Multidimensional Core-Collapse Simulations in FLASH & some Microphysics in 1D

Evan O'Connor
Hubble Fellow, NCSU
#MICRA2015, August 17-21, 2015

Core Collapse Supernovae

- CCSNe are one of the brightest astrophysical phenomena in the modern universe.

- They are an important site for nucleosynthesis and the mechanism for unbinding elemental products of stellar evolution and spreading them throughout the galaxy. They help trigger star formation, and are the source both neutron stars and black holes.

- Why I like CCSNe is that they combine many different areas of theoretical, experimental, and observational physics together in one extreme environment.

SN1987A

Anglo-Australian Observatory

- **Astrophysics**
- **Nuclear Physics**
- **Neutrino Physics**
- **General Relativity**
- **Computational Physics**

Computational Codes

- First half of talk will be on nuGR1D, an open-source, general-relativistic, spherically-symmetric, neutrino-radiation hydrodynamics code for core-collapse & NuLib

Available at http://www.GR1Dcode.org;
EO ApJS 219 24 (2015)

- Multi-dimensional simulations performed with FLASH and with FLASH + GR1D's neutrino transport (EO & Couch *in prep.*)

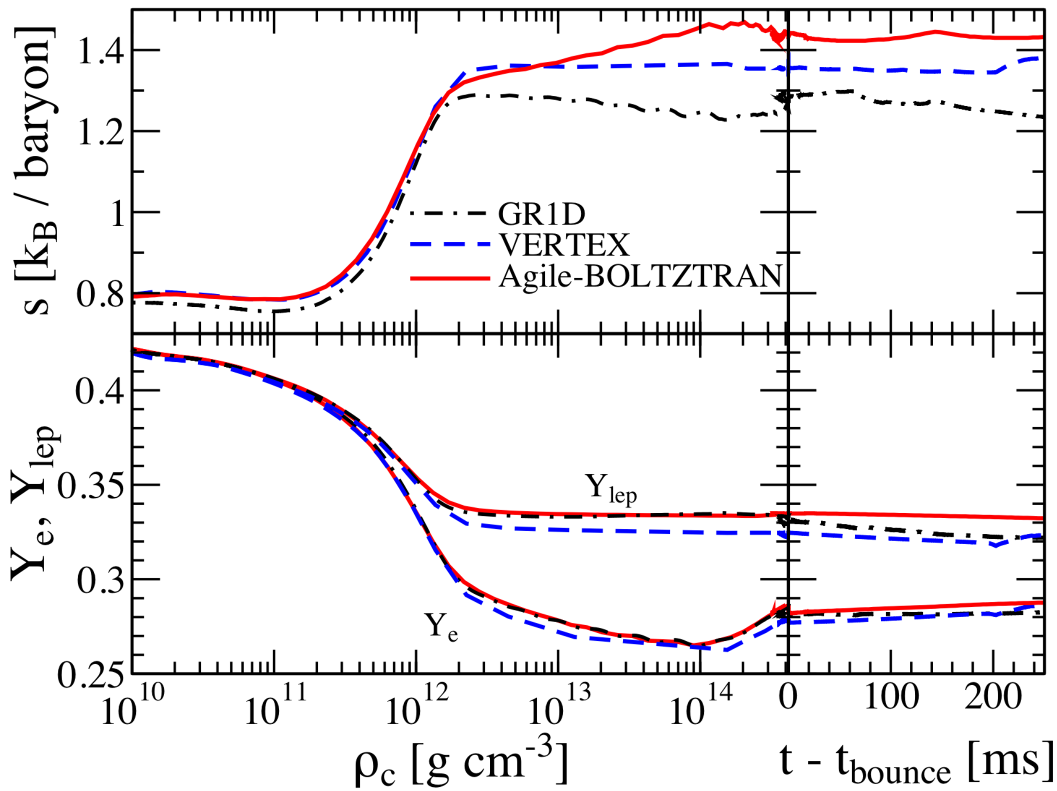
Available at http://www.flash.uchicago.edu
(neutrino radiation not yet open source)

nuGR1D

http://www.GR1Dcode.org
http://www.nulib.org

- GR1Dv2 is a open-source general relativistic neutrino-radiation hydrodynamics code for studying stellar collapse

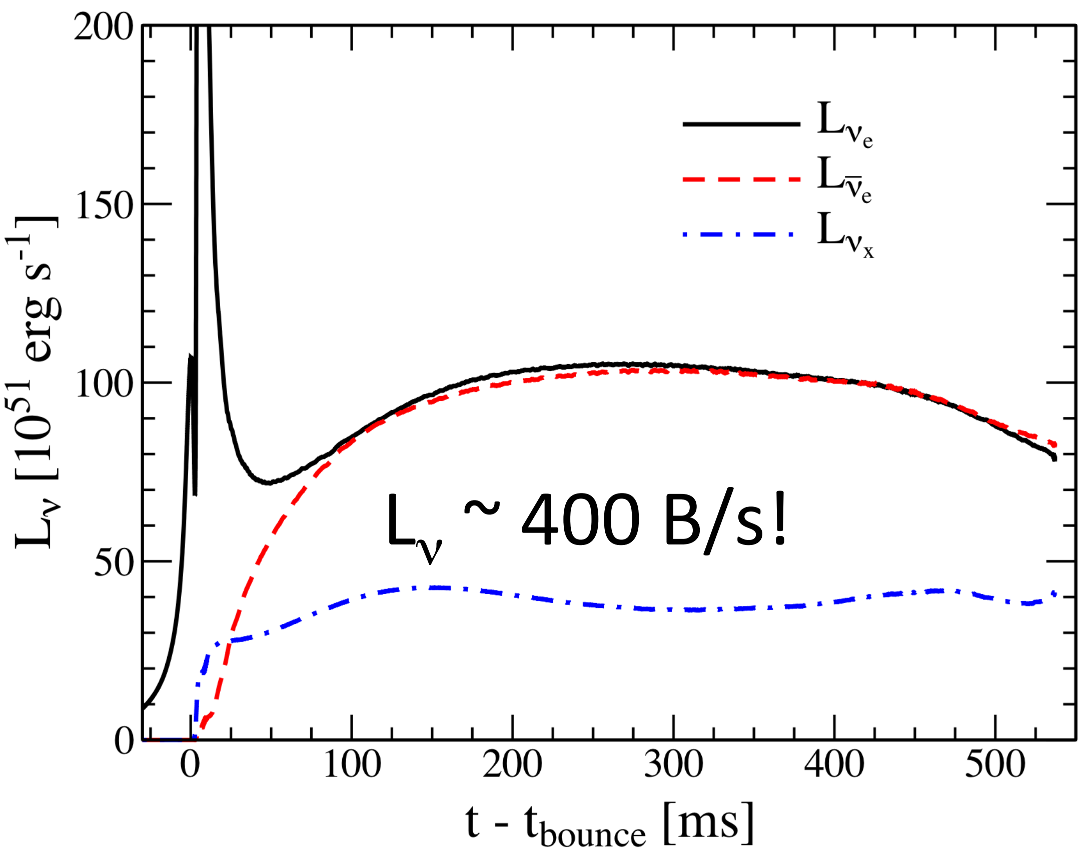
- Neutrino transport is a moment formalism closed via the M1 closure (analytic Eddington tensor)
- 1D, full velocity dependence, full GR.
- Uses NuLib for neutrino interactions
  www.nulib.org
- Compares well with Boltzmann solution



EO ApJS 219 24 (2015); Liebendoerfer et al. (2005)

nuGR1D

- nuGR1D can go all the way to black hole formation in failed core-collapse supernovae

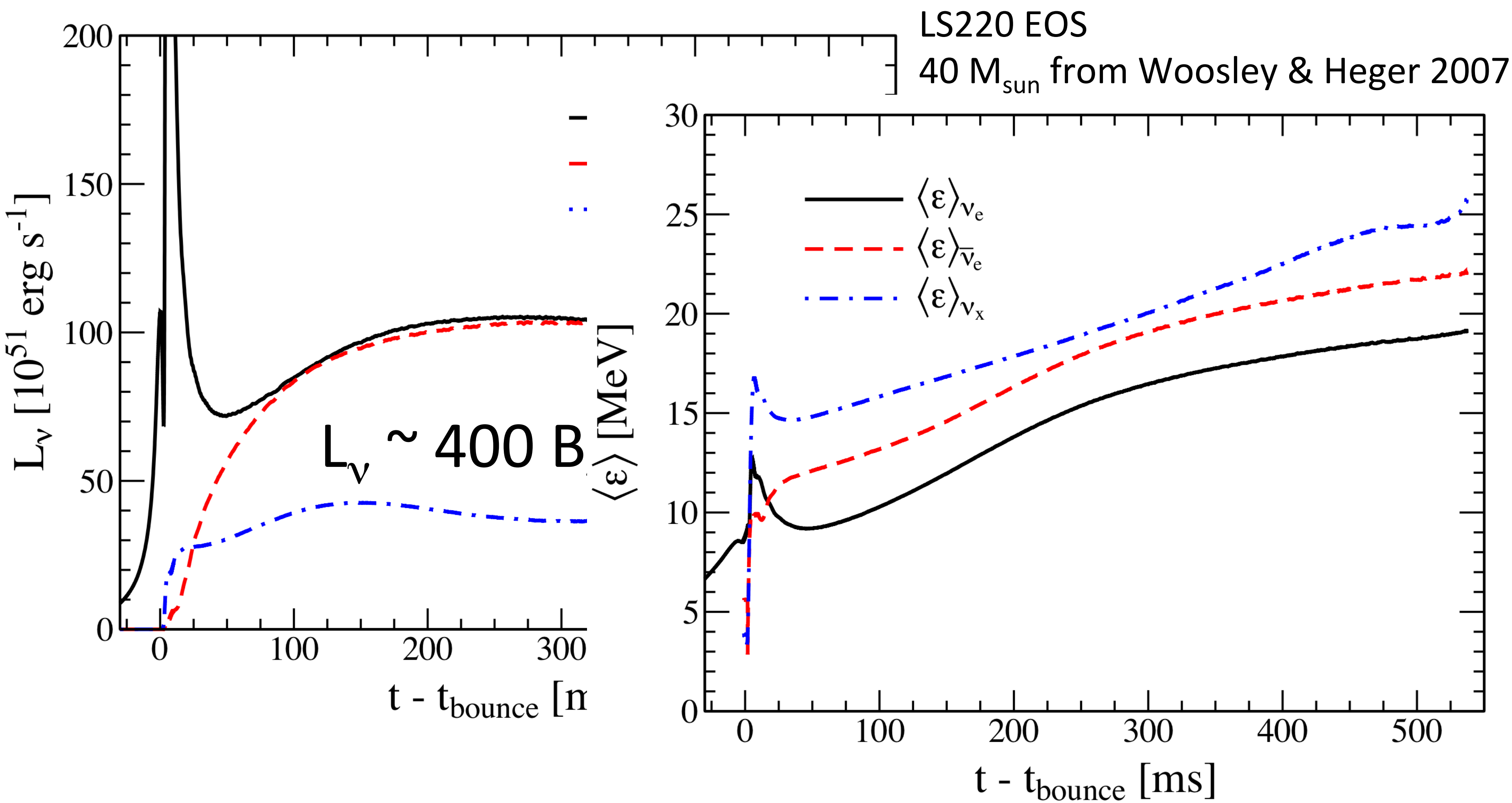


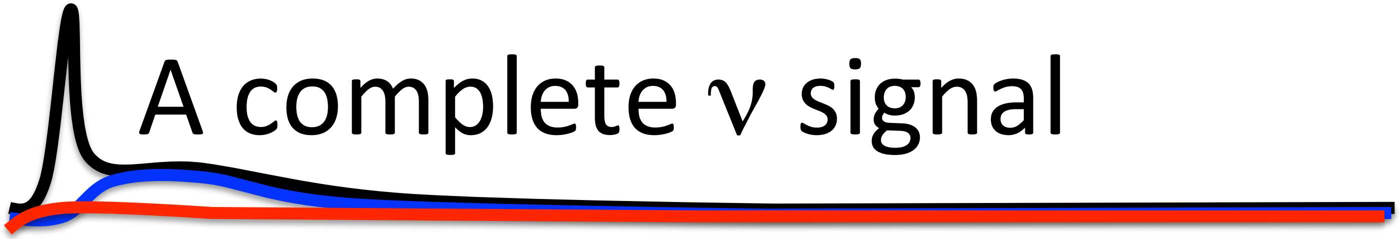
LS220 EOS

40 M_{sun} from Woosley & Heger 2007

nuGR1D

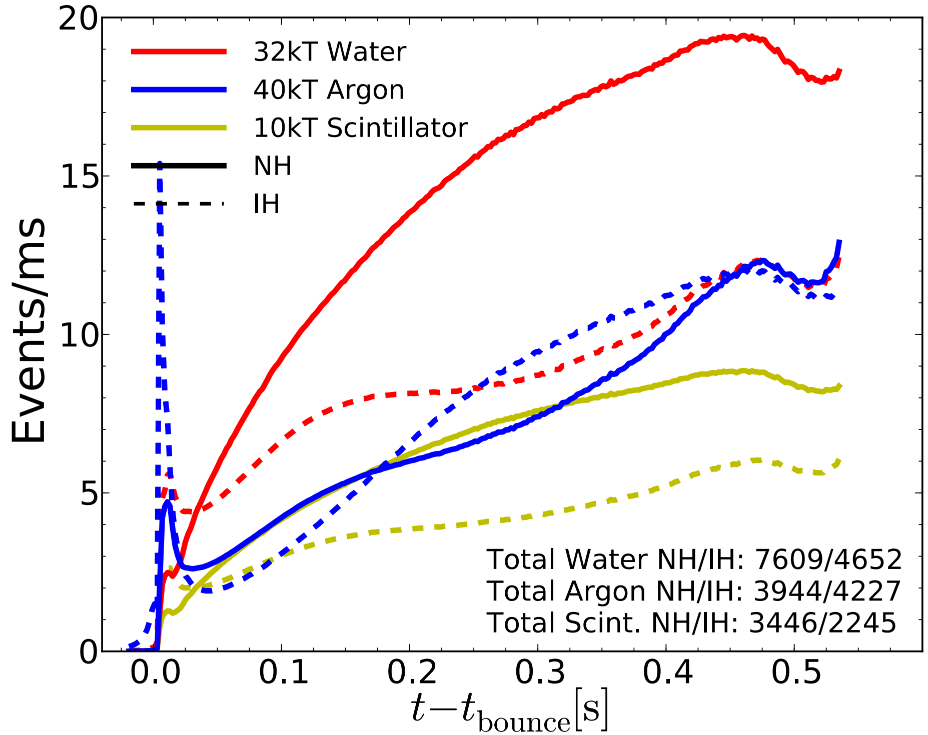
- nuGR1D can go all the way to black hole formation in failed core-collapse supernovae





A complete ν signal

- Neutrino response in water, Liquid Argon, Scintillator with SNOwGLoBES



- 10 kpc
- Ignores collective oscillations
- Includes all SNOwGLoBES channe
- Dominated by:
  - Water: Inverse β decay
  - Argon: ν_e capture on ^{40}Ar
  - Scint: Inverse β decay
- No shocks at resonances

θ_{13} large enough to make MSW resonances adiabatic, small enough to ignore mixing

Dighe & Smirnov (2000)

NH

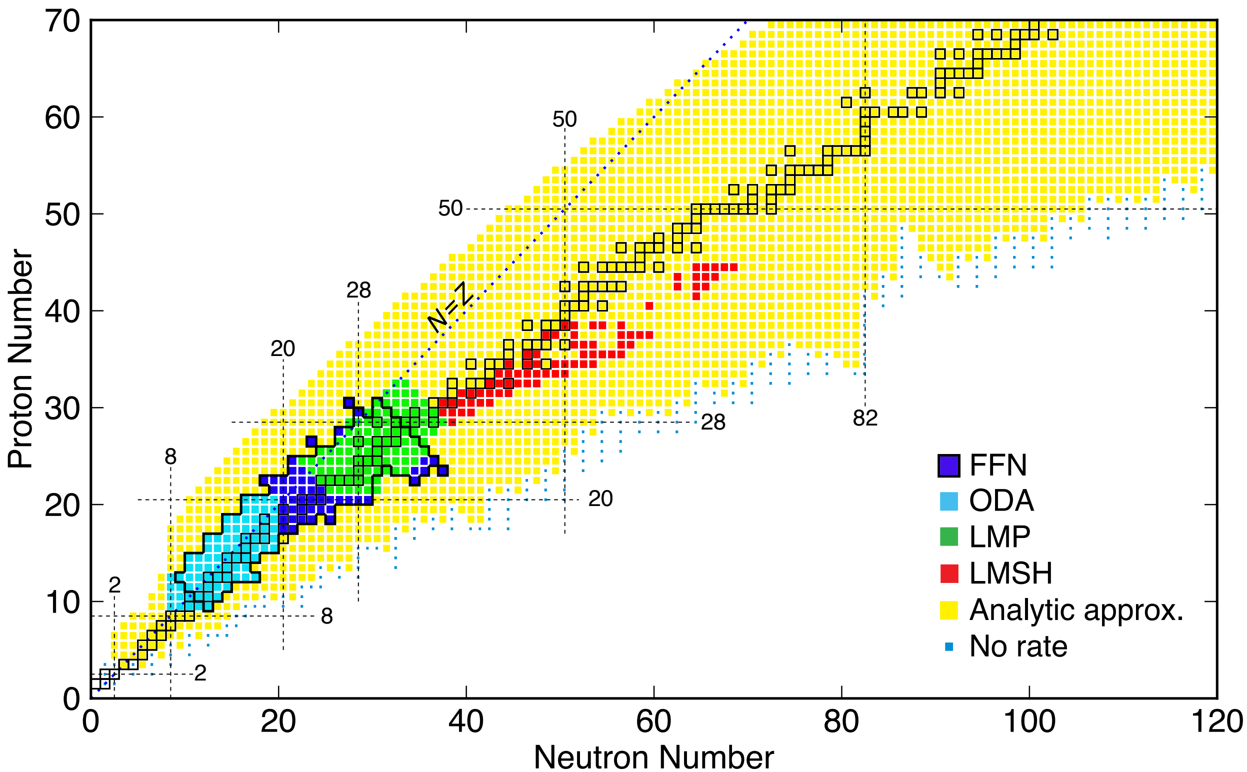
$$N_{\nu_e} = N^0_{\nu_x}$$
$$N_{\bar{\nu}_e} = \cos^2\theta_\odot N^0_{\bar{\nu}_e} + \sin^2\theta_\odot N^0_{\nu_x}$$
$$4N_{\nu_x} = \cos^2\theta_\odot N^0_{\nu_x} + \sin^2\theta_\odot N^0_{\bar{\nu}_e} + N^0_{\nu_e} + 2N^0_{\nu_x}$$

IH

$$N_{\nu_e} = \sin^2\theta_\odot N^0_{\nu_e} + \cos^2\theta_\odot N^0_{\nu_x}$$
$$N_{\bar{\nu}_e} = N^0_{\nu_x}$$
$$4N_{\nu_x} = \sin^2\theta_\odot N^0_{\nu_x} + \cos^2\theta_\odot N^0_{\nu_e} + N^0_{\bar{\nu}_e} + 2N^0_{\nu_x}$$

Electron Capture Rates

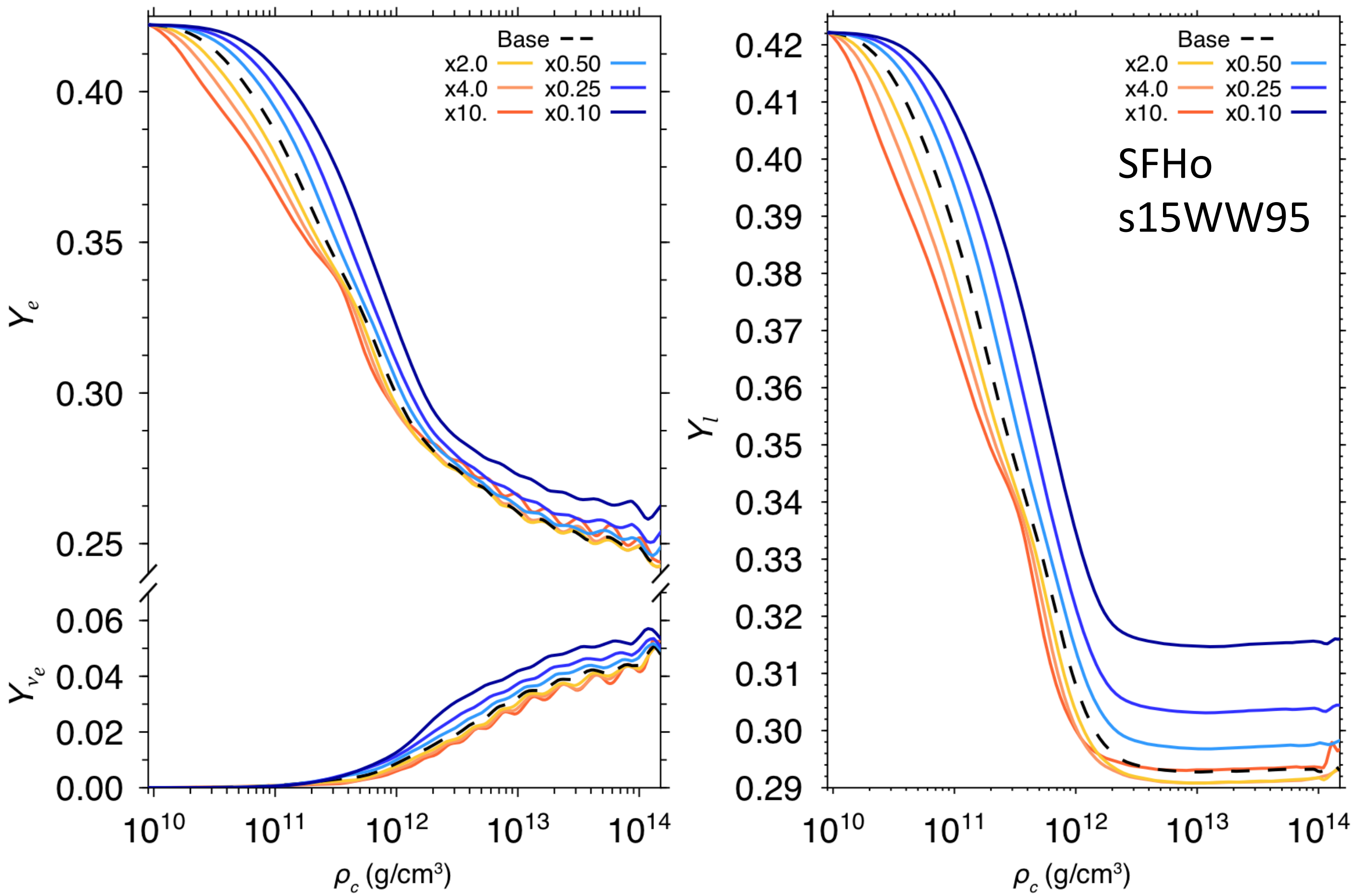
- As part of an upcoming update to NuLib, we have developed a suite of electron capture rates calculations on individual heavy nuclei
- EOS of Hempel et al. (2012) & Steiner et al. (2013), for example, predict full distribution of nuclei



Figures by Chris Sullivan
Sullivan et al. *in prep*

Electron Capture Rates

- Statistical and systematic variations in the electron capture rates have modest effect on the collapse phase dynamics

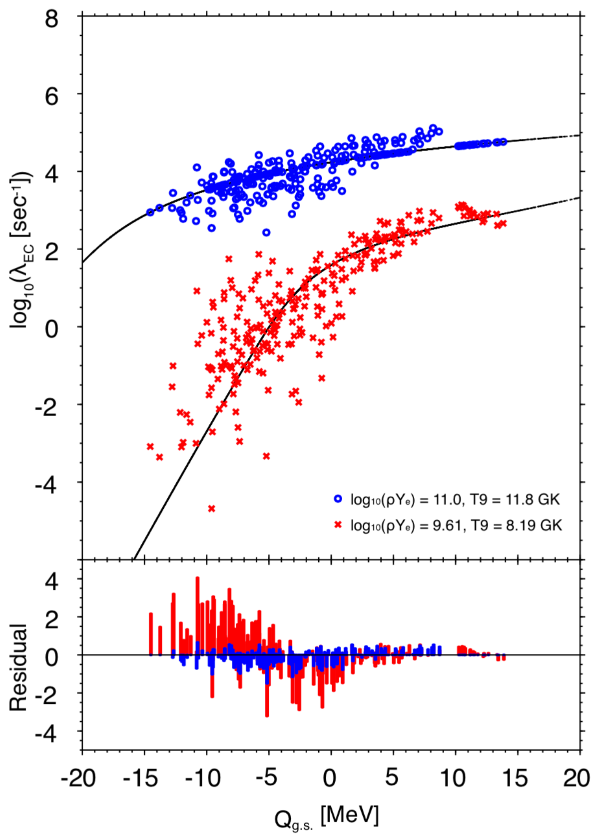


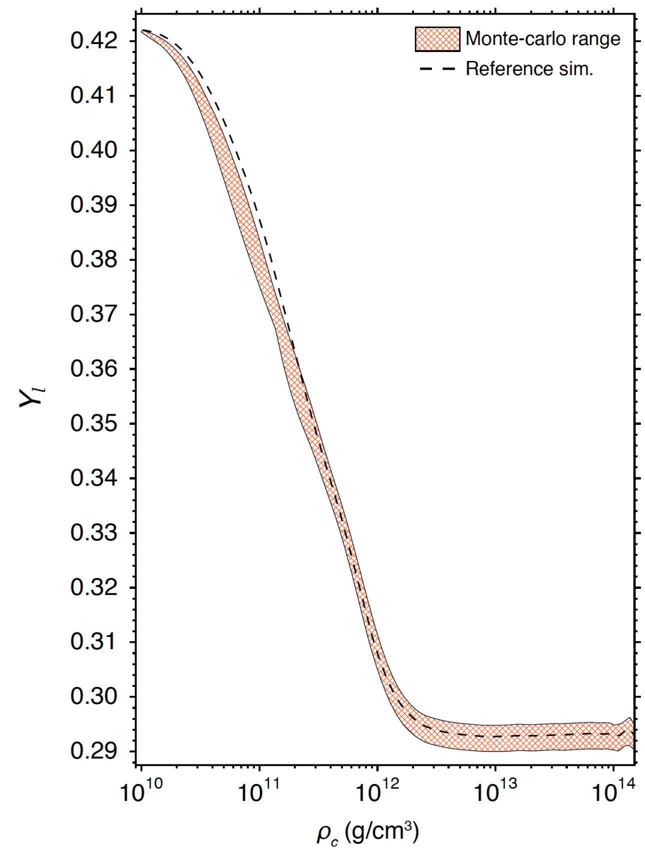
Figures by Chris Sullivan

Sullivan et al. *in prep*

Electron Capture Rates

- Statistical and systematic variations in the electron capture rates have modest effect on the collapse phase dynamics



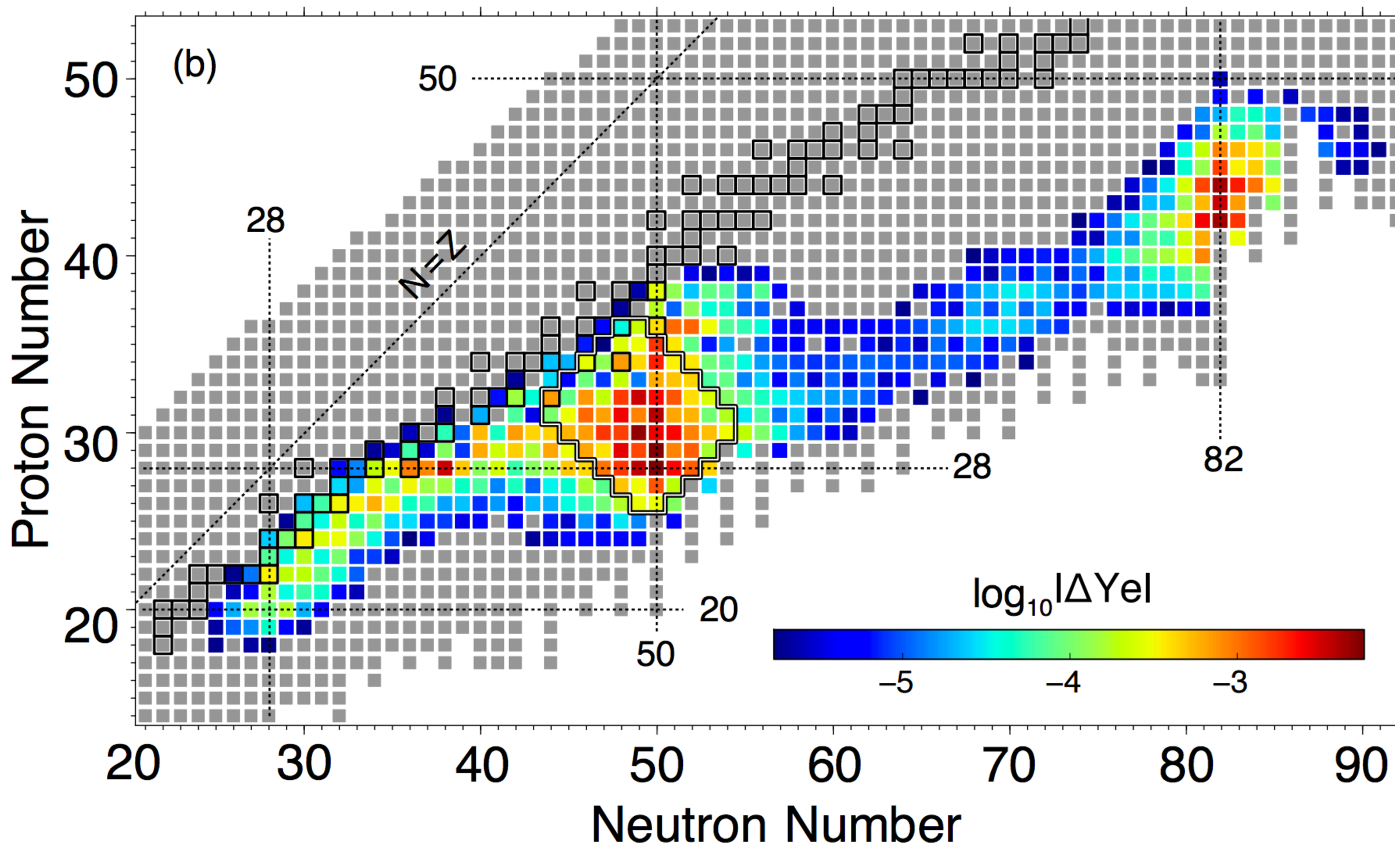


Figures by Chris Sullivan

Electron Capture Rates

- What nuclei are undergoing electron capture during collapse?
- These nuclei would be the most important to study experimentally in future rare isotope facilities and theoretically to derive robust rates

Colors show measure of deleptonization due to particular nuclide



Electron capture on ^{78}Ni occurs the most--4% of all captures!

Figures by Chris Sullivan; Sullivan et al. *(in prep)*

Computational Codes

- First half of talk will be on nuGR1D, an open-source, general-relativistic, spherically-symmetric, neutrino-radiation hydrodynamics code for core-collapse & NuLib

Available at http://www.GR1Dcode.org;
EO ApJS 219 24 (2015)

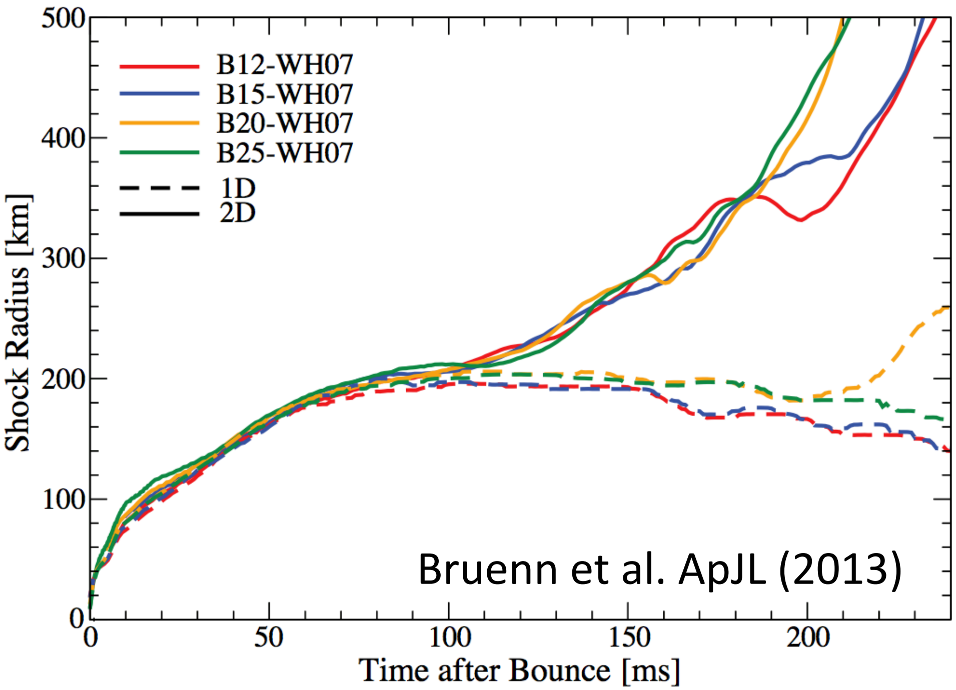
- Multi-dimensional simulations performed with FLASH and with FLASH + GR1D's neutrino transport (EO & Couch *in prep.*)

Available at http://www.flash.uchicago.edu
(neutrino radiation not yet open source)

s12, s15, s20, and s25 in FLASH

Oakridge selected 4 models to study in 2D

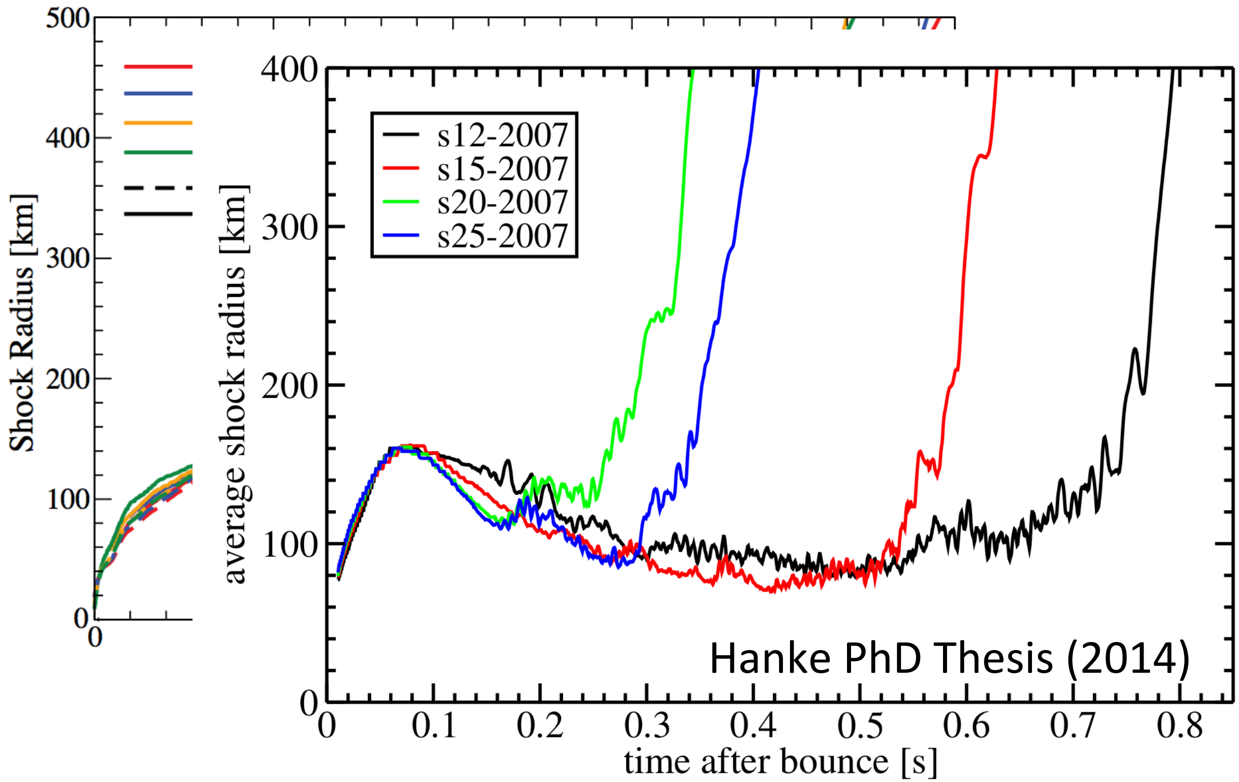
- Woosley & Heger 2007: $12M_{sun}$, $15M_{sun}$, $20M_{sun}$, and $25M_{sun}$
- LS220 EOS, GR Effective Potential, MGFLD, Ray-by-Ray+



s12, s15, s20, and s25 in FLASH

Oakridge selected 4 models to study in 2D

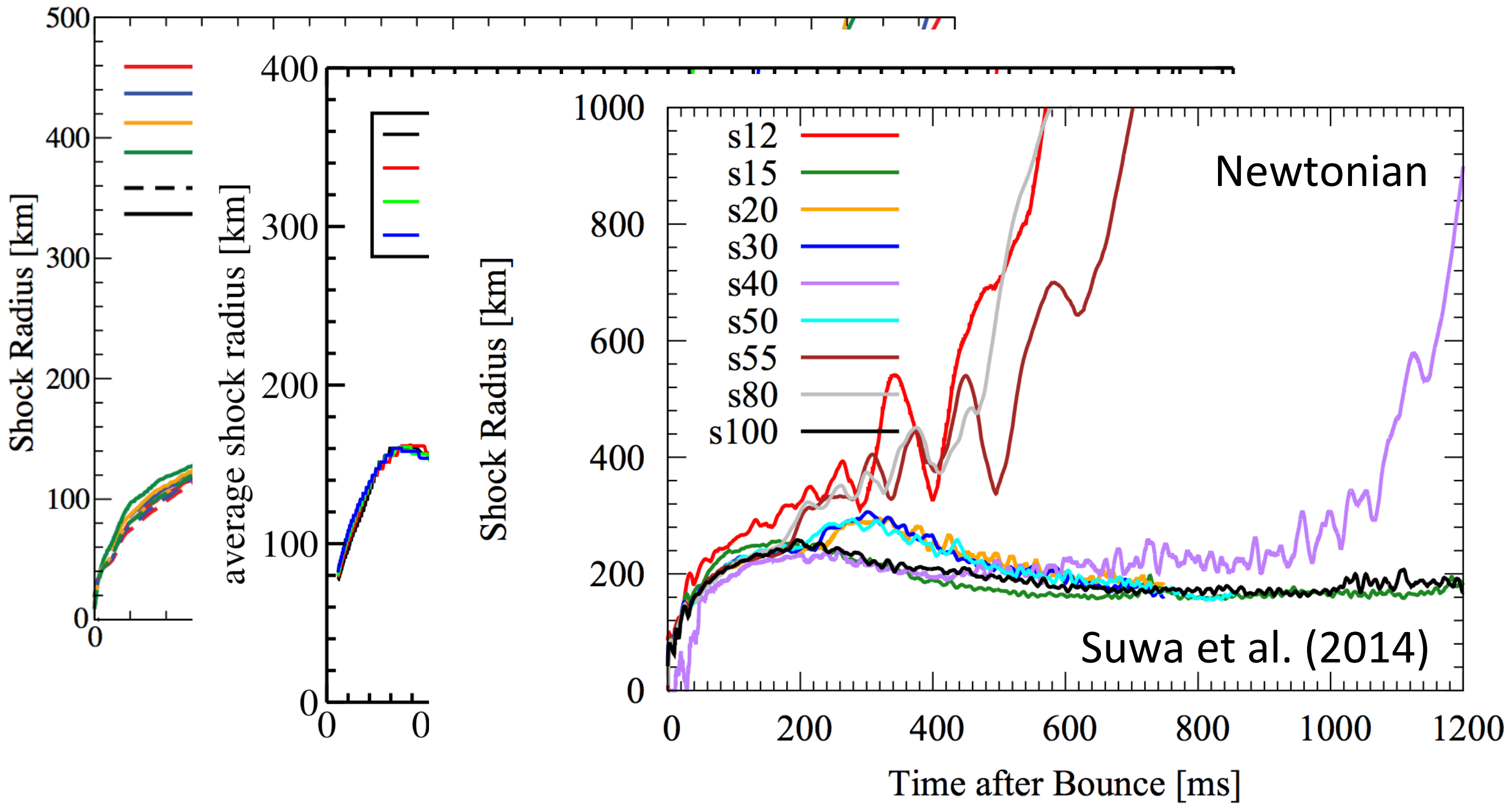
- Woosley & Heger 2007: $12M_{sun}$, $15M_{sun}$, $20M_{sun}$, and $25M_{sun}$
- LS220 EOS, GR Effective Potential, MGFLD, Ray-by-Ray+



s12, s15, s20, and s25 in FLASH

Oakridge selected 4 models to study in 2D

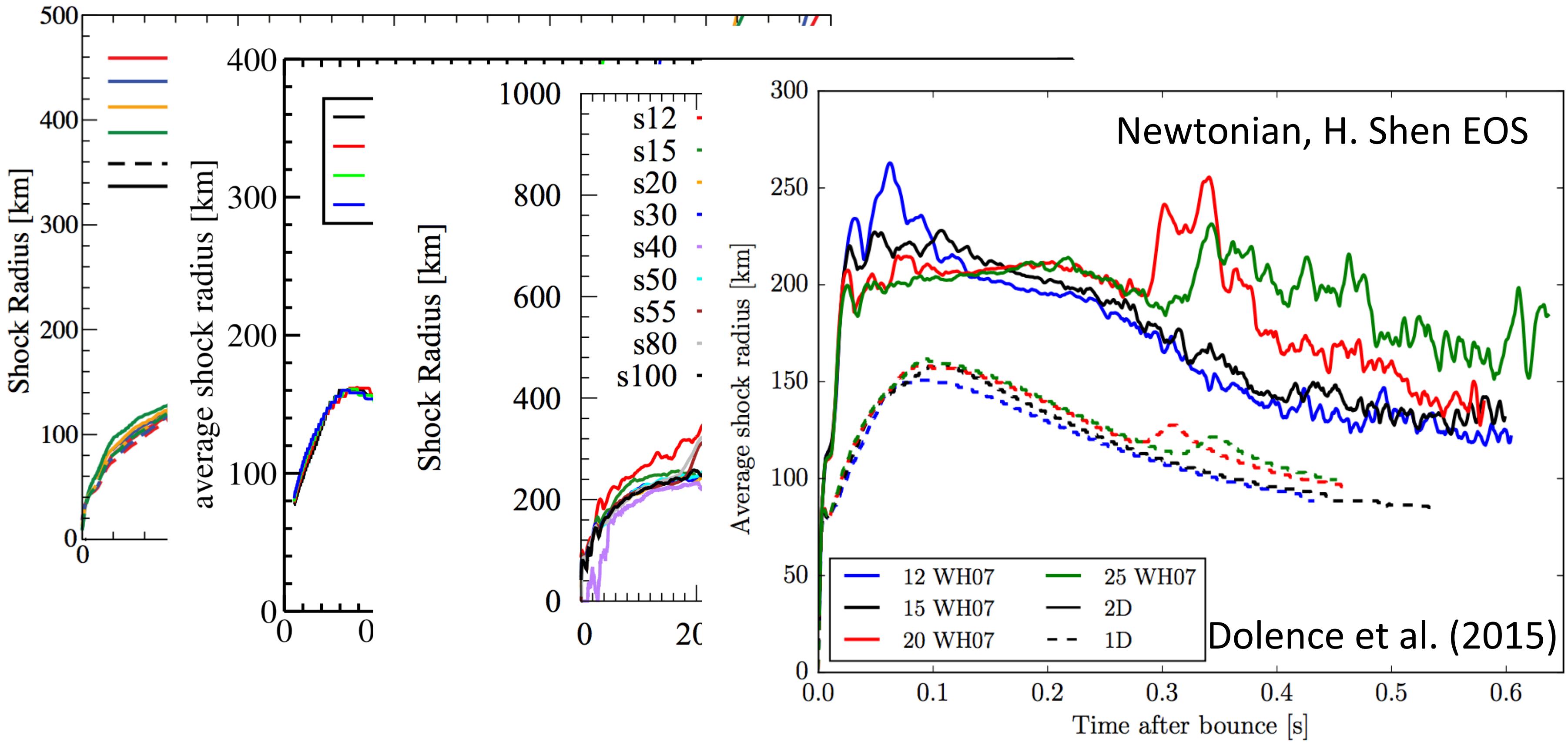
- Woosley & Heger 2007: $12M_{sun}$, $15M_{sun}$, $20M_{sun}$, and $25M_{sun}$
- LS220 EOS, GR Effective Potential, MGFLD, Ray-by-Ray+



s12, s15, s20, and s25 in FLASH

Oakridge selected 4 models to study in 2D

- Woosley & Heger 2007: $12M_{sun}$, $15M_{sun}$, $20M_{sun}$, and $25M_{sun}$
- LS220 EOS, GR Effective Potential, MGFLD, Ray-by-Ray+



Multi-D Core-Collapse in FLASH

FLASH is a multiphysics, multiscale simulation code

- Spherical (1D), Cylindrical (2D), Cartesian (3D)
- Mesh refinement gives effectively 0.5 degree resolution, smallest grid zone 500m
- HLLC Riemann Solver with PPM reconstruction, Unsplit Hydro
- Neutrino Leakage scheme
- Newtonian gravity

All in FLASH 4.3

movie

3D simulation with neutrino leakage
Couch & O'Connor (2014)

Multi-D M1 in FLASH

preliminary,
O'Connor & Couch in prep

FLASH is a multiphysics, multiscale simulation code

In this work, we:

1. Implement GR1D's M1 radiation transport scheme
   - Initially excluding velocity & energy coupling terms
   - Map from GR1D after bounce to capture important physics during collapse
2. Extend gravity solver to include Effective General Relativistic Potential (Marek et al. 2006 Case A)
3. Simulate 5 stars in 1D & 2D, Newtonian & GR gravity

Multi-D M1 in FLASH

preliminary,
O'Connor & Couch in prep

From Rampp & Janka (2002)

1D spherical Newtonian:

$$\partial_t E + \frac{1}{r^2}\partial_r[r^2 F^r] = \eta - \kappa_a E\,,$$

$$\partial_t F^r + \frac{1}{r^2}\partial_r[r^2 P^{rr}] = -[\kappa_s + \kappa_a]F^r + \frac{P^{\theta\theta} + P^{\phi\phi}}{r}\,,$$

1D spherical Eff. GR:

$$\partial_t E + \frac{1}{r^2}\partial_r[\alpha r^2 F^r] = \alpha\eta - \alpha\kappa_a E - \alpha F^r \partial_r \phi\,,$$

$$\partial_t F^r + \frac{1}{r^2}\partial_r[\alpha r^2 P^{rr}] = -\alpha[\kappa_s + \kappa_a]F^r + \alpha\frac{P^{\theta\theta} + P^{\phi\phi}}{r} - \alpha E \partial_r \phi$$

Multi-D M1 in FLASH

preliminary, O'Connor & Couch in prep

From Rampp & Janka (2002)

2D cylindrical Newtonian:

$$\partial_t E + \frac{1}{r}\partial_r[rF^r] + \partial_z[F^z] = \eta - \kappa_a E\,,$$

$$\partial_t F^r + \frac{1}{r}\partial_r[rP^{rr}] + \partial_z[P^{zr}] = -[\kappa_s + \kappa_a]F^r + \frac{P^{\phi\phi}}{r}\,,$$

$$\partial_t F^z + \frac{1}{r}\partial_r[rP^{rz}] + \partial_z[rP^{zz}] = -[\kappa_s + \kappa_a]F^z\,.$$

2D cylindrical Eff. GR:

$$\partial_t E + \frac{1}{r}\partial_r[\alpha rF^r] + \partial_z[\alpha F^z] = \alpha\eta - \alpha\kappa_a E - \alpha F^i\partial_i\phi\,,$$

$$\partial_t F^r + \frac{1}{r}\partial_r[\alpha rP^{rr}] + \partial_z[\alpha P^{zr}] = -\alpha[\kappa_s + \kappa_a]F^r + \alpha\frac{P^{\phi\phi}}{r} - \alpha E\partial_r\phi\,,$$

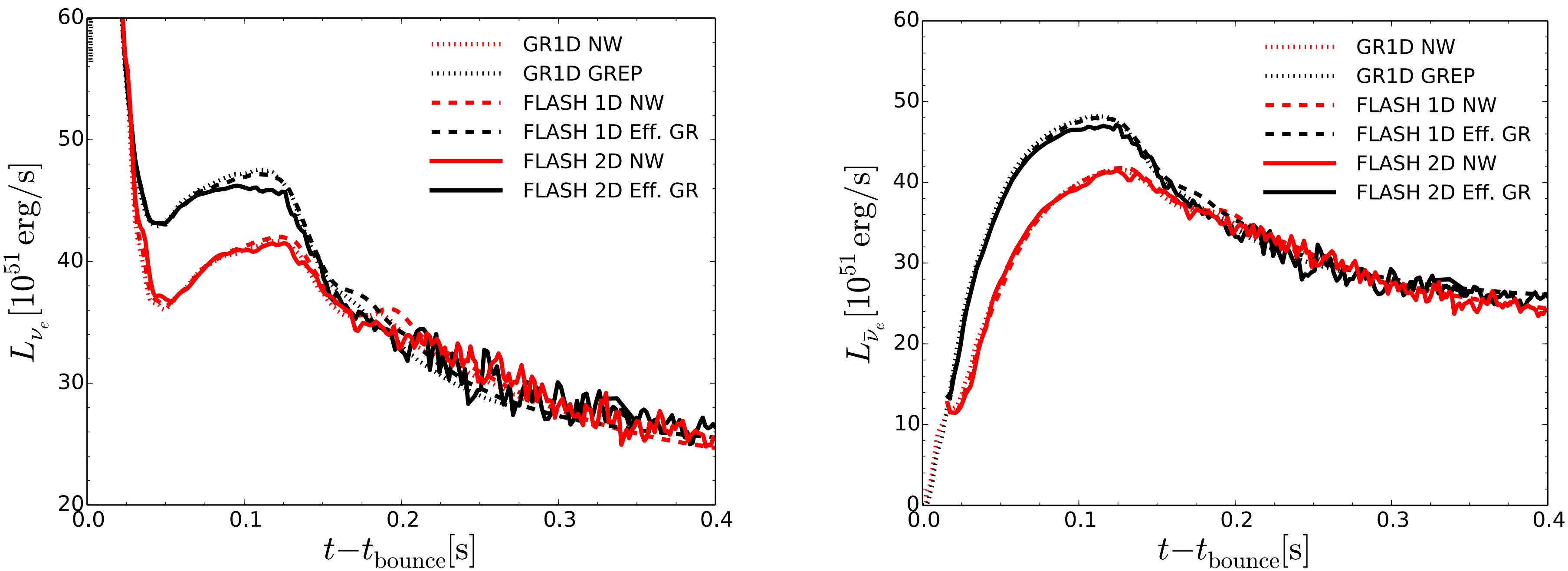
$$\partial_t F^z + \frac{1}{r}\partial_r[\alpha rP^{rz}] + \partial_z[\alpha rP^{zz}] = -\alpha[\kappa_s + \kappa_a]F^z - \alpha E\partial_z\phi\,.$$

1D-1D-2D check

preliminary, O'Connor & Couch in prep

Compare GR1D (with Effective Potential, full velocity dependence and energy group coupling) to FLASH 1D and FLASH 2D. GR & 2D increase heating!

s15WW95, LS220 EOS



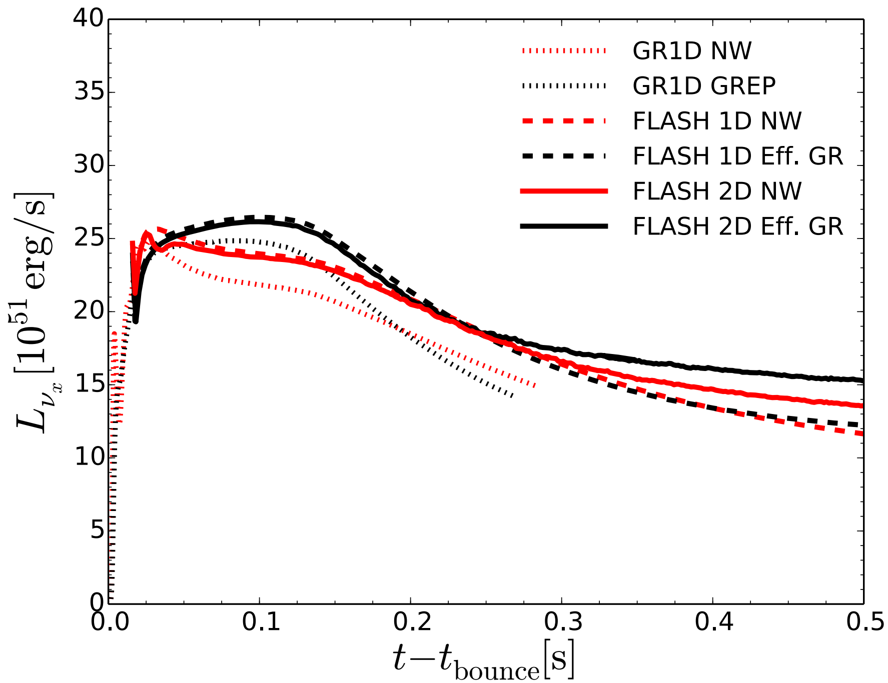
See Liebendoerfer et al. (2001); Mueller et al. (2012) for similar results

1D-1D-2D check

preliminary,
O'Connor & Couch in prep

Compare GR1D (with Effective Potential, full velocity dependence and energy group coupling) to FLASH 1D and FLASH 2D. GR & 2D increase heating!

s15WW95, LS220 EOS



See Liebendoerfer et al. (2001); Mueller et al. (2012) for similar results

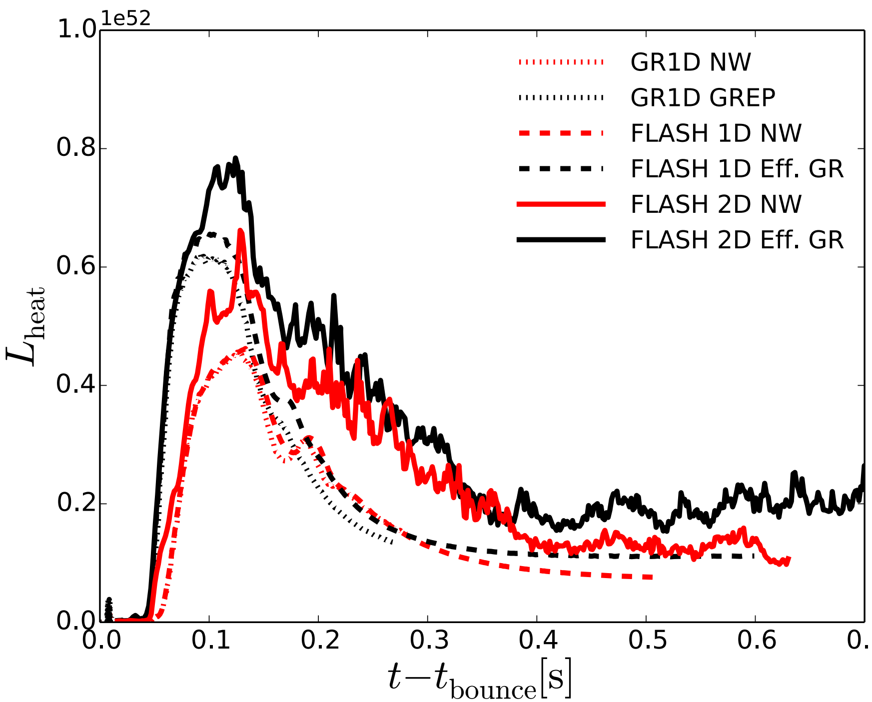
1D-1D-2D check

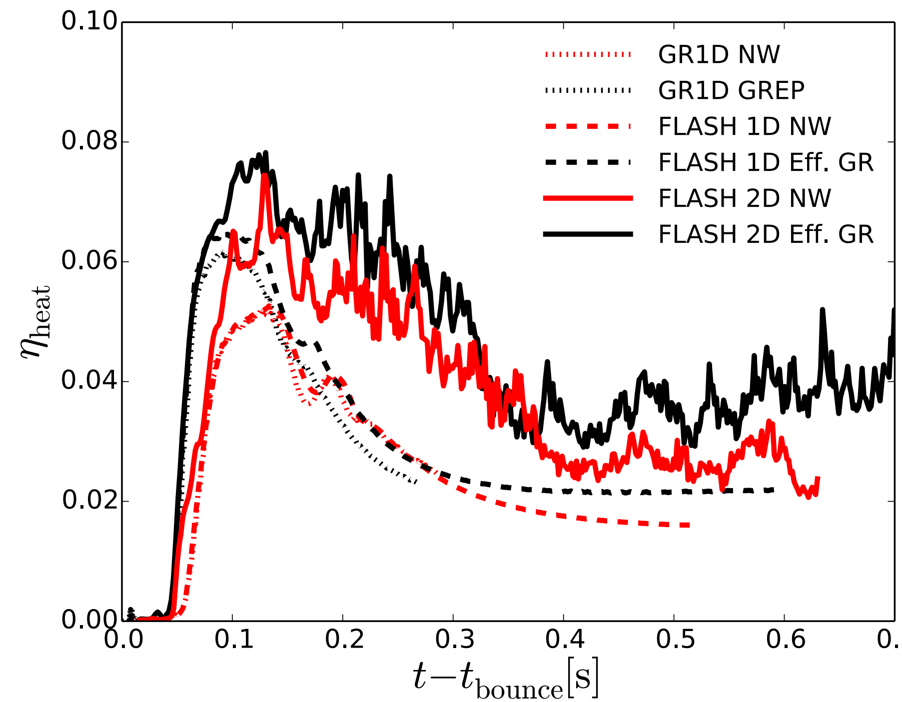
preliminary, O'Connor & Couch in prep

Compare GR1D (with Effective Potential, full velocity dependence and energy group coupling) to FLASH 1D and FLASH 2D. GR & 2D increase heating!

$$\eta_{\rm heat} = \frac{L_{\rm heat}}{(L_{\nu_e}+L_{\bar{\nu}_e})|_{\rm gain}}$$

s15WW95, LS220 EOS





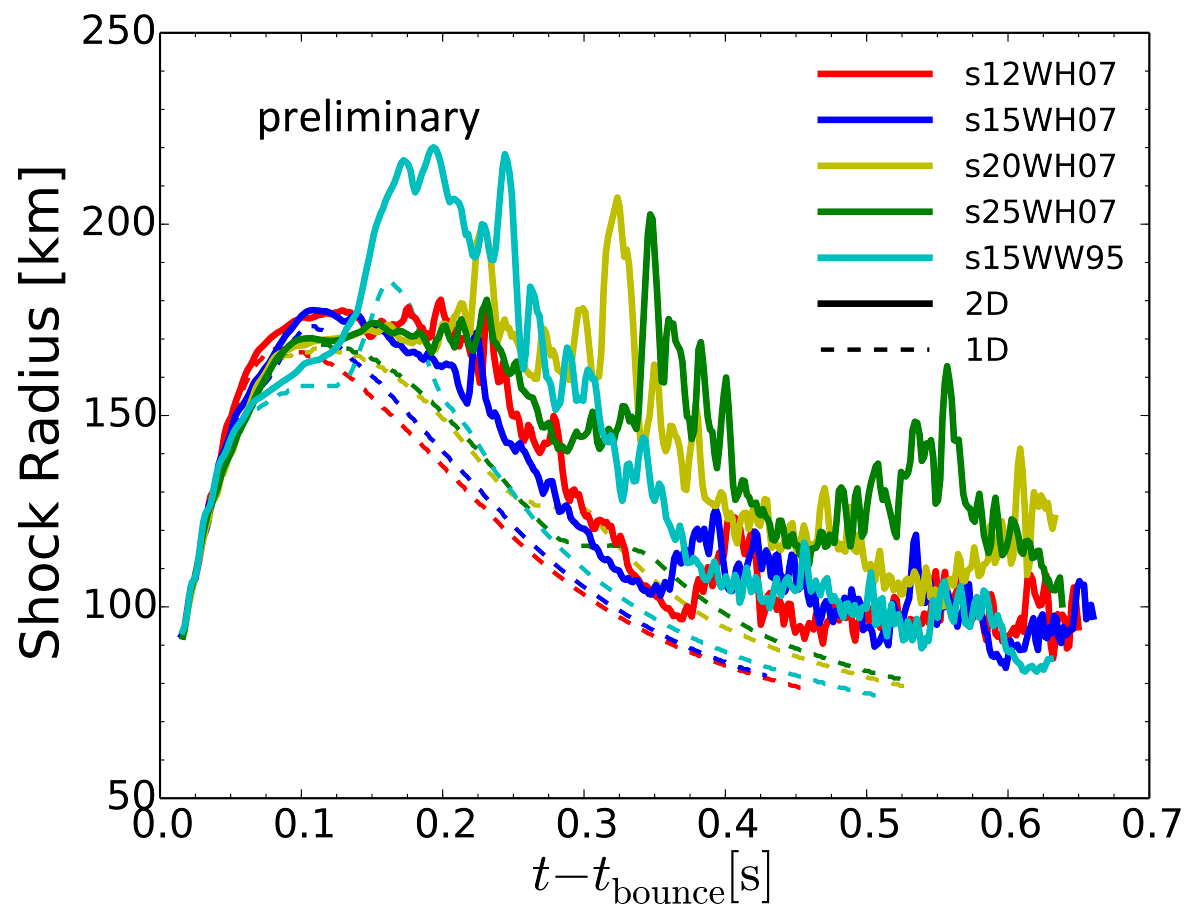
See Liebendoerfer et al. (2001); Mueller et al. (2012) for similar results

Newtonian Gravity

preliminary,
O'Connor & Couch in prep

All Newtonian simulations we perform in 1D and 2D fail up to at 650ms after bounce

- 2D simulations stay very spherical until ~100-150ms after bounce
- 2D gives appreciable boost to heating efficiency ~30%

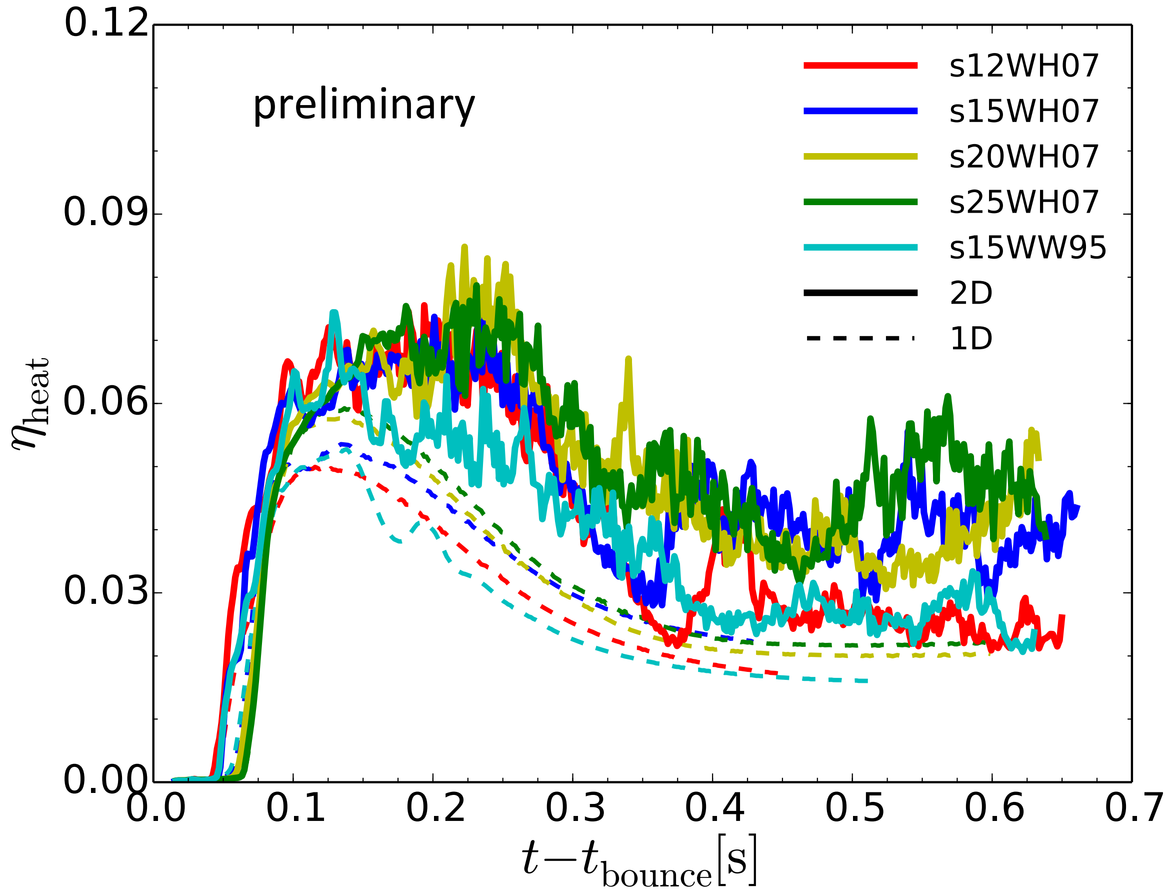


Newtonian Gravity

preliminary,
O'Connor & Couch in prep

All Newtonian simulations we perform in 1D and 2D fail up to at 650ms after bounce

- 2D simulations stay very spherical until ~100-150ms after bounce
- 2D gives appreciable boost to heating efficiency ~30%

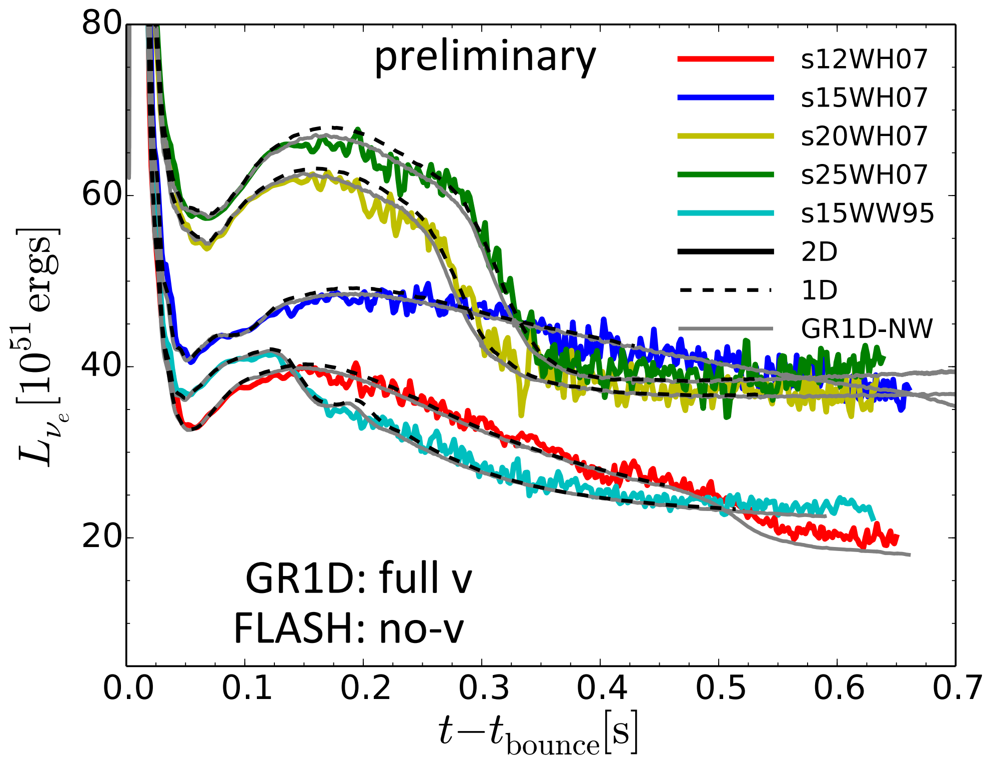


Newtonian Gravity

preliminary, O'Connor & Couch in prep

The failure to explodes means the accretion rate is identical to 1D, neutrino signal, while modulated, closely follows 1D

- Velocity terms, energy-group coupling, and inelastic scattering have little effect on ν_e and anti-ν_e neutrinos
- Significant effect on ν_x because of inelastic scattering
- PNS convection at late times influences ν_x

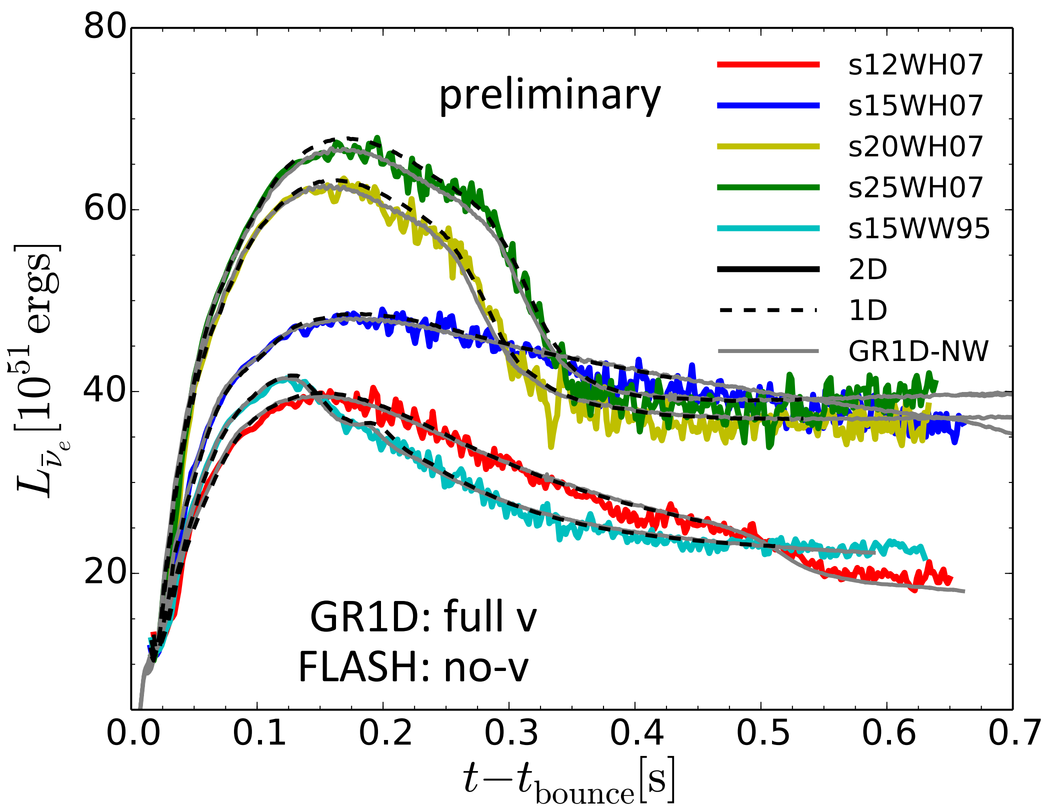


Newtonian Gravity

preliminary, O'Connor & Couch in prep

The failure to explodes means the accretion rate is identical to 1D, neutrino signal, while modulated, closely follows 1D

- Velocity terms, energy-group coupling, and inelastic scattering have little effect on ν_e and anti-ν_e neutrinos
- Significant effect on ν_x because of inelastic scattering
- PNS convection at late times influences ν_x

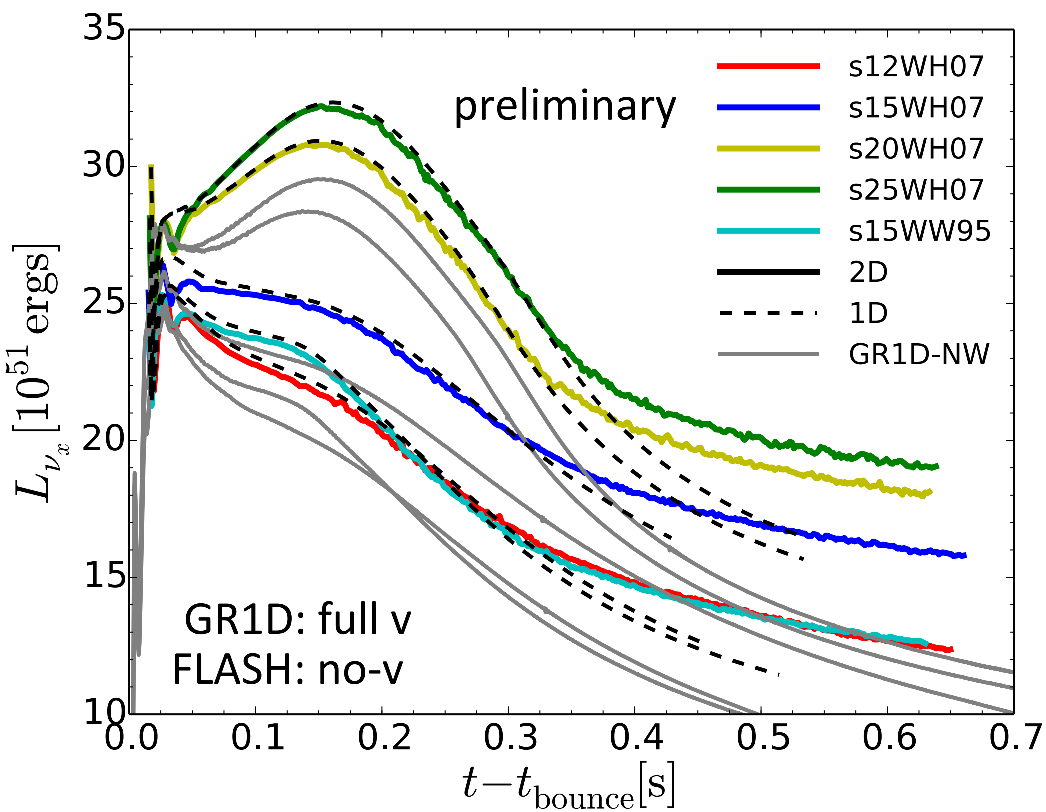


Newtonian Gravity

preliminary,
O'Connor & Couch in prep

The failure to explodes means the accretion rate is identical to 1D, neutrino signal, while modulated, closely follows 1D

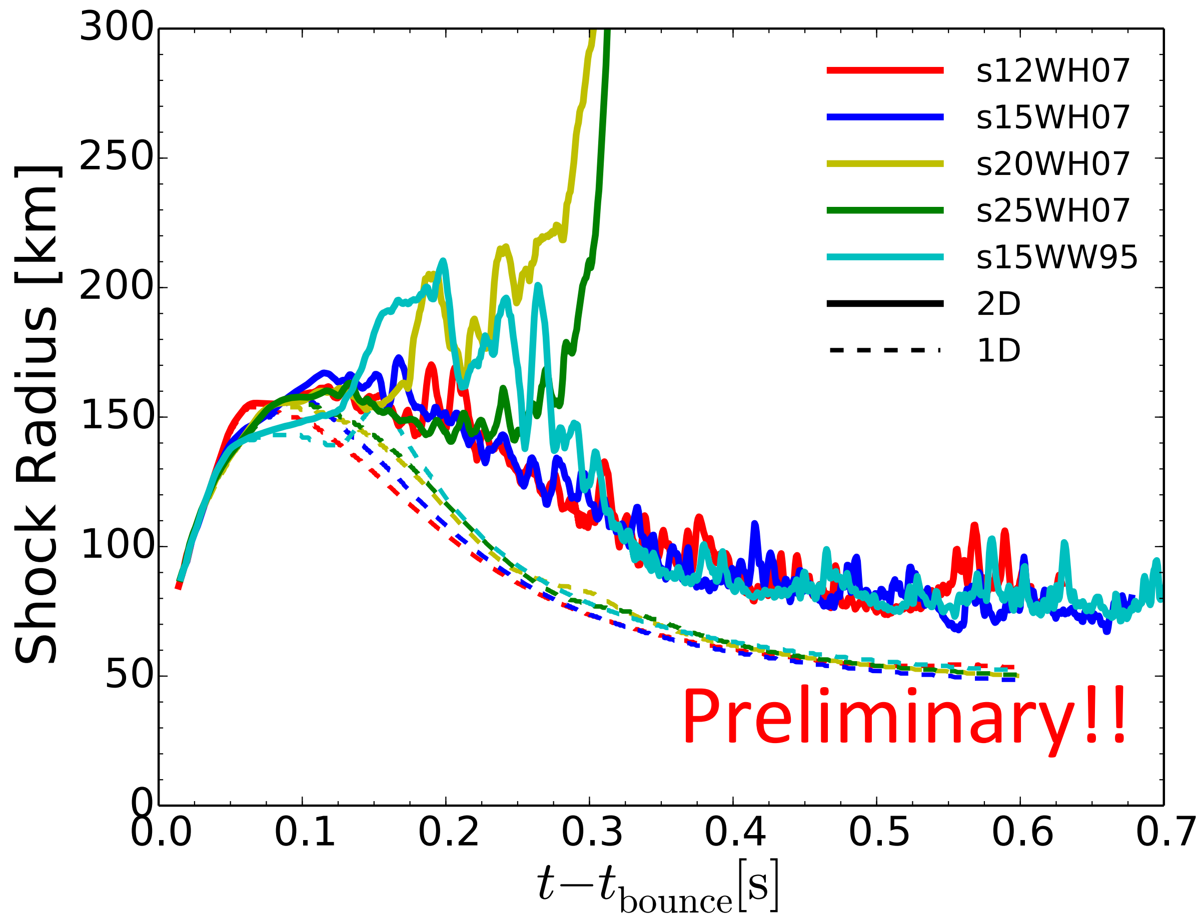
- Velocity terms, energy-group coupling, and inelastic scattering have little effect on ν_e and anti-ν_e neutrinos
- Significant effect on ν_x because of inelastic scattering
- PNS convection at late times influences ν_x



Effective GR Gravity

preliminary, O'Connor & Couch in prep

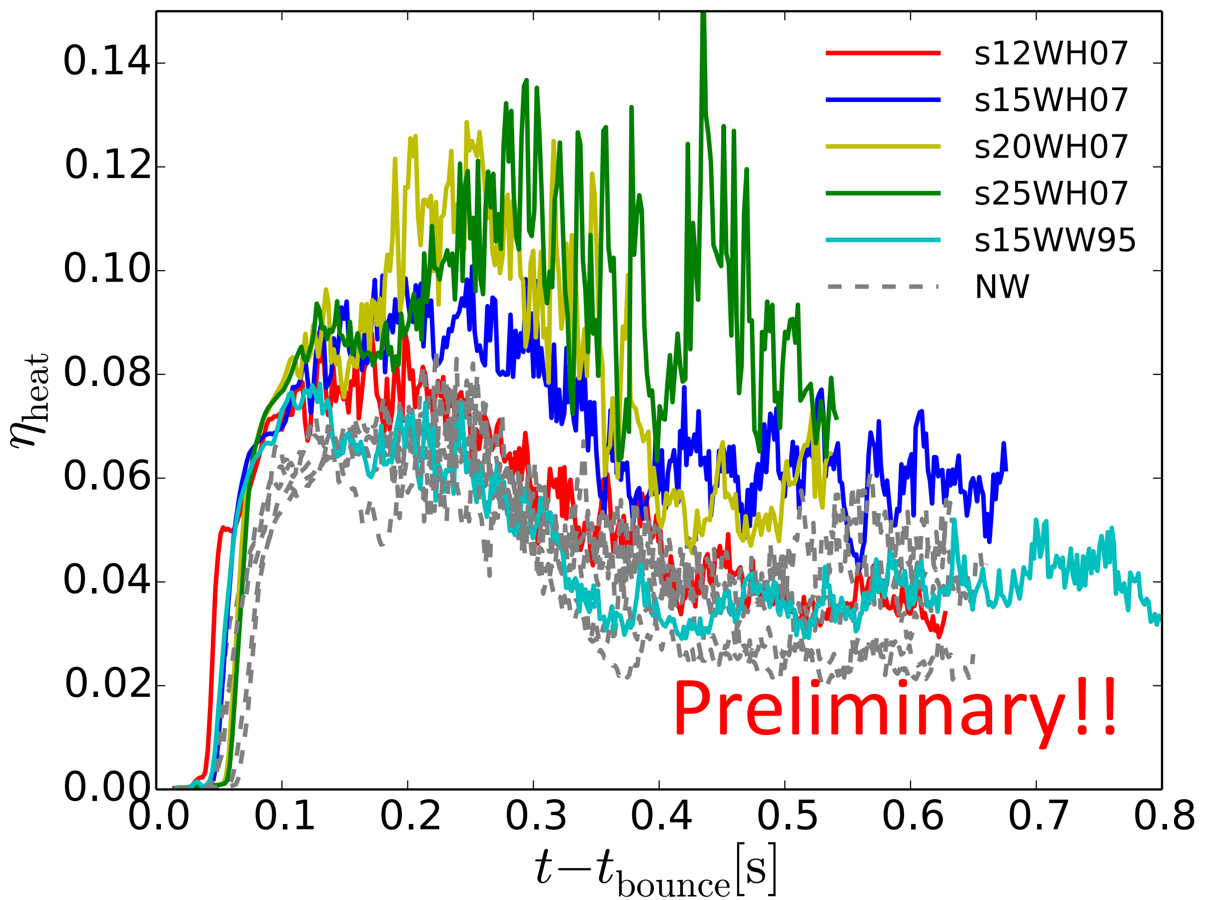
- In FLASH, we find that the GR effective potential is suggesting successful explosions in s20 and s25 after ~300ms but not s12 or s15
- Heating Efficiency is enhanced in all models via GR
- Similar to other studies with similar initial data
- Still differences e.g. convection is stronger



Effective GR Gravity

preliminary, O'Connor & Couch in prep

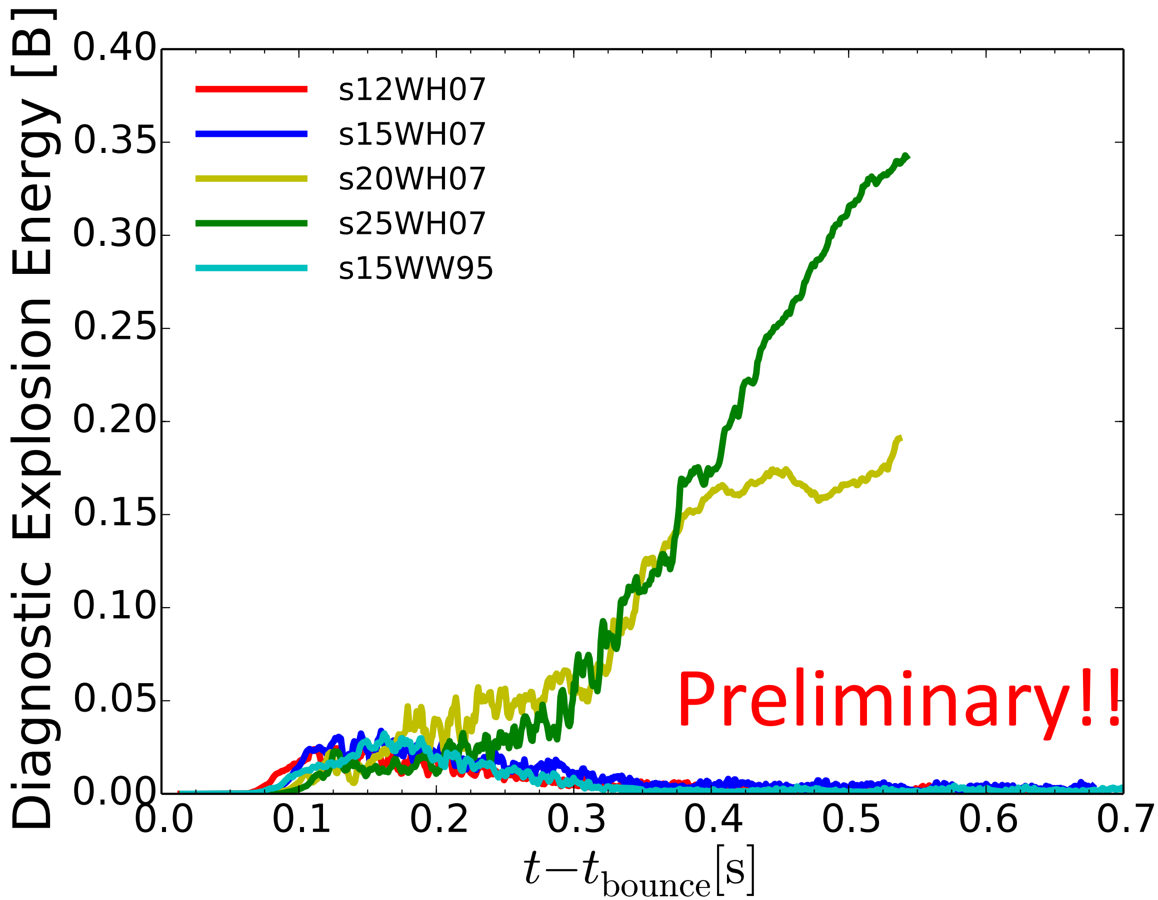
- In FLASH, we find that the GR effective potential is suggesting successful explosions in s20 and s25 after ~300ms but not s12 or s15
- Heating Efficiency is enhanced in all models via GR
- Similar to other studies with similar initial data
- Still differences e.g. convection is stronger



Effective GR Gravity

preliminary, O'Connor & Couch in prep

- In FLASH, we find that the GR effective potential is suggesting successful explosions in s20 and s25 after ~300ms but not s12 or s15
- Heating Efficiency is enhanced in all models via GR
- Similar to other studies with similar initial data
- Still differences e.g. convection is stronger



Summary

- Variations in electron capture rates during the collapse phase had a modest effect on the initial conditions for the post bounce evolution

- Newtonian core collapse simulations in FLASH with Newtonian gravity fail to explode

- GR effective potential leads to systematically higher heating rates than Newtonian gravity and gives explosions in 2D in FLASH