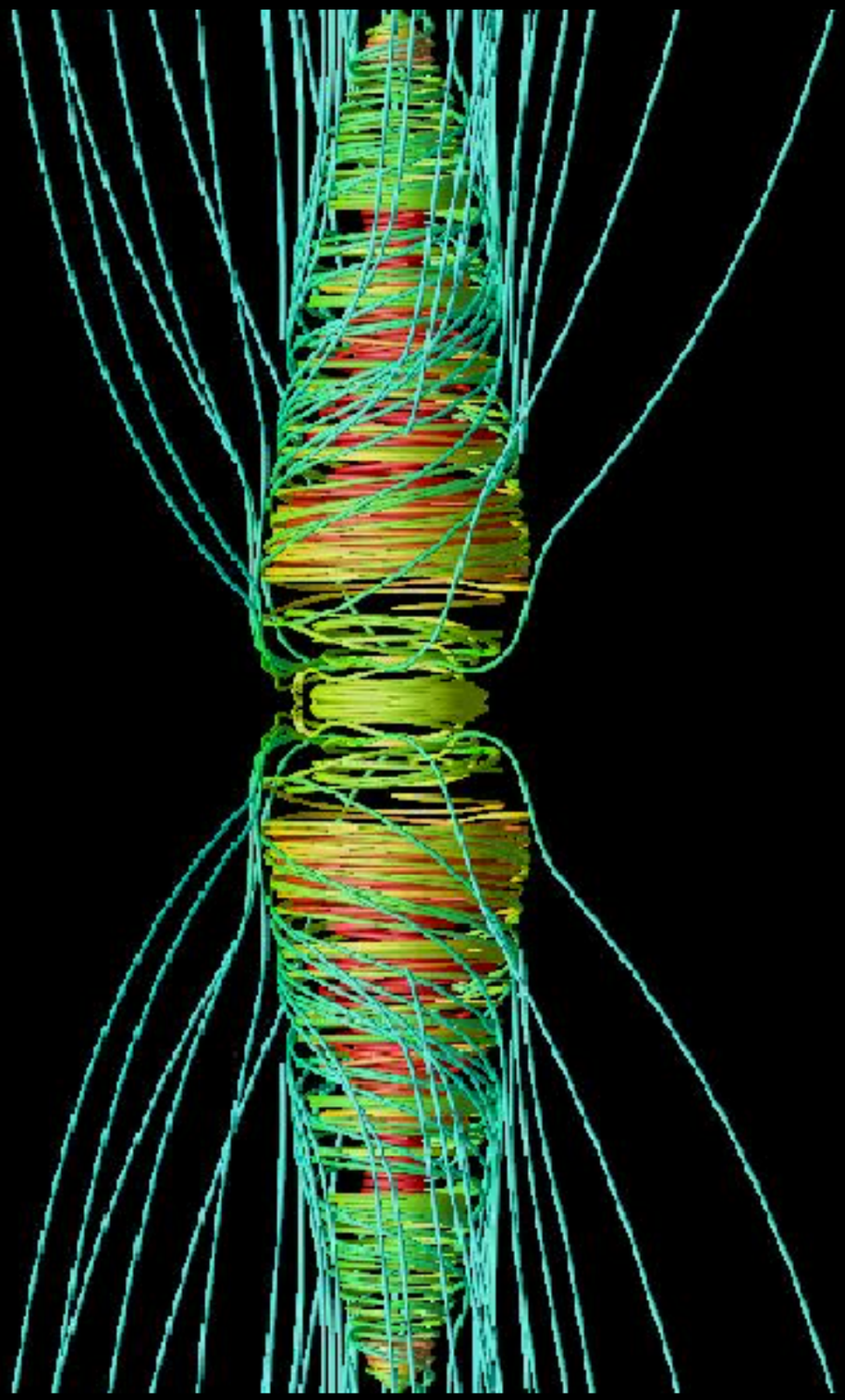
## Rapid rotation



Burrows+07

## Magnetorotational mechanism

# Magnetorotational mechanism



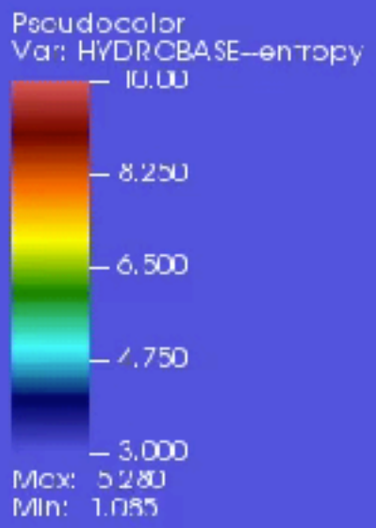
Burrows+07

Explosion energy:

$\sim 10^{52}$ erg

Credit: NASA

Time since bounce:  -4.95 ms




Mösta+'14

t = -3.00 ms

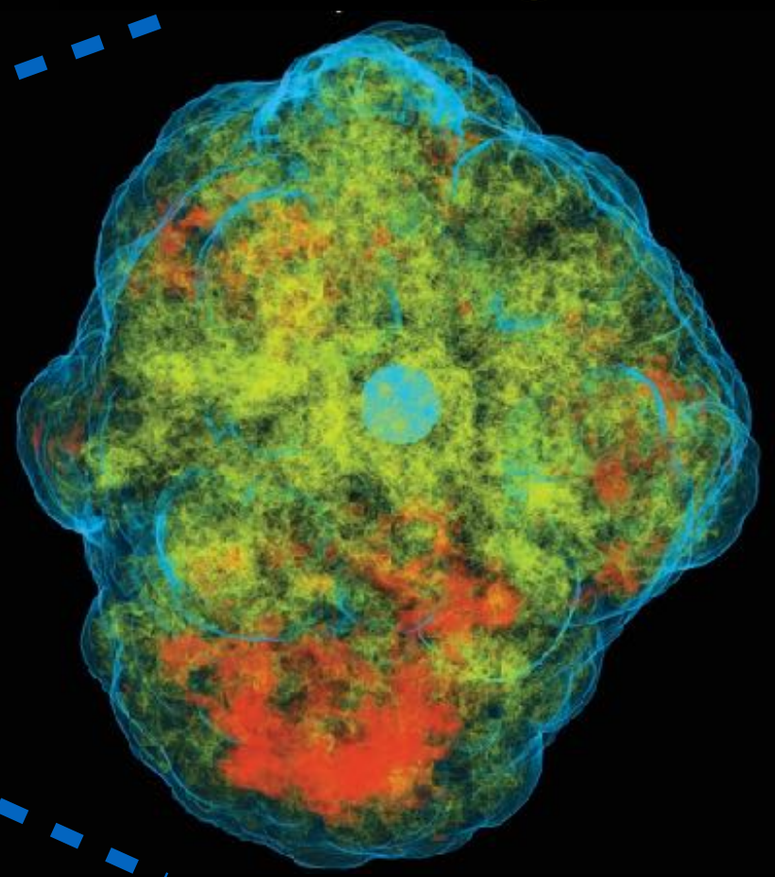
Mösta+’14, ‘15

# Thank you!

# Observing central engine

RSG Betelgeuse
200 pc

Central engine

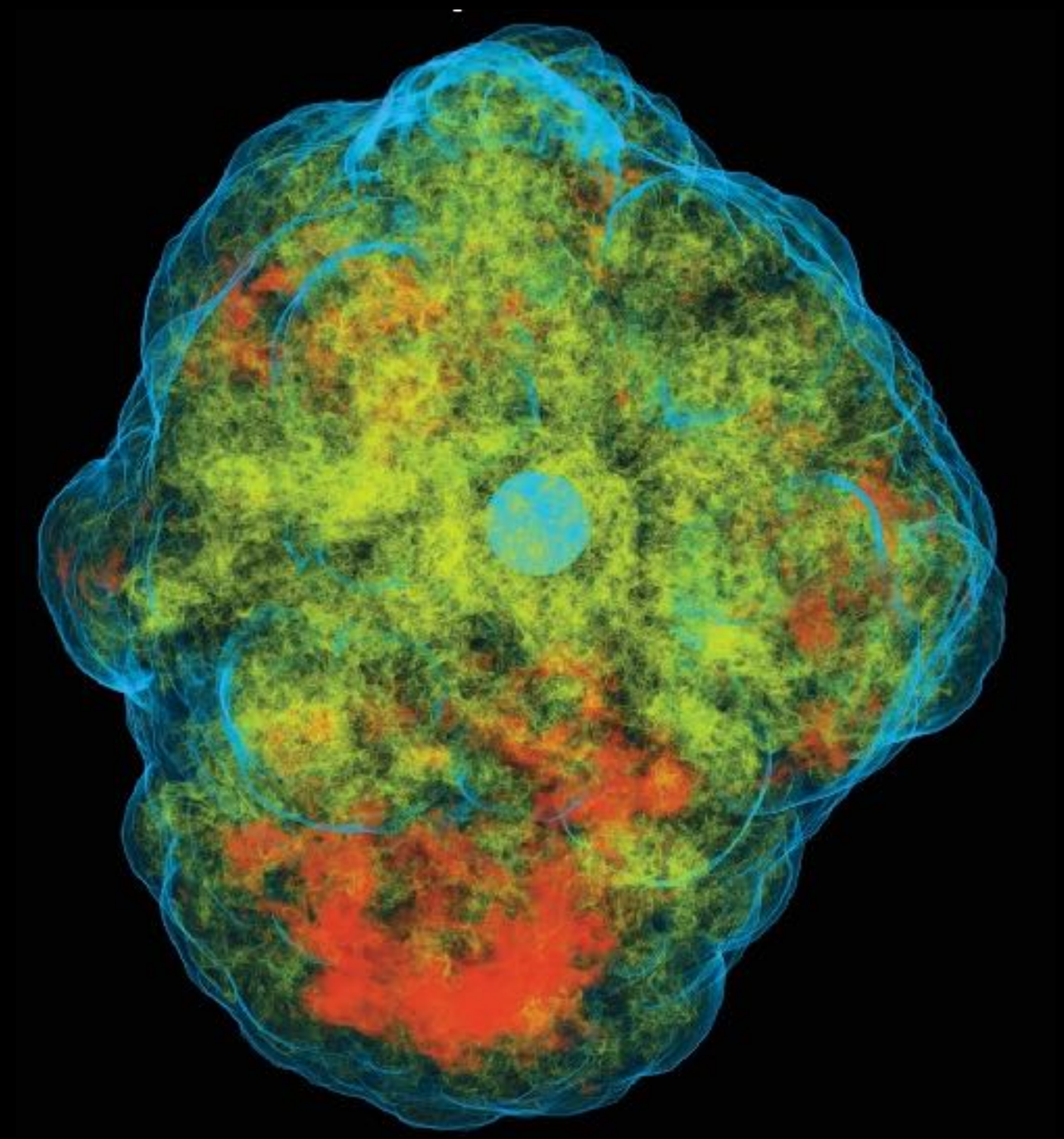


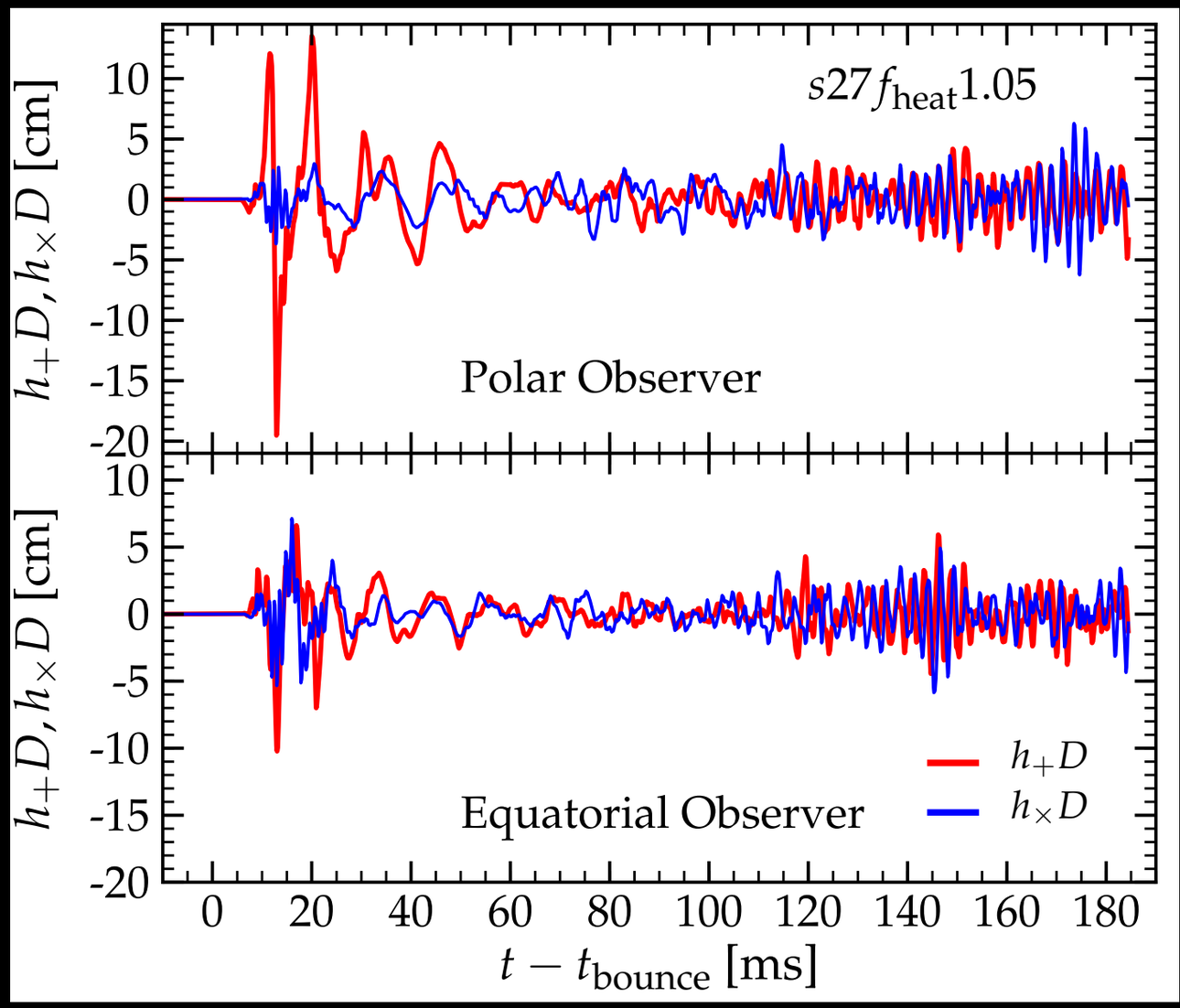
~300 km

~800 million km

HST

# Gravitational Waves - Slow Rotation






Ott, Abdikamalov+‘13


-1.57 ms

# What can we learn from gravitational waves