Supernova Modeling: Progress and Challenges

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What are supernovae, and what are they doing in our neutrino conference?

The peak optical luminosity of a supernova is comparable to that of an entire galaxy.

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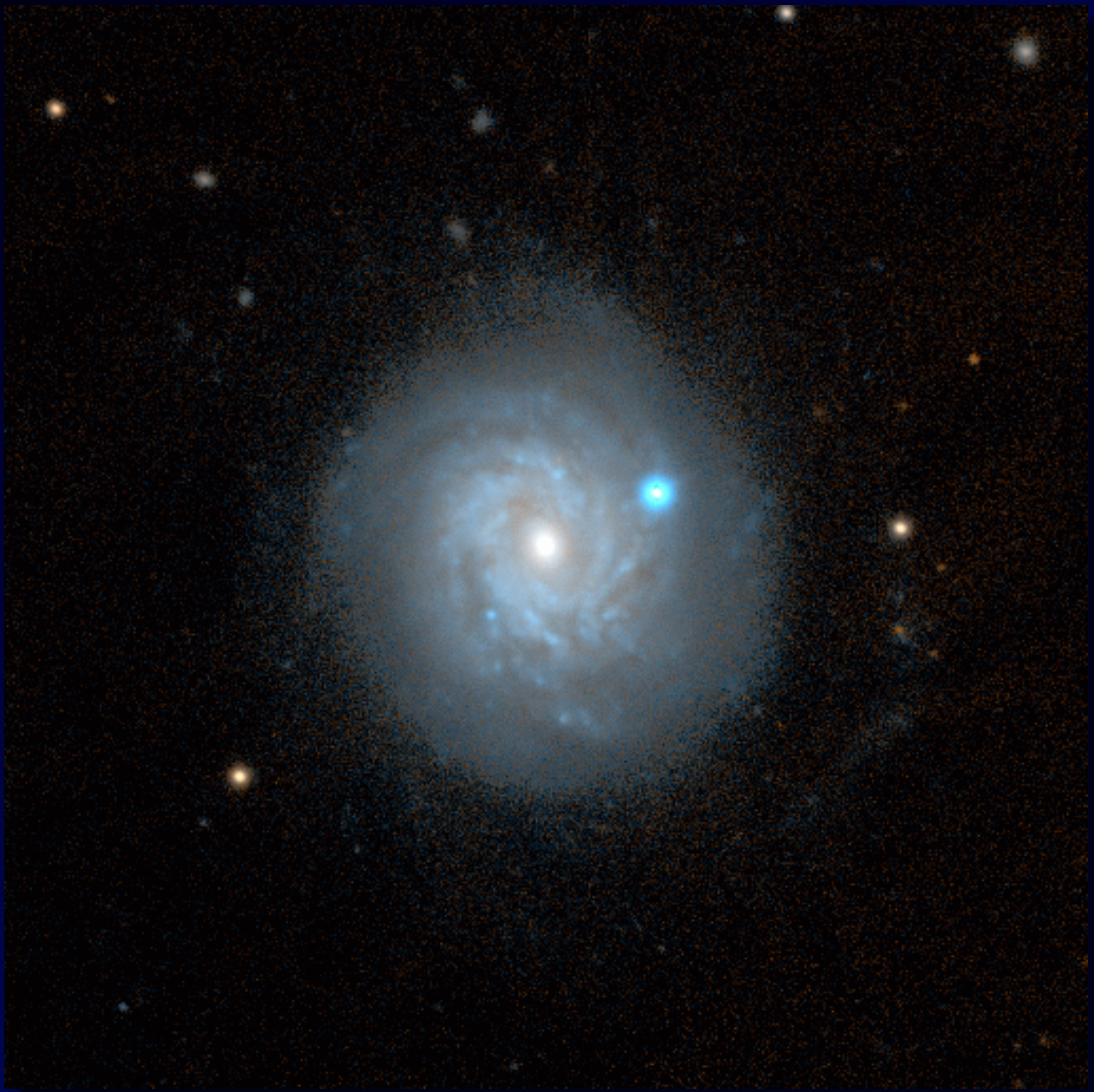

SN 1998aq

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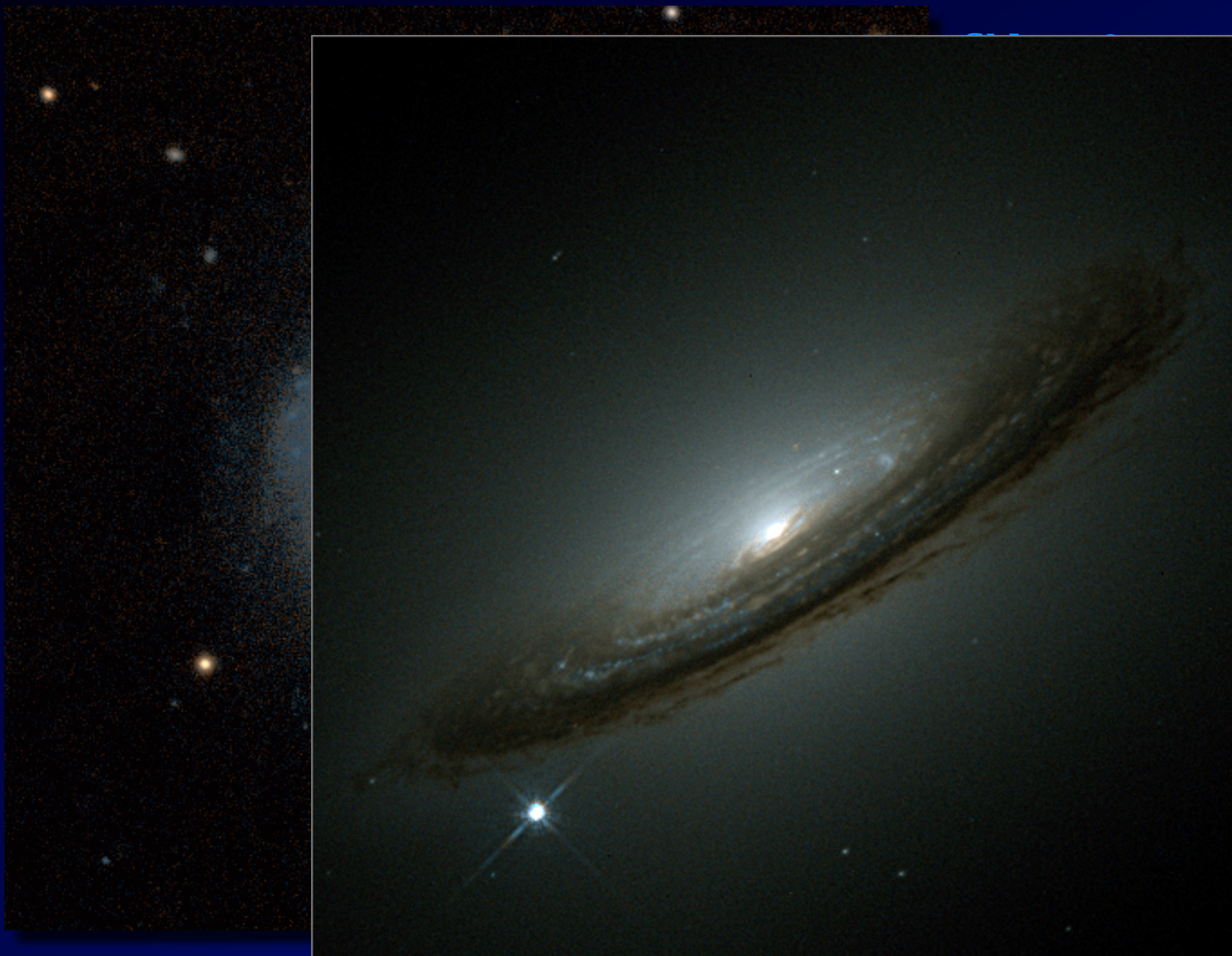
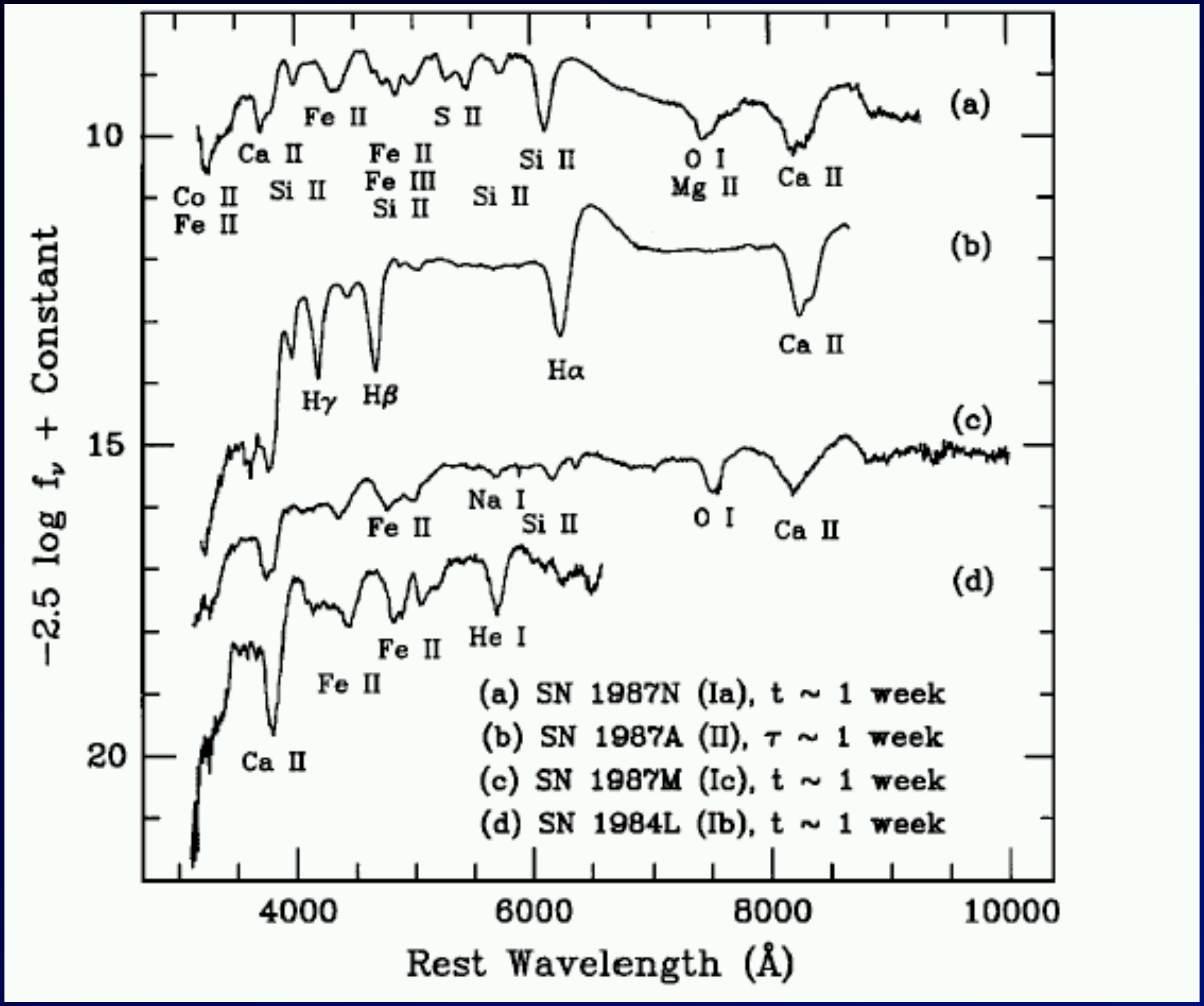


SN 1994D

Astronomers classify supernovae according to their spectra.



Filippenko (1997)

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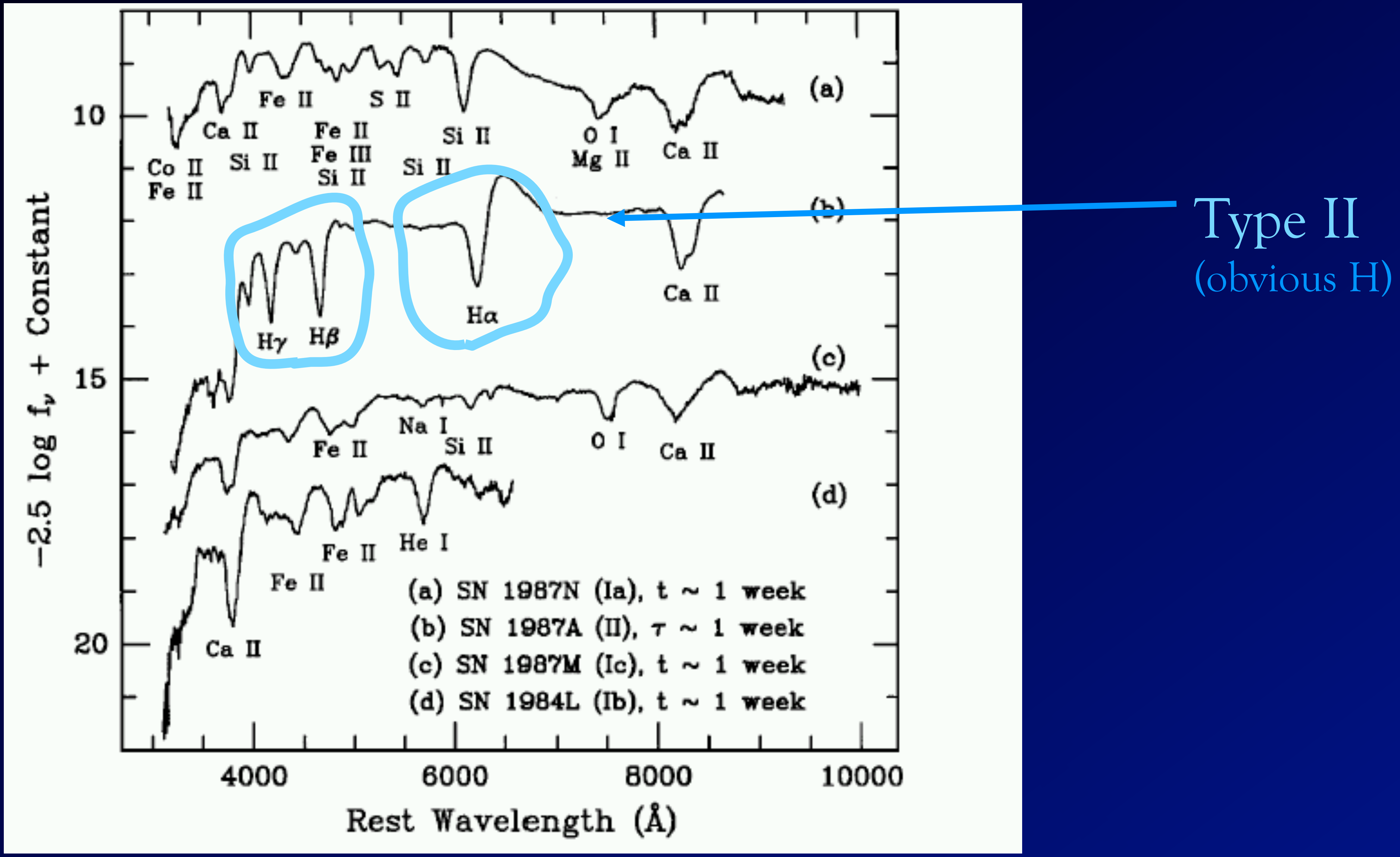

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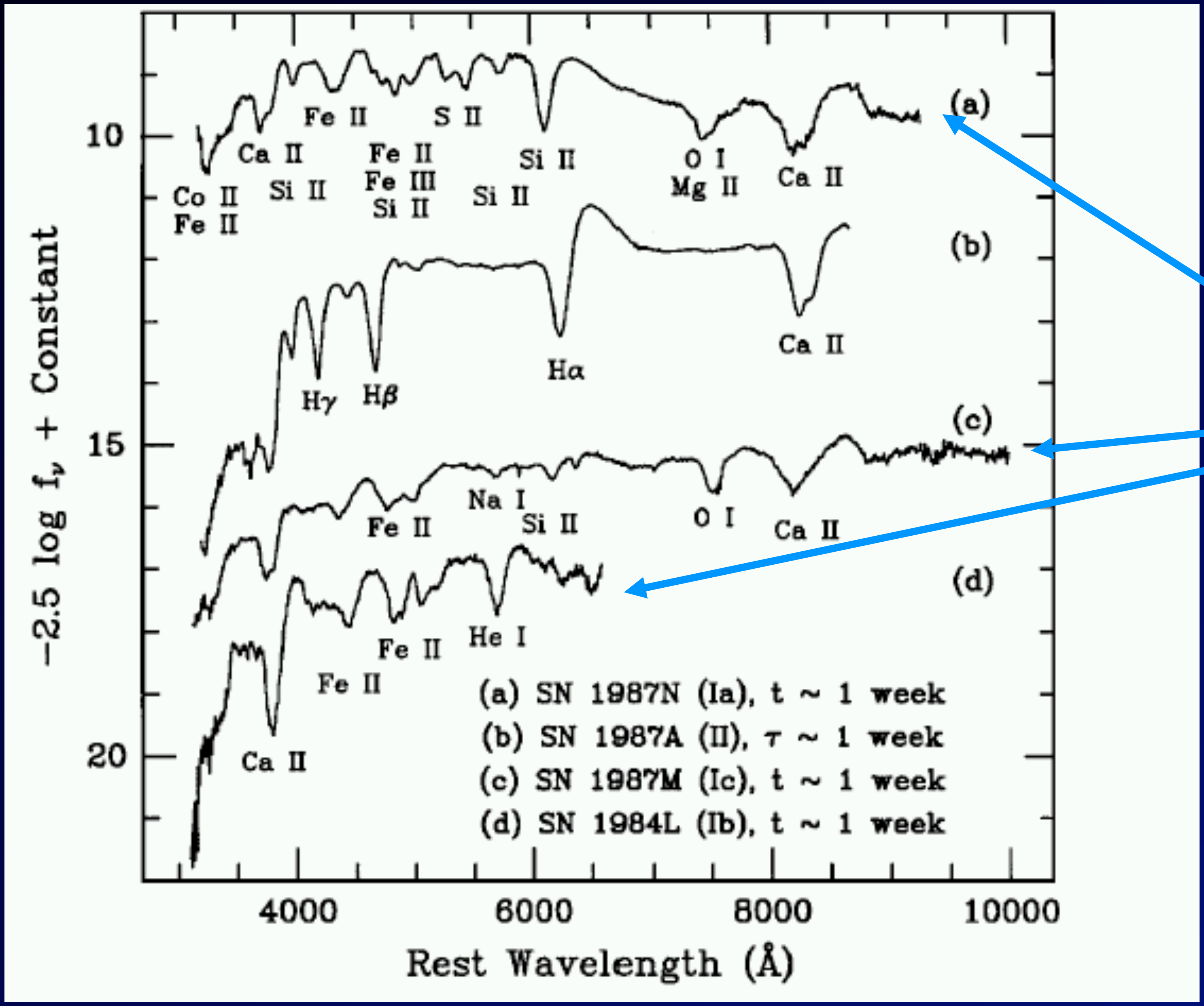

Type I
(no H)

Filippenko (1997)

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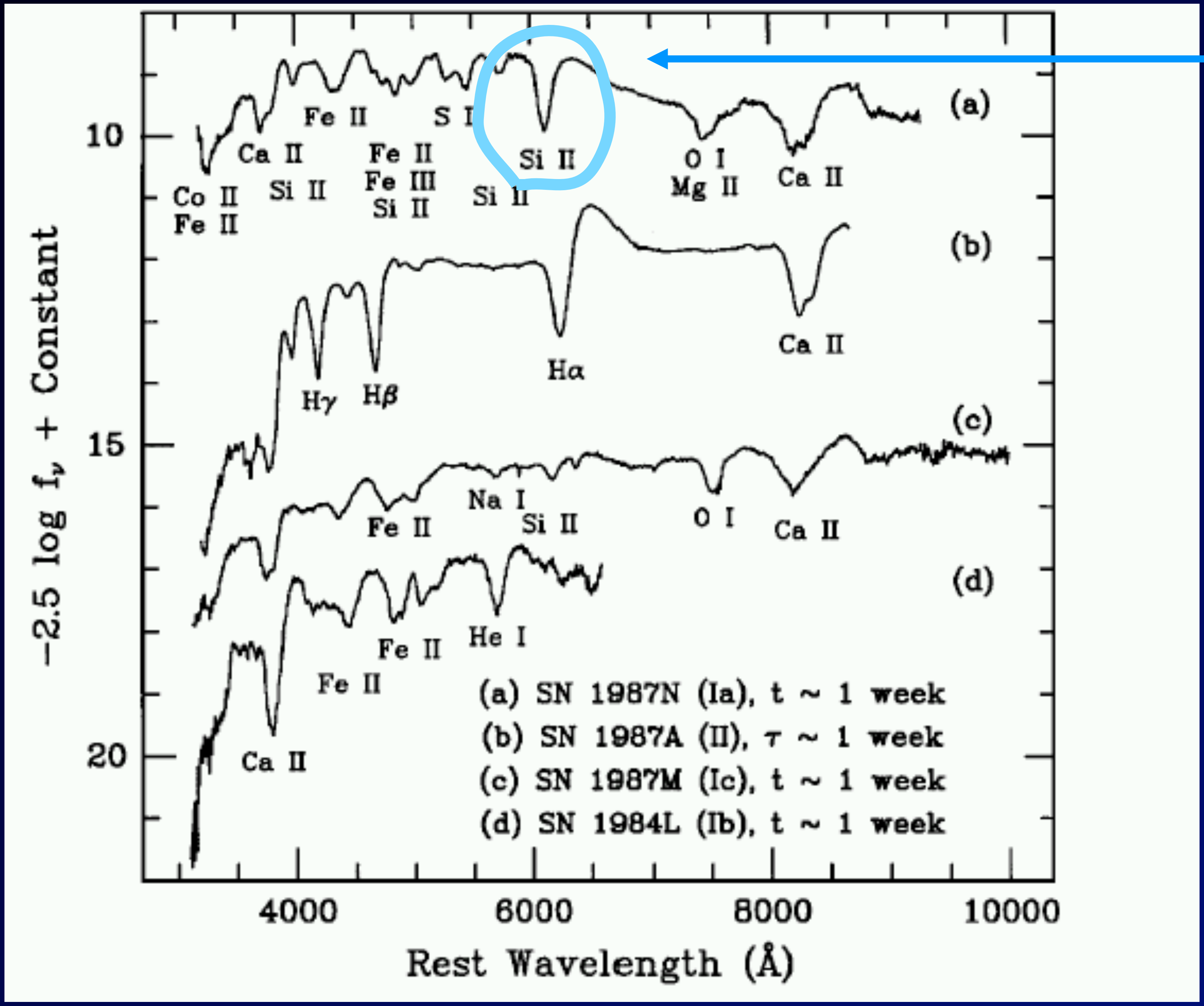

Type Ia
(no H, strong Si)

Filippenko (1997)

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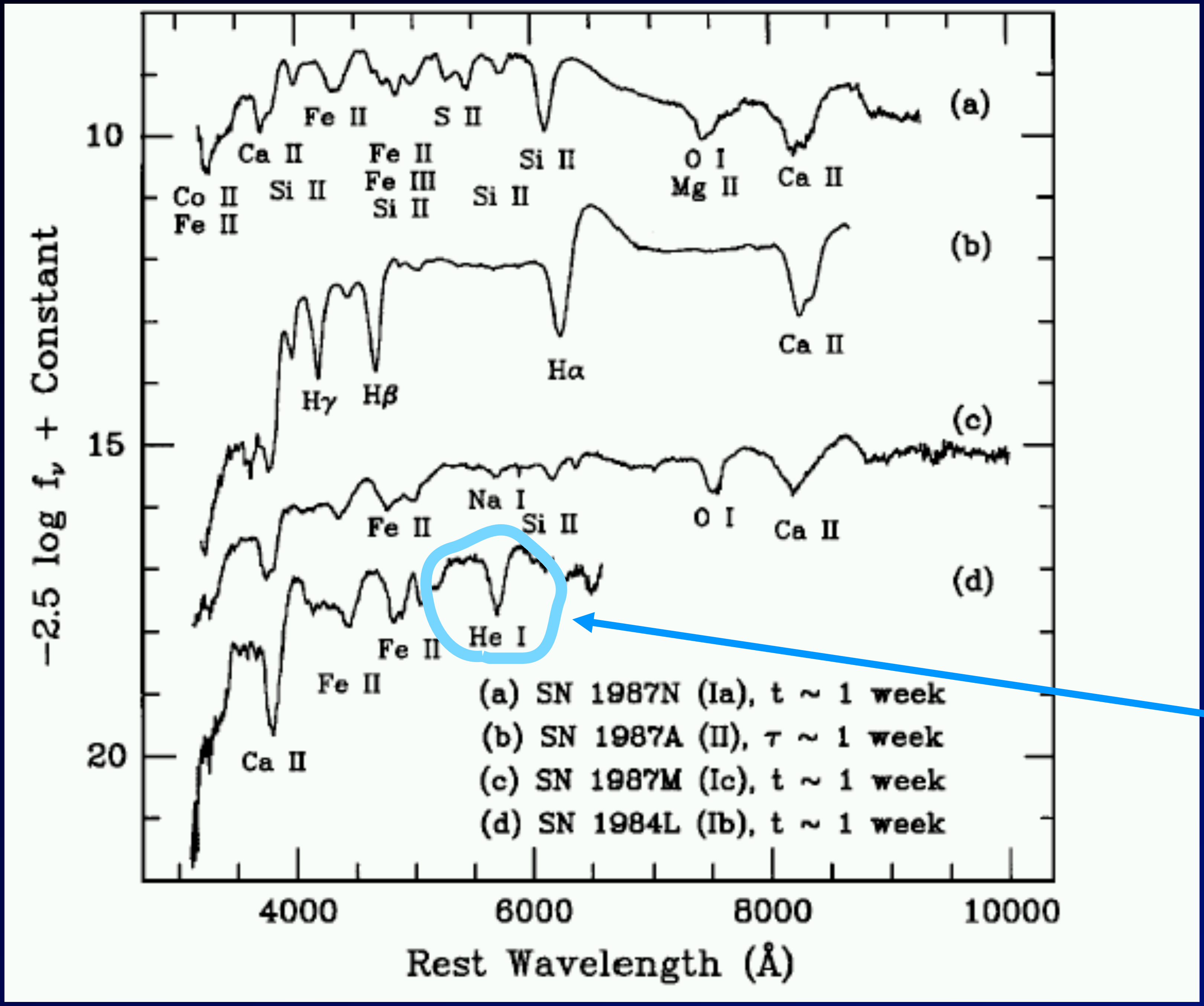

Type Ib
(no H, obvious He)

Filippenko (1997)

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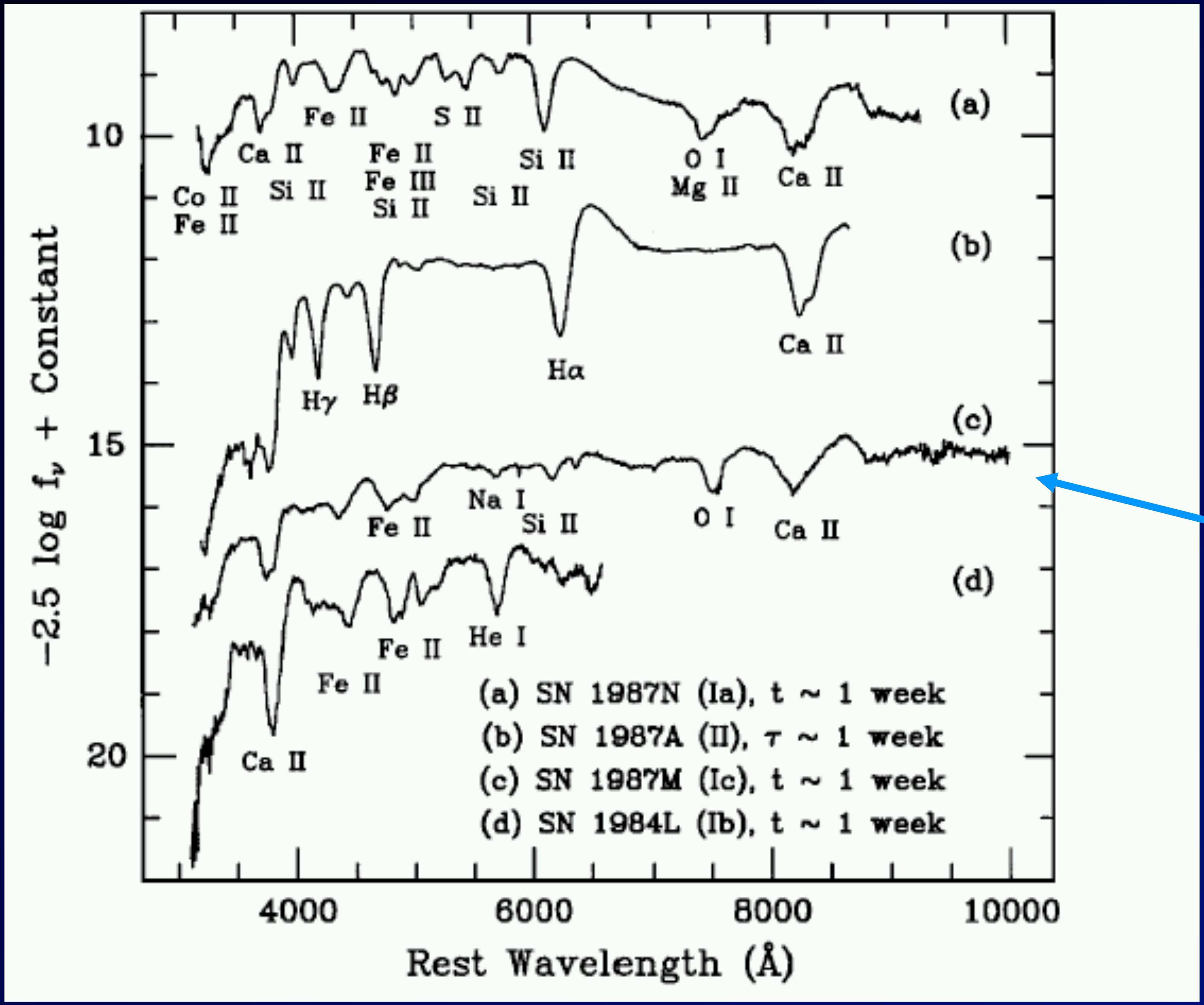

Type Ic
(no H, He, Si)

Filippenko (1997)

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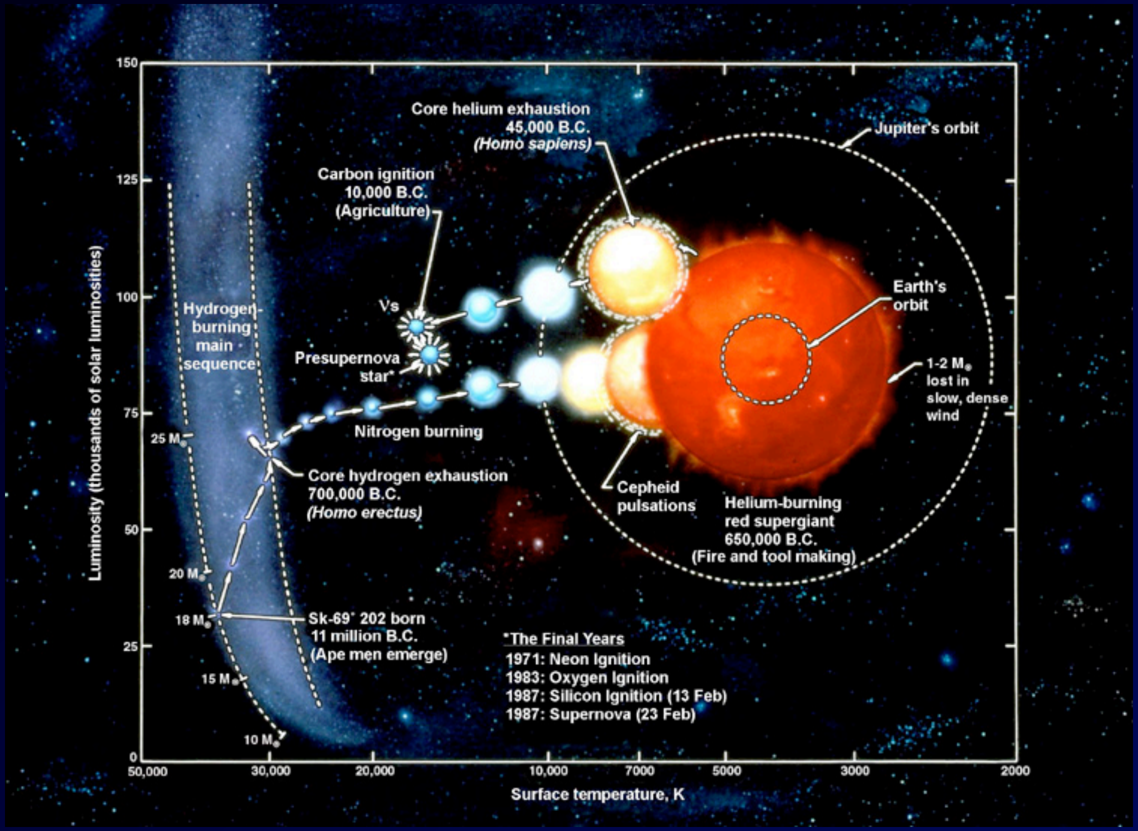

Type Ib/Ic/II: Core collapse at completion of the burning stages of an individual star with $M > 8\ M_\odot$; tiny fraction of released gravitational energy transferred to envelope

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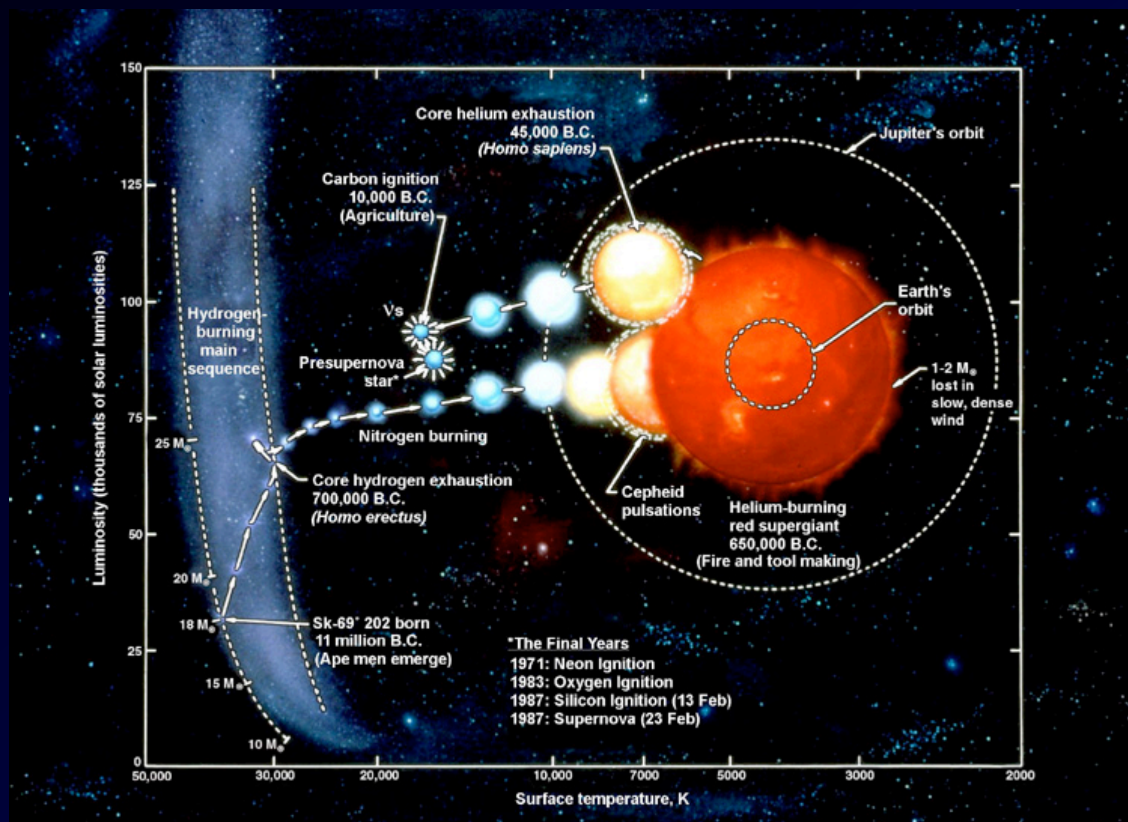

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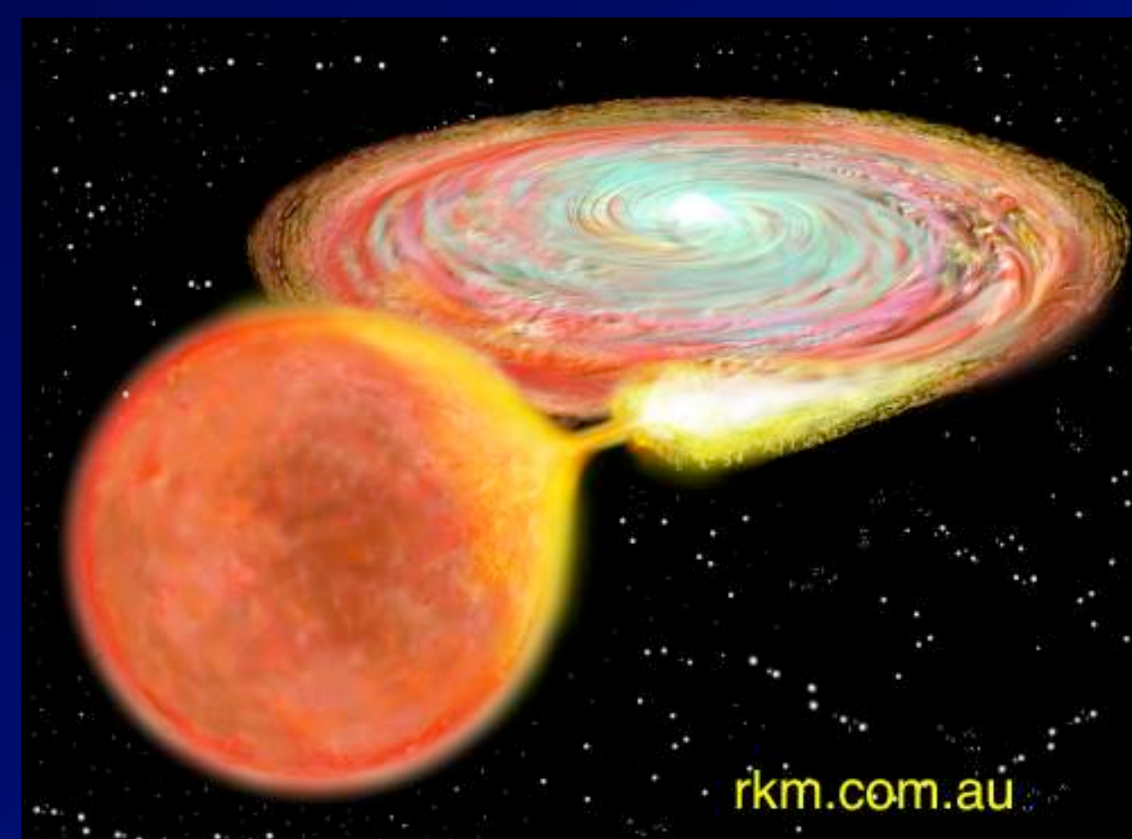

Type Ia: Thermonuclear explosion that consumes an entire white dwarf (remnant of a star with $M < 8\ M_\odot$), resulting from accretion

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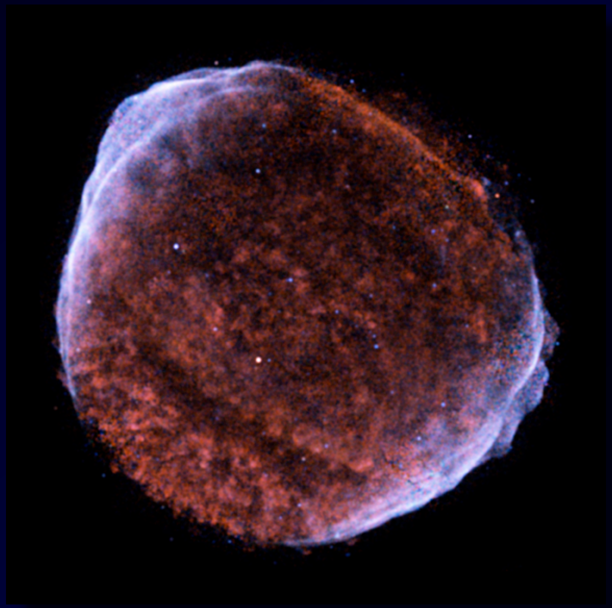
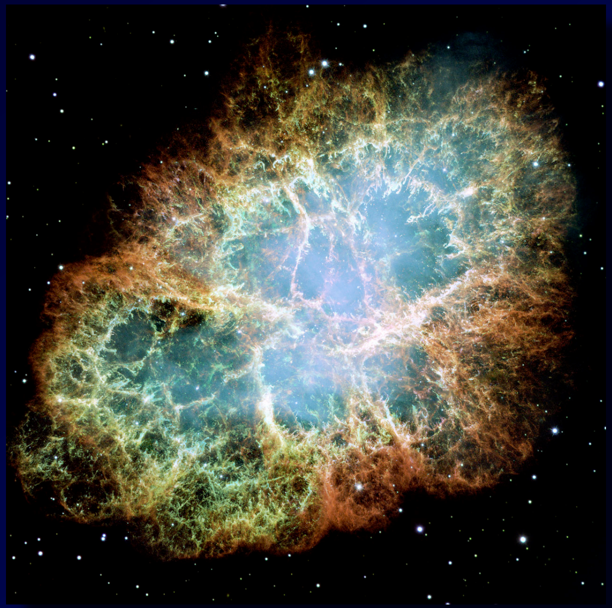
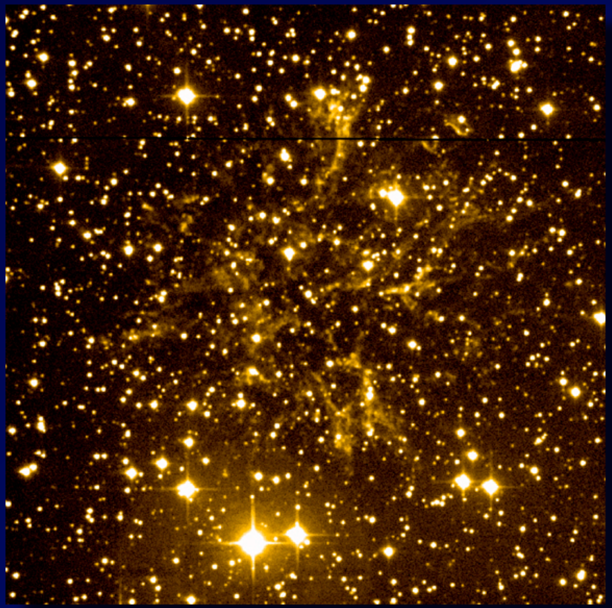


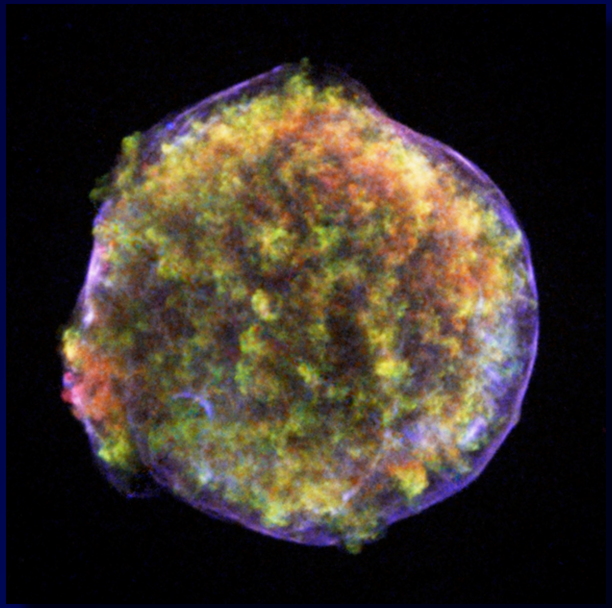
SN 1006 (X-ray) Type Ia



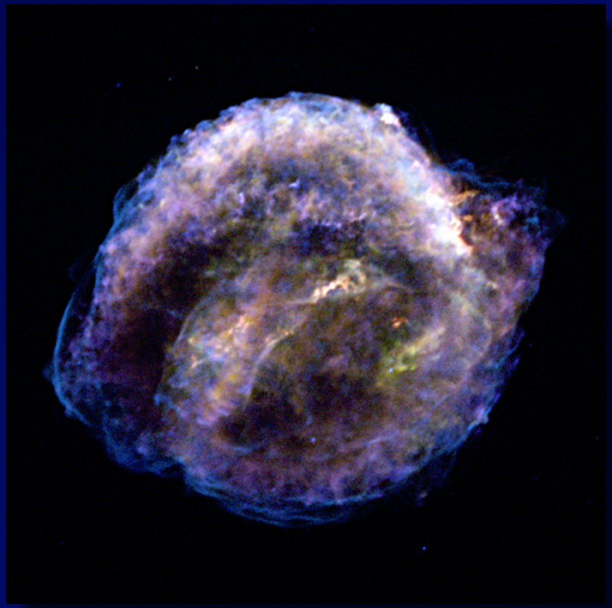
SN 1054 (Optical) Type II



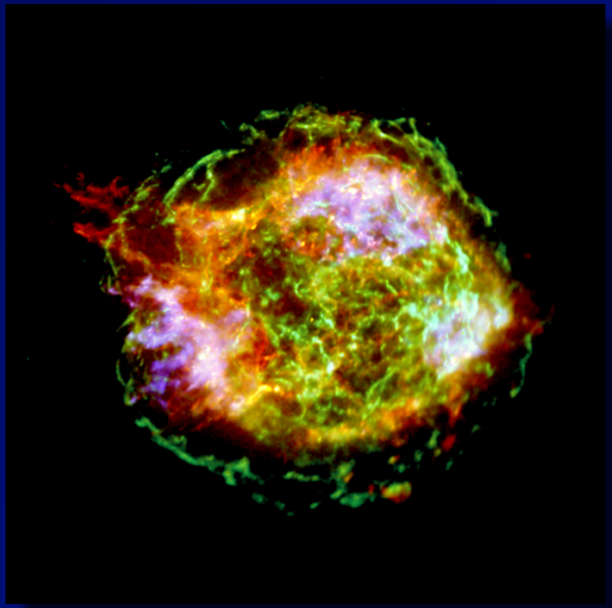
SN 1181 (Optical) Type II



SN 1572 (X-ray) Type Ia



SN 1604 (X-ray) Type Ia



Cas A 1667? (X-ray) Type II

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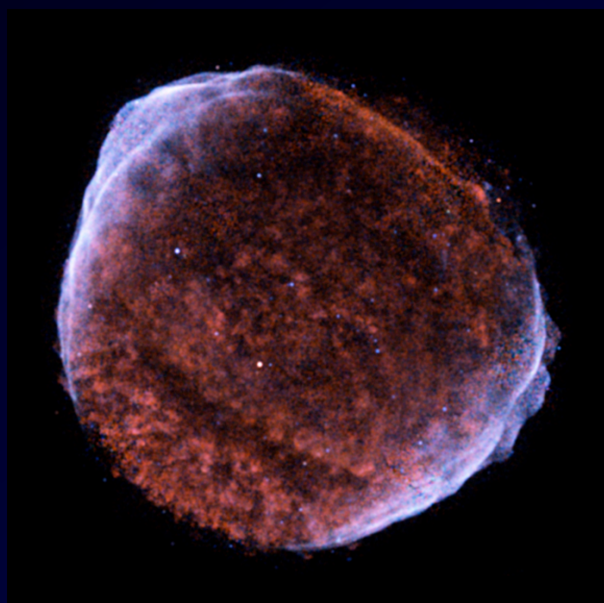

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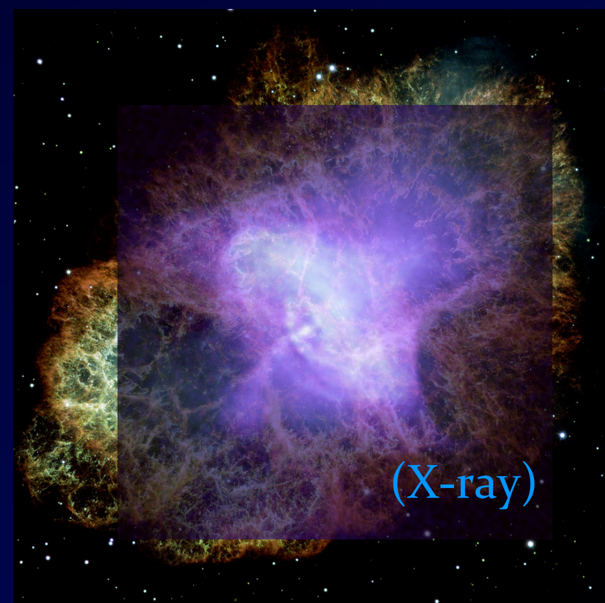

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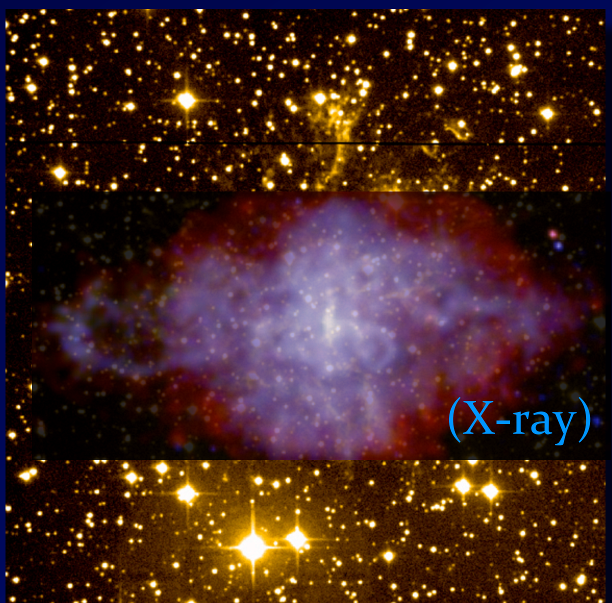

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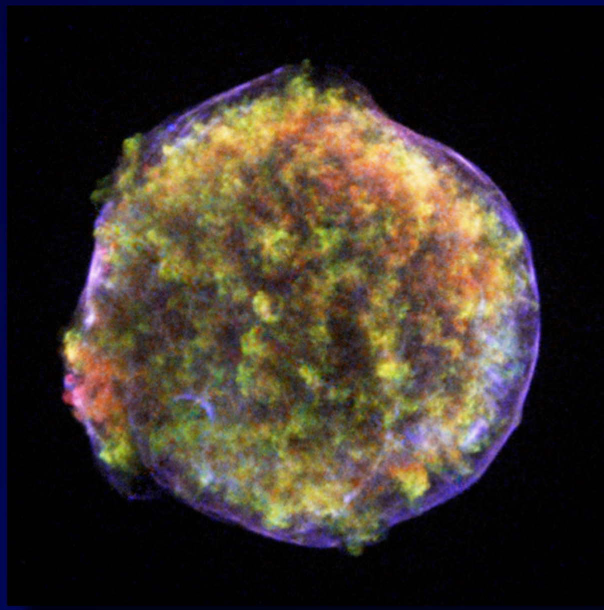

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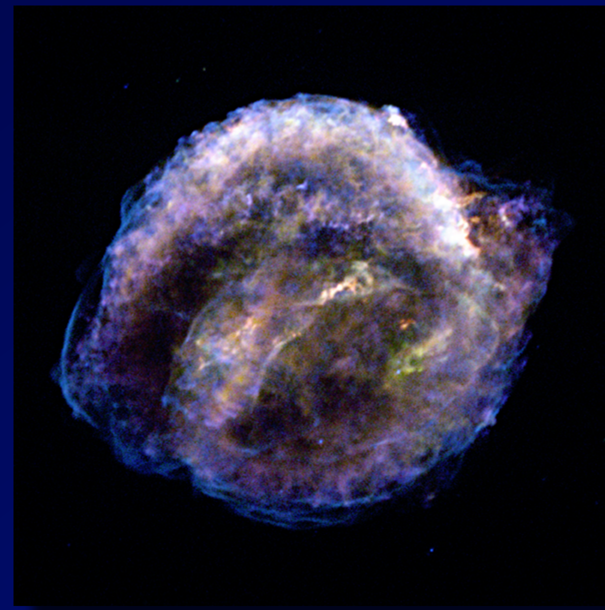

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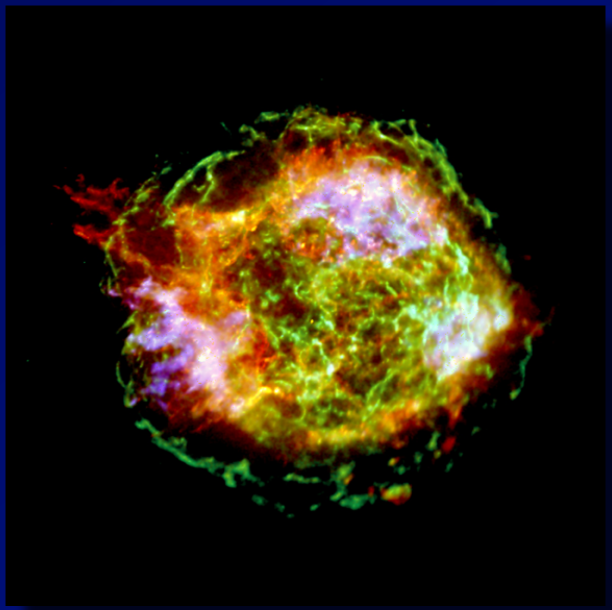

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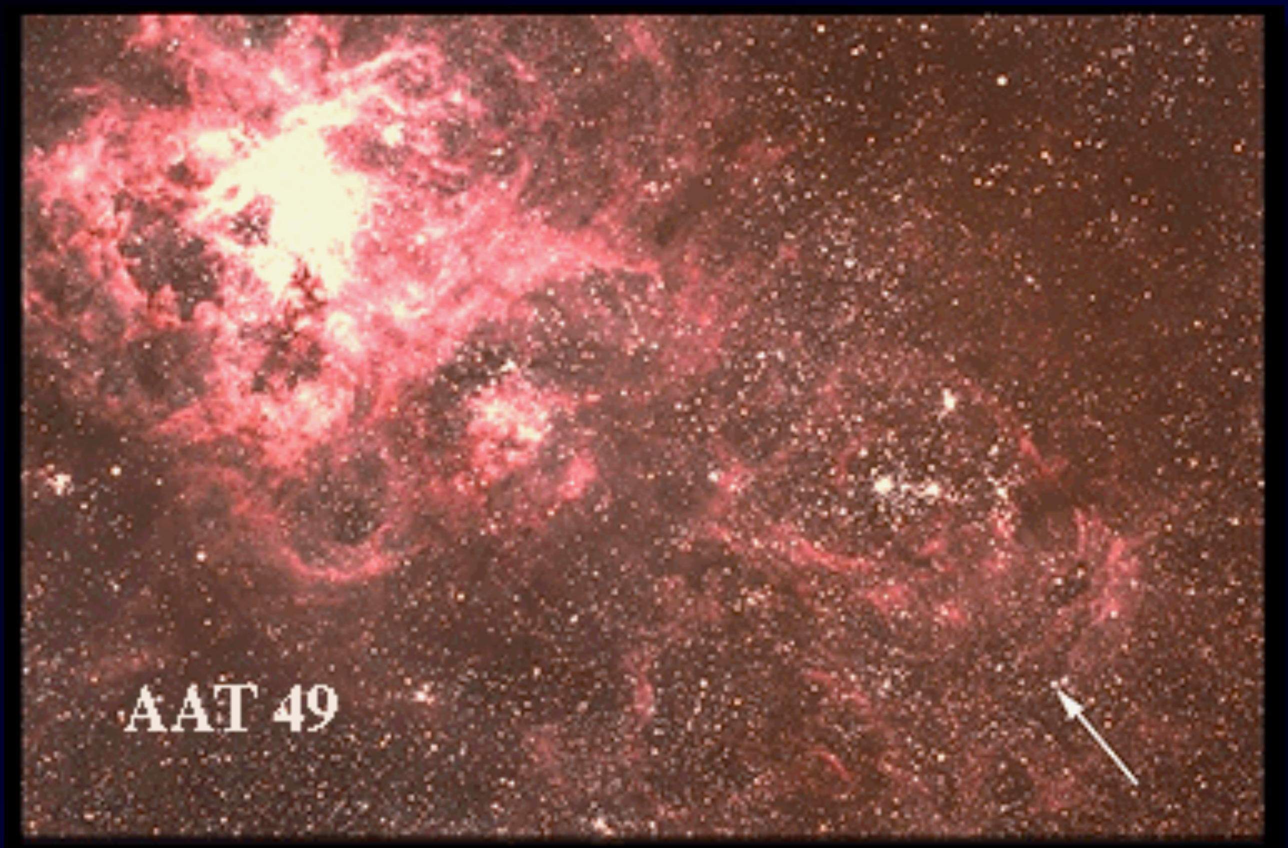

Tarantula Nebula

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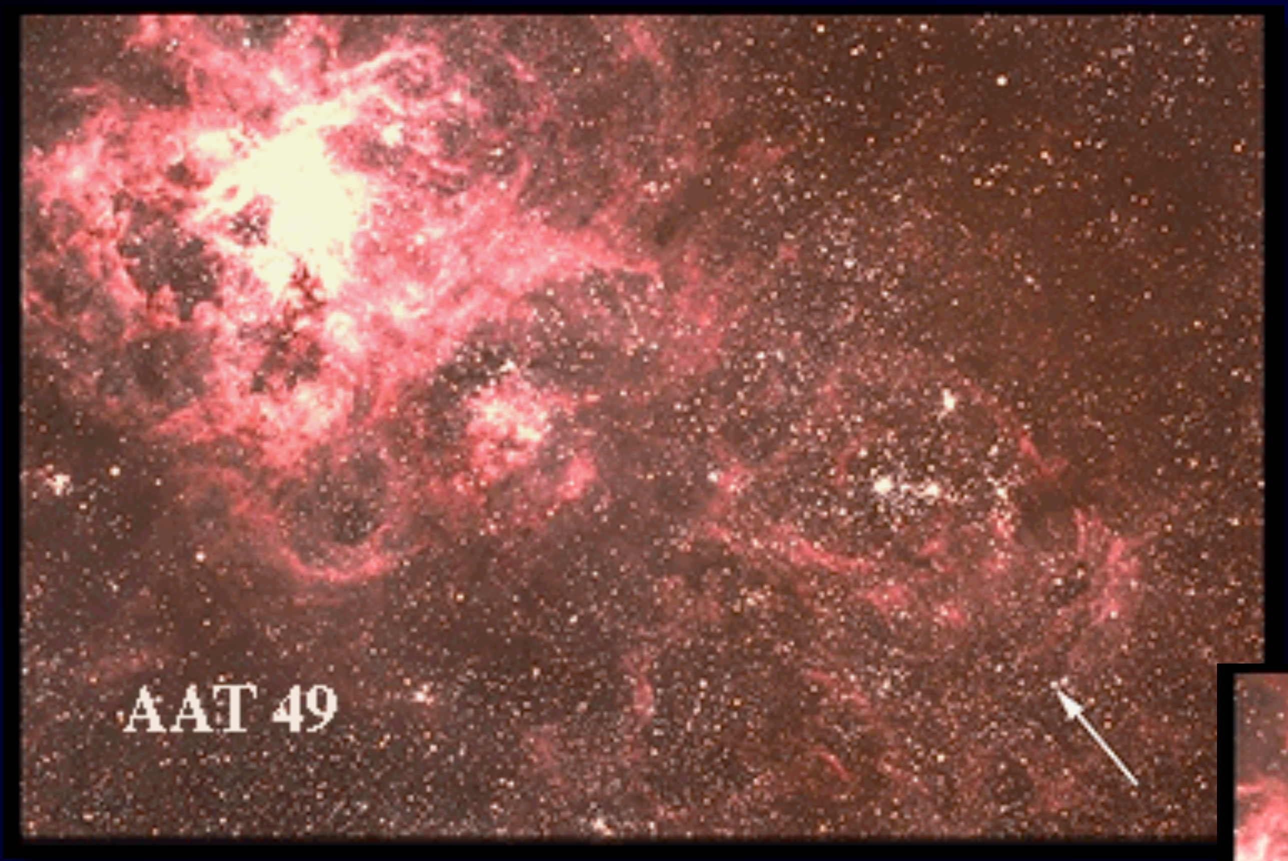

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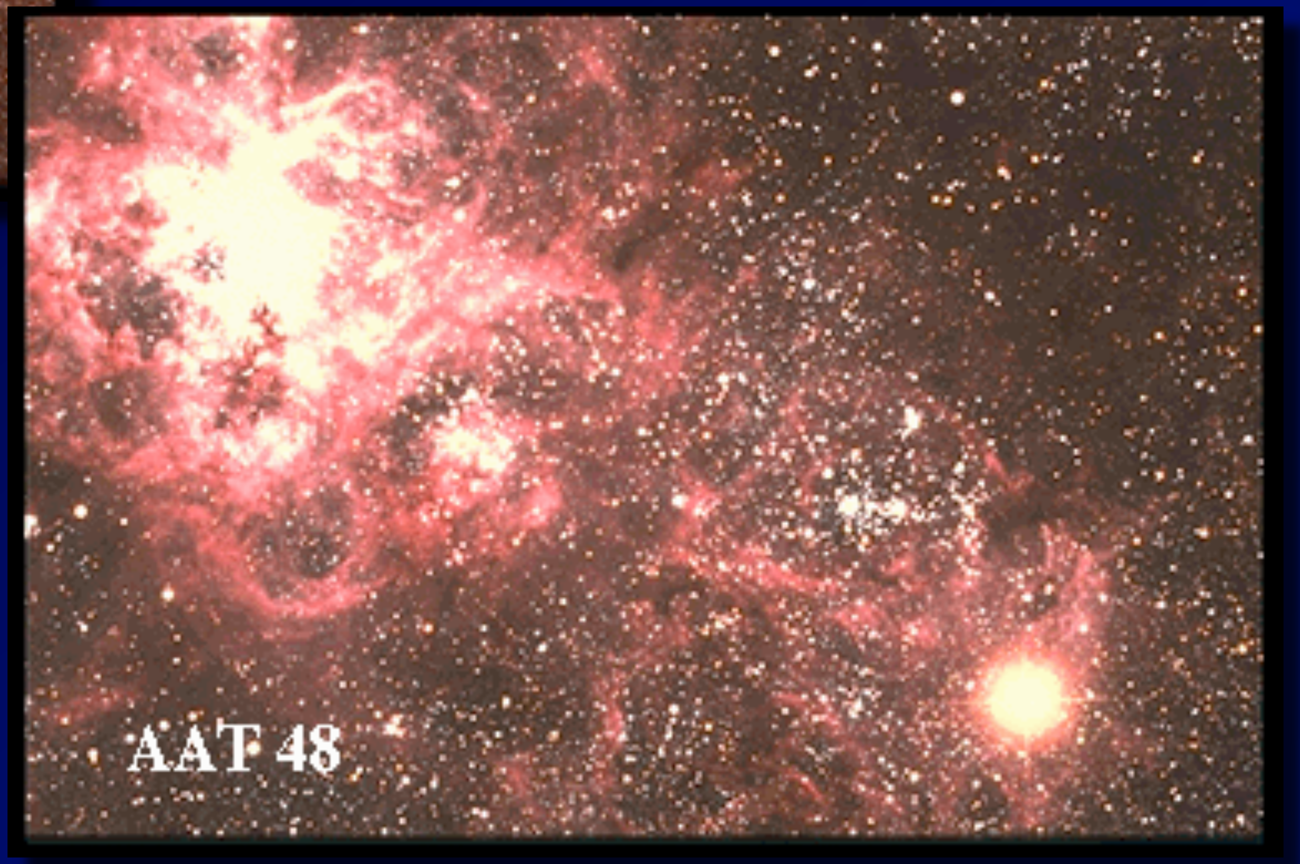

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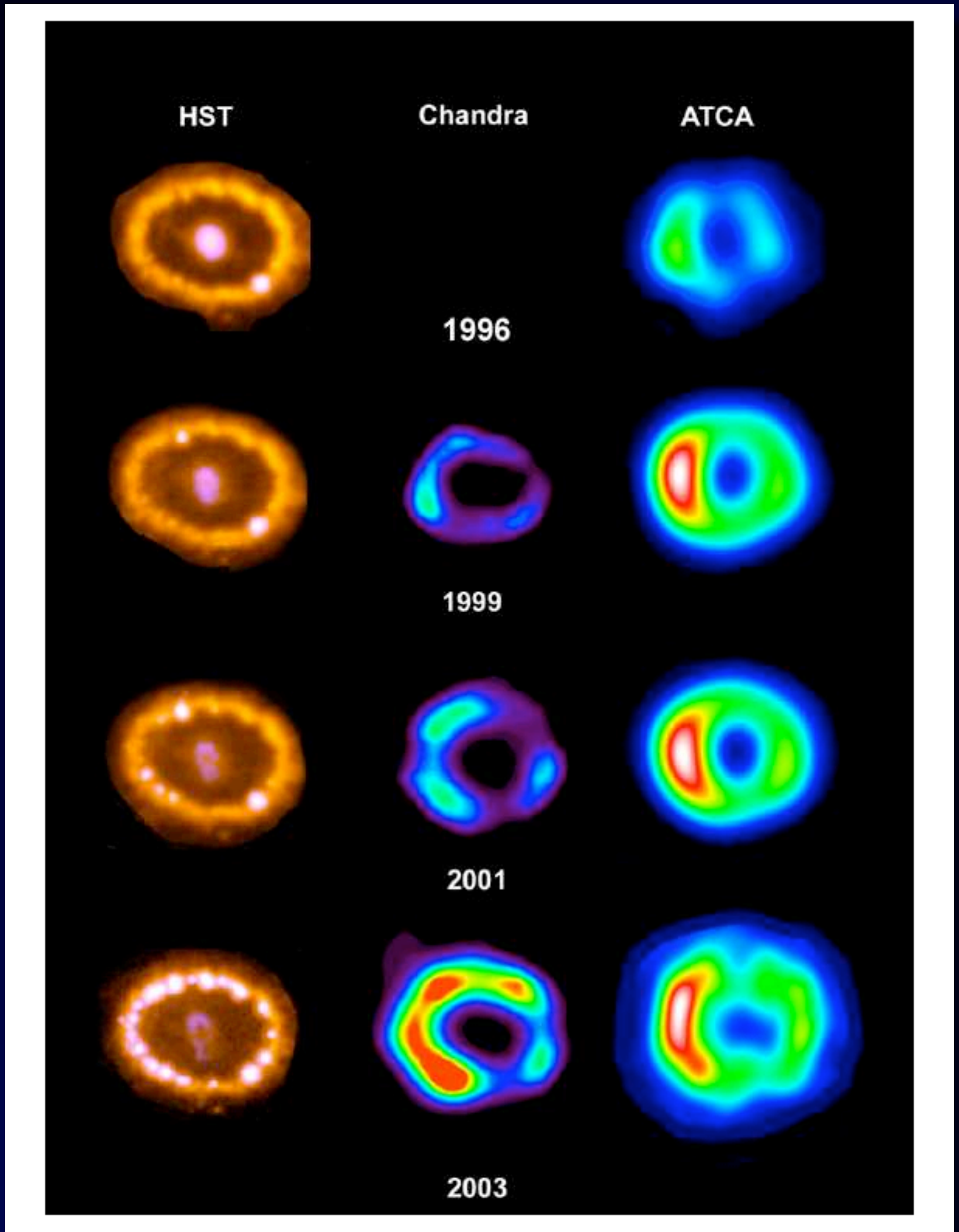

UV/Optical/IR X-ray Radio

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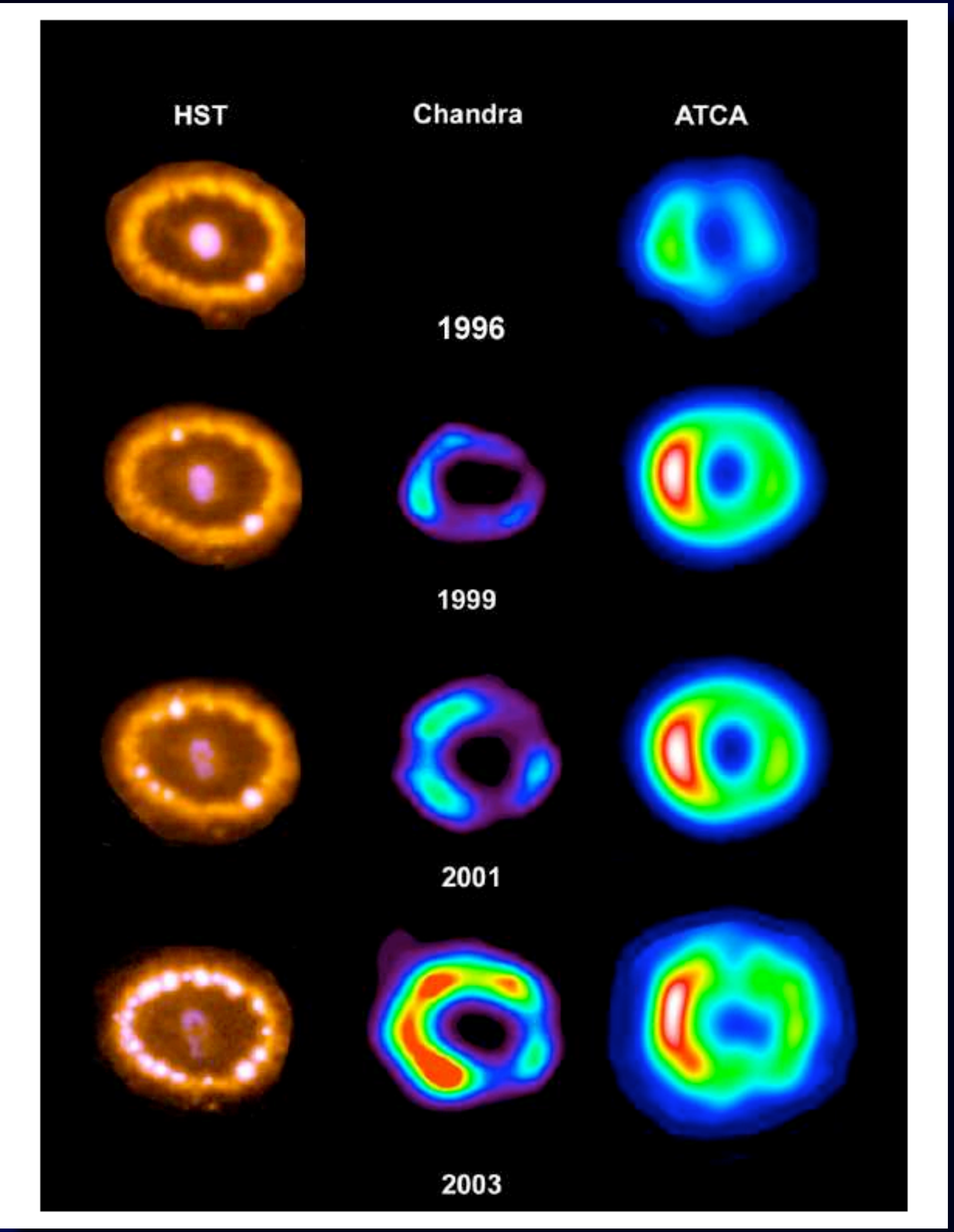

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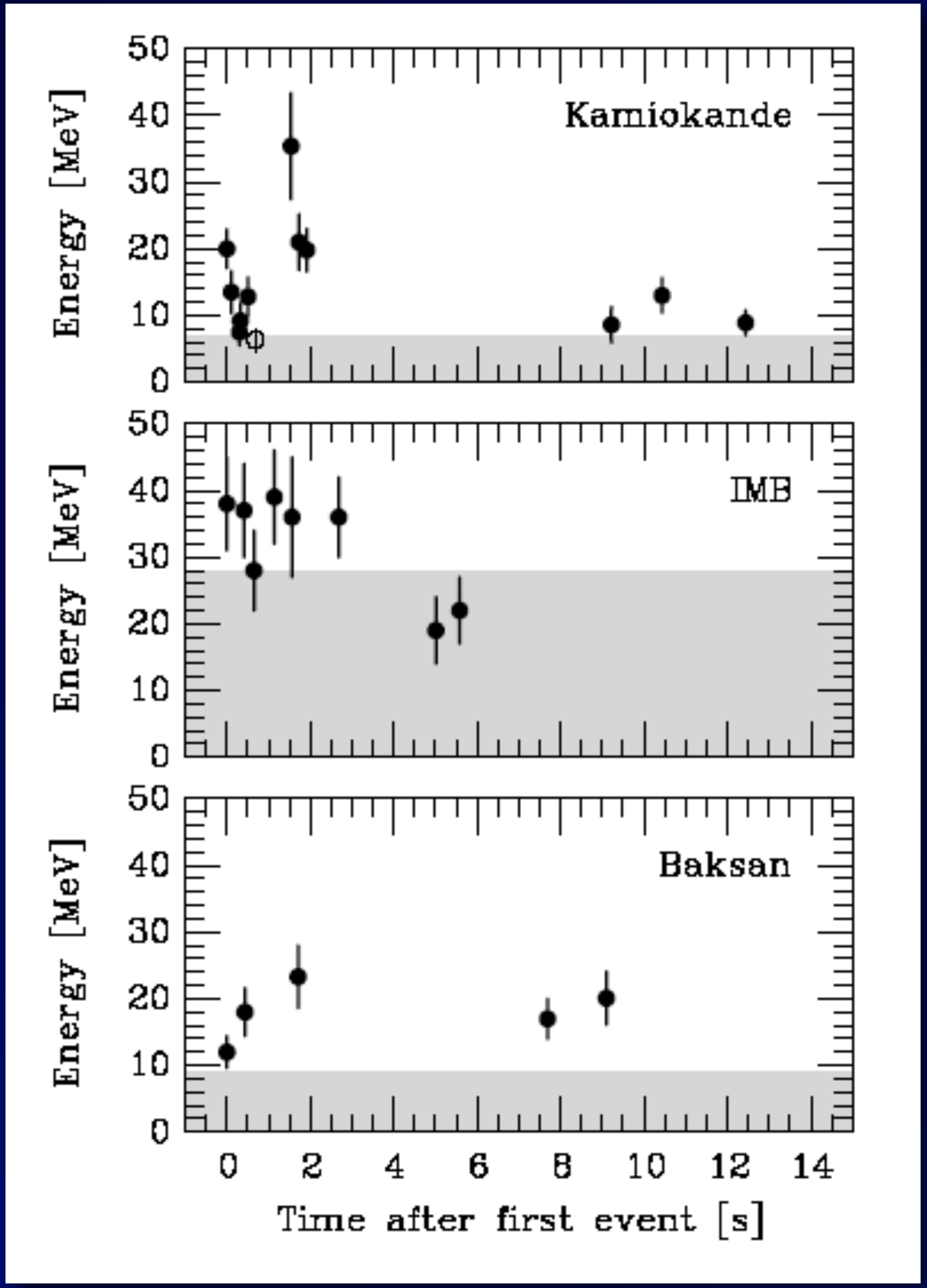

Raffelt

Why is there neutrino emission from core-collapse supernovae?

A massive star develops a degenerate core, which can only get so big…

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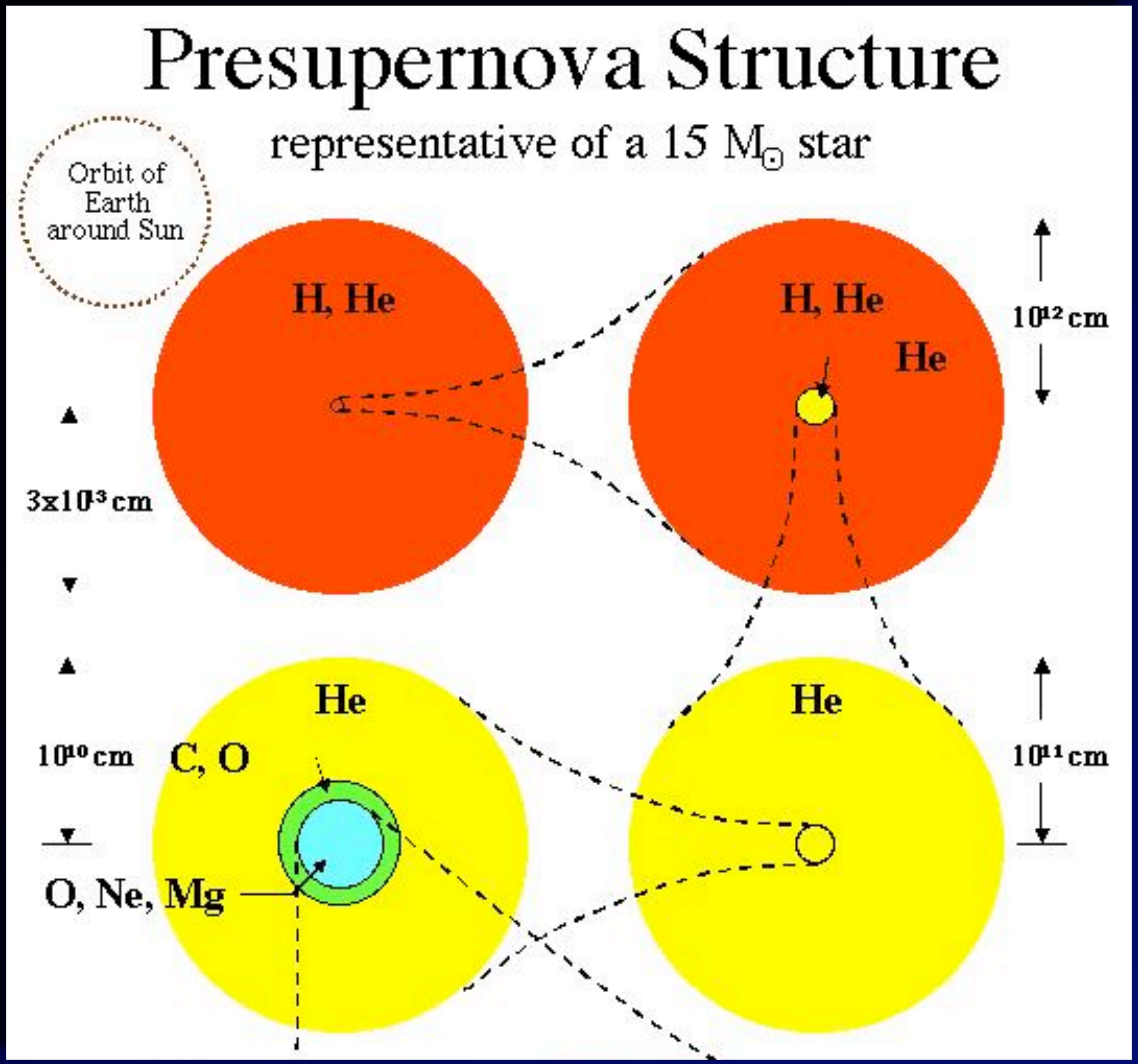

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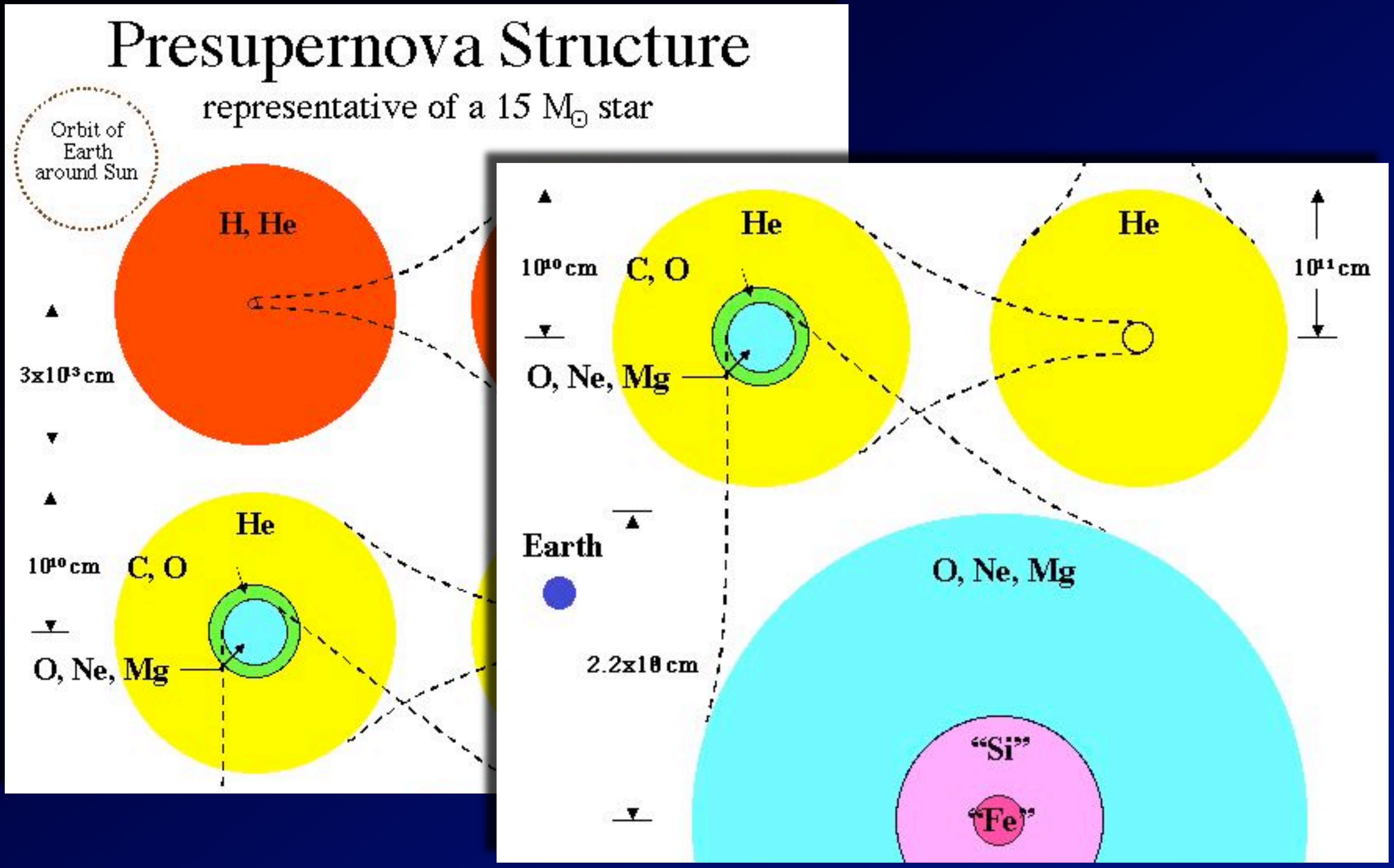

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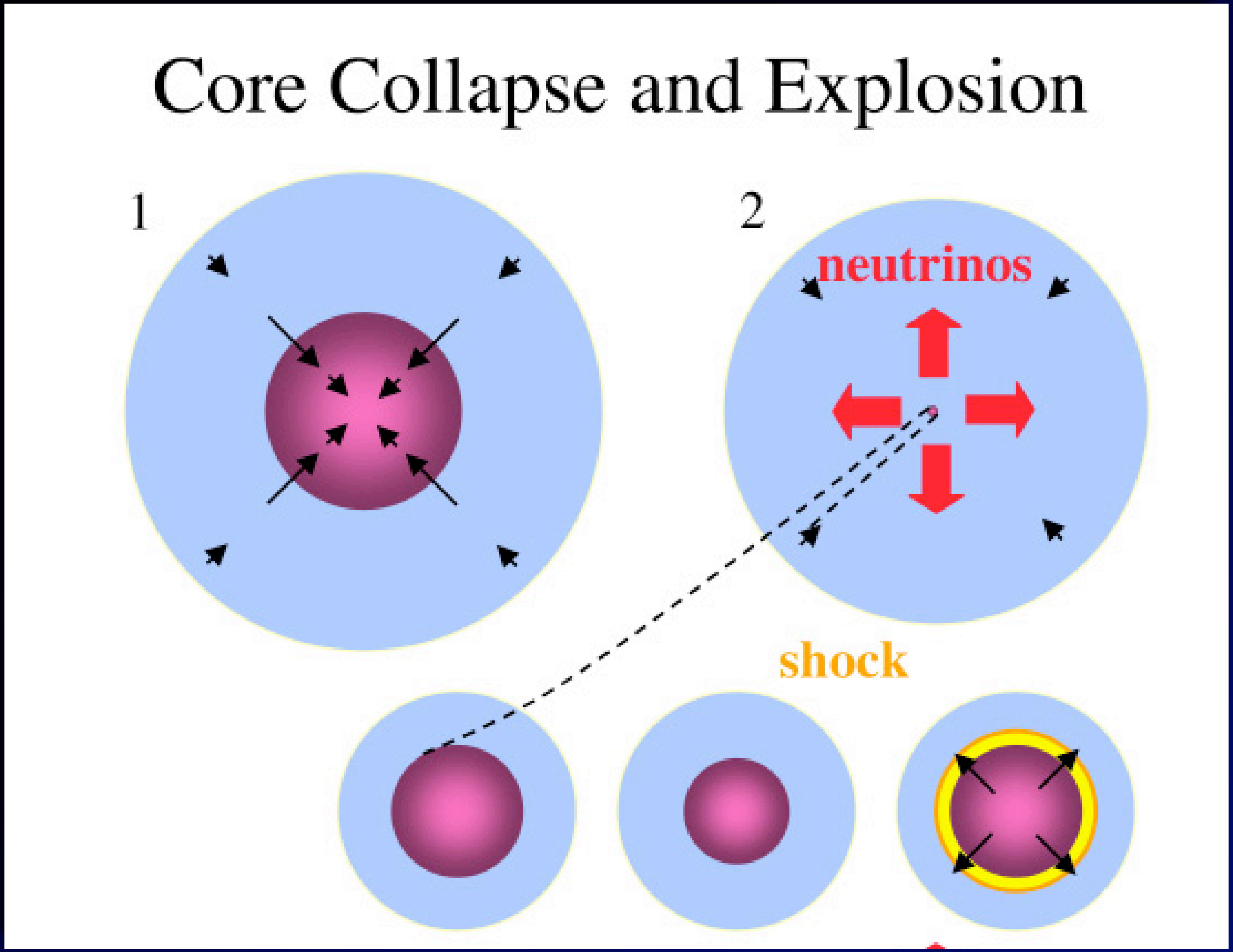
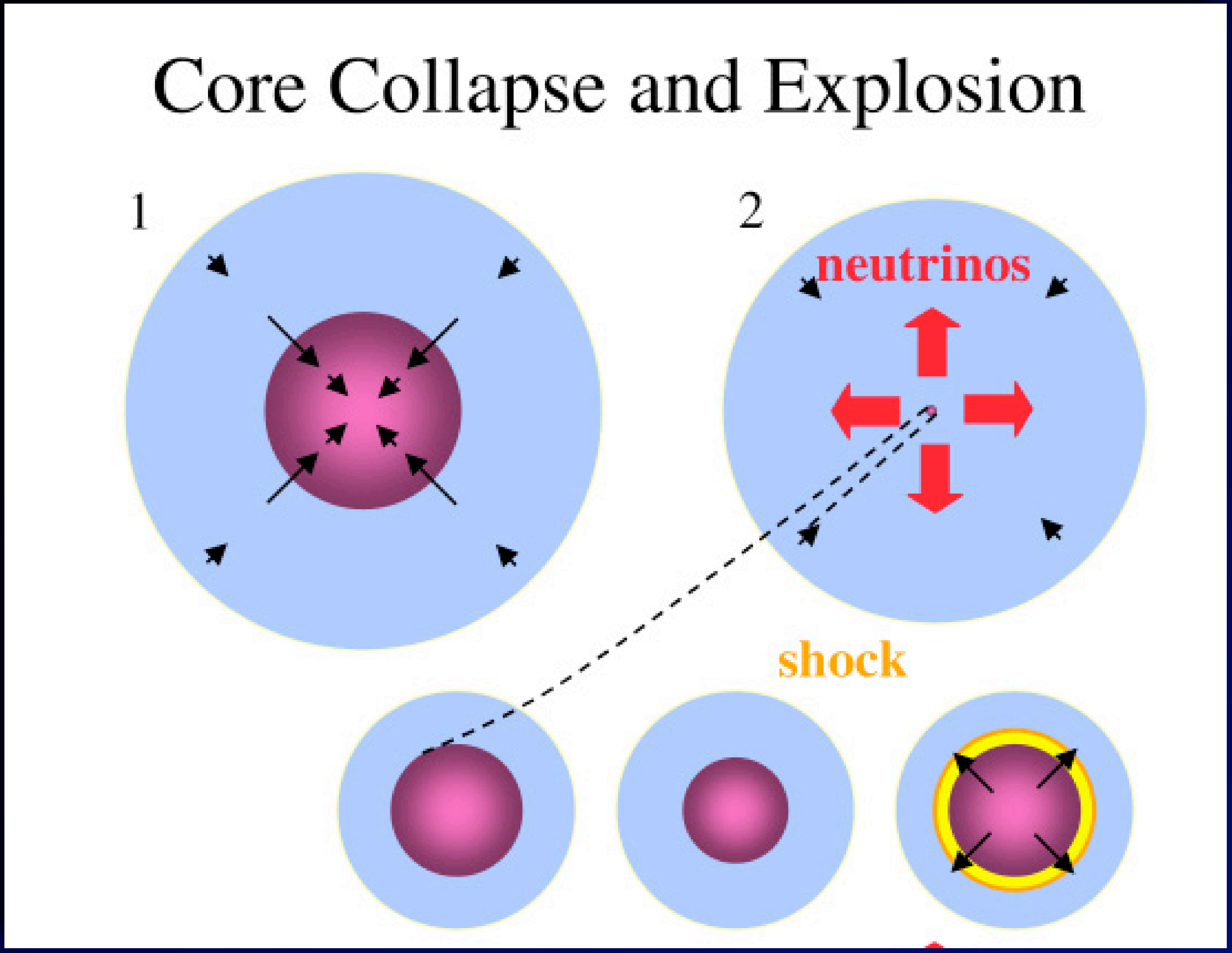


A shock forms and stalls. Neutrino heating and cooling affect its fate.



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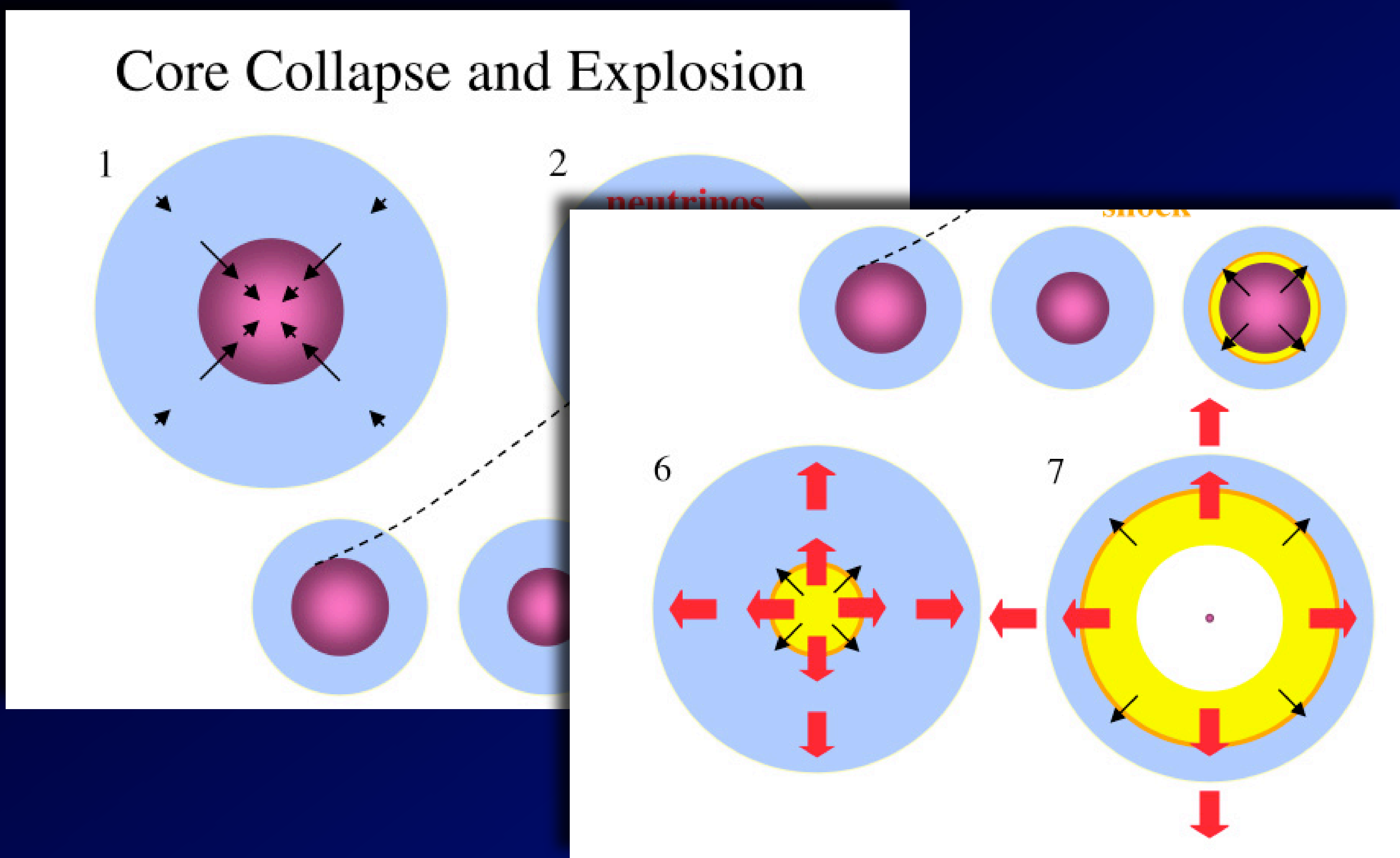

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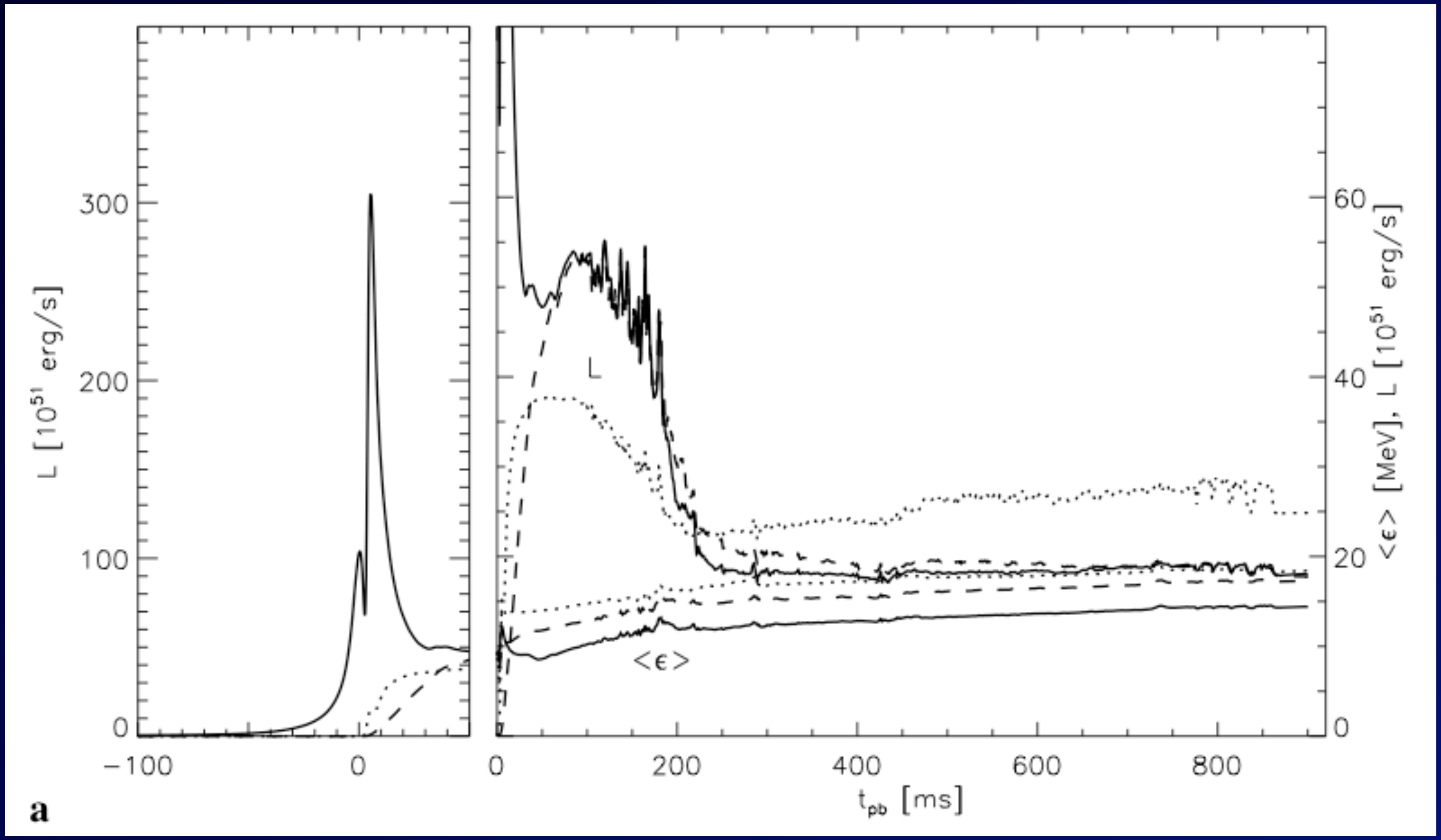

Buras et al. (2005)

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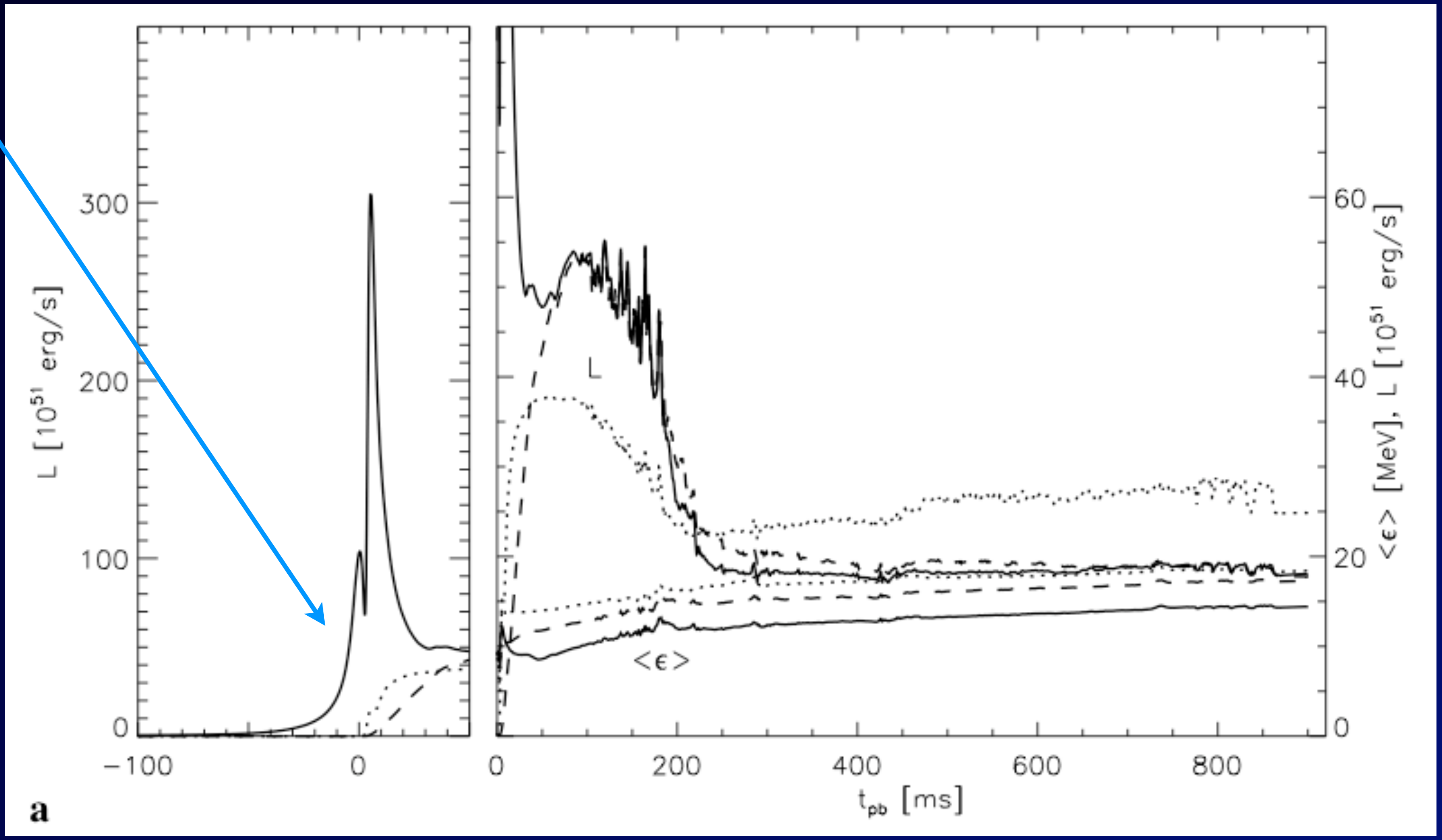
1. Infall



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$$e^- + \text{“}p\text{”} \rightarrow \text{“}n\text{”} + \nu_e$$

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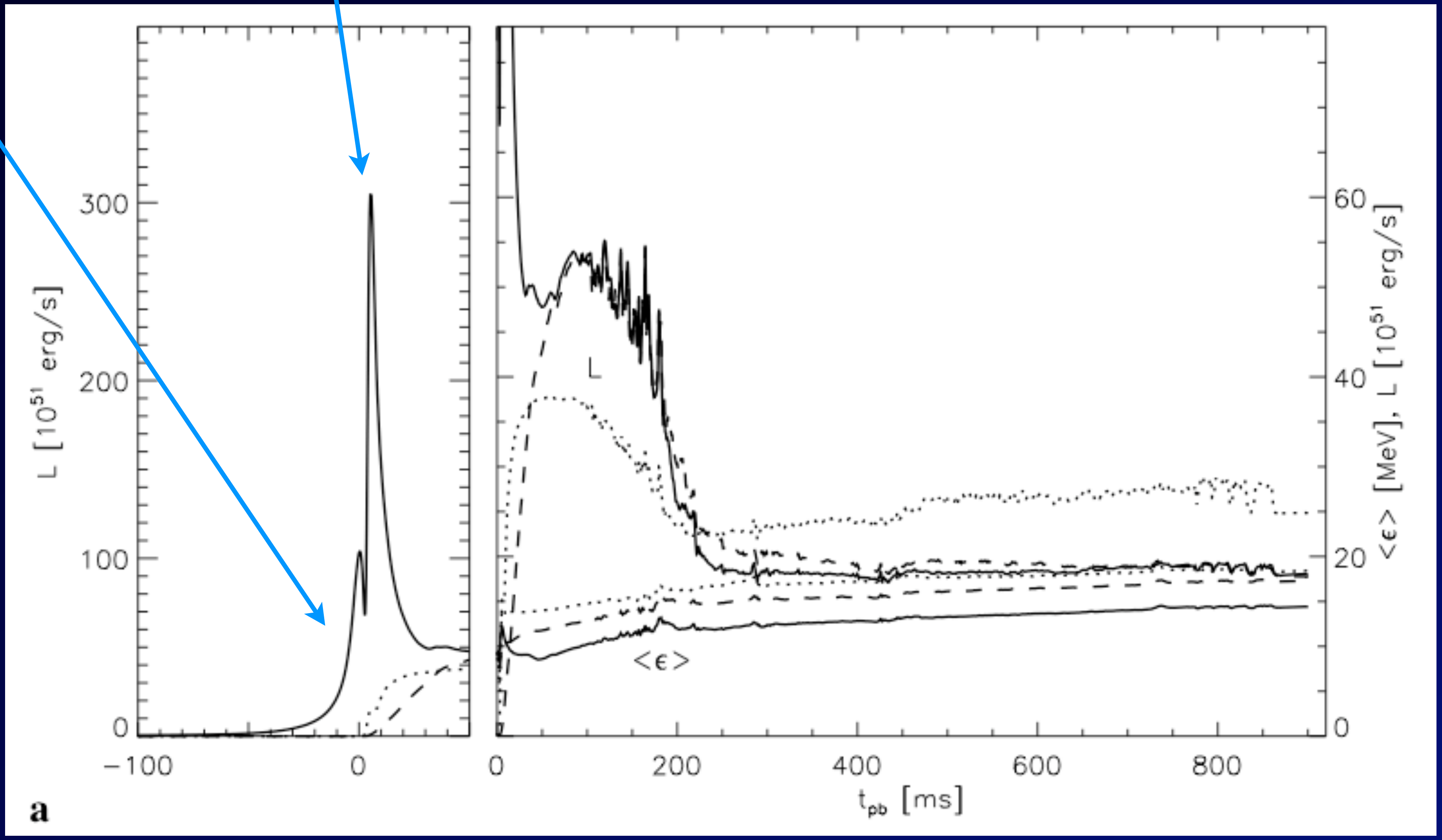
2. Shock breakout

1. Infall



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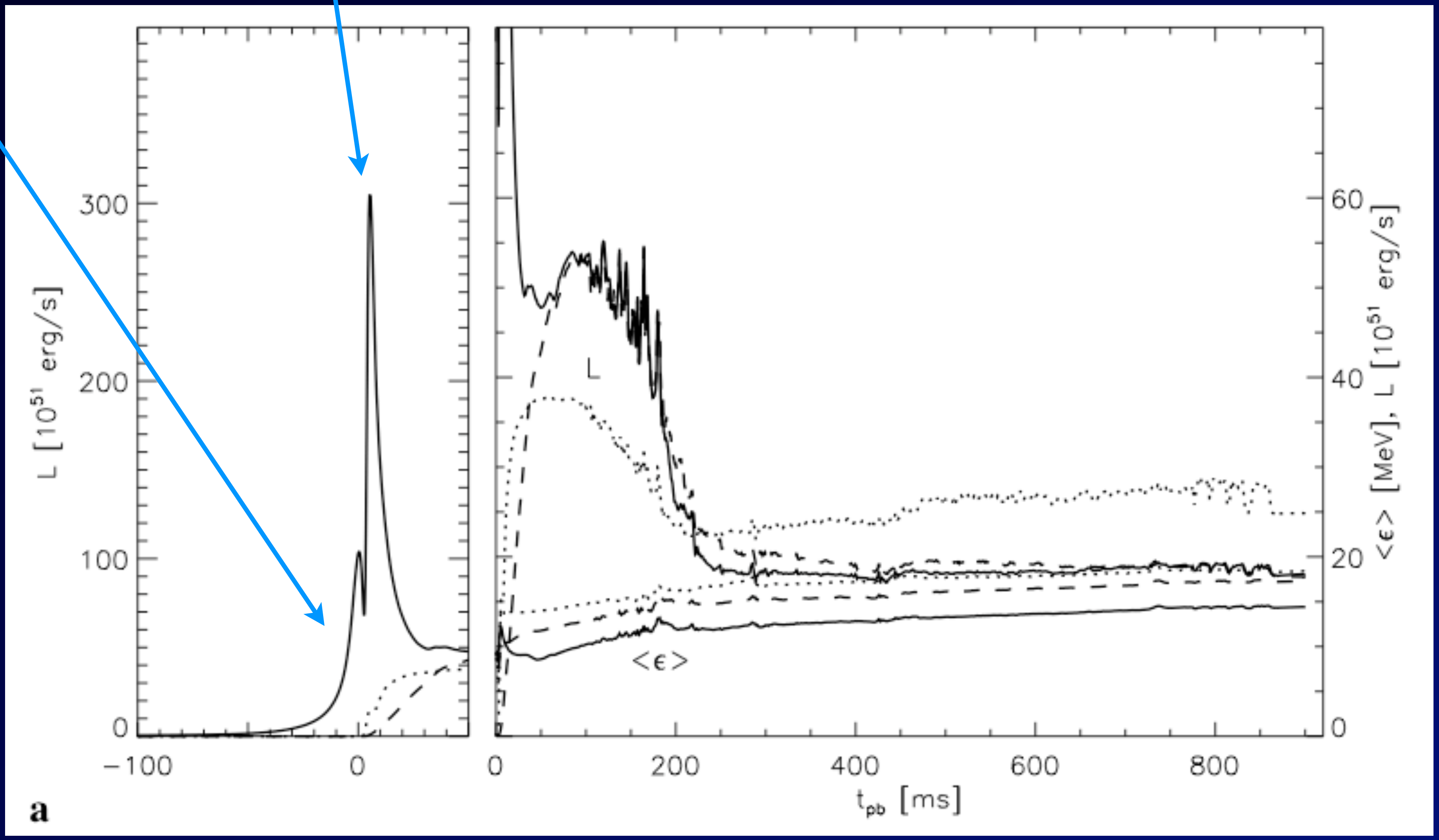

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$$e^+ + e^- \rightarrow \nu_{e,\mu,\tau} + \overline{\nu}_{e,\mu,\tau}$$

$$N + N \rightarrow N + N + \nu_{e,\mu,\tau} + \overline{\nu}_{e,\mu,\tau}$$

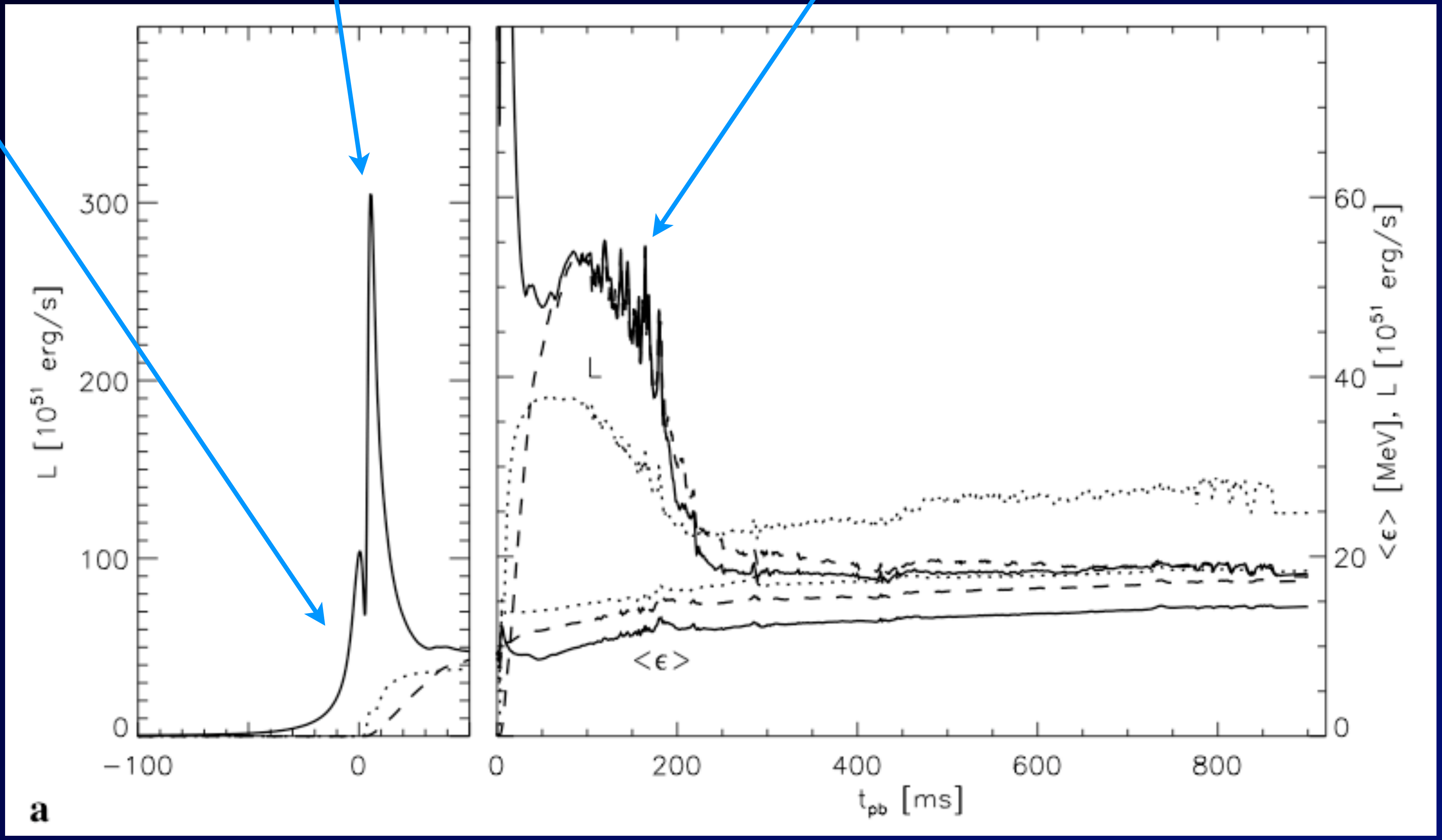
Scattering

At least five phases of neutrino emission can be identified.

2. Shock breakout

3. Accretion

1. Infall



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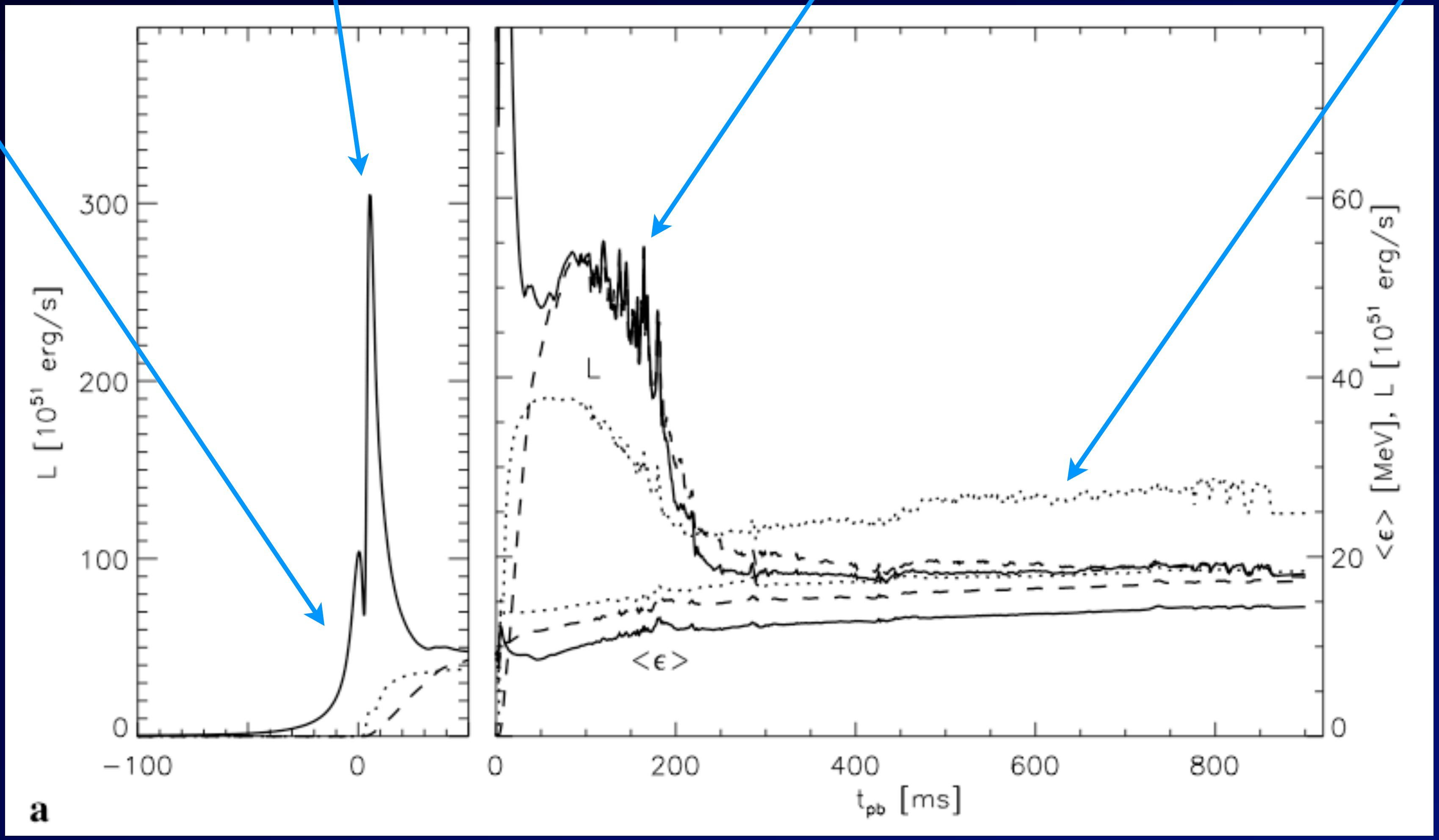

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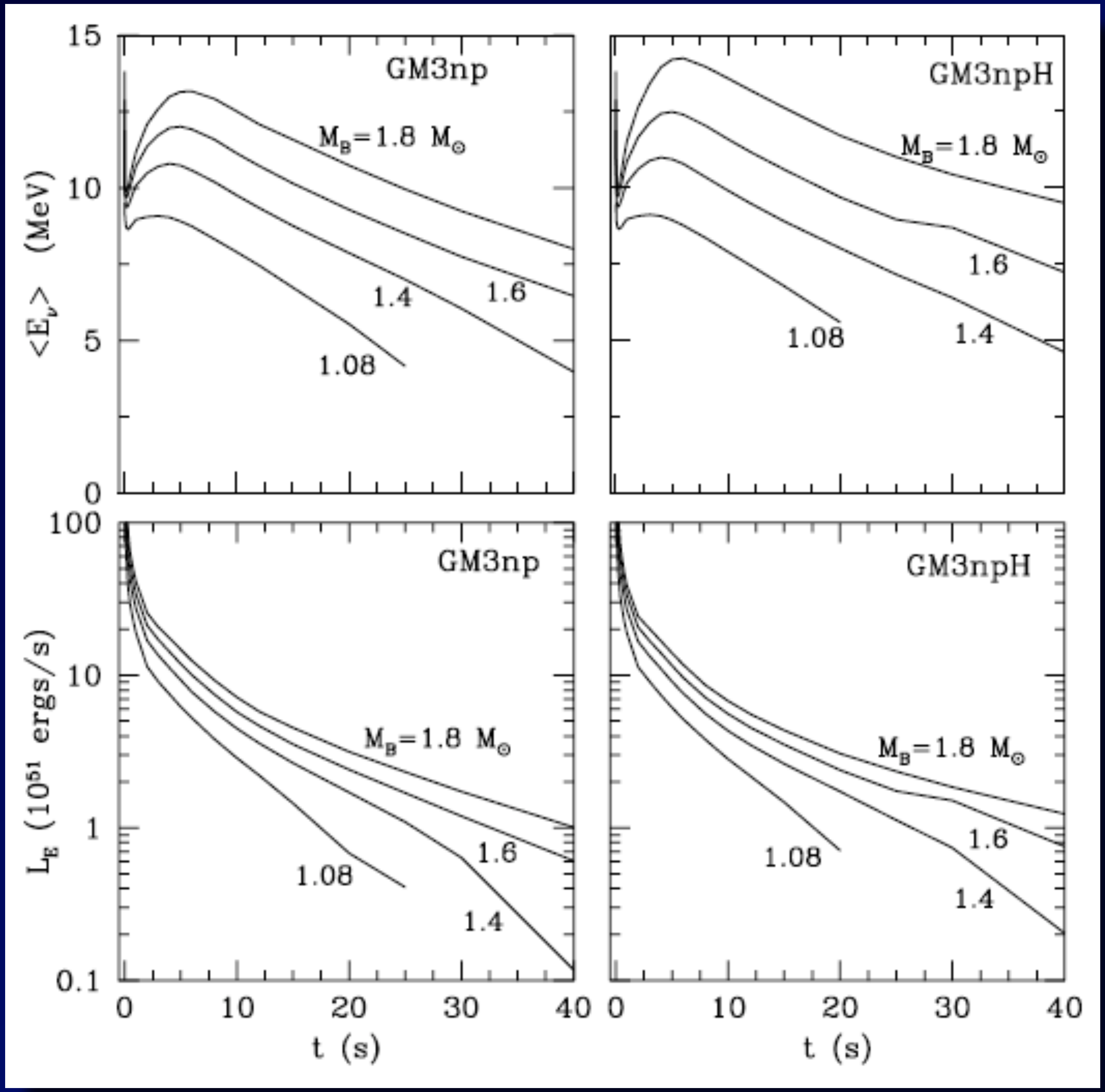

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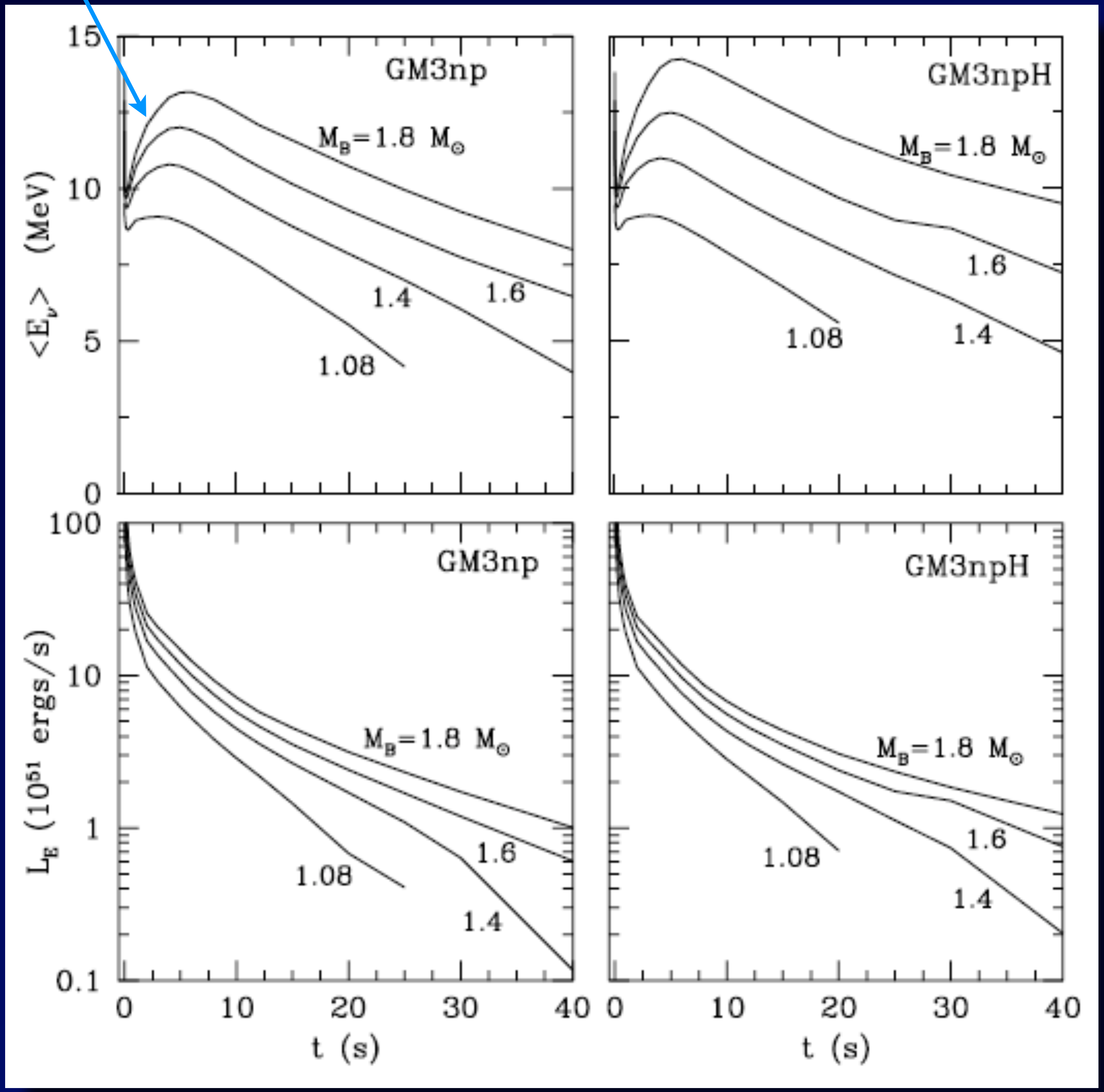

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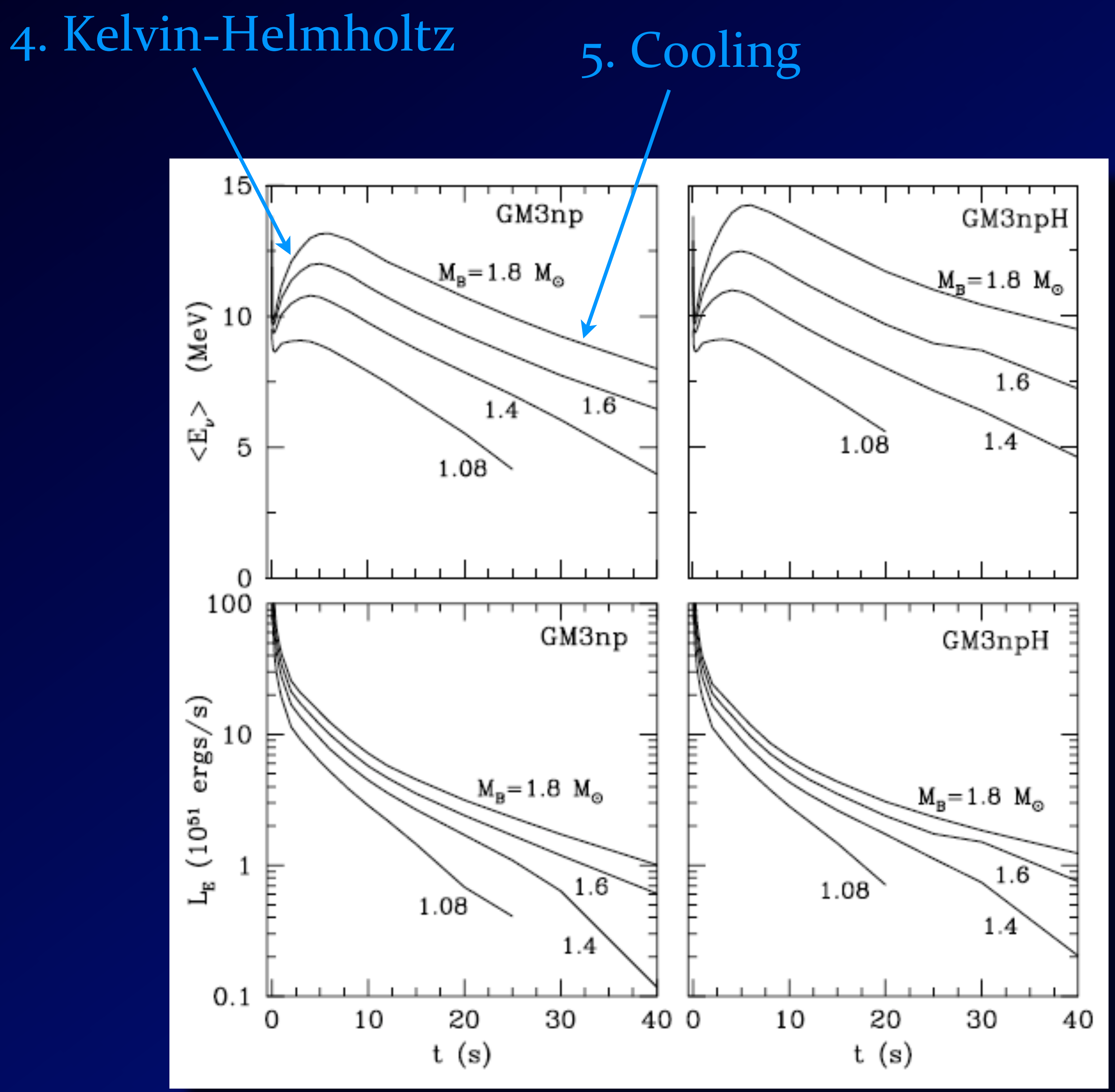

Core-collapse supernova

Massive stellar progenitor

Infall

Bounce; shock formation, stall, and revival

- Neutron star kick
- Gravitational waves

Kelvin-Helmholtz contraction, then cooling of neutron star

(If rapid rotation: accretion disk and jet formation)

- (If H/He envelope lost, i.e. if Type Ib/Ic: Gamma-ray burst)

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

Deleptonization and energy release via ν emission

- e^- capture / ν_e emission
- ν pair emission

(ν pair annihilation helps power jet?)

- (ν emission from accretion disk)

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$\lesssim$ 1% of total energy release

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$\lesssim$ 10% of total energy release

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Deleptonization and energy release via ν emission

- e^- capture / ν_e emission
- ν pair emission

~90% of total energy release

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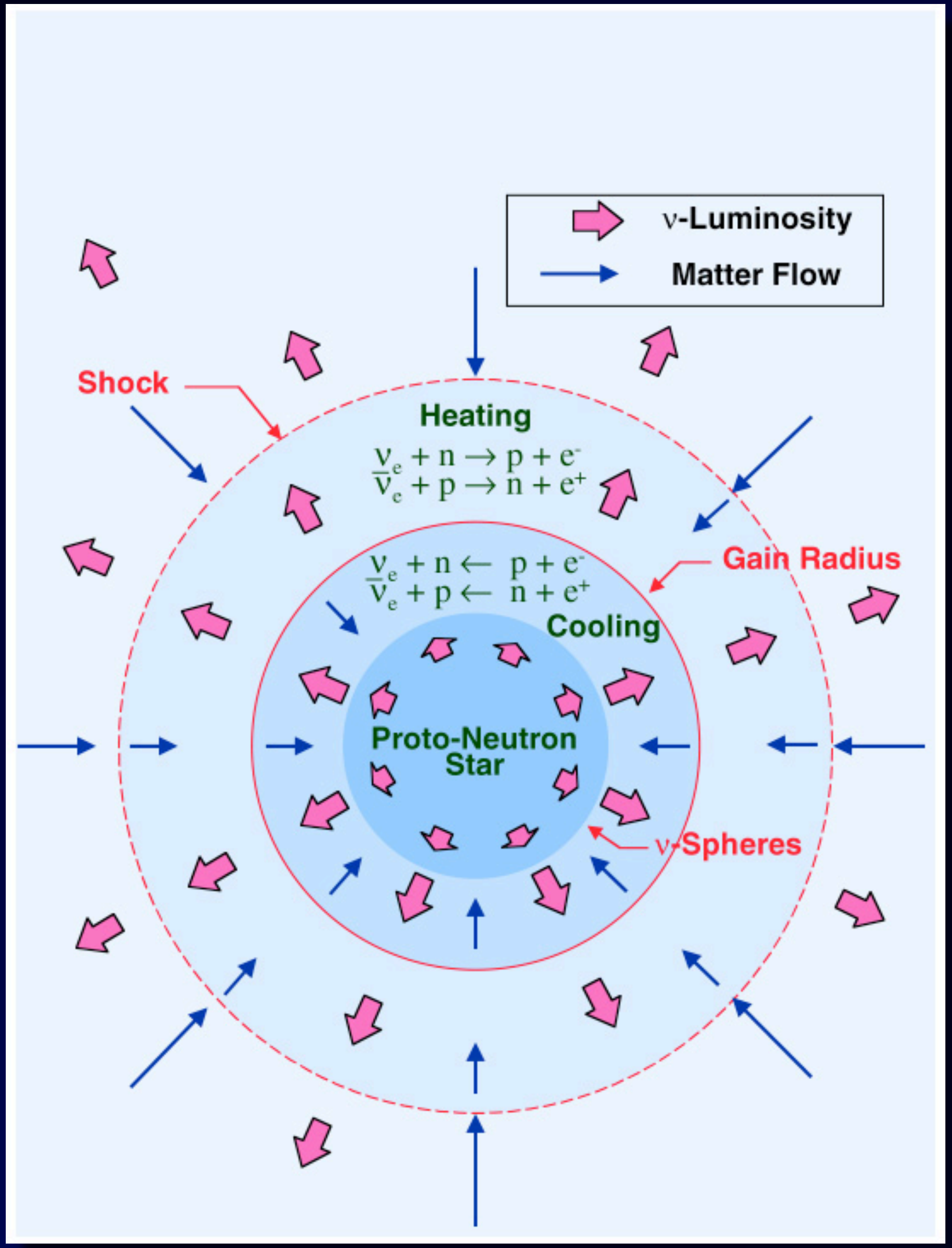
What goes into simulations of stellar collapse and its aftermath?

Heating/cooling rates depend on accurate evolution of neutrino distributions.



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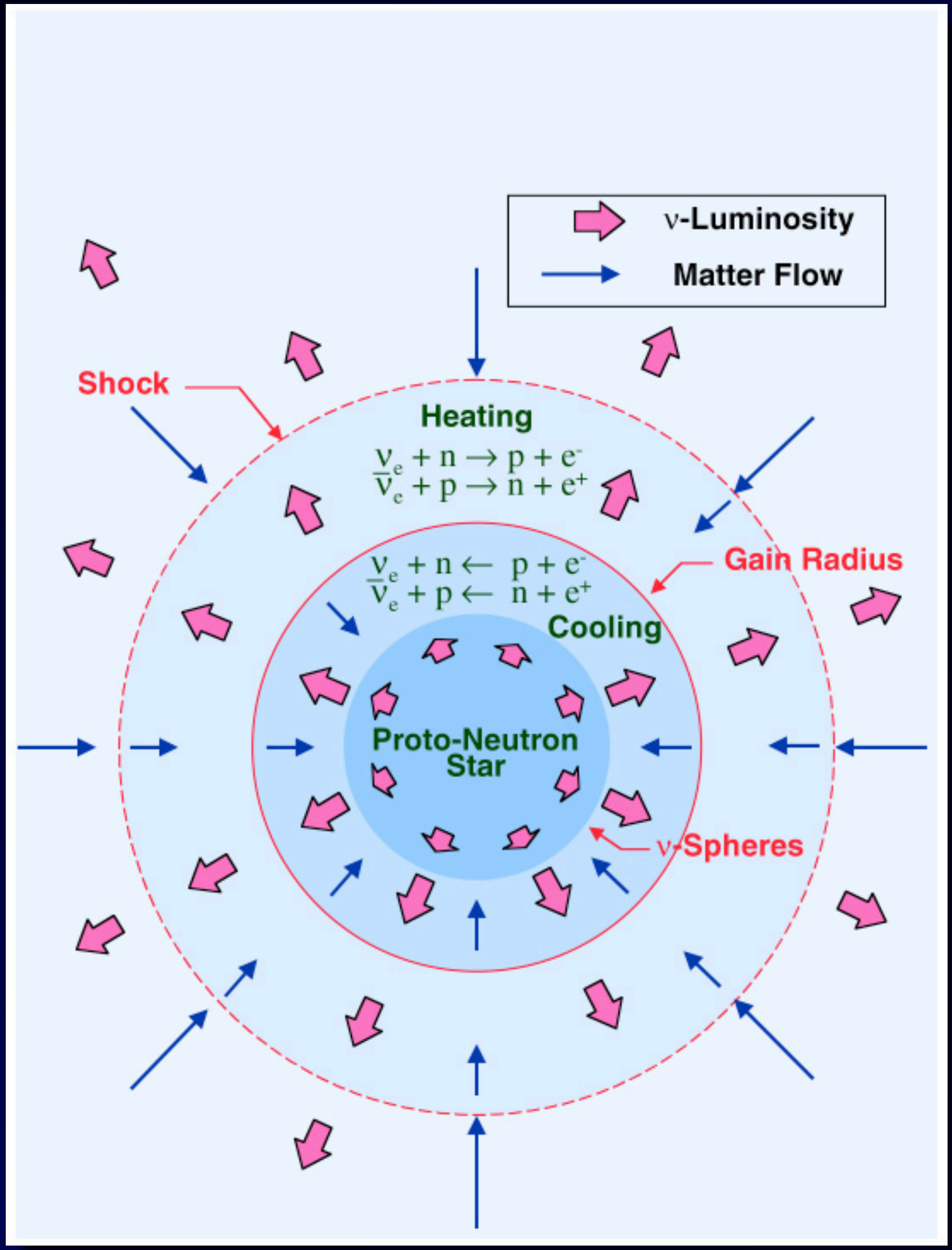

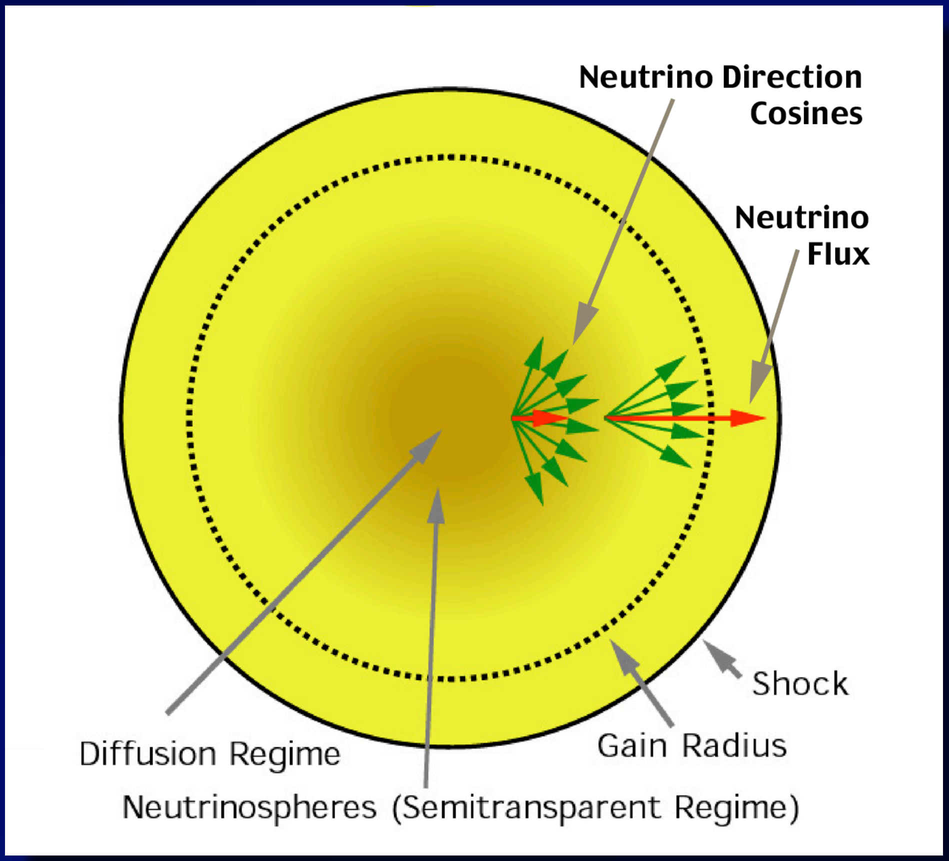

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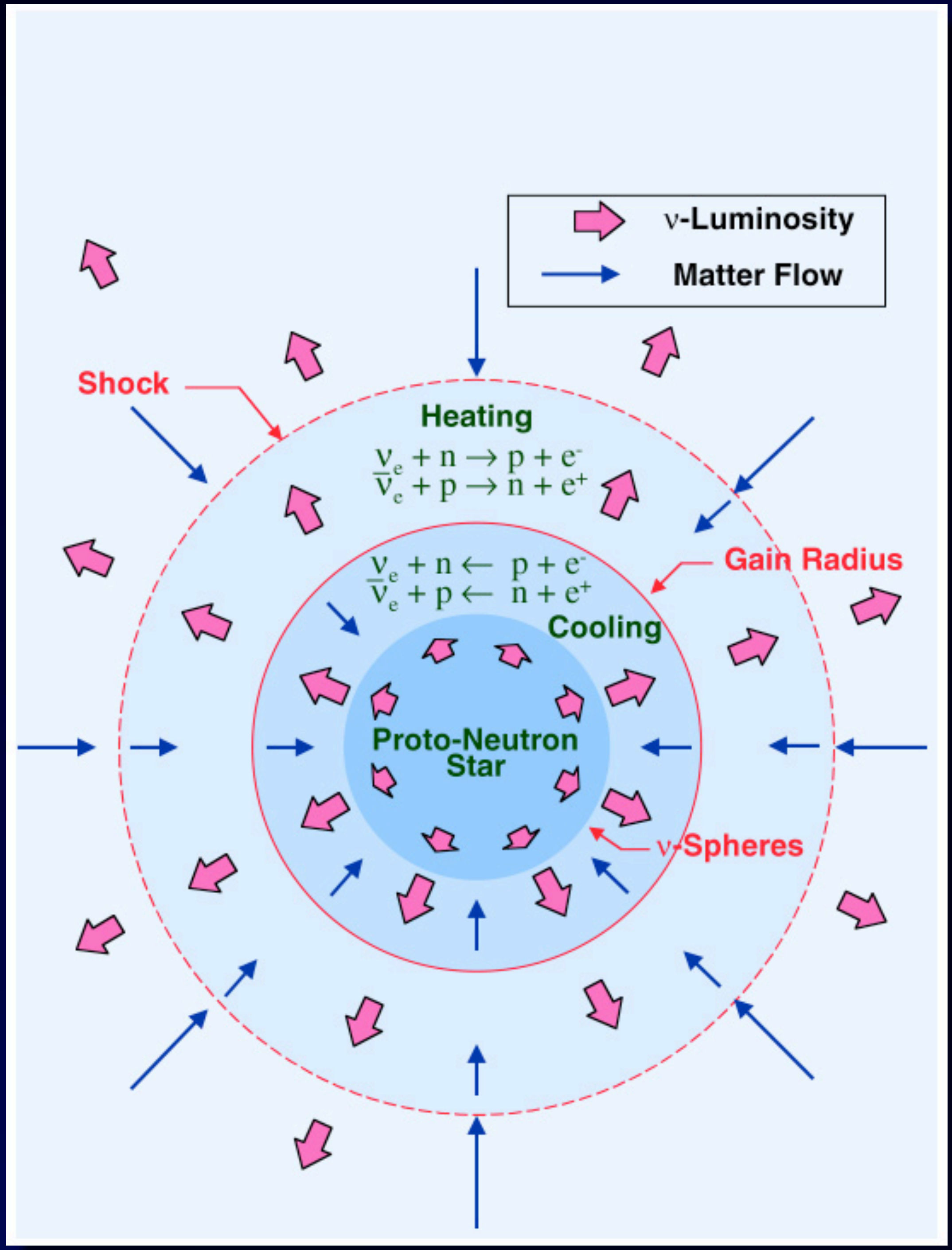
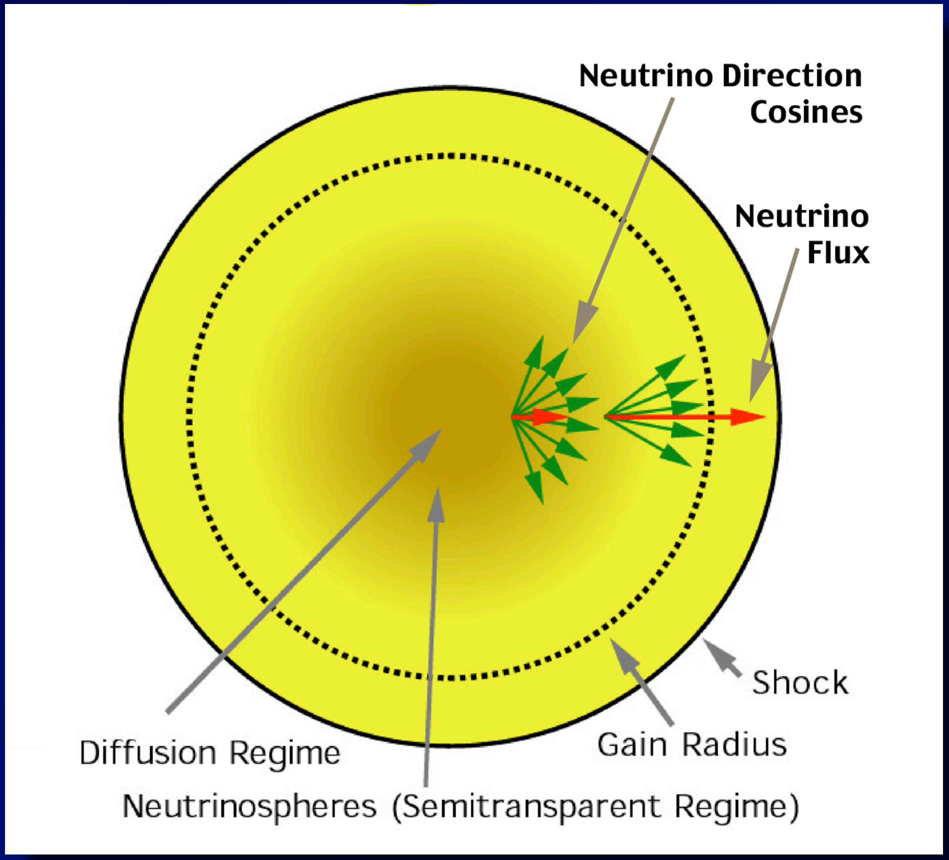


$$f(t, \mathbf{x}, \mathbf{p})$$



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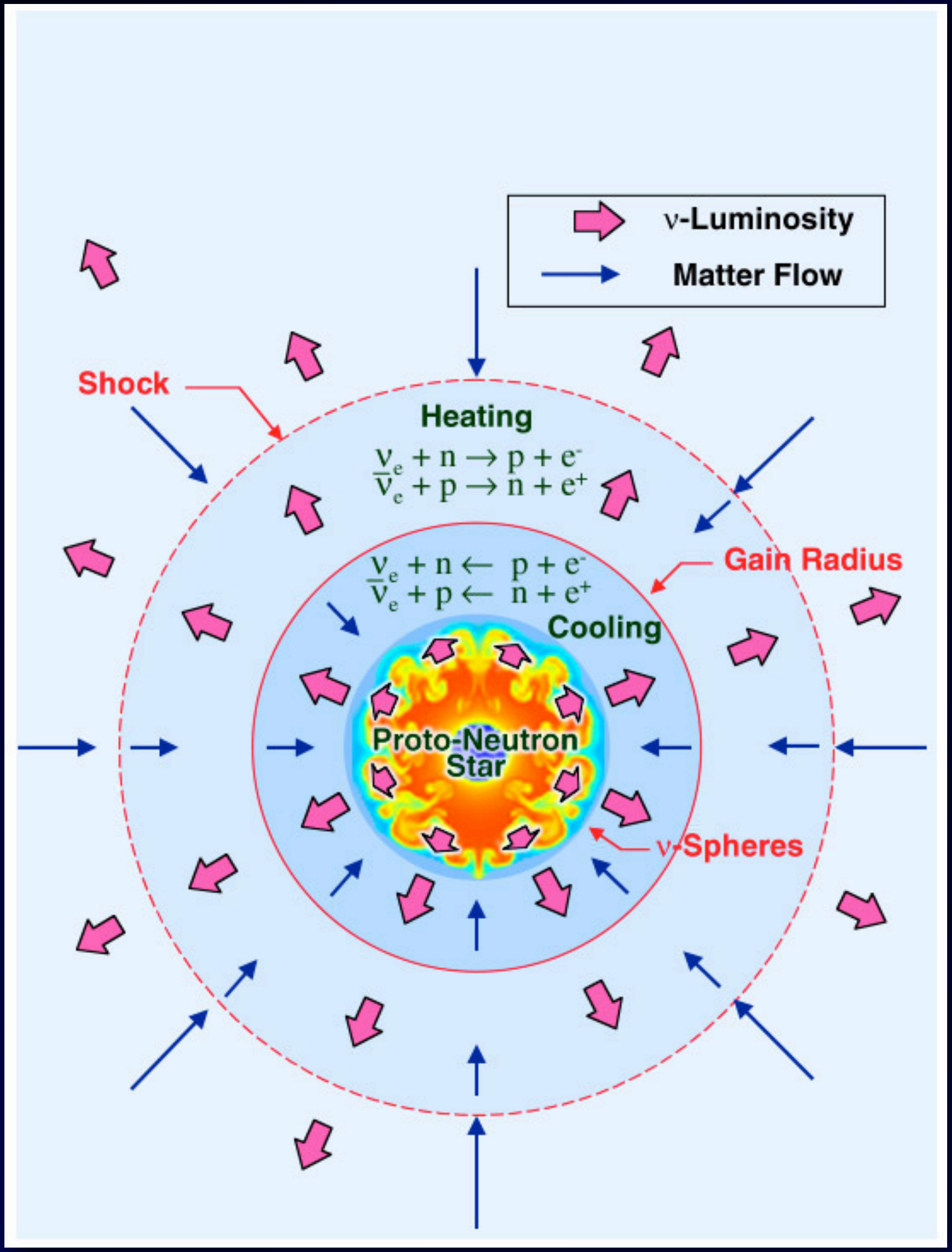

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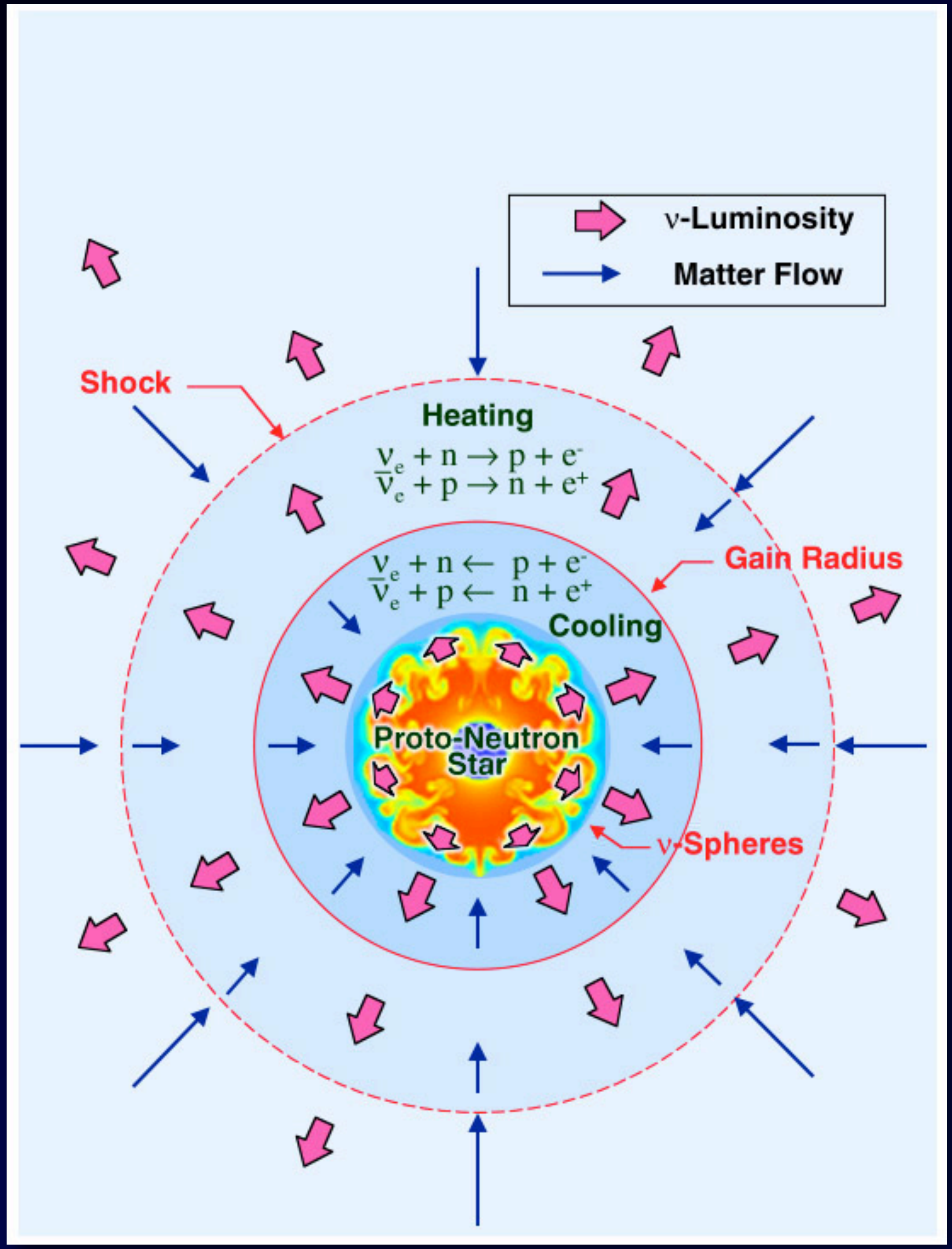

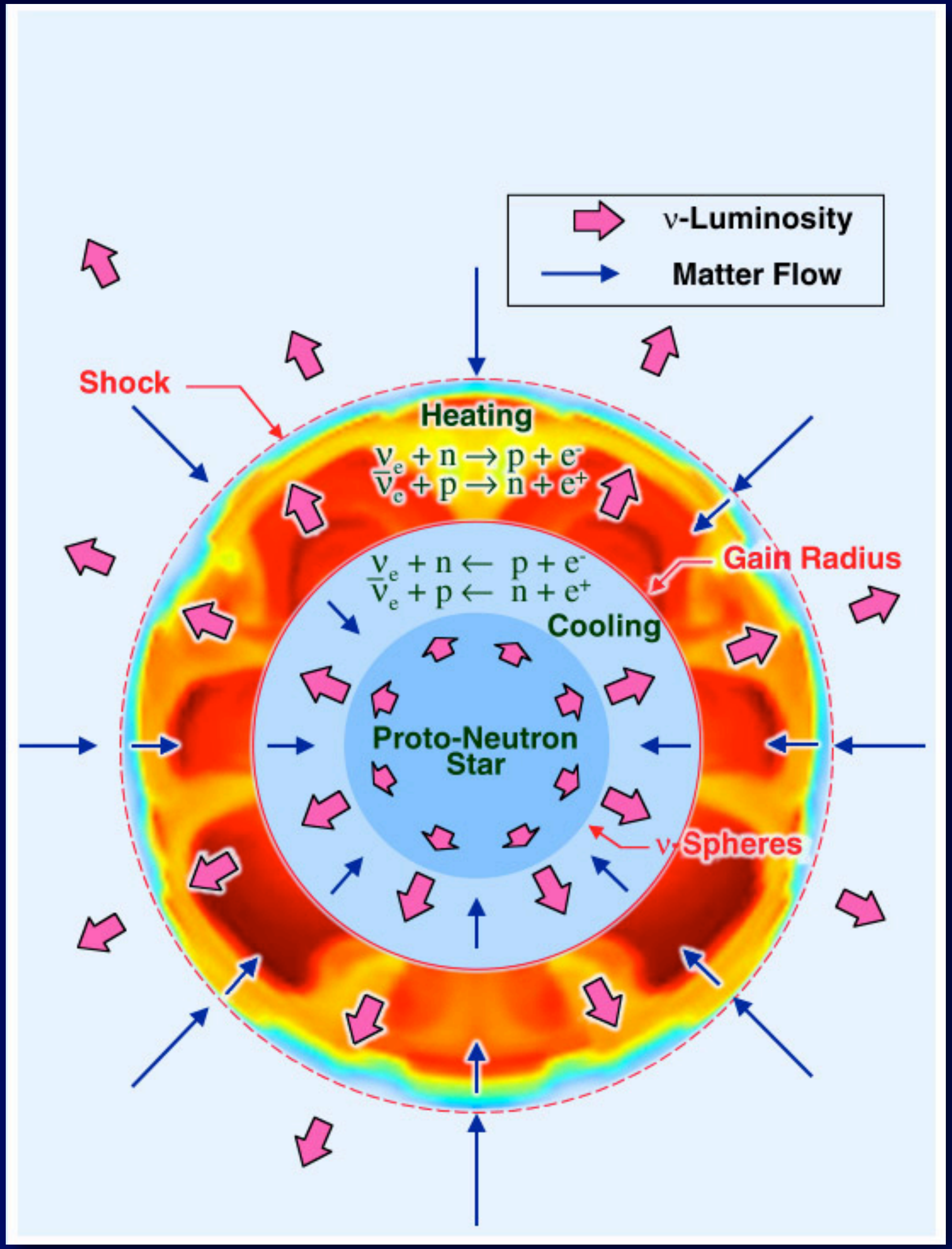

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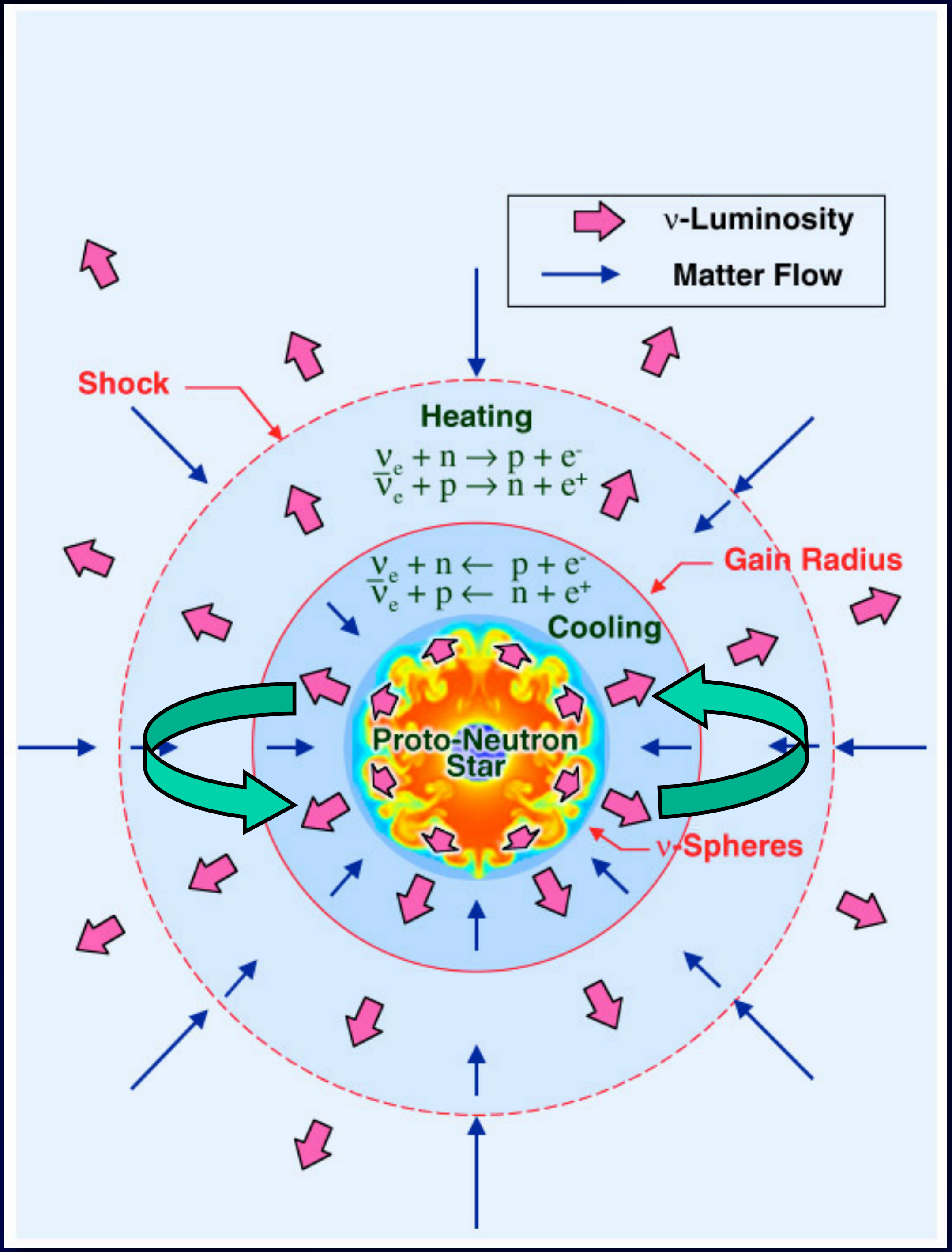

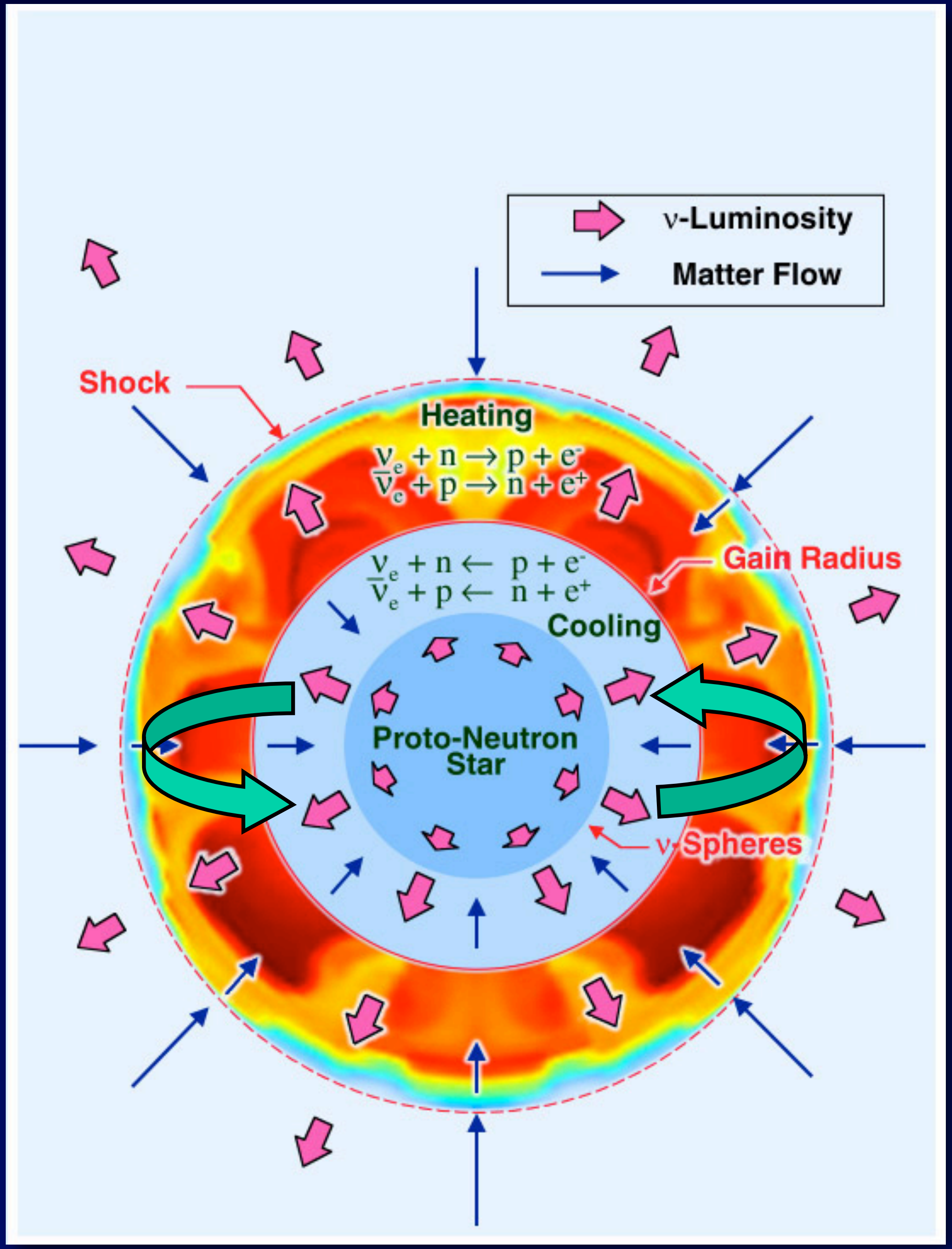

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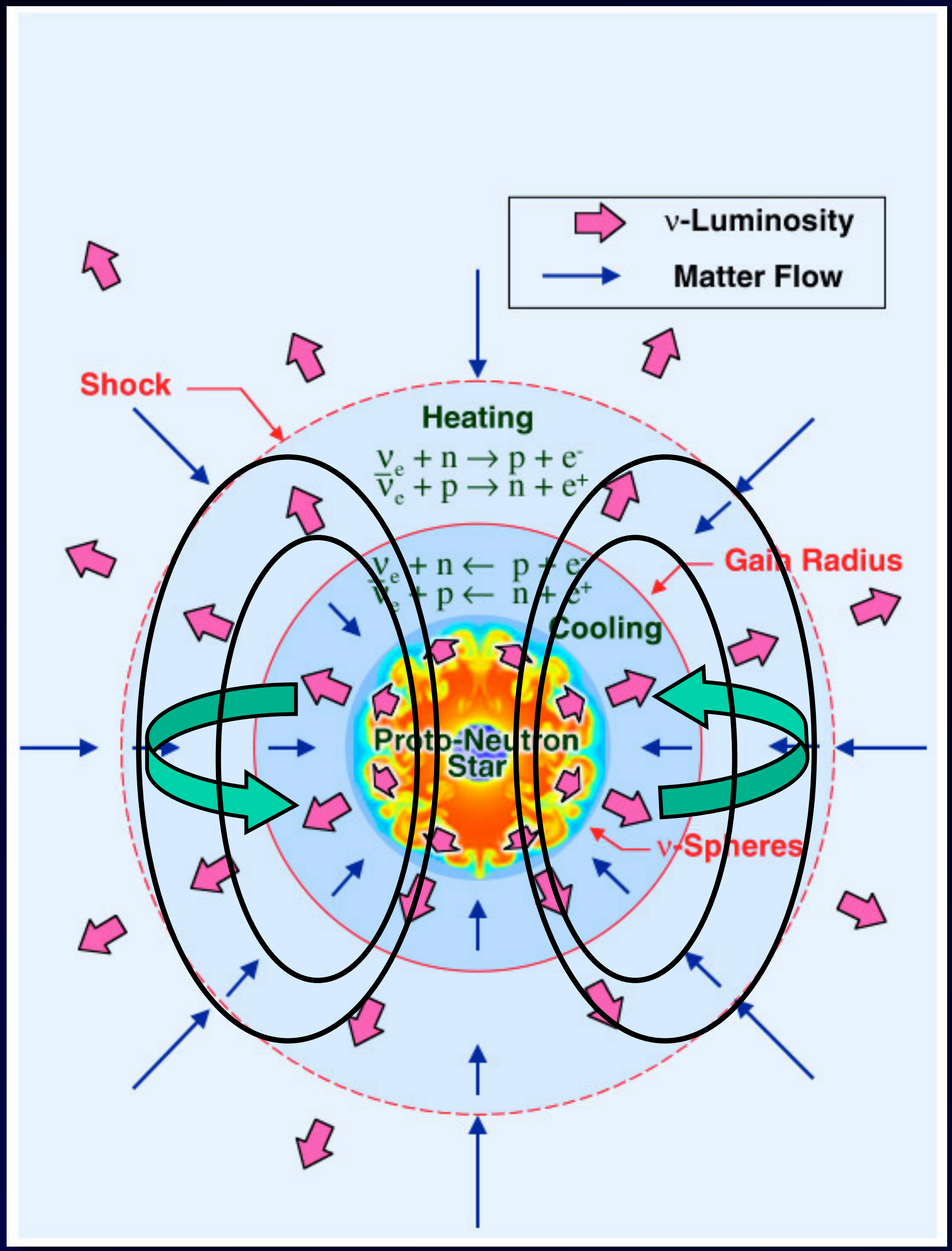

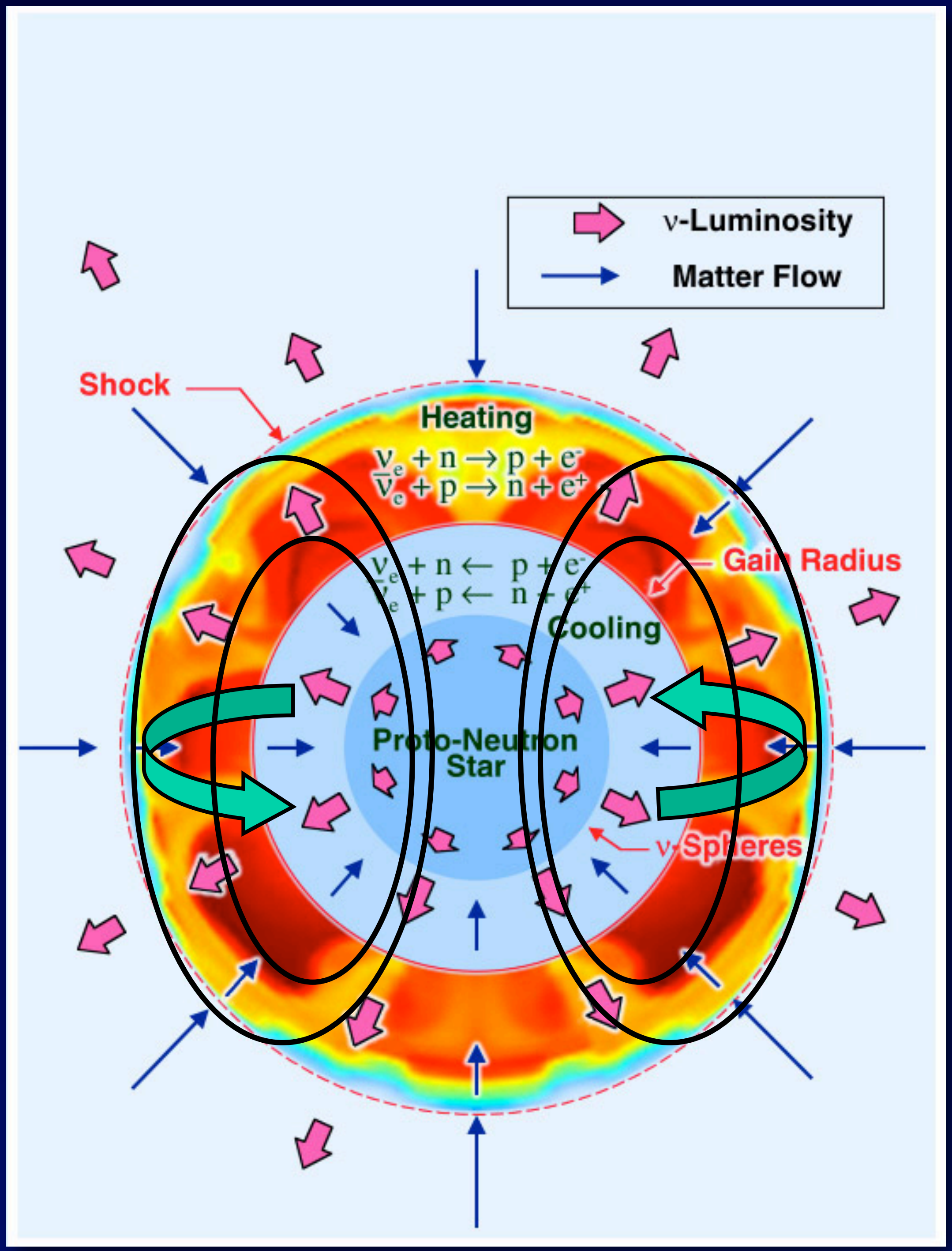

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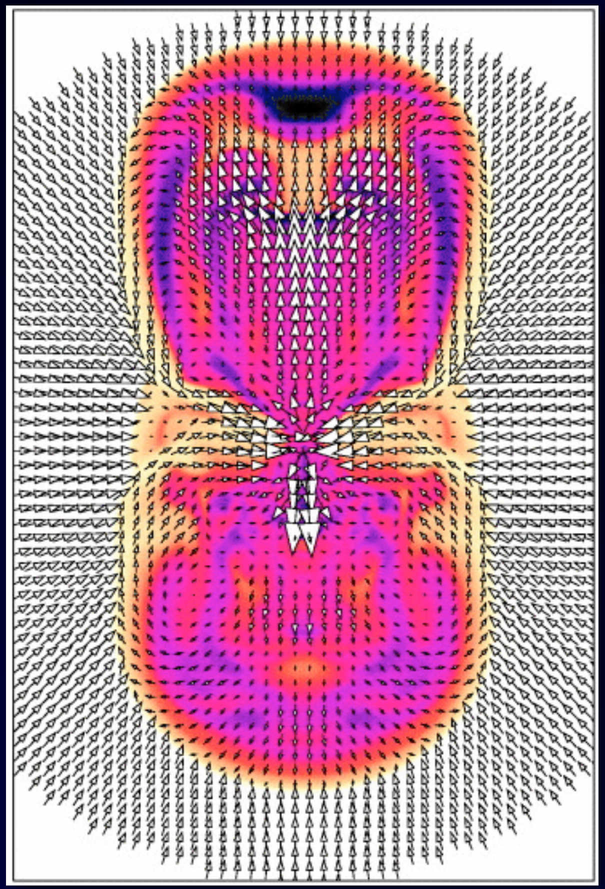

Aspherical explosion morphology

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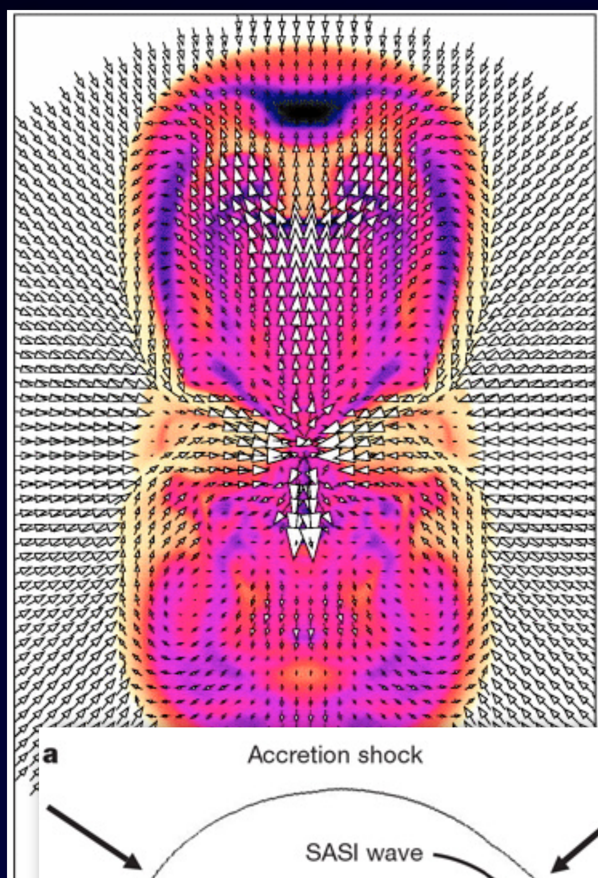

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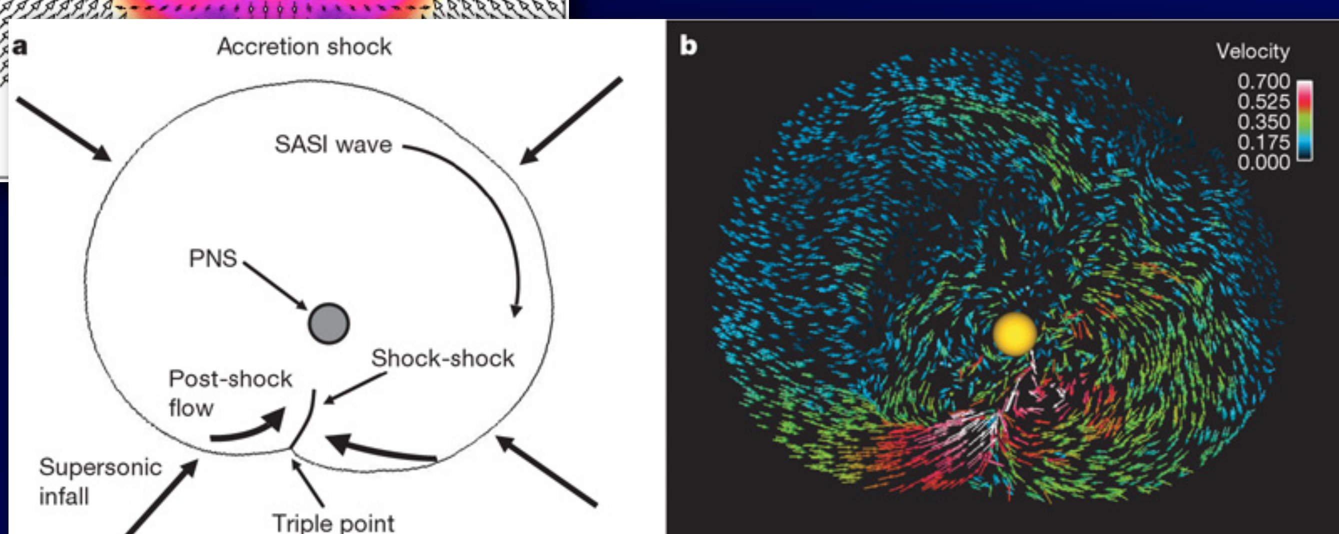

Pulsar spin

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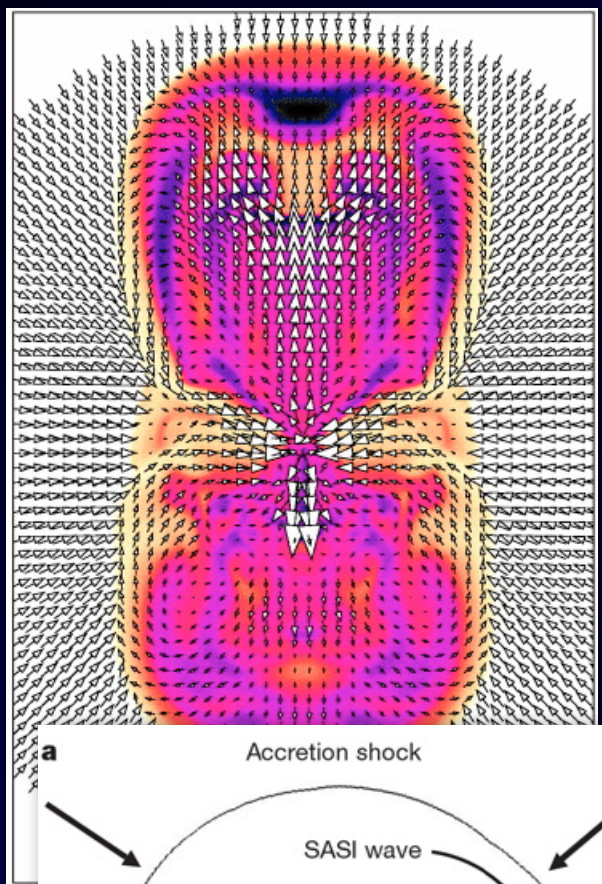
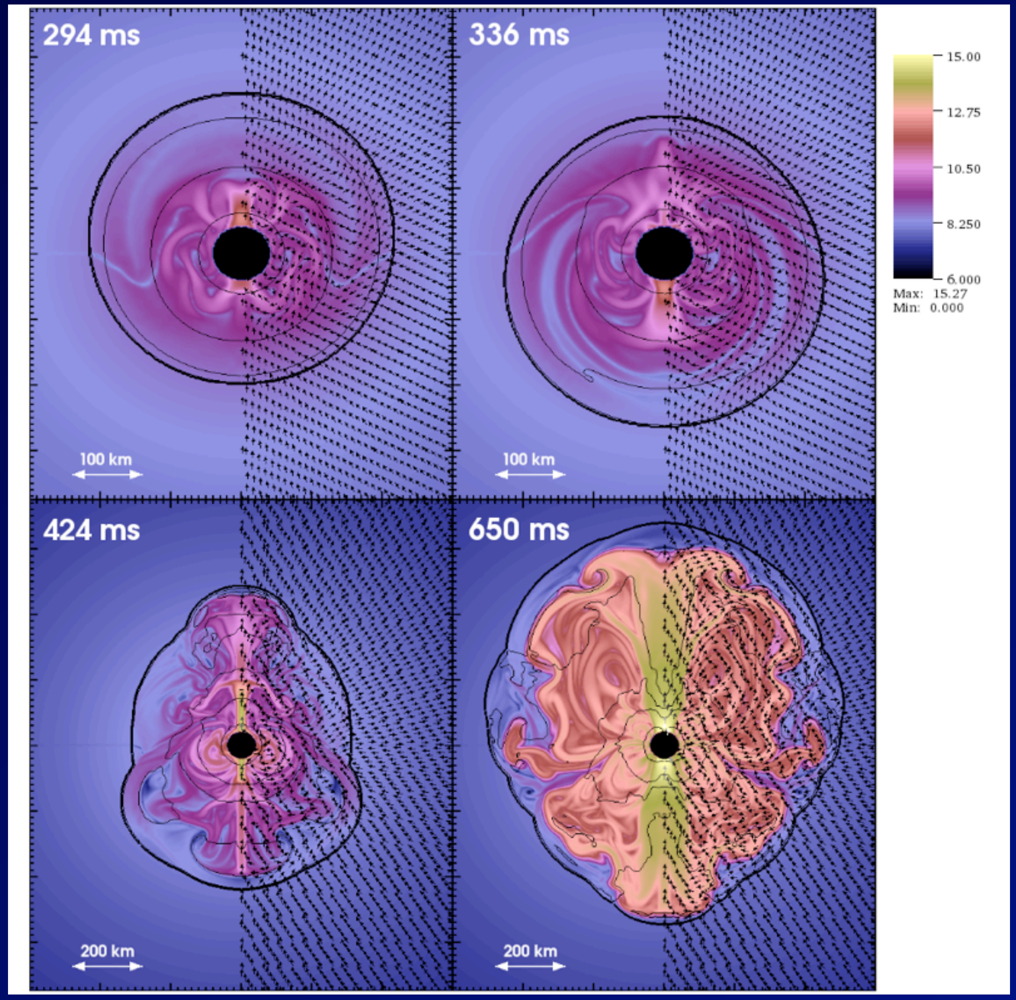
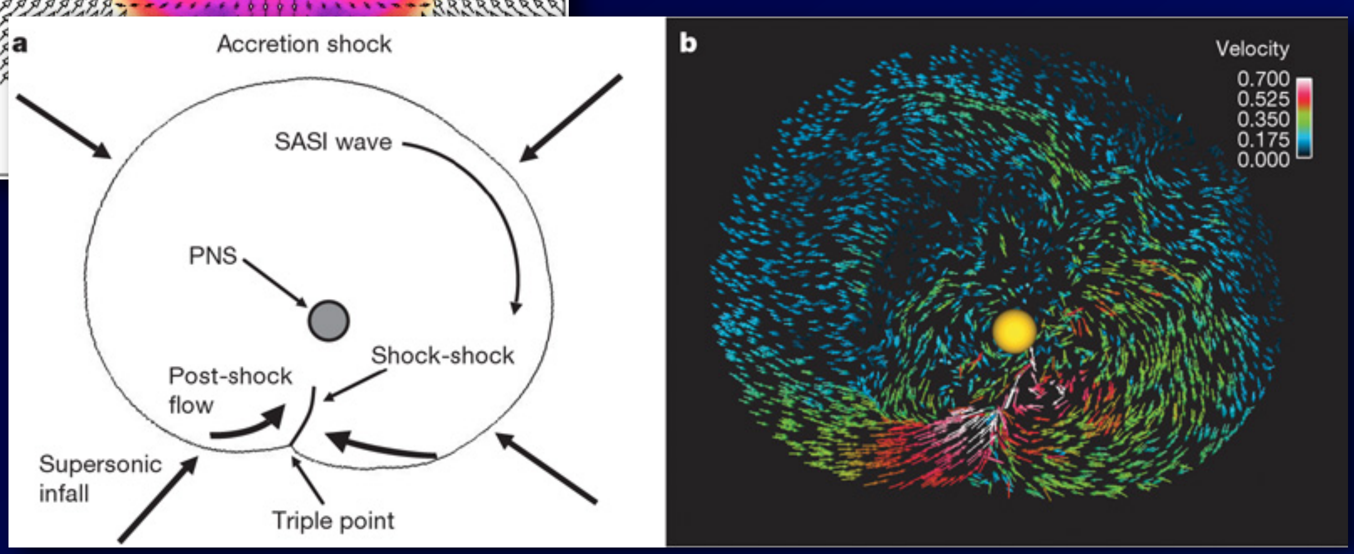


Aspherical explosion morphology

Endeve et al. (2008)



Magnetic field generation



Pulsar spin

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- Tangent bundle

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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 at finite temperature in neutron-rich conditions is required.

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- Neutrino flavor mixing should be included (spacetime trajectories are still classical, but flavor content must be evolved quantum mechanically on macroscopic scales).

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  - Spherical symmetry, neutrinos only, "free streaming" only; high resolution in neutrino energy and in rare cases angles

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What is the status of simulations focusing on the explosion mechanism?

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	ν pair emission from accretion
Kelvin-Helmholtz contraction, then cooling of neutron star	Deleptonization and energy release via ν emission
	e^- capture / ν_e emission
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(If rapid rotation: accretion disk and jet formation)	(ν pair annihilation helps power jet?)
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Late 1990s / Early 2000s: Cold water thrown on the panacea of post-shock convection by (2D/1D + 1D, 2D + 1D) simulations (Mezzacappa et al., Janka et al.)

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Neutrino radiation transport

(Magneto)hydrodynamics

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1S										
2S										
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1S										
2S										
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Explosion

Running

Dud

Development

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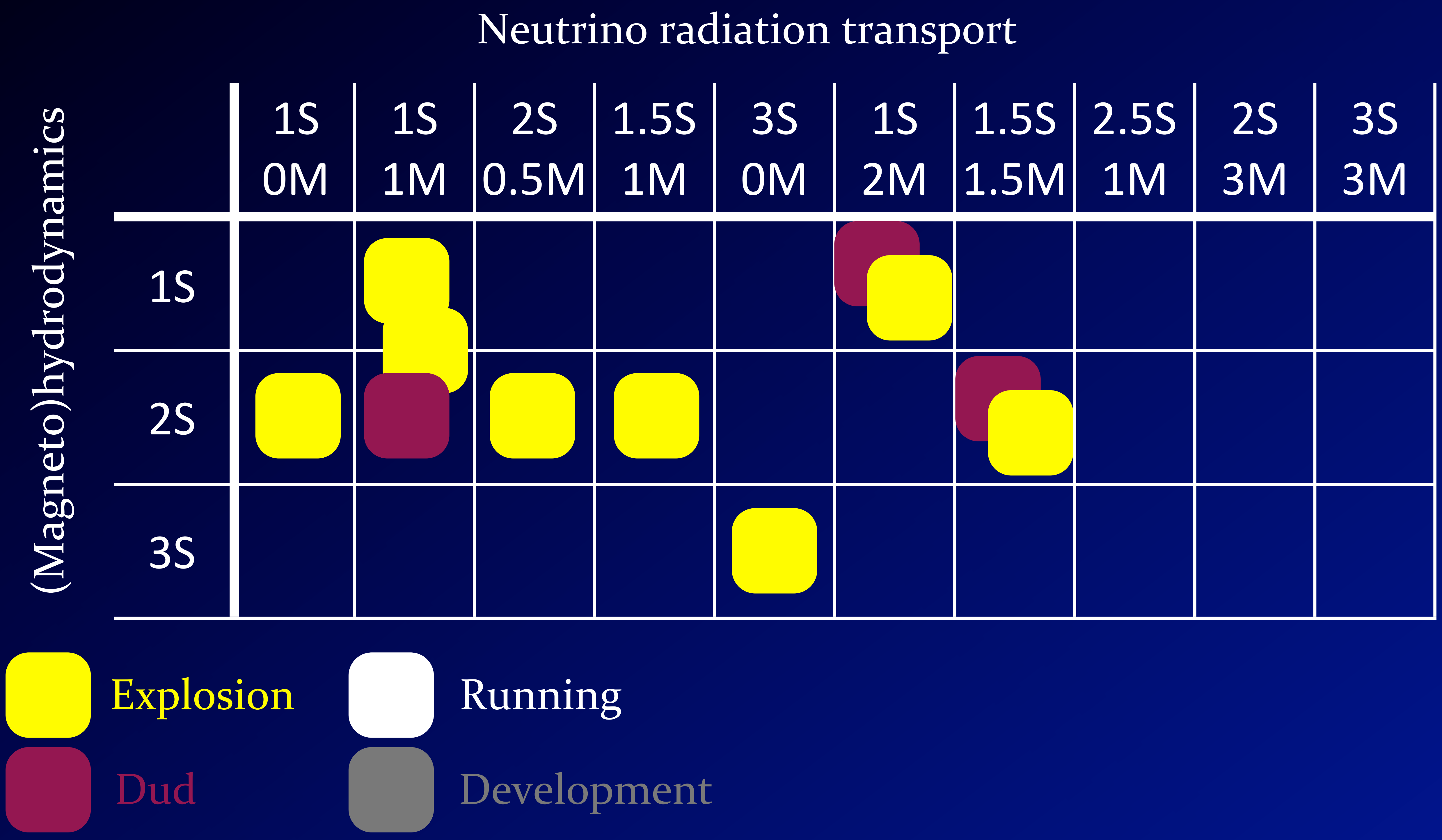

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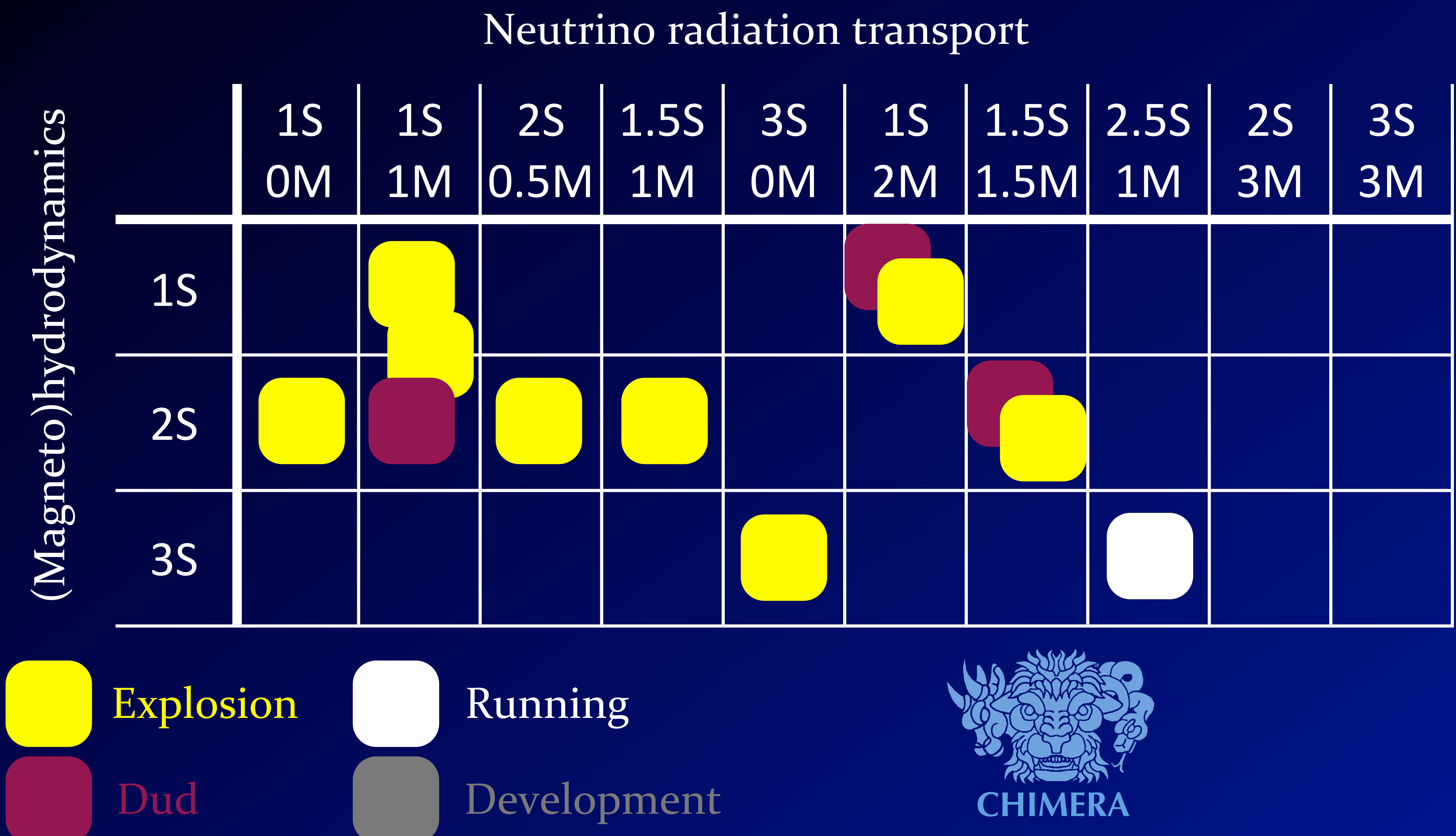

CHIMERA

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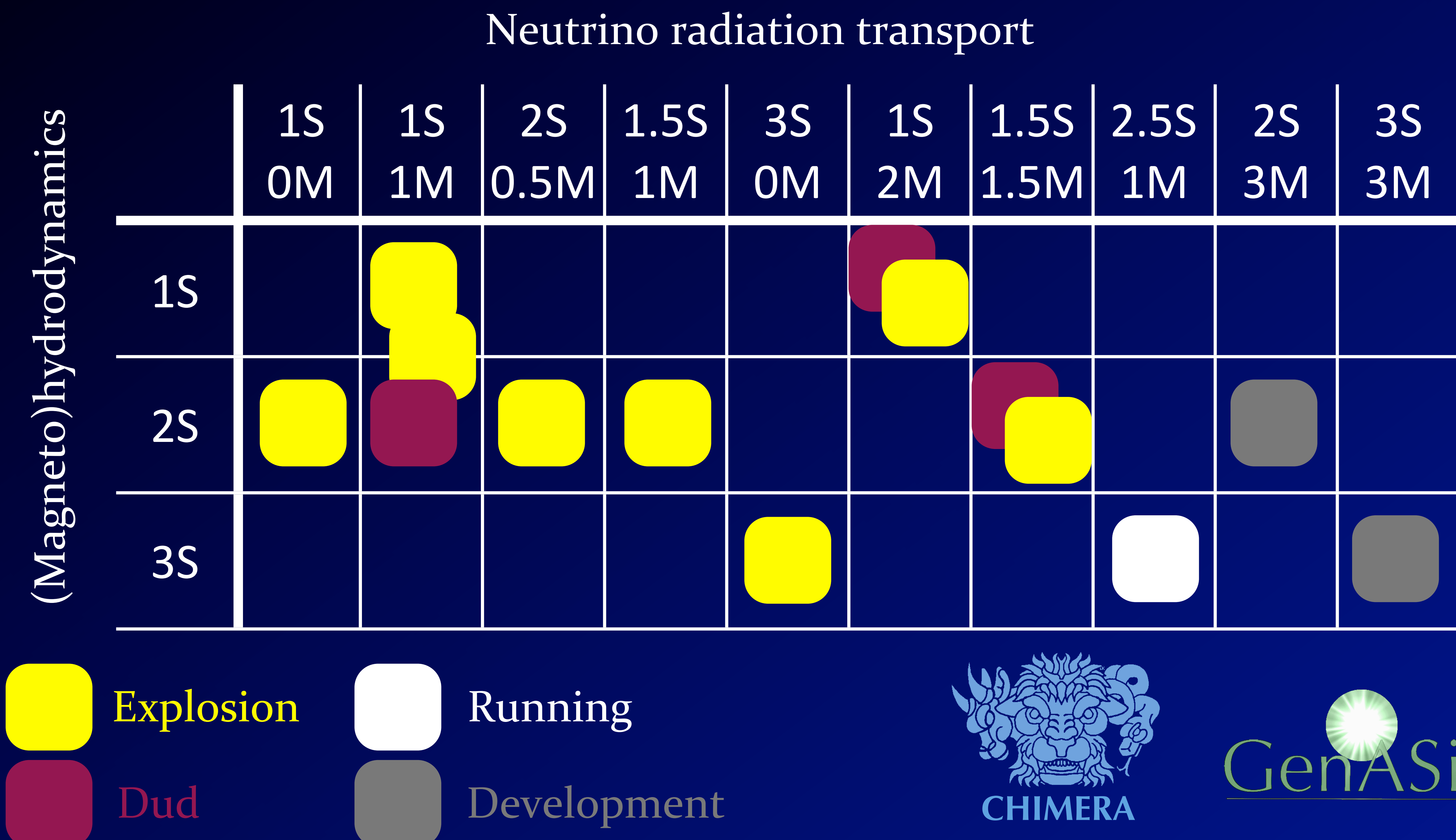


CHIMERA

GenASiS

Oak Ridge National Laboratory

The University of Tennessee Knoxville

Budiardja
Cardall
Endeve
Hix
Lentz
Messer
Mezzacappa
Parete-Koon

FAU

Bruenn
Marronetti
Yakunin
Dirk

NC STATE UNIVERSITY

Blondin
Warren

UCSD

Fuller

Funded by

Office of Science
U.S. DEPARTMENT OF ENERGY

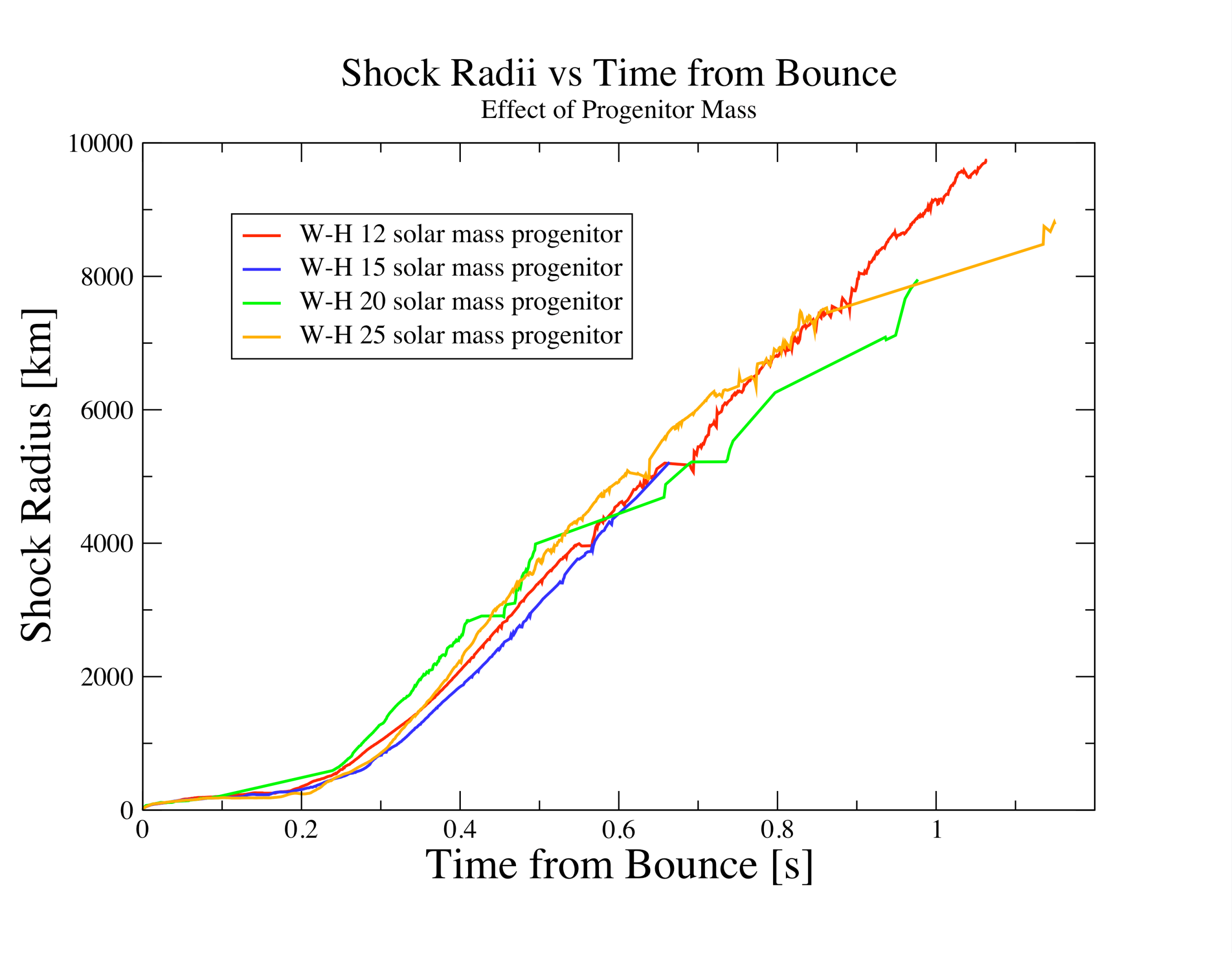
National Science Foundation NSF

National Aeronautics and Space Administration U.S.A.

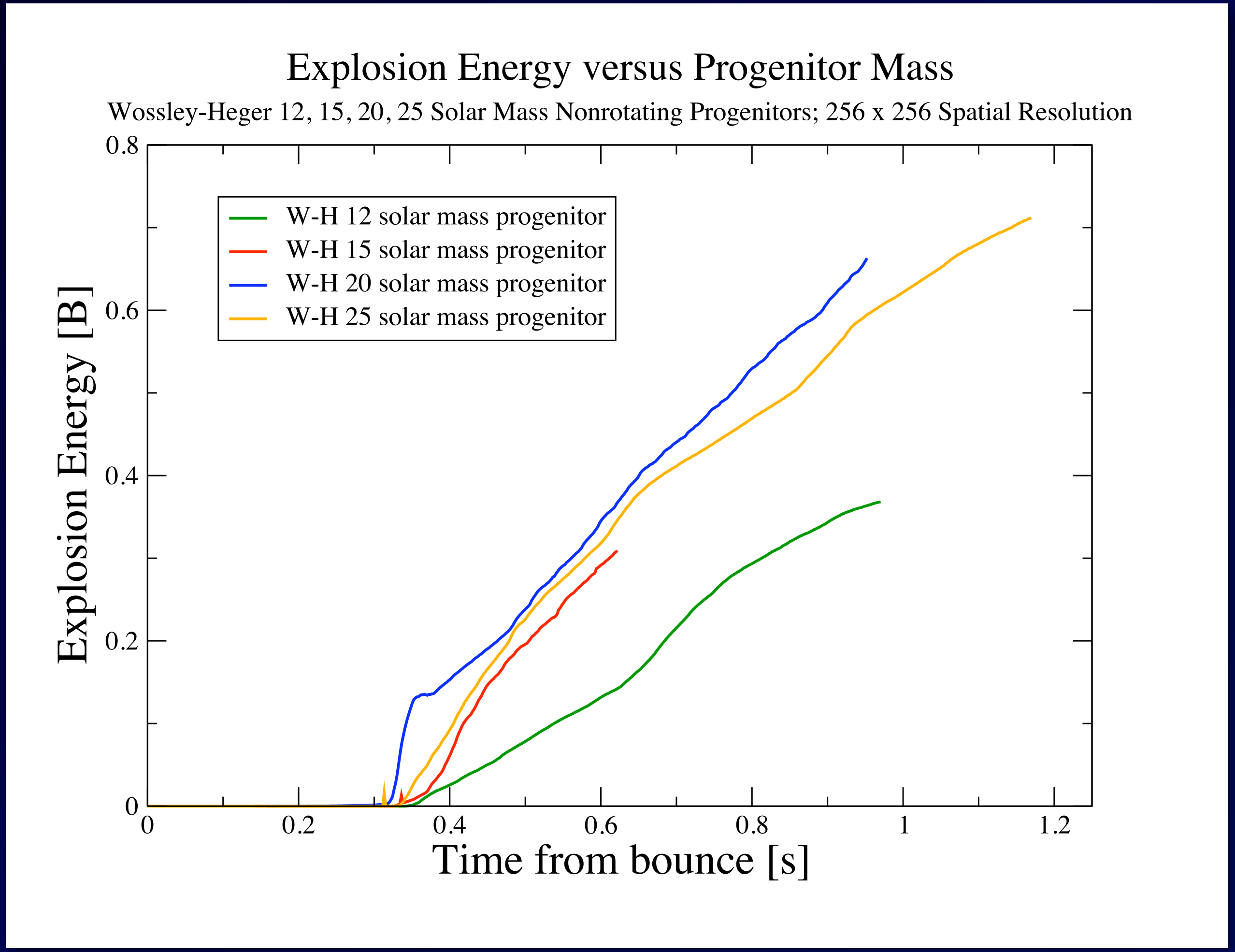
Collaborators

- *Solvers: D'Azevedo*
- *Data Management: Barreto, Canon, Klasky, Podhorszki*
- *Networking: Beck, Moore, Rao*
- *Visualization: Ahern, Daniel, Ma, Meredith, Pugmire, Toedte*
- *Cray Center of Excellence: Levesque, Wichmann*

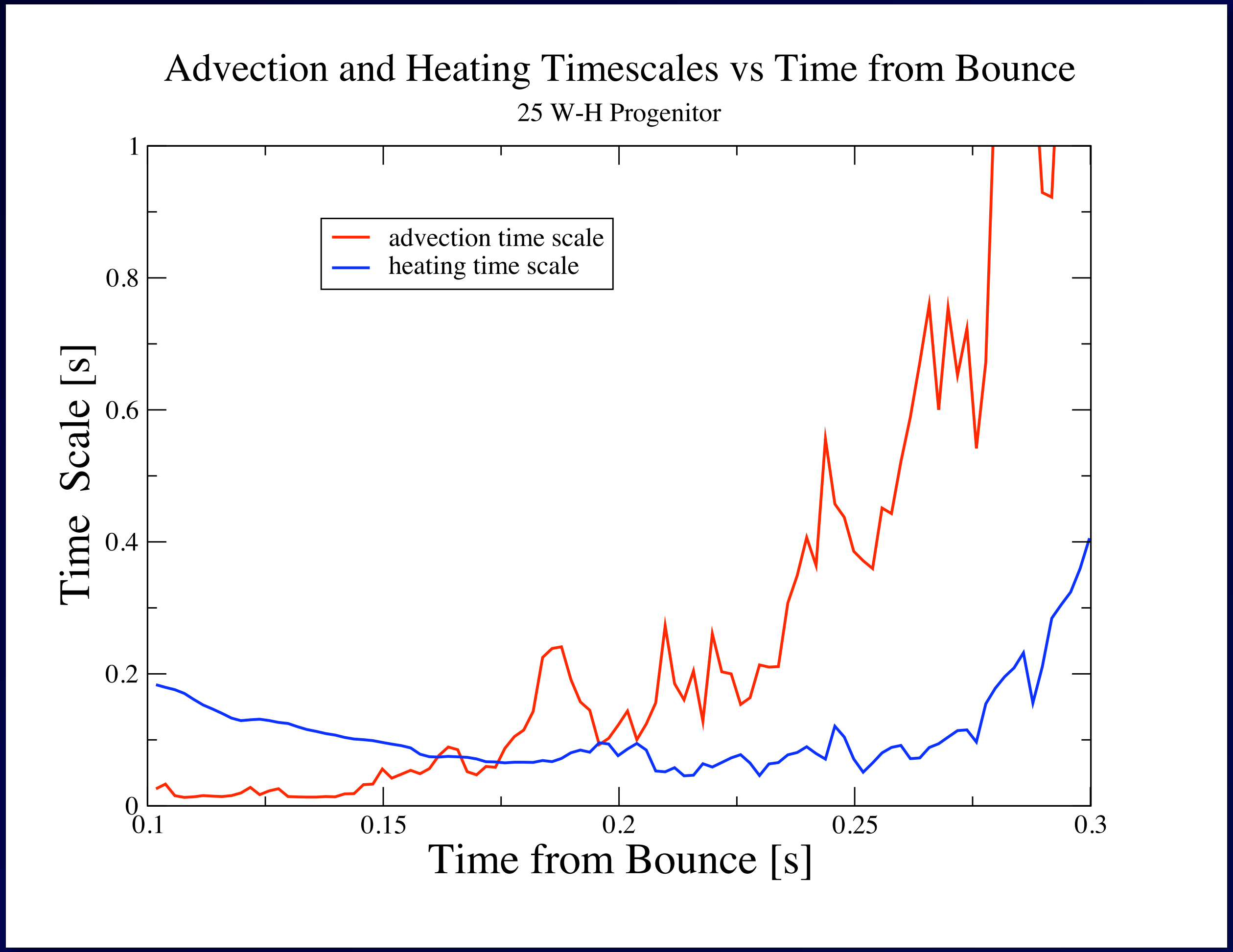
Movie



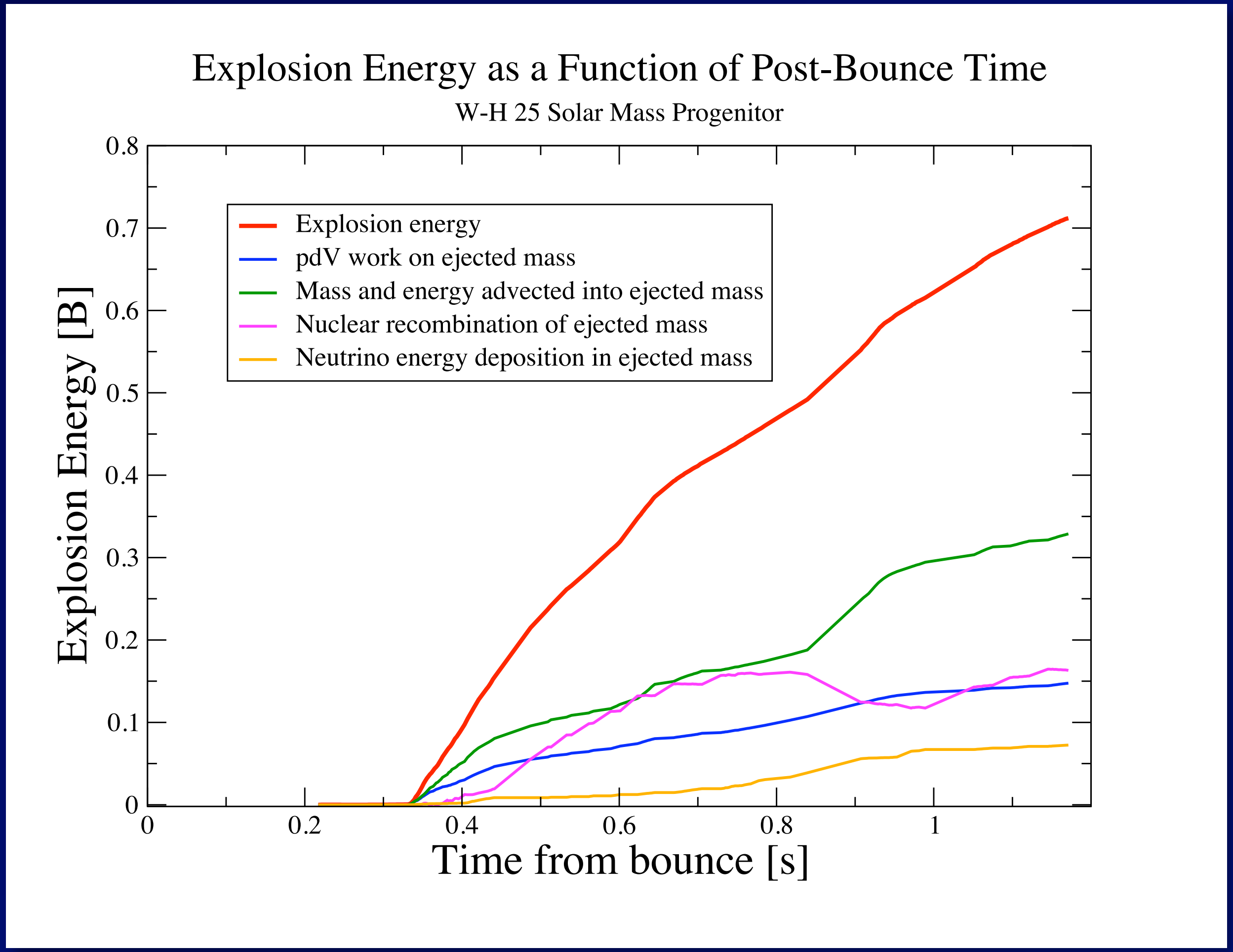
Shock Radii vs Time from Bounce
Effect of Progenitor Mass
W-H 12 solar mass progenitor
W-H 15 solar mass progenitor
W-H 20 solar mass progenitor
W-H 25 solar mass progenitor
Shock Radius [km]
Time from Bounce [s]



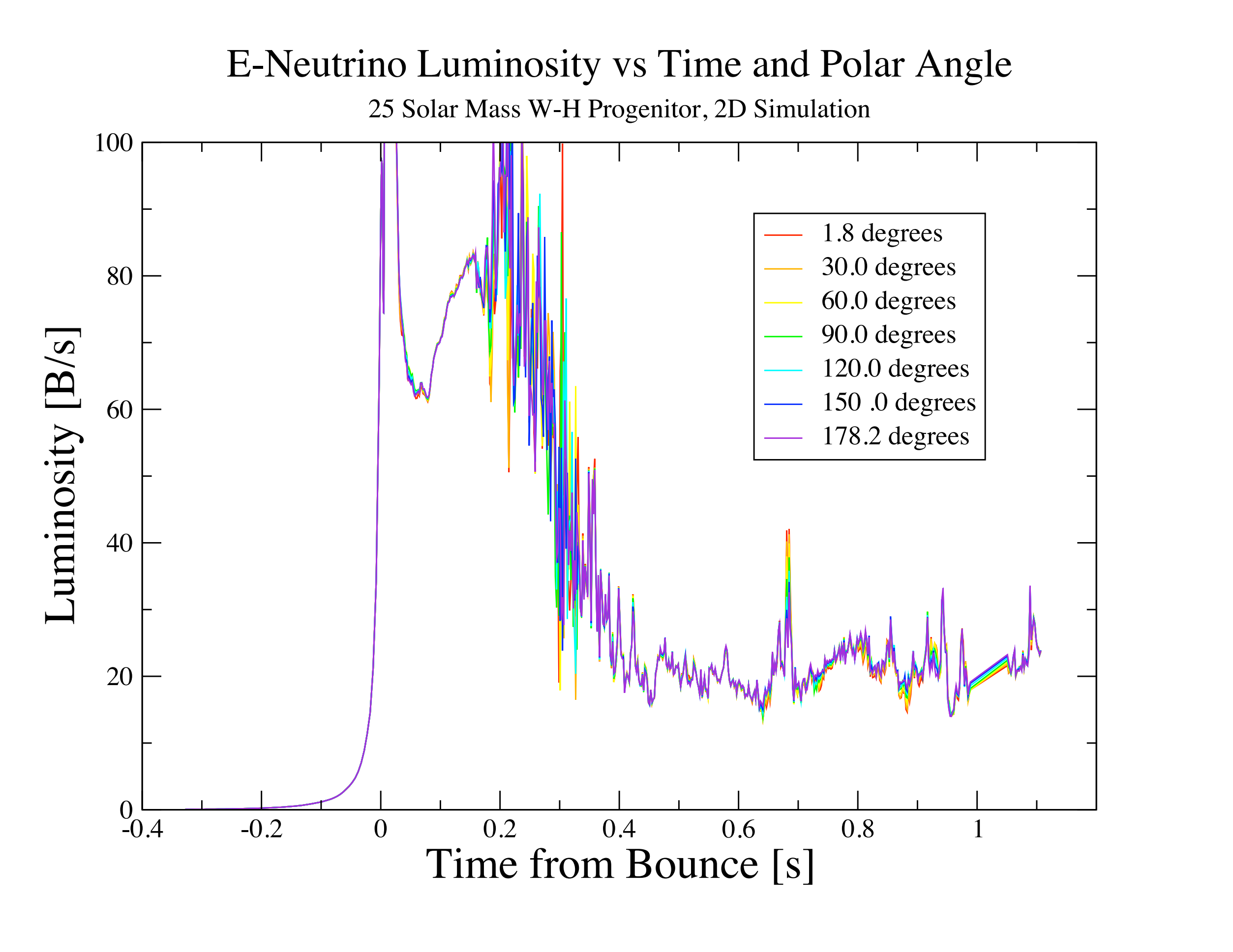
Explosion Energy versus Progenitor Mass
Wossley-Heger 12, 15, 20, 25 Solar Mass Nonrotating Progenitors; 256 x 256 Spatial Resolution
W-H 12 solar mass progenitor
W-H 15 solar mass progenitor
W-H 20 solar mass progenitor
W-H 25 solar mass progenitor
Explosion Energy [B]
Time from bounce [s]

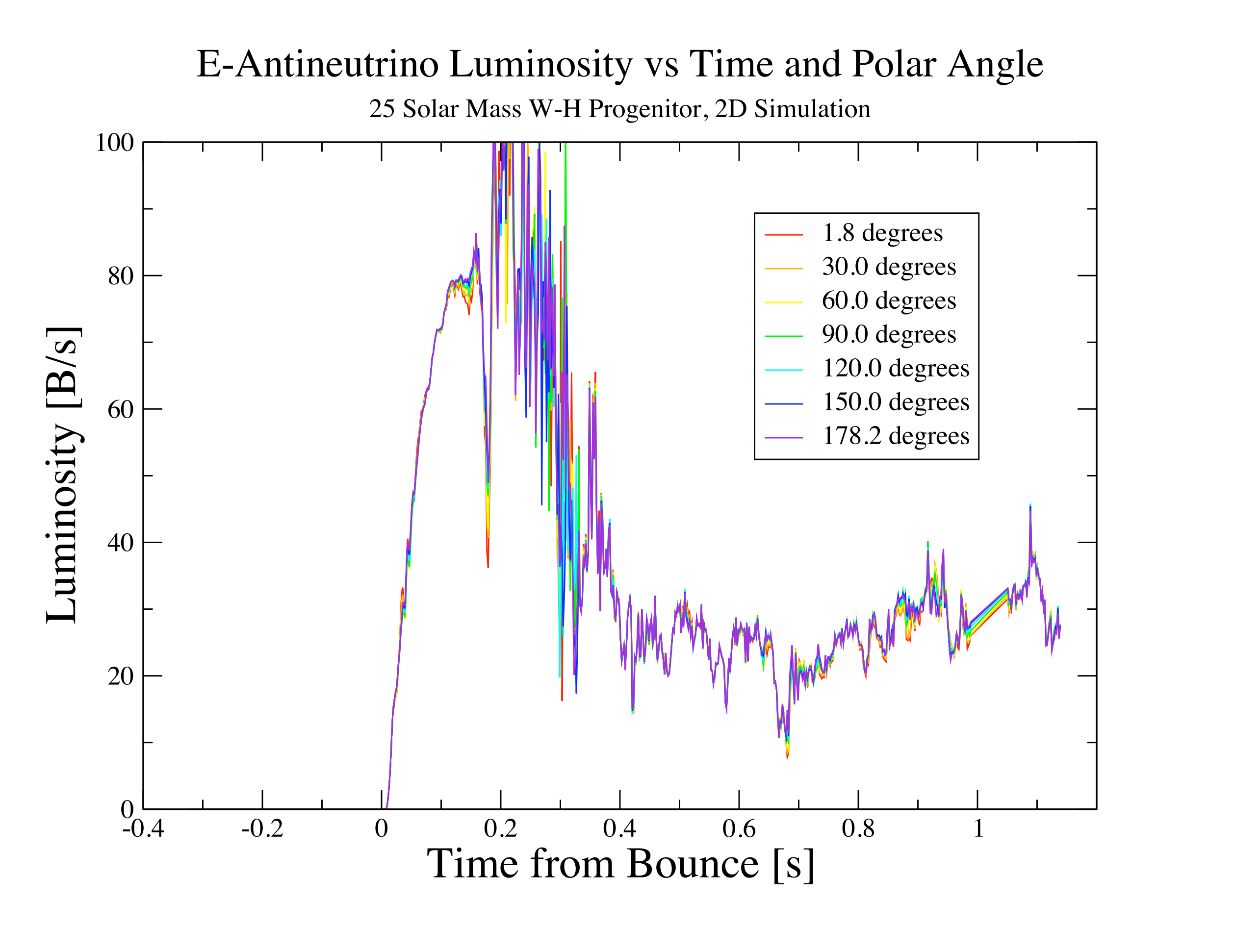


Advection and Heating Timescales vs Time from Bounce
25 W-H Progenitor
advection time scale
heating time scale
Time Scale [s]
Time from Bounce [s]



Explosion Energy as a Function of Post-Bounce Time
W-H 25 Solar Mass Progenitor
Explosion energy
pdV work on ejected mass
Mass and energy advected into ejected mass
Nuclear recombination of ejected mass
Neutrino energy deposition in ejected mass
Explosion Energy [B]
Time from bounce [s]


E-Neutrino Luminosity vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2D Simulation
Luminosity [B/s]
Time from Bounce [s]
1.8 degrees
30.0 degrees
60.0 degrees
90.0 degrees
120.0 degrees
150 .0 degrees
178.2 degrees


E-Antineutrino Luminosity vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2D Simulation
Luminosity [B/s]
Time from Bounce [s]
1.8 degrees
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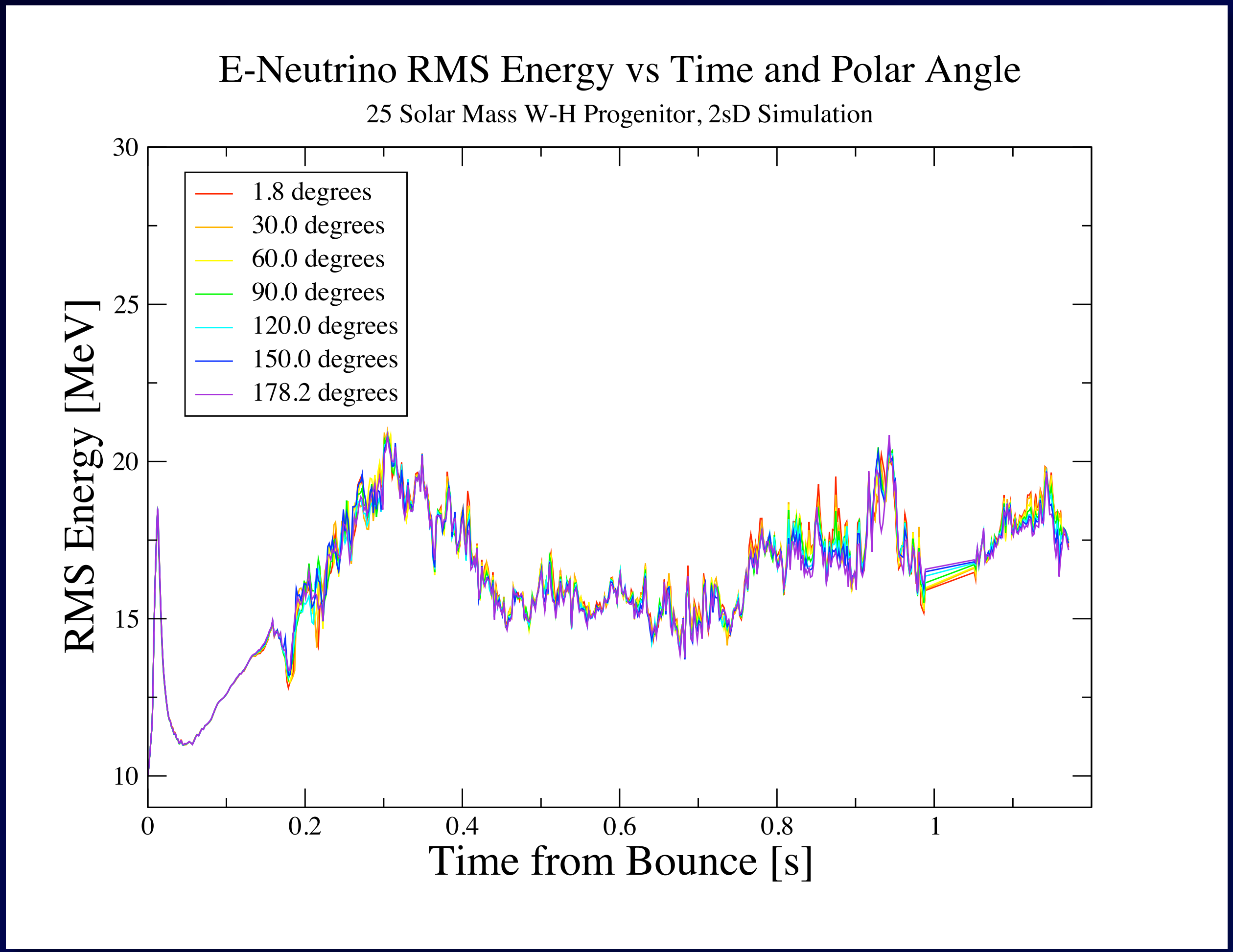
E-Neutrino RMS Energy vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2sD Simulation
RMS Energy [MeV]
Time from Bounce [s]
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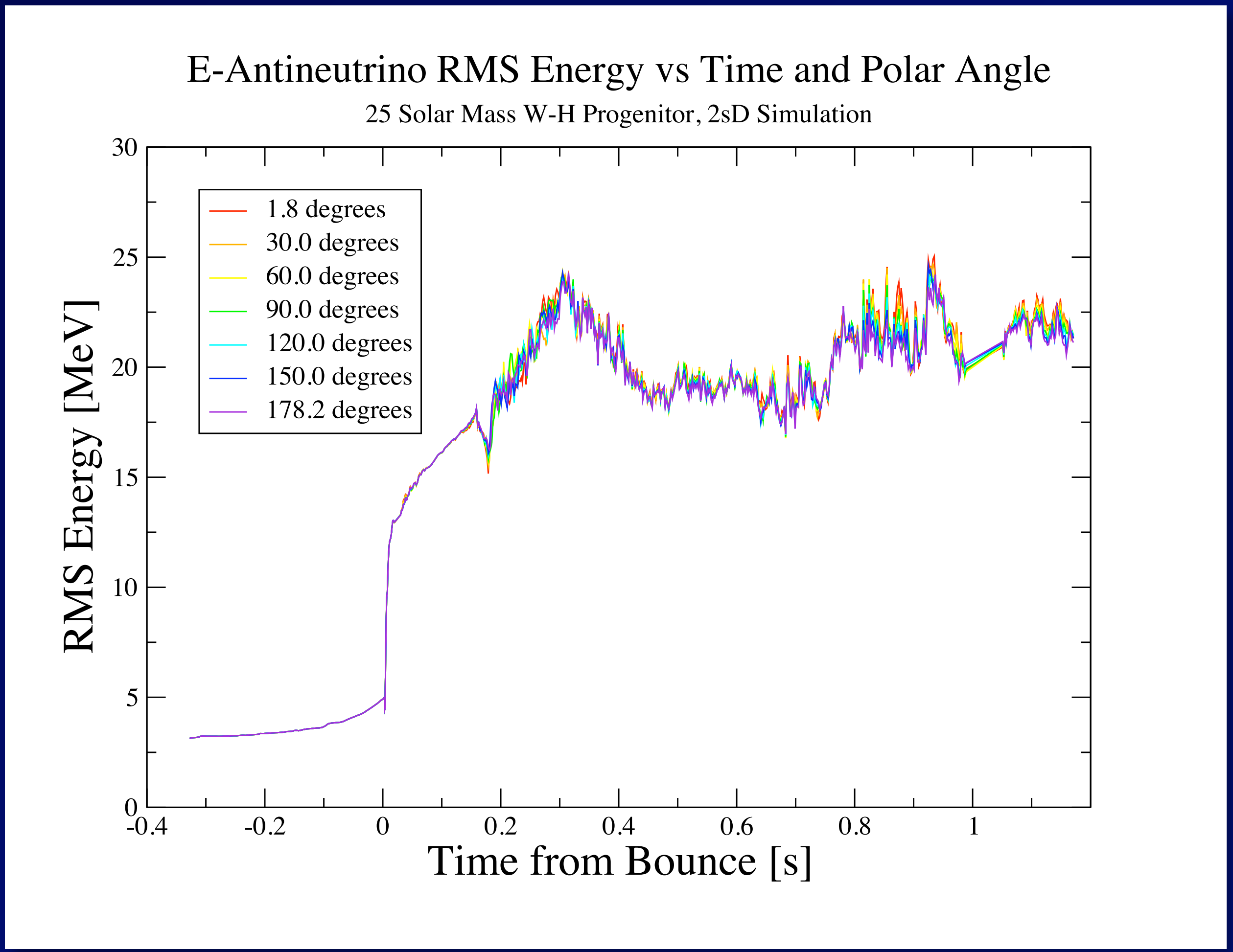
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At least in the ORNL simulations, the inclusion of **inelastic** neutrino/nucleon scattering makes a noticeable difference.

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- However there are theoretical reasons to doubt the acoustic mechanism (Weinberg and Quataert 2007).

There are agreements and disagreements among recent multiphysics supernova simulations.

- The neutrino-driven explosions occur earlier than the acoustic ones.
  - The absence of neutrino-driven explosions in the Princeton simulations may be due to the absence of energy redistribution processes in the neutrino transport, and the absence of even approximate general relativity.
  - The absence of the acoustic mechanism in the ORNL and Garching simulations could be due to the fact that the neutrino-driven explosions take off before it can develop.
  - However there are theoretical reasons to doubt the acoustic mechanism (Weinberg and Quataert 2007).
- The ORNL 15 $M_\odot$ explosion takes off earlier than the Garching one, but the latter uses a different, and rotating, progenitor.

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The two groups with the best neutrino transport see SASI-aided neutrino-driven explosions.

…and Challenges

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Simulations aimed at the explosion mechanism:

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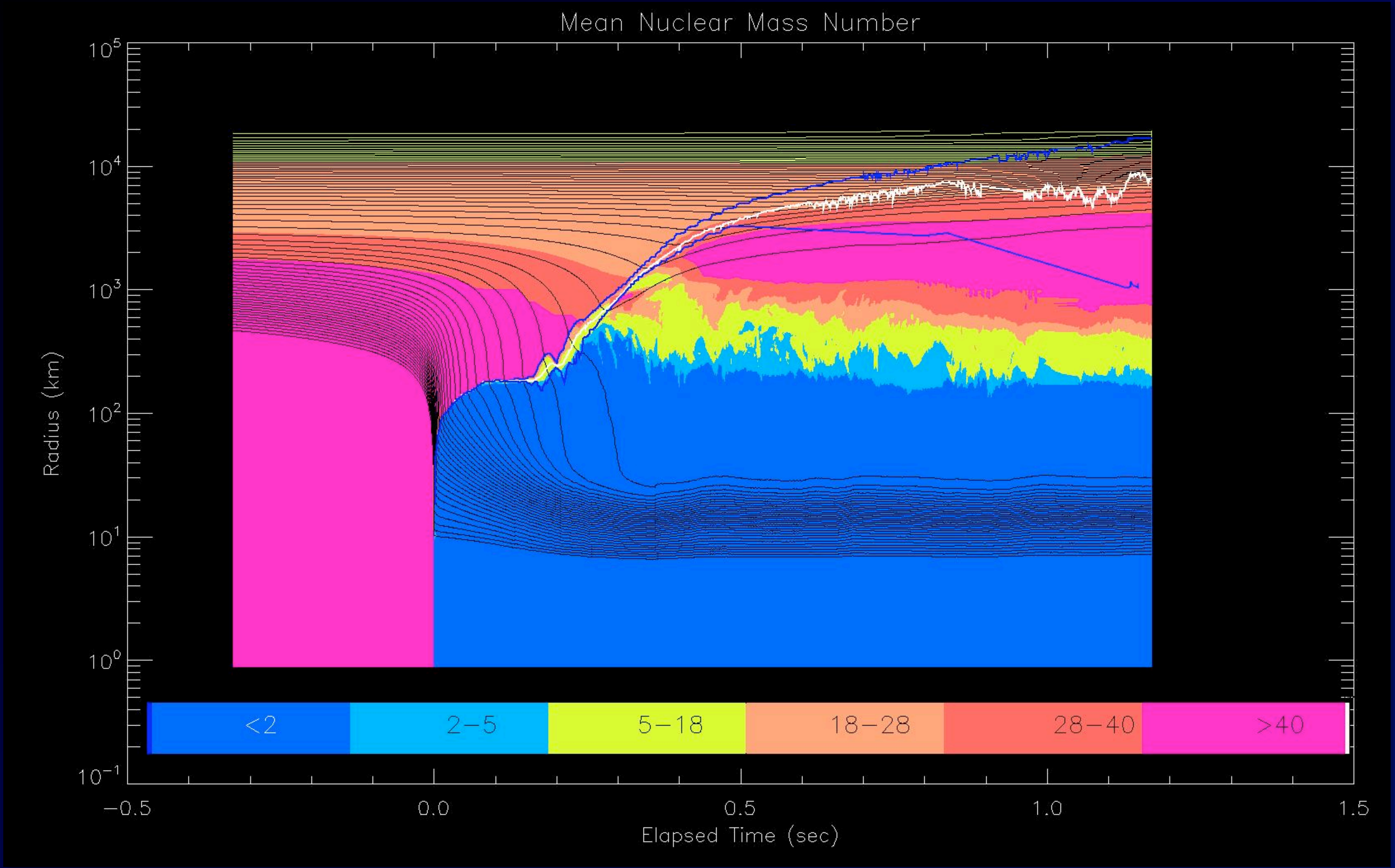
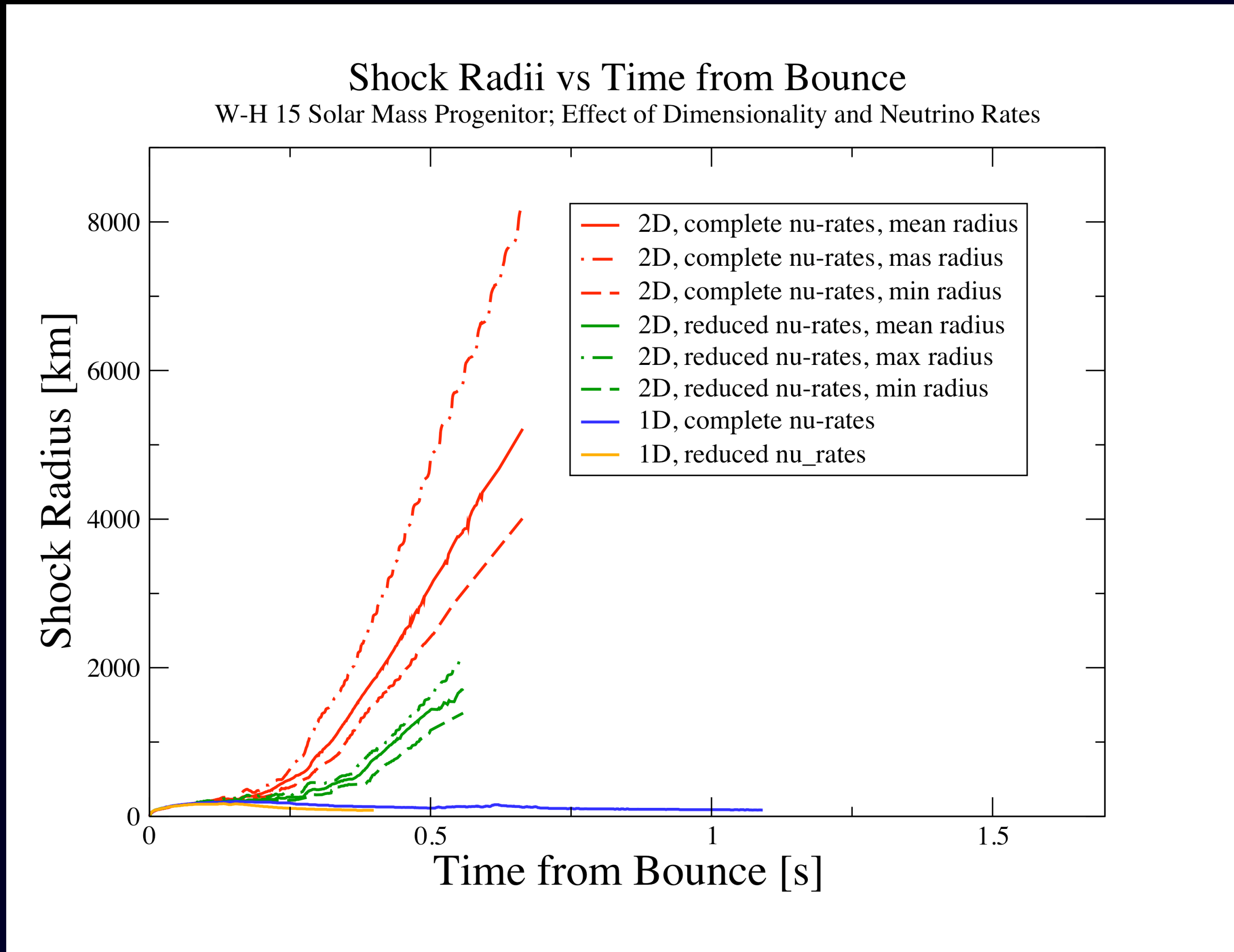
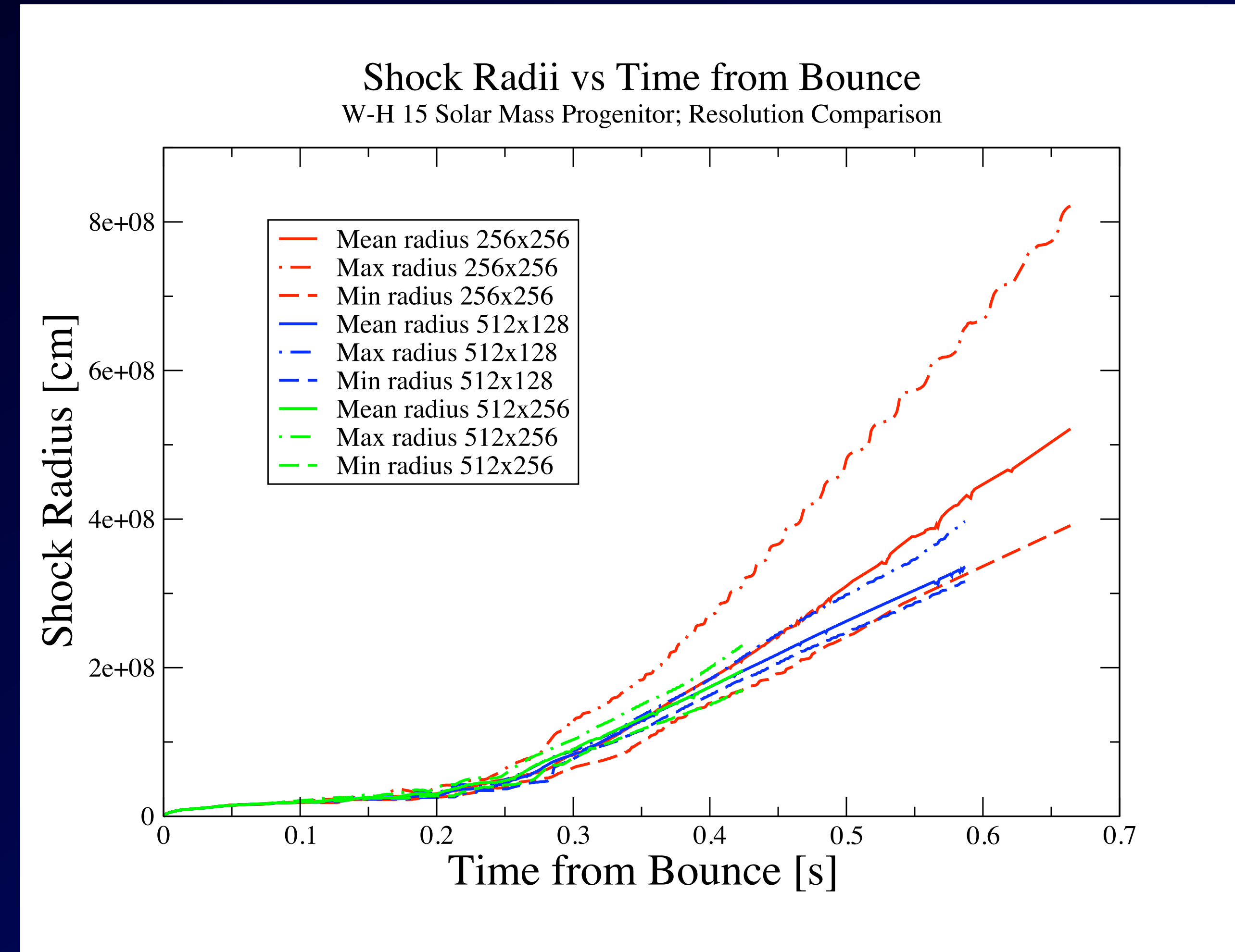
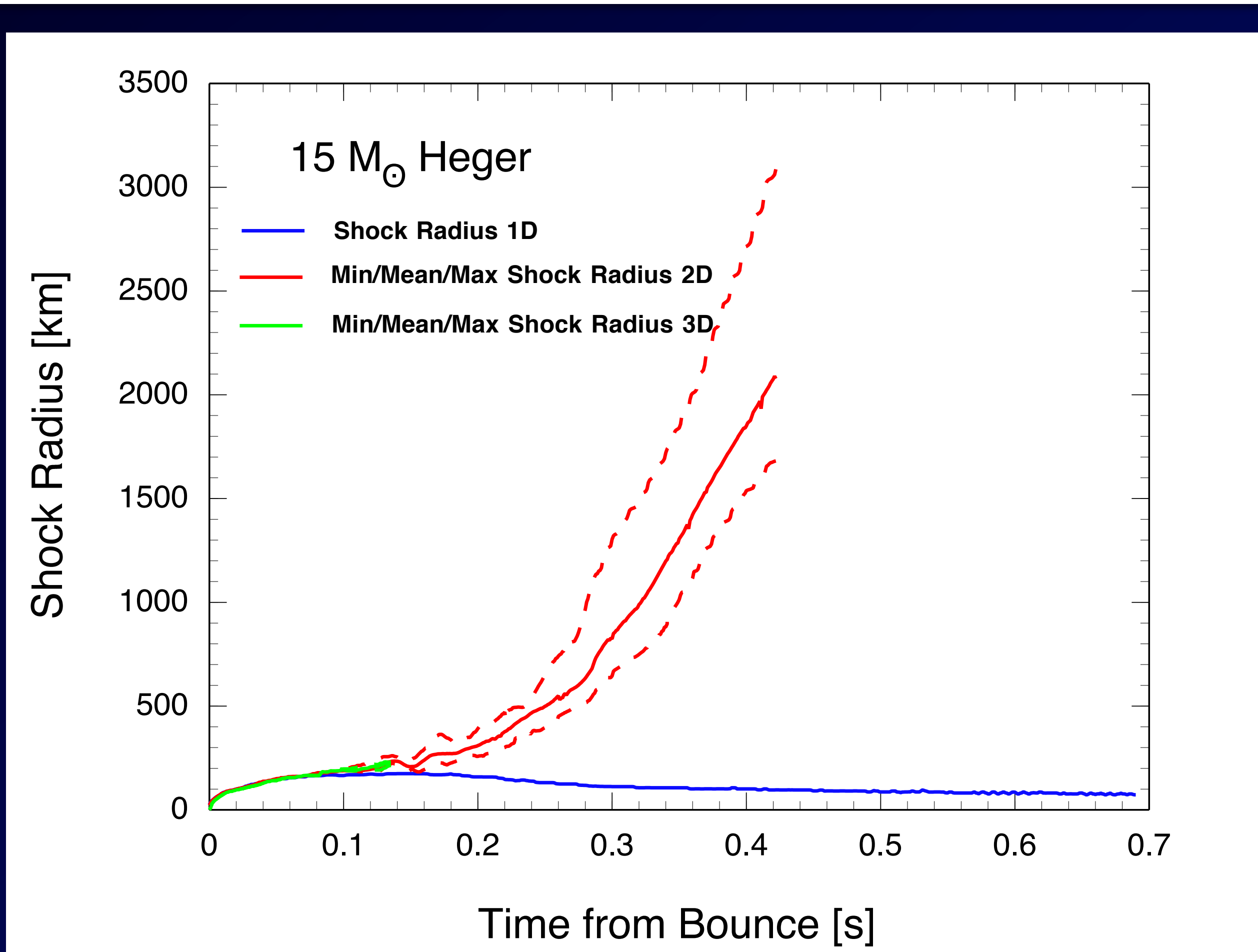
- Do not include flavor mixing physics.



Mean Nuclear Mass Number
Radius (km)
Elapsed Time (sec)
<2
2–5
5–18
18–28
28–40
>40


Shock Radii vs Time from Bounce
W-H 15 Solar Mass Progenitor; Effect of Dimensionality and Neutrino Rates
2D, complete nu-rates, mean radius
2D, complete nu-rates, mas radius
2D, complete nu-rates, min radius
2D, reduced nu-rates, mean radius
2D, reduced nu-rates, max radius
2D, reduced nu-rates, min radius
1D, complete nu-rates
1D, reduced nu_rates
Shock Radius [km]
0
2000
4000
6000
8000
0
0.5
1
1.5
Time from Bounce [s]


Shock Radii vs Time from Bounce
W-H 15 Solar Mass Progenitor; Resolution Comparison
Mean radius 256x256
Max radius 256x256
Min radius 256x256
Mean radius 512x128
Max radius 512x128
Min radius 512x128
Mean radius 512x256
Max radius 512x256
Min radius 512x256
Shock Radius [cm]
0
2e+08
4e+08
6e+08
8e+08
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time from Bounce [s]


15 M⊙ Heger
Shock Radius 1D
Min/Mean/Max Shock Radius 2D
Min/Mean/Max Shock Radius 3D
Shock Radius [km]
0
500
1000
1500
2000
2500
3000
3500
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Time from Bounce [s]