



Analytic Model for Supernova Neutrinos

TOMMY LAM

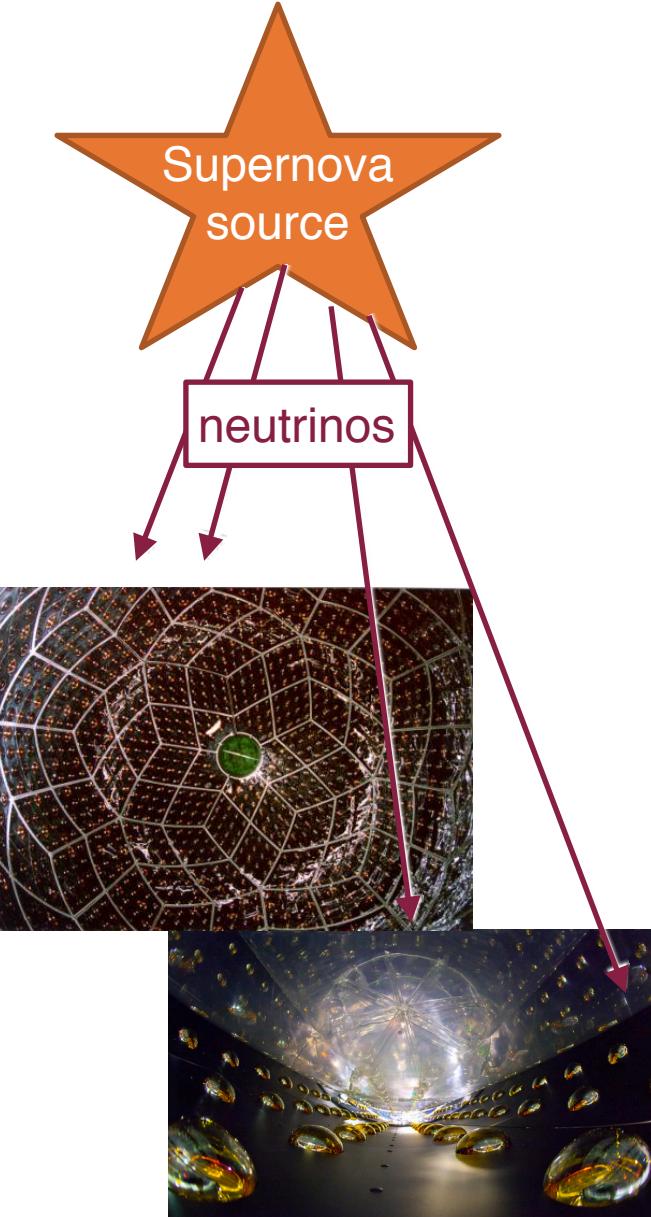
Outline

- Introduction
- Müller's Simple Model
- Modified Simple Model
- Conclusion

Introduction

Introduction

- Goal: Given a terrestrial supernova neutrino detection, determine the source's properties
- Developing a fast method that would parse through a set of progenitors and predict a signal
- Comparing predicted signals and terrestrial supernova detections would narrow down the set of candidates



Introduction

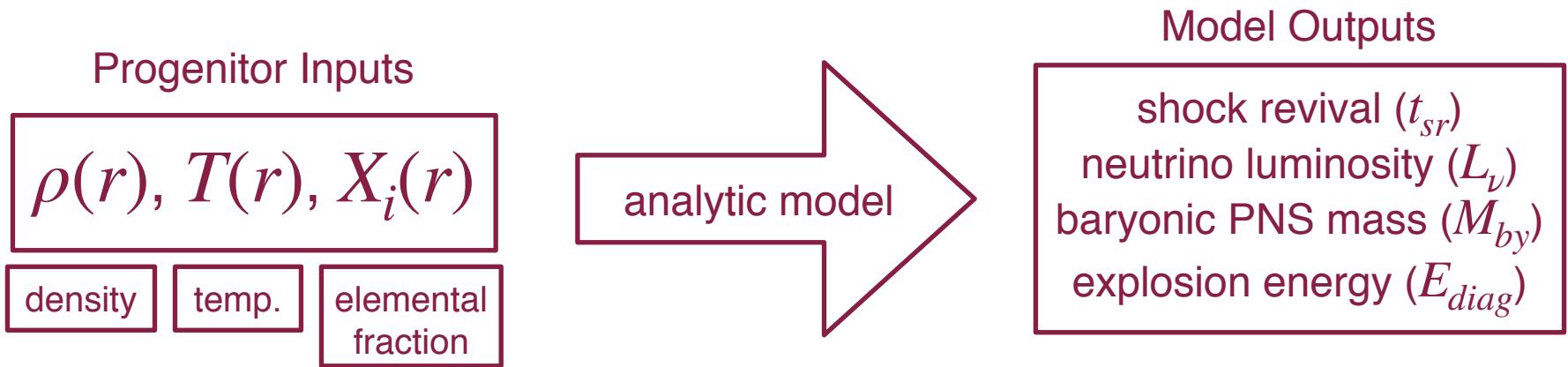
- Informed by a variety of simulations, an analytic model can be developed to emulate the supernovae properties for a given progenitor
- Having an analytic model to quickly determine this would be valuable for a variety of neutrino and dark matter experiments

Introduction

- B. Müller et al. (2016) developed a simple analytic model with the interest of describing the landscape of explosion energies and neutron star/black hole masses
- Though there is some neutrino emission information, there is an opportunity to improve on the model

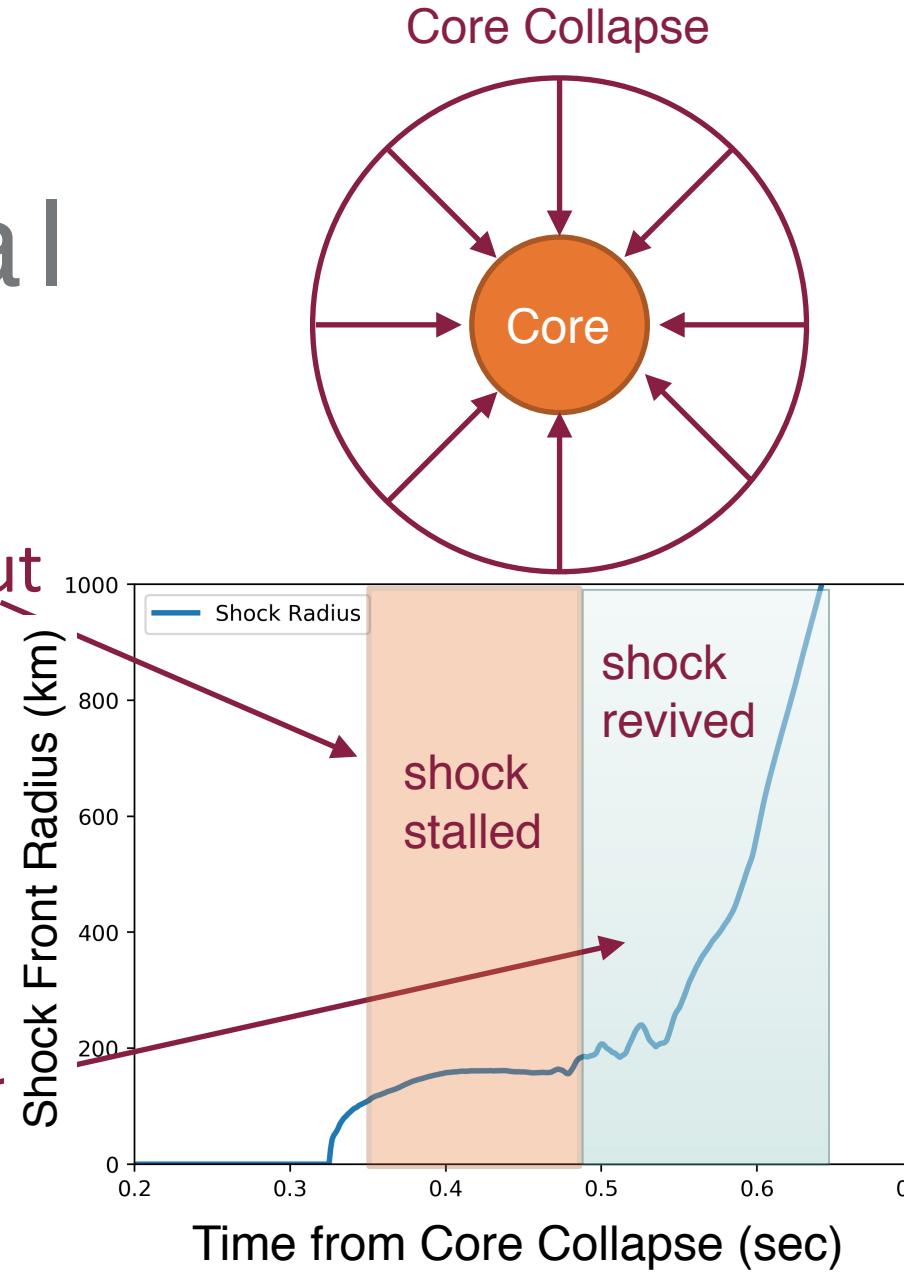
Müller's Simple Model

Müller's Simple Model



Shock Revival

- In the early stage of a supernova, the initial core-collapse starts the explosion but stalls
- The proto-neutron star (PNS) forms and contributes to the explosion through ν emission
- The moment where the stalled shock is revived is the shock revival time (t_{sr})



G. Raffelt (1996).

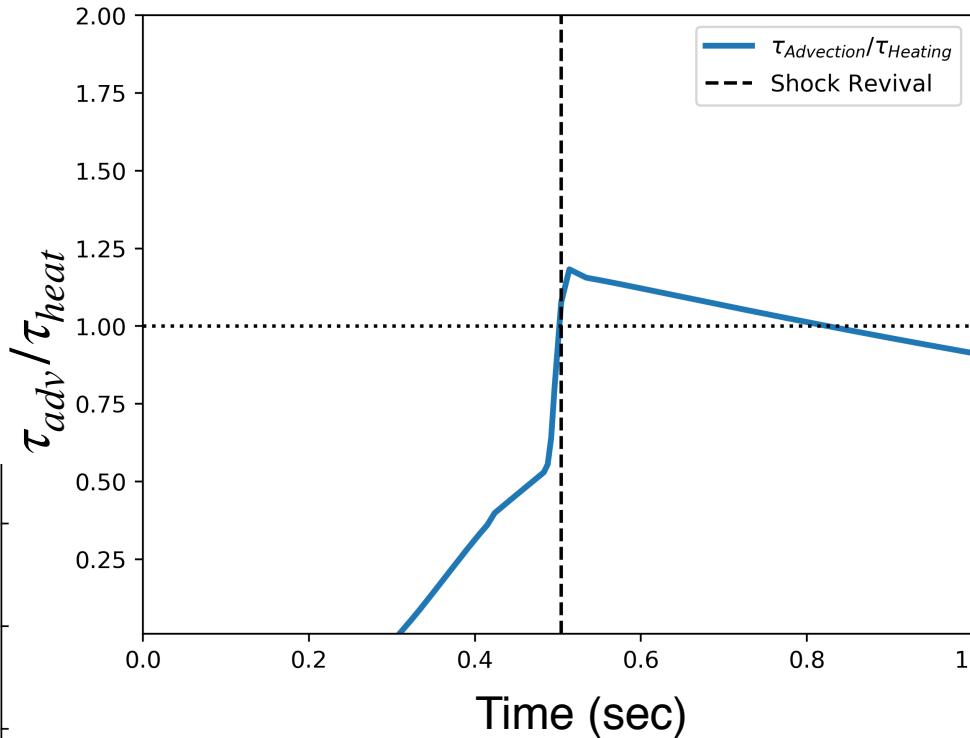
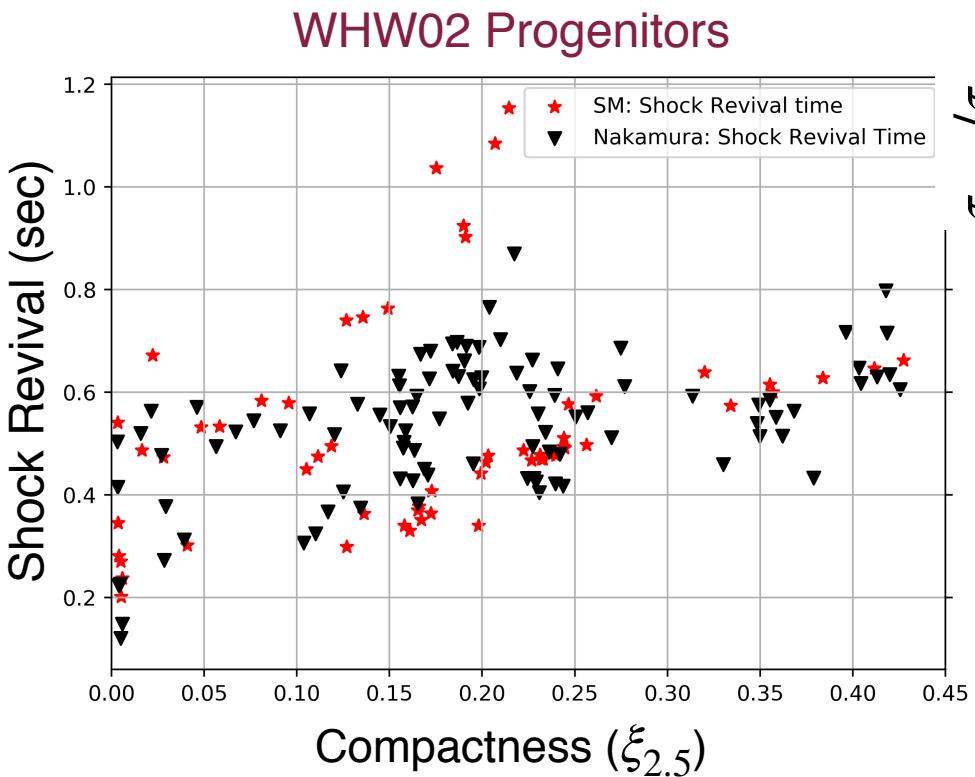
B. Muller et al. (2016). K. Kotake et al. (2018).

Shock Revival

- t_{sr} is determined by comparing advection time-scales (τ_{adv}) vs. neutrino heating time-scales (τ_{heat})
- τ_{adv} = time-scale where accreted matter is exposed to neutrino heating in gain region
- τ_{heat} = time required to inject enough energy in gain region to make it unbound

Shock Revival

WH07 s20 Progenitor



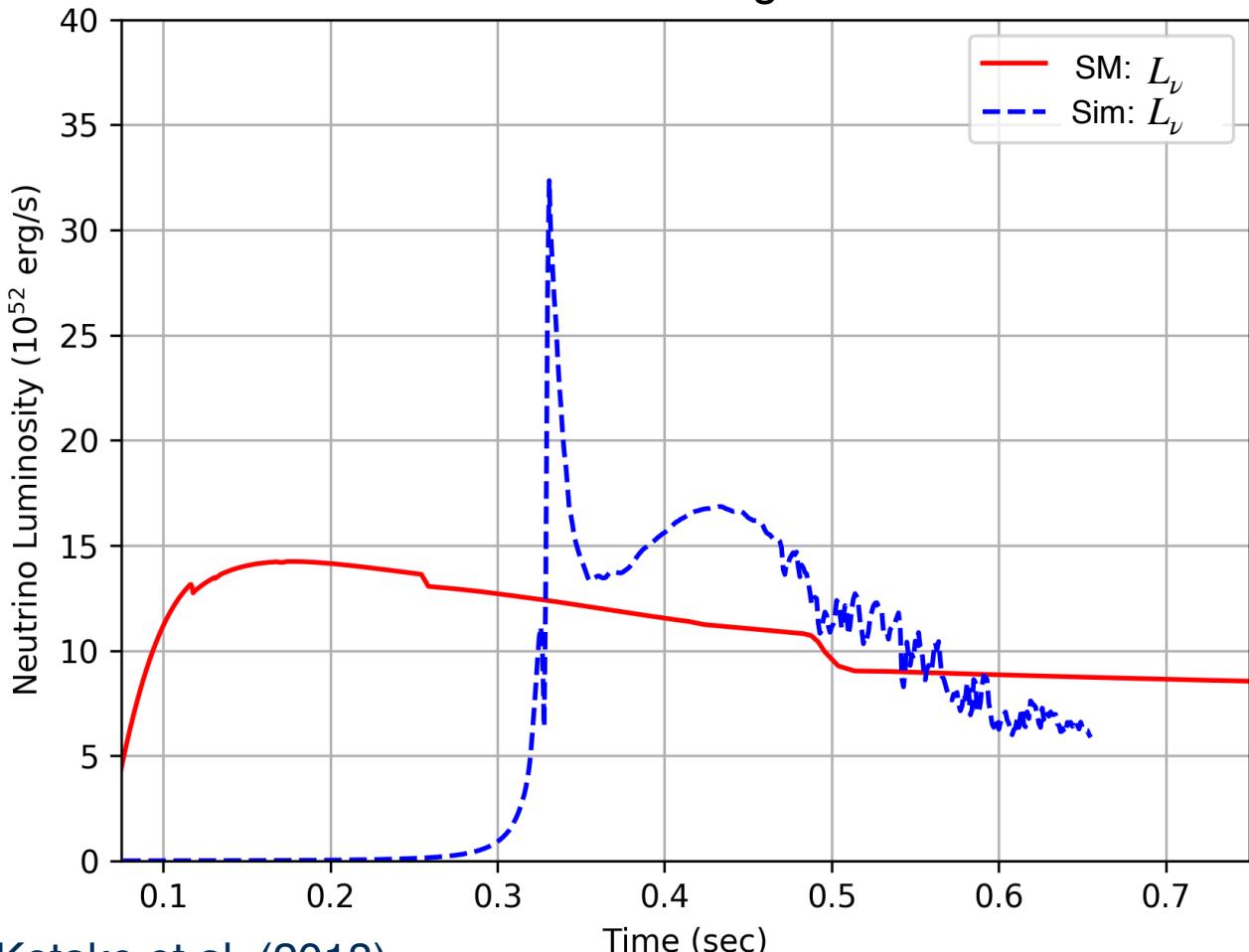
Neutrino Luminosity (L_ν)

- Neutrino Luminosity: Total radiated power from both electron and anti-electron neutrinos
- Contributions
 - Energy from accreted matter in the gain region converting to luminosity
 - Energy emitting from the PNS cooling down

$$L_\nu = \alpha \left(L_{acc} + L_{diff} \right), \alpha = \sqrt{1 - \frac{2GM}{r_{PNS}}}$$

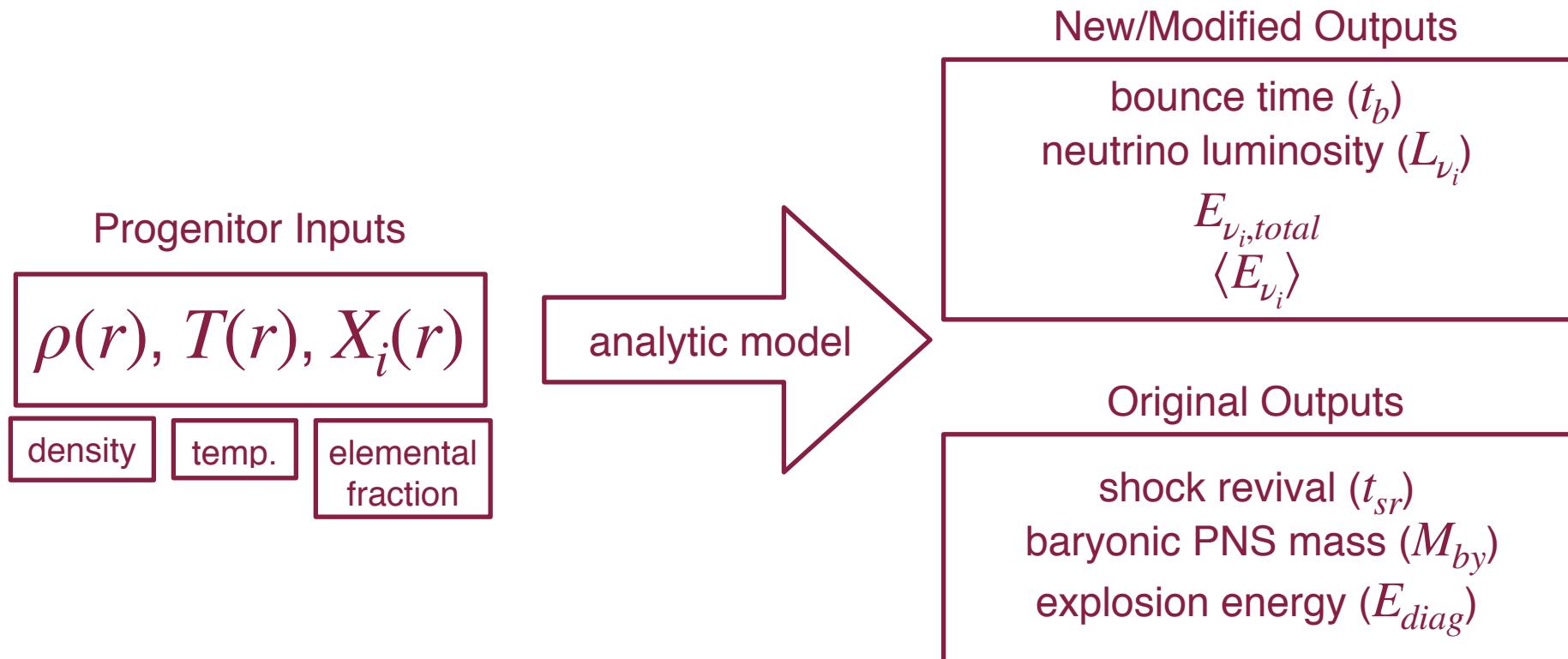
Neutrino Luminosity

WH07 s20 Progenitor



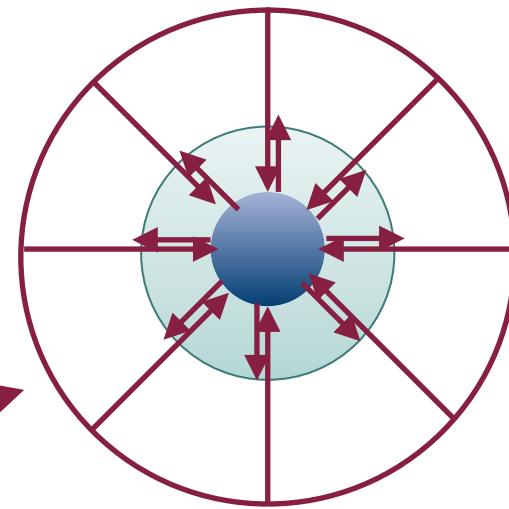
Modified Simple Model

Modified Simple Model

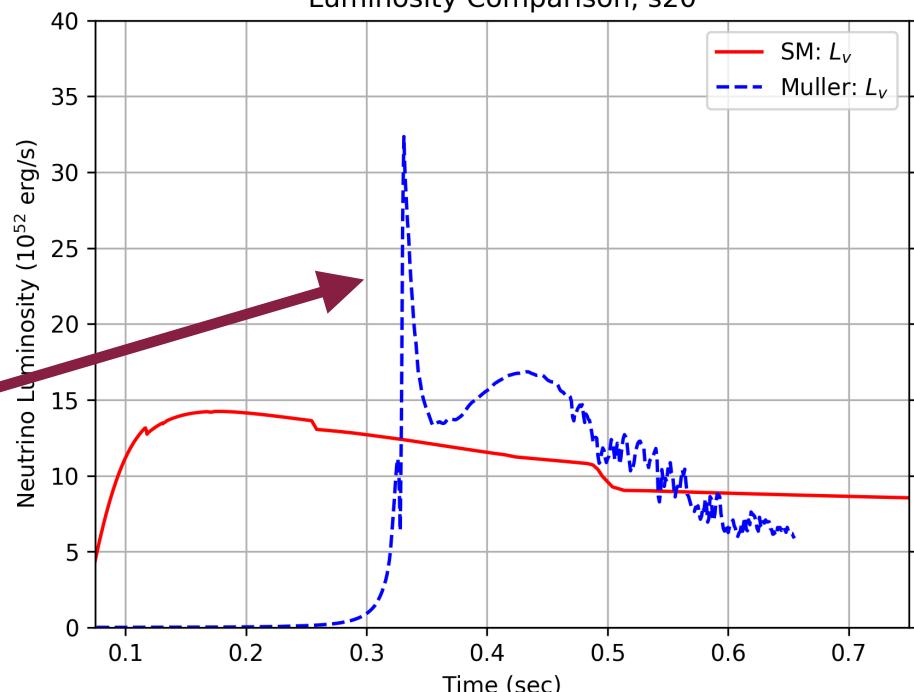


Bounce Time

- In the developing PNS star, the instant it reaches critical density and the accreted matter “bounces” off the PNS is the bounce time (t_b)
- Also the time where the neutronization burst occurs (contributes to the electron neutrino luminosity)



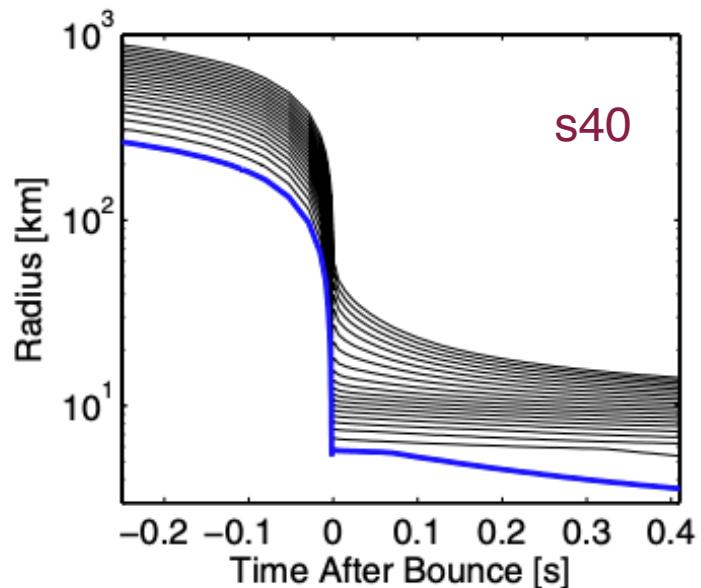
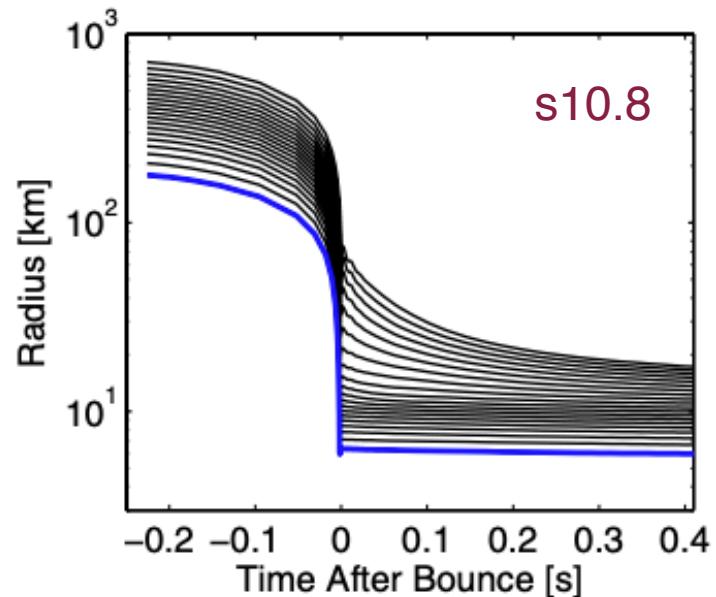
Luminosity Comparison, s20



03 / Modified Simple Model

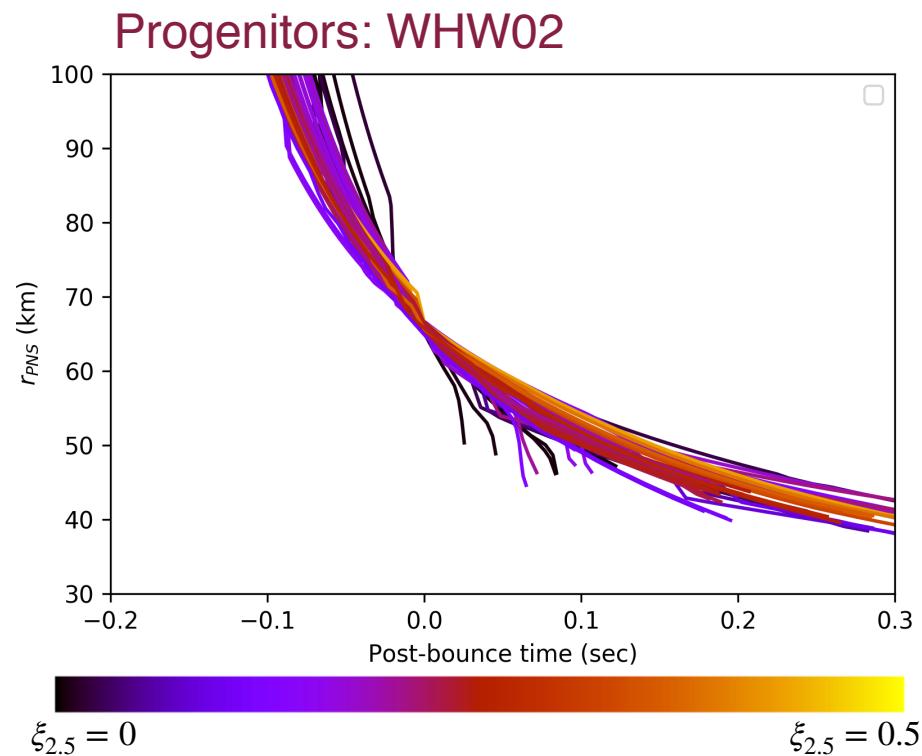
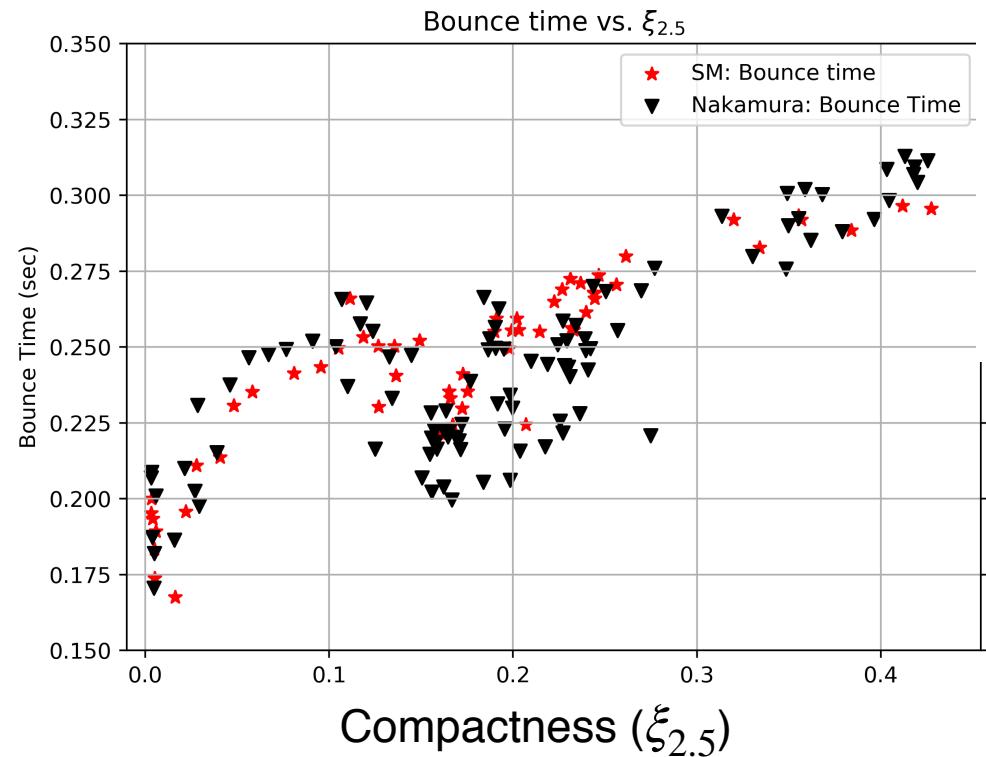
Bounce Time

- T. Fischer et al.'s simulations have shown a strong correlation between the PNS radius and the bounce time through the E.o.S
- Using the simple model's prediction for the PNS radius, we can use it to determine t_b



Bounce Time

WHW02 Progenitors



Neutrino Luminosity

- Using Müller's simple model

- $L_{\nu_e} = \alpha(L_{acc} + L_{diff})/2 + \text{neutronization burst}$

- $L_{\bar{\nu}_e} = \alpha(L_{acc} + L_{diff})/2$

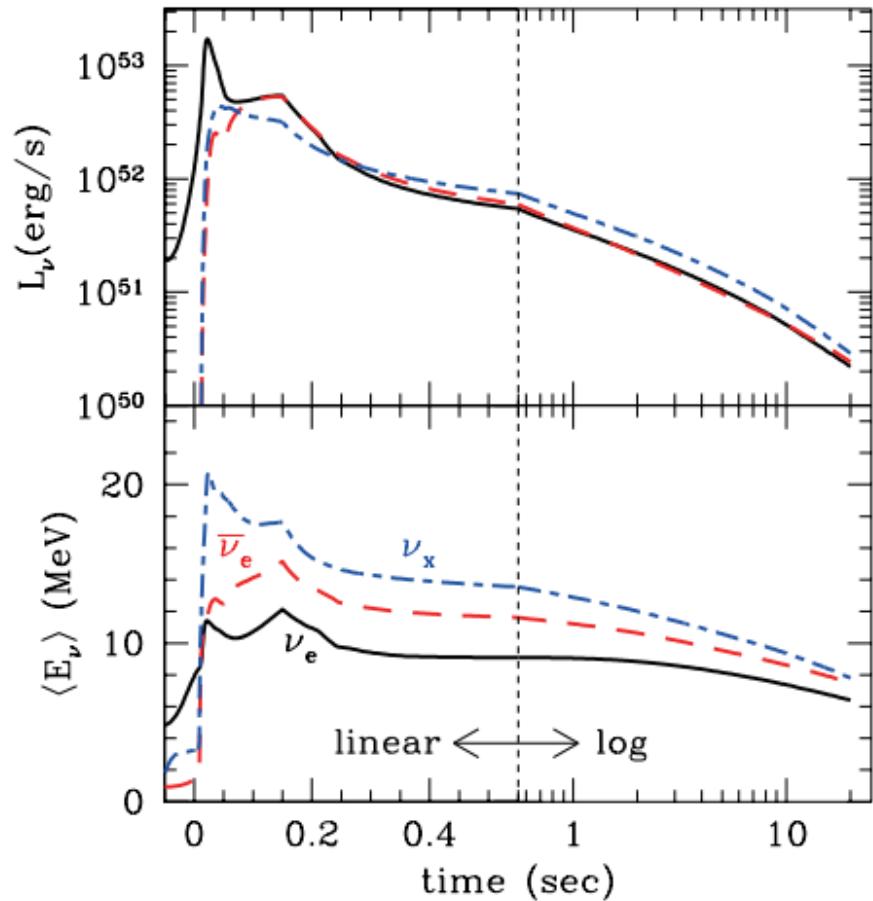
- $L_{\nu_x} = \alpha(L_{diff})/2$

- Neutronization Burst

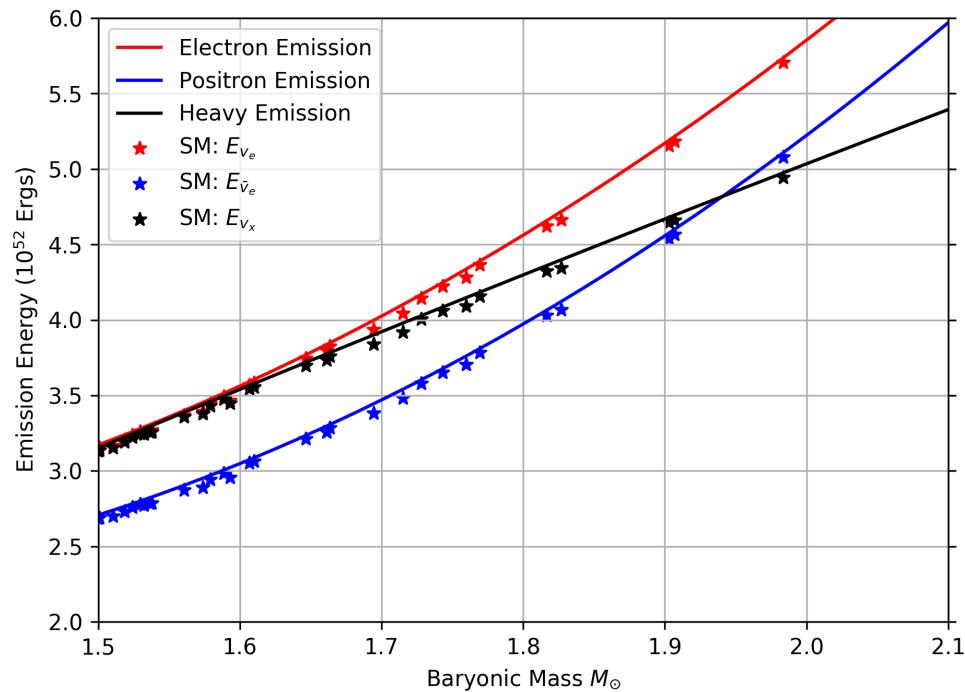
- Modeled with a Gaussian occurring at the bounce time

Neutrino Luminosity

- For late-time luminosity, we follow a power law similar to Nakazato's simulations
- $L_\nu(t > t_{sr}) \propto \frac{1}{(1 - \Delta t/\tau)^{.8}}$



Neutrino Luminosity



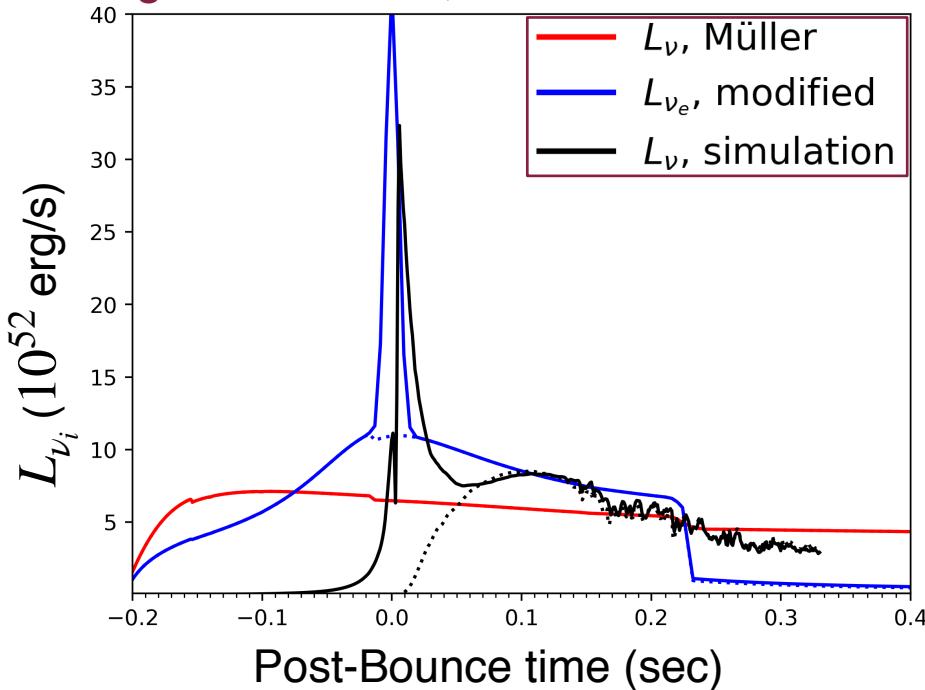
Z (M_\odot)	M_{init} (M_\odot)	t_{revive} (ms)	$M_{b,\text{NS}}$ (M_\odot)	$E_{\nu_e,\text{tot}}$ (10^{52} erg)	$E_{\bar{\nu}_e,\text{tot}}$ (10^{52} erg)	$E_{\nu_x,\text{tot}}$ (10^{52} erg)
0.02	13	100	1.50	3.15	2.68	3.19
		200	1.59	3.51	3.04	3.45
		300	1.64	3.83	3.33	3.59
	20	100	1.47	3.03	2.56	3.06
		200	1.54	3.30	2.82	3.27
		300	1.57	3.49	3.00	3.35
	30	100	1.62	3.77	3.23	3.72
		200	1.83	4.80	4.24	4.51
		300	1.98	5.76	5.16	4.99
	50	100	1.67	3.76	3.24	3.85
		200	1.79	4.39	3.85	4.28
		300	1.87	4.95	4.38	4.51
0.004	13	100	1.50	3.15	2.68	3.18
		200	1.58	3.51	3.03	3.45
		300	1.63	3.75	3.26	3.57
	20	100	1.63	3.68	3.12	3.72
		200	1.73	4.11	3.55	4.04
		300	1.77	4.43	3.84	4.20
	30	—	—	9.49	8.10	4.00
		100	1.67	3.83	3.19	3.81
		200	1.79	4.54	3.89	4.30
		300	1.91	5.20	4.51	4.61

Table 1

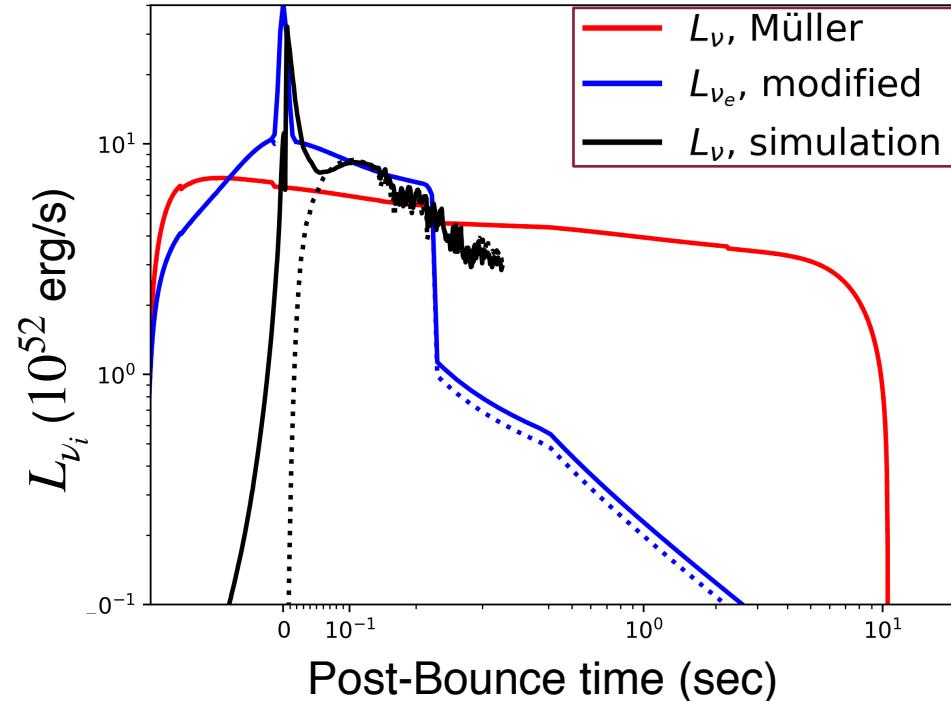
Neutrino Luminosity

- solid = ν_e
- dotted = $\bar{\nu}_e$

Progenitor: WH07, s20.0



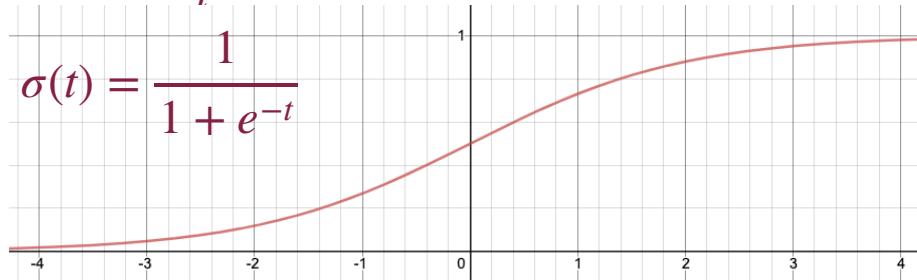
Progenitor: WH07, s20.0





Average Neutrino Energy

- From Nakazato's simulations, there seems to be a strong correlation between $\langle E_{\nu_i} \rangle$ and M_{by}
- For simplicity, define $\langle E_{\nu_i} \rangle \propto \sigma(\Delta t) = \text{sigmoid}$



Z	M_{init} (M_{\odot})	t_{revive} (ms)	$M_{b,\text{NS}}$ (M_{\odot})	$\langle E_{\nu_e} \rangle$ (MeV)	$\langle E_{\bar{\nu}_e} \rangle$ (MeV)	$\langle E_{\nu_x} \rangle$ (MeV)
0.02	13	100	1.50	9.08	10.8	11.9
		200	1.59	9.49	11.3	12.0
		300	1.64	9.91	11.7	12.1
	20	100	1.47	9.00	10.7	11.8
		200	1.54	9.32	11.1	11.9
		300	1.57	9.57	11.4	12.0
	30	100	1.62	9.32	11.1	12.1
		200	1.83	10.2	12.1	12.5
		300	1.98	11.1	13.0	12.8
	50	100	1.67	9.35	11.0	12.1
		200	1.79	9.98	11.7	12.3
		300	1.87	10.6	12.4	12.4
0.004	13	100	1.50	9.07	10.8	11.9
		200	1.58	9.47	11.3	12.0
		300	1.63	9.76	11.6	12.1
	20	100	1.63	9.28	11.0	12.0
		200	1.73	9.71	11.4	12.2
		300	1.77	10.1	11.9	12.3
	30	—	—	17.5	21.7	23.4
		100	1.67	9.10	10.9	12.0
		200	1.79	9.77	11.7	12.3
		300	1.91	10.5	12.5	12.5

Conclusion

Conclusion

- Take Müller's simple model of supernova neutrinos and improved upon the model's neutrino emission prediction
 - modified L_ν (late time and neutronization burst)
 - included $\langle E_{\nu_i} \rangle$, $E_{\nu_i, total}$, t_{bounce} to match Nakazato et al. (2013), Nakamura et al. (2015), and Kotake et al. (2018).

Next Steps

- Depending on what set of simulations one is interested in, model can be tuned/modified to match said simulations
- Use the outputs of the simple model as an input to quick neutrino oscillation models to determine the terrestrial neutrino signal

The End

Thank you very much

Extra

Mass Accretion

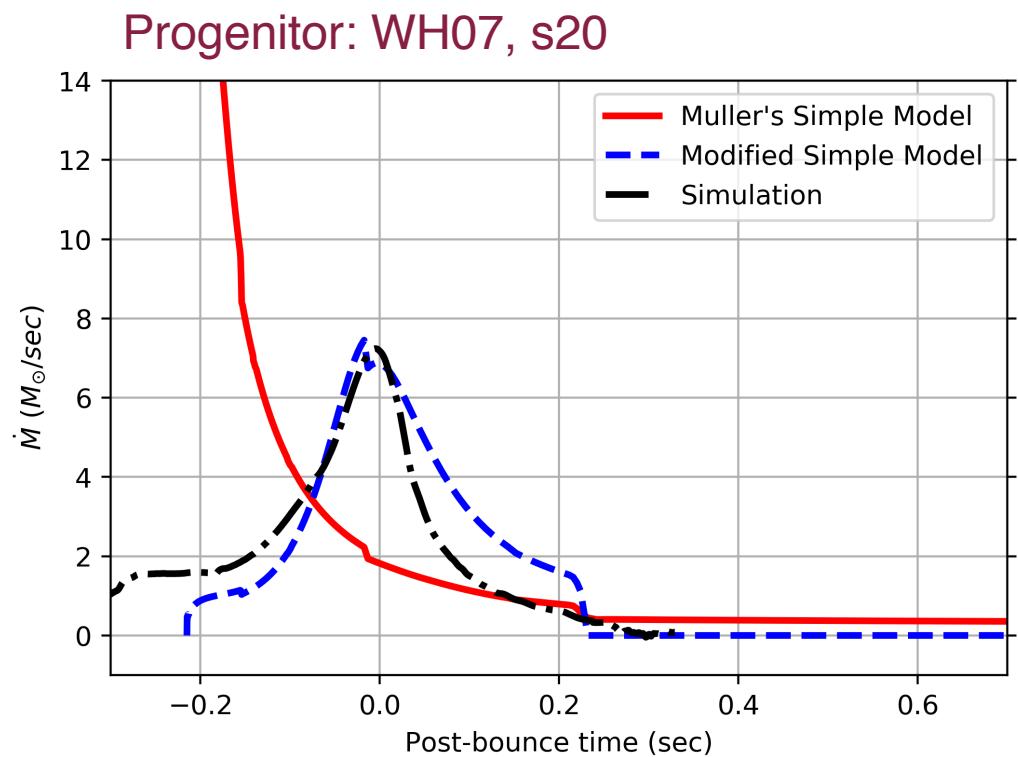
- Define:

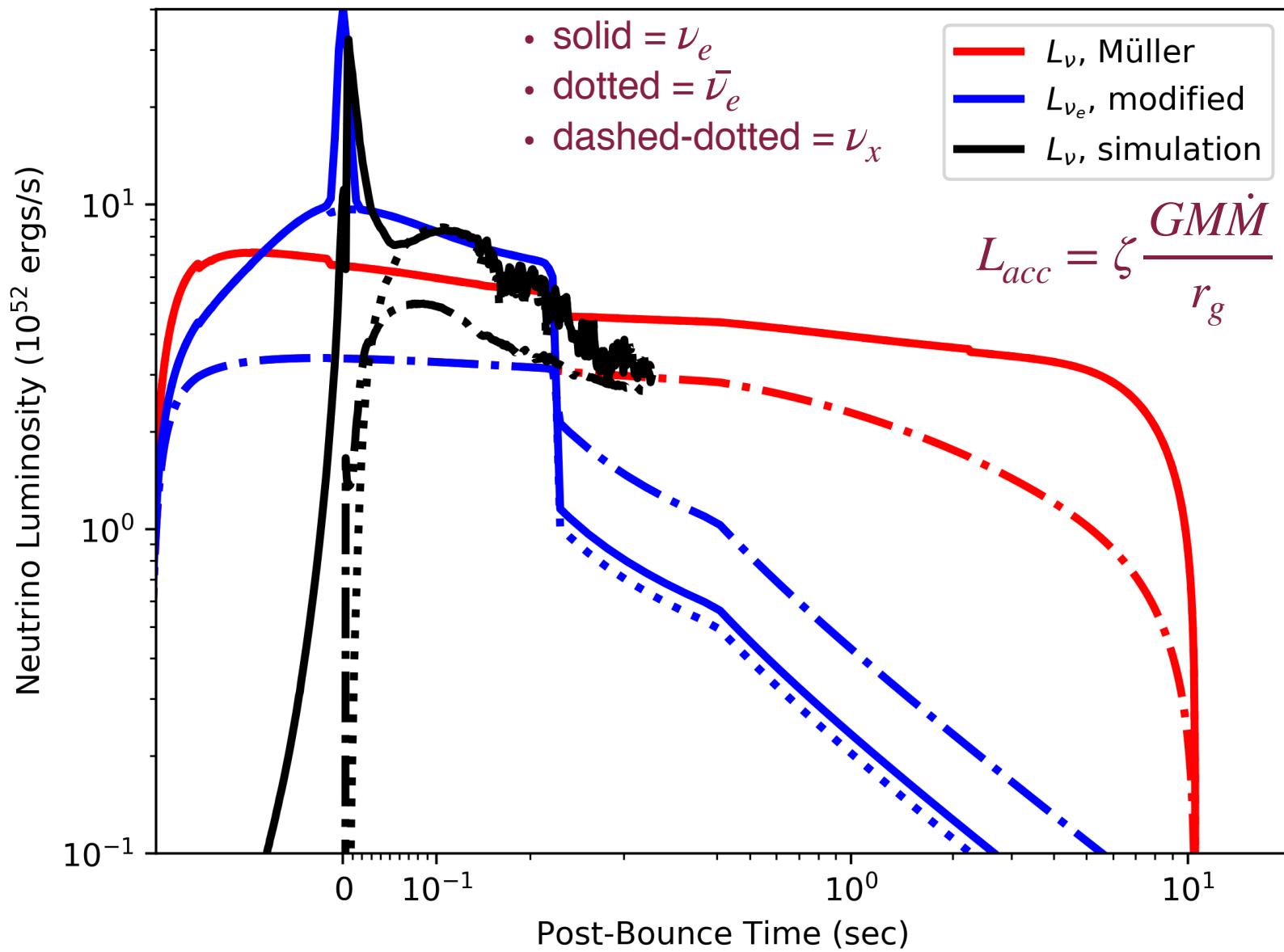
$$\bullet \dot{M}_{mod} = \frac{2M}{D(t_{ff})} \frac{\rho}{\bar{\rho} - \rho}$$

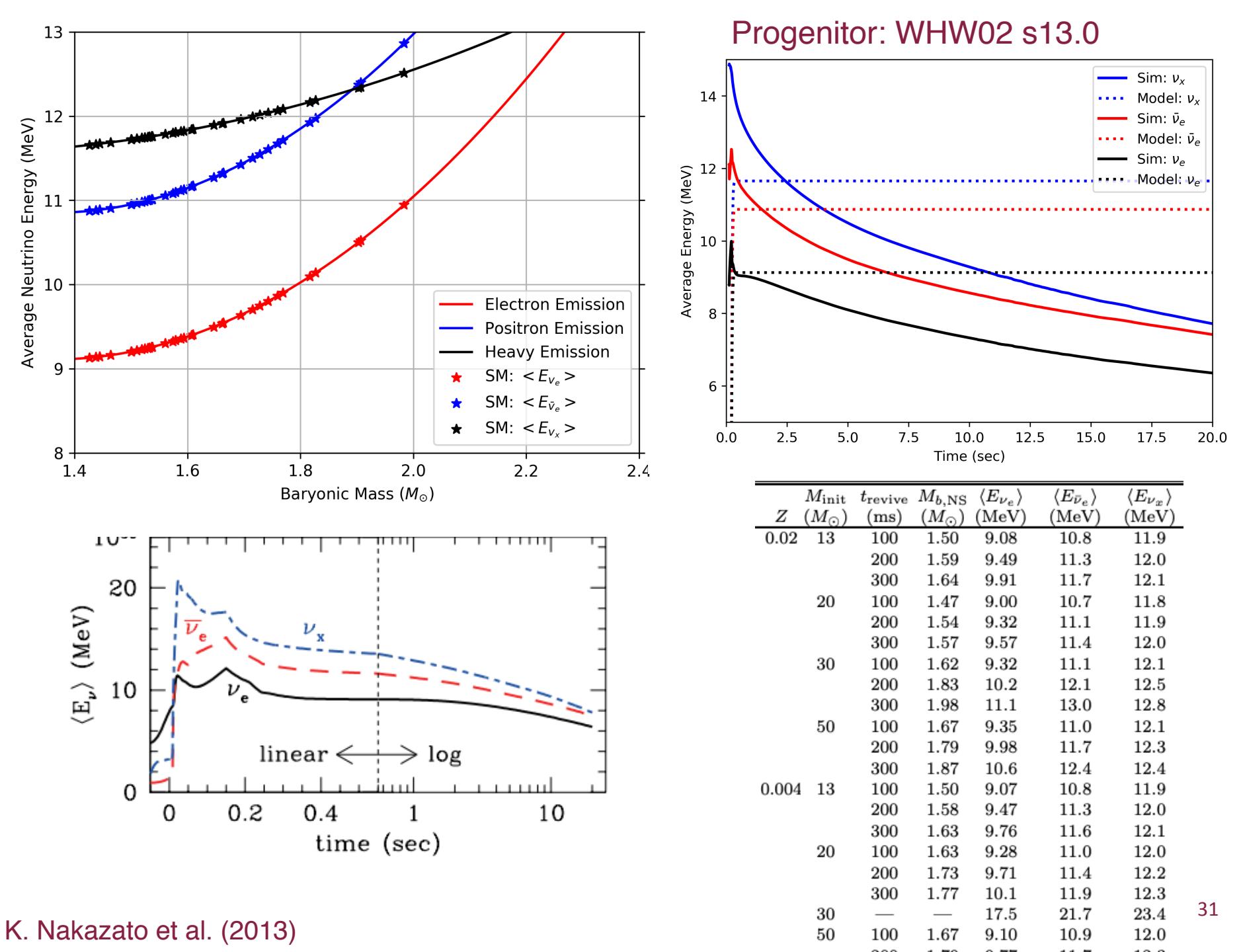
$$\bullet D(t) = \ln(1 - \Delta t/t_{decay}) + \Delta t + t_{offset}$$

$$\bullet \Delta t = t - t_b$$

$$\bullet t_{decay} = 0.04$$

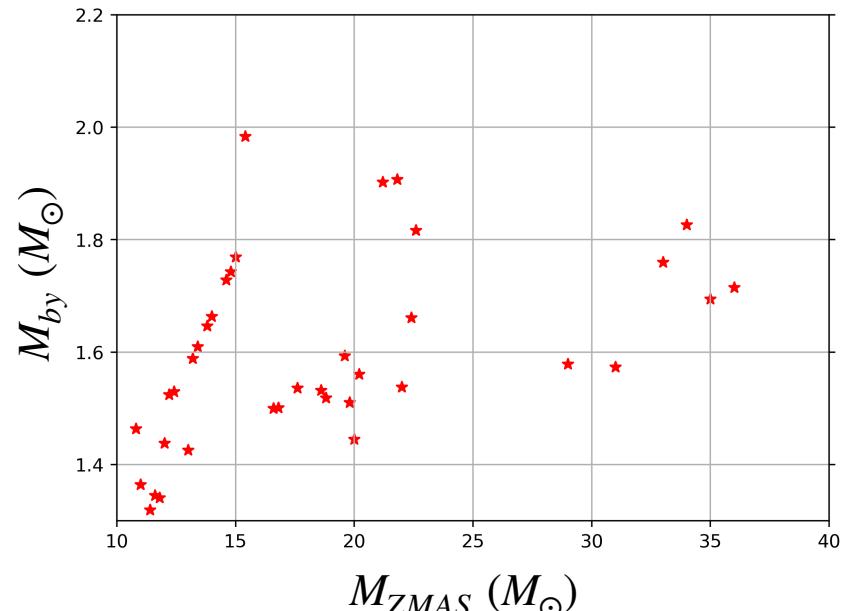




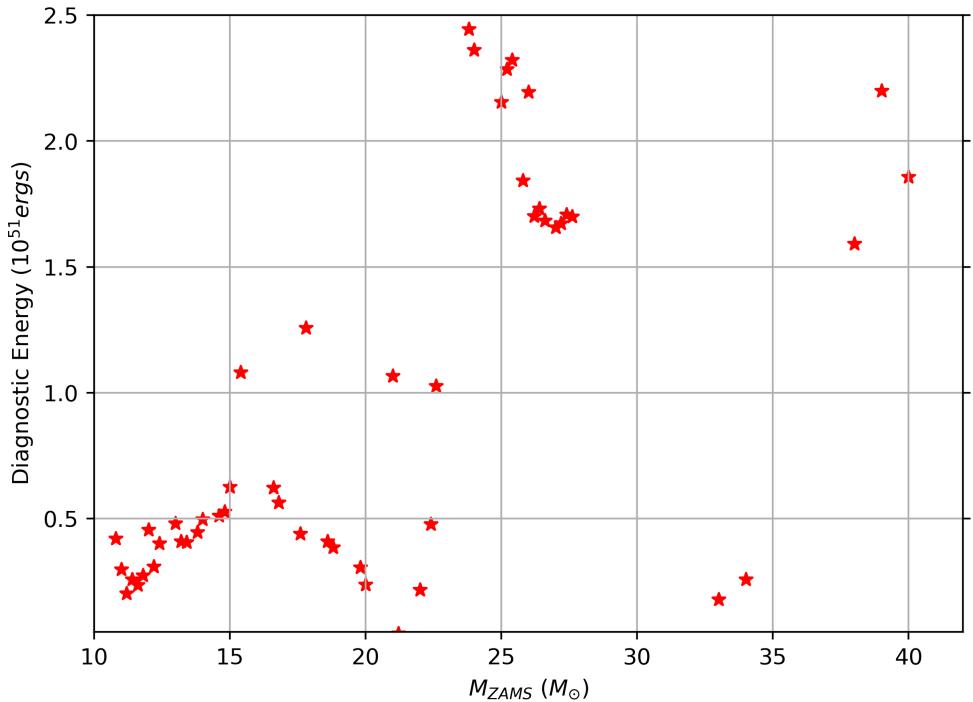
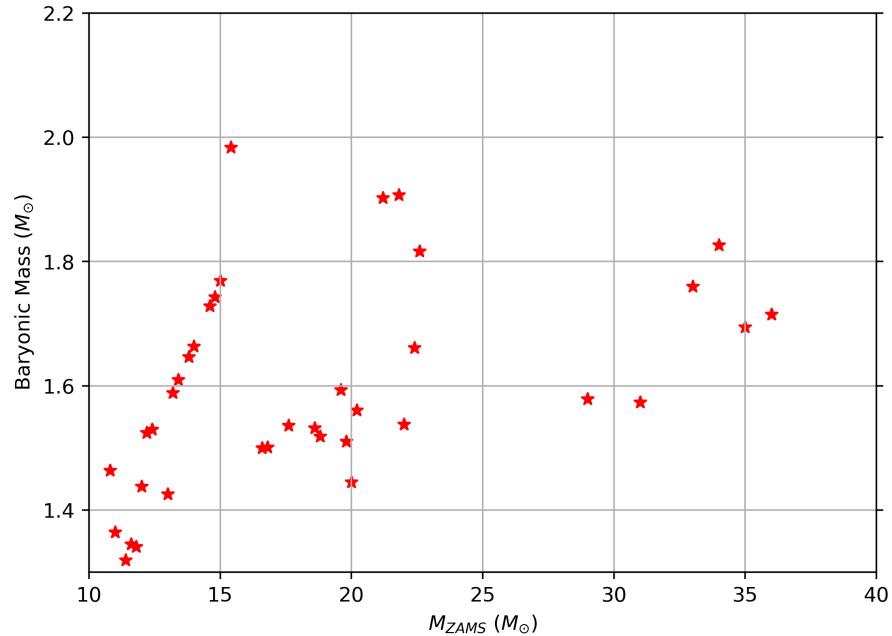


Explosion Phase

- Once shock revival has occurred and the neutrino luminosity calculated, explosion energy and the baryonic mass of the PNS is determined from the remaining information



Explosion Phase



02 / Müller's Simple Model

Tunable Fixed Parameters

Müller's

parameter	explanation	standard value	typical range
α_{out}	volume fraction of outflows	0.5	0.3 ... 0.7
α_{turb}	shock expansion due to turbulent stresses	1.18	1 ... 1.4
β_{expl}	shock compression ratio during explosion phase	4	3 ... 7
ζ	efficiency factor for conversion of accretion energy into ν luminosity	0.8	0.5 ... 1
$\tau_{1.5}$	cooling time-scale for $1.5 M_{\odot}$ neutron star	1.2 s	0.6 s ... 3 s

Additional

Parameters	Explanation	Value
t_{decay}	The rate at which the delayed time function returns to t_{ff}	0.04 sec
r_{cut}	Minimum radius that is included in mass accretion normalization	500 km
p_{late}	Power of the rational power law of late time luminosity	0.8
τ_{late}	Time scaling for late time luminosity	0.12 sec
$r_{\text{Gain},th}$	Gain Radius threshold value to determine bounce time	92.9 km