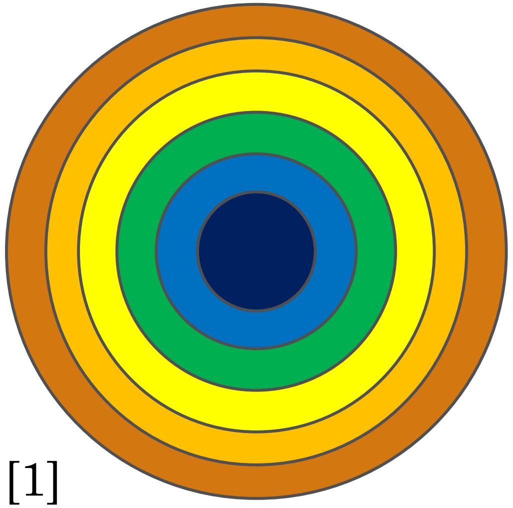
Impact of late time neutrino emission on the DSNB

(Ekanger et al., in prep)

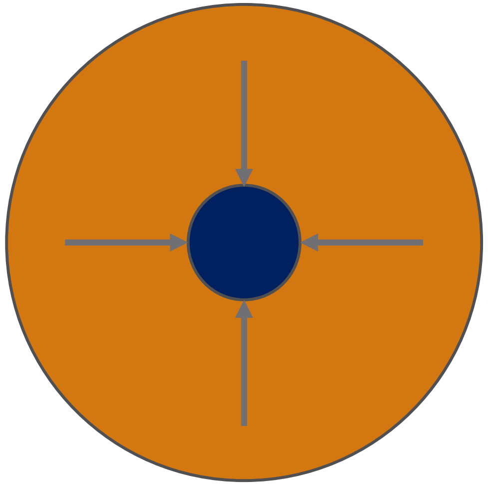
Nick Ekanger

Core Collapse Supernovae (CCSNe)



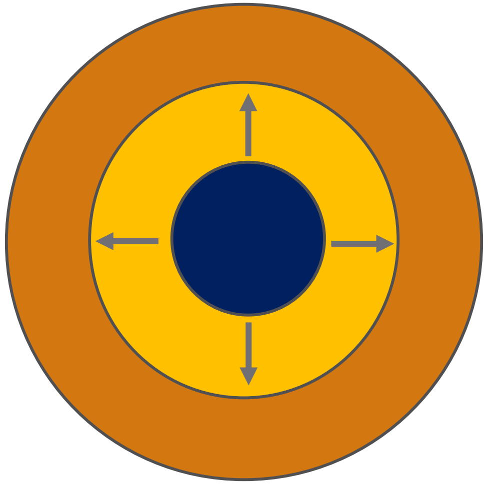
[1]

8 $M_\odot$, Iron fused in core of progenitor, radiation pressure decreases

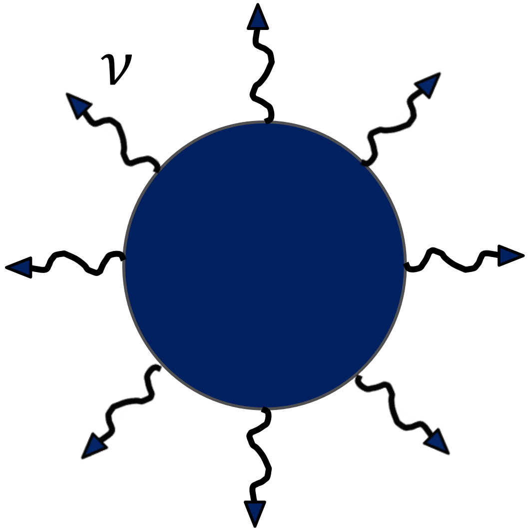


~1.4 $M_\odot$ core collapses, $e^- + p \rightarrow n + \nu_e$, neutron degeneracy

Infalling material bounces off core, pressure shock wave

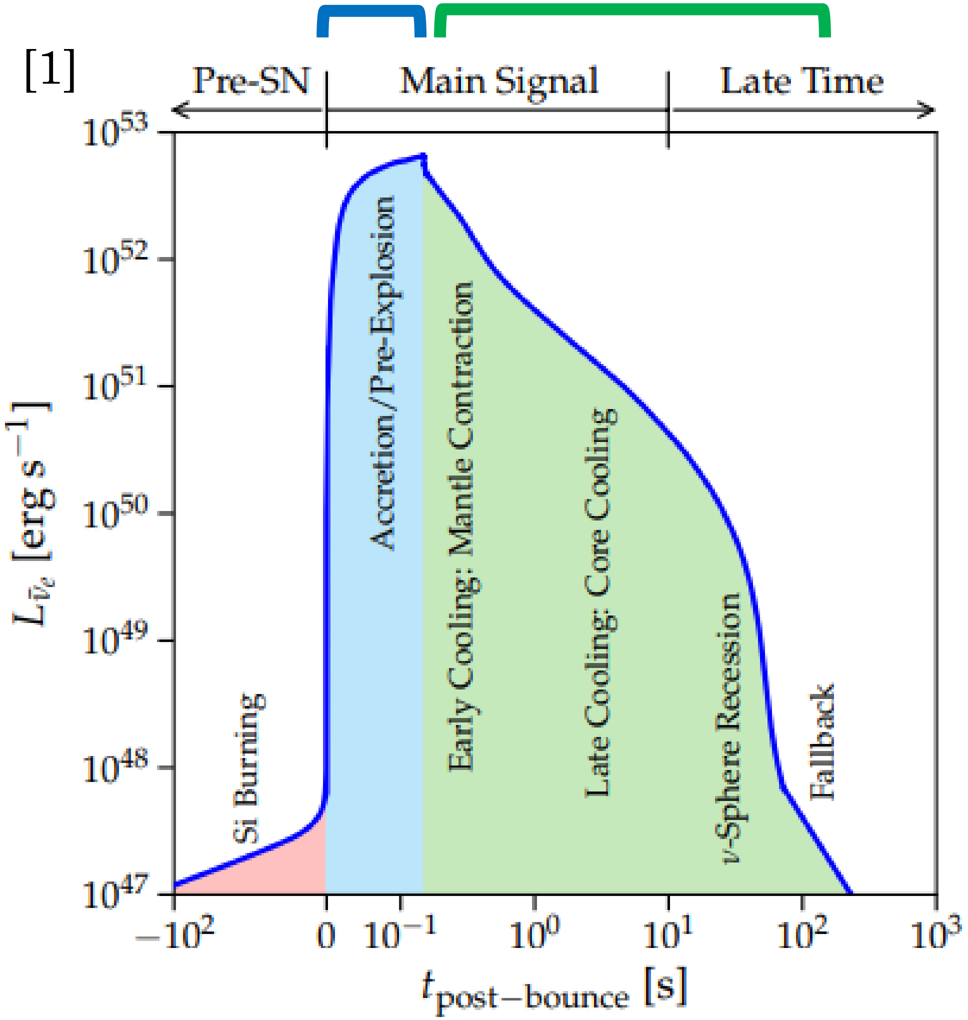


Neutrinos revive shock, cooling protoneutron star



[1] Burrows et al. (2021)

Neutrinos from CCSNe

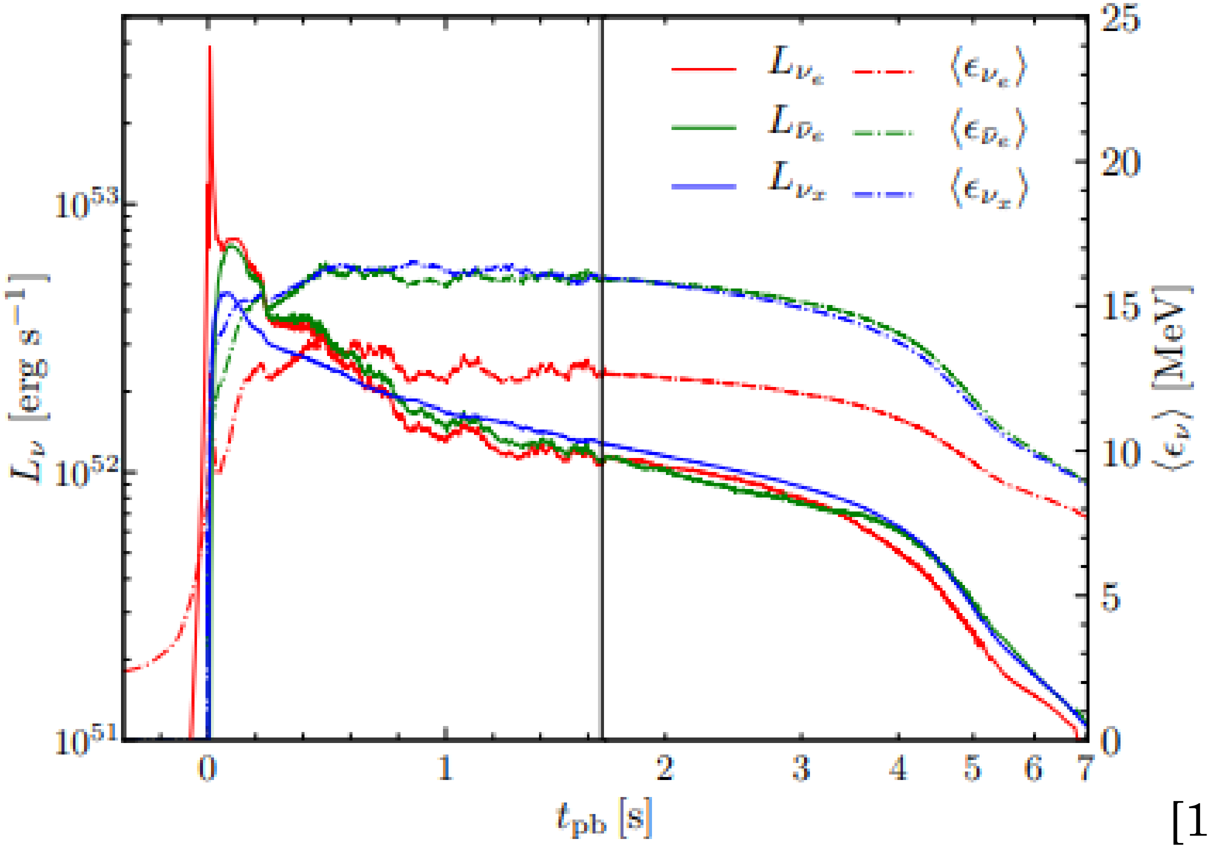


- Early signal:
  - High luminosity, high mean energy from accretion
  - Simulations typically focus on this
- Late signal:
  - After shock revival, PNS cools
  - Luminosity and mean energy decrease
- SN1987A only case of SN neutrinos

[1] Li et al. (2021)

Neutrinos from Simulation

- Estimate neutrino emission from simulations:
  - Robust, dynamic mass accretion phase
  - Few with long term cooling components



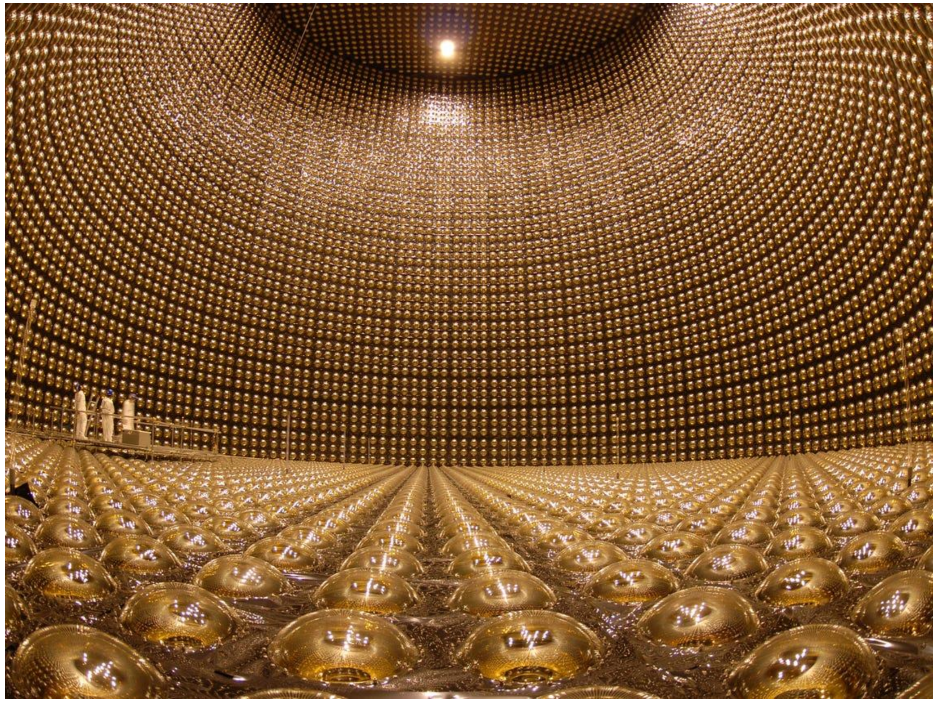
[1]

[1] Bollig et al. (2021)

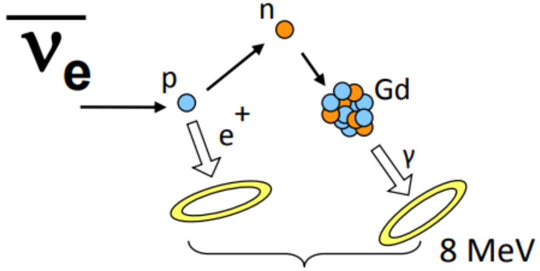
Diffuse Supernova Neutrino Background (DSNB)

- Sum distribution of CCSNe over cosmological history
  - Individual CCSNe events cannot be detected
- Detectable at SK through IBD
  - $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Gadolinium upgrade (SK-Gd)

[1]



[2]



ΔT~30μs
Vertices within 50cm

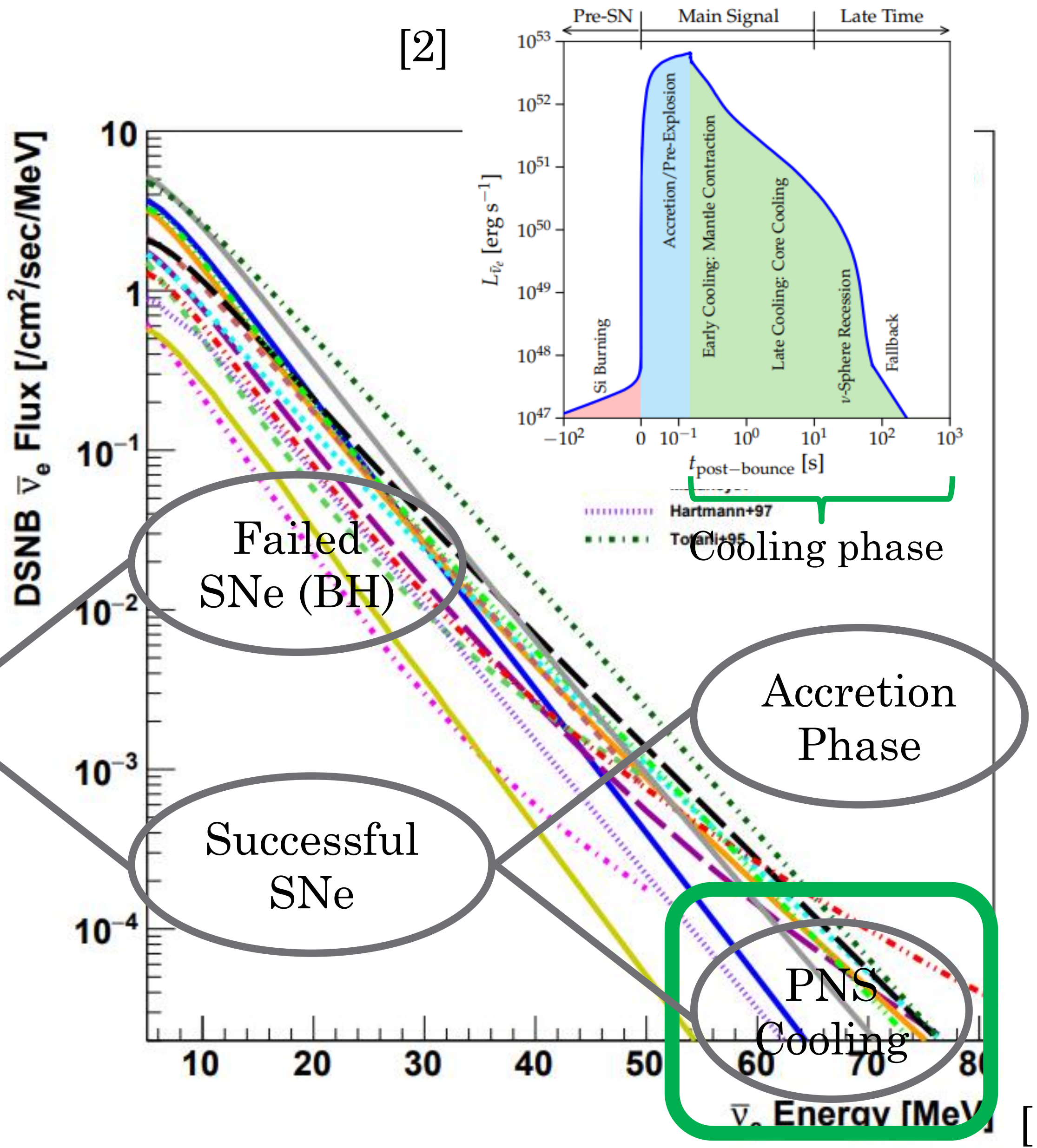
[1] https://www.businessinsider.com/super-kamiokande-neutrino-detector-is-unbelievably-beautiful-2018-6
[2] https://www.mpi-hd.mpg.de/WIN2015/talks/neutrino2_ikeda.pdf

DSNB Uncertainty

- DSNB uncertainty
  - CC Rate (from SFR)
  - Neutrino emission
    - Failed SNe (BH)
    - Successful SNe
      - Accretion Phase
      - PNS Cooling

$$\boxed{\frac{d\phi}{dE}} = c\int \boxed{R_{CC}(z)}\,\boxed{\frac{dN}{dE'}}(1+z)\left|\frac{dt}{dz}\right|dz$$

[2]

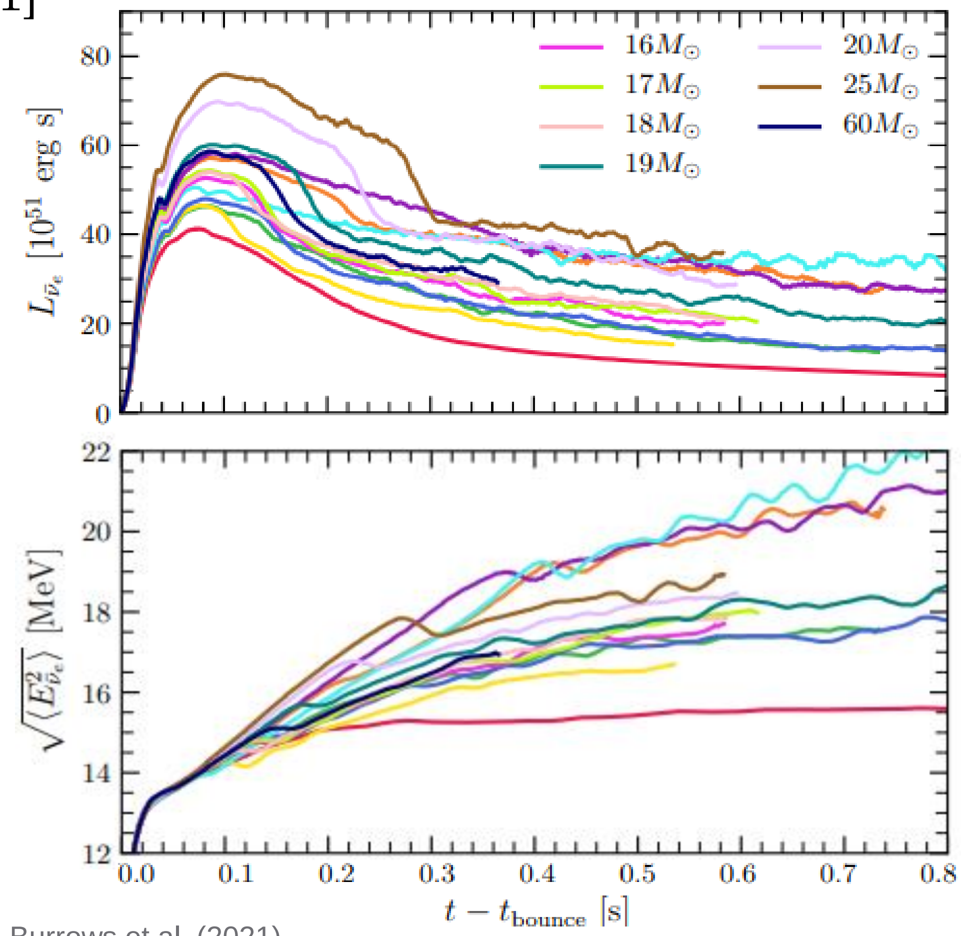


[1]

[1] Abe et al. (2021)
[2] Li et al. (2021)

First, Set the Stage

[1]



- Our Model
  - 3D simulations give neutrino emission for accretion phase
  - Assume standard SFR [2]
  - Neutrino emission from BH
    - Choose conservative BH fraction: (M > 40 $M_\odot$, ~10%)
    - Signal from two 40 $M_\odot$ [3] simulations
  - Need cooling phase neutrino emission

[1] Burrows et al. (2021)
[2] Yuksel et al. (2008), Horiuchi et al. (2011)
[3] Hudepohl (2014)

Estimate Cooling Phase 5 Ways

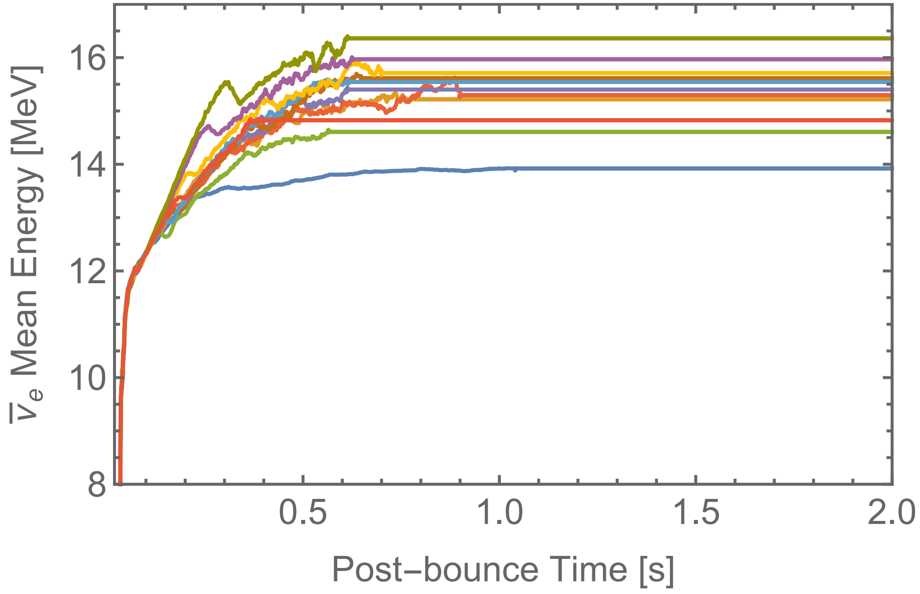
- Need mean energy and energy liberated by neutrinos
  - $\gtrsim$50% of energy liberation occurs in cooling phase!
- Without many long-term multi-dimensional simulations, we estimate the cooling phase by:

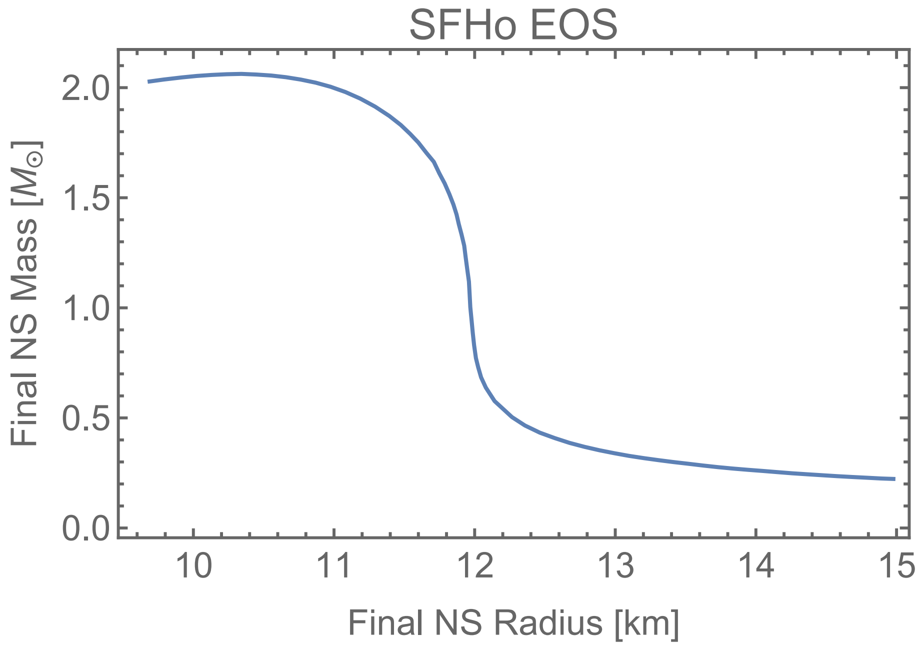
1. Constant mean energy
2. Analytical solution
3. Correlation method
4. Renormalized correlation methods
   - Shen EOS
   - LS220 EOS

Constant Mean Energy

(‘Const’)

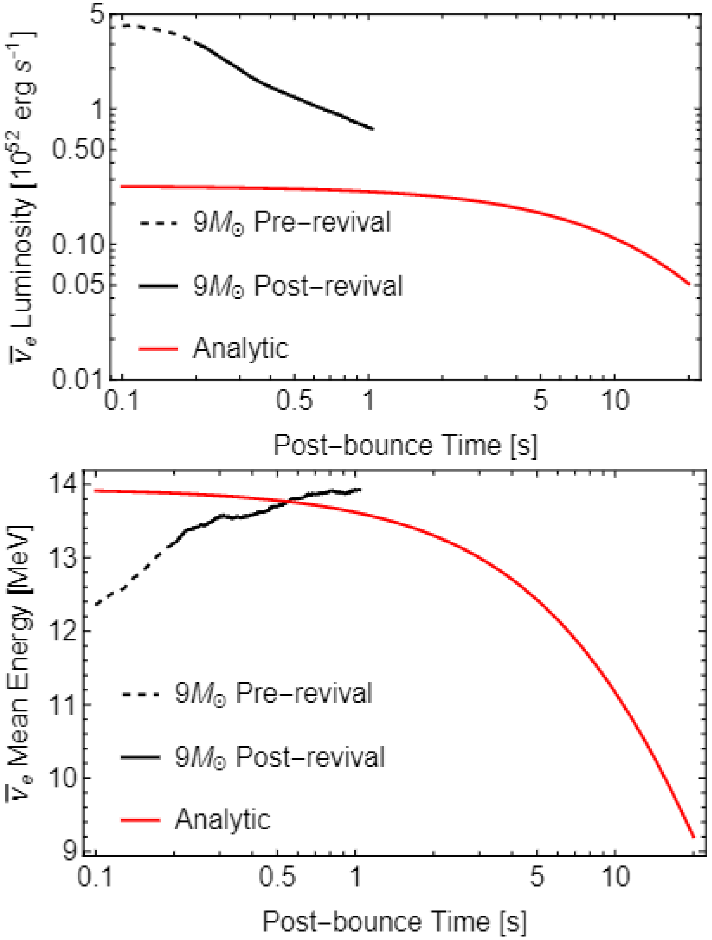
- Mean energy:
  - Assume it retains value at end of simulation
  - Expected to reduce as PNS cools, so represents upper limit
- Liberated energy:
  - Assume ~energy liberated = gravitational binding energy
  - Determined from PNS mass/radius and SFHo EOS





Analytic Solution

('Analyt')



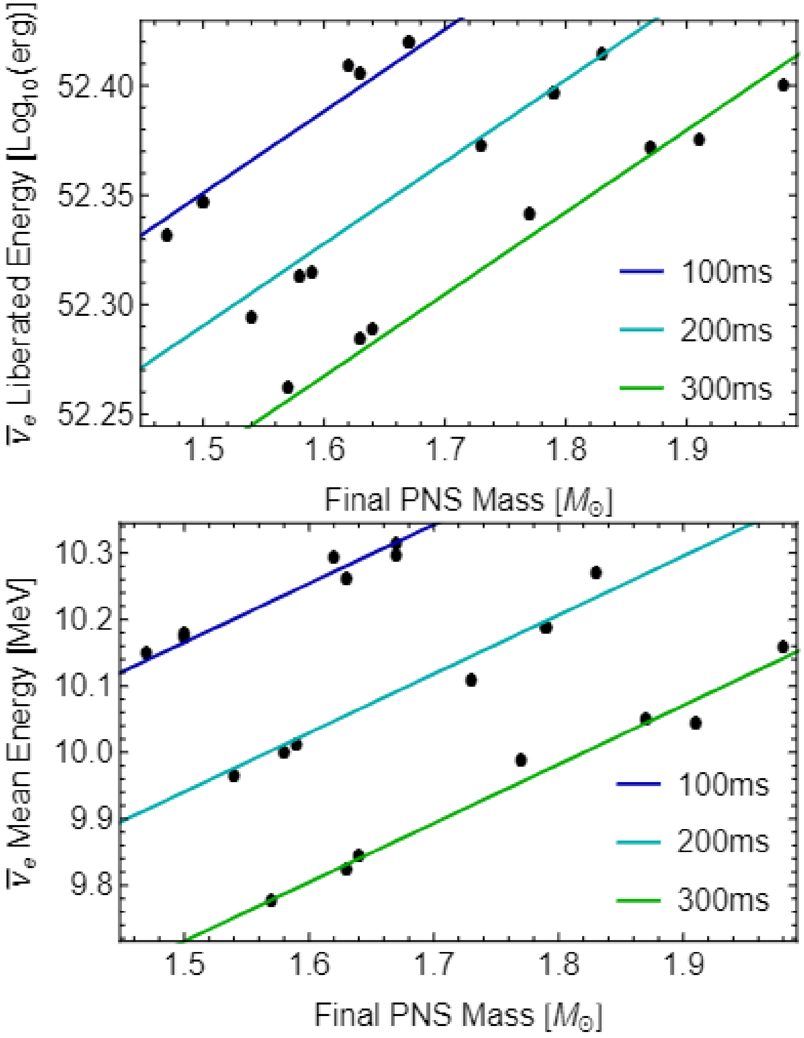
- Analytic function to estimate [1] neutrino luminosity and mean energy
  - PNS info: mass, radius, total energy liberated
  - + correction factors for density (g) and scattering off heavy nuclei (β)
- g, β adjusted to best fit mean energy
- Mean energy ~ reasonable, but luminosity fit is poor
  - Despite this, integrating luminosity ~ grav binding energy

[1] Suwa et al. (2021)

Final Mass-Revival Time Correlation

('Corr')

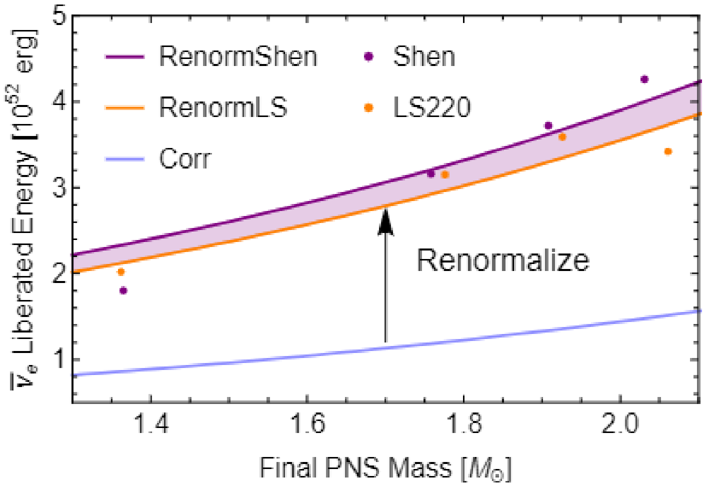
- Found linear correlation with 1D cooling phase sims [1]
  - 'Supernova Neutrino Database'
  - Both mean energy and log of liberated energy
- Greater final mass → greater neutrino emission
- Earlier revival time → greater neutrino emission

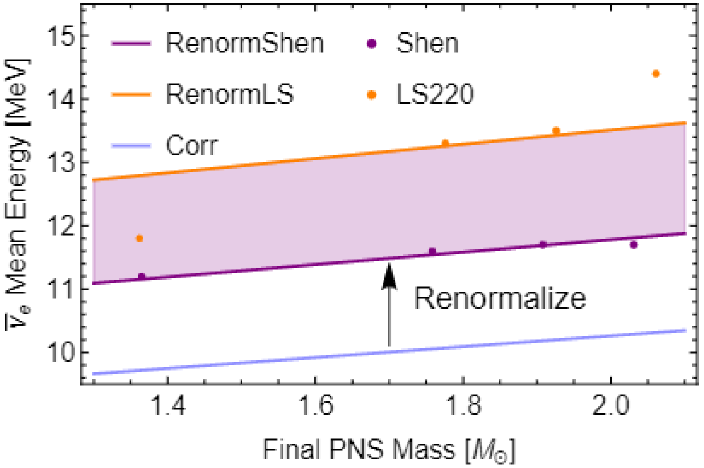


[1] Nakazato et al. (2013)

Renormalized Correlations

('RenormShen/LS')





- Neutrino emission from 'Corr' method systematically lower than others
- Renormalize correlations to another simulation suite [1]
  - Re-fit through data well
  - Depends on EOS:
    - Mean energy differences are large

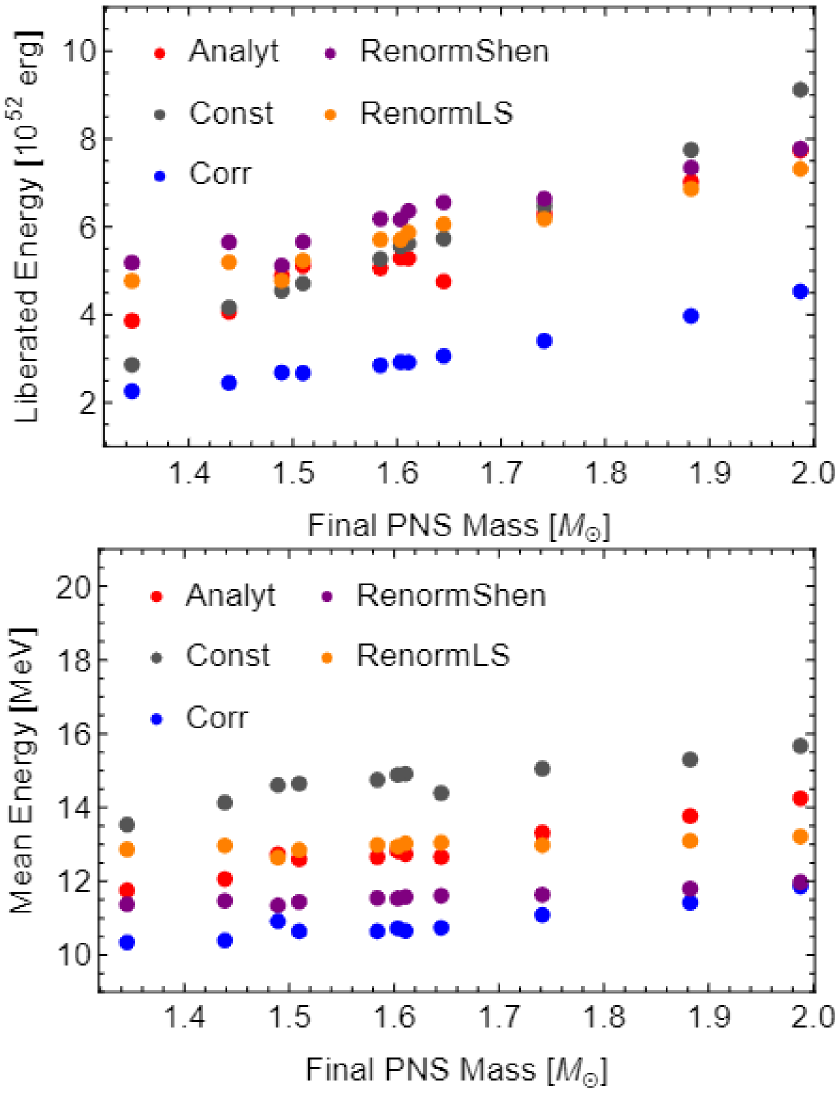
[1] Hudepohl (2014)

Results

- ‘Corr’ / ‘Const’ are lower / upper estimates
- Liberated energies similar
  - Mean energies drive differences in event rates
- Factor of ~3 difference in event rates (R_ν) and flux (ϕ)

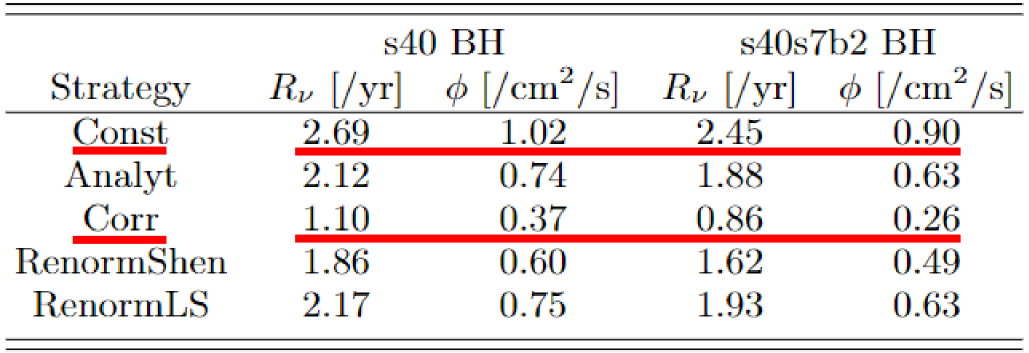
	s40 BH		s40s7b2 BH	
Strategy	R_ν [/yr]	ϕ [/cm^2/s]	R_ν [/yr]	ϕ [/cm^2/s]
Const	2.69	1.02	2.45	0.90
Analyt	2.12	0.74	1.88	0.63
Corr	1.10	0.37	0.86	0.26
RenormShen	1.86	0.60	1.62	0.49
RenormLS	2.17	0.75	1.93	0.63

Total $\bar{\nu}_e$ energies: early hydro data + late cooling estimations (~0-20s post-bounce)



Conclusion

- Factor of ~3 difference in predicted DSNB rates at SK-Gd
  - Under current SK flux limits [1]
  - Comes primarily from uncertainty in cooling phase mean energy



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- In absence of many long-term, multidimensional simulations
  - Among 5 methods, recommend ‘RenormLS’
  - Recommend ‘Analyt’ if more simulation data is available

[1] Abe et al. (2021)

Thank you!