Core-Collapse Supernova Neutrinos

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with Christian Ott
INT 12-2A Workshop 1
July 2-6, 2012

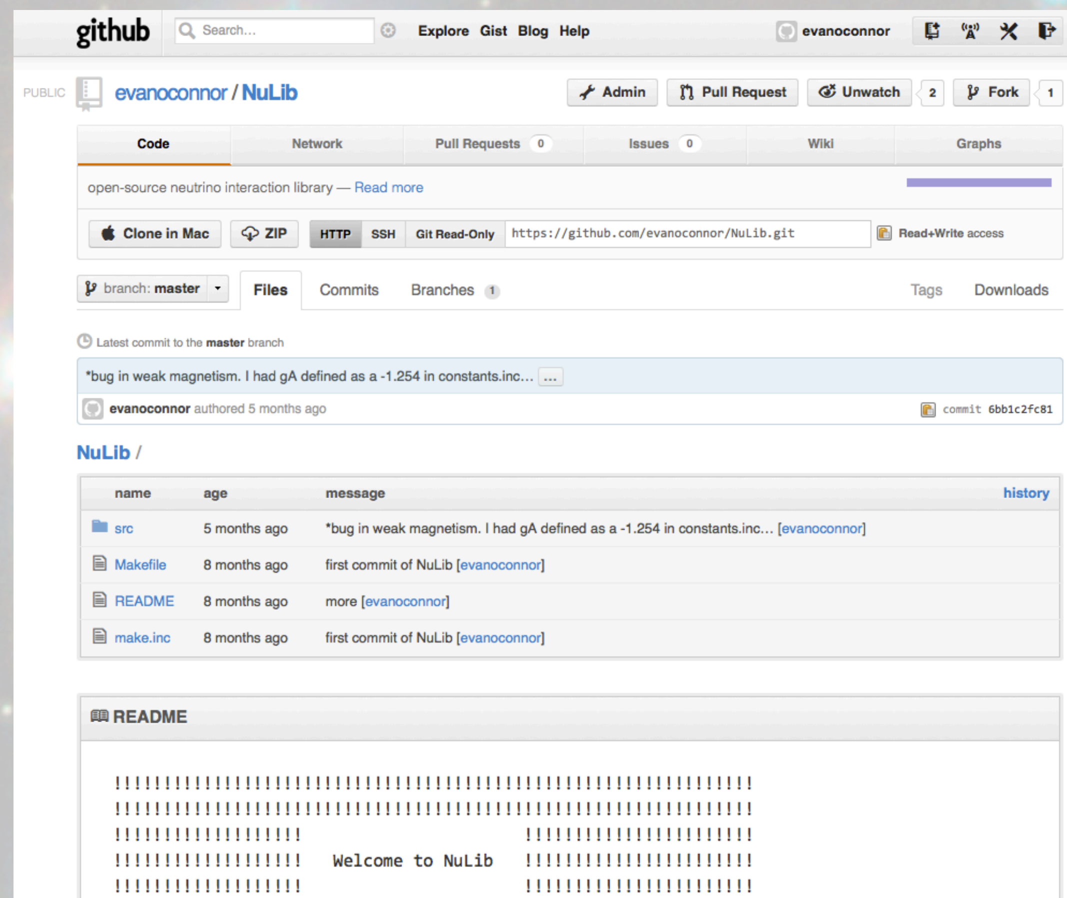
Overview

- `NuLib`
  - Motivation
  - Current Status
- Core-Collapse Supernovae: Models and Observable Signals: From the Neutrino Sector
  - Transport
  - Motivate our Study
  - Look at Progenitor Dependence of Neutrino Signal

NuLib

- NuLib is an open-source neutrino microphysics library
- Intention is to create a one-stop-shop for everything neutrino
- inspired by ReacLib, a collection of reaction rates for astrophysical models.
- used for benchmarking current codes, validating and developing new codes
- provide venue for nuclear theorists to provide new/improved interaction rates
- github repository for easy distribution and collaborative efforts

http://www.nulib.org



NuLib

- NuLib provides routines for calculating neutrino cross sections, opacities, emissivities, kernals, Fermi functions/integrals, …
- Ideally, routines are optimized for on the fly evaluation of neutrino interaction rates
- Also provides routines for developing tables for fast on-the-fly interpolation of rates
- Currently includes a base set of neutrino interactions: Bruenn '85; Burrows, Reddy, Thompson '06

```
!scatterings
logical :: add_nue_scattering_n = .true.
logical :: add_nue_scattering_p = .true.
logical :: add_nue_scattering_heavies = .true.
logical :: add_nue_scattering_electrons = .true.
logical :: add_nue_scattering_alphas = .true.
logical :: add_anue_scattering_n = .true.
logical :: add_anue_scattering_p = .true.
logical :: add_anue_scattering_heavies = .true.
logical :: add_anue_scattering_electrons = .true.
logical :: add_anue_scattering_alphas = .true.
logical :: add_numu_scattering_n = .true.
logical :: add_numu_scattering_p = .true.
logical :: add_numu_scattering_heavies = .true.
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logical :: add_nutau_scattering_p = .true.
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logical :: add_anutau_scattering_alphas = .true.
```

```
!emissivities
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logical :: add_anue_emission_epannihil = .true.
logical :: add_numu_emission_epannihil = .true.
logical :: add_anumu_emission_epannihil = .true.
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logical :: add_nue_emission_NNBrems = .true.
logical :: add_anue_emission_NNBrems = .true.
logical :: add_numu_emission_NNBrems = .true.
logical :: add_anumu_emission_NNBrems = .true.
logical :: add_nutau_emission_NNBrems = .true.
logical :: add_anutau_emission_NNBrems = .true.
```

```
!corrections
logical :: do_weak_mag_corrections = .true.
logical :: do_ionion_correlation = .true.
logical :: do_heavyscat_formfactor = .true.
logical :: do_electronpolarization_correction = .true.

!absorptions
logical :: add_nue_absorption_on_n = .true.
logical :: add_anue_absorption_on_p = .true.
logical :: add_nue_absorption_on_A = .true.
```

NuLib

Scattering			Charged Current Emission / Absorption			Thermal Emission / Absorption		
$\nu + A$	$\leftrightarrow$	$\nu + A$	$p + e^-$	$\leftrightarrow$	$\nu_e + n$	$e^- + e^+$	$\leftrightarrow$	$\nu + \bar{\nu}$
$\nu + e$	$\leftrightarrow$	$\nu + e$	$n + e^+$	$\leftrightarrow$	$\bar{\nu}_e + p$	γ^*	$\leftrightarrow$	$\nu + \bar{\nu}$
$\nu + N$	$\leftrightarrow$	$\nu + N$	$A'(Z, A) + e^-$	$\leftrightarrow$	$\nu_e + A(Z-1, A)$	NN	$\leftrightarrow$	$NN + \nu + \bar{\nu}$
$\nu_x + \bar{\nu}_e$	$\leftrightarrow$	$\nu_x + \bar{\nu}_e$	n	$\leftrightarrow$	$p + e^- + \bar{\nu}_e$	$\nu_x + \bar{\nu}_x$	$\leftrightarrow$	$\nu_e + \bar{\nu}_e$
$\nu_x + \nu_e$	$\leftrightarrow$	$\nu_x + \nu_e$	$n + N$	$\leftrightarrow$	$p + e^- + \nu_e + N$			
			$p + e^- + N$	$\leftrightarrow$	$n + \nu_e + N$			

- `NuLib` will ultimately include many more neutrino interactions:
  - inelastic interactions of neutrinos with electrons, nucleons, ions
  - kernels for pair-processes
  - detailed electron capture rates

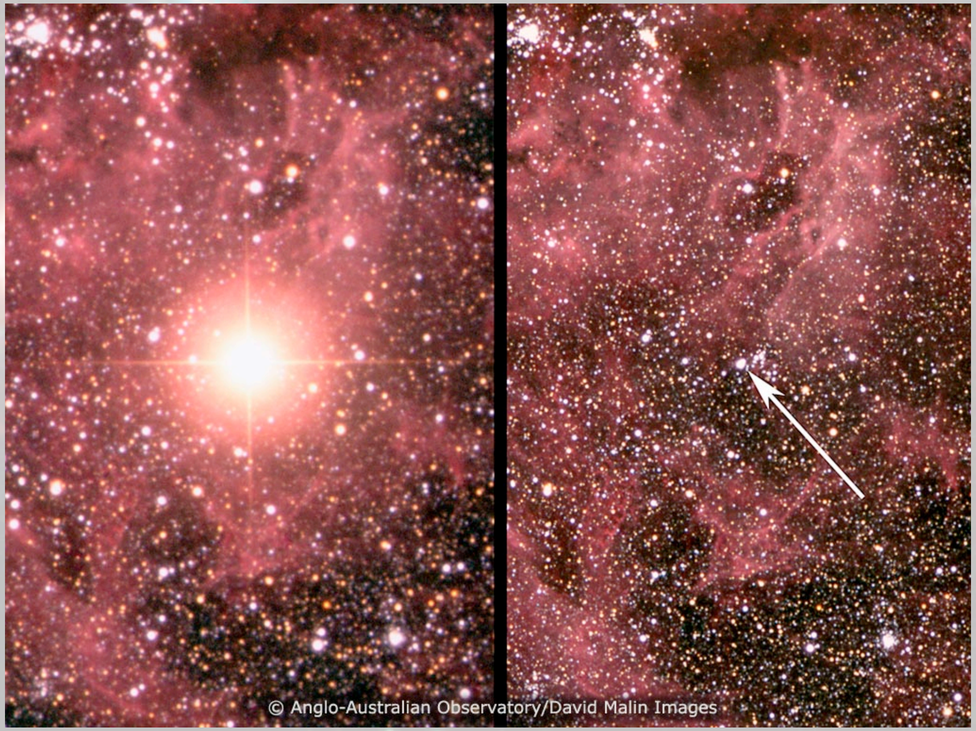
- covering all high energy astrophysical systems:
  - Core-Collapse Supernovae
  - Protoneutron star cooling
  - Neutron star—Black Hole mergers
  - Neutron star—Neutron star mergers

- and neutrino transport techniques:
  - full transport
  - moment scheme
  - grey schemes
  - leakage schemes

Anyone interested, in contribution, developing, using, or commenting please do

Core-Collapse Supernova Neutrinos

- We are using `NuLib` in our new neutrino transport code `nuGR1D`
- `nuGR1D`, is the combination of a new two-moment neutrino transport code and `GR1D`
- `GR1D` is a spherically-symmetric general relativistic Eulerian hydrodynamics code for studying stellar collapse. Open source, www.stellarcollapse.org
- `nuGR1D` is a general relativistic M1 scheme based on Shibata et al. 2011, Audit et al. 2002. It is coupled to `GR1D`. Will be open source when complete.



nuGR1D

- Define the neutrino moment tensor as follows Shibata *et al.* (2011):

$$M^{\alpha\beta}_{(\nu)} = E_{(\nu)} n^\alpha n^\beta + F^\alpha_{(\nu)} n^\beta + F^\beta_{(\nu)} n^\alpha + P^{\alpha\beta}_{(\nu)}$$

$$n^\alpha = (1/\alpha, -\beta^i/\alpha)$$
$$n^\alpha = (1/\alpha, 0)$$

- Here *E*, F^α, $P^{\alpha\beta}$, are the moments in the *laboratory frame*
- Thorne's (1981) moment formalism gives evolution equations for the moment tensor:

$$\nabla_\beta M^{\alpha\beta}_{(\nu)} - \frac{\partial}{\partial \nu}\left(\nu M^{\alpha\beta\gamma}_{(\nu)} \nabla_\gamma u_\beta\right) = S^\alpha_{(\nu)}$$

- For simplicity we ignore the energy-coupling term and velocity dependence. Generally bad, but will show it is acceptable for this study

nuGR1D

- For GR1D, evolution equations become

$$\partial_t E_{(\nu)} + \frac{1}{r^2}\partial_r\left(\frac{\alpha r^2}{X^2} F_{r,(\nu)}\right) = \alpha^2 \mathcal{S}^t_{(\nu)}$$

$$\partial_t F_{r,(\nu)} + \frac{1}{r^2}\partial_r\left(\frac{\alpha r^2}{X^2} P_{rr,(\nu)}\right) = \alpha X^2 \mathcal{S}^r_{(\nu)} + \alpha \frac{E_{(\nu)}(1-p_{(\nu)})}{r}$$

- Source terms are calculated using NuLib and tabulate in ρ,T,Y_e,E space

$$\mathcal{S}^t = (\eta_{(\nu)} - \kappa_{a,(\nu)} E_{(\nu)})/\alpha\,,$$

$$\mathcal{S}^r = -(\kappa_{a,(\nu)} + \kappa_{s,(\nu)}) F_{r,(\nu)}/X^2$$

- Flux equation uses analytic closure and solved via Audit *et al.* (2002)

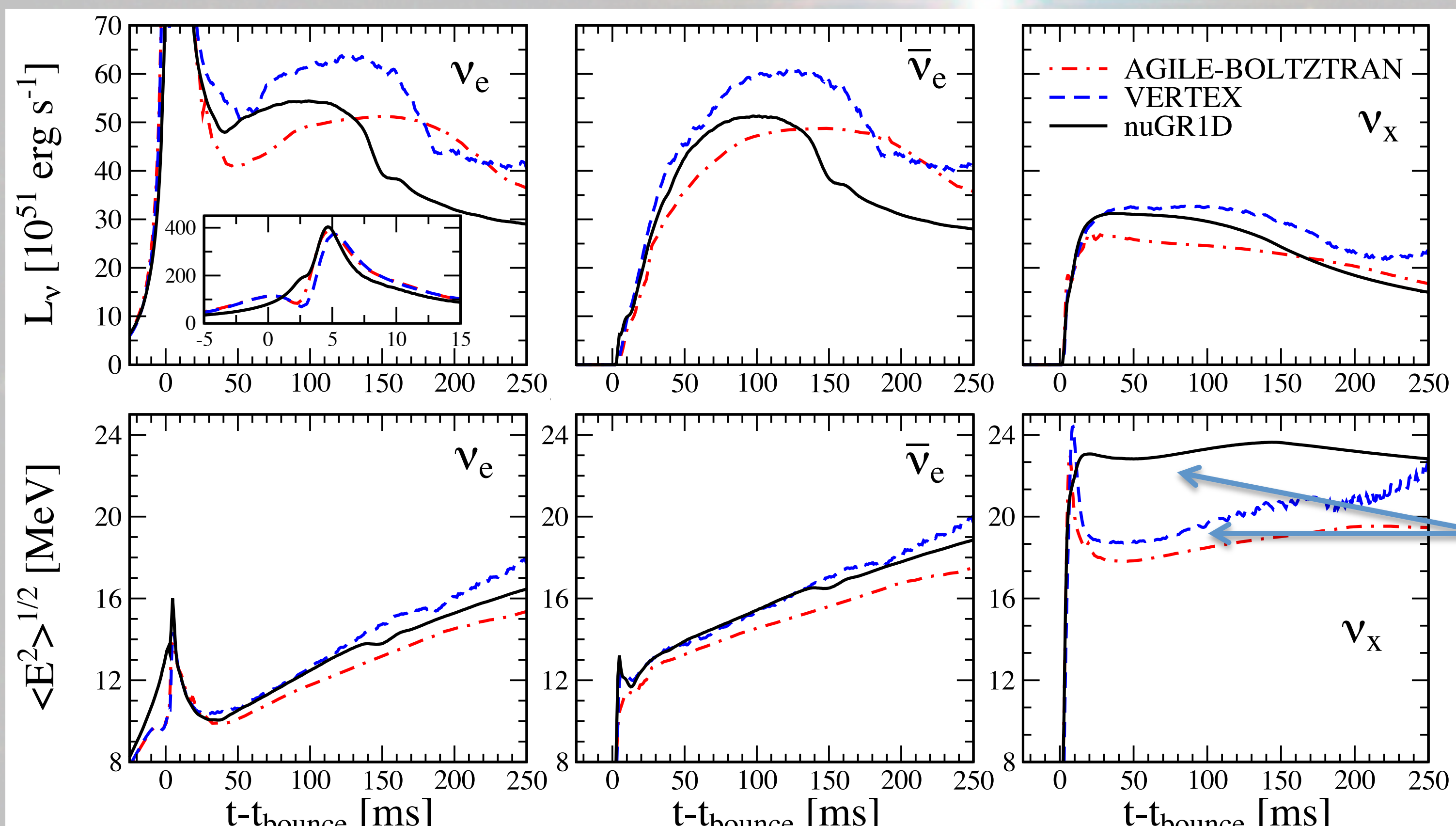
$$P_{ii,(\nu)} = \frac{3p_{(\nu)}-1}{2} P_{ii,(\nu),\mathrm{thin}} + \frac{3(1-p_{(\nu)})}{2} P_{ii,(\nu),\mathrm{thick}}$$

where $p_{(\nu)} = \frac{1}{3} + \frac{f^2_{(\nu)}}{15}(6 - 2f_{(\nu)} + 6f^2_{(\nu)})$

Comparison to Full ν Transport

We compare nuGR1D to Liebendoerfer *et al.* (2005) "Supernova Simulations with Boltzmann Neutrino Transport: A Comparison of Methods"

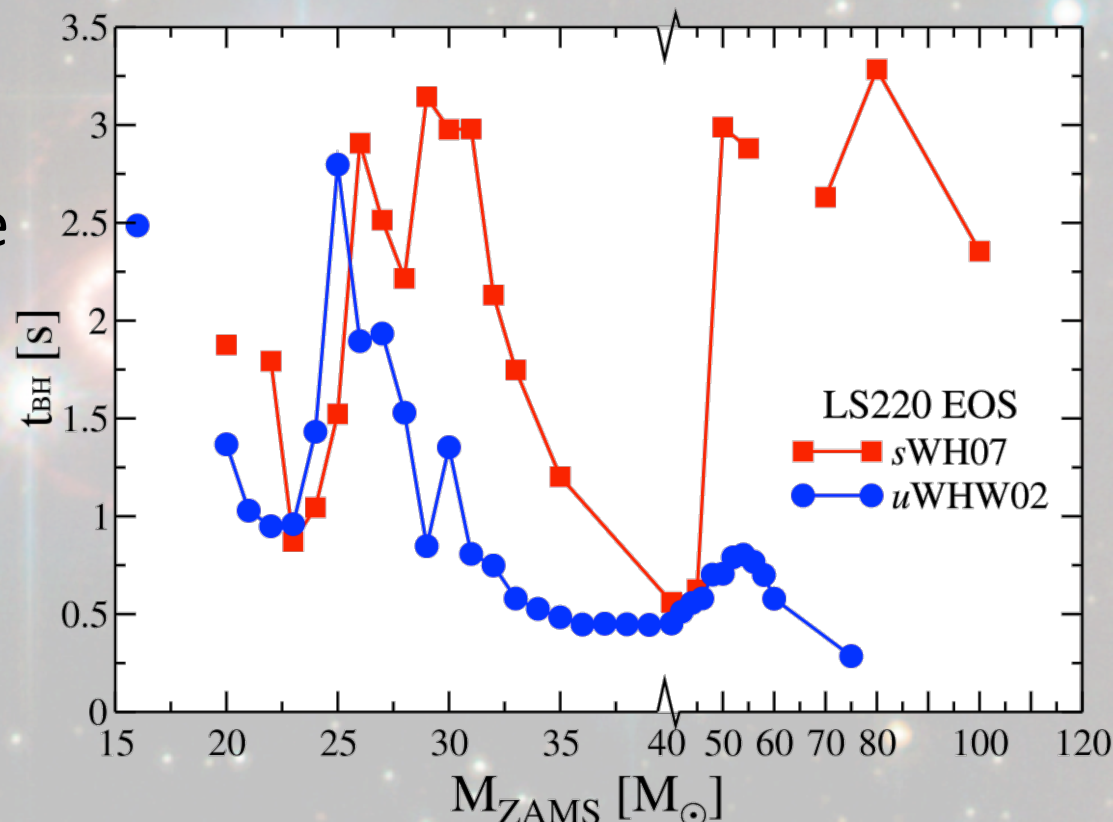
Agile-BOLTZTRAN (Liebendoerfer et al. 2001, …) & VERTEX* (Rampp & Janka 2002)



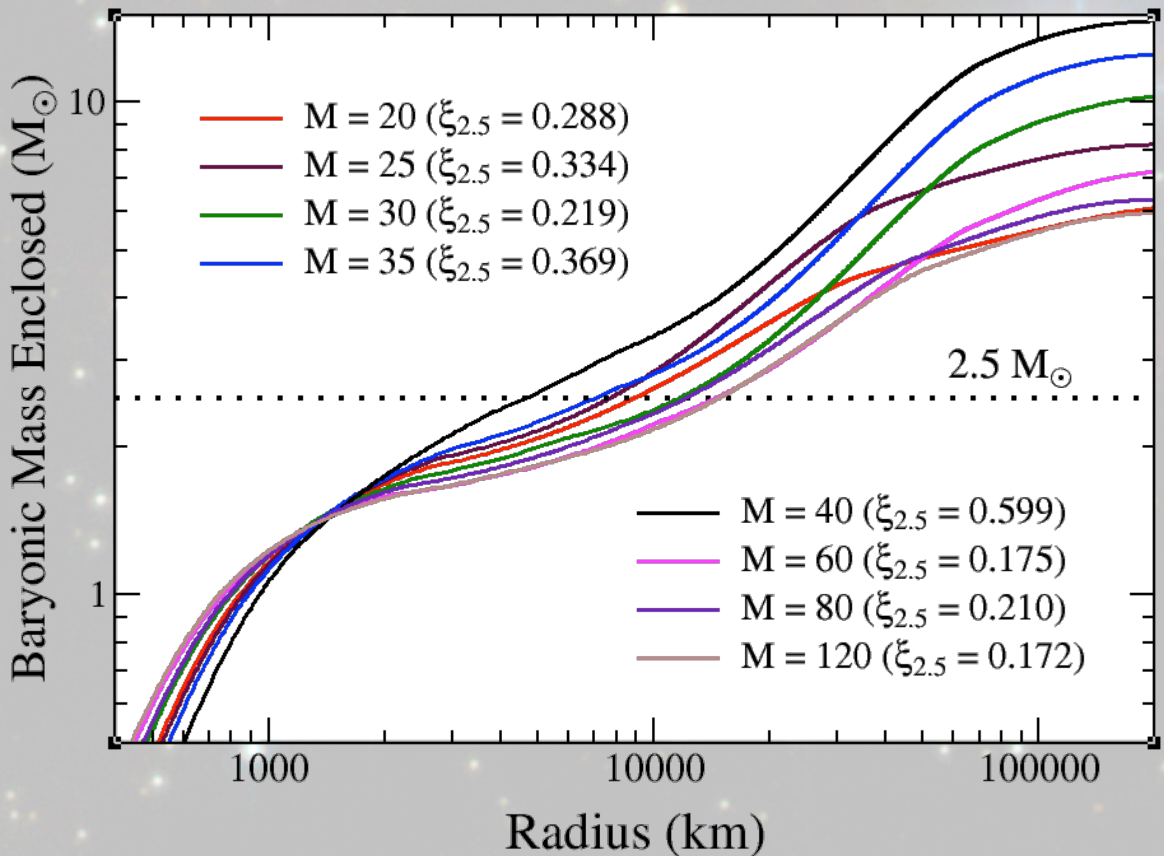
due to lack of inelastic scattering

Motivation:

- In O'Connor and Ott (2011) we studied progenitor dependence of black hole formation
- Black hole formation properties of massive stars do not correlate with ZAMS mass



Motivation:



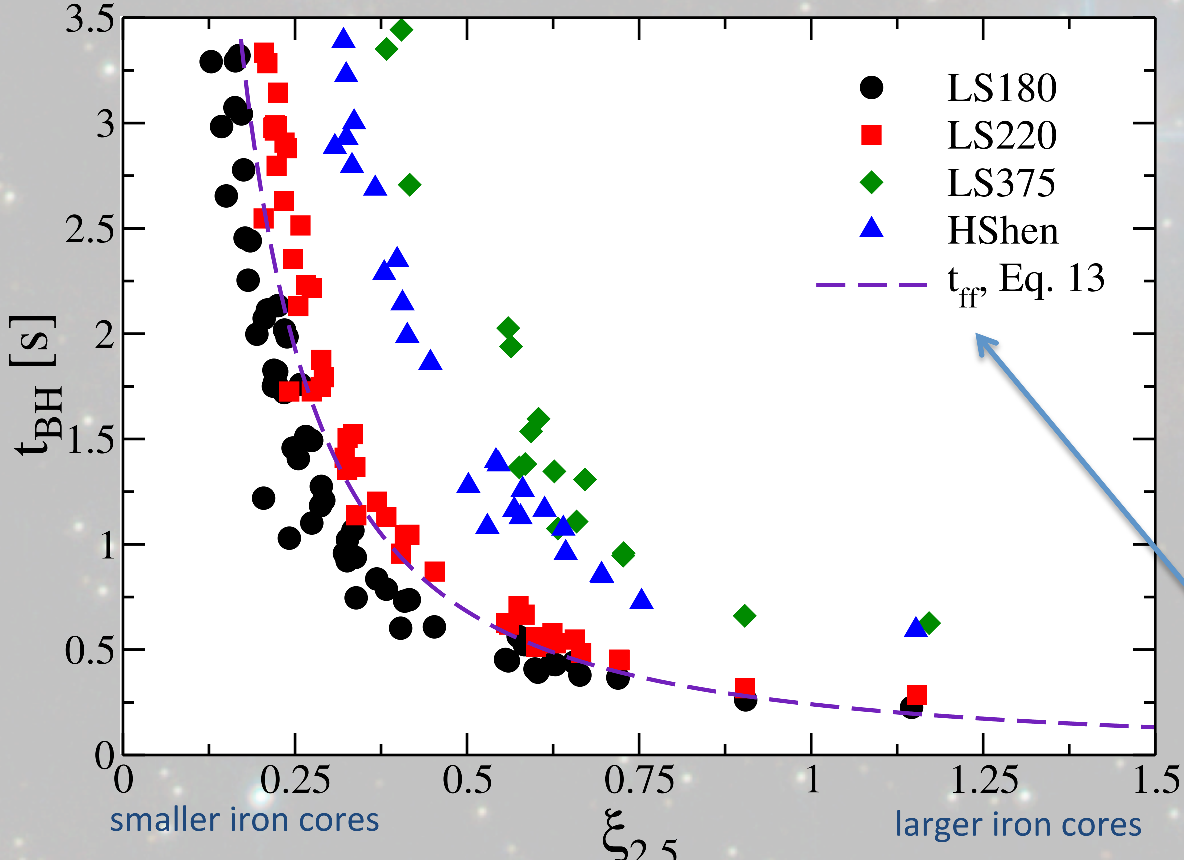
- ξ_M is a measure of the compactness of the progenitor's inner M solar masses

$$\xi_M = \frac{M / M_{sun}}{R_M / 1000km}$$

- In OC&O'11, we chose 2.5 solar masses as this is the relevant mass scale for black hole formation

Motivation:

Black Hole Formation Time vs. $\xi_{2.5}$



EO & Ott ApJ **730** 70 (2011)

- BH formation time set by progenitor structure and EOS
- Of course, many will explode in nature...

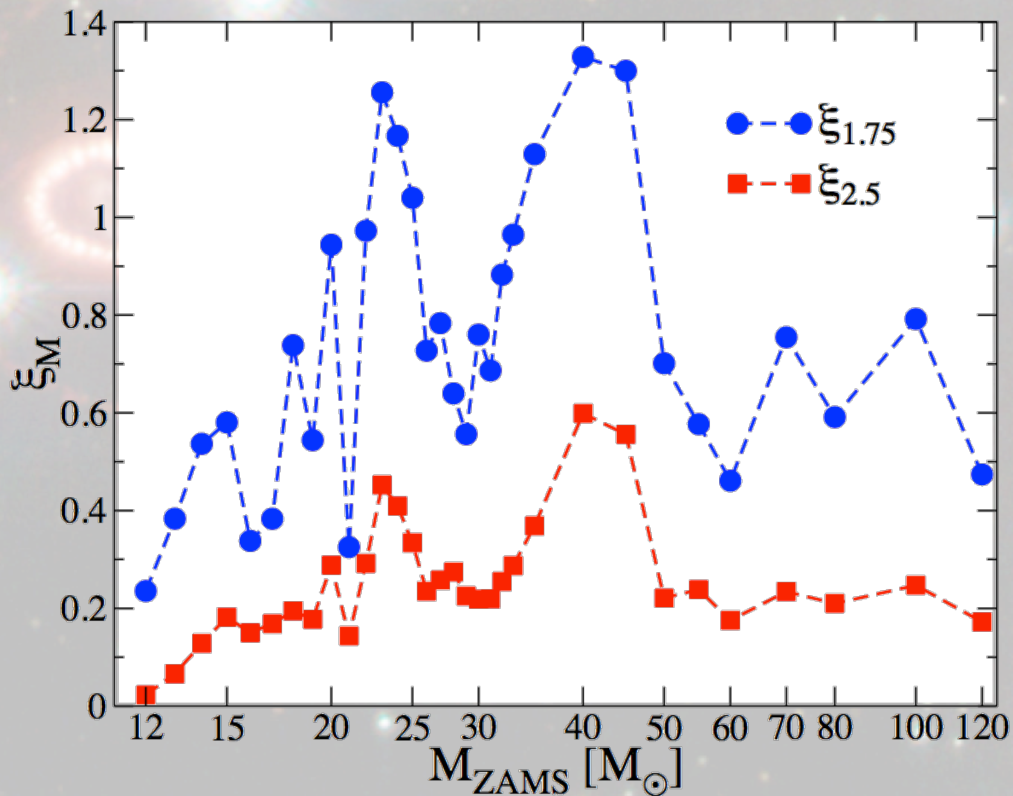
- Free fall time of a test particle is half the orbital period

$$t_{ff} = \frac{1}{2}\sqrt{\frac{4\pi^2 a^3}{GM^*}} = \pi\sqrt{\frac{r_*^3}{8GM^*}}$$

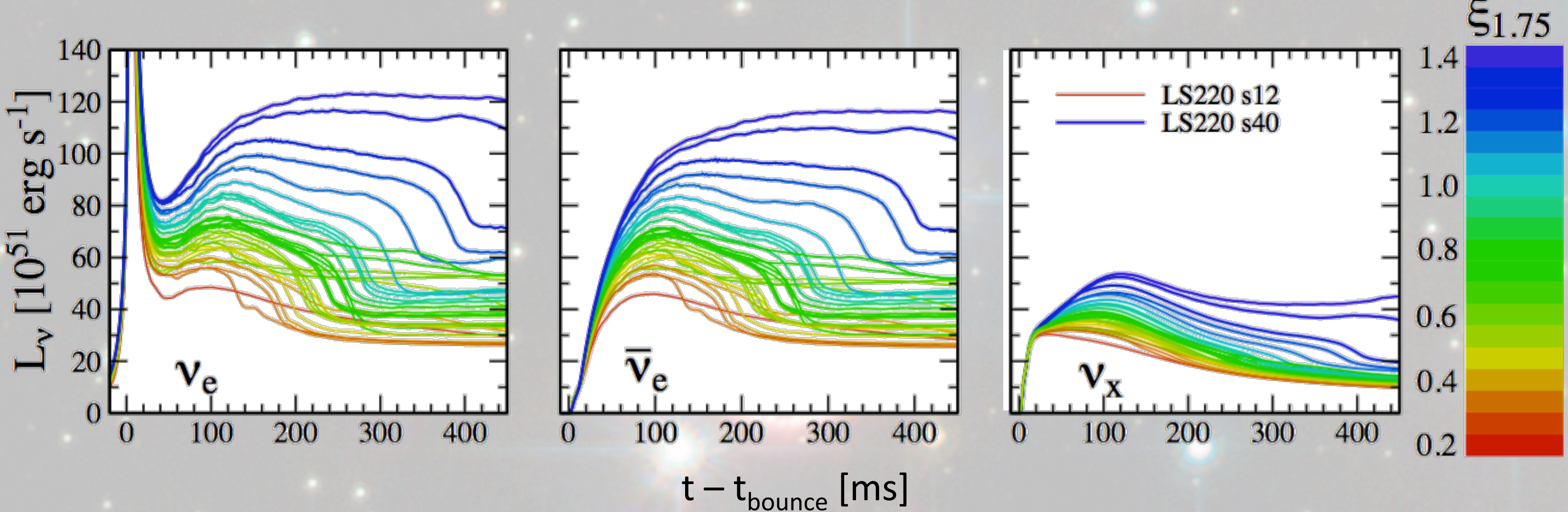
$$t_{ff}^{2.5M_\odot} = \pi\sqrt{\frac{(2.5M_\odot)^2}{8G(\xi_{2.5})^3}}$$

Models

- We use the 32 solar metallicity models from Woosley & Heger (2007) ranging is ZAMS mass from 12 to 120 M_{sun}
- We use 2 EOS:
  LS220, Hshen
- perform core collapse and 450ms of postbounce preexplosion evolution with `nuGR1D`
- We look for trends with the compactness, $\xi_{1.75}$
- chose 1.75M_{sun} as this is relevant mass scale for early phase

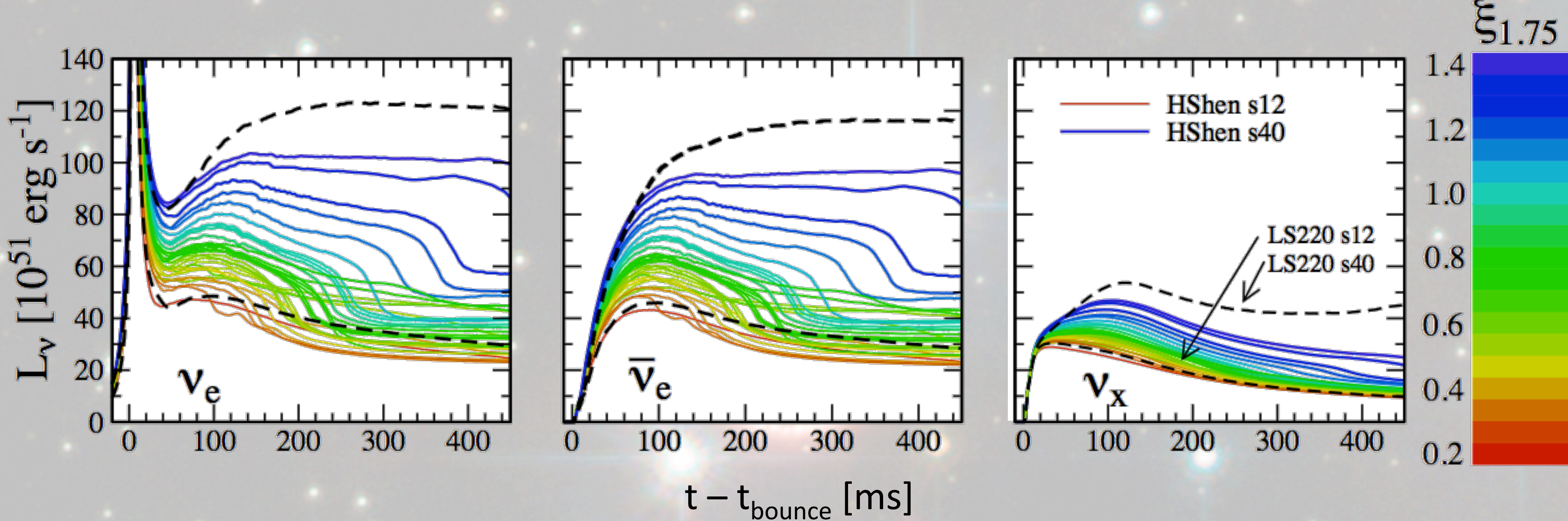


Results - Luminosities



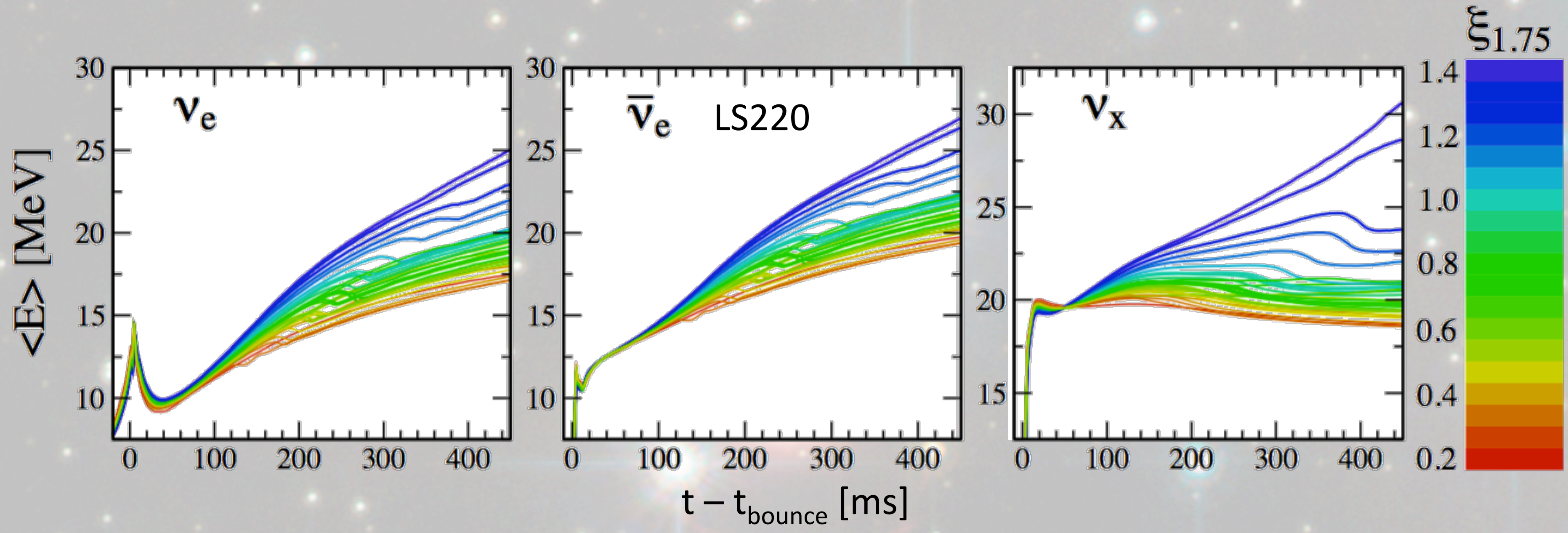
- Luminosities of all species increase with $\xi_{1.75}$ in a predictable way: low $\xi_{1.75}$ have small accretion rates and low protoneutron star temperatures

Results - Luminosities



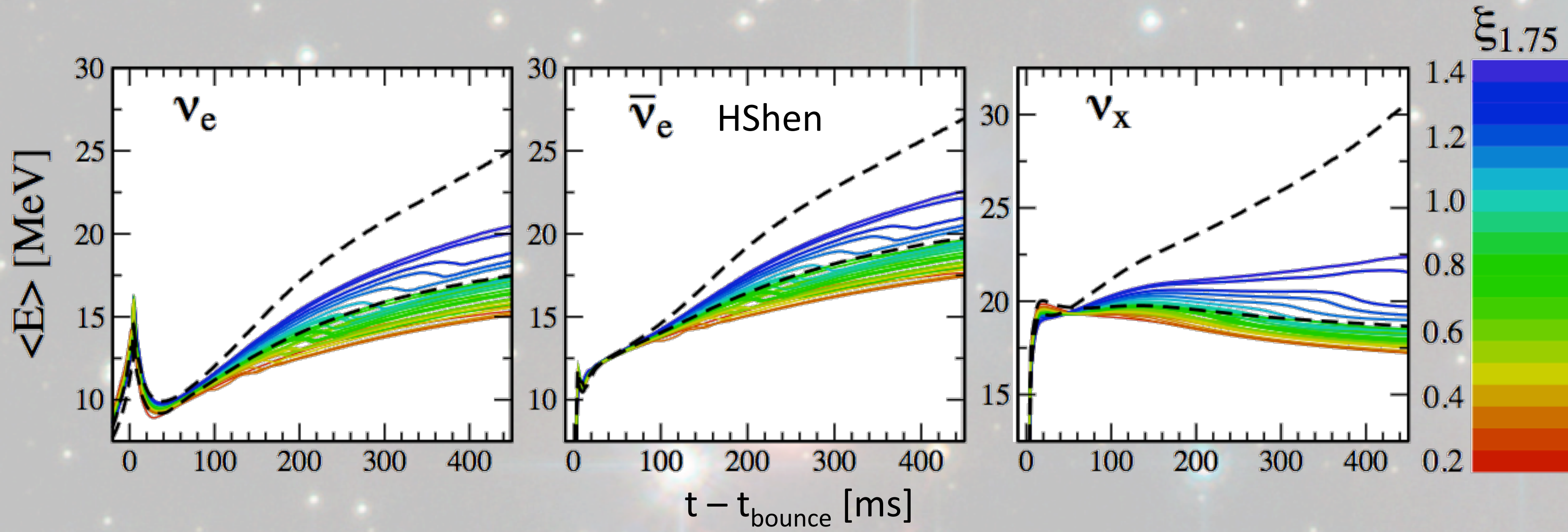
- Luminosities of all species increase with $\xi_{1.75}$ in a predictable way: low $\xi_{1.75}$ have small accretion rates and low protoneutron star temperatures
- There is a slight EOS dependence, the HShen EOS gives lower luminosities—the neutrinosphere radii are large than the LS220 case

Results – Average Energies



- Average energies of all species also increase with $\xi_{1.75}$ in a predictable way: low $\xi_{1.75}$ models have lower temperature and less compact protoneutron stars.

Results – Average Energies

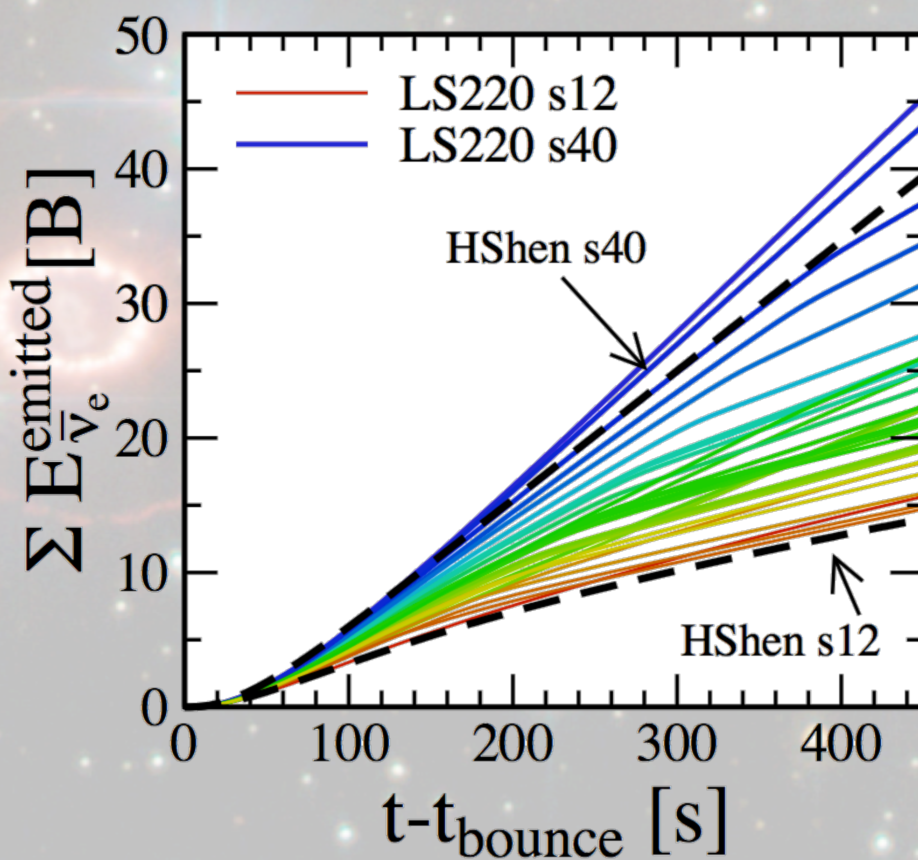


- Average energies of all species also increase with $\xi_{1.75}$ in a predictable way: low $\xi_{1.75}$ models have lower temperatures and less compact protoneutron stars.
- There is a stronger EOS dependence, the HShen EOS can give up to 5MeV lower average energies.
- At late times, high $\xi_{1.75}$ models are close to black hole formation---very high average energies.

More Quantitative

- Cumulative emitted electron antineutrino energy also is proportional to $\xi_{1.75}$
- electron antineutrinos are the predominate neutrino detected on Earth from a core-collapse supernova

$$\bar{\nu}_e + p \rightarrow e^+ + n$$



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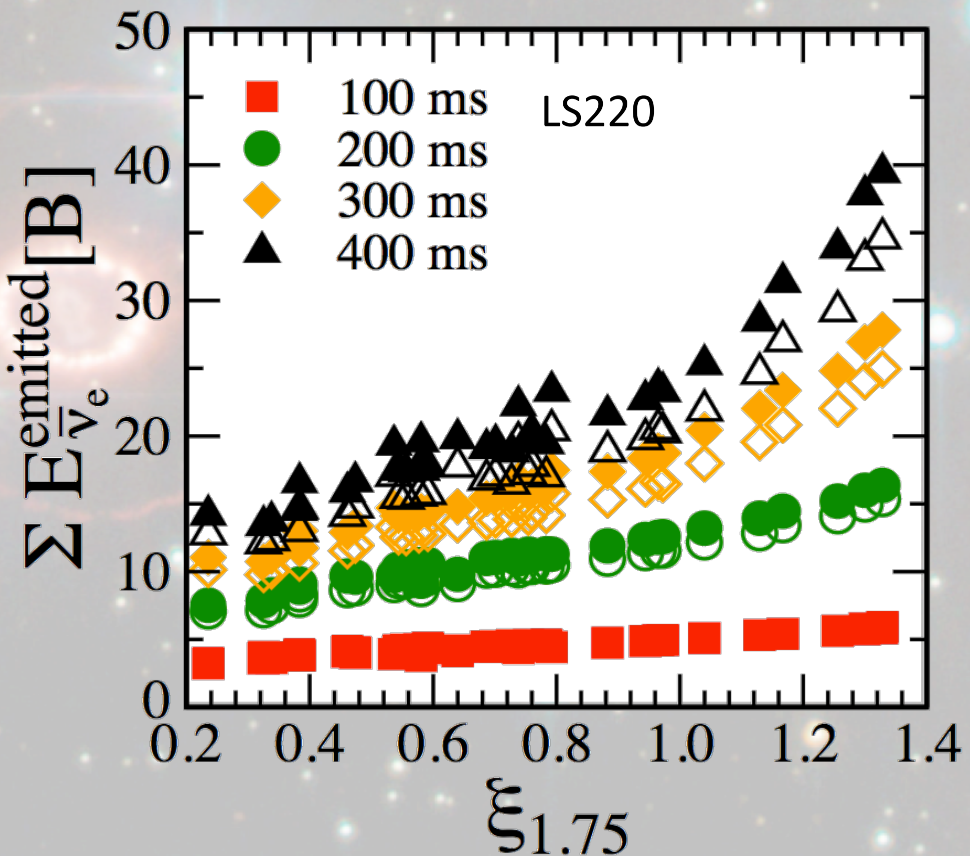
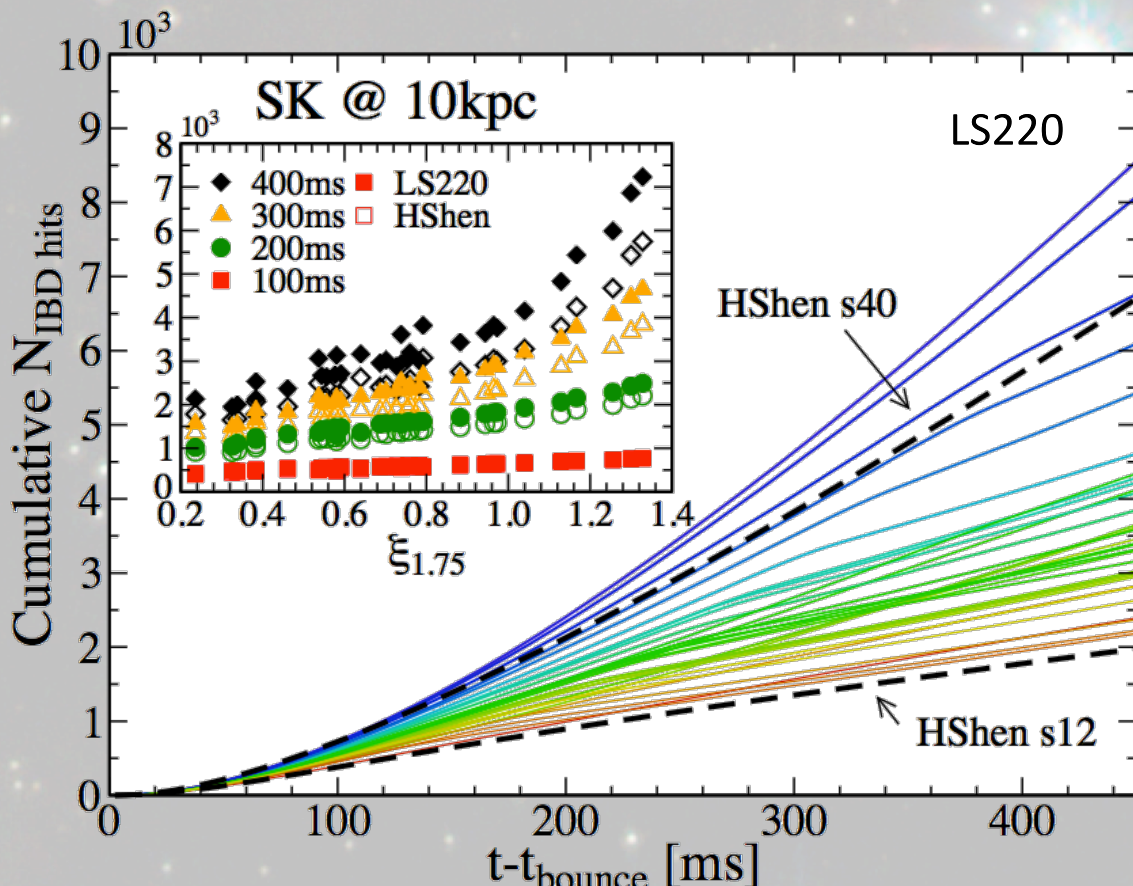


Detection on Earth

- We use SNOwGLoBES (Scholberg 2012) to reconstruct the number of events in a Super-K-like ν detector for a 10 kpc supernova



- Same trends as cumulative ν energy
- Stronger EOS dependence as cross sections are very sensitive to energies
- The early postbounce preexplosion ν signal will tell us the compactness of the progenitor star!

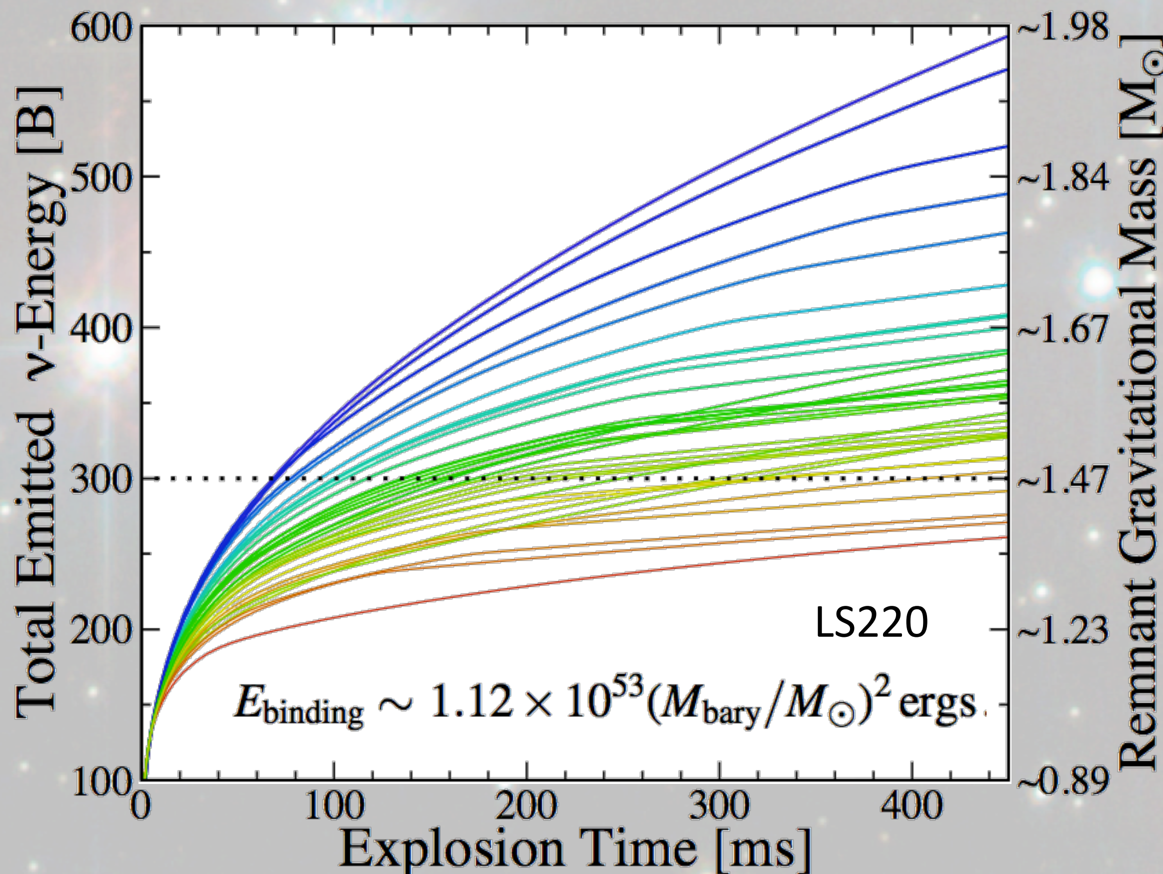
Detection on Earth

- Another method of probing the progenitor star's structure is through the total emitted neutrino energy

- Assume explosion is launched at postbounce time *t*

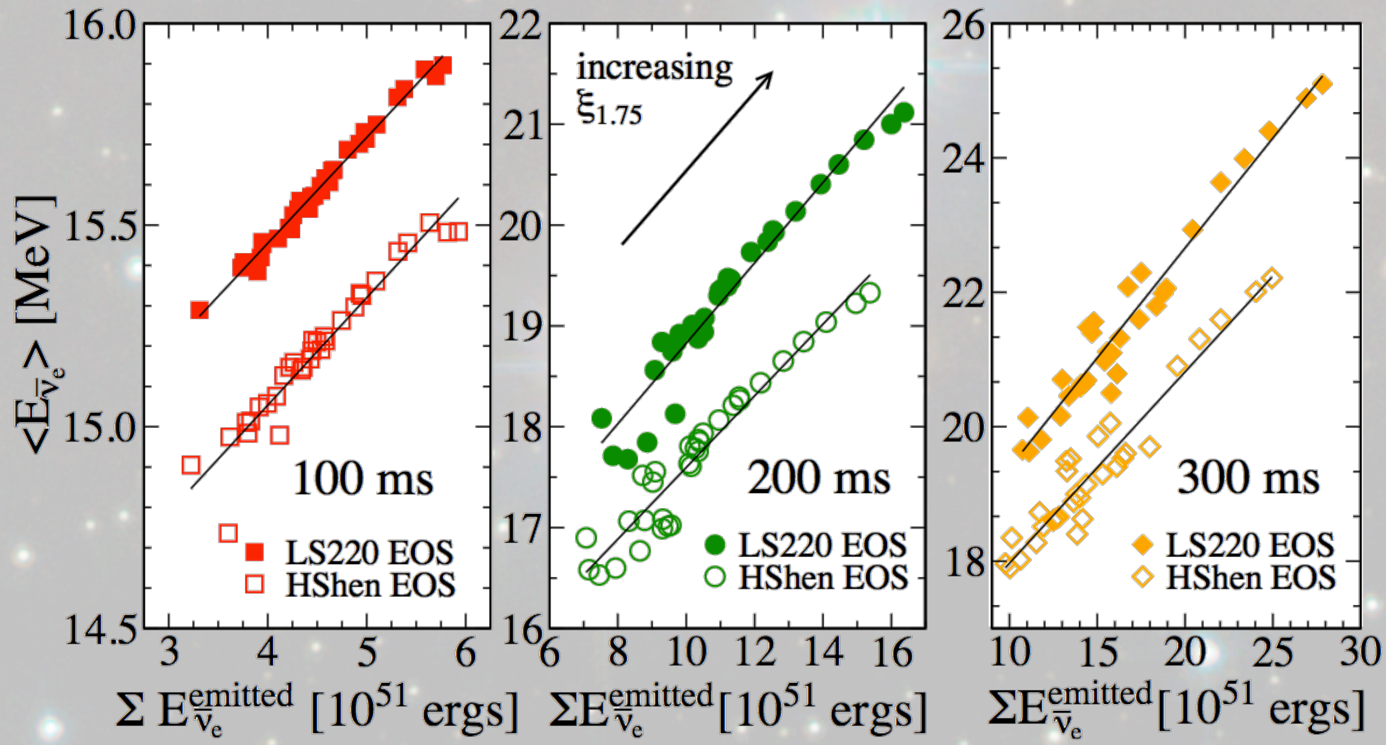
- Convert baryonic mass into total emitted ν energy

- Estimate of explosion time and total ν energy gives compactness and remnant mass!



Degeneracies ☹

- Nuclear equation of state is not completely degenerate with progenitor compactness



- Accurate observations will allow EOS to be probed, otherwise it will cloud $\xi_{1.75}$ determination

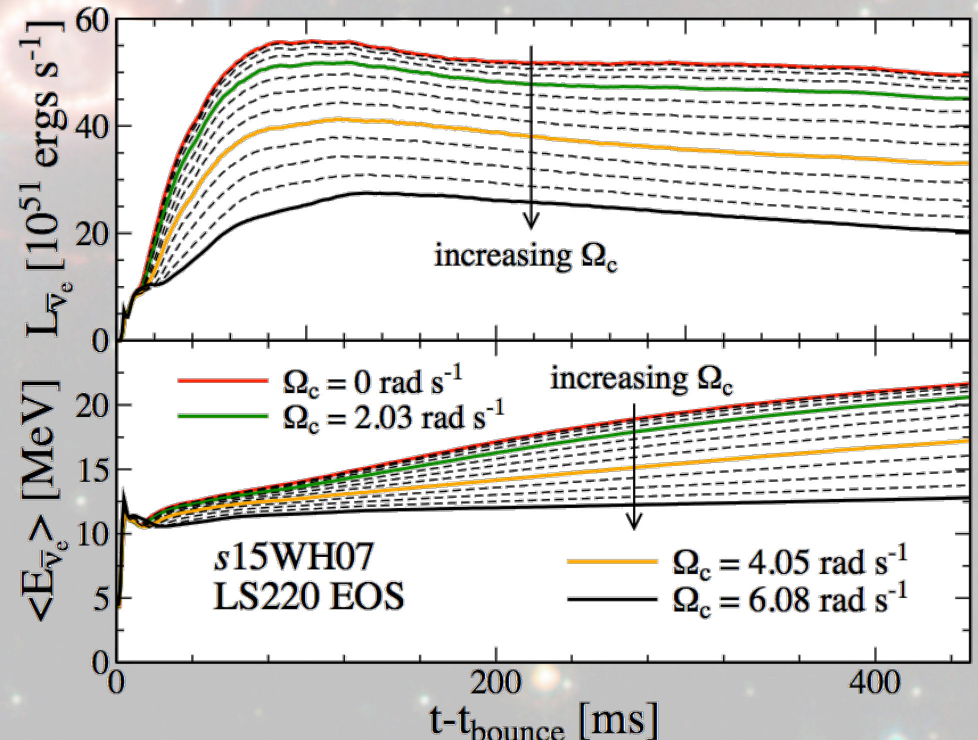
Degeneracies ☹

Distance

- If distance is uncertain, one cannot nail down total emitted energy.
- The energy spectrum would not be changed

Rotation

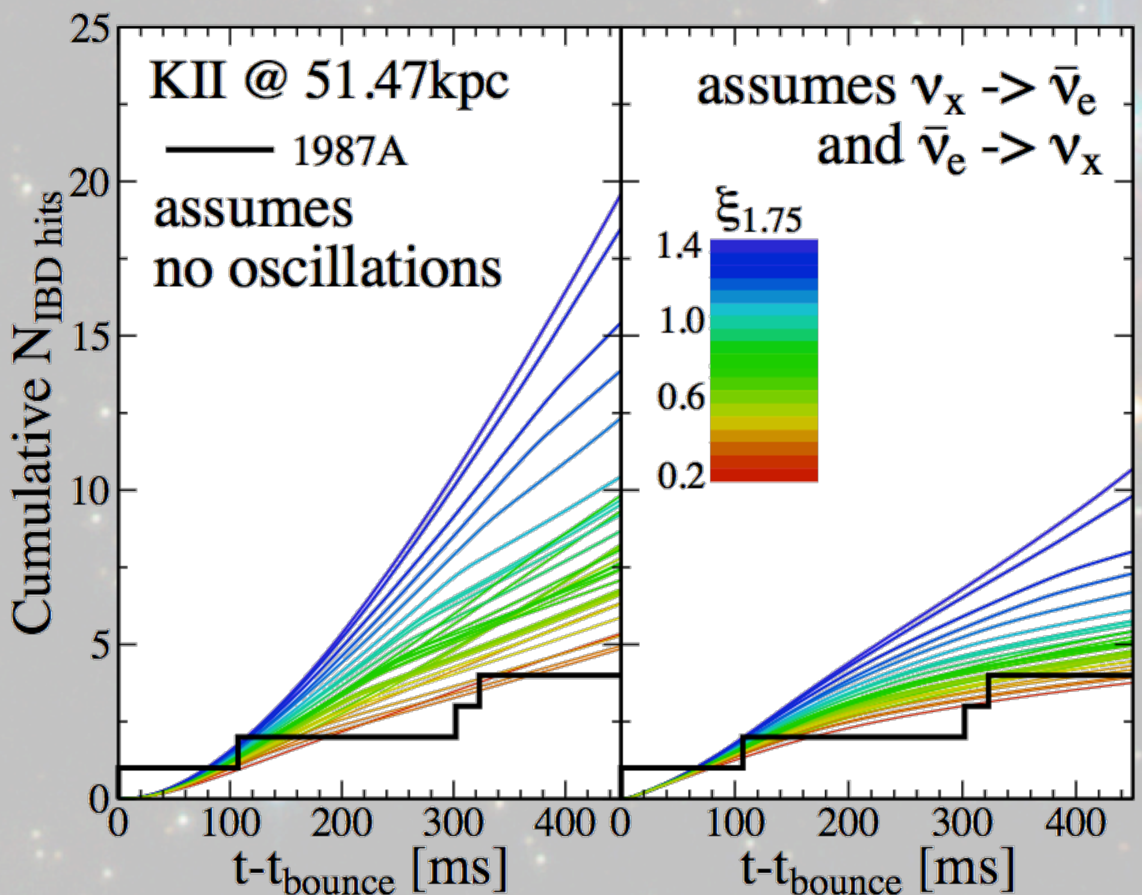
- 1.5D rotation simulations show that significant rotation will alter ν signal



Neutrino Oscillations

- both MSW and collective will complicate picture

1987A



- We use SNOwGLoBES to predict the neutrino signal of our models for K-II at 51.47kpc
- We overlay 1987A's first four events
- Very small number statistics so not much can be said
- 1987A progenitor was not a high $\xi_{1.75}$ progenitor that exploded late

Summary

- Next galactic core-collapse supernova will be well observed in neutrinos
- Early postbounce, preexplosion rates of inverse beta decay interactions will relay direct information on the progenitor structure of the core
- Will allow us to connect inner core structure with presupernova structure of the rest of the star
- Several theoretical hurdles to overcome before precise quantitative conclusions can be reached
- Use `NuLib`!