Overview of core-collapse supernova simulations

Christian Y. Cardall

Oak Ridge National Laboratory

Physics Division

University of Tennessee, Knoxville

Department of Physics and Astronomy

What is a core-collapse supernova?

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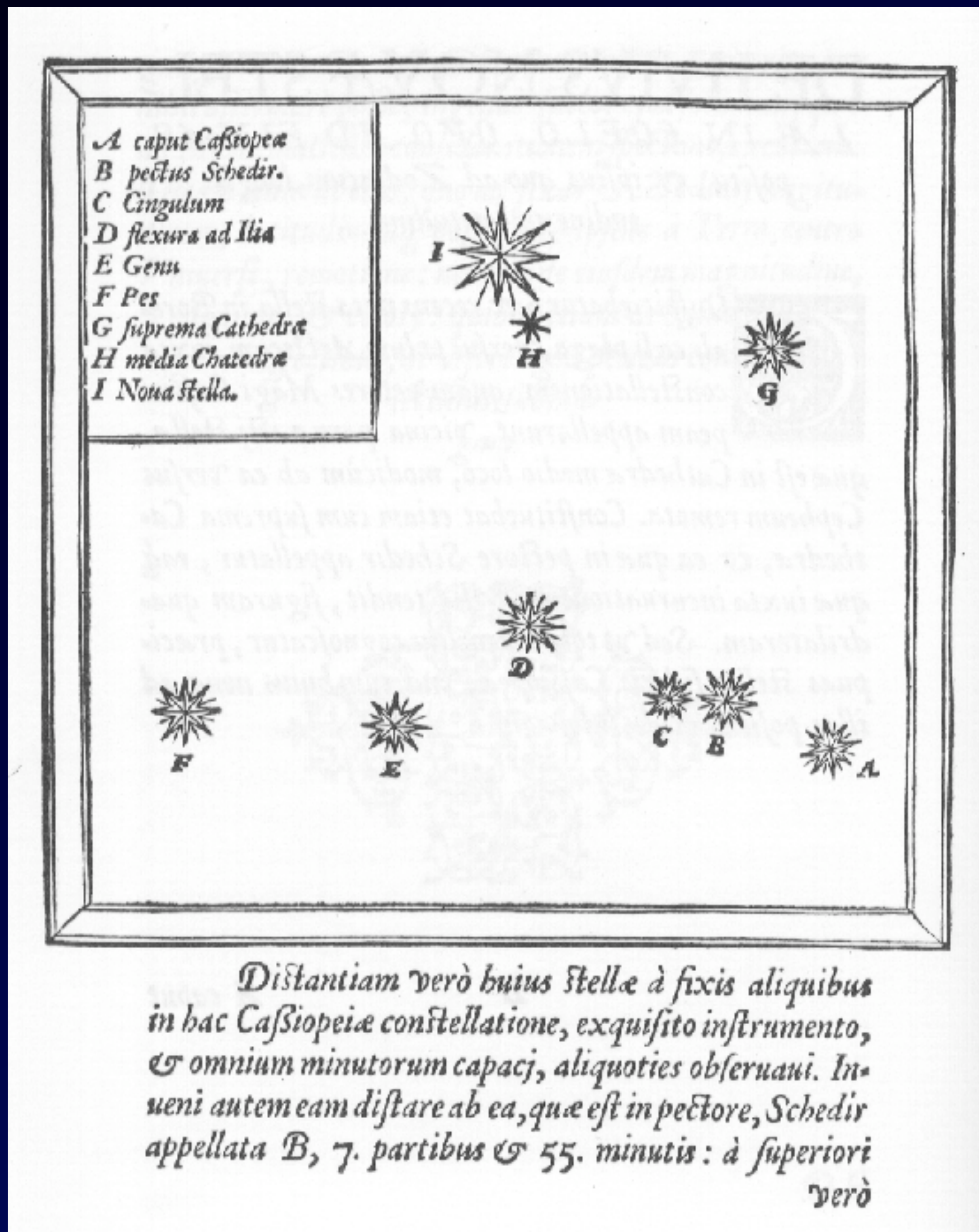

Distantiam verò huius stellæ à fixis aliquibus in hac Caßiopeiæ constellatione, exquisito instrumento, & omnium minutorum capacj, aliquoties obseruaui. Inueni autem eam distare ab ea, quæ est in pectore, Schedir appellata B, 7. partibus & 55. minutis: à superiori verò

Tycho Brahe, *De Nova et Aevi Memoria Prius Visa Stella* (1573)

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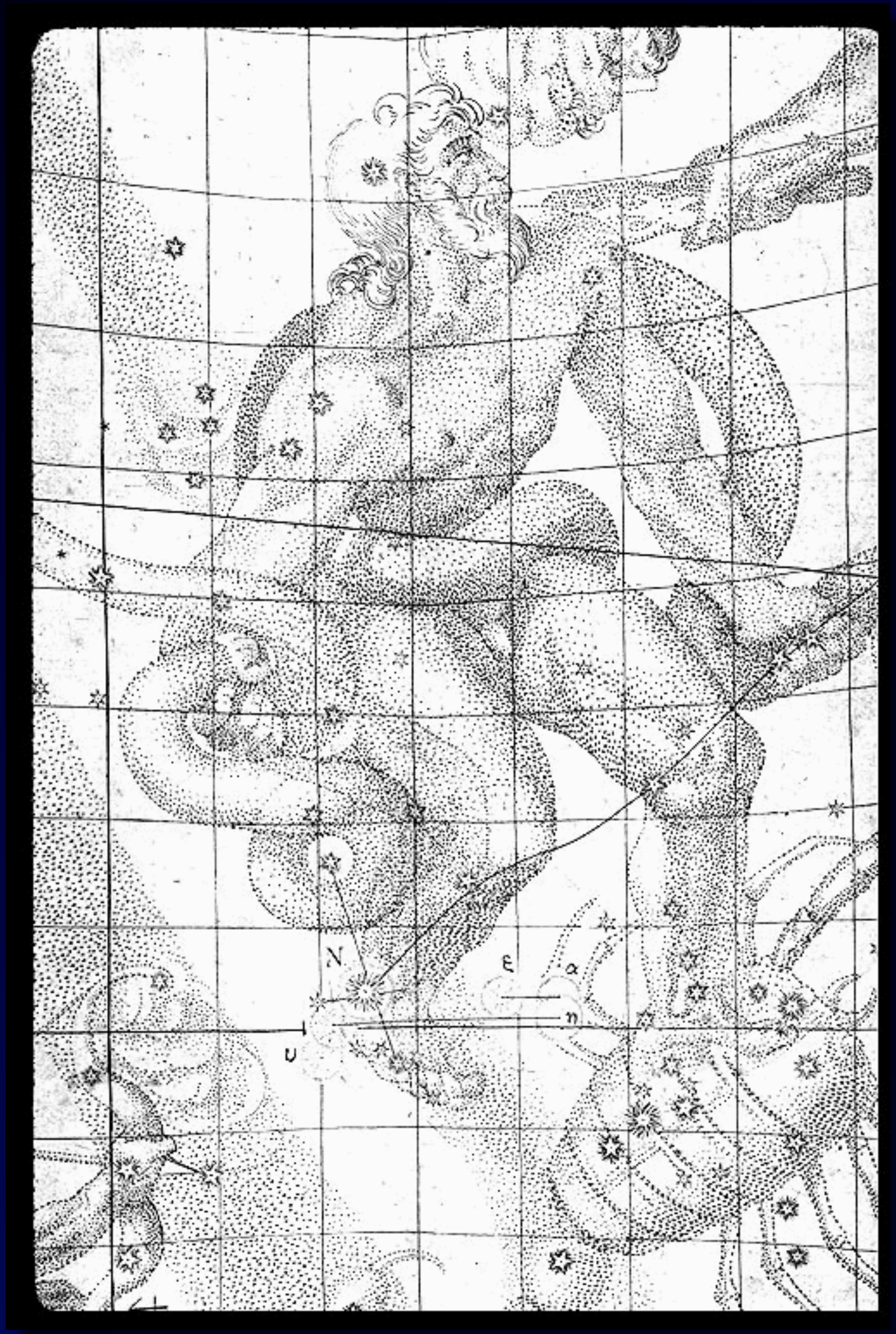

Johannes Kepler, *De Stella Nova in Pede Serpentarii*, (1606)

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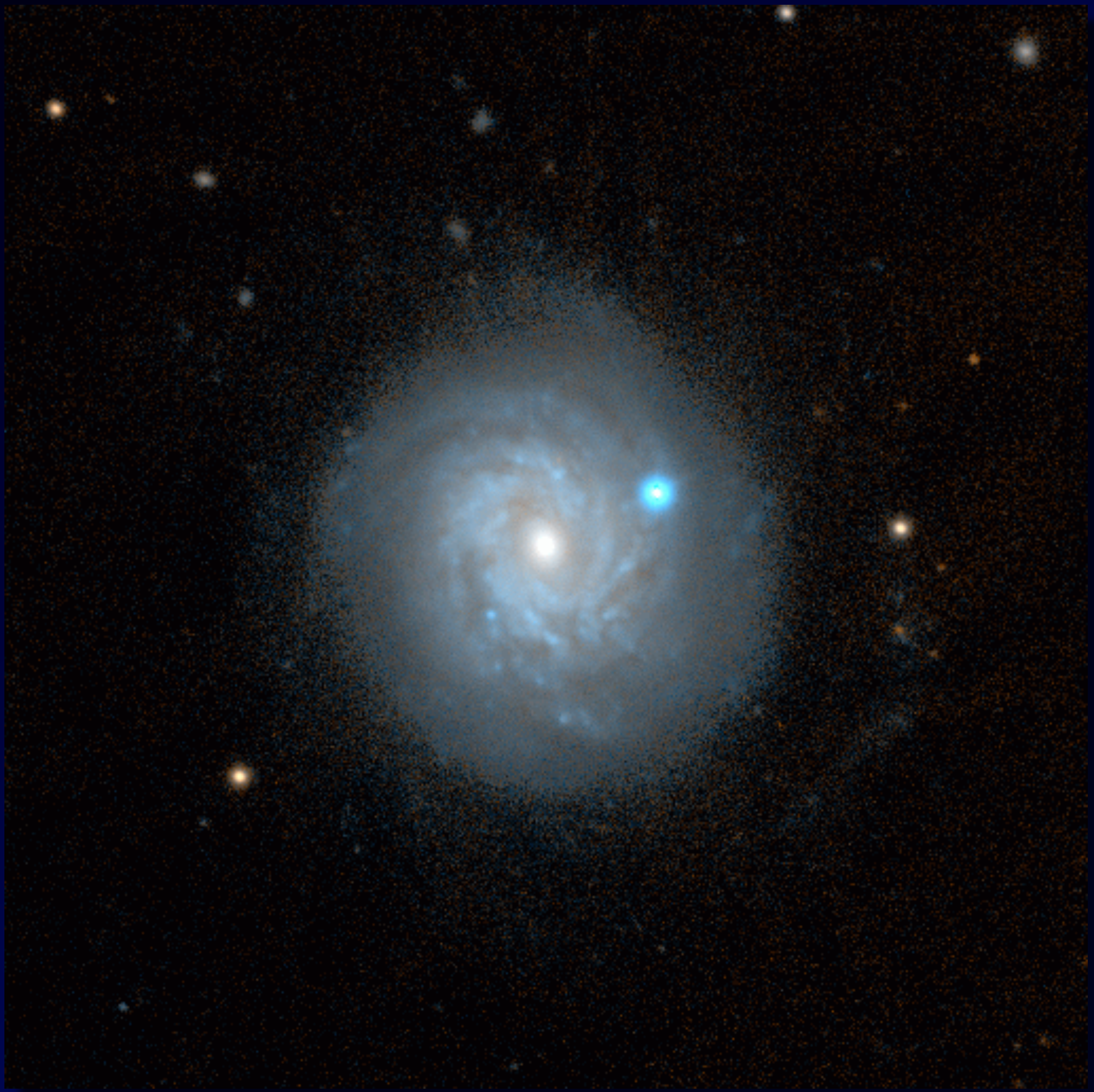

SN 1998aq

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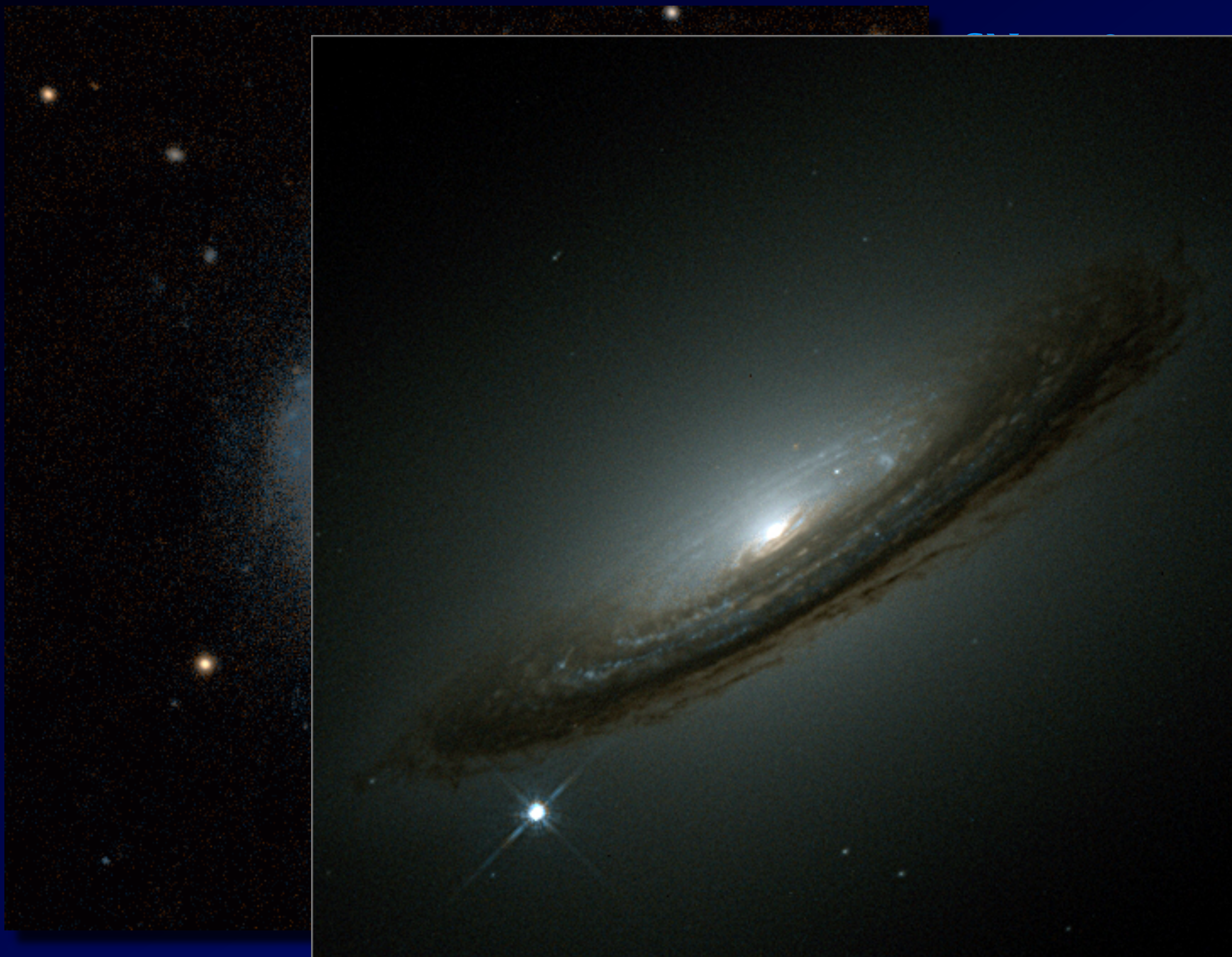

SN 1994D

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“Hauptnovae” (Baade 1929).

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JANUARY, 1940 REVIEWS OF MODERN PHYSICS VOLUME 12

Types of Novae*

F. ZWICKY
Norman Bridge Laboratory, California Institute of Technology, Pasadena, California

K. FINAL REMARKS

In the discussion given in the preceding it was pointed out that the data at our disposal enabled us to establish the fact that the frequency function $n(M)$ of novae in dependence of the absolute magnitude M at maximum brightness possesses two maxima at $M \cong -7$ and $M \cong -14.3$, from which fact we conclude the existence of two separate classes of novae, designated as common novae and supernovae.* It will be of interest to

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* Baade and I first introduced the term "supernovae" in seminars and in a lecture course on astrophysics at the California Institute of Technology in 1931.

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Baade

Zwicky

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38. Supernovae and Cosmic Rays. W. BAADE, *Mt. Wilson Observatory*, AND F. ZWICKY, *California Institute of Technology*.—Supernovae flare up in every stellar system (nebula) once in several centuries.

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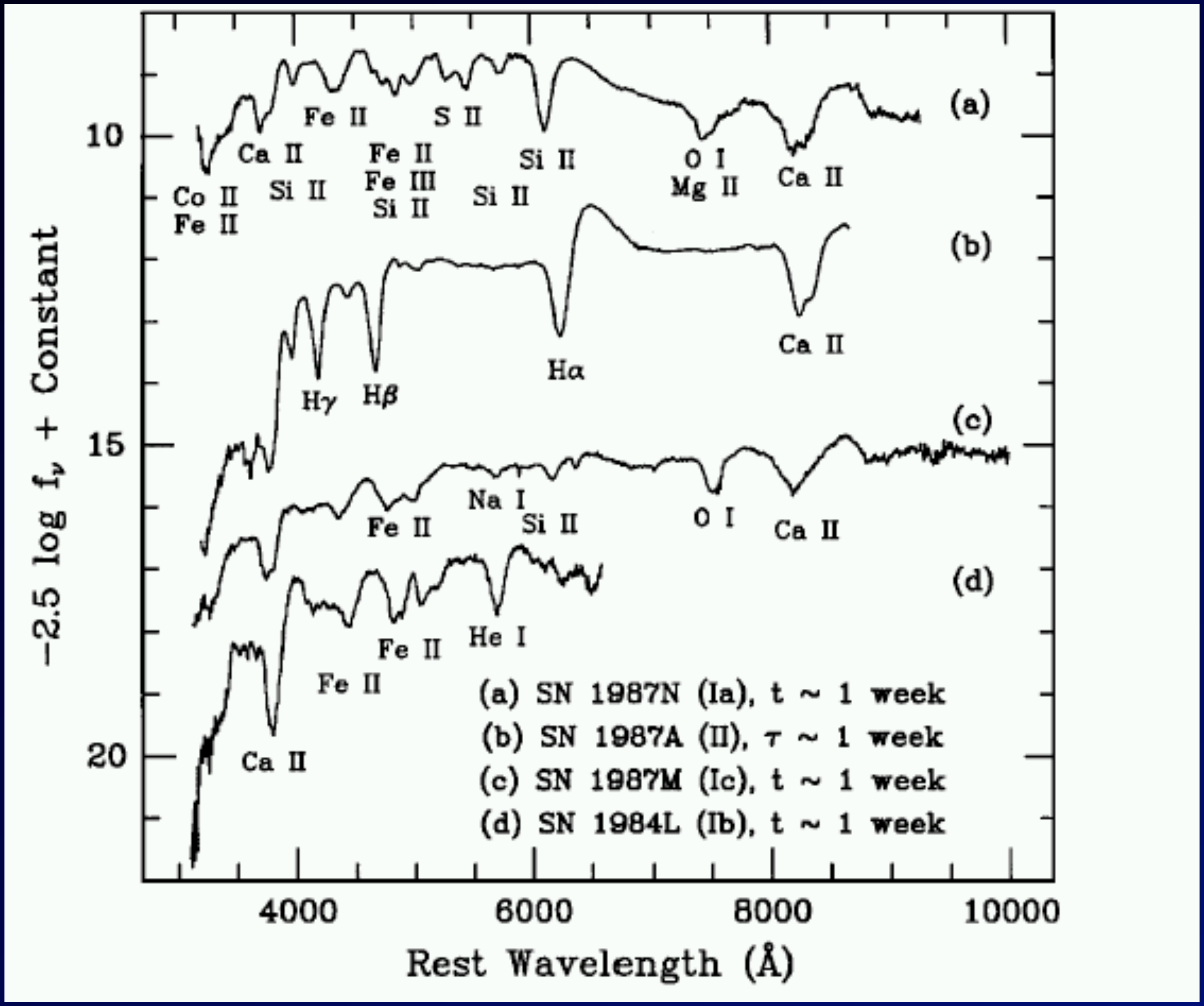
With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

Astronomers classify supernovae according to their spectra.



Filippenko (1997)

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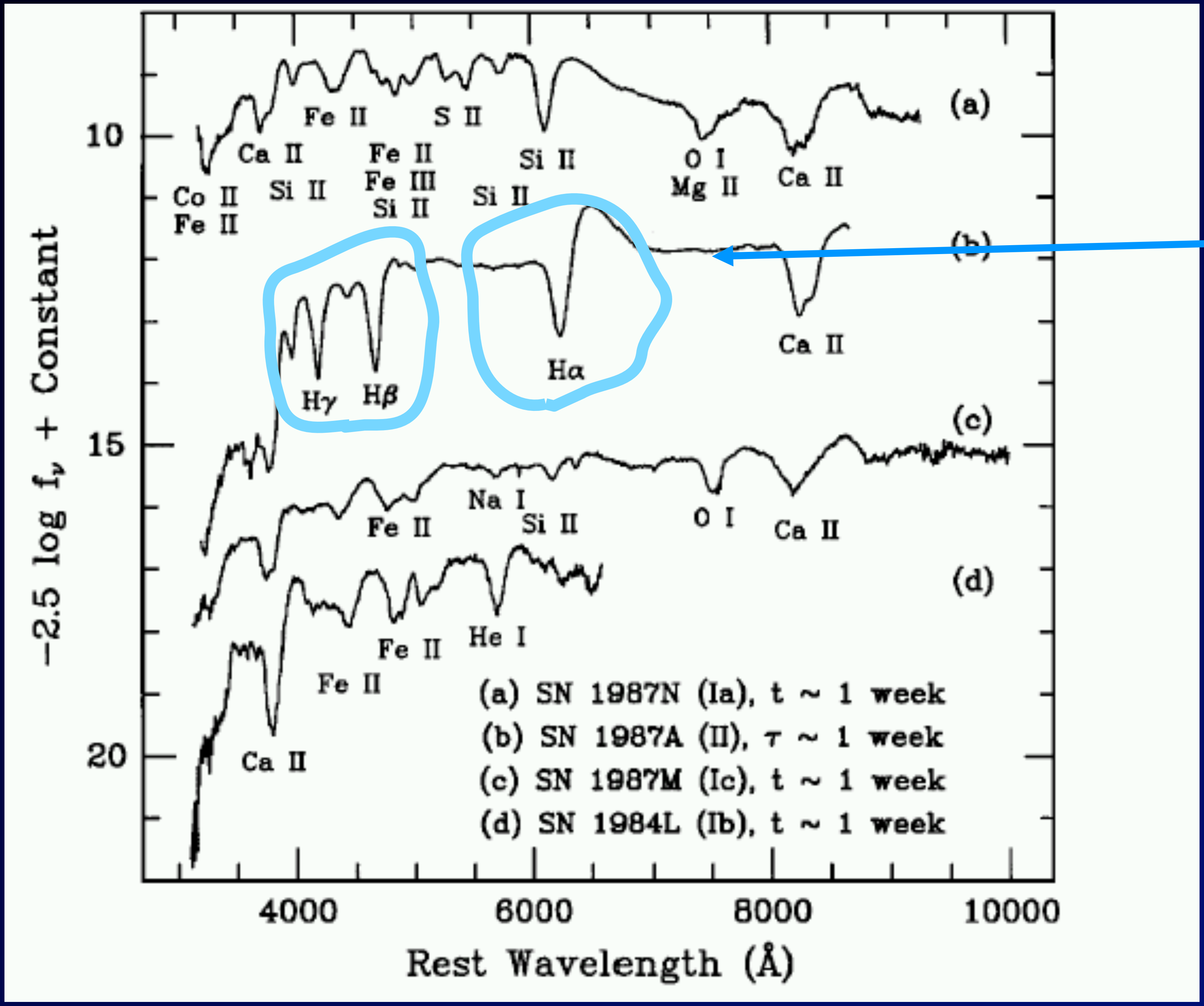

Type II
(obvious H)

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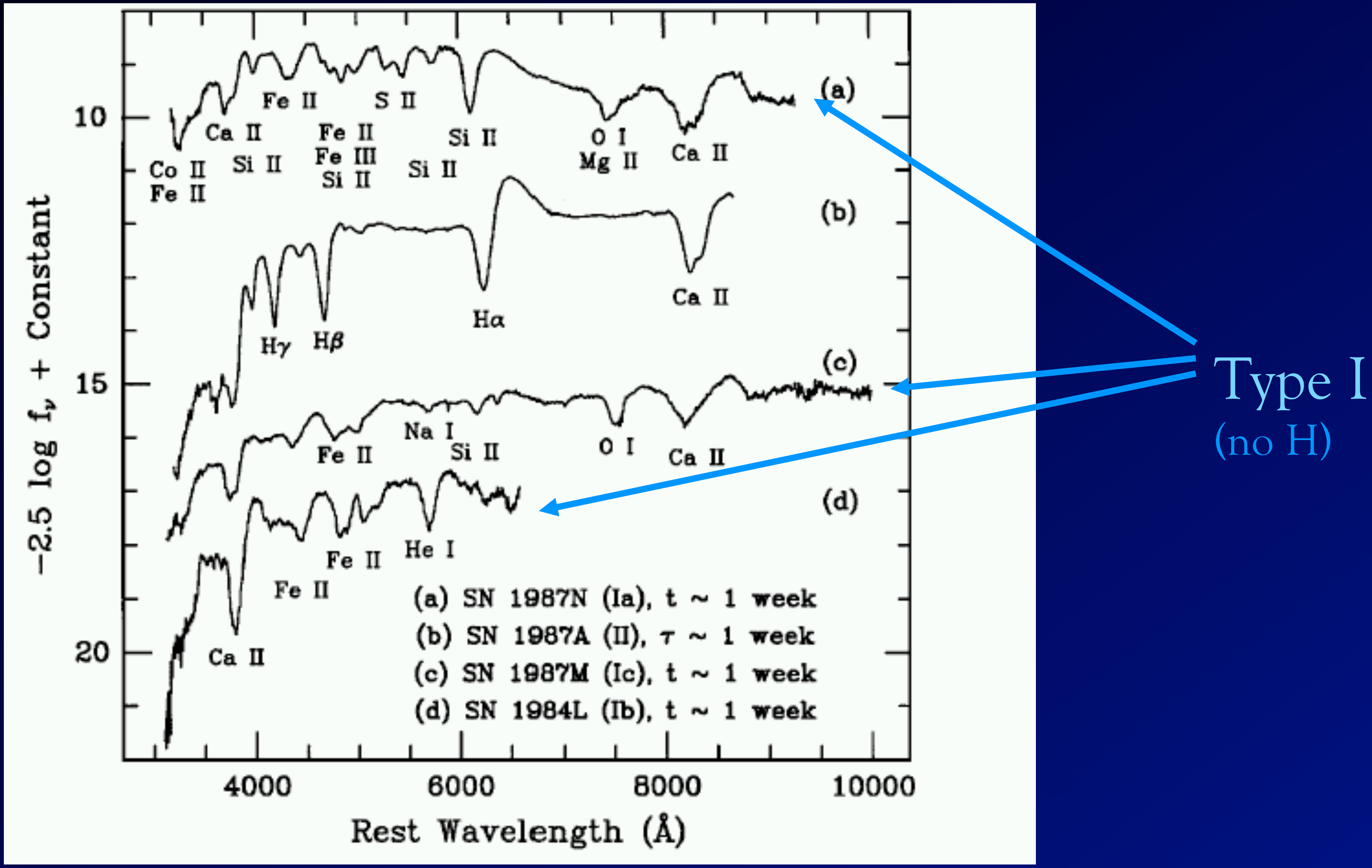

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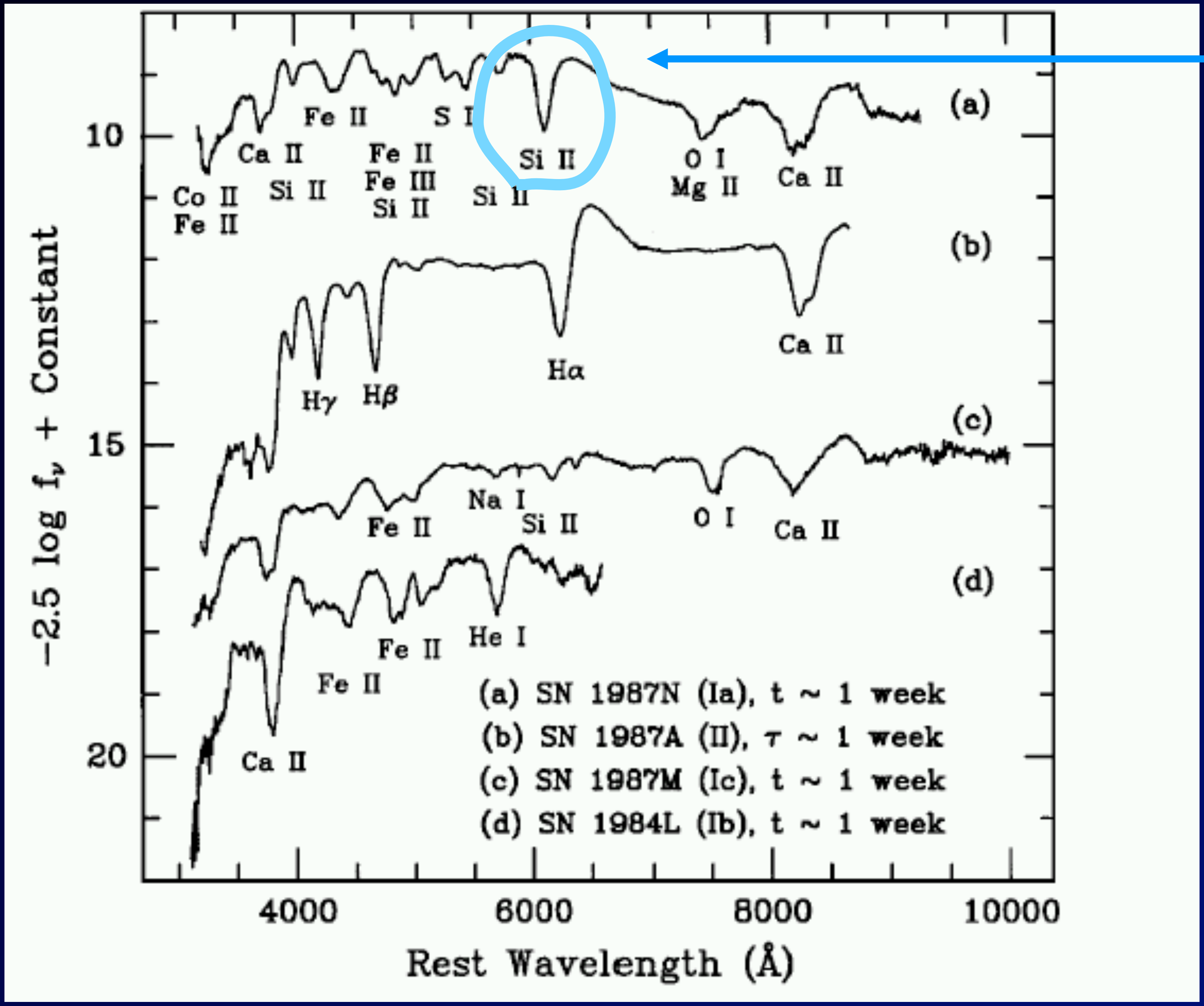

Type Ia
(no H, strong Si)

Filippenko (1997)

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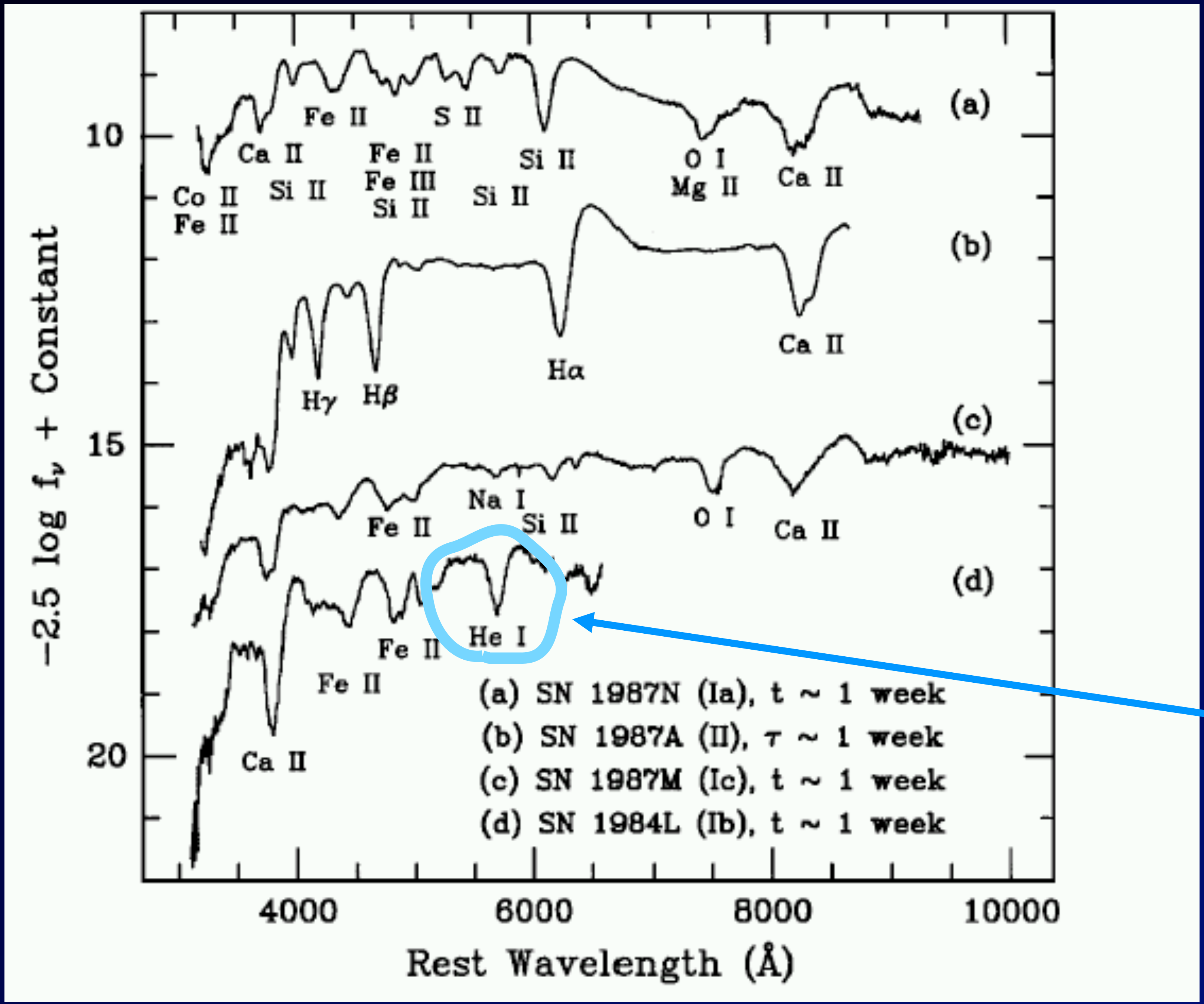

Type Ib
(no H, obvious He)

Filippenko (1997)

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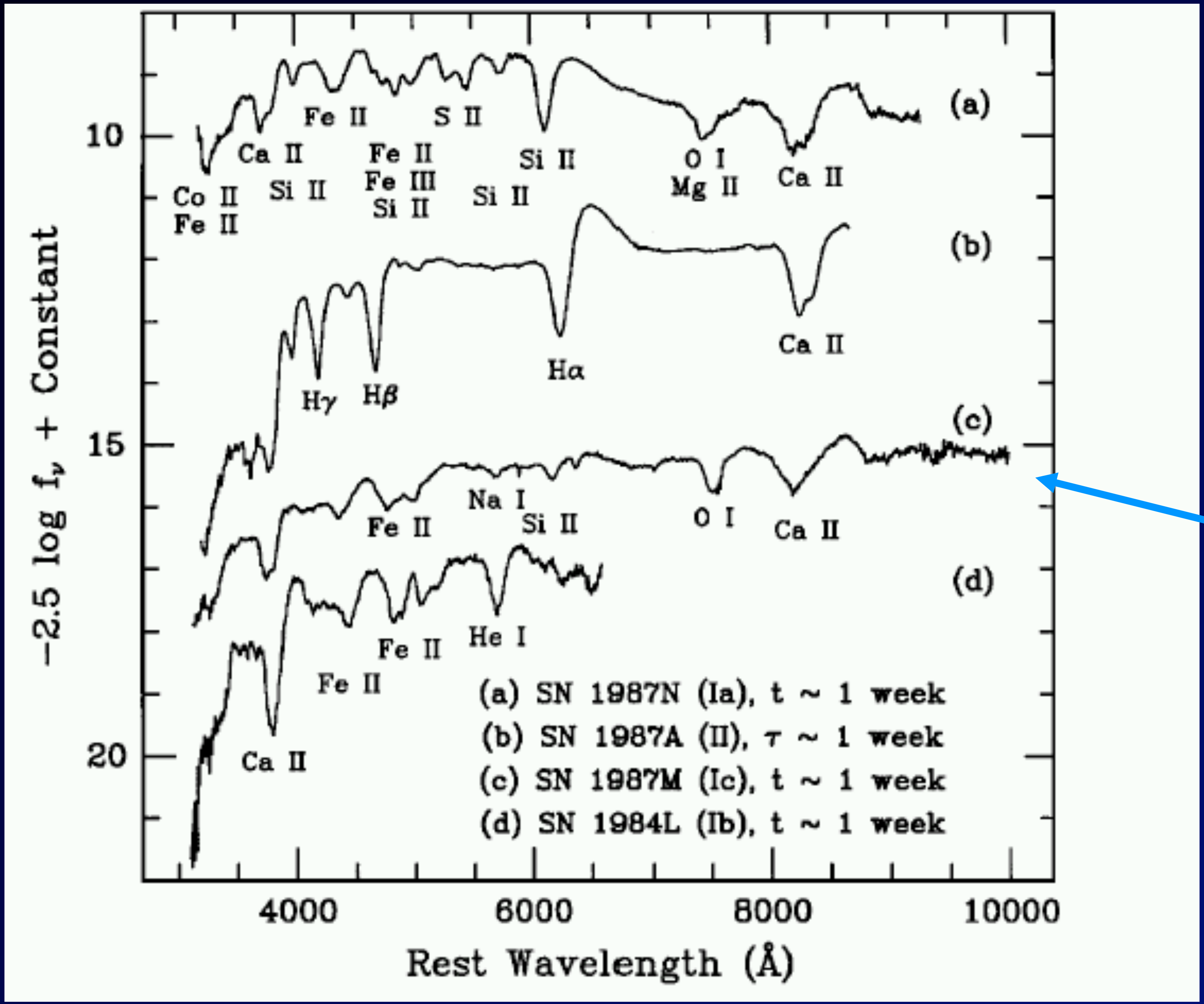

Type Ic
(no H, He, Si)

Filippenko (1997)

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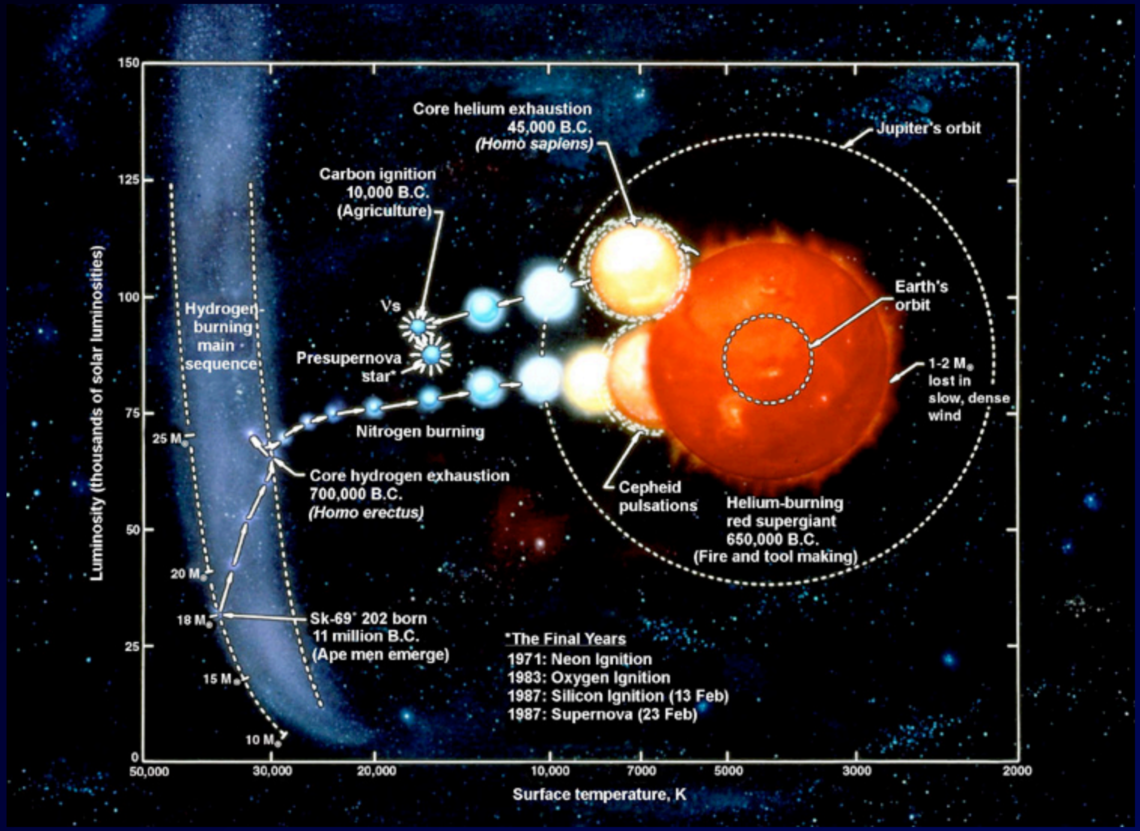

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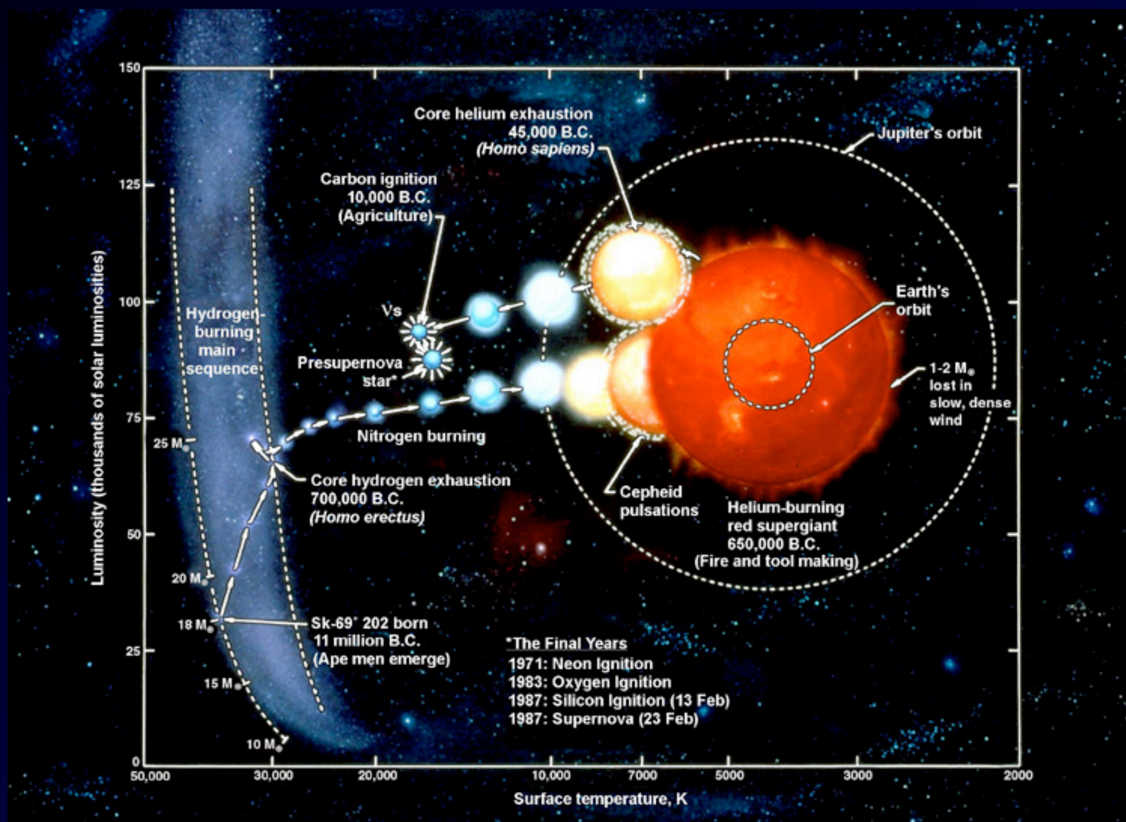

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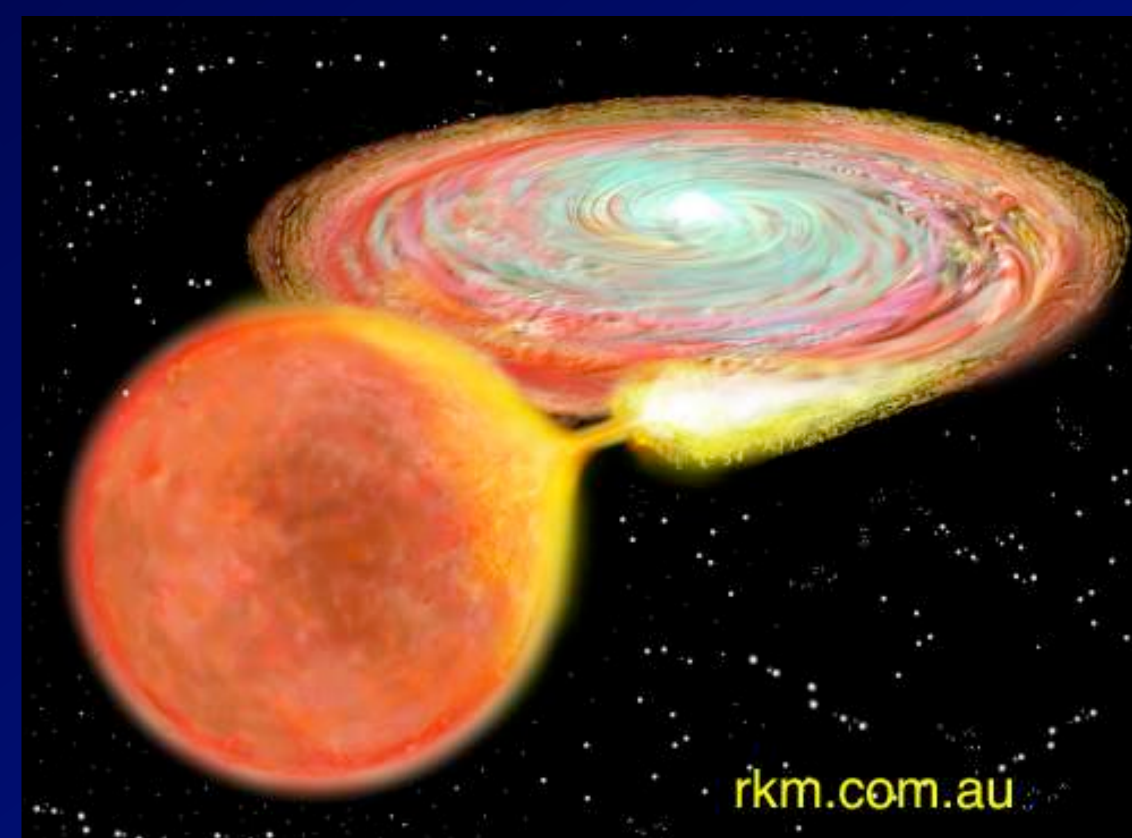
Type Ia: Thermonuclear explosion that consumes an entire white dwarf (remnant of a star with $M < 8\ M_\odot$), resulting from accretion



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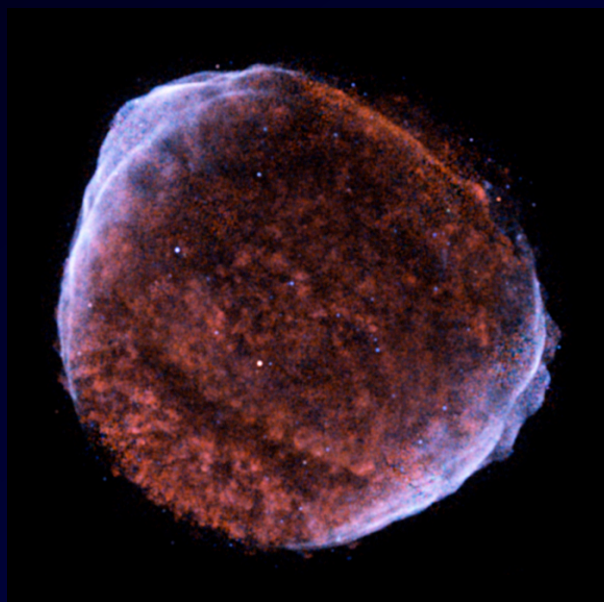
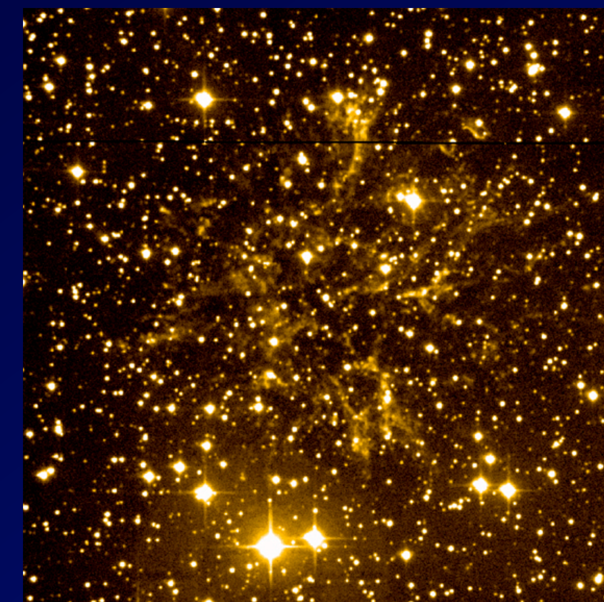
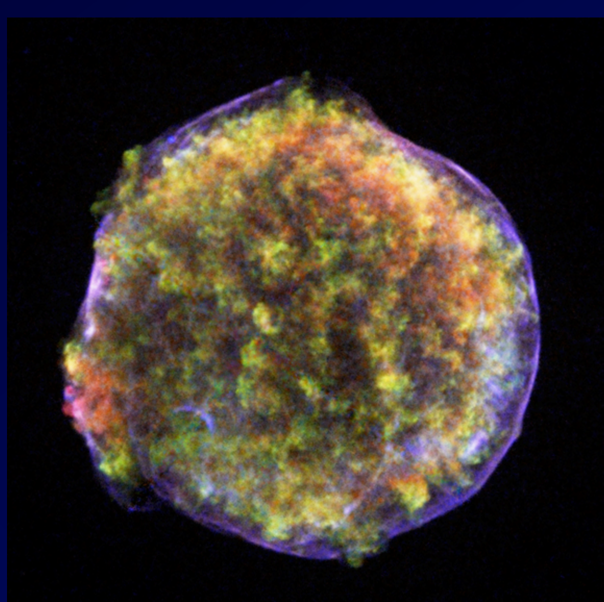


SN 1006 (X-ray) Type Ia

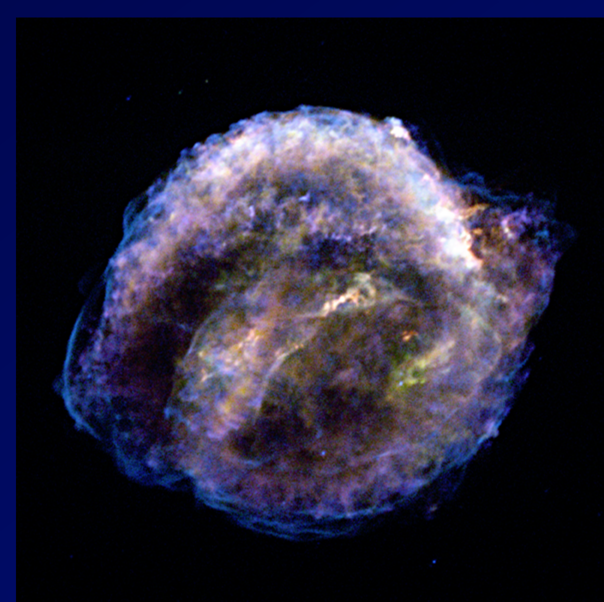
SN 1054 (Optical) Type II



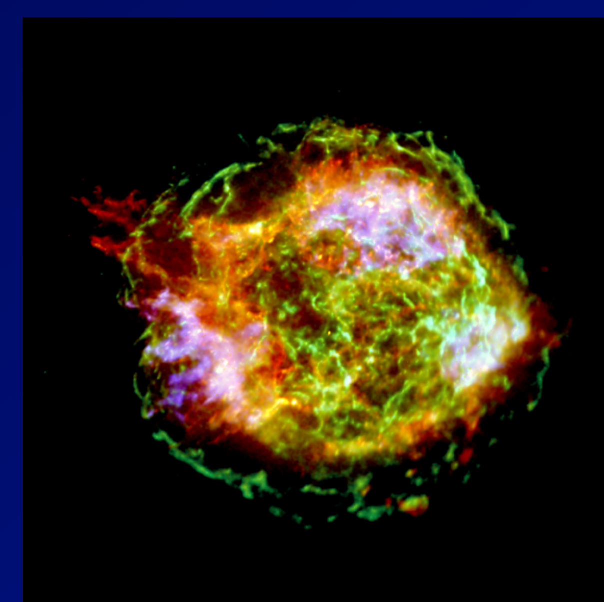
SN 1181 (Optical) Type II



SN 1572 (X-ray) Type Ia



SN 1604 (X-ray) Type Ia



Cas A 1667? (X-ray) Type II

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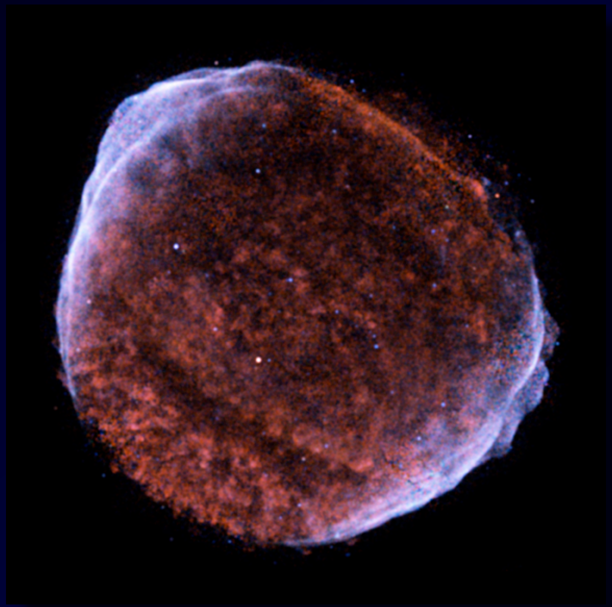

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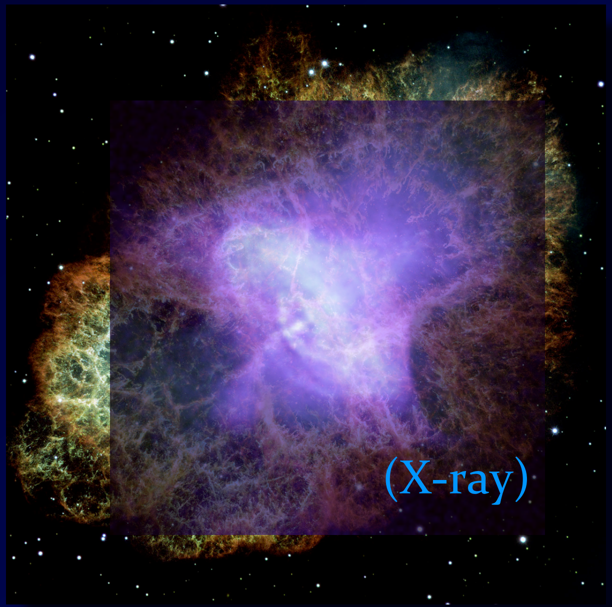

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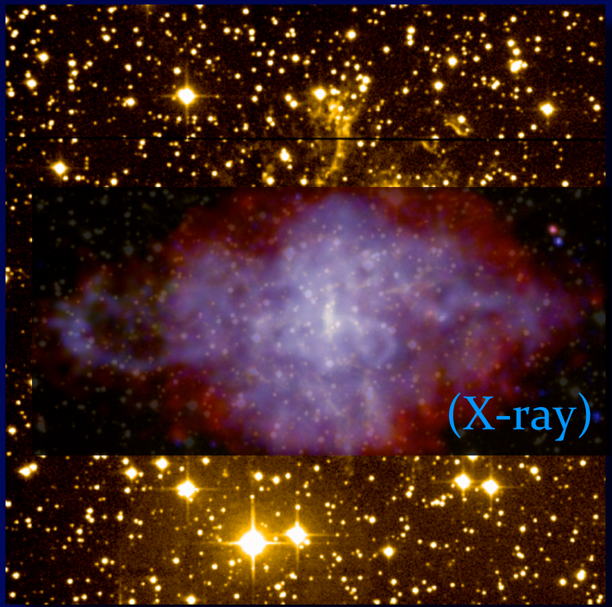

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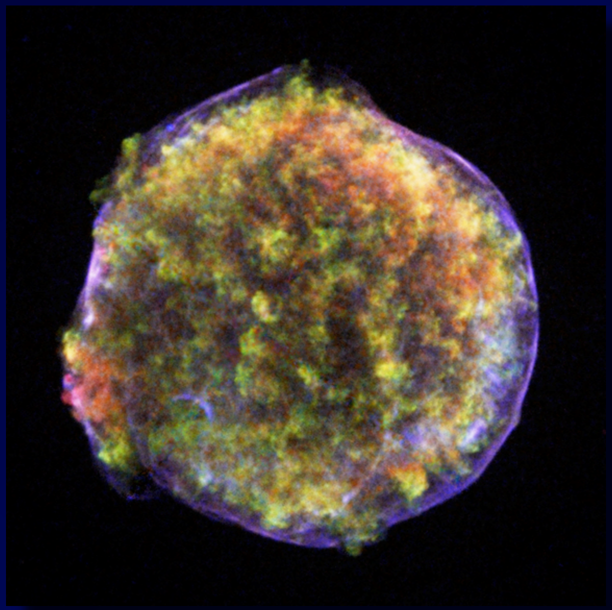

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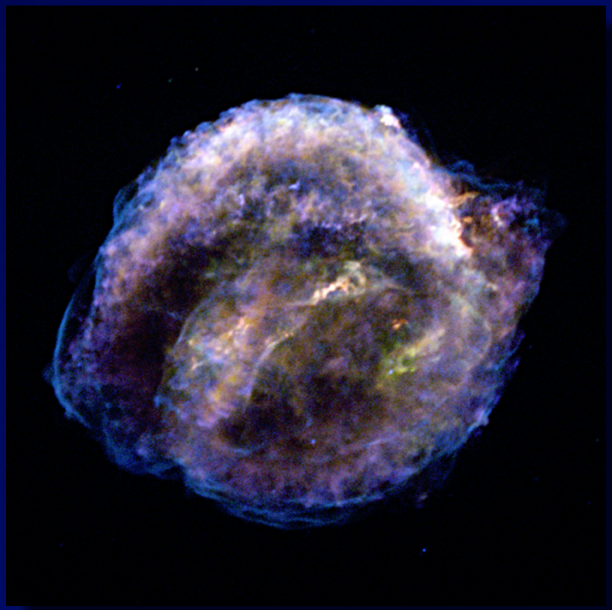

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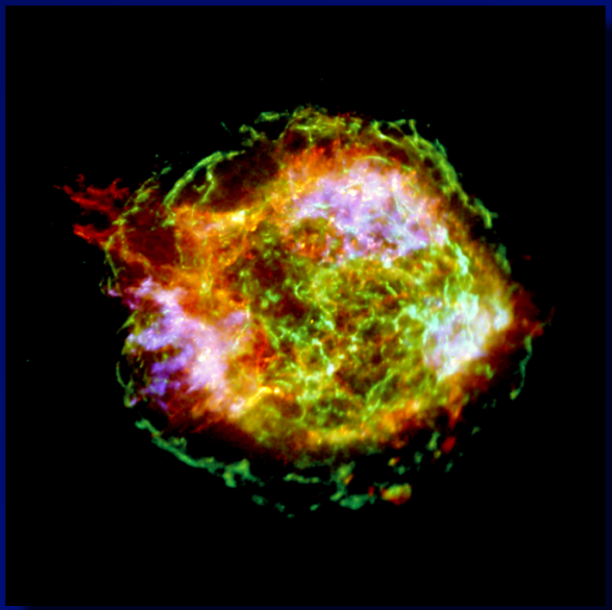

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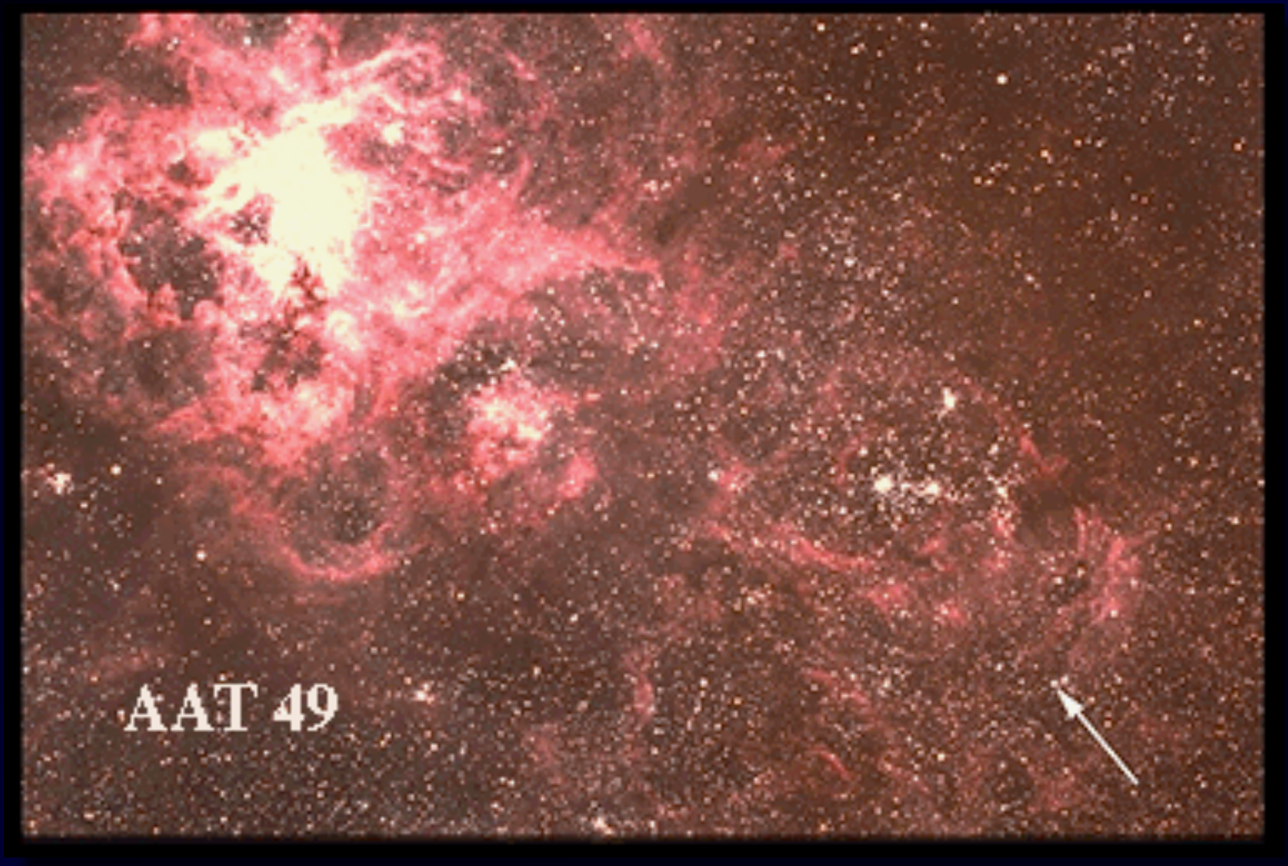

Tarantula Nebula

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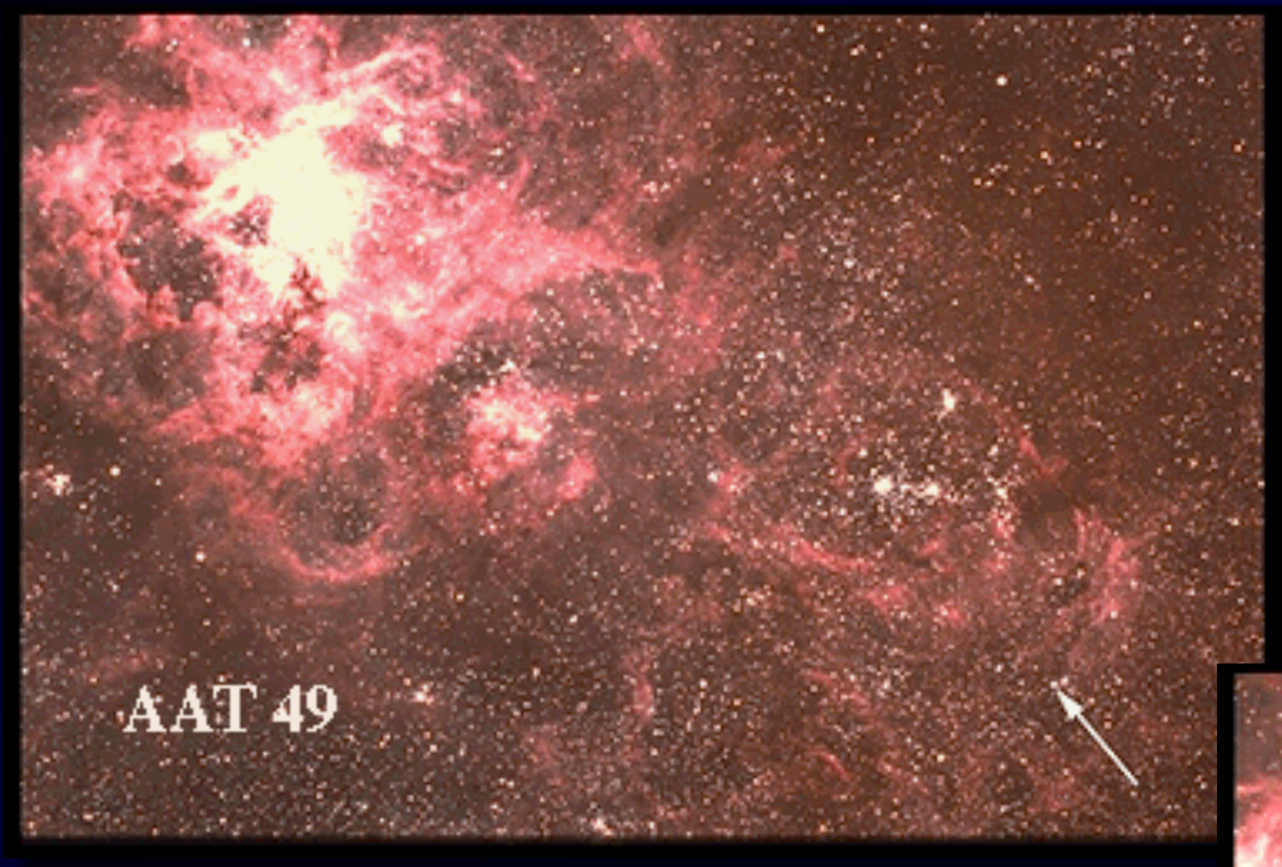

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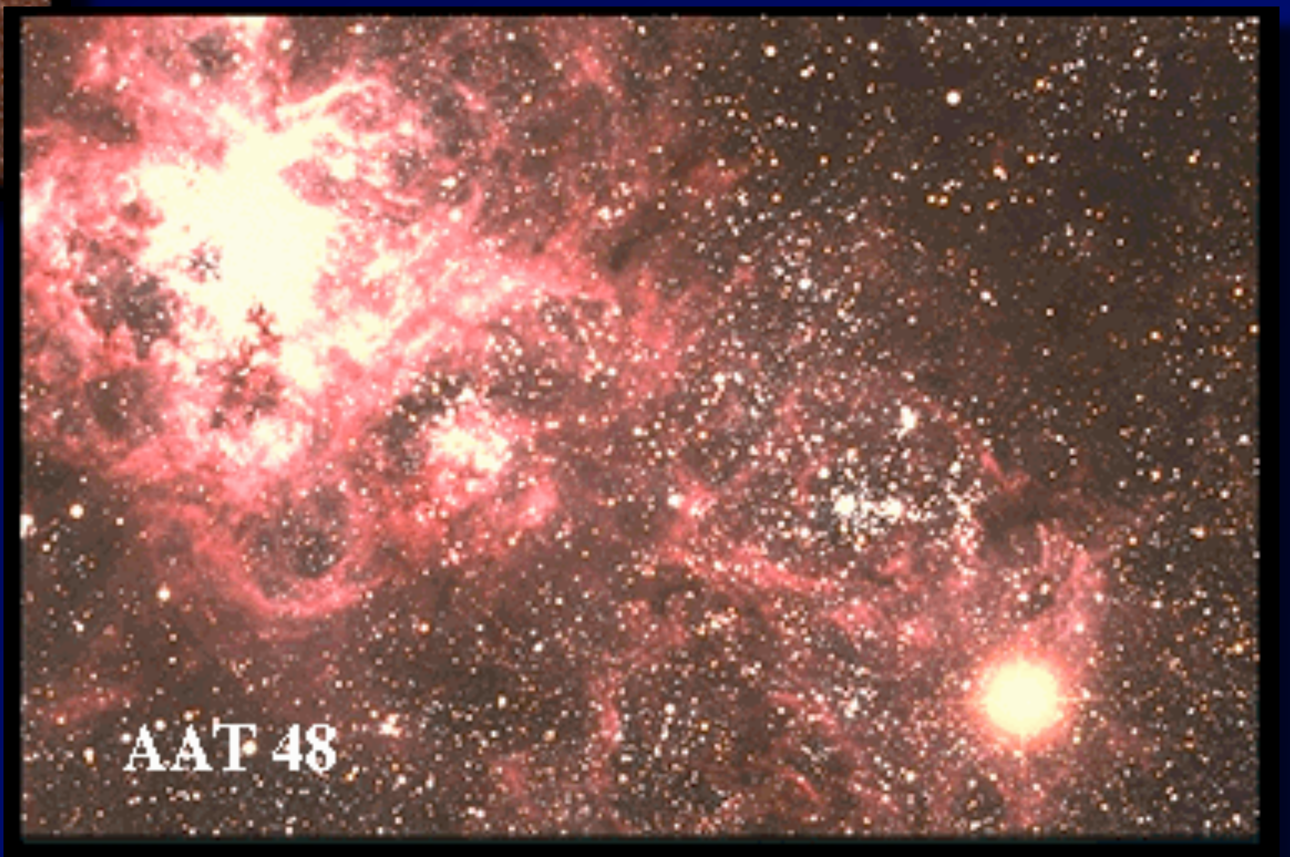

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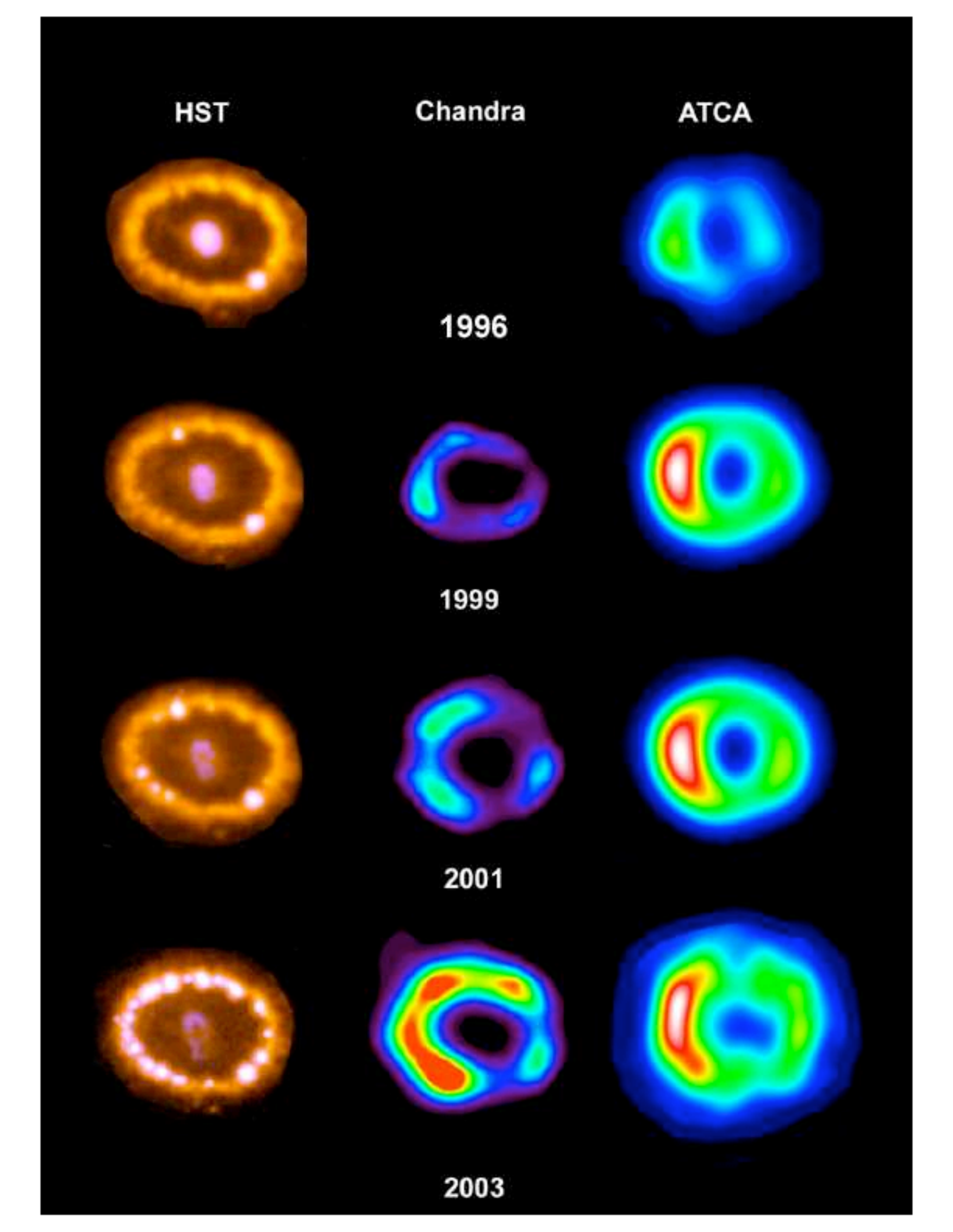

UV/Optical/IR X-ray Radio

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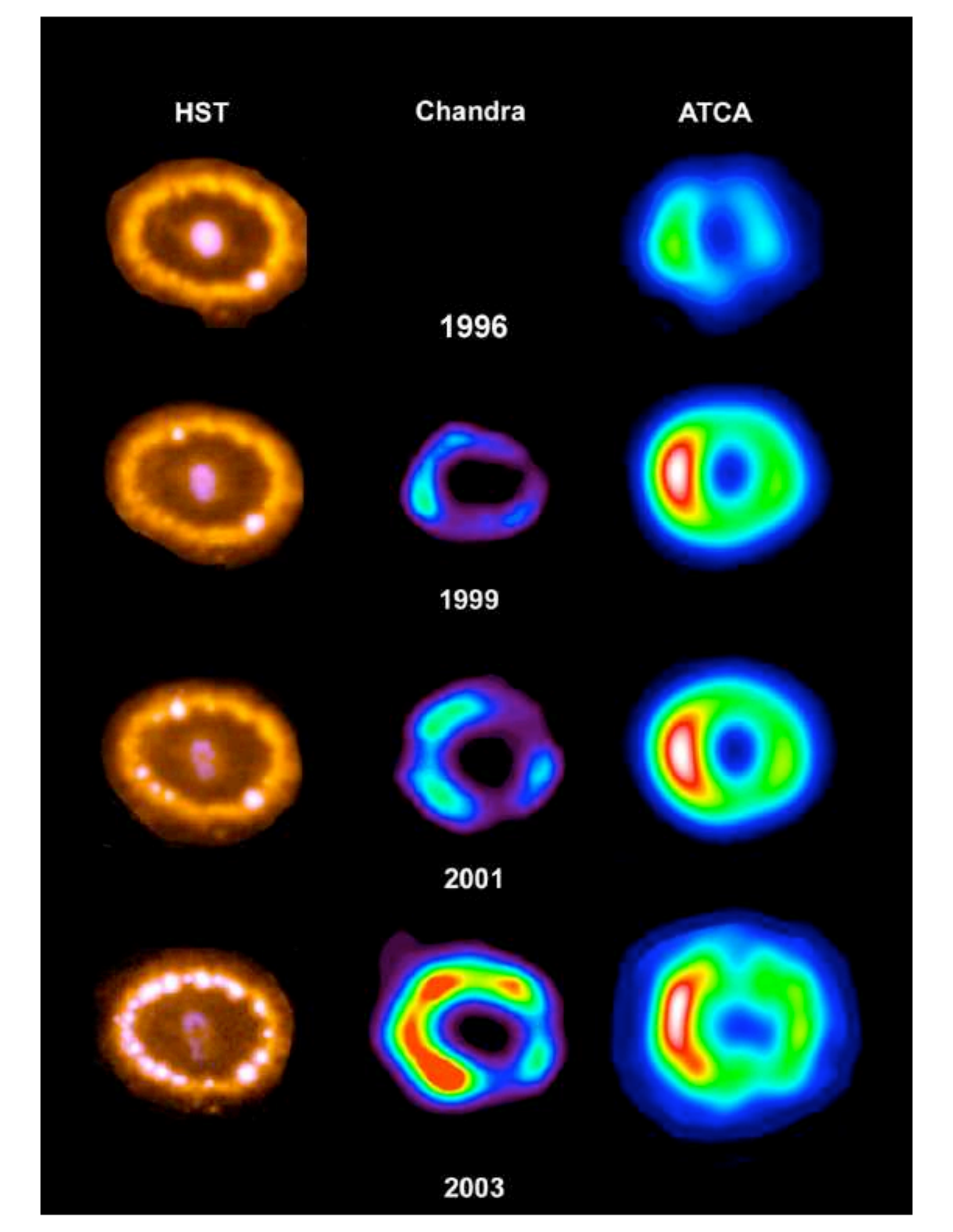

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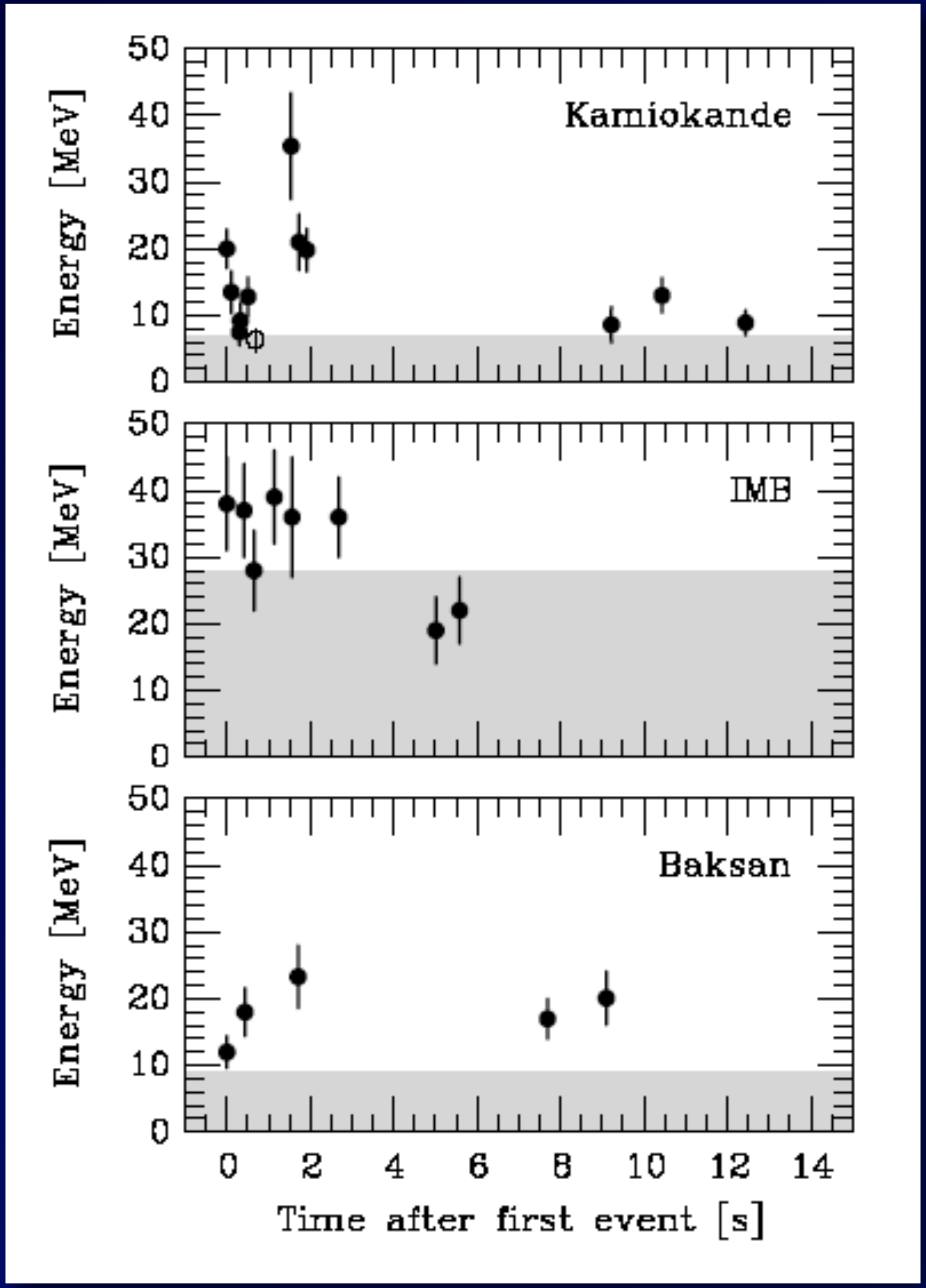

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Core-collapse ν extravaganza

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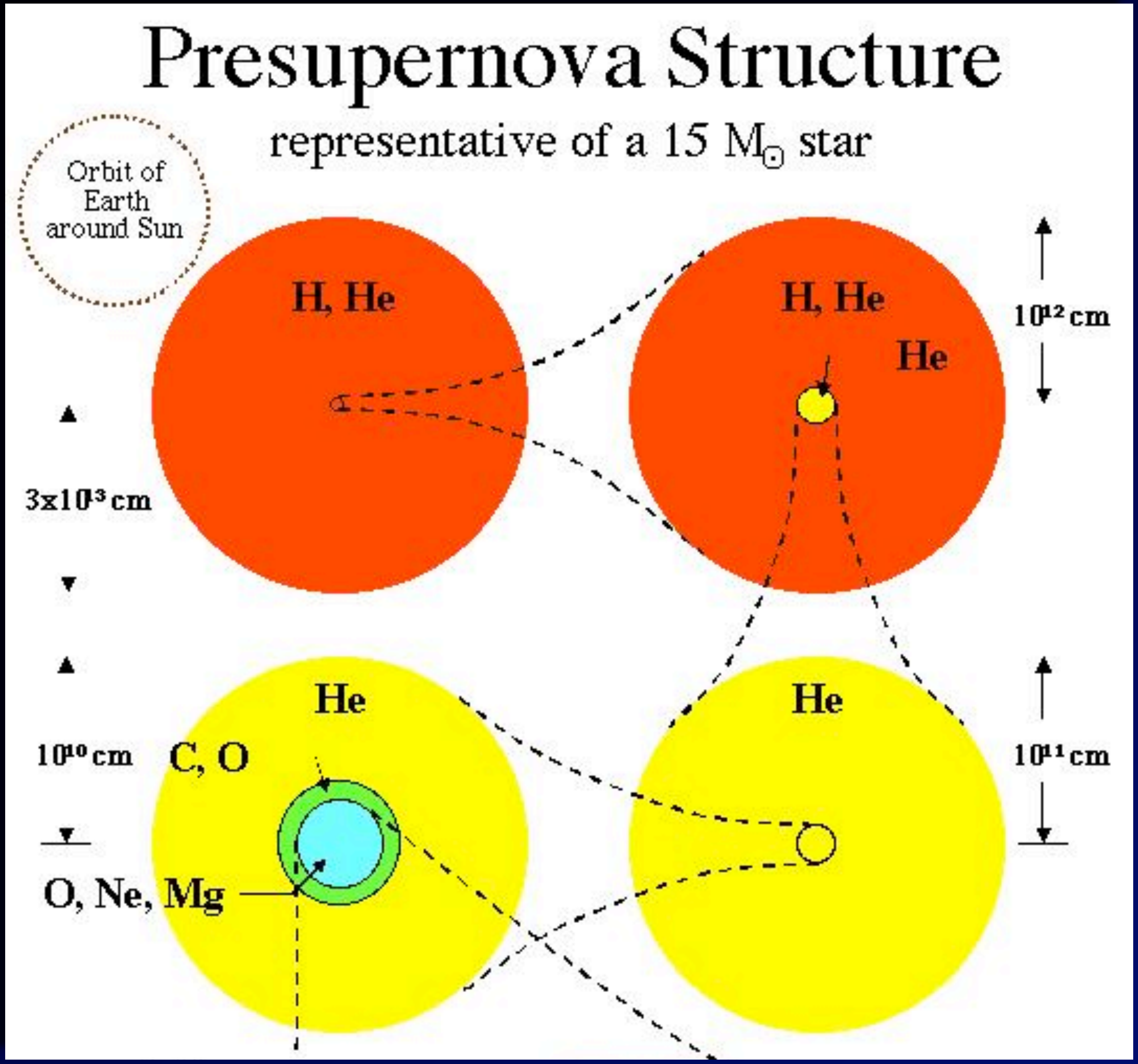

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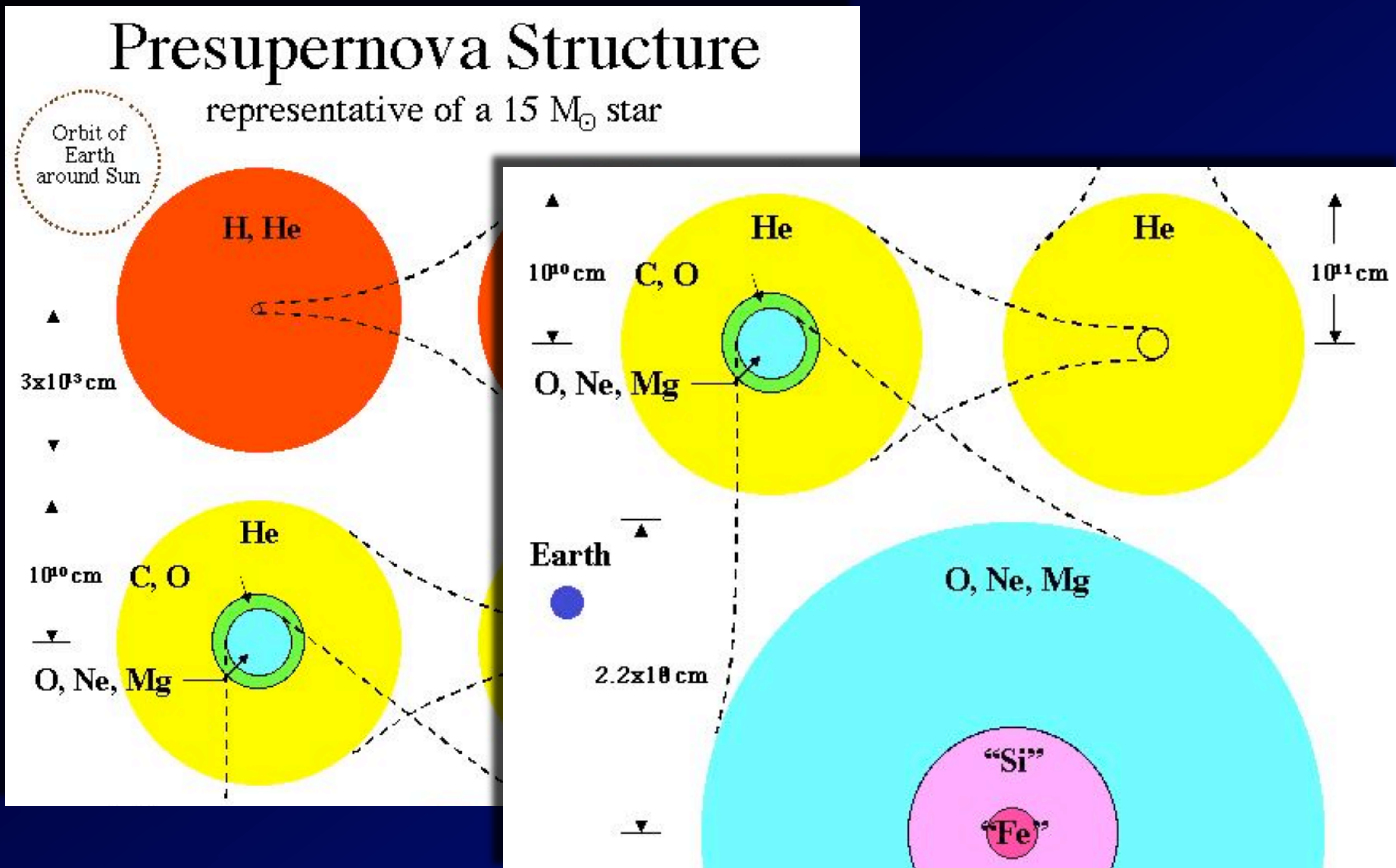

Core-collapse supernova

Core-collapse ν extravaganza

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Core-collapse ν extravaganza

Massive stellar progenitor

Core-collapse supernova

Massive stellar progenitor

Core-collapse ν extravaganza

e^- degeneracy, ν pair emission

…before undergoing catastrophic collapse, which halts when the nuclear equation of state stiffens.

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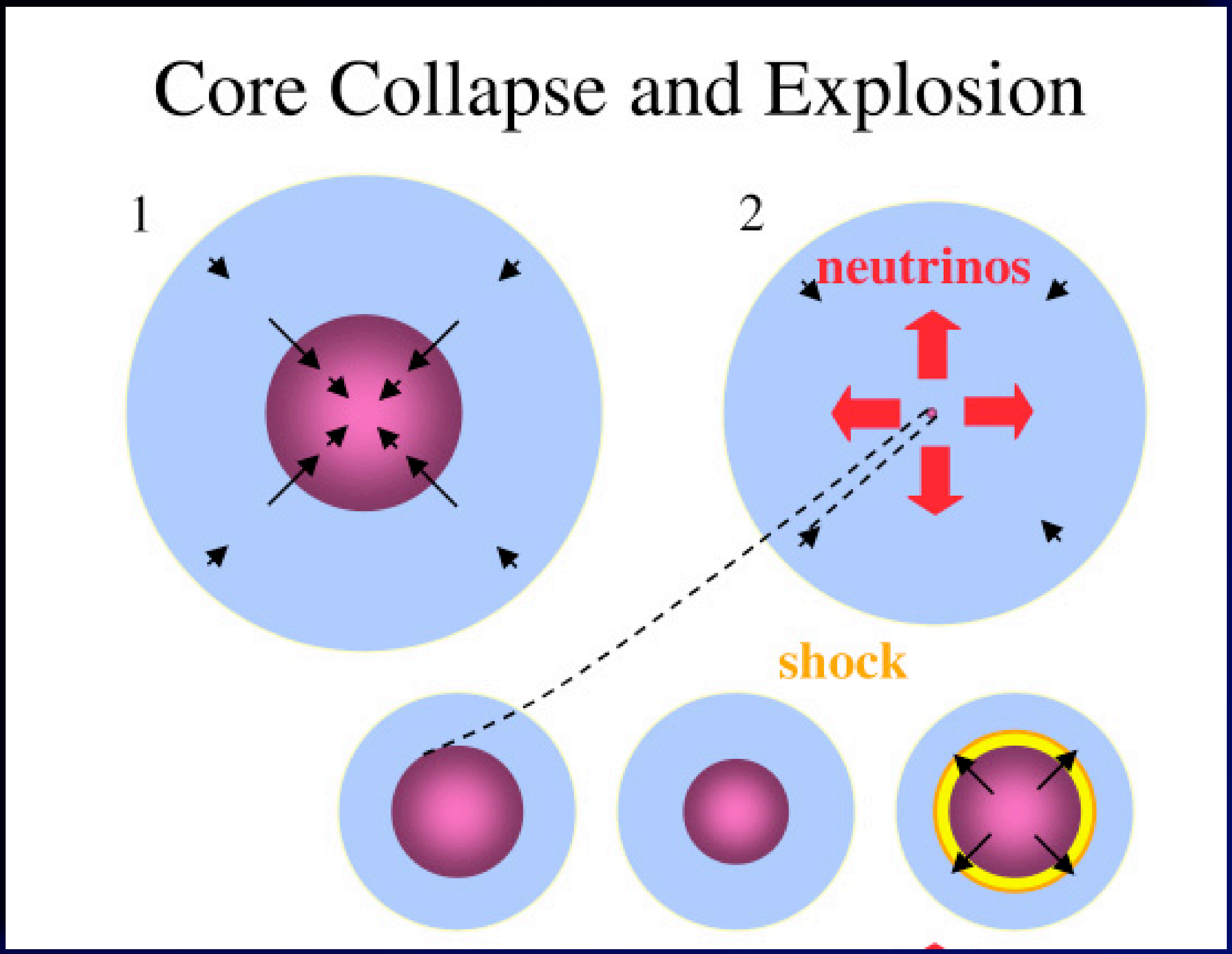


Core-collapse supernova

Massive stellar progenitor

Core-collapse ν extravaganza

e^- degeneracy, ν pair emission

Core-collapse supernova

Massive stellar progenitor

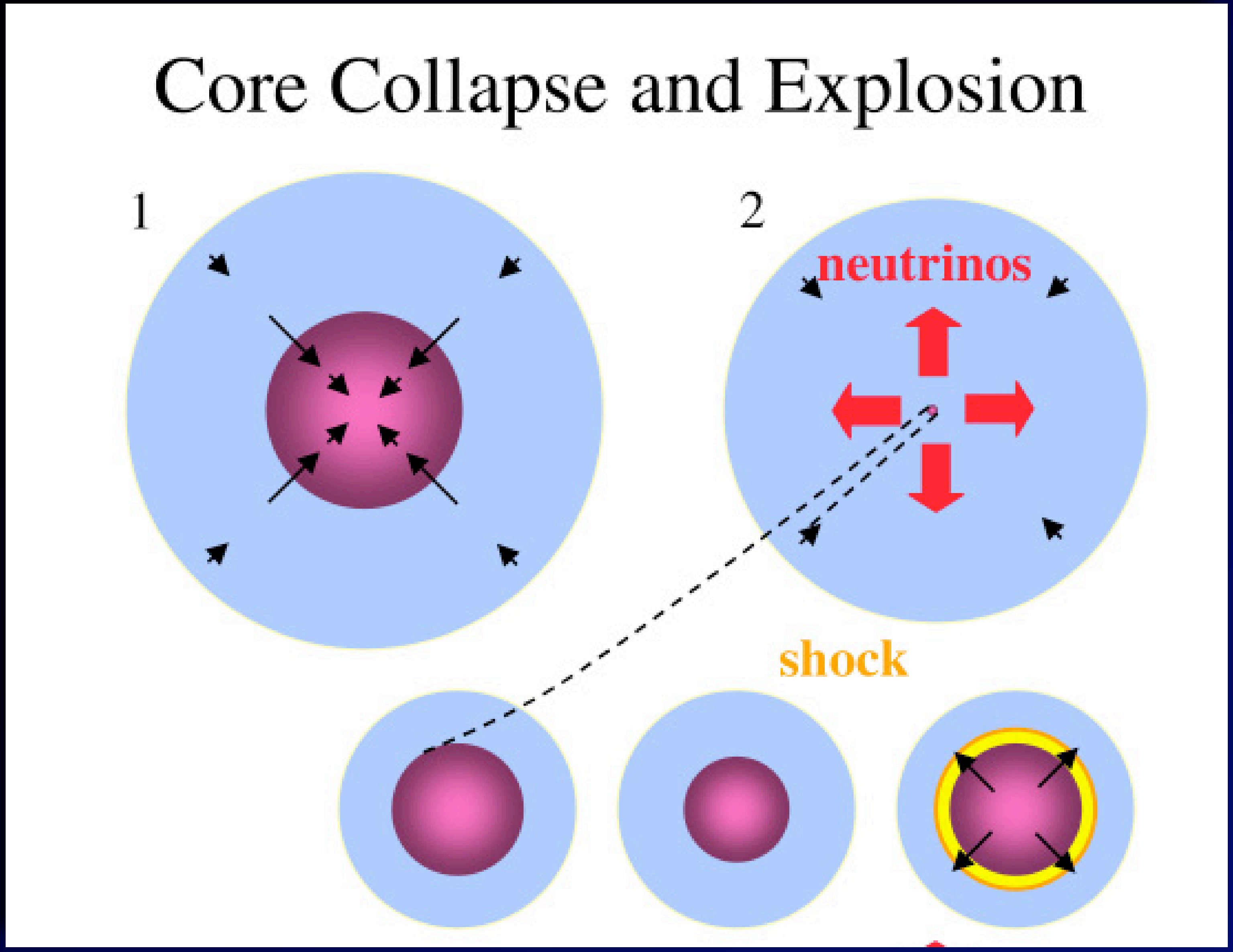
Infall

Core-collapse ν extravaganza

e^- degeneracy, ν pair emission

Core-collapse supernova	Core-collapse ν extravaganza
Massive stellar progenitor	e^- degeneracy, ν pair emission
Infall	e^- capture / ν_e emission

A shock forms and stalls. Neutrino heating/cooling and changes in nuclear composition impact its fate.



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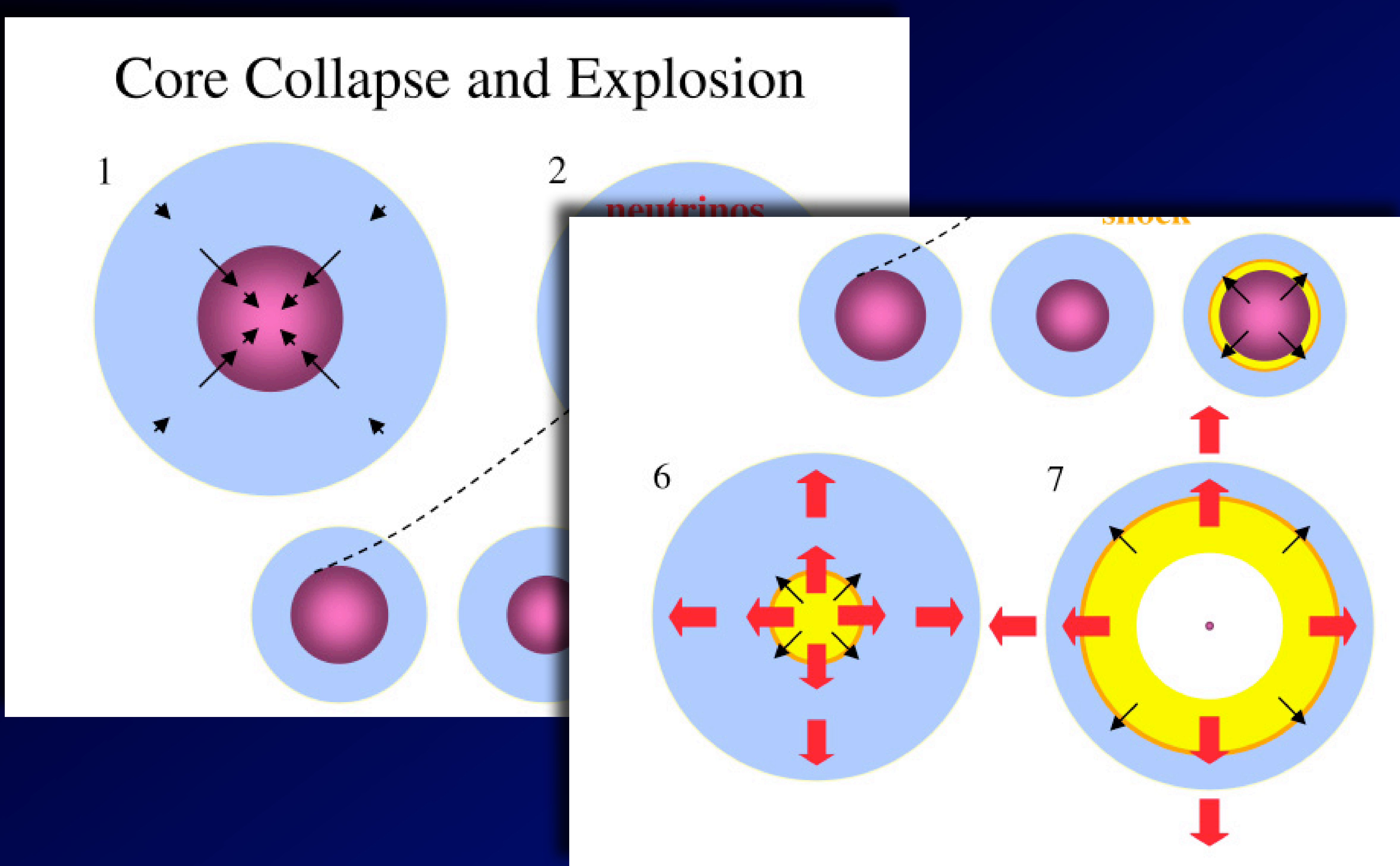

Core-collapse supernova

Massive stellar progenitor

Infall

Core-collapse ν extravaganza

e^- degeneracy, ν pair emission

e^- capture / ν_e emission

Core-collapse supernova

Massive stellar progenitor

Infall

Bounce; shock formation, stall, and revival

Core-collapse ν extravaganza

e^- degeneracy, ν pair emission

e^- capture / ν_e emission

Core-collapse supernova

Massive stellar progenitor

Infall

Bounce; shock formation, stall, and revival

- Neutron star kick

Core-collapse ν extravaganza

e^- degeneracy, ν pair emission

e^- capture / ν_e emission

Core-collapse supernova

Massive stellar progenitor

Infall

Bounce; shock formation, stall, and revival

- Neutron star kick
- Gravitational waves

Core-collapse ν extravaganza

e^- degeneracy, ν pair emission

e^- capture / ν_e emission

Core-collapse supernova

Massive stellar progenitor

Infall

Bounce; shock formation, stall, and revival

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Core-collapse ν extravaganza

e⁻ degeneracy, ν pair emission

e⁻ capture / ν_e emission

ν emission weakens shock,
ν absorption strengthens it

Core-collapse supernova	Core-collapse ν extravaganza
Massive stellar progenitor	e^- degeneracy, ν pair emission
Infall	e^- capture / ν_e emission
Bounce; shock formation, stall, and revival	ν emission weakens shock, ν absorption strengthens it
Neutron star kick	ν_e burst at shock breakout
Gravitational waves	

Core-collapse supernova

Massive stellar progenitor

Infall

Bounce; shock formation, stall, and revival

- Neutron star kick
- Gravitational waves

Core-collapse ν extravaganza

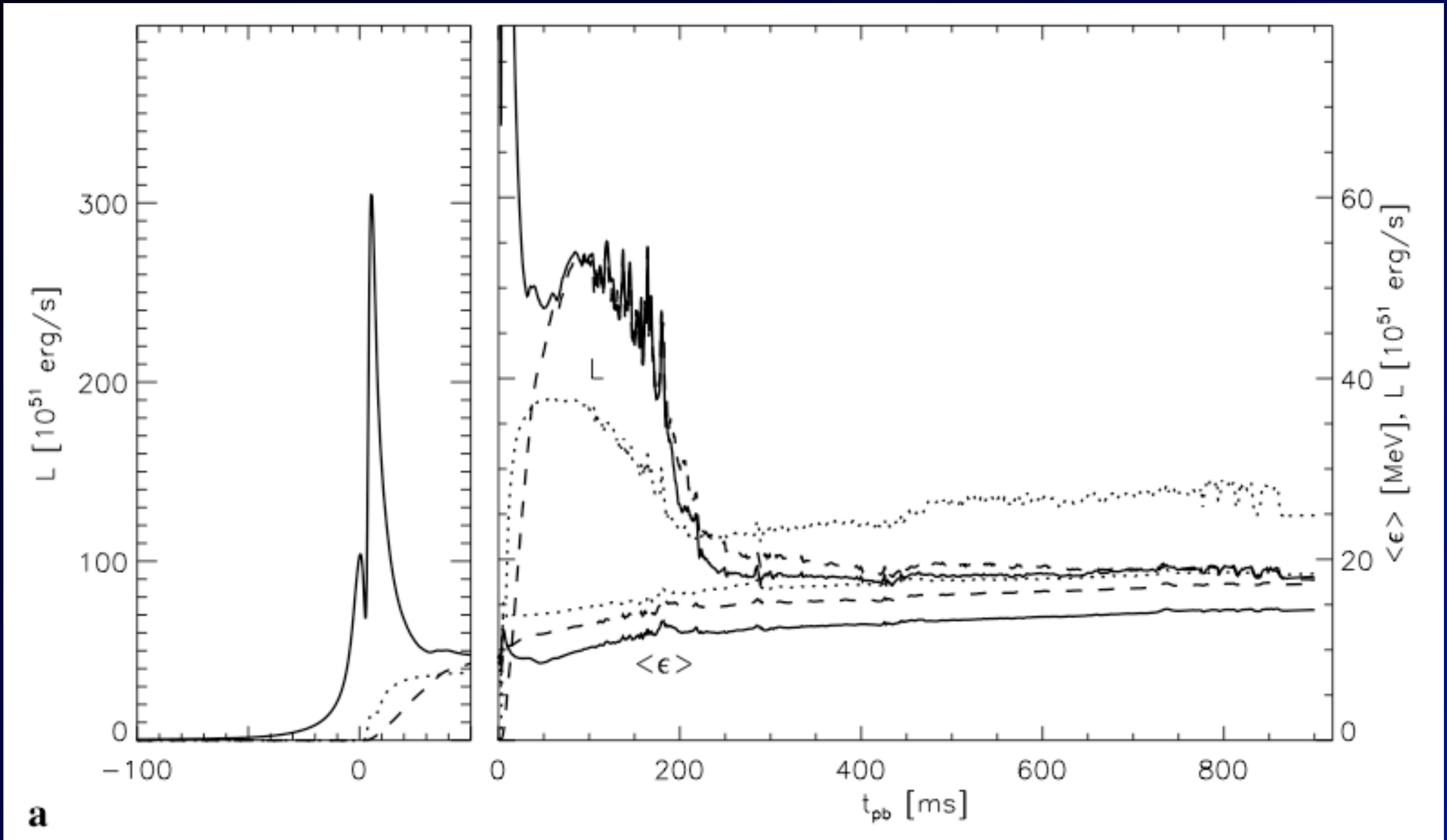
e^- degeneracy, ν pair emission

e^- capture / ν_e emission

ν emission weakens shock, ν absorption strengthens it

- ν_e burst at shock breakout
- ν pair emission from accretion

Shock breakout burst and accretion luminosity



Buras et al. (2005)

Core-collapse supernova

Massive stellar progenitor

Infall

Bounce; shock formation, stall, and revival

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Core-collapse ν extravaganza

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Core-collapse supernova

Massive stellar progenitor

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$\lesssim$ 1% of total energy release

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$\lesssim$ 10% of total energy release

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Bounce; shock formation, stall, and revival

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- Gravitational waves

Kelvin-Helmholtz contraction, then cooling of neutron star

~90% of total energy release

(If rapid rotation: accretion disk and jet formation)

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Core-collapse ν extravaganza

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Explosive nucleosynthesis,
r-process nucleosynthesis

Core-collapse supernova

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Enrichment of ISM

Core-collapse ν extravaganza

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ν absorption affects outcomes

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ν emission contributes to long-term cooling

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ν absorption affects outcomes

~1% of total energy release

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~0.01% of total energy release

ν emission contributes to long-term cooling

Can the central features be simply derived?

Can the central features be simply derived?

From nature's perspective: YES

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The basic features of neutrino emission can be estimated by fairly simple means.

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From a perspective of anthropocentric chauvinism: NO

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From a perspective of anthropocentric chauvinism: NO

Elucidation of the explosion mechanism requires detailed simulation.

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$$2 E_N + E_R = -E_G$$

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Changes in total energy must be compensated by energy loss to neutrinos.

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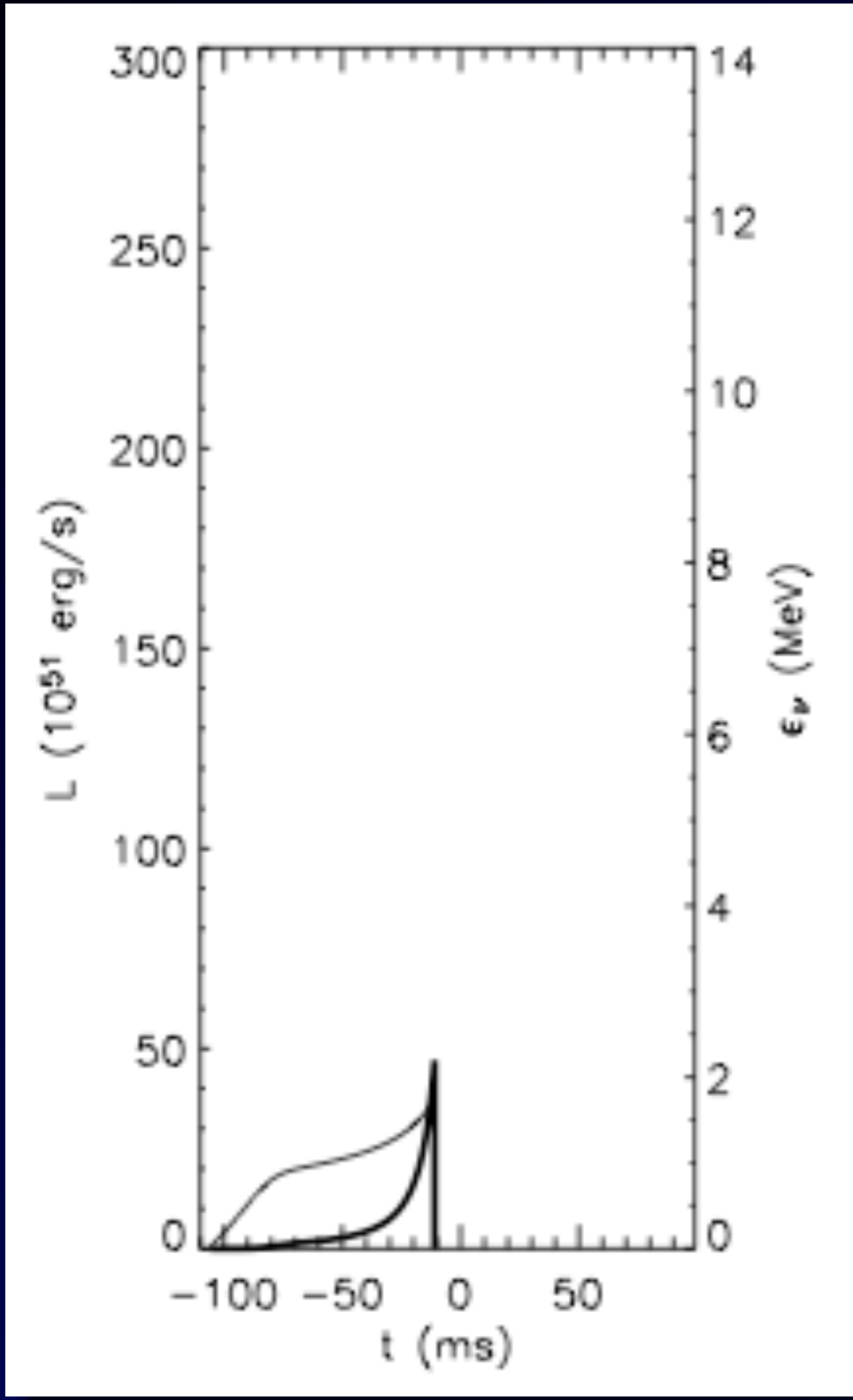
Total neutrino emission

$$E_\nu \approx 1.7 \times 10^{53}\ \text{erg} \left(\frac{M}{1.5\ M_\odot}\right)^2 \left(\frac{11\ \text{km}}{R}\right)$$

ν emission: infall and 'rebound-to-transparency' burst



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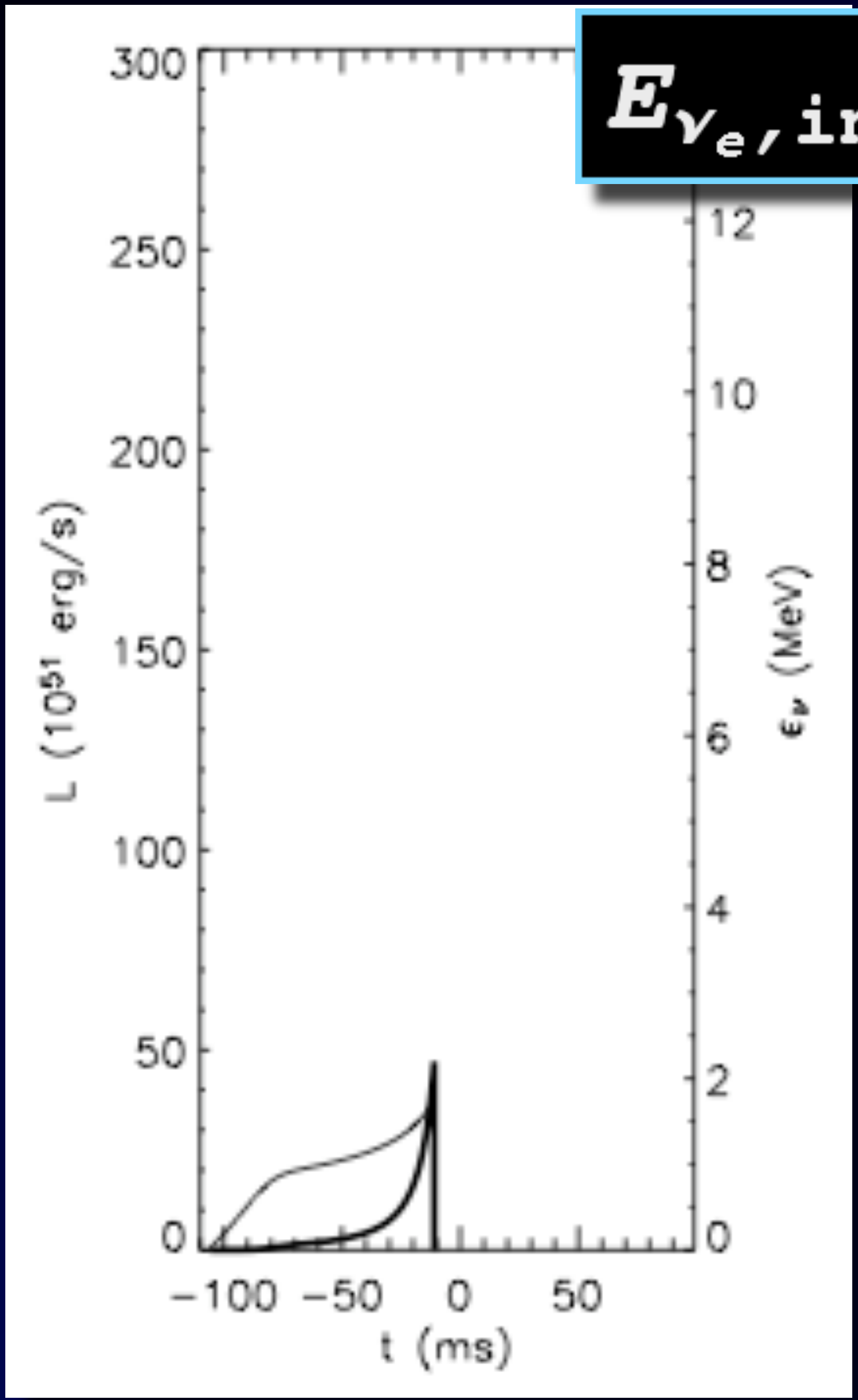

$E_{\nu_e,\mathrm{infall}} \approx 5.0 \times 10^{50}$ erg

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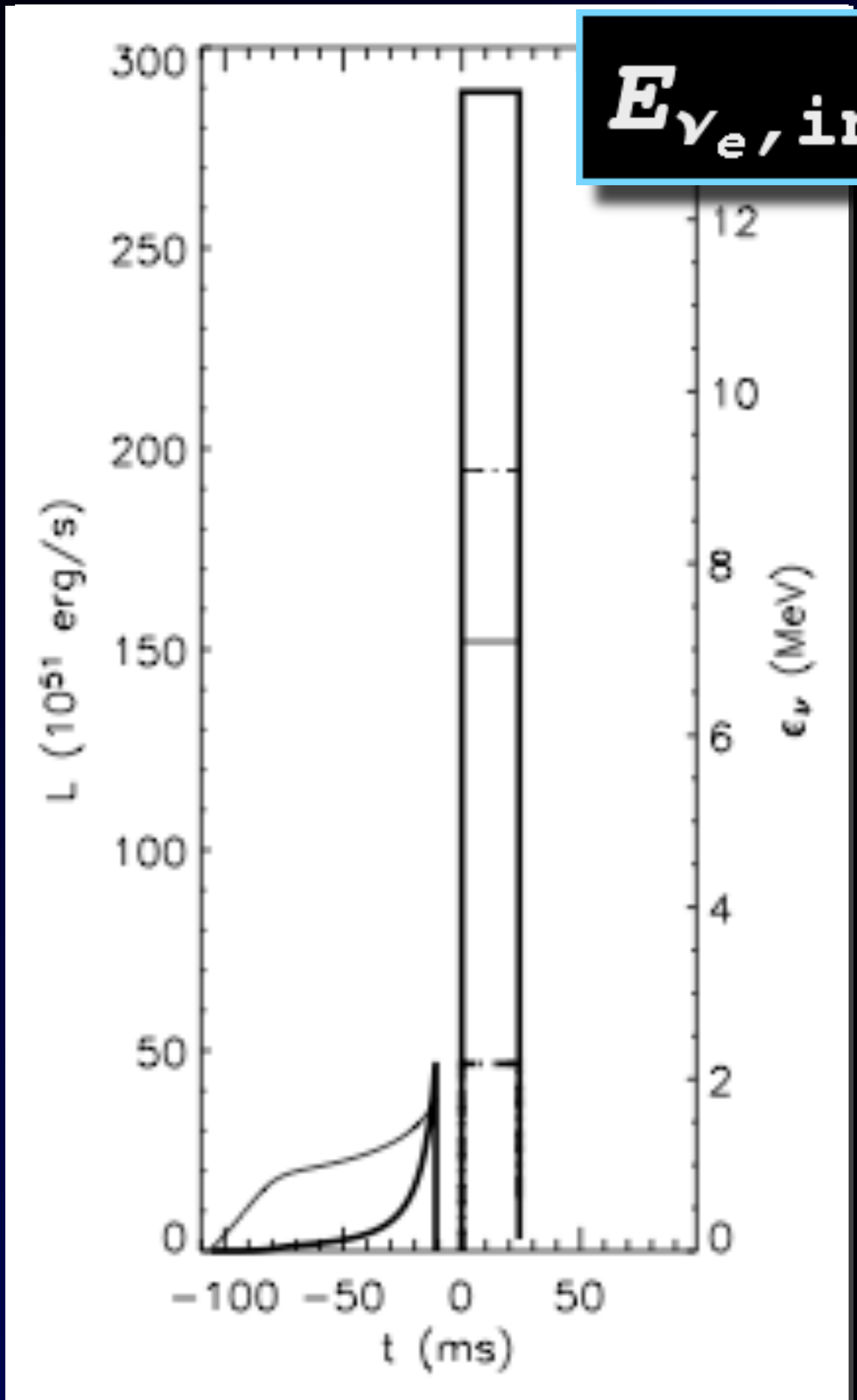

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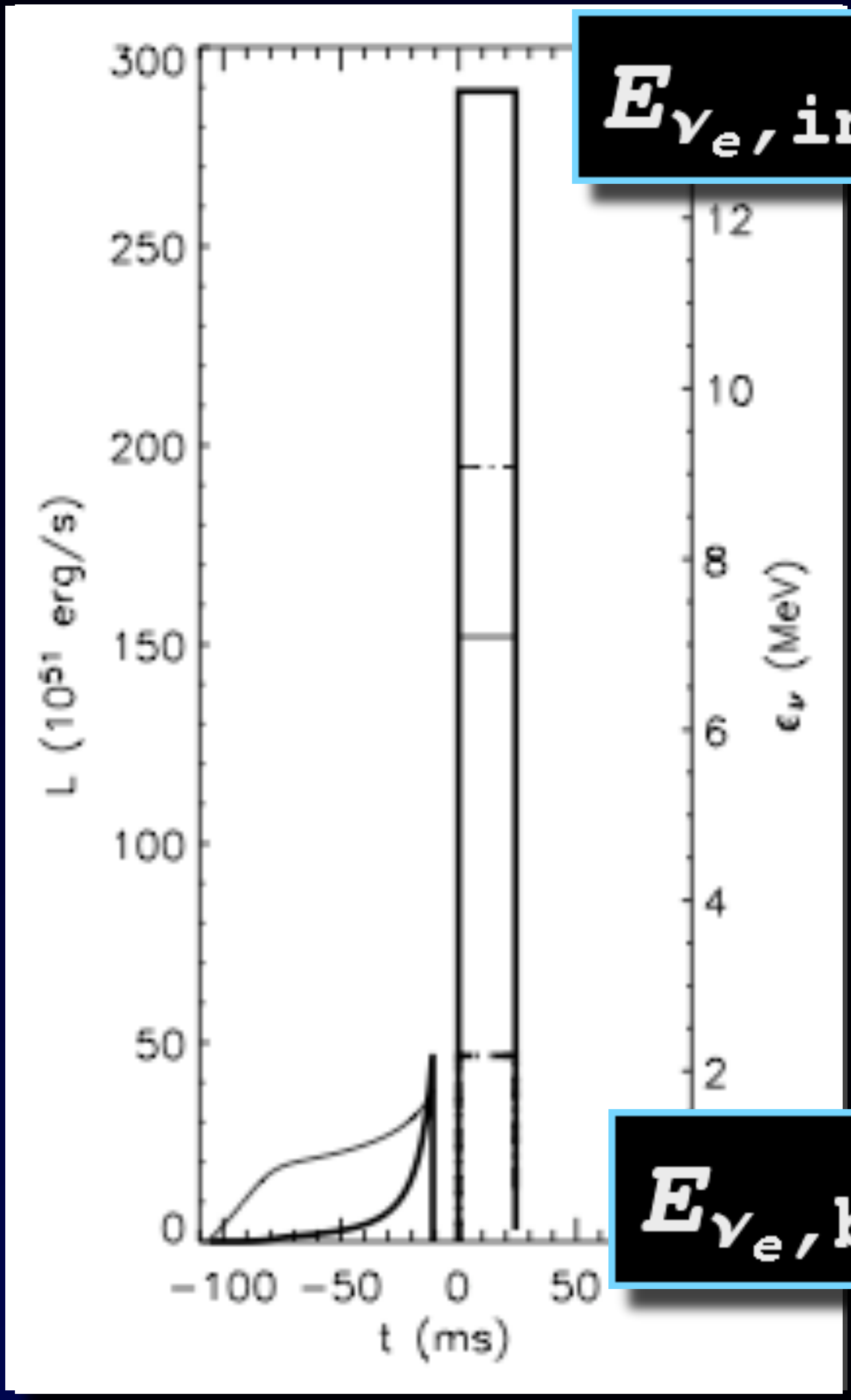

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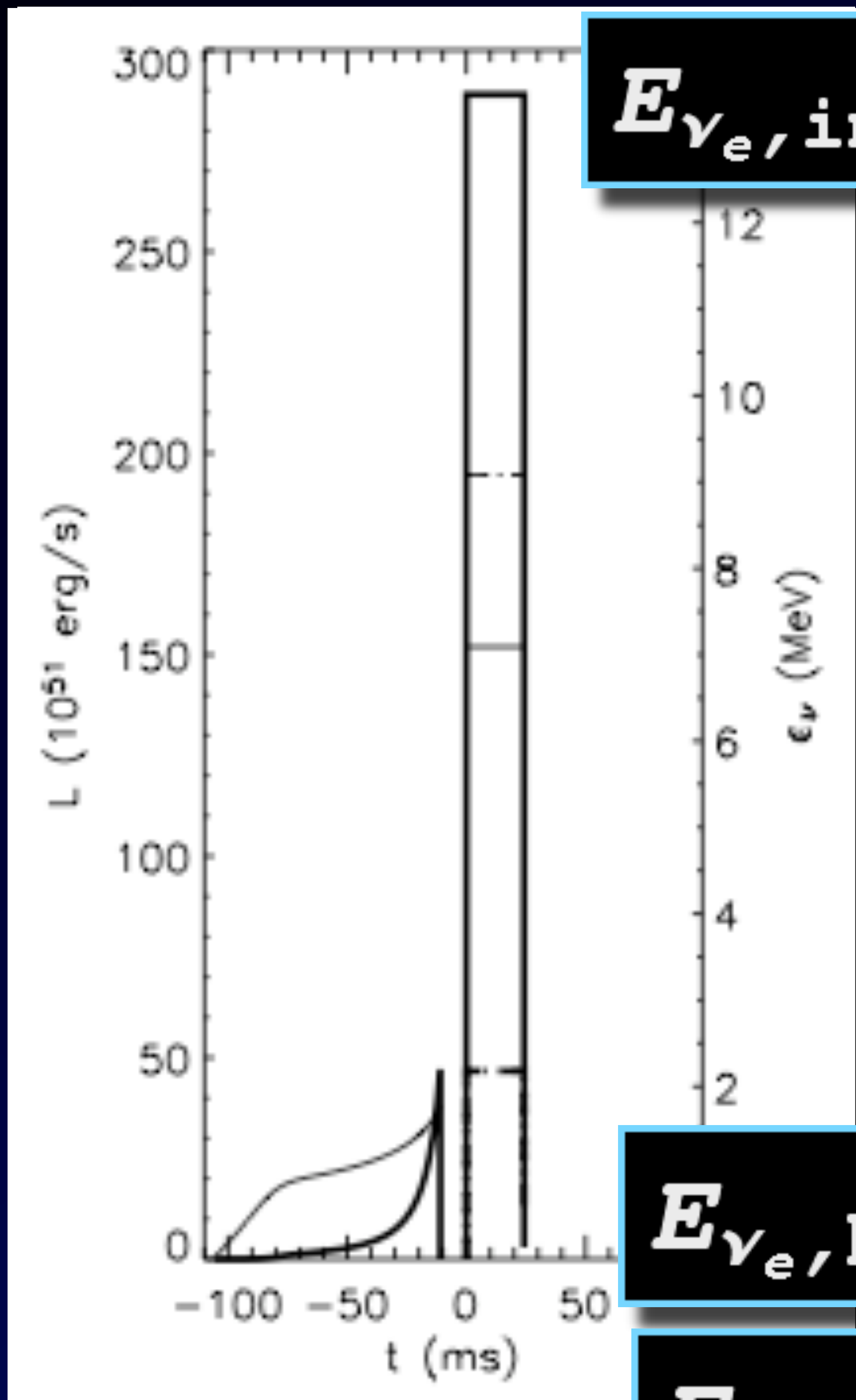

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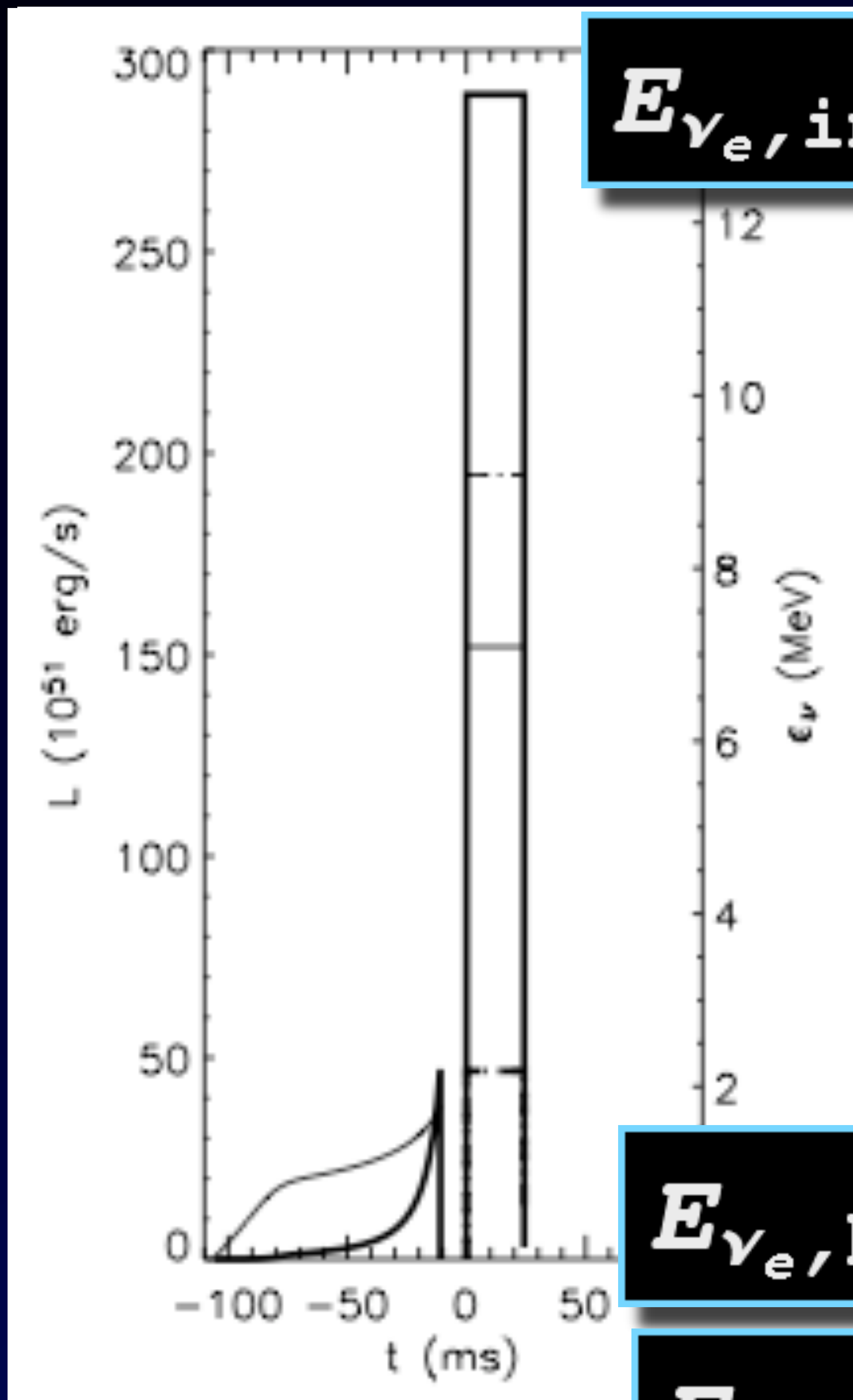

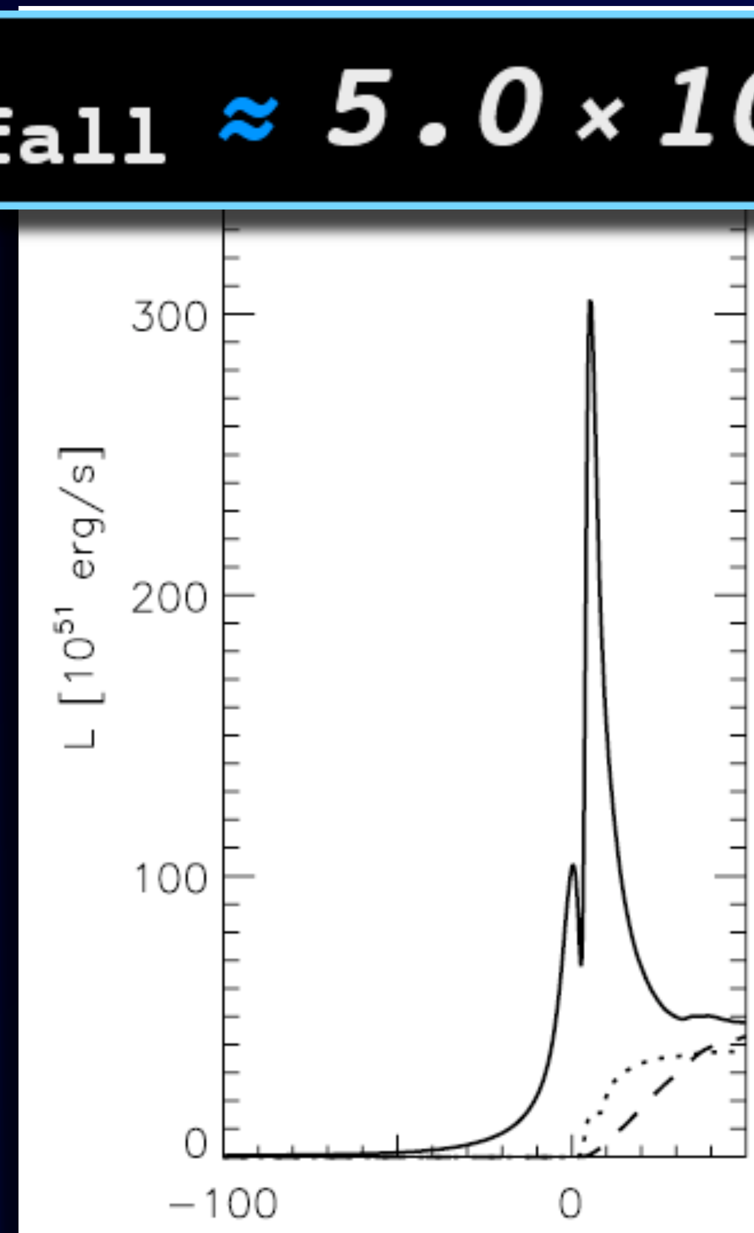

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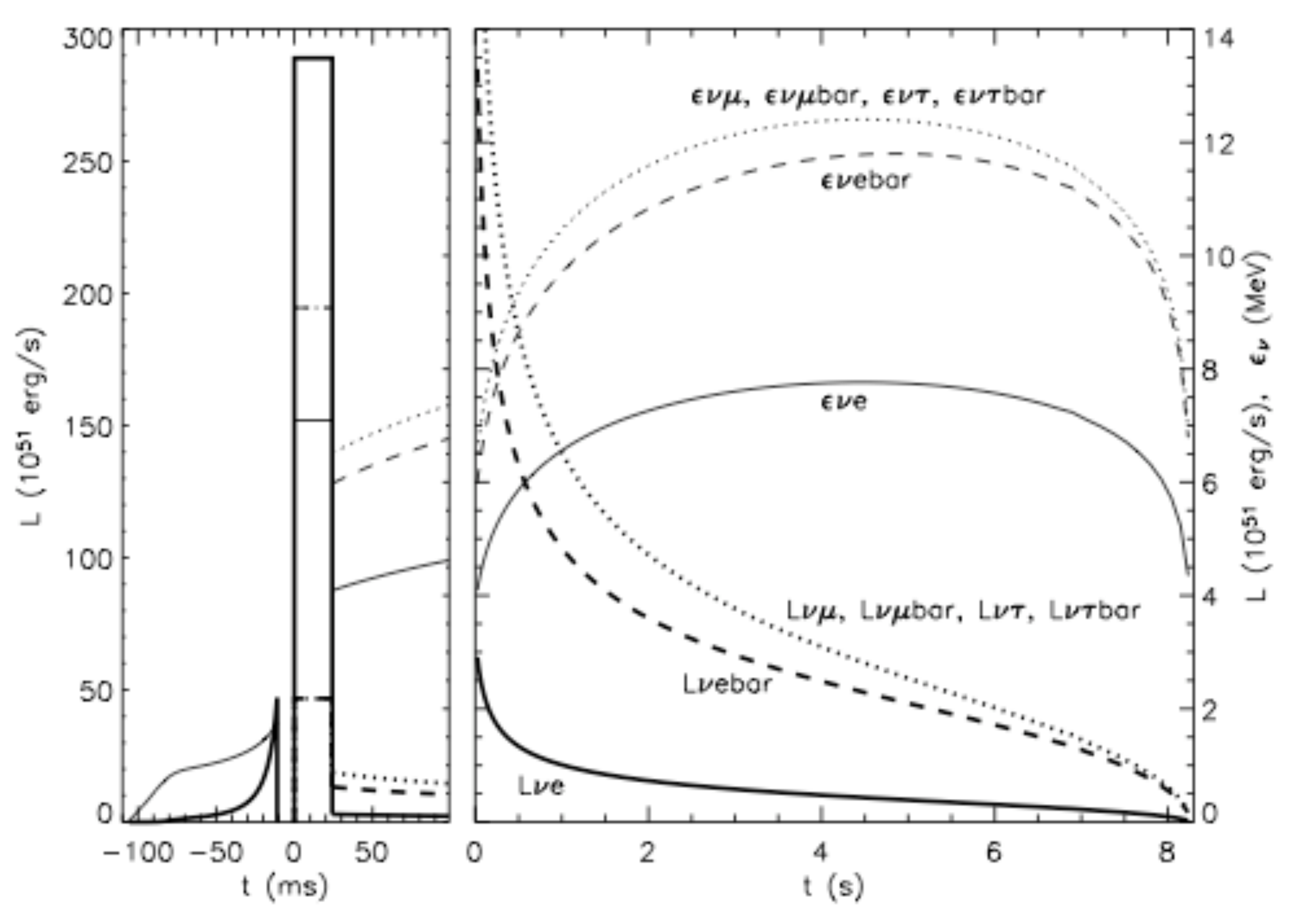
ν emission: Kelvin-Helmoltz contraction, final cooling



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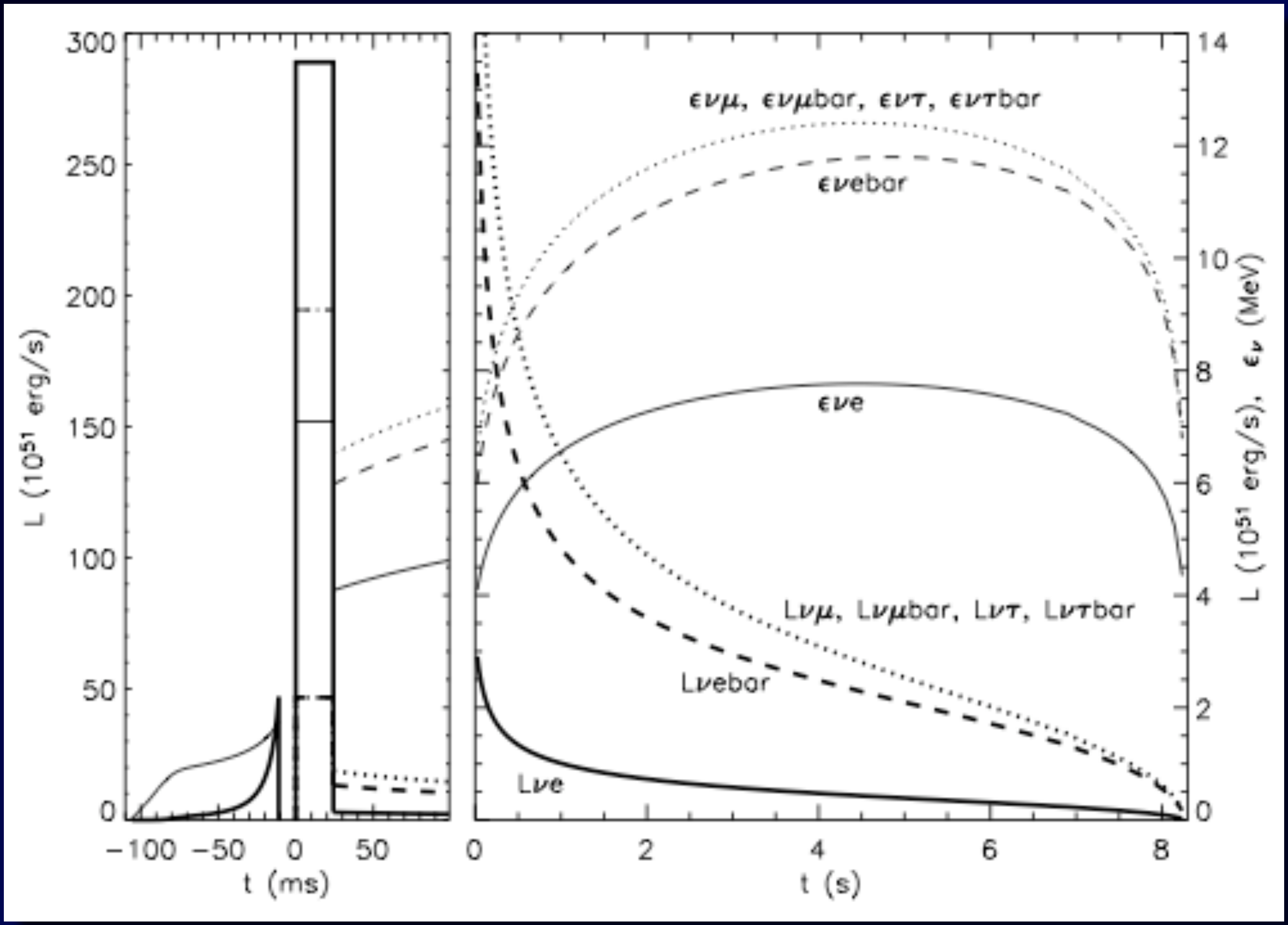

$$E_{\sum\nu,\mathrm{cooling}} \approx 1.5\times10^{53}\ \mathrm{erg}$$

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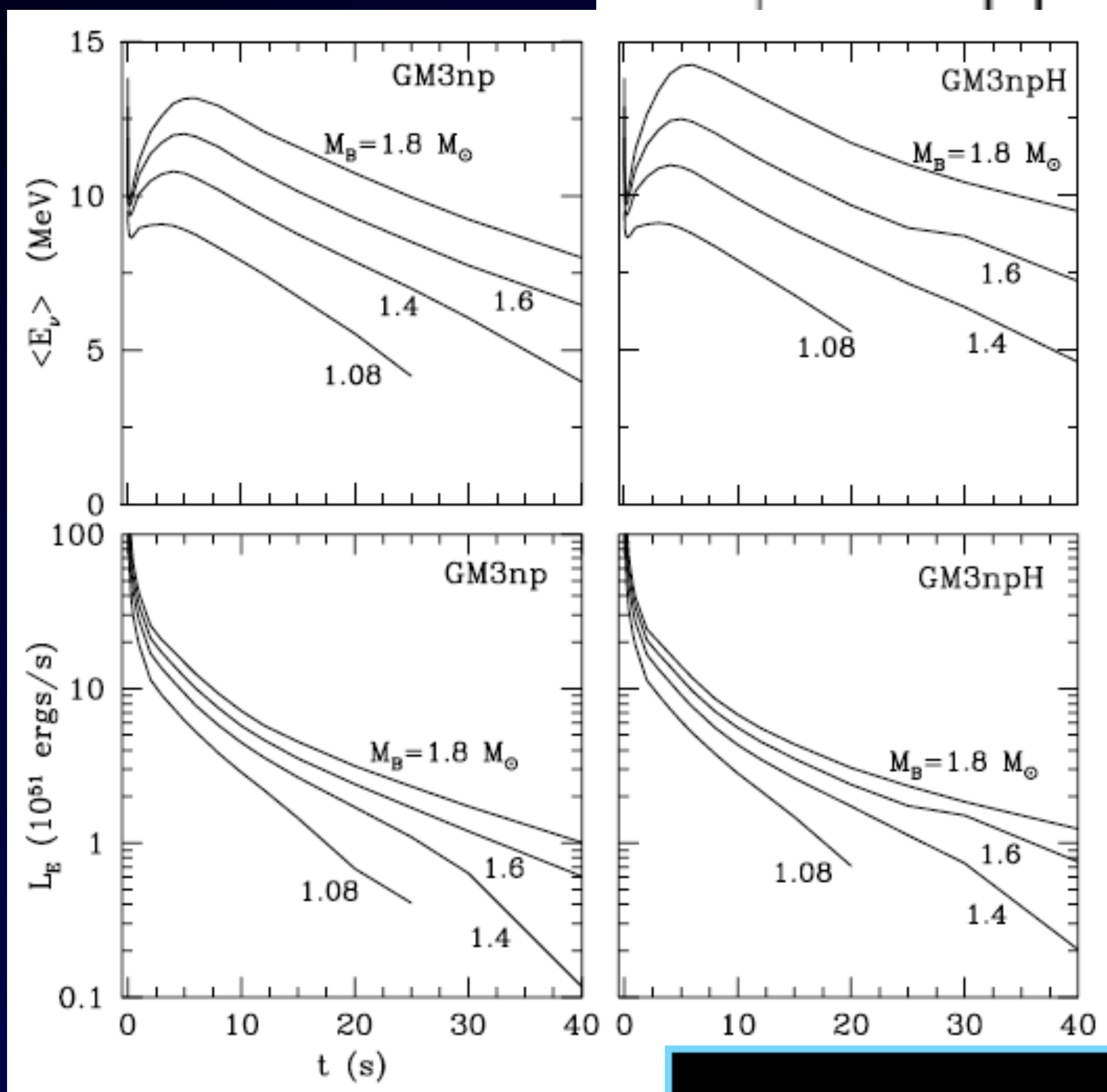

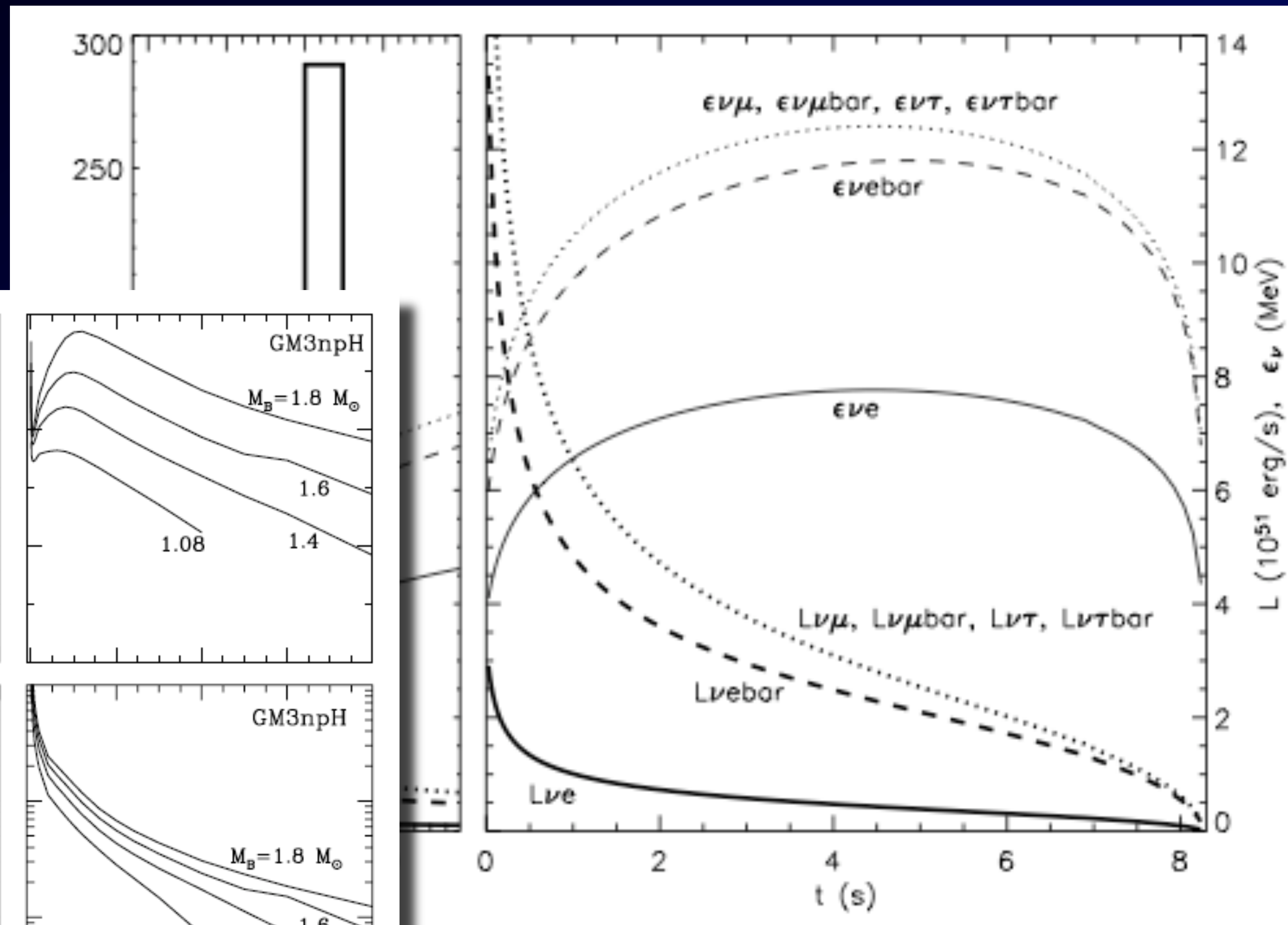

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What is a core-collapse supernova?

Can the central features be simply derived?

What is the explosion mechanism?

What about neutrino flavor mixing?

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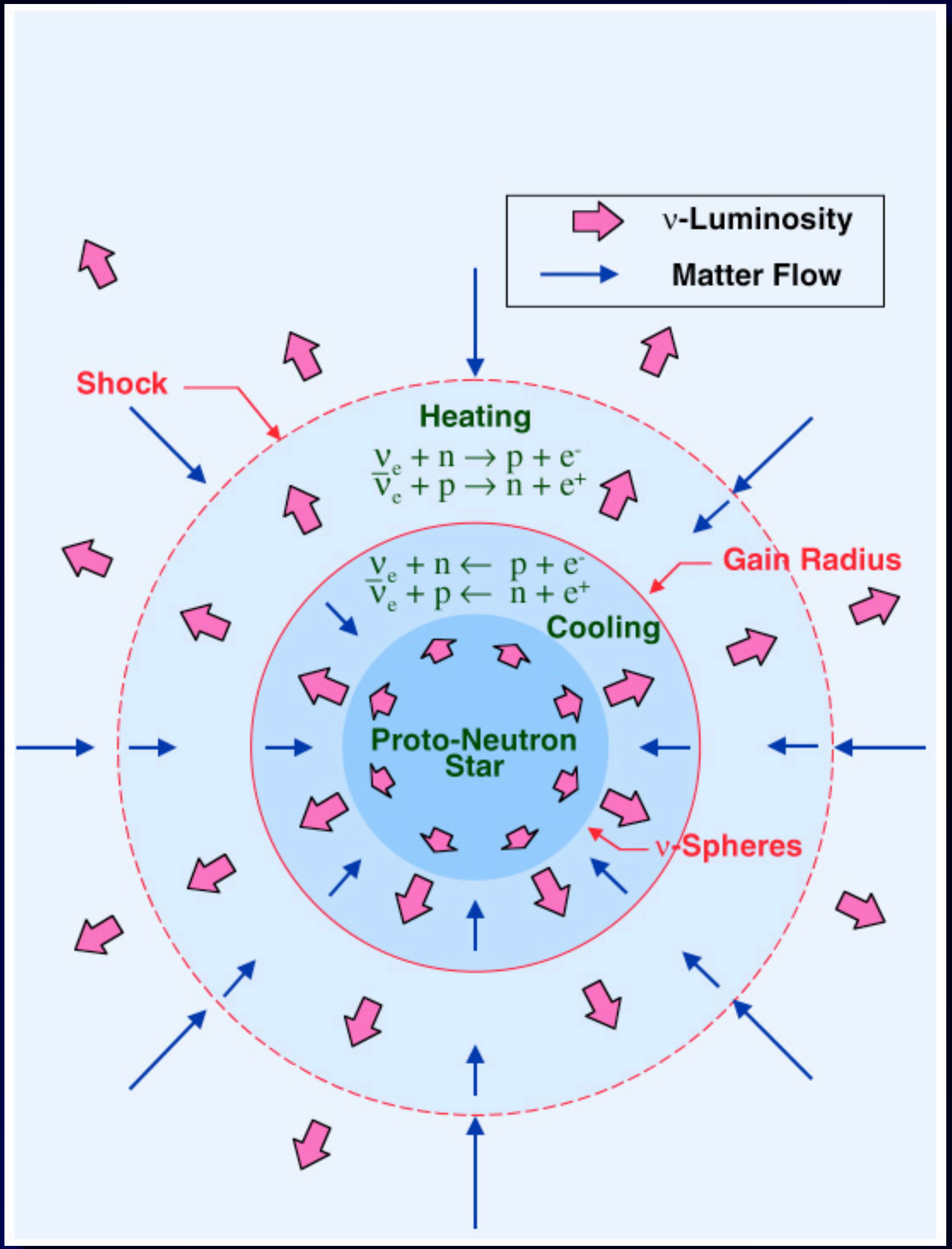

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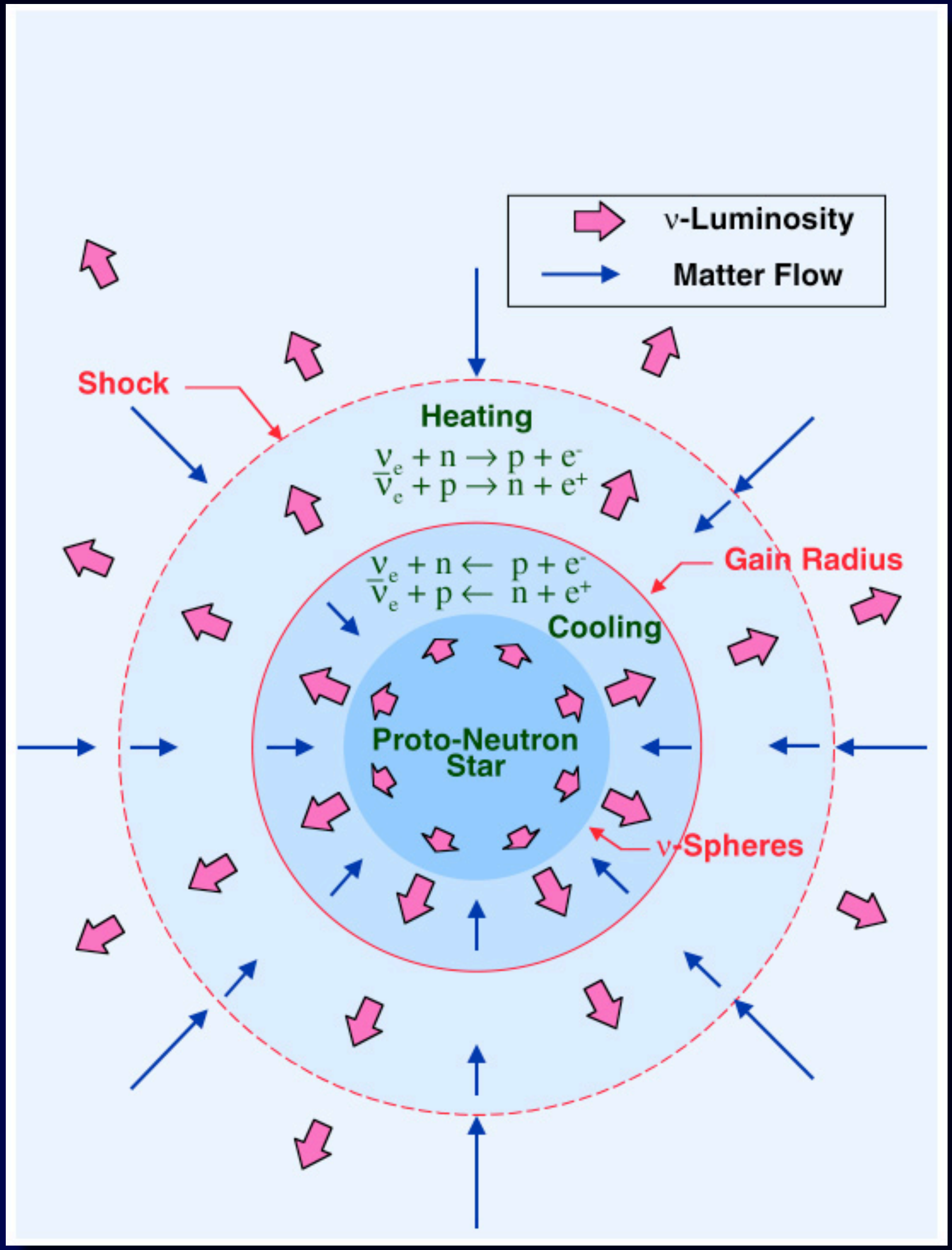

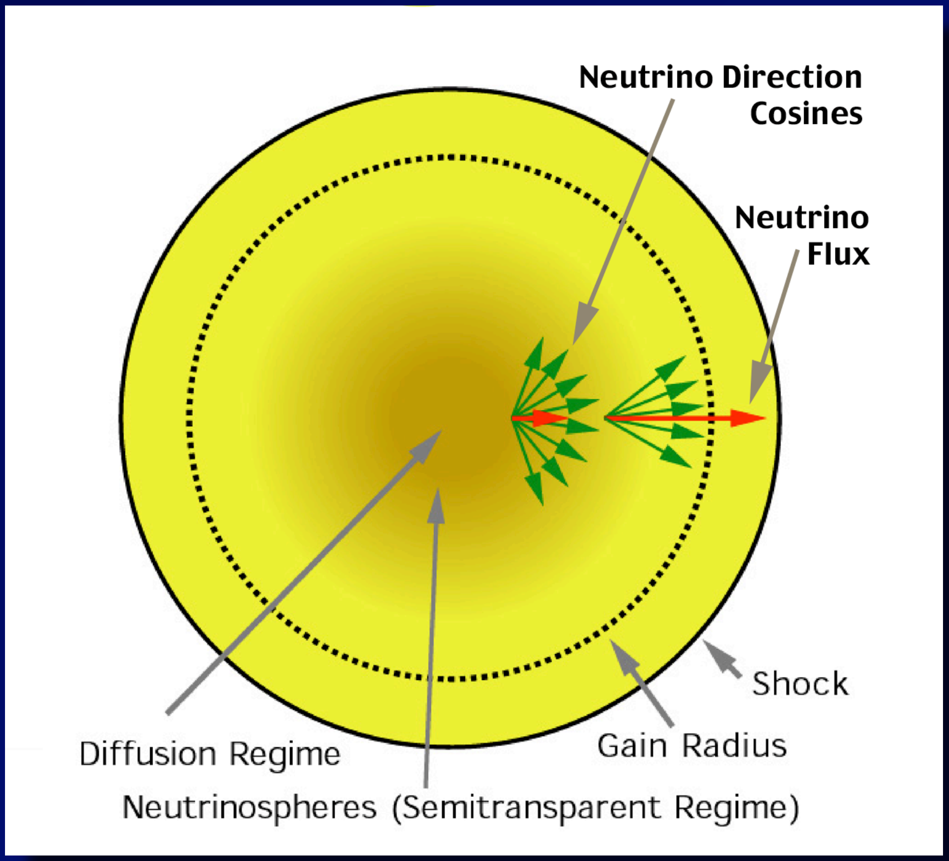

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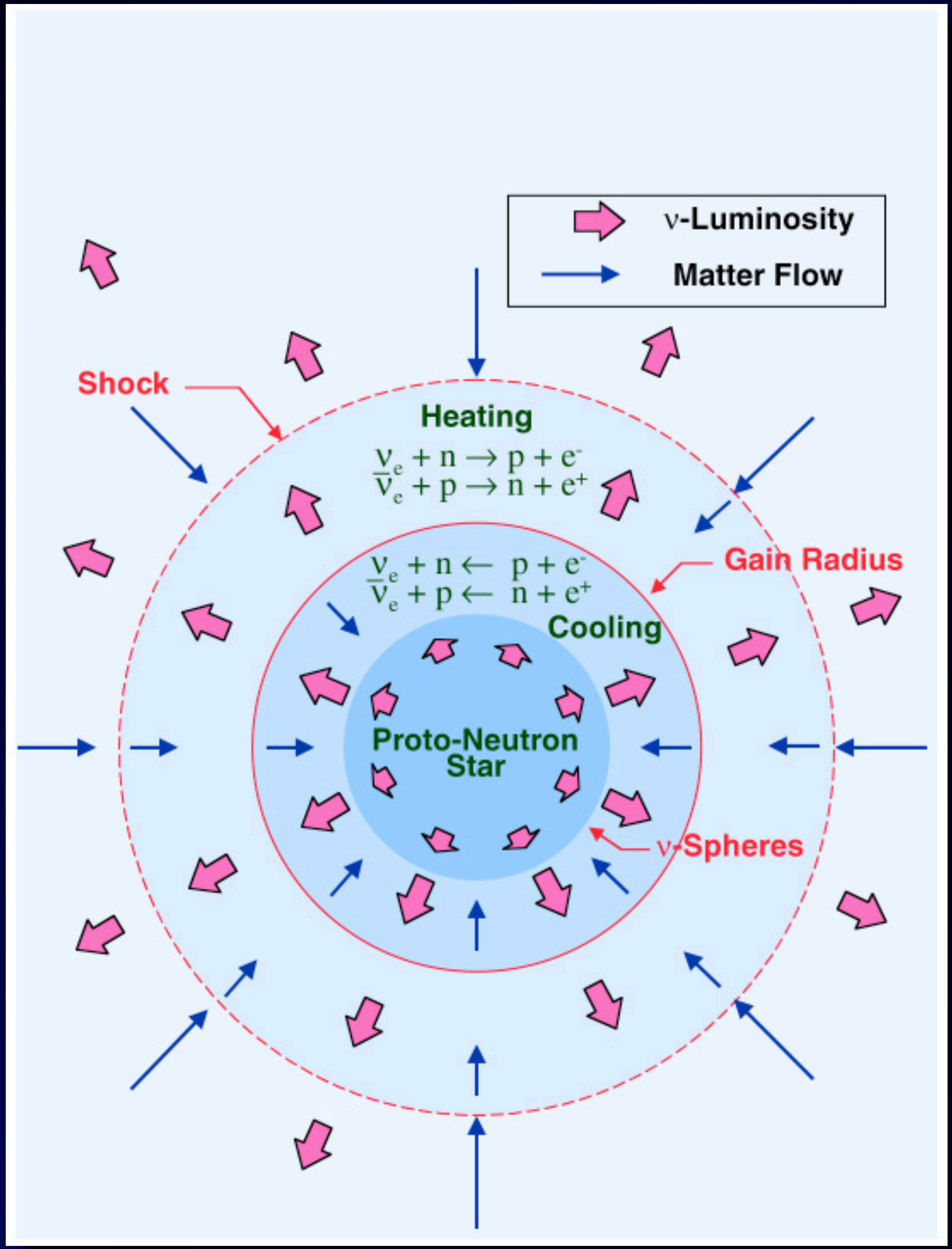
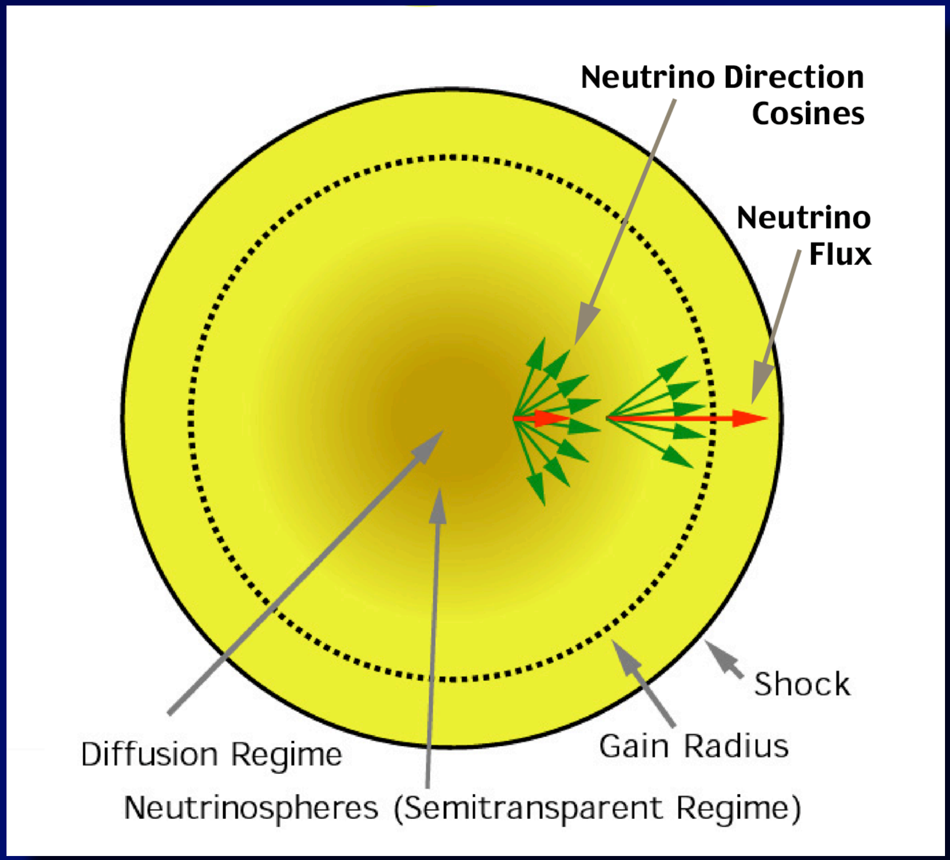


$$f(t, \mathbf{x}, \mathbf{p})$$



The challenge of high dimensionality

$f = f[t, \vec{x}, \vec{p}]$

f : several species

t : 10^6 time steps

$\vec{x}$: $256 \times 128 \simeq 3 \times 10^4$

$\vec{p}$: $32 \times 32 \times 32 \simeq 3 \times 10^4$

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$\vec{p}$: $32 \times 32 \times 32 \simeq 3 \times 10^4$

2D + 3D: solution vector of several 10^9 elements

3D + 3D: solution vector approaching 10^{12} elements

The challenge of high dimensionality

$$f = f[t, \vec{x}, \vec{p}]$$

f : several species

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The challenge of accuracy

$E_{explosion} \sim 10^{51}$ erg

$E_{neutrinos} \sim 10^{53}$ erg

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Careful numerical methods to simultaneously conserve energy and lepton number

Two observables, beyond explosion, related to ν transport:

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Accretion continues until the stalled shock is reinvigorated: relation between *neutron star mass* and *delay to explosion*

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Accretion continues until the stalled shock is reinvigorated: relation between *neutron star mass* and *delay to explosion*

The abundance of nuclei with a closed shell of 50 neutrons

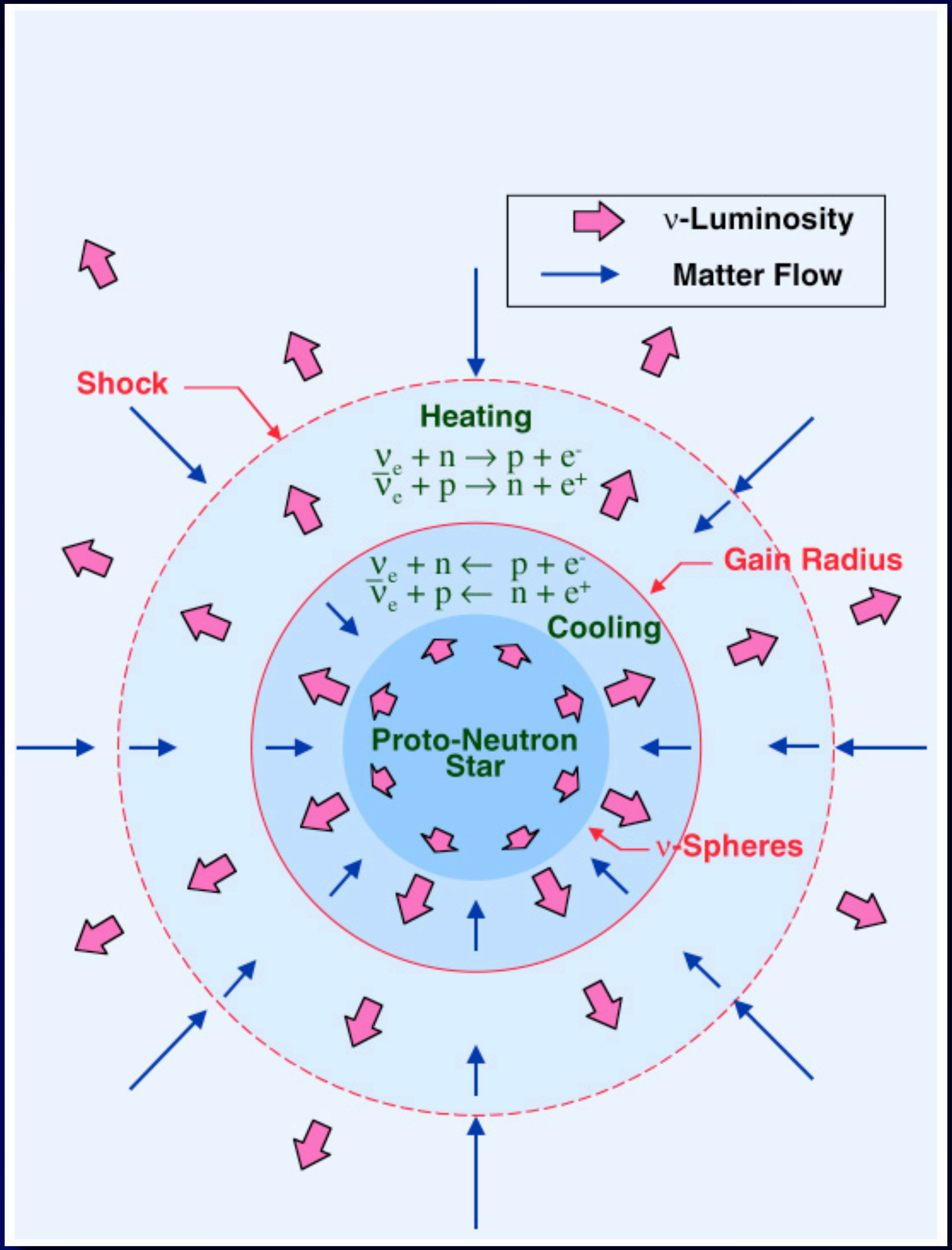
The electron fraction...

$$Y_e \equiv \frac{n_{e^-} - n_{e^+}}{n_{\mathrm{baryons}}} \approx \frac{n_{\mathrm{proton}}}{n_{\mathrm{proton}} + n_{\mathrm{neutron}}}$$

...is set by ν interactions:

$$\nu_e + n \leftrightarrow p + e^-$$
$$\bar{\nu}_e + p \leftrightarrow n + e^+$$

Proto neutron star convection



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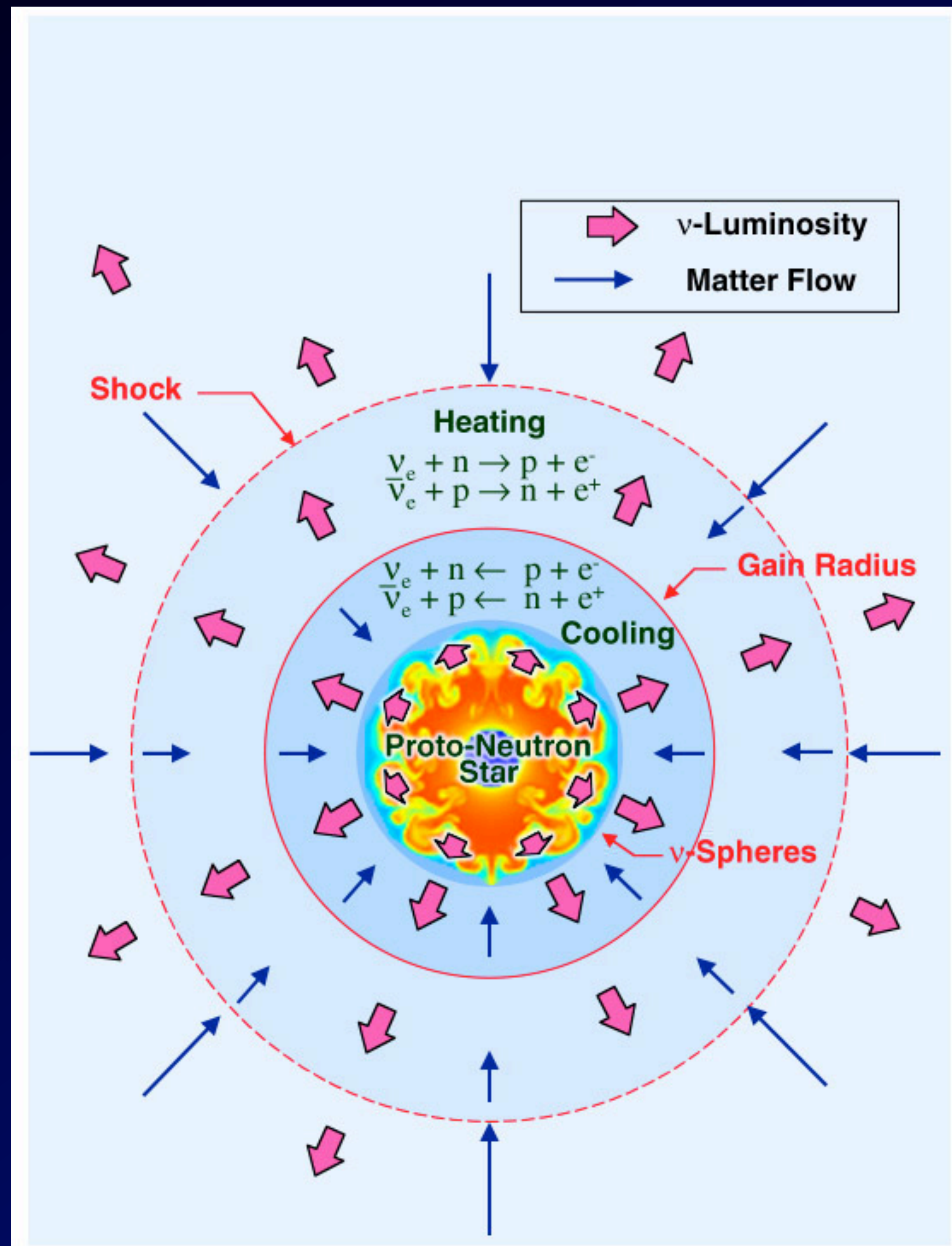

Fluid dynamics:

"1.5D"

Neutrino transport:

1D + 1D

Fluid dynamics:
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Neutrino transport:
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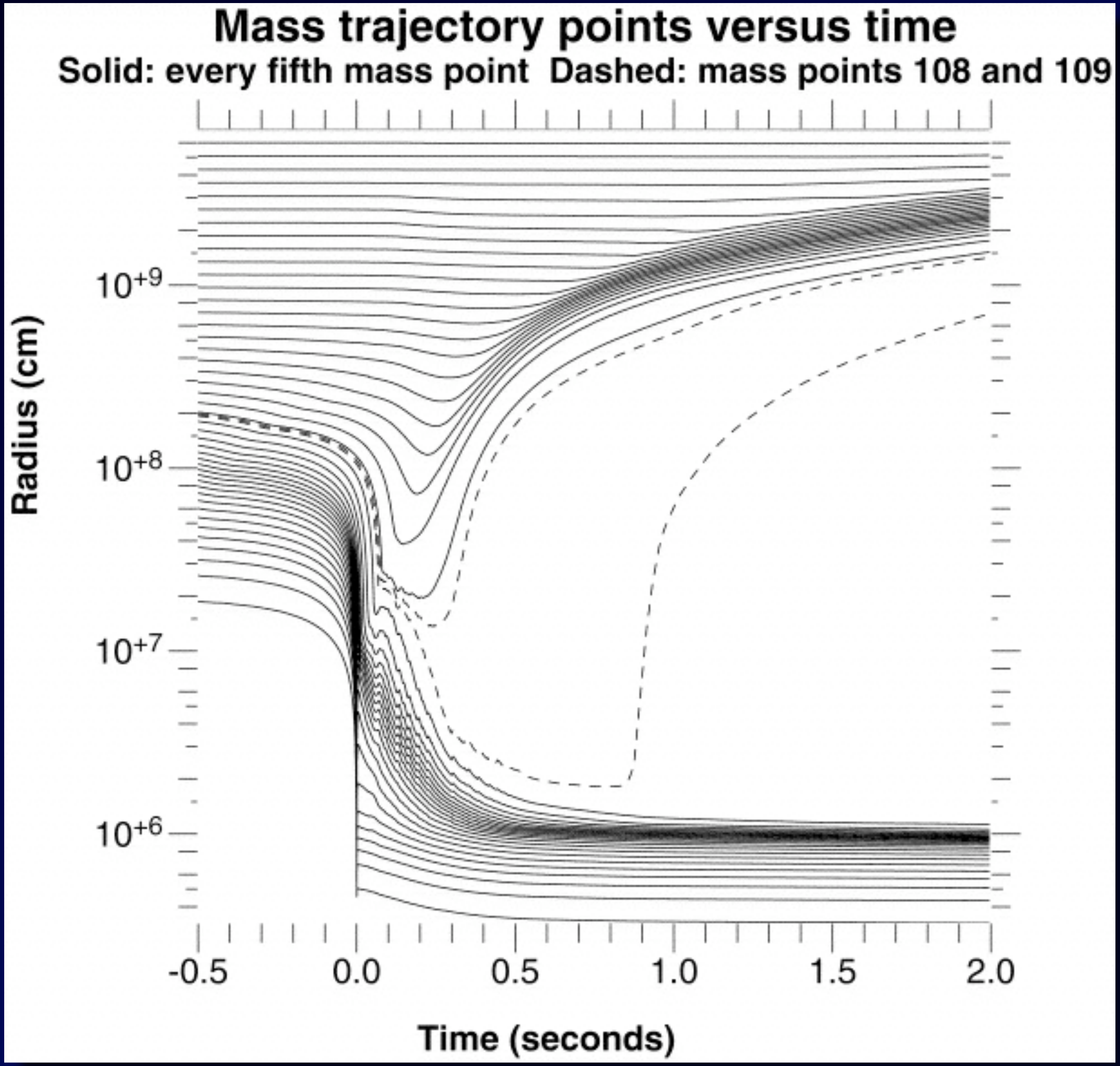

Totani, Sato, Dalhed, & Wilson (1998)

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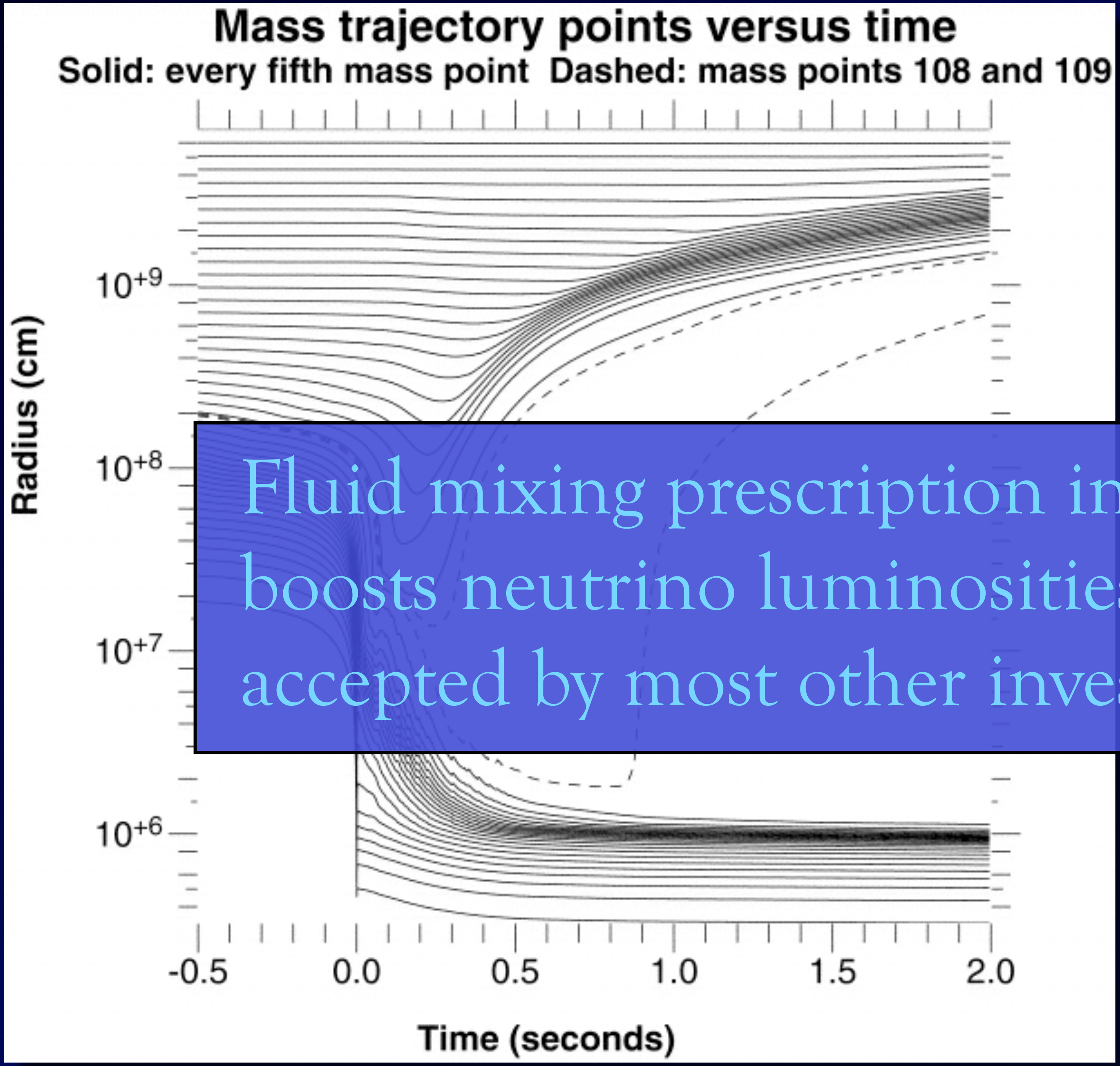
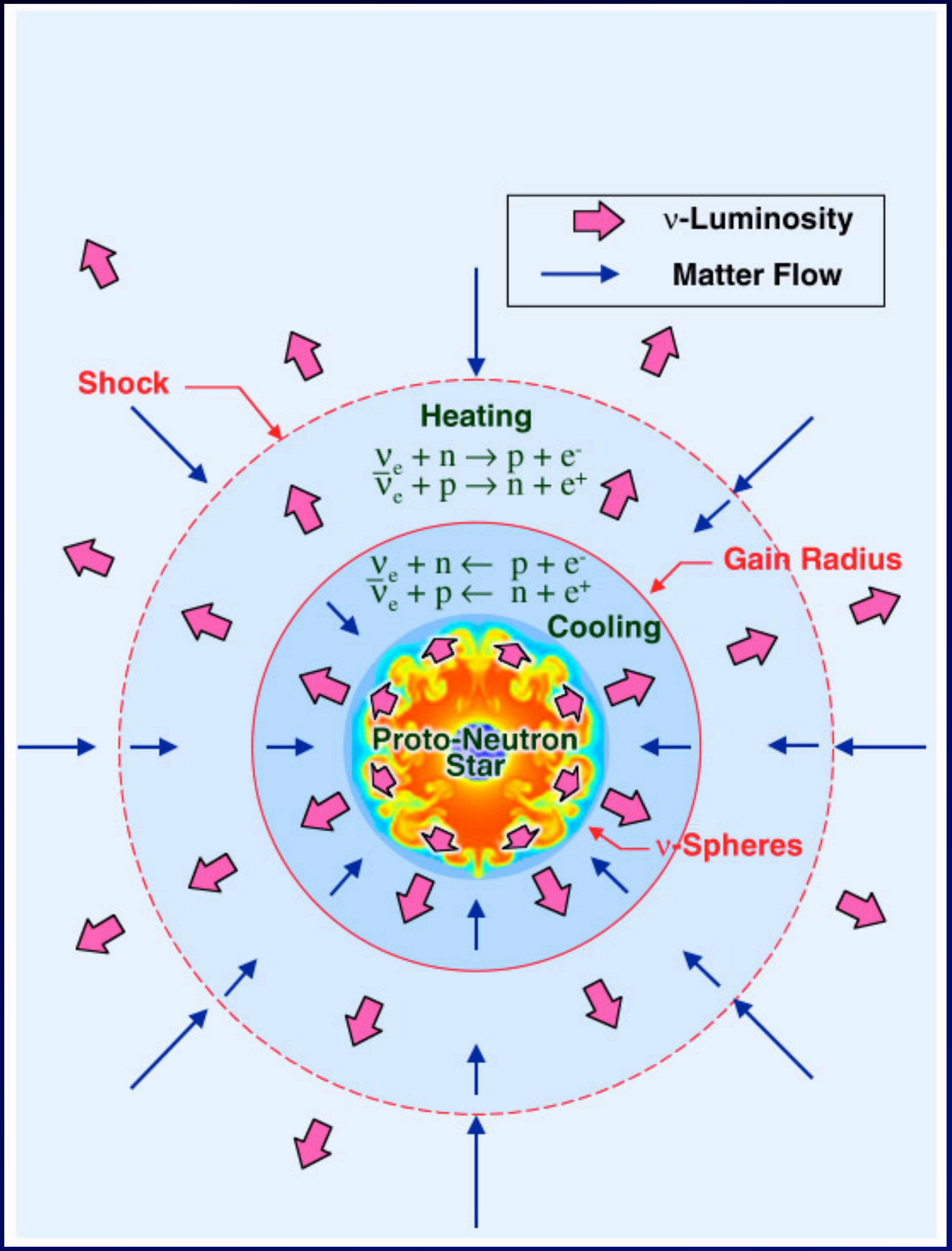


Totani, Sato, Dalhed, & Wilson (1998)

Fluid mixing prescription in the core boosts neutrino luminosities; not accepted by most other investigators

Post-shock convection



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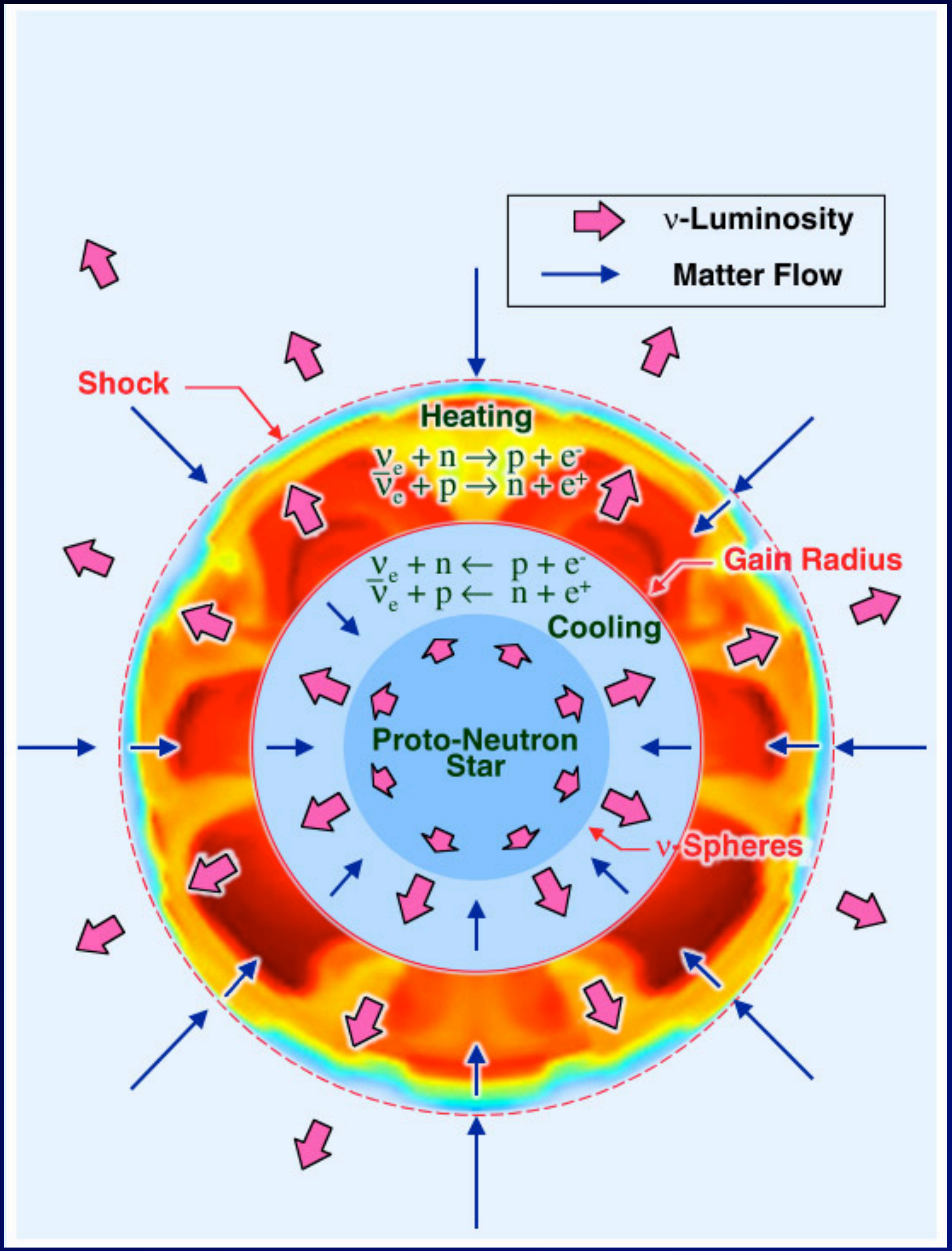

Fluid dynamics:

2D

Neutrino transport:

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Fluid dynamics:
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Neutrino transport:
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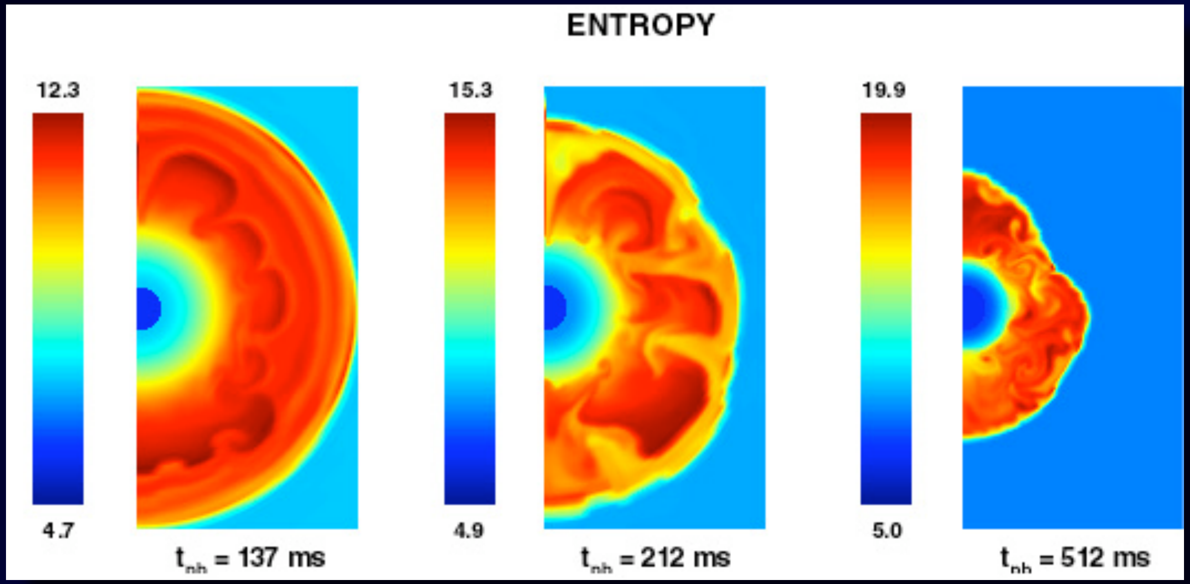
Mezzacappa et al. (1998)



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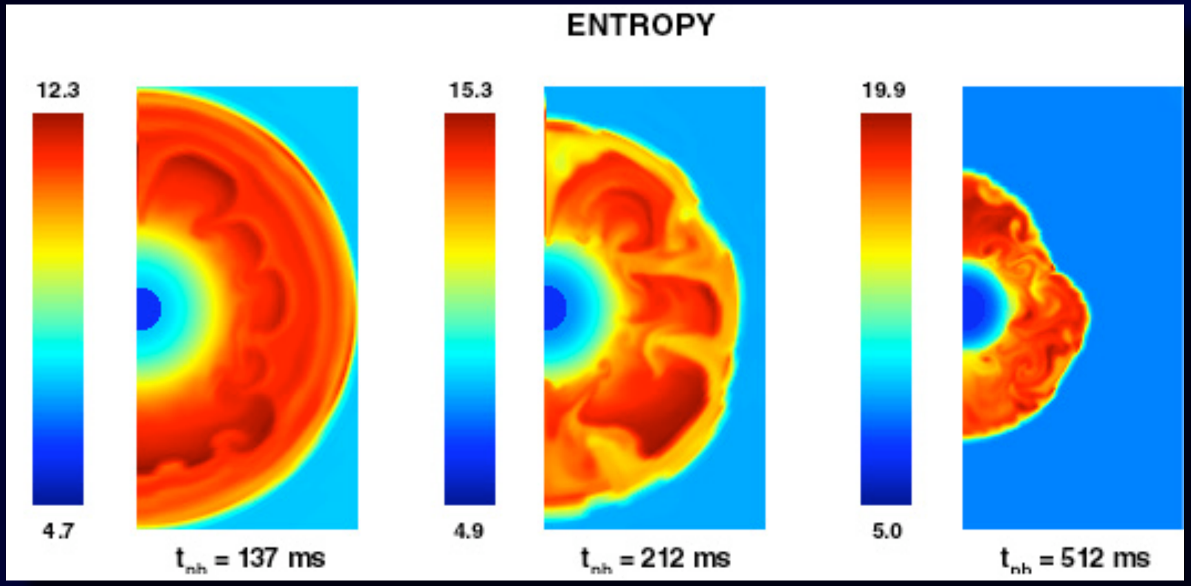


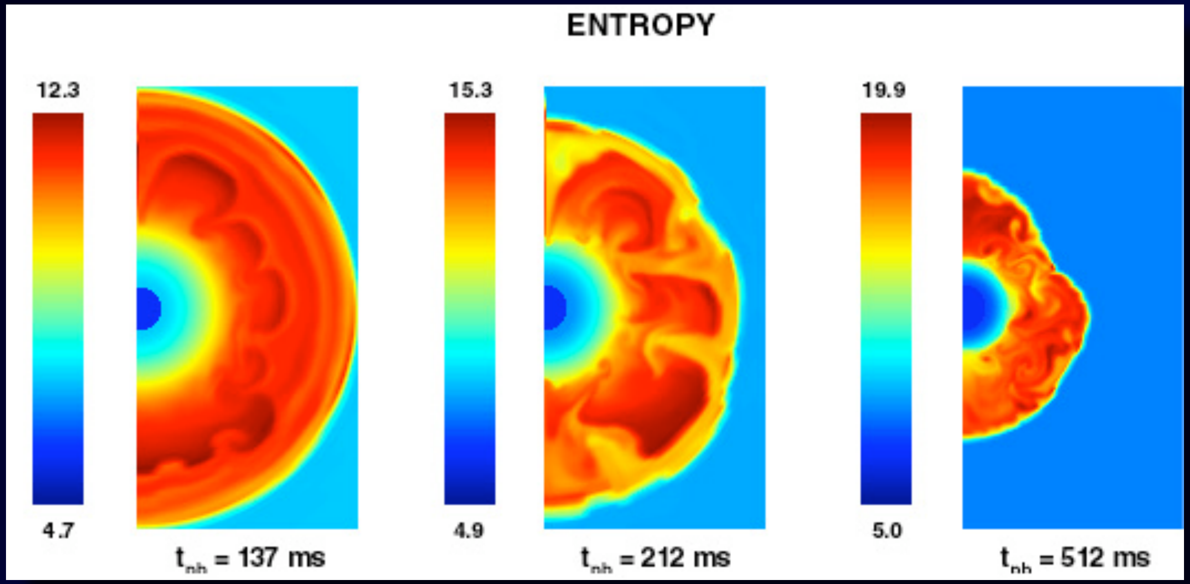
Fluid dynamics:
2D, 3D

Neutrino transport:
2D + 0D, 3D + 0D

Fluid dynamics:
2D

Neutrino transport:
1D + 1D

Mezzacappa et al. (1998)



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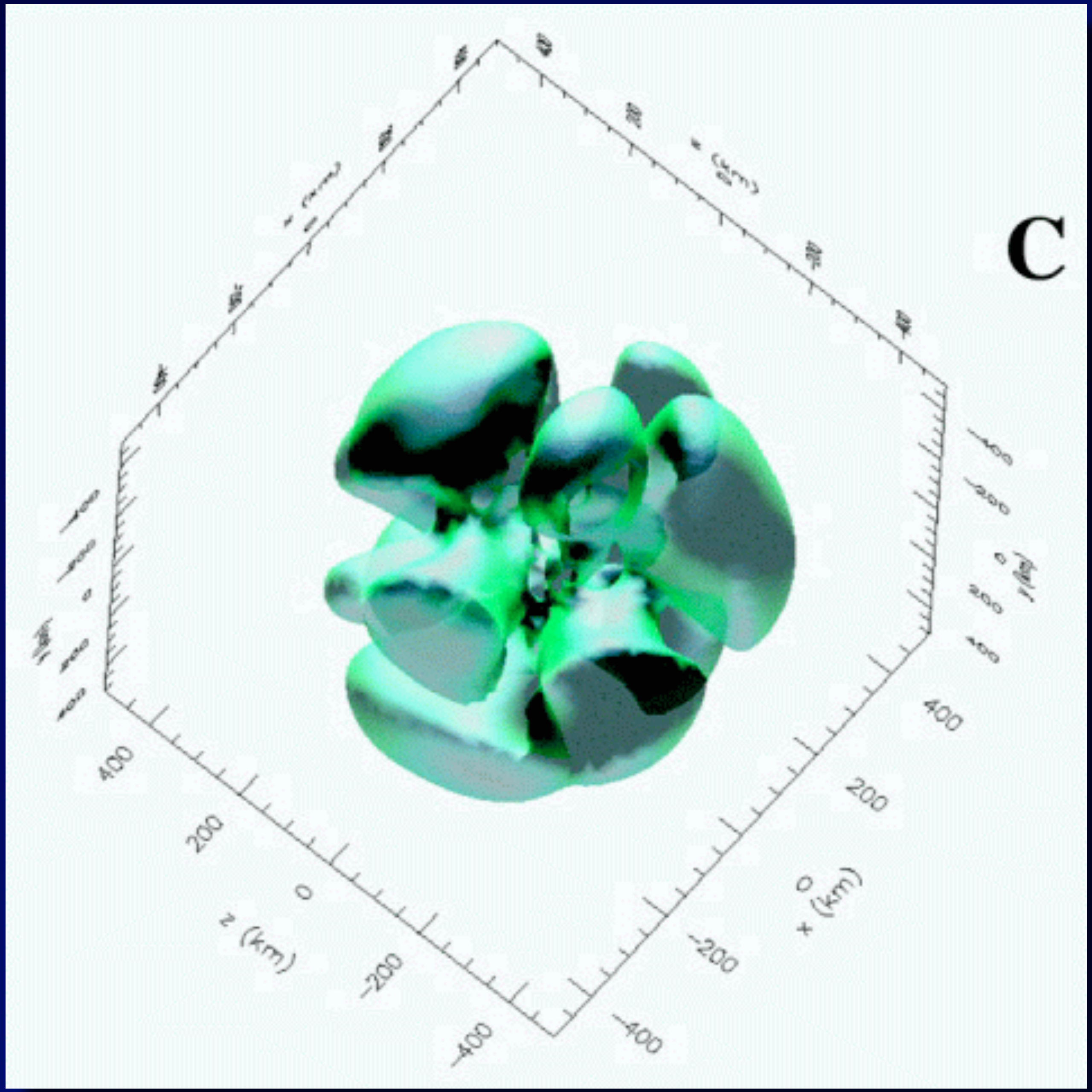
Fryer & Warren (2002)



Fluid dynamics:
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Neutrino transport:
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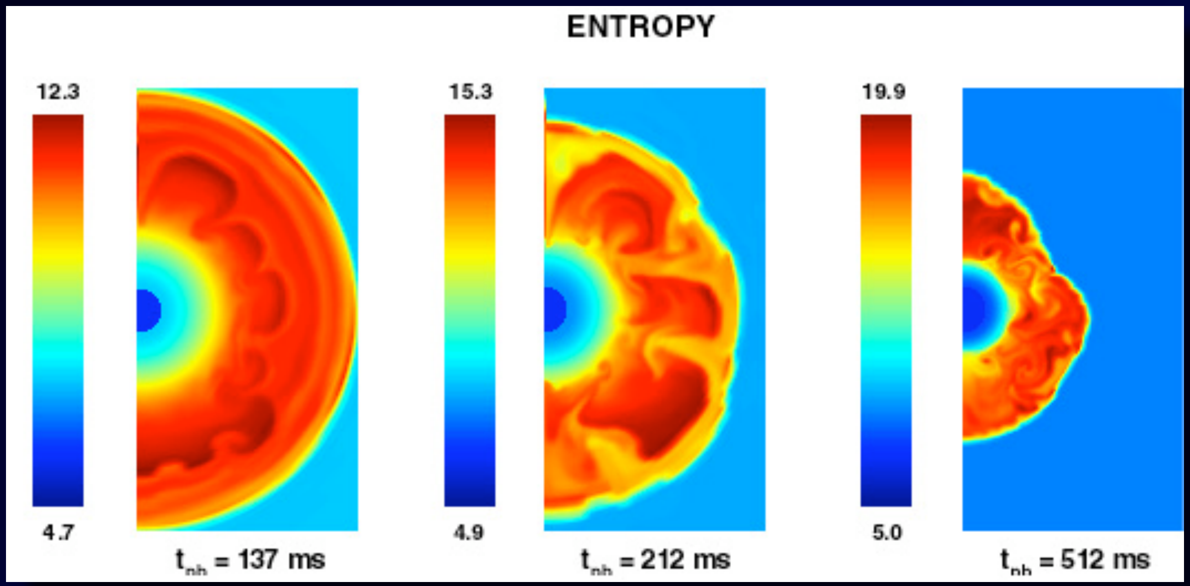


Fluid dynamics:
2D, 3D

Neutrino transport:
2D + 0D, 3D + 0D

Fryer & Warren (2002)

Neutron star mass too small; heating drives explosion too soon.

N=50 overproduction; Y_e too low.

Fluid dynamics:

1D

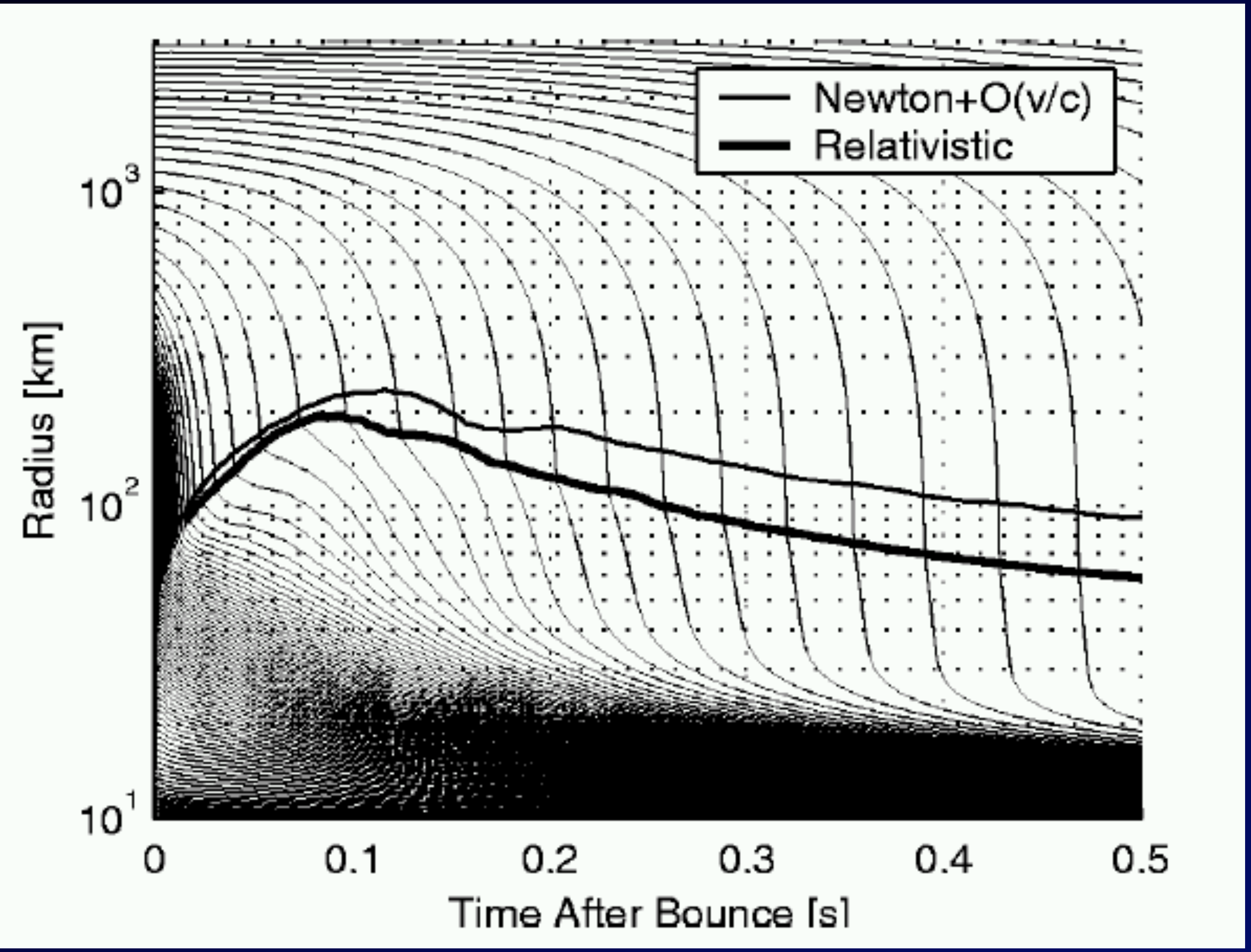
Neutrino transport:

1D + 2D

Fluid dynamics:
1D

Neutrino transport:
1D + 2D

Liebendörfer et al.
(2001, 2004)



Fluid dynamics:
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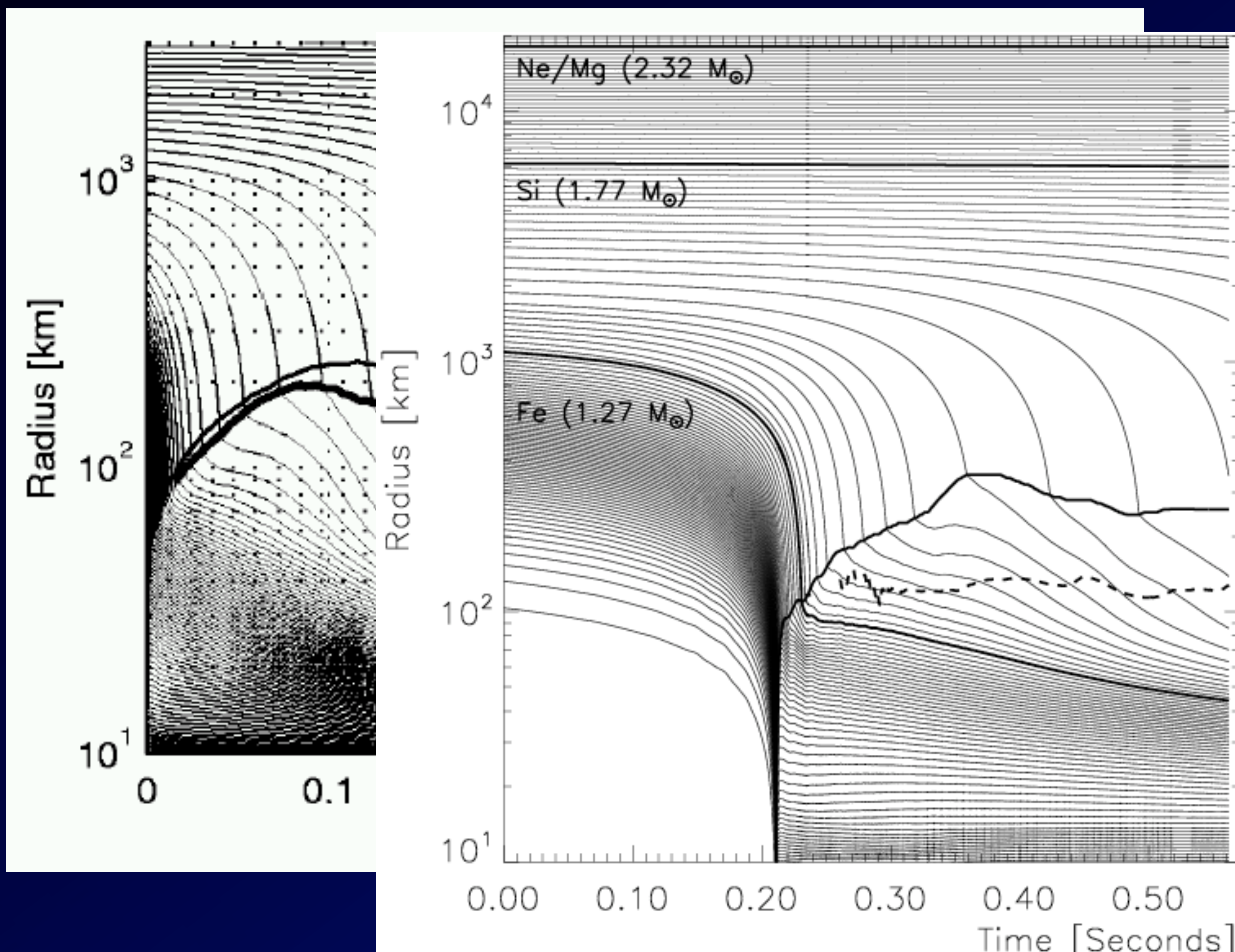

Rampp & Janka (2000, 2002)

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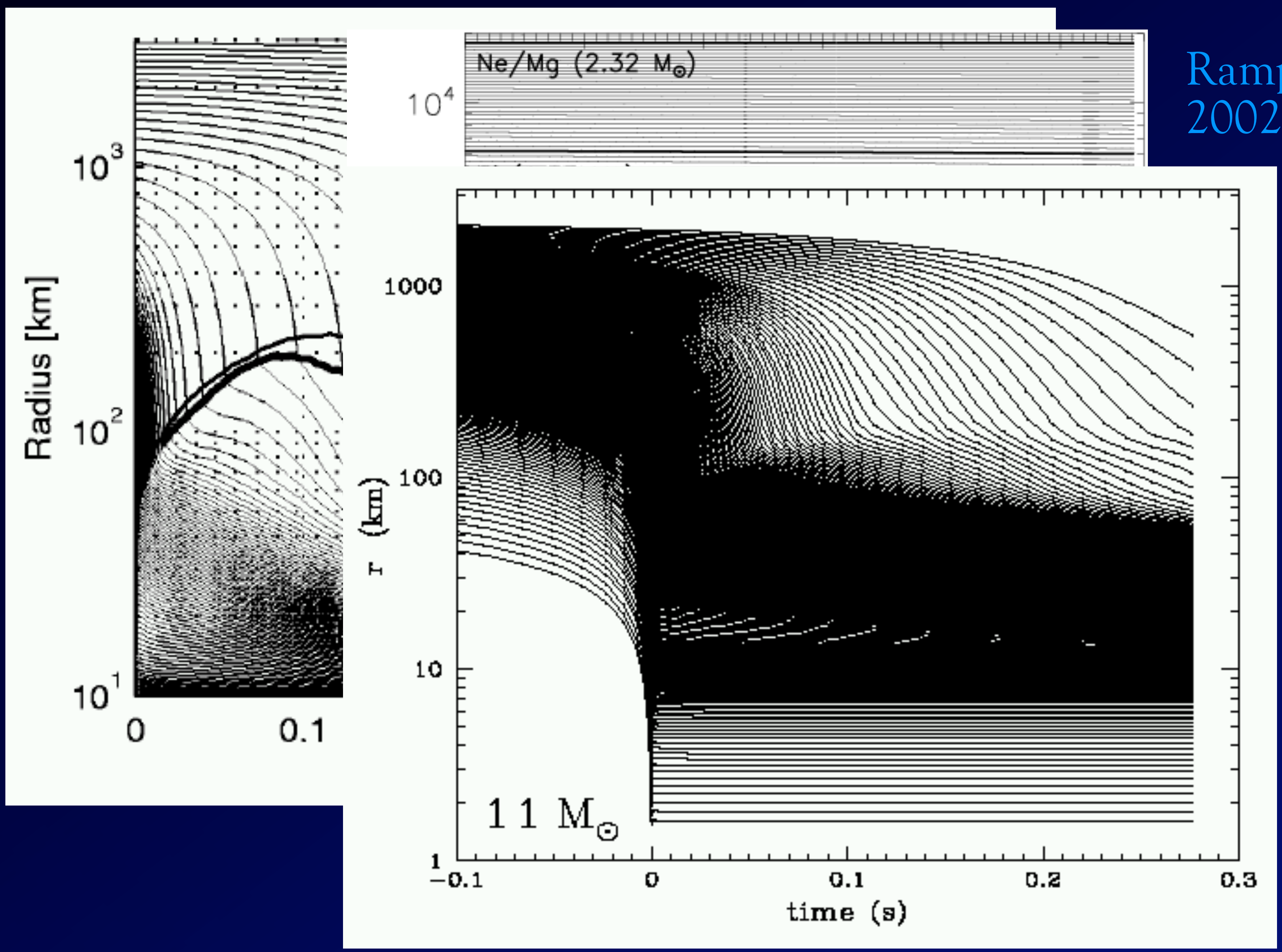

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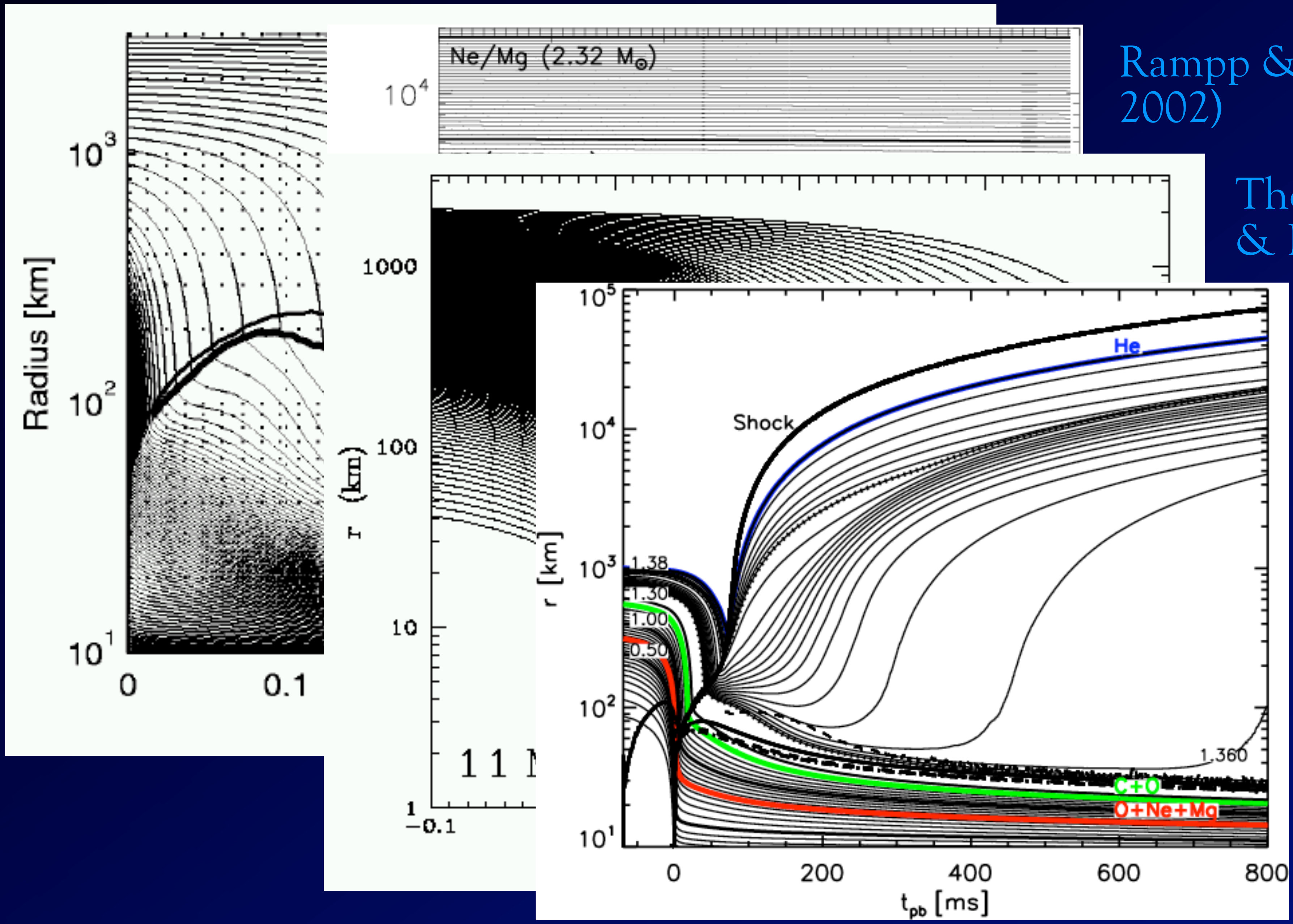

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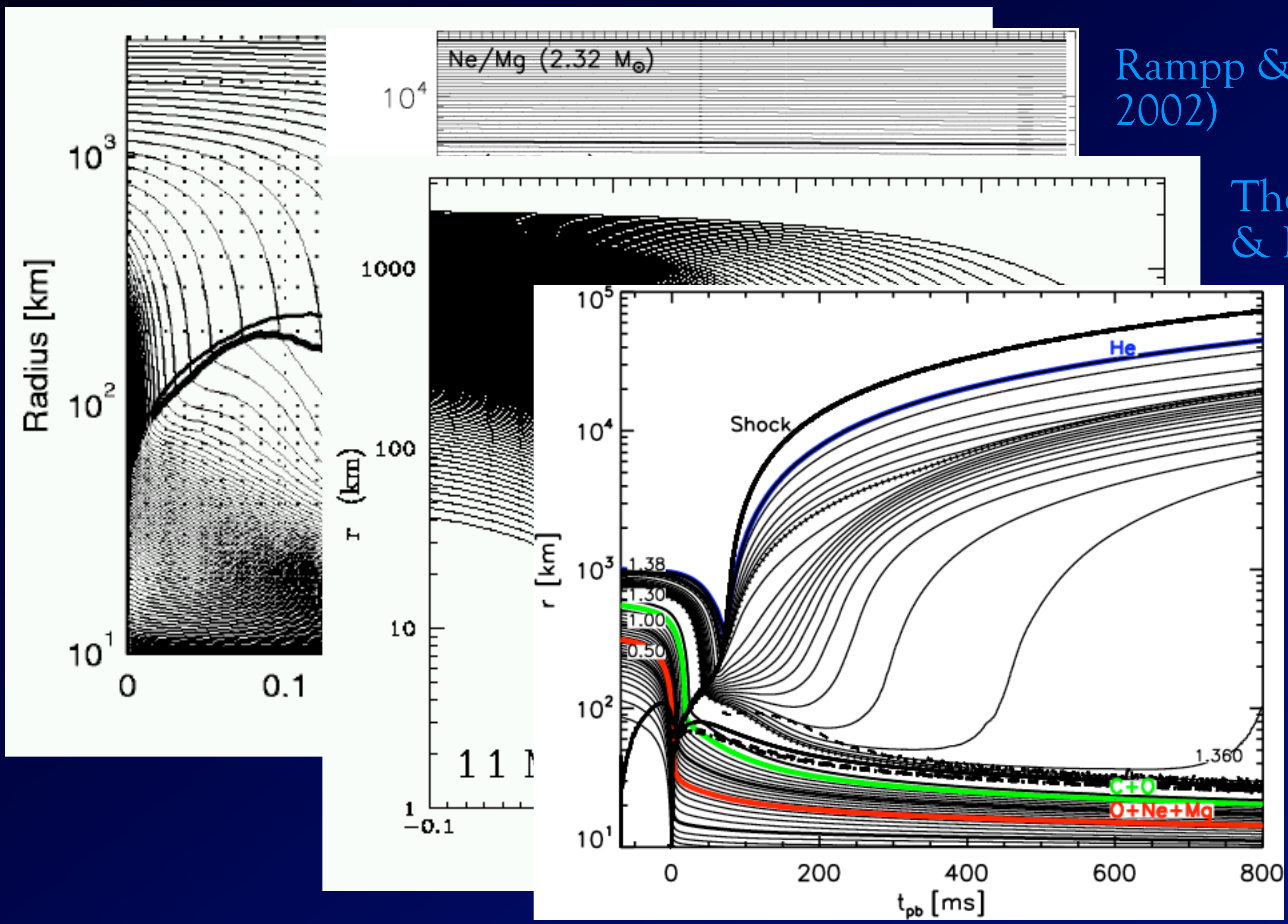

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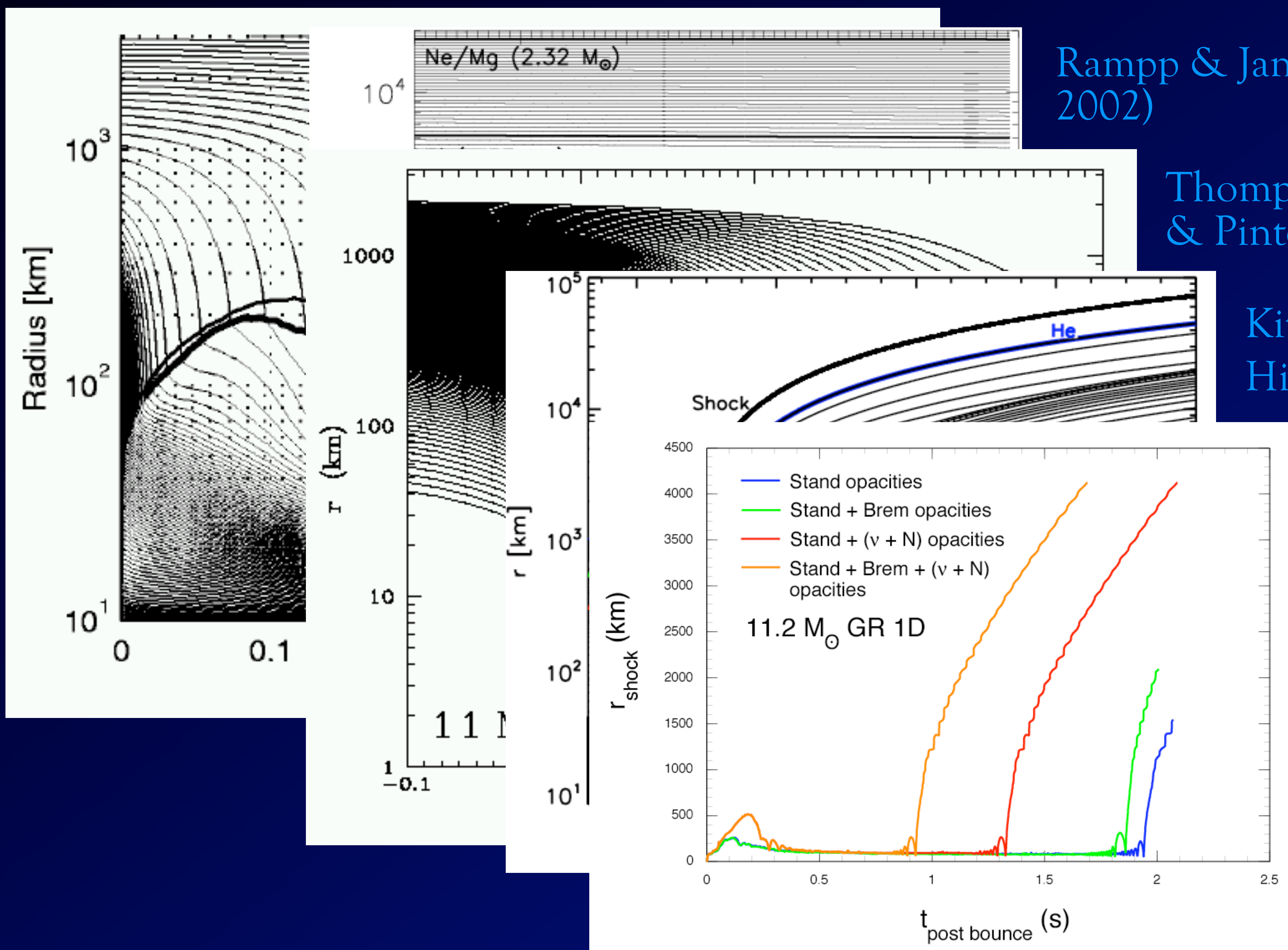

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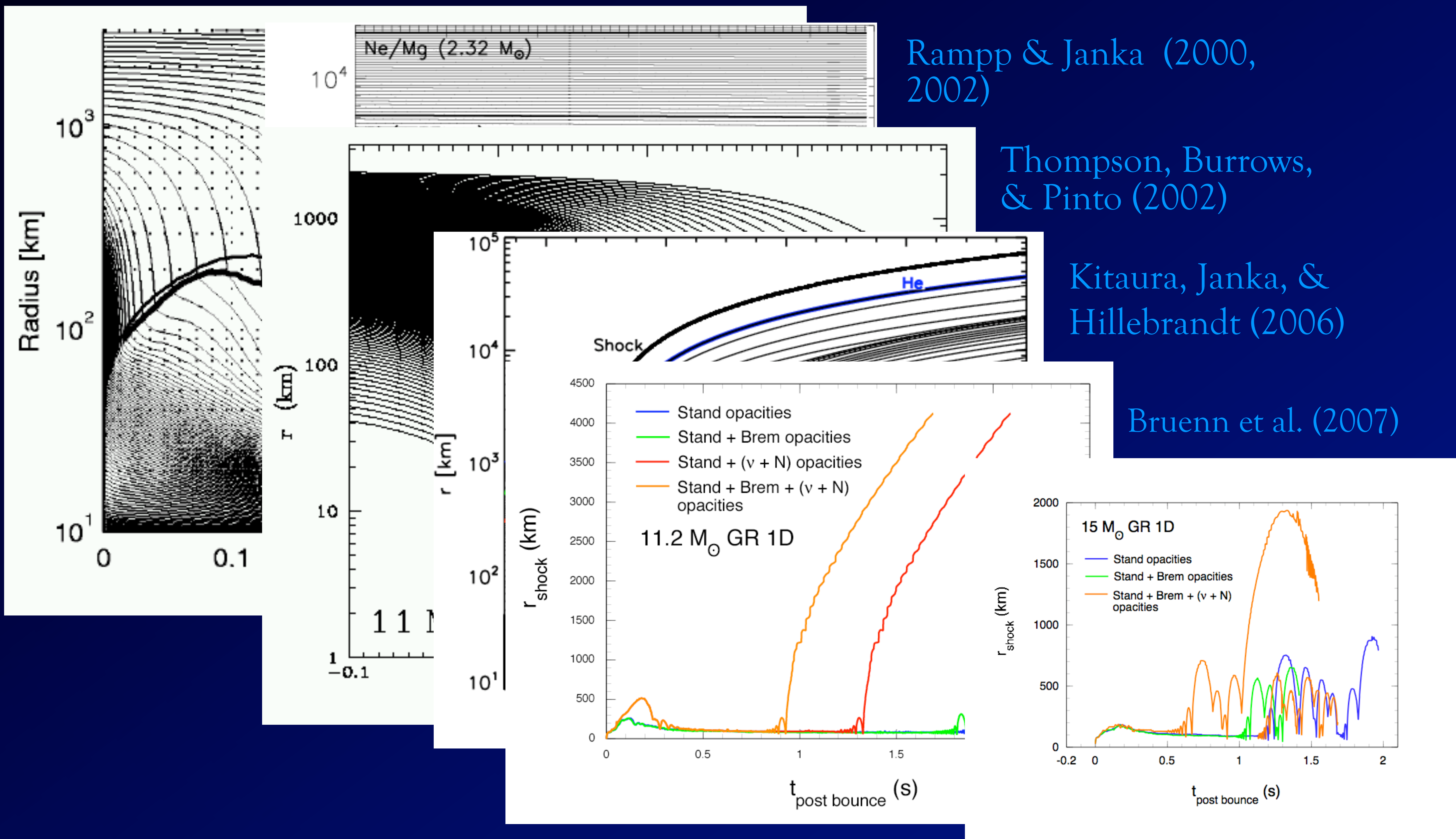

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Rampp & Janka (2000, 2002)

Thompson, Burrows, & Pinto (2002)

Kitaura, Janka, & Hillebrandt (2006)

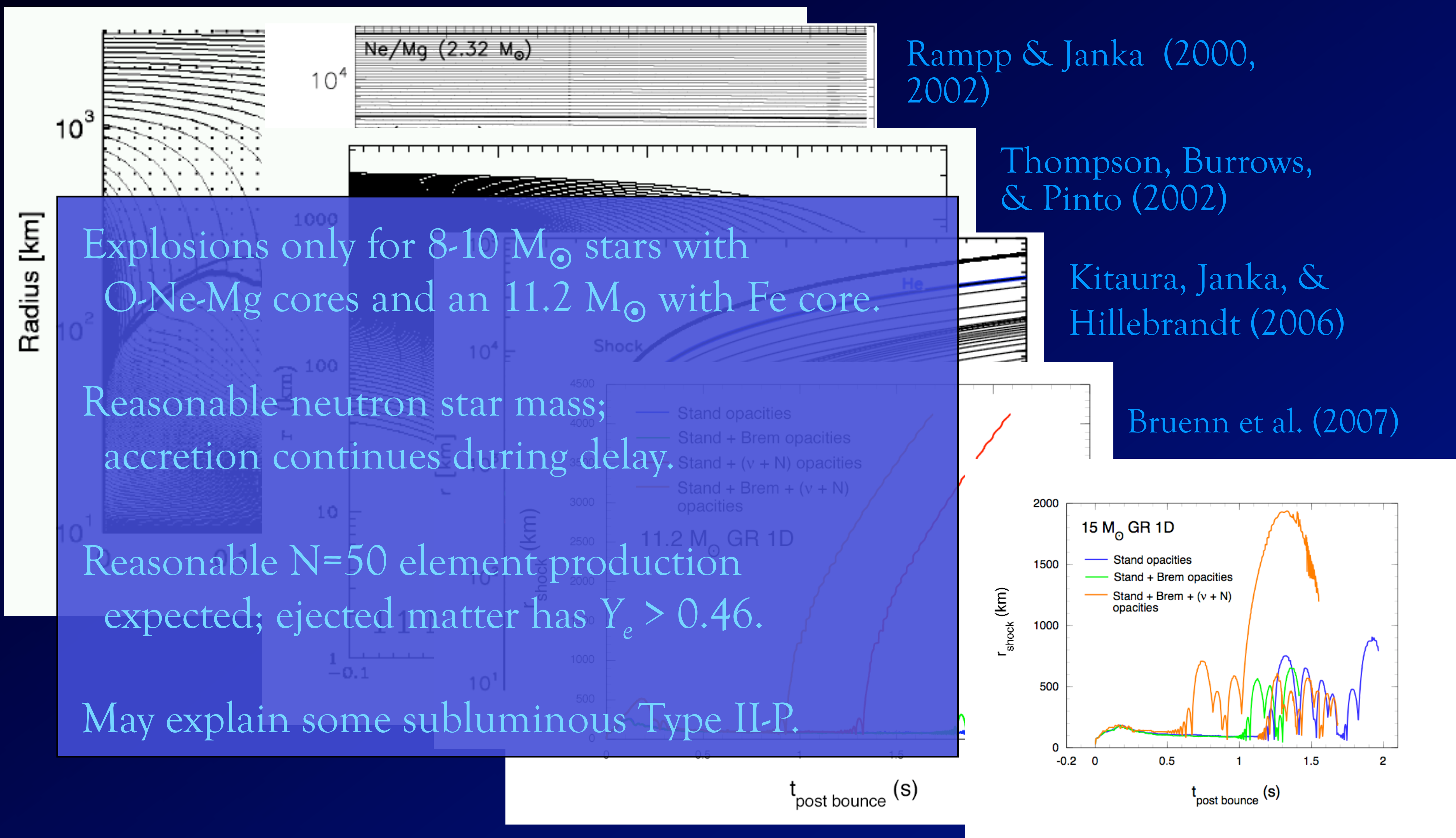
Bruenn et al. (2007)

Explosions only for 8-10 $M_\odot$ stars with O-Ne-Mg cores and an 11.2 $M_\odot$ with Fe core.

Reasonable neutron star mass; accretion continues during delay.

Reasonable N=50 element production expected; ejected matter has $Y_e > 0.46$.

May explain some subluminous Type II-P.



Convection, rotation, and magnetic fields all come into play.

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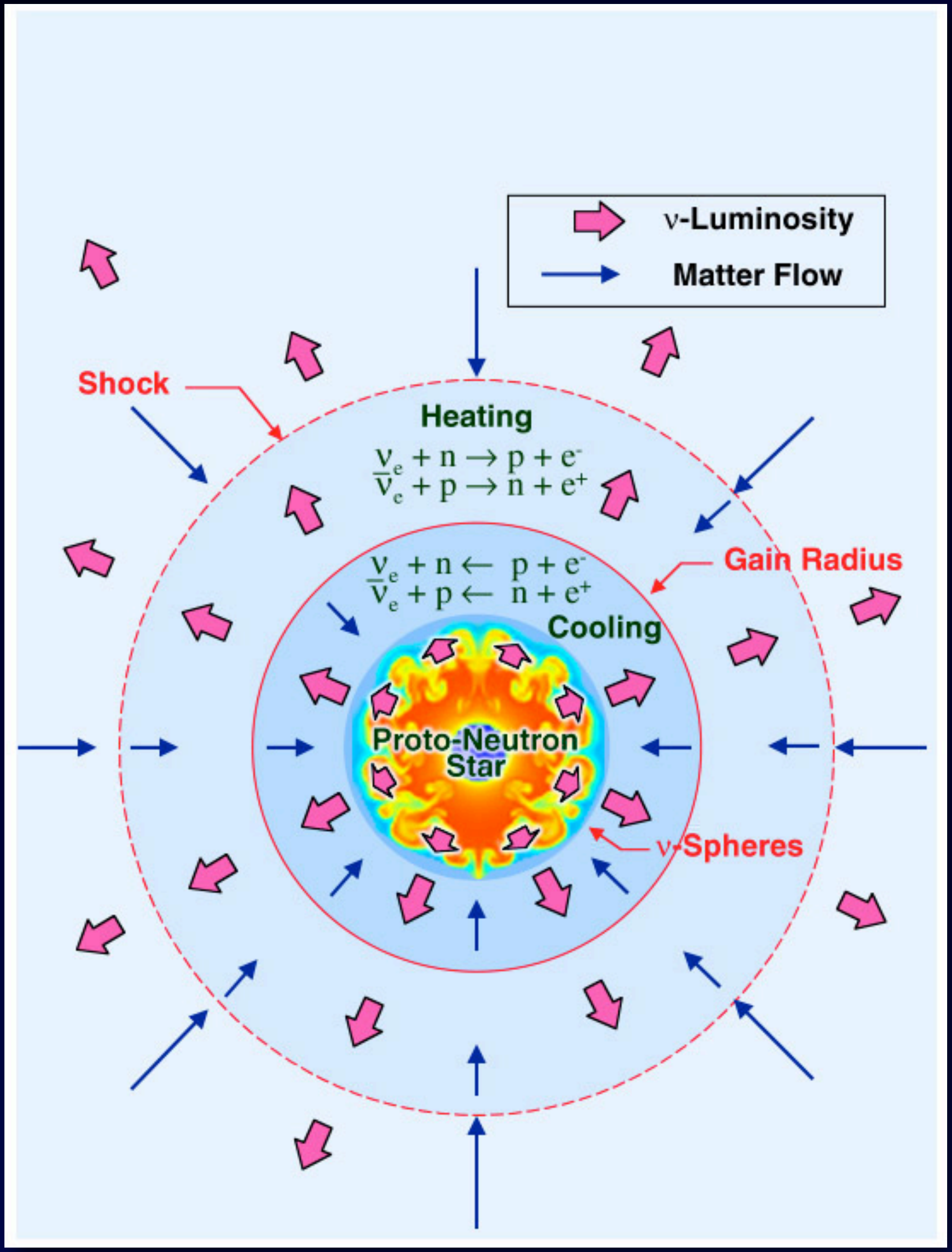

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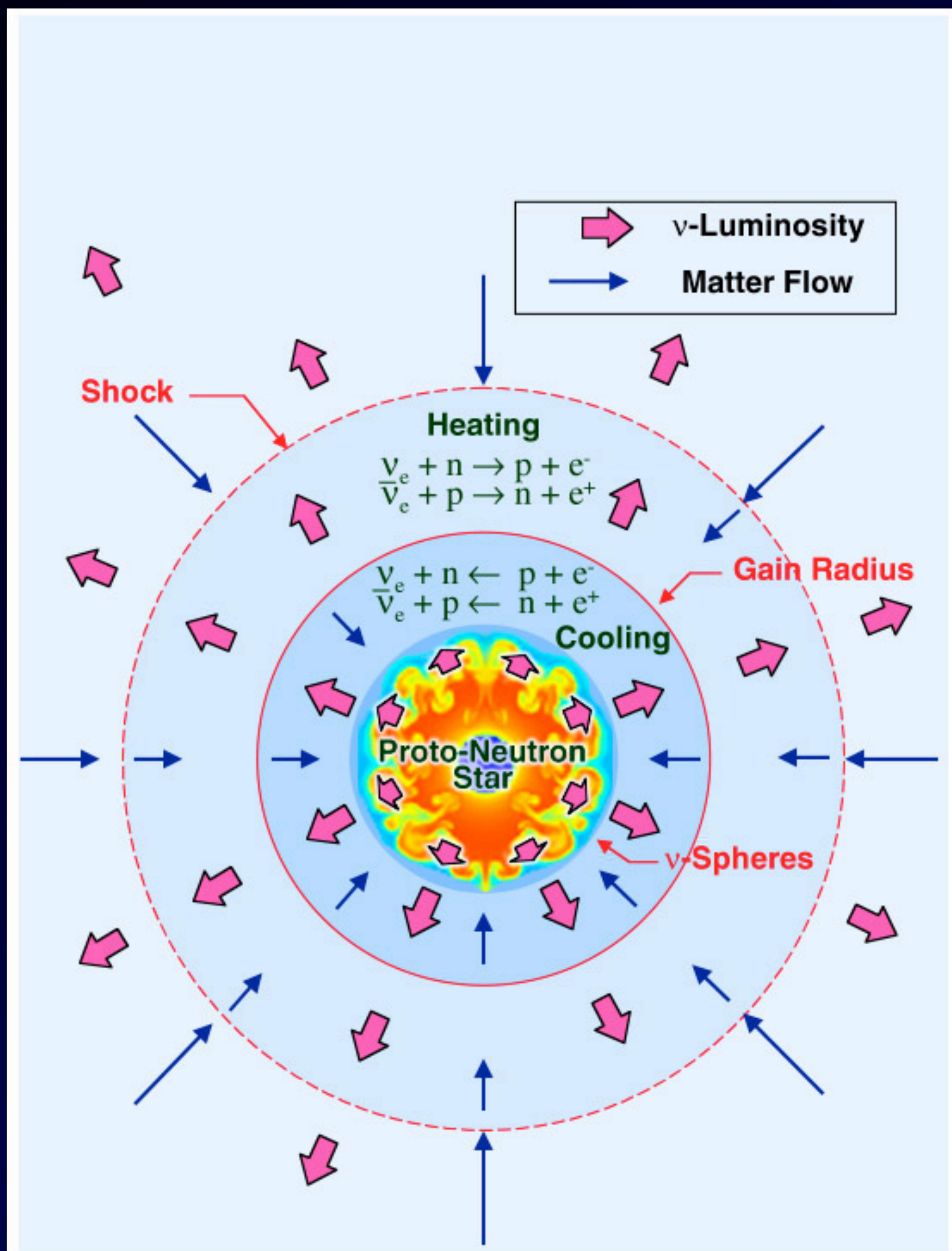

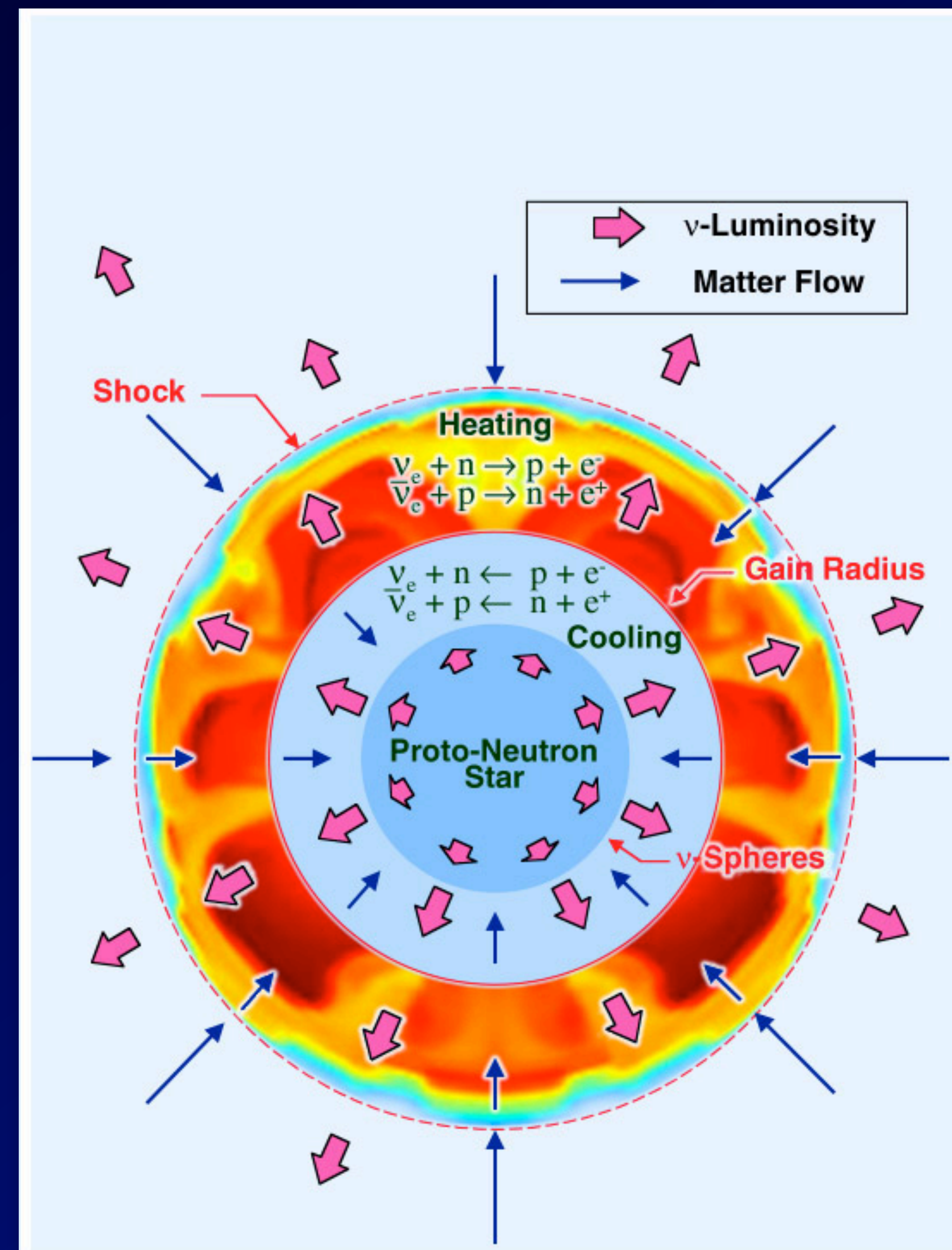

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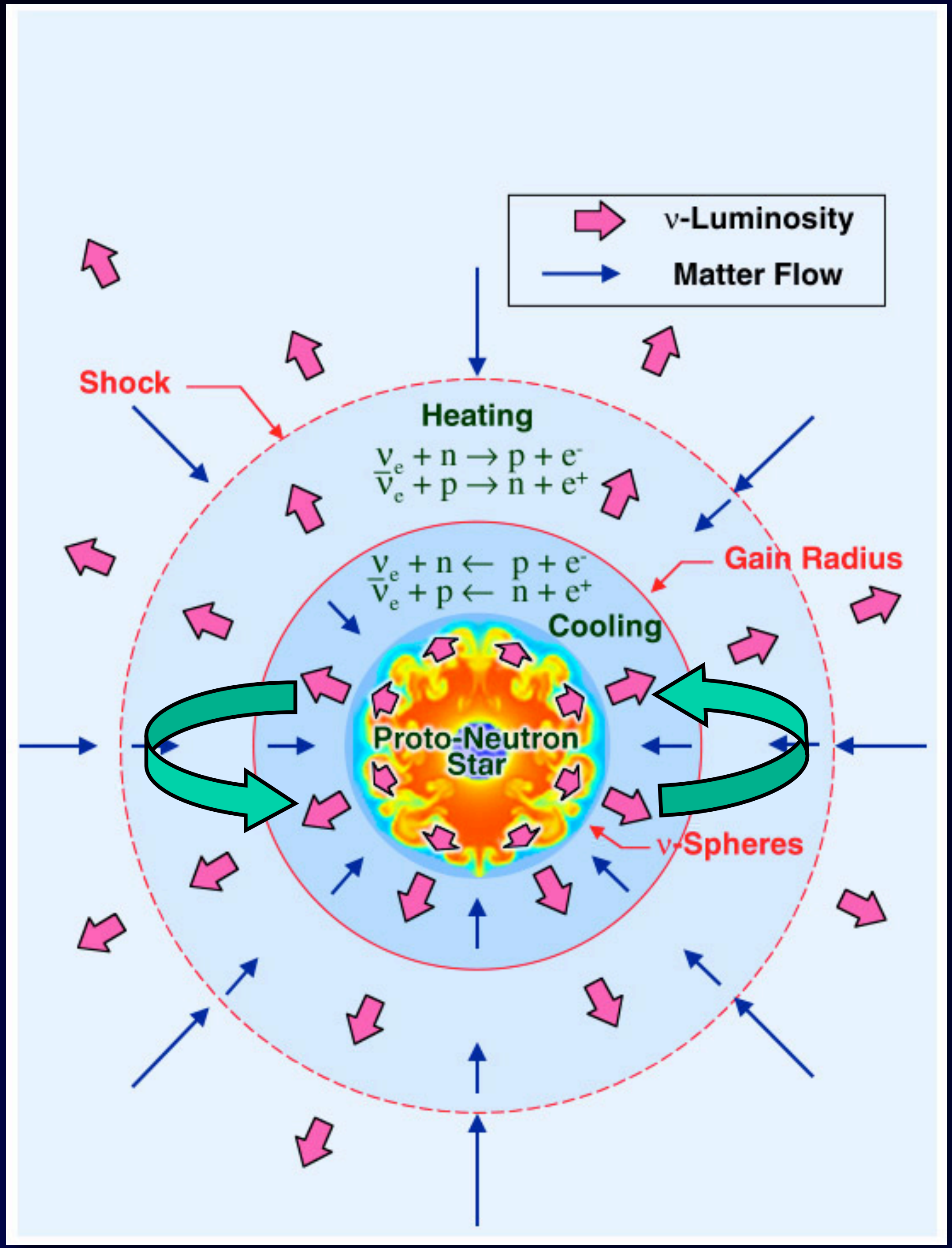

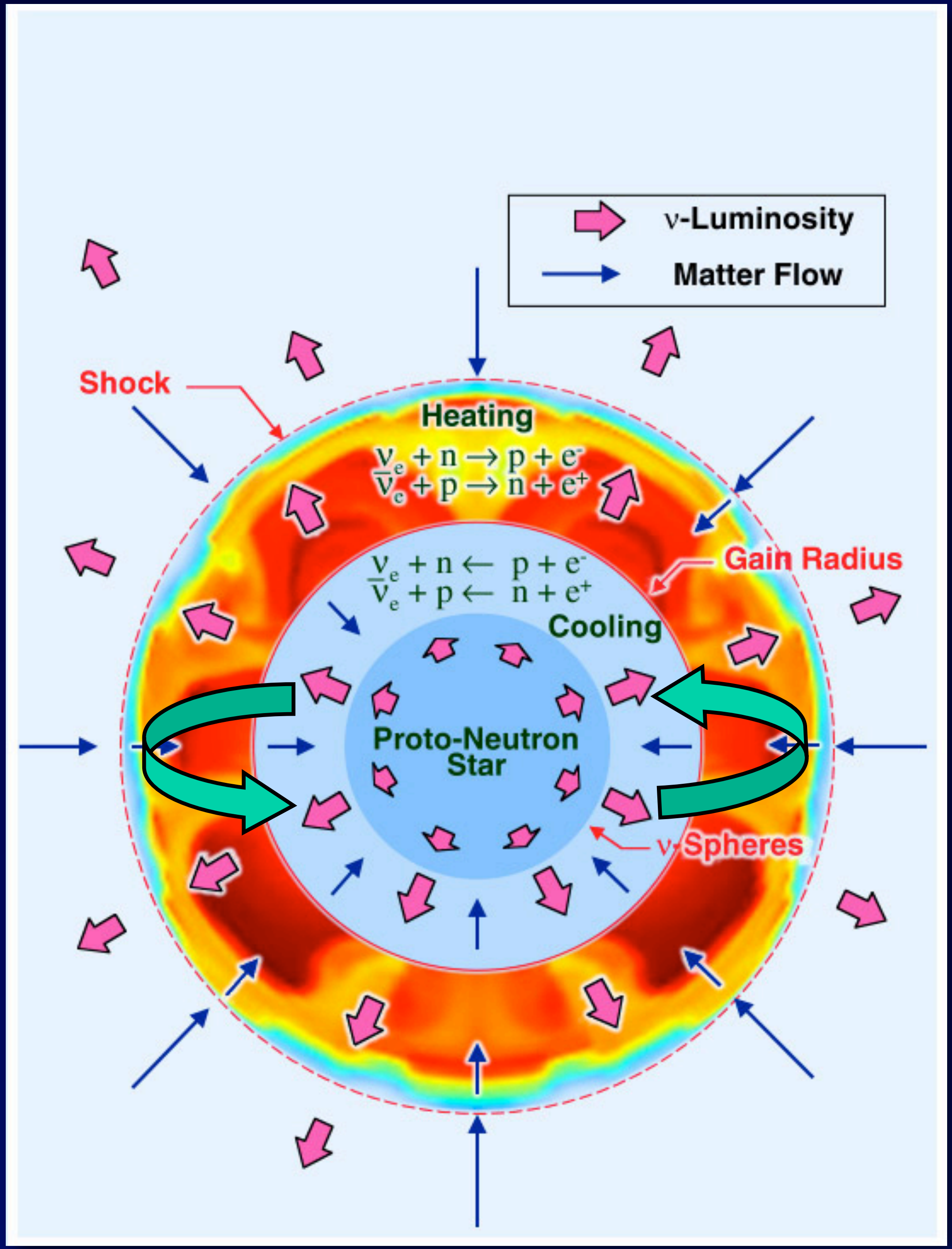

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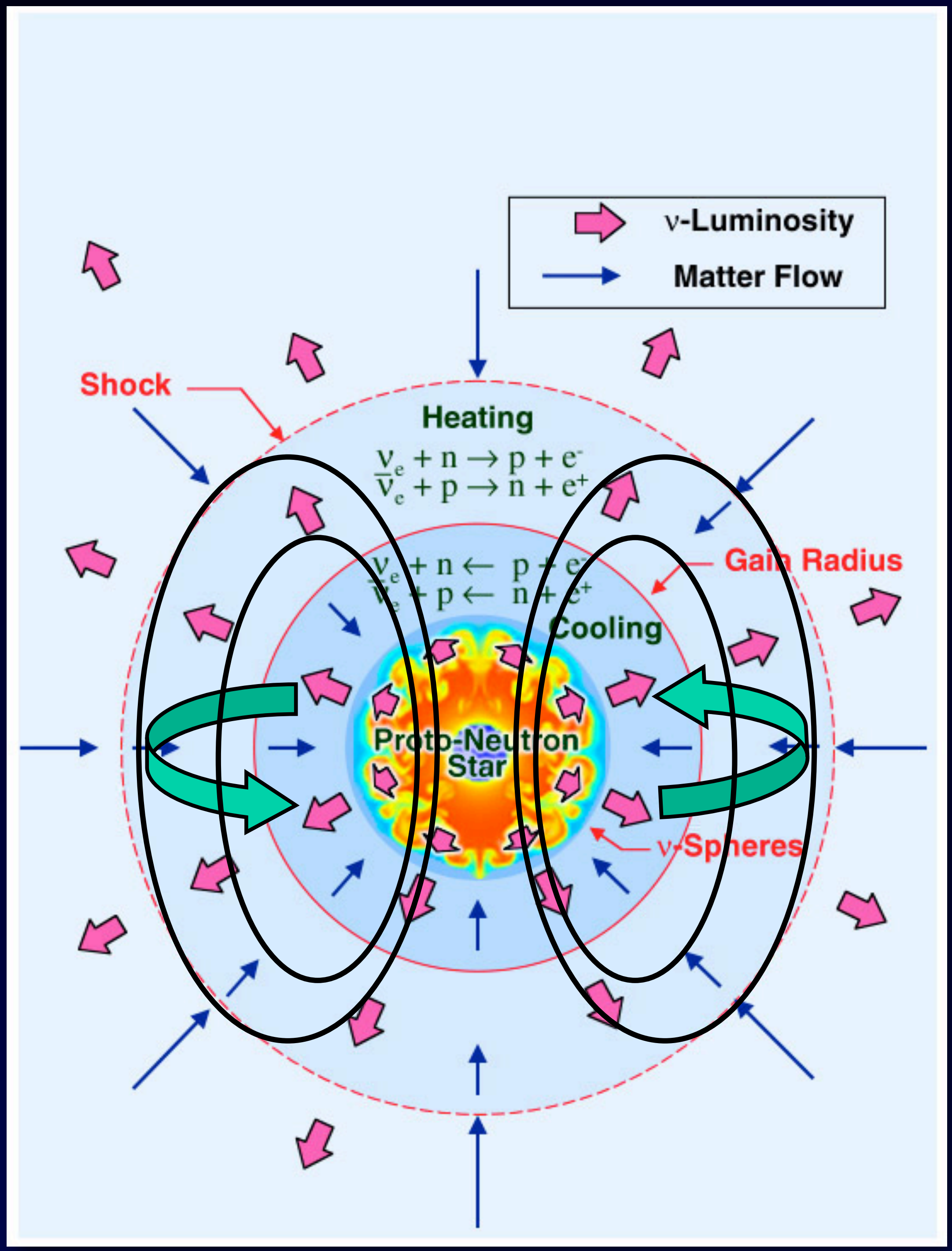

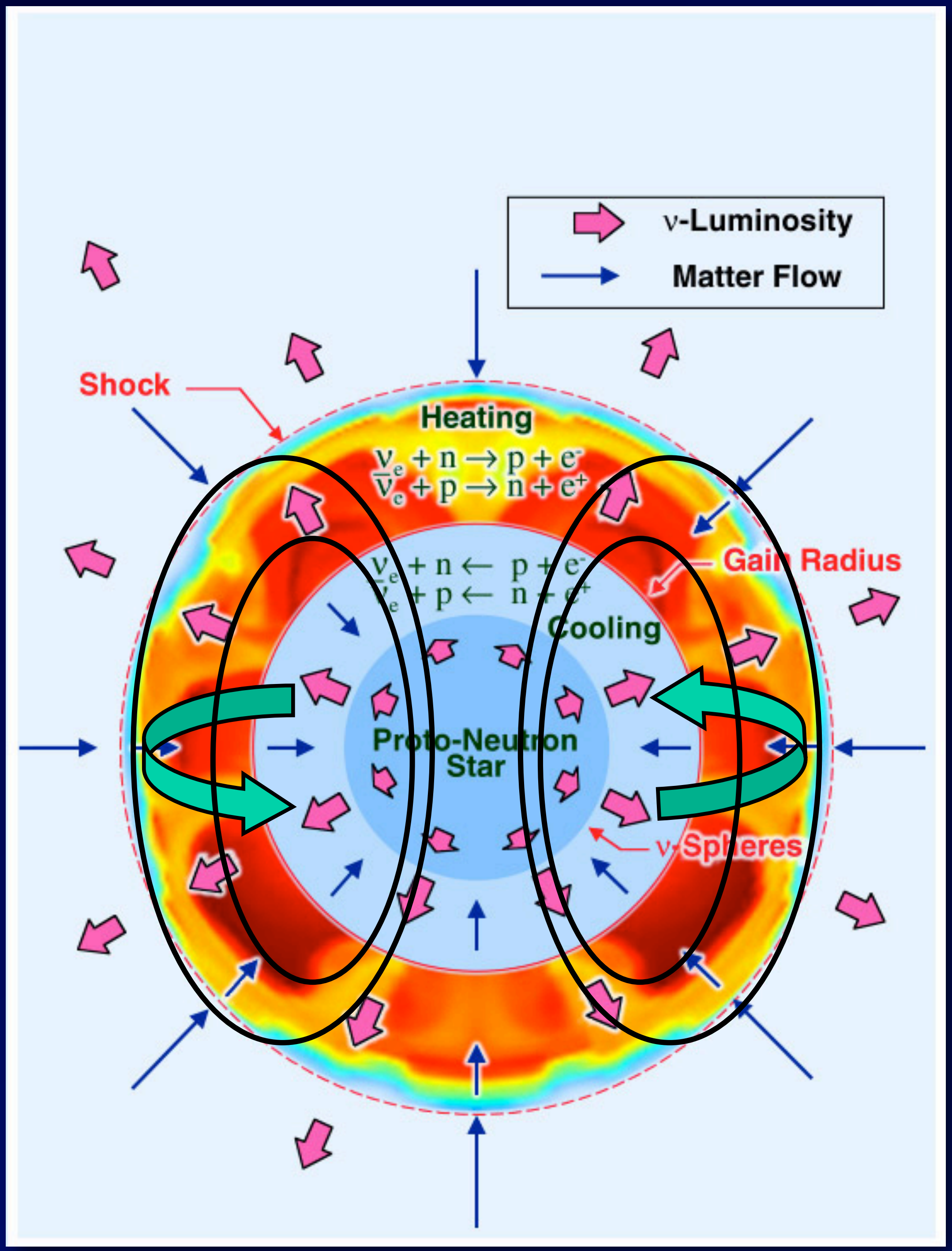

The stationary accretion shock is intrinsically unstable and could generate phenomena traditionally attributed to progenitor rotation.

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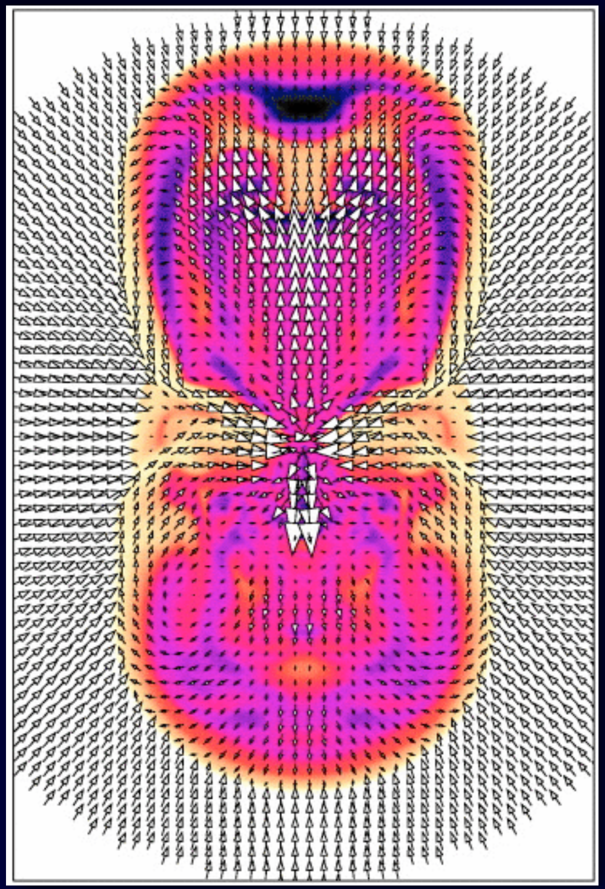
Blondin, Mezzacappa, and DeMarino (2003)



Aspherical explosion morphology

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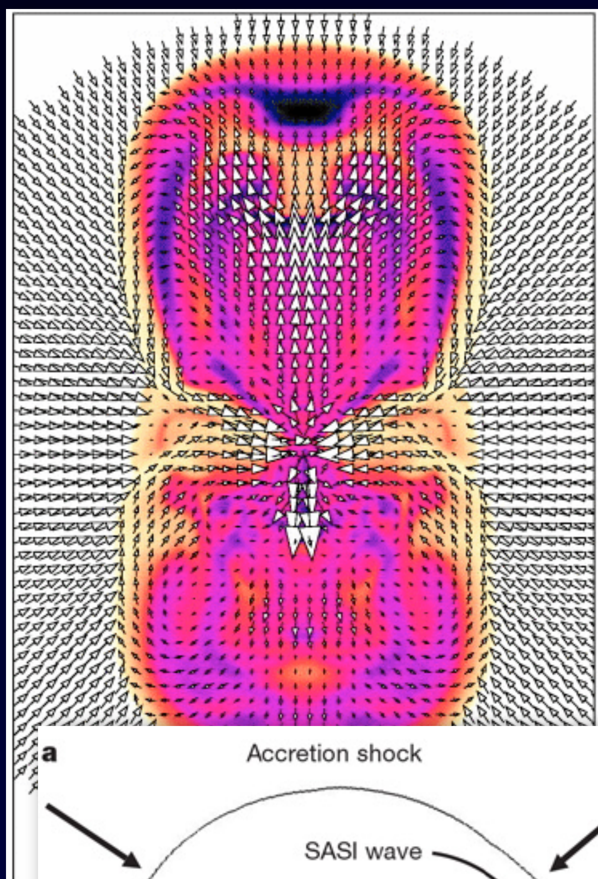

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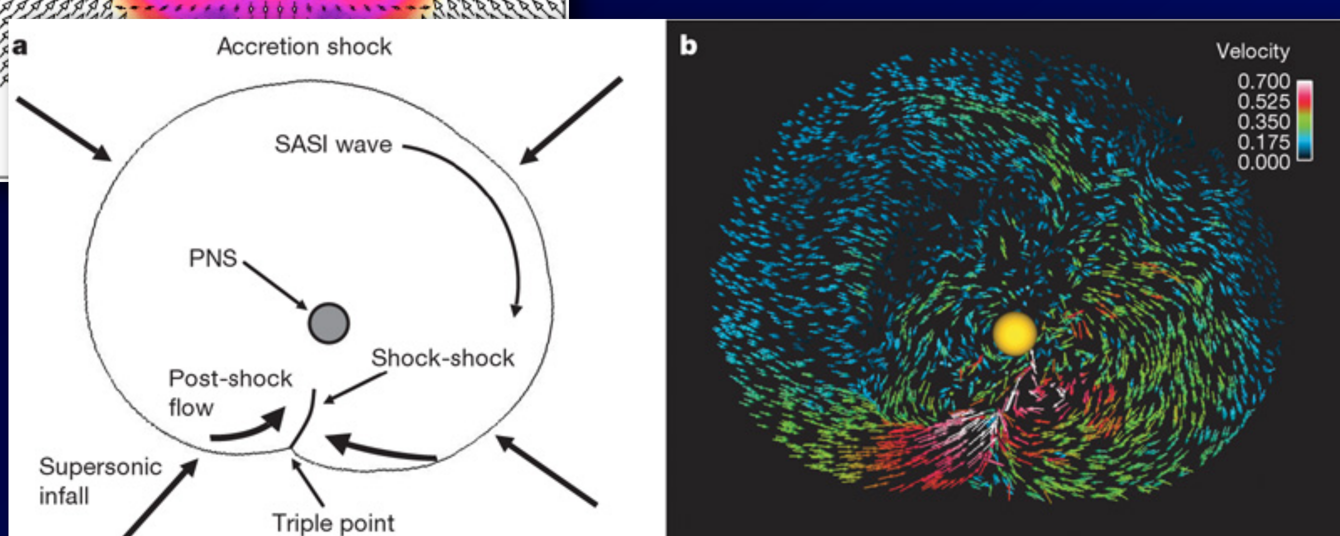
Aspherical explosion morphology



Blondin and Mezzacappa (2007)

Pulsar spin

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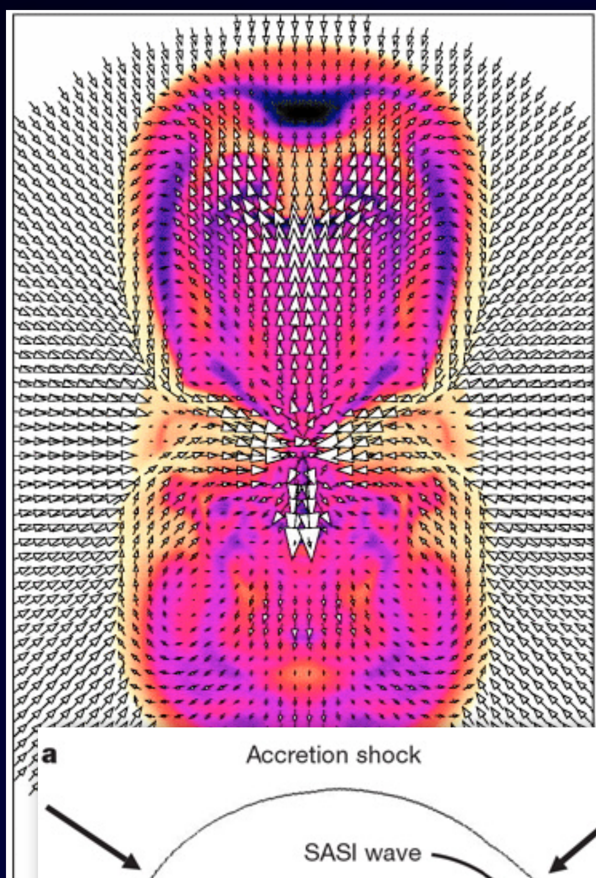
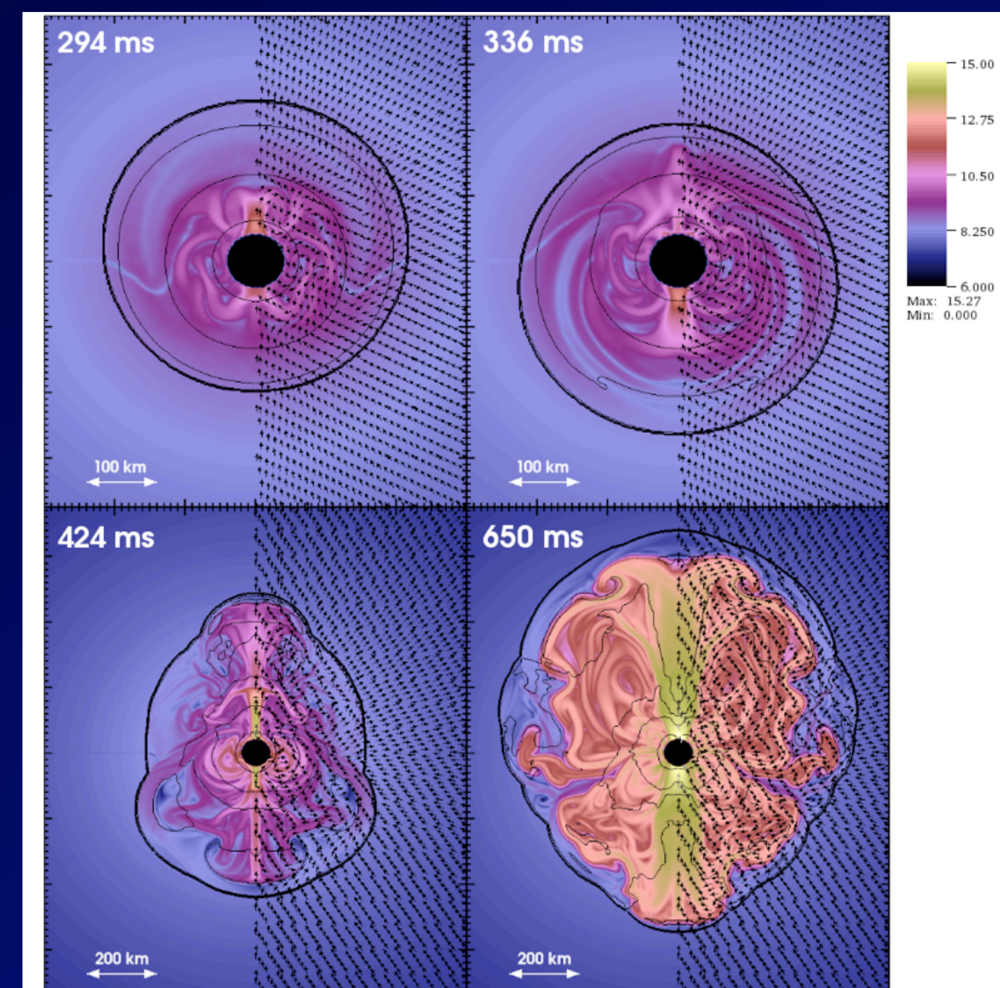
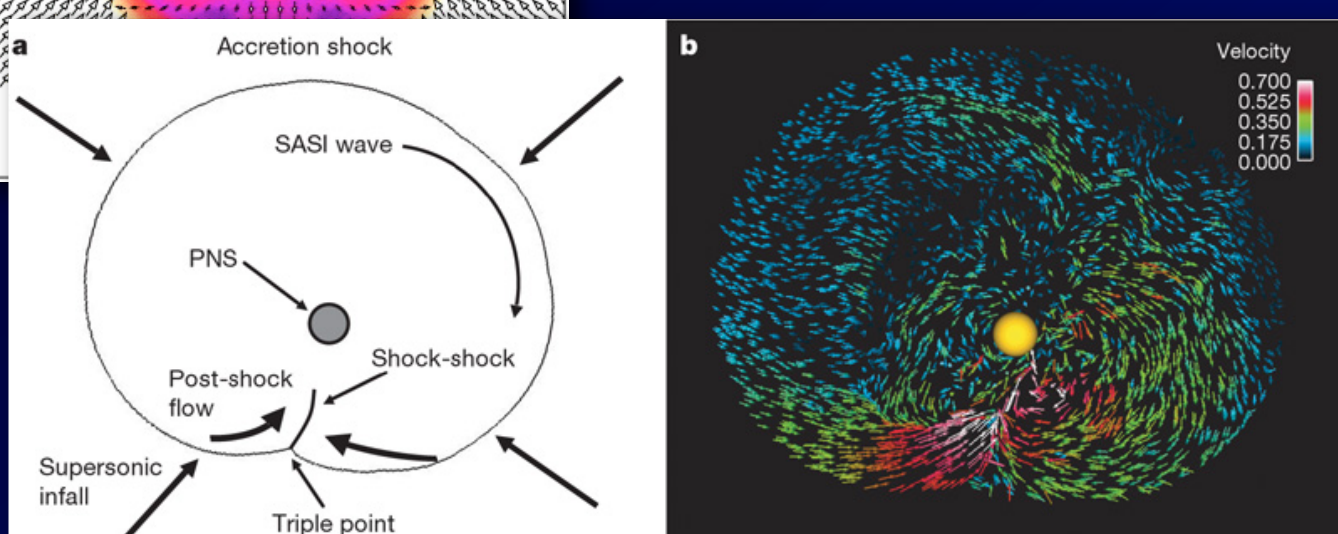


Aspherical explosion morphology

Endeve et al. (2008)



Magnetic field generation



Blondin and Mezzacappa (2007)

Pulsar spin

Fluid dynamics:

2D

Neutrino transport:

2D + 1D

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2D

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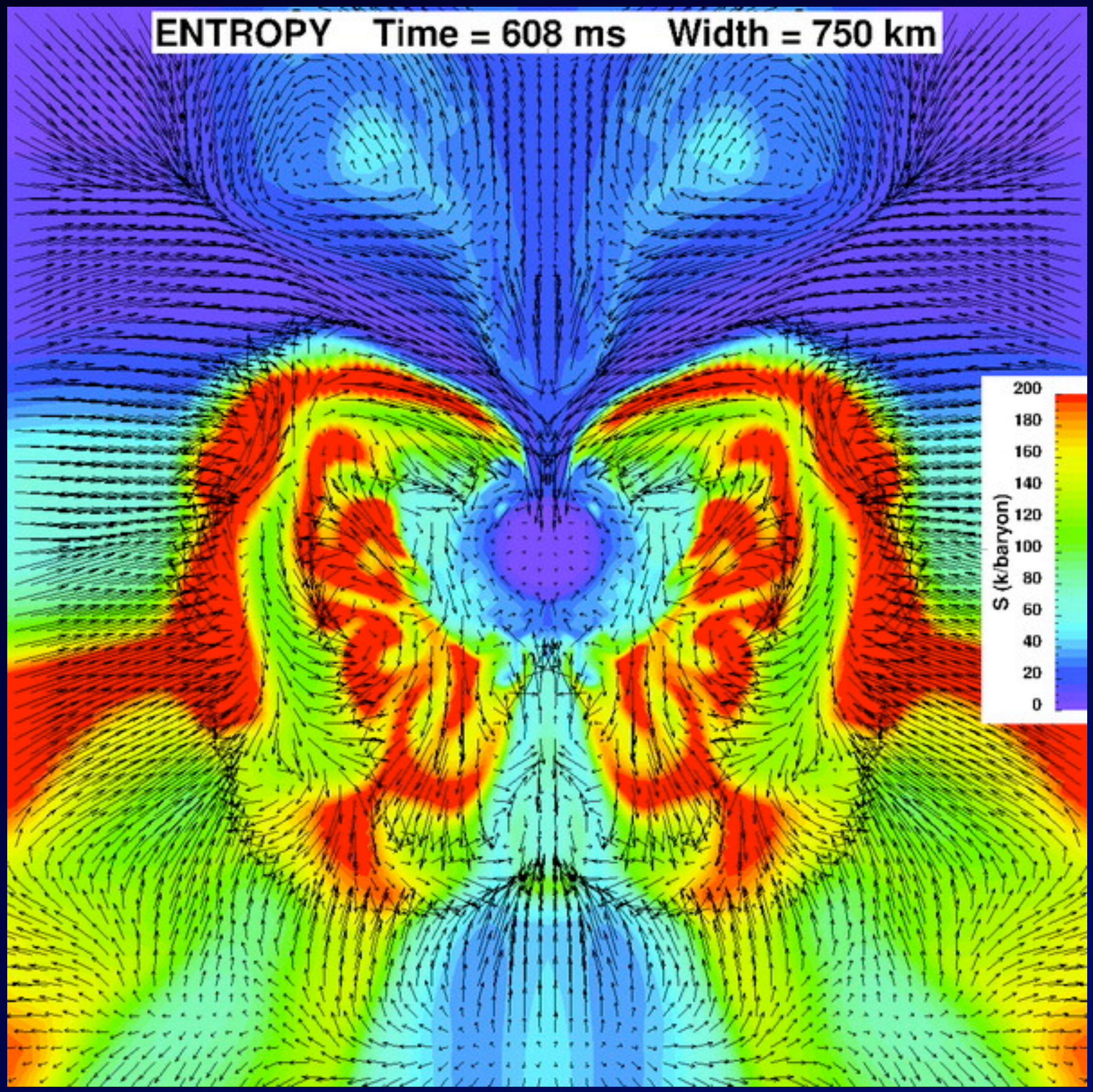

Fluid dynamics:
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Neutrino transport:
2D + 1D

Magnetofluid dynamics:
"2.5D"

Neutrino transport:
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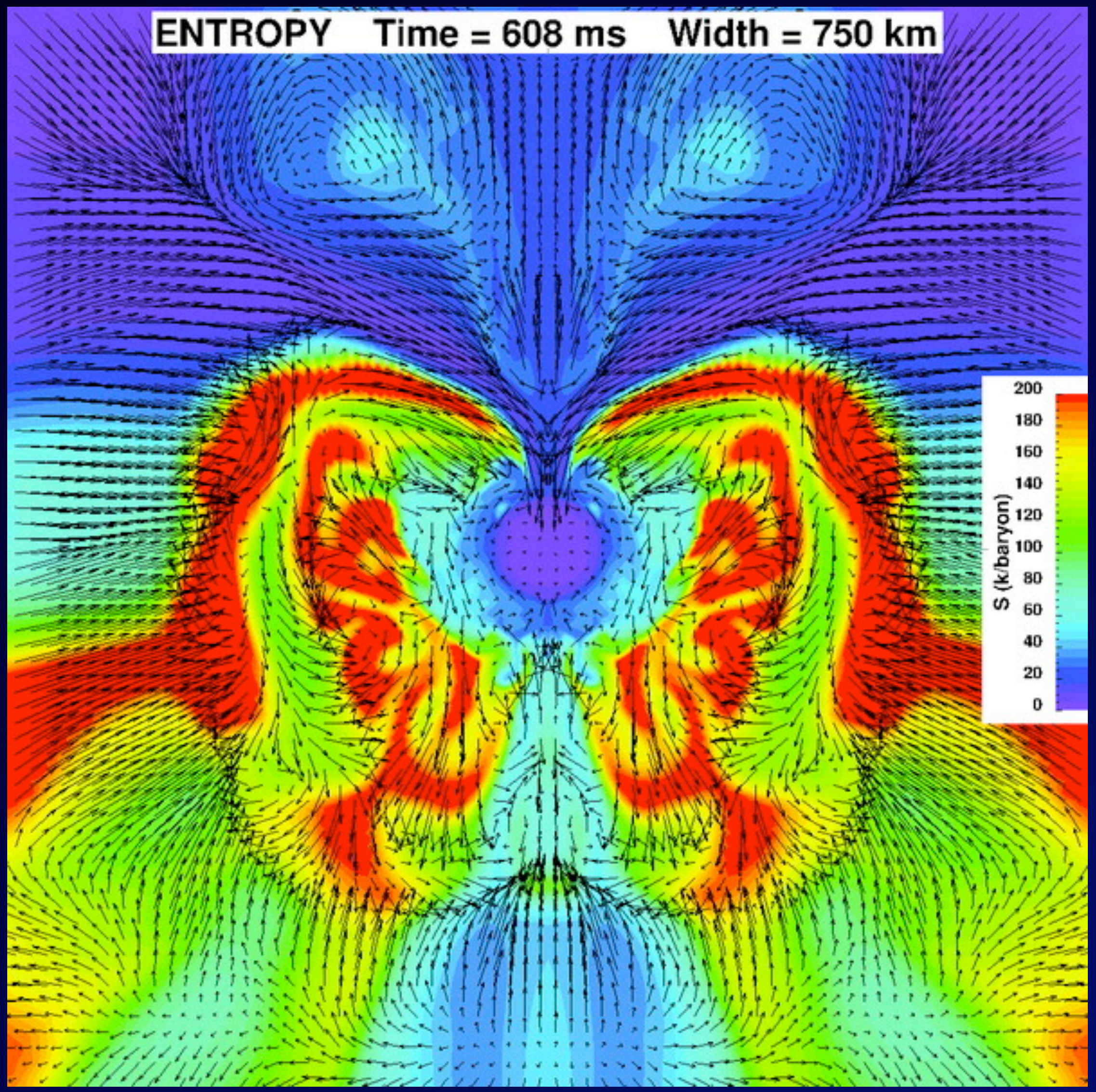
Burrows et al. (2006)



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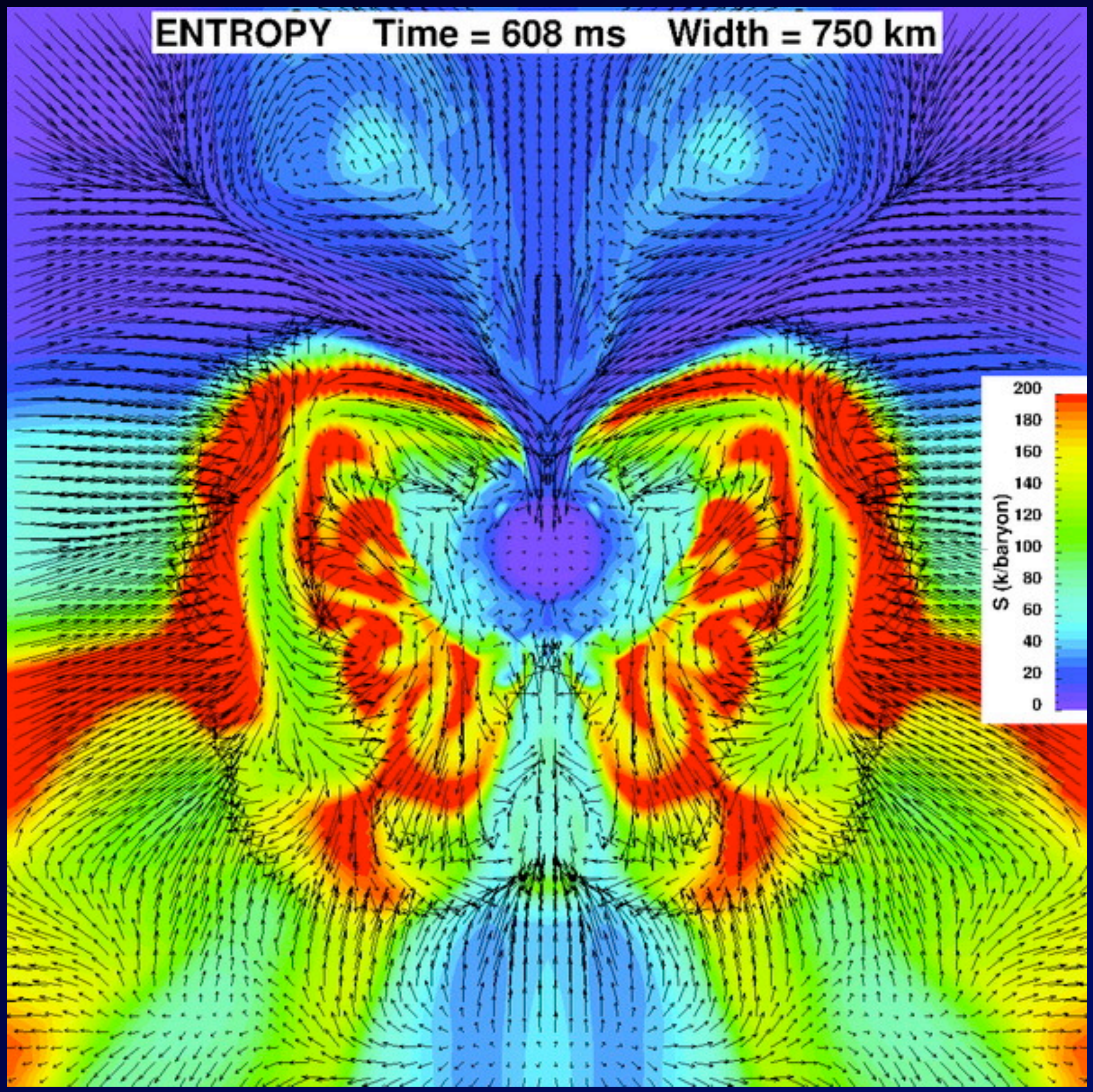

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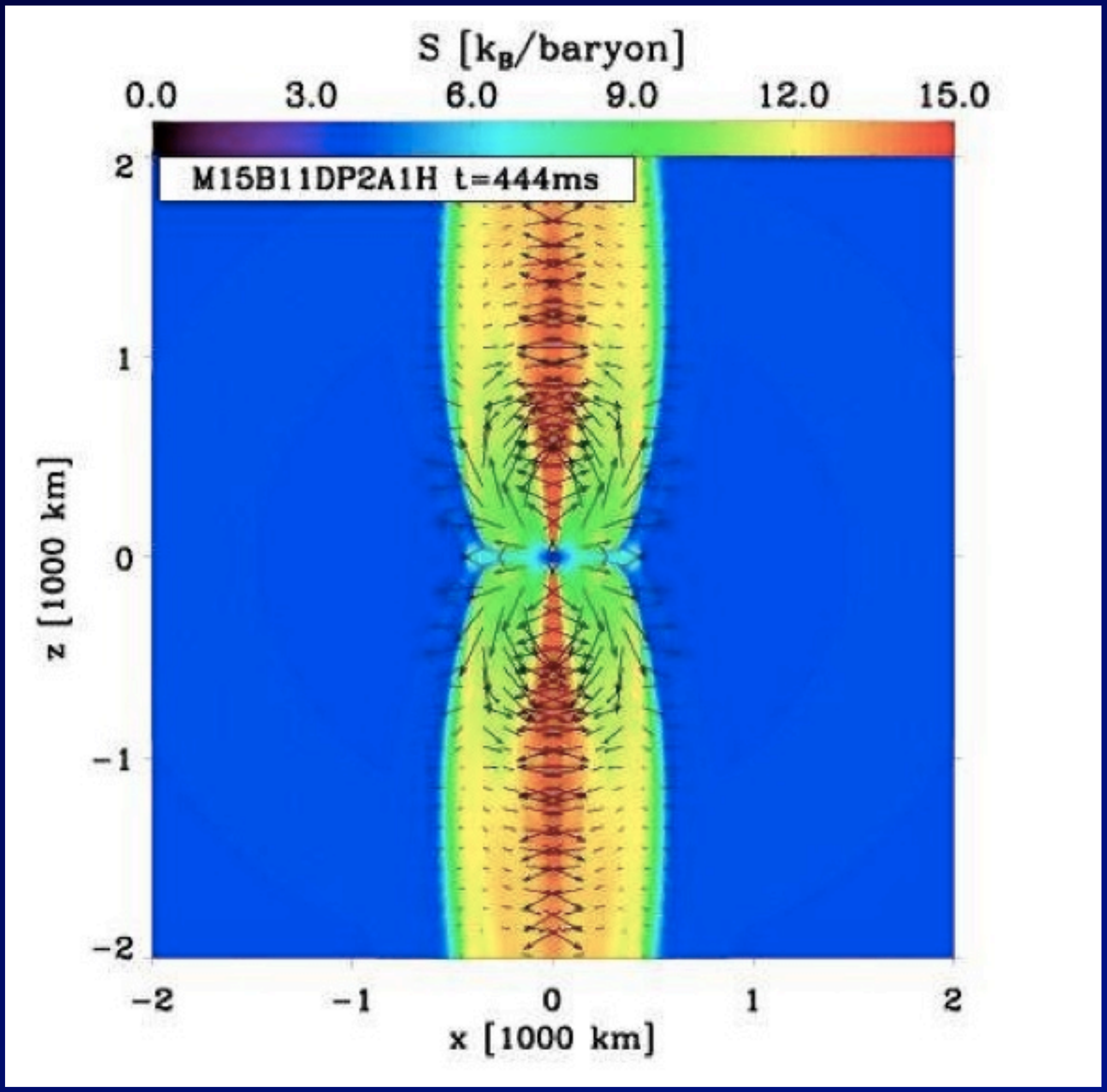

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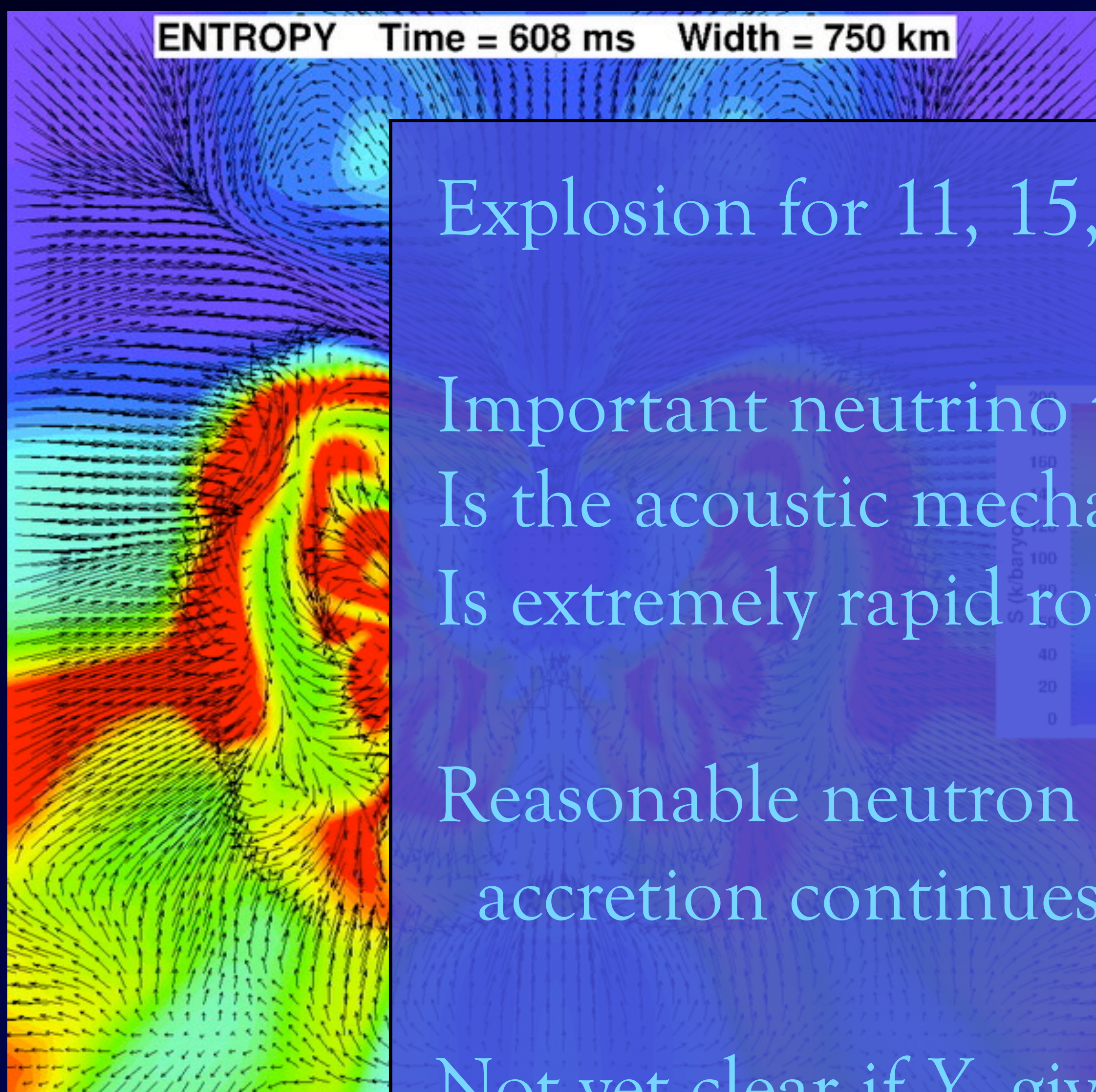
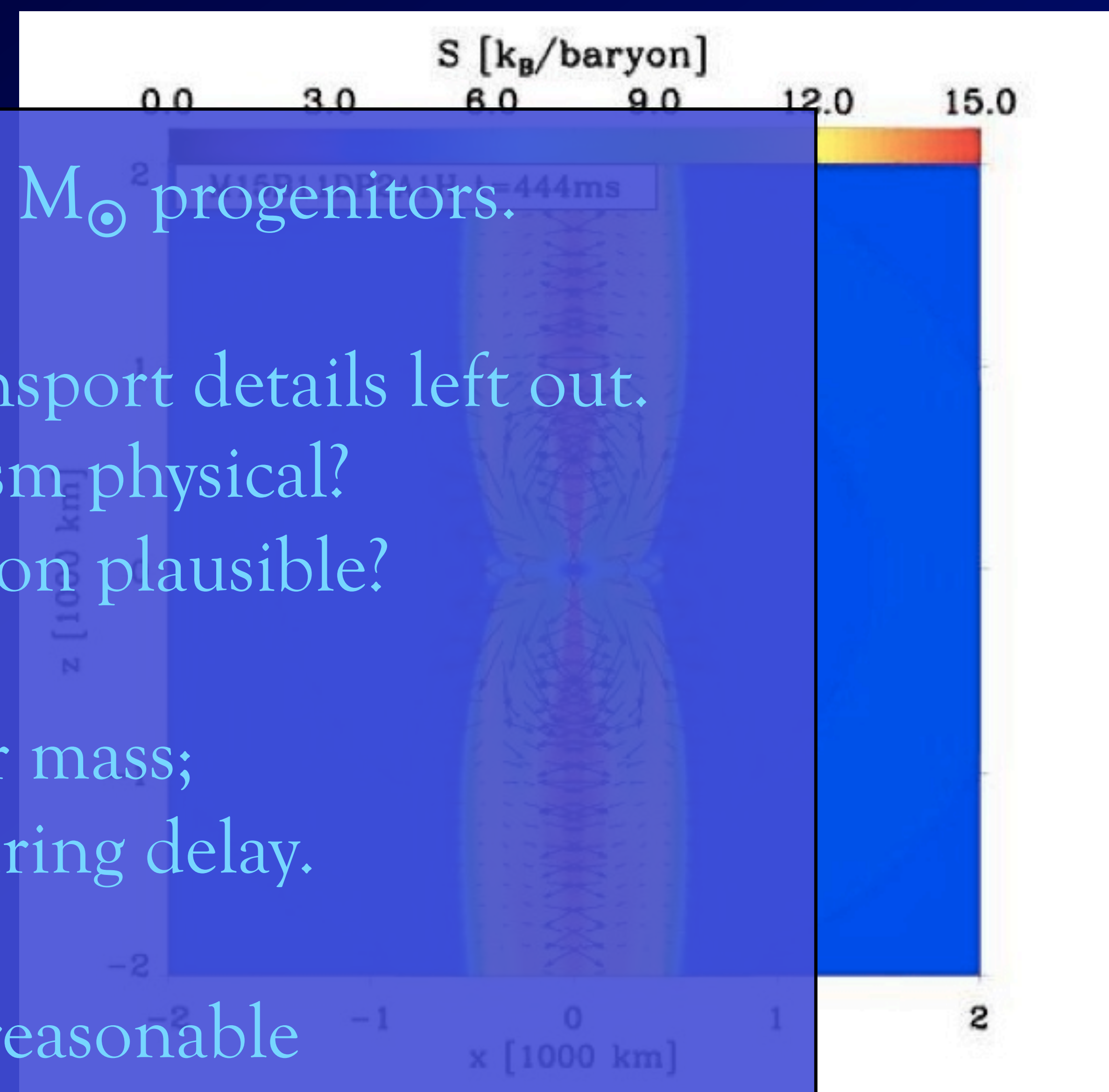


Burrows et al. (2007)



Explosion for 11, 15, 25 $M_\odot$ progenitors.

Important neutrino transport details left out.
Is the acoustic mechanism physical?
Is extremely rapid rotation plausible?

Reasonable neutron star mass;
accretion continues during delay.

Not yet clear if Y_e gives reasonable
nucleosynthesis or if the models are resolved.

Fluid dynamics:

2D

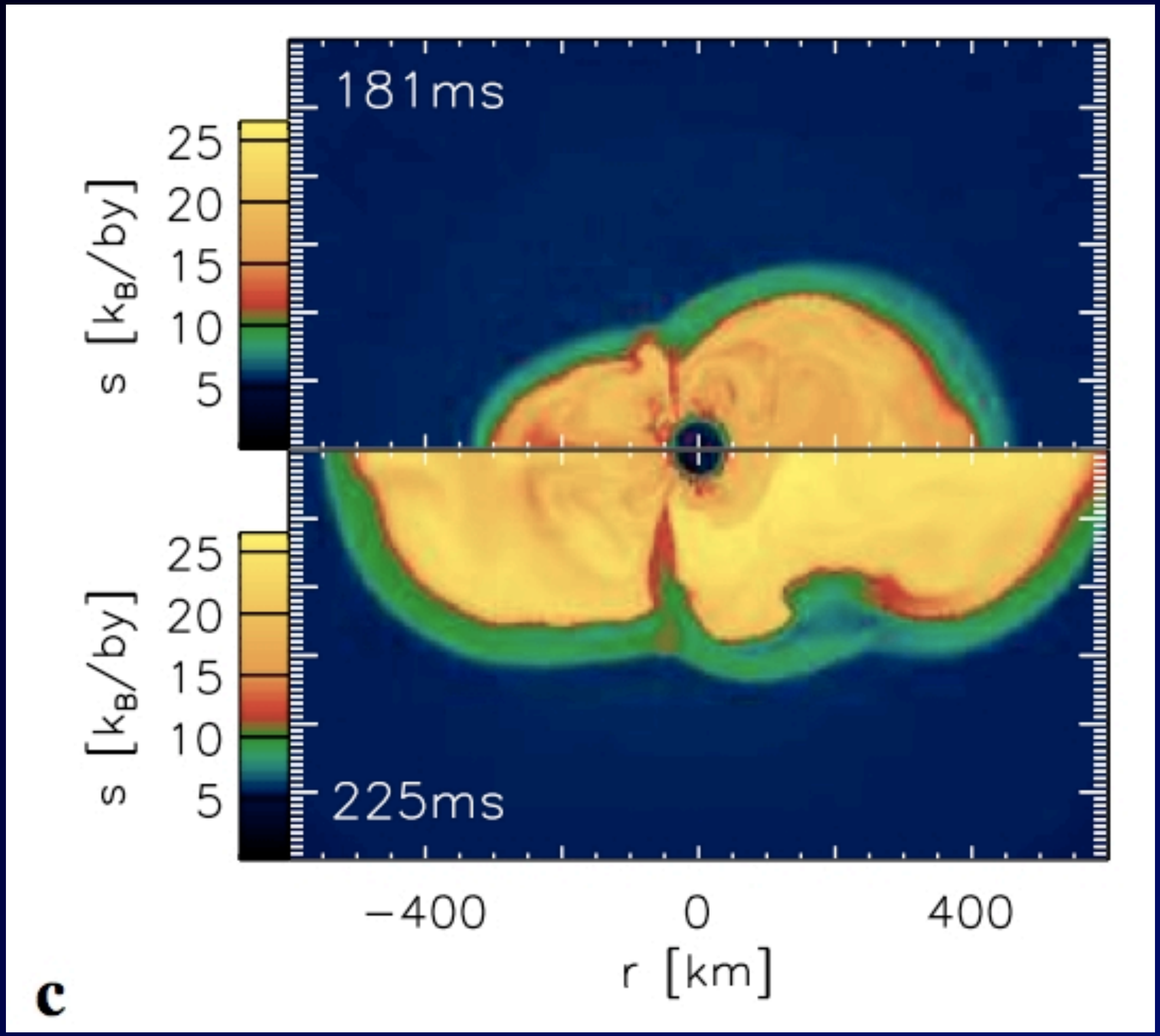
Neutrino transport:

1.5D + 2D

Fluid dynamics:
2D

Neutrino transport:
1.5D + 2D

Buras et al. (2006)



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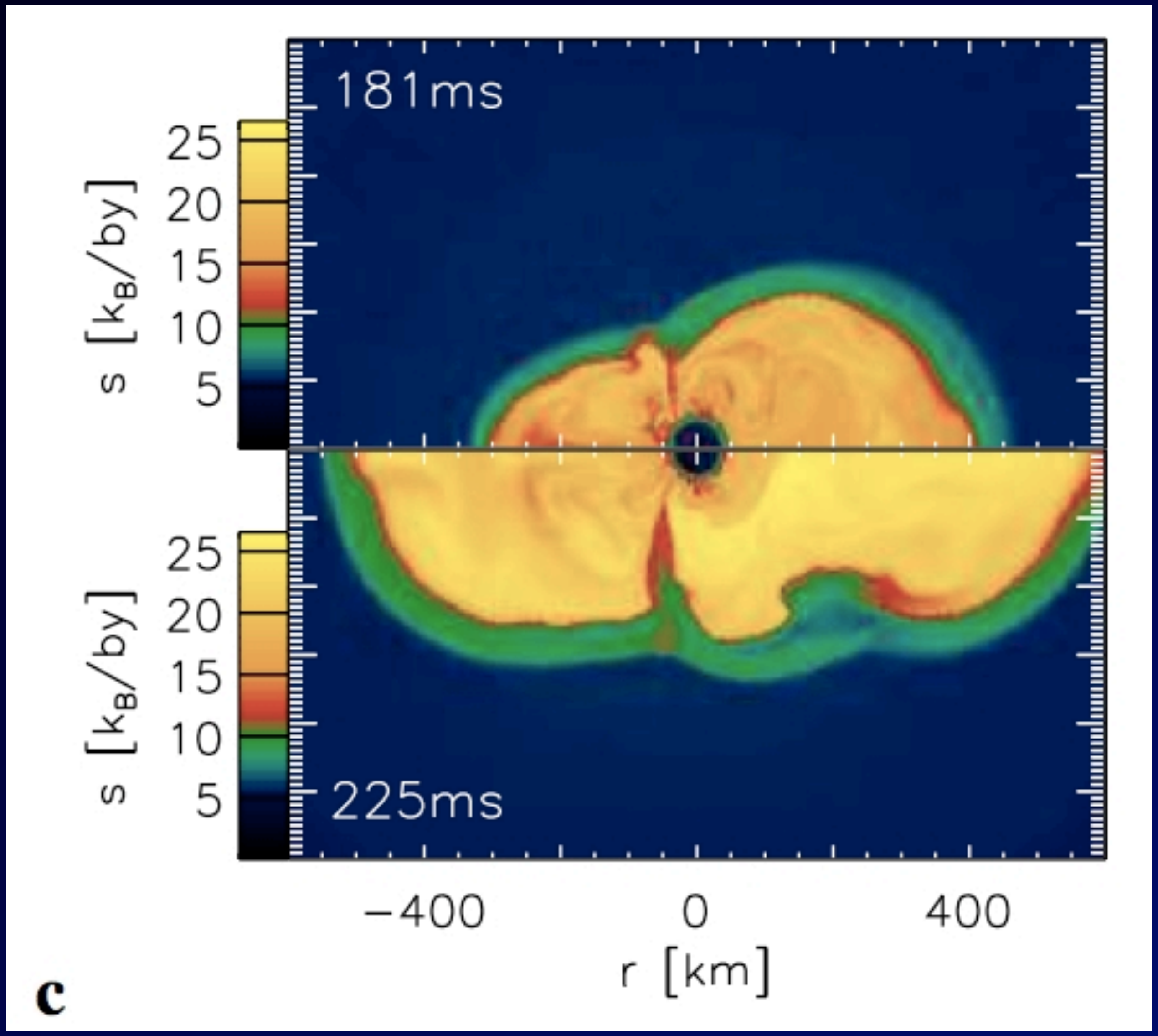

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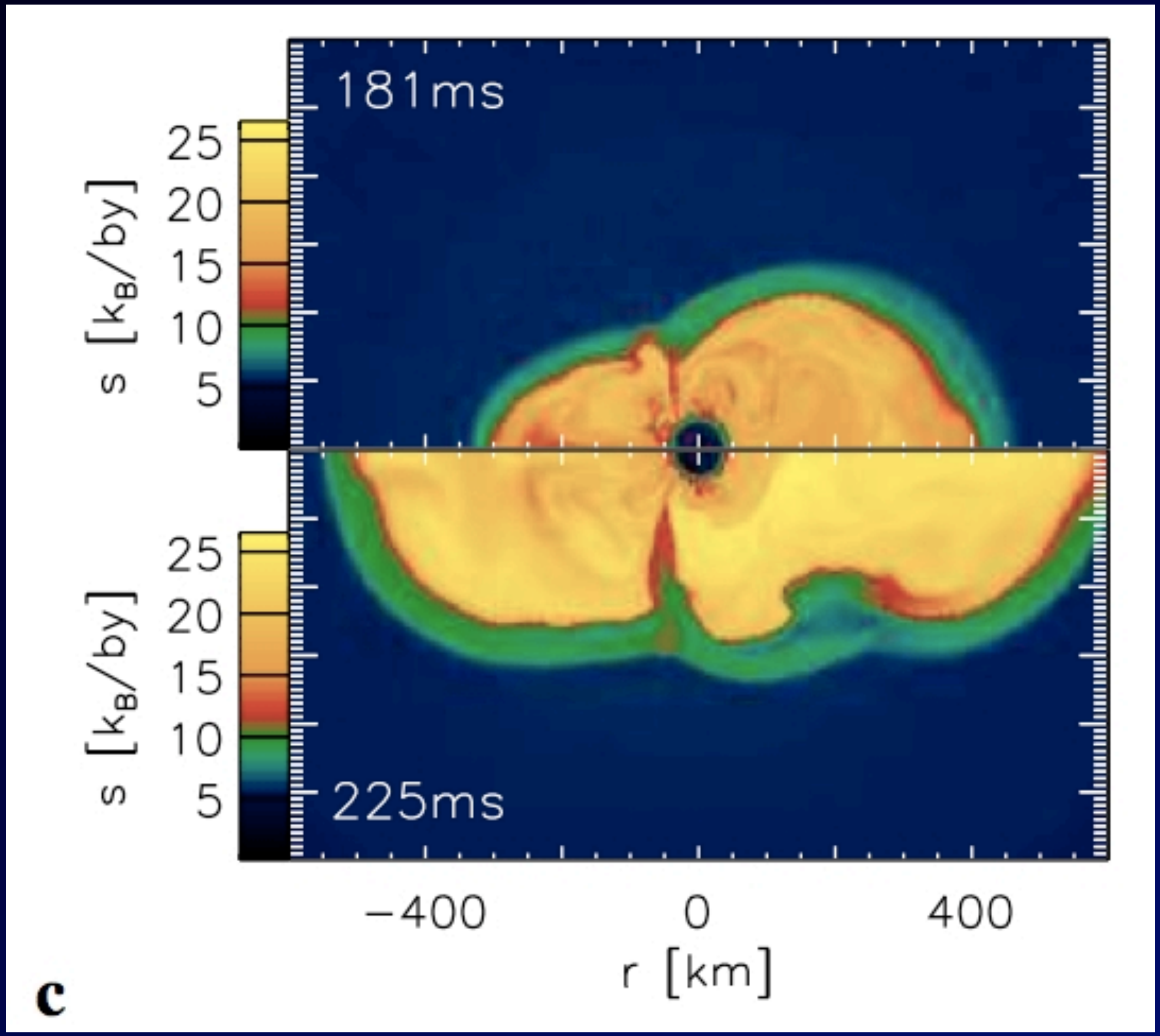

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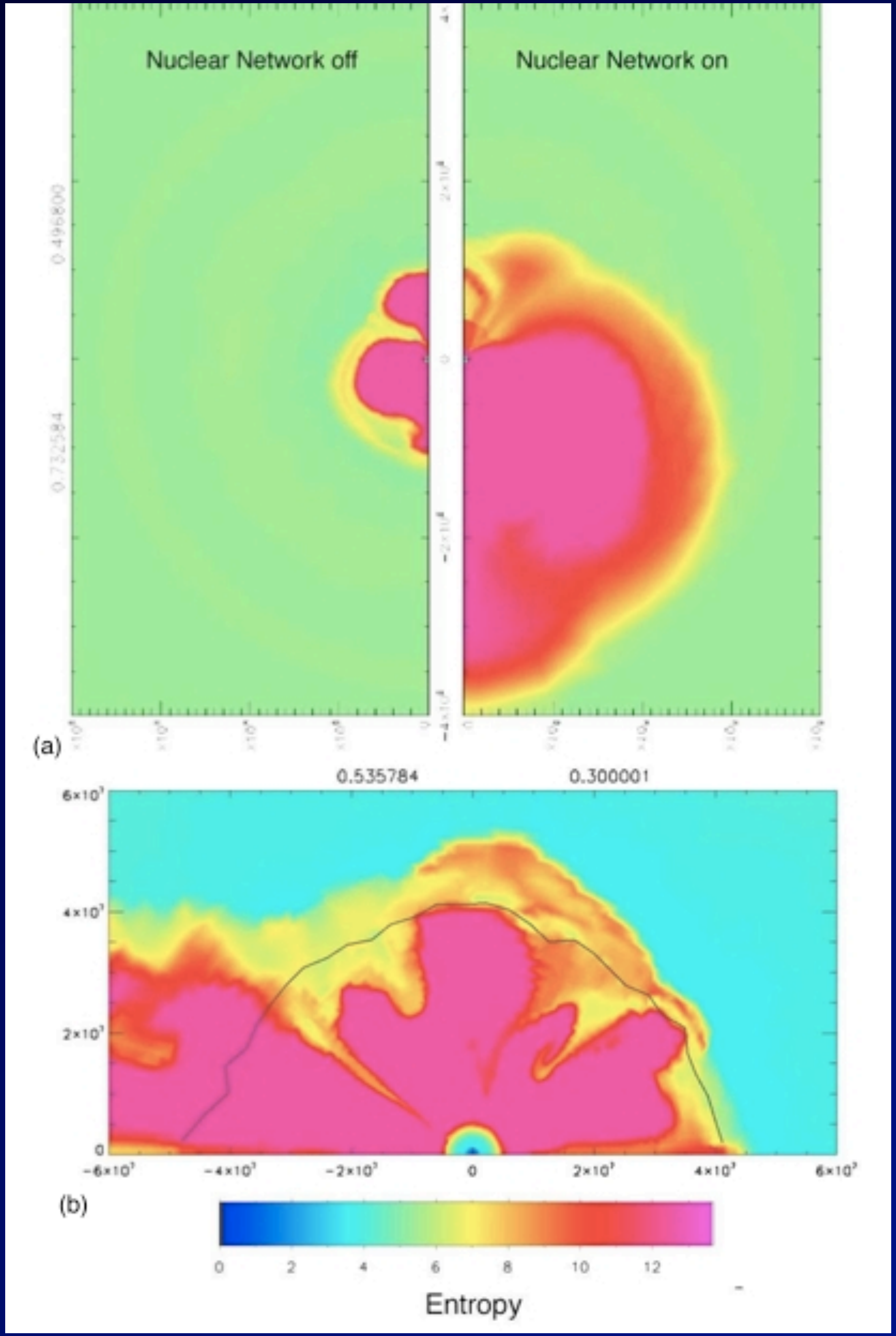

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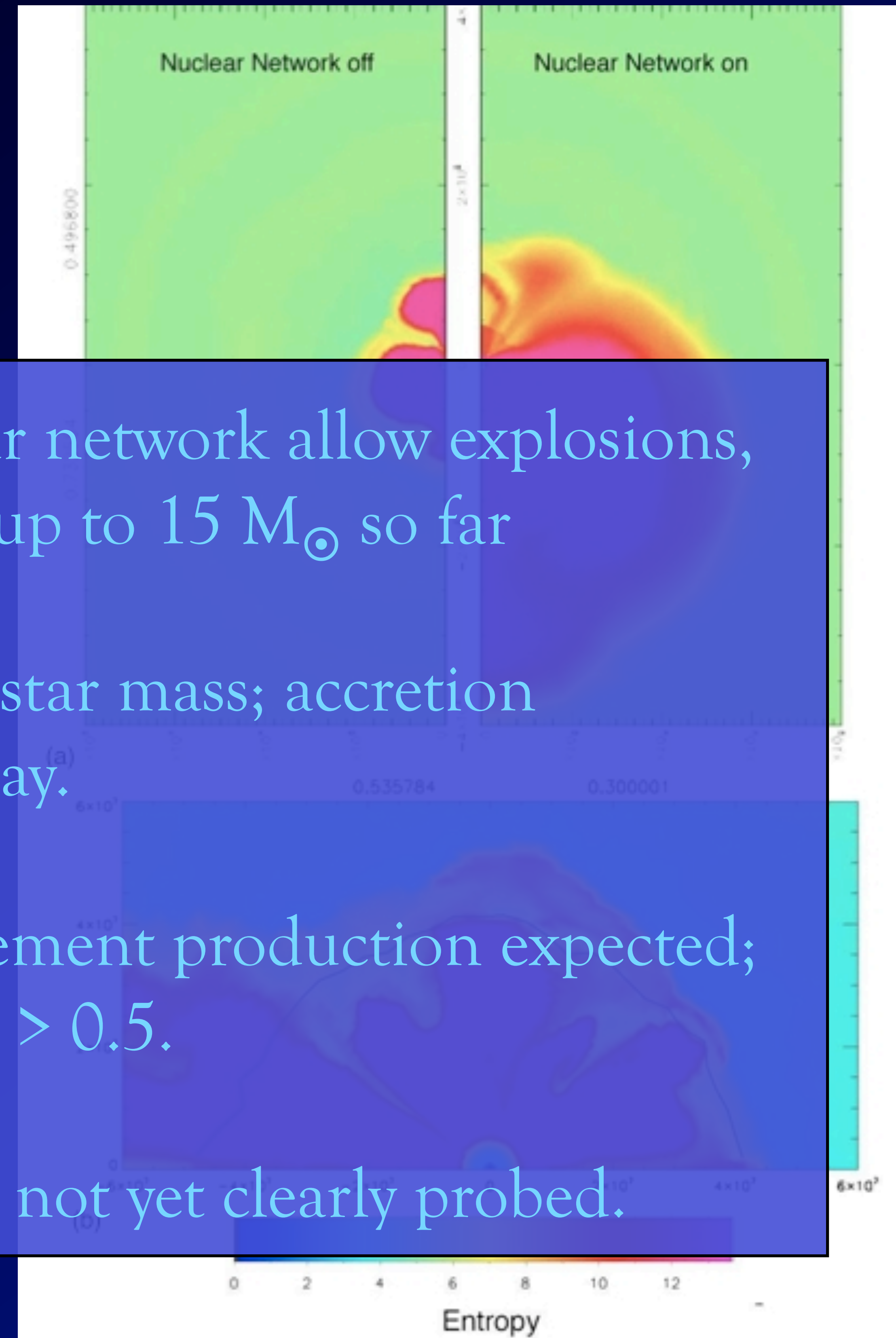

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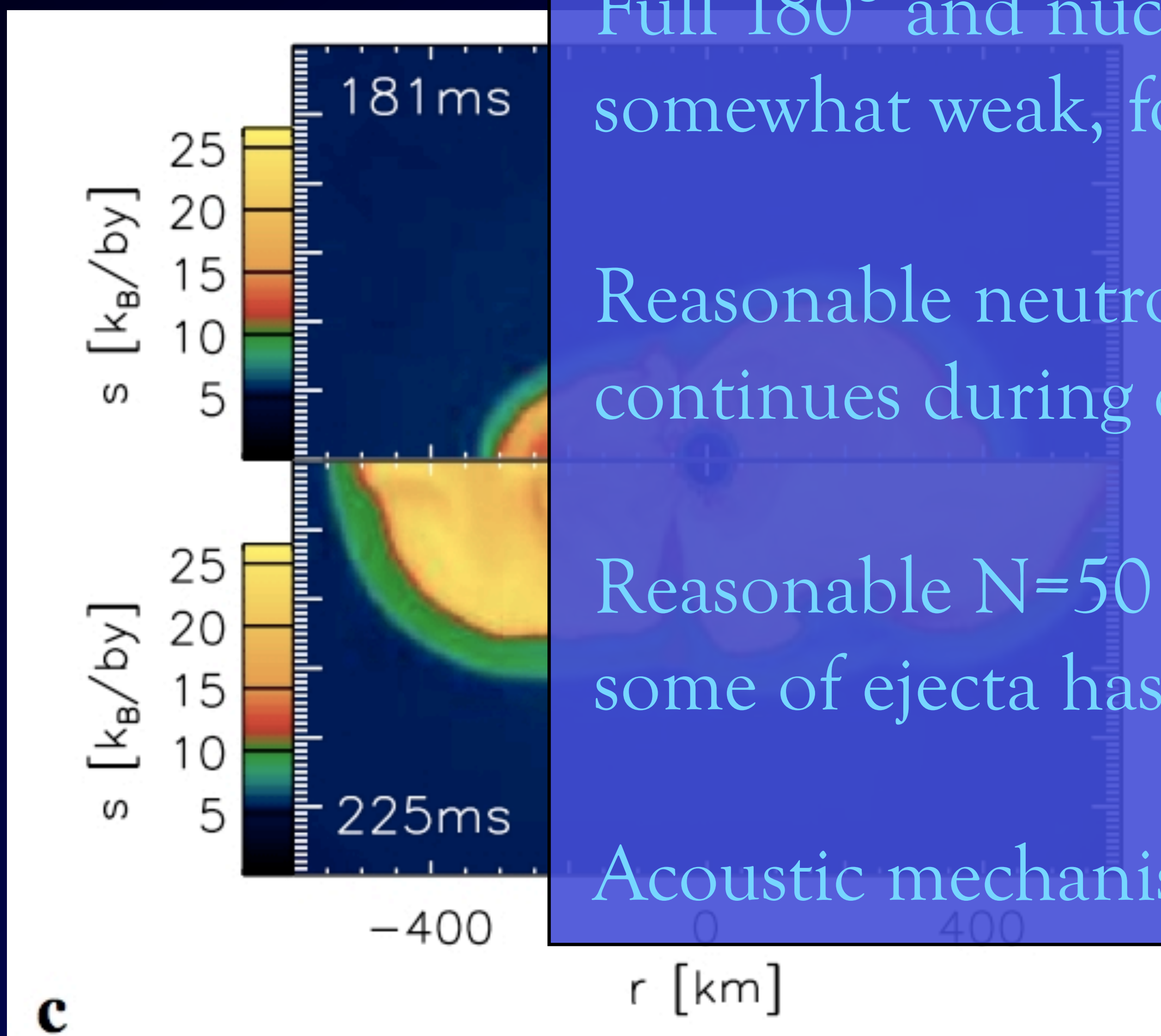

Full 180° and nuclear network allow explosions, somewhat weak, for up to 15 $M_\odot$ so far

Reasonable neutron star mass; accretion continues during delay.

Reasonable N=50 element production expected; some of ejecta has $Y_e > 0.5$.

Acoustic mechanism not yet clearly probed.

Determining what combination of

neutrino heating,

changes in nuclear composition, and

fluid and magnetic field instabilities

nature uses to reenergize the shock and launch the explosion will require:

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Detailed simulations

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Detailed simulations

Comparison against observations

Simulation of collapse and launch of the explosion involves a wide range of physics.

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Tangent bundle

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- Tangent bundle
- Magnetofluid

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- Tangent bundle
- Magnetofluid
- Neutrino distributions

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- Tangent bundle:
  - Spacetime includes all three space dimensions, with good resolution on a wide range of length and time scales.

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- Momentum space includes all three dimensions, with good resolution of energies and angles.

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Tangent bundle:

- Spacetime includes all three space dimensions, with good resolution on a wide range of length and time scales.
- Momentum space includes all three dimensions, with good resolution of energies and angles.
- Self-gravity is treated with general relativity.

Simulation of collapse and launch of the explosion involves a wide range of physics.

Magnetofluid:

Simulation of collapse and launch of the explosion involves a wide range of physics.

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  - The treatment of ideal magnetohydrodynamics must be able to handle shocks.

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Magnetofluid:

The treatment of ideal magnetohydrodynamics must be able to handle shocks.

Nuclear composition changes involving strong, electromagnetic, and weak reactions should be tracked in regimes ranging from fully kinetic through (quasi-)NSE, for a very wide range of species.

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The treatment of ideal magnetohydrodynamics must be able to handle shocks.

Nuclear composition changes involving strong, electromagnetic, and weak reactions should be tracked in regimes ranging from fully kinetic through (quasi-)NSE, for a very wide range of species.

An equation of state that includes bulk nuclear matter in neutron-rich conditions is required.

Simulation of collapse and launch of the explosion involves a wide range of physics.

Neutrino distributions:

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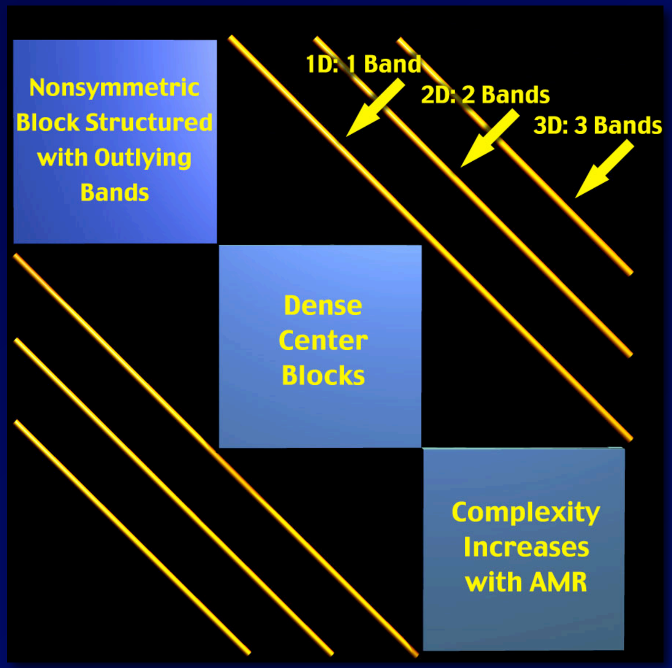

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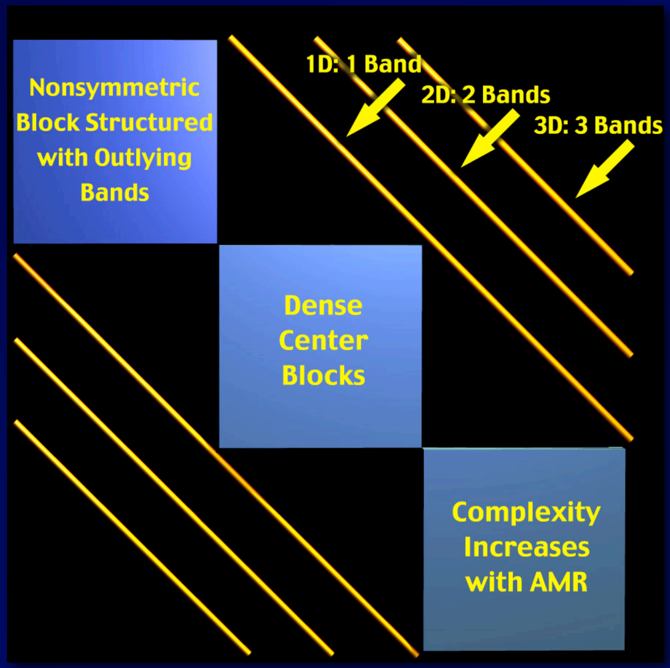

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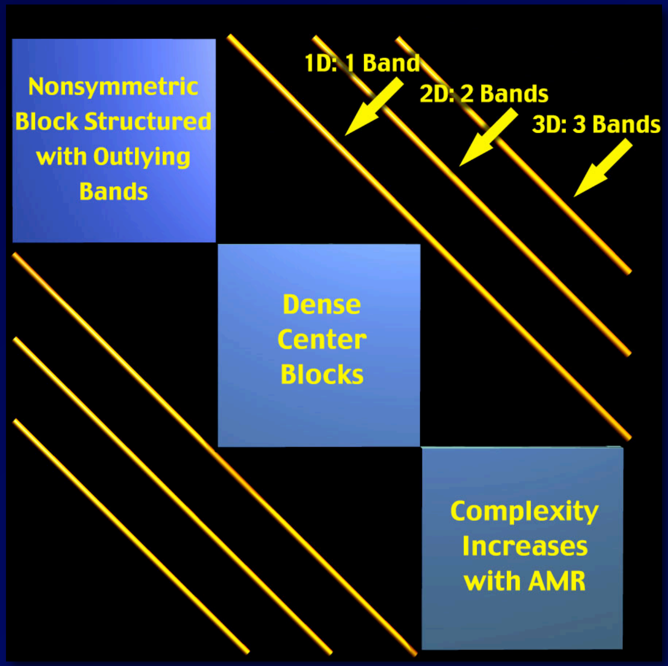

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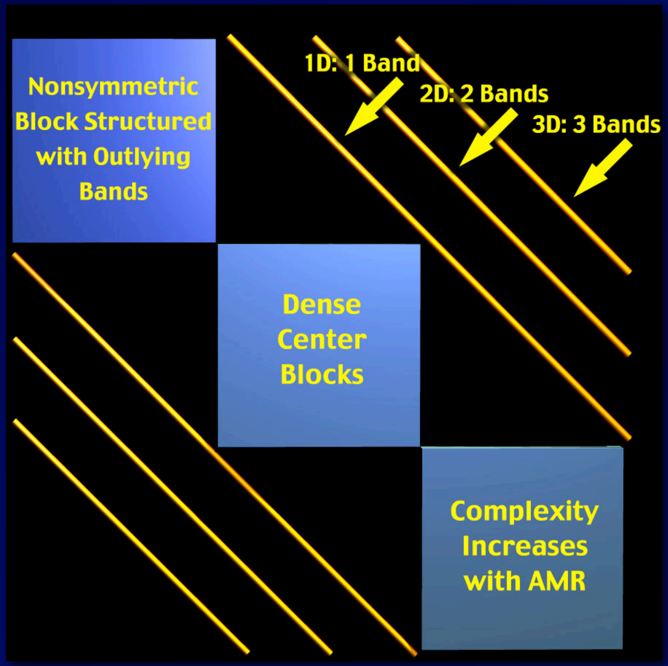

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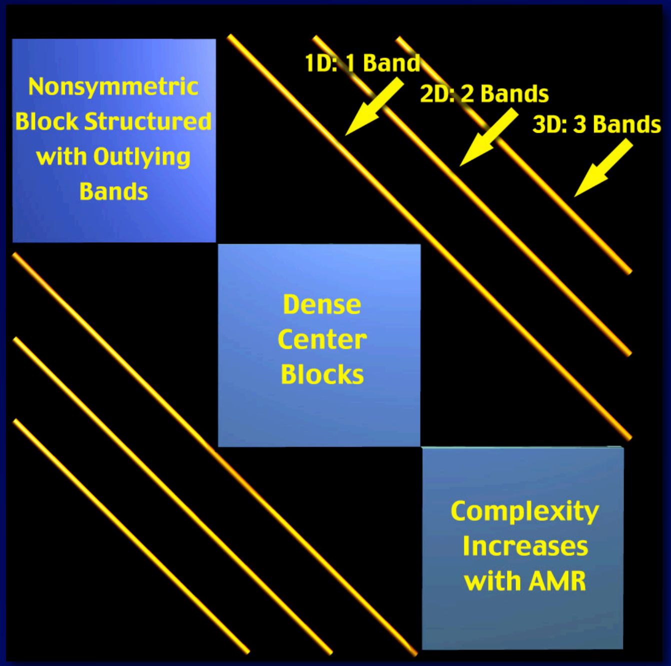

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- There may be tradeoffs between 'intelligence' and efficiency, but the bottom line is accuracy as a function of wall time.

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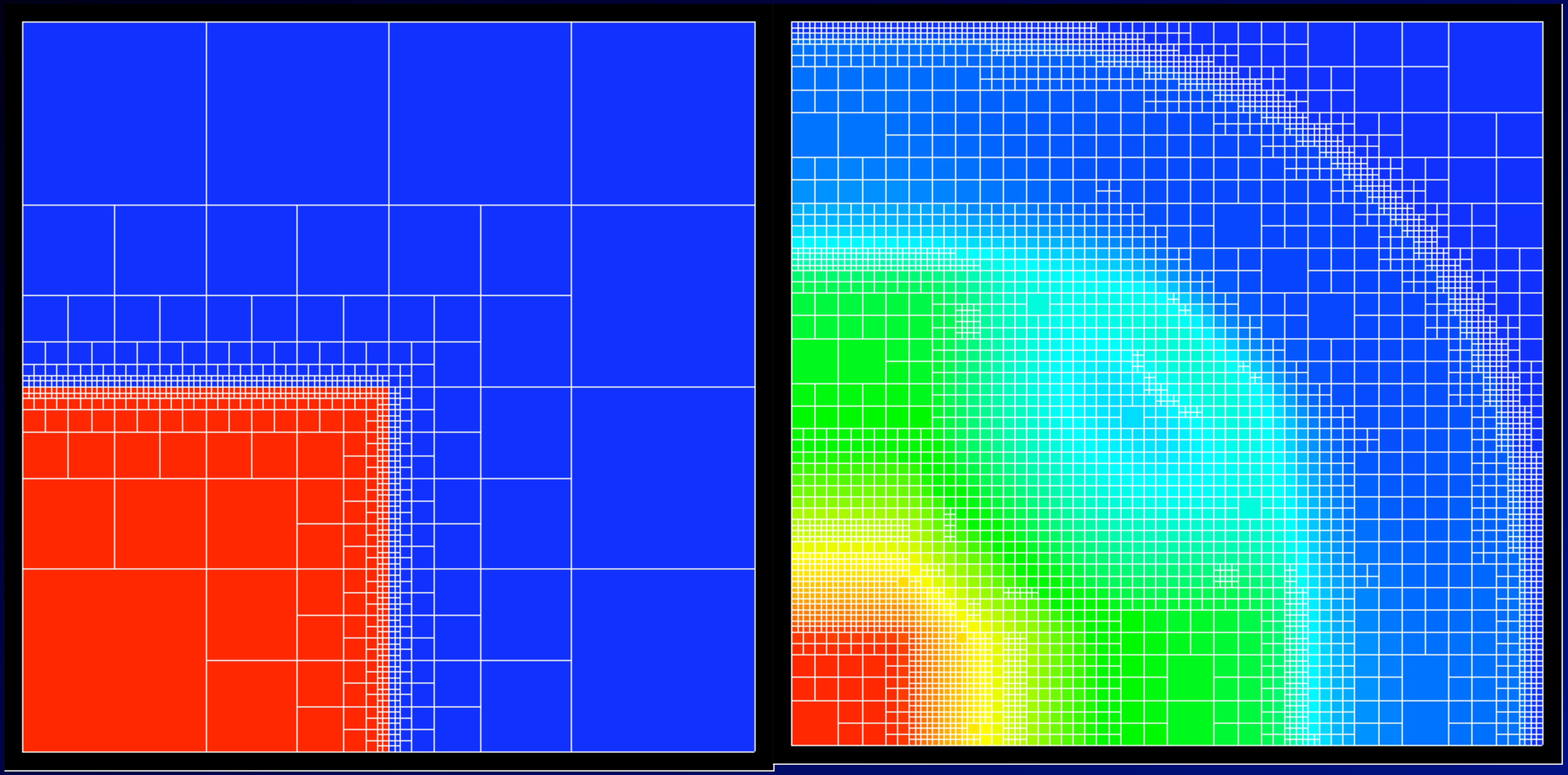
GenASiS: *Ge*neral *A*strophysical *Si*mulation *S*ystem

Adaptive mesh refinement



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Explosion

Running

Dud

Development

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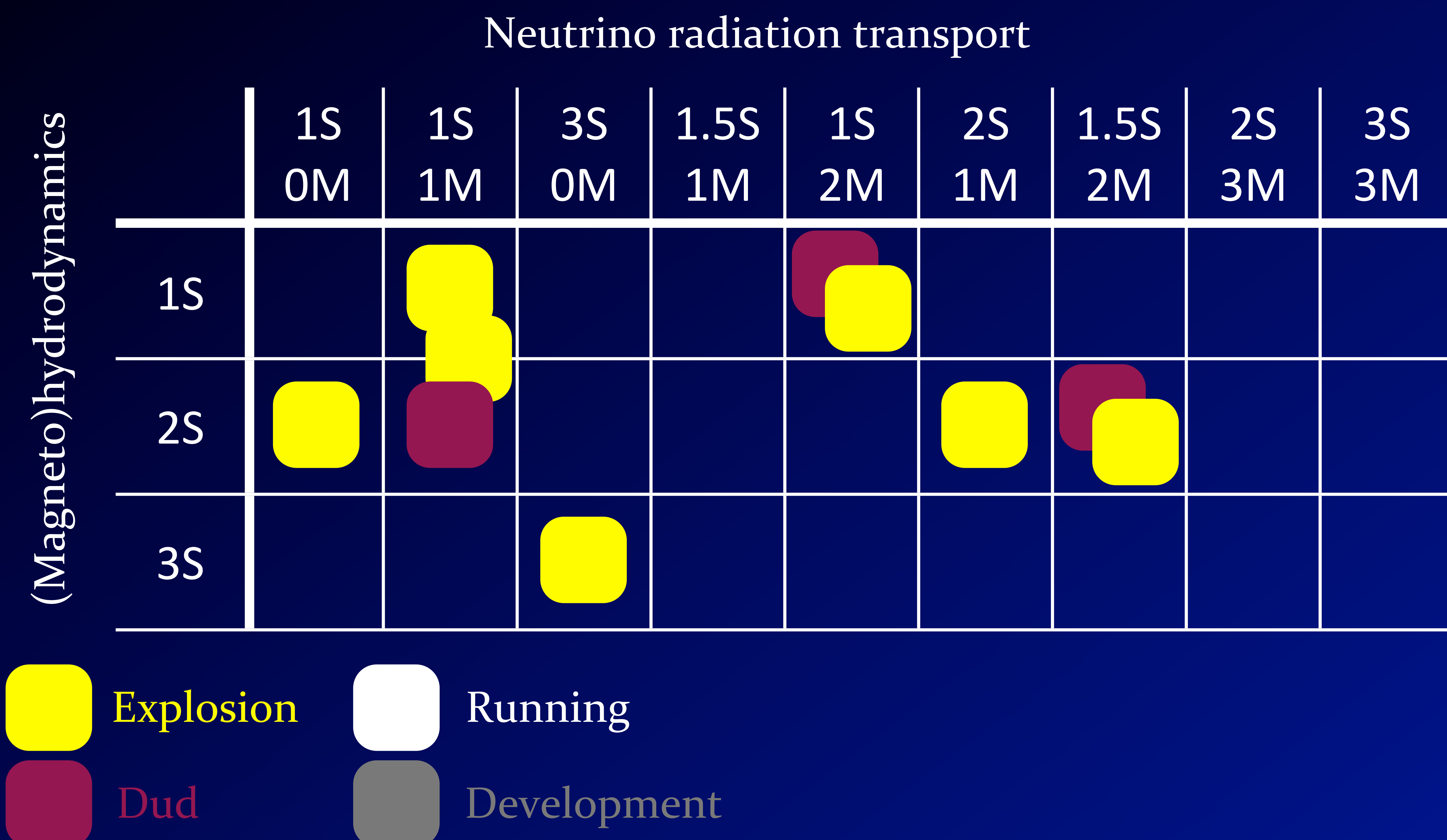

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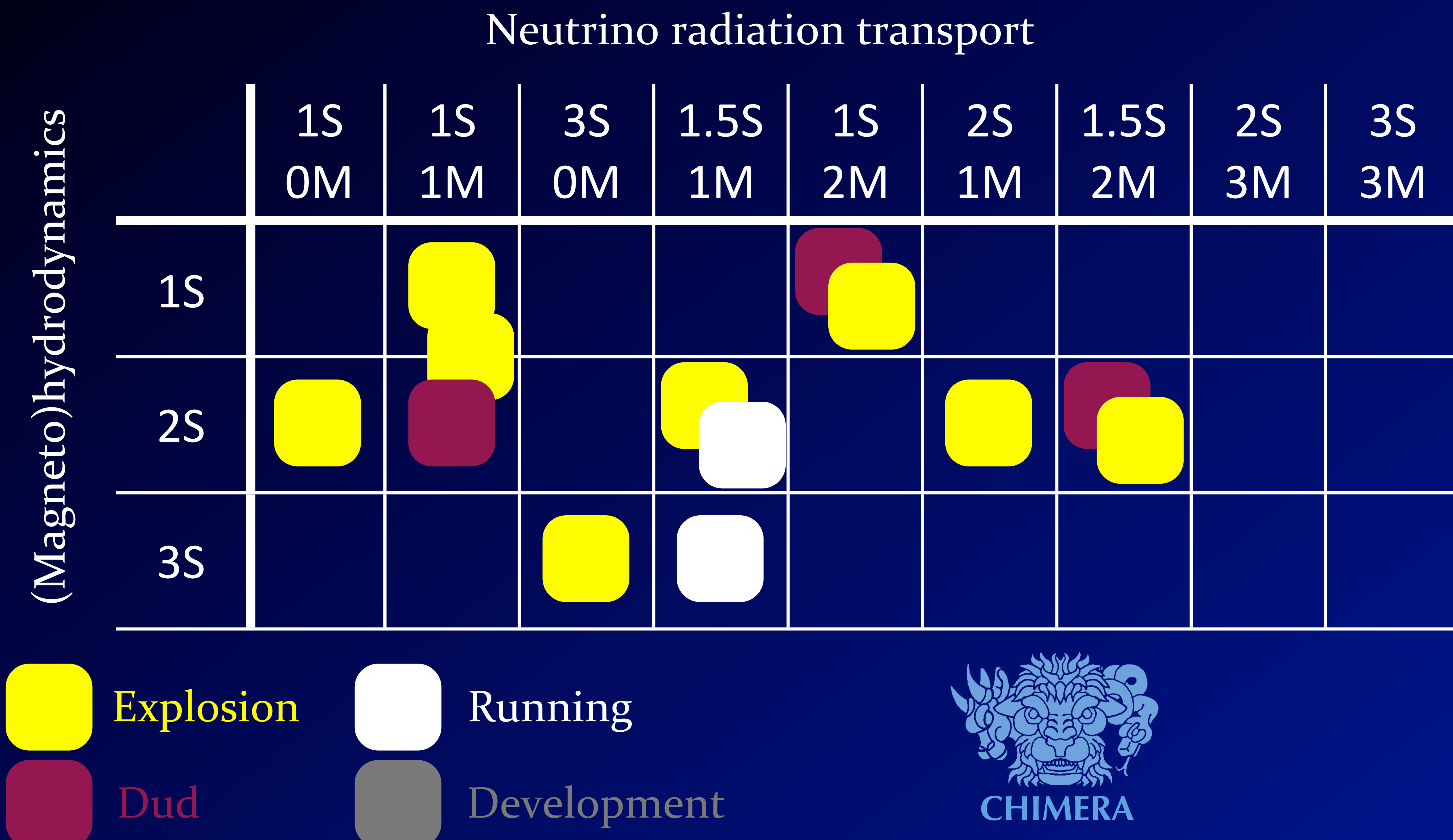

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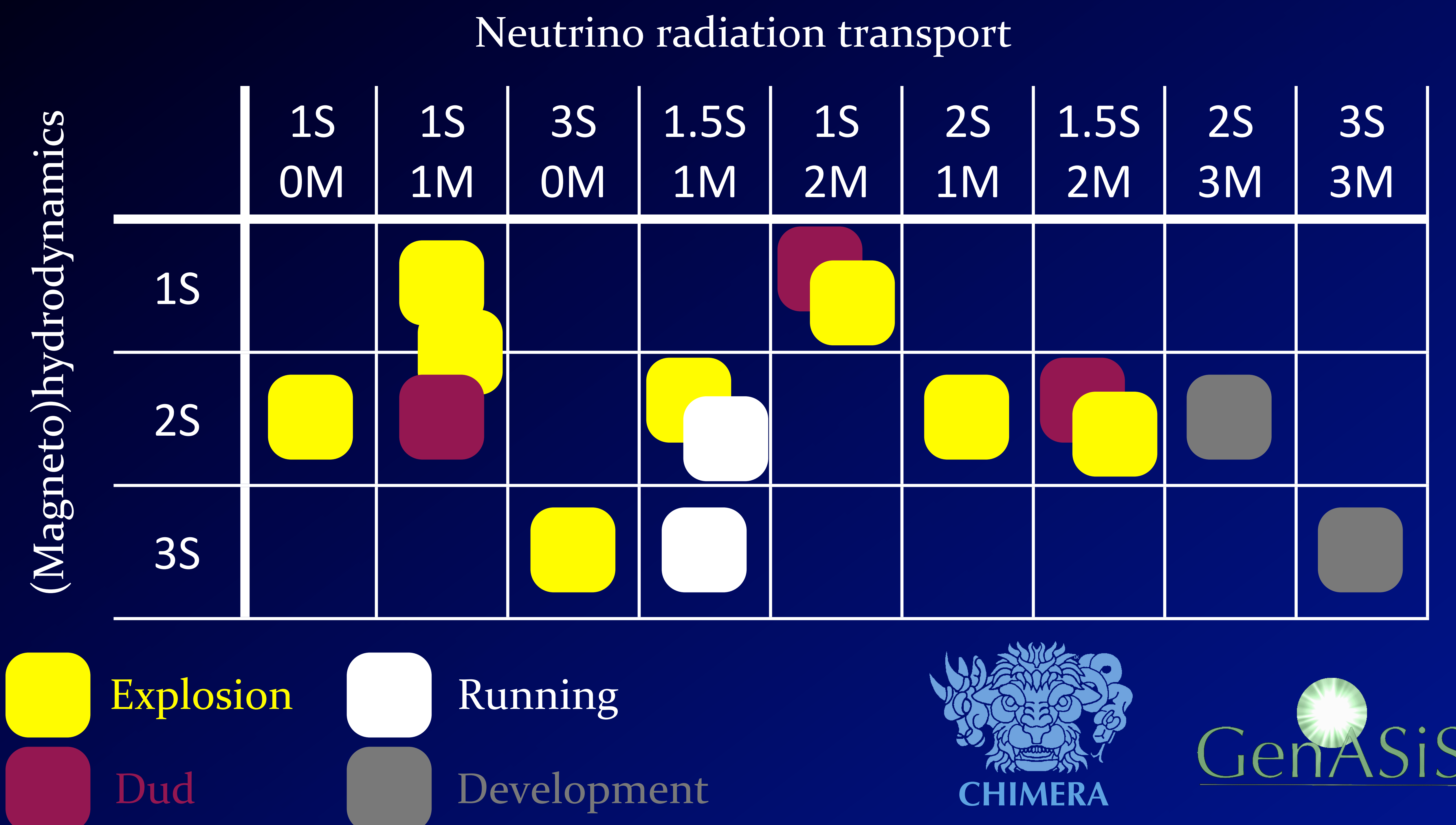

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These events also involve neutrino and gravitational wave signals; in some cases, the longer gamma-ray bursts; enrichment of the interstellar medium; neutron star kicks; and pulsar/magnetar phenomena.

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Understanding the explosion mechanism, which gives rise to the optical display that first caught humans’ attention, requires detailed simulation.

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Detailed simulations of the full seven-dimensional problem on the world's largest supercomputers will need to continue for many years into the future.

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An understanding of neutrino properties is needed in order to make full use of supernova neutrinos as a probe of the explosion mechanism.

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CYC arXiv:0712.1188 (Phys.Rev.D78:085017,2008)