Supernova neutrinos

J Tseng
Neutrino Summer School
UC Santa Barbara
6 July 2026

NASA, ESA, Allison Loll/Jeff Hester (ASU). Ack: Davide De Martin (ESA/Hubble)

Lectures

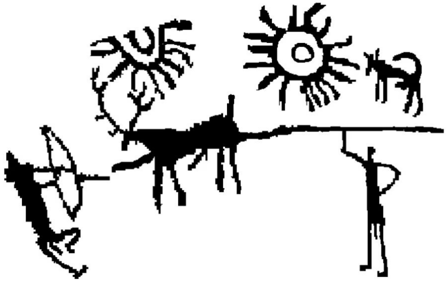
1. What's a supernova?
2. What do neutrinos have to do with supernovae?
3. What can we learn from supernova neutrinos?
4. Observing supernova neutrinos
5. The next Galactic core-collapse supernova

Some resources

- P Podsiadlowski, “Supernovae and gamma-ray bursts”, in TD Oswalt and MA Barstow (eds), *Planets, Stars and Stellar Systems*, vol 4, Springer 2013.
- AW Alsabti, P Murdin, eds, *Handbook of Supernovae*, Springer, 2016.
  - Latest edition: https://link.springer.com/referencework/10.1007/978-3-319-20794-0
- SNEWS2 white paper: S Al Kharusi et al., *New J Phys* **23**, 031201 (2021).
- SNEWS2 workshop at Laurentian (14-17 June 2019)
  - https://snews2.0.snolab.ca/
- SNνD@LNGS (29 May - 1 June 2023)
  - https://supernova.sites.lngs.infn.it/index.html
- And of course INSS 2026!

Chapter 1
What’s a supernova?

What is a supernova?

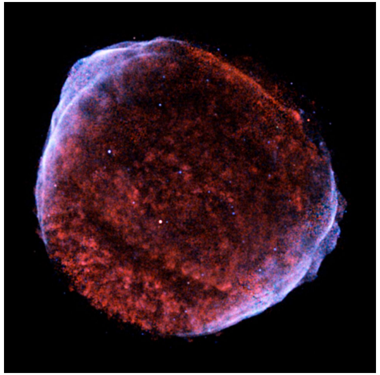


“Two suns? No, it’s a supernova drawn 6,000 years ago, say scientists”, *The Guardian*, 10 Jan 2018

- Basic idea: it’s an exploding star
- Emphasis on observational character
  - “Nova”: it’s new - problematic if you thought the heavens were unchanging
  - “Super”: it’s very bright
- Supernovae were observed and recorded in history

Historical supernovae (remnants)

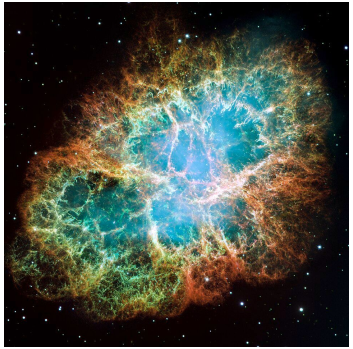
1006



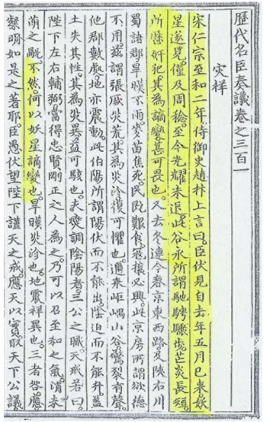
Smithsonian Institution, X-ray

1054

visible during day for 23d, at night for 2y



NASA/ESA/J Hester/A Loll



歷代名臣奏議卷之三百

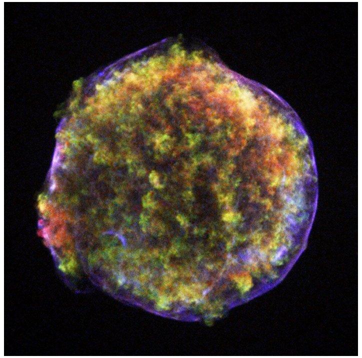
災祥

?
Filipovic et al., arxiv 2206.00392

1181

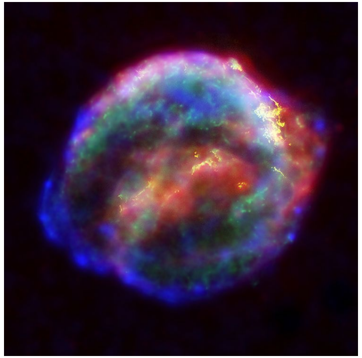
Chandra/XMM-Newton/Pan-STARRS/WISE

1572 (Tycho’s)



Chandra, X-ray

1604 (Kepler’s)



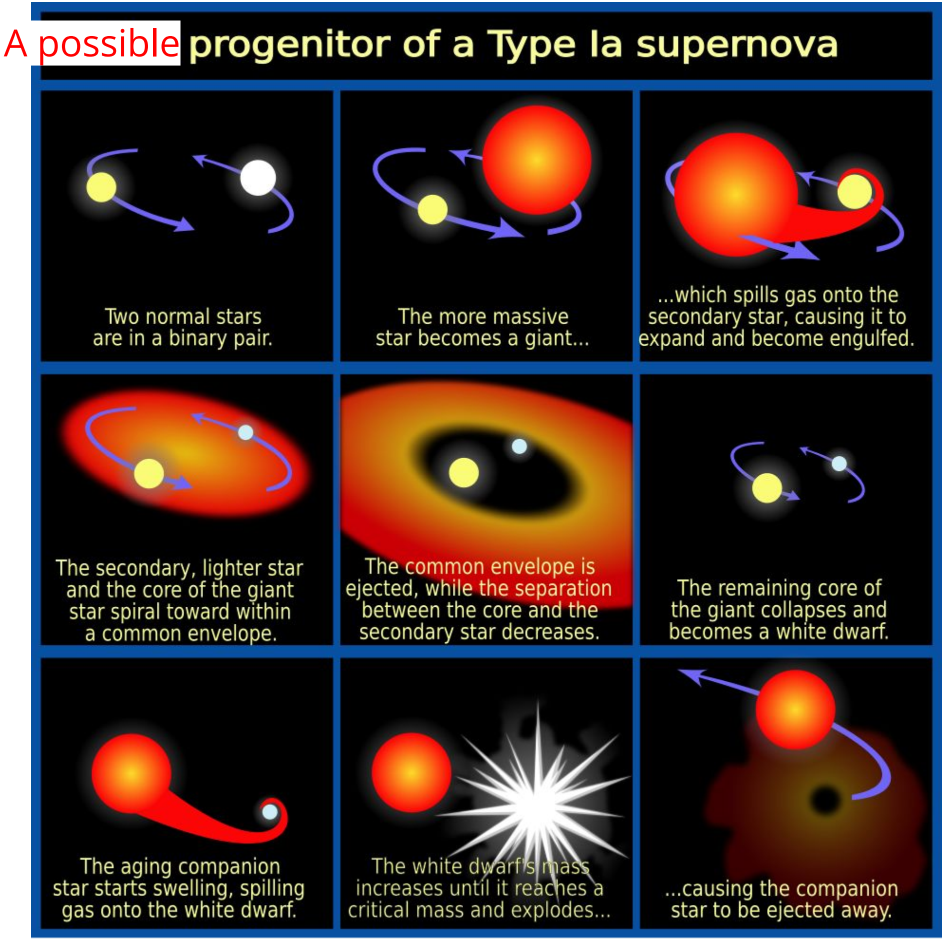
CXO/HST/Spitzer

Supernova categories

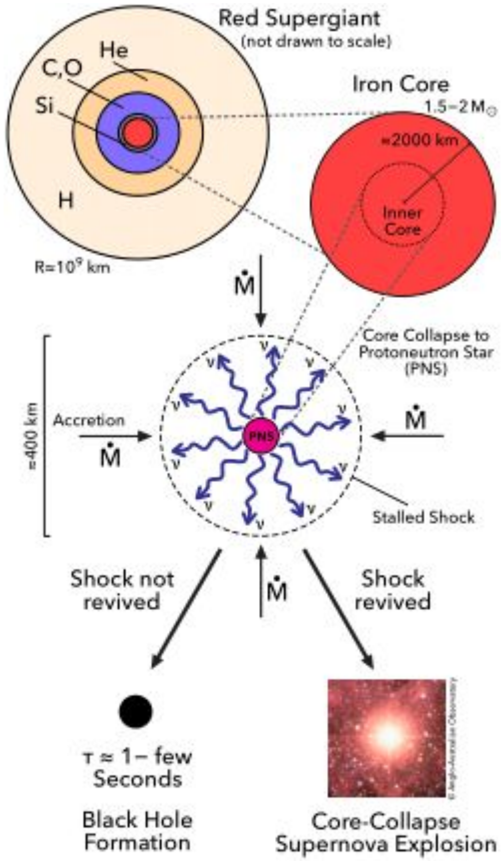
- Observational categories (R Minkowski 1941)
  - Type I: no H lines in spectrum
  - Type II: H lines present in spectrum
- Initially thought these categories corresponded to underlying mechanism
  - Subdivide by other spectral features, lightcurve, etc
  - Will avoid historical discussion here
- Possible mechanisms:
  - Thermonuclear explosion a leading hypothesis
    - Think of the time in which this discussion occurred
  - Gravitational collapse of a massive star
  - Merger of compact objects

White dwarf explosion

- Type Ia usually attributed to fusion-driven explosions of white dwarfs
- Accretion approaching Chandrasekhar limit (~1.4M☉)
  - If beyond limit, collapse to neutron star
  - This would destroy heavy elements, but we see them in spectra
- Unclear on accretion source
  - Main sequence star -> periodic outbursts (nova)
  - Massive star?
  - Other white dwarf?
- Chandrasekhar limit → some uniformity in explosion Even if actual explosion mechanism not entirely clear
  - *Standardizable* candle



NASA/ESA/A Feild, Wikipedia, CC BY 3.0



Core collapse supernovae (CCSN)

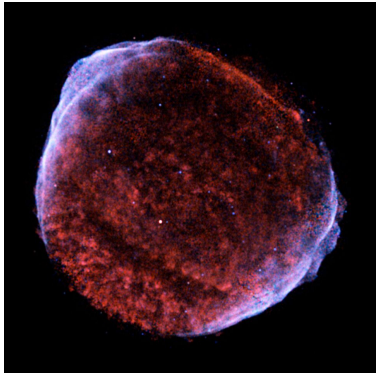
- Stars burn light elements via nuclear fusion to produce heavier elements
  - Cycles of burning and contracting to ignite heavior elements
- Massive stars (>11M☉) form Fe core
  - No more energy to be gained by forming heavier elements
  - Grow core until exceed Chandrasekhar limit (gravitational vs electron degeneracy pressure) of 1.44M☉
- Photo-disassociation of Fe and He (endothermic)
  - Reverses many years of producing heavy elements
- Electron captures p + e → n + electron neutrino
  - Neutrinos carry energy away most efficiently (path length ~100Ly)
  - Photon would take 10y to escape
  - Removes even more electron degeneracy pressure → free fall
- Collapse stops when reach nuclear densities
  - Shock ~10^{44} J rapidly dissipated in still-accreting matter
- Total energy release ~ NS binding energy 3x10^{46} J (~10% NS mass)
  - Exceeds binding energy of outer core (~ 10^{44} J)
  - Need just 1% of neutrino energy to restart explosion

Core-collapse supernovae (CCSN)

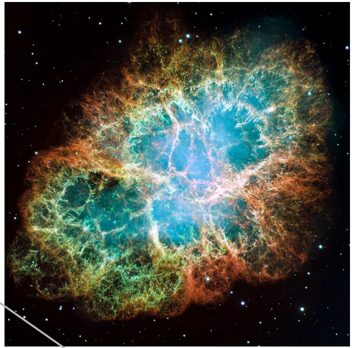
	Progenitor mass ($M_\odot$)	SN type	Remnant
Electron capture (ONeMg core)	8-10	IIp	Neutron star
Fe core	10+	IIp, IIL, IIb, Ib/c, hypernova	Neutron star, black hole
Pair instability (e^+e^- pair production, runaway fusion)	140-250	IIp	none
Photodisintegration (direct photodisintegration)	250+	?	Massive black hole

Historical galactic supernovae

- 1006 (Type Ia)
- 1054 Crab Nebula (ECSN)
- 1181 (Type Iax, white dwarf merger)
- 1572 (Tycho, Type Ia)
- 1604 (Kepler, Type Ia)

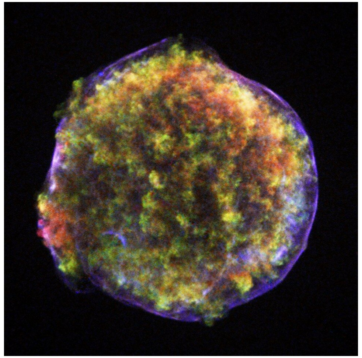


Smithsonian Institution, X-ray

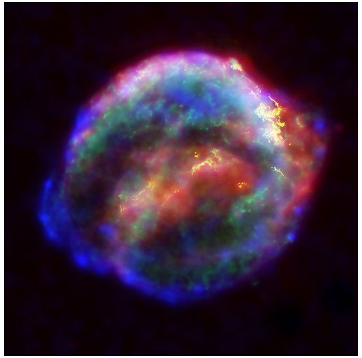


NASA/ESA/J Hester/A Loll

Chandra/XMM-Newton/Pan-STARRS/WISE



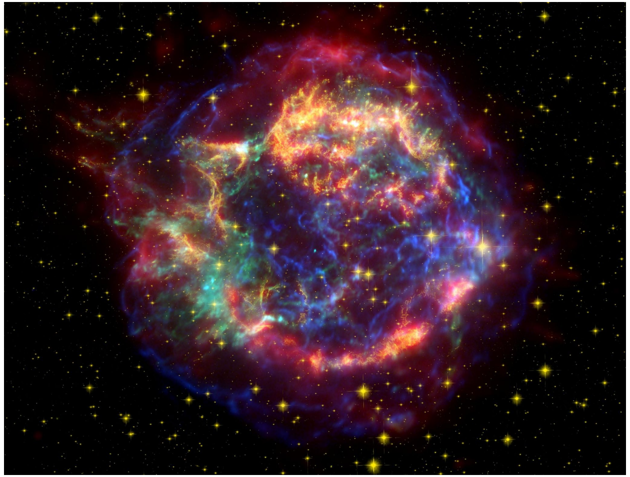
Chandra, X-ray



CXO/HST/Spitzer

Cassiopeia A

HST/Spitzer/Chandra composite



- Type IIb (CCSN)
- Light should have arrived ~1660
- No definite observations at the time
    - Dust absorption?
    - Certain regions of galaxy (esp opposite Galactic Center) will be unobservable in optical wavelengths, but could be in IR and neutrinos

SN 1885A (Andromeda)

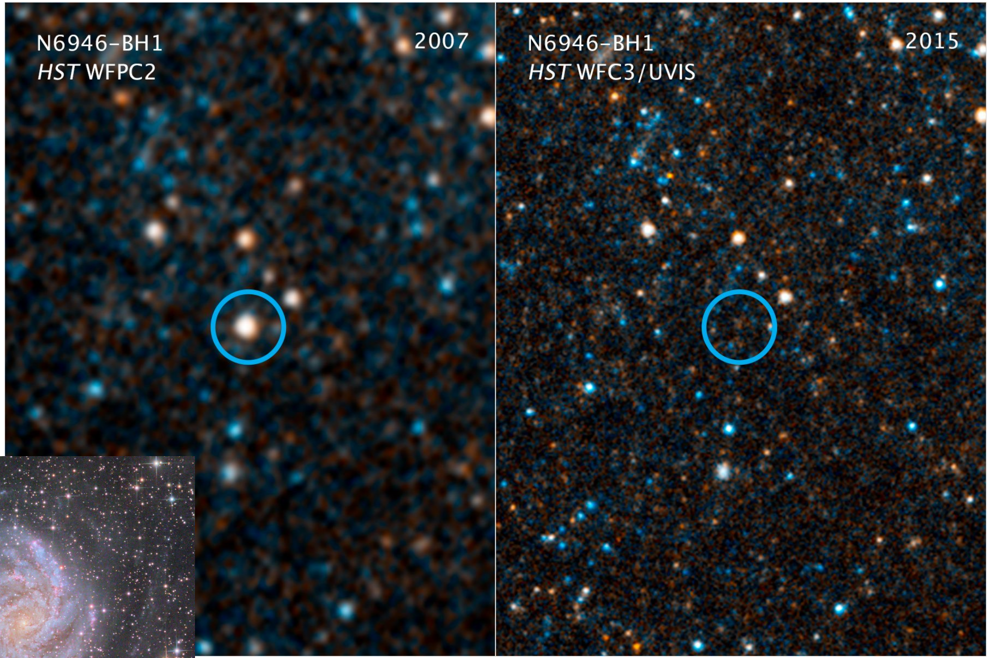
- Andromeda (M31) ~700 kpc away
- Type Ia
- The only supernova observed in Andromeda over ~century of observations

Failed supernovae

- Black hole formation: likely failure to revive shock/explosion
  → may not see in visible spectrum!

- Search for disappearing massive stars → failed SN $0.16^{+0.23}_{-0.12}$ at 90% CL [Neustadt et al 2021, MNRAS, 508, 516]
- Consistent with search in PTF/ZTF surveys over 10 yr, 231 galaxies, $>17M_\odot$ [Byrne & Fraser 2022, 2201.12187]

- Some candidates:
  - N6946-BH1 (NGC6946, 7.7Mpc)
  - M31-2014-DS1 (700kpc)
    [K De et al., arxiv:2410.14778]



NASA, ESA, and C Kochanek (OSU)

Andrei Gusan, 29 Dec 2024

Chapter 2

What do neutrinos have to do with supernovae?

One day during the Cold War...

- *This Week's Citation Classic* No 4 (28 Jan 1981) on SA Colgate, RH White, "The hydrodynamic behavior of supernovae explosions", *ApJ* **143**, 626 (1966). Colgate (LLNL):

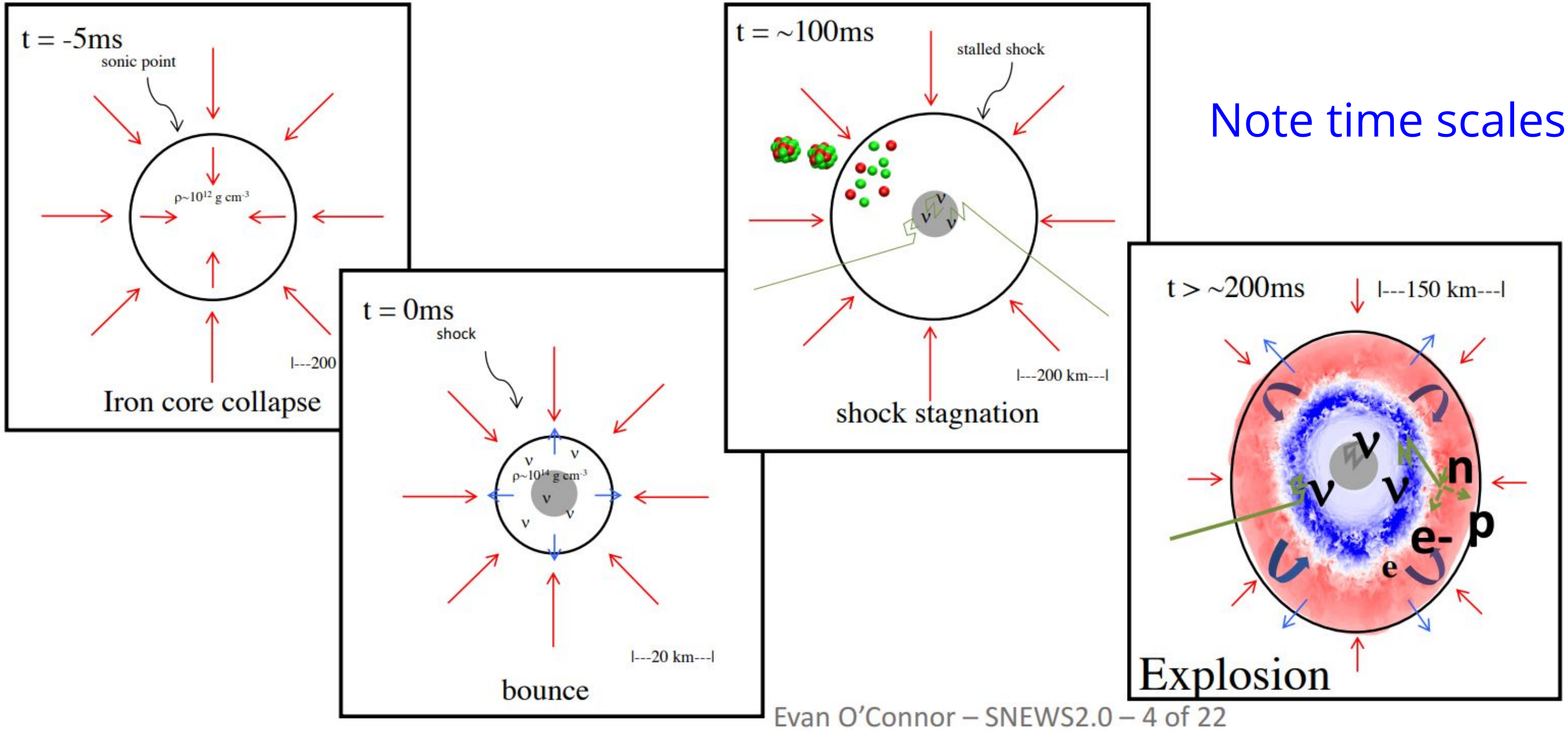
It is ironic that this work started because of an argument with Soviet scientists during the negotiations for the Cessation of Nuclear Weapons Tests in Geneva in 1959. It was claimed by me that the radiation emissions from a supernova might trigger the then proposed detection net for high altitude nuclear 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?'

Dr Strangelove (1964)

Supernova energies

	Total energy (foe = 10^{44}J = 10^{51} erg)	Neutrino energy (foe)	Kinetic energy (foe)	EM radiation (foe)
Type Ia	1.5	0.1	1.3 - 1.4	~0.01
CCSN	100	100	1	0.001 - 0.01

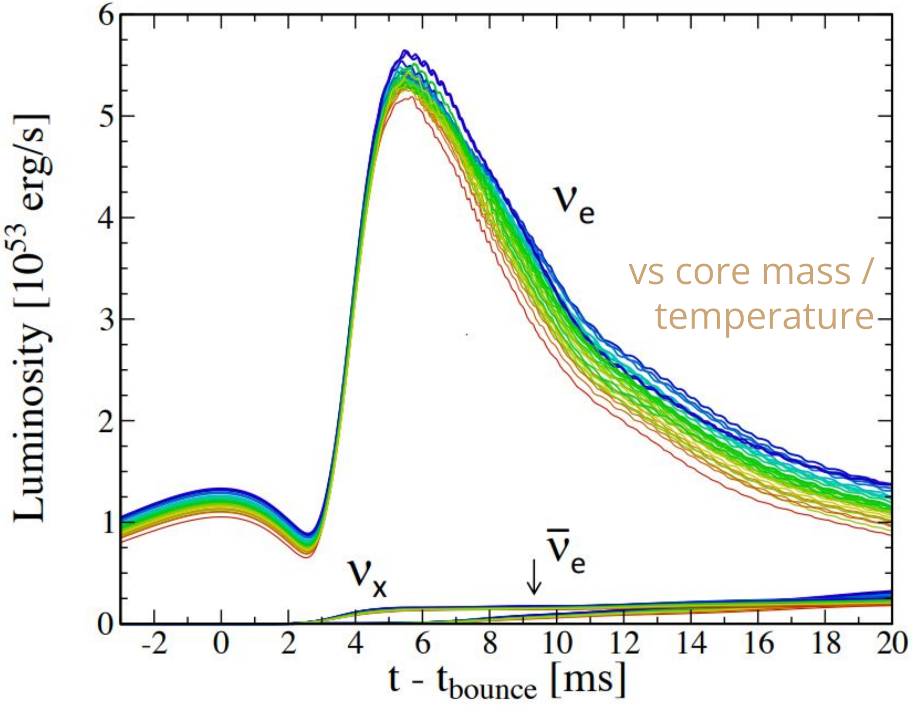
Core collapse stages



Note time scales

Neutronization burst

- At nuclear densities, rapid p captures of e → burst of ν_e
- Neutrinos trapped (few ms) until density at shock decreases
- Little dependence on progenitor
  - Universal CCSN characteristic (should be)



From Evan O’Connor, SNEWS2

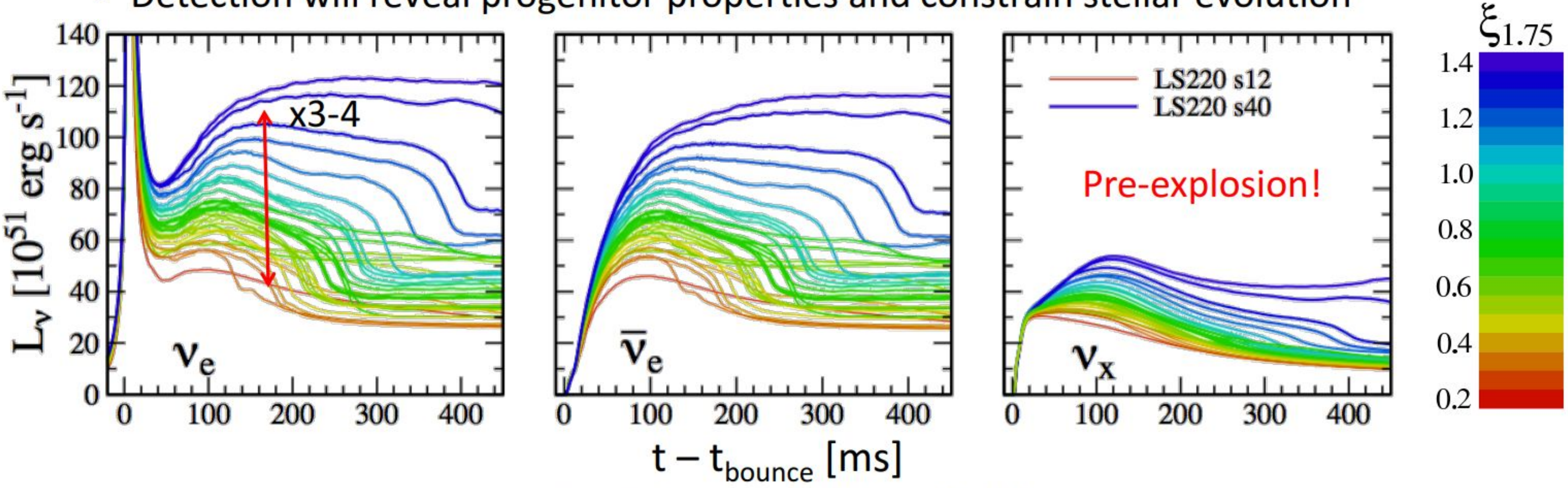
Accretion phase

- Infalling matter heated by shock, cooled by emitting neutrinos
  - Charged current processes
  - Thermal production processes, including pair production
- Heavier neutrino species primarily produced via thermal processes
  - Temperature not high enough for CC processes

Accretion Phase

- The accretion phase introduces first progenitor dependence of luminosities
  - High 'compactness': higher mass accretion -> more binding energy released -> higher luminosities

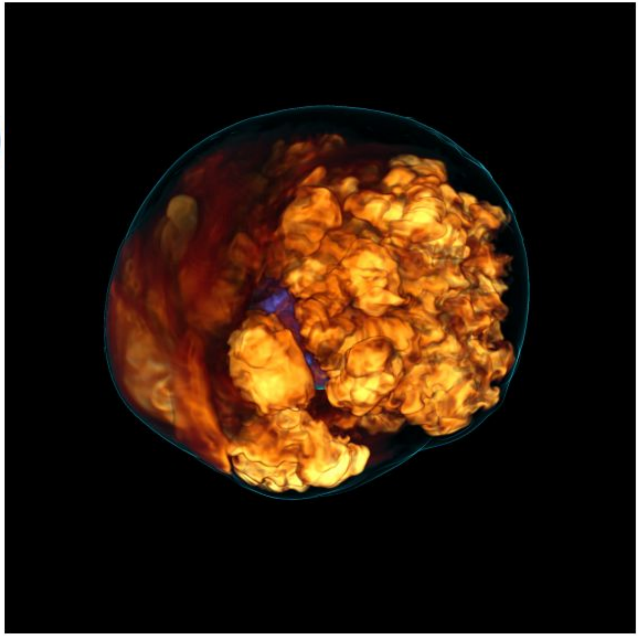
- Detection will reveal progenitor properties and constrain stellar evolution



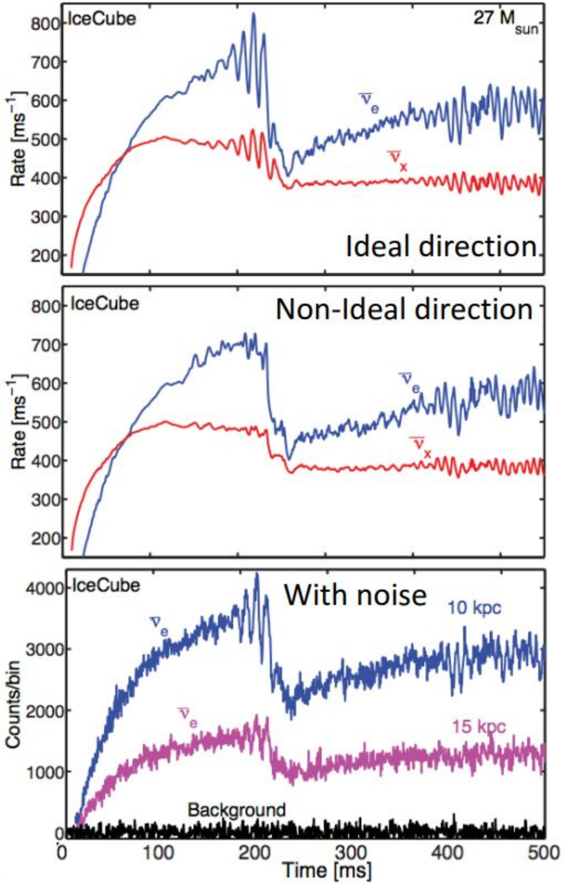
Evan O'Connor – SNEWS2.0 – 15 of 22

Accretion Phase - SASI

- Standing Accretion Shock Instability (SASI) can impact signal, periodic variations.

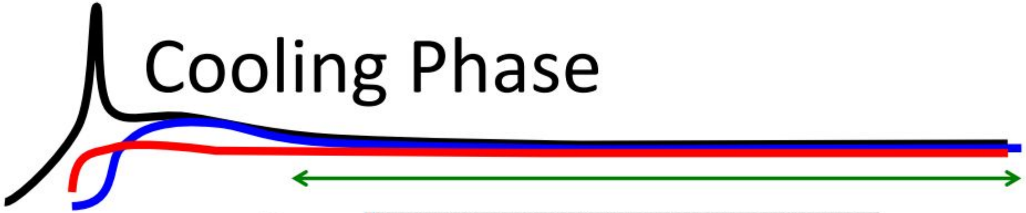


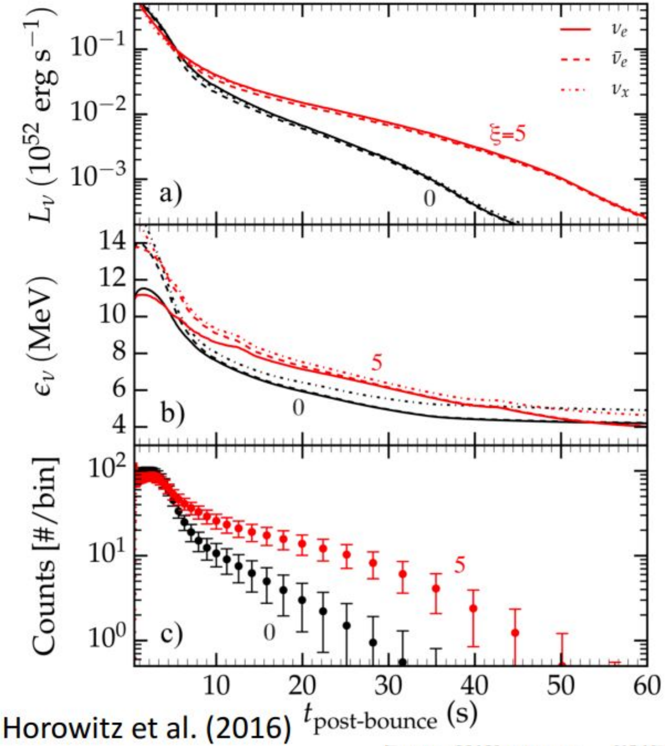
Tamborra et al. (2013); Mirizzi et al. (2015)



Evan O'Connor – SNEWS2.0 – 16 of 22

Cooling Phase



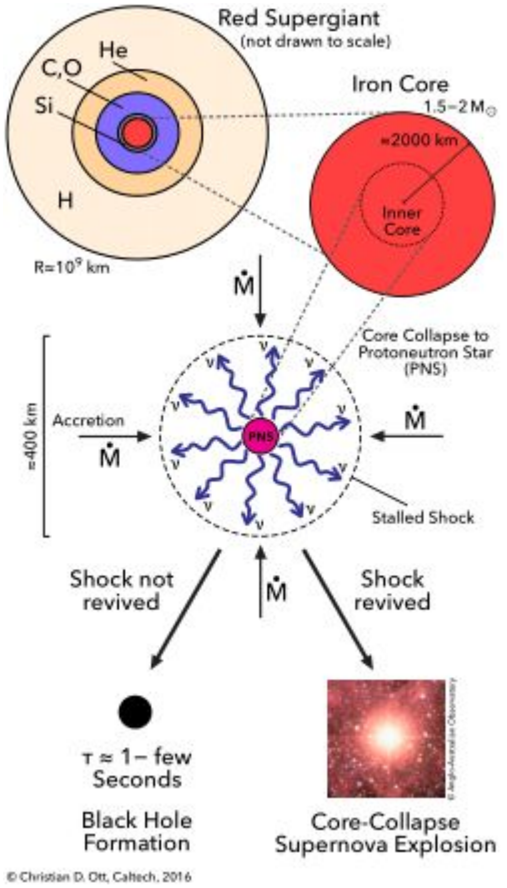


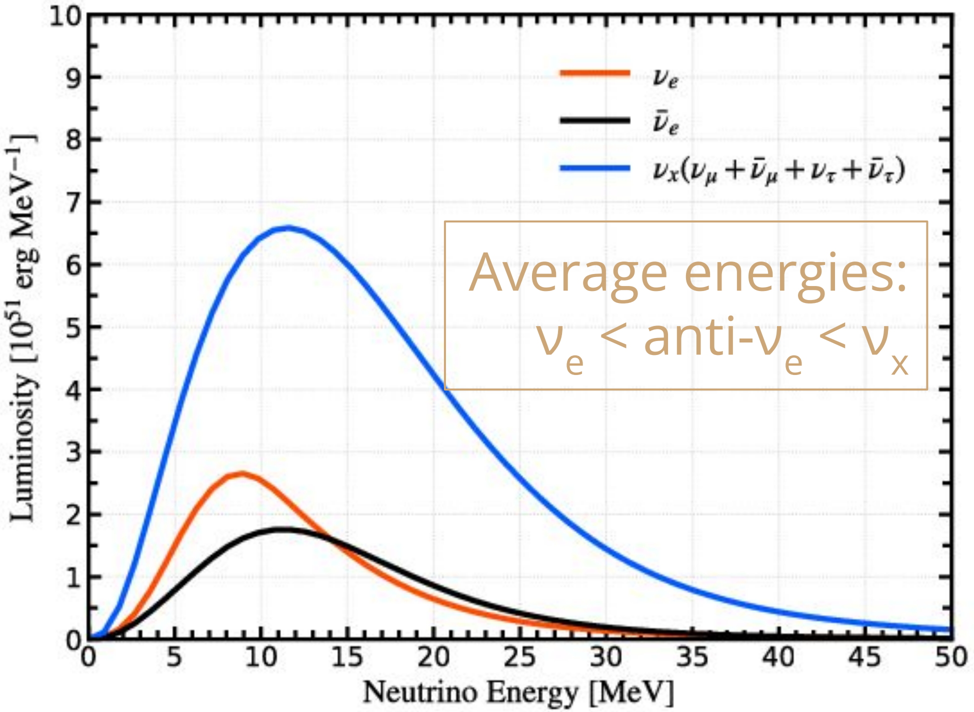
Horowitz et al. (2016)

Evan O'Connor – SNEWS2.0 – 19 of 22

- How the protoneutron star cools relays info about the EOS -> traced by neutrino emission
- Variations in neutrino luminosities and energies can be detectable and help constrain the nuclear EOS
- Particularly, differences in the <E> between $\bar{\nu}_e$ and ν_e is important and can impact nucleosynthesis

Neutrinos and core-collapse supernovae

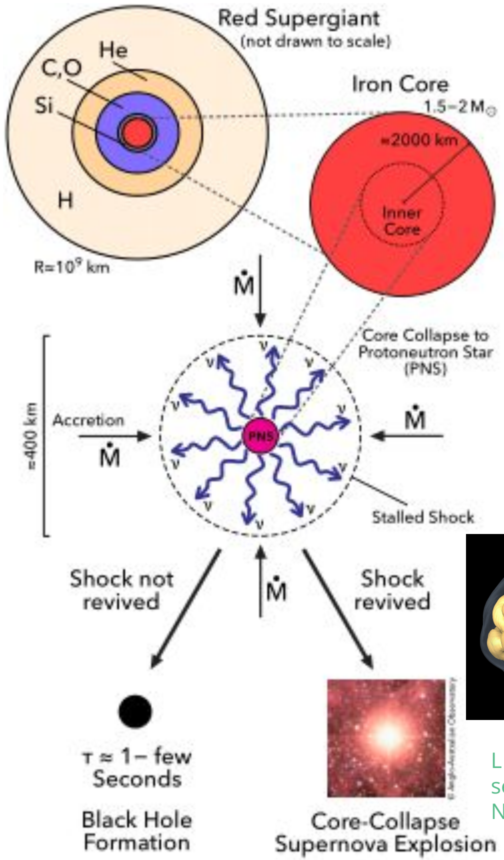




Average energies:
ν_e < anti-ν_e < ν_x

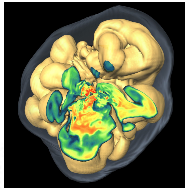
From Super-K, arxiv:2403.06760, based on Nakazato SN model

Neutrinos and core-collapse supernovae

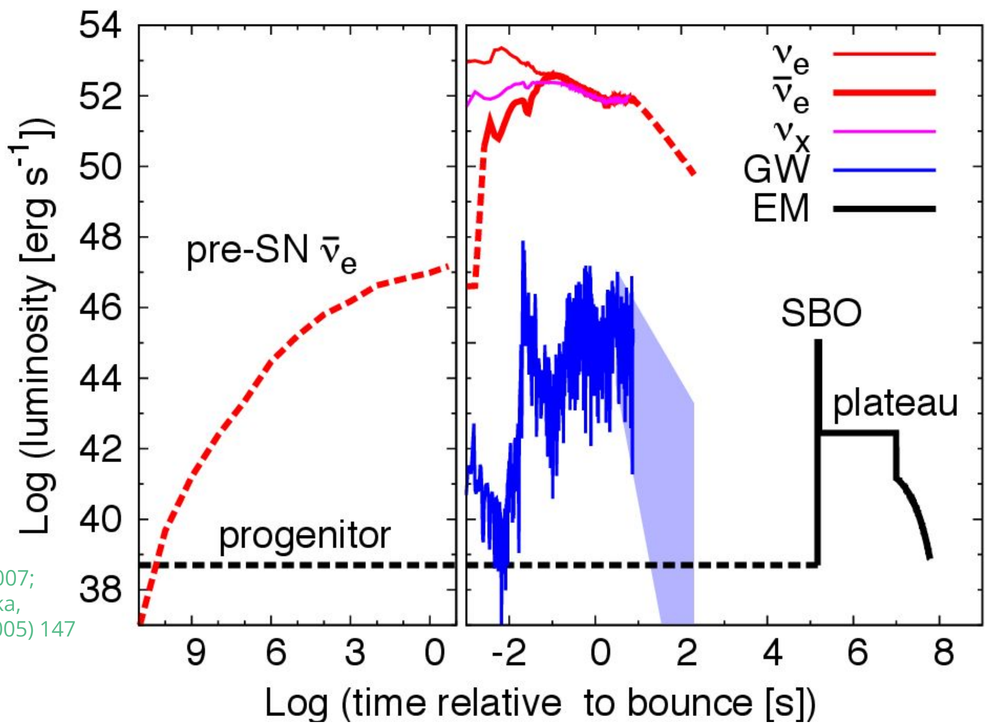


© Christian D. Ott, Caltech, 2016

15Msun, 0.5s



L Scheck, MPA, 2007; see Woolsey, Janka, Nature Phys 1 (2005) 147



17 $M_{\odot}$ progenitor, 2D axisymmetric simulation

K Nakamura et al., MNRAS 461 (2016) 3296; pre-SN Odrzywolek et al. (2004)

CCSN models

- Elements of computational model
  - Magnetohydrodynamics
  - General relativity
  - Nuclear reactions
  - Nuclear equation of state
  - Neutrino transport, interactions
- 1D, 2D, 3D
- Explodability: stalled shock, revival, asymmetry
- Almost exclusive focus on single, non-rotating progenitor
  - Most supergiants in binary systems
  - Core often assumed to be non-rotating due to friction

Neutrino-driven supernova explosion movies

- https://wwwmpa.mpa-garching.mpg.de/ccsnarchive/movies/

Not all supernovae are alike

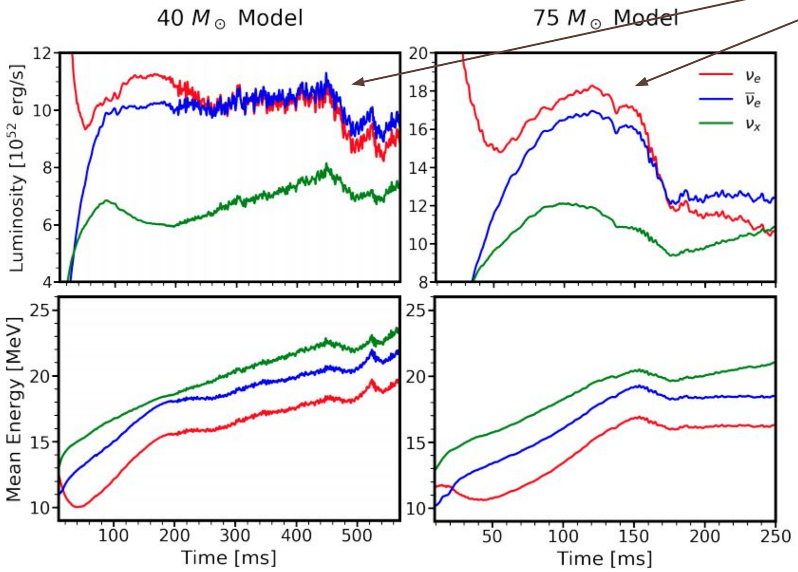
Also note that most massive stars exist in binary systems, but models are of single stars

Oscillations (standing accretion shock instability)

Long accretion (with angular momentum)

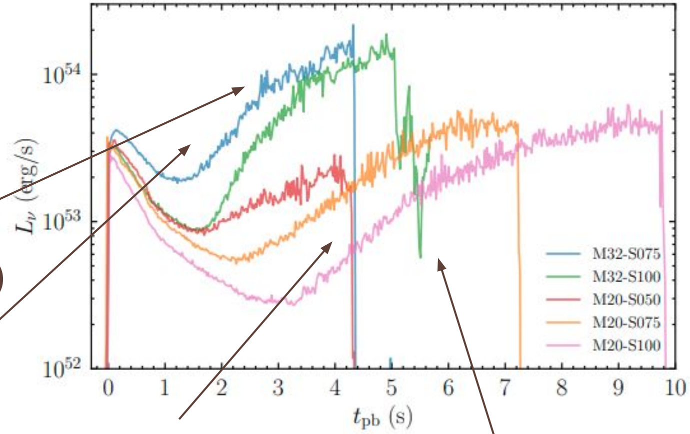
Abrupt cut-off

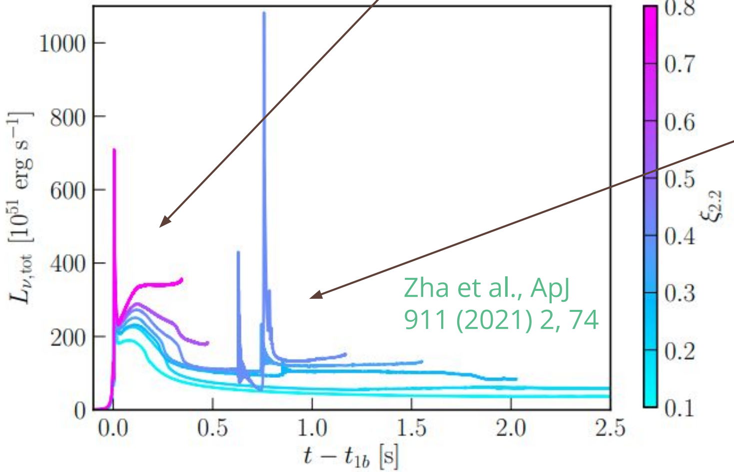
Secondary bursts (e.g., hadron-quark phase transition)



Walk et al., PRD 101, 123013 (2020)

Fujibayashi et al., ApJ 919 (2021) 2, 80

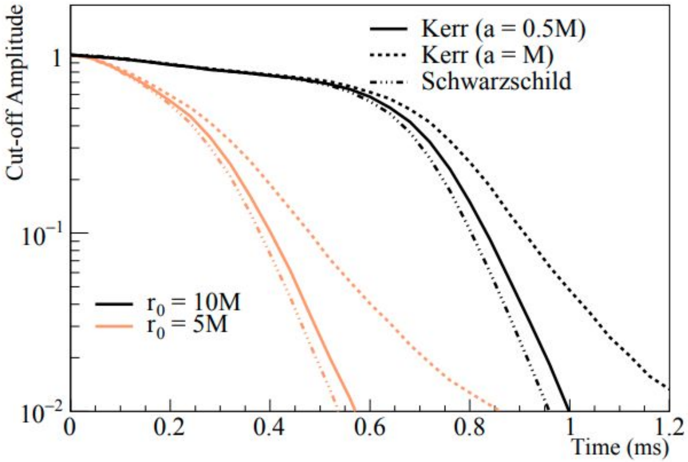


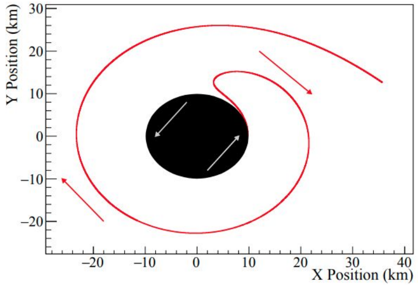


Zha et al., ApJ 911 (2021) 2, 74

Black hole cut-off

- How abrupt?
  - Simulations usually don't use full GR
  - Stop when approximations fail
  - Many simulations also consider only radial neutrino emission
- Non-radial neutrino trajectories soften cut-off
  - Characteristic √27M time constant from leakage near photosphere of non-rotating BH [Podurets 1964; Ames and Thorne 1968]
    - O(0.1)ms for non-rotating BH
    - Systematic uncertainty with current experiments
  - Longer smearing for extreme rotation
  - Cut-off may encode information about PNS mass and rotation
- Neutrino echoes [Gullen et al, ApJ 926 (2022) 2, 212]
  - Scattering of neutrinos off surrounding material
  - Further softens cut-off, obscures √27M time constant





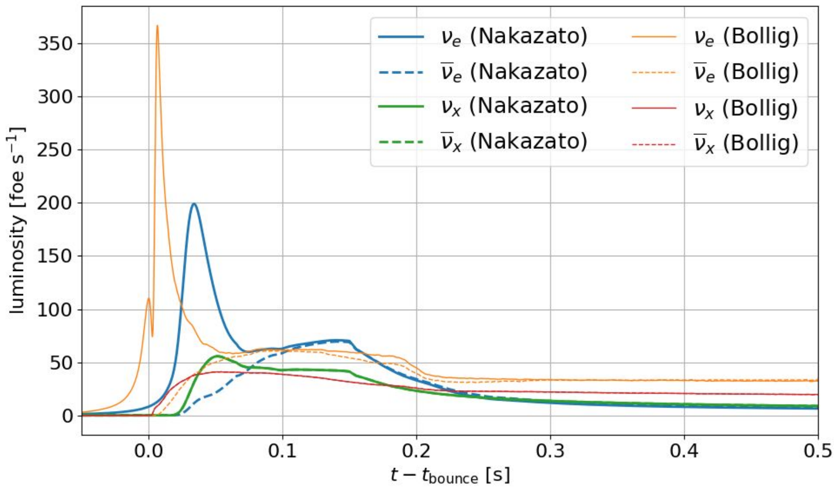
Sample neutrino trajectory around rotating BH

Wang, PRD 104 (2021) 10, 104030

SNEWPY

- Python package to bring together models of supernovae, physics, detectors
- Can be used as a front-end of SNOwGLOBES
- Useful for comparison of models and estimating effects of different physics
  - Mass hierarchy
  - Matter effects
  - Heavy neutrinos
  - Quantum decoherence
- Many models simulate different progenitor masses, equations of state

https://snewpy.readthedocs.io/en/stable/index.html



List of collapse models

- Bollig 2016
- Bugli 2021
- Fischer 2020
- Fornax 2019/21/22
- Kuroda 2020
- Mori 2023
- Nakazato 2013
- O'Connor 2013/15
- Sukhbold 2015
- Tamborra 2014
- Walk 2018/19
- Warren 2020
- Zha 2021

Recently implemented pre-supernova models as well

- Kato 2017
- Odrzywolek 2010
- Patton 2017
- Yoshida 2016

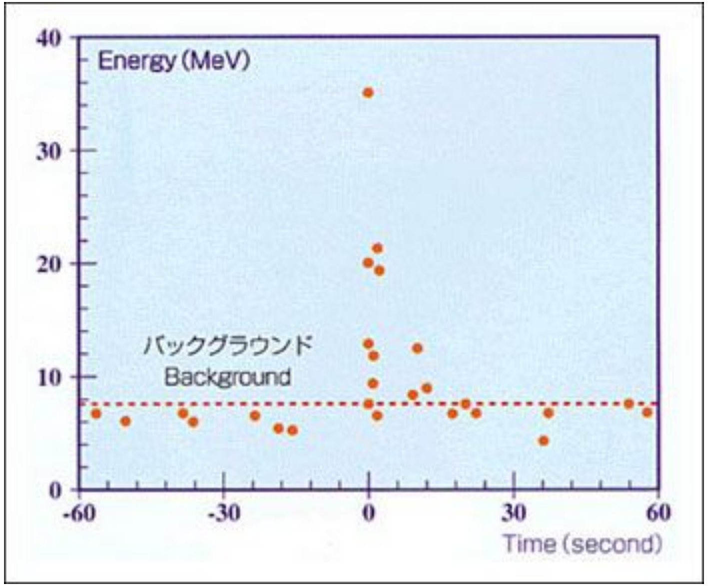
Are there enough neutrinos to detect?

- Neutrino intensity drops as $1/D^2$
- Typical scales:
  - D = 10 kpc
  - 100 foi = 10^{53} erg
  - Average detected neutrino energy ~20 MeV
  - IBD cross section around 20 MeV is $O(10^{-41})$ cm^2
  - Number of H targets in water: $O(10^{32})$ per kT
- O(100) events/kT at 10 kpc
- O(10) events/kT at 50 kpc (Large Magellanic Cloud, such as SN1987A)
- O(0.1) events/kT at 700 kpc (Andromeda)
  - It would have to be a big neutrino burst for Super/Hyper-Kamiokande to see it
- We will only see a significant neutrino flux for Galactic CCSN

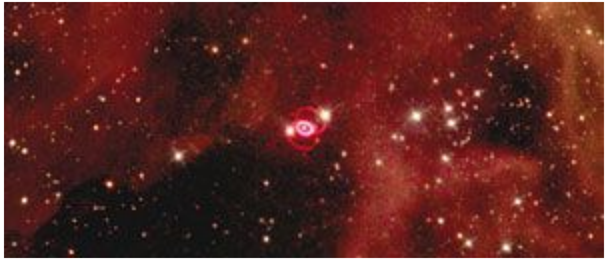
All the data: SN1987A

23 Feb 1987

Kamiokande



2-3 hours later:
Ian Shelton
(Toronto)
Oscar Duhalde
(Las Campanas)
Albert Jones
(AAVSO)



HST, 1990’s

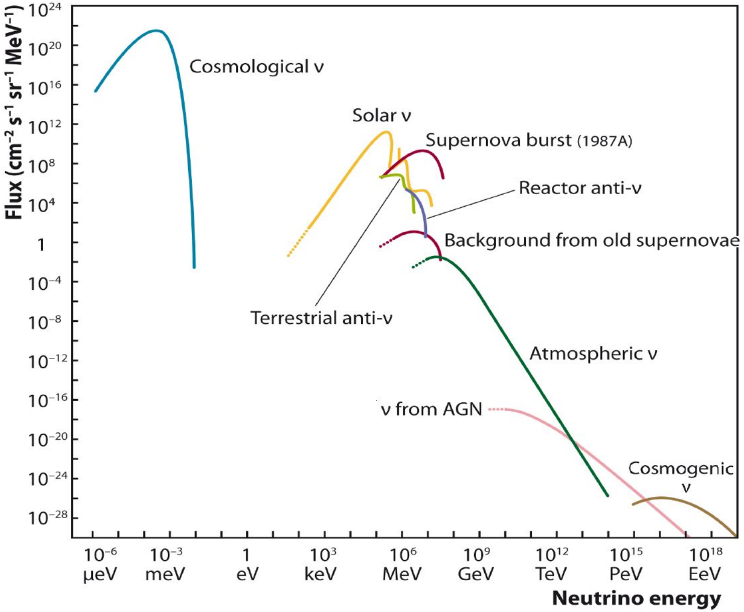
Chapter 3
What can we learn from supernova neutrinos?

Particle physics from core-collapse supernovae

- There's much to learn about neutrinos and particle physics from a supernova burst
  - Most intense burst of neutrinos in the Universe
  - You've already learned a lot about new physics and neutrinos (see lectures by Matheus Hostert)
  - Aim to give flavor here of the breadth of topics - and continuing influence of 24 neutrino events 40 years ago!

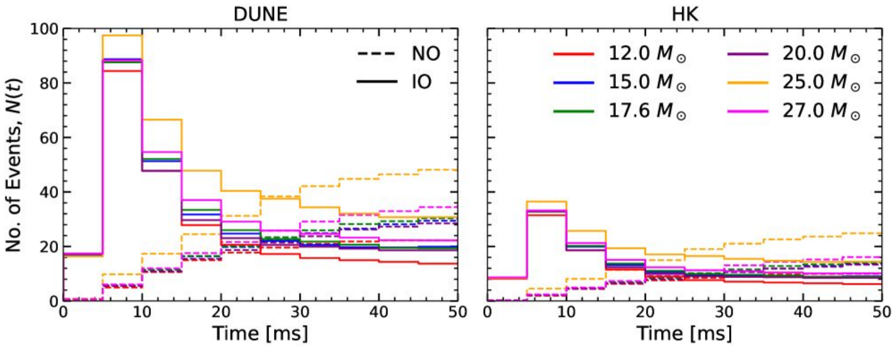
- There's also a lot of astrophysics

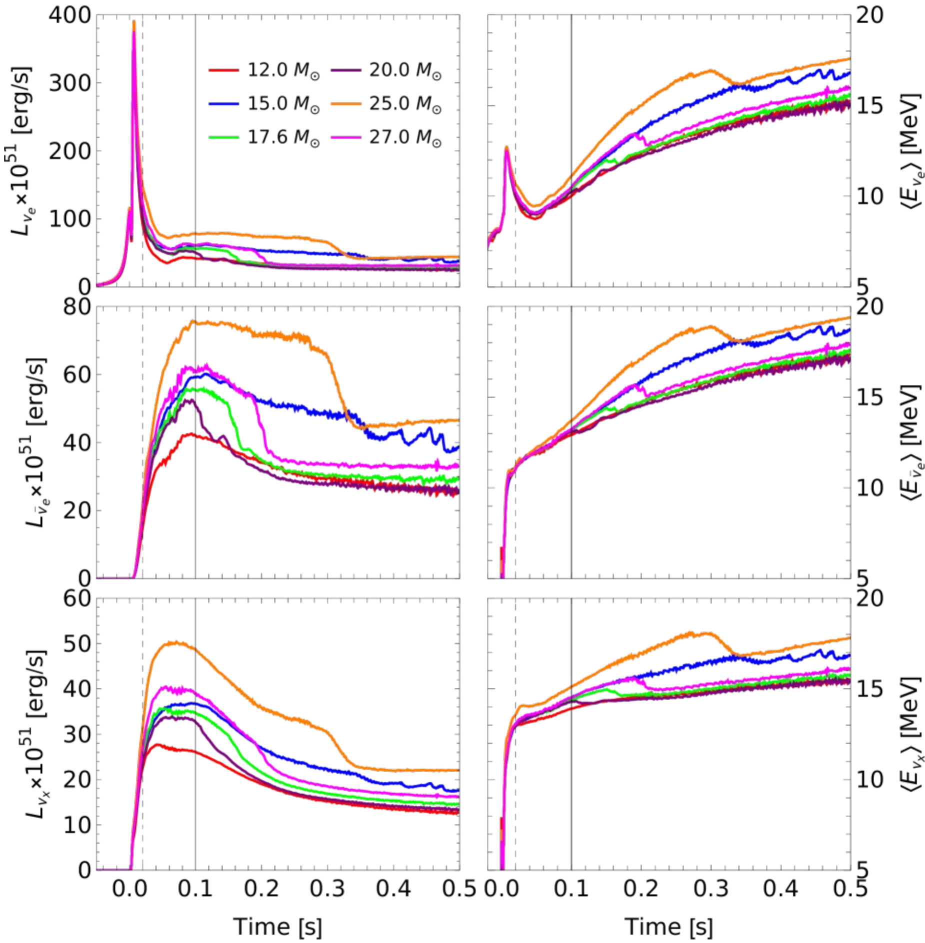
- Diffuse Supernova Neutrino Background (DSNB) - dependent on astrophysics of CCSN as well as particle properties



Neutrino mass ordering

- P Sarmah, S Chakraborty, A Medhi, D Bose, MM Devi, https://arxiv.org/abs/2606.06580
- Compares DUNE and HK
- Rise in luminosity of heavier neutrinos faster than anti-νe (general feature of CCSN simulation models, accretion phase)
- Neutronization burst: νe seen in IO, but oscillated away in NO scenario





But could new physics intervene?

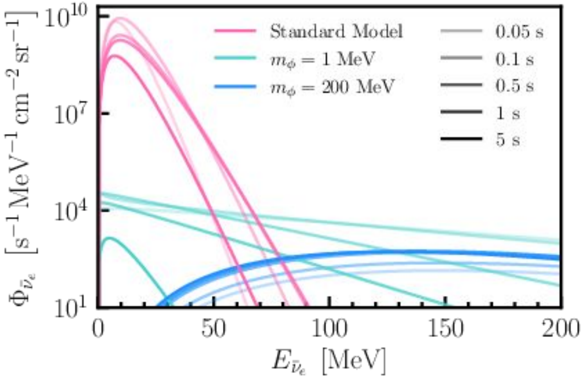
Neutrino properties

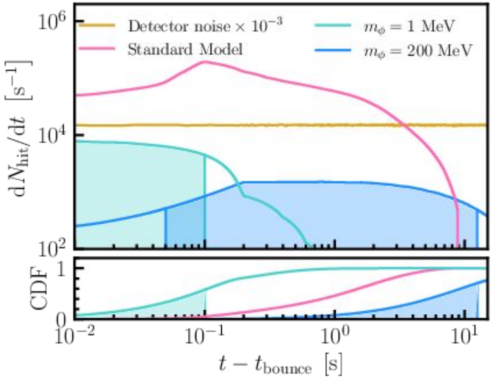
- Dirac vs Majorana? (D Delepine, A Yebra, arxiv:2602.05055)
    - Resonant spin-flavor precession of neutrinos during cooling phase, with small neutrino magnetic moment
    - Different signatures for Dirac and Majorana neutrinos
- Pseudo-Dirac neutrinos (M Sen, arxiv:2205.13291)
- Millicharge neutrino (PD Neto, AF Esmaeili, et al., arxiv:2604.26013)
    - Intervening magnetic field induces time-of-flight delay
    - Can reinterpret SN ToF limits on neutrino mass as charge constraint
    - SN1987A bound 10^{-17}e, future Galactic burst ~10^{-19}e
- CP violation (A Popov, A Studenikin, arxiv:2406.05171)
    - Strong magnetic field in CCSN can induce new resonances in neutrino oscillations for Majorana neutrinos with CP-violating phases
- Quantum entanglement (JD Martin, D Neill et al., PRD 108, 123010 (2023))
    - Hot and dense neutrino gas: coherent forward scattering of neutrinos
    - "Fast flavor" oscillations → change flavor composition at detection

Captured light DM

(from Lazar, Li, Arguelles, Brdar, arxiv:2403.09781)

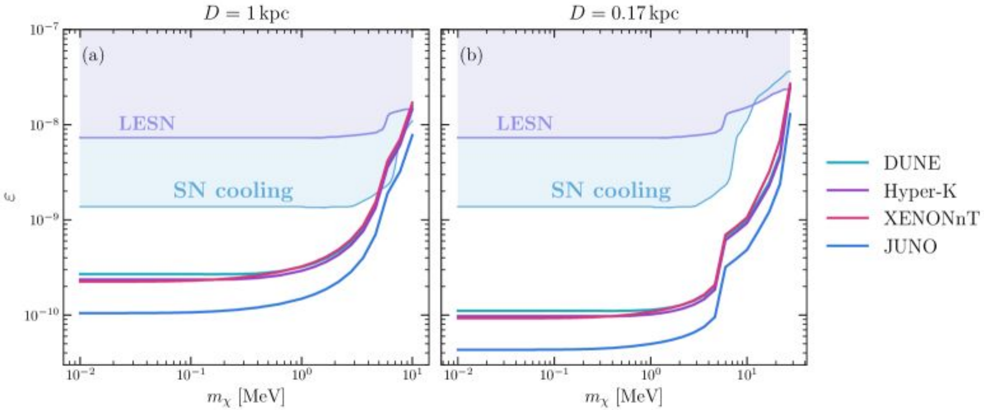
- Probe Beyond-Standard Model physics coupled to neutrinos
- Light X kept in star → modified burst duration, energy
- Small couplings: X streams more freely than ν, exit earlier with higher E
- ν→X implies X→ν: decay in flight





Non-neutrino millicharged particles

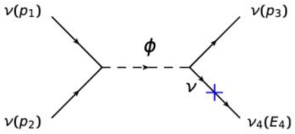
- mCP's could be produced in large numbers in CCSN
- Traditional limit based on flux during cooling phase, low-energy supernova (LESN) constraint also induces time-of-flight delay relative to SN neutrinos → search window
- mCP-induced electron recoil signals at XENONnT, JUNO, DUNE, HK
- For 10^{-9} charges and masses < MeV, observe more than 10 events in year following SN
- Bounds from mCP-followers could be stronger than cooling-based limit for close star

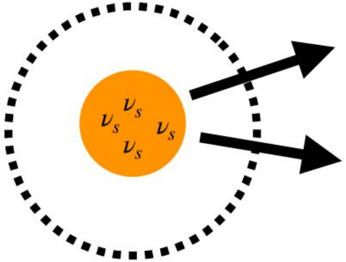


More dark matter

- Axion-like particles (AL Foguel, ES Fraga, arxiv:2604.103017; A Lella, P Carenza et al., PRD 107, 103017)
    - New light particles produced in cooling phase
- Dark matter halo heating using dark radiation from SN (S Vogl, XJ Xu, arxiv:2411.18052)
    - Dark photon, dark Higgs, gauged B-L and Lμ-Lτ models
    - SN1987A limits still allow significant effects on halo of dwarf spheroid galaxies
- Neutrino-Majoron couplings (P Iváñez-Ballesteros, MC Volpe, arxiv:2410.11517)
- Sterile neutrinos via magnetic moment (V Brdar, A de Gouvêa et al., arxiv:2302.10965)
- Sterile neutrino dark matter from self-interactions (Chen, Sen, Tucker et al., JCAP 2022)

Main lesson: lots of possibilities arise from intense supernova neutrino burst





Mostly from A Lella et al., PRD 107, 103017 (2023)

SN1987A limits

- Standard and non-standard neutrino properties
  - EW Kolb, MS Turner, PRD 36, 2895 (1987)
  - GG Raffelt, Mod Phys Lett A 05, 2581 (1990)
- QCD axions
  - MS Turner, PRL 60, 1797 (1988)
  - RP Brinkmann, MS Turner, PRD 38, 2338 (1988)
  - JH Chang, R ESsig, SD McDermott, JHEP 09, 051 (2018)
  - G Lucente, L Mastrototaro, P Carenza, L Di Luzio, M Giannotti, A Mirizzi, PRD 105, 123020 (2022)
- Axion-like particles
  - JH Chang et al (2018)
- Muonic bosons
  - A Caputo, G Raffelt, E Vitagliano, PRD 105, 035022 (2022)
- Light Z' with non-mixing polarizations: D Das, P Ghosh, R Puri, arxiv:2606.23769 (22 June 2026)

- Dark photons
  - W DeRocco, PW Graham, D Kasen, G Marques-Tavares, S Rajendran, JHEP 02, 171 (2019)
- Gravitons (large extra dimensions)
  - S Hannestad, G Raffelt, PRL 87, 051301 (2011)
- Unparticles
  - S Hannestad, G Raffelt, YYY Wong, PRD 76, 121701 (2007)
- Scalars mixed with Higgs bosons
  - S Balaji, PSB Dev, J Silk, Y Zhang, J Cosmol Astropart Phys 12, 024 (2022)
- Particles escaping in extra dimension (shorten duration of neutrino burst)
  - A Friedland, M Giannotti, PRL 100, 031602 (2008)
- Neutrino non-radiative decay
  - P Iváñez-Ballesteros, MC Volpe, https://arxiv.org/abs/2307.03549
- Muonic dark forces
  - CA Manzari, JM Camalich, J Spinner, R Ziegler, https://arxiv.org/abs/2307.03143

A burst from 40 years ago still overshadows new physics

SVP Fallon, J Halverson et al., arxiv:2606.14575

QCD axion in F-theory

- Strongly coupled limit of string theory
- Not going to pretend to understand the ins and outs
- Observes that regime “that arguably contains the vast majority of known F-theory topologies” have axion mass > 15 meV
- SN1987A neutrinos disfavor large regions of “moduli space”
    - Just take this as an example that SN1987A neutrinos still strong constraint on physics

Where does new physics appear with SN neutrinos?

SN envelope

ν's decouple

vacuum
propagation

~10km

νe scattering
MSW effects

"neutrinosphere"

Large ν density

Where does new physics appear with SN neutrinos?

SN envelope

ν's decouple

~10km

"neutrinosphere"

Captured DM

Large ν density

νν scattering
Collective effects
NSI

Quantum entanglement
Thermal light DM production

νe scattering
MSW effects

NSI

vacuum
propagation

ν→DM boost
ν→CνB
DM→CνB
DM→DSNB

"Any crazy stuff that theorists can think about" (M Sen, SNvD 2023@LNGS)

Summary

- There's a lot of physics to learn from ~10s of supernova neutrinos
- With ~ two dozen neutrino events from SN1987A, often still provide strongest constraint
  - People still writing papers looking back at that data, 40 years hence!
- Imagine what would happen if we could capture the next Galactic CCSN in all its messengers: neutrinos, gravitational waves, electromagnetic
- At the same time, we should also be bathed in all the neutrinos from all the CCSN in the observable universe
  - Physics should leave an imprint in this Diffuse Supernova Neutrino "Background" (DSNB)

Tomorrow

- DSNB
- Detecting supernova neutrinos
- The next Galactic CCSN