Neutrinos from Pre-supernova Stars

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INT - Neutrinos from the Lab to the Cosmos

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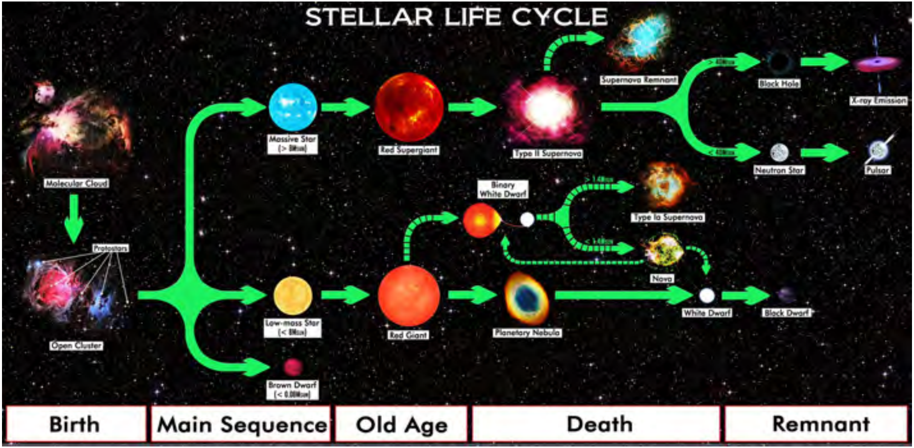
George M. Fuller, Yang Sun, Surja K. Ghorui

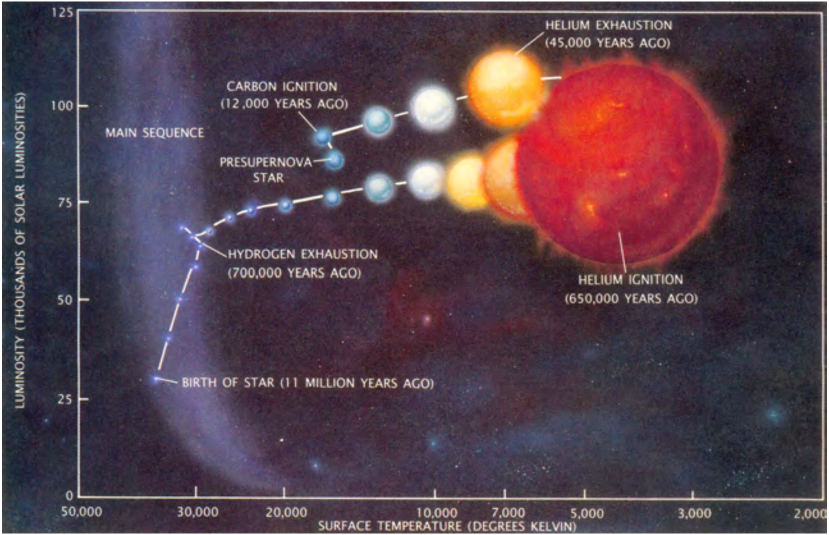
January 29, 2020

Stellar Evolution



R.N. Bailey, CC BY 4.0

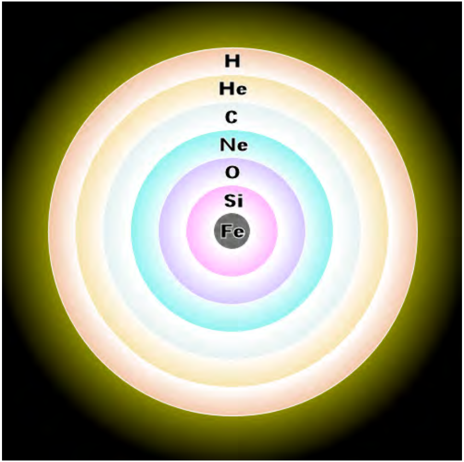
Massive Stellar Evolution



Weaver & Woosley, ***Sci Am***, **1987**

Stellar Burning Shells

R. J. Hall, CC BY 2.5



Structure at end of star's life. 8-12 $M_\odot$ stars may have O-Ne-Mg cores.

Stellar Evolution Timescales

George Djorgovski, Caltech AY20 lecture notes

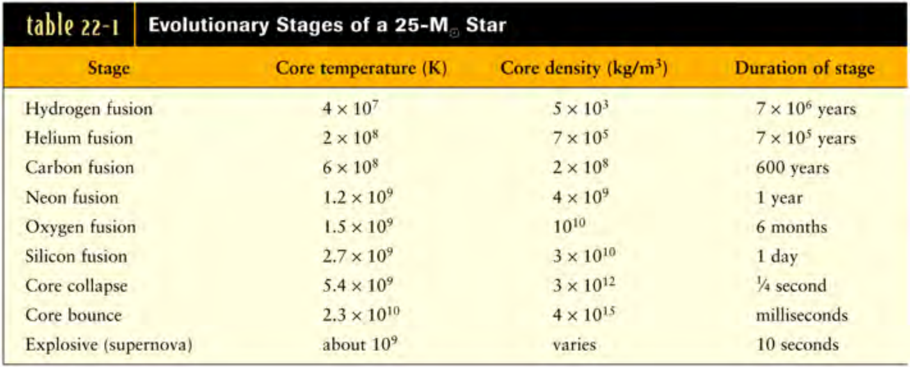
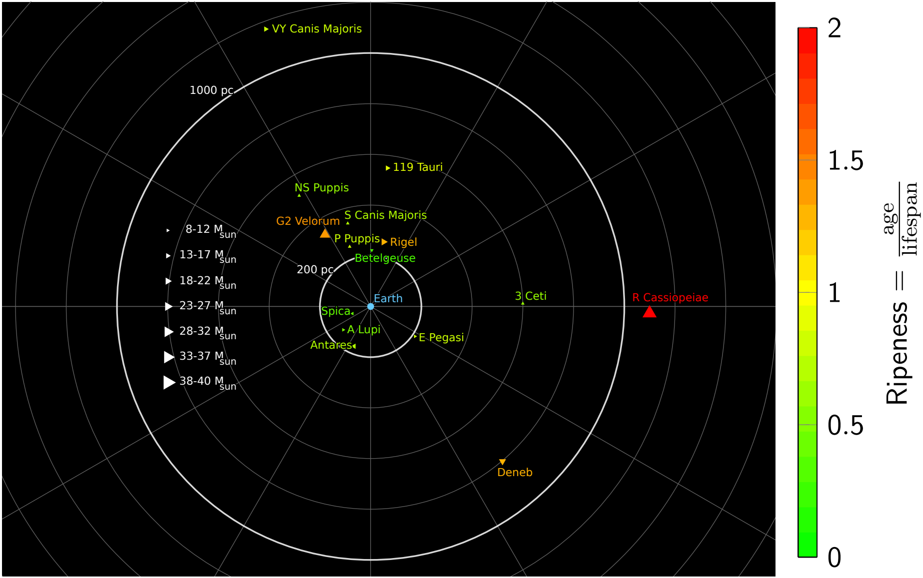


table 22-1 **Evolutionary Stages of a 25-$M_\odot$ Star**

Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

Evolution speeds dramatically at at carbon burning due to neutrinos

Nearby Pre-Supernova Candidates



Misch et al (in preparation)

Antares. Up next, neutrino production and detectability.

170 pc   12.6 $M_\odot$ 15 Myr   Ripeness 0.35-1.31 (0.72)

WISE false color infrared

Processing by Judy Schmidt, CC BY 2.0

VLTI reconstruction of surface of Antares

By ESO/K. Ohnaka, CC BY 4.0

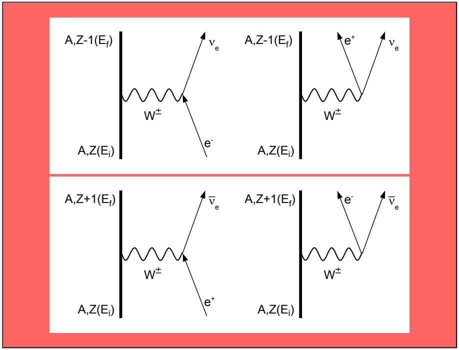
Neutrino Production Mechanisms in Evolved Massive Stars

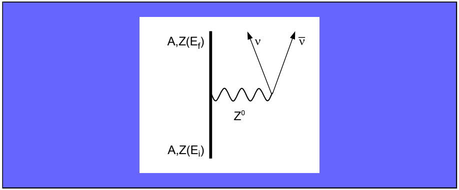
Thermal:

- Pair annihilation
  $e^- + e^+ \rightarrow \nu + \overline{\nu}$
- Bremsstrahlung
  $e^- \rightarrow \nu + \overline{\nu}$
- Photo process
  $e^- + \gamma \rightarrow e^- + \nu + \overline{\nu}$
- Plasmon decay
  $\gamma \rightarrow \nu + \overline{\nu}$

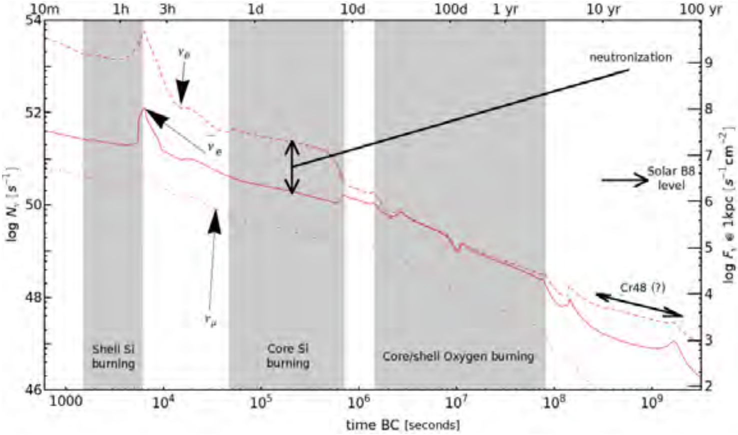
Nuclear:

- Beta processes (electron/positron capture and emission)
- Neutral current de-excitation





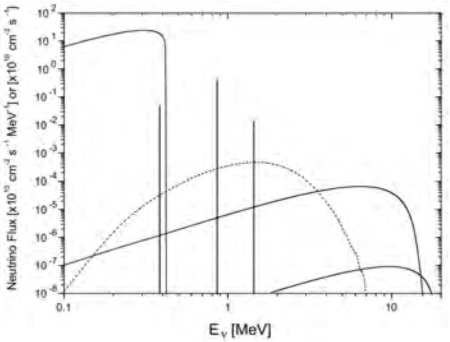
Pre-collapse Neutrino Luminosity



Odrzywolek & Heger (2010)

- Neutrino production in 15 $M_\odot$ star
- **At Si burning, nuclear component kicks in**

Pair-annihilation vs Solar Neutrino Spectrum



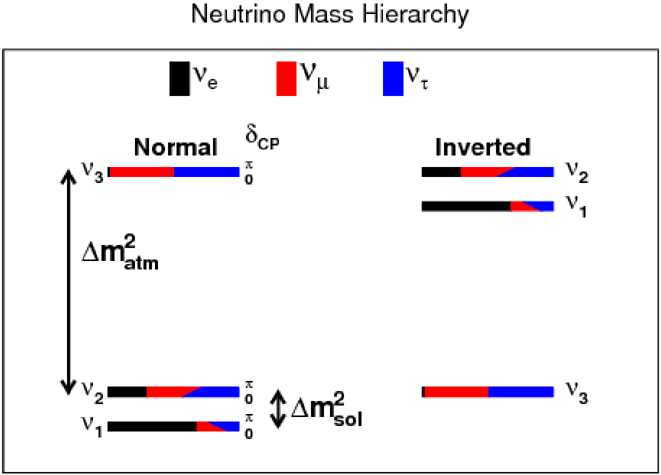
Odrzywolek et al, Astroparticle Physics, 21, 303 (2004)

- Dashed: Pair annihilation spectrum for 20 $M_{\odot}$ star at 1 kpc during silicon burning
- Solid: Solar neutrino spectrum

Already detect solar neutrinos, so expect to detect close pre-supernova.

Neutrino Mass Hierarchy

Qian, X. et al. Prog.Part.Nucl.Phys. 83 (2015)



Relative masses known, but order unknown

Collapse Mechanisms

Cores supported by electron degeneracy

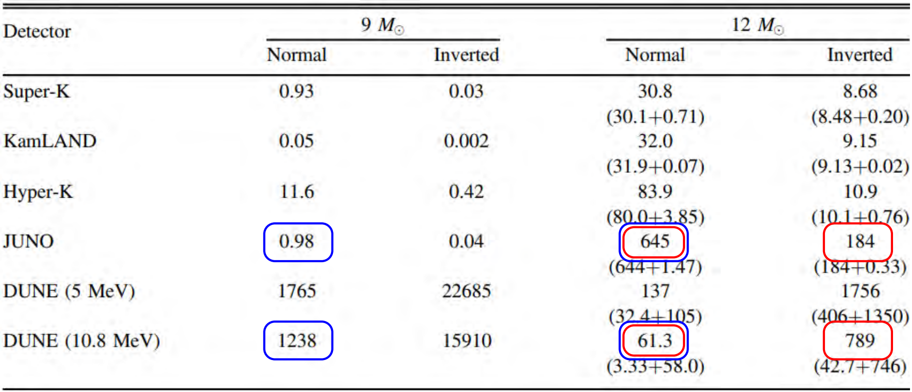
O-Ne-Mg

- Fusion does not proceed to iron
- Instability from electron capture
- Produces mostly ν_e

Iron

- Heavier nuclei
- Instability from GR
- Produces ν and $\overline{\nu}$

Detection Events for Pre-Supernova



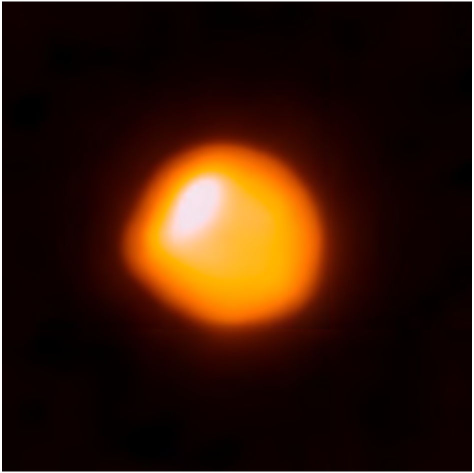
Detector	9 $M_\odot$		12 $M_\odot$	
	Normal	Inverted	Normal	Inverted
Super-K	0.93	0.03	30.8 (30.1+0.71)	8.68 (8.48+0.20)
KamLAND	0.05	0.002	32.0 (31.9+0.07)	9.15 (9.13+0.02)
Hyper-K	11.6	0.42	83.9 (80.0+3.85)	10.9 (10.1+0.76)
JUNO	0.98	0.04	645 (644+1.47)	184 (184+0.33)
DUNE (5 MeV)	1765	22685	137 (32.4+105)	1756 (406+1350)
DUNE (10.8 MeV)	1238	15910	61.3 (3.33+58.0)	789 (42.7+746)

Kato et al (2017)

- All progenitors at 200 pc
- DUNE sees ν_e, others see $\overline{\nu}_e$
- Comparing signals yields information about: collapse mechanism (O-Ne-Mg or Fe) and neutrino mass hierarchy

Betelgeuse. Up next, neutrino spectra.

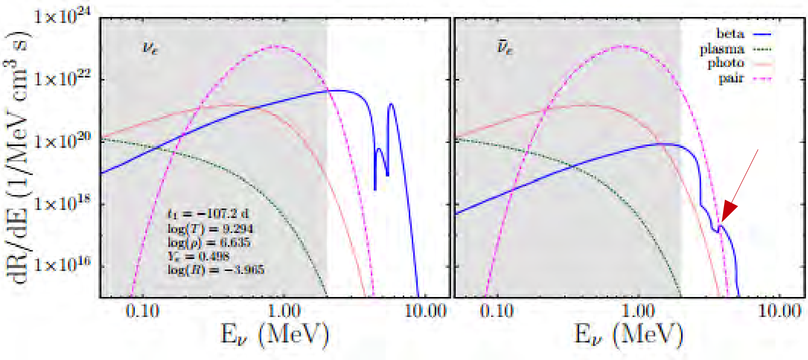
222 pc 7.7-20 (11.6) $M_\odot$ 8.0-8.5 Myr Ripeness 0.12-1.23 (0.32)



ALMA view of surface of Betelgeuse

Orion nebula with Betelgeuse in top left

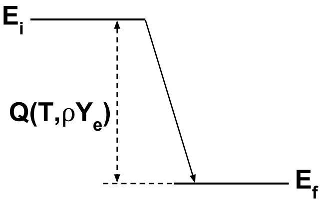
Detailed Pre-collapse Neutrino Spectra



Patton et al (2017)

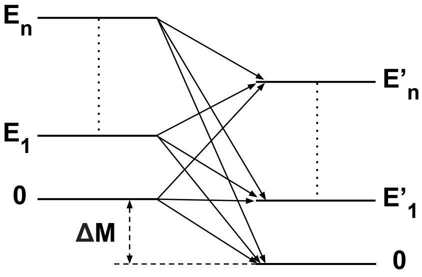
- Nuclear neutrinos dominate in some energy regions
- **Certain spectral features due to specific nuclei (the indicated peak is from positron capture on ^{32}P)**
- These nuclear spectra from single Q-value method of LMS (2001)

Single Q-value vs Full Structure



Single Q-value

- Consult published rate tables (FFN, Oda et al, LMP, etc.)
- Choose effective Q-value and reaction rate to match
- Construct spectra from Q-value and rate



Full structure

- Compute transition energies and strengths for all allowed transitions
- Construct spectra from thermally populated initial states

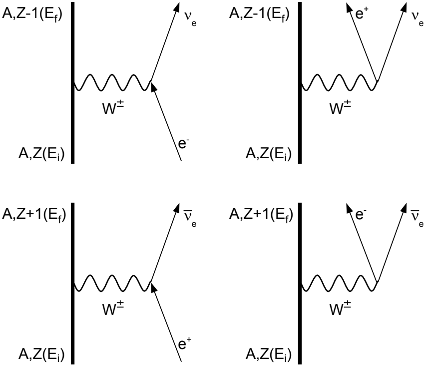
Rigel. Up next, CC nuclear neutrino spectra.

260 pc   21 $M_\odot$ 8 Myr   Ripeness 0.80-1.99 (1.30)

Rigel illuminating the Witch Head Nebula

By Robert Gendler, CC BY 4.0

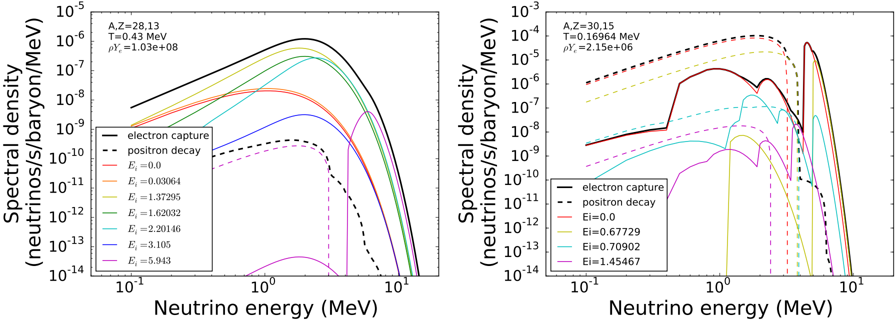
Results: Charged Current Processes



- Charged lepton can be electron or positron
- Produces electron flavored (anti-)neutrino
- **Initial and final states can be excited states**

Charged Current Neutrino Spectra

Impact of structure varies by nucleus.



Misch & Fuller (2016)

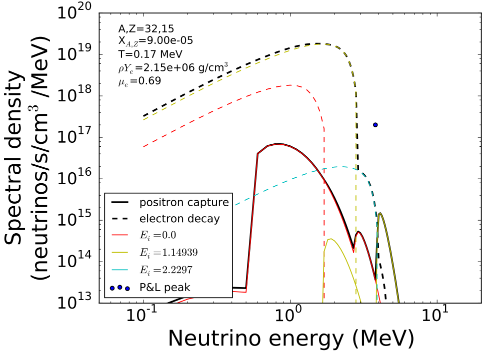
^{28}**Al neutrino spectrum.** Effects of structure less apparent.

^{30}**P neutrino spectrum.** Single states dominate different energies.

^{32}P Anti-Neutrino Spectrum

Structure particularly important in ^{32}P anti-neutrino spectrum.

- Patton et al peak correctly located, but high by 2 orders of magnitude
- Correct accounting of nuclear structure moves most capture neutrinos down in energy

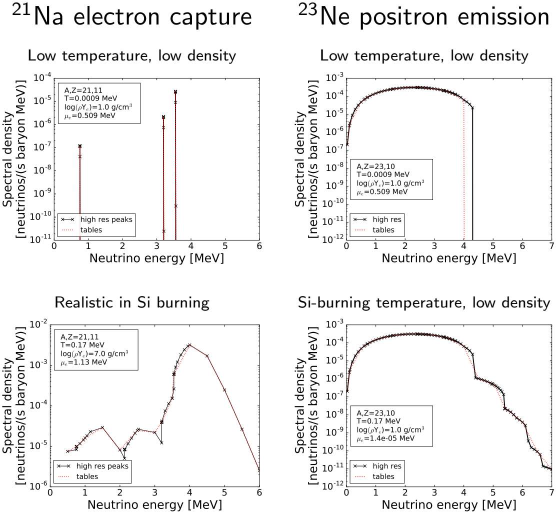


adapted from Misch & Fuller (2016)

Charged Current Neutrino Spectra

We have created catalog of nuclear neutrino spectra.

- Used experimental data supplemented with shell model
- 0.5 MeV neutrino energy resolution
- Included additional energy points at low-temperature capture peaks
- Smooth spectra integrable with trapezoid method
- *Not all spectra integrable*



^{21}Na electron capture

^{23}Ne positron emission

Low temperature, low density

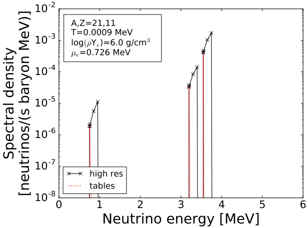
Low temperature, low density

Realistic in Si burning

Si-burning temperature, low density

Misch, Sun, Fuller (2018)

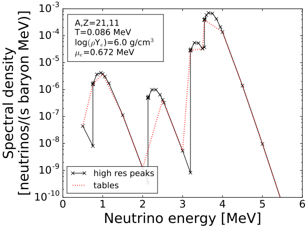
Problematic ^{21}Na e^{-} Capture Spectra



Low temperature, modest density

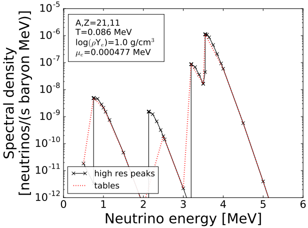
Integrates poorly, misses bulk

Misch, Sun, Fuller (2018)



Modest temperature, modest density

Integrates imprecisely, misses tops of peaks



Modest temperature, low density

Misses peak from excited state

- High resolution would make all spectra integrable and *update rate tables*

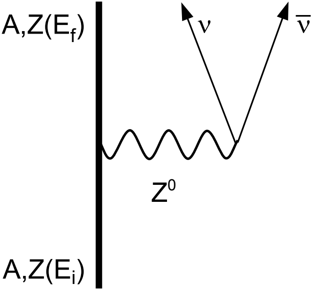
VY Canis Majoris. Up next, NC nuclear neutrino spectra.

1170 pc   17 $M_\odot$ 8.2 Myr   Ripeness 0.17-1.98 (0.81)

Nebula surrounding VY Canis Majoris

HST data, processing by Judy Schmidt, CC BY 2.0

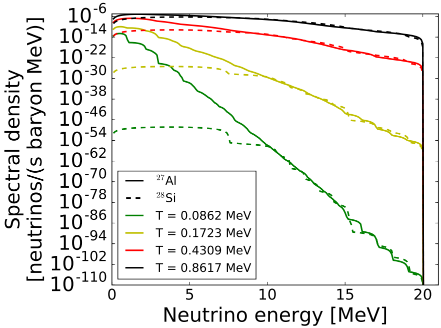
Results: Neutral Current Neutrino Pairs



- Nucleus relaxes from excited state. Final state may be excited.
- Can produce any flavor (anti)neutrinos
- Nuclear structure, strength, and thermal averages computed similarly to the beta processes

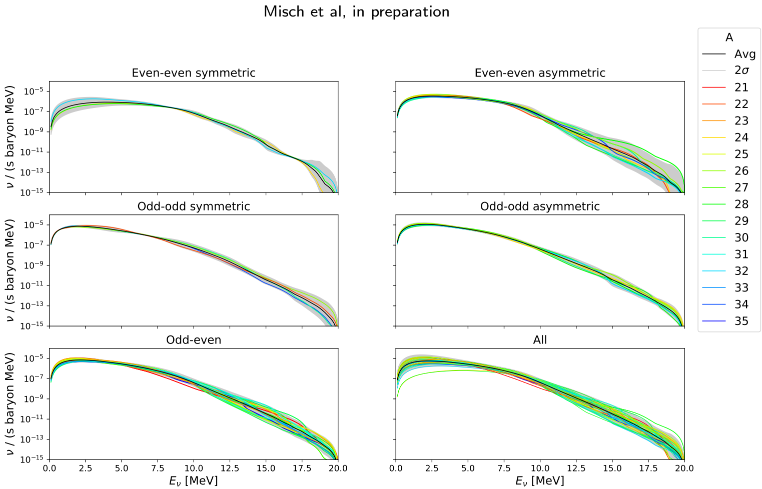
Neutral Current Neutrino Spectra

- 0.1 MeV neutrino energy resolution (adequate for integration)
- ^{27}Al (solid) and ^{28}Si (dashed)
- Little contribution at low temperature
- Rises *very rapidly* with increasing temperature
- Structure important below 10 MeV neutrino energy, but spectra nearly identical above



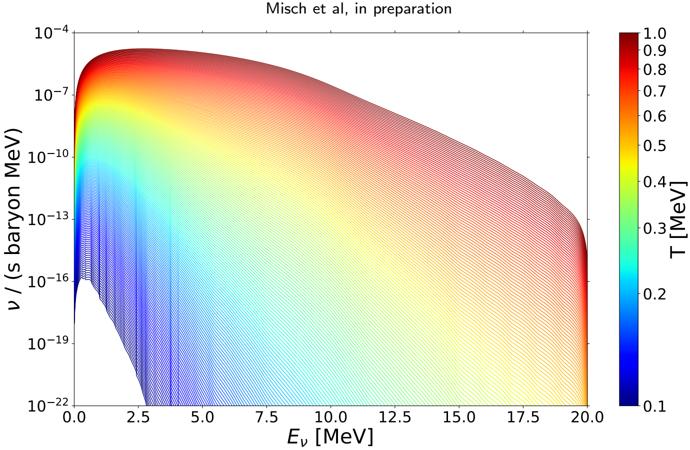
Misch, Sun, Fuller (2018)

NC Neutrino Spectra



Neutral current de-excitation spectra at $T = 0.8617$ MeV

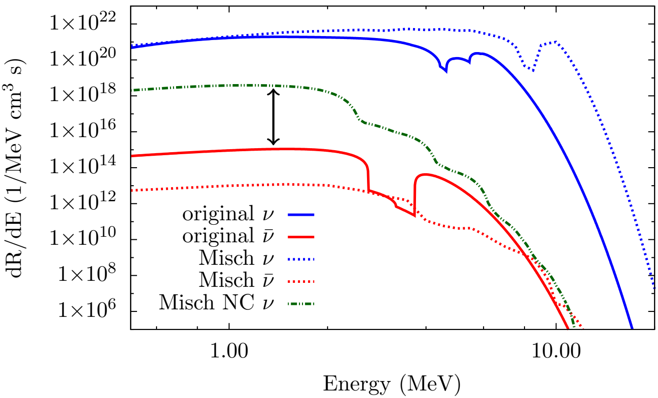
Average NC Neutrino Spectra



Spectra averaged over all computed sd-shell nuclei

Oxygen Burning Nuclear ν Spectra

Kelly Patton (preliminary)

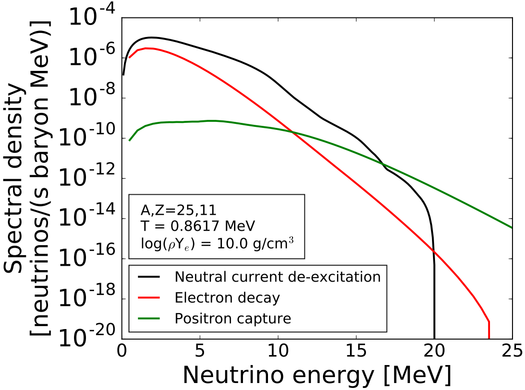


- NC de-excitation dominates antineutrino production
- Could push detectability threshold out to 2-10 kpc!

Onset of Collapse Nuclear $\overline{\nu}$ Spectra

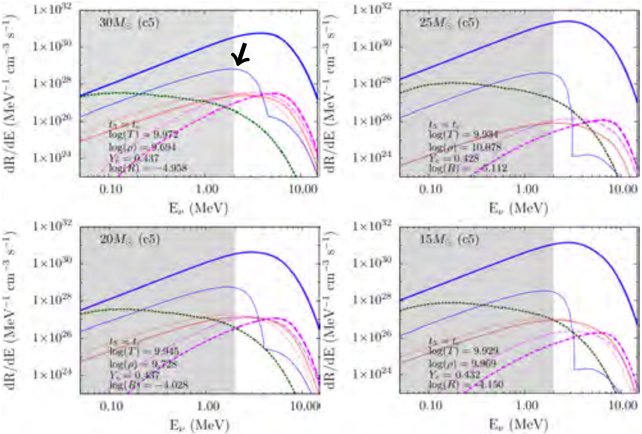
^{25}Na antineutrino spectrum in early collapse conditions.

- Low-mass nucleus, but correct electron fraction
- Above $E_\nu \sim 15$ MeV uncertain due to exclusion of initial nuclear states above ~ 20 MeV
- Up to 17 MeV neutrino energy, neutral current dominates
- **This process omitted from models**



Misch, Sun, Fuller (2018)

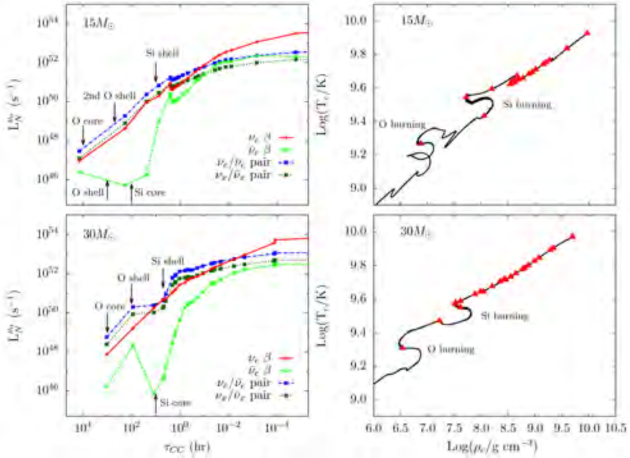
(Almost) Full Spectra at Onset of Collapse


Patton et al (2017)

- Nuclei (blue) dominate $\overline{\nu}$ (thin) production at onset of collapse
- These do not include NC de-excitation
- This is just the core

Neutrino Luminosities

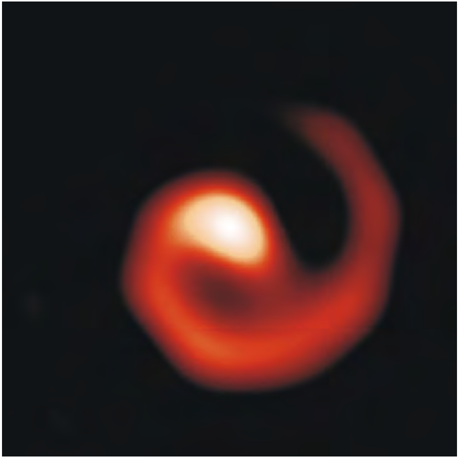
Patton et al (2017)



- Integrated over entire star
- Main contributors sensitive to mass

WR 104

2300 pc   10-25 $M_\odot$ Age ???   Ripeness ???



Highly evolved Wolf-Rayet star WR 104 and tidal tails. Imminent GRB? Aimed at us?!

By Keck Telescope - APOD NASA, Public Domain

Sher 25

7600 pc 40 $M_\odot$ 4 Myr Ripeness 2.0-3.47

Sher 25 at 1 o'clock relative to NGC 3603

By NASA, ESA, Public Domain

WR 124

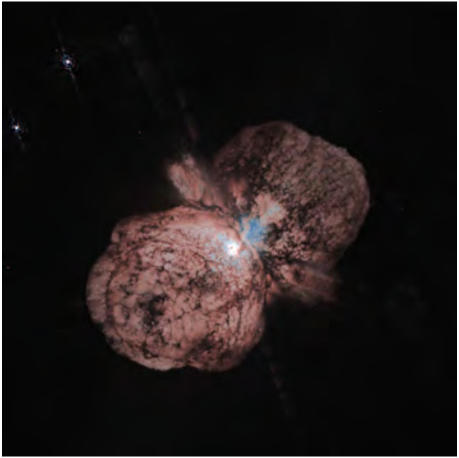
9000 pc   33 $M_\odot$ 8.6 Myr   Ripeness 3.8

Nebula M1-67 surrounding WR 124

Hubble Legacy Archive, processing by Judy Schmidt, CC0

η Carinae. Up next, summary and conclusions.

2300 pc   30-80 $M_\odot$, 100-200 $M_\odot$ < 3 Myr   Ripeness ???



Homunculus Nebula surrounding η Carinae

By Jon Morse (University of Colorado) & NASA Hubble Space Telescope, Public Domain

Ongoing and Future Work

Currently working to incorporate neutral current de-excitation spectra into a realistic calculation.

Expanding nuclear neutrino spectrum catalogs.

- Higher nuclear mass
- Higher neutrino energy resolution
- Higher temperature/density resolution

Summary

Motivation

- We may soon detect pre-supernova neutrinos
- Need nuclear structure to get correct neutrino spectra
- Neutral current de-excitation is likely important at late times

Completed

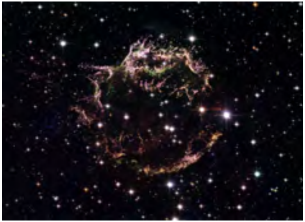
- We have computed charged current neutrino spectra at 0.5 MeV resolution for 70 sd-shell nuclei on the FFN temperature-density grid
- We include for the first time in any catalog neutral current de-excitation at 0.1 MeV resolution
- Data currently available on the JINA-CEE website at `http://www.jinaweb.org/html/mischnuspectra.html`

Ongoing

- Checking impact of neutral current in stellar model
- Expanding catalog to fp-shell and enhancing resolution

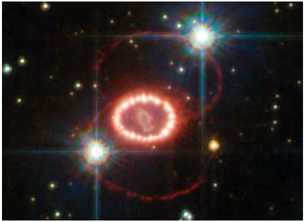
Supernova Remnants. Questions?

Cassiopeia A (visible); HST

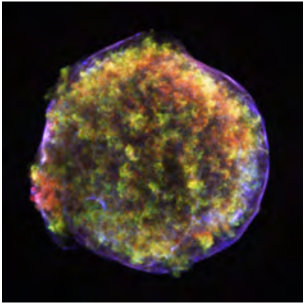


Simeis 147; Rogelio Bernal Andreo

SN 1987A; HST



SN 1572 (Tycho's Nova); Chandra



SN 1054 (Crab Nebula); HST

W49B; Chandra, Palomar, & VLA

Nearby Supernova Candidates

Star	D [pc]	Mass [$M_\odot$]	Age [Myr]	Ripeness
Spica	77	10.3-12.6, 11.4	12.5	0.37-0.60, 0.47
α Lupi	142	9.1-11.1, 10.1	16-20, 18	0.35-0.71, 0.51
Antares	170	11-14.3, 12.6	10-20, 15	0.35-1.31, 0.72
ϵ Pegasi	211	10.9-12.5, 11.7	15.5-24.5, 20.0	0.52-1.16, 0.80
Betelgeuse	222	7.7-20, 11.6	8.0-8.5, 8.25	0.12-1.23, 0.32
π Puppis	250	11.5-11.9, 11.7	16.1-23.9, 20.0	0.62-1.00, 0.80
Rigel	260	18-24, 21	7-9, 8	0.80-1.99, 1.30
γ^2 Velorum	336	27.4-29.6, 28.5	3.5-5.5, 4.5	1.03-1.92, 1.45
σ Canis Majoris	340	12.2-12.4, 12.3	15.9-16.9, 16.4	0.71-0.78, 0.74
NS Puppis	520	9.7	25.1	0.64
119 Tauri	550	11.6-16.37, 14.37	11.4-14.9, 13.9	0.45-1.35, 0.92
3 Ceti	600	8.4-9.6, 9.0	26.1-33.3, 29.7	0.47-0.83, 0.63
Deneb	802	15-23, 19	10?	0.74-2.01, 1.29
ρ Cassiopeiae	1100	40	4-6, 5	2.67-4.01, 3.34
VY Canis Majoris	1170	9-25, 17	8.2	0.17-1.98, 0.81