NEUTRINOS FROM CORE COLLAPSE SUPERNOVAE (SNe)

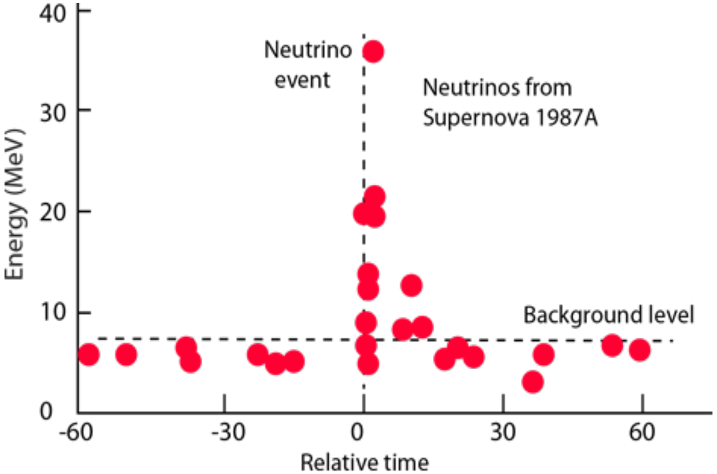
Cecilia Lunardini

Arizona State University

Topics

- Introduction
- overview and highlights*
  - Theory
  - Experiment
- Synergies, new directions
  - Connections with HEP, astro
- Discussion

First and *only* SN nu detection: SN1987A



* Focus on recent advancements, apologies for omissions

Introduction

Stellar death

- $M \gtrsim 8\, M_{sun}$: iron core forms
- Loss of pressure → core collapses into proto-neutron star (PNS)
- $O(10)\, s$ neutrino burst cools the PNS
  - $L_\nu \sim G\, M^2_f/R_f - G\, M^2_i/R_i \sim 3\; 10^{53}$ ergs   ($R_f \sim 10$ Km)
- (revived) shockwave drives explosion of star

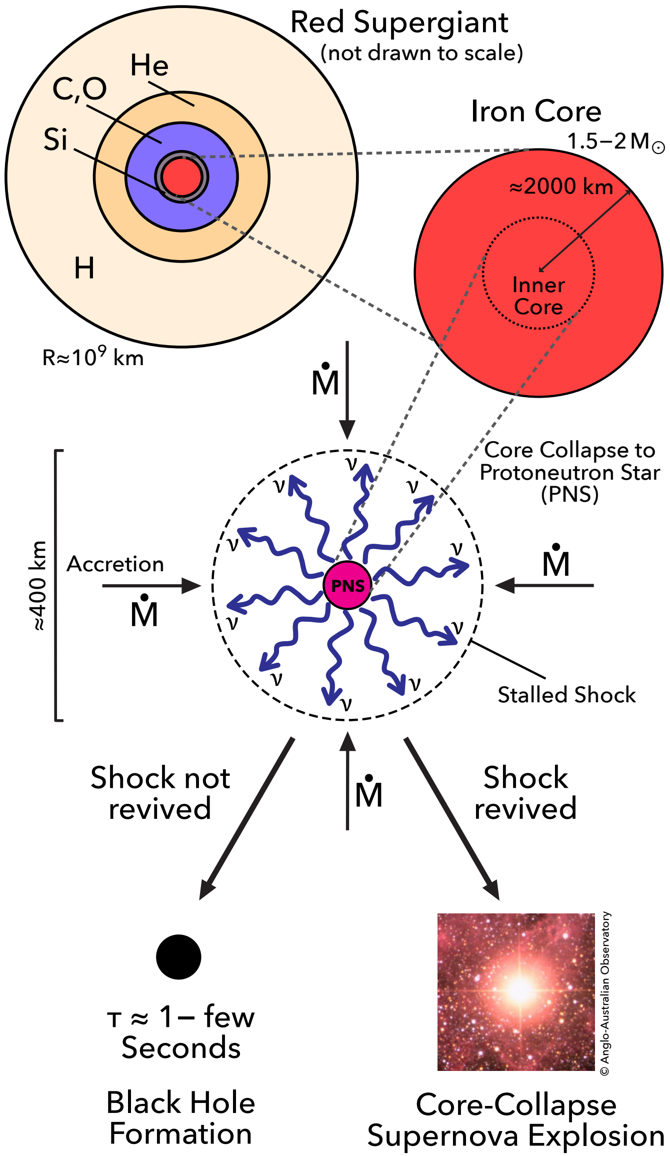


Fig. from C. Ott, *Comput.Sci.Eng.* 18 (2016) 5, 78-92

Neutrino cooling and heating

- *ν thermalize* in ultra-dense matter
  - Surface emission of $\nu_e, \bar{\nu}_e, \nu_x, \bar{\nu}_x$ (x=μ,τ)
  - Approx. thermal spectrum, E ~ 10-20 MeV
  - ordering of spectra due to different decoupling radii:

$$\langle E_e \rangle \lesssim \langle E_{\bar{e}} \rangle \lesssim \langle E_x \rangle$$

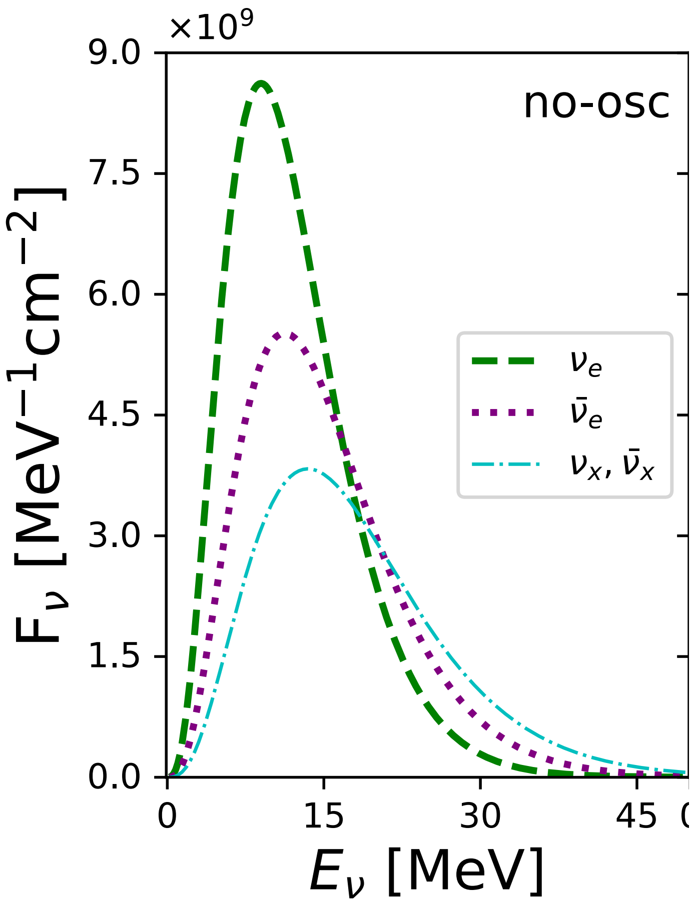


Fig: Maria M. Saez, Universe **2023**, *9*(11)

- ν heating helps launch stalled shock
    - Competition with mass accretion

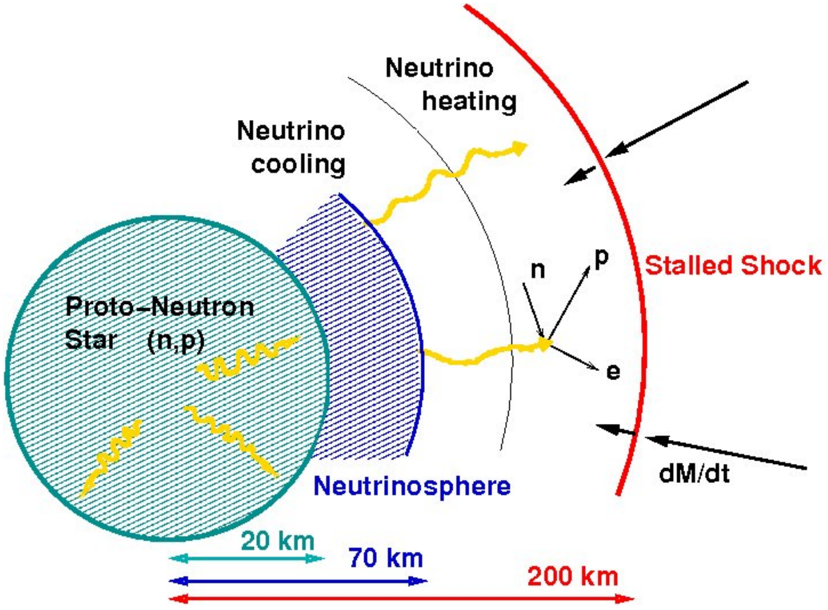


Figure: Amol Dighe, talk at WHEPP XV, 2017

Direct narrative of near-core physics

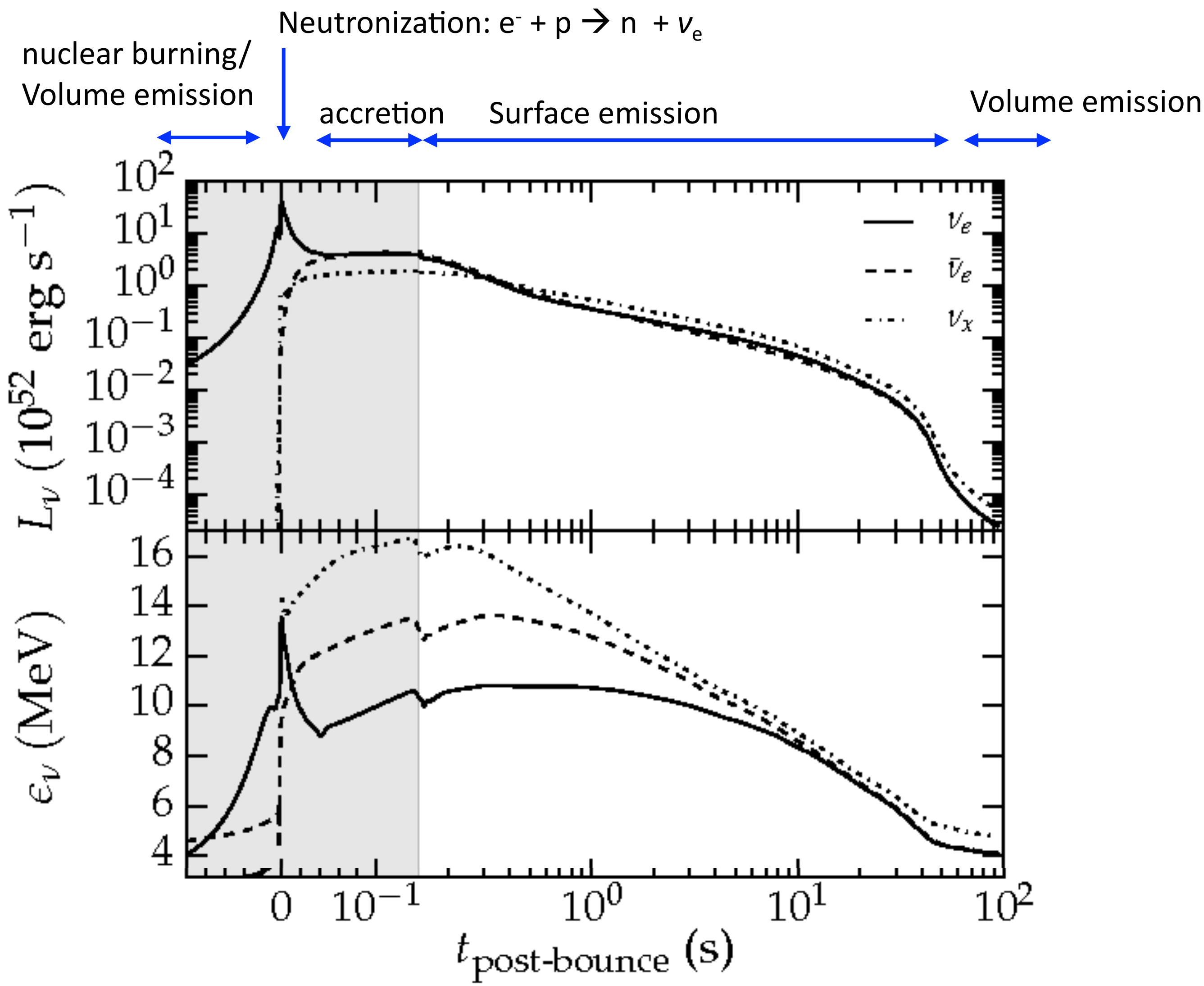
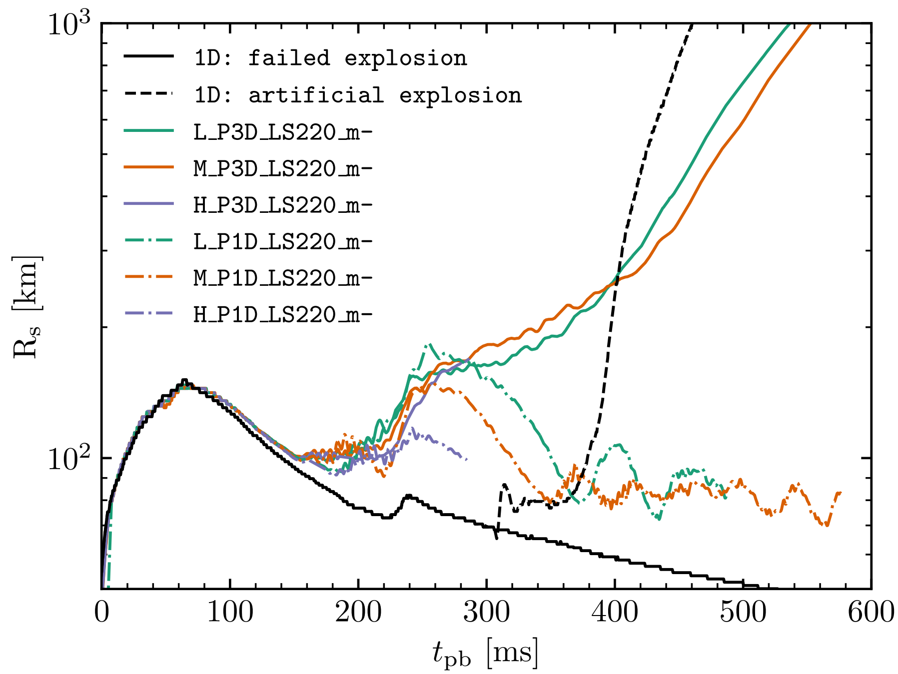


Figure from Roberts and Reddy, Handbook of Supernovae, Springer Intl., 2017

Status and highlights: theory

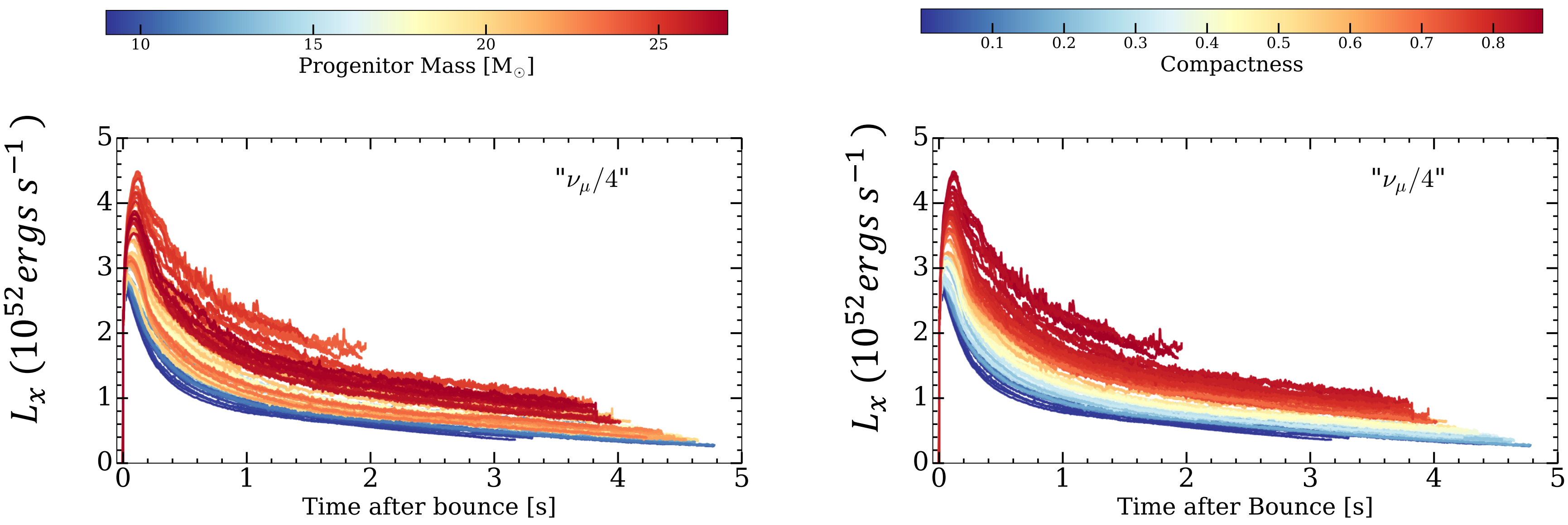
Numerical simulations: progress toward 3D

- Understanding neutrino-driven shock-revival: from 2D to 3D
  - neutrino heating efficiency increased by multi-D effects: convection, Standing Accretion Shock Instability (SASI)
  - Characterize failed revival (black hole formation)



Bollig et al.,
Astrophys.J. 915 (2021) 1, 28

- Neutrino spectra and luminosities: mapping the parameter space
  - Comprehensive catalogues spanning stellar population
  - Multi-D *and multi-second* simulations
  - Identify key dependences (e.g., compactness: $\xi_{2.5} = \frac{M/M_\odot}{R(M{=}2.5\ M_\odot)/1000\ km}$)



FORNAX 2D multi-second simulations, M=9 – 27 M_{sun}

Vartanyan and Burrows, MNRAS 526 (4) (2023) 5900–5910 ; Plot from public data: https://dvartany. github.io/data/

Poster: Ko Nakamura

References (representative papers only):

3DnSNe : Nakmura, Takiwaki, Kotake, MNRAS 514 (2022) 3, 3941-3952; Matsumoto, Takiwaki, Kotake, MNRAS 528 (2024) L96

3DGRMHD : Shibagaki, Kuroda, Kotake, Takiwaki and Fischer, *MNRAS*, (2024) stae1361

CHIMERA : Bruenn, Blondin, Lentz, Messer et al., ApJ., Suppl. 248 (1) (2020)

FLASH-M1 : O'Connor, *ApJ.Suppl.* 219 (2015) 2, 24 ; O'Connor and Couch, *Astrophys.J.* 865 (2018) 2, 81

FORNAX : Vartanyan and Burrows, MNRAS 526 (4) (2023) 5900–5910

VERTEX : Bollig, Yadav, Kresse, Janka, Mueller and Heger, ApJ. 915 (1) (2021) 28.

Flavor conversion

- Flux permutation:

$$F_e = p\, F_e^0 + (1-p)F_x^0$$

  - $p = p(E,t)$, Cumulative effect of conversion in star, vacuum, Earth
  - Hardening of ν_e and $\bar{\nu}_e$ spectra due to $\nu_x \to \nu_e$, $\nu_x \to \bar{\nu}_e$

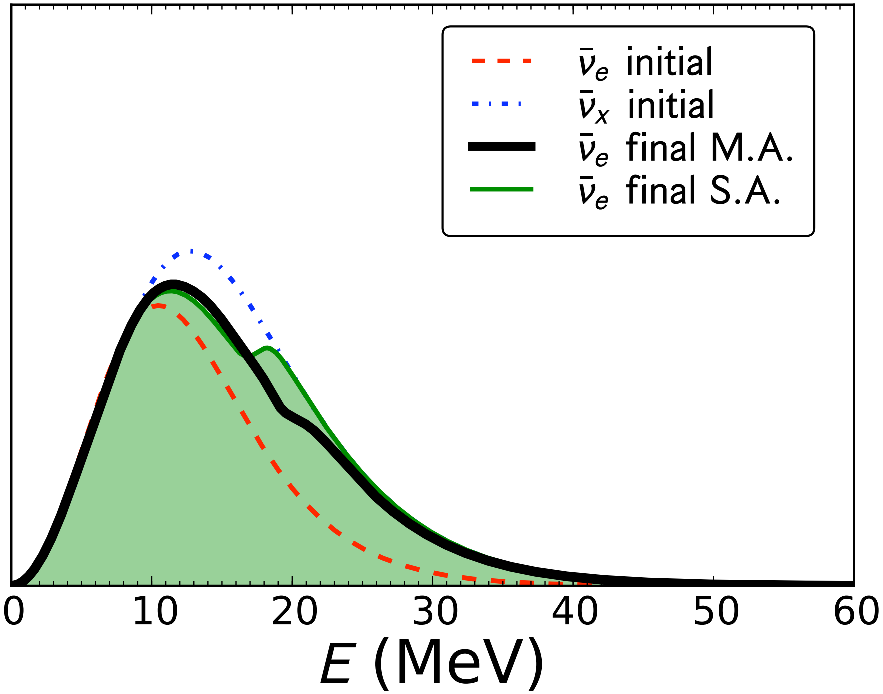
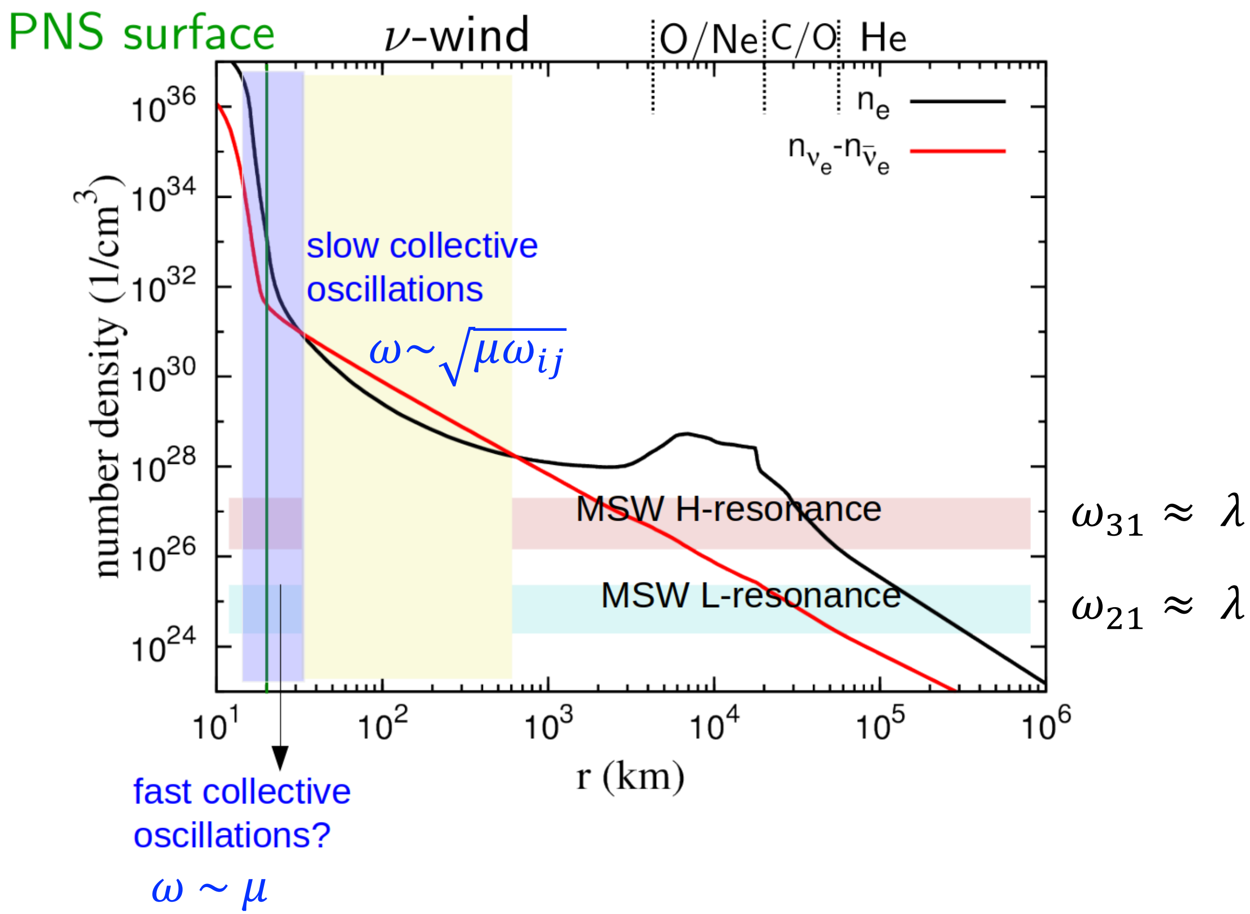


Fig. from Duan and Friedland, PRL 106:091101,2011

Interplay of frequencies

- Vacuum: $\omega_{ij} = \Delta m^2_{ij}/2E$
- ν-matter scattering: MSW effect $\lambda = \sqrt{2} G_F n_e$
- $\nu - \nu$ scattering :
  $\mu \simeq \sqrt{2} G_F n_\nu^{\text{eff}}$

collective oscillations, *no general solution*, work in progress



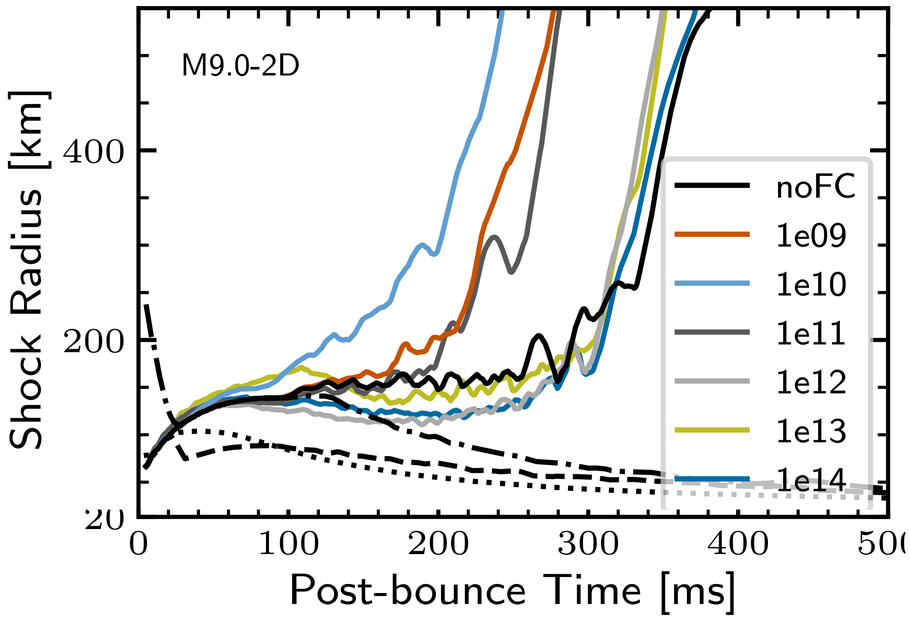
Duan, Fuller & Qian, PRD74 (2006),
Duan et al., PRD74 (2006)

Fig. from Fischer et al.,
Prog. Part. Nucl. Phys. 137 (2024) 104107

Collective oscillations: r < 1000 Km

- Impact on r-process nucleosynthesis

- *Fast mode* (r < 100 Km) *:* impact on shock-revival
  - Increased or de-creased neutrino heating behind shock (depending on progenitor star)



Ehring, Abbar, Janka and Raffelt, PRD 107 (10) (2023)
Nagakura, PRL 130 (21) (2023)
Ehring et al., PRL 131 (6) (2023) 061401 (figure credit)

References (representative papers only):

Zaizen and Nagakura*, PRD* 107 (2023) 12, 123021 ; Nagakura, *PRD* 108 (2023) 10, 103014 ; Akaho, Liu, Nagakura, Zaizen and Yamada, PRD109, no.2, 023012 (2024)

Xiong, Wu, Abbar, Bhattacharyya, George, et al. PRD 108 (2023) 6, 063003

Cornelius, Shalgar and Tamborra, JCAP02, 038 (2024)

Grohs, Richers, Couch, Foucart, Froustey, Kneller and McLaughlin, ApJ 963, no.1, 11 (2024) ; Froustey, Richers, Grohs, Flynn, Foucart, Kneller McLaughlin, PRD109, no.4, 043046 (2024)

Matter-driven conversion

- *adiabatic* resonant conversion
  - For Fe-core SNe, before shockwave effects
- *Unique:* H-resonance driven by θ_{13}
  - Requires $\rho \sim 10^3\ g\ cm^{-3}$
  - $\nu_e \rightarrow \nu_3$ (normal ordering)

↓

$p \sim sin^2\theta_{13} \sim 2\ 10^{-2}$ → complete ν_e conversion!

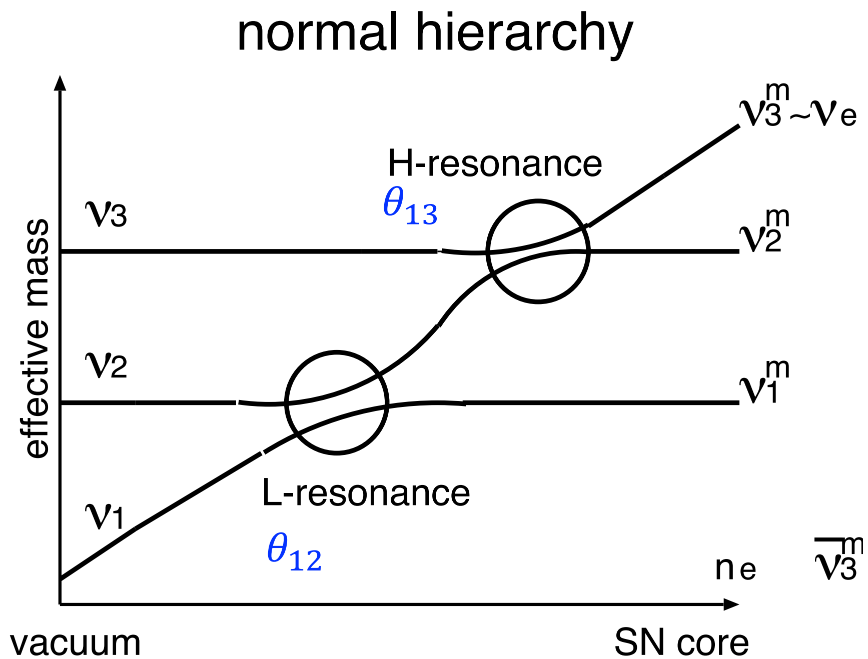


Fig. from Takahashi and Sato, Prog.Theor.Phys. 109 (2003) 919-931

Mikheev and A. Y. Smirnov, Sov. Phys. JETP 64 (1986) 4 ; Dighe and Smirnov, PRD 62 (2000) 033007

Complexities…

- Resonant interplays of collective and matter-driven effects

- Late time/large radii phenomena
  - Adiabaticity breaking at shockwave front
  - Turbulent matter density profile behind shock
  - Decoherence

- Progenitor-dependent effects
  - non-adiabatic H-resonance in ONeMg-core Sne

- Oscillations in Earth

overview and highlights: experiments

Real-time detectors with spectrum sensitivity

- Water Cherenkov, liquid scintillator
  - $\bar{\nu}_e + p \to n + e^+$ (main)
  - $\nu_\alpha + e^- \to \nu_\alpha + e^-$
  - $\bar{\nu}_e , \nu_e$ CC on nuclei
- Liquid Argon
  - $\nu_e + {}^{40}Ar \to e^- + {}^{40}K^*$ (main)
  - $\bar{\nu}_e + {}^{40}Ar \to e^+ + {}^{40}Cl^*$
  - $\nu_\alpha + e^- \to \nu_\alpha + e^-$
- Ice/seawater
  - $\bar{\nu}_e + p \to n + e^+$
  - *luminosity only, background-limited

Experiment	Type	Mass [kt]	Location	events
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K
IceCube	String/$\bar{\nu}_e$	2500*	South Pole	320K/330K
KM3NeT	String/$\bar{\nu}_e$	150*	Italy/France	17K/18K
LVD	$C_nH_{2n}/\bar{\nu}_e$	1	Italy	190/190
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190
Borexino	$C_nH_{2n}/\bar{\nu}_e$	0.278	Italy	52/52
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.78	Canada	150/150
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000
Baksan	$C_nH_{2n}/\bar{\nu}_e$	0.24	Russia	45/45
HALO	Lead/ν_e	0.079	Canada	4/3
HALO-1kT	Lead/ν_e	1	Italy	53/47
DUNE	Ar/ν_e	40	USA	2700/2500
MicroBooNe	Ar/ν_e	0.09	USA	6/5
SBND	Ar/ν_e	0.12	USA	8/7
DarkSide-20k	Ar/any ν	0.0386	Italy	-
XENONnT	Xe/any ν	0.006	Italy	56
LZ	Xe/any ν	0.007	USA	65
PandaX-4T	Xe/any ν	0.004	China	37

Table: Al Kharusi et al., New J. Phys. 23 031201 (2021)
D=10 kpc. **bold** : operating detectors as of 2021

What can we learn?

- Flavor composition, spectra, luminosities
- Time evolution of near-core physics
  - Accretion, cooling, etc.
- Tests of physics Beyond the Standard Model

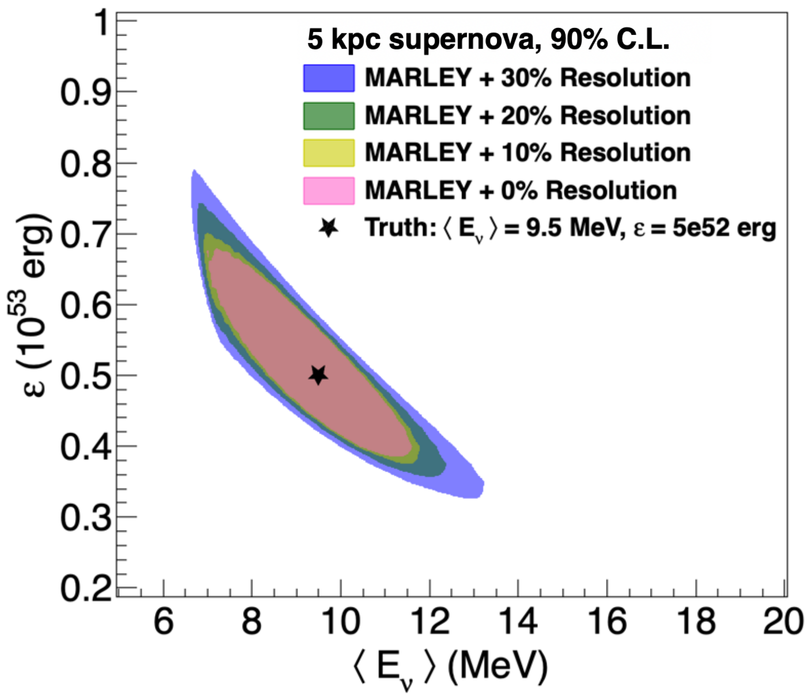


Fig: DUNE collab. *Eur.Phys.J.C* 81 (2021) 5, 423

Future detectors: complementarity

- DUNE (LAr)
  - *Sensitivity to ν_e* : ν_e from electron capture, θ_{13} -driven resonance (ν_e disappearance)

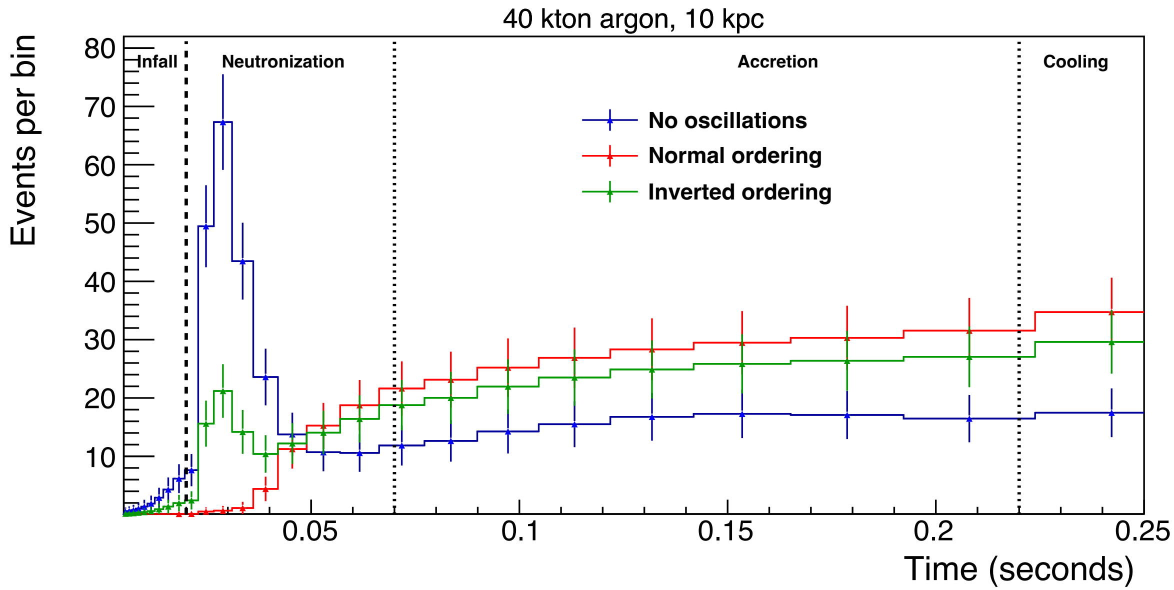


Fig: DUNE collab. *Eur.Phys.J.C* 81 (2021) 5, 423

- HyperKamiokande (Water Cherenkov)
  - *Largest mass (M~220 kt)* → extend sensitivity distance to Mpc scale; reach M31 galaxy

Poster: F. Nakanishi

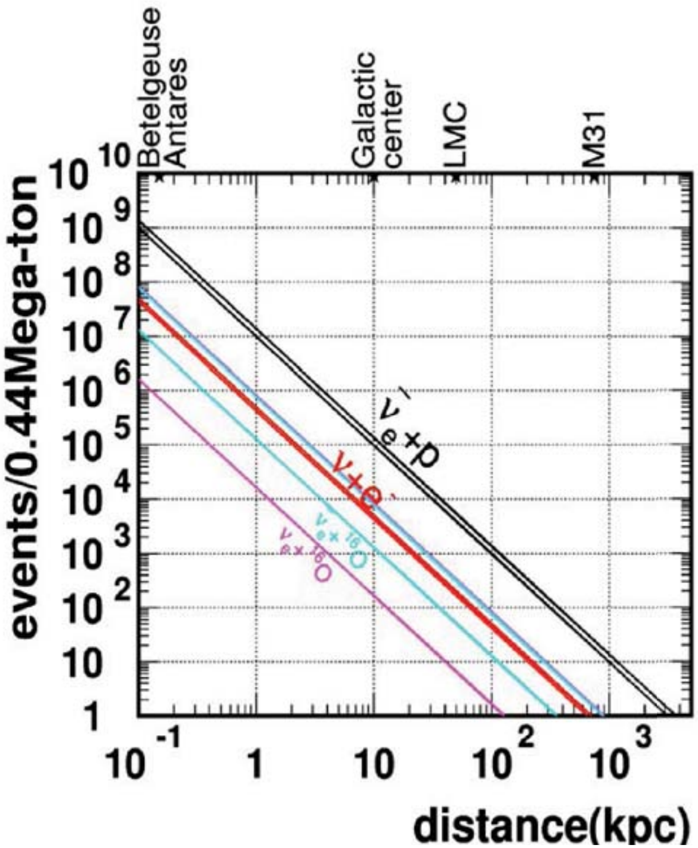


Fig. from H. Sekiya, 2017 *J. Phys.: Conf. Ser.* **888** 012041

Poster: K. Saito
(Kamland + SuperK)

- JUNO (Liquid scintillator)
  - *Low energy threshold* → pre-SN neutrinos (~ 1 day before collapse), late time spectra, etc.
  - *high energy resolution* → spectral features due to oscillations, BSM, …

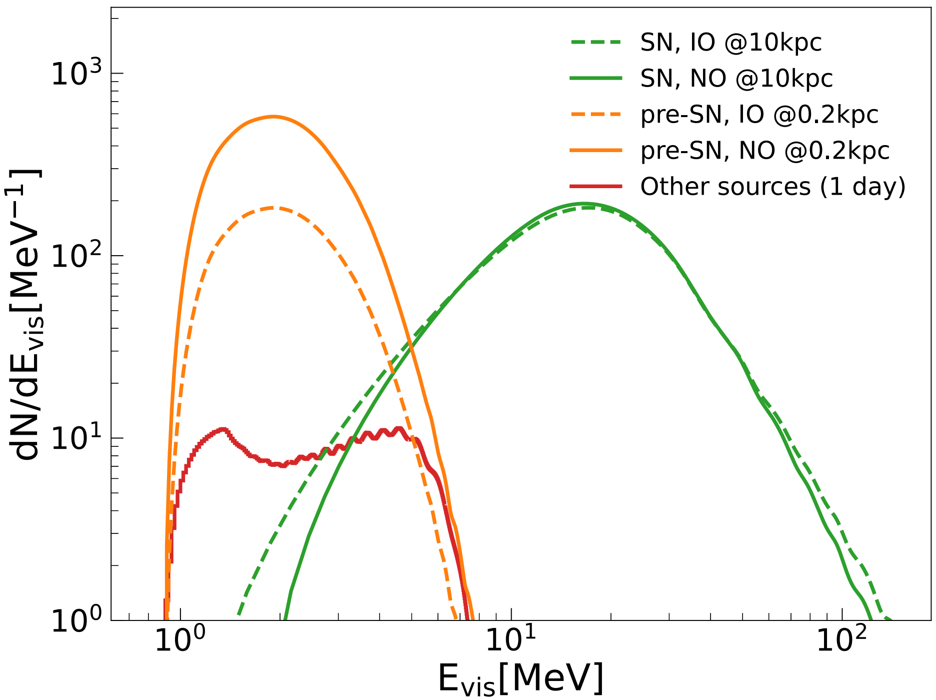


Fig: JUNO coll., JCAP 01 (2024) 057

Other concepts

- Km^3 detectors: IceCube, Km3NeT

poster: Isabel A. Goos

- Dark Matter detectors
  - coherent scattering, sensitive to non-electron flavors

poster: R.J. Mota Peres

poster: D. Ramírez García

- New Liquid Scintillator technologies
  - Water-based, LiquidO, …

poster: M. Hughes

poster: L. Pattavina

- Paleo detectors

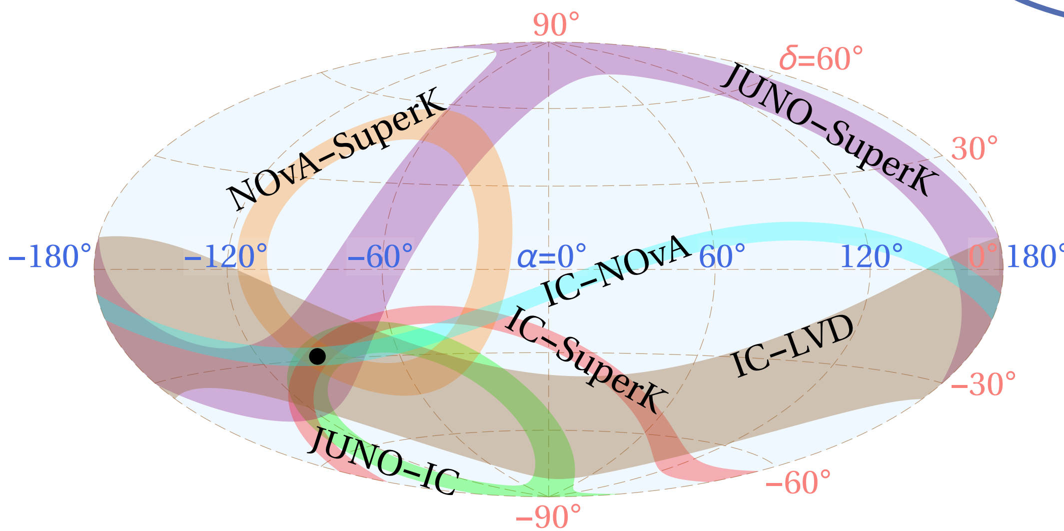
poster: L. Apollonio

Multi-detector/multimessenger coordination

- Supernova Early Warning System
  - Timing and localization
  - Engage broader community
  - open-source software

Poster: A. Habig

Poster: A. Molinario (LVD)



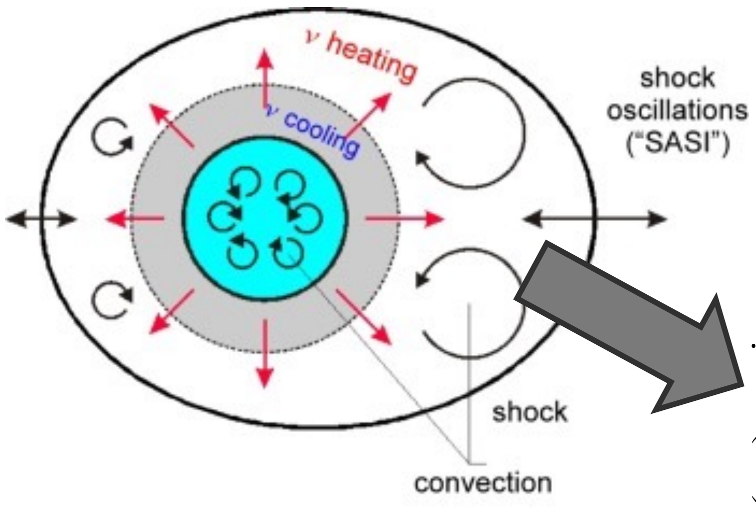
Al Kharusi et al., New J. Phys. 23 031201 (2021) ; SNEWPY at https://github.com/SNEWS2/snewpy

Fig. from Brdar, Lindner, Xu, JCAP 1804 (2018) 025

Synergies, new directions

Synergy with gravitational waves (GW)

- GW from near-core dynamics, $f = O(100)\ Hz$
- likely to be observed at LIGO-Virgo-KAGRA for galactic SN



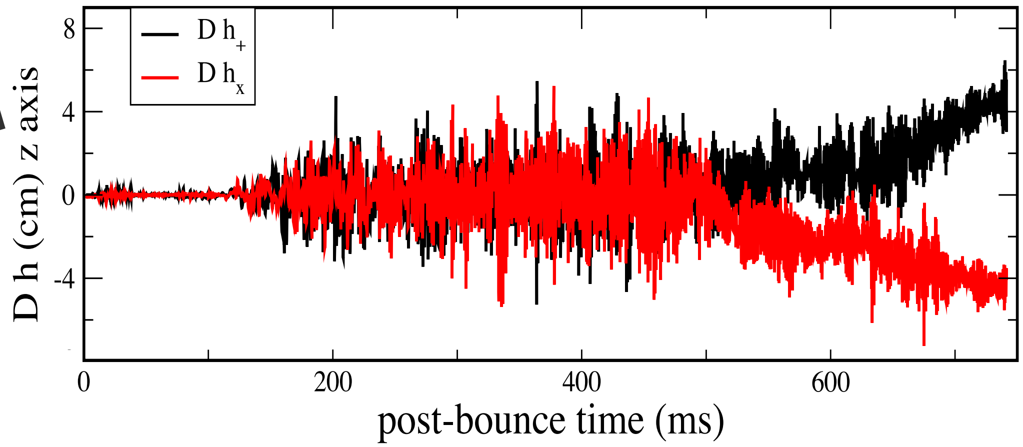
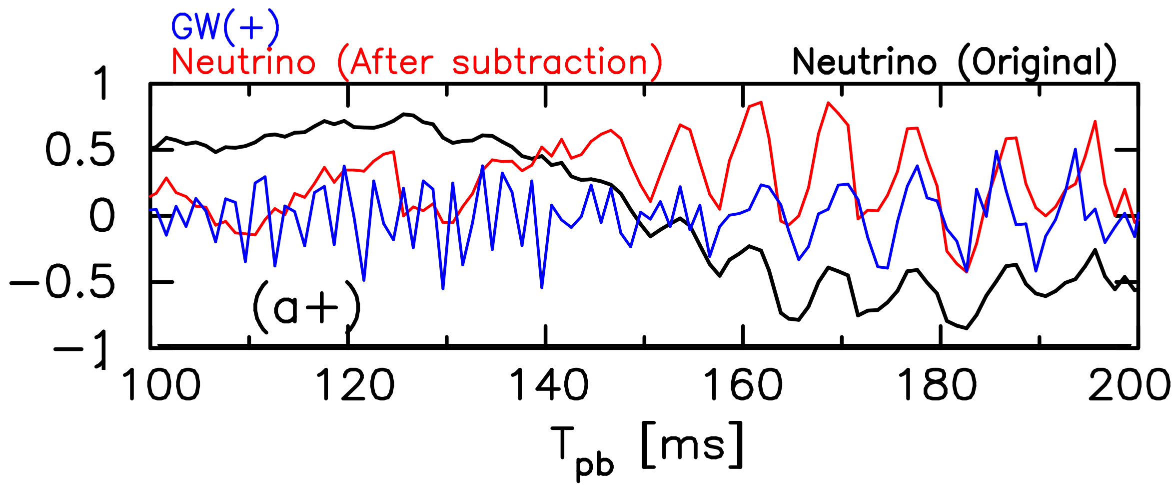


Fig. from Mezzacappa et al., (2023), PRD 107 (4), 043008

GW + neutrinos: enhanced potential

- Improve alert: timing, localization
- test near-core physics: SASI, neutron star cooling, …



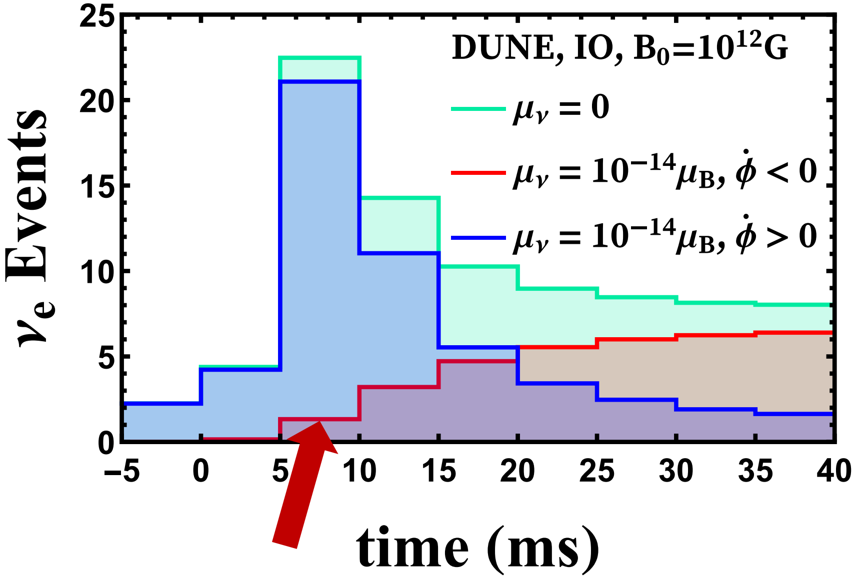
Kuroda, Kotake, Hayama and Takami, ApJ, 851:62, 2017 (fig. credit)
Lin, Rijal, Lunardini, Morales and Zanolin, *PRD* 107 (2023) 8, 083017
Drago, Andresen, Di Palma, Tamborra and Torres-Forne', PRD 108, 10, 103036 (2023)

Testing for new physics: what if....

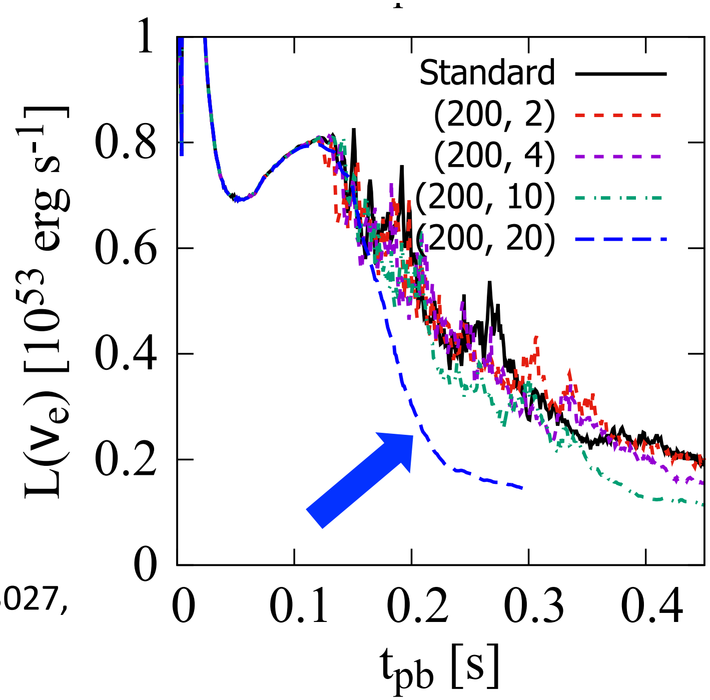
- Suppressed neutrino emission?
  - Extra cooling due light particles: sterile neutrinos, axion-like particles, …
- Anomalous flavor composition at Earth?
  - Neutrino decay, e.g., $\nu_3 \to \nu_1$
  - Oscillations due to non-standard interactions
- Spectral distortions?
  - Exotic absorption channels (scattering on Dark Matter)
  - Oscillations due to non-standard interactions
- Anomalous time delays?
  - Lorentz-violation, …

- Magnetic Moment of Dirac neutrinos + “twisting” magnetic field

Jana and Porto, PRL 132 (2024) 10, 101005



- With axion-like particles in simulation

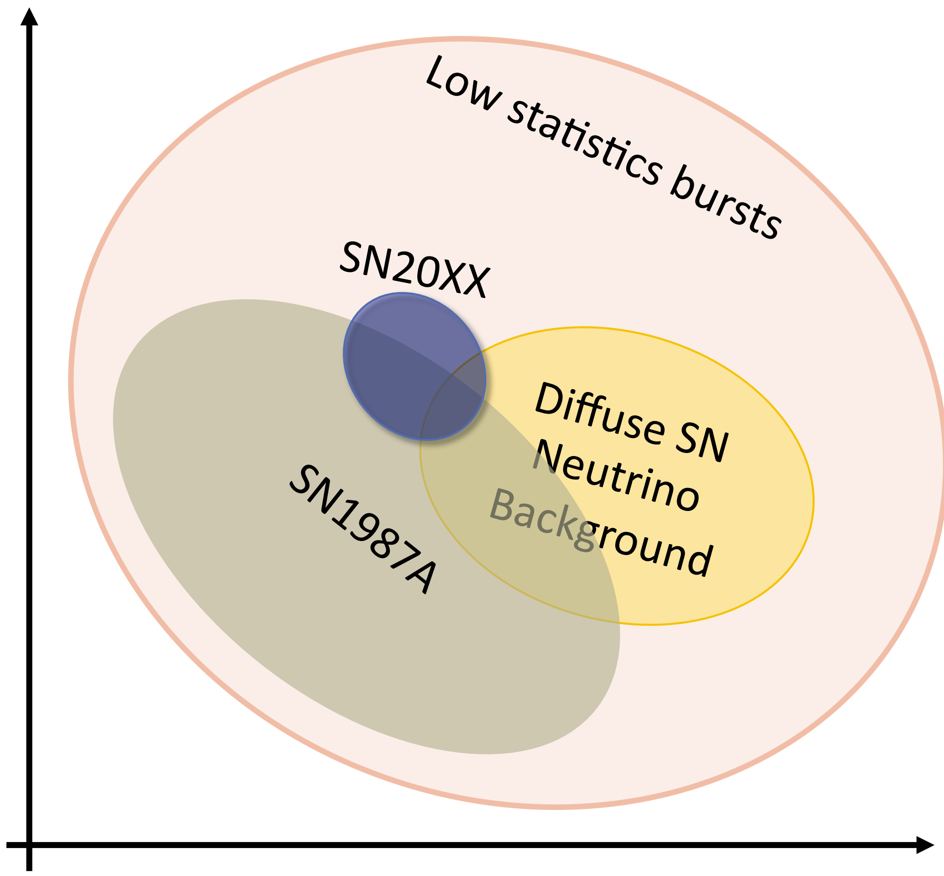


Mori, Takiwaki, Kotake, Horiuchi, PRD 108 (2023) 6, 063027,
Betranhandy and E. O’Connor, PRD 106, 063019 (2022)

Discussion

From one to many: toward a population study

- The future: global analysis of multiple data sets
  - Test stellar *population*
  - Disentangle stellar physics from neutrino/particle physics



Questions for future study

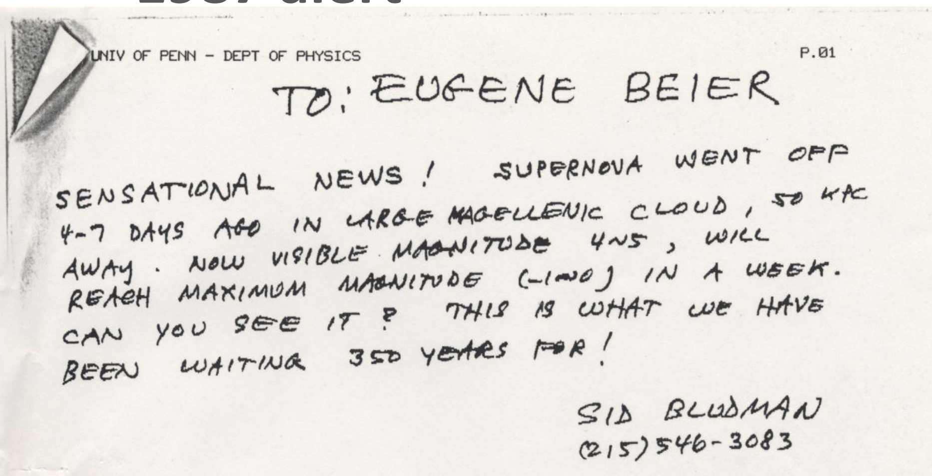
- Are we prepared for the next galactic supernova?
  - Will decision-making be fast enough?
  - What if it’s very close to Earth (Betelgeuse, etc.)?
  - Public impact of early warning?

- Numerical simulations: neutrino-focused developments
  - What’s the next most important improvement, and how long will it take?

- What near-core quantities can be measured with neutrinos + GW + astro?
  - Properties of core's nuclear matter (Equation of State, etc.)
  - Existence and features of hydrodynamic phenomena in the accretion phase (SASI, etc.)
  - Shockwave propagation parameters
- How well can we test flavor conversion?
  - Can we measure conversion probabilities?
  - use time evolution to disentangle neutrino-driven oscillations from matter effects?

Thank you!

1987 alert


UNIV OF PENN – DEPT OF PHYSICS P.01

TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF 4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC AWAY. NOW VISIBLE MAGNITUDE 4½, WILL REACH MAXIMUM MAGNITUDE (-1 to 0) IN A WEEK. CAN YOU SEE IT? THIS IS WHAT WE HAVE BEEN WAITING 350 YEARS FOR!

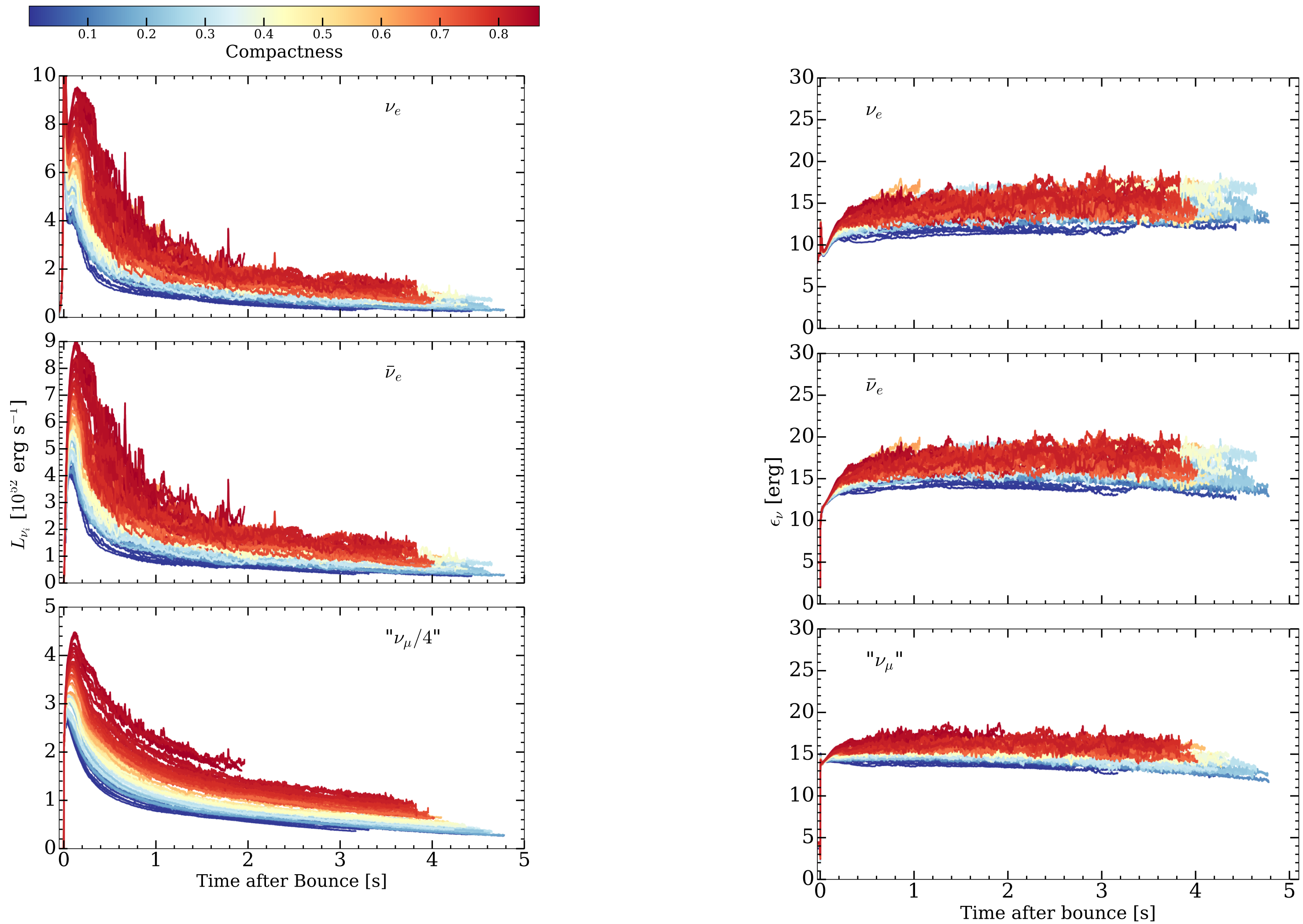
SID BLUDMAN
(215) 546-3083

https://www-sk.icrr.u-tokyo.ac.jp/en/news/detail/324

20xx alert

Courtesy of Jost Migenda,
SNEWS 2.0 coll.

BACKUP



FORNAX 2D multi-second simulations, M=9 – 27 M_{sun}

D. Vartanyan, A. Burrows, MNRAS 526 (4) (2023) 5900–5910 ; data available at https://dvartany. github.io/data/

Flavor conversion: Hamiltonian

$$F_e = p\, F_e^0 + (1-p) F_x^0$$

$$\mathsf{H}_E = \mathsf{H}_E^{\rm vac} + \mathsf{H}_E^{\rm m} + \mathsf{H}_E^{\nu\nu}$$

$$\mathsf{H}_E^{\rm vac} = \mathsf{U}\,{\rm diag}\left(-\frac{\omega_{21}}{2}, +\frac{\omega_{21}}{2}, \omega_{31}\right)\mathsf{U}^\dagger\ ,$$

vacuum

$$\mathsf{H}^{\rm m} = \sqrt{2}G_{\rm F}\ {\rm diag}(N_e, 0, 0)$$

ν-matter scattering: MSW effect

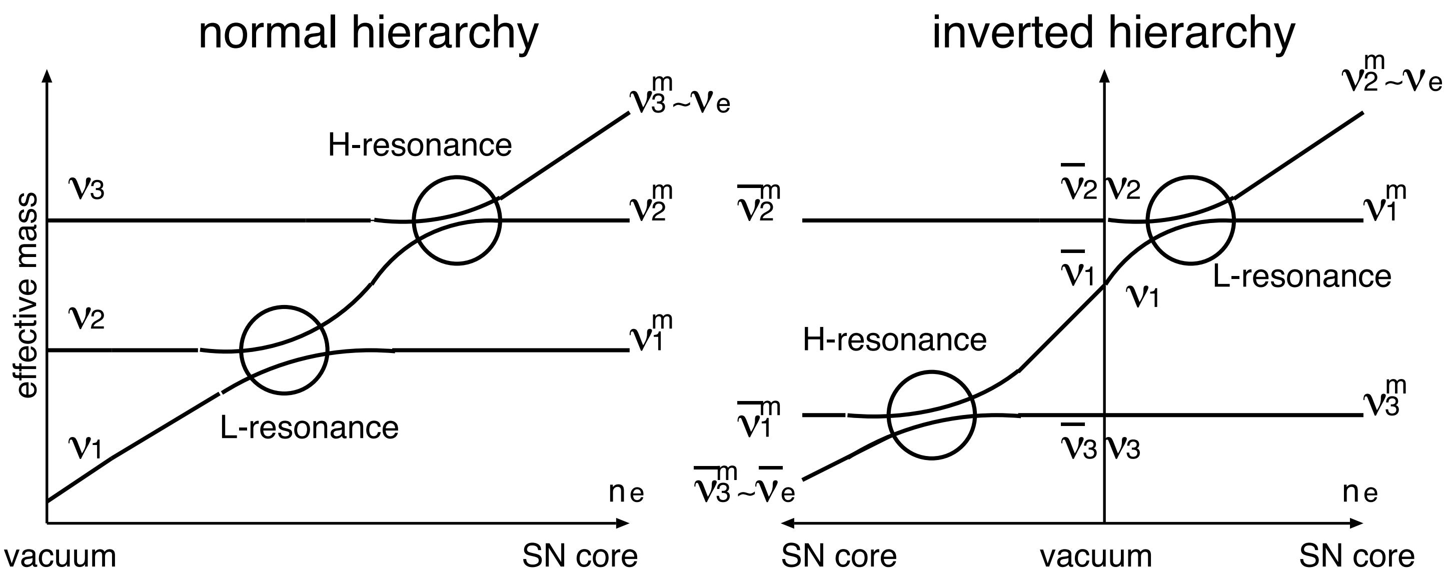
$$\mathsf{H}_E^{\nu\nu} = \sqrt{2}G_F \int dE'(\rho_{E'} - \bar{\rho}_{E'})(1-\cos\theta)$$

$\nu - \nu$ scattering :
collective oscillations,
no general solution

θ = angle between incident momenta

Wolfenstein, PRD 17 1978, Mikheyev & Smirnov, Yad. Fiz. 42, 1985 ;
Duan, Fuller & Qian, PRD74 (2006), Duan et al., PRD74 (2006)

Matter-driven conversion and mass ordering



Complexities…

Table 4.1: Known types of neutrino flavor oscillations that can occur in CCSNe and in BNSMs (first column). The second column labels whether a given type is of collective nature or not. The third to sixth columns denotes whether they affect the physical processes and/or nucleosynthesis outcome. The symbols ✓, ✗, and ? stand for "yes", "no", and "not explored yet" respectively.

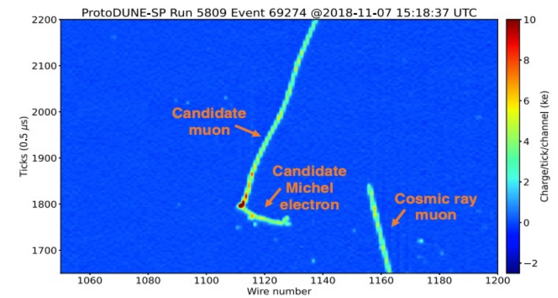
Type	Collective?	SN explosion	SN ν wind nucleosynthesis	ν process	BNSM r-process
Slow mode	✓	✗	maybe	✓	✗
Fast mode	✓	✓	✓	✓	✓
Synchronized MSW	✓	✗	✗	✗	✗
Matter neutrino resonance	✓	✗	✗	✗	maybe
Collisional induced	✓	?	?	?	likely
MSW transformation	✗	✗	✗	✓	✗
Parametric resonance	✗	✗	✗	?	✗

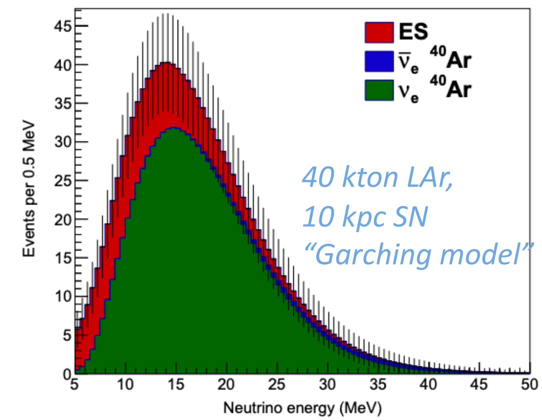
Table from Fischer et al., *Prog. Part. Nucl. Phys.* 137 (2024) 104107

DUNE sensitivity to SN neutrinos

- **DUNE Far Detector** employs liquid argon TPC (LArTPC) technology that allows excellent 3D imaging with few mm resolution, excellent energy measurement, and particle identification.
  - Placed 1,5 km deep underground at **SURF** (Lead, SD).
  - **4 x 17 kton modules** in phased approach for DUNE FD:
    - Phase I: FD-1 horizontal drift LArTPC, FD-2 vertical drift LArTPC.
    - Phase II: FD-3 & FD-4 with possible enhanced low energy physics capabilities.
- **Measurement of core-collapse SN** ν's in DUNE will provide information about:
  - **Supernova physics**: Core collapse mechanism, SN evolution in time, black hole formation.
  - **Neutrino physics:** ν flavor transformation, ν absolute mass, other ν properties.
- **Diffuse background supernova ν's** are also potentially detectable.
- DUNE will have **burst pointing** resolution (~5 deg) and participate in SNEWs.

Michel e- in ProtoDUNE-SP data





ν events for different SN models in 40 kton LAr & 10 kpc SN

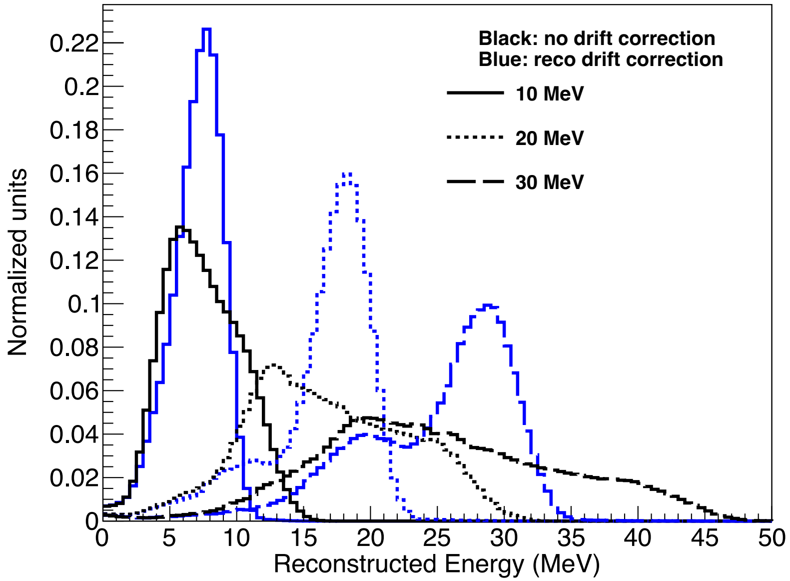
Channel	Liver-more	GKVM	Garching
$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$	2648	3295	882
$\overline{\nu}_e + ^{40}\mathrm{Ar} \rightarrow e^+ + ^{40}\mathrm{Cl}^*$	224	155	23
$\nu_X + e^- \rightarrow \nu_X + e^-$	341	206	142
Total	3213	3656	1047

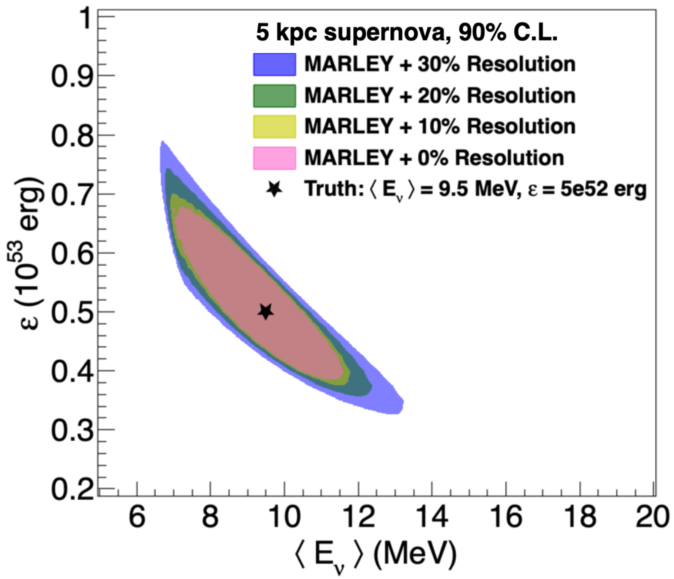
Main interactions: CC (ν_e) ES (ν_x).

ν_e flavor dominates → LAr only future prospect for a large, cleanly tagged SN ν_e sample, which dominates in neutronization phase.

courtesy of D. Pershey and C. Cuesta on behalf of the DUNE collaboration

- Energy resolution: ~10-20%
  - MARLEY



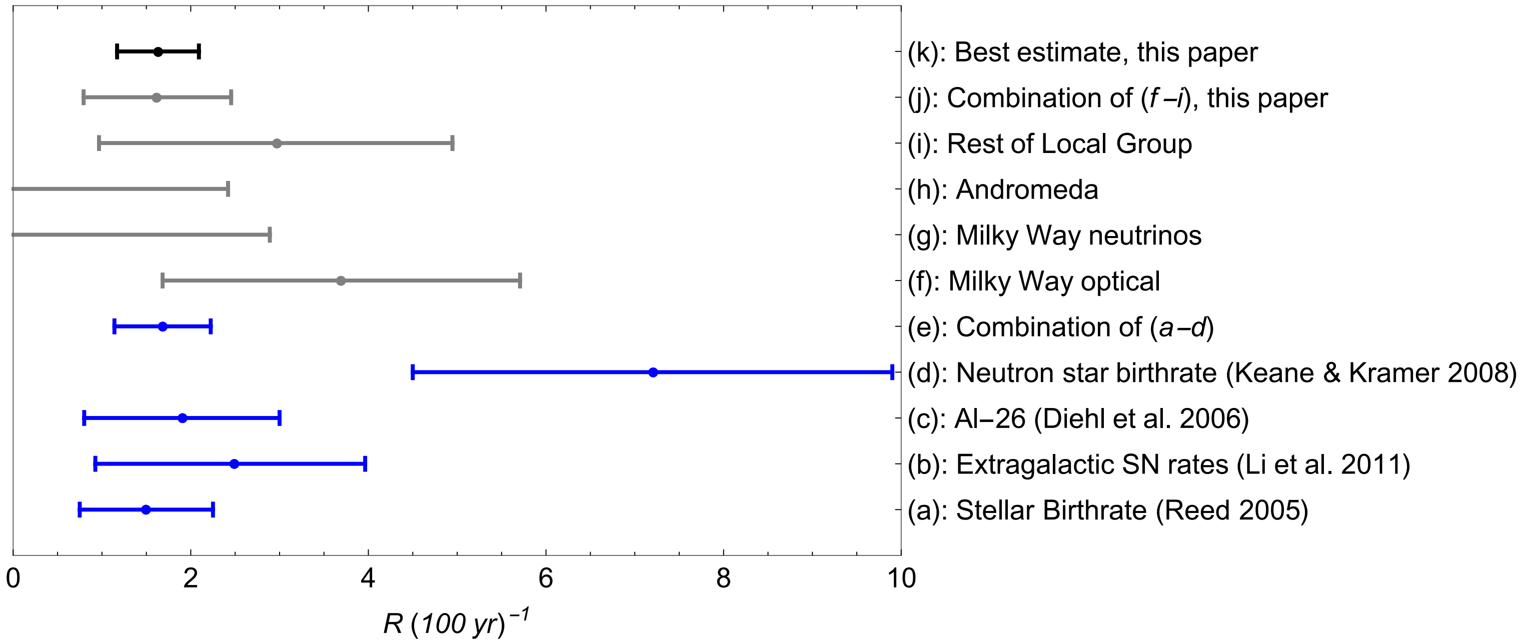


DUNE collab. *Eur.Phys.J.C* 81 (2021) 5, 423

Supernova burst searches

- SuperK IV archival search : SNR(D<100 kpc) < 0.29 yr^{-1}

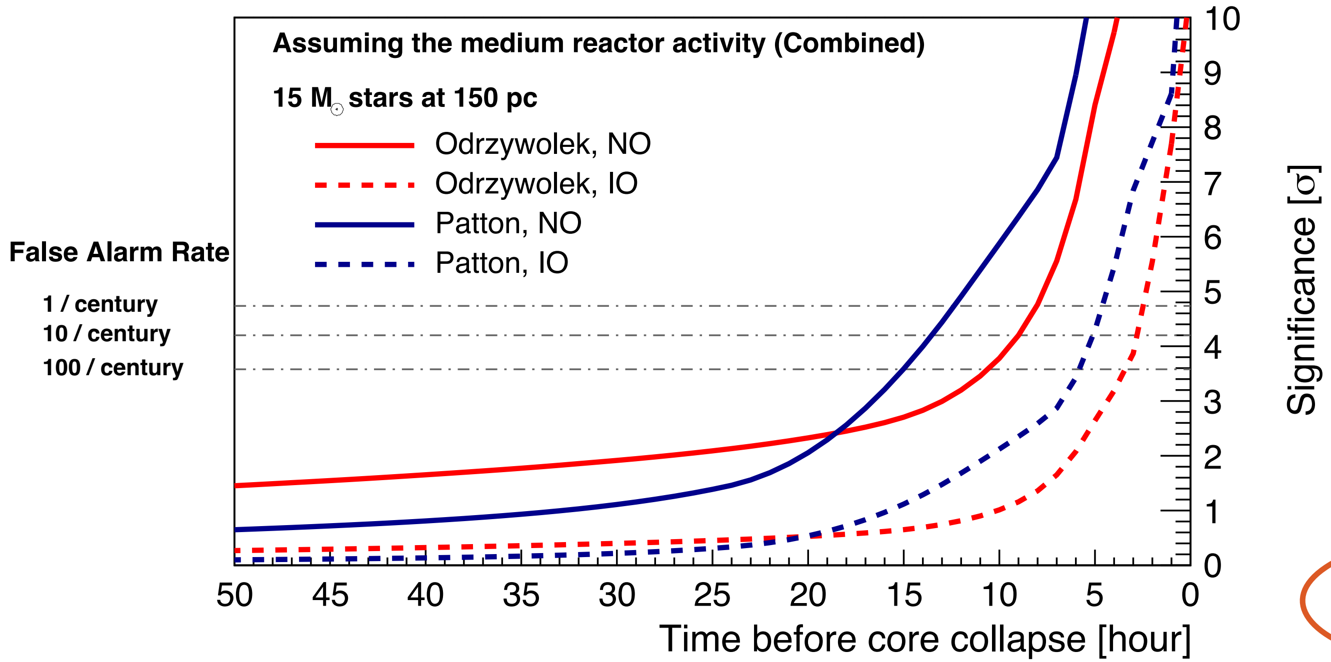
M. Mori et al. (SuperK coll.) *Astrophys.J.* 938 (2022) 1, 35



Rozwadowska, Vissani and Cappellaro, New Astron. 83 (2021), 101498

Preparedness: pre-SN neutrinos sensitivity

- Alert ~12 hours pre-collapse, for 15 Msun star at D=150 pc (e.g., Betelgeuse)
- SuperK-Gd at 0.033% Gd concentration

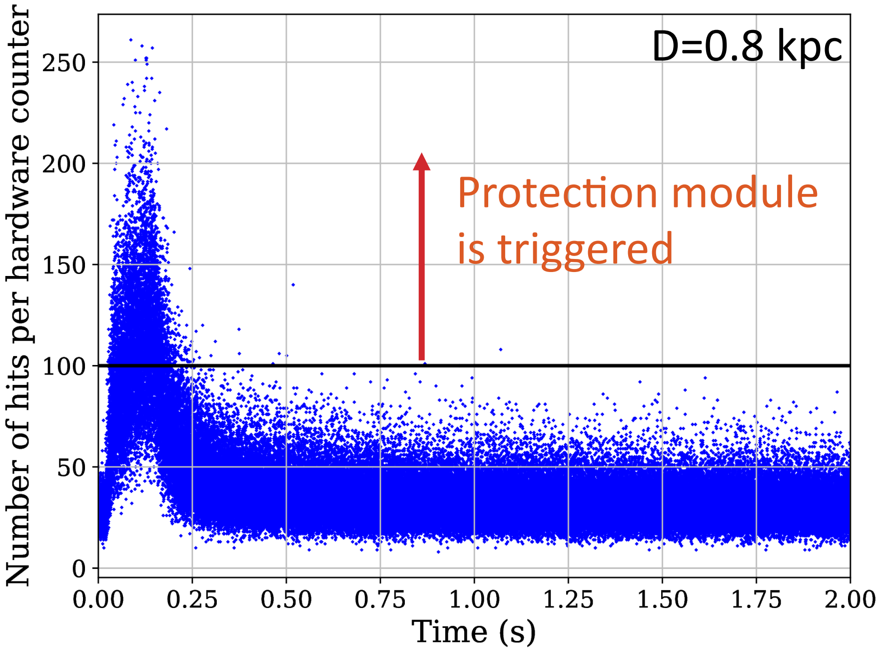


Poster: K. Saito

SuperK + KAMLAND, Abe et al., arxiv:2404.09920 ; see also Machado et al., Astrophys. J., 935, 40

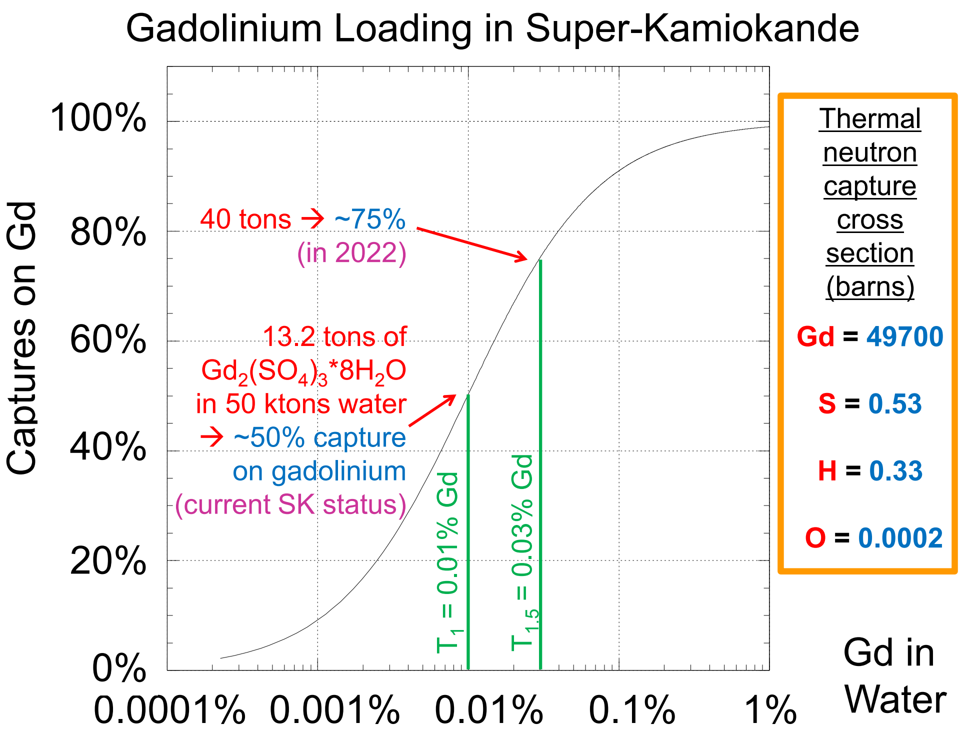
Preparedness: near-Earth supernova

- Danger of Data Acquisition System overload!
  - New SuperK preotection module with veto



M. Mori et al. (SuperK. coll.), arxiv:2404.08725

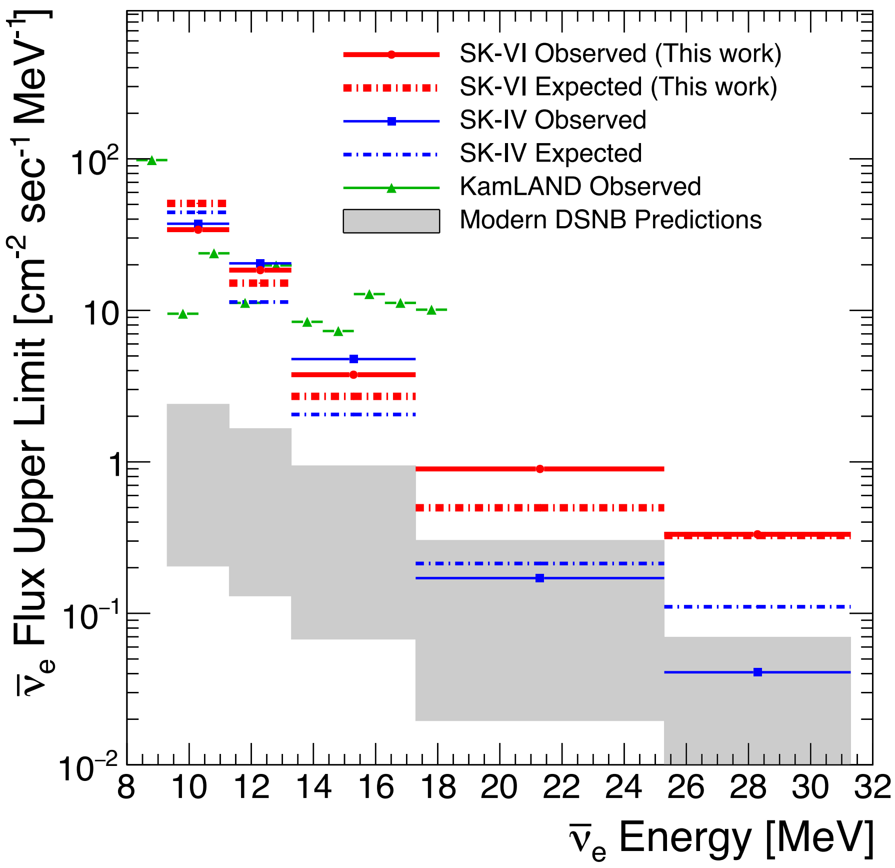
Super-Gd loading progress



Li, Vagins and Wurm, Universe 8 (2022) 3, 181

DSNB - limits

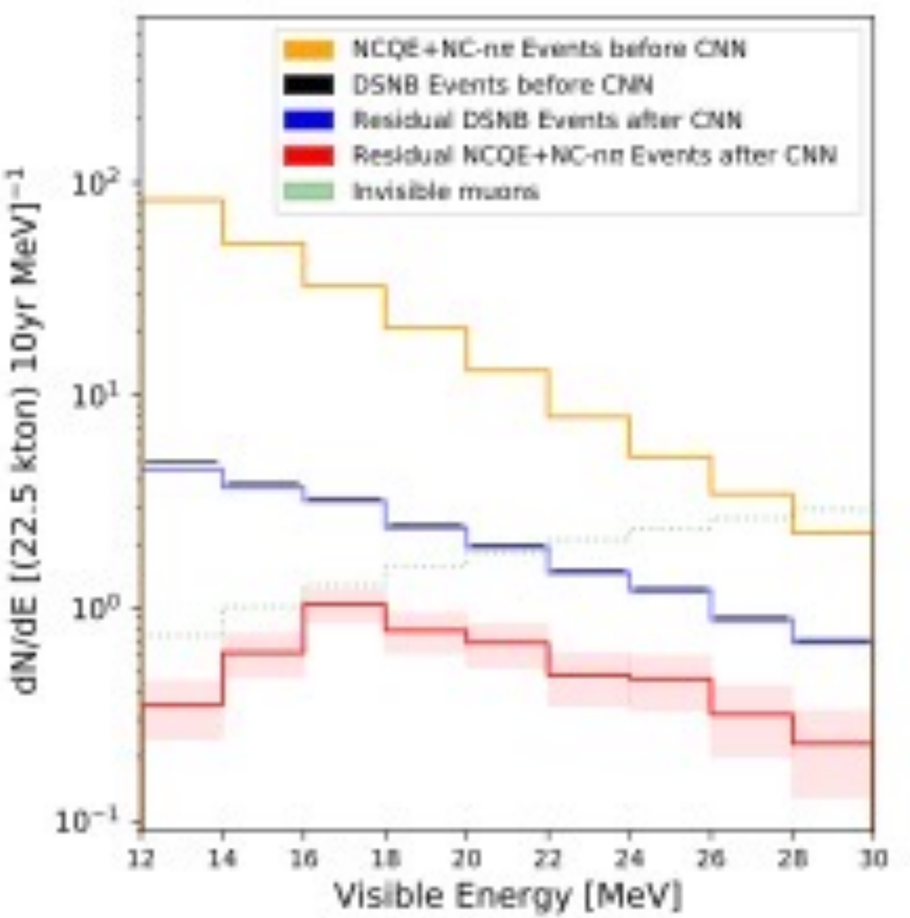
- SuperK-Gd, 0.01% Gd (capture efficiency 50%)
  - Increased to 0.033% in 2024 (eff. 75%)
  - target is 0.1% (eff. 90%)



Harada et al. (SuperK coll.) *Astrophys.J.Lett.* 951 (2023) 2, L27

Machine Learning and DSNB

- Use Convolutional Neural Network for NC background reduction at SuperK-Gd
  - O(10^2) abatement
  - Maintain 96% signal efficiency



Maksimovic, Nieslony and Wurm, *JCAP* 11 (2021) 11, 051