Core-Collapse Supernovae Neutrino Signal

Outline

- SN Theory from a microphysics/neutrino perspective
  - Collapse Phase
  - Neutronization Burst
  - Accretion/Explosion Phase
  - Cooling Phase

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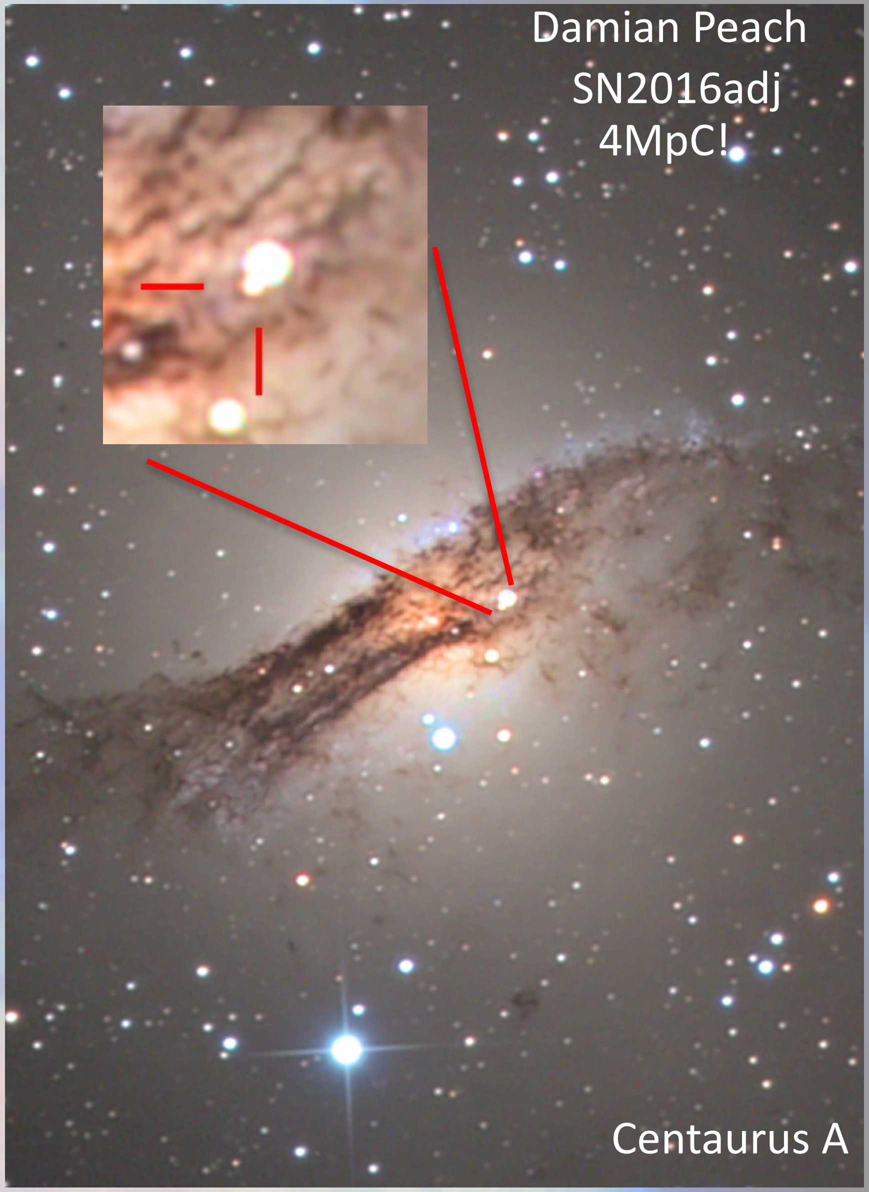
Core Collapse Supernovae

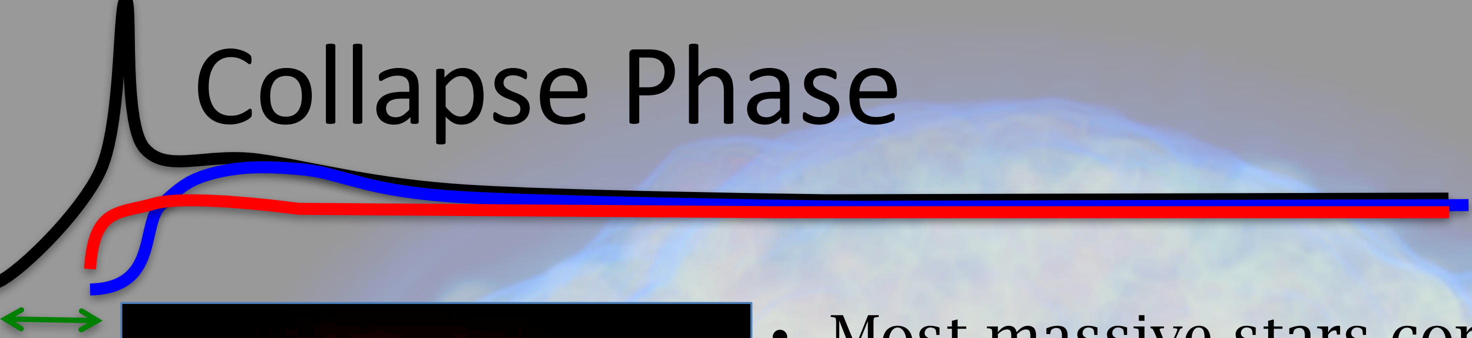
- CCSNe are one of the brightest astrophysical phenomena in the modern universe.

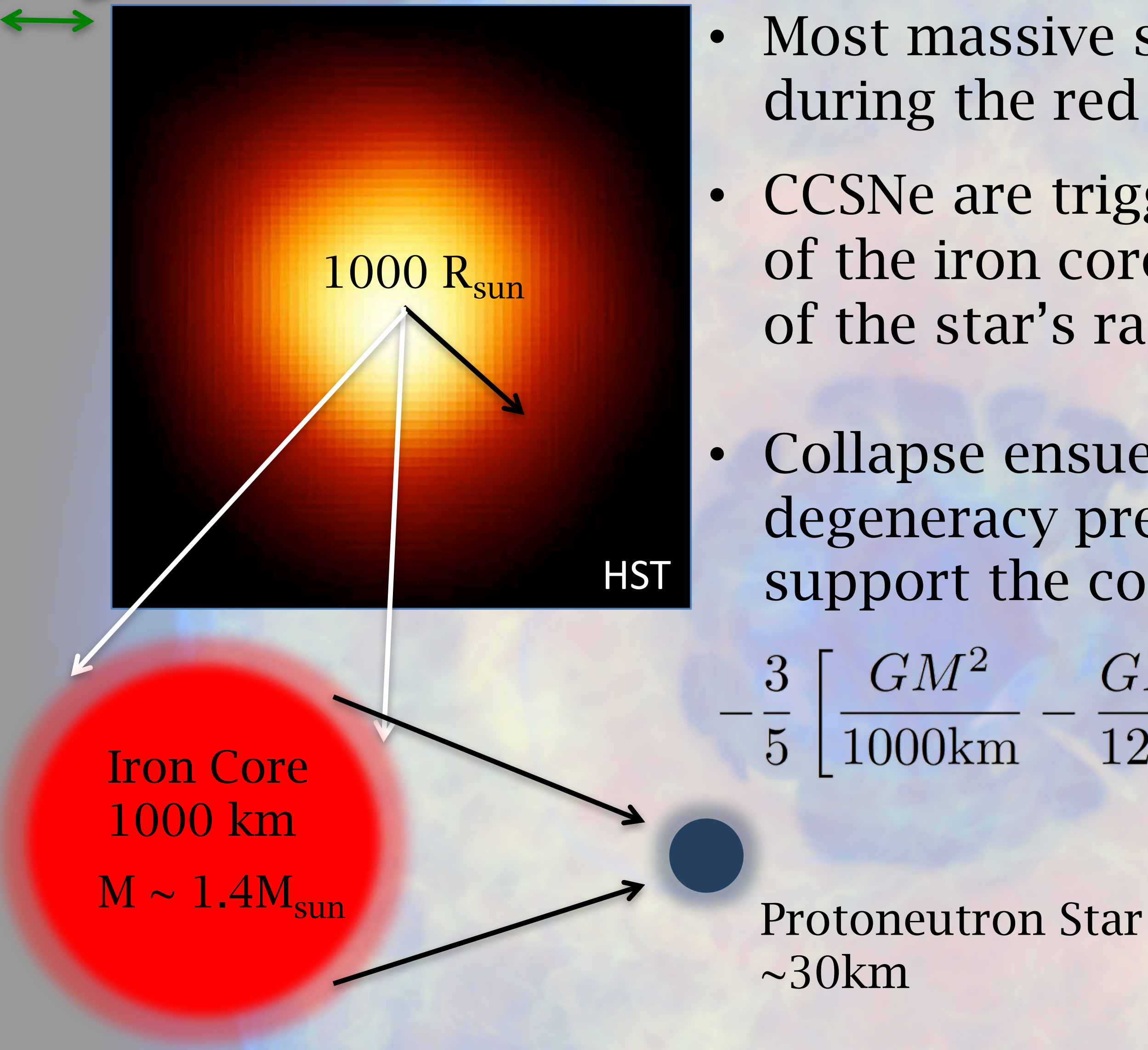
- They are an important site for nucleosynthesis and the mechanism for unbinding elemental products of stellar evolution and spreading them throughout the galaxy. They help trigger star formation, and are the source both neutron stars and black holes.

- Central engine provides an unique and fantastic laboratory for studying high density/temperature and neutron rich conditions. Requires us being able to observe central engine -> Neutrinos!



Collapse Phase

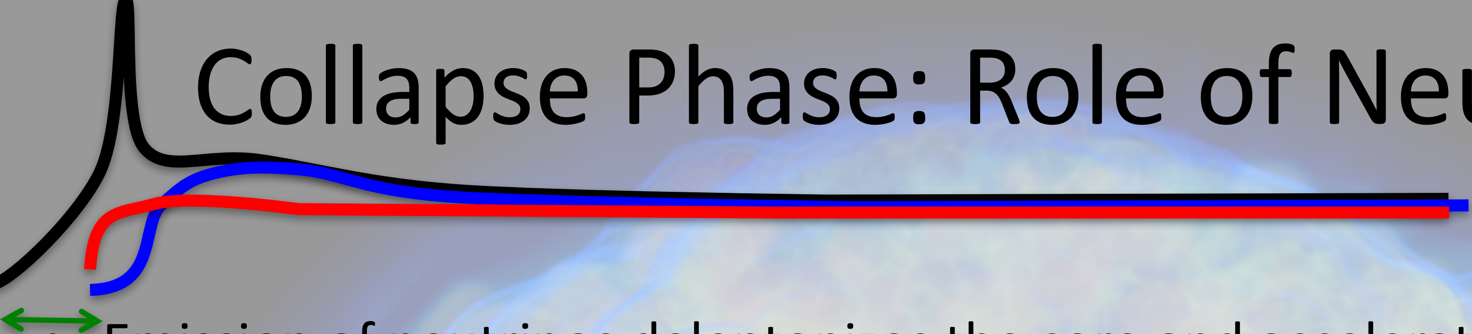




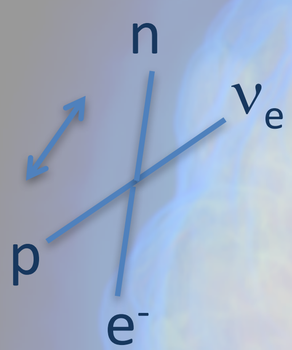
- Most massive stars core collapse during the red supergiant phase
- CCSNe are triggered by the collapse of the iron core (~1000km, or $1/10^6$ of the star's radius)
- Collapse ensues because electron degeneracy pressure can no longer support the core against gravity

$$-\frac{3}{5}\left[\frac{GM^2}{1000\mathrm{km}} - \frac{GM^2}{12\mathrm{km}}\right] \sim 300 \times 10^{51}\mathrm{ergs}$$

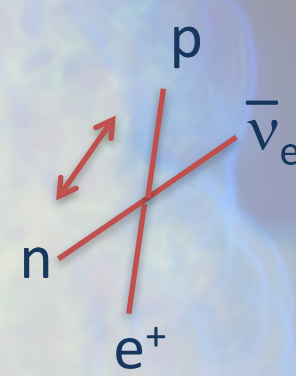
Collapse Phase: Role of Neutrinos



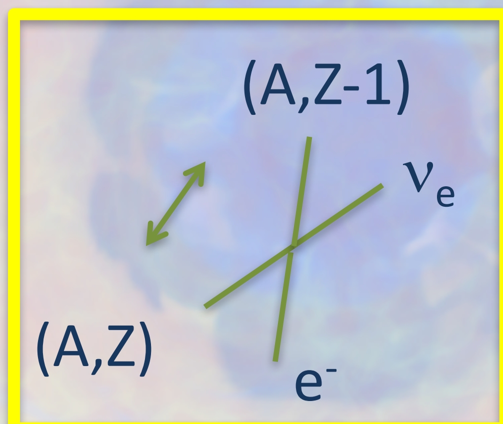
- Emission of neutrinos deleptonizes the core and accelerates collapse
- The emission ultimately sets the final Ye of the core and therefore its mass at bounce



- Charged current processes dominate production
- Thermal production processes are highly suppressed because temperature is so low



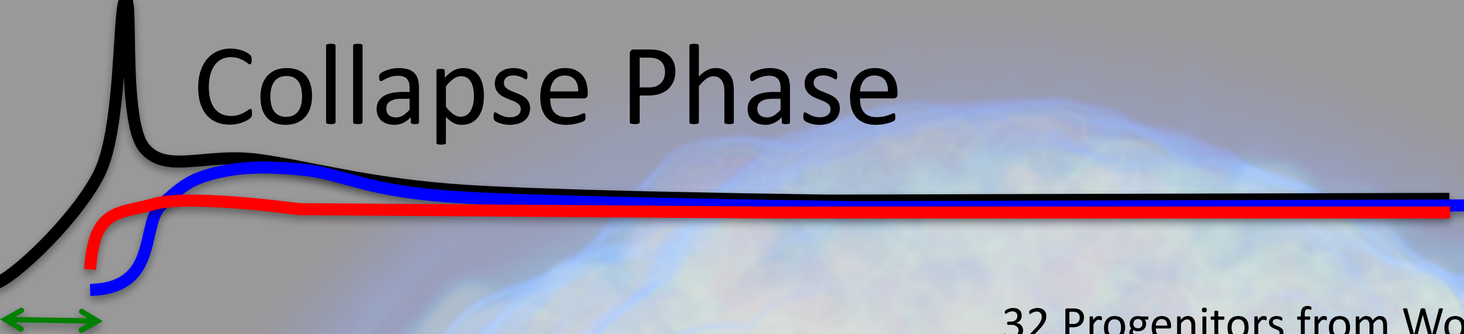
Electron capture on free protons. Cross section is very high, but suppressed because number of free protons is low



Positron capture on free neutrons. Emissivity is suppressed (by 4 order of magnitude) because positron density is very low due to high electron chemical potential

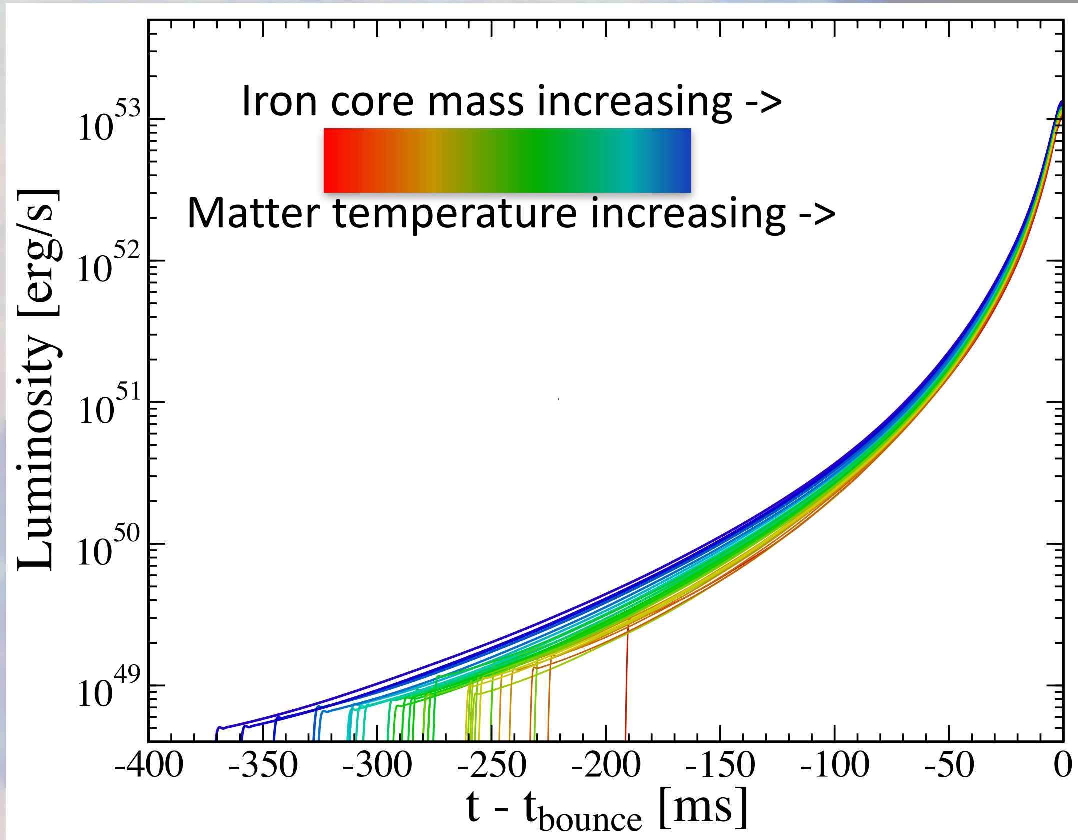
Electron capture on heavy nuclei. Abundance is very high, cross section is somewhat suppressed because of energetic cost of converting proton to neutron in a nucleus.

Collapse Phase



- e-captures produce ν_e, only abundant ν produced during collapse
- Other ν production suppressed by several orders of magnitude
- As the iron core grows in mass, e-capture rate goes up because more mass, easier capture

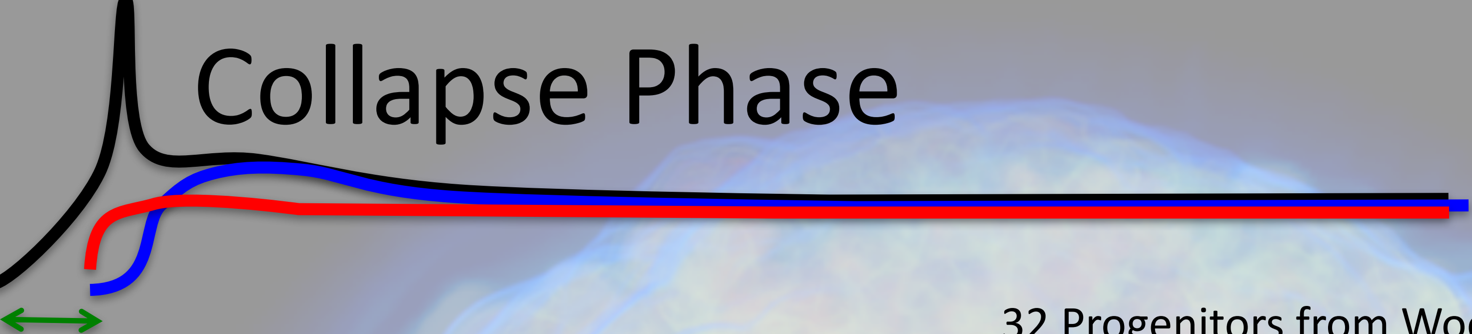
32 Progenitors from Woosley & Heger (2007)



Open source: GR1D (GR1Dcode.org) & NuLib (nulib.org)

- Low <E> & luminosity, hard to detect, little variation with progenitor

Collapse Phase



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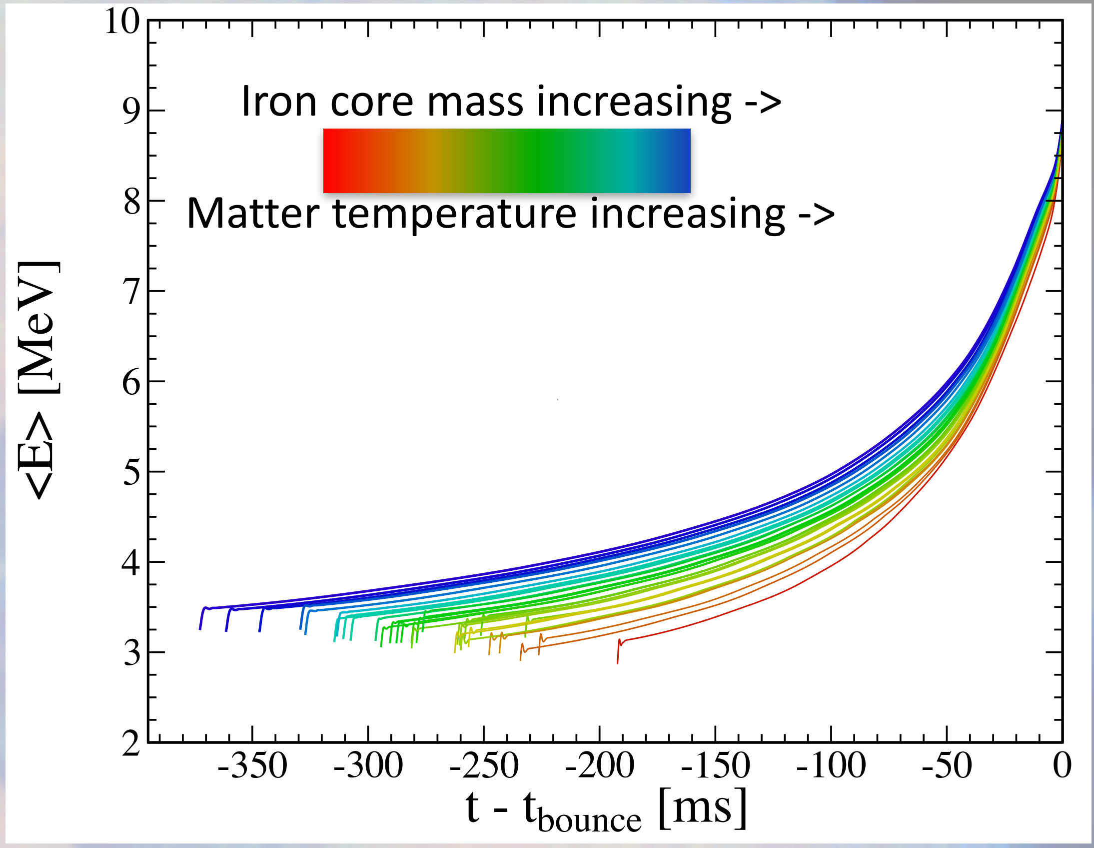

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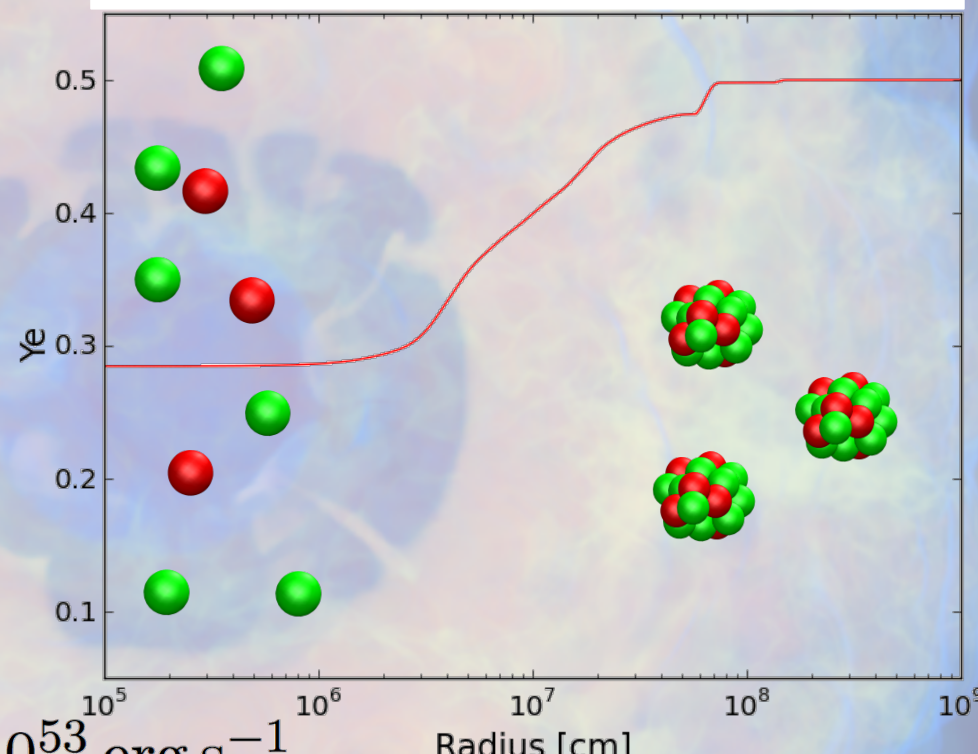
Neutronization Burst

- Recall neutrino processes during collapse phase, e-capture on protons was suppressed because lack of protons, even though the cross section is quite high
- When the matter reaches nuclear density and the supernova shock forms, it liberates the nucleons from the nuclei
- Recently freed protons now rapidly capture electrons, produce ν_e

10ms duration, starting just before bounce



$$\frac{1}{2}\frac{M_\odot}{m_N}\times 0.2\times\frac{10\,\mathrm{MeV}}{5\,\mathrm{ms}}\sim 4\times 10^{53}\,\mathrm{erg\,s^{-1}}$$

Neutronization Burst

- ν_e's take a bit of time (few ms) before the density at the shock is low enough for the ν's to escape
- anti-ν_e and ν_x neutrinos luminosity is low. anti-ν_e are suppressed because high electron degeneracy, ν_x because T is low
- Little progenitor dependence, universal nature of collapse

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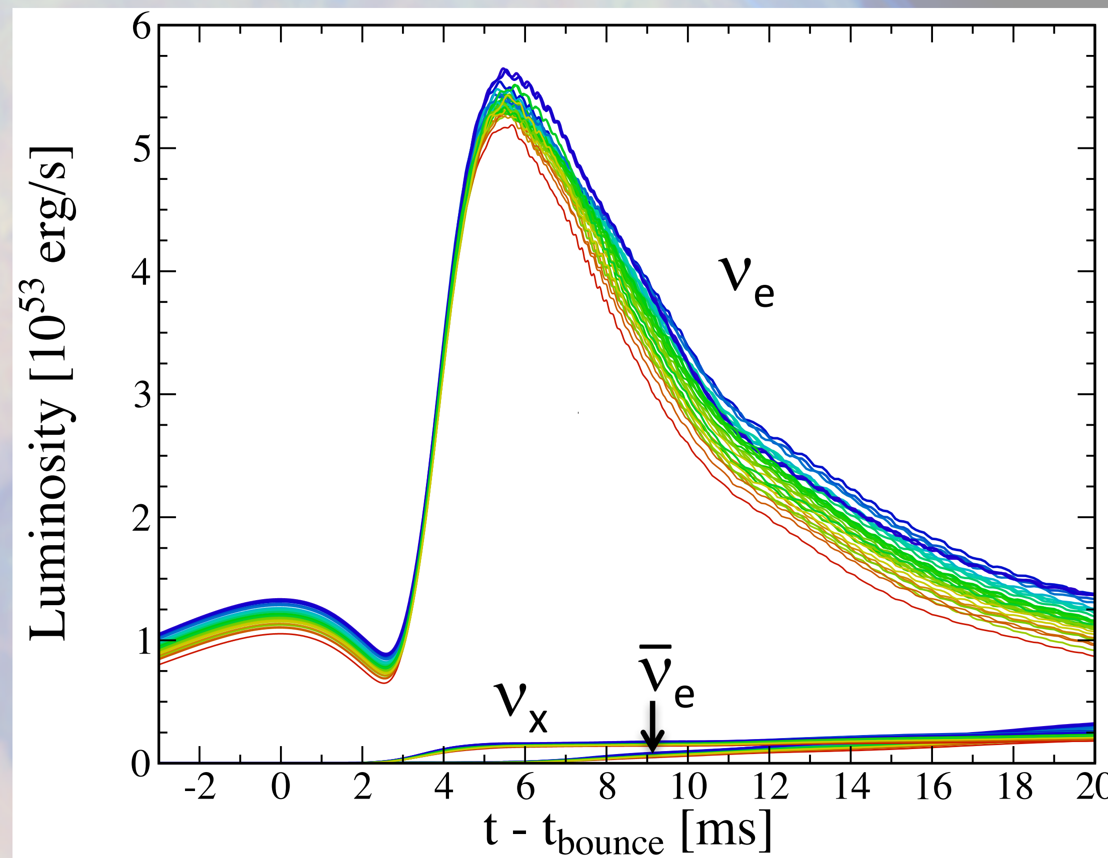

Iron core mass increasing ->

Matter temperature increasing ->

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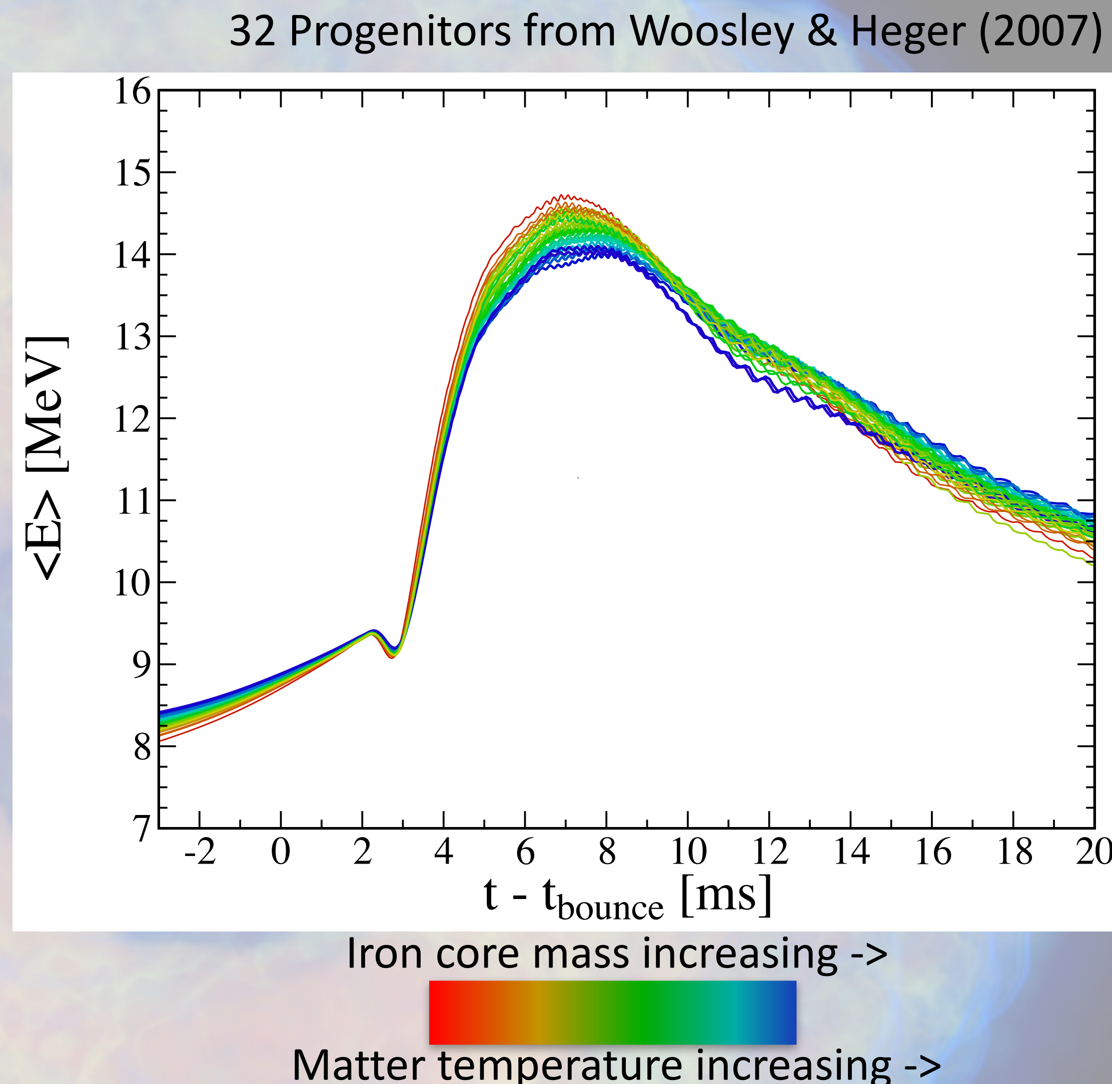
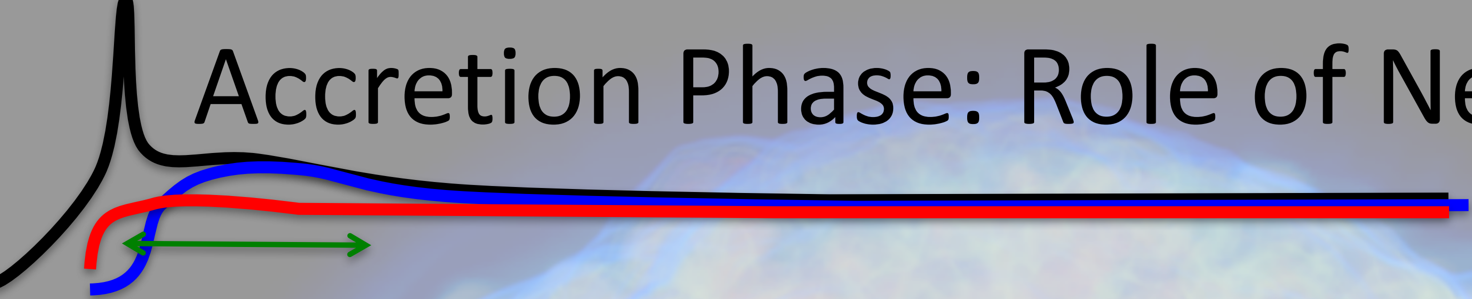
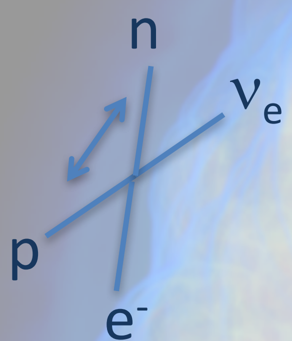


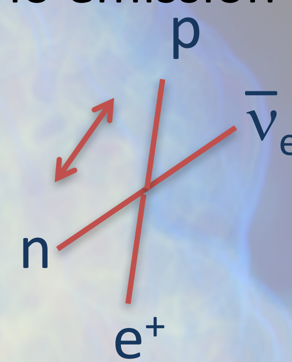
Accretion Phase: Role of Neutrinos



- After the burst, ν_e and anti-ν_e emission is powered by accretion
- Infalling matter is shock heated and then is cooled via neutrino emission

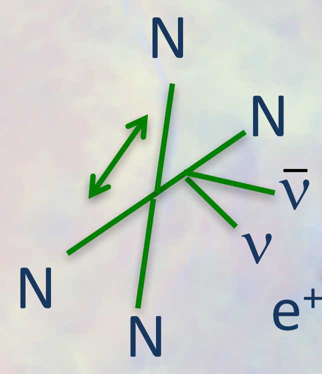


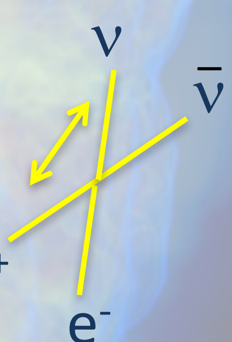
- Charged current processes dominant production
- Thermal production processes dominate at high densities where neutrinos are trapped for seconds+



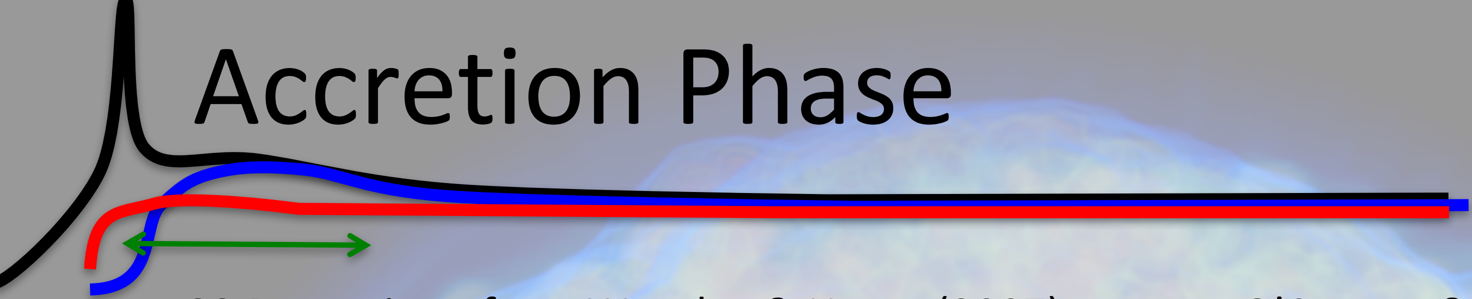
- After ~10-20ms, positron production no longer inhibited

- Thermal emission is dominant production process for heavy lepton neutrinos as T is too low for charged-current processes with μ's and τ's

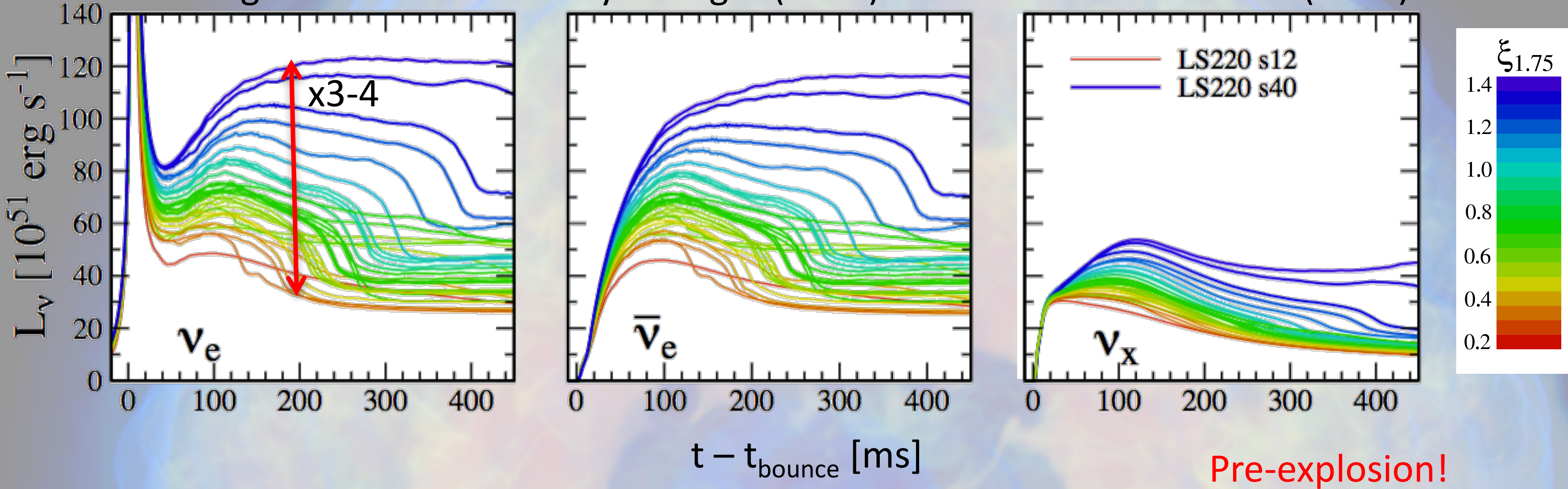




Accretion Phase



32 Progenitors from Woosley & Heger (2007) O'Connor & Ott (2013)

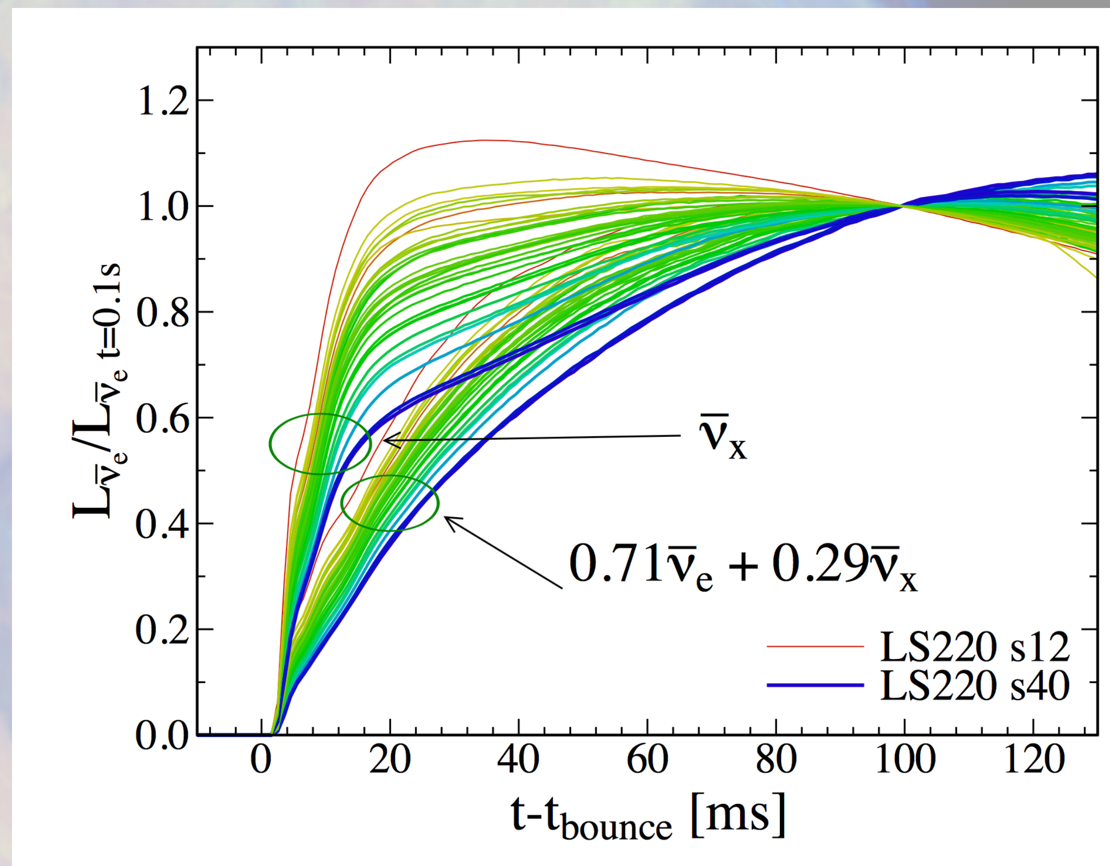


- The accretion phase is first time we see significant progenitor dependence of luminosities
  - High 'compactness' progenitors have higher mass accretion rates -> more gravitational binding energy released -> higher neutrino luminosities

- Most common massive stars generally have low compactness, represented by red lines, rarer, more massive (although not exclusively) stars have higher compactness (blue lines) and higher neutrino luminosities

Extracting Hierarchy

- Electron anti-neutrino production is suppressed because of electron degeneracy -- Slower Rise
- MSW oscillations result in different neutrino signals at Earth for the different hierarchies
- Examining rise time can reveal hierarchy, independent of progenitor and equation of state



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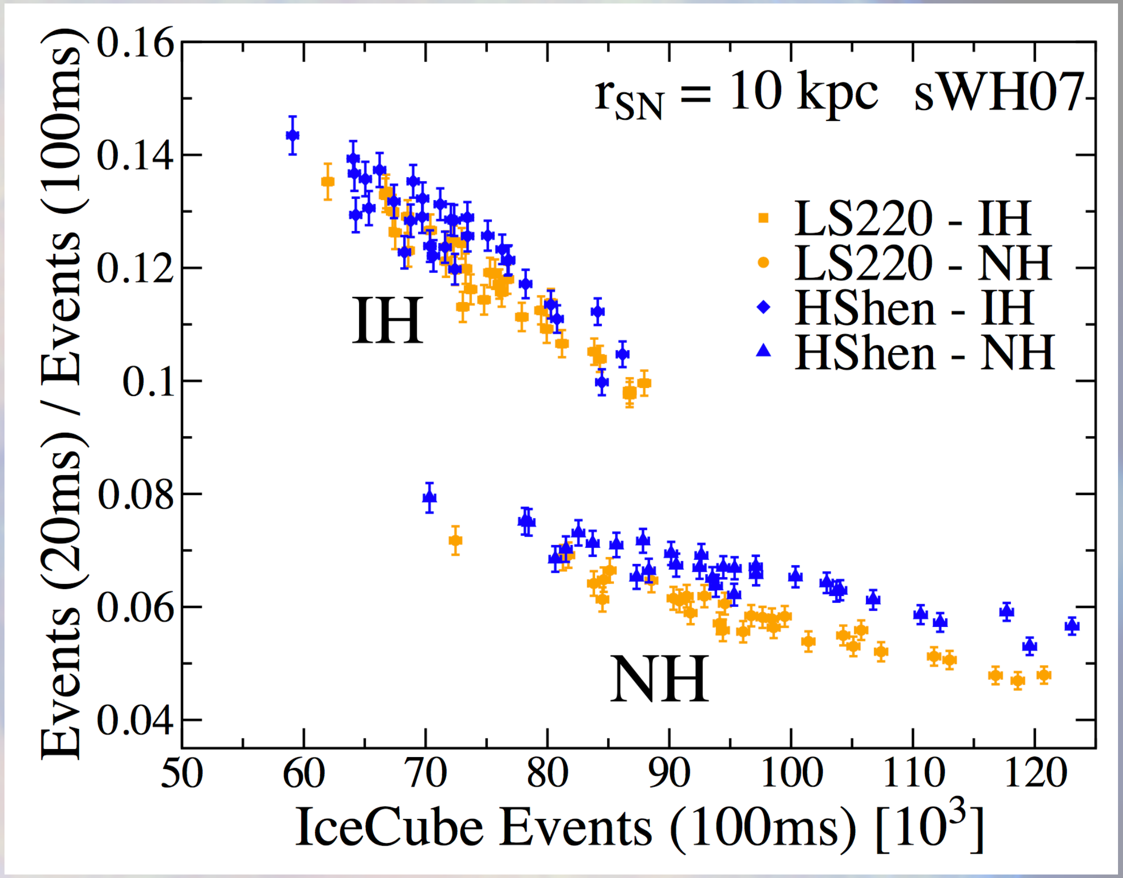
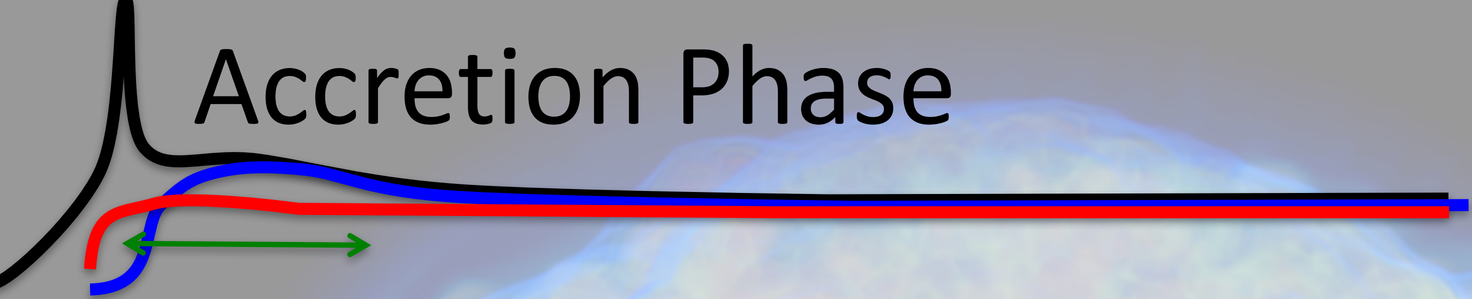
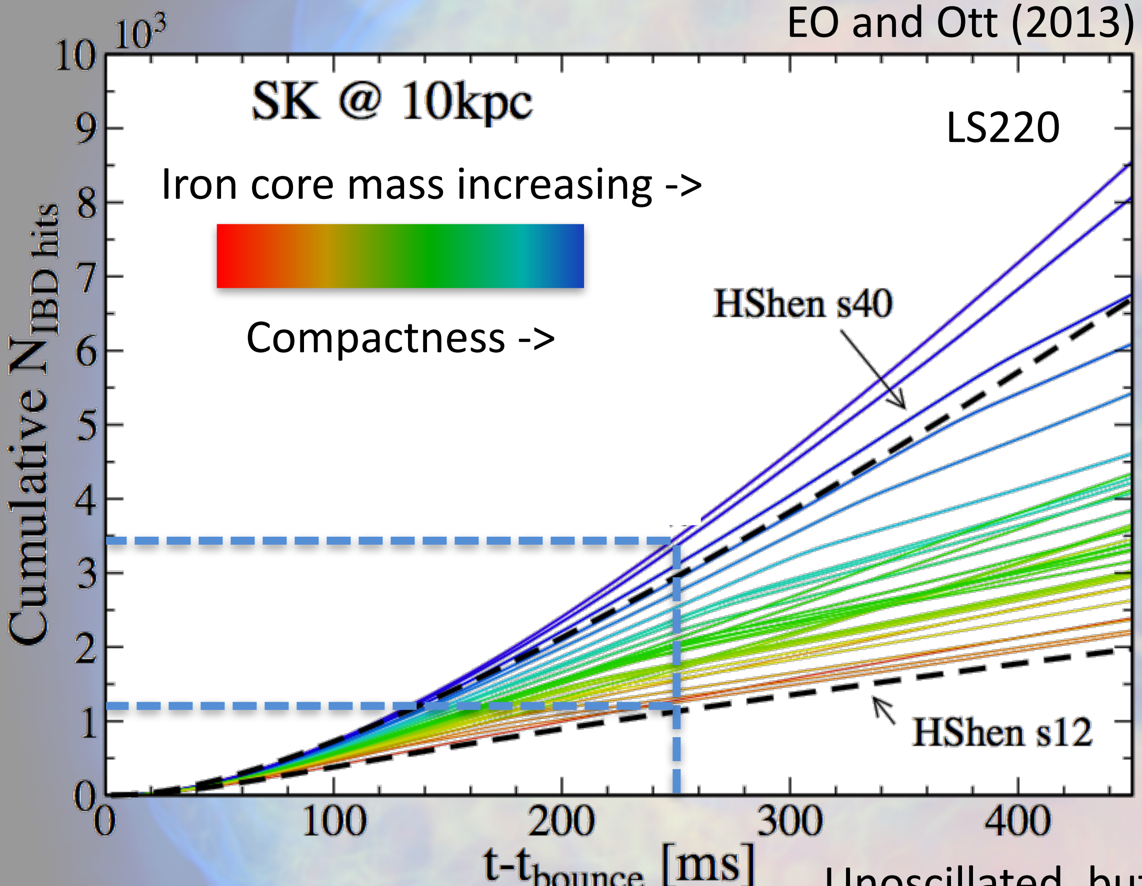


Accretion Phase



- We use SNOwGLoBES (Beck et al. 2011) to reconstruct the number of interactions in a Super-K-like ν detector for a 10 kpc supernova

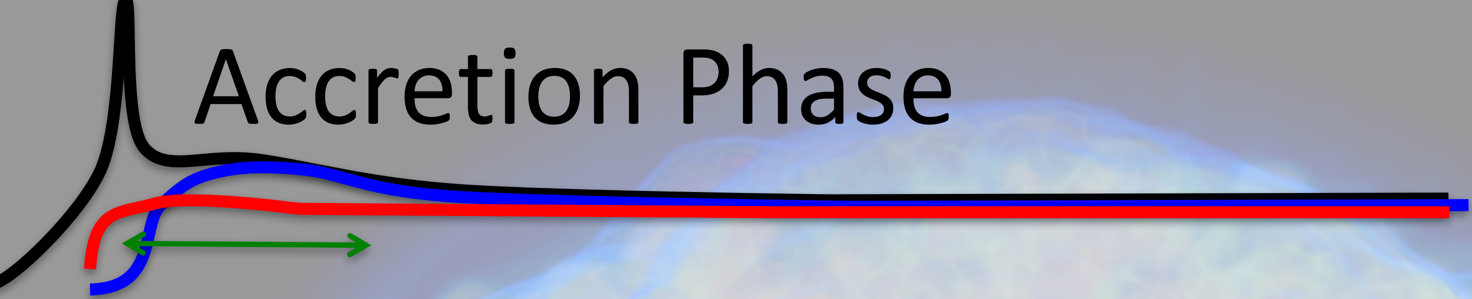
EO and Ott (2013)



Unoscillated, but ν_x also scales with compactness

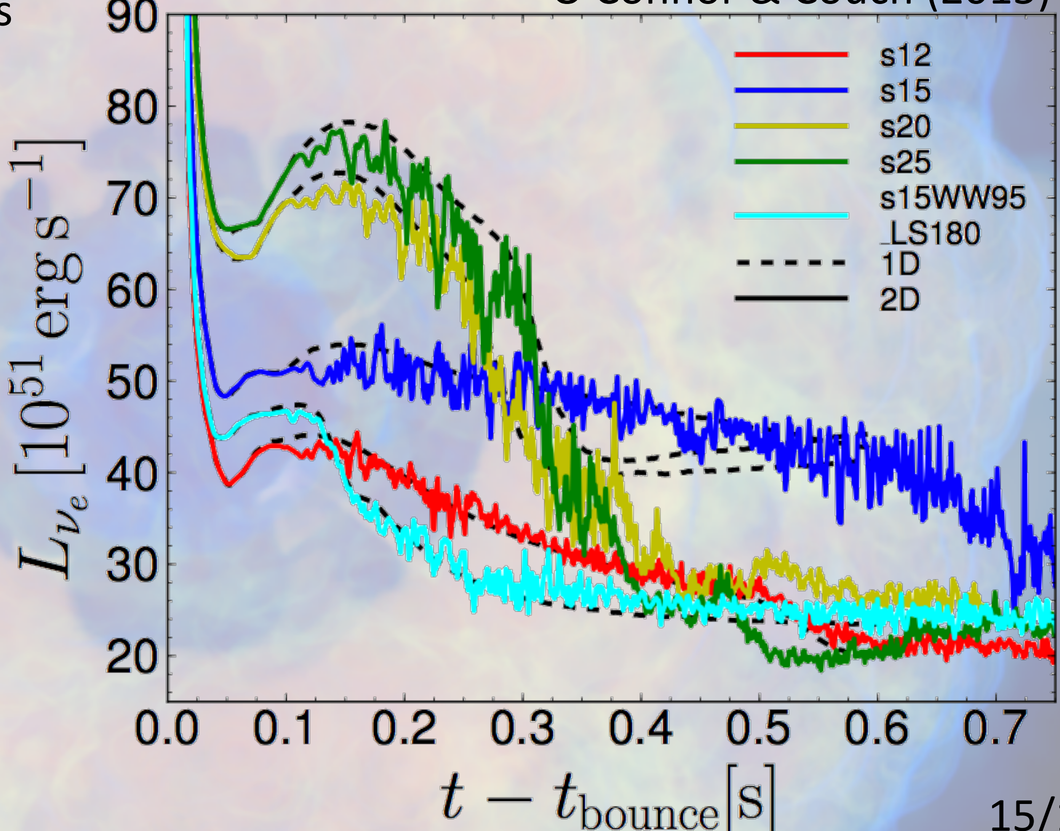
- Higher luminosities give higher interaction rates
- Small EOS dependence
- The early postbounce preexplosion ν signal will tell us information on the structure of the progenitor star!
- Does this carry over to multi-D?

Accretion Phase



- If/when an explosion sets in, the accretion onto the central object slows/ceases
- This reduces the amount of gravitational energy that can be released as neutrinos and the accretion component of the neutrino luminosity falls.
- Up until then, the luminosity follows the 1D prediction.
- For detection we often rely on the assumption that no direction is special.
- The ν luminosity is mainly unaffected by some multi-D effects e.g. convection, SASI.
- However, others, like strong rotation and the LESA do impact ν signal

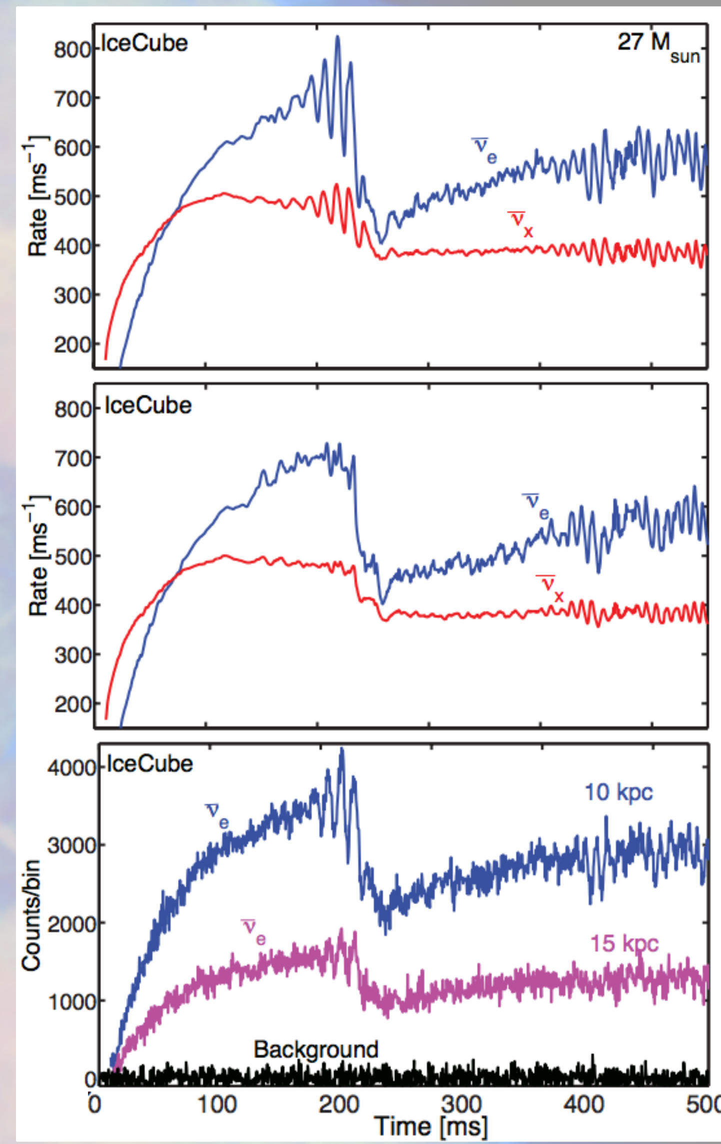
O’Connor & Couch (2015)



Accretion Phase - SASI

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

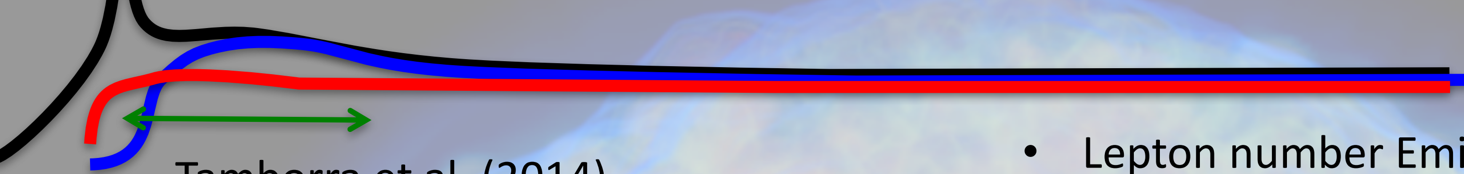
- SASI – Standing/Stationary Accretion Shock Instability
- Convection and SASI impact signal at lower order, can even be coherent/periodic, but do not systematically shift luminosity/energy
- Observable in HyperK and IceCube, perhaps not Dune



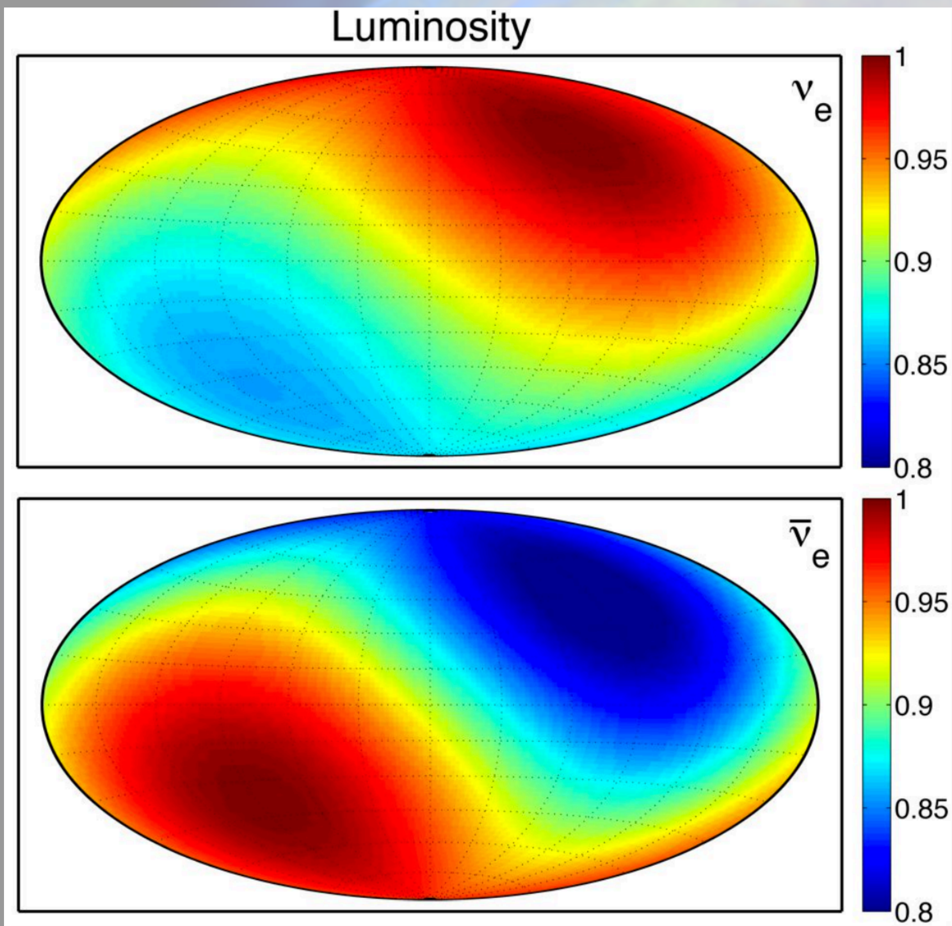
Movie…

Couch & O’Connor (2014)

Accretion Phase - LESA

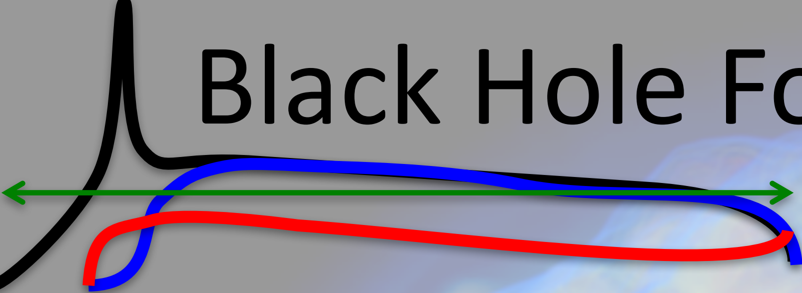


Tamborra et al. (2014)



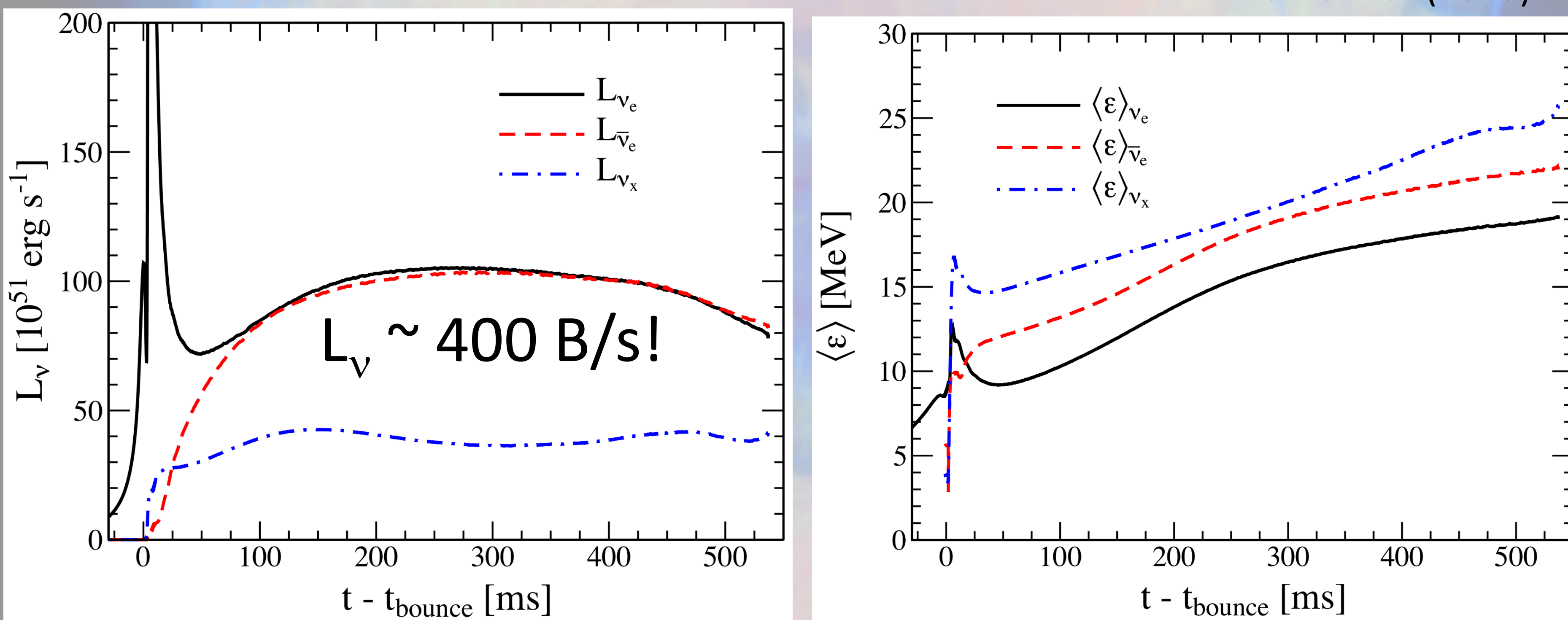
- Lepton number Emission Self-sustained Asymmetry - LESA
- Discovered in 3D runs of the Garching group
  - Develops within 150ms of bounce
  - Creates a dipole in lepton number
  - Results in observer-angle dependent luminosity variations ~ 20%
  - Direction is sustained
- Stills need confirmation from other groups
- Total luminosity show much smaller variation with observer angle (~few %)
- Measurements of both neutrino and antineutrino luminosities important
- Combination could lead to experimental confirmation of LESA (need to confim)

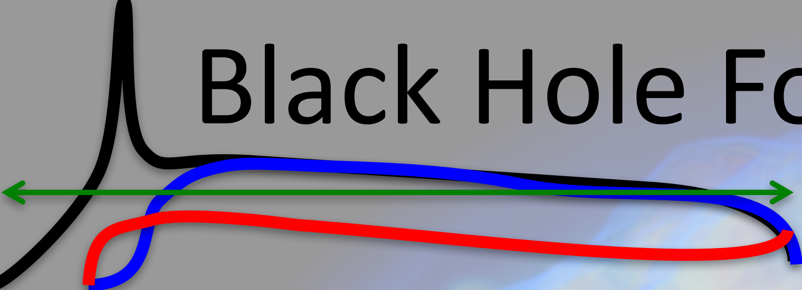
Black Hole Formation



- For many reasons, we may expect a failed supernova rate up to ~30%
- Smoking gun signature is prompt shutoff of neutrinos
- Give detailed information regarding progenitor and nuclear EOS

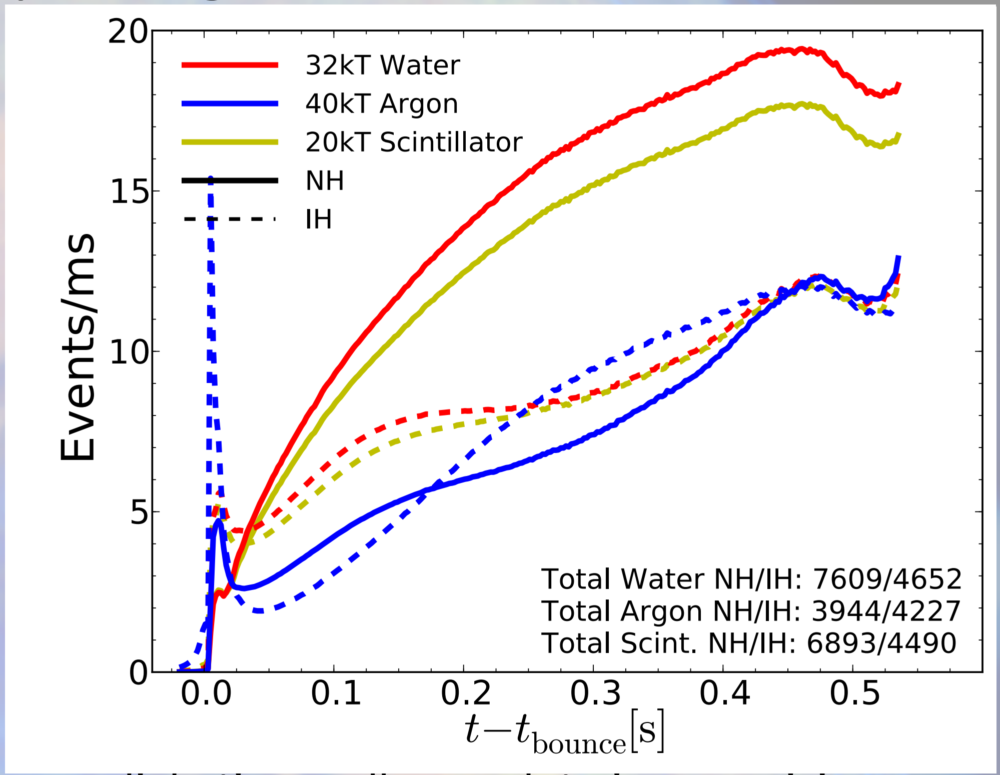
O'Connor (2015)





Black Hole Formation

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



- 10 kpc
- Ignores collective oscillations
- Includes all SNOwGLoBES channels
- 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

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

IH

$$
\begin{aligned}
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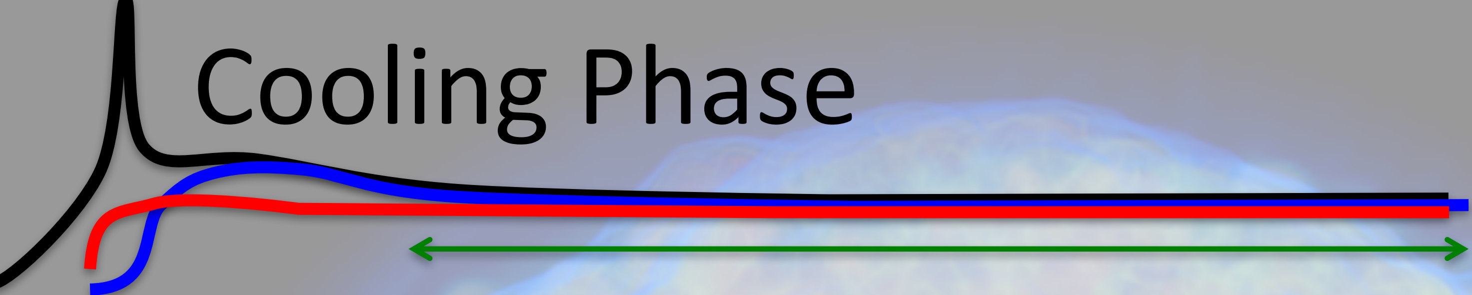
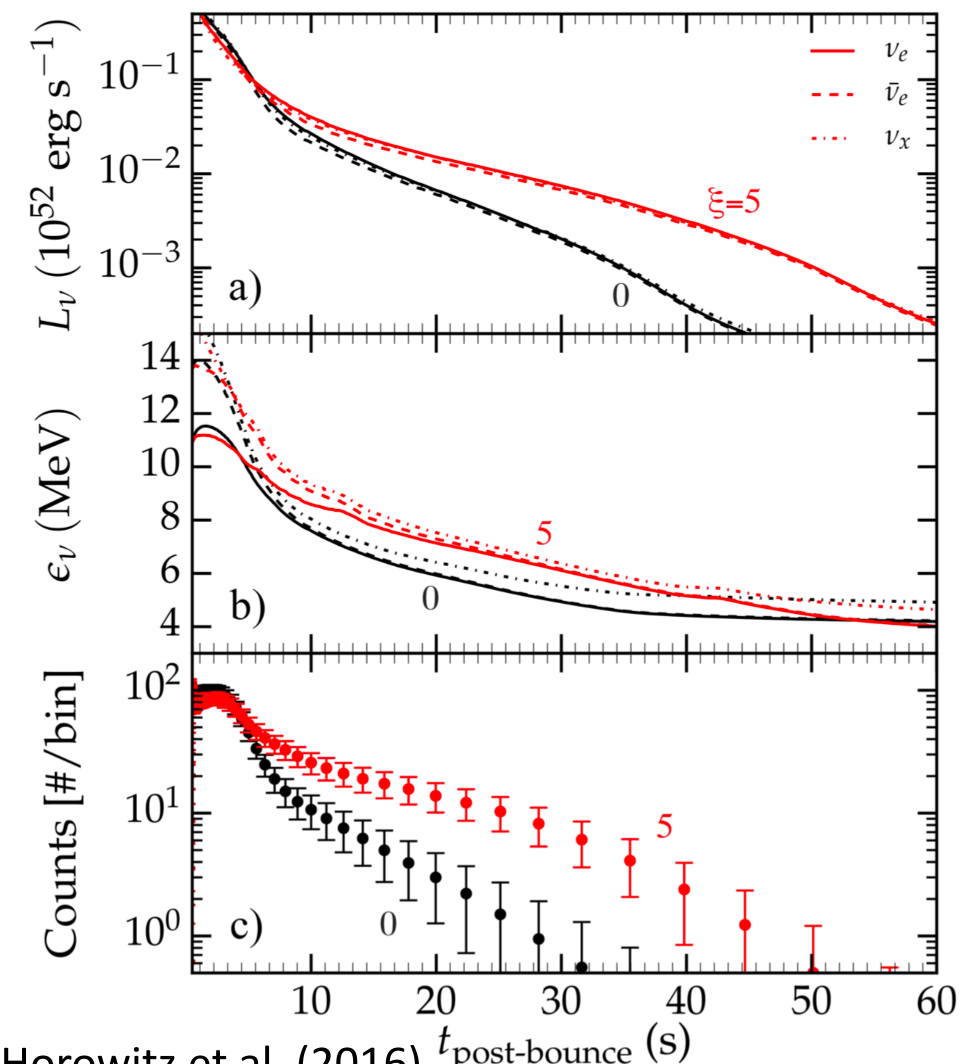
\end{aligned}
$$

Cooling Phase



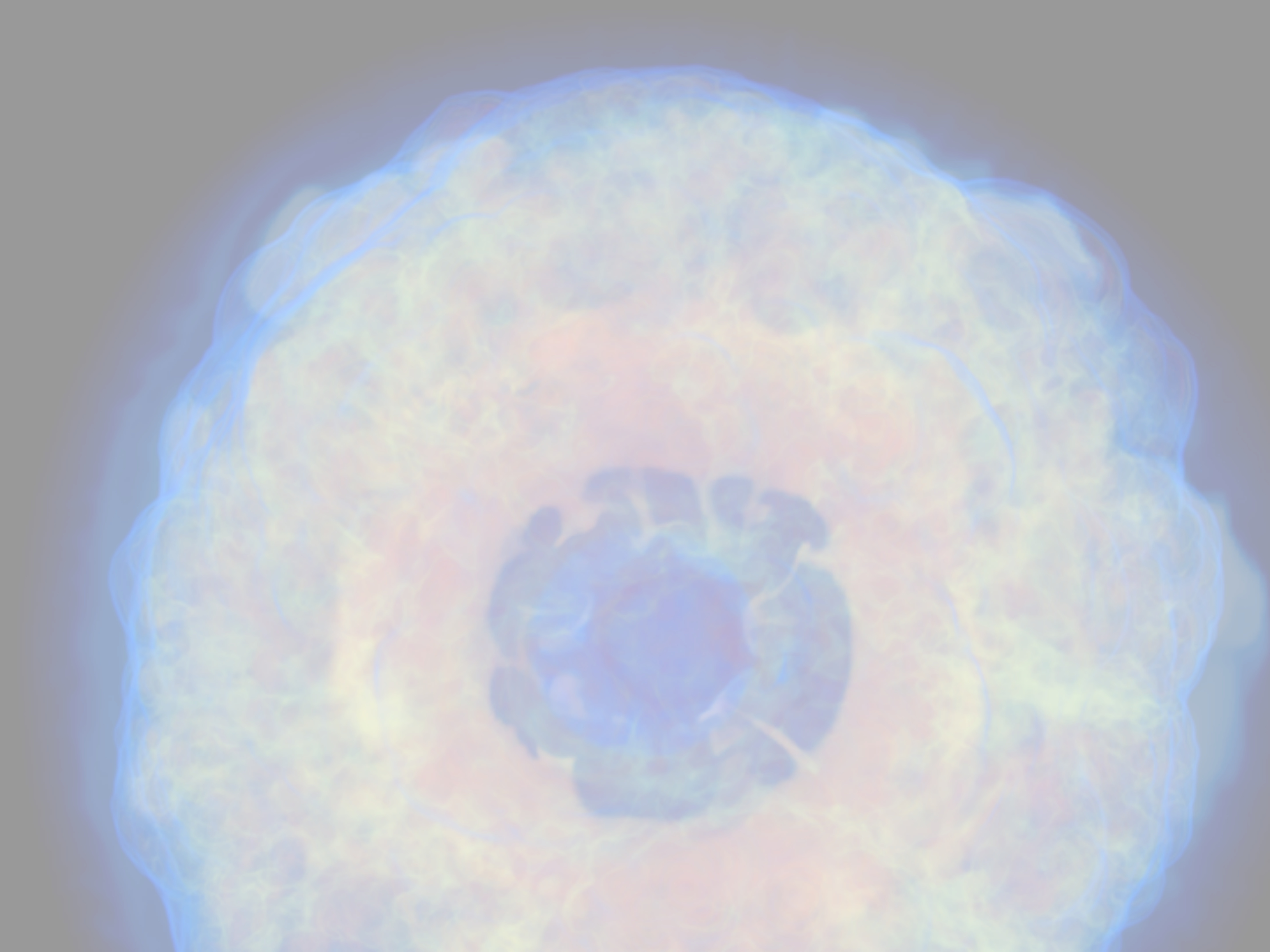


Horowitz et al. (2016)

- 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 ν_e and $\bar{\nu}_e$ is important and can impact nucleosynthesis

Summary

- Neutrinos enable us to study the central engine of core-collapse supernovae like no other probe can.
- Since they help drive the evolution of the central engine, neutrinos can relay information on the structure, dynamics, nuclear physics.
- Each species carries important and complementary info so we need to measure them all!



Neutronization Burst

- Other microphysics can alter the neutronization burst
- Variation in electron capture rates during collapse can change the bounce-time structure and alter how fast the neutrinos escape
- Decreased rates give larger inner core at bounce which is pushed out faster -> neutrinos escape faster

Sullivan et al. (2016)