# Section 7.
# Mechanism of core-collapse supernovae

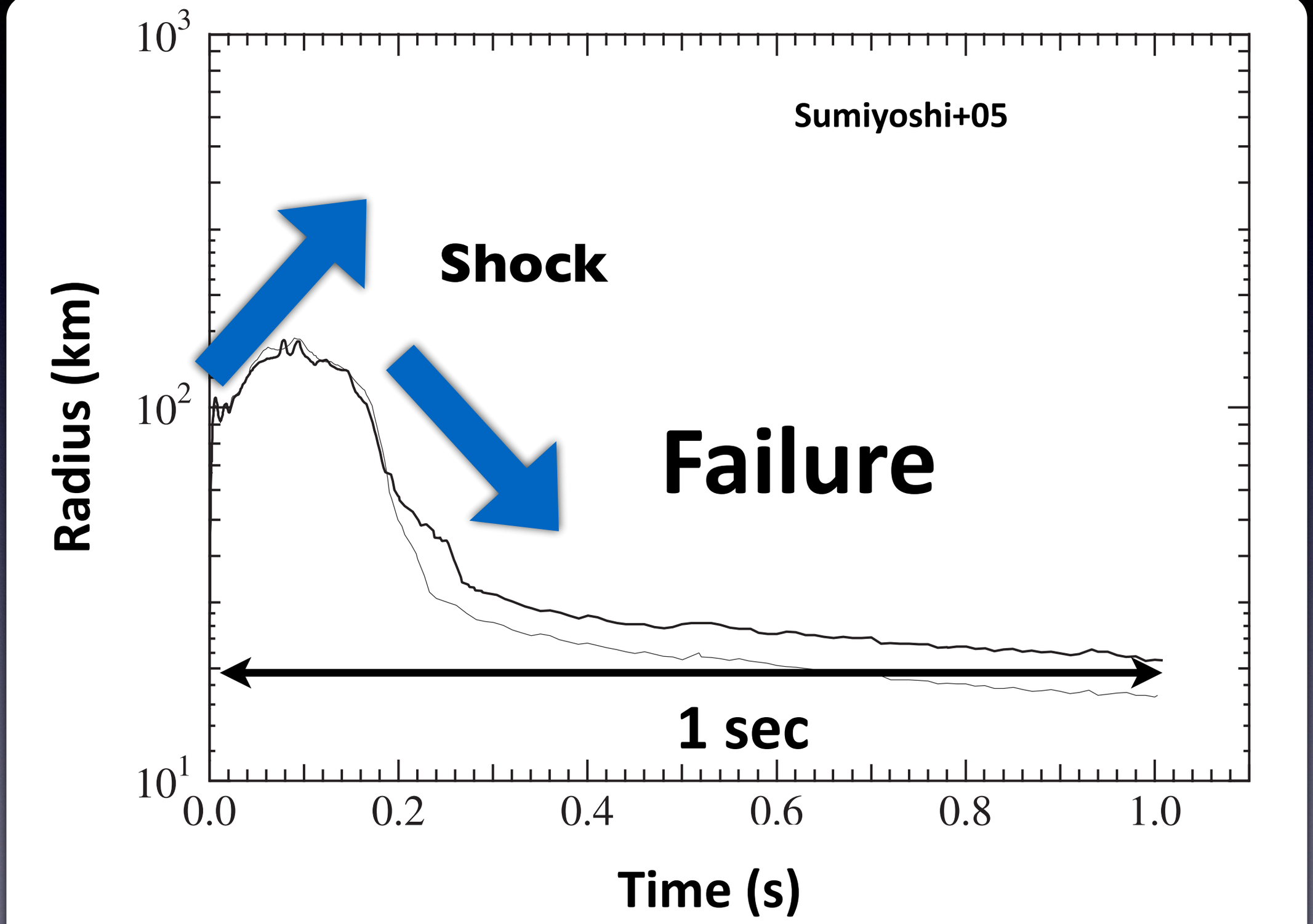
## 7.1 Energetics

## 7.2 Mechanism of core-collapse supernovae

**Let's understand these questions with the words of physics**

- Why are stars so luminous?
- Why do stars show $L \sim M^4$?
- Why do stars evolve?
- Why does the destiny of stars depend on the mass?
- Why do some stars explode?
- Why don't normal star explode?
- Why does stellar core collapses?
- Why is the energy of supernova so huge?
- …

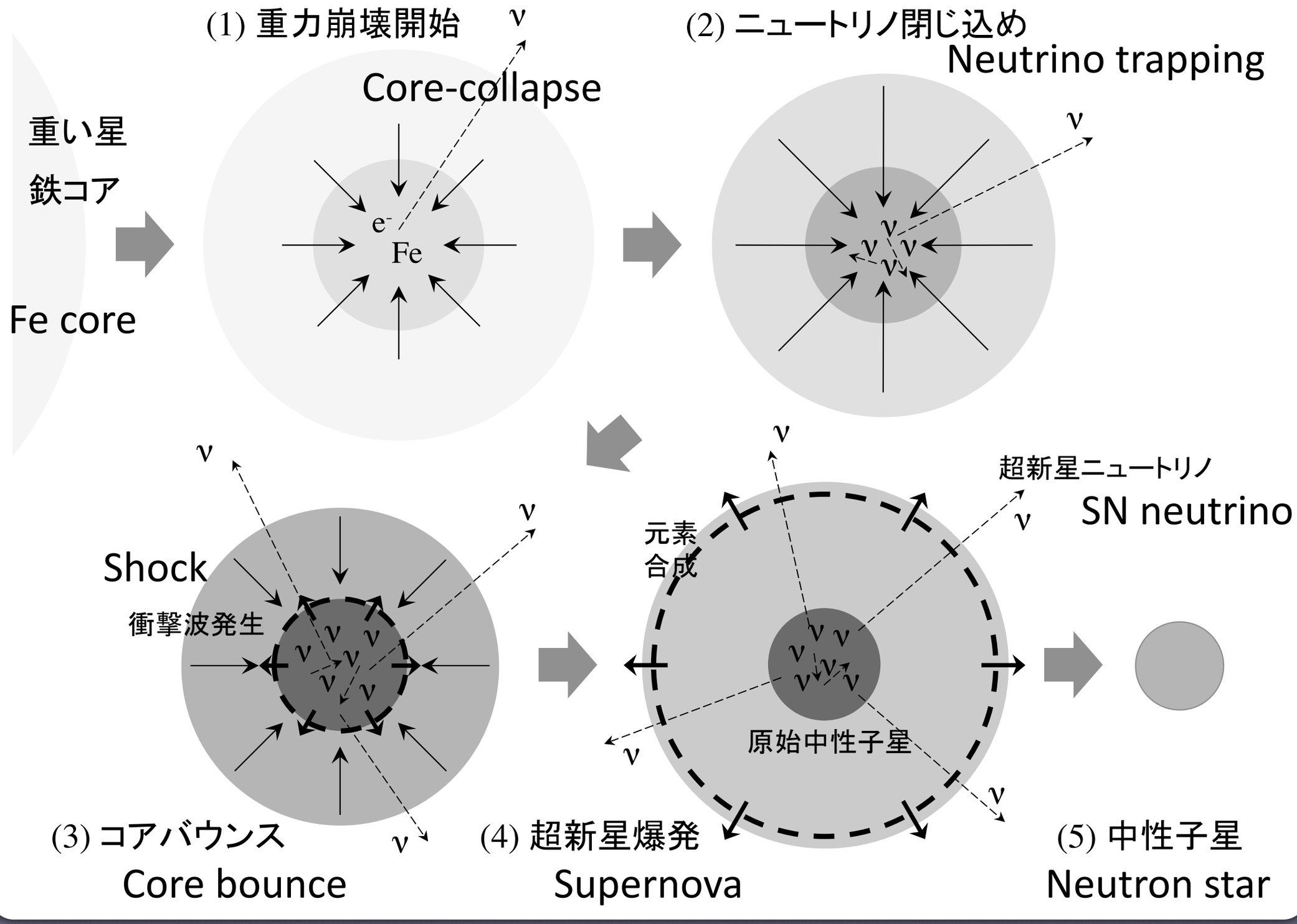
# Results of simulations (1D)





**Why do stars finally explode?**

**Why is it difficult to reproduce explosions?**

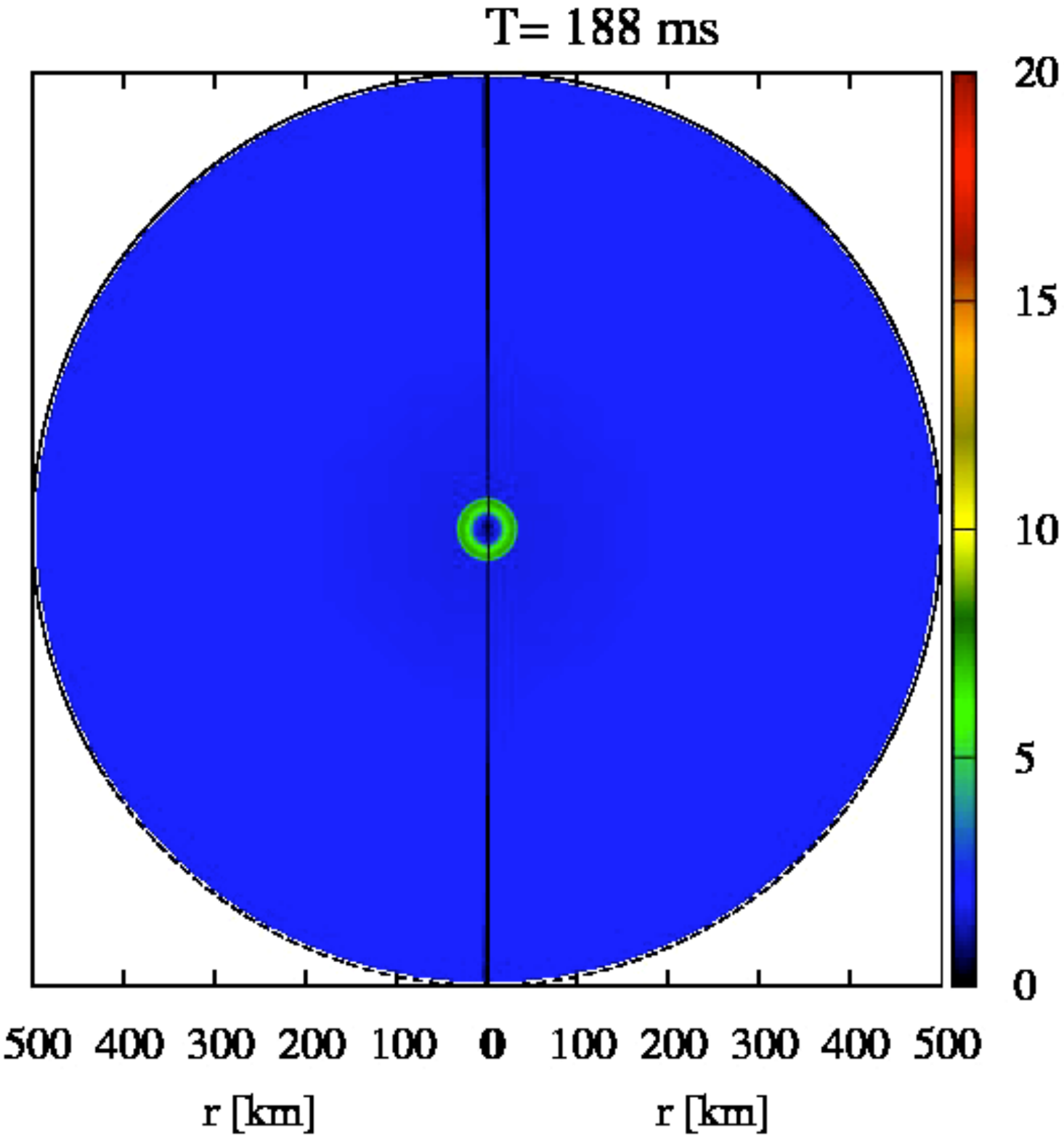


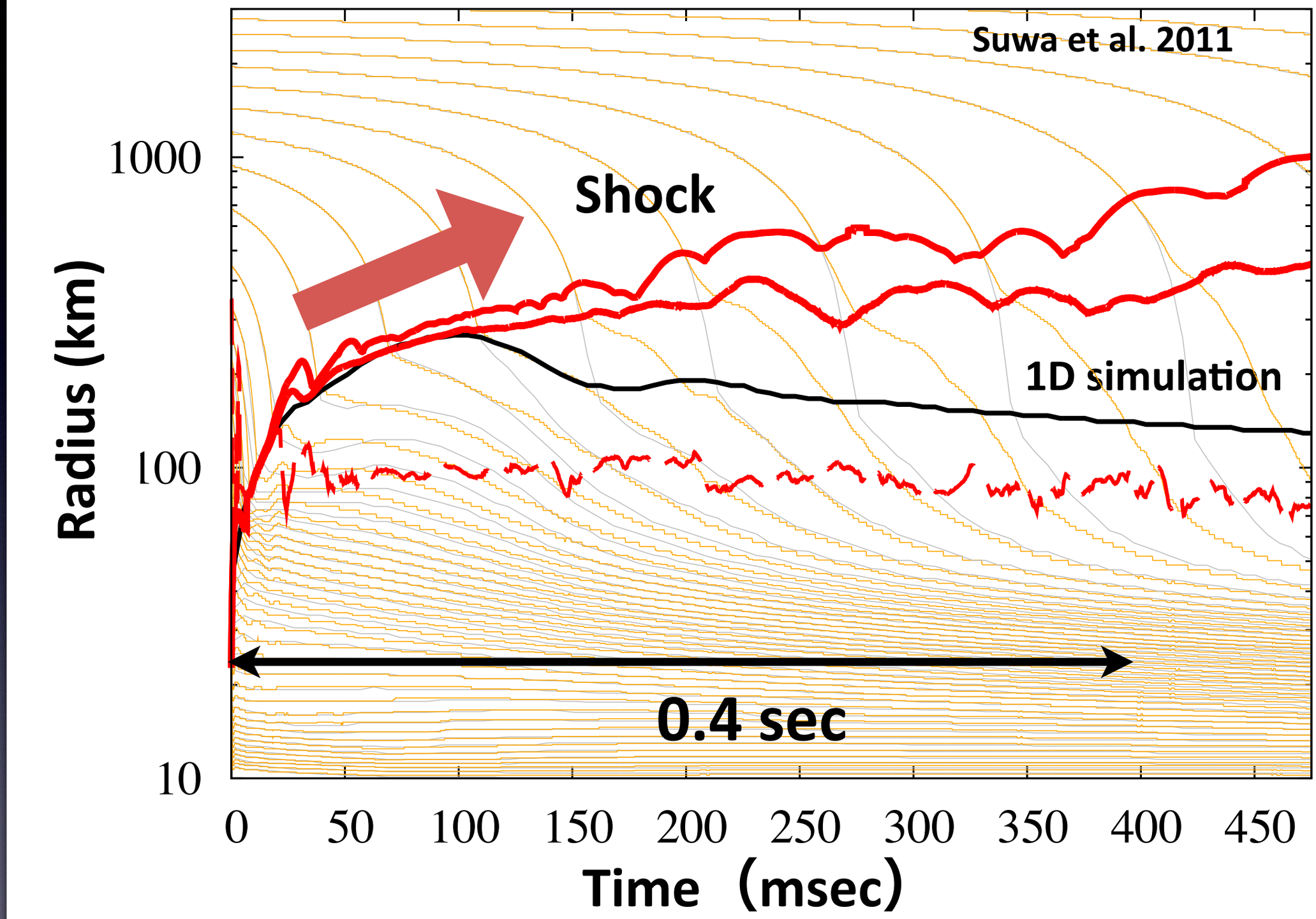

(C) 原子核から読み解く超新星爆発の世界

住吉光介さん著 (Kosuke Sumiyoshi)


S20.0 ENTROPY
LEA VELOCITY
Time = -168.0 ms
Radius = 500.00 km
(C) A. Burrows

Suwa et al. 2011





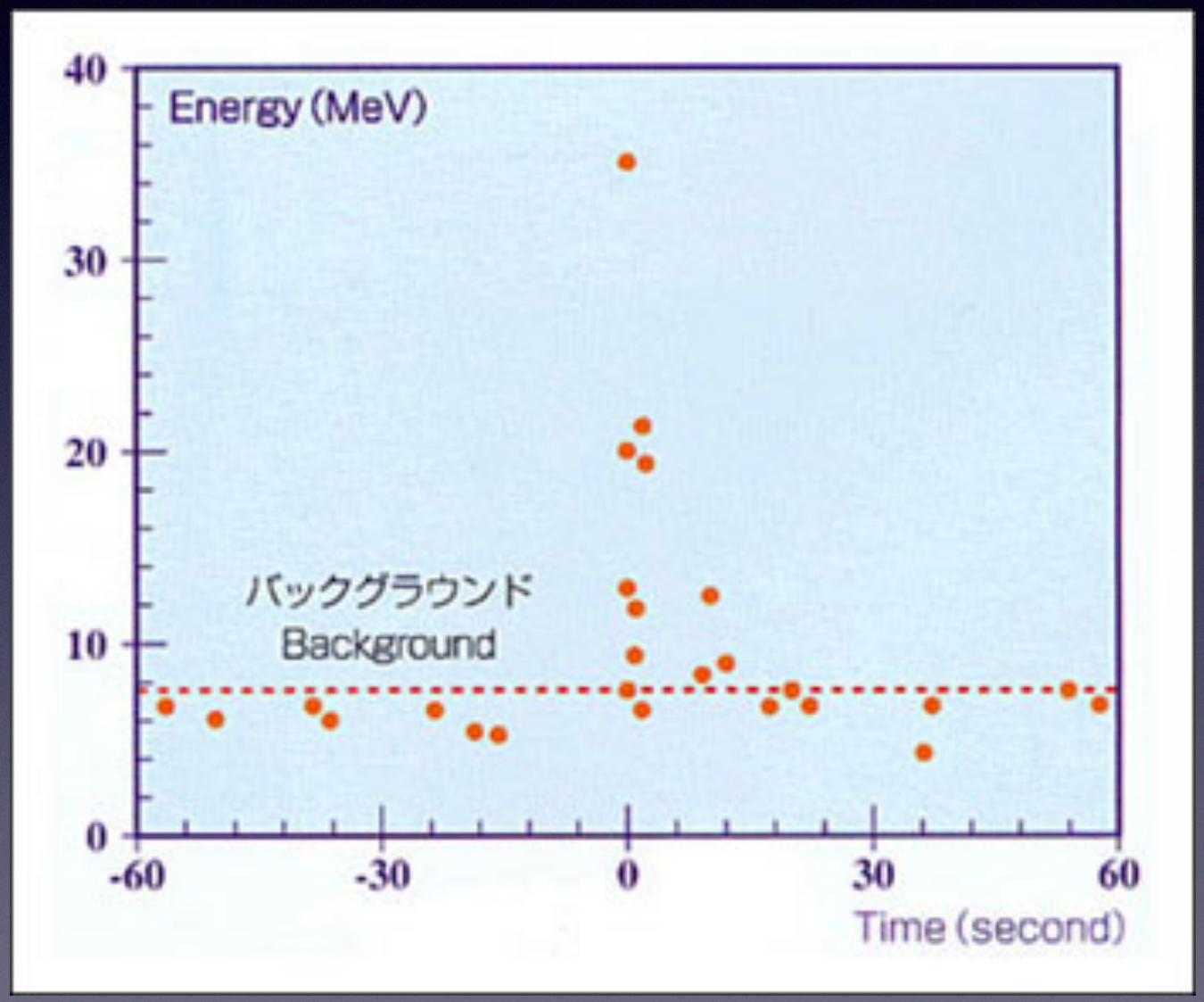

E ~ $10^{50}$ erg (smaller than observations by 1 order of magnitude)

**One of the biggest mystery in modern astrophysics**

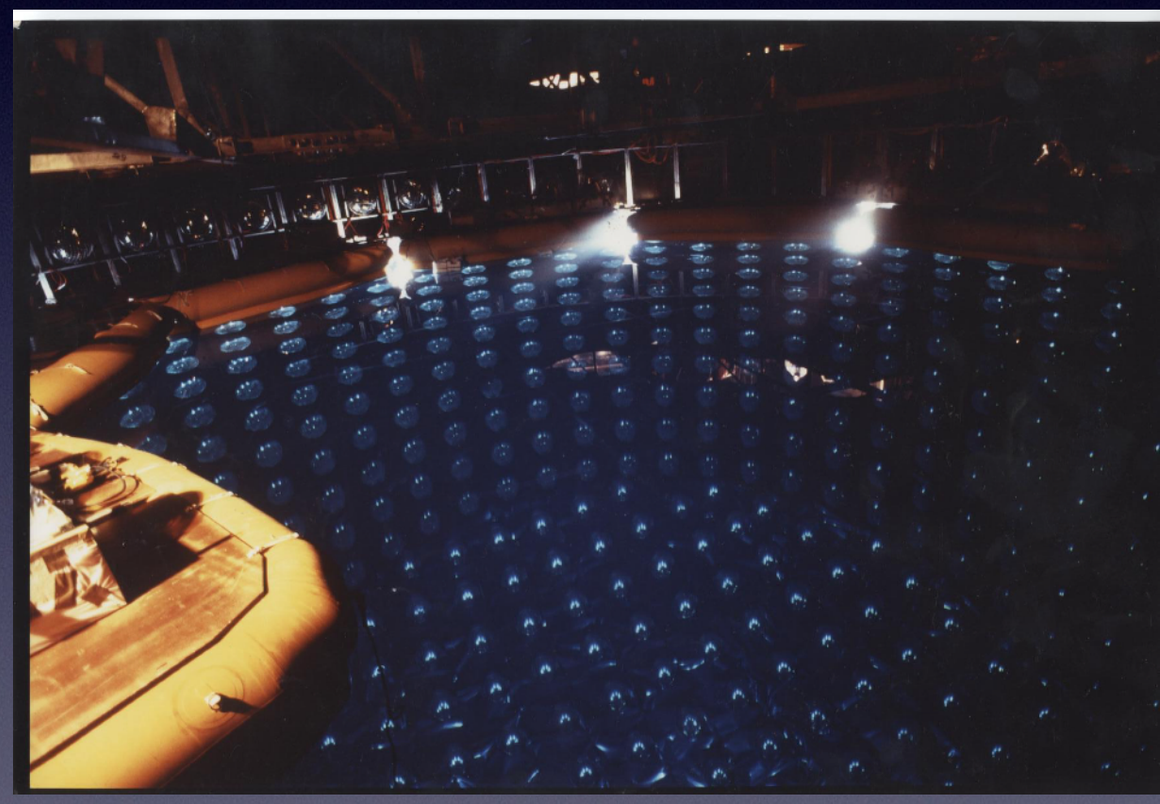
# SN 1987A (in Large Magellanic cloud, 50 kpc)



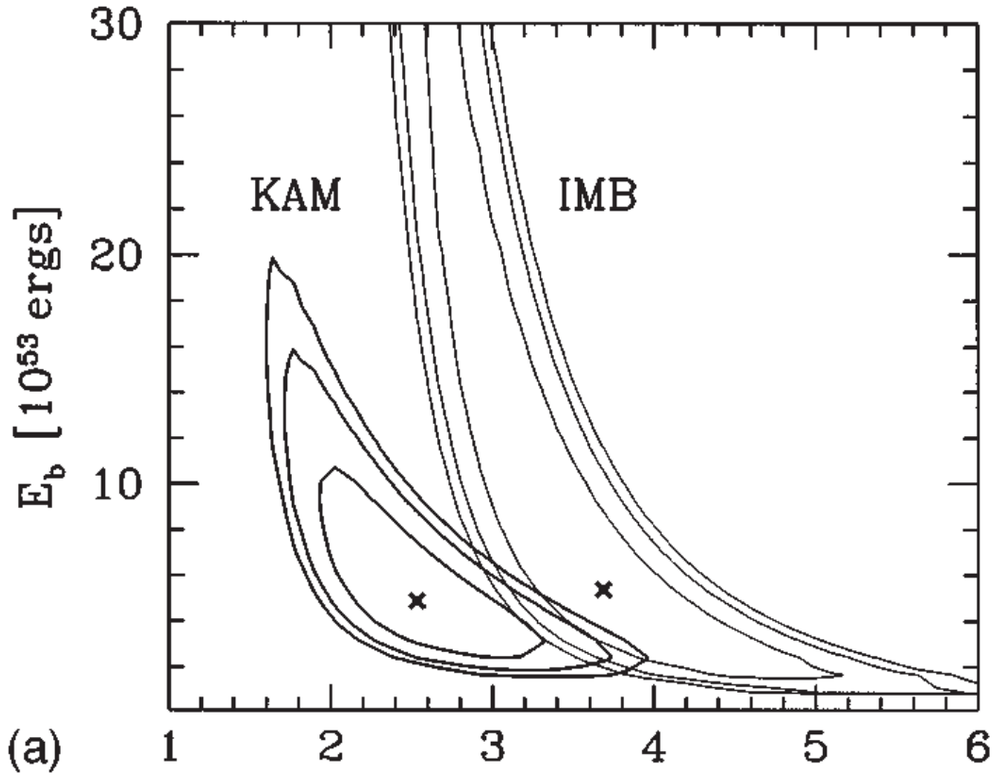
# Neutrino detection From SN 1987A




## Kamiokande



(C) ICRR




Jegerlehner et al. 1996

**$E_{nu}$ ~ $10^{53}$ erg!!**
**=> Foundation of neutrino-driven mechanism**

*** Observed energy**
**(anti electron neutrino) x 6**

# Assignment 4

**Kamiokande detected 11 neutrino events from SN 1987A.**
**By this fact, estimate total neutrino energy**
**that SN 1987A released**

**- You can assume the same numbers for all the flavors (6 flavors).**
**- protons in water are main reactor (Cross section σ ~ $10^{-41}$ $cm^2$ )**
**- Effective volume of Kamiokande 2 kton**
**- Distance to the LMC is 50 kpc**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

# レポート課題 4

カミオカンデで11イベントのニュートリノが観測された。
このことから、SN 1987Aがニュートリノとして放出した
総エネルギーを概算せよ

* すべてのフレーバーのニュートリノが同数放出されたと仮定して良い
* 主な反応は水分子中の陽子 (反応断面積$\sigma \sim 10^{-41}$ cm$^2$ )
* カミオカンデの有効体積 2 kton
* 大マゼラン雲までの距離 50 kpc

$$\bar{\nu_e} + p \rightarrow e^+ + n$$

# Timescales of core-collapse supernovae

**Core-collapse** **Bounce** **Shock revival** **Breakout**

**~0.1 sec** **~0.1-1 sec** **~1 day (~$10^5$ sec)**

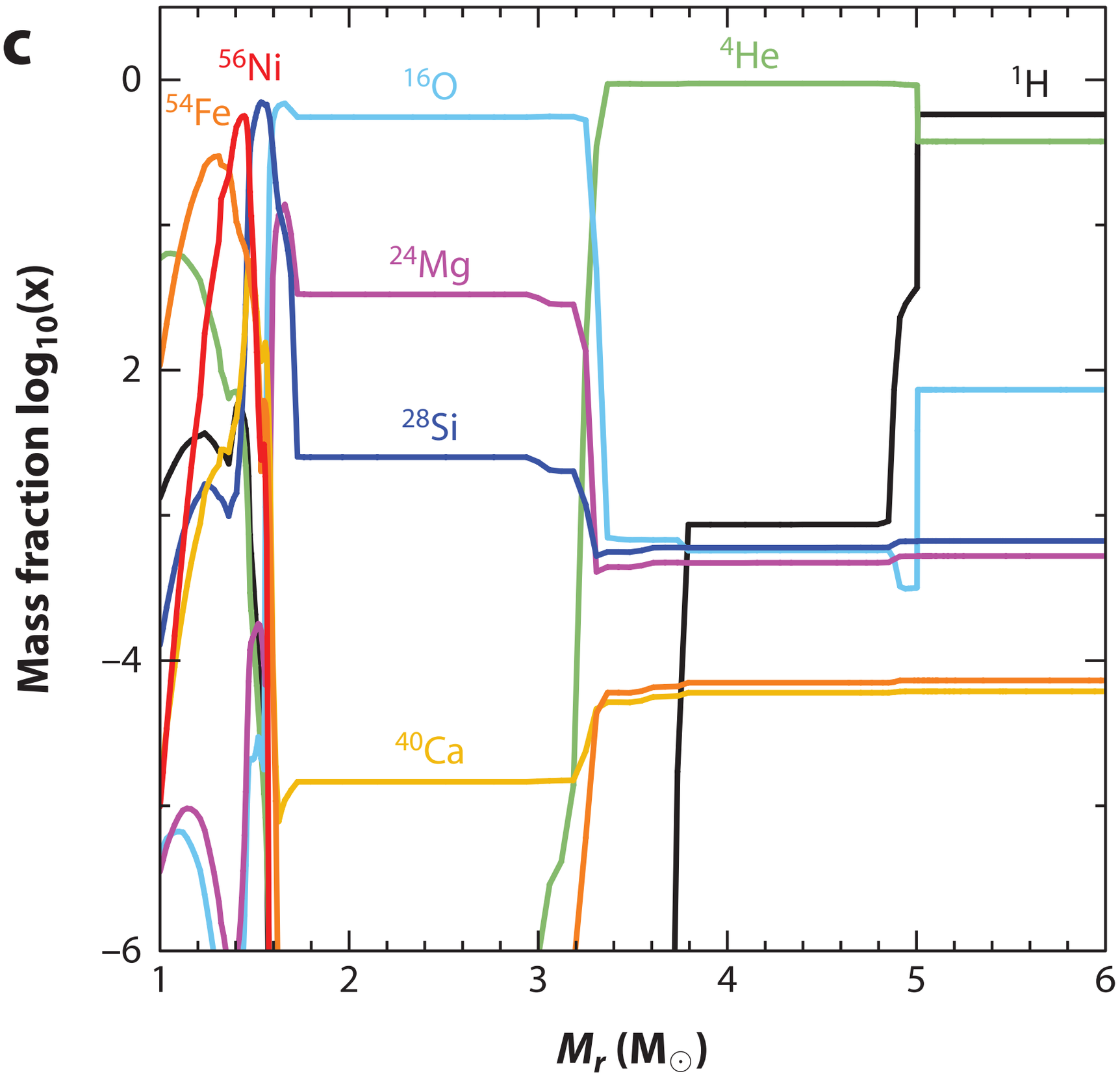


**Shock breakout**
**t(breakout) = R(RSG)/v(SN)**
**~ $10^{14}/10^9$ ~ $10^5$ sec**
**~ 1 day**

**R(RSG) ~ 1000 Rsun**
**~ $10^{14}$ cm**

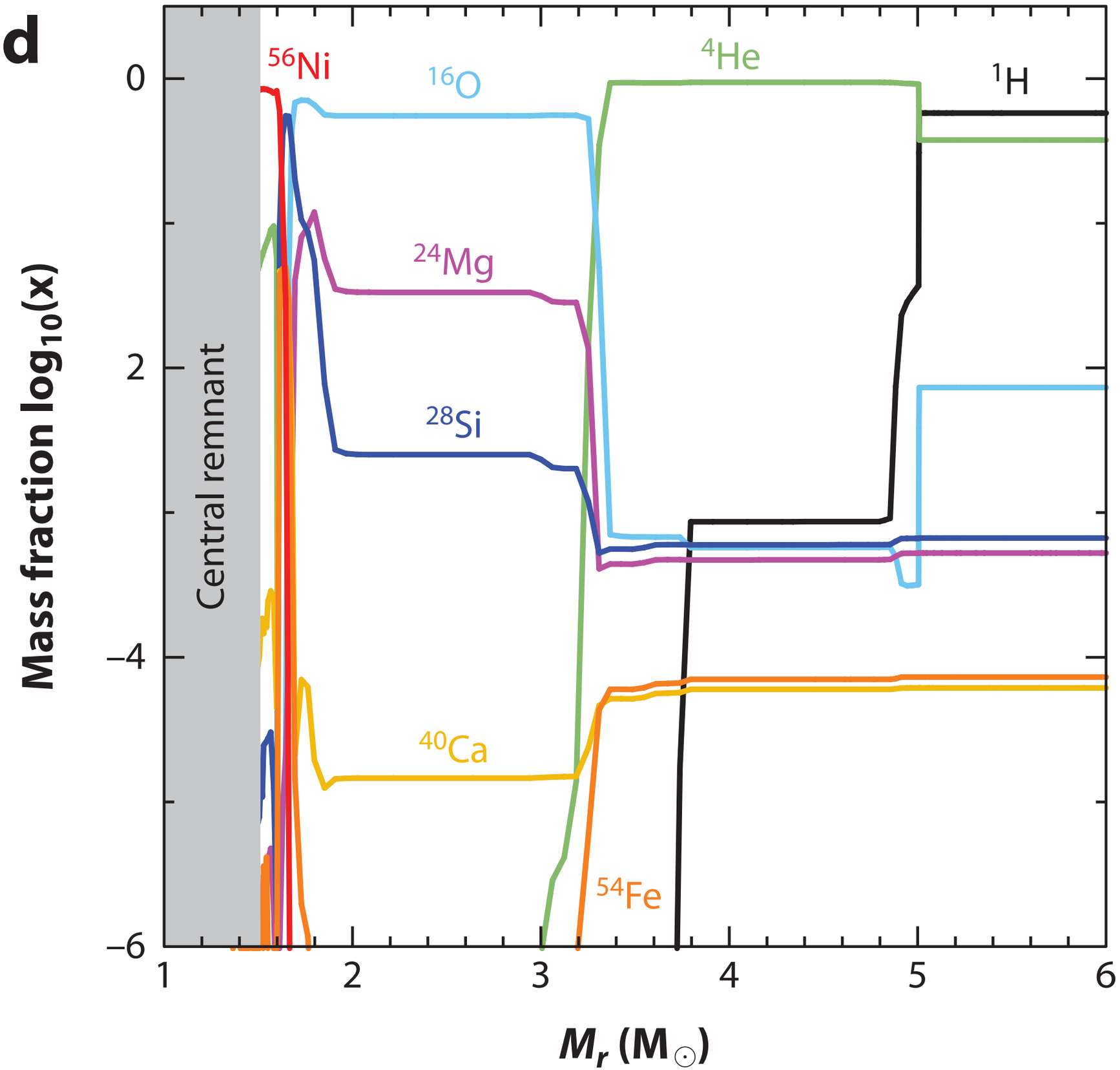
**v(SN) ~ 10,000 km/s**
**($10^9$ cm/s)**

Before




Nomoto+13

After




Nomoto+13

# Summary: Core-collapse supernovae

- **Energetics**
  - Gravitational energy Eg ~ $10^{53}$ erg
  - Kinetic energy Ek ~ $10^{51}$ erg
- **Explosion mechanism**
  - Core-collapse => Bounce => Shock stalled => neutrino heating
  - Neutrino detection from SN 1987A
  - Detailed mechanism is not yet understood

Thermodynamics

Electromagnetism

Classical mechanics

Statistical mechanics

**Astrophysics**

Hydrodynamics

Quantum mechanics

Relativity

Nuclear physics