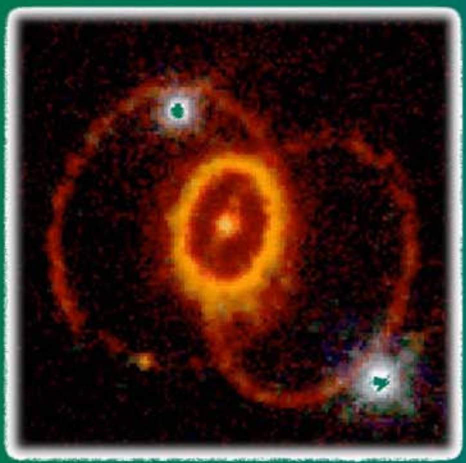
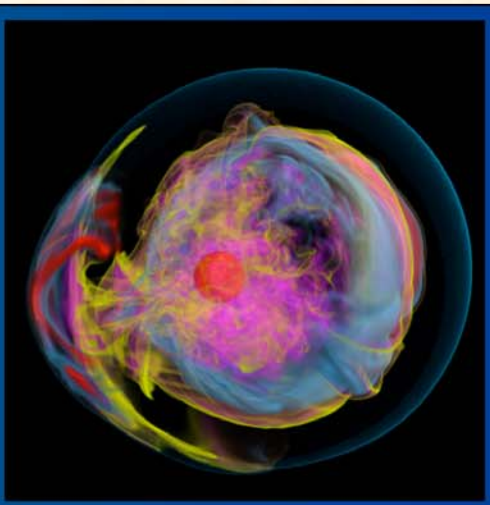
Exploding Stars on Supercomputers





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Terascale Supernova Initiative

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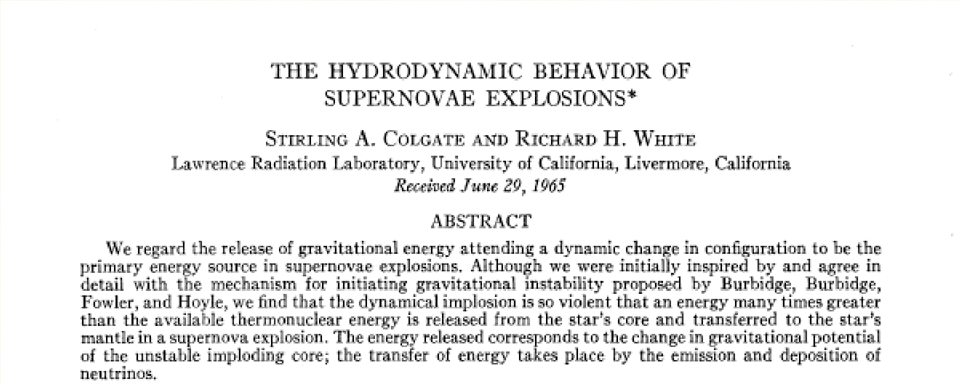
Supernova modeling marked the genesis of computational astrophysics


THE HYDRODYNAMIC BEHAVIOR OF SUPERNOVAE EXPLOSIONS*

STIRLING A. COLGATE AND RICHARD H. WHITE
Lawrence Radiation Laboratory, University of California, Livermore, California
Received June 29, 1965

ABSTRACT

We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, and Hoyle, we find that the dynamical implosion is so violent that an energy many times greater than the available thermonuclear energy is released from the star's core and transferred to the star's mantle in a supernova explosion. The energy released corresponds to the change in gravitational potential of the unstable imploding core; the transfer of energy takes place by the emission and deposition of neutrinos.

Colgate & White 1966, **ApJ**,143, 626

J. Wilson w/ Cray-2

"The reason this paper is cited so many times is because it started the new endeavor of hydrodynamic stellar modeling. It is ironic that this work started because of an argument with Soviet scientists during the negotiations for the Cessation of Nuclear Weapons Tests in Geneva in 1959. It was claimed by me that the radiation emissions from a supernova might trigger the then proposed detection net for high altitude nuclear explosions that the Soviets were proposing. This objection of a possible false triggering of the system was brushed aside by the Soviet Ambassador Tsarpkin because, 'Who knows what a supernova would look like?'" - S. Colgate *The Scientist* 12/1/1980

Two guys in the ORNL CAVE

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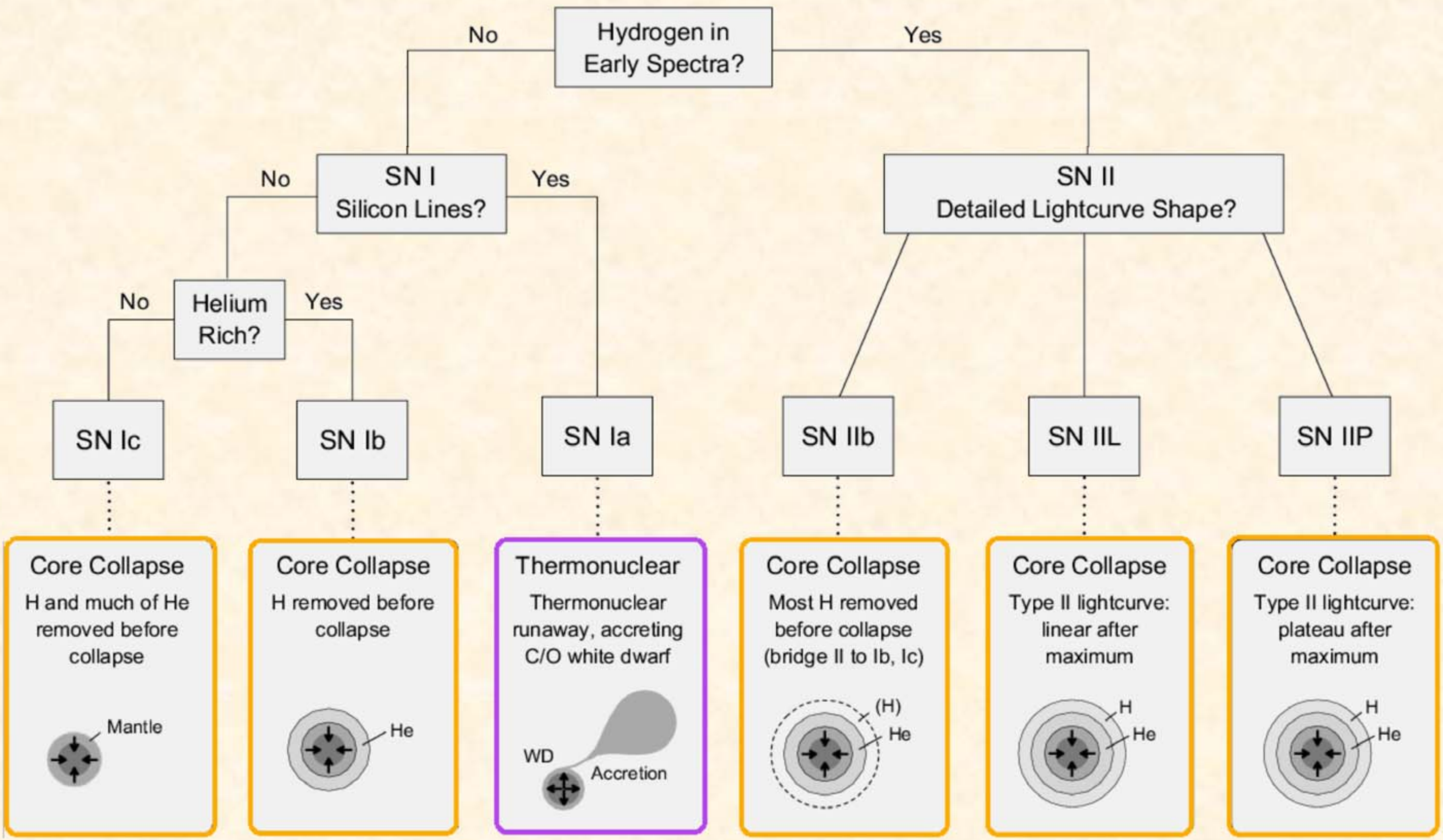
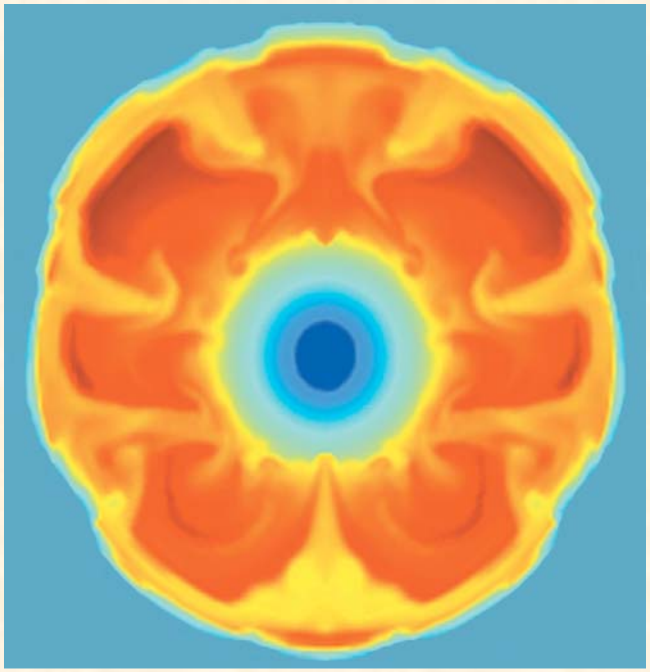
Supernova Types

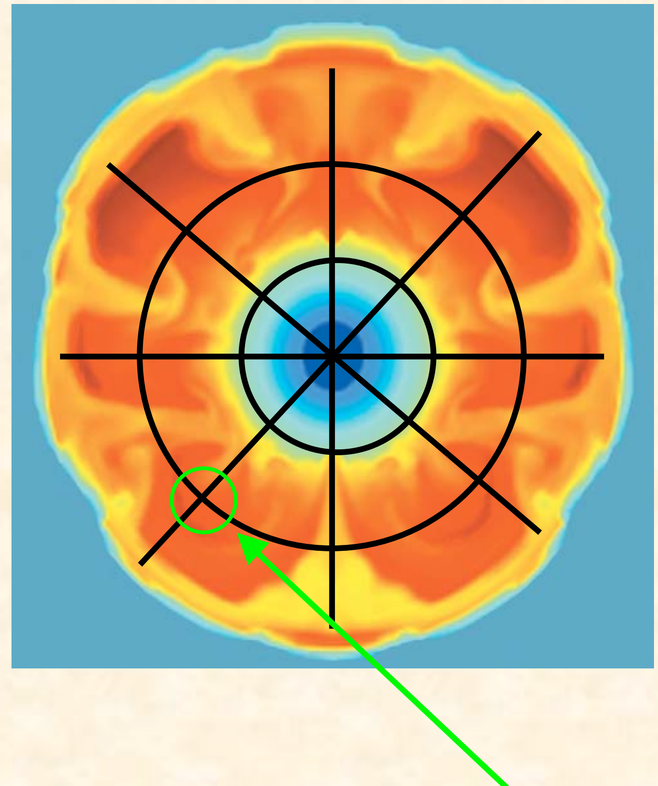


Computing Supernova Evolution

Infinite Number of Points



Finite Number of Points

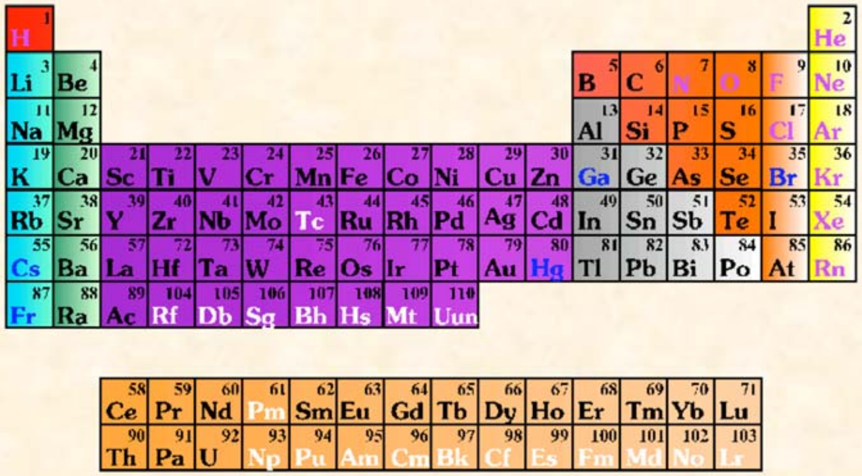


$$\frac{\partial(r^2\rho F)}{\partial m} \rightarrow \frac{(r^2{}_{i+1}\rho_{i+1}F_{i+1} - r^2{}_i\rho_i F_i)}{\Delta m_{i+1/2}} \qquad F_{i,j}$$

Different physical mechanisms require different collections of algorithmic techniques

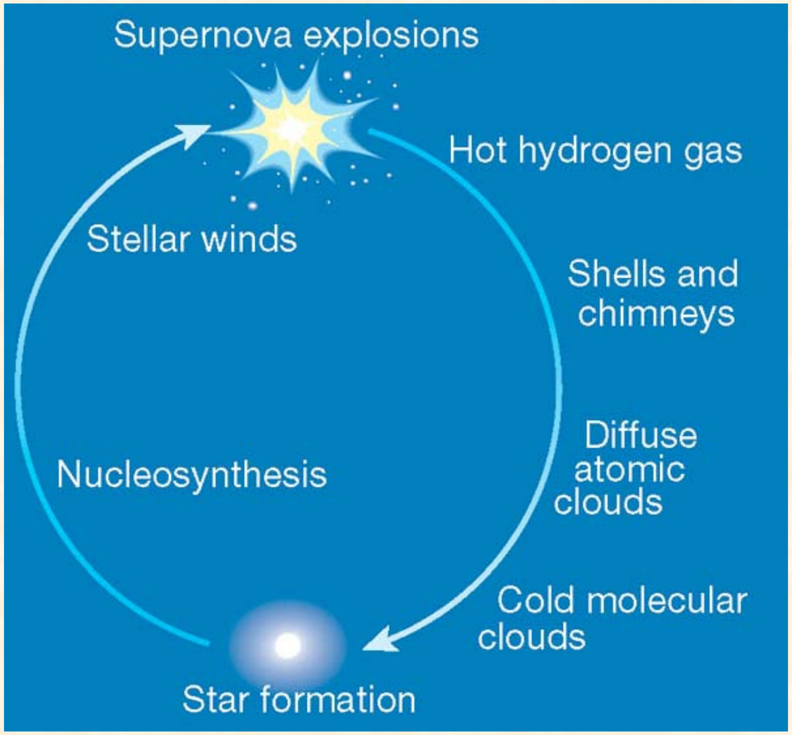
Core-collapse		Thermonuclear	
Compressible hydrodynamics	Finite-volume (PPM), finite-difference schemes	Compressible hydrodynamics	Finite-volume (PPM), finite-difference schemes
Strong gravity	Elliptic solvers - multigrid, multipole; GR - hyperbolic hydrodynamics and field equations	Need precise gravity calculations (buoyancy)	Elliptic solvers - multigrid, multipole
Neutrino transport	Linear system solution (sparse, non-symmetric)	Flame tracking	Front-tracking schemes, level sets
Nuclear matter equation of state	Requires fast mathematical primitives and carefully constructed data structures	Nuclear burning	Linear system solution (sparse, non-symmetric)
Requires large local memories for adequate phase space resolution in transport calculations		Requires large global memory to span vastly disparate spatial scales (+LES)	

Why Are Supernovae Interesting?



Core collapse supernovae are the dominant source of the elements between oxygen and iron.

Thermonuclear supernovae are responsible for essentially all of the iron in your blood.



Core collapse supernovae trigger star formation.

Thermonuclear supernovae have been used as 'standard candles' to determine the size, shape, and overall nature of the Universe

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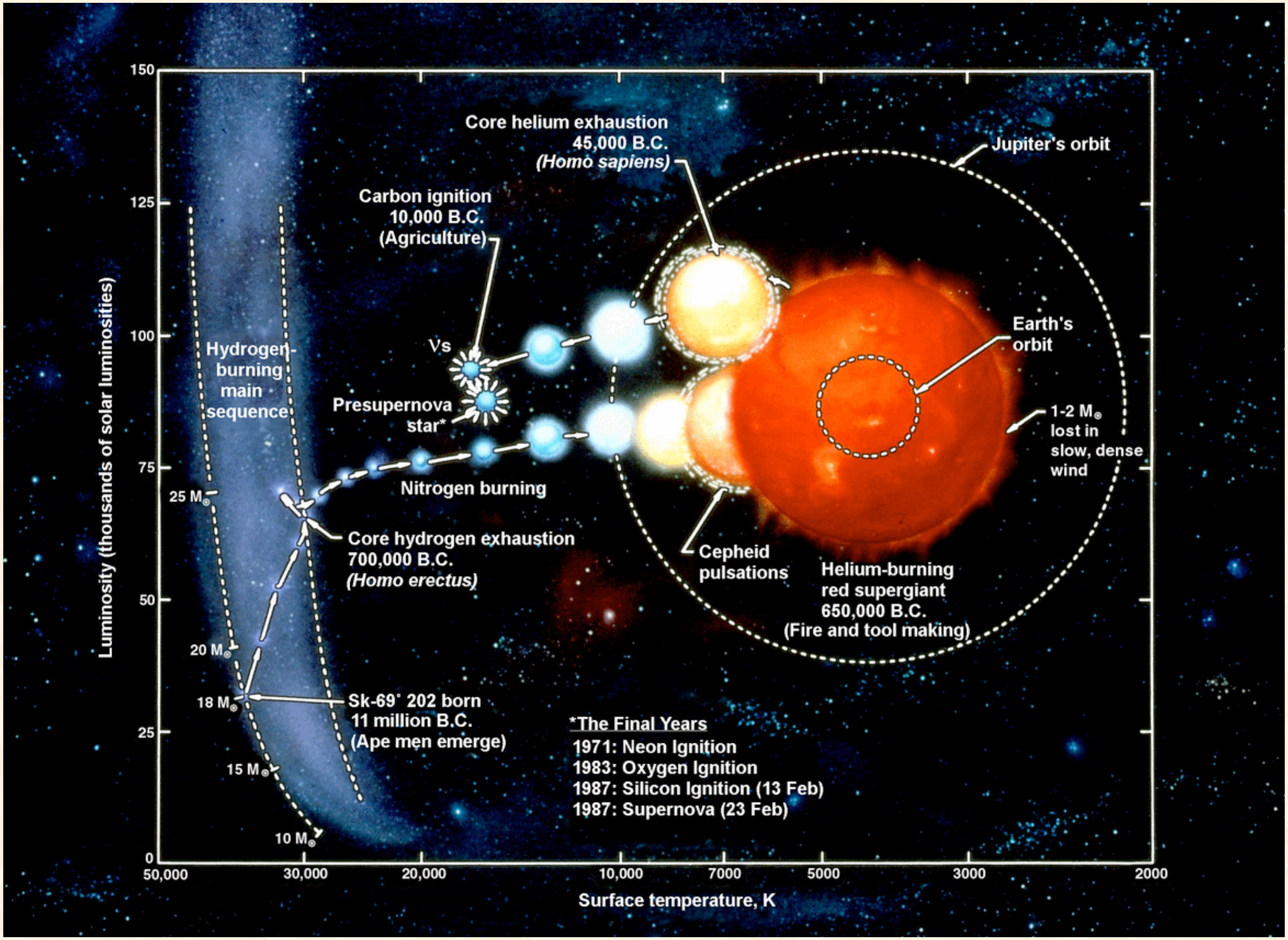
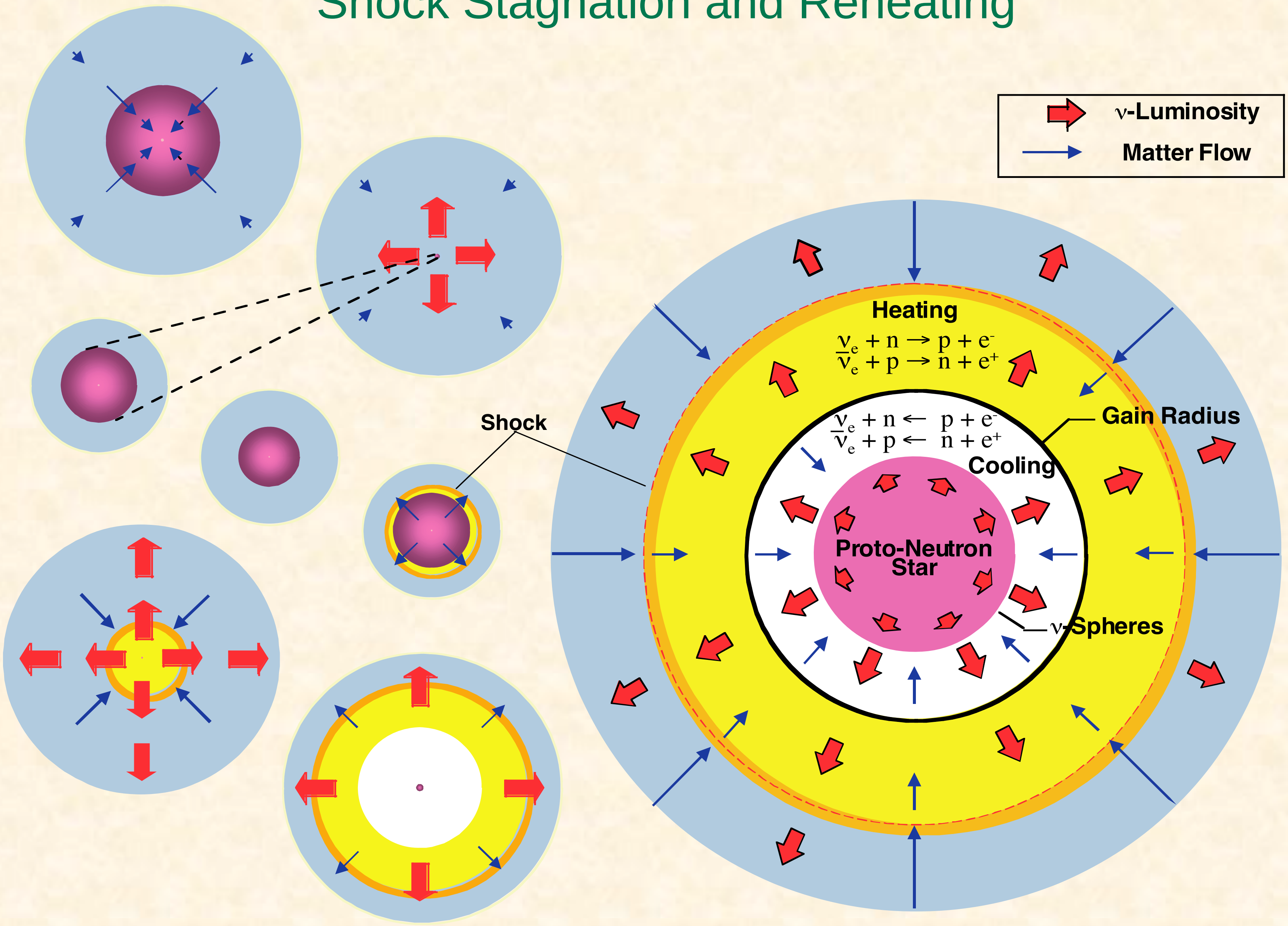
How do core-collapse supernovae explode?



Scientific American

Shock Stagnation and Reheating

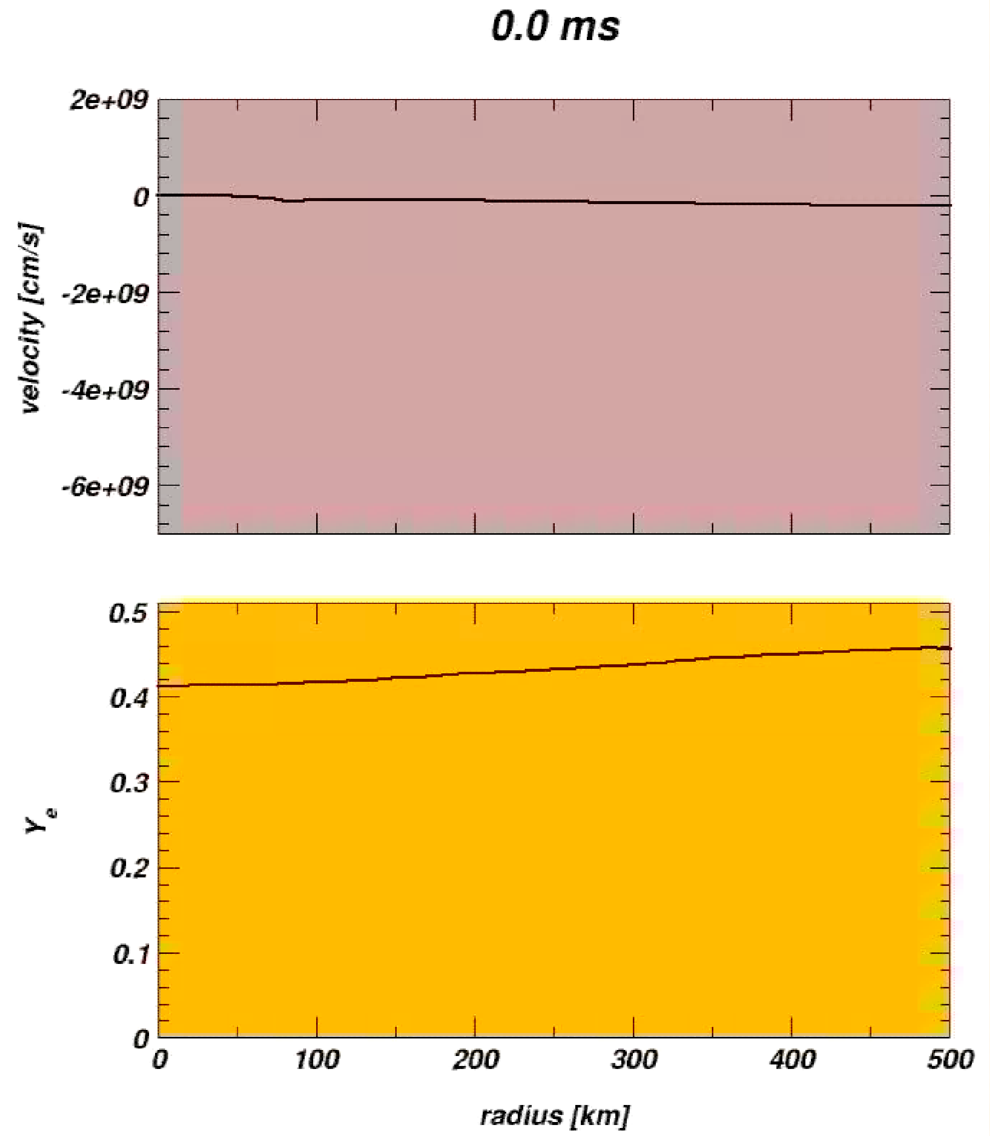


Spherically-symmetric simulations with AGILE-BOLTZTRAN

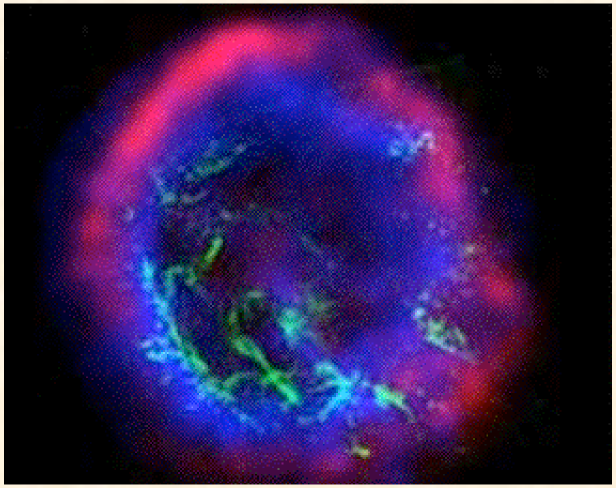
AGILE-BOLTZTRAN

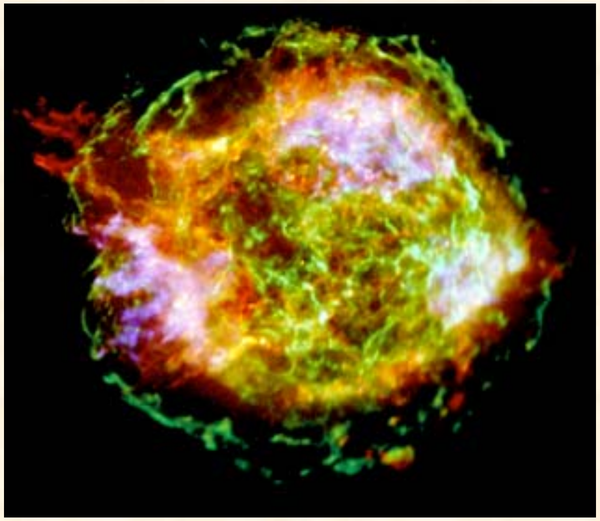
Implicit, adaptive Lagrangian hydrodynamics coupled to fully-implicit Boltzmann neutrino transport solver. Fully generally relativistic, both in hydro and transport.

- **Microphysics to be added**
- **“New” physics (e.g. neutrino mixing) to be explored**
- **Optimizations to be undertaken**
- **Analysis tools to be built**
- **Software interfaces to be built**



When, where, and how is spherical symmetry is broken?



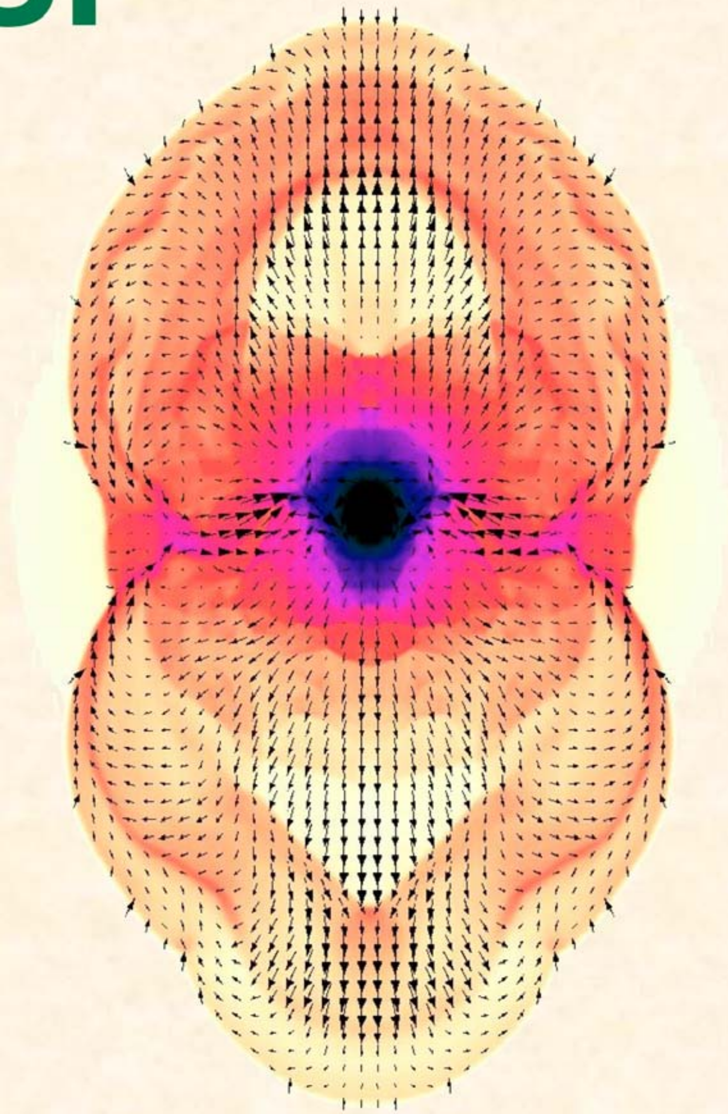


All images: NASA

SASI

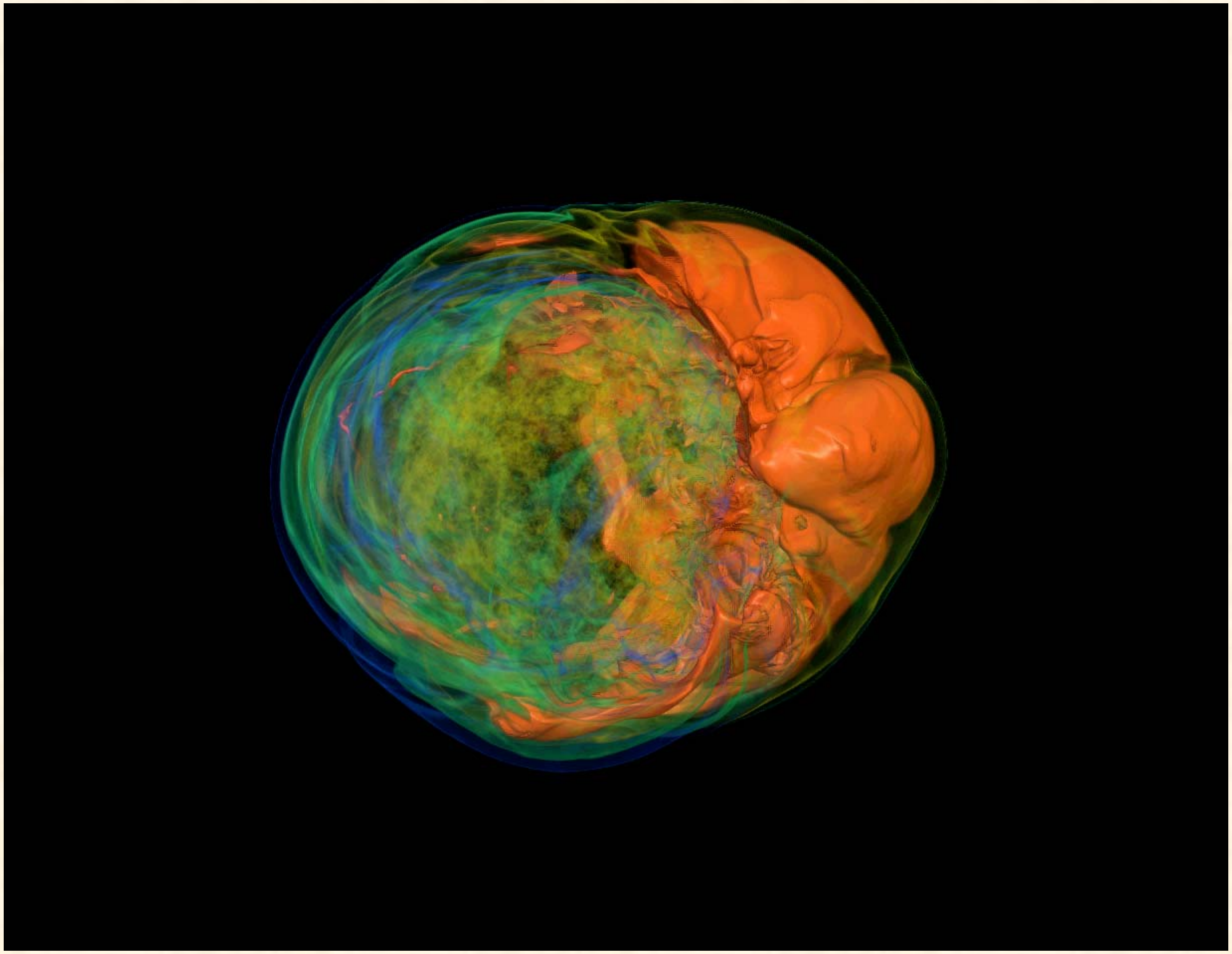
Standing pressure waves within the cavity of a spherical accretion shock are amplified with each oscillation. The shock becomes significantly distorted after only a few periods.

In core-collapse supernovae, the SASI will operate in conjunction (competition?) with neutrino-driven convection.



Blondin, Mezzacappa, & DeMarino (2003)
Blondin & Mezzacappa (2005)

Development of the SASI



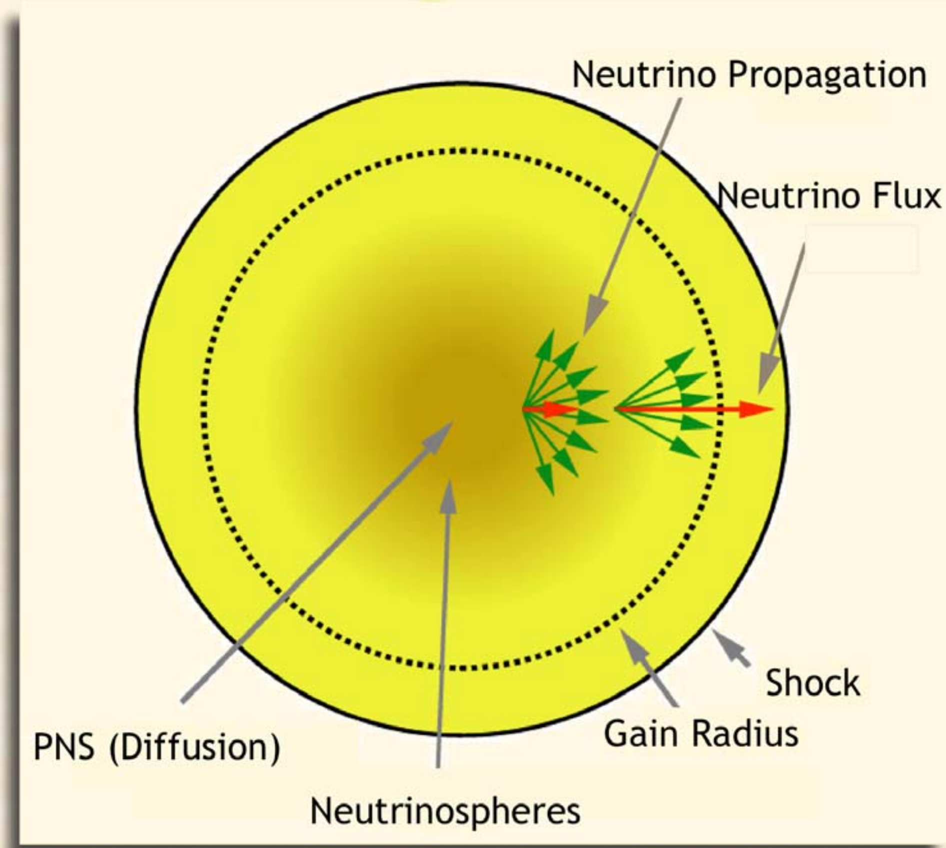
Visualization: Kwan-Liu Ma, UCD

Can the SASI help explain pulsar spin periods?
Neutron star natal kicks? Other observables?

Conclusions

- Blowing up stars is just plain fun…
- ..and also happens to involve most of modern physics...
- ….and stretches the capabilities of even the world's largest computational resources.

The Need for Accurate Neutrino Transport



$$
\begin{aligned}
\frac{1}{c}\frac{\partial F}{\partial t} &+ 4\pi\mu\frac{\partial(r^2\rho F)}{\partial m} \\
&+ \frac{1}{r}\frac{\partial[(1-\mu^2)F]}{\partial\mu} \\
&+ \frac{1}{c}\left(\frac{\partial ln\rho}{\partial t}+\frac{3v}{r}\right)\frac{\partial[\mu(1-\mu^2)F]}{\partial\mu} \\
&+ \frac{1}{c}\left[\mu^2\left(\frac{\partial ln\rho}{\partial t}+\frac{3v}{r}\right)-\frac{v}{r}\right]\frac{1}{E^2}\frac{\partial(E^3F)}{\partial E} \\
&= \frac{j}{\rho}-\tilde{\chi}F \\
&+ \frac{1}{c}\frac{1}{h^3c^3}E^2\int d\mu' R_{\mathrm{IS}}F \\
&- \frac{1}{c}\frac{1}{h^3c^3}E^2F\int d\mu' R_{\mathrm{IS}} \\
&+ \frac{1}{h^3c^4}\left(\frac{1}{\rho}-F\right)\int dE'E'^2d\mu'\tilde{R}^{\mathrm{in}}_{\mathrm{NES}}F \\
&- \frac{1}{h^3c^4}F\int dE'E'^2d\mu'\tilde{R}^{\mathrm{out}}_{\mathrm{NES}}\left(\frac{1}{\rho}-F\right) \\
&+ \frac{1}{h^3c^4}\left(\frac{1}{\rho}-F\right)\int dE'E'^2d\mu'\tilde{R}^{\mathrm{em}}_{\mathrm{PAIR}}\left(\frac{1}{\rho}-\bar{F}\right) \\
&- \frac{1}{h^3c^4}F\int dE'E'^2d\mu'\tilde{R}^{\mathrm{abs}}_{\mathrm{PAIR}}\bar{F}
\end{aligned}
$$

The net heating rate in the gain region depends sensitively on the neutrino spectra and angular distribution.

$$
\dot{\varepsilon} = \frac{X_n}{\lambda_0^a}\frac{L_{\nu_e}}{4\pi r^2}\left\langle E_{\nu_e}^2\right\rangle\left\langle\frac{1}{\mathbf{F}}\right\rangle + \frac{X_p}{\lambda_0^a}\frac{L_{\bar{\nu}_e}}{4\pi r^2}\left\langle E_{\bar{\nu}_e}^2\right\rangle\left\langle\frac{1}{\bar{\mathbf{F}}}\right\rangle
$$

spectra

angular distribution

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