Current Topics in Astroparticle Physics

Nov 9 – 11, 2022
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(dedicated to the science of Georg G. Raffelt)

In this edition of **Current Topics in Astroparticle Physics**, we will set the stage for discussing both the longstanding and the new puzzles in astroparticle theory and experiment. Among the plethora of topics available, we shall mildly favour those to which our honoured Georg G. Raffelt devoted part of his extraordinary career. We will discuss (quite) weakly interacting particles (neutrinos, the hypothetical axion, or weakly interacting dark matter candidates), their role in astrophysics and cosmology, and conversely, what we can learn about their properties from astrophysical and cosmological arguments and observations.

Max-Planck-Institut für Astrophysik

ORIGINS Excellence Cluster

SFB 1258 Neutrinos Dark Matter Messengers

Current Topics in Astroparticle Physics

Max Planck Institute for Physics, Munich, November 9-11, 2022

Georg's Footprints on Supernova Neutrinos

and on my Own Work

Hans-Thomas Janka

Max-Planck-Institut für Astrophysik

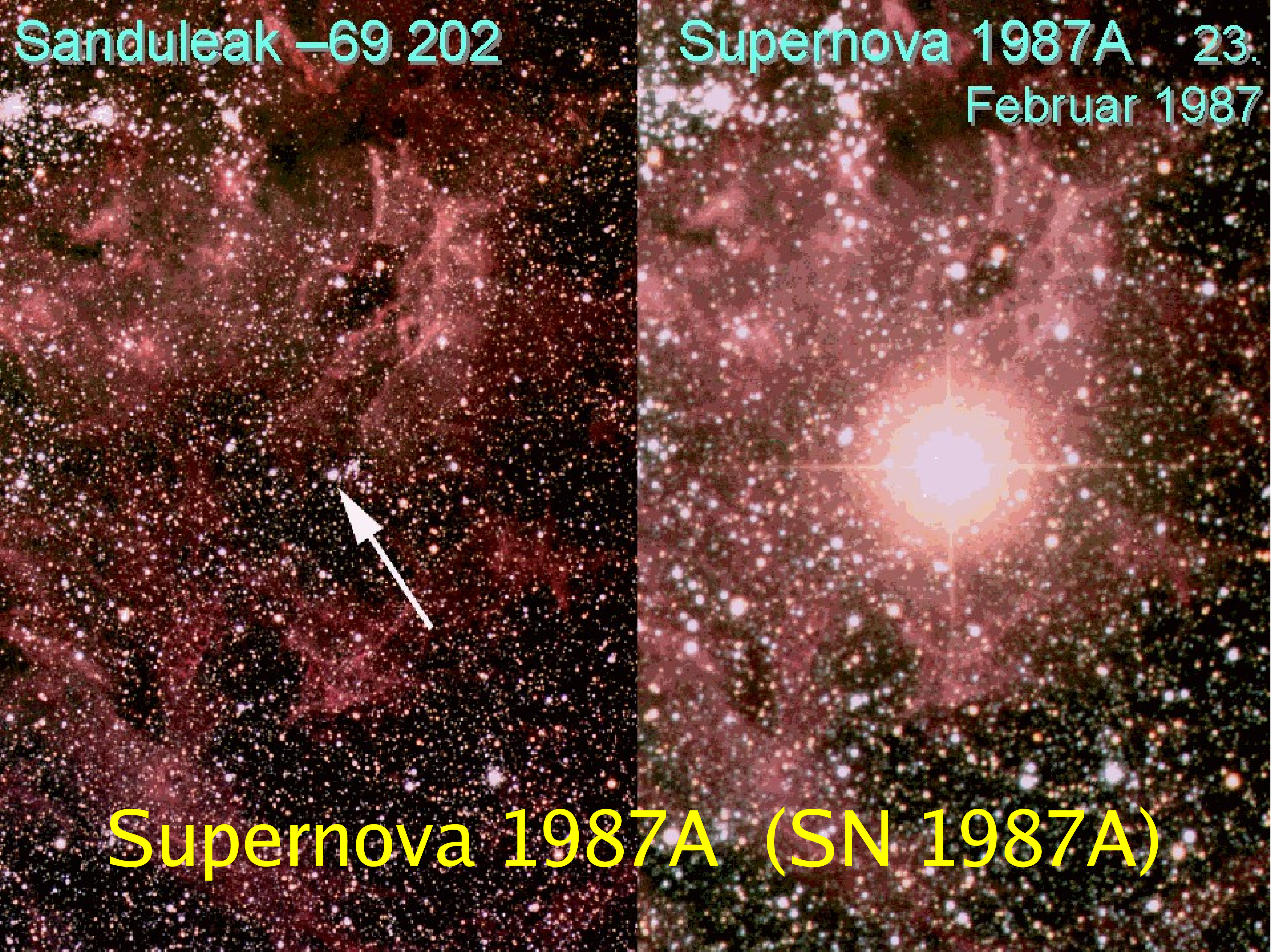
Garching

Image: Blondin & Mezzacappa

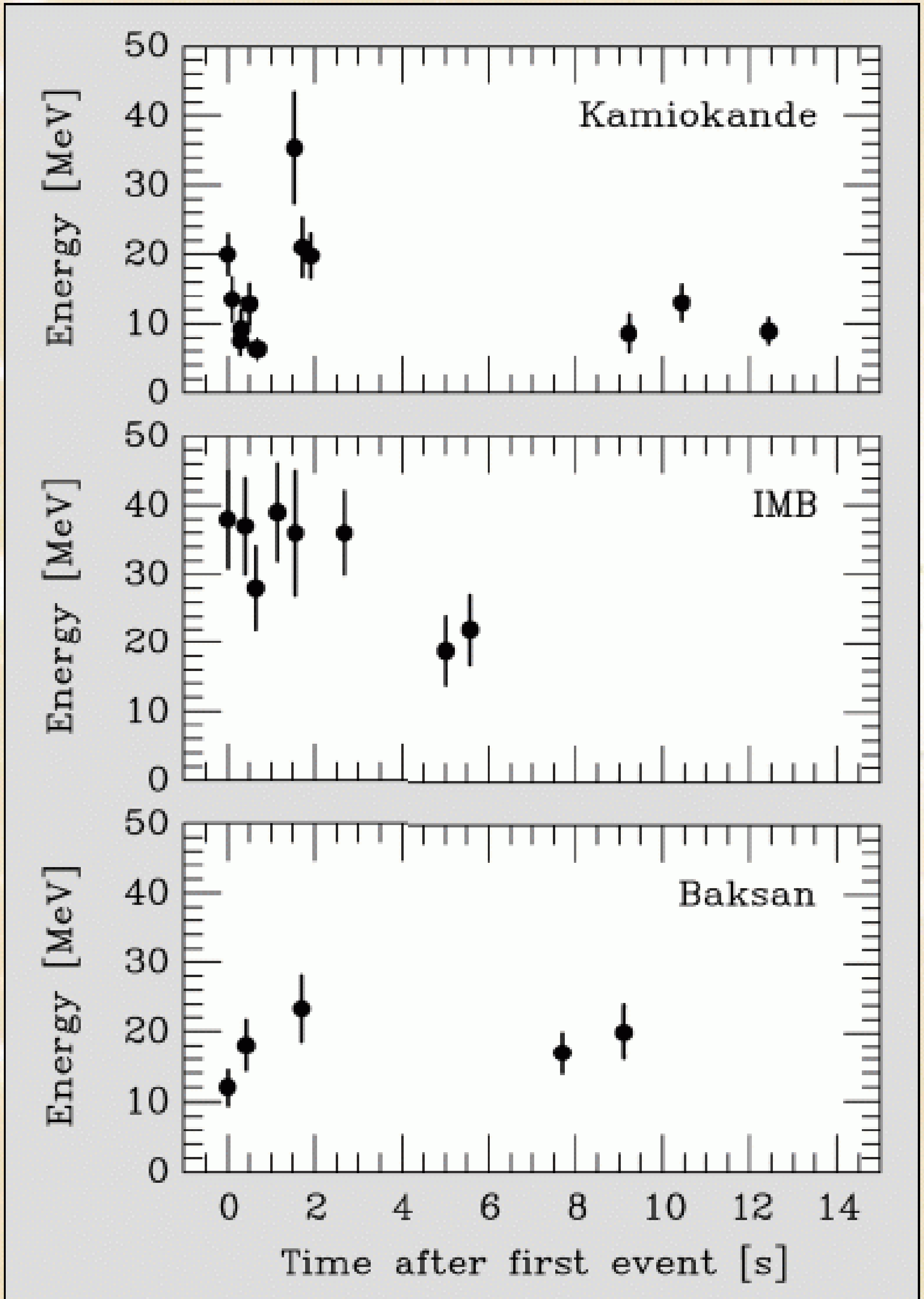
Georg becomes 65!

Tribute to a

- Long-time collaborator
- Supporter and mentor
- Companion and friend


Sanduleak –69 202
Supernova 1987A 23. Februar 1987
Supernova 1987A (SN 1987A)

Neutrino Burst of Supernova 1987A



Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous

TECHNISCHE UNIVERSITÄT MÜNCHEN

SFB 375

LMU

Max–Planck–Institute fuer Physik und Astrophysik

SFB 375: 1995–2006

SFB

SFB-TR27: 2007–2011

SFB 1258

Neutrinos

Dark Matter

Messengers

SFB 1258: 2017–2024+ ?

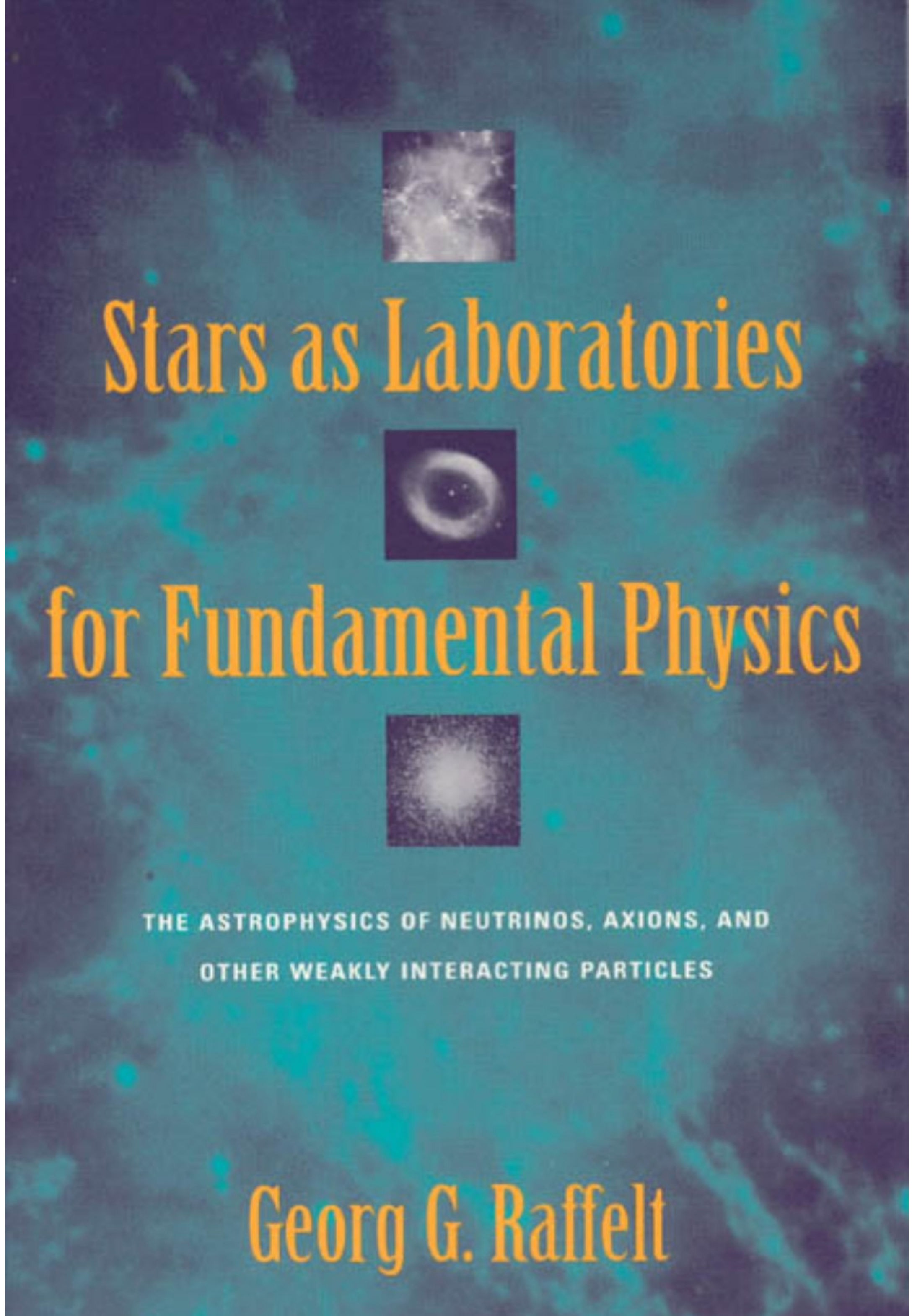
Georg's Achievements

116 papers on supernova neutrinos

(28 joint papers on this topic)

Nearly 9000 citations according to ADS
(individual papers up to ~500)

Wide spectrum of topics



University of Chicago Press 1996

Nucleon Spin Fluctuations & Neutrino Interactions

PHYSICAL REVIEW D VOLUME 54, NUMBER 4 15 AUGUST 1996

Supernova neutrino scattering rates reduced by nucleon spin fluctuations: Perturbative limit

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(Received 4 December 1995; revised manuscript received 5 March 1996)

In a nuclear medium, spin-dependent forces cause the nucleon spins to fluctuate with a rate Γ_σ. We have previously shown that as a consequence the effective axial-vector current neutrino-nucleon scattering cross section is reduced. Here, we calculate this reduction explicitly in the perturbative limit $\Gamma_\sigma \ll T$. By virtue of an exact sum rule of the spin-density structure function, we express the modified cross section in terms of the matrix element for neutrino-nucleon scattering in the presence of a spin-dependent nuclear potential. This representation allows for a direct comparison with, and confirmation of, Sawyer's related perturbative result. In a supernova core with a typical temperature $T=10$ MeV, the perturbative limit is relevant for densities $\rho \lesssim 10^{13}$ g cm^{-3} and thus applies around the neutrino sphere. There, the cross-section reduction is of order a few percent and thus not large; however, a new mode of energy transfer between neutrinos and nucleons is enabled which may be important for neutrino spectra formation. We derive an analytic perturbative expression for the rate of energy transfer. [S0556-2821(96)00216-0]

VOLUME 76, NUMBER 15 PHYSICAL REVIEW LETTERS 8 APRIL 1996

Nucleon Spin Fluctuations and the Supernova Emission of Neutrinos and Axions

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In the hot and dense medium of a supernova (SN) core, the nucleon spins fluctuate so fast that the axial-vector neutrino opacity and the axion emissivity are expected to be significantly modified. Axions with $m_a \lesssim 10^{-2}$ eV are not excluded by SN 1987A. A substantial transfer of energy in neutrino-nucleon (νN) collisions is enabled which may alter the spectra of SN neutrinos relative to calculations where energy-conserving νN collisions had been assumed near the neutrinosphere.

PHYSICAL REVIEW D VOLUME 55, NUMBER 2 15 JANUARY 1997

Reduction of weak interaction rates in neutron stars by nucleon spin fluctuations: Degenerate case

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(Received 8 April 1996)

Nucleon spin fluctuations in a dense medium reduce the ''naive'' values of weak interaction rates (neutrino opacities, neutrino emissivities). We extend previous studies of this effect to the degenerate case which is appropriate for neutron stars a few ten seconds after formation. If neutron-neutron interactions by a one-pion exchange potential are the dominant cause of neutron spin fluctuations, a perturbative calculation of weak interaction rates is justified for $T \lesssim 3m/(4\pi\alpha_\pi^2) \approx 1$ MeV, where m is the neutron mass and $\alpha_\pi \approx 15$ the pion fine-structure constant. At higher temperatures, the application of Landau's theory of Fermi liquids is no longer justified; i.e., the neutrons cannot be viewed as simple quasiparticles in any obvious sense. [S0556-2821(97)00402-5]

Neutrino Reaction Rates in Supernova Cores

THE ASTROPHYSICAL JOURNAL, 507:339–352, 1998 November 1

SUPERNOVA NEUTRINO OPACITY FROM NUCLEON-NUCLEON BREMSSTRAHLUNG AND RELATED PROCESSES

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ABSTRACT

Elastic scattering on nucleons, $\nu N \to N\nu$, is the dominant supernova (SN) opacity source for μ and τ neutrinos. The dominant energy- and number-changing processes were thought to be $\nu e^- \to e^- \nu$ and $\nu\bar{\nu} \leftrightarrow e^+e^-$ until Suzuki showed that the bremsstrahlung process $\nu\bar{\nu}NN \leftrightarrow NN$ was actually more important. We find that for energy exchange, the related "inelastic scattering process" $\nu NN \leftrightarrow NN\nu$ is even more effective by about a factor of 10. A simple estimate implies that the ν_μ and ν_τ spectra emitted during the Kelvin-Helmholtz cooling phase are much closer to that of $\bar{\nu}_e$ than had been thought previously. To facilitate a numerical study of the spectra formation we derive a scattering kernel that governs both bremsstrahlung and inelastic scattering and give an analytic approximation formula. We consider only neutron-neutron interactions; we use a one-pion exchange potential in Born approximation, nonrelativistic neutrons, and the long-wavelength limit, simplifications that appear justified for the surface layers of an SN core. We include the pion mass in the potential, and we allow for an arbitrary degree of neutron degeneracy. Our treatment does not include the neutron-proton process and does not include nucleon-nucleon correlations. Our perturbative approach applies only to the SN surface layers, i.e., to densities below about 10^{14} g cm^{-3}.

THE ASTROPHYSICAL JOURNAL, 587:320–326, 2003 April 10

ELECTRON NEUTRINO PAIR ANNIHILATION: A NEW SOURCE FOR MUON AND TAU NEUTRINOS IN SUPERNOVAE

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Received 2002 May 7; accepted 2002 December 12

ABSTRACT

We show that in a supernova core the annihilation process $\nu_e\bar{\nu}_e \to \nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$ is always more important than the traditional reaction $e^+e^- \to \nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$ as a source for muon and tau neutrino pairs. We study the impact of the new process by means of a Monte Carlo transport code with a static stellar background model and by means of a self-consistent hydrodynamic simulation with Boltzmann neutrino transport. Nucleon bremsstrahlung $NN \to NN\nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$ is also included as another important source term. Taking into account $\nu_e\bar{\nu}_e \to \nu_{\mu,\tau}\bar{\nu}_{\mu,\tau}$ increases the ν_μ and ν_τ luminosities by as much as 20%, while the spectra remain almost unaffected. In our hydrodynamic simulation, the shock was somewhat weakened. Elastic $\nu_{\mu,\tau}\nu_e$ and $\nu_{\mu,\tau}\bar{\nu}_e$ scattering is not negligible but less important than $\nu_{\mu,\tau}e^{\pm}$ scattering. Its influence on the $\nu_{\mu,\tau}$ fluxes and spectra is small after all other processes have been included.

Subject headings: elementary particles — methods: numerical — neutrinos — supernovae: general

Supernova Neutrino Spectra Formation

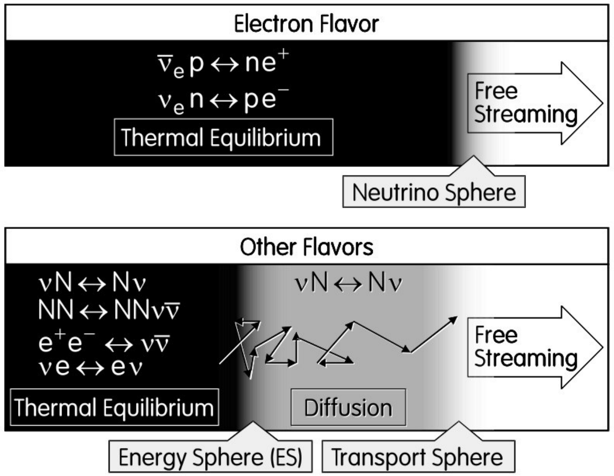

FIG. 1.—Schematic picture of neutrino spectra formation in the atmosphere of an SN core.

THE ASTROPHYSICAL JOURNAL, 561:890–914, 2001 November 10

MU- AND TAU-NEUTRINO SPECTRA FORMATION IN SUPERNOVAE

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Received 2001 May 16; accepted 2001 July 17

ABSTRACT

The μ- and τ-neutrinos emitted from a proto–neutron star are produced by nucleonic bremsstrahlung $NN \to NN\nu\bar{\nu}$ and pair annihilation $e^+e^- \to \nu\bar{\nu}$, reactions that freeze out at the "energy sphere." Before escaping from there to infinity, the neutrinos diffuse through the "scattering atmosphere," a layer in which their main interaction is elastic scattering on nucleons $\nu N \to N\nu$. If these collisions are taken to be isoenergetic, as in all numerical supernova simulations, the neutrino flux spectrum escaping to infinity depends only on the medium temperature $T_{\rm ES}$ and the thermally averaged optical depth $\bar{\tau}_{\rm ES}$ at the energy sphere. For $\bar{\tau}_{\rm ES} = 10$–50, one finds for the spectral flux temperature of the escaping neutrinos $T_{\rm flux} = 0.5$–$0.6 T_{\rm ES}$. Including energy exchange (nucleon recoil) in $\nu N \to N\nu$ can shift $T_{\rm flux}$ both up and down. $\Delta T_{\rm flux}$ depends on $\bar{\tau}_{\rm ES}$, on the scattering atmosphere's temperature profile, and on $T_{\rm ES}$. Based on a
find that for typical conditions, $\Delta T_{\rm flux}/T_{\rm flux}$ is between -10% and -20% and even
er choices does not exceed -30%. The exact value of $\Delta T_{\rm flux}/T_{\rm flux}$ is surprisingly
ımed value of the nucleon mass; i.e., the exact efficiency of energy transfer between
ns is not important as long as it can occur at all. Therefore, calculating the ν_μ and
ieem to require a precise knowledge of the nuclear medium's dynamical structure

THE ASTROPHYSICAL JOURNAL, 590:971–991, 2003 June 20

MONTE CARLO STUDY OF SUPERNOVA NEUTRINO SPECTRA FORMATION

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Received 2002 August 1; accepted 2003 February 28

ABSTRACT

The neutrino flux and spectra formation in a supernova core is studied by using a Monte Carlo code. The dominant opacity contribution for ν_μ is elastic scattering on nucleons $\nu_\mu N \to N\nu_\mu$, where ν_μ always stands for either ν_μ or ν_τ. In addition, we switch on or off a variety of processes that allow for the exchange of energy or the creation and destruction of neutrino pairs, notably nucleon bremsstrahlung $NN \to NN\nu_\mu\bar{\nu}_\mu$, the pair annihilation processes $e^+e^- \to \nu_\mu\bar{\nu}_\mu$ and $\nu_e\bar{\nu}_e \to \nu_\mu\bar{\nu}_\mu$, recoil and weak magnetism in elastic nucleon scattering, elastic scattering on electrons $\nu_\mu e^\pm \to e^\pm\nu_\mu$, and elastic scattering on electron neutrinos and antineutrinos $\nu_\mu\nu_e \to \nu_e\nu_\mu$ and $\nu_\mu\bar{\nu}_e \to \bar{\nu}_e\nu_\mu$. The least important processes are neutrino-neutrino scattering and e^+e^- annihilation. The formation of the spectra and fluxes of ν_μ is dominated by the nucleonic processes, i.e., bremsstrahlung and elastic scattering with recoil, but also $\nu_e\bar{\nu}_e$ annihilation and $\nu_\mu e^\pm$ scattering contribute significantly. When all processes are included, the spectral shape of the emitted neutrino flux is always "pinched," i.e., the width of the spectrum is smaller than that of a thermal spectrum with the same average energy. In all of our cases we find that the average $\bar{\nu}_\mu$ energy exceeds the average $\bar{\nu}_e$ energy by only a small amount, 10% being a typical number. Weak-magnetism effects cause the opacity of ν_μ to differ slightly from that of $\bar{\nu}_\mu$, translating into differences of the luminosities and average energies of a few percent. Depending on the density, temperature, and composition profile, the flavor-dependent luminosities L_{ν_e}, $L_{\bar{\nu}_e}$, and L_{ν_μ} can mutually differ from each other by up to a factor of 2 in either direction.

Using a nominal Fermi-Dirac fit to approximate the spectrum is physically motivated because a truly thermal neutrino flux would follow this behavior. On the other hand, the neutrino flux emitted from an SN core is not very close to being thermal so that the limiting behavior of the fit function is not a strong argument. Therefore, we consider an alternative fit function for which analytic simplicity is the main motivation,

$$\boxed{f_\alpha(\epsilon) = \left(\frac{\epsilon}{\bar{\epsilon}}\right)^\alpha e^{-(\alpha+1)\epsilon/\bar{\epsilon}} .} \qquad (14)$$

For any value of α we have $\langle\epsilon\rangle = \bar{\epsilon}$ while

$$\frac{\langle\epsilon^2\rangle}{\langle\epsilon\rangle^2} = \frac{2+\alpha}{1+\alpha} . \qquad (15)$$

Put another way, $\bar{\epsilon}$ is the average energy, while α represents the amount of spectral pinching. For general moments the analogous relation is

$$\frac{\langle\epsilon^k\rangle}{\langle\epsilon^{k-1}\rangle} = \frac{k+\alpha}{1+\alpha}\bar{\epsilon} . \qquad (16)$$

Analysis of SN 1987A Neutrino Detection

PHYSICAL REVIEW D VOLUME 54, NUMBER 1 1 JULY 1996

Neutrino oscillations and the supernova 1987A signal

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(Received 22 January 1996)

We study the impact of neutrino oscillations on the interpretation of the supernova (SN) 1987A neutrino signal by means of a maximum-likelihood analysis. We focus on oscillations between $\overline{\nu}_e$ with $\overline{\nu}_\mu$ or $\overline{\nu}_\tau$ with those mixing parameters that would solve the solar neutrino problem. For the small-angle MSW solution ($\Delta m^2 \approx 10^{-5}$ eV^2, $\sin^2 2\Theta_0 \approx 0.007$), there are no significant oscillation effects on the Kelvin-Helmholtz cooling signal; we confirm previous best-fit values for the neutron-star binding energy and average spectral $\overline{\nu}_e$ temperature. There is only marginal overlap between the upper end of the 95.4% C.L. inferred range of $\langle E_{\overline{\nu}_e} \rangle$ and the lower end of the range of theoretical predictions. Any admixture of the stiffer $\overline{\nu}_\mu$ spectrum by oscillations aggravates the conflict between experimentally inferred and theoretically predicted spectral properties. For mixing parameters in the neighborhood of the large-angle MSW solution ($\Delta m^2 \approx 10^{-5}$ eV^2, $\sin^2 2\Theta_0 \approx 0.7$) the oscillations in the SN are adiabatic, but one needs to include the regeneration effect in the Earth which causes the Kamiokande and IMB detectors to observe different $\overline{\nu}_e$ spectra. For the solar vacuum solution ($\Delta m^2 \approx 10^{-10}$ eV^2, $\sin^2 2\Theta_0 \approx 1$) the oscillations in the SN are nonadiabatic; vacuum oscillations take place between the SN and the detector. If one of the two large-angle solutions were borne out by the upcoming round of solar neutrino experiments, one would have to conclude that the SN 1987A $\overline{\nu}_\mu$ and/or $\overline{\nu}_e$ spectra had been much softer than predicted by current treatments of neutrino transport. [S0556-2821(96)02613-6]

PHYSICAL REVIEW D **72,** 063001 (2005)

Analysis of the SN 1987A neutrinos with a flexible spectral shape

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(Received 27 July 2005; published 8 September 2005)

We analyze the neutrino events from the supernova (SN) 1987A detected by the Kamiokande-II (KII) and Irvine-Michigan-Brookhaven (IMB) experiments. For the time-integrated flux we assume a quasi-thermal spectrum of the form $(E/E_0)^\alpha e^{-(\alpha+1)E/E_0}$ where α plays the role of a spectral index. This simple representation not only allows one to fit the total energy $E_{\rm tot}$ emitted in $\bar{\nu}_e$ and the average energy $\langle E_{\bar{\nu}_e} \rangle$, but also accommodates a wide range of shapes, notably antipinched spectra that are broader than a thermal distribution. We find that the pile-up of low-energy events near threshold in KII forces the best-fit value for α to the lowest value of any assumed prior range. This applies to the KII events alone as well as to a common analysis of the two data sets. The preference of the data for an ''unphysical'' spectral shape implies that one can extract meaningful values for $\langle E_{\bar{\nu}_e} \rangle$ and $E_{\rm tot}$ only if one fixes a prior value for α. The tension between the KII and IMB data sets and theoretical expectations for $\langle E_{\bar{\nu}_e} \rangle$ is not resolved by an antipinched spectrum.

Supernova Neutrino Diagnostics with IceCube

Detecting the neutrino mass hierarchy with a supernova at IceCube

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Online at stacks.iop.org/JCAP/2003/i=06/a=005

JCAP 06(2003)005

Abstract. IceCube, a future km^3 antarctic ice Cherenkov neutrino telescope, is highly sensitive to a galactic supernova (SN) neutrino burst. The Cherenkov light corresponding to the total energy deposited by the SN neutrinos in the ice can be measured relative to background fluctuations with a statistical precision much better than 1%. If the SN is viewed through the Earth, the matter effect on neutrino oscillations can change the signal by more than 5%, depending on the flavour-dependent source spectra and the neutrino mixing parameters. Therefore, IceCube together with another high-statistics experiment like Hyper-Kamiokande can detect the Earth effect, an observation that woul
mixing scenarios that are difficult to pin down with lon
particular, the normal mass hierarchy can be clearly d
angle is not too small, $\sin^2\theta_{13} \gtrsim 10^{-3}$. The small flavo
the SN neutrino fluxes and spectra that are found in s
suffice for this purpose. Although the absolute calibrat
may exceed 5%, the Earth effect would typically vary l
duration of the SN signal, obviating the need for a pre
IceCube with its unique geographic location and exp
decisive role as a 'co-detector' to measure SN neutrin
powerful stand-alone SN detector that can verify the

PHYSICAL REVIEW D **80,** 087301 (2009)

Reconstructing the supernova bounce time with neutrinos in IceCube

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(Received 19 August 2009; published 15 October 2009)

Generic model predictions for the early neutrino signal of a core-collapse supernova (SN) imply that IceCube can reconstruct the bounce to within about ± 3.5 ms at 95% C.L. (assumed SN distance 10 kpc), relevant for coincidence with gravitational-wave detectors. The timing uncertainty scales approximately with the distance squared. The offset between true and reconstructed bounce time of up to several ms depends on the neutrino flavor oscillation scenario. Our work extends the recent study of Pagliaroli *et al.* [Phys. Rev. Lett. **103**, 031102 (2009)] and demonstrates IceCube's superb timing capabilities for neutrinos from the next nearby SN.

Supernova Neutrino Diagnostics with IceCube

PHYSICAL REVIEW D **82,** 063007 (2010)

Fast time variations of supernova neutrino fluxes and their detectability

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(Received 10 June 2010; published 21 September 2010)

In the delayed explosion scenario of core-collapse supernovae, the accretion phase shows pronounced convective overturns and a low-multipole hydrodynamic instability, the standing accretion shock instability. These effects imprint detectable fast time variations on the emerging neutrino flux. Among existing detectors, IceCube is best suited to this task, providing an event rate of $\sim$1000 ms^{-1} during the accretion phase for a fiducial SN distance of 10 kpc, comparable to what could be achieved with a megaton water Cherenkov detector. If the standing accretion shock instability activity lasts for several hundred ms, a Fourier component with an amplitude of 1% of the average signal clearly sticks out from the shot noise. We analyze in detail the output of axially symmetric hydrodynamical simulations that predict much larger amplitudes up to frequencies of a few hundred Hz. If these models are roughly representative for realistic SNe, fast time variations of the neutrino signal are easily detectable in IceCube or future megaton-class instruments. We also discuss the information that could be deduced from such a measurement about the physics in the SN core and the explosion mechanism of the SN.

PHYSICAL REVIEW D **90,** 045032 (2014)

Neutrino emission characteristics and detection opportunities based on three-dimensional supernova simulations

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(Received 3 June 2014; published 25 August 2014)

The neutrino emission characteristics of the first full-scale three-dimensional supernova simulations with sophisticated three-flavor neutrino transport for three models with masses 11.2, 20, and $27M_\odot$ are evaluated in detail. All the studied progenitors show the expected hydrodynamical instabilities in the form of large-scale convective overturn. In addition, the recently identified lepton-number emission self-sustained asymmetry (LESA) phenomenon is generic for all our cases. Standing accretion-shock instability (SASI) activity appears in the 20 and $27M_\odot$ cases, partly in the form of a spiral mode, inducing large but direction- and flavor-dependent modulations of neutrino emission. These modulations can be clearly identified in the existing IceCube and future Hyper-Kamiokande detectors, depending on the distance and detector location relative to the main standing accretion-shock instability sloshing direction.

PRL **111,** 121104 (2013) PHYSICAL REVIEW LETTERS week ending 20 SEPTEMBER 2013

Neutrino Signature of Supernova Hydrodynamical Instabilities in Three Dimensions

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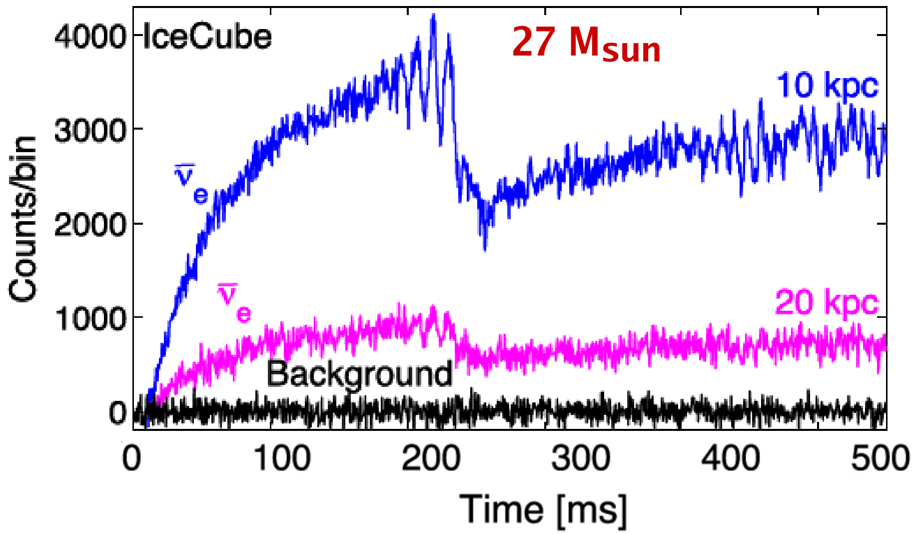
(Received 31 July 2013; published 18 September 2013)

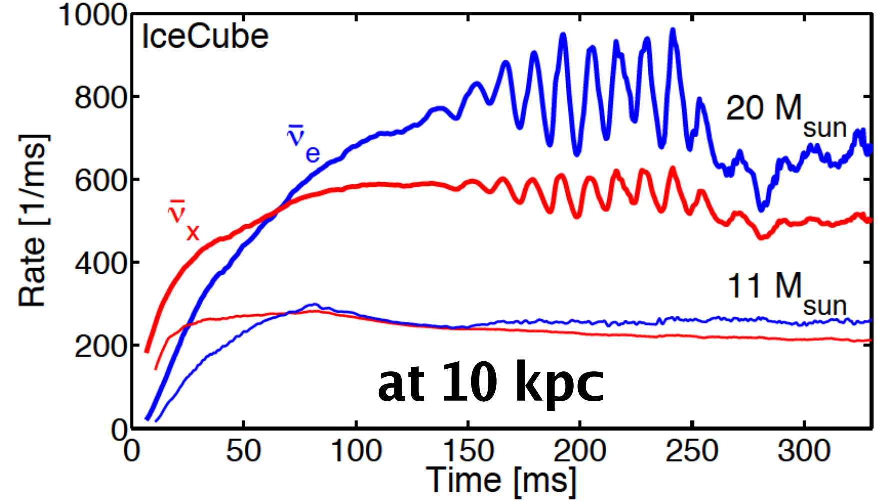
The first full-scale three-dimensional core-collapse supernova (SN) simulations with sophisticated neutrino transport show pronounced effects of the standing accretion shock instability (SASI) for two high-mass progenitors (20 and $27M_\odot$). In a low-mass progenitor ($11.2M_\odot$), large-scale convection is the dominant nonradial hydrodynamic instability in the postshock accretion layer. The SASI-associated modulation of the neutrino signal (80 Hz in our two examples) will be clearly detectable in IceCube or the future Hyper-Kamiokande detector, depending on progenitor properties, distance, and observer location relative to the main SASI sloshing direction. The neutrino signal from the next galactic SN can, therefore, diagnose the nature of the hydrodynamic instability.

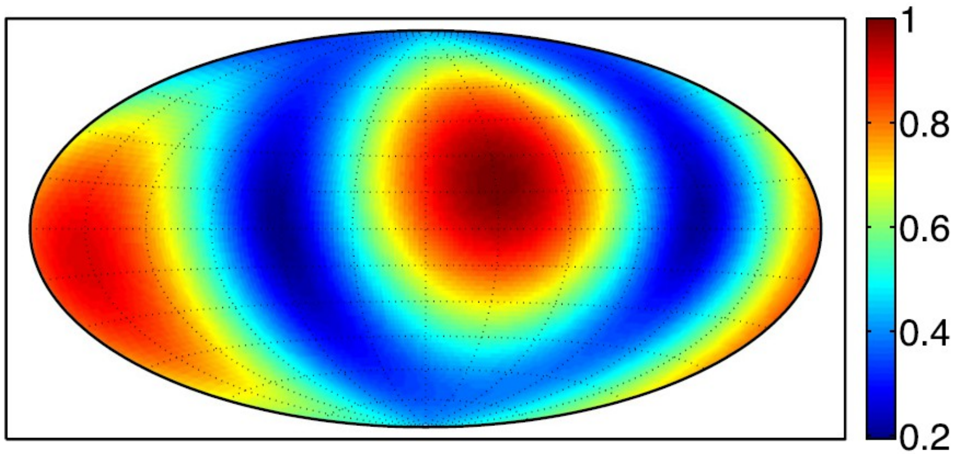
3D Core-Collapse Models: Neutrino Signals

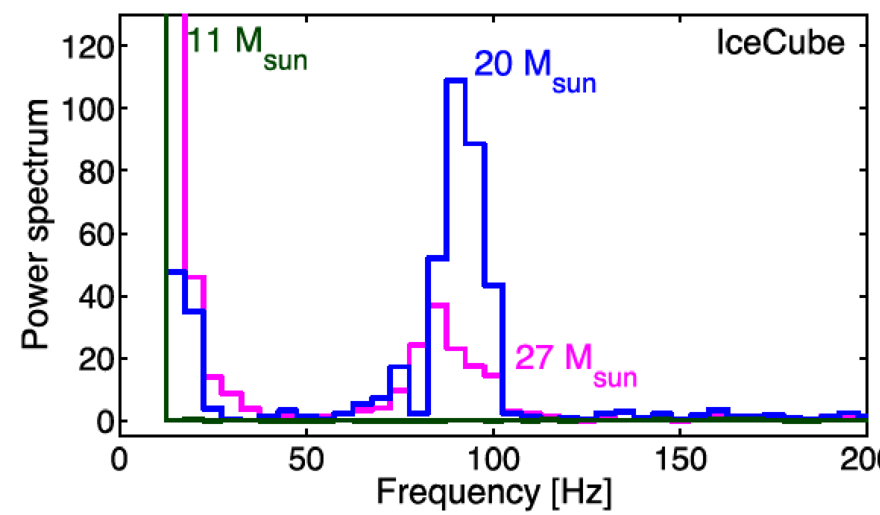
11.2, 20, 27 M_{sun} progenitors (WHW 2002)

SASI produces modulations of neutrino emission (and gravitational-wave signal).









Tamborra et al., PRL 111, 121104 (2013); PRD 90, 045032 (2014)

$$f_{\mathrm{SASI}}^{-1} \sim \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{|v|} + \int_{R_{\mathrm{NS}}}^{R_{\mathrm{S}}} \frac{dr}{c_{\mathrm{s}} - |v|}$$

LESA:
An Unexpected Discovery in 3D Supernova Models

Dipole asymmetry of the electron lepton-number emission

THE ASTROPHYSICAL JOURNAL, 792:96 (20pp), 2014 September 10 doi:10.1088/0004-637X/792/2/96

SELF-SUSTAINED ASYMMETRY OF LEPTON-NUMBER EMISSION: A NEW PHENOMENON DURING THE SUPERNOVA SHOCK-ACCRETION PHASE IN THREE DIMENSIONS

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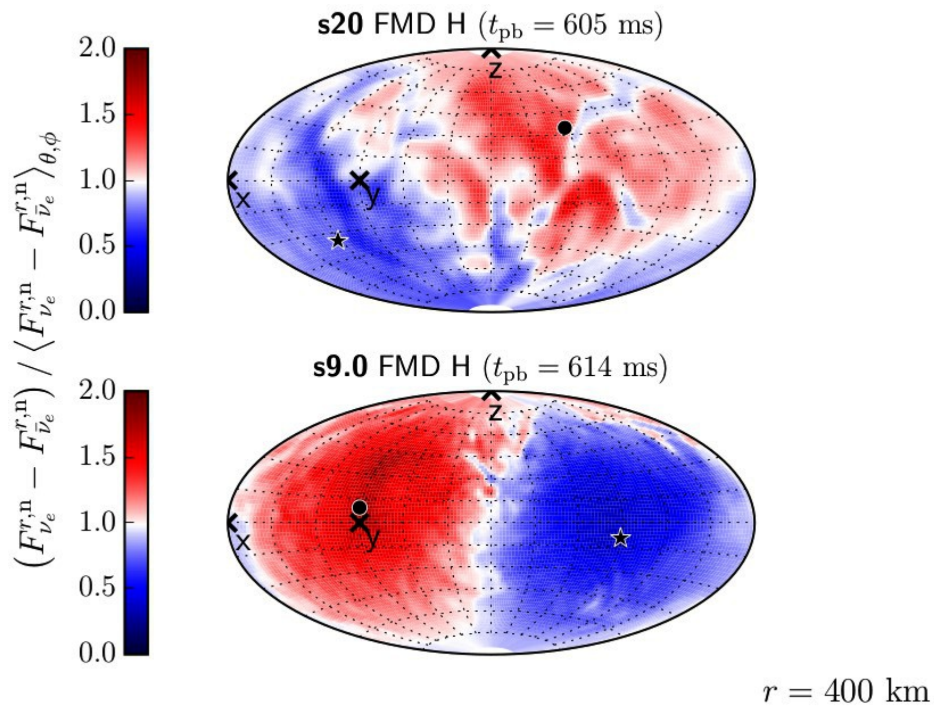
ABSTRACT

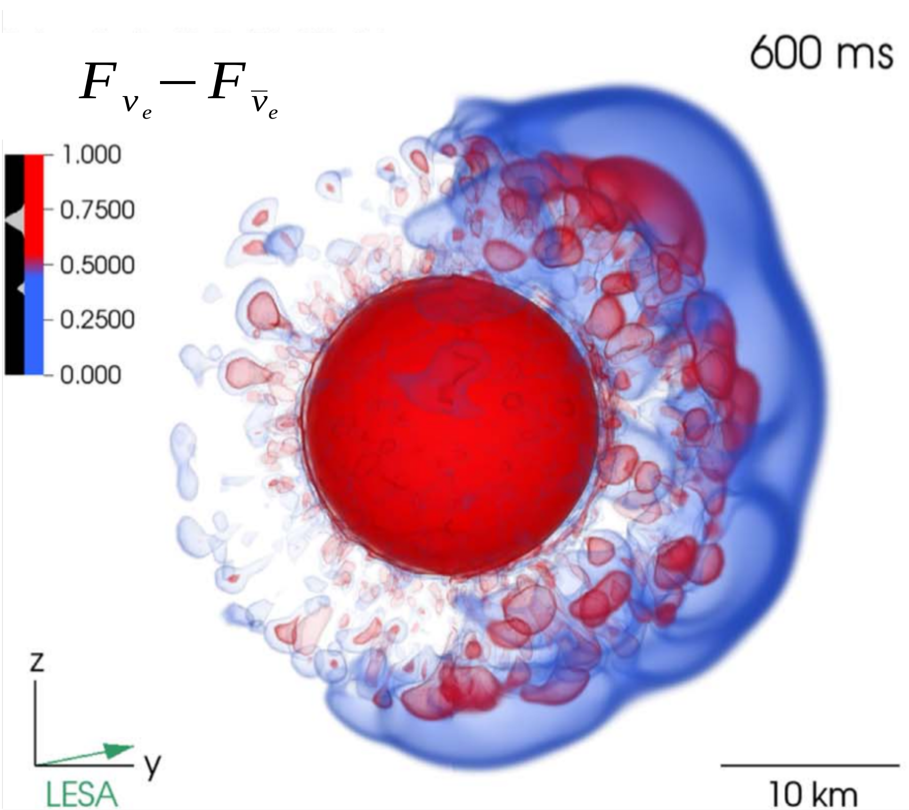
During the stalled-shock phase of our three-dimensional, hydrodynamical core-collapse simulations with energy-dependent, three-flavor neutrino transport, the lepton-number flux (ν_e minus $\bar{\nu}_e$) emerges predominantly in one hemisphere. This novel, spherical-symmetry breaking neutrino-hydrodynamical instability is termed LESA for "Lepton-number Emission Self-sustained Asymmetry." While the individual ν_e and $\bar{\nu}_e$ fluxes show a pronounced dipole pattern, the heavy-flavor neutrino fluxes and the overall luminosity are almost spherically symmetric. Initially, LESA seems to develop stochastically from convective fluctuations. It exists for hundreds of milliseconds or more and persists during violent shock sloshing associated with the standing accretion shock instability. The ν_e minus $\bar{\nu}_e$ flux asymmetry originates predominantly below the neutrinosphere in a region of pronounced proto-neutron star (PNS) convection, which is stronger in the hemisphere of enhanced lepton-number flux. On this side of the PNS, the mass accretion rate of lepton-rich matter is larger, amplifying the lepton-emission asymmetry, because the spherical stellar infall deflects on a dipolar deformation of the stalled shock. The increased shock radius in the hemisphere of less mass accretion and minimal lepton-number flux ($\bar{\nu}_e$ flux maximum) is sustained by stronger convection on this side, which is boosted by stronger neutrino heating due to $\langle\epsilon_{\bar{\nu}_e}\rangle > \langle\epsilon_{\nu_e}\rangle$. Asymmetric heating thus supports the global deformation despite extremely nonstationary convective overturn behind the shock. While these different elements of the LESA phenomenon form a consistent picture, a full understanding remains elusive at present. There may be important implications for neutrino-flavor oscillations, the neutron-to-proton ratio in the neutrino-heated supernova ejecta, and neutron-star kicks, which remain to be explored.

LESA and its Consequences

Dipole asymmetry of the electron lepton-number emission

Glas, THJ, Just, Melson, & Stockinger, ApJ (2019)





Consequences of LESA:

- Neutron-star kicks (~10~100 km/s)
- Supernova nucleosynthesis in ν-heated ejecta is direction dependent
- Viewing-angle dependent lepton flux
- Neutrino-flavor oscillations are direction dependent

Neutrino Flavor Conversion in Supernovae

Astroparticle Physics 1 (1993) 165–183
North-Holland

Astroparticle Physics

Neutrino flavor conversion in a supernova core

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Received 9 September 1992

If ν_μ or ν_τ mix with ν_e, neutrino oscillations and collisions in a supernova (SN) core allow these flavors effectively to participate in β equilibrium and thus to obtain a large chemical potential. If a sterile species mixes with ν_e, these effects lead to an anomalous loss of energy and lepton number. We study flavor conversion in a SN core on the basis of a new kinetic equation which rigorously includes neutrino interference and degeneracy effects. Our discussion serves as an example and illustration of the properties of this "non-Abelian Boltzmann equation".

Nuclear Physics B406 (1993) 423–451
North-Holland

NUCLEAR PHYSICS B

General kinetic description of relativistic mixed neutrinos

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Received 16 December 1992
(Revised 20 April 1993)
Accepted for publication 22 June 1993

We derive a general Boltzmann-type collision integral for mixed neutrinos interacting with each other and with a medium. Our treatment is fully relativistic in that antineutrino degrees of freedom are included. This collision integral allows one to account for the simultaneous effects of neutrino oscillations in a medium and for the effects of collisions. Our result generalizes previous attempts of unify the first- and second-order interaction effects in a single self-consistent equation. Most importantly, our equation includes effects non-linear in the neutrino density matrices (or occupation numbers) such as Pauli blocking of neutrino final states or neutrino refraction in a medium of neutrinos. We apply the definition of the entropy of a non-equilibrium Fermi gas to the case of mixed neutrinos, and we prove that our collision integrals obey the relevant thermodynamic inequalities.

PHYSICAL REVIEW D **74**, 105010 (2006)

Self-induced conversion in dense neutrino gases: Pendulum in flavor space

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(Received 4 September 2006; published 14 November 2006)

Neutrino-neutrino interactions can lead to collective flavor conversion effects in supernovae and in the early universe. We demonstrate that the case of bipolar oscillations, where a dense gas of neutrinos and antineutrinos in equal numbers completely converts from one flavor to another even if the mixing angle is small, is equivalent to a pendulum in flavor space. Bipolar flavor conversion corresponds to the swinging of the pendulum, which begins in an unstable upright position (the initial flavor), and passes through momentarily the vertically downward position (the other flavor) in the course of its motion. The time scale to complete one cycle of oscillation depends logarithmically on the vacuum mixing angle. Likewise, the presence of an ordinary medium can be shown analytically to contribute to a logarithmic increase in the bipolar conversion period. We further find that a more complex (and realistic) system of unequal numbers of neutrinos and antineutrinos is analogous to a spinning top subject to a torque. This analogy easily explains how such a system can oscillate in both the bipolar and the synchronized mode, depending on the neutrino density and the size of the neutrino-antineutrino asymmetry. Our simple model applies strictly only to isotropic neutrino gasses. In more general cases, and especially for neutrinos streaming from a supernova core, different modes couple to each other with unequal strength, an effect that can lead to kinematical decoherence in flavor space rather than collective oscillations. The exact circumstances under which collective oscillations occur in nonisotropic media remain to be understood.

PRL **118,** 021101 (2017) PHYSICAL REVIEW LETTERS week ending 13 JANUARY 2017

Fast Pairwise Conversion of Supernova Neutrinos: A Dispersion Relation Approach

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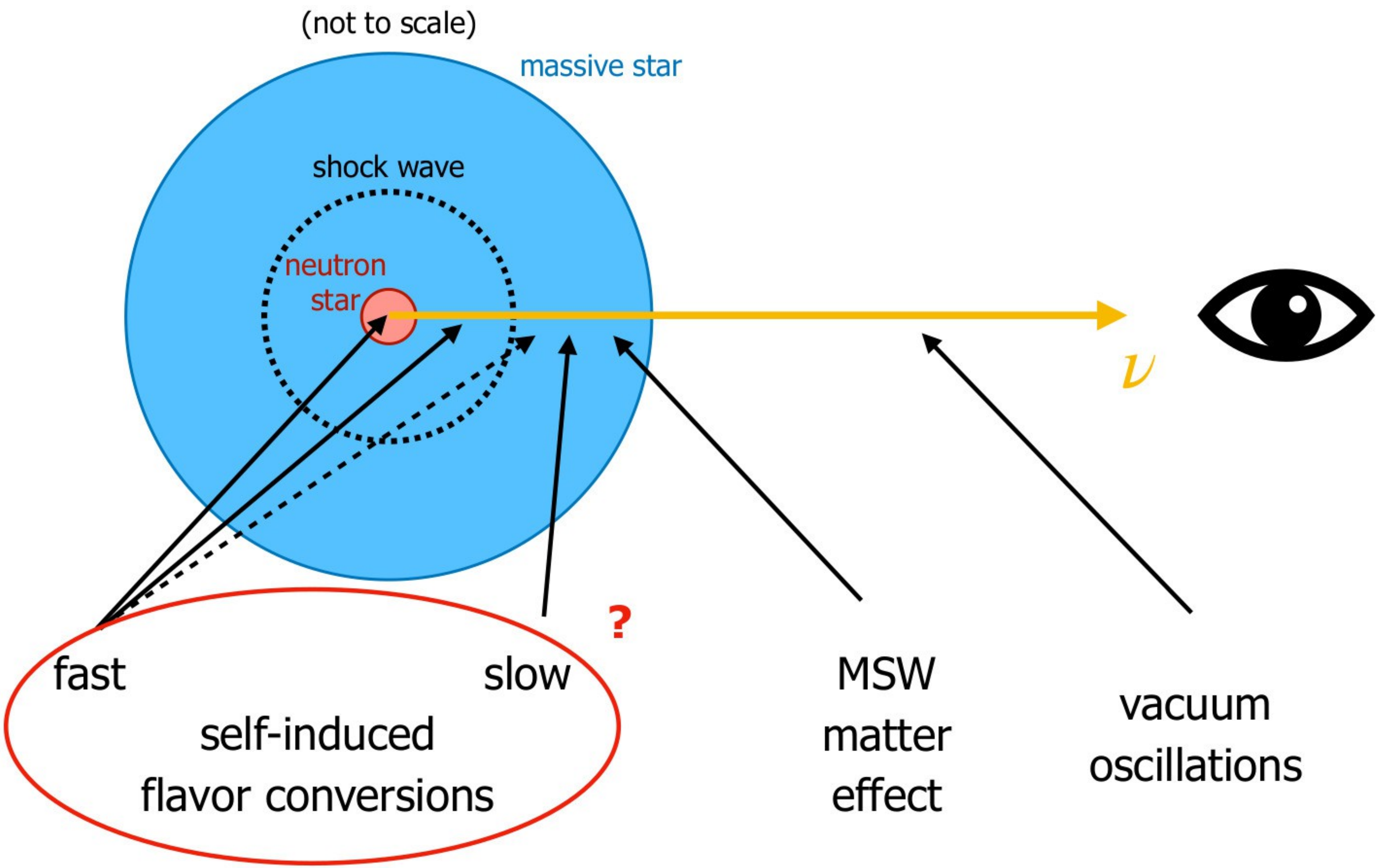
(Received 10 October 2016; published 10 January 2017)

Collective pair conversion $\nu_e\bar{\nu}_e \leftrightarrow \nu_x\bar{\nu}_x$ by forward scattering, where $x = \mu$ or τ, may be generic for supernova neutrino transport. Depending on the local angular intensity of the electron lepton number carried by neutrinos, the conversion rate can be "fast," i.e., of the order of $\sqrt{2}G_F(n_{\nu_e} - n_{\bar{\nu}_e}) \gg \Delta m^2_{\rm atm}/2E$. We present a novel approach to understand these phenomena: a dispersion relation for the frequency and wave number $(\Omega, \mathbf{K})$ of disturbances in the mean field of $\nu_e\nu_x$ flavor coherence. Runaway solutions occur in "dispersion gaps," i.e., in "forbidden" intervals of Ω and/or $\mathbf{K}$ where propagating plane waves do not exist. We stress that the actual solutions also depend on the initial and/or boundary conditions, which need to be further investigated.

Regions of Neutrino-Flavor Conversions



Kinetic Equation for Neutrino Transport

Flavor-dependent phase-space densities (occupation number matrices)

$$\varrho = \begin{pmatrix} f_{\nu_e} & f_{\langle\nu_e|\nu_\mu\rangle} & f_{\langle\nu_e|\nu_\tau\rangle} \\ f_{\langle\nu_\mu|\nu_e\rangle} & f_{\nu_\mu} & f_{\langle\nu_\mu|\nu_\tau\rangle} \\ f_{\langle\nu_\tau|\nu_e\rangle} & f_{\langle\nu_\tau|\nu_\mu\rangle} & f_{\nu_\tau} \end{pmatrix}$$

Diagonal: Usual occupation numbers
Off-diag: Flavor coherence information

and similar for $\bar{\nu}$

Transport equation

$$\underbrace{\left(\partial_t + \vec{v}\cdot\vec{\nabla}_r\right.}_{\text{Streaming}} \underbrace{\left.- \vec{F}\cdot\vec{\nabla}_p\right)}_{\text{Gravitational forces}} \varrho(t,\vec{r},\vec{p}) = \underbrace{-\mathrm{i}\,[\mathcal{H}(t,\vec{x},\vec{p}),\varrho(t,\vec{x},\vec{p})]}_{\text{Flavor oscillations}} + \underbrace{\mathcal{C}[\varrho(t,\vec{x},\vec{p})]}_{\text{Collisions}}$$

Hamiltonian for flavor oscillations

$$H = \underbrace{\frac{M^2}{2E}}_{\text{vacuum}} + \underbrace{\sqrt{2}G_F n_e}_{\text{MSW effect}} + \underbrace{\sqrt{2}G_F \int \frac{d^3p}{(2\pi)^3}\left(\rho - \bar{\rho}\right)\left(1 - v_q v_p\right)}_{\nu\nu\text{ self-induced}}$$

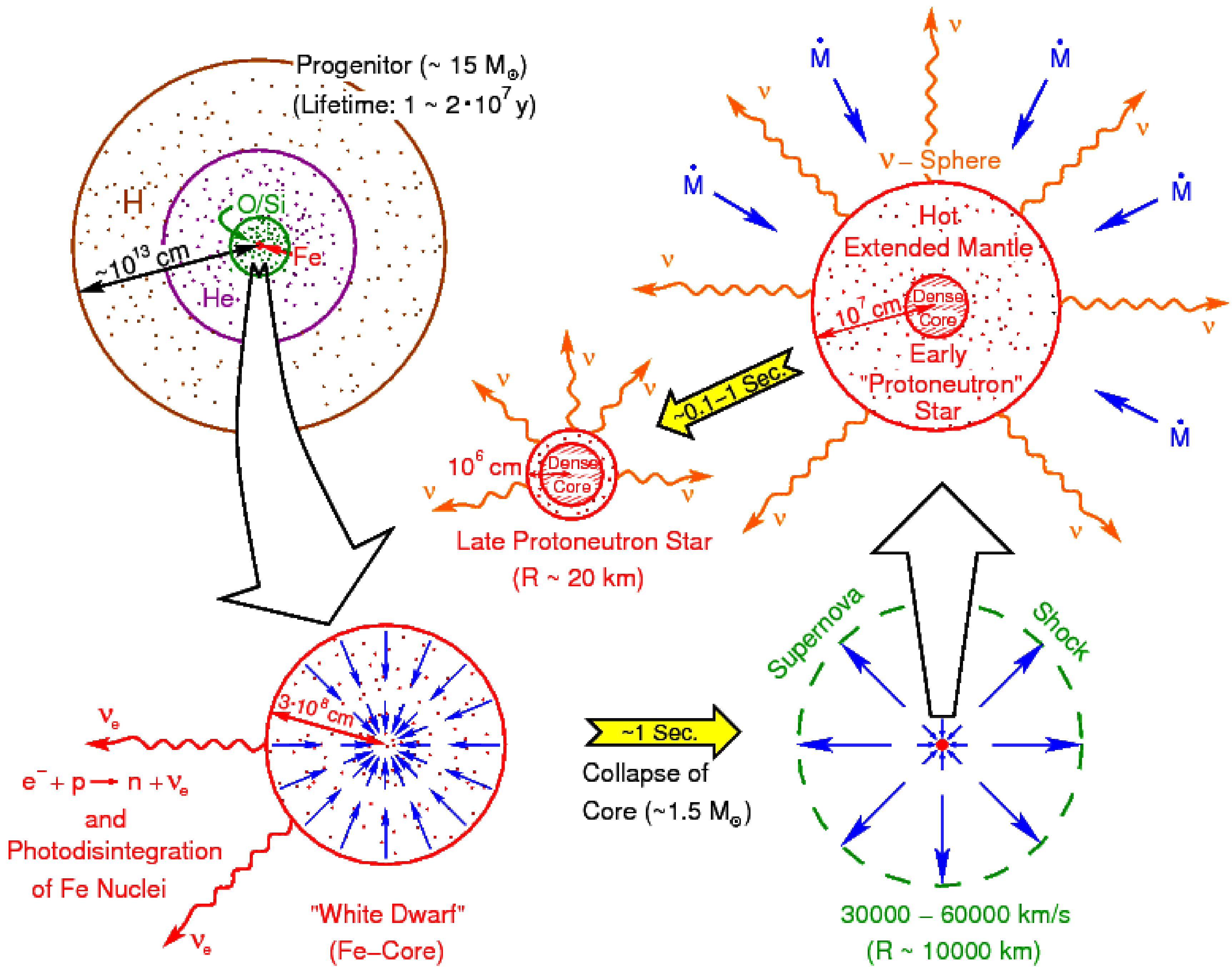
- $e^- + p \rightleftharpoons n + \nu_e$
- $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
- $e^- + A \rightleftharpoons \nu_e + A^*$

β

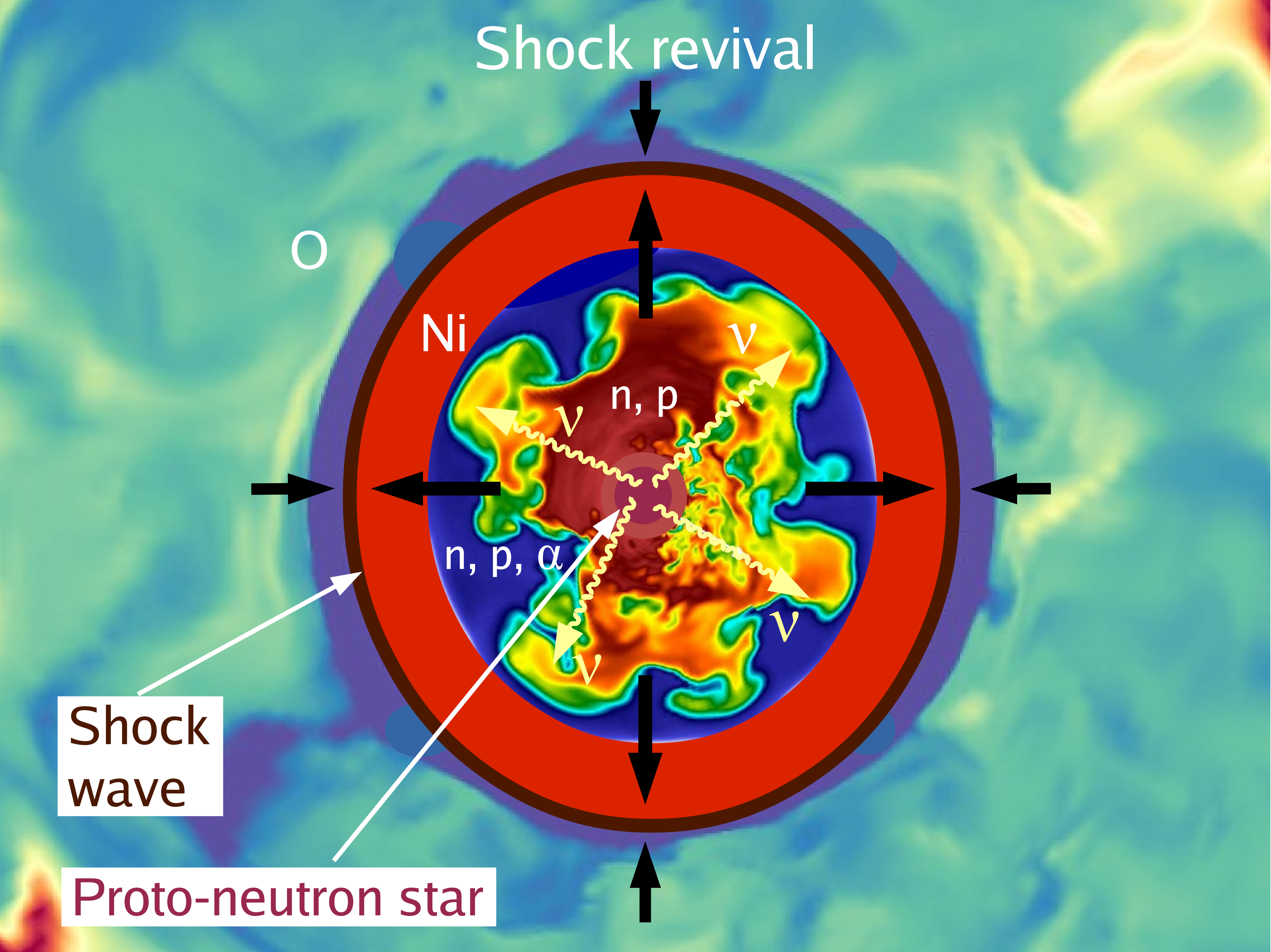
- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^\pm \rightleftharpoons \nu + e^\pm$
- $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
- $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$
- $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$
  ($\nu_x = \nu_\mu$, $\bar{\nu}_\mu$, ν_τ, or $\bar{\nu}_\tau$)
- $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

- **Flavor evolution is caused by off-diagonal $\mathcal{H}$ elements (vacuum or nu-nu term)**
- **For $\Delta m^2 = 0$, nu-nu term can still cause run-away modes!**

Stellar Collapse and Supernova Stages

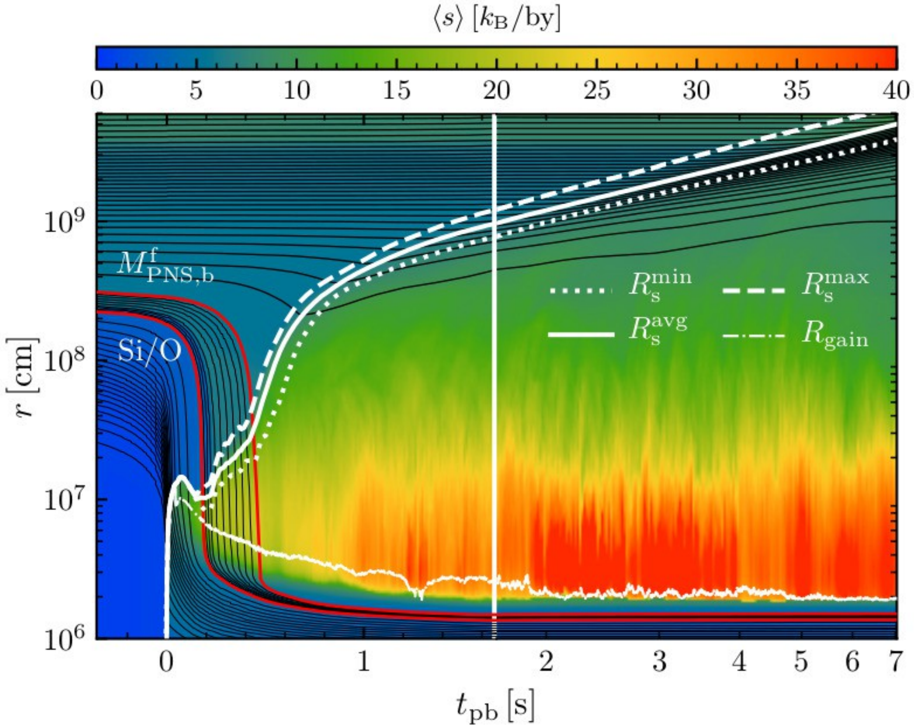


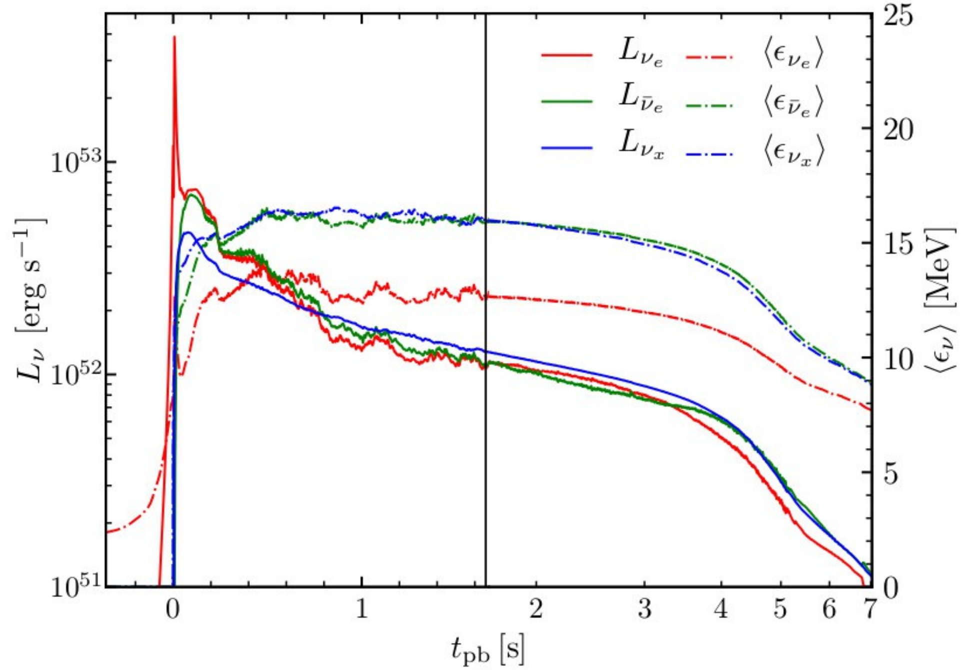
adapted from A. Burrows (1990)


Shock revival
O
Ni
n, p
ν
ν
n, p, α
ν
ν
Shock wave
Proto-neutron star

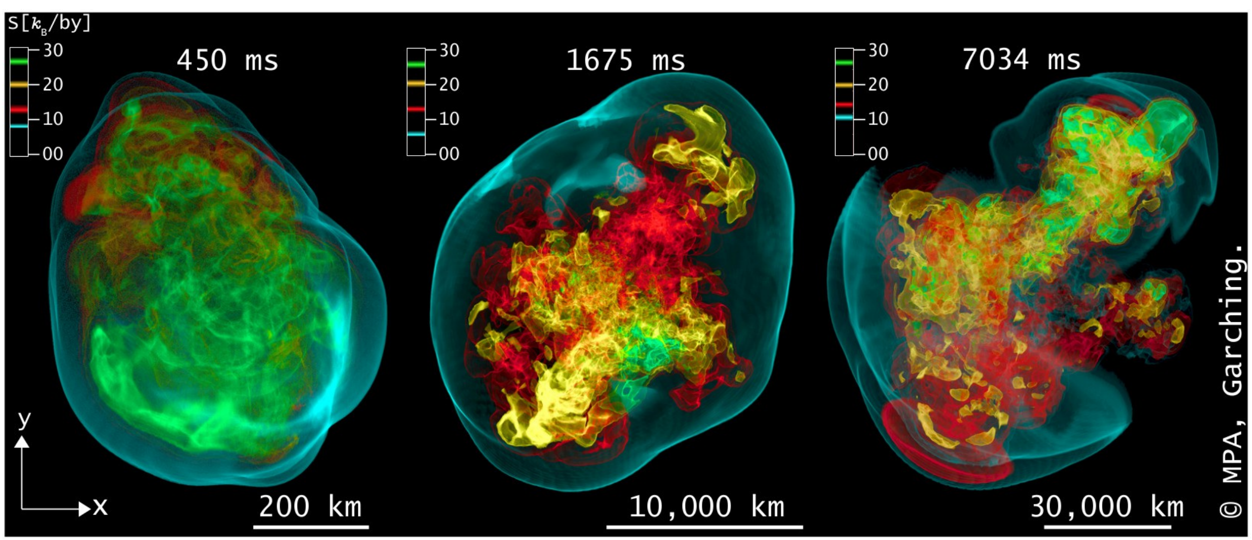
3D Explosion of ~19 M_{sun} Star

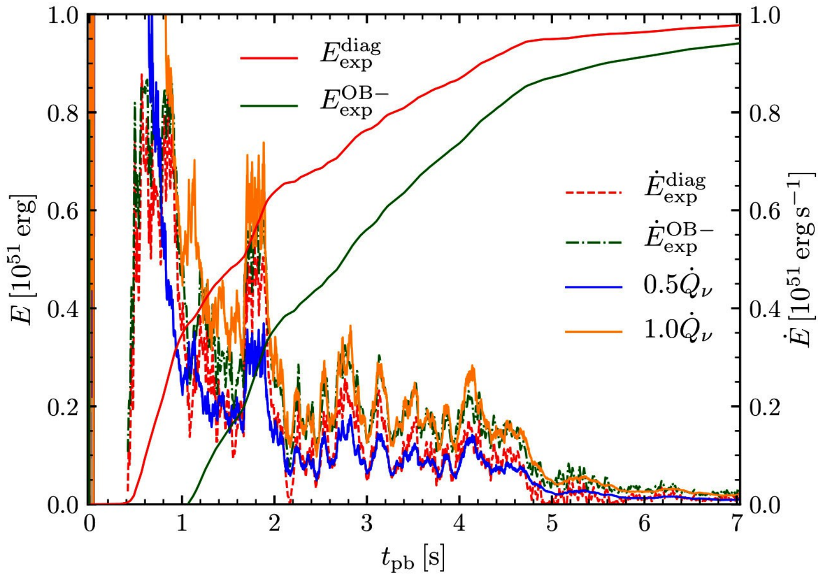
Explosion energy saturates at 10^{51} ergs after 7 seconds

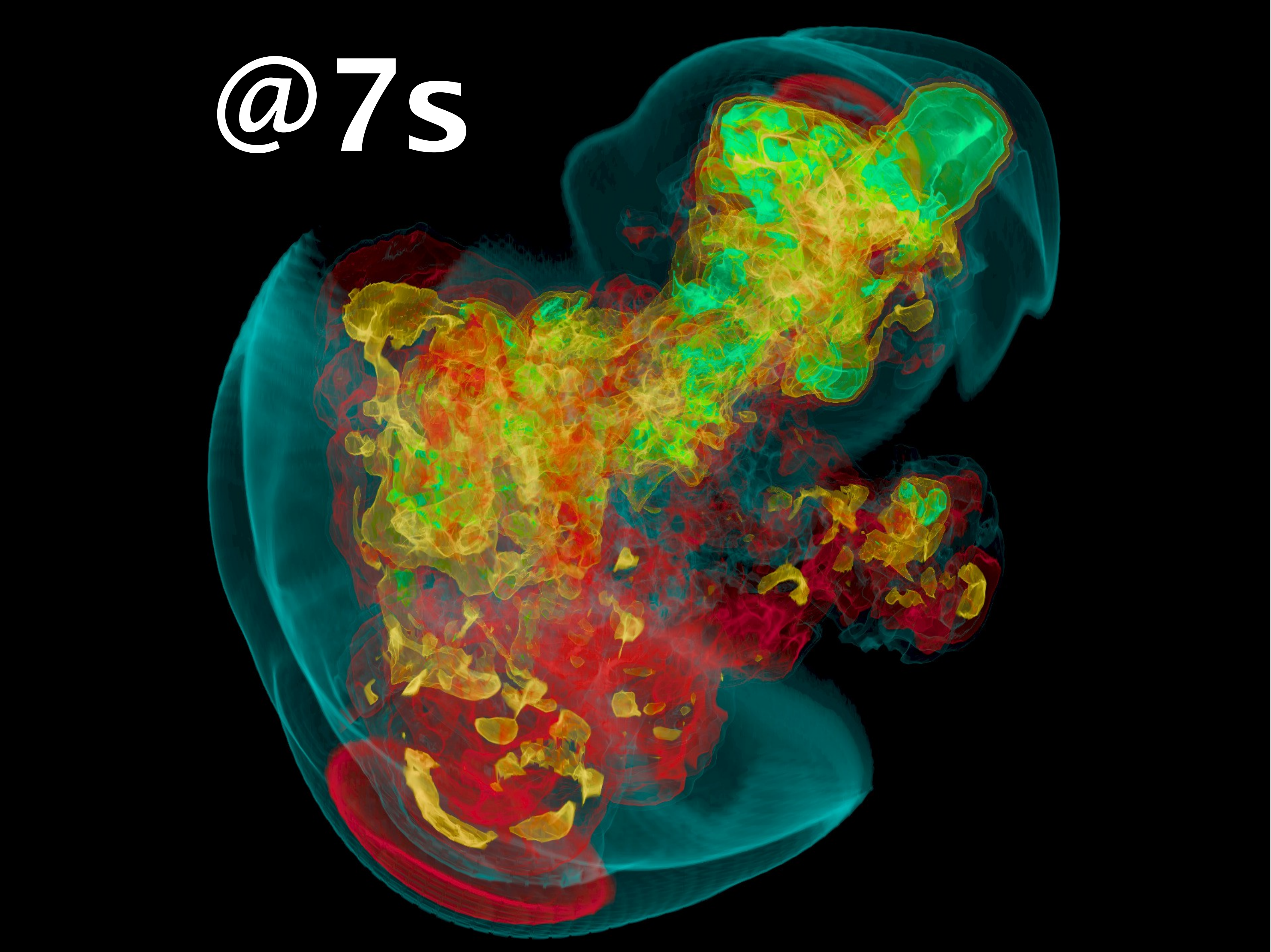




R. Bollig et al., ApJ 915 (2021) 28



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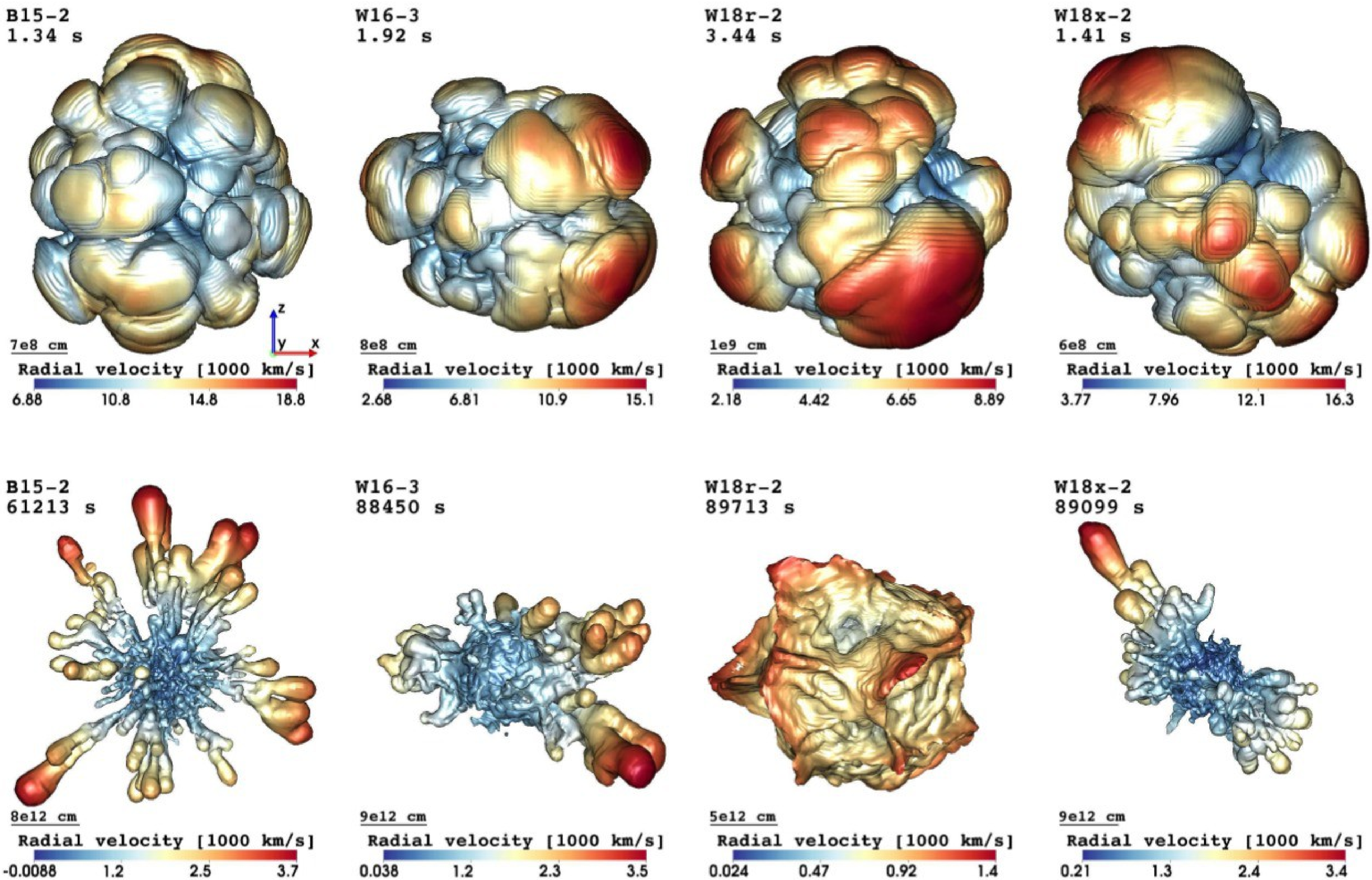
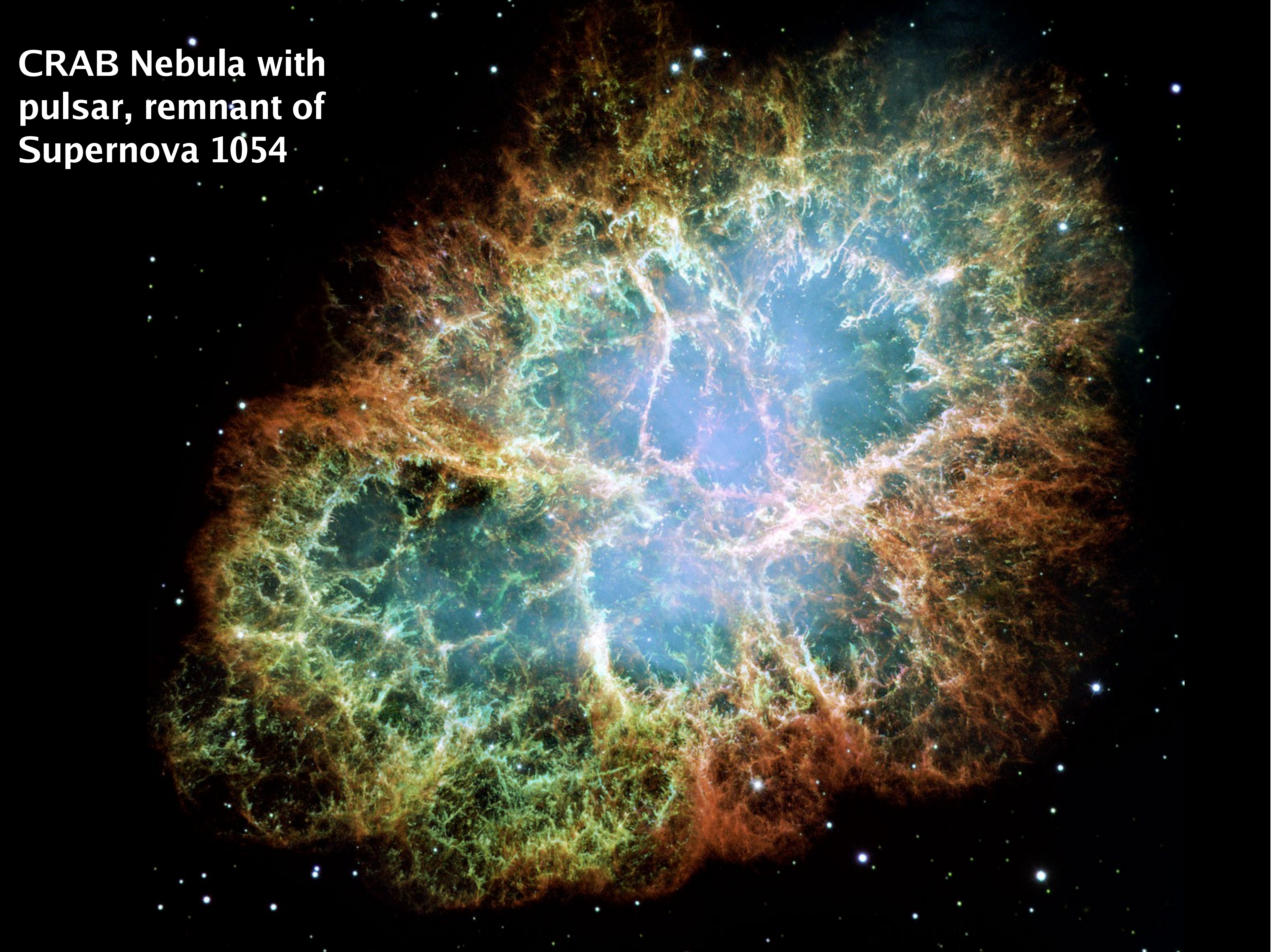
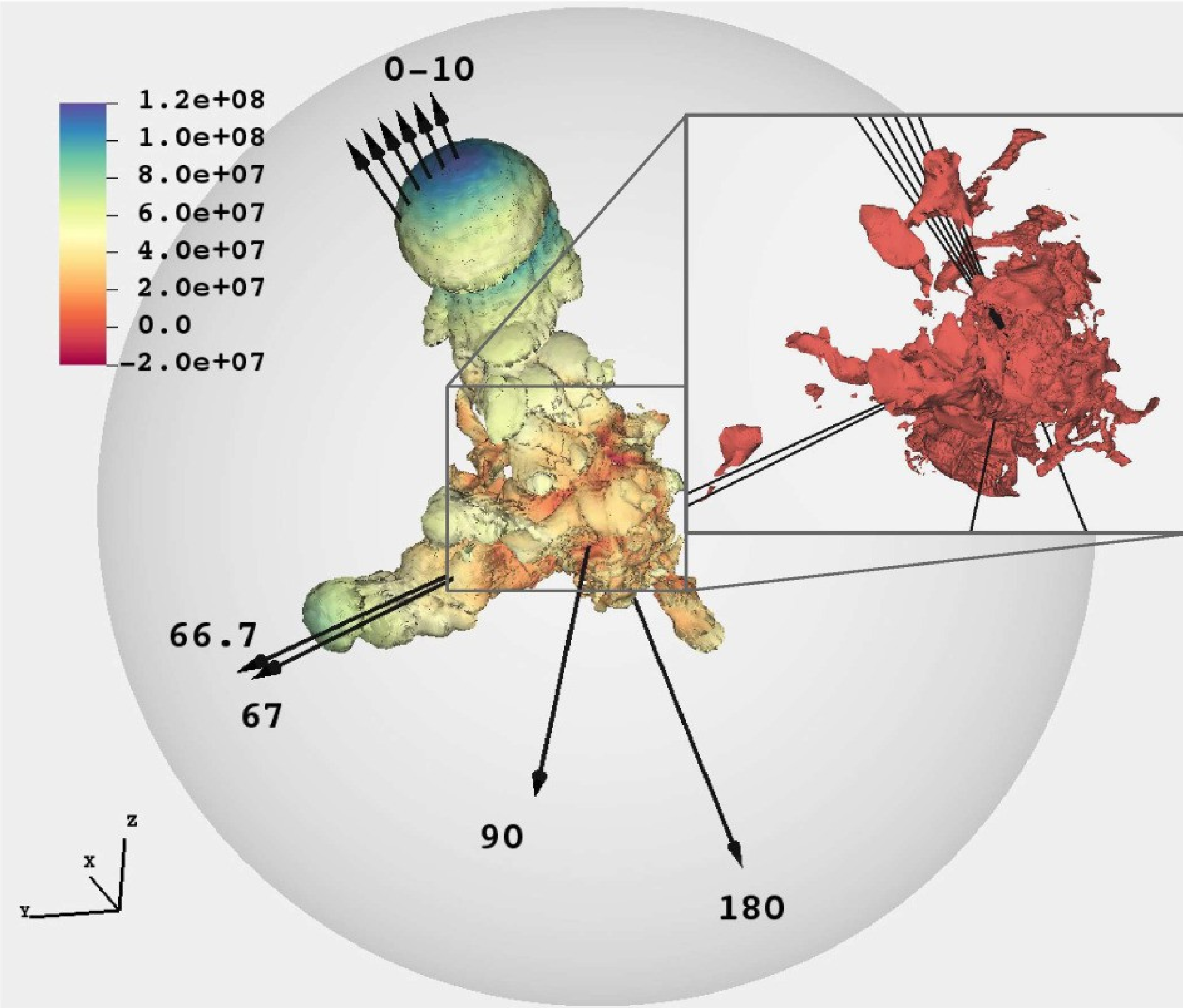
3D SN Models: Different Morphologies



Utrobin et al., A&A 624 (2019) A116



CRAB Nebula with pulsar, remnant of Supernova 1054


0-10
1.2e+08
1.0e+08
8.0e+07
6.0e+07
4.0e+07
2.0e+07
0.0
-2.0e+07
66.7
67
90
180
z
x
y

"Crab-like" Supernovae 2005cs & 2020cxd

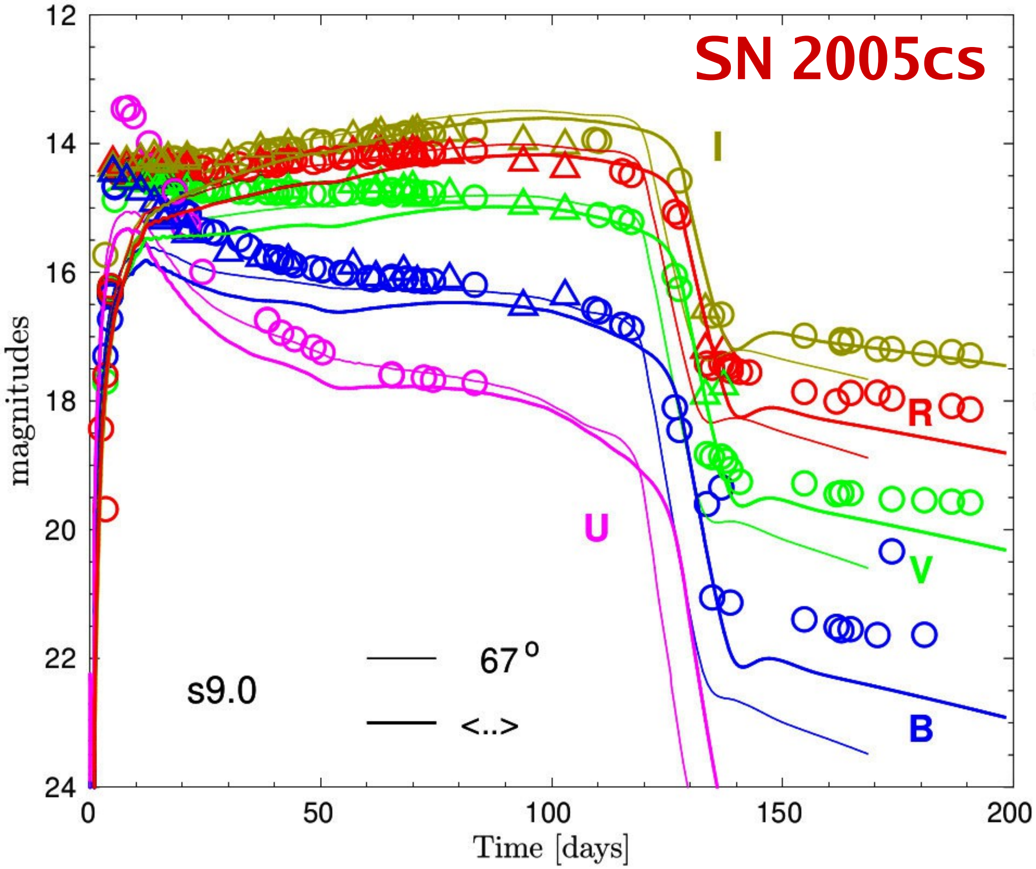
Low-mass, low-energy supernovae from Fe-core progenitors

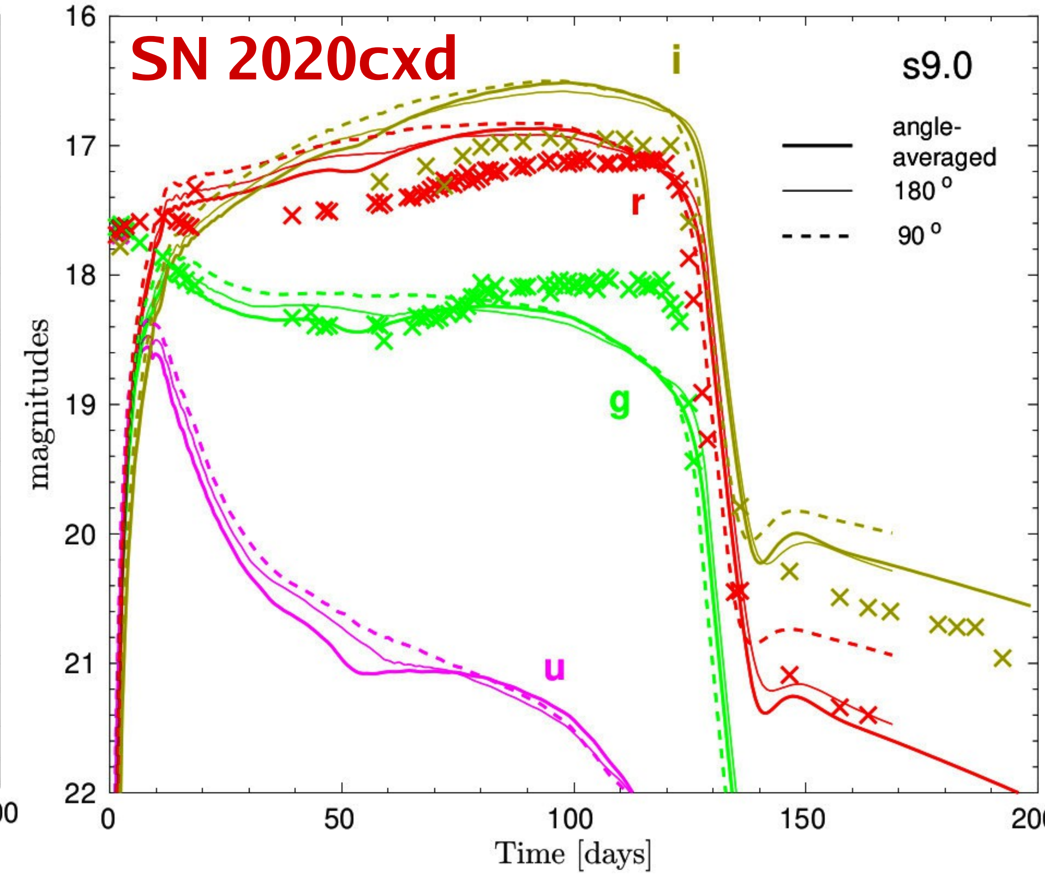
Multi-band light curves from 3D explosion models agree very well with observations!

Progenitor ~9 M_{sun} with Fe-core

- **Explosion energy: ~7*10^{49} erg**
- **Ni+Fe mass: ~3*10^{-3} M_{sun}**
- **Ejecta mass: ~7.4 M_{sun}**

Kozyreva et al., MNRAS 514 (2022) 4173





Nebular Spectra of Neutrino-driven Low-energy Explosion of 9.0 M_{sun} Fe-core Progenitor

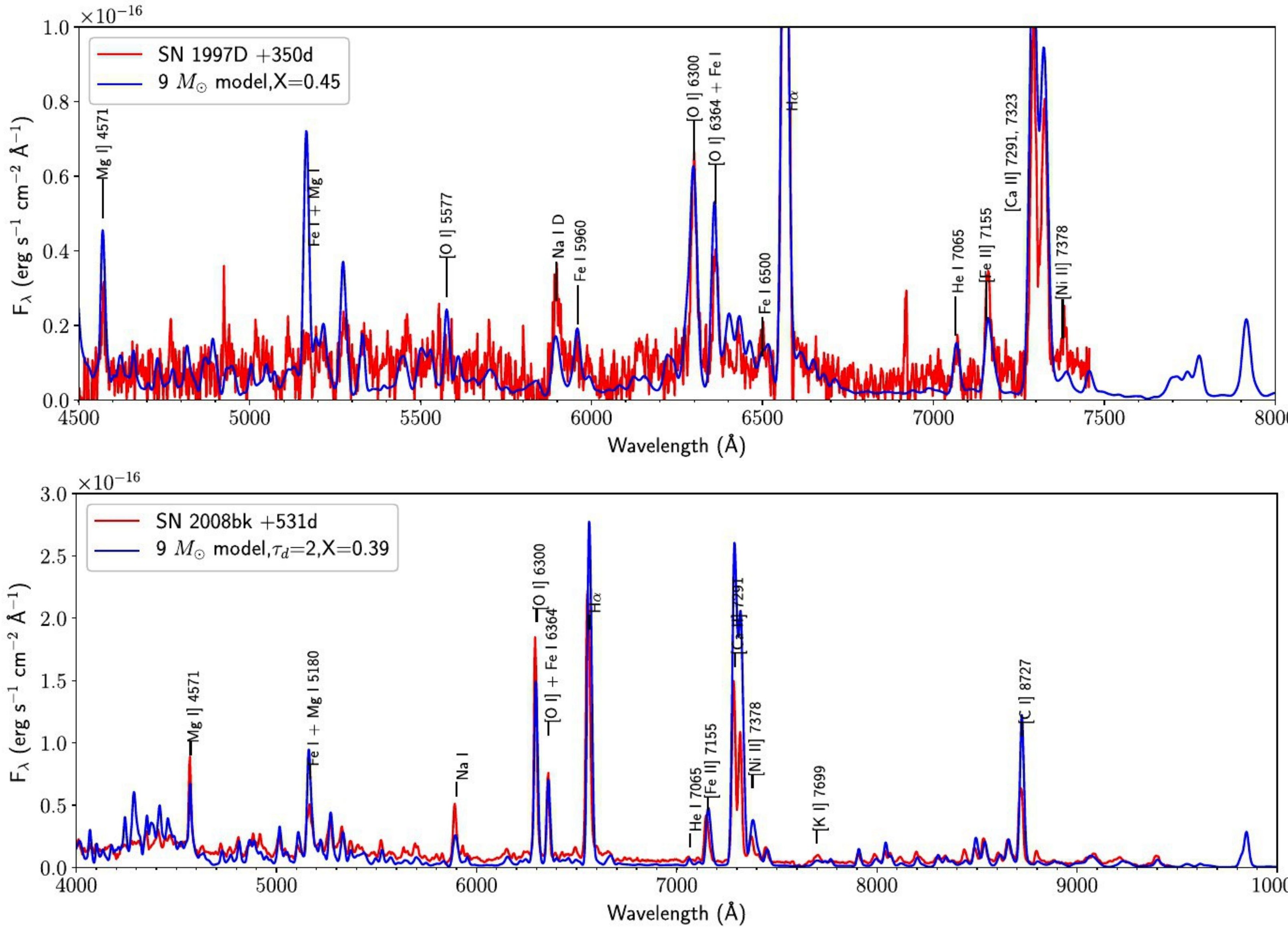
Spectra and line profiles of 1D explosion model:

Good agreement with SN 1997D and SN 2008bk; SN 2005cs unclear

All cases show clear O and He lines and no high $^{58}Ni/^{56}Ni$ ratio

ECSNe disfavored; explosions of low-mass Fe-core progenitors more likely

Jerkstrand et al., MNRAS 475 (2018) 277



Low-energy Supernovae Constrain Radiative Particle Decays

Energy deposition by radiative decays of axion-like particles (ALPs) must not over-power low-energy, low-luminosity SNe

PHYSICAL REVIEW LETTERS **128,** 221103 (2022)

Low-Energy Supernovae Severely Constrain Radiative Particle Decays

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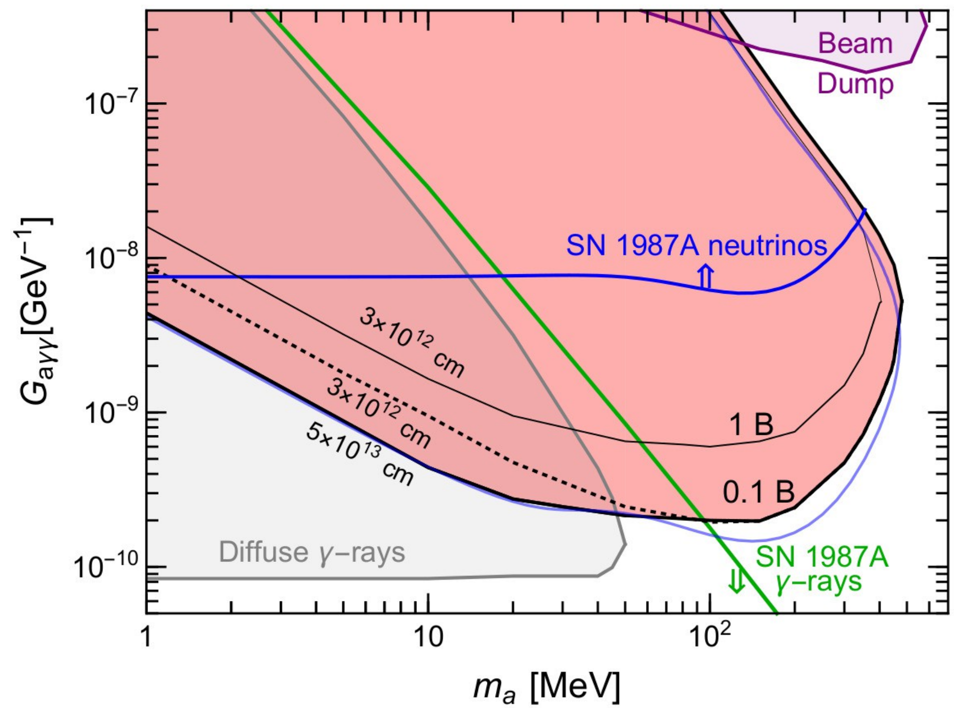
The hot and dense core formed in the collapse of a massive star is a powerful source of hypothetical feebly interacting particles such as sterile neutrinos, dark photons, axionlike particles (ALPs), and others. Radiative decays such as $a \to 2\gamma$ deposit this energy in the surrounding material if the mean free path is less than the radius of the progenitor star. For the first time, we use a supernova (SN) population with particularly low explosion energies as the most sensitive calorimeters to constrain this possibility. These SNe are observationally identified as low-luminosity events with low ejecta velocities and low masses of ejected ^{56}Ni. Their low energies limit the energy deposition from particle decays to less than about 0.1 B, where 1 B(bethe) $= 10^{51}$ erg. For 1–500 MeV-mass ALPs, this generic argument excludes ALP-photon couplings $G_{a\gamma\gamma}$ in the $10^{-10} - 10^{-8}$ GeV^{-1} range.



Caputo, THJ, et al., PRL 128 (2022) 221103

Particle Bounds from Supernovae & Neutrinos

Nuclear Physics B 590 (2000) 562–574

www.elsevier.nl/locate/npe

Heavy sterile neutrinos: bounds from big-bang nucleosynthesis and SN 1987A

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Abstract

Cosmological and astrophysical effects of heavy (10–200 MeV) sterile Dirac neutrinos, mixed with the active ones, are considered. The bounds on mass and mixing angle from both supernovae and big-bang nucleosynthesis are presented.

PHYSICAL REVIEW D **105,** 035022 (2022)

Editors' Suggestion

Muonic boson limits: Supernova redux

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We derive supernova (SN) bounds on muon-philic bosons, taking advantage of the recent emergence of muonic SN models. Our main innovations are to consider scalars ϕ in addition to pseudoscalars a and to include systematically the generic two-photon coupling $G_{\gamma\gamma}$ implied by a muon triangle loop. This interaction allows for Primakoff scattering and radiative boson decays. The globular-cluster bound $G_{\gamma\gamma} < 0.67 \times 10^{-10}$ GeV^{-1} carries over to the muonic Yukawa couplings as $g_a < 3.1 \times 10^{-9}$ and $g_\phi < 4.6 \times 10^{-9}$ for $m_{a,\phi} \lesssim 100$ keV, so SN arguments become interesting mainly for larger masses. If bosons escape freely from the SN core the main constraints originate from SN 1987A γ rays and the diffuse cosmic γ-ray background. The latter allows at most 10^{-4} of a typical total SN energy of $E_{\rm SN} \simeq 3 \times 10^{53}$ erg to show up as γ rays, for $m_{a,\phi} \gtrsim 100$ keV implying $g_a \lesssim 0.9 \times 10^{-10}$ and $g_\phi \lesssim 0.4 \times 10^{-10}$. In the trapping regime the bosons emerge as quasi-thermal radiation from a region near the neutrino sphere and match L_ν for $g_{a,\phi} \simeq 10^{-4}$. However, the 2γ decay is so fast that all the energy is dumped into the surrounding progenitor-star matter, whereas at most $10^{-2} E_{\rm SN}$ may show up in the explosion. To suppress boson emission below this level we need yet larger couplings, $g_a \gtrsim 2 \times 10^{-3}$ and $g_\phi \gtrsim 4 \times 10^{-3}$. Muonic scalars can explain the muon magnetic-moment anomaly for $g_\phi \simeq 0.4 \times 10^{-3}$, a value hard to reconcile with SN physics despite the uncertainty of the explosion-energy bound. For generic axionlike particles, this argument covers the "cosmological triangle" in the $G_{a\gamma\gamma}$–m_a parameter space.

Strong Supernova 1987A Constraints on Bosons Decaying to Neutrinos

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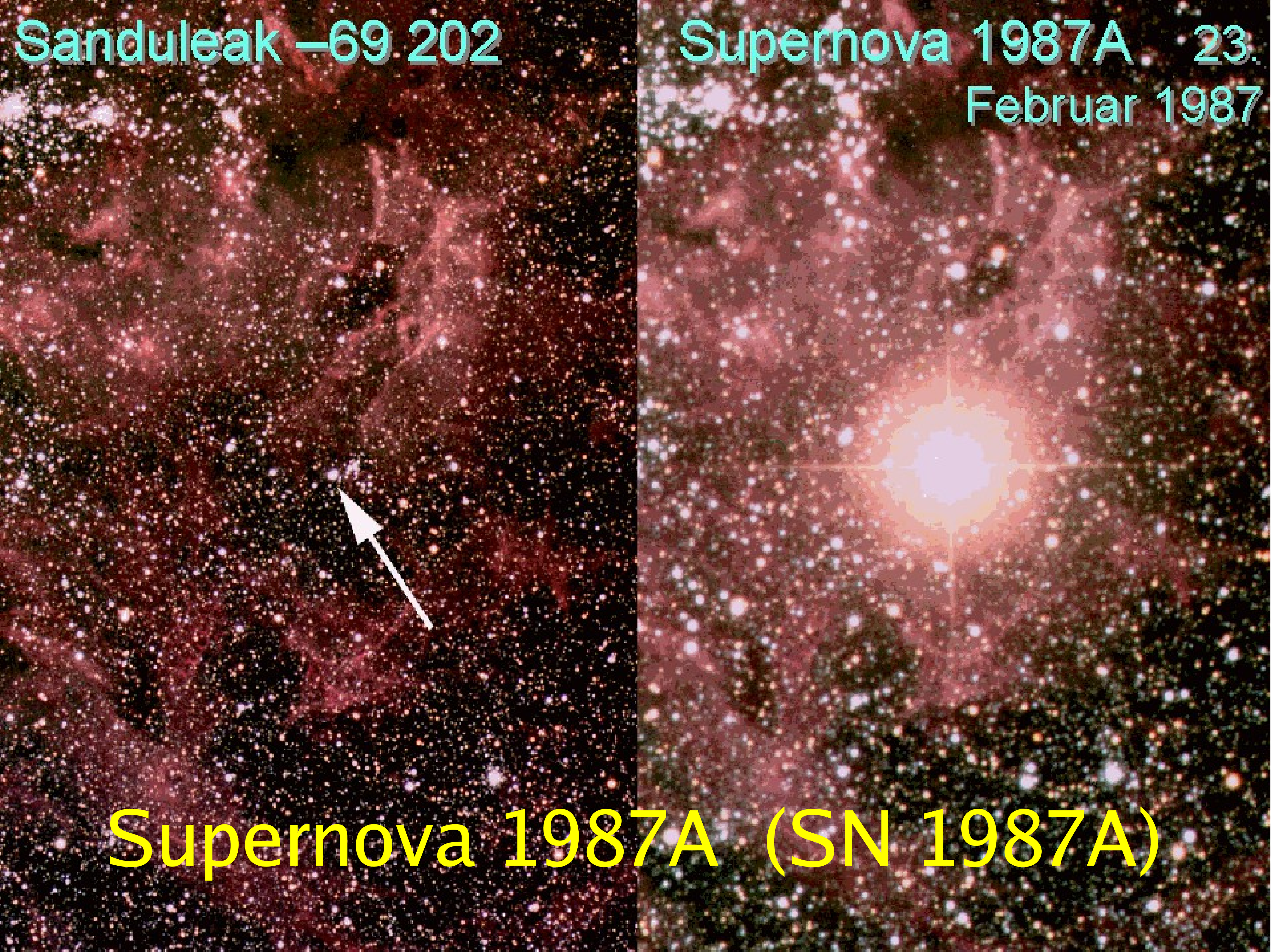
(Dated: September 27, 2022)

Majoron-like bosons would emerge from a supernova (SN) core by neutrino coalescence of the form $\nu\nu \to \phi$ and $\bar\nu\bar\nu \to \phi$ with 100 MeV-range energies. Subsequent decays to (anti)neutrinos of all flavors provide a flux component with energies much larger than the usual flux from the "neutrino sphere." The absence of 100 MeV-range events in the Kamiokande II and IMB signal of SN 1987A implies that $\lesssim 0.03$ of the total energy was thus emitted and provides the strongest constraint on the majoron-neutrino coupling of $g \lesssim 10^{-9}\,{\rm MeV}/m_\phi$ for 100 eV $\lesssim m_\phi \lesssim$ 100 MeV. It is straightforward to extend our new argument to other hypothetical feebly interacting particles.

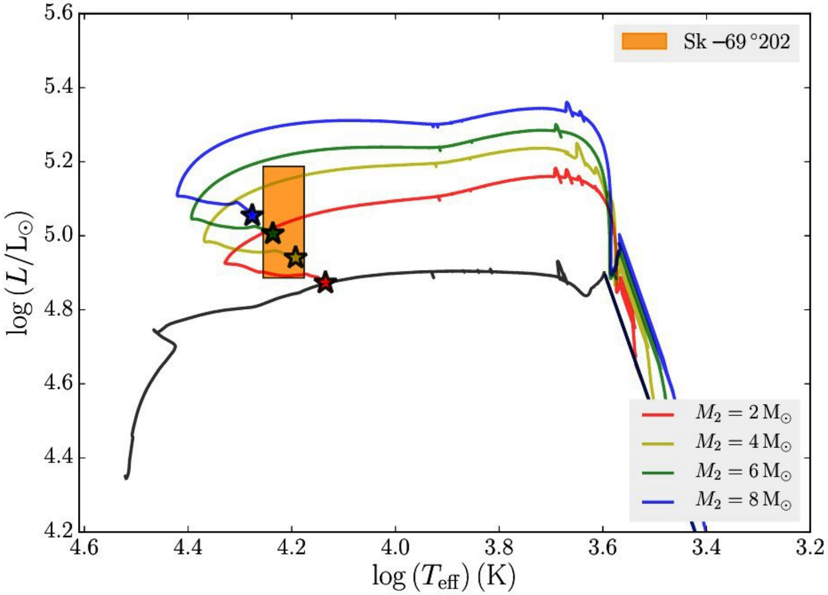


Sanduleak –69 202
Supernova 1987A 23. Februar 1987
Supernova 1987A (SN 1987A)

Binary-star Models for SN1987A: Bolometric Light Curves from 3D Explosions

Hertzsprung-Russell Diagram for SN 1987A Progenitors

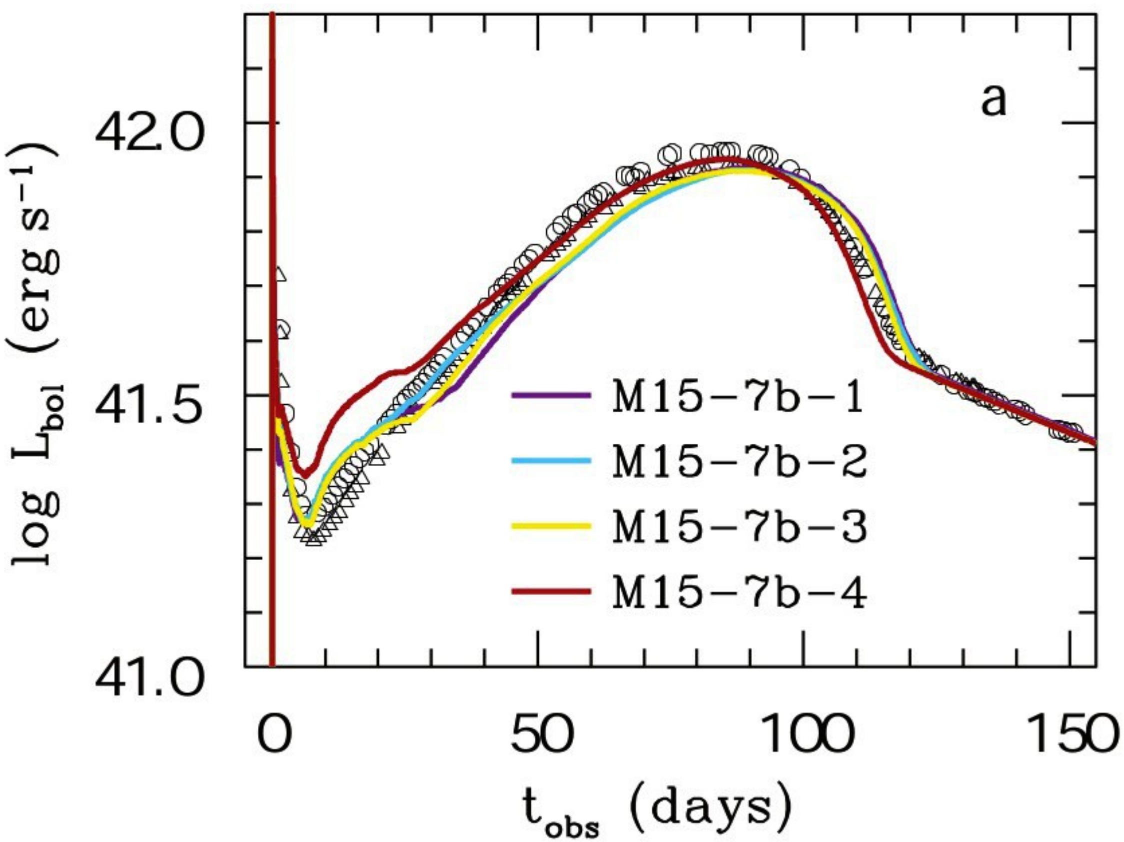
Binary Merger Scenario



$M_1 = 16\,M_\odot$ Menon & Heger (2017)

Menon & Heger (2017);
Binary merger progenitors, following an original suggestion by Podsiadlowski and coworkers (1990ff)

Utrobin et al., ApJ 914 (2021) 4



Binary-star vs. Single-star Models for SN1987A:

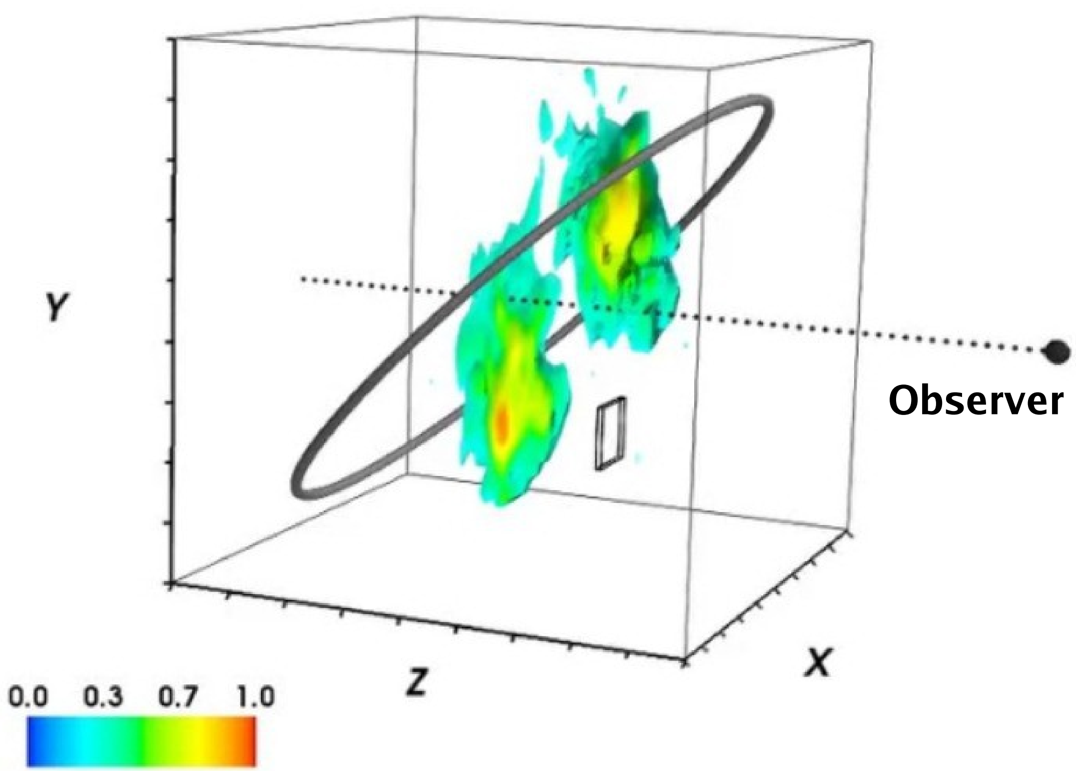
Table 6. Comparative analysis of single-star and binary-merger models

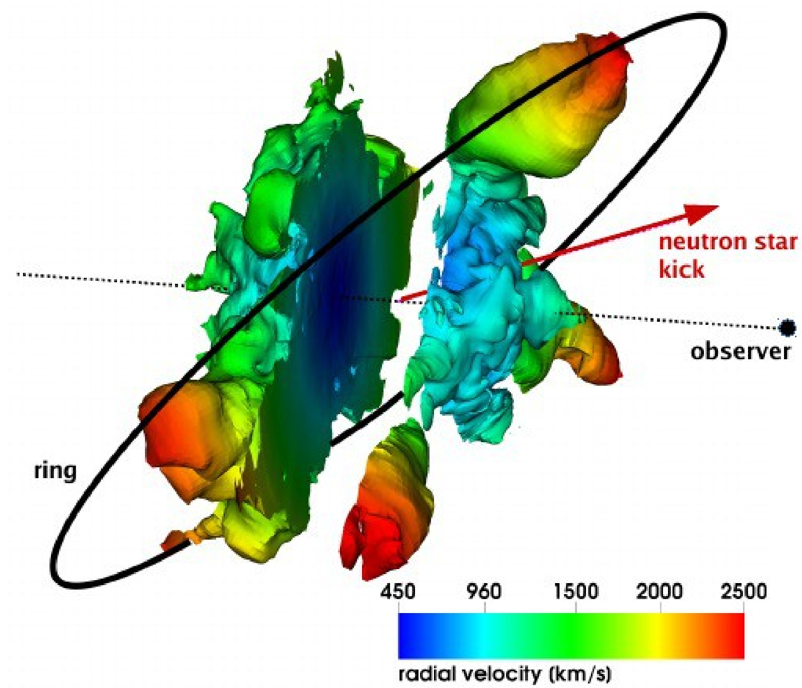
Observational constraint	Single-star	Binary-merger
	B15-2 / W18x-2	M15-7b-3 / M15-8b-1
1. location of Sanduleak −69°202 in the HRD	− / +	+ / +
2. production of ^{56}Ni in 3D simulations	+ / +	+ / +
3. maximum velocity of the bulk of ^{56}Ni	+ / −	+ / −
4. minimum velocity of hydrogen matter	+ / +	+ / +
5. mass of hydrogen with $v < 2000\,\mathrm{km\,s^{-1}}$	− / −	+ / +
6. dome shape of the light curve	+ / −	+ / +
7. global shape of the light curve	− / −	+ / −
8. evolution of the photospheric velocity	+ / −	+ / −
9. oxygen mass in the SN ejecta	− / −	+ / +
10. 3D shape of the ^{56}Ni ejecta	− / +	+ / −
11. X-ray and gamma-ray emission	+ /	+ / −
12. gamma-ray decay lines	+ / −	− / −
Total score	7 : 12 / 4 : 11	11 : 12 / 6 : 12

Utrobin et al., ApJ 914 (2021) 4

3D Geometry of SN1987A: Observations vs. Models

3D isosurfaces of iron and silicon ([FeII]+[SiI])

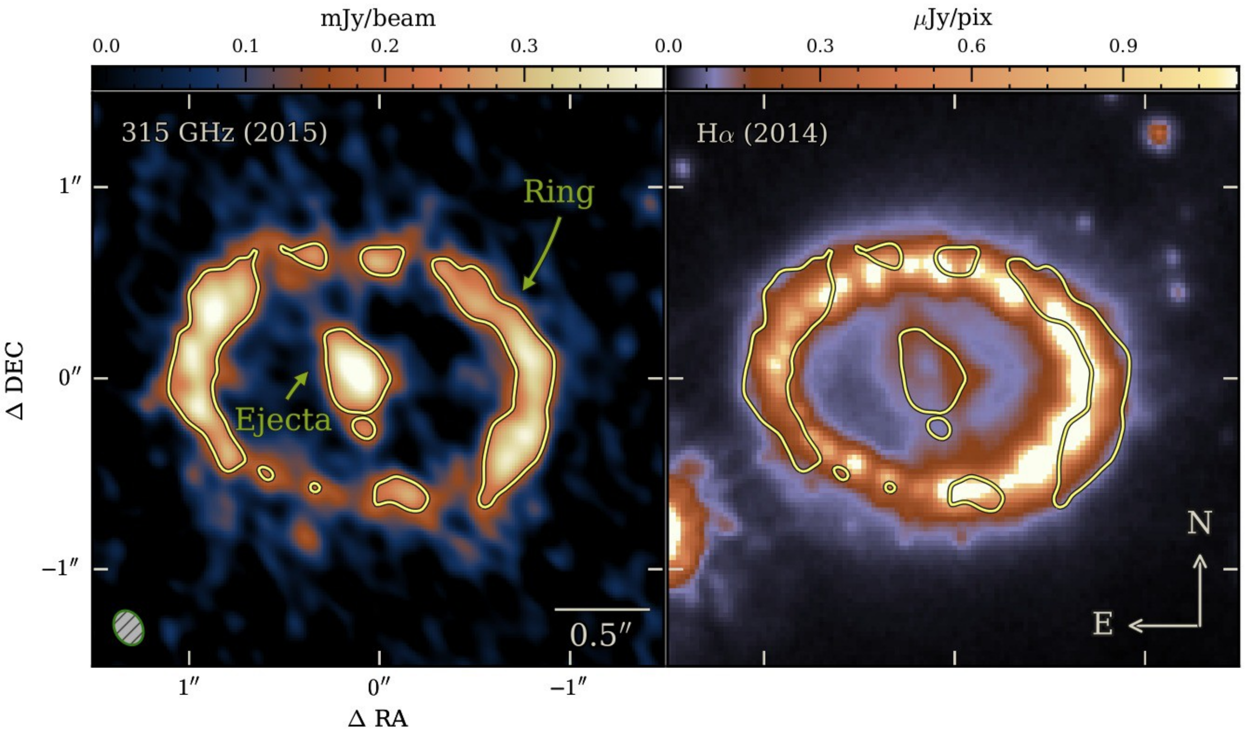


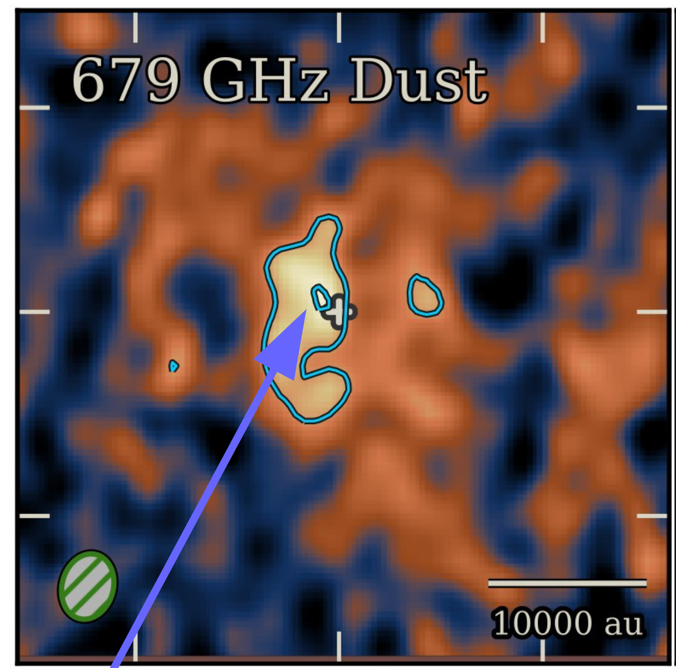


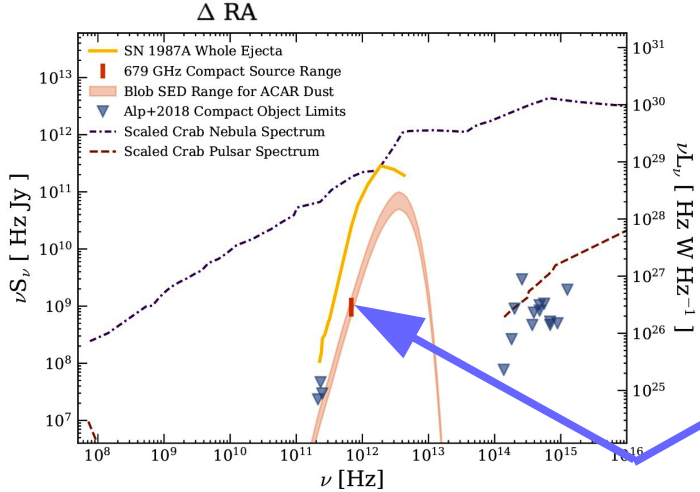
<u>HST & VLT obs.</u> (Larsson et al., ApJ 833 (2016) 147) <u>3D model L15</u> (Janka et al., arXiv:1705.01159)

A Compact Object in SN1987A?

High angular resolution ALMA images of dust and molecules in the ejecta of SN 1987A







5-sigma hot "blob" north-east of ejecta center:

Compact source would be compatible with recent limits by Alp et al. (ApJ 864 (2018) 174).

Luminosity can be explained by energy input from a thermally cooling NS (or, less likely, accretion by BH)

(Cigan et al., ApJ 886 (2019) 51; Page et al., ApJ 898 (2020) 125)

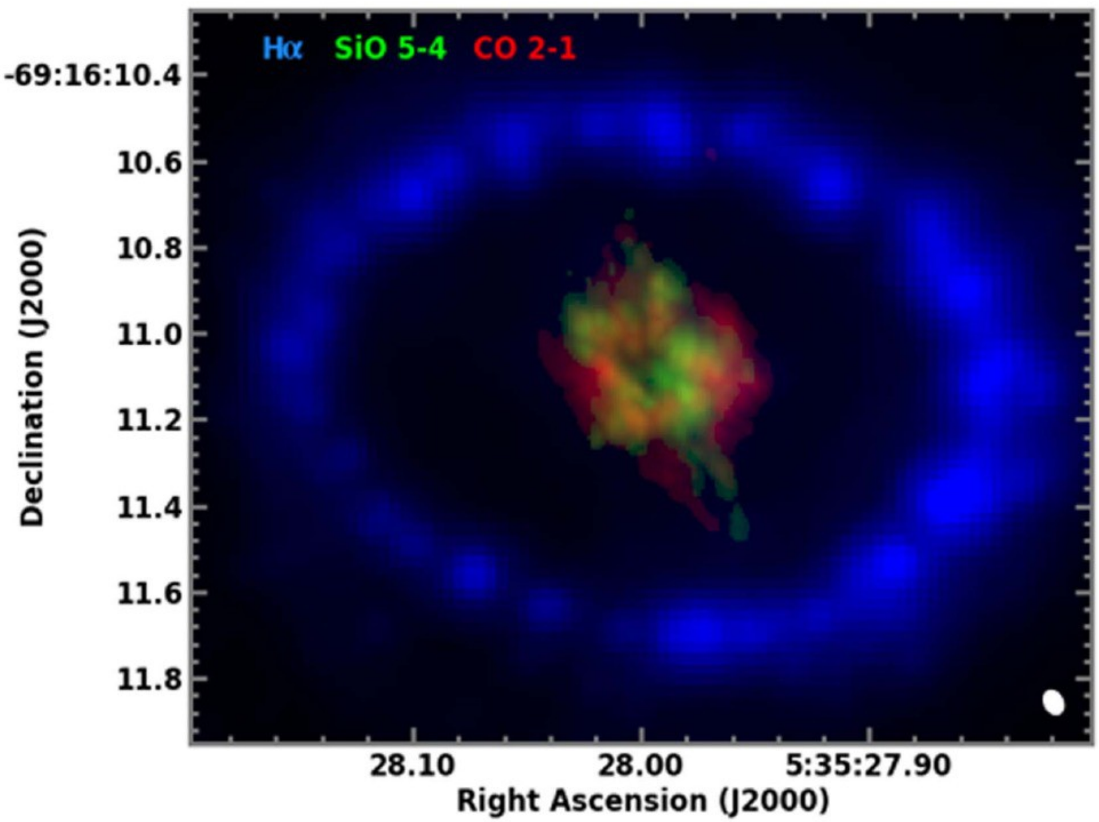
More Questions & Challenges .... and More Work for Georg!

- What are the effects of neutrino flavor oscillations in supernovae ?
- Can we learn more from SN 1987A neutrinos using state-of-the-art explosion models?
- Better BSM particle constraints through better models!
- A core-collapse supernova in the Milky Way!

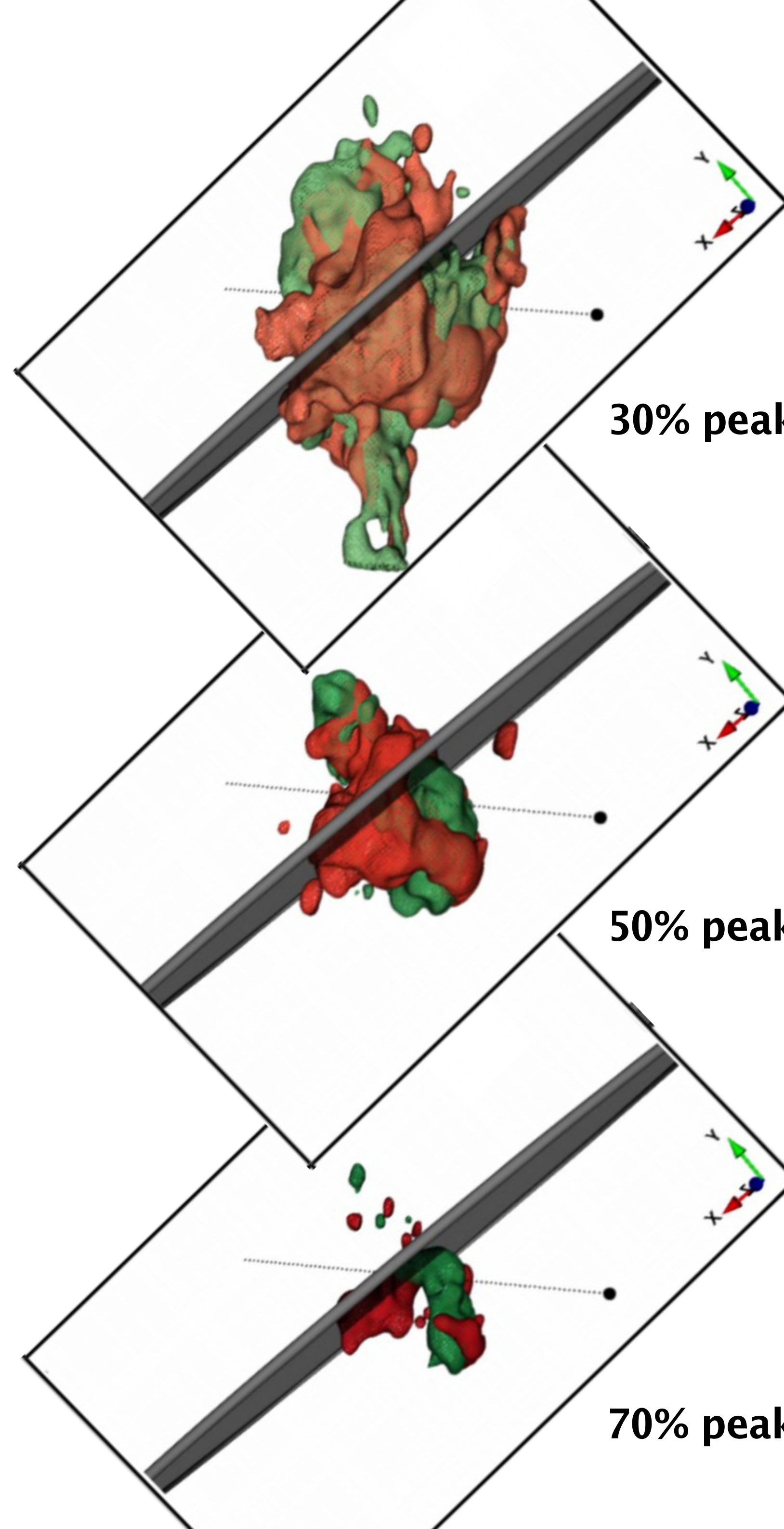
All the best and many more years of productivity and fun!

3D Geometry of SN1987A: Observations vs. Models

Molecular CO 2-1 and SiO 5-4 emission observed by ALMA



Abellán et al., ApJL 842 (2017) L24



3D Geometry of SN1987A: Observations vs. Models

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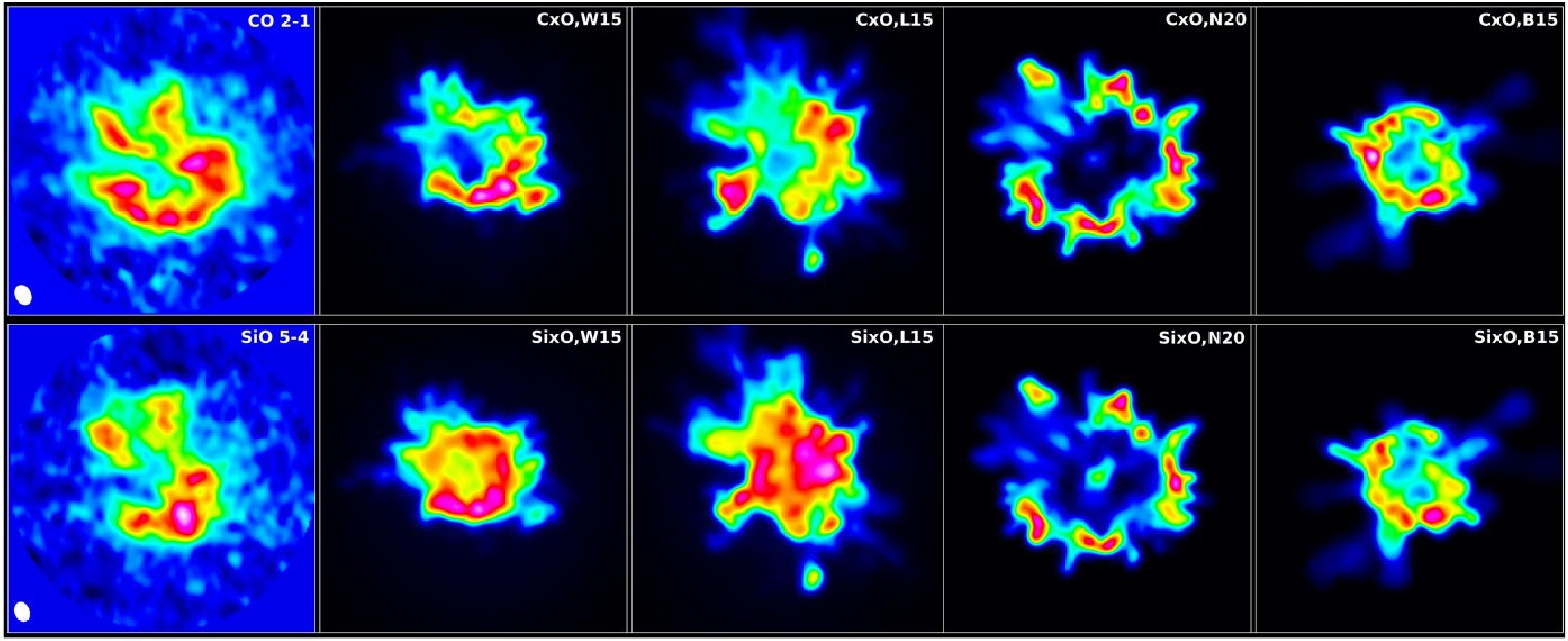
Abellán et al., ApJL 842 (2017) L24



W15 L15 N20 B15

3D Geometry of SN1987A: Observations vs. Models

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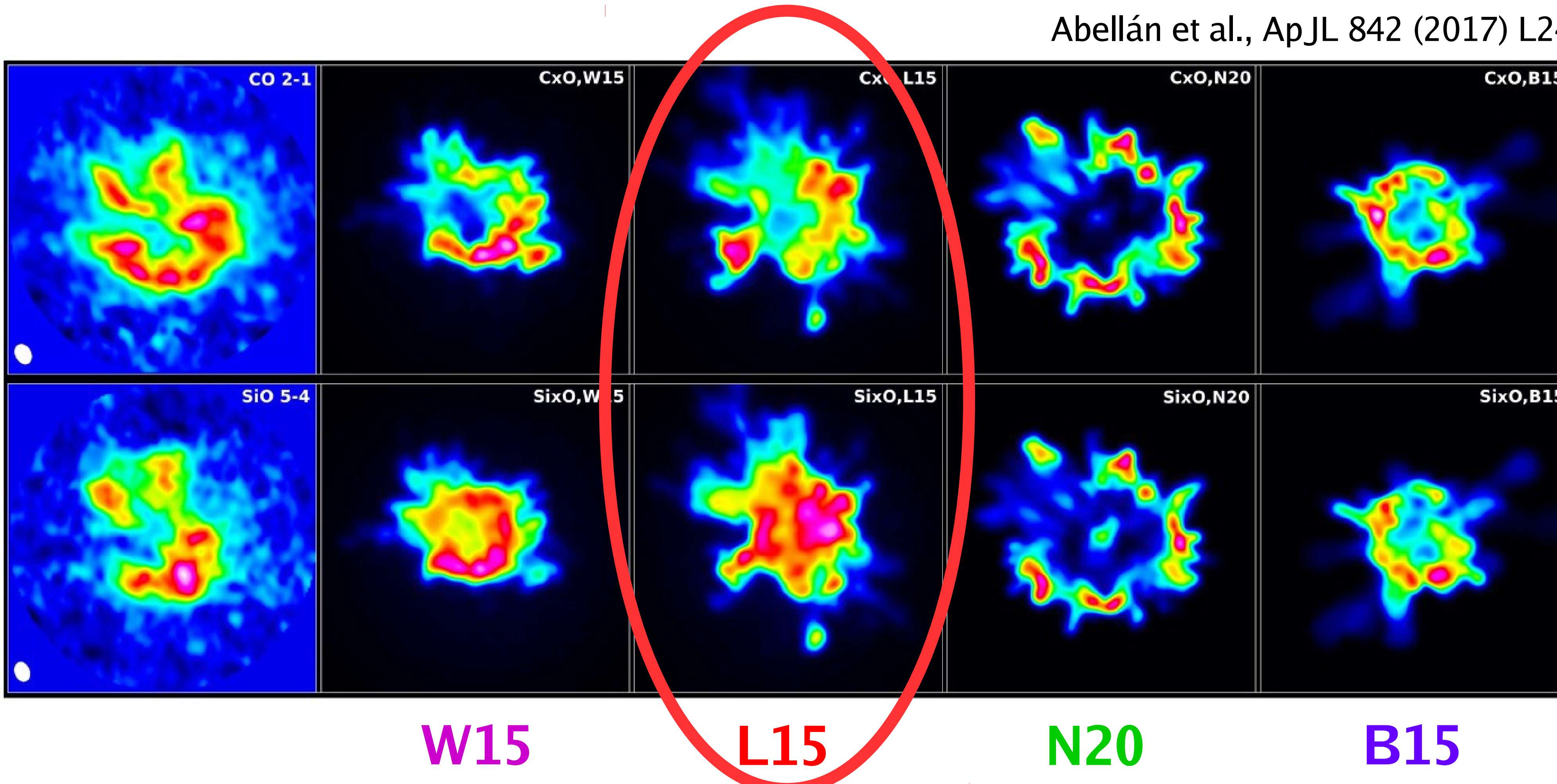
Abellán et al., ApJL 842 (2017) L24



3D SN from Binary Model

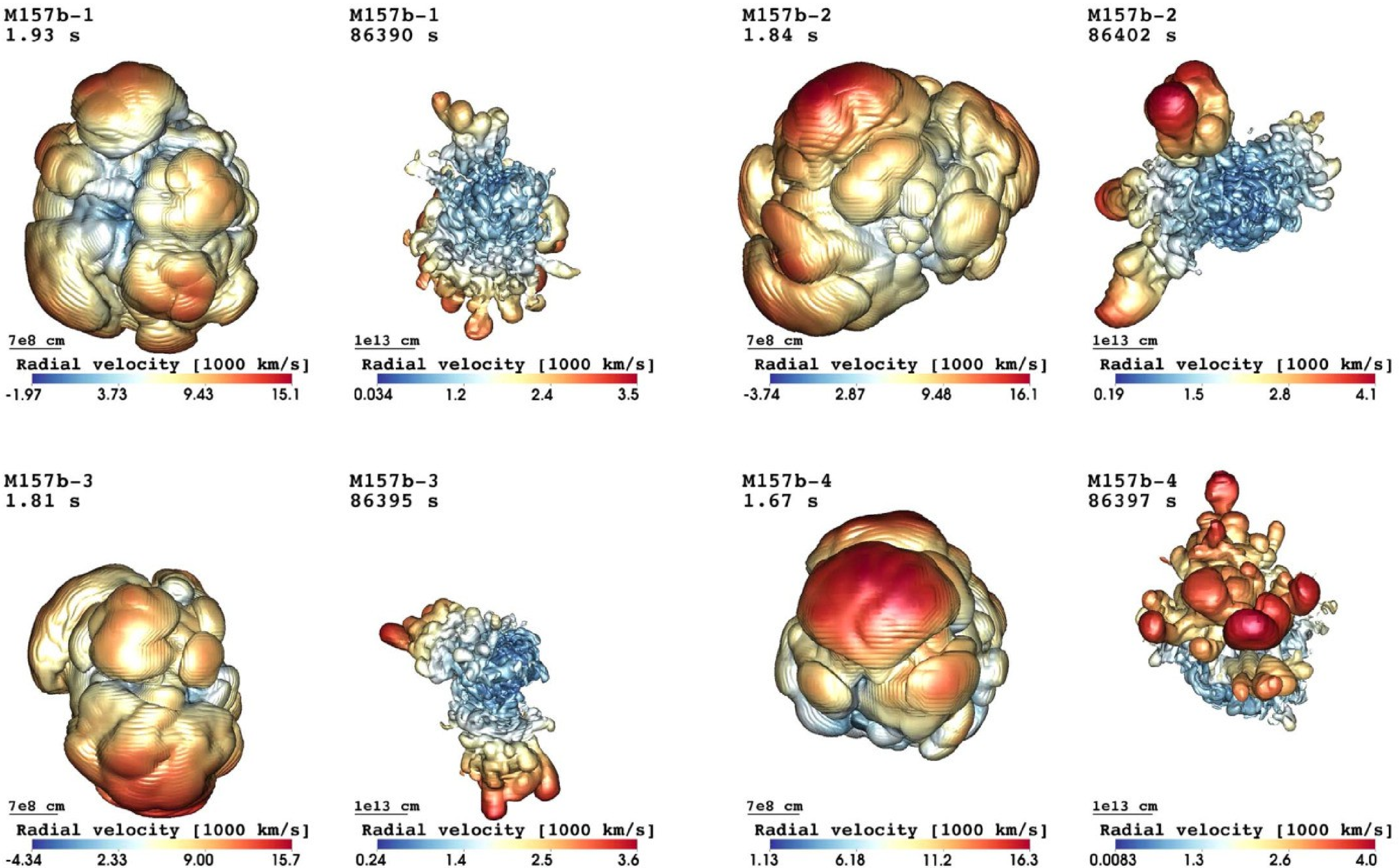


Figure 9. Morphology of radioactive ^{56}Ni-rich ejecta in models M15-7b-1, M15-7b-2, M15-7b-3, and M15-7b-4. See caption of Figure 5 for details.

Utrobin et al., ApJ 914 (2021) 4