Core-collapse supernova explosions

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Introduction

Stellar collapse and its aftermath

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Stellar collapse and its aftermath

Explosion simulations

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Conclusion

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

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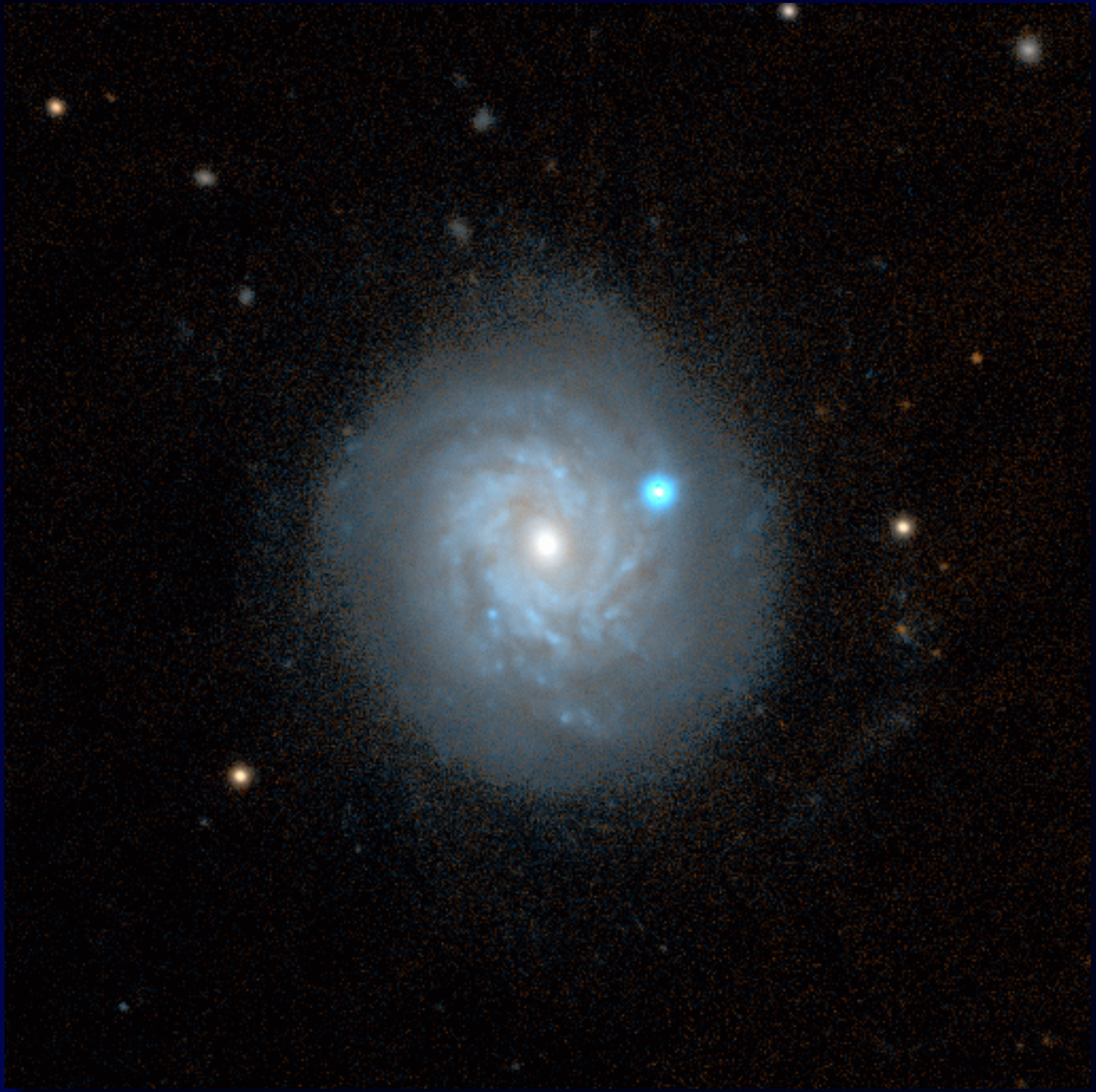
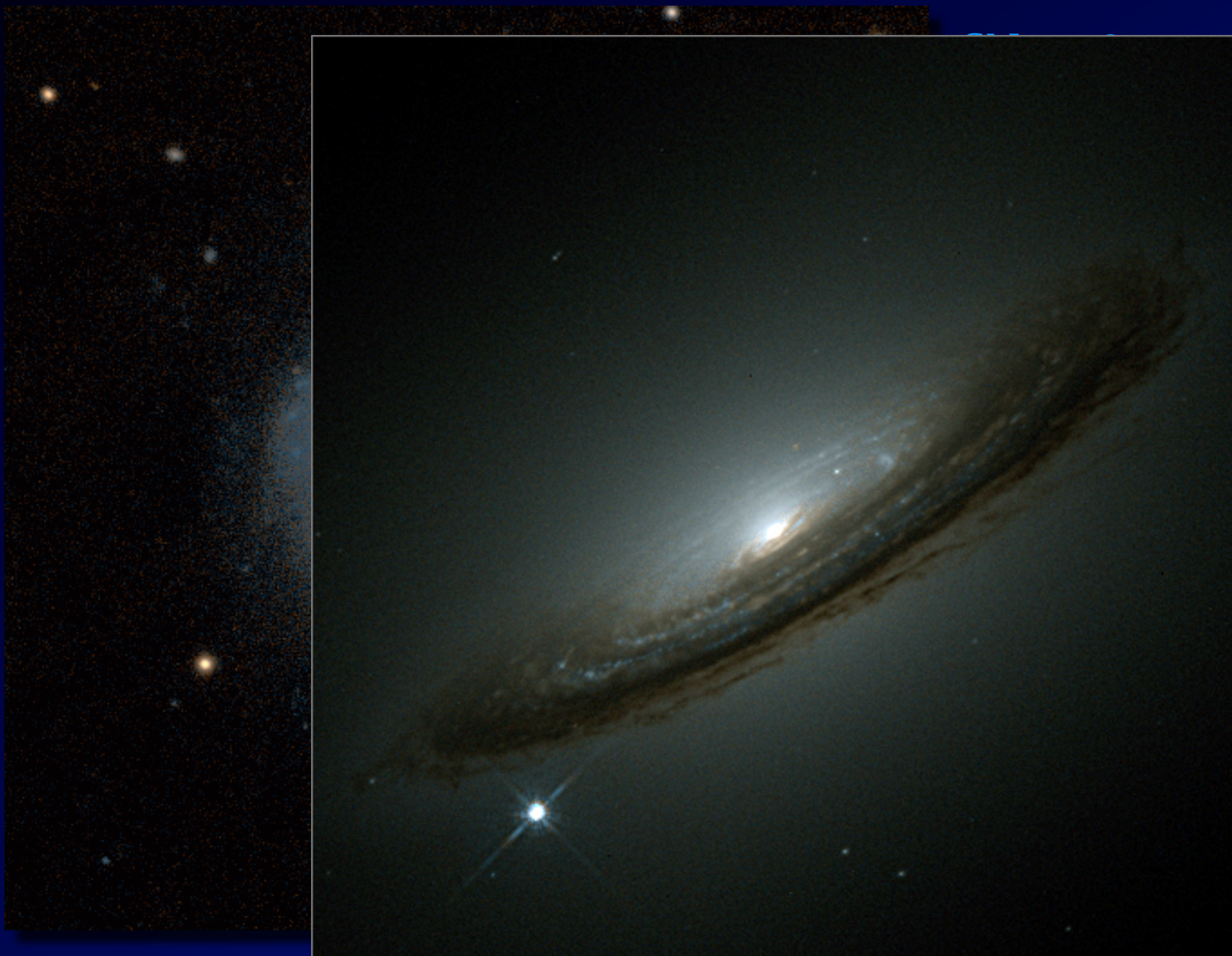


SN 1998aq

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



SN 1994D

Baade and Zwicky proposed a physical scenario.

JANUARY 15, 1934 PHYSICAL REVIEW VOLUME 45

Proceedings
of the
American Physical Society

MINUTES OF THE STANFORD MEETING, DECEMBER 15–16, 1933

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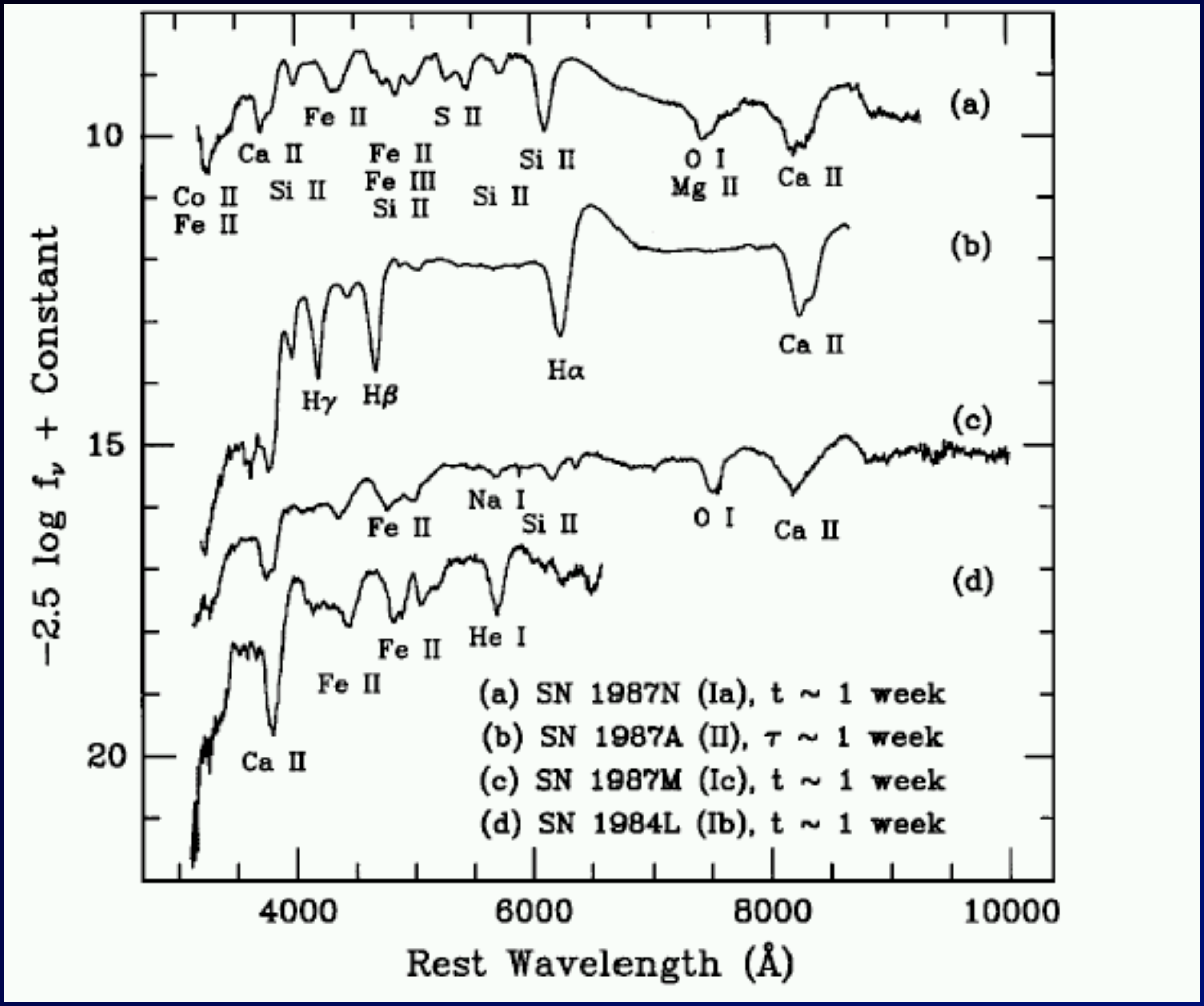
With all reserve we advance the view that supernovae represent the transitions from ordinary stars into *neutron stars*, which in their final stages consist of extremely closely packed neutrons.

Astronomers classify supernovae according to their spectra.



Filippenko (1997)

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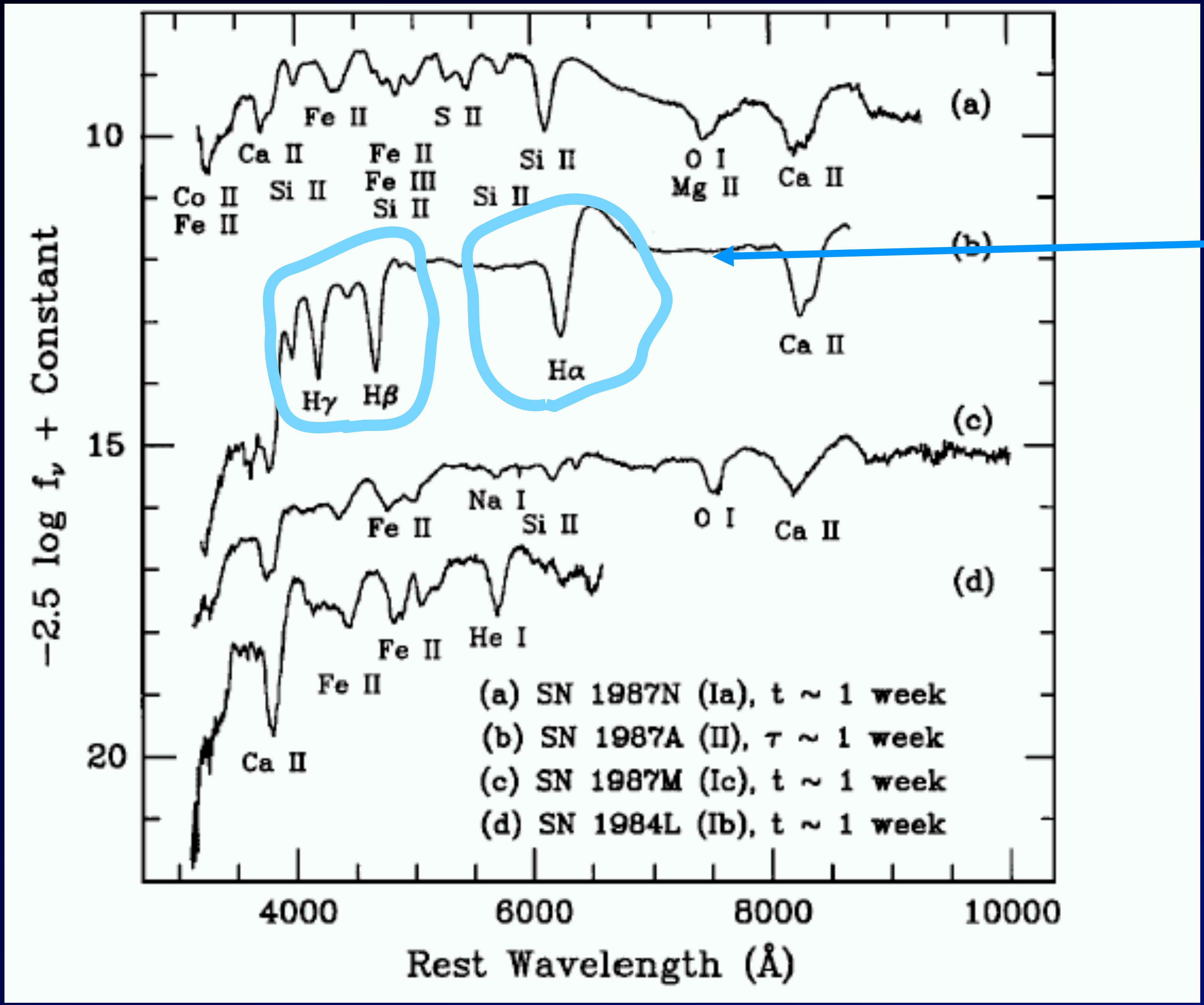

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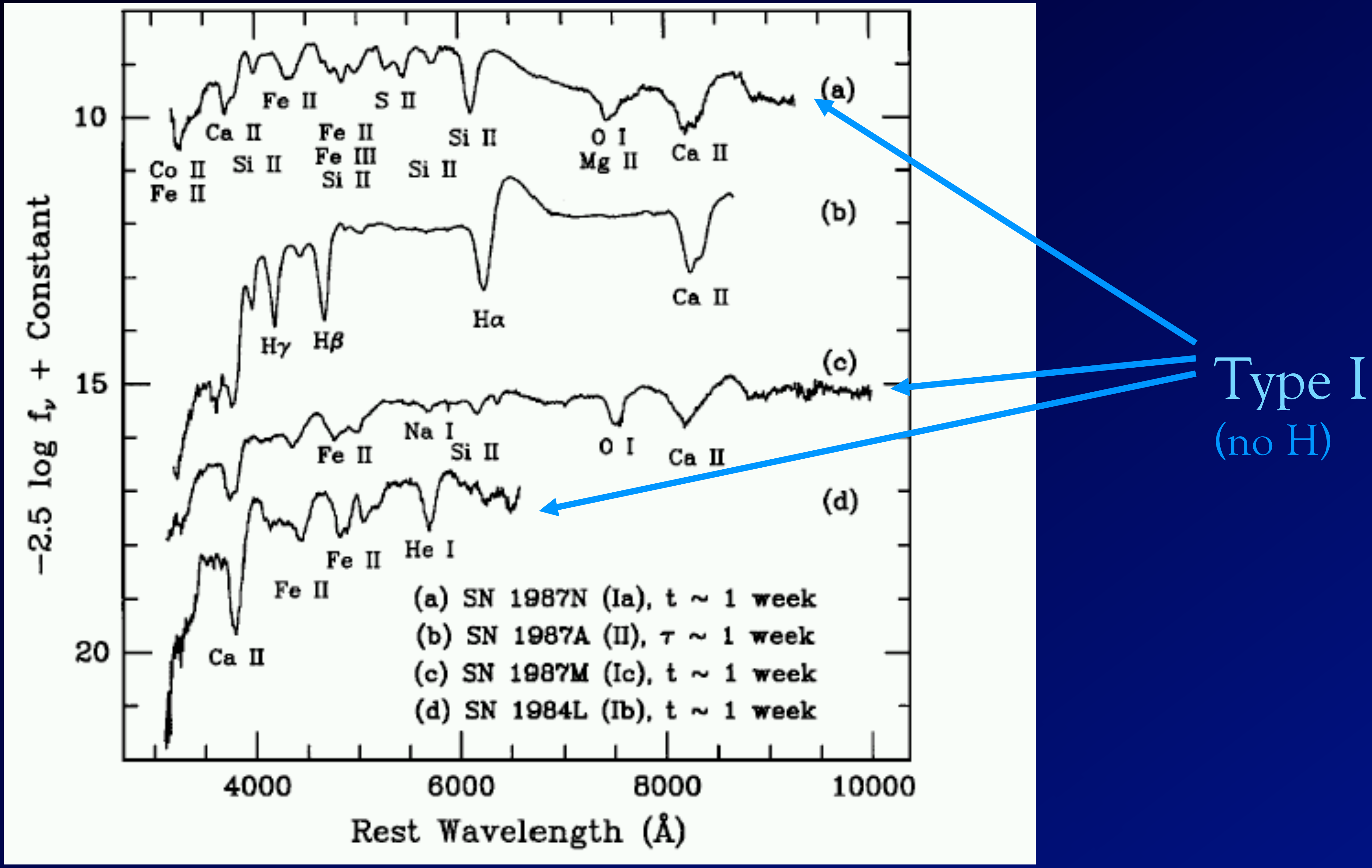

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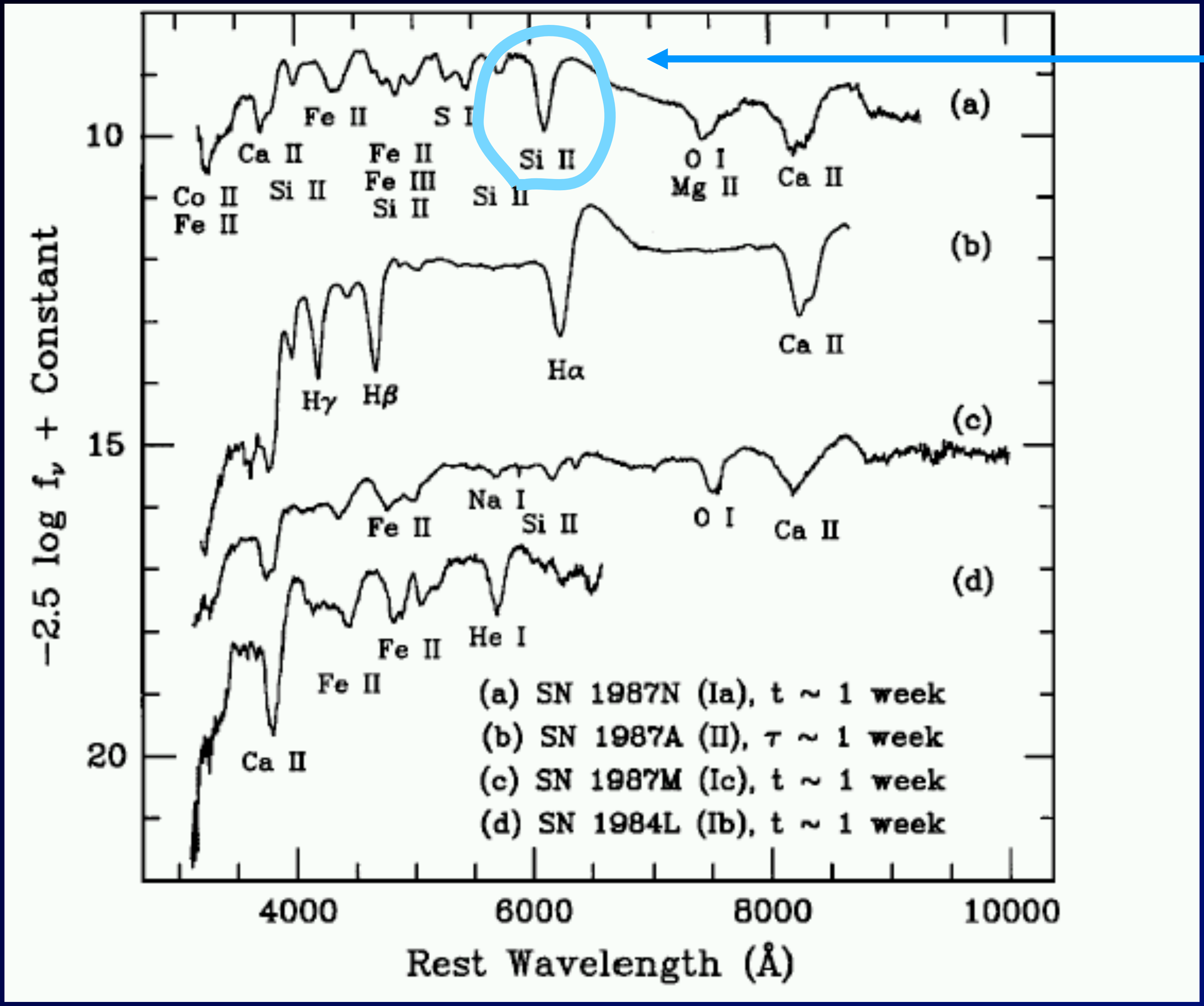

Type Ia
(no H, strong Si)

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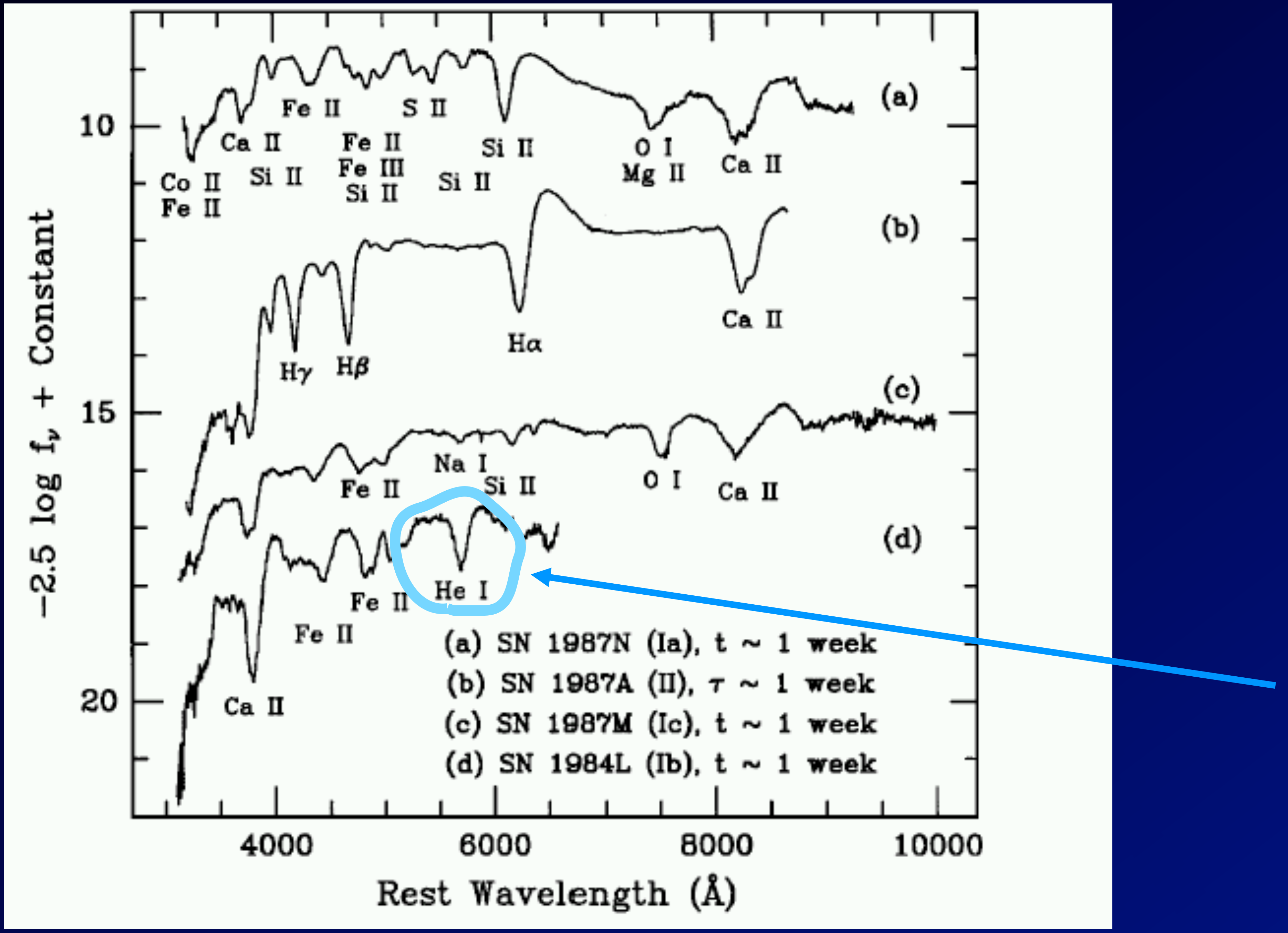

Filippenko (1997)

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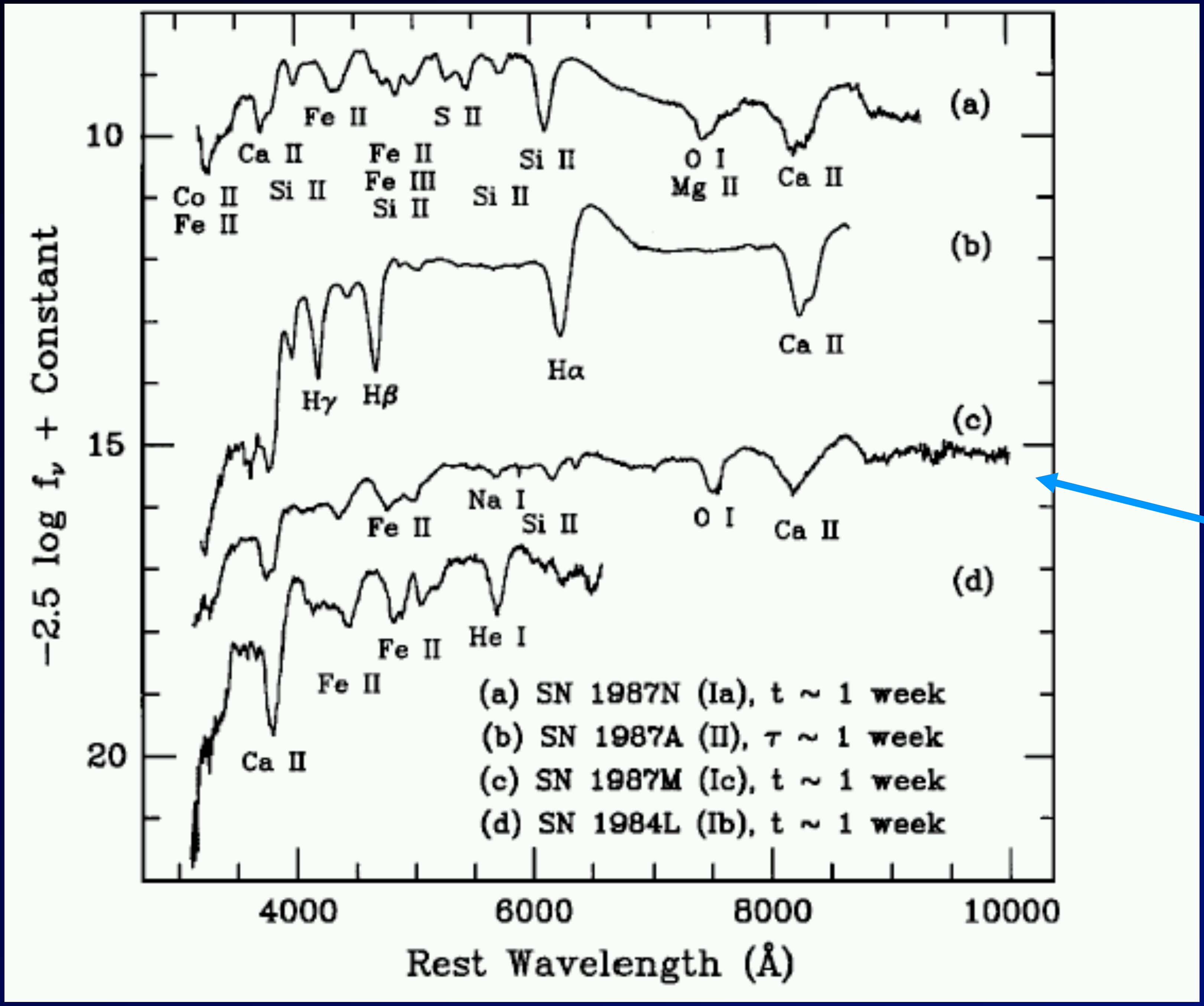

Type Ic
(no H, He, Si)

Filippenko (1997)

Astrophysicicists classify supernovae according to the underlying physical scenario.

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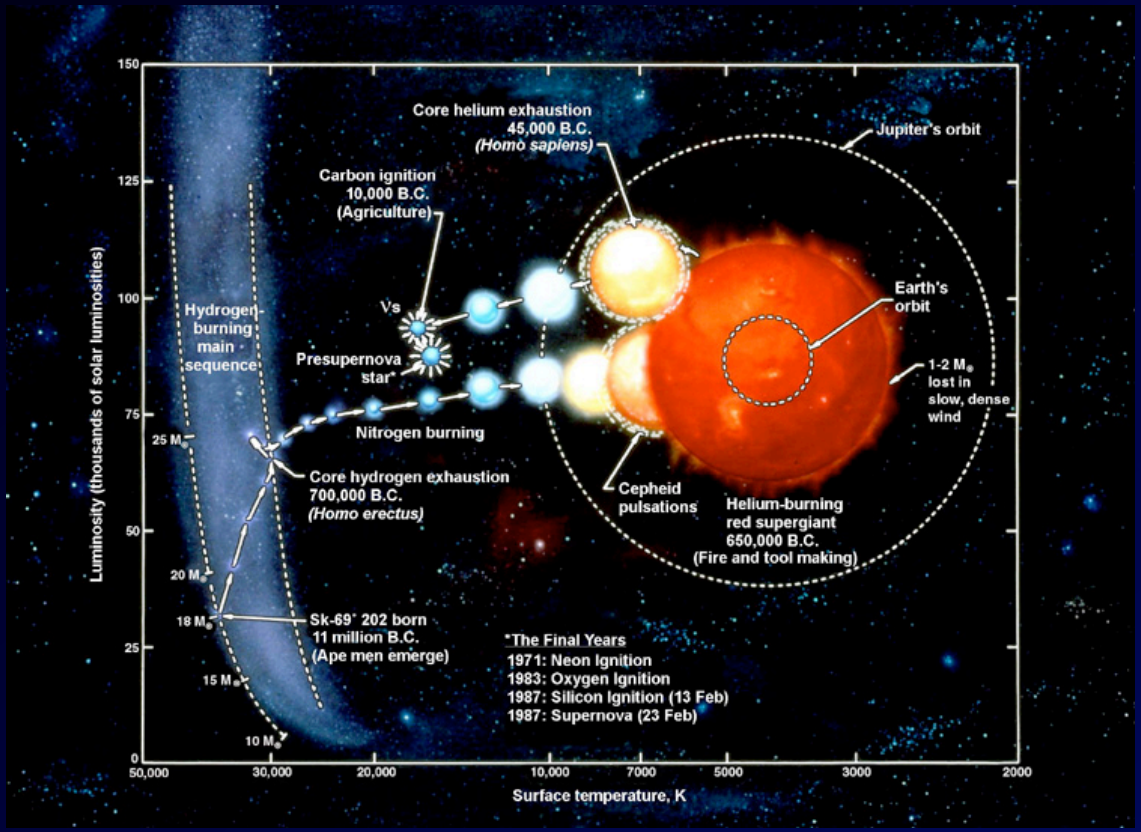

Type Ib/Ic/II: Core collapse at completion of the burning stages of an individual star with $M > 8\ M_\odot$; tiny fraction of released gravitational energy transferred to envelope

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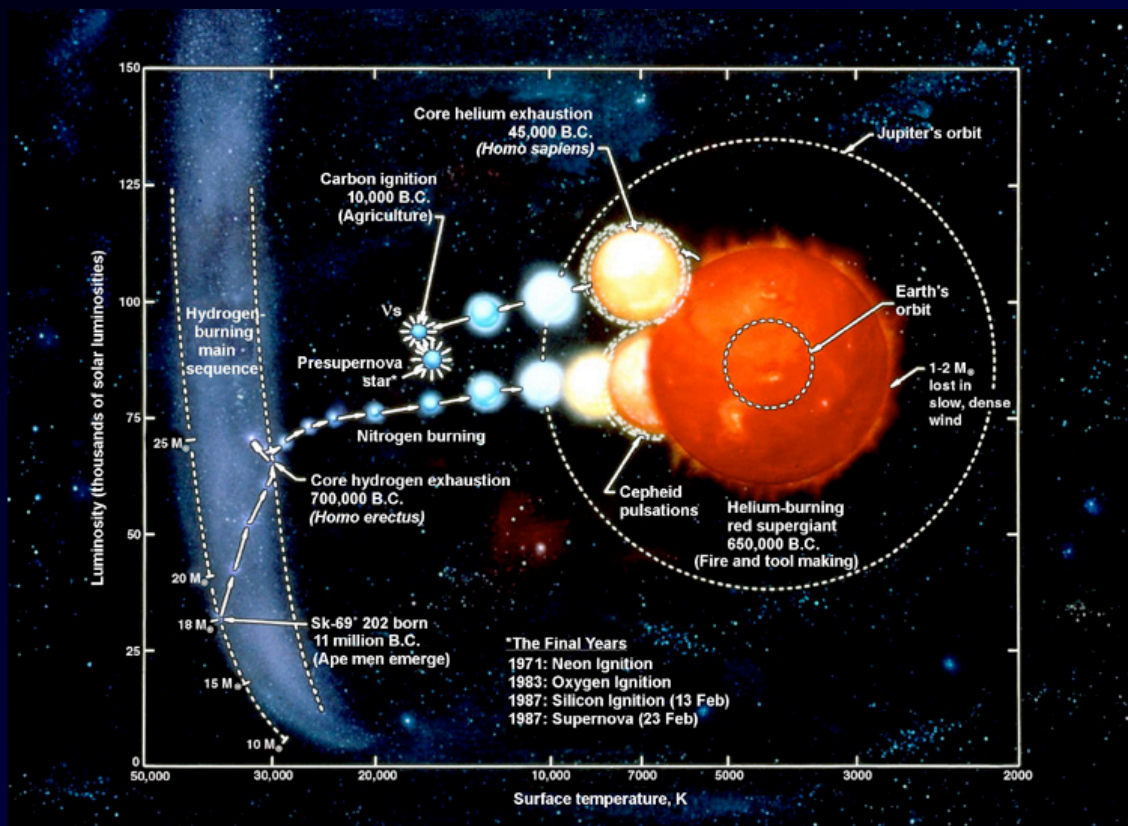

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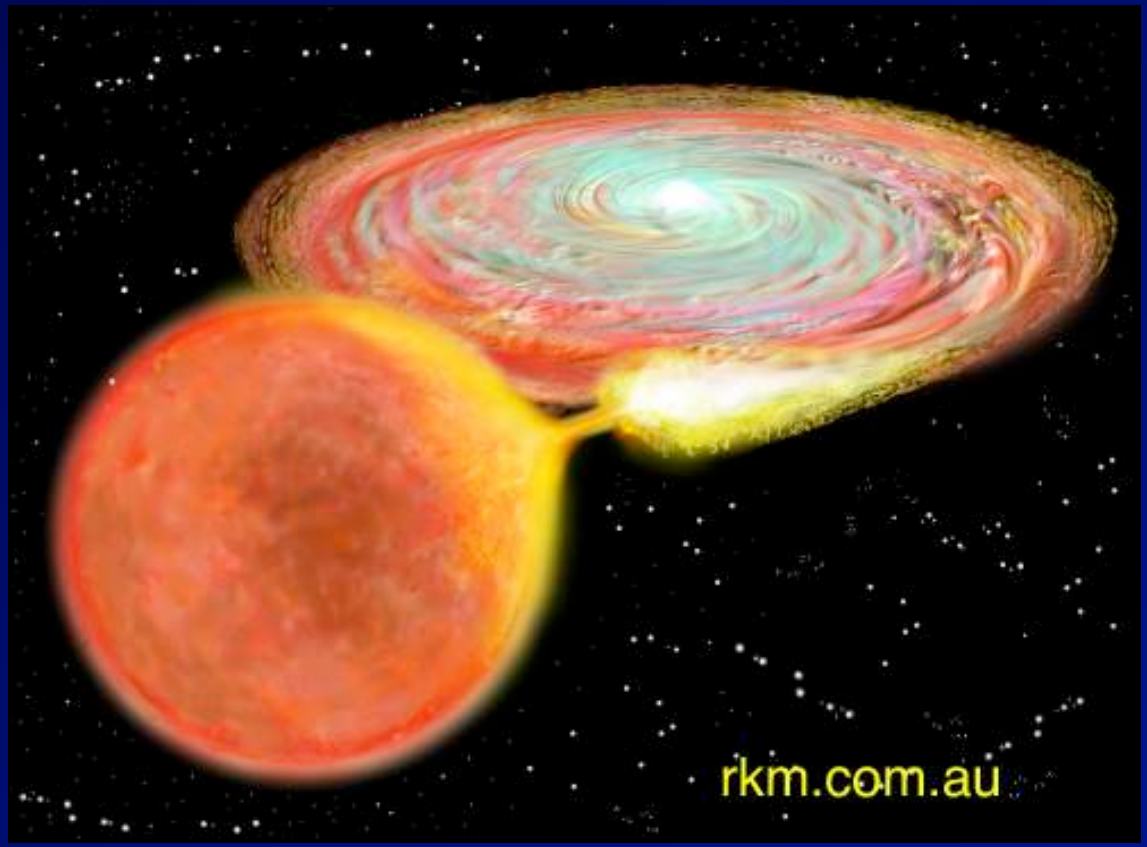

Type Ia: Thermonuclear explosion that consumes an entire white dwarf (remnant of a star with $M < 8\ M_\odot$), resulting from accretion

Remnants of historical Galactic supernovae support the two scenarios, which occur with comparable frequency.

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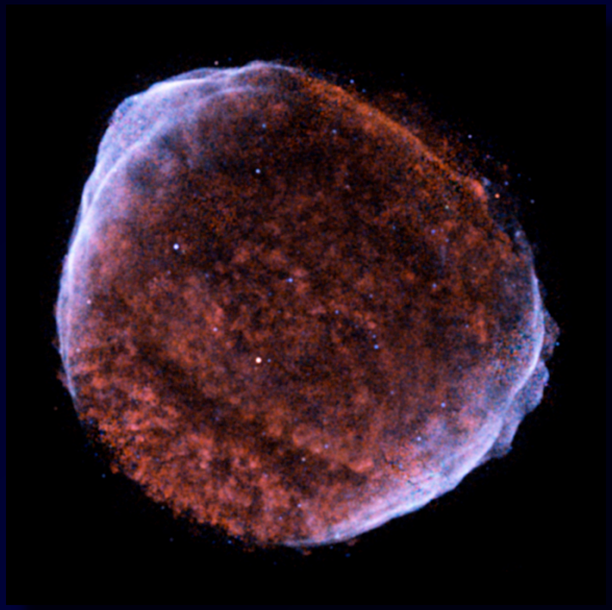
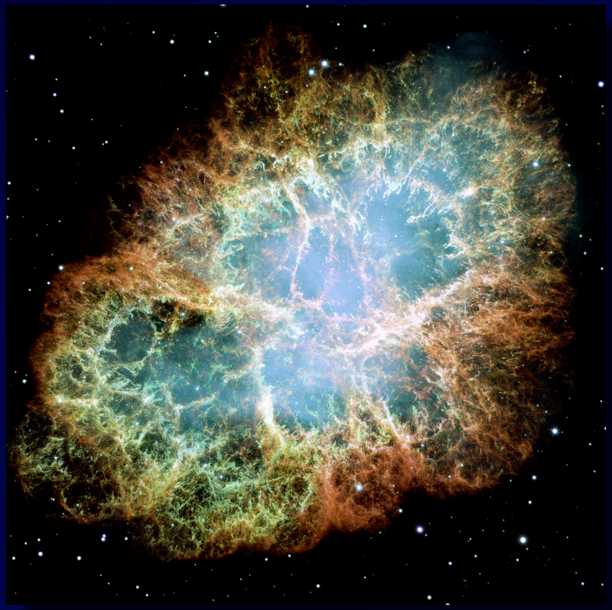
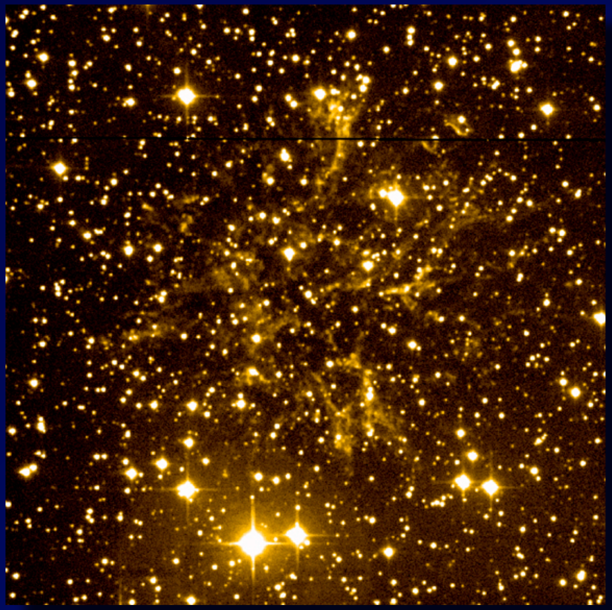


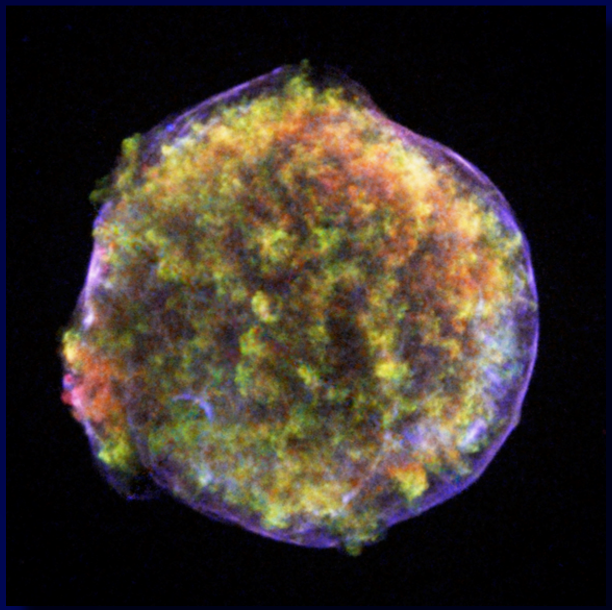
SN 1006 (X-ray) Type Ia



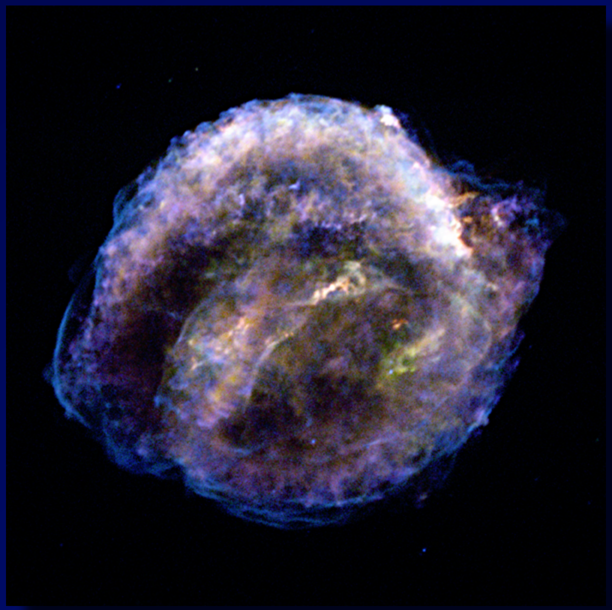
SN 1054 (Optical) Type II



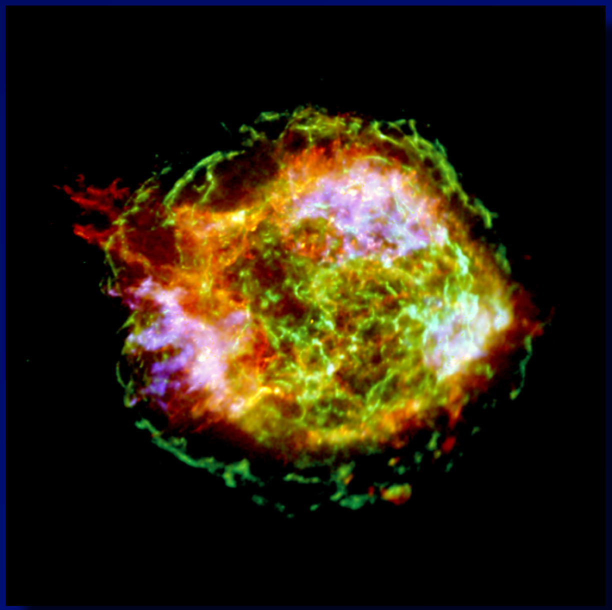
SN 1181 (Optical) Type II



SN 1572 (X-ray) Type Ia



SN 1604 (X-ray) Type Ia



Cas A 1667? (X-ray) Type II

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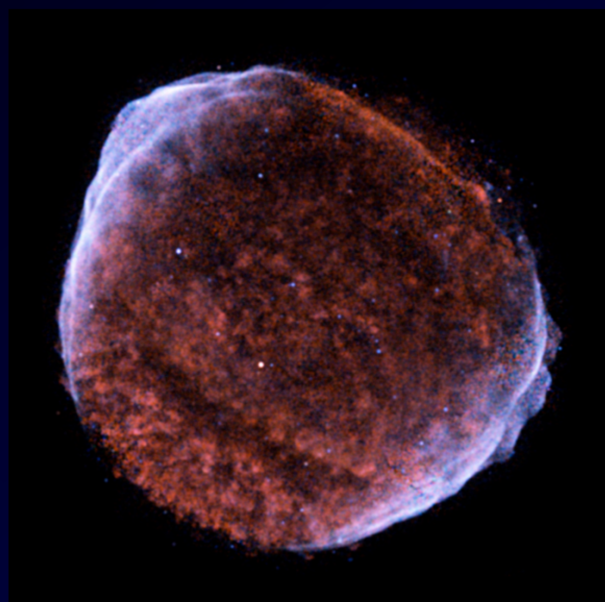

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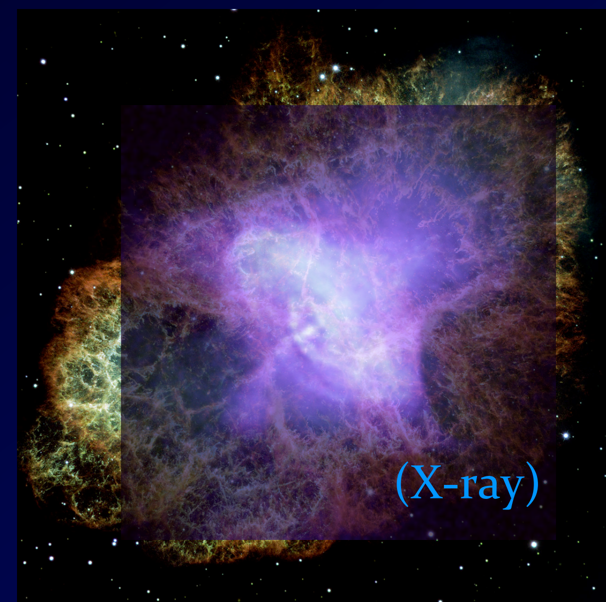

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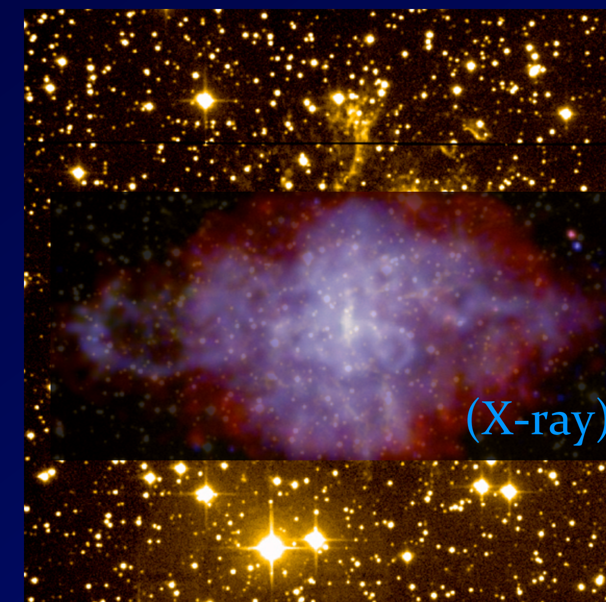

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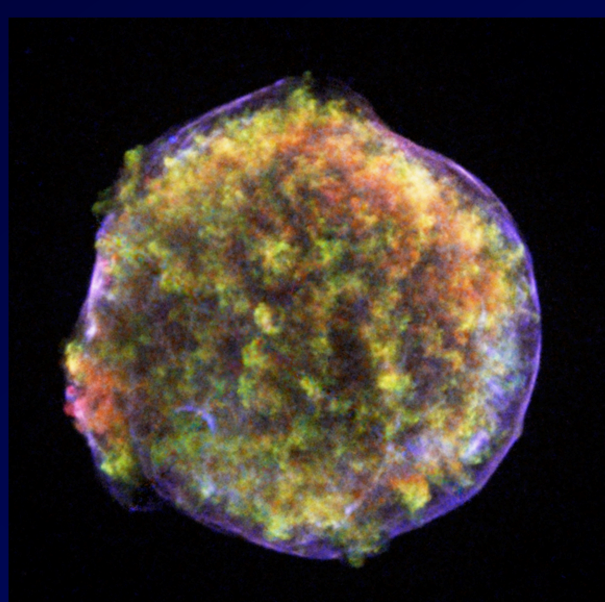

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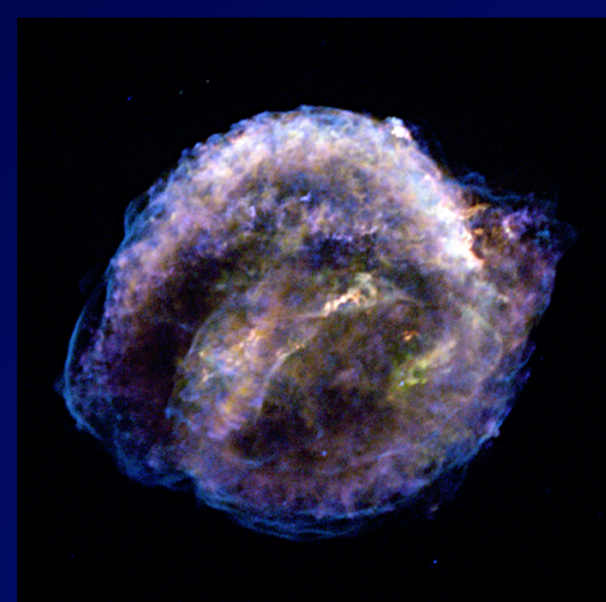

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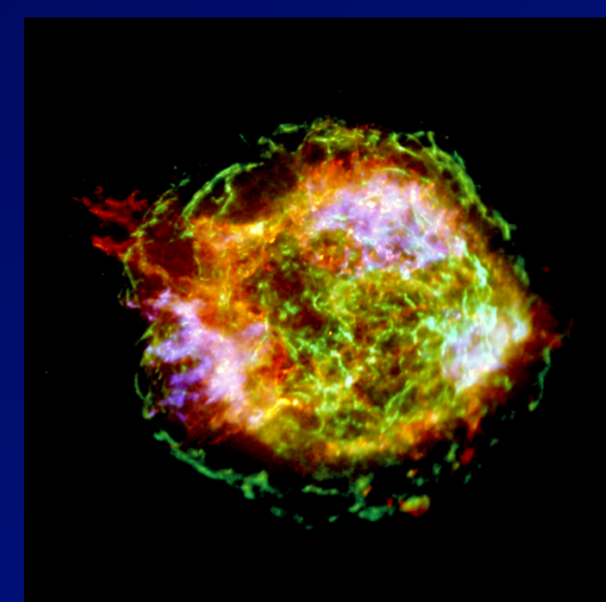

Cas A 1667? (X-ray) Type II

SN 1987A went off in our Galactic neighborhood...

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Tarantula Nebula

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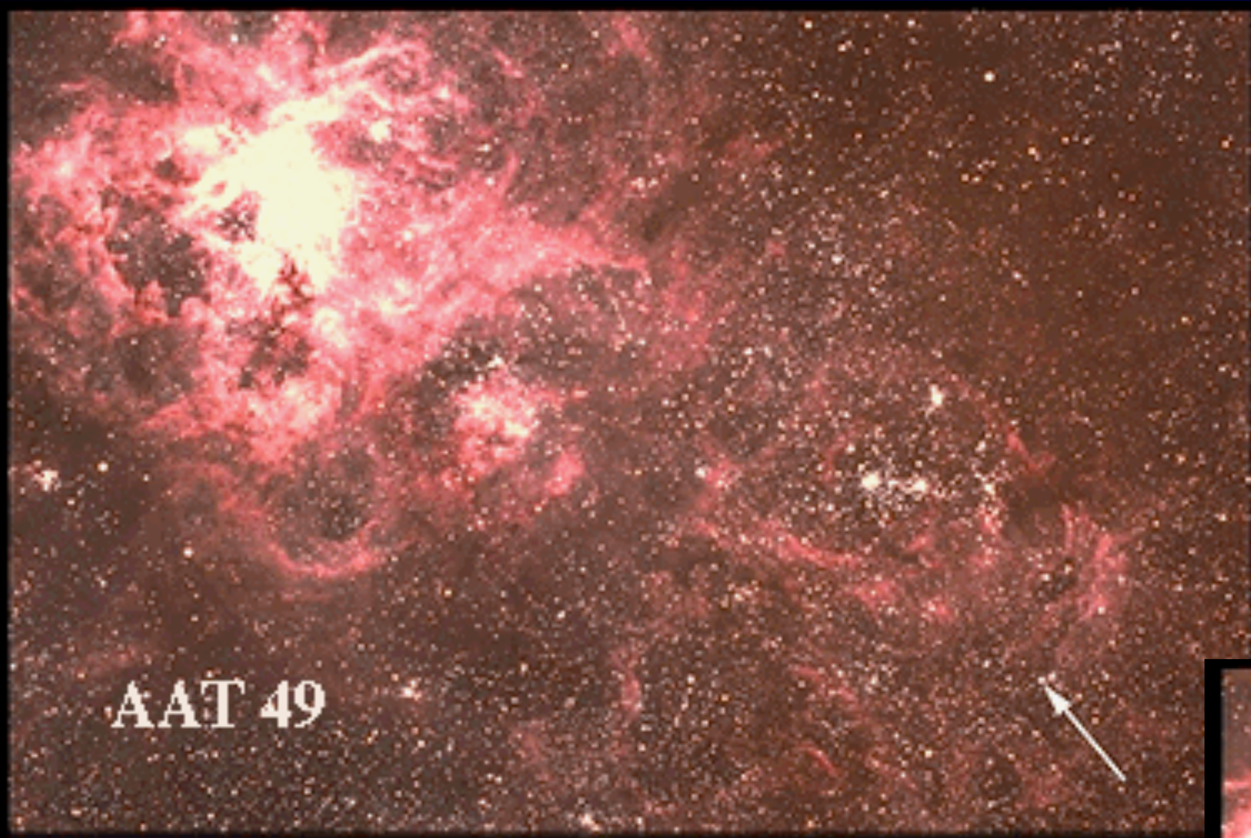

Tarantula Nebula

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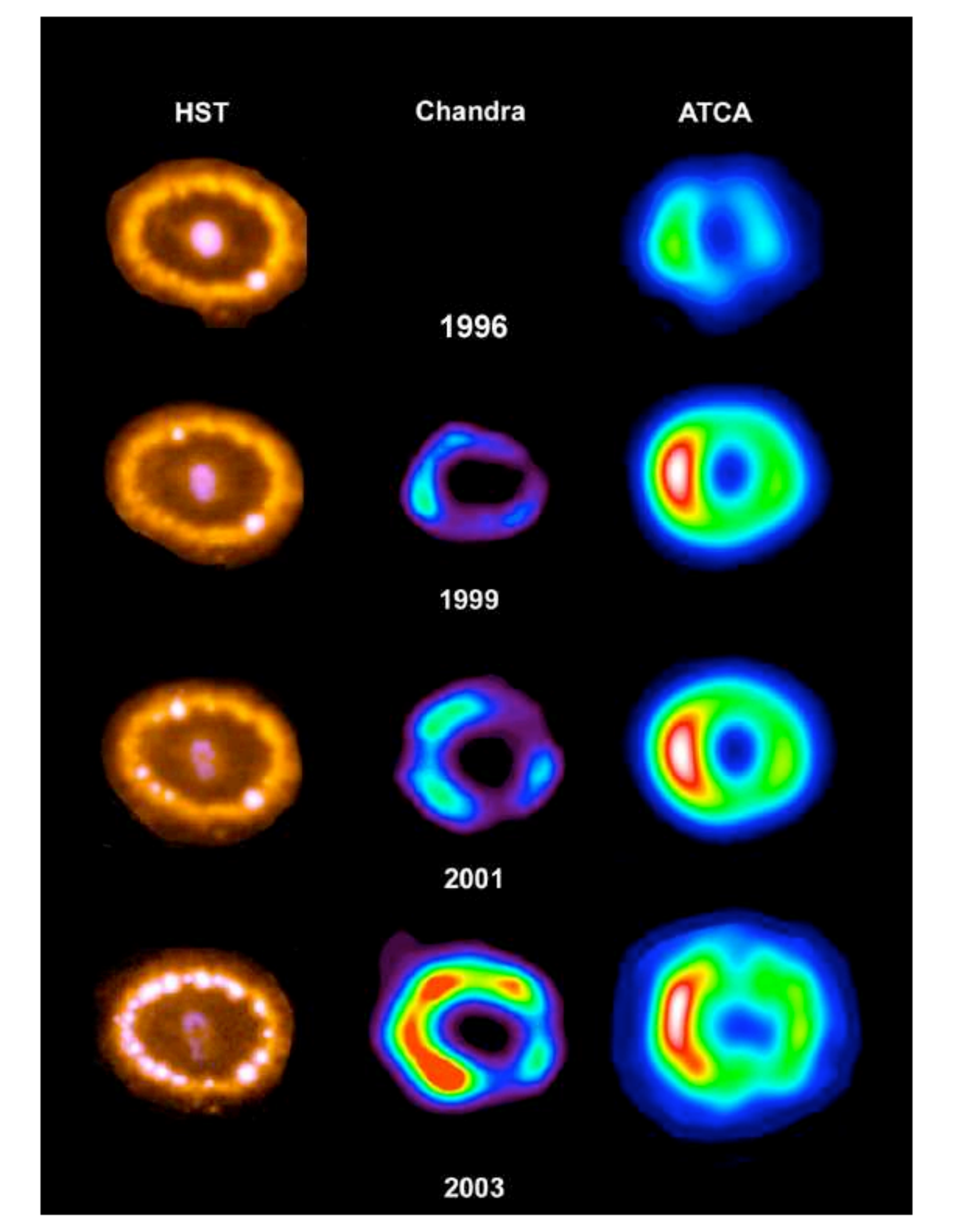

UV/Optical/IR X-ray Radio

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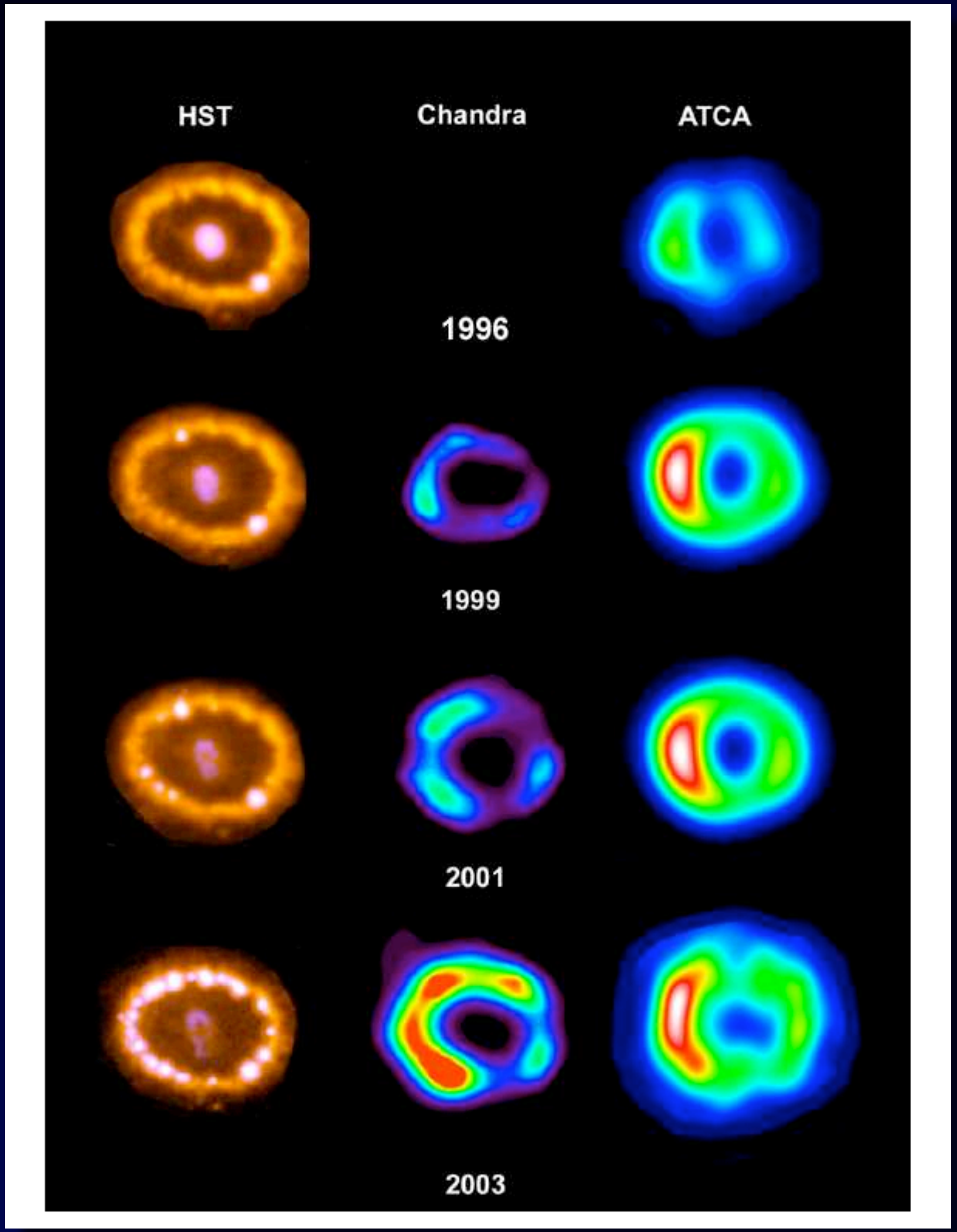
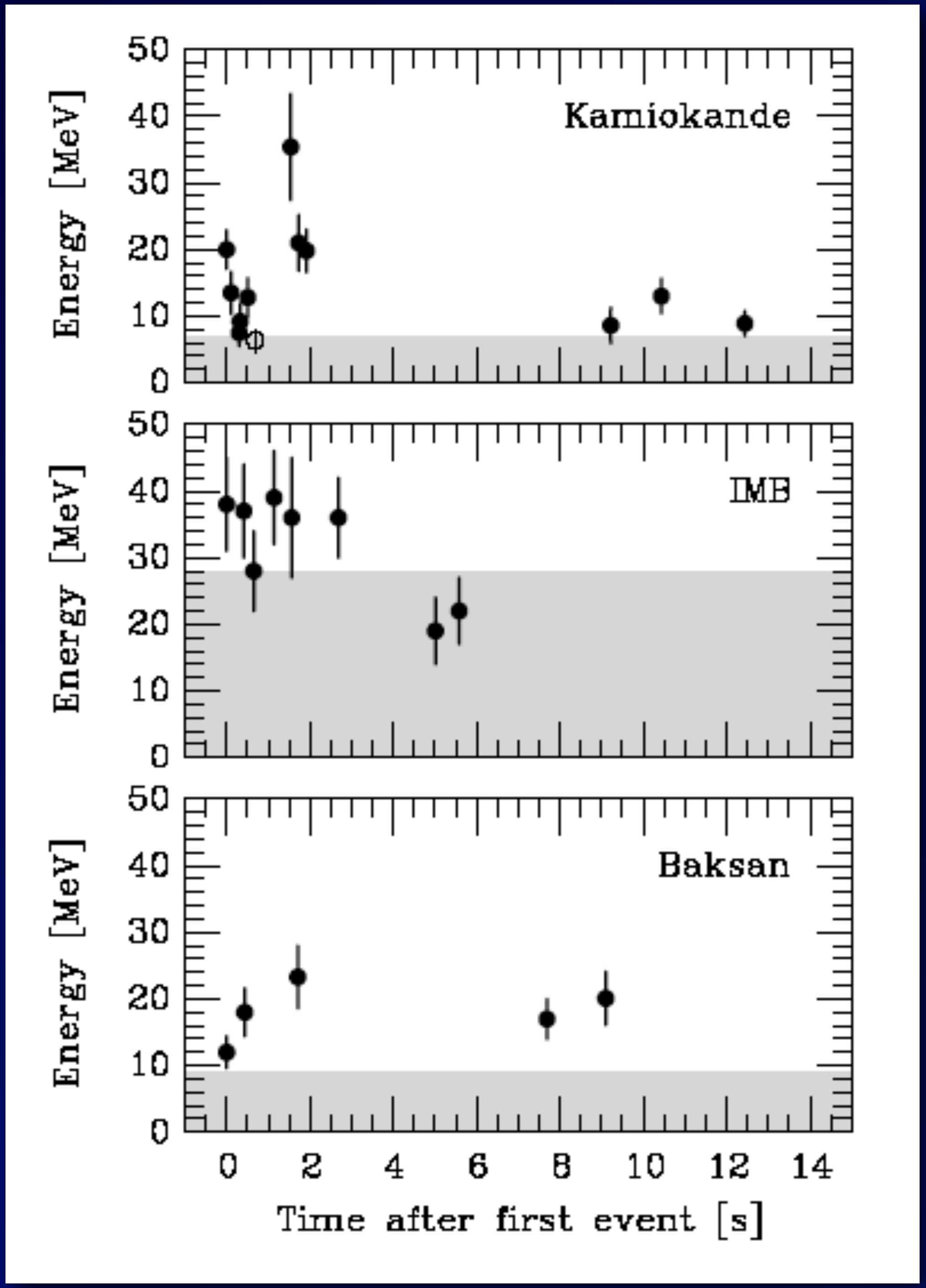


UV/Optical/IR X-ray Radio



Raffelt

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Core-collapse supernova

Core-collapse supernova

Core-collapse ν extravaganza

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

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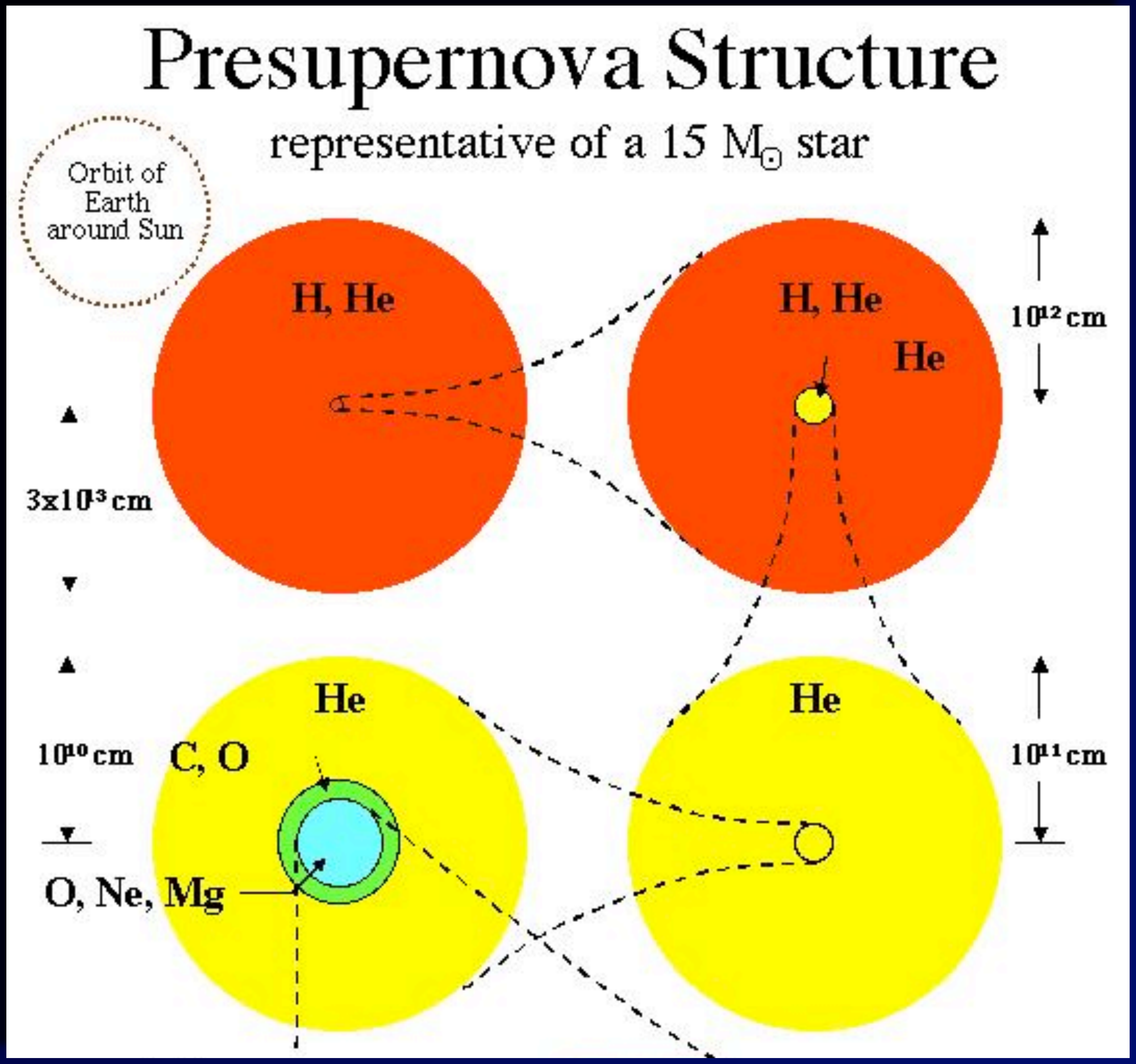
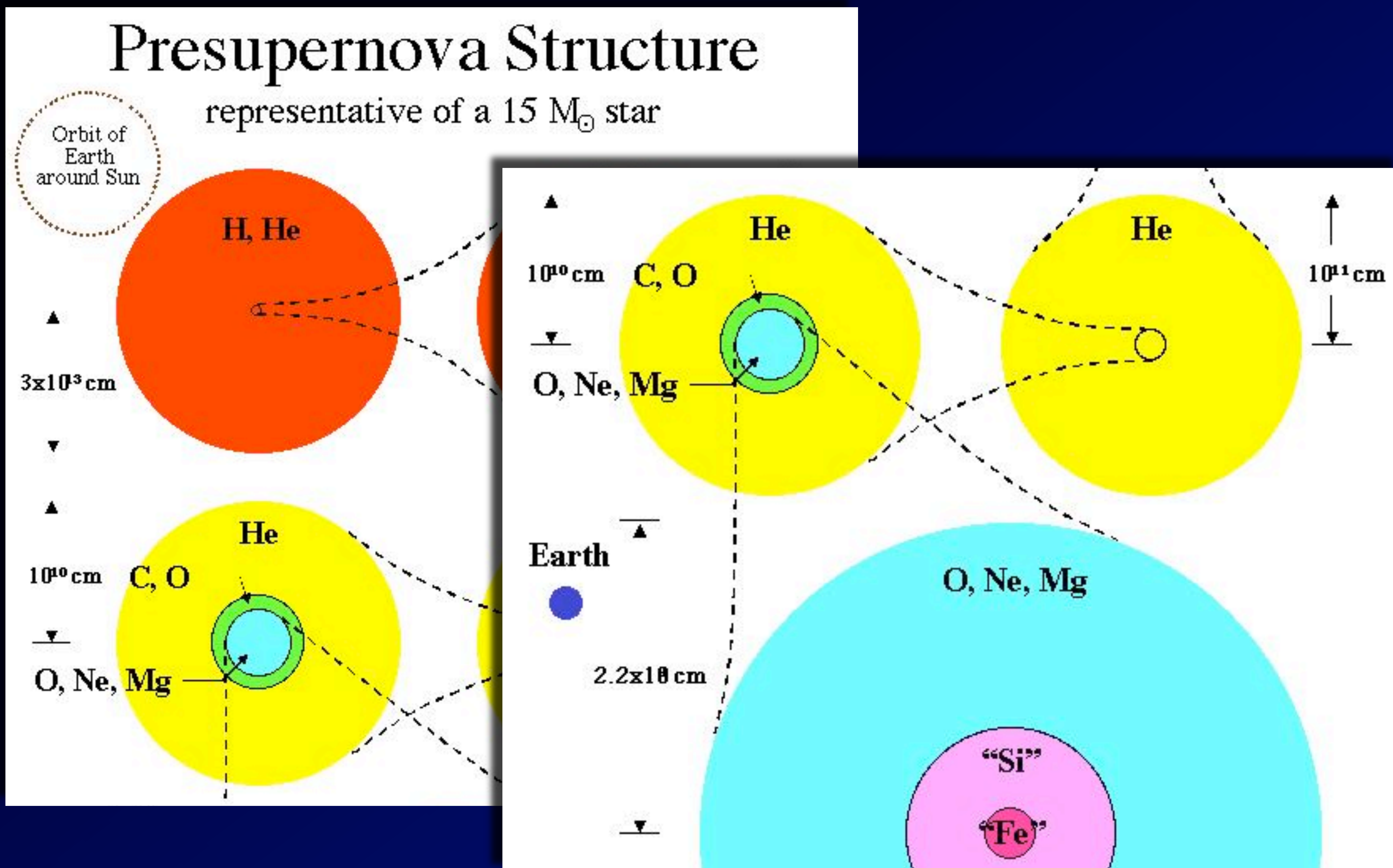


A massive star develops a degenerate core, which can only get so big…



Core-collapse supernova

Core-collapse ν extravaganza

Core-collapse supernova

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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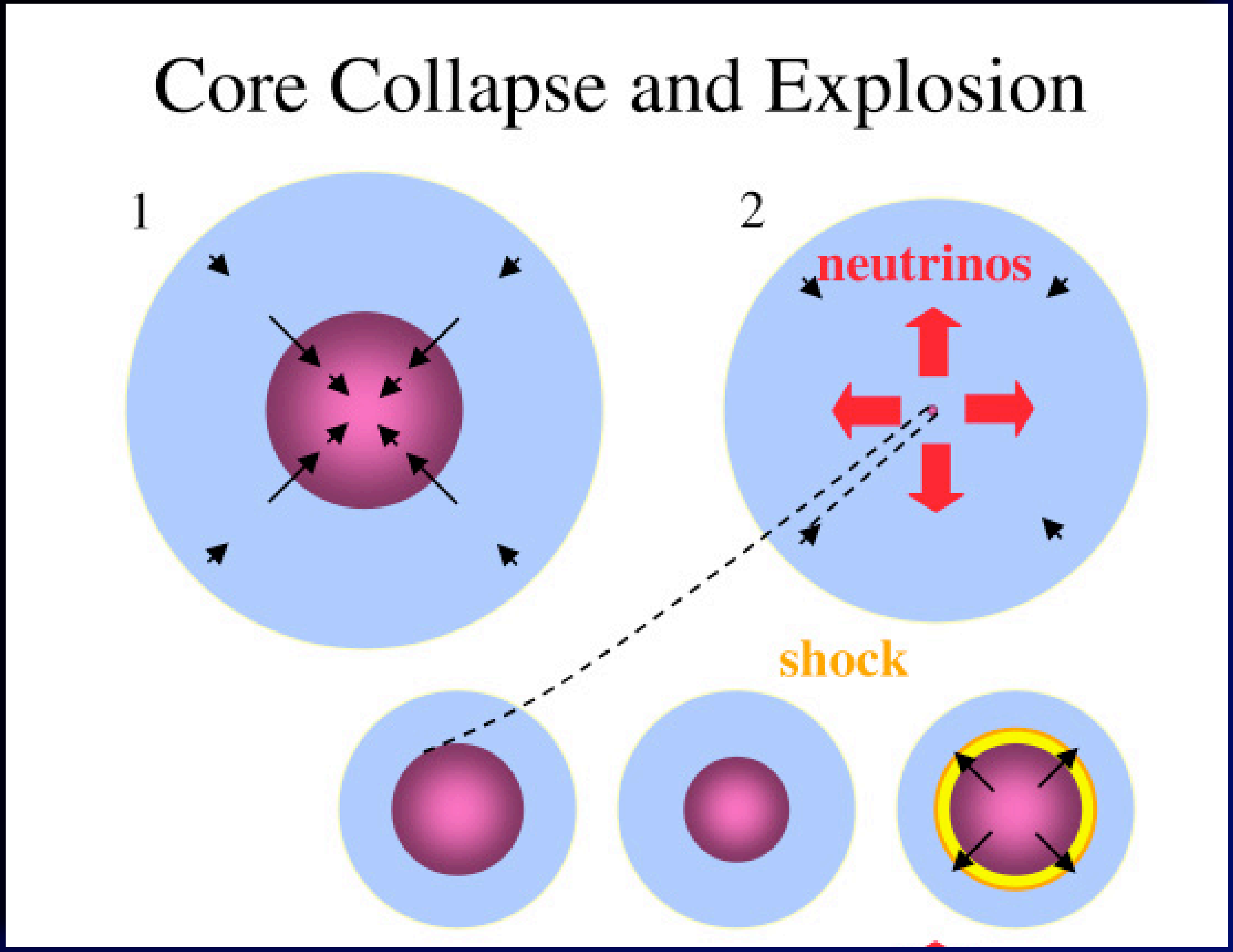


Core-collapse supernova

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

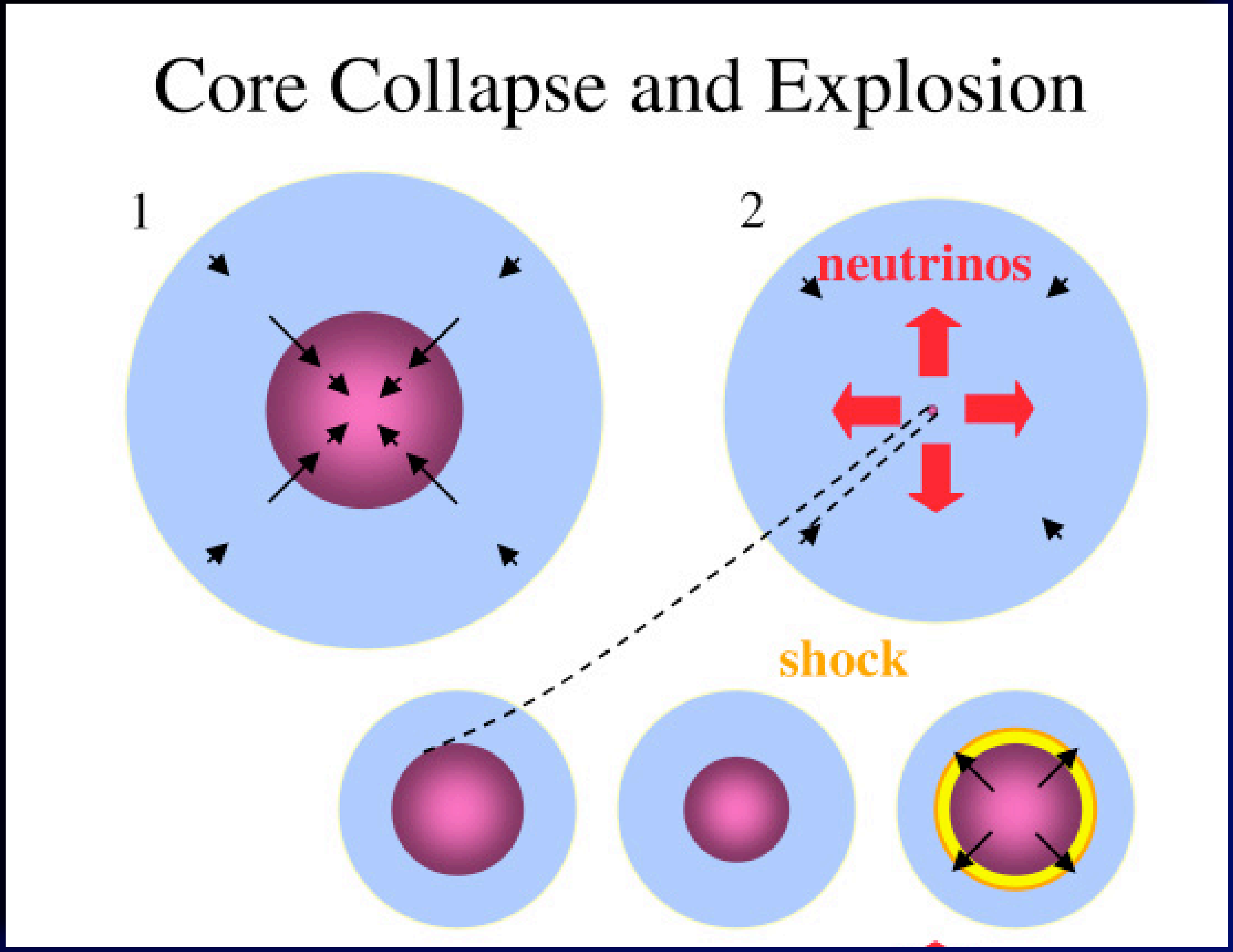
Core-collapse supernova

- Massive stellar progenitor
- Infall

Core-collapse ν extravaganza

- e^- degeneracy, ν pair emission
- 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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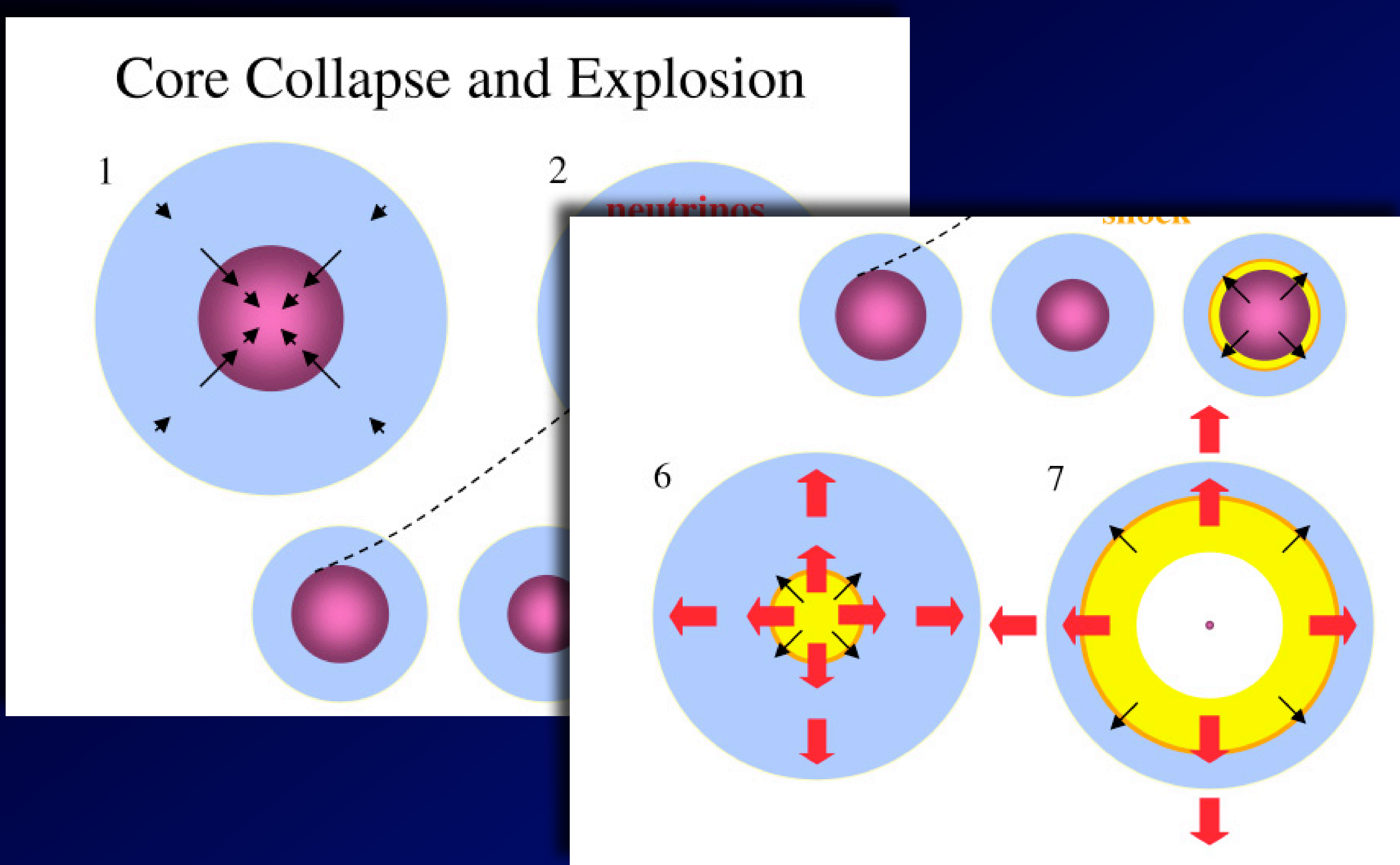

Core-collapse supernova

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

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Bounce; shock formation, stall, and revival

- Neutron star kick
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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

Massive stellar progenitor

Infall

Bounce; shock formation, stall, and revival

- Neutron star kick
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Core-collapse ν extravaganza

e^- degeneracy, ν pair emission

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ν emission weakens shock, ν absorption strengthens it

- ν_e burst at shock breakout

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

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

Core-collapse ν extravaganza

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Deleptonization and energy release via ν emission

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Deleptonization and energy release via ν emission

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

Core-collapse supernova	Core-collapse ν extravaganza
Massive stellar progenitor	e^- degeneracy, ν pair emission
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Bounce; shock formation, stall, and revival	ν emission weakens shock, ν absorption strengthens it
Neutron star kick	ν_e burst at shock breakout
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Kelvin-Helmholtz contraction, then cooling of neutron star	Deleptonization and energy release via ν emission
	e^- capture / ν_e emission
	ν pair emission
(If rapid rotation: accretion disk and jet formation)	

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

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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
	ν pair emission
(If rapid rotation: accretion disk and jet formation)	(ν pair annihilation helps power jet?)
(If H/He envelope lost, i.e. if Type Ib/Ic: Gamma-ray burst)	

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Massive stellar progenitor	e^- degeneracy, ν pair emission
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(If rapid rotation: accretion disk and jet formation)	(ν pair annihilation helps power jet?)
(If H/He envelope lost, i.e. if Type Ib/Ic: Gamma-ray burst)	(ν emission from accretion disk)

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

$\lesssim$ 1% of total energy release

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)

Core-collapse supernova	Core-collapse ν extravaganza
Massive stellar progenitor	e^- degeneracy, ν pair emission
Infall	e^- capture / ν_e emission
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Kelvin-Helmholtz contraction, then cooling of neutron star	Deleptonization and energy release via ν emission
	e^- capture / ν_e emission
	ν pair emission
(If rapid rotation: accretion disk and jet formation)	(ν pair annihilation helps power jet?)
(If H/He envelope lost, i.e. if Type Ib/Ic: Gamma-ray burst)	(ν emission from accretion disk)

$\lesssim$ 10% of total energy release

Core-collapse supernova	Core-collapse ν extravaganza
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Infall	e^- capture / ν_e emission
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Kelvin-Helmholtz contraction, then cooling of neutron star	Deleptonization and energy release via ν emission
	e^- capture / ν_e emission
	ν pair emission
(If rapid rotation: accretion disk and jet formation)	(ν pair annihilation helps power jet?)
(If H/He envelope lost, i.e. if Type Ib/Ic: Gamma-ray burst)	(ν emission from accretion disk)

~90% of total energy release

Core-collapse supernova

Core-collapse ν extravaganza

Core-collapse supernova

Explosive nucleosynthesis,
r-process nucleosynthesis

Core-collapse ν extravaganza

Core-collapse supernova

Core-collapse ν extravaganza

Explosive nucleosynthesis,
r-process nucleosynthesis

- Enrichment of ISM

Core-collapse supernova

Explosive nucleosynthesis,
r-process nucleosynthesis

Enrichment of ISM

Core-collapse ν extravaganza

ν absorption affects outcomes

Core-collapse supernova

Explosive nucleosynthesis,
r-process nucleosynthesis

- Enrichment of ISM

Supernova remnant expansion

Core-collapse ν extravaganza

ν absorption affects outcomes

Core-collapse supernova

Explosive nucleosynthesis,
r-process nucleosynthesis

- Enrichment of ISM

Supernova remnant expansion

- Optical emission powered by recombination, radioactive decay, pulsar spin-down; light curves, spectra, spectropolarimetry

Core-collapse ν extravaganza

ν absorption affects outcomes

Core-collapse supernova

Explosive nucleosynthesis, *r*-process nucleosynthesis

- Enrichment of ISM

Supernova remnant expansion

- Optical emission powered by recombination, radioactive decay, pulsar spin-down; light curves, spectra, spectropolarimetry
- Radio synchrotron emission

Core-collapse ν extravaganza

ν absorption affects outcomes

Core-collapse supernova

Explosive nucleosynthesis, *r*-process nucleosynthesis

- Enrichment of ISM

Supernova remnant expansion

- Optical emission powered by recombination, radioactive decay, pulsar spin-down; light curves, spectra, spectropolarimetry
- Radio synchrotron emission
- X-ray synchrotron, thermal and line emission

Core-collapse ν extravaganza

ν absorption affects outcomes

Core-collapse supernova

- Explosive nucleosynthesis, *r*-process nucleosynthesis
  - Enrichment of ISM
- Supernova remnant expansion
  - Optical emission powered by recombination, radioactive decay, pulsar spin-down; light curves, spectra, spectropolarimetry
  - Radio synchrotron emission
  - X-ray synchrotron, thermal and line emission
  - Acceleration of cosmic rays, high-energy photons

Core-collapse ν extravaganza

- ν absorption affects outcomes

Core-collapse supernova

Explosive nucleosynthesis, *r*-process nucleosynthesis

- Enrichment of ISM

Supernova remnant expansion

- Optical emission powered by recombination, radioactive decay, pulsar spin-down; light curves, spectra, spectropolarimetry
- Radio synchrotron emission
- X-ray synchrotron, thermal and line emission
- Acceleration of cosmic rays, high-energy photons

Core-collapse ν extravaganza

ν absorption affects outcomes

π production

Core-collapse supernova

Explosive nucleosynthesis, *r*-process nucleosynthesis

- Enrichment of ISM

Supernova remnant expansion

- Optical emission powered by recombination, radioactive decay, pulsar spin-down; light curves, spectra, spectropolarimetry
- Radio synchrotron emission
- X-ray synchrotron, thermal and line emission
- Acceleration of cosmic rays, high-energy photons

Core-collapse ν extravaganza

ν absorption affects outcomes

π production

- High-energy ν emission from π and μ decay

Core-collapse supernova

Explosive nucleosynthesis,
r-process nucleosynthesis

- Enrichment of ISM

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- Radio synchrotron emission
- X-ray synchrotron, thermal and line emission
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Compact remnant evolution

Core-collapse ν extravaganza

ν absorption affects outcomes

π production

- High-energy ν emission from π and μ decay

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~1% of total energy release

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~0.01% of total energy release

ν emission contributes to long-term cooling

At least five phases of neutrino emission can be identified.

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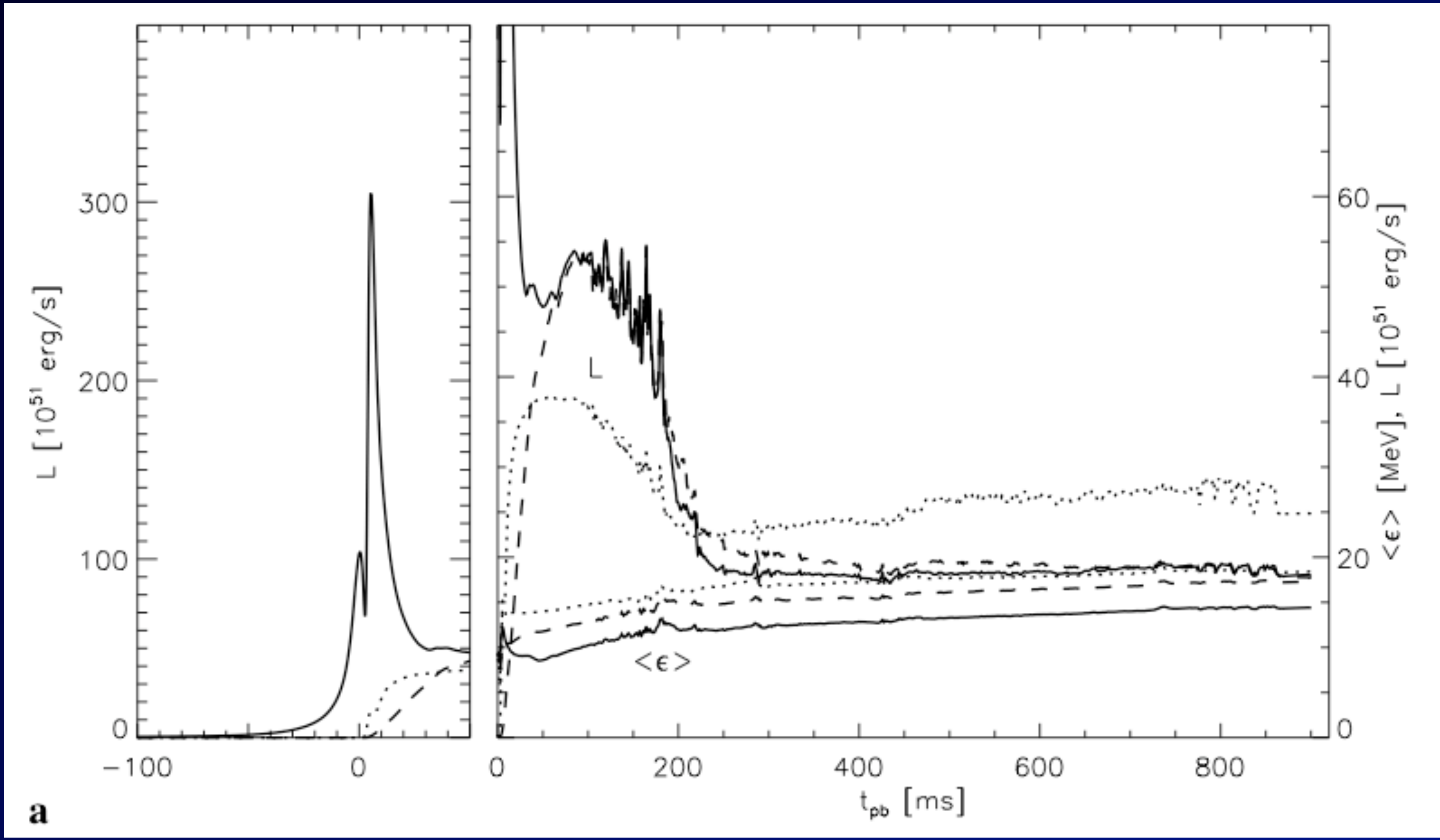

Buras et al. (2005)

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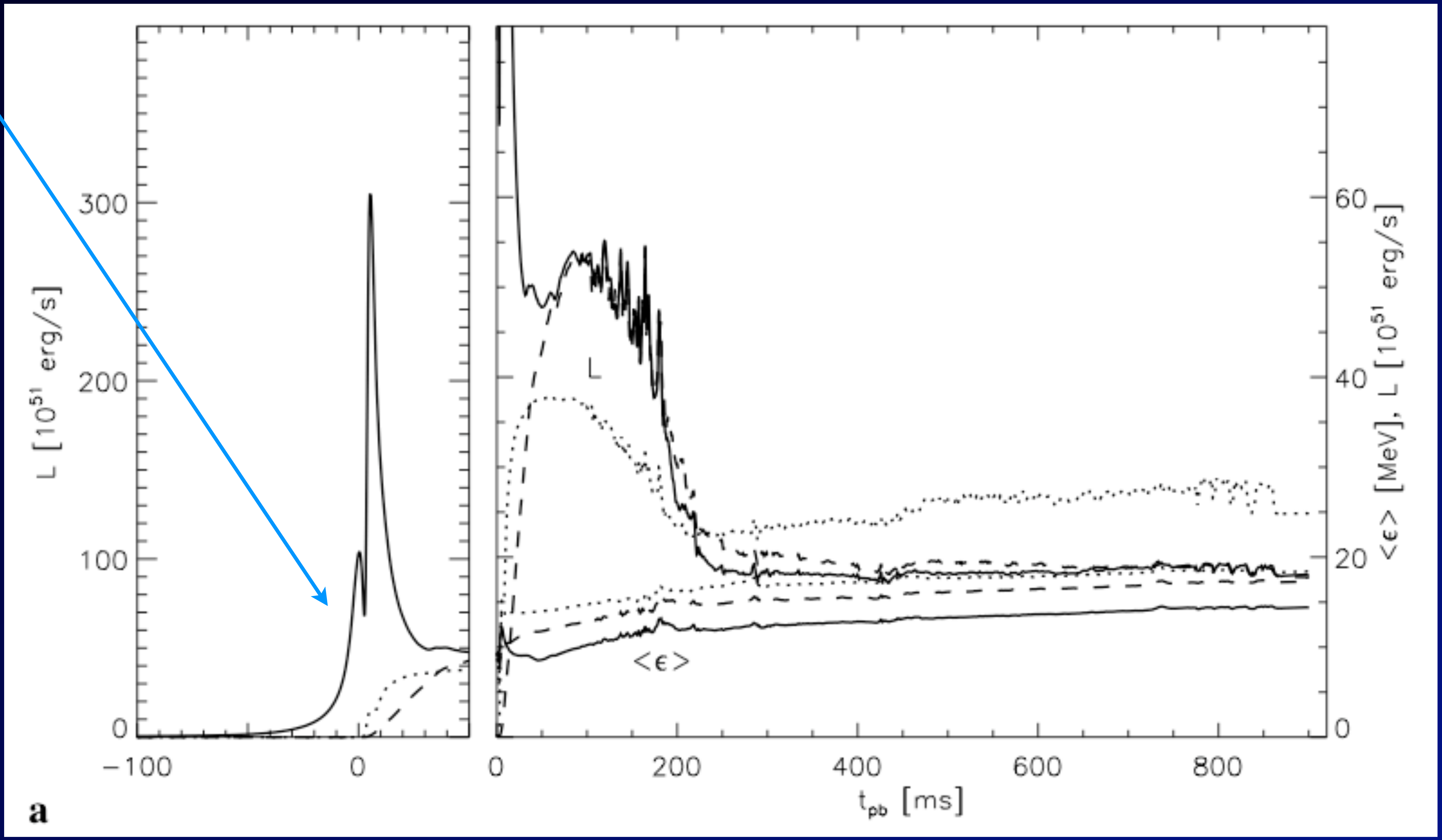

Buras et al. (2005)

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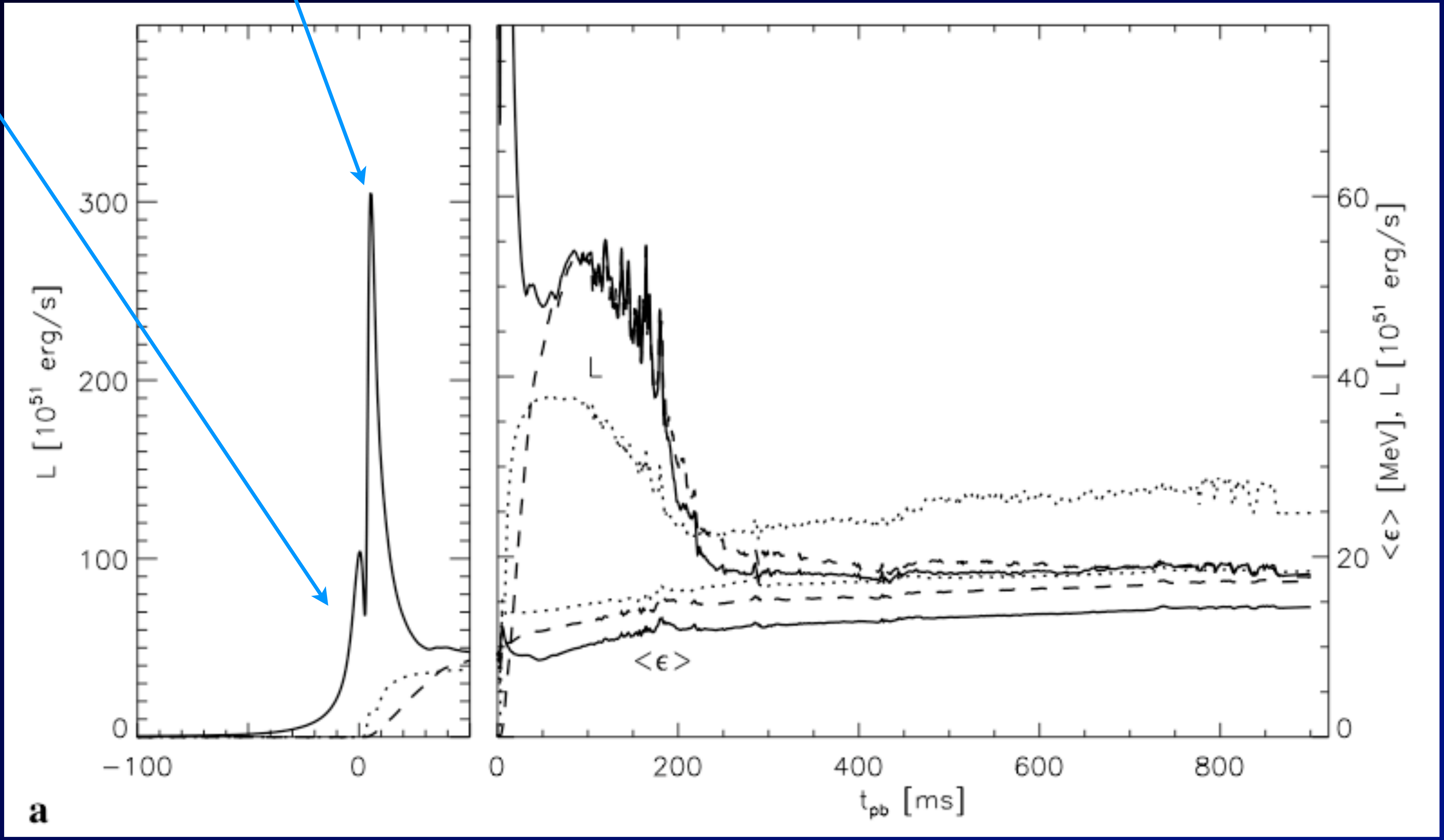

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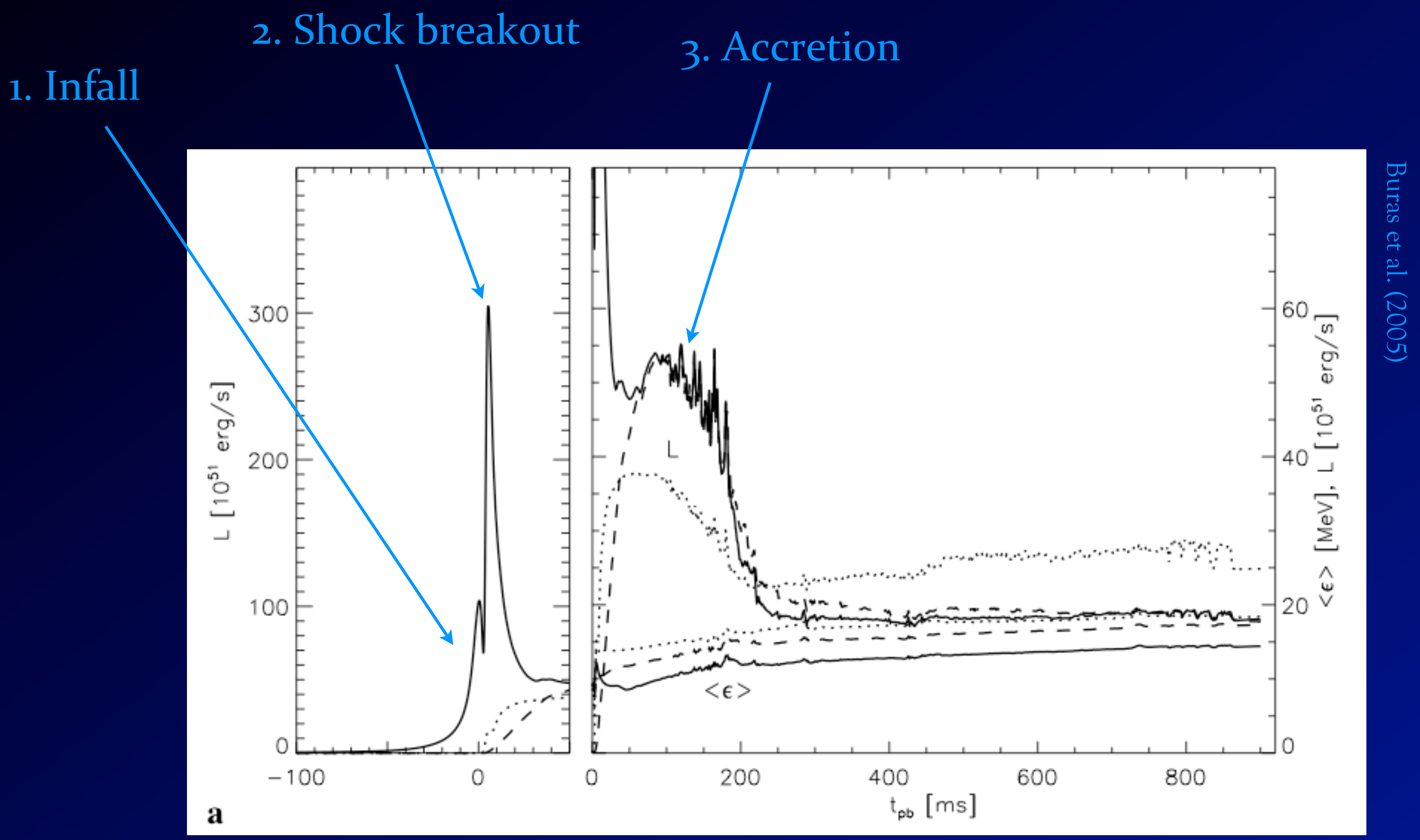

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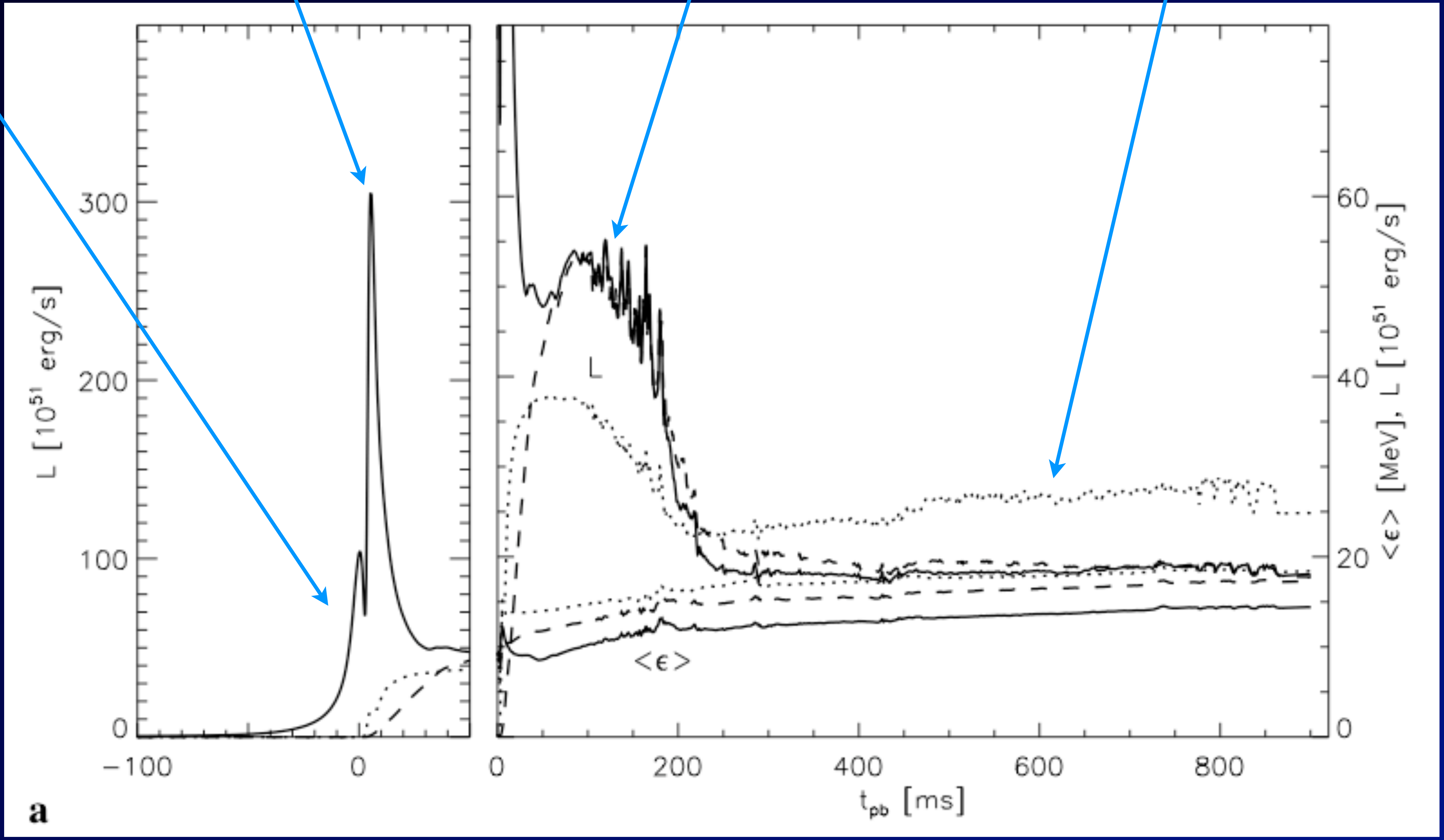

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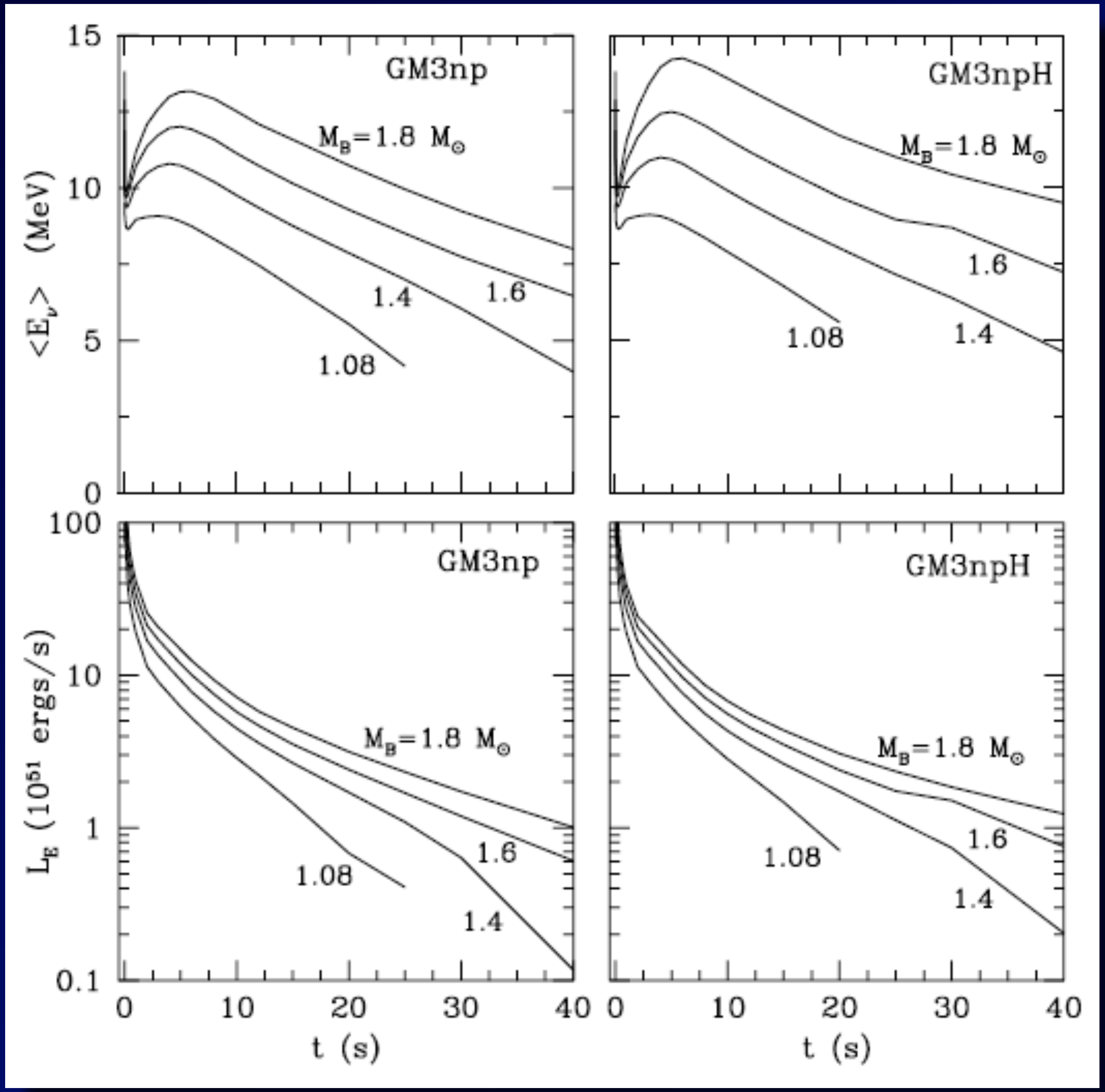

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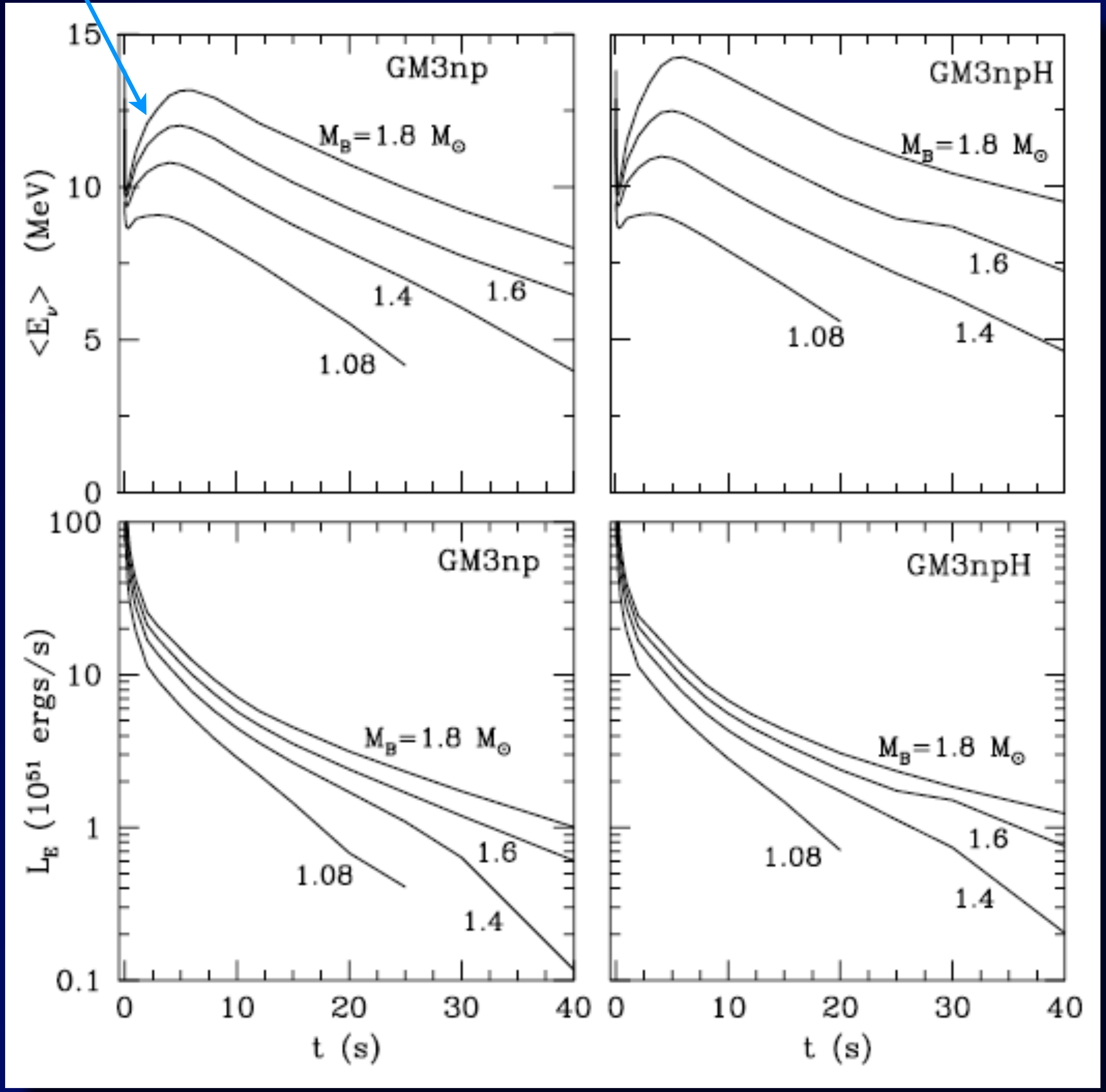

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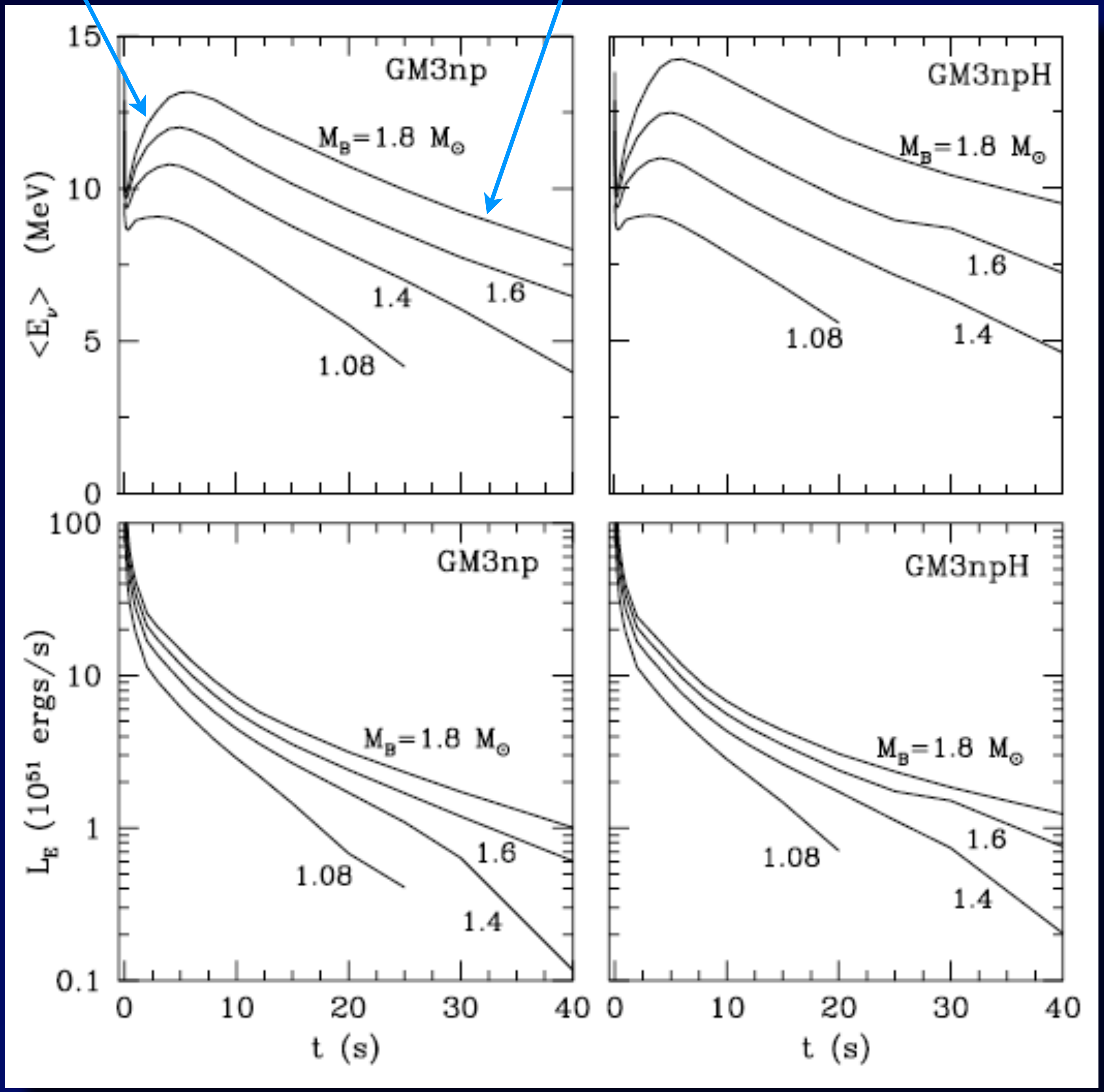

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Elucidation of the explosion mechanism requires detailed simulation.

Introduction

Stellar collapse and its aftermath

Explosion simulations

Conclusion

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Massive stellar progenitor	e^- degeneracy, ν pair emission
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Gravitational waves	ν pair emission from accretion
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(If rapid rotation: accretion disk and jet formation)	(ν pair annihilation helps power jet?)
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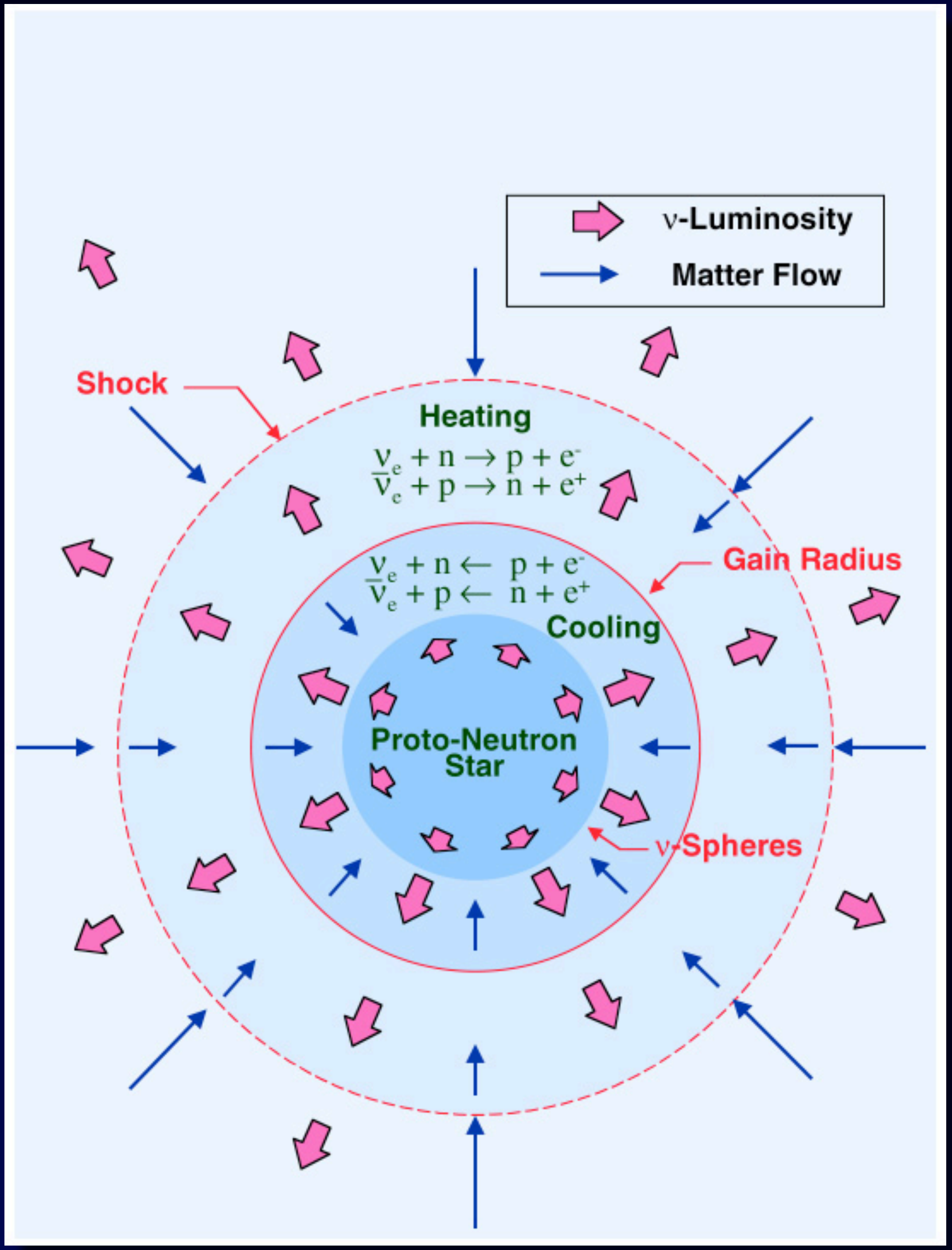

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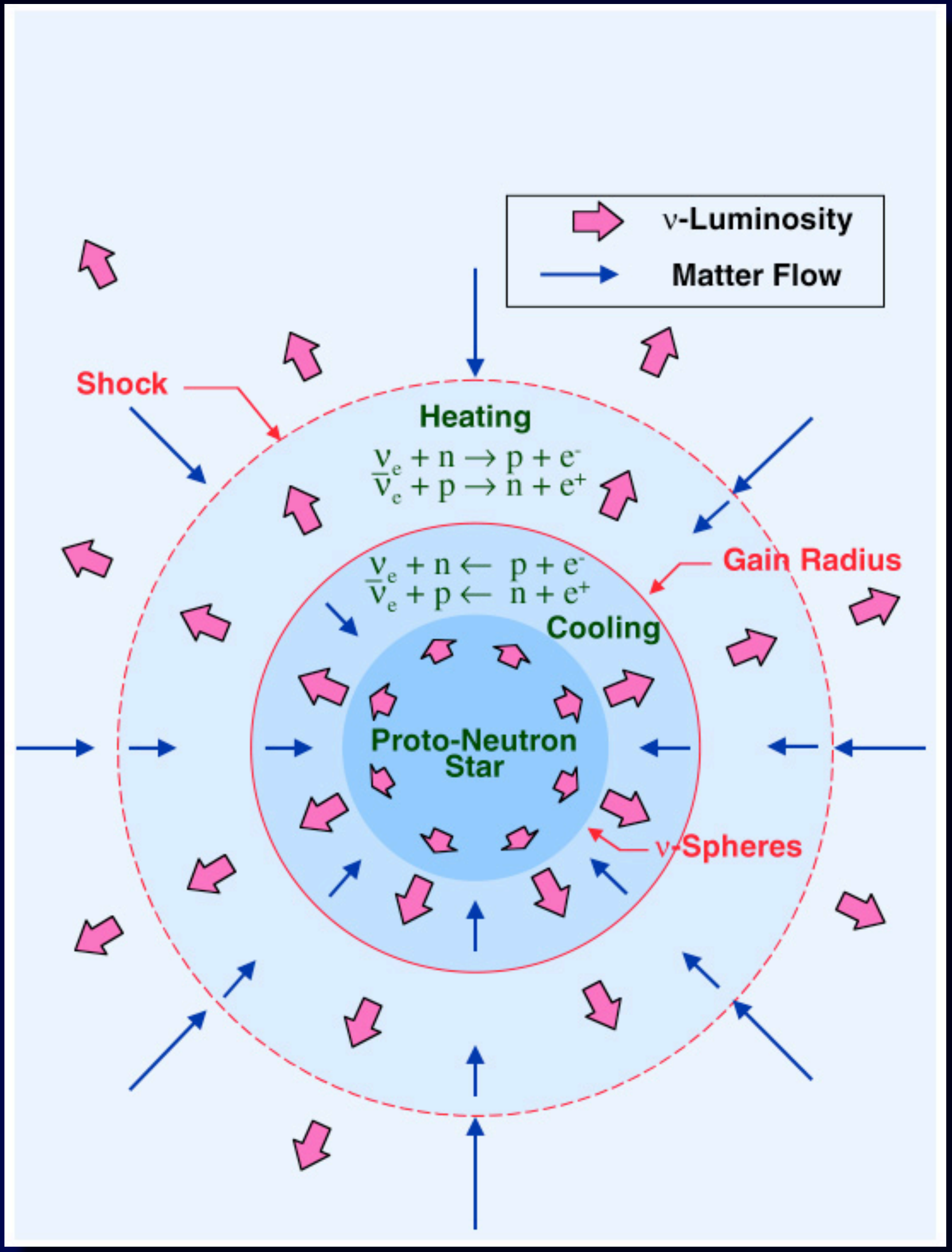

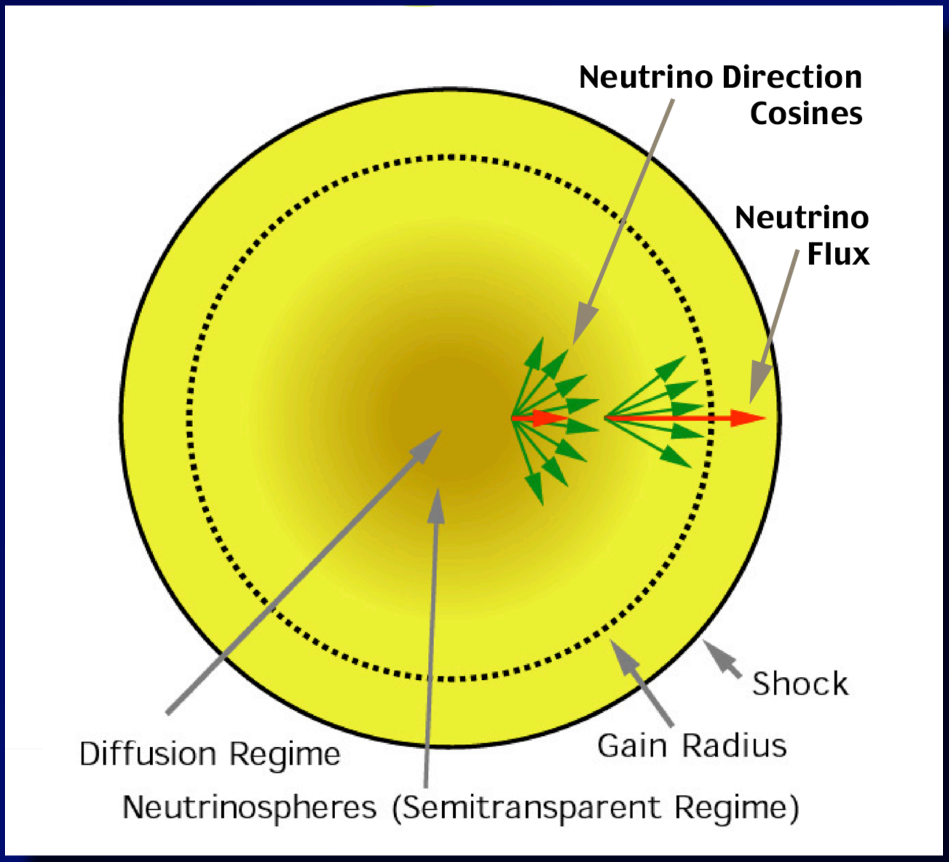

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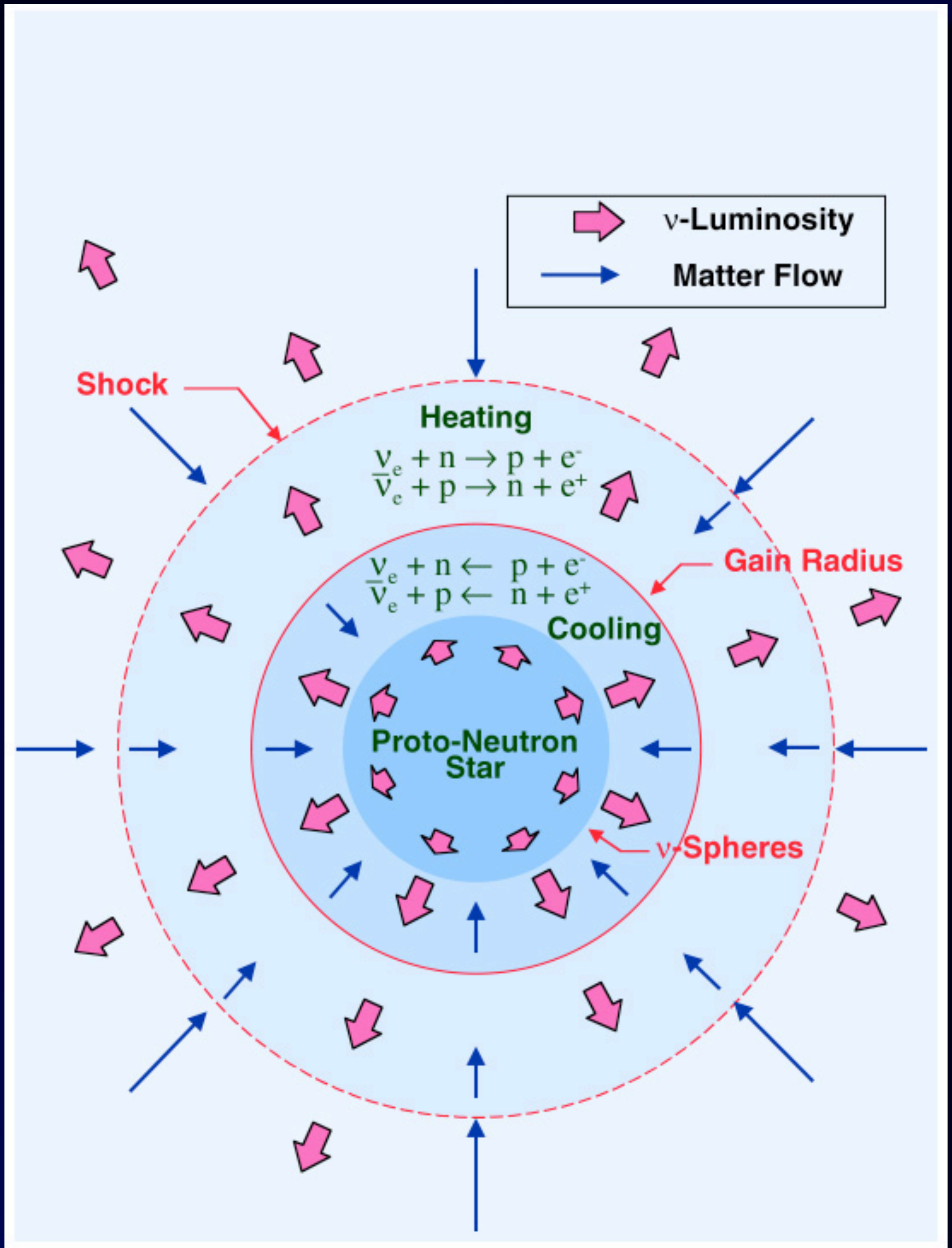
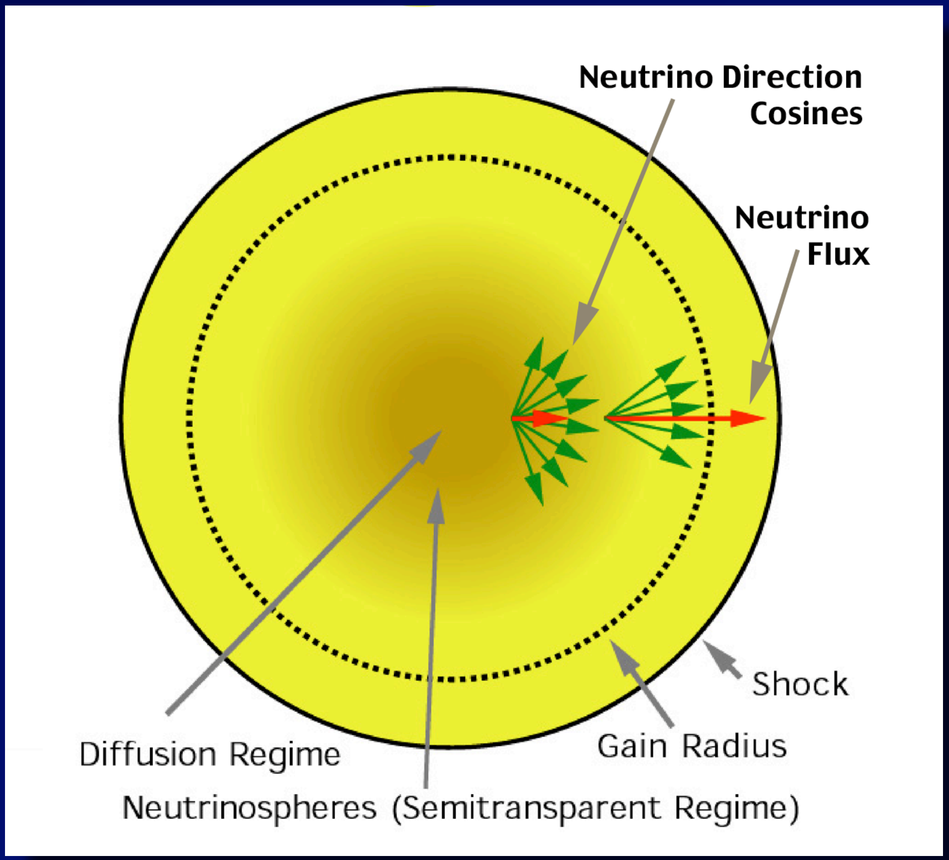


$$f(t, \mathbf{x}, \mathbf{p})$$



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An equation of state that includes bulk nuclear matter 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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Dolgov (1981)
Rudzky (1990)
Barbieri and Dolgov (1991)
Sigl and Raffelt (1993)
McKellar and Thomson (1994)
Qian and Fuller (1995)
Sirera and Perez (1999)
Yamada (2000)
Prakash et al. (2001)
Strack and Burrows (2005)
Cardall (2008)
Cardall (in preparation)

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Use the interaction picture to set up a diagrammatic formalism to handle interactions.

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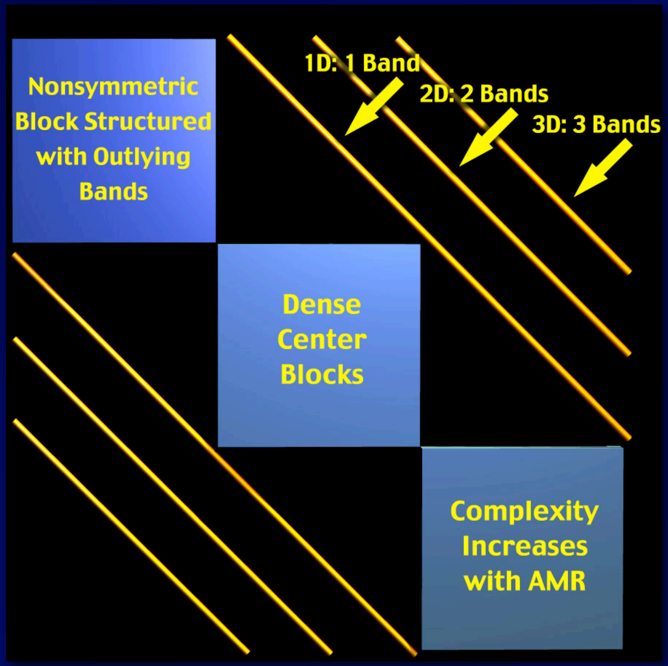
As an example, consider how easily the inversion of dense blocks arising from momentum space coupling can exhaust **exascale** resources.



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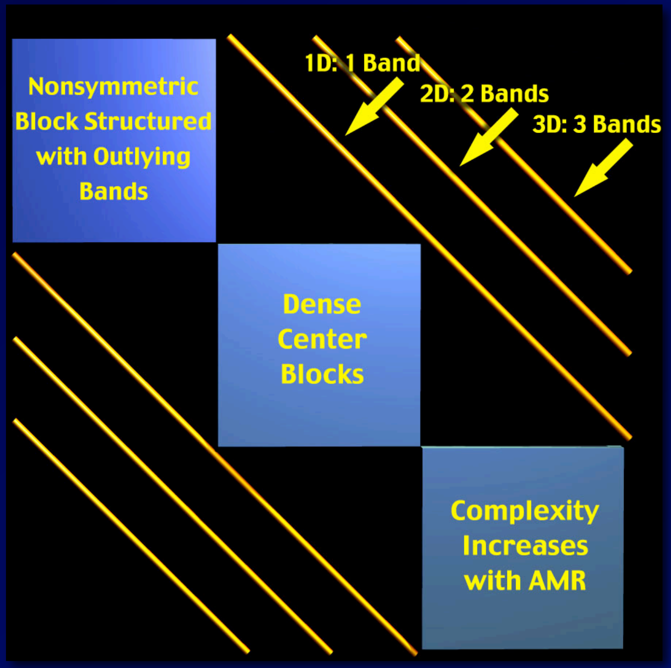

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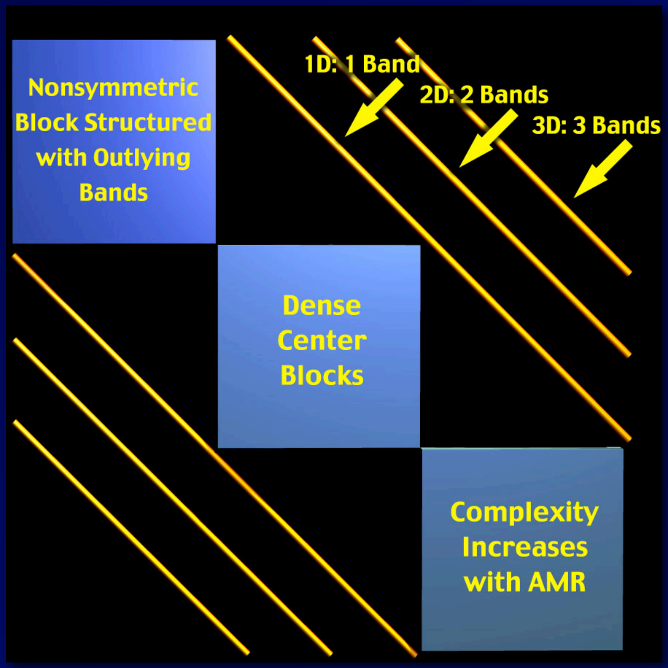

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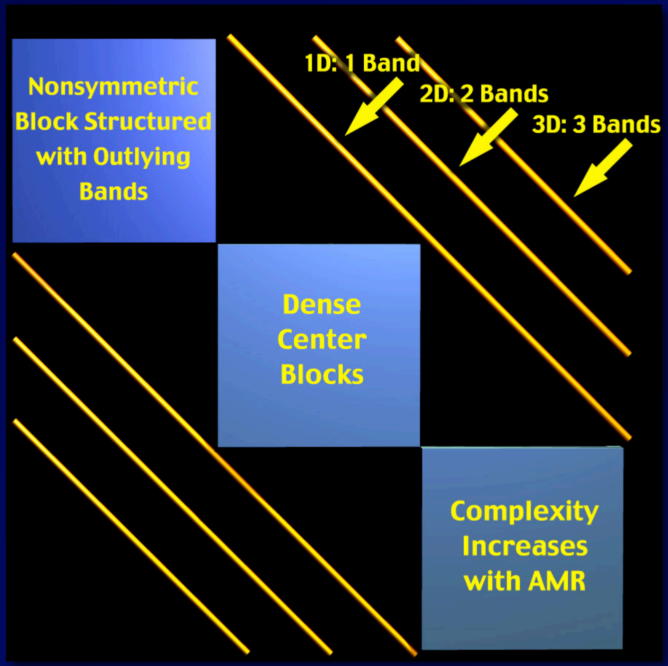

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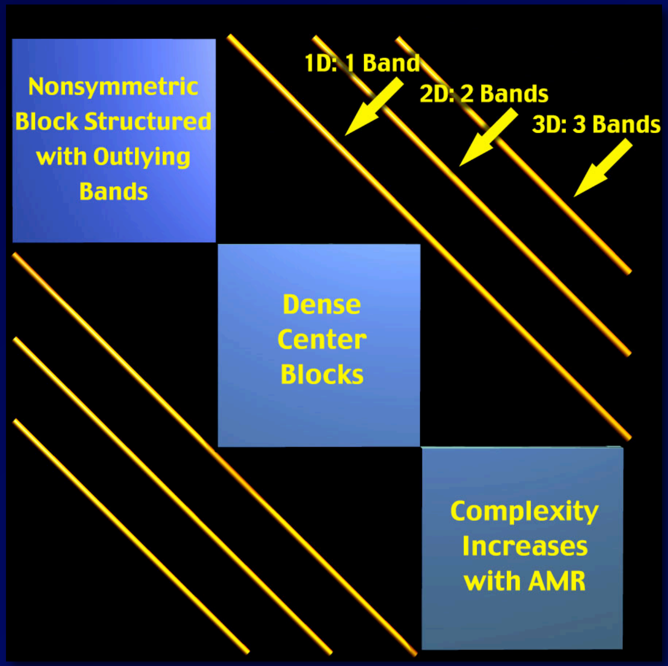

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$$T_{\rm wall} \sim 7 \text{ weeks} \left(\frac{N_t}{10^6}\right) \left(\frac{N_{\rm iterations}}{20}\right) \left(\frac{N_{\mathbf{x}}}{10^6}\right) \left(\frac{N_{\mathbf{p}}}{10^5}\right)^2 \left(\frac{R_{\rm FLOP}}{10^{18}\ {\rm s}^{-1}}\right) \left(\frac{\epsilon_{\rm FLOP}}{0.05}\right)$$

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The abundance of nuclei with a closed shell of 50 neutrons

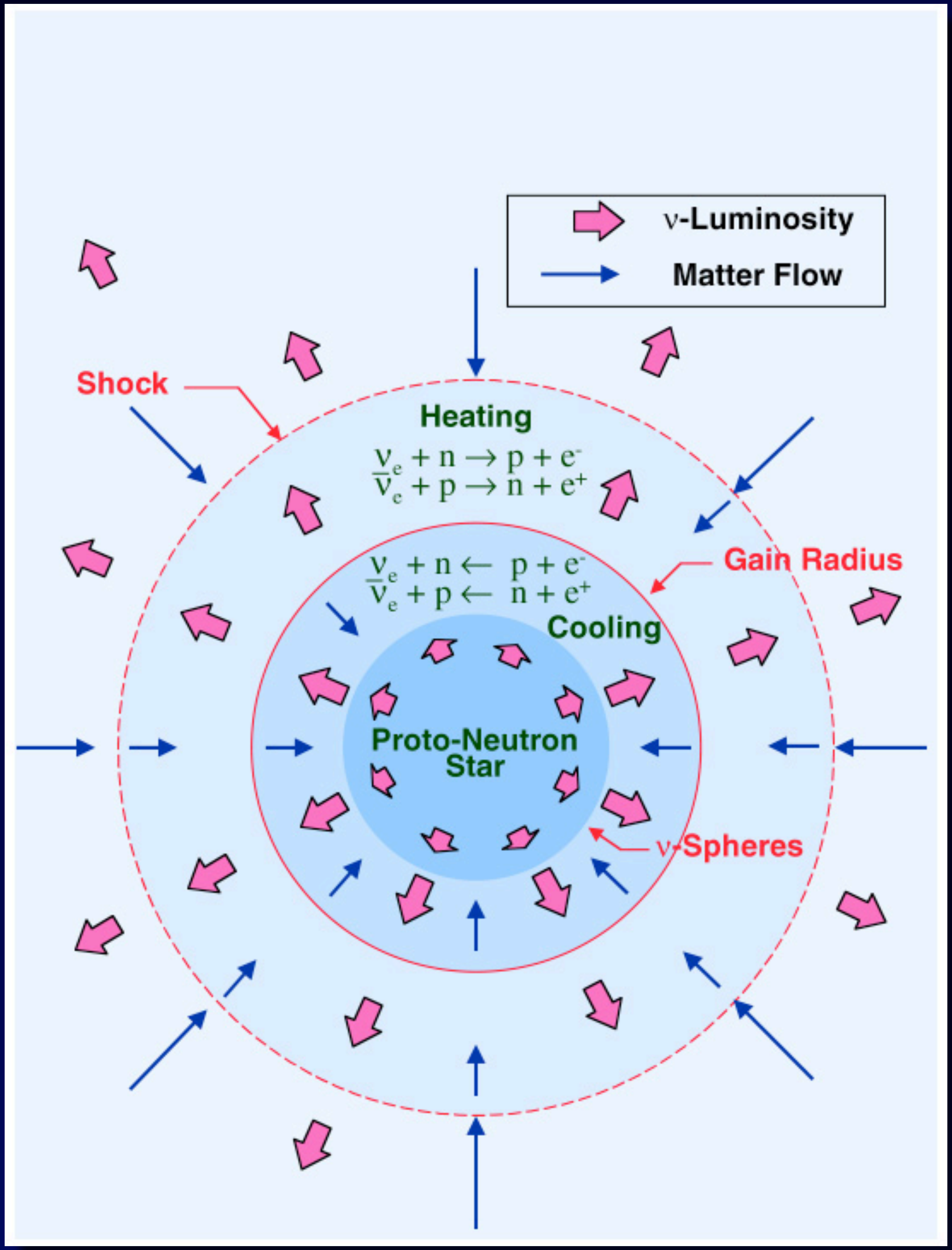
The electron fraction…

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

…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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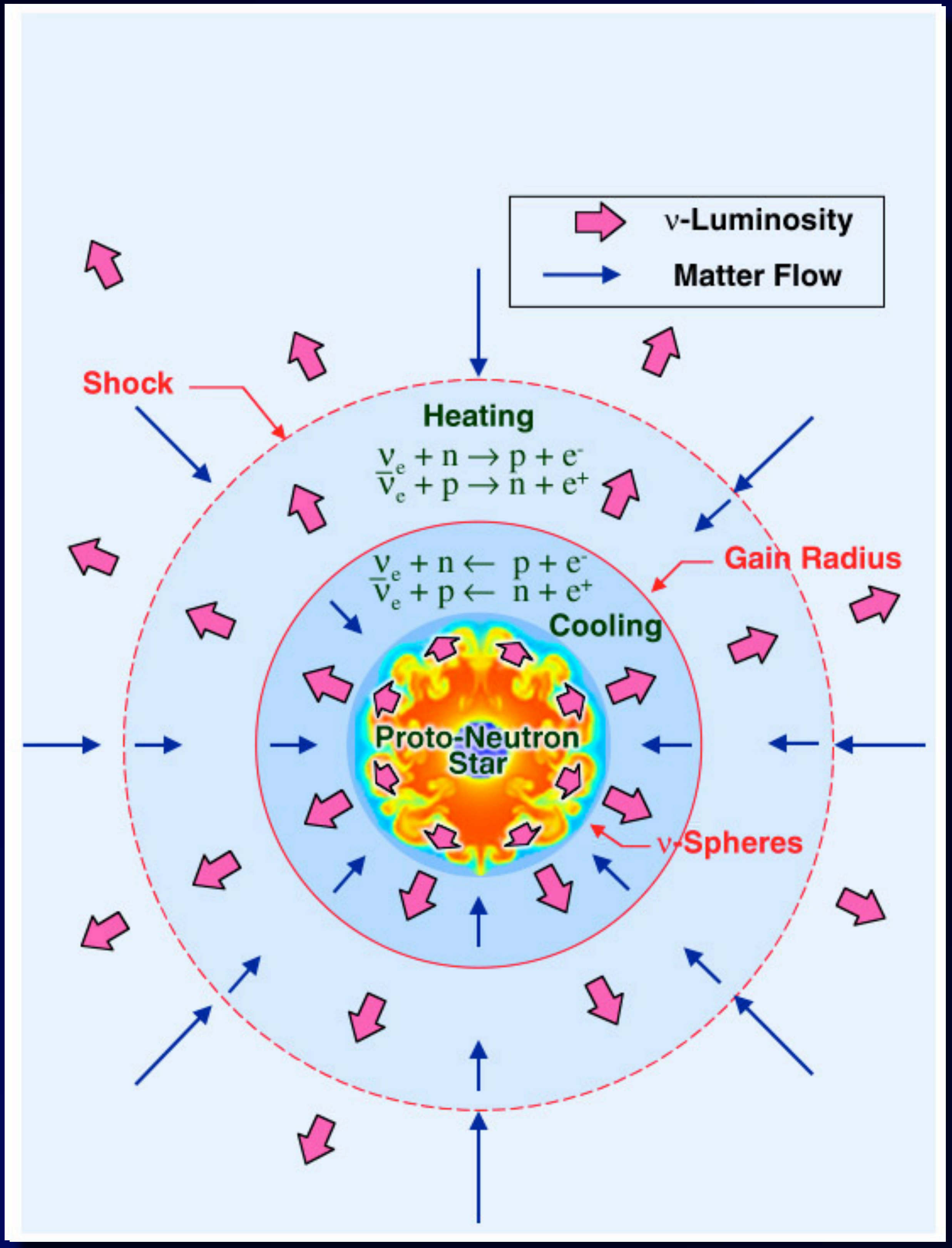

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"1.5D"

Neutrino transport:

1D + 1D

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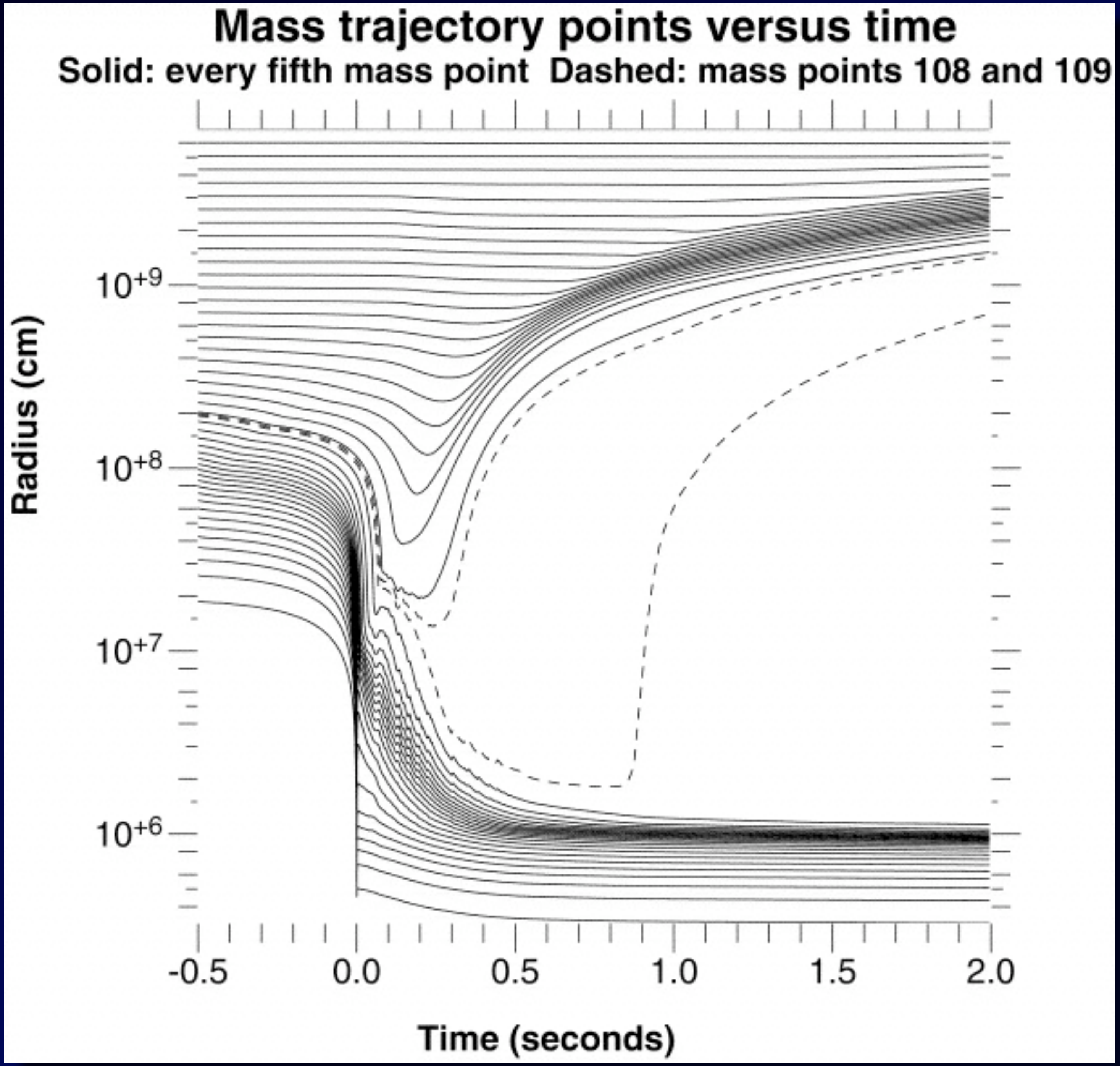

Totani, Sato, Dalhed, & Wilson (1998)

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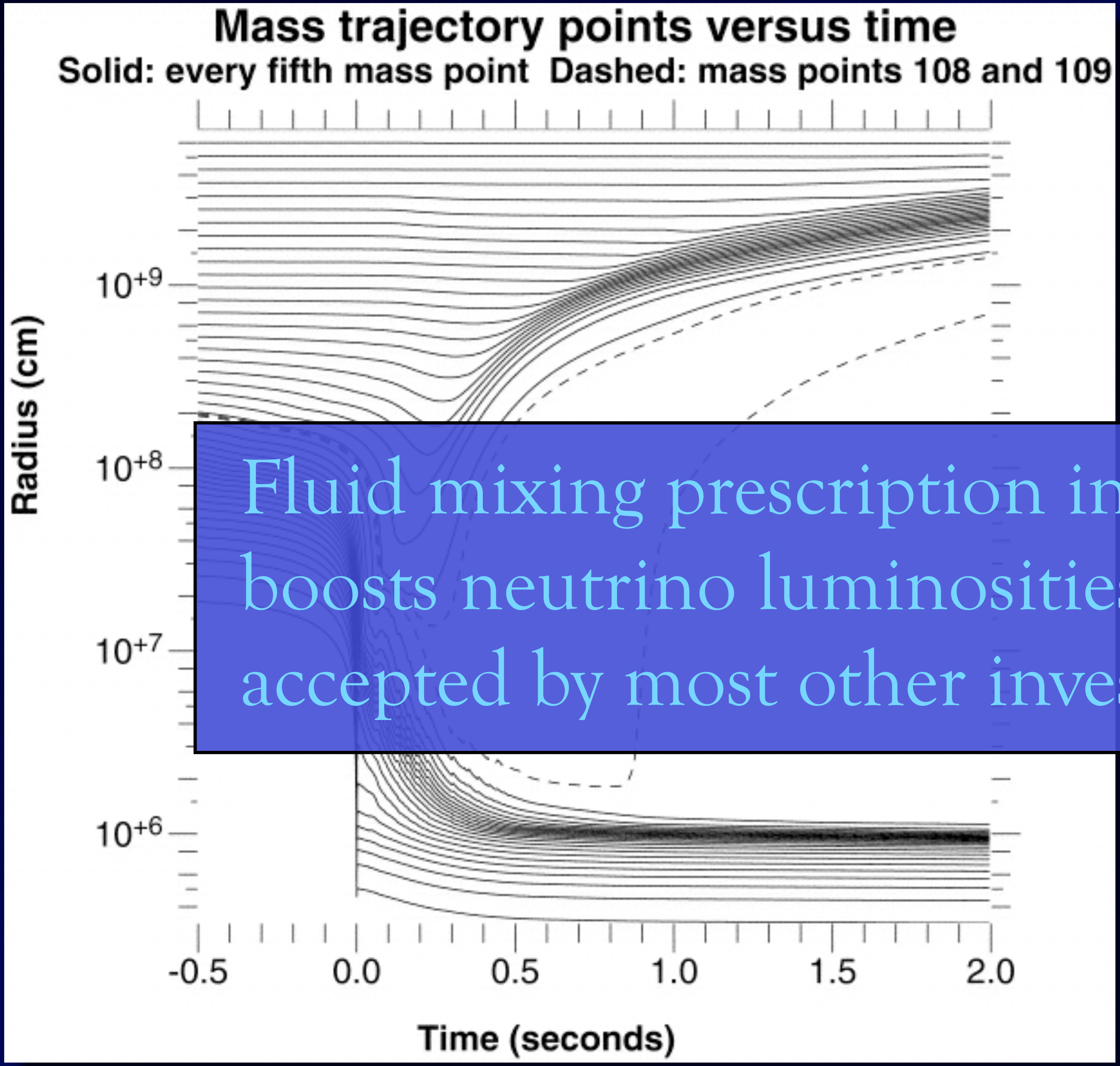
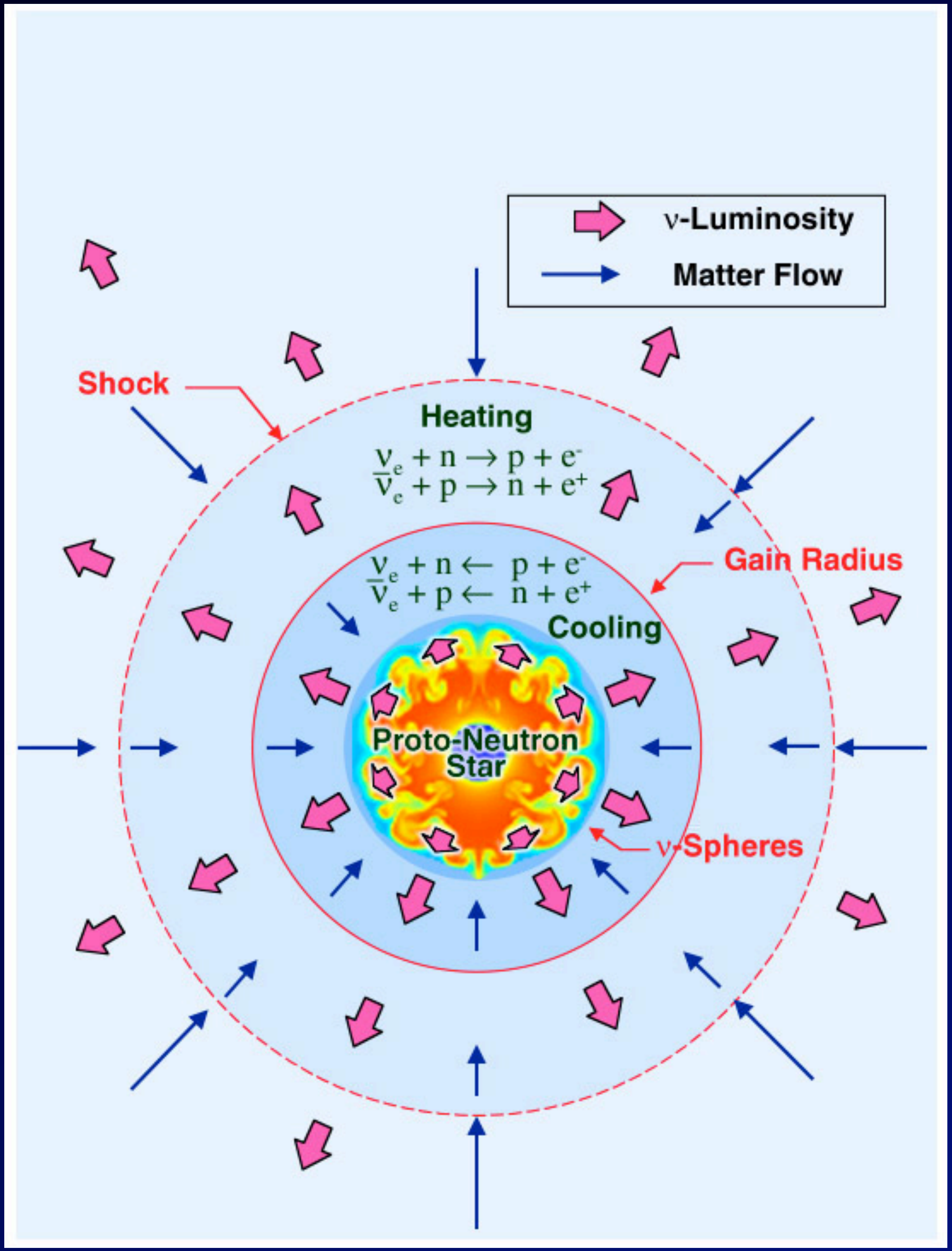


Totani, Sato, Dalhed, & Wilson (1998)

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

Post-shock convection



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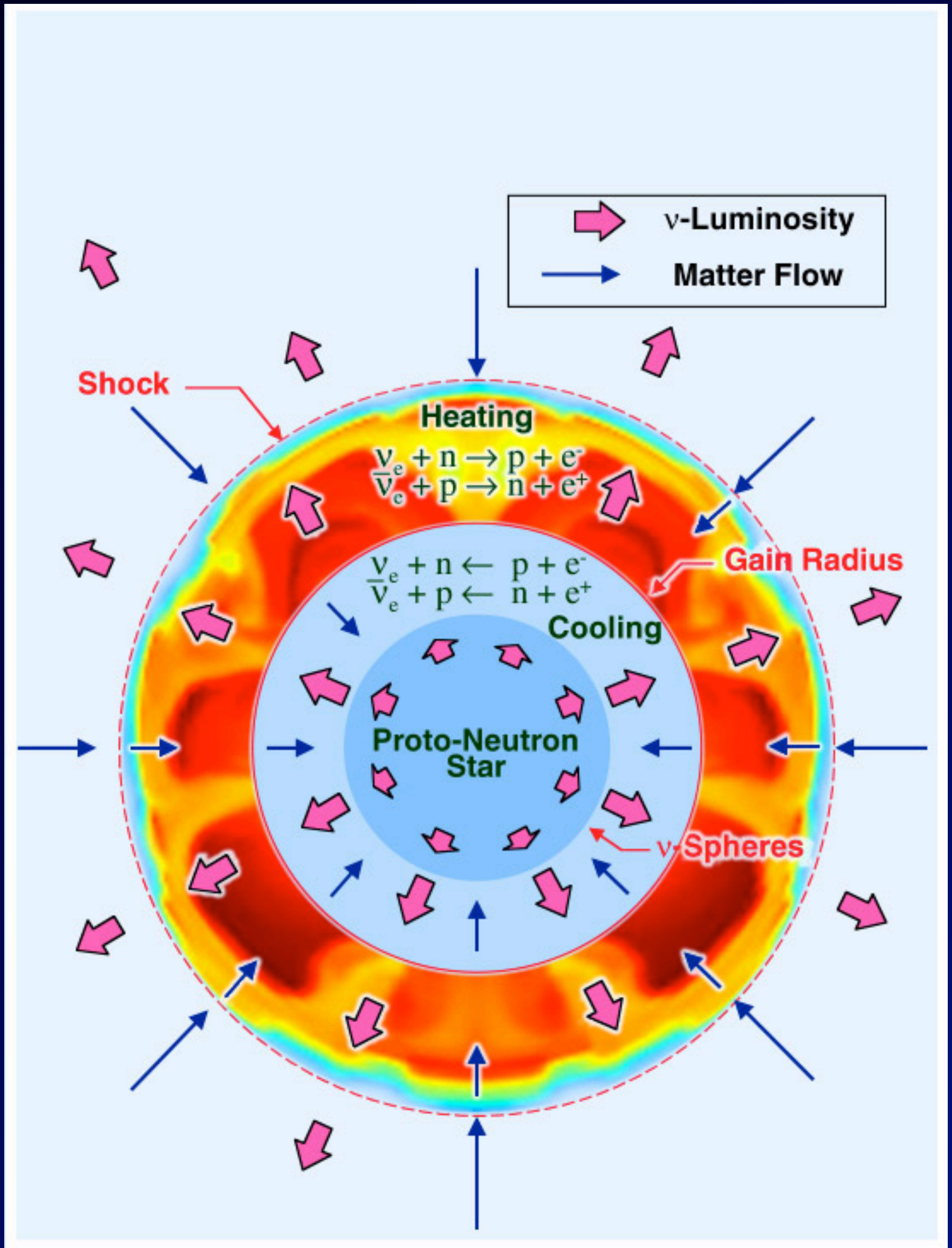

Fluid dynamics:

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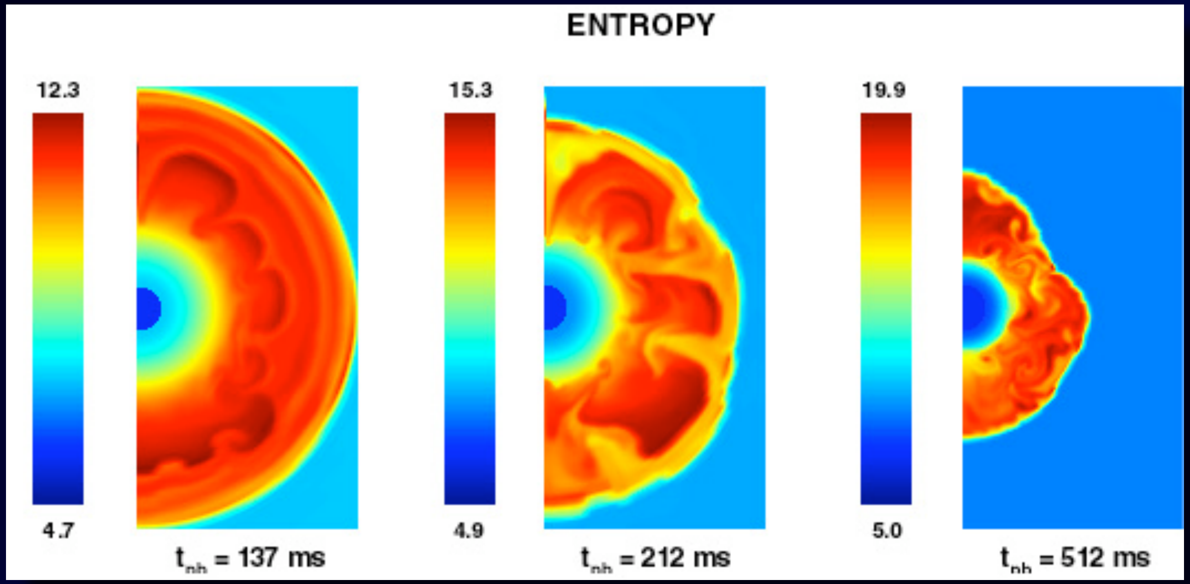

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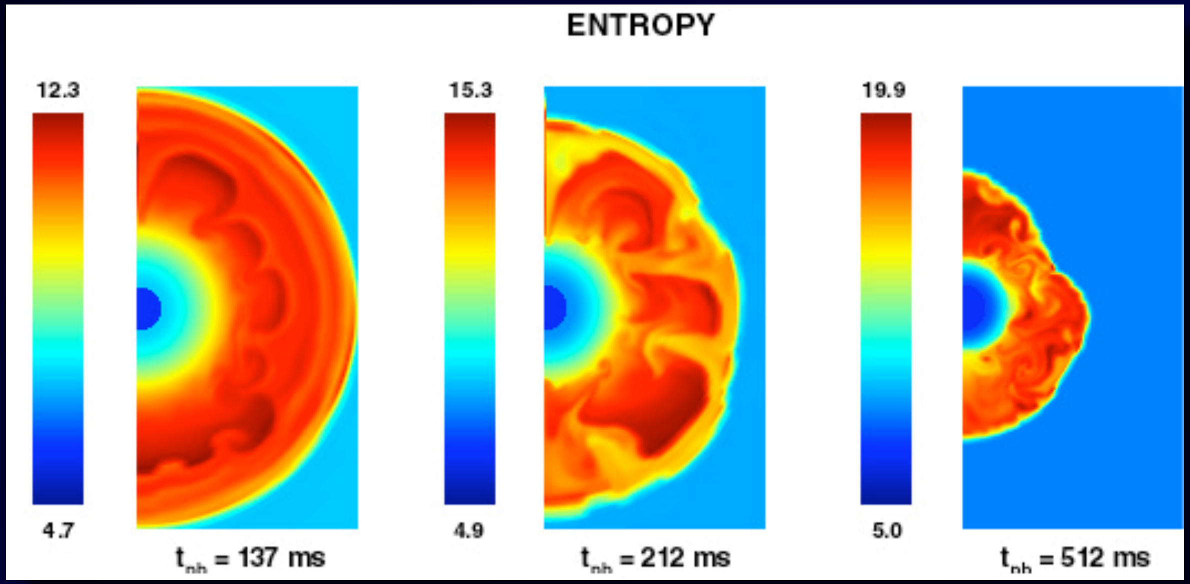

Fluid dynamics:
2D, 3D

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2D + 0D, 3D + 0D

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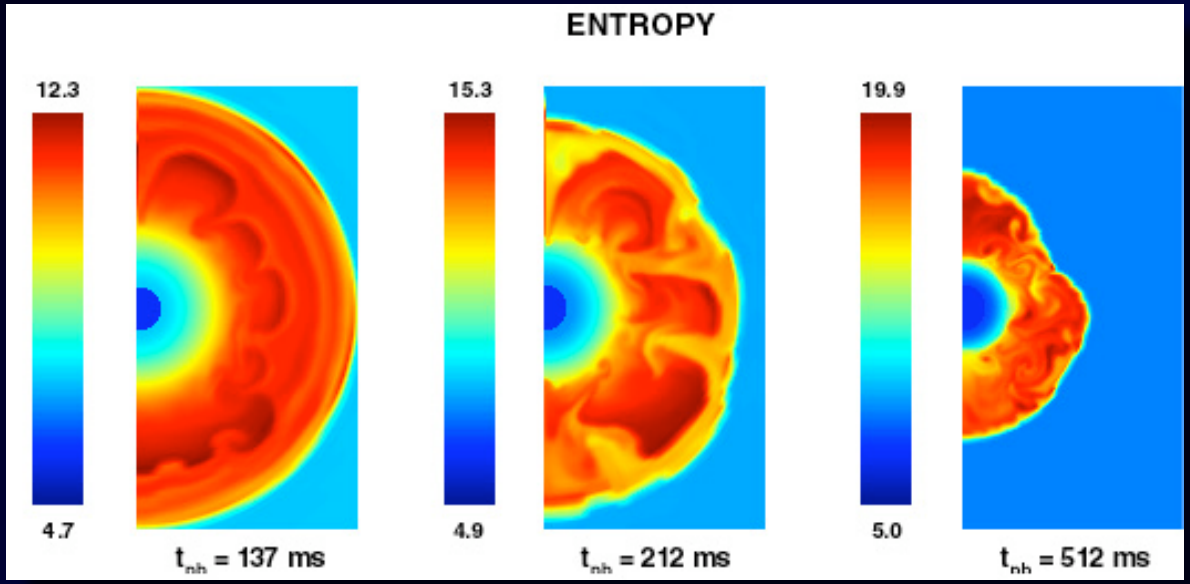
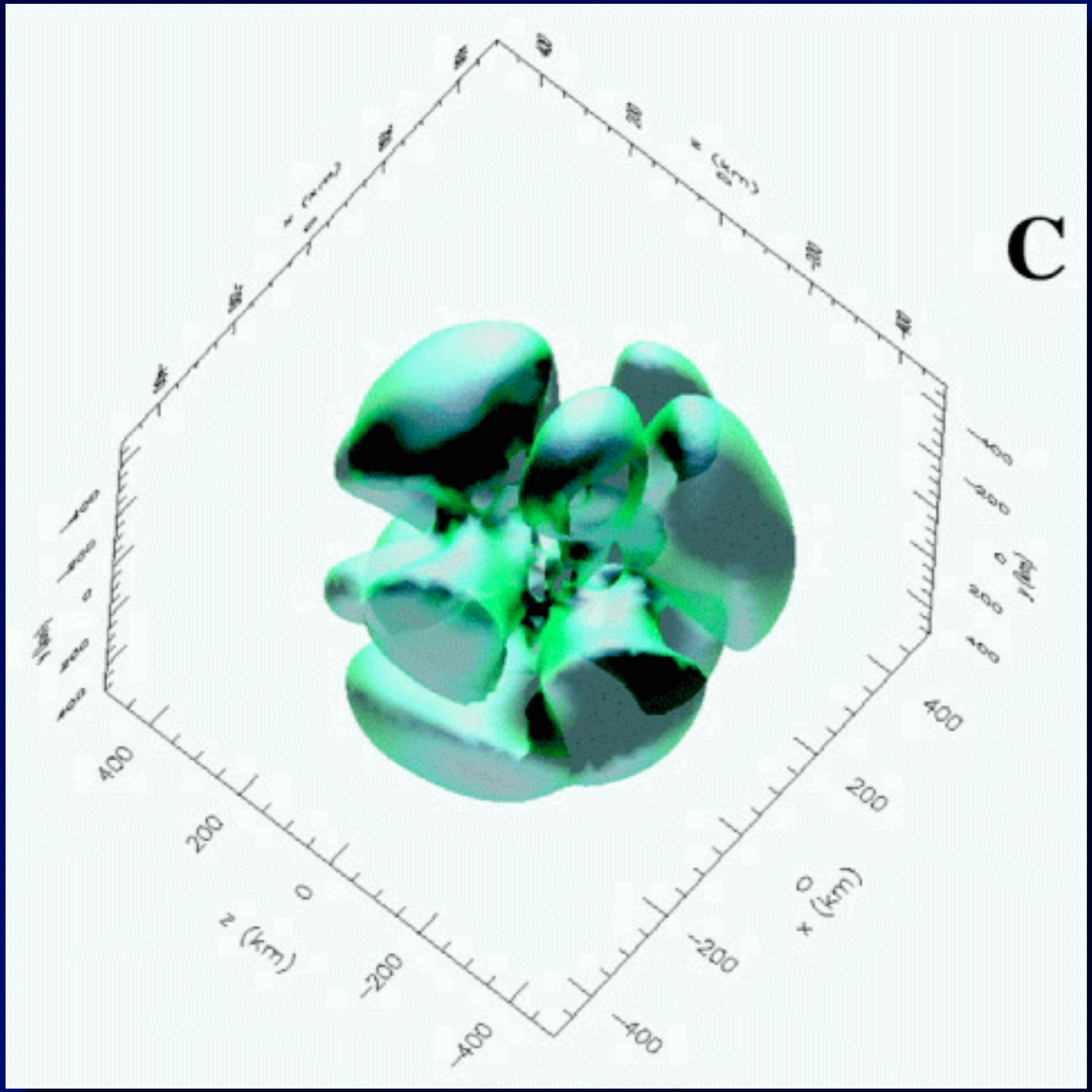


Fryer & Warren (2002)



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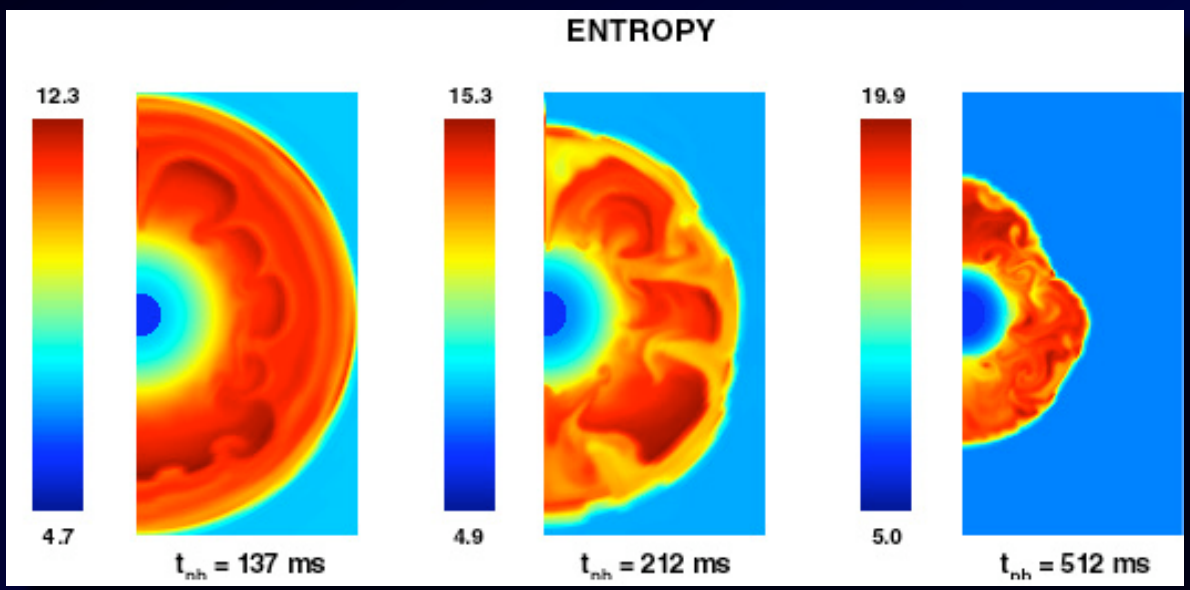

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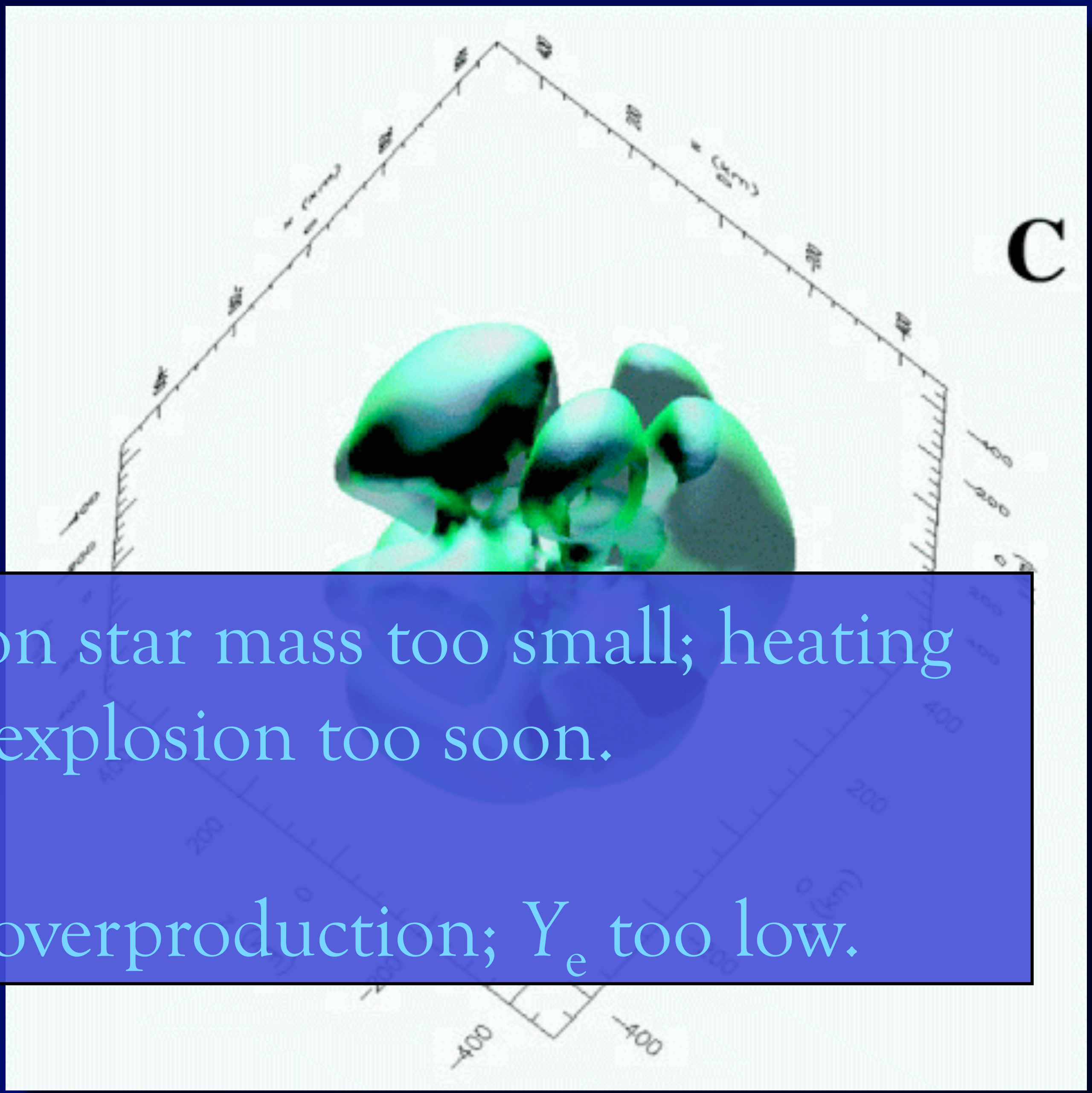
2D, 3D

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

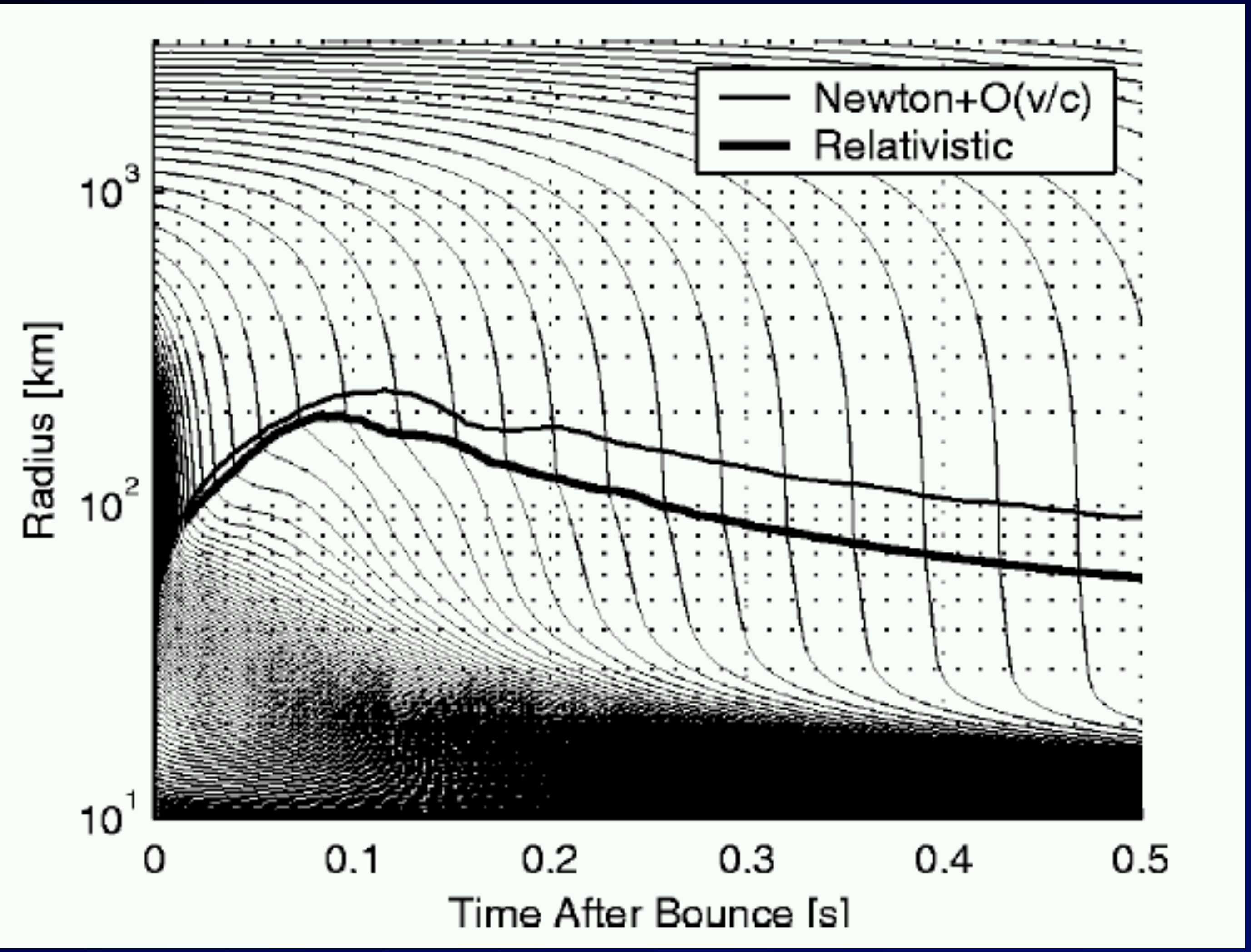
Neutrino transport:

1D + 2D

Fluid dynamics:
1D

Neutrino transport:
1D + 2D

Liebendörfer et al. (2001, 2004)

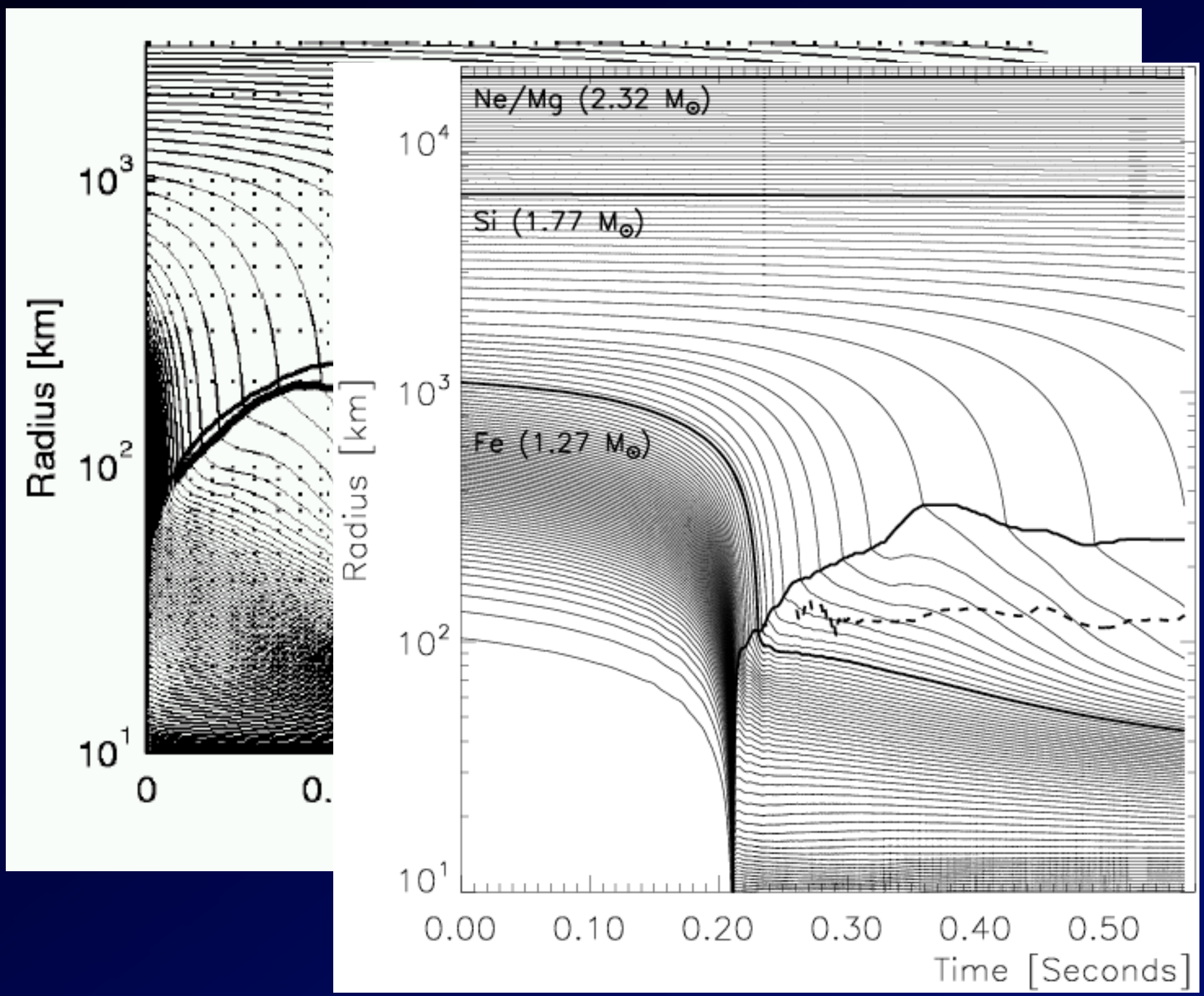


Fluid dynamics:
1D

Neutrino transport:
1D + 2D

Liebendörfer et al. (2001, 2004)

Rampp & Janka (2000, 2002)



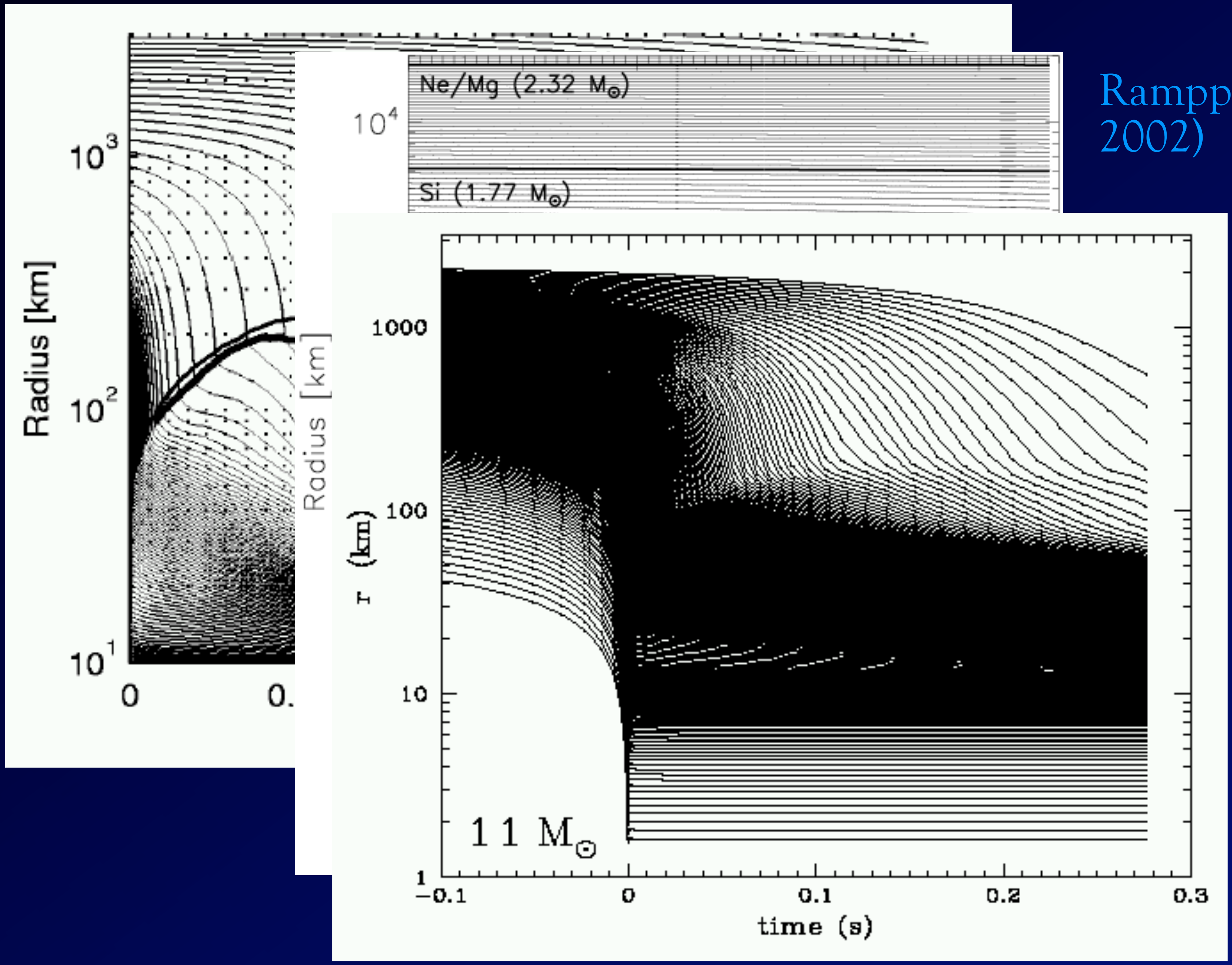
Fluid dynamics:
1D

Neutrino transport:
1D + 2D

Liebendörfer et al. (2001, 2004)

Rampp & Janka (2000, 2002)

Thompson, Burrows, & Pinto (2002)



Fluid dynamics:
1D

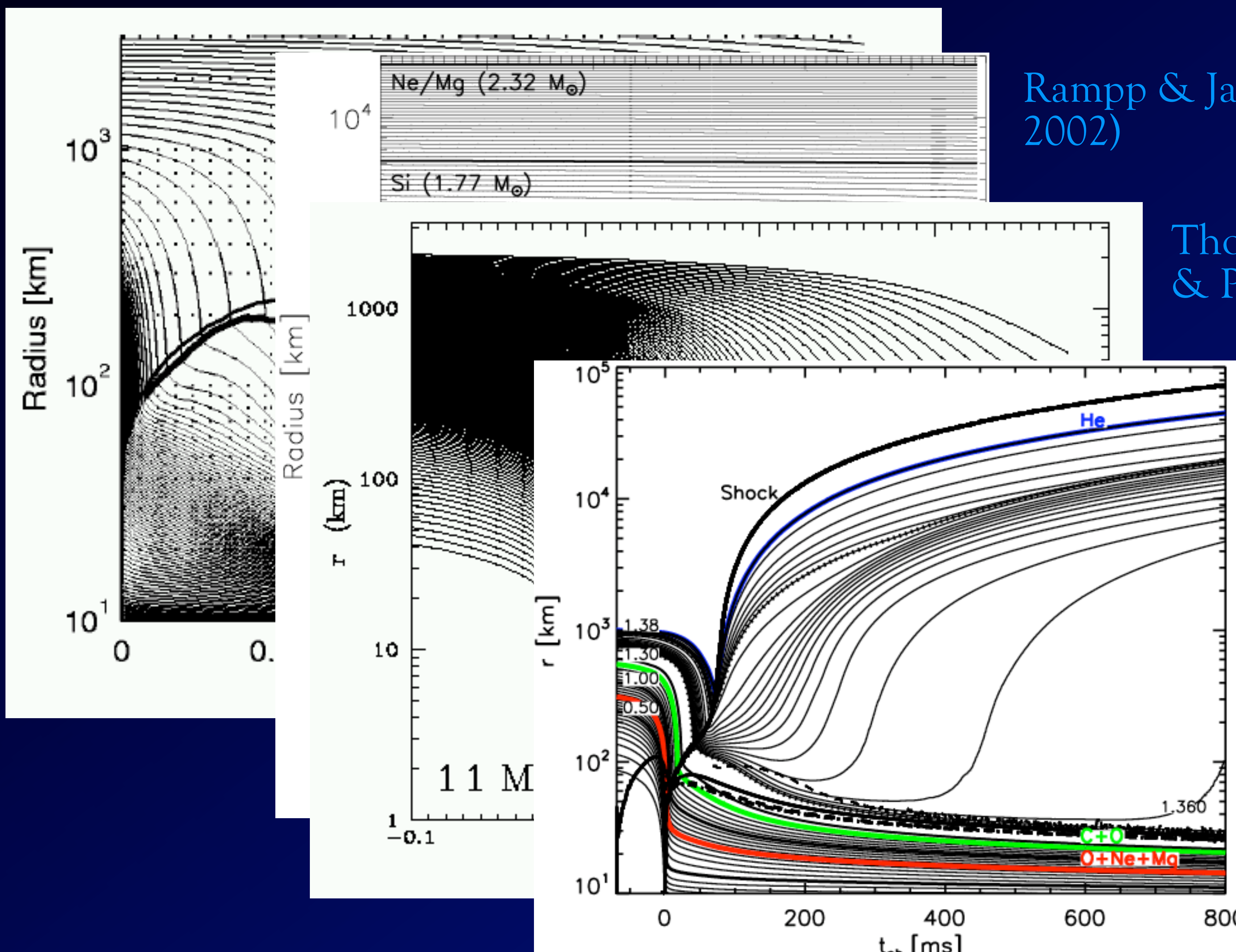
Neutrino transport:
1D + 2D

Liebendörfer et al. (2001, 2004)

Rampp & Janka (2000, 2002)

Thompson, Burrows, & Pinto (2002)

Kitaura, Janka, & Hillebrandt (2006)



Fluid dynamics:
1D

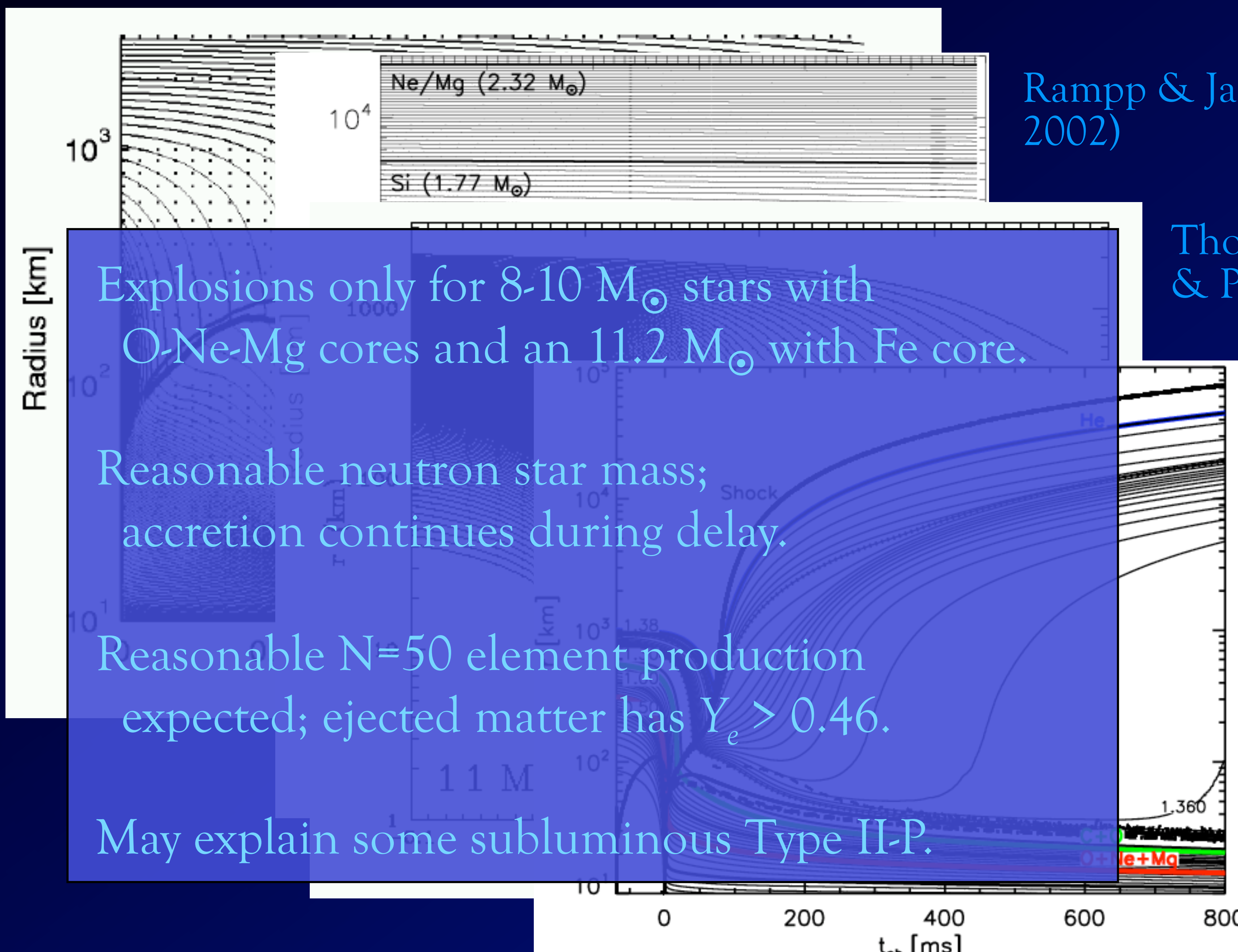
Neutrino transport:
1D + 2D

Liebendörfer et al. (2001, 2004)

Rampp & Janka (2000, 2002)

Thompson, Burrows, & Pinto (2002)

Kitaura, Janka, & Hillebrandt (2006)



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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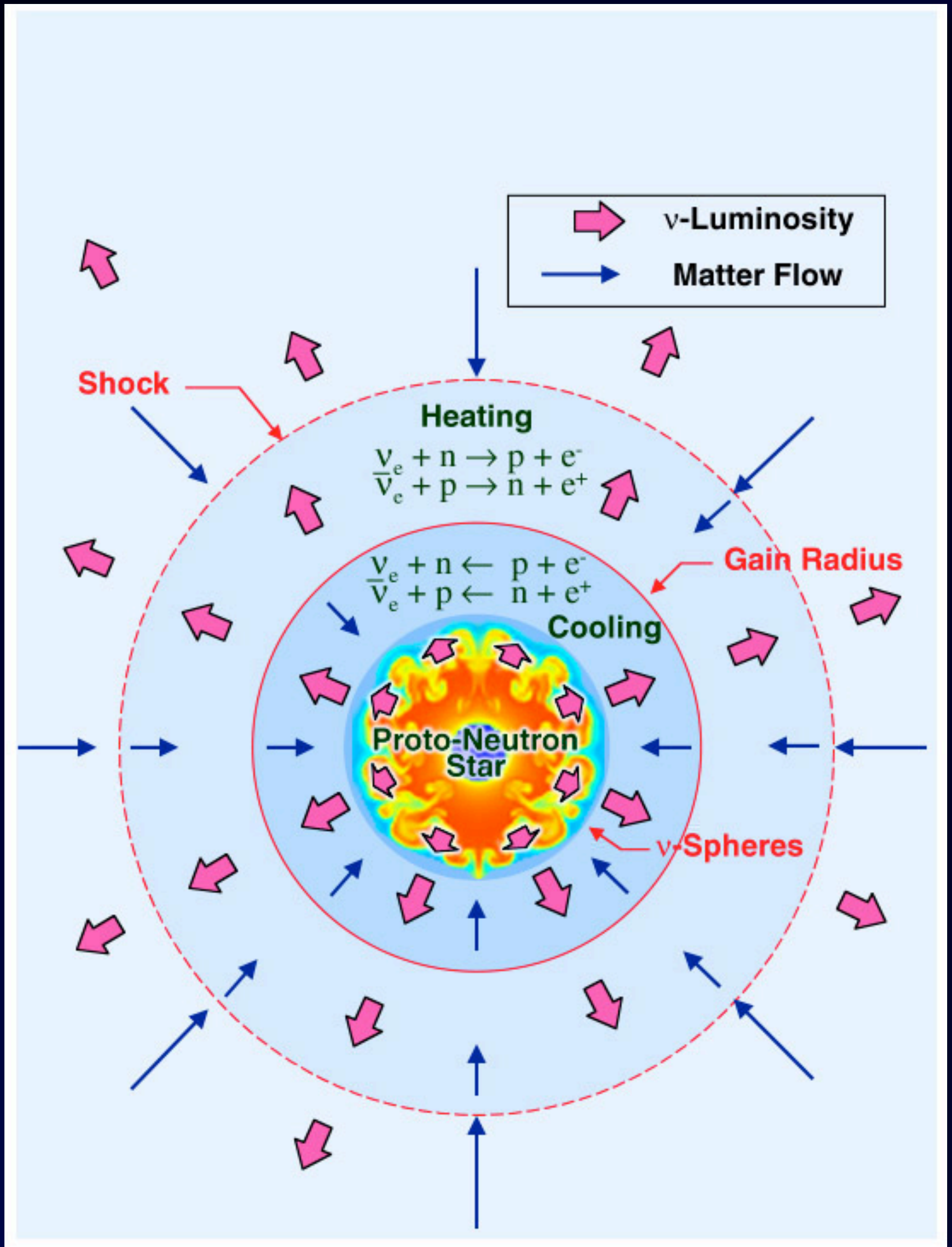
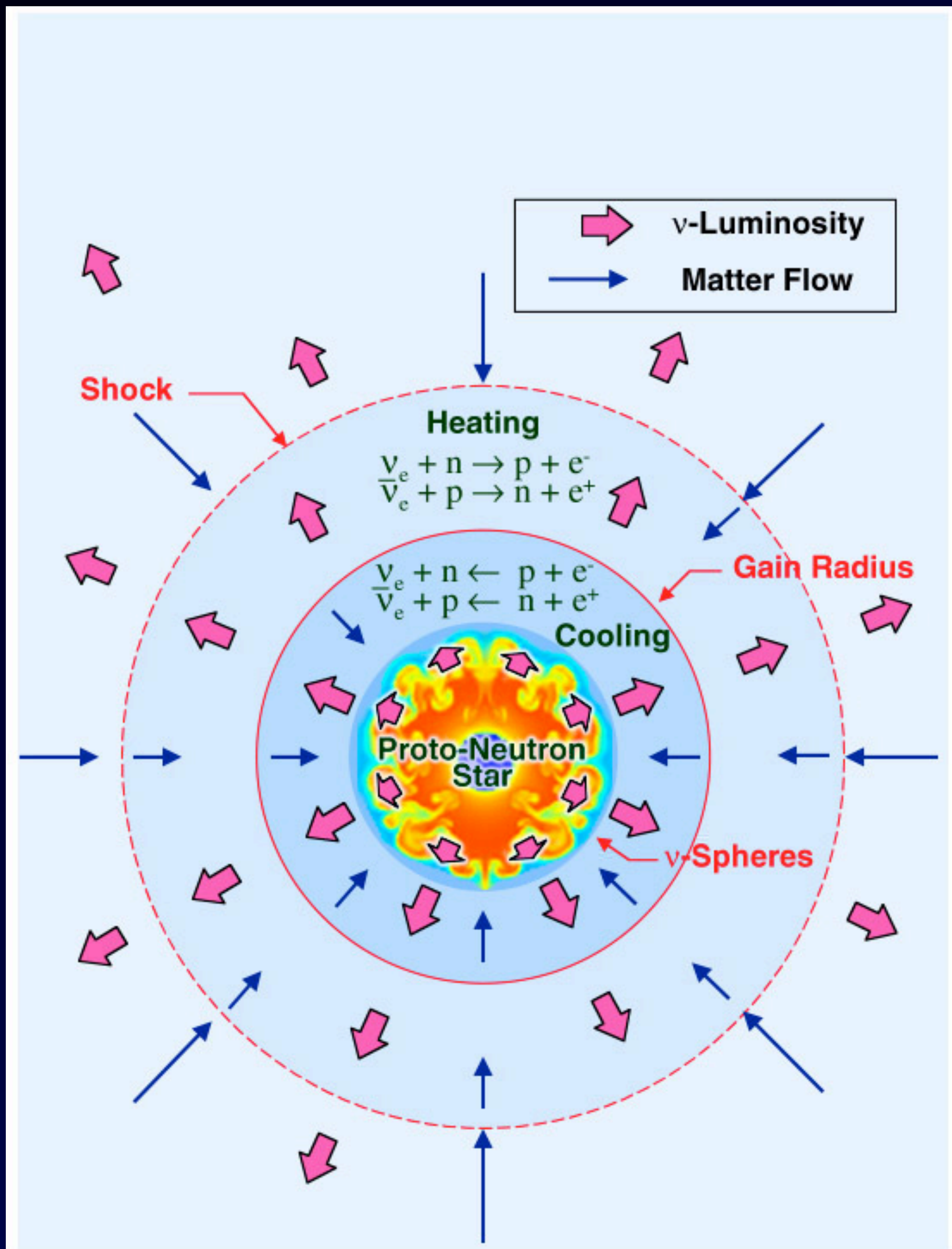
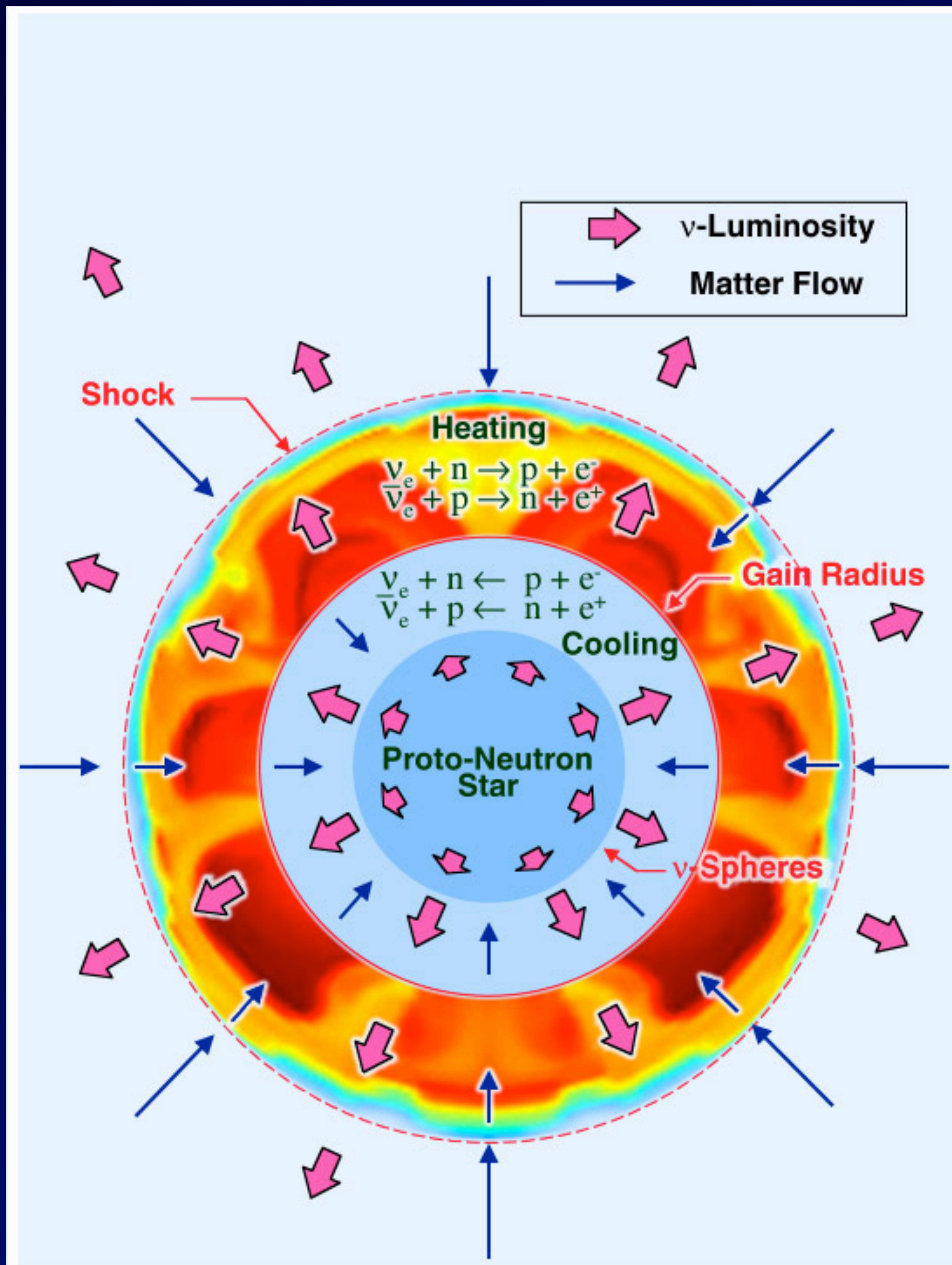
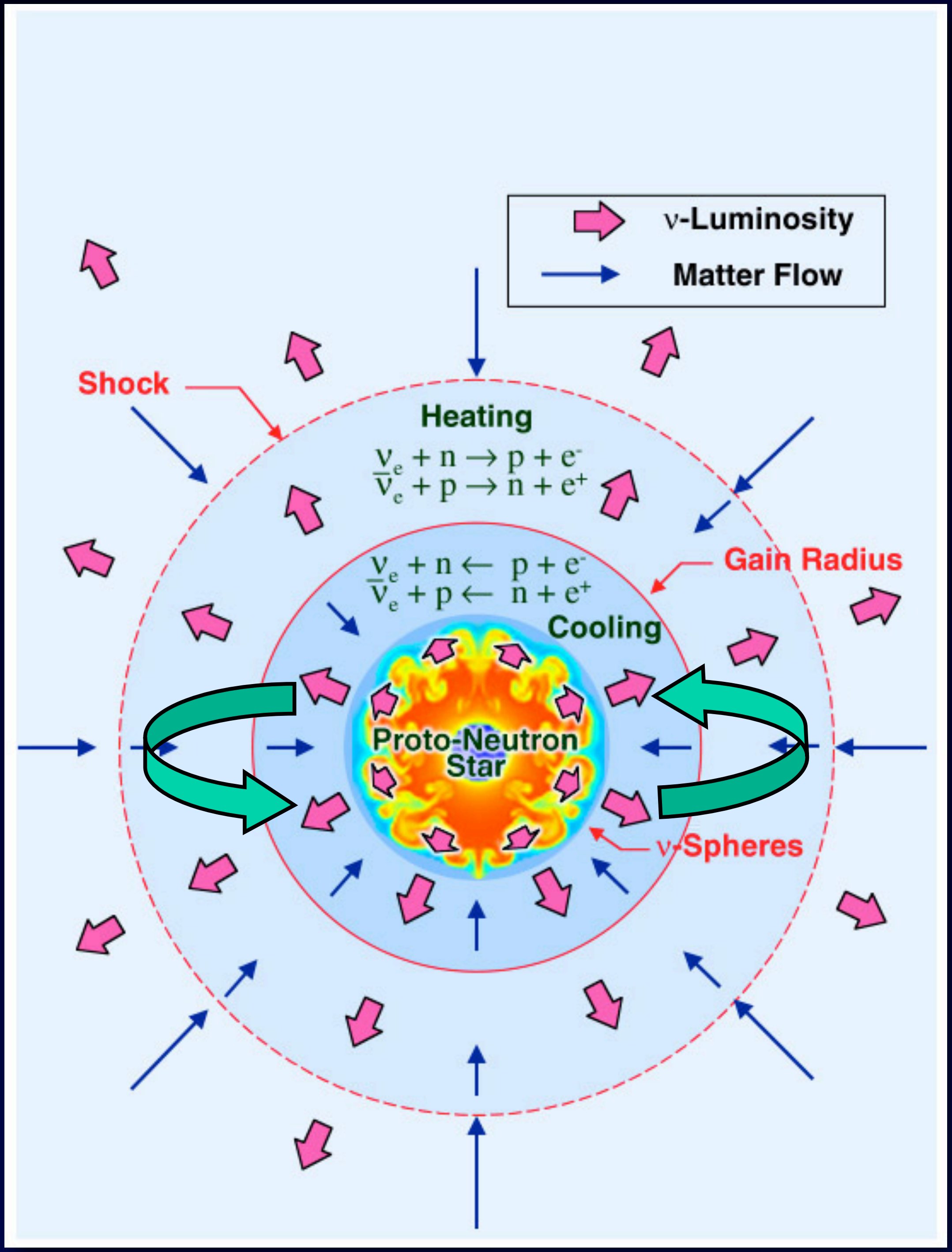


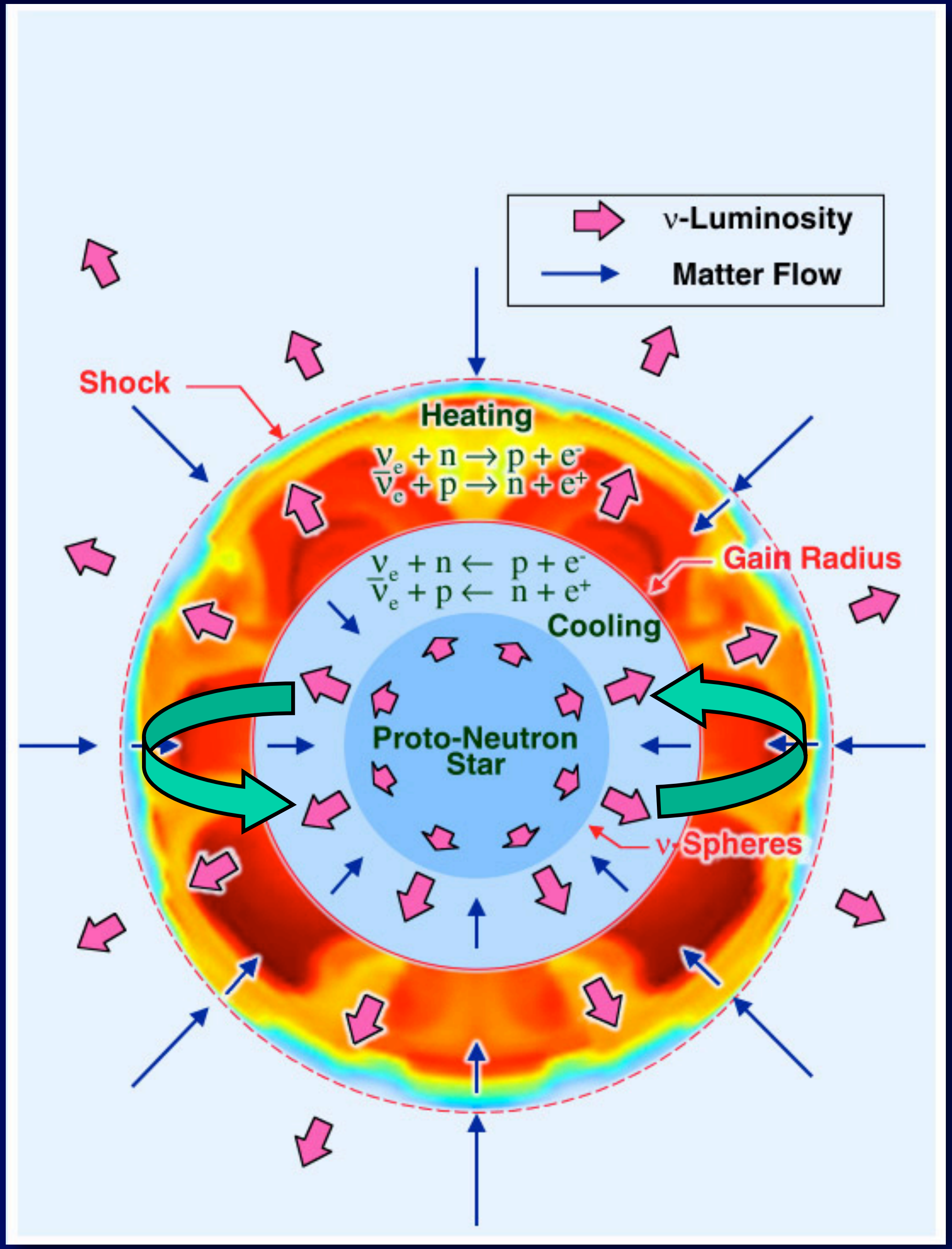
Convection, rotation, and magnetic fields all come into play.



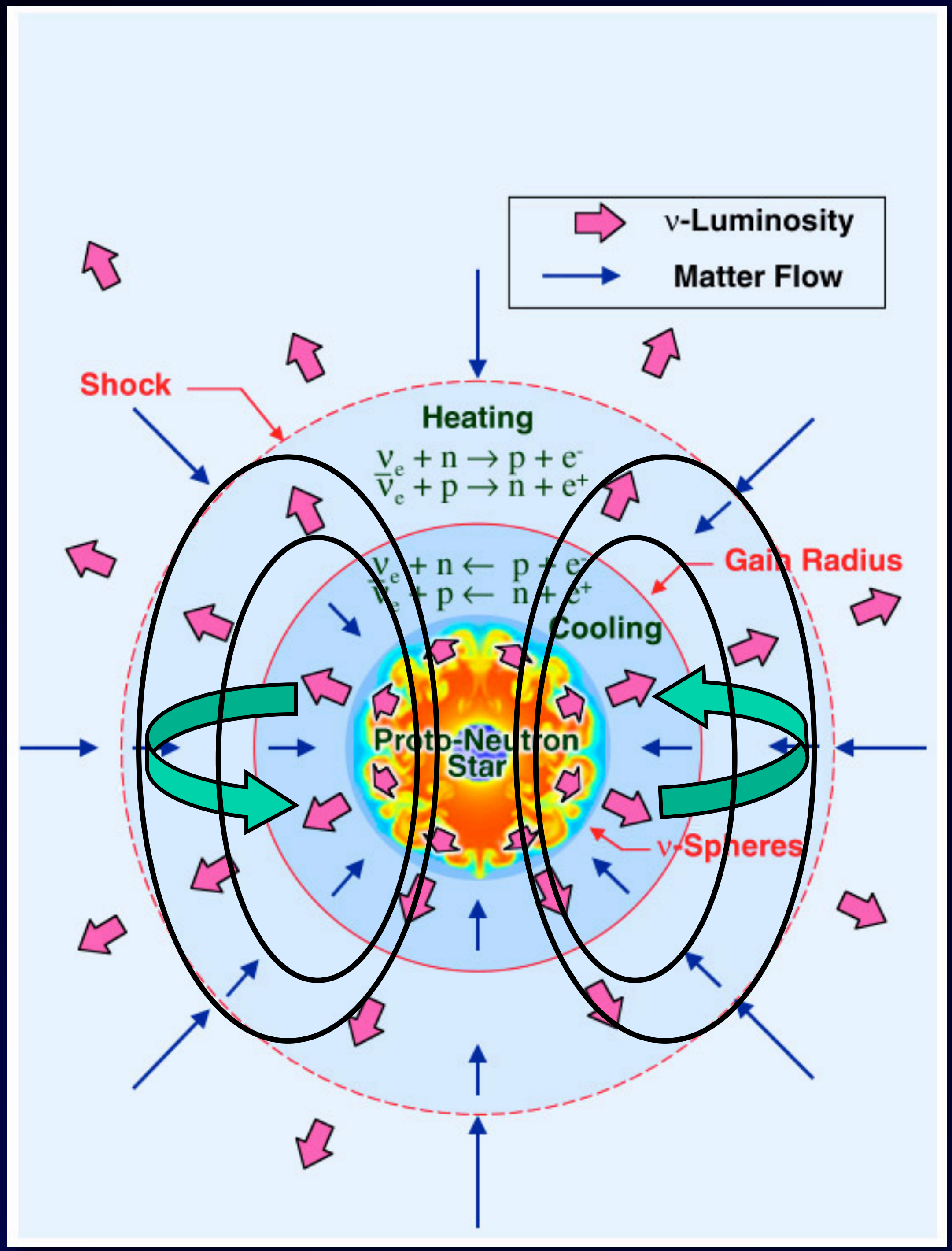


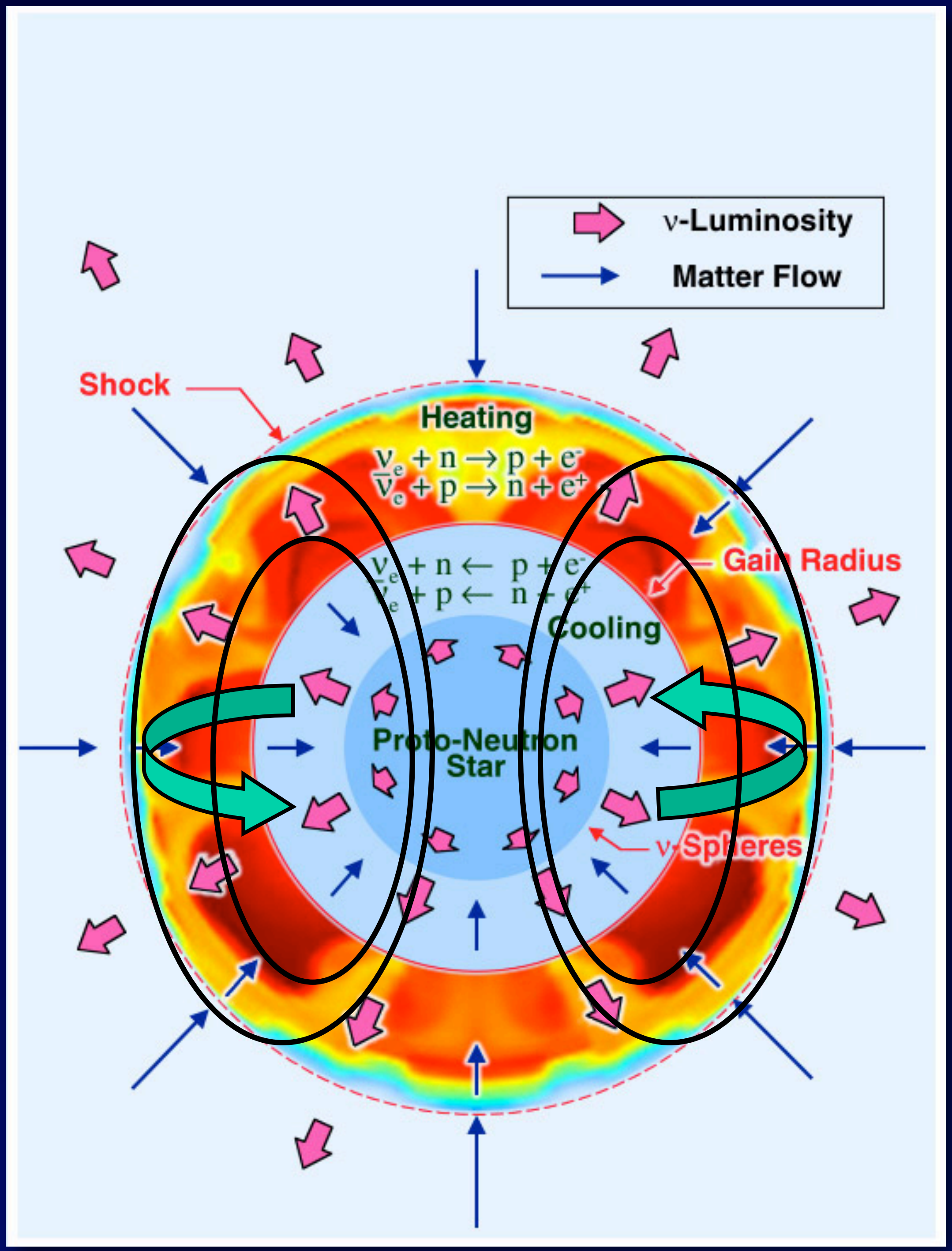
Convection, rotation, and magnetic fields all come into play.





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





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

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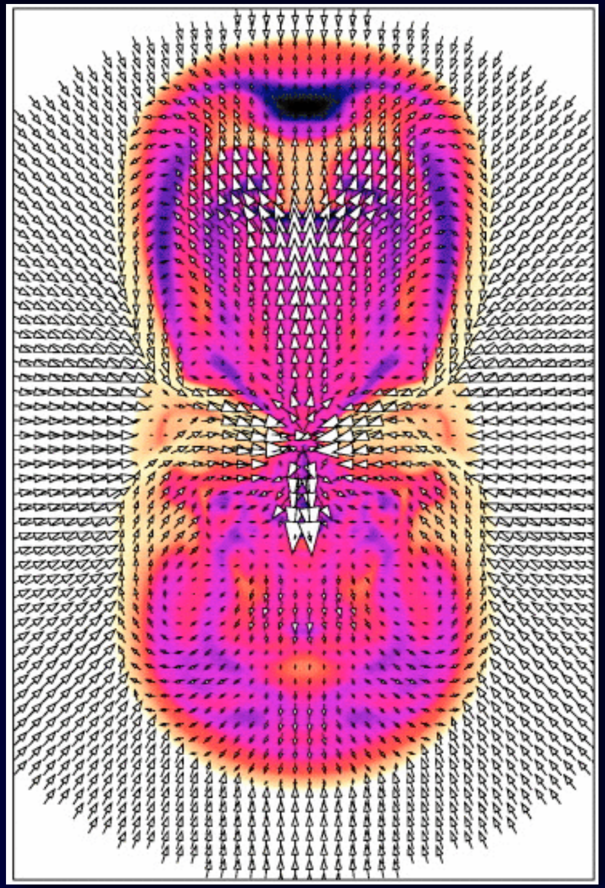
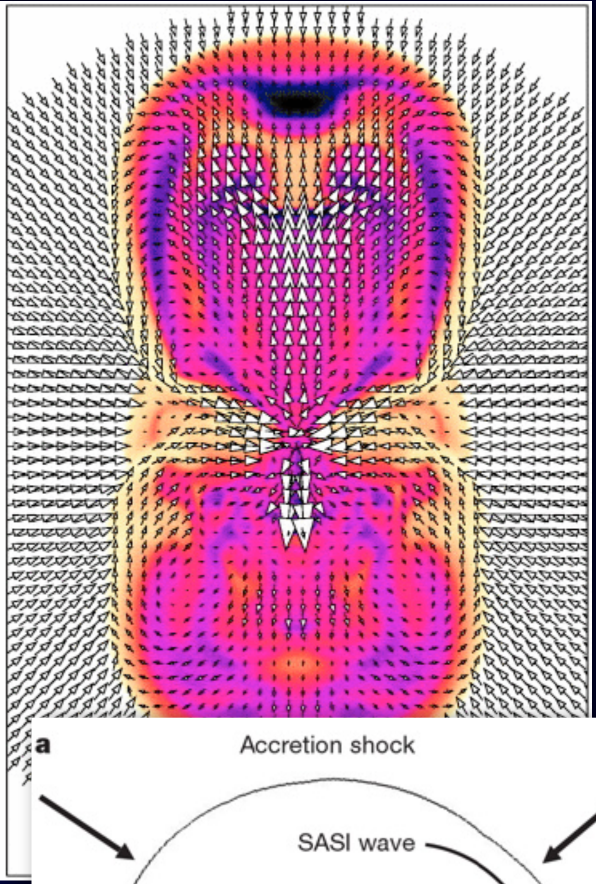
Blondin, Mezzacappa, and DeMarino (2003)



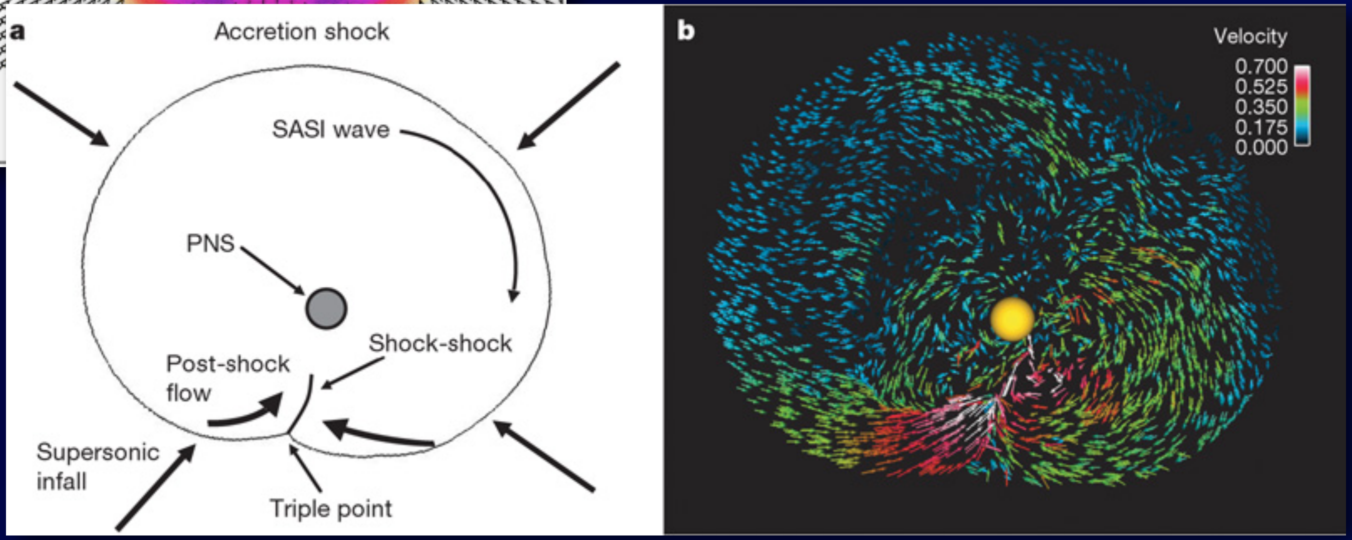
Aspherical explosion morphology

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

Blondin, Mezzacappa, and DeMarino (2003)



Aspherical explosion morphology

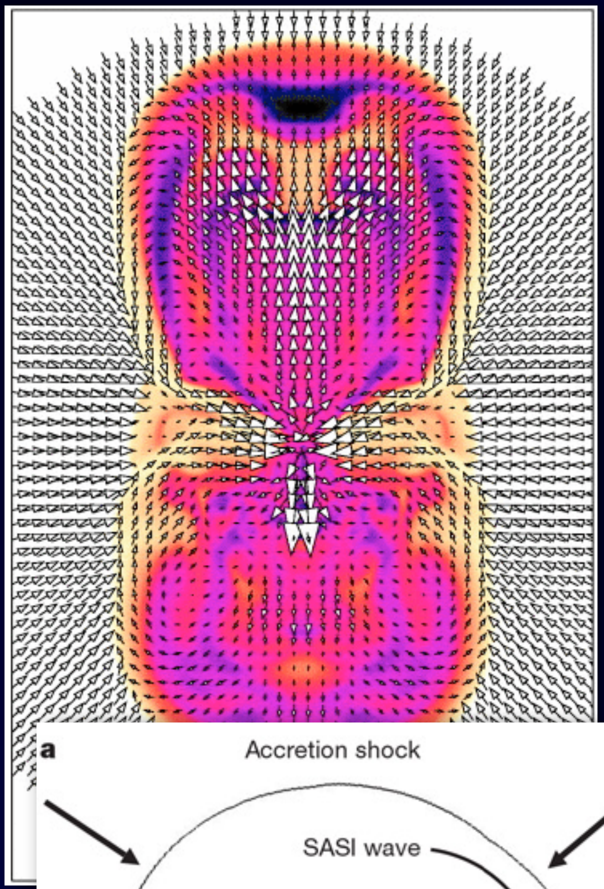


Pulsar spin

Blondin and Mezzacappa (2007)

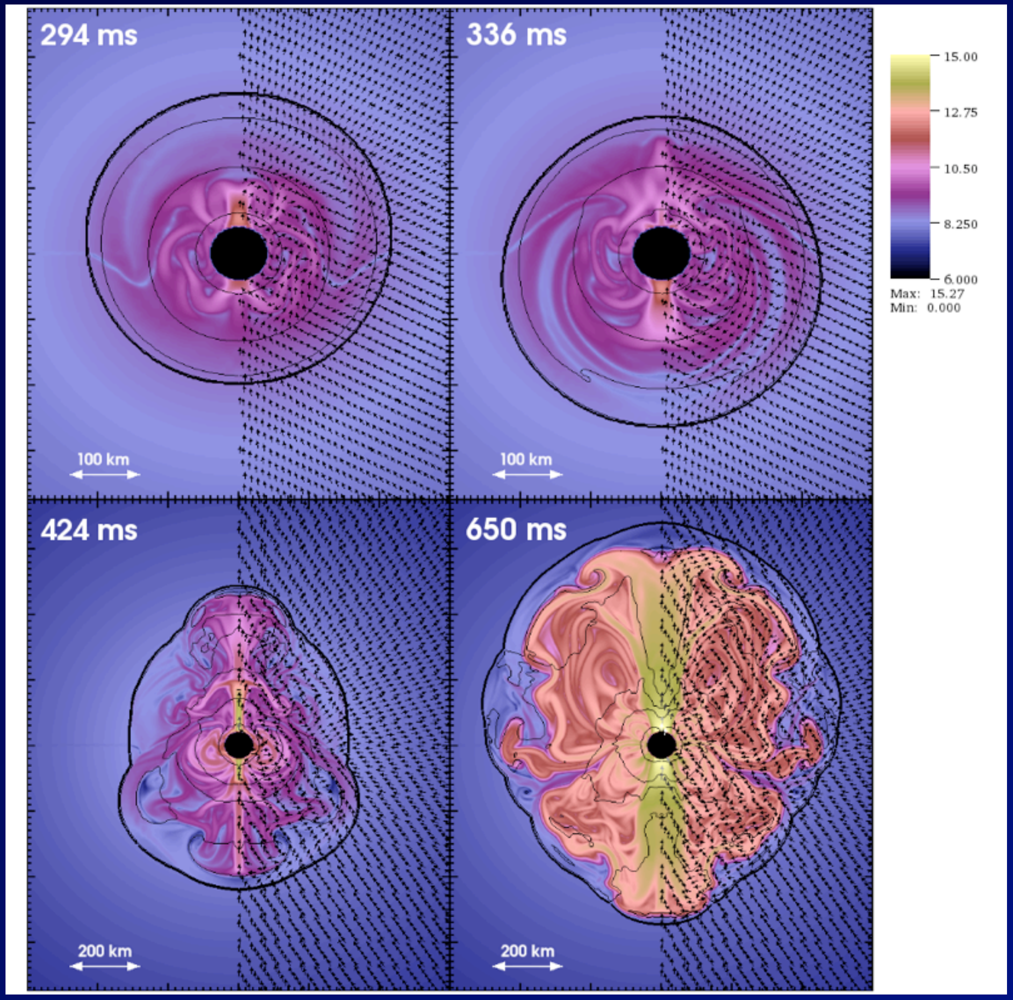
The stationary accretion shock is intrinsically unstable and could generate phenomena traditionally attributed to progenitor rotation.

Blondin, Mezzacappa, and DeMarino (2003)

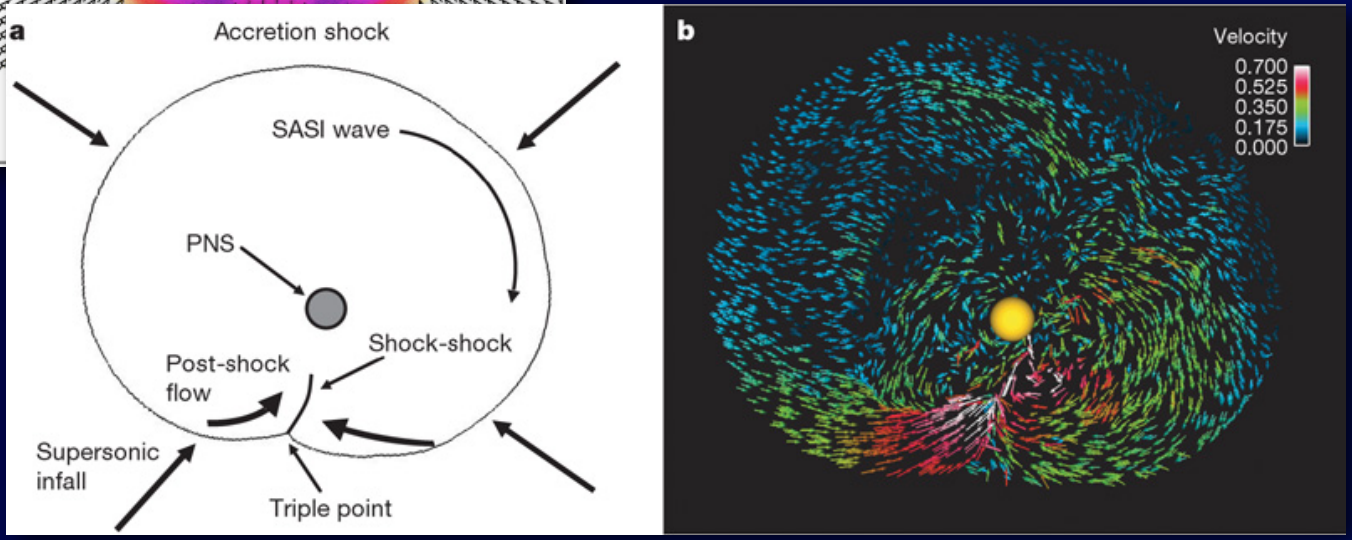


Aspherical explosion morphology

Endeve et al. (2008)



Magnetic field generation



Blondin and Mezzacappa (2007)

Pulsar spin

Fluid dynamics:

2D

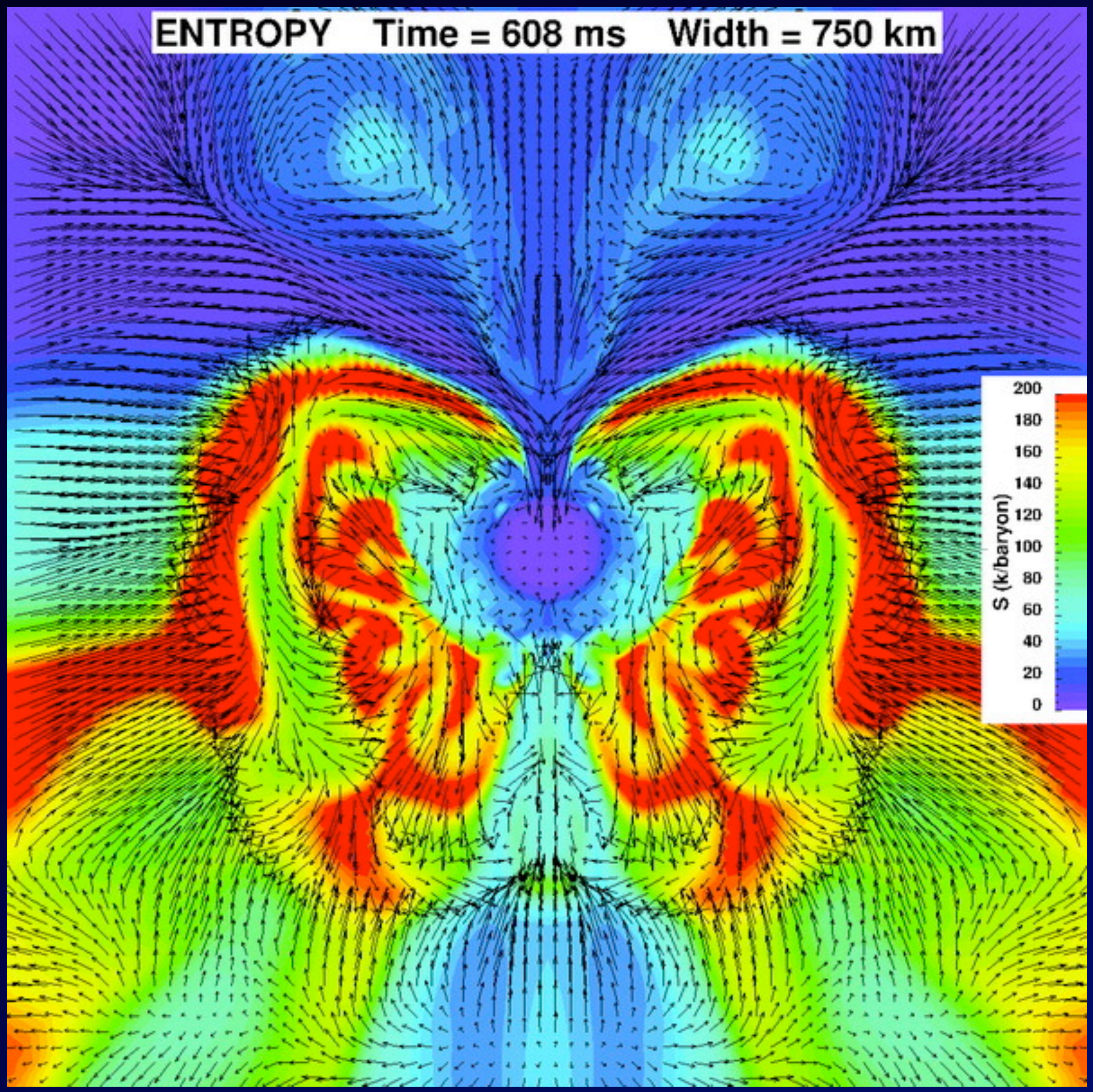
Neutrino transport:

2D + 1D

Fluid dynamics:
2D

Neutrino transport:
2D + 1D

Burrows et al. (2006)



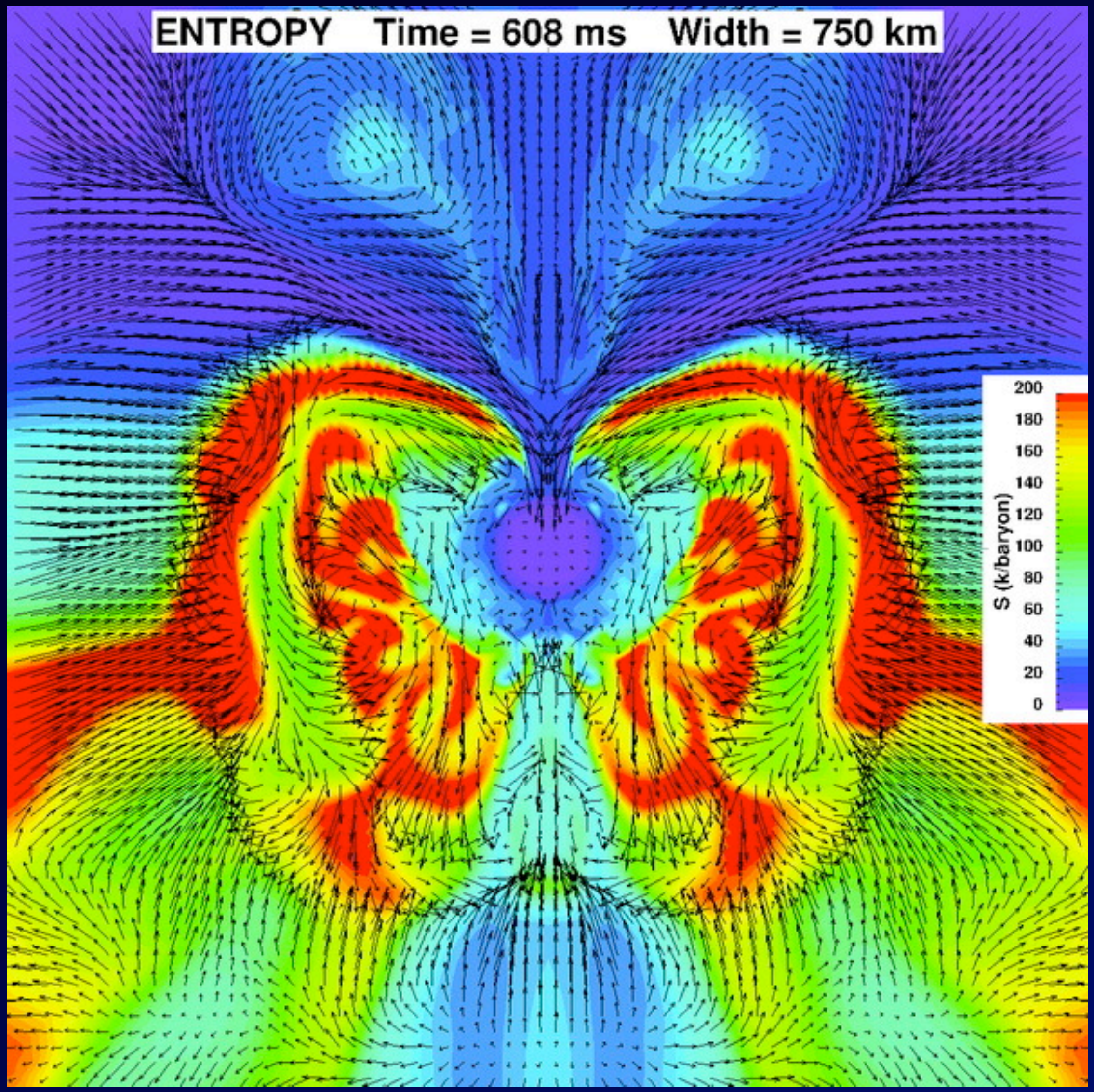
Fluid dynamics:
2D

Neutrino transport:
2D + 1D

Magnetofluid dynamics:
"2.5D"

Neutrino transport:
2D + 1D

Burrows et al. (2006)



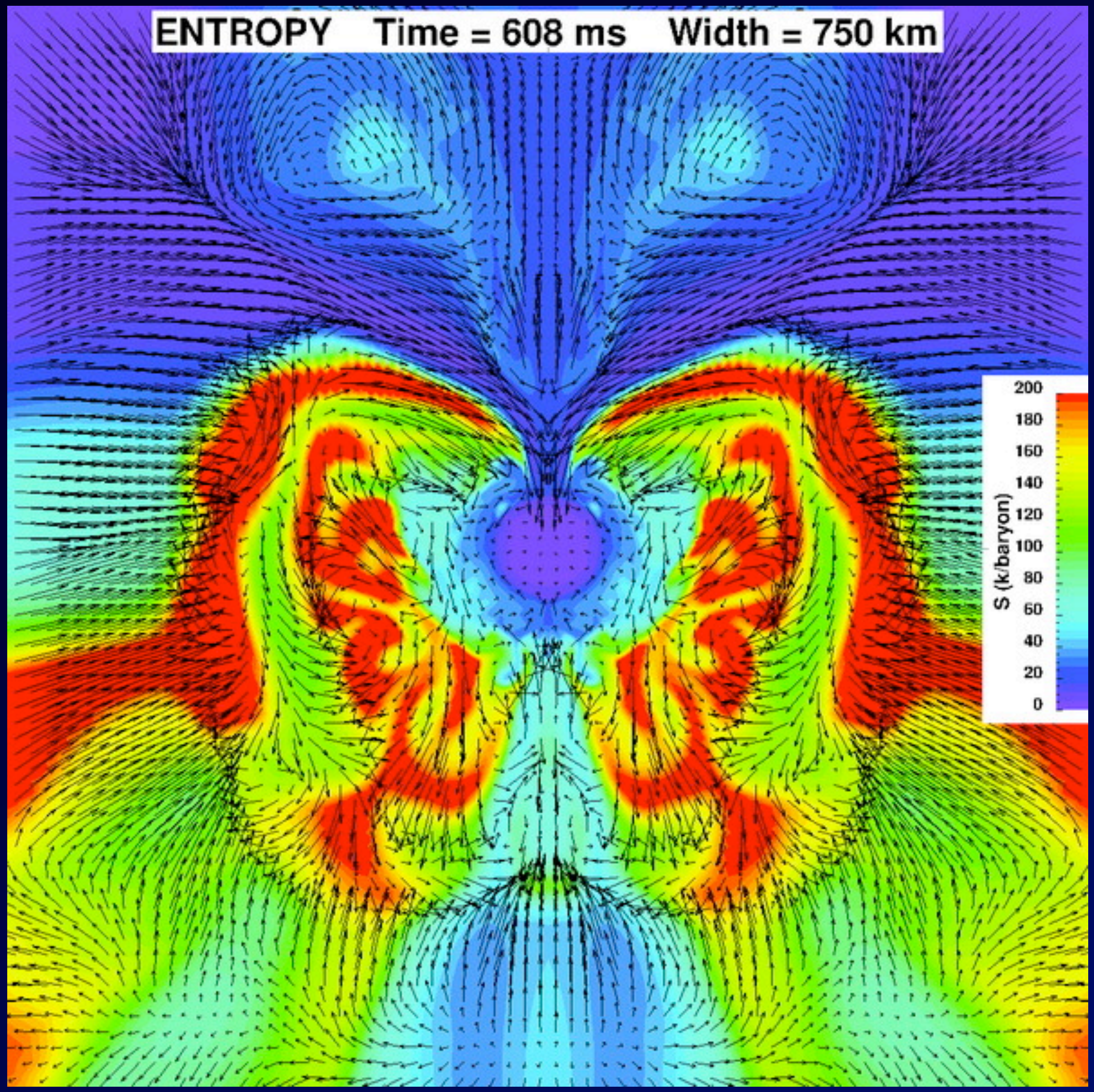
Fluid dynamics:
2D

Neutrino transport:
2D + 1D

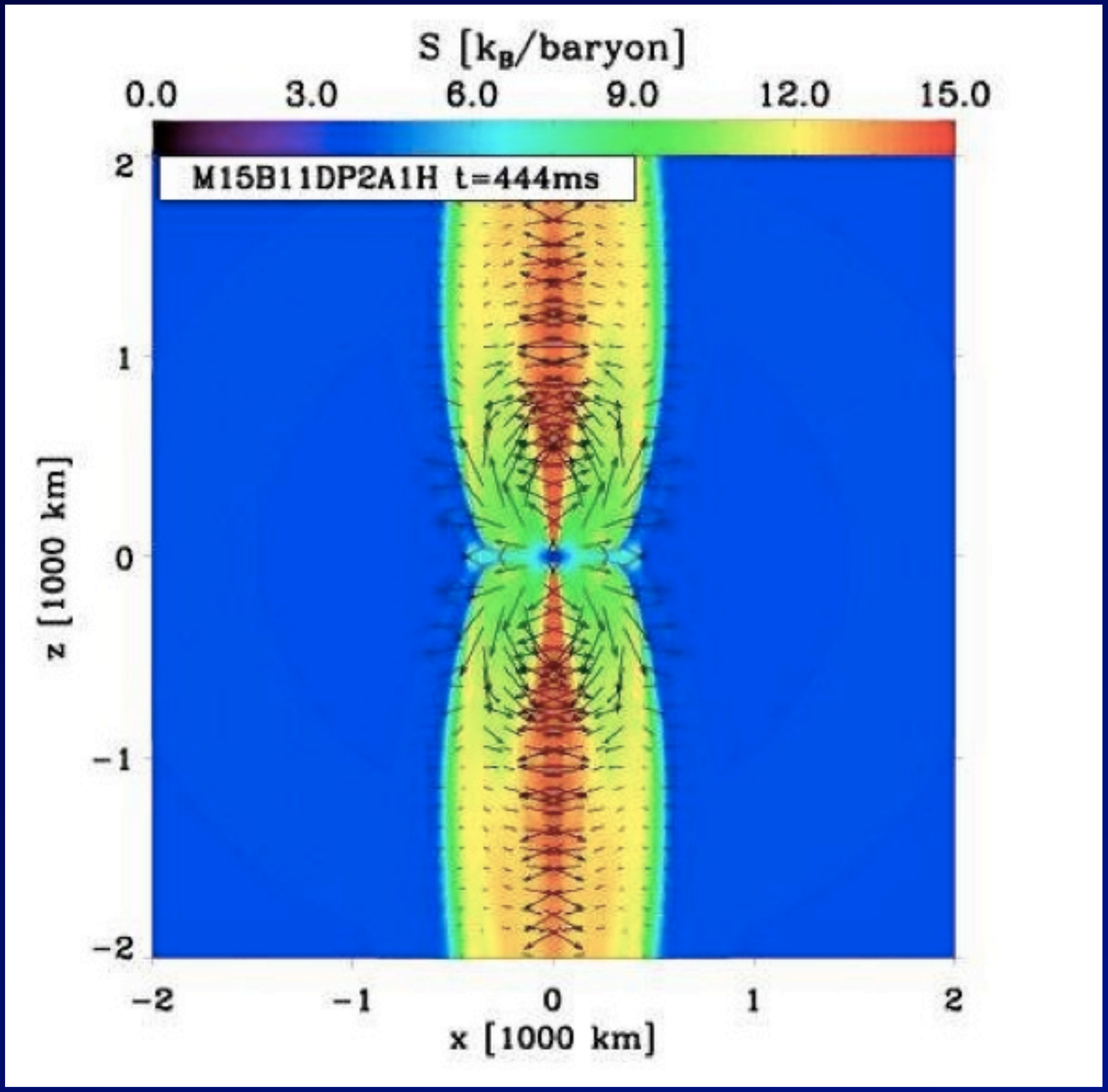
Magnetofluid dynamics:
"2.5D"

Neutrino transport:
2D + 1D

Burrows et al. (2006)



Burrows et al. (2007)



Fluid dynamics:
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Neutrino transport:
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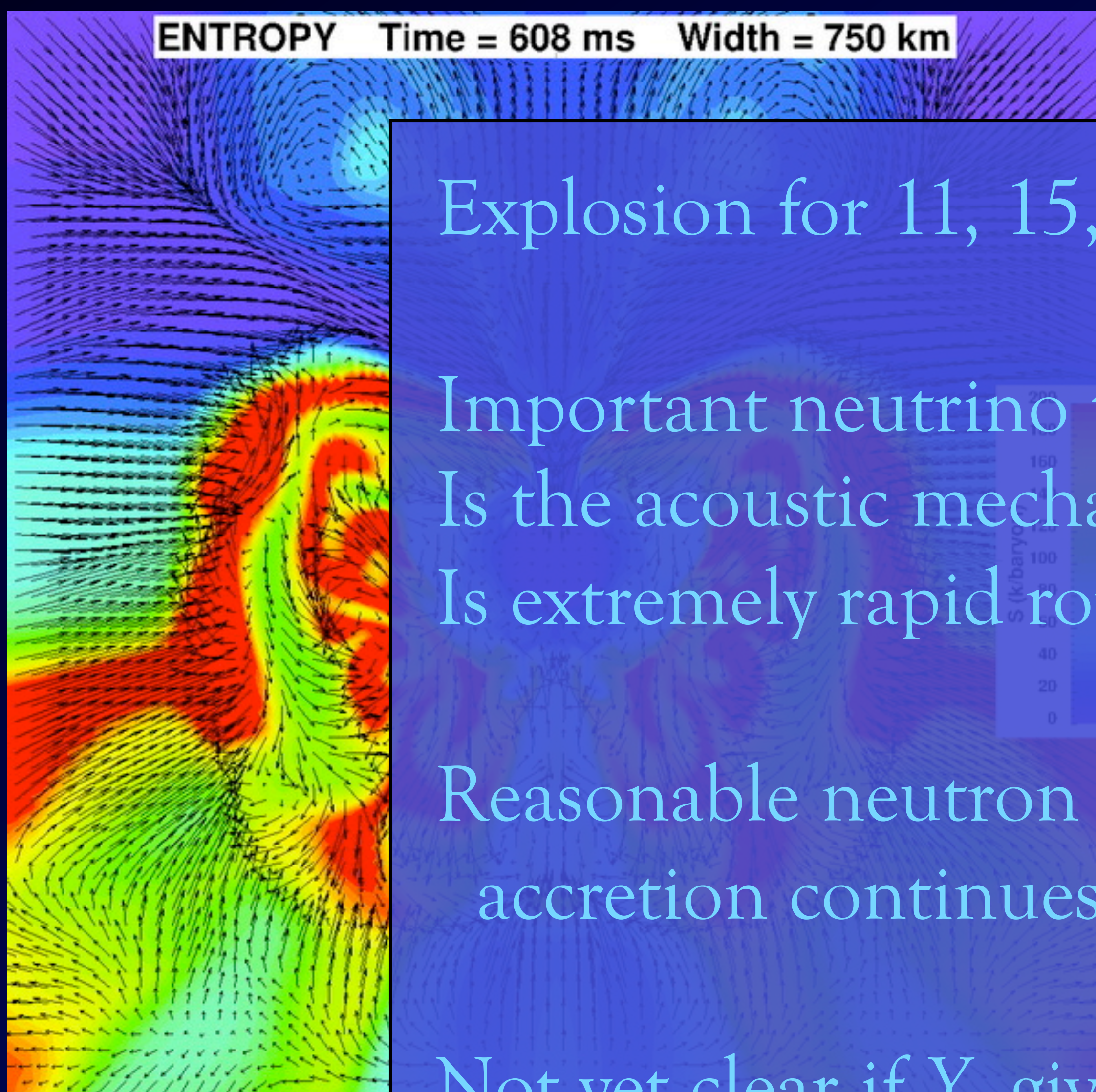

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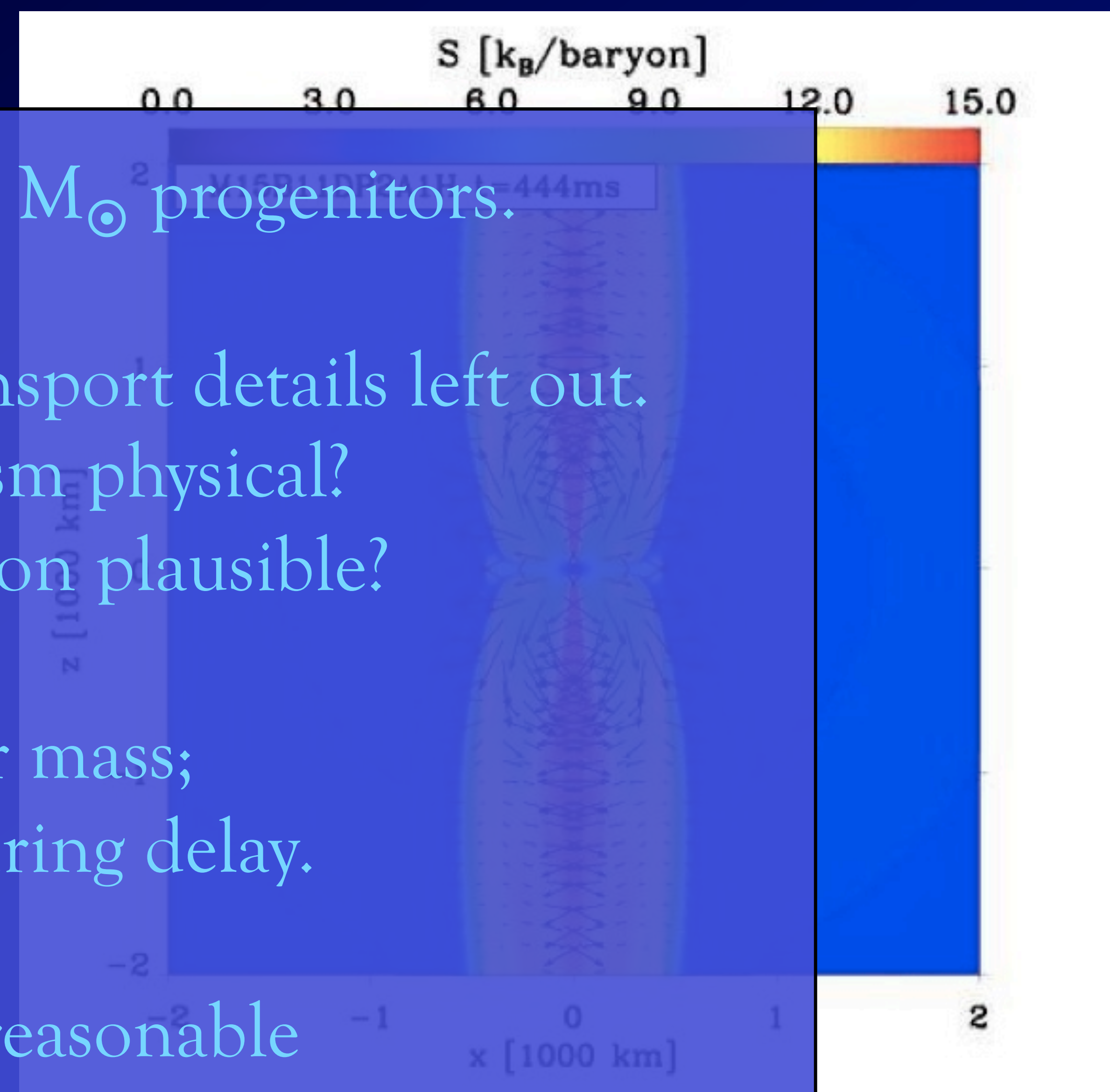


Explosion for 11, 15, 25 $M_\odot$ progenitors.

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

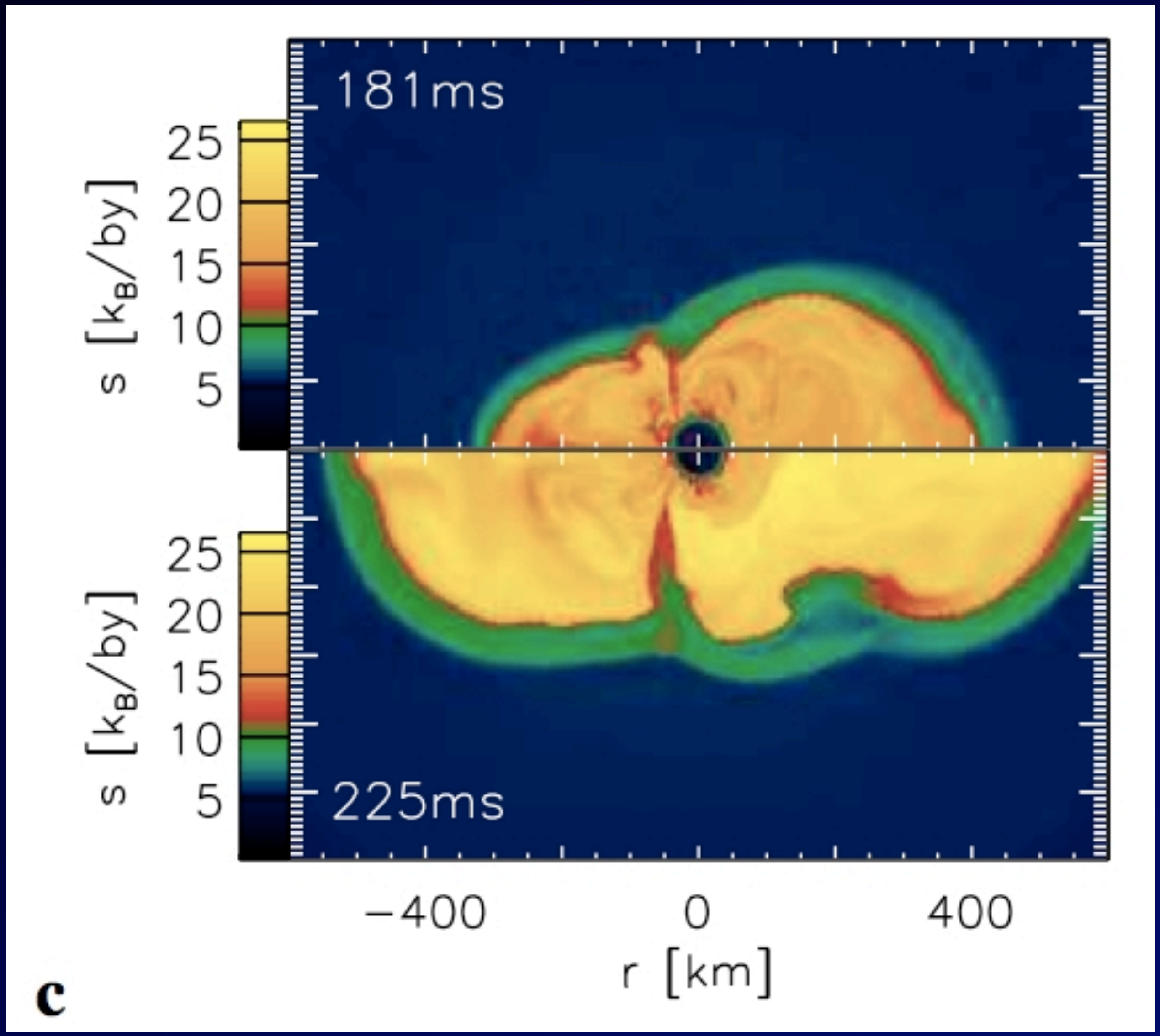
Neutrino transport:

1.5D + 2D

Fluid dynamics:
2D

Neutrino transport:
1.5D + 2D

Buras et al. (2006)



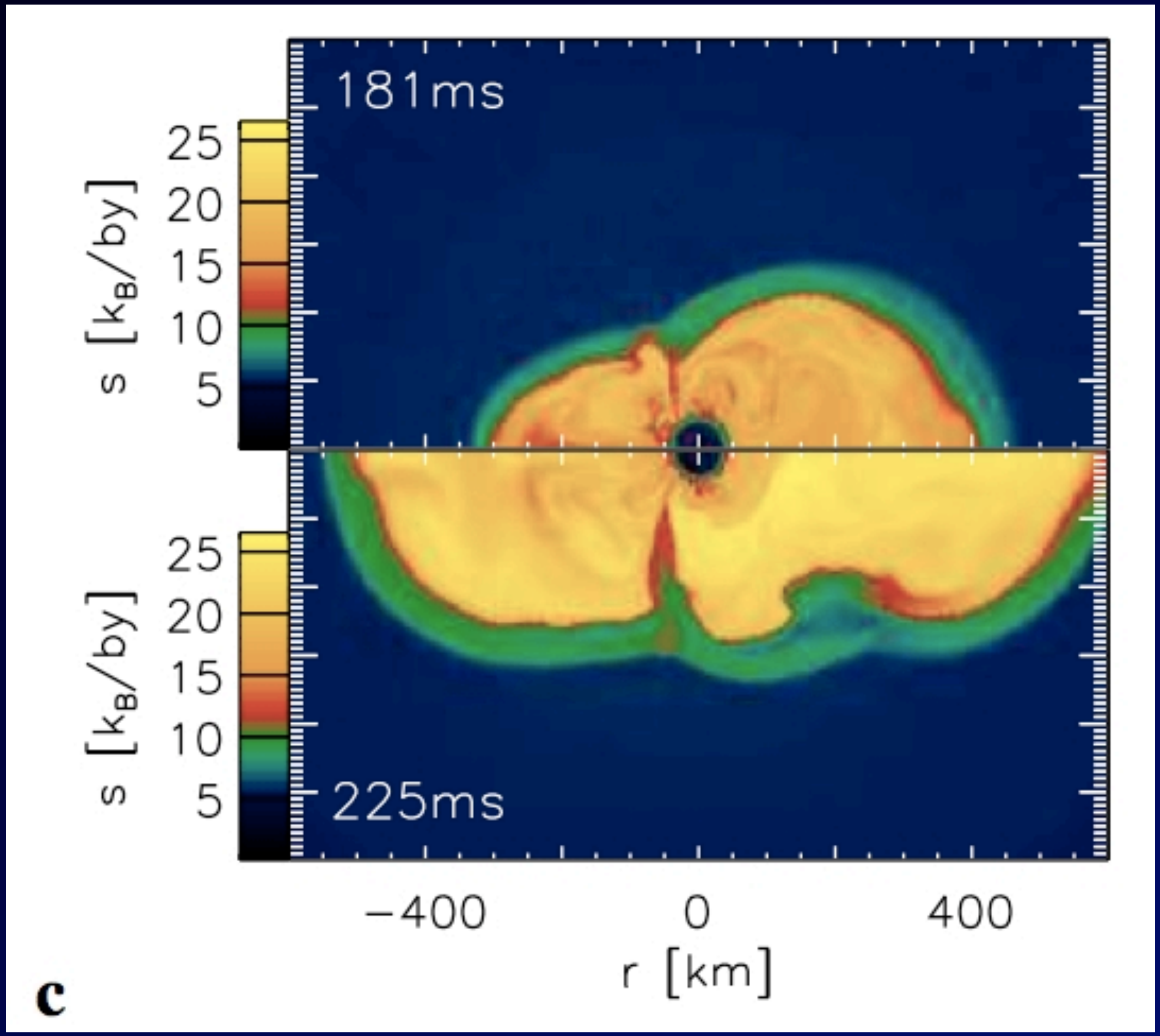
Fluid dynamics:
2D

Neutrino transport:
1.5D + 2D

Fluid dynamics:
2D

Neutrino transport:
1.5D + 1D

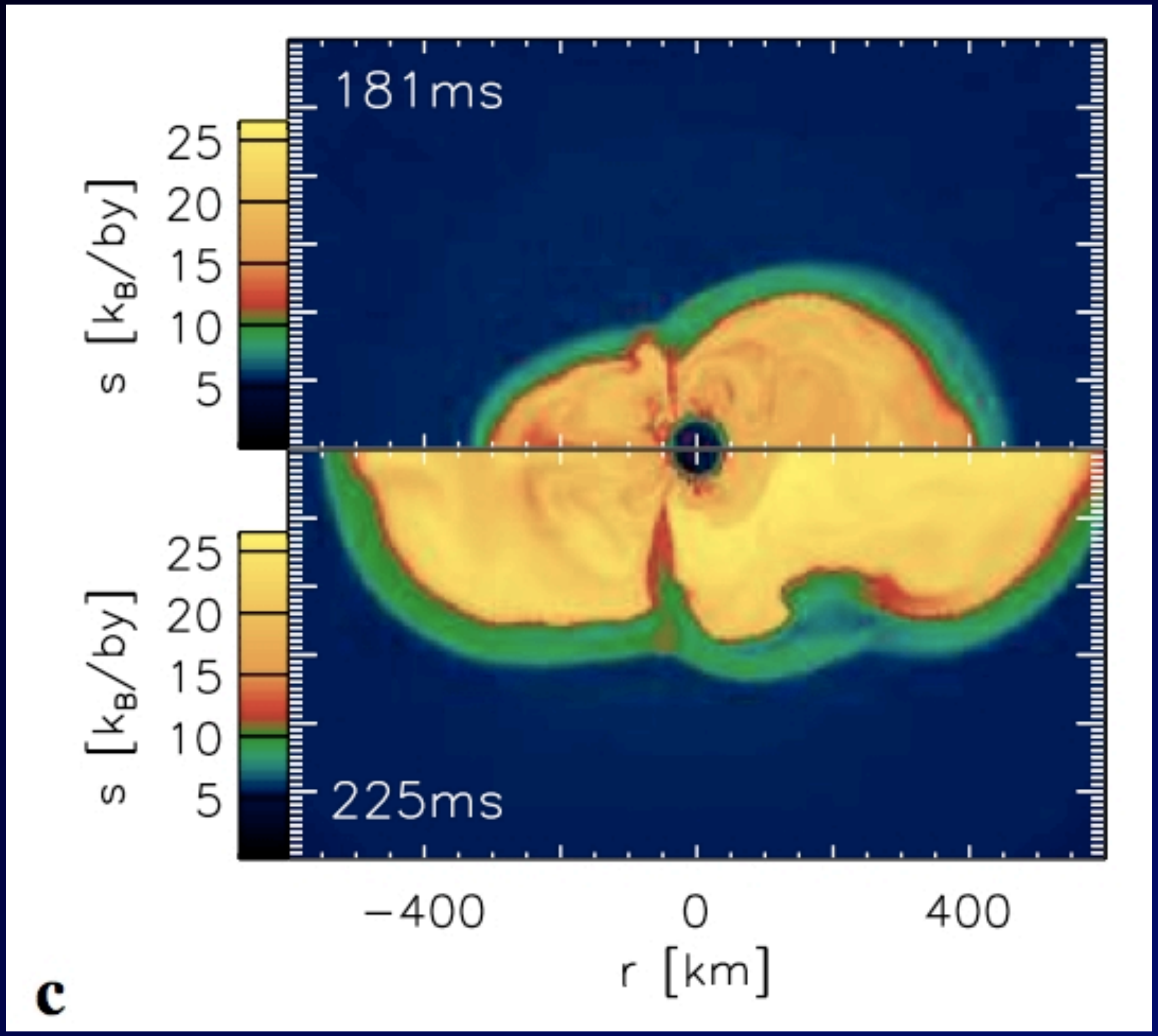
Buras et al. (2006)



Fluid dynamics:
2D

Neutrino transport:
1.5D + 2D

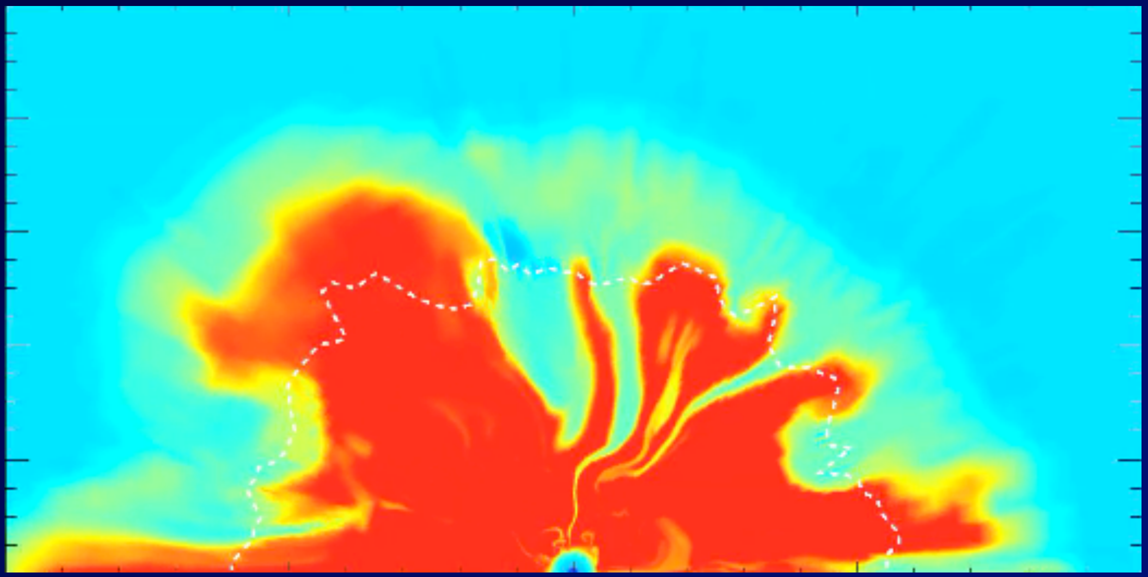
Buras et al. (2006)



Fluid dynamics:
2D

Neutrino transport:
1.5D + 1D

Bruenn et al. (2006)



Fluid dynamics:
2D

Neutrino transport:
1.5D + 2D

Fluid dynamics:
2D

Neutrino transport:
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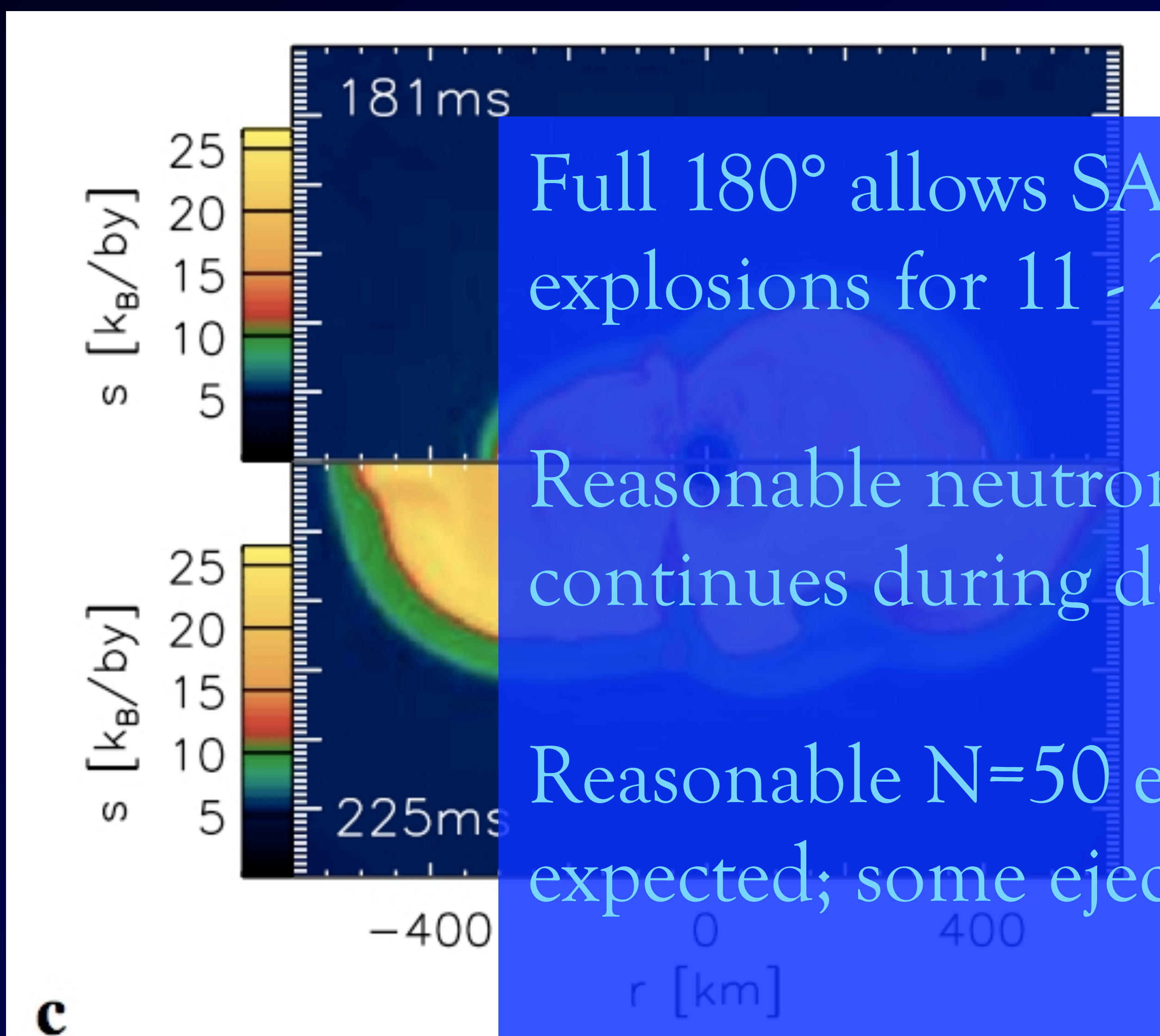

Bruenn et al. (2006)

Full 180° allows SASI-aided neutrino-driven explosions for 11 - 25 $M_\odot$

Reasonable neutron star mass; accretion continues during delay.

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

Acoustic mechanism not yet clearly probed.

Introduction

Stellar collapse and its aftermath

Explosion simulations

Conclusion

Introduction

Stellar collapse and its aftermath

Explosion simulations

Conclusion

A key feature of the history of supernova simulations is the ongoing increase in total dimensionality.

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Neutrino radiation transport

(Magneto)hydrodynamics

	1S 0M	1S 1M	3S 0M	1.5S 1M	1S 2M	2S 1M	1.5S 2M	2S 3M	3S 3M
1S									
2S									
3S									

A key feature of the history of supernova simulations is the ongoing increase in total dimensionality.

Neutrino radiation transport

(Magneto)hydrodynamics

	1S 0M	1S 1M	3S 0M	1.5S 1M	1S 2M	2S 1M	1.5S 2M	2S 3M	3S 3M
1S									
2S									
3S									

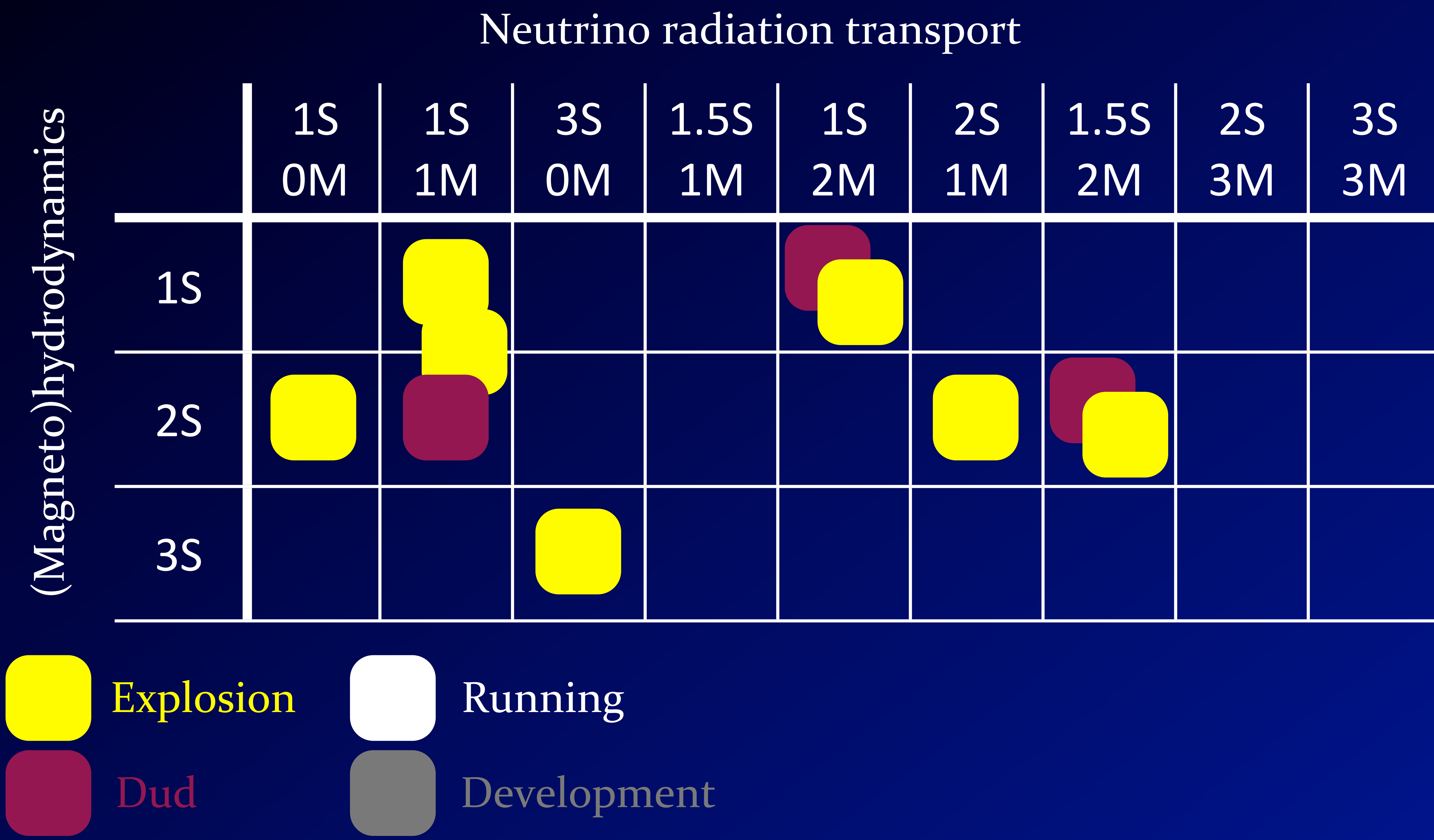
Explosion

Running

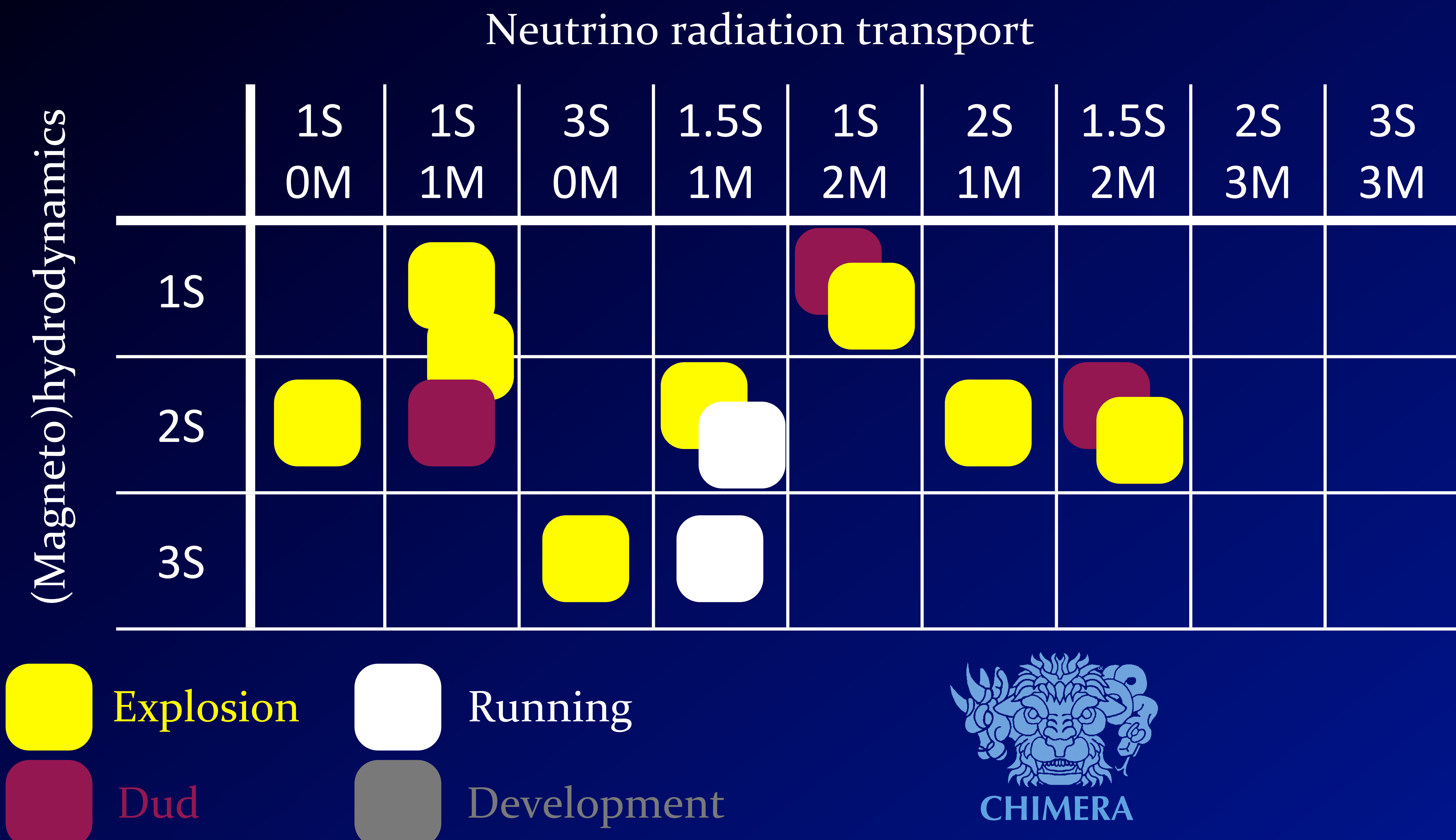
Dud

Development

A key feature of the history of supernova simulations is the ongoing increase in total dimensionality.



A key feature of the history of supernova simulations is the ongoing increase in total dimensionality.



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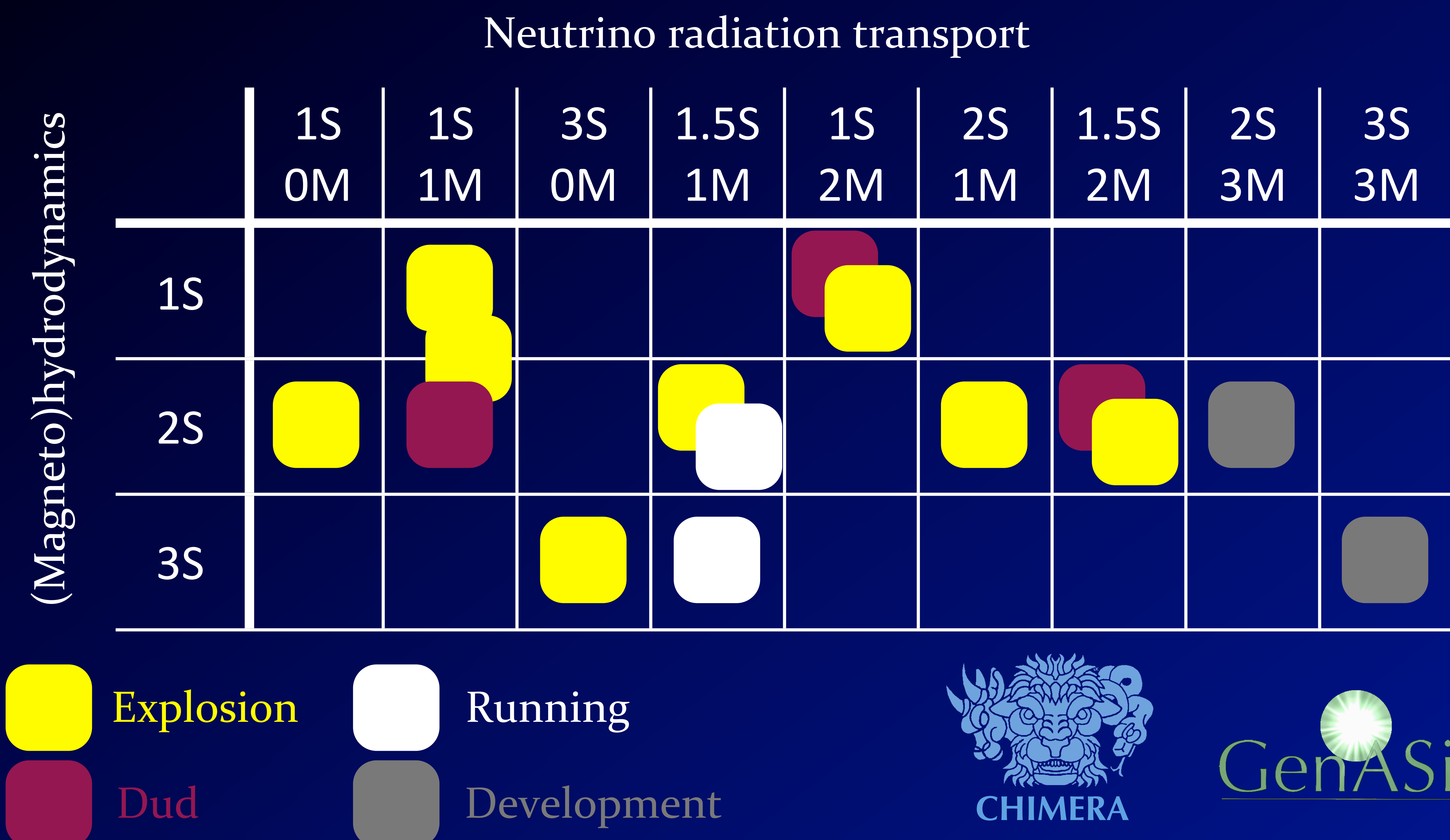

CHIMERA

GenASiS

The Oak Ridge and Garching groups both see SASI-aided neutrino-driven explosions across a range of progenitor masses.

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The Tucson / Princeton group does not see neutrino-driven explosions, but instead SASI-aided acoustically-driven explosions at a later time.

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Differences include but are not limited to

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Differences include but are not limited to

“Ray-by-ray” neutrino transport vs. flux-limited diffusion

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The Tucson / Princeton group does not see neutrino-driven explosions, but instead SASI-aided acoustically-driven explosions at a later time.

Differences include but are not limited to

- “Ray-by-ray” neutrino transport vs. flux-limited diffusion
- Inclusion of Doppler shift terms, completeness of energy exchange interactions in neutrino transport

The Oak Ridge and Garching groups both see SASI-aided neutrino-driven explosions across a range of progenitor masses.

The Tucson / Princeton group does not see neutrino-driven explosions, but instead SASI-aided acoustically-driven explosions at a later time.

Differences include but are not limited to

- "Ray-by-ray" neutrino transport vs. flux-limited diffusion
- Inclusion of Doppler shift terms, completeness of energy exchange interactions in neutrino transport
- Treatment of gravity: partially relativistic, partially conservative

Simulations of the explosion mechanism lack flavor mixing and adequate evolution time.

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Calculations of flavor mixing lack multidimensionality, collisions, Doppler and gravitational redshift and aberration, self-consistency with the fluid background, and time dependence.

Bruenn
Marronetti
Yakunin
Dirk

Blondin
Warren

Fuller

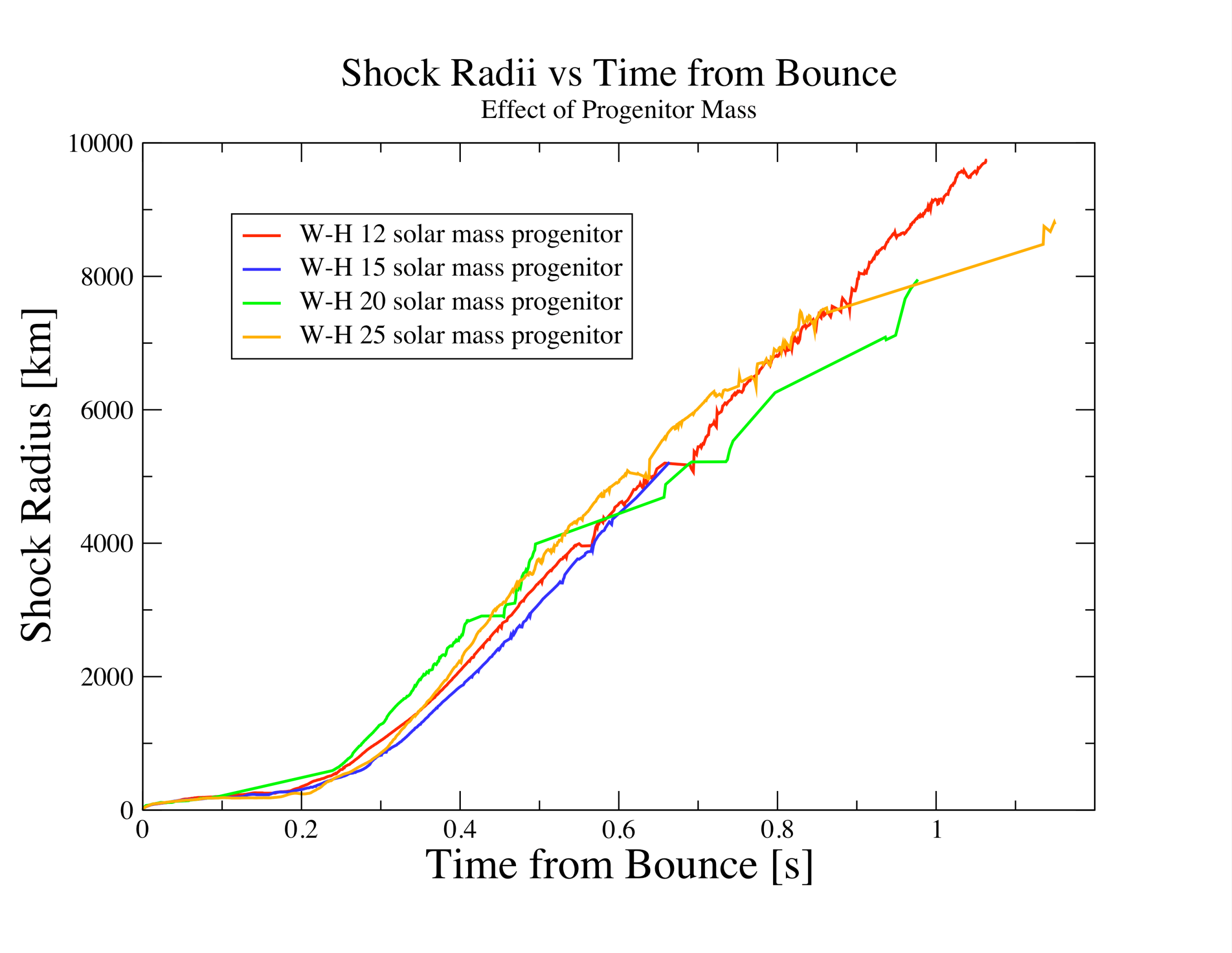
Budiardja
Cardall
Endeve
Hix
Lentz
Messer
Mezzacappa
Parete-Koon

<u>Collaborators</u>

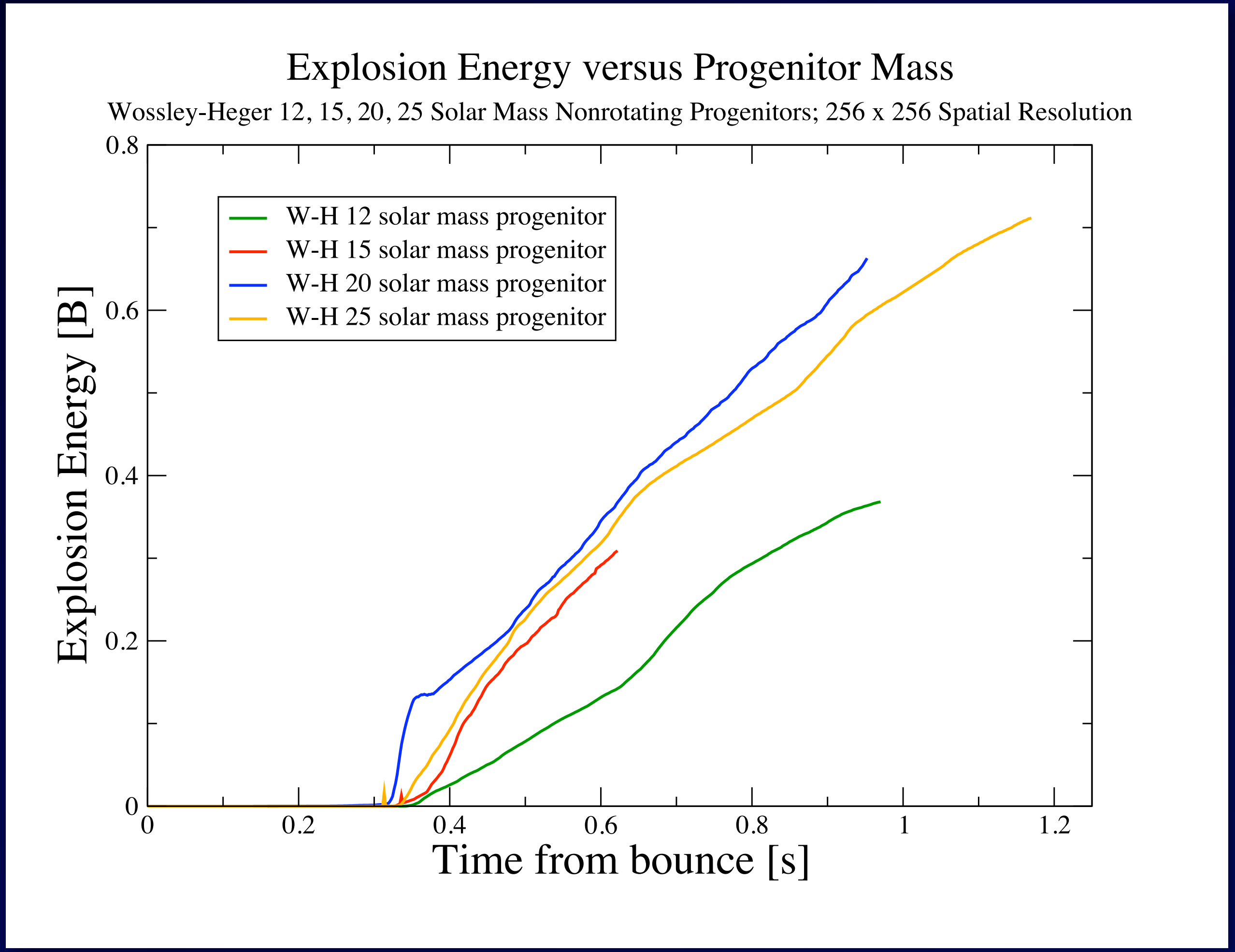
- *Solvers: D'Azevedo*
- *Data Management: Barreto, Canon, Klasky, Podhorszki*
- *Networking: Beck, Moore, Rao*
- *Visualization: Ahern, Daniel, Ma, Meredith, Pugmire, Toedte*
- *Cray Center of Excellence: Levesque, Wichmann*

<u>Funded by</u>

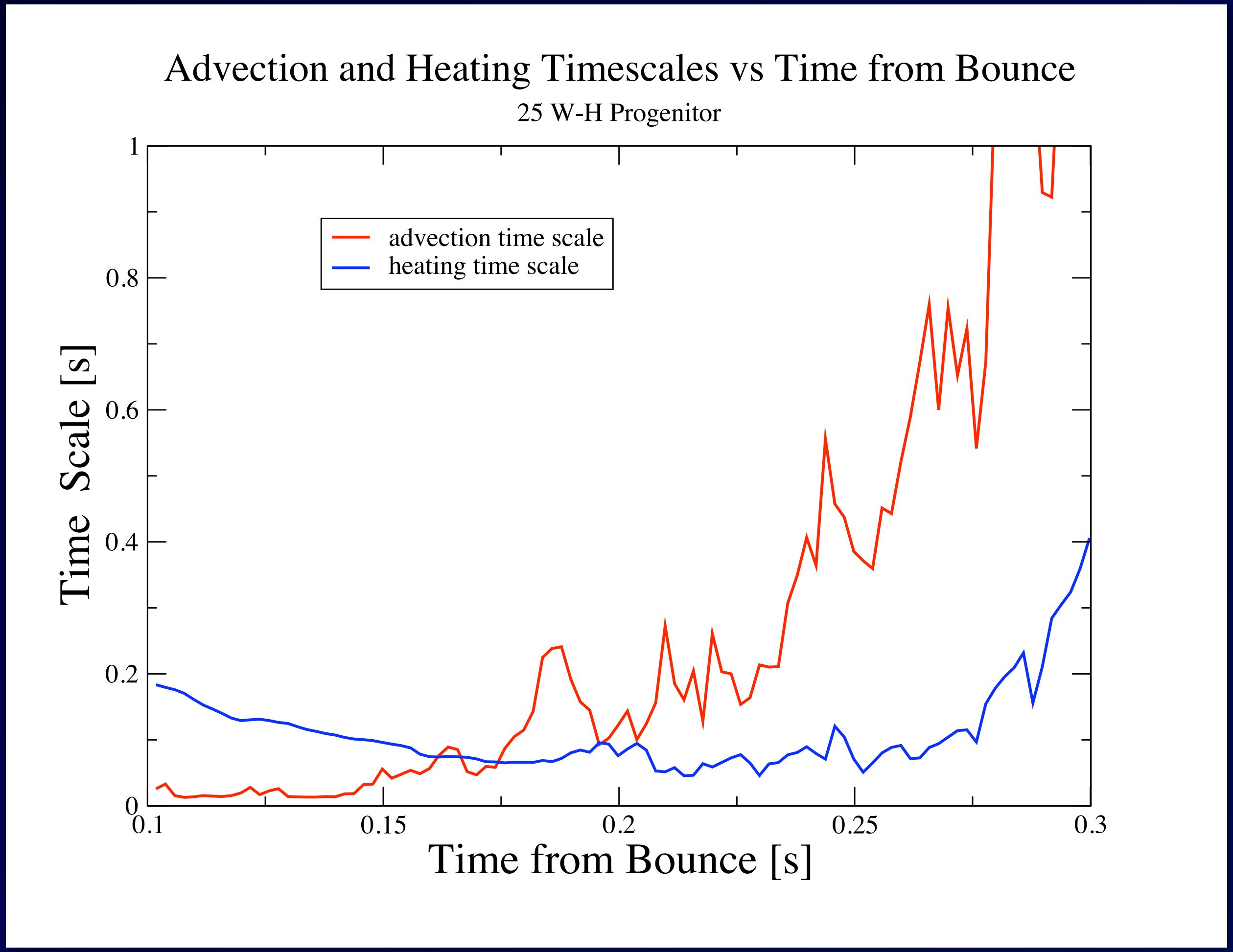
Office of Science
U.S. DEPARTMENT OF ENERGY



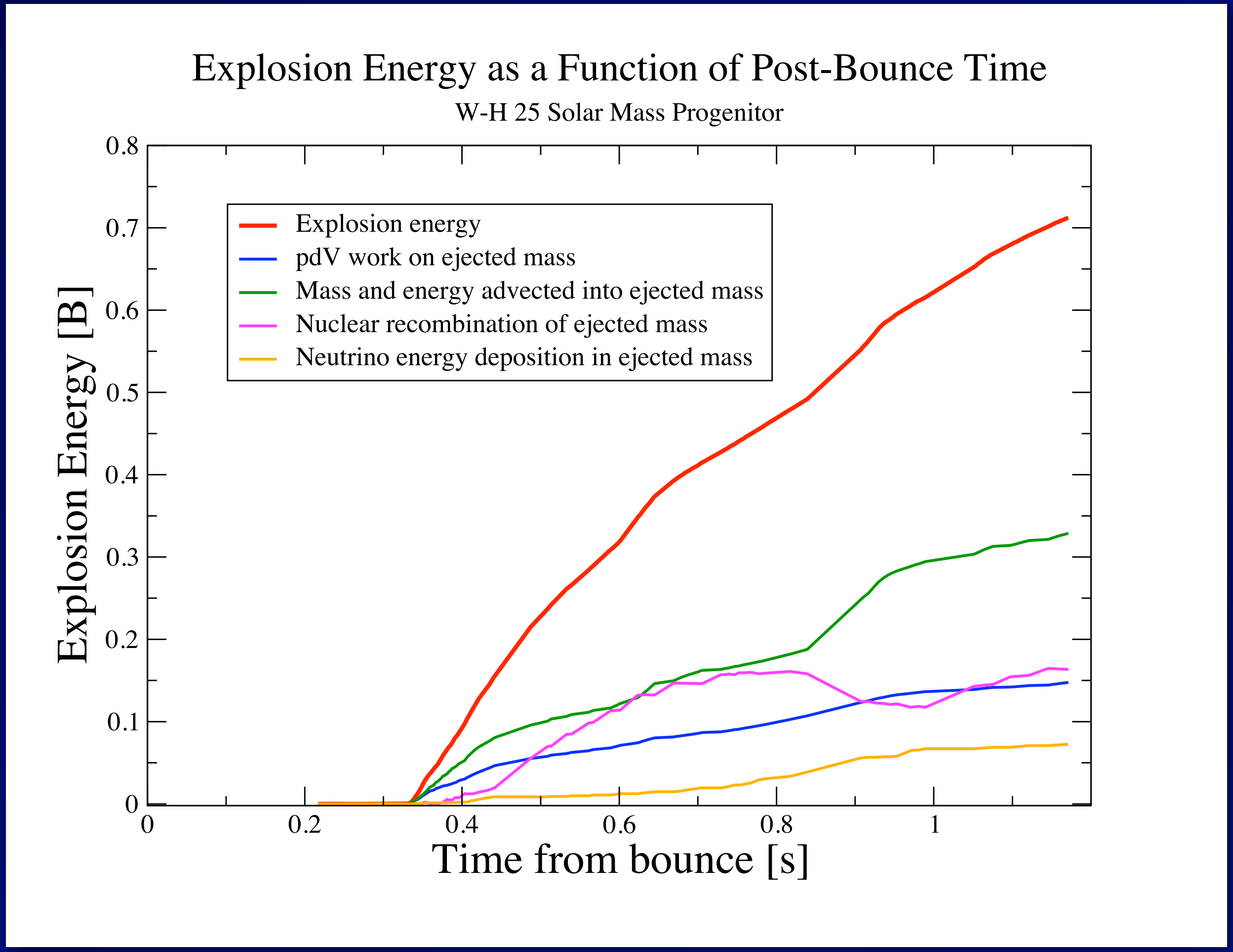
Shock Radii vs Time from Bounce
Effect of Progenitor Mass
W-H 12 solar mass progenitor
W-H 15 solar mass progenitor
W-H 20 solar mass progenitor
W-H 25 solar mass progenitor
Shock Radius [km]
Time from Bounce [s]



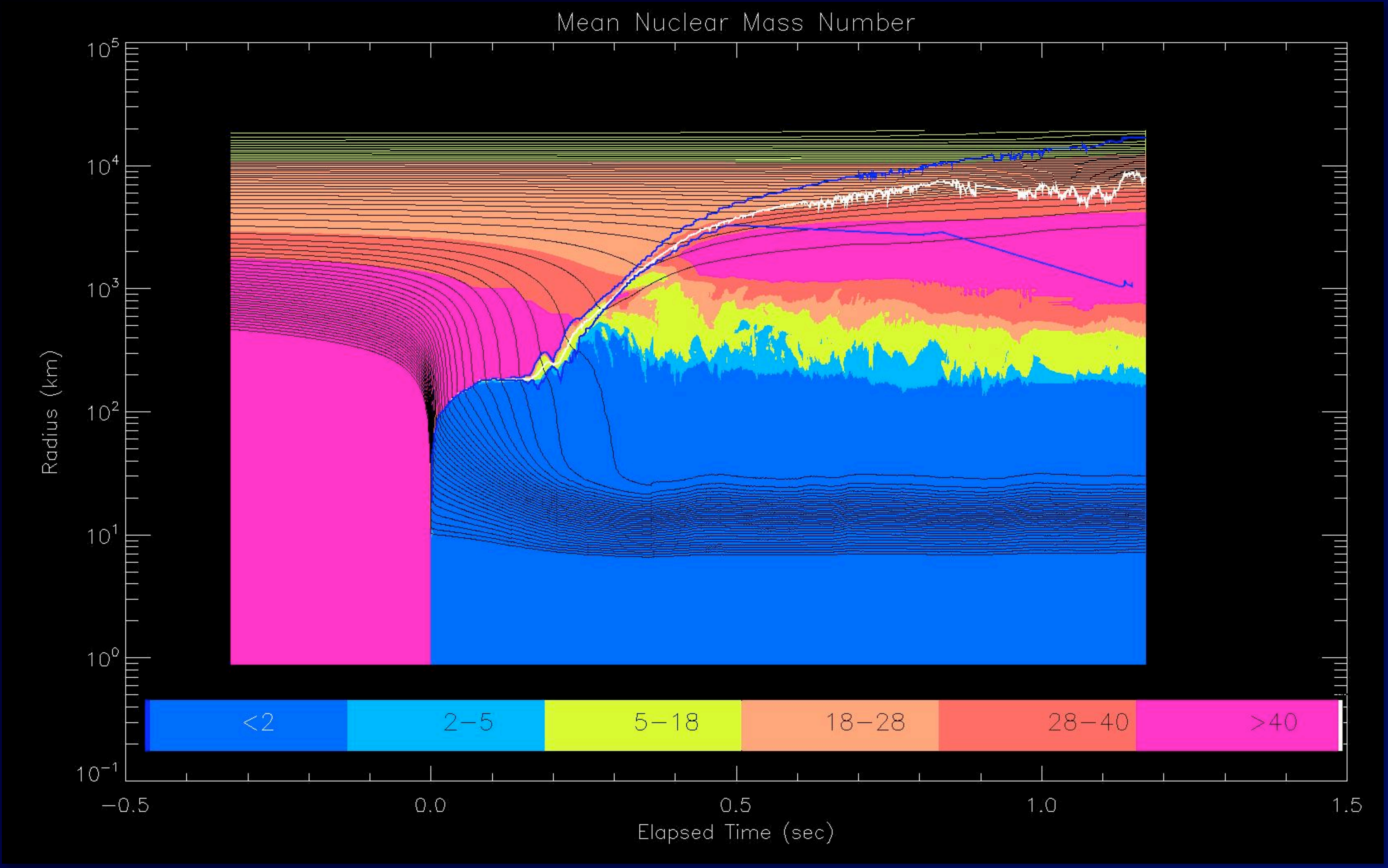
Explosion Energy versus Progenitor Mass
Wossley-Heger 12, 15, 20, 25 Solar Mass Nonrotating Progenitors; 256 x 256 Spatial Resolution
W-H 12 solar mass progenitor
W-H 15 solar mass progenitor
W-H 20 solar mass progenitor
W-H 25 solar mass progenitor
Explosion Energy [B]
Time from bounce [s]



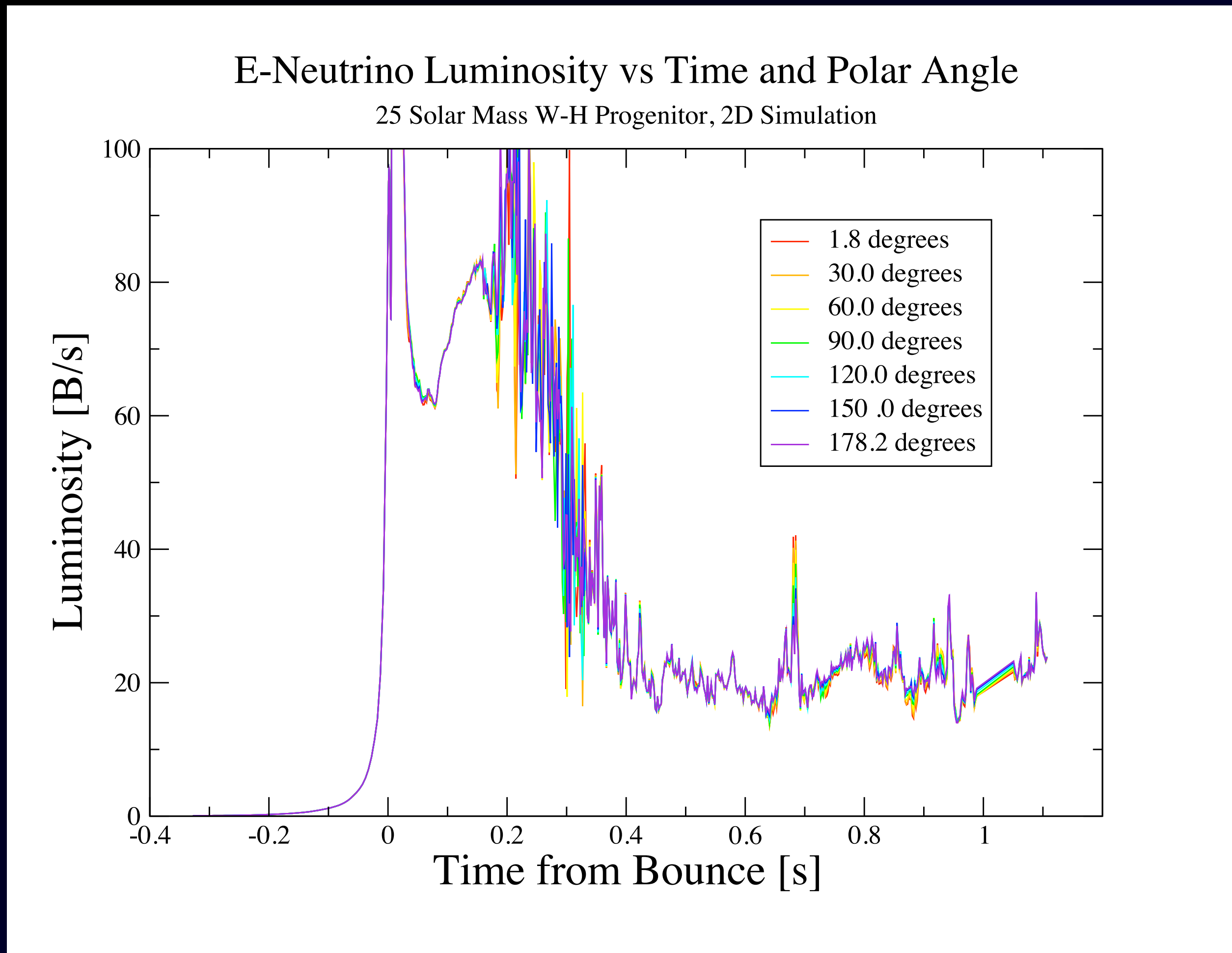
Advection and Heating Timescales vs Time from Bounce
25 W-H Progenitor
advection time scale
heating time scale
Time Scale [s]
Time from Bounce [s]

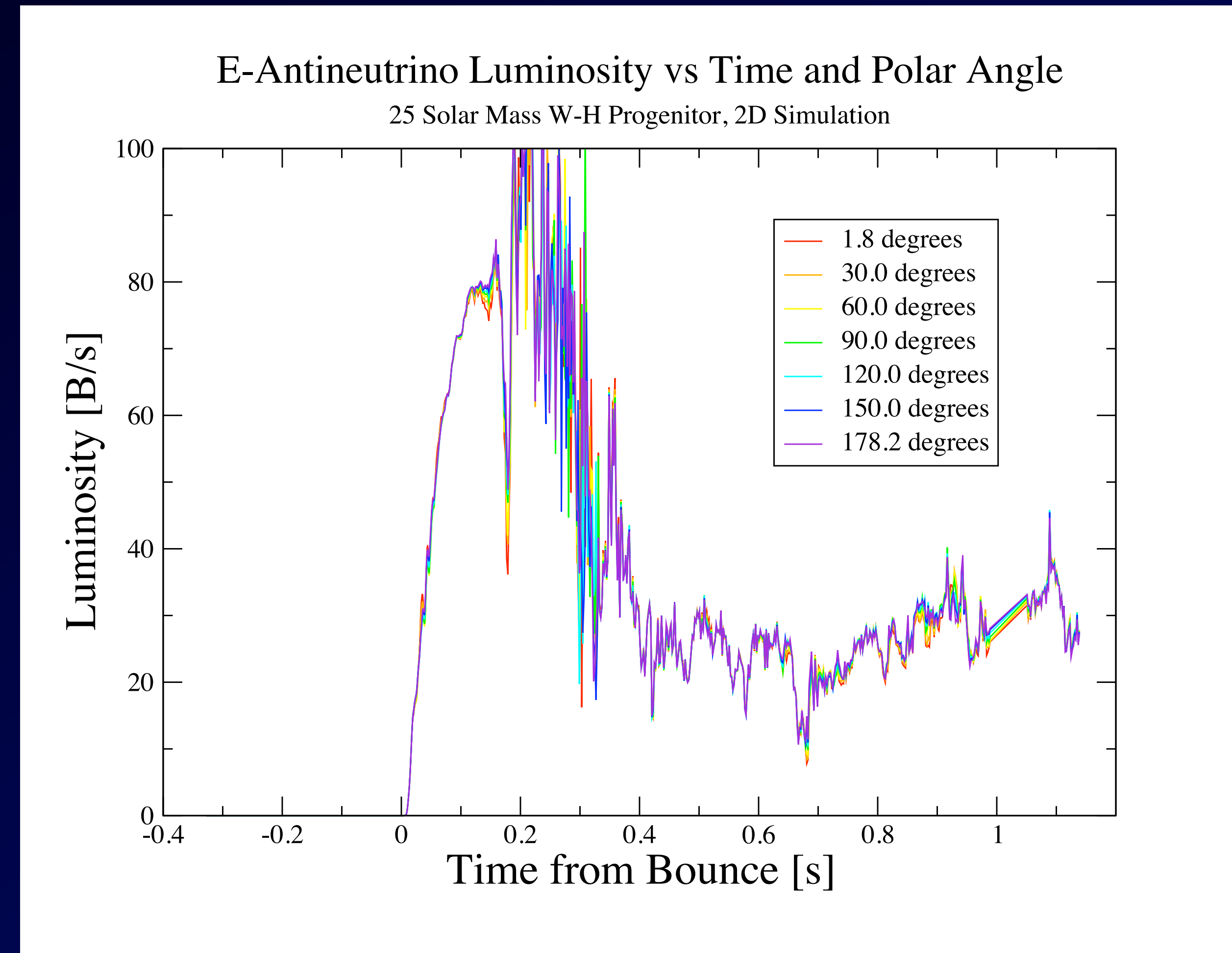


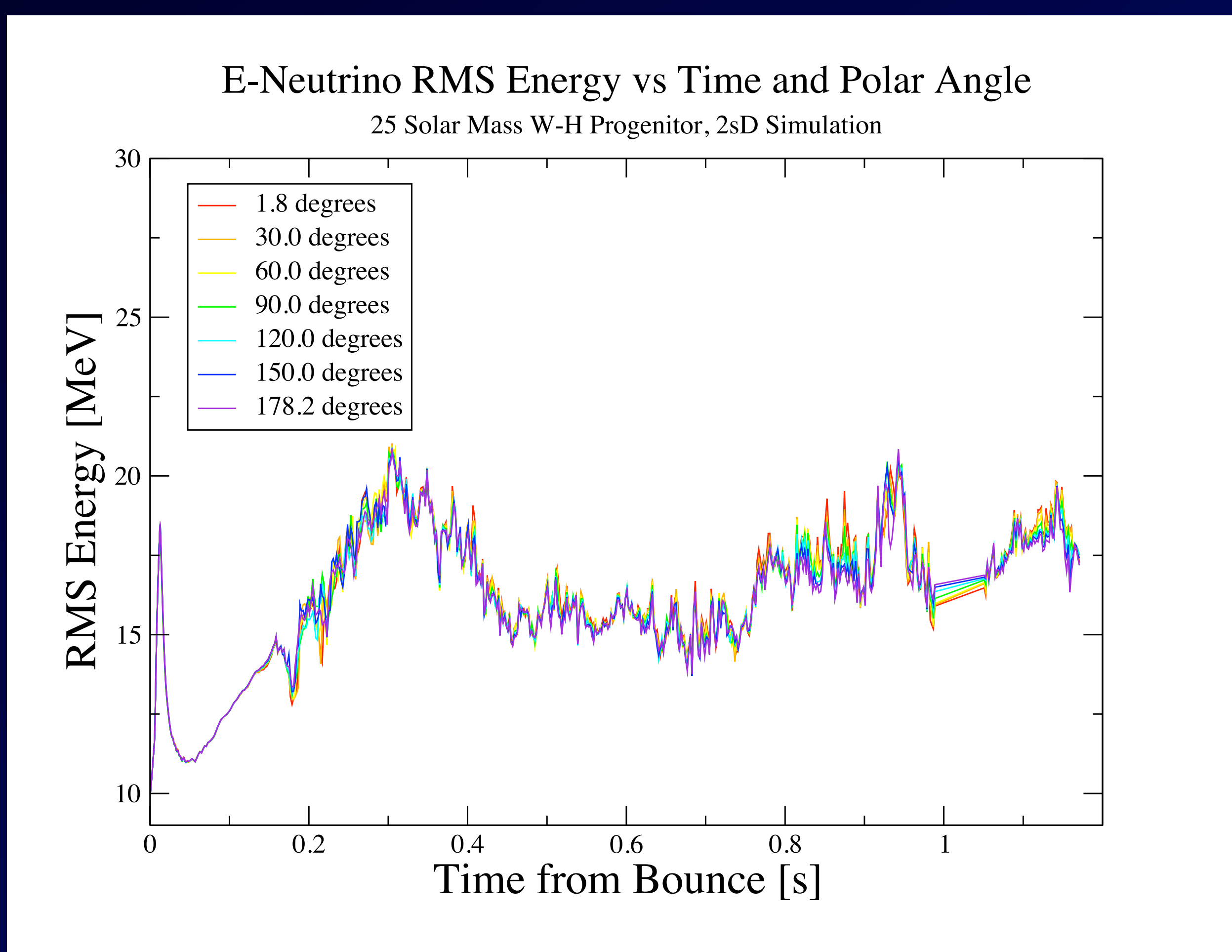
Explosion Energy as a Function of Post-Bounce Time
W-H 25 Solar Mass Progenitor
Explosion energy
pdV work on ejected mass
Mass and energy advected into ejected mass
Nuclear recombination of ejected mass
Neutrino energy deposition in ejected mass
Explosion Energy [B]
Time from bounce [s]

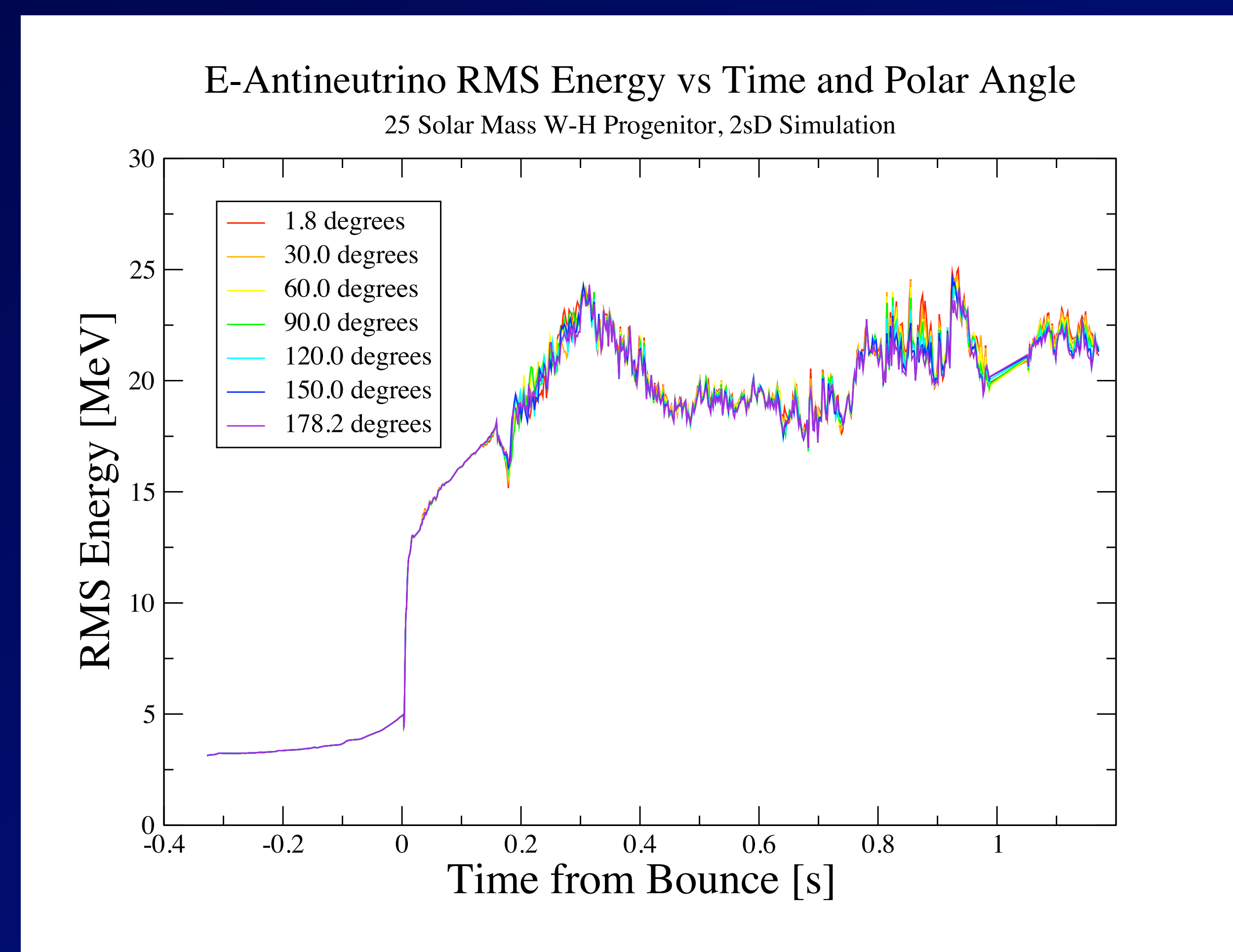


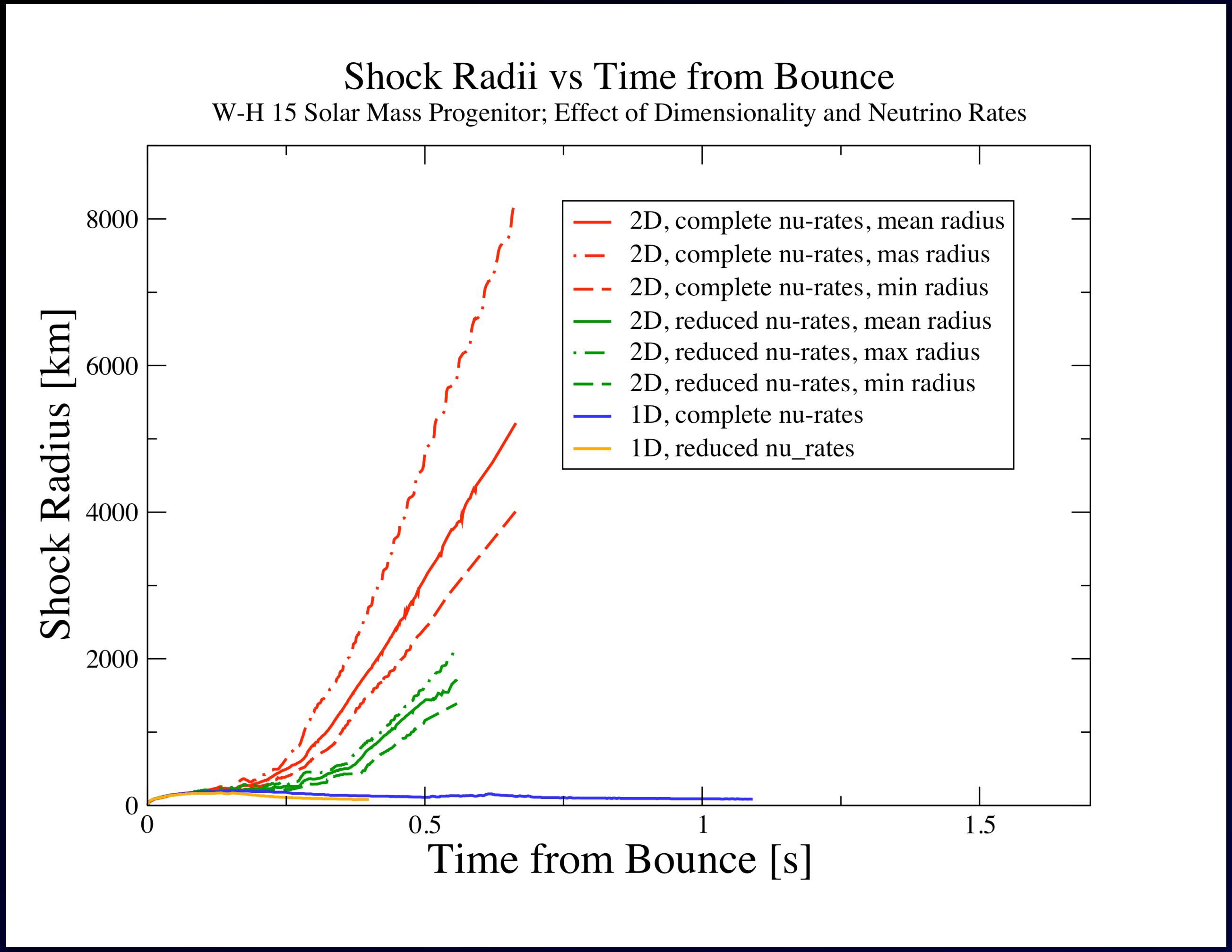
Mean Nuclear Mass Number
Radius (km)
Elapsed Time (sec)
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
−0.5
0.0
0.5
1.0
1.5
<2
2−5
5−18
18−28
28−40
>40


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
0
20
40
60
80
100
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

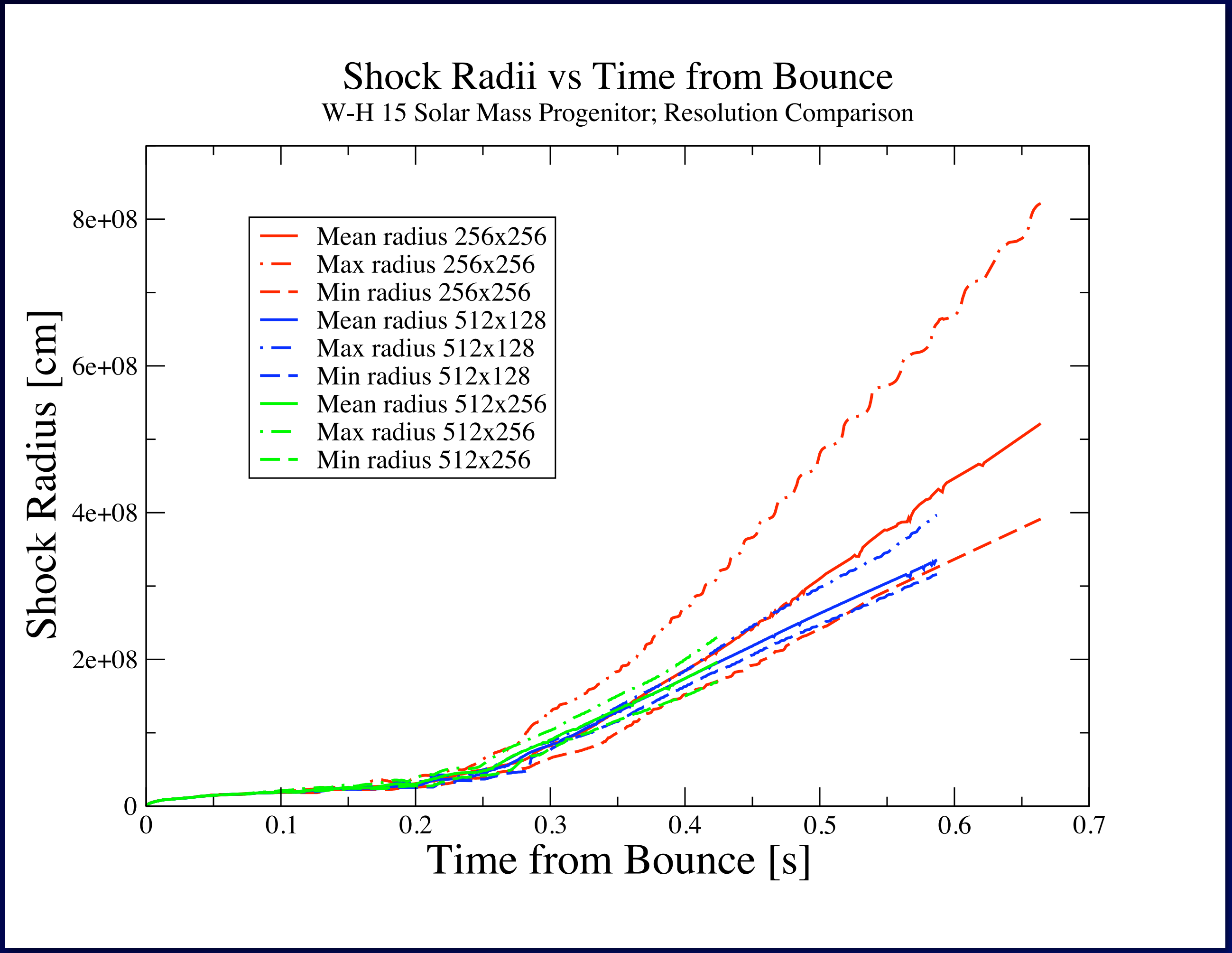

E-Antineutrino Luminosity vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2D Simulation
Luminosity [B/s]
Time from Bounce [s]
1.8 degrees
30.0 degrees
60.0 degrees
90.0 degrees
120.0 degrees
150.0 degrees
178.2 degrees
0
20
40
60
80
100
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1


E-Neutrino RMS Energy vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2sD Simulation
RMS Energy [MeV]
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
10
15
20
25
30
0
0.2
0.4
0.6
0.8
1

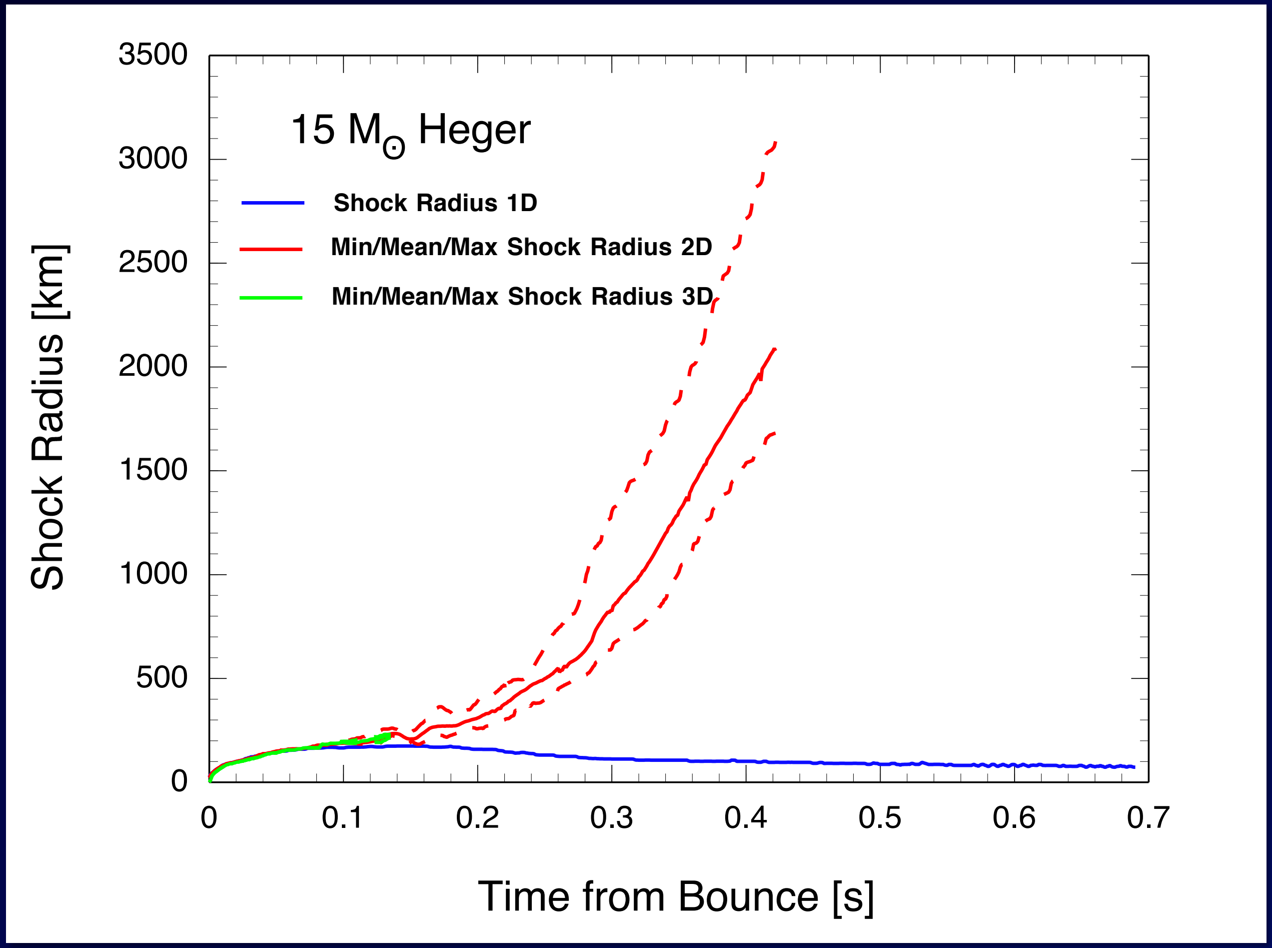

E-Antineutrino RMS Energy vs Time and Polar Angle
25 Solar Mass W-H Progenitor, 2sD Simulation
RMS Energy [MeV]
Time from Bounce [s]
1.8 degrees
30.0 degrees
60.0 degrees
90.0 degrees
120.0 degrees
150.0 degrees
178.2 degrees
0
5
10
15
20
25
30
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1



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]
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]
Time from Bounce [s]



15 $M_{\odot}$ Heger
Shock Radius 1D
Min/Mean/Max Shock Radius 2D
Min/Mean/Max Shock Radius 3D
Shock Radius [km]
Time from Bounce [s]