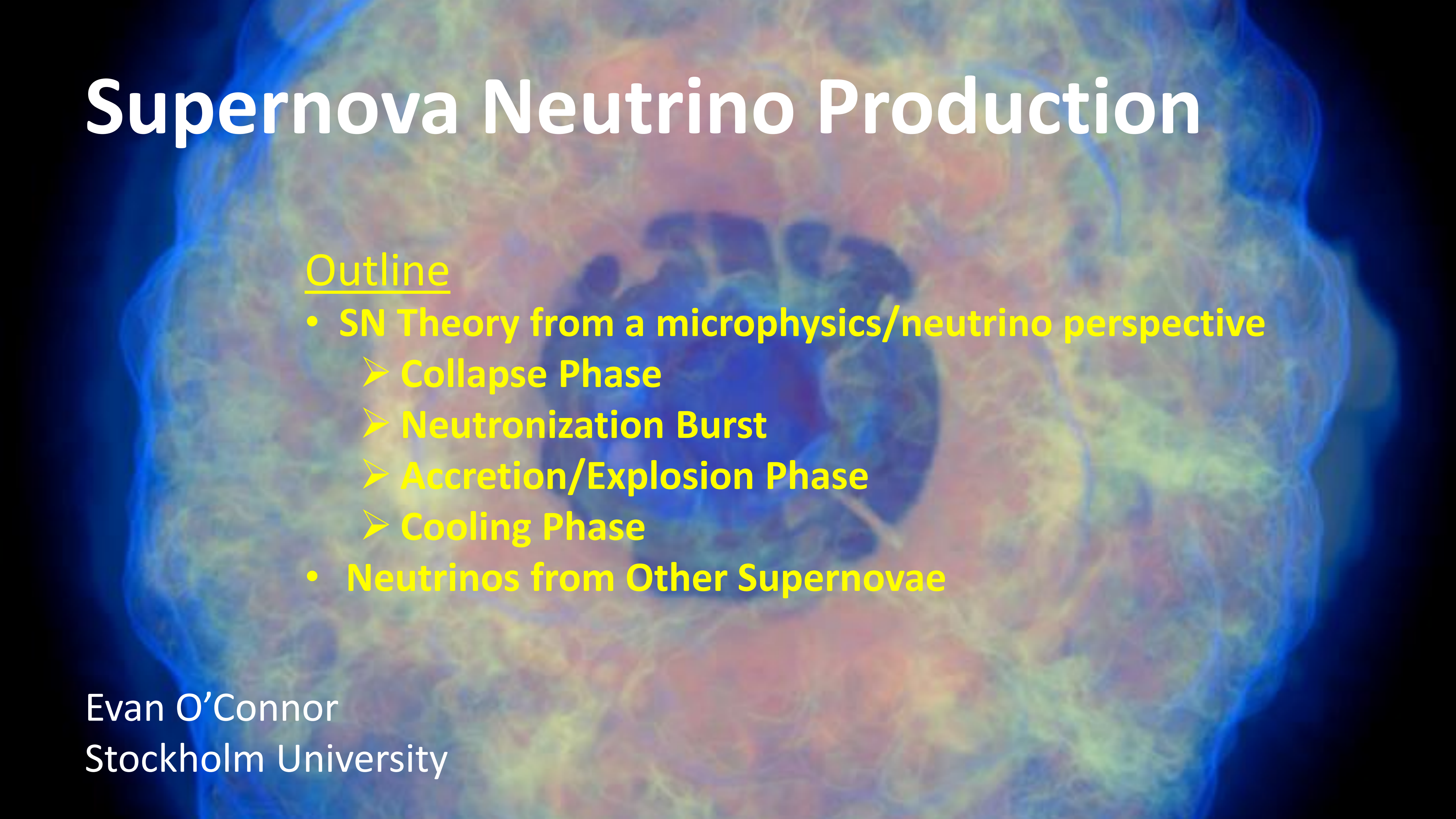


Supernova Neutrino Production

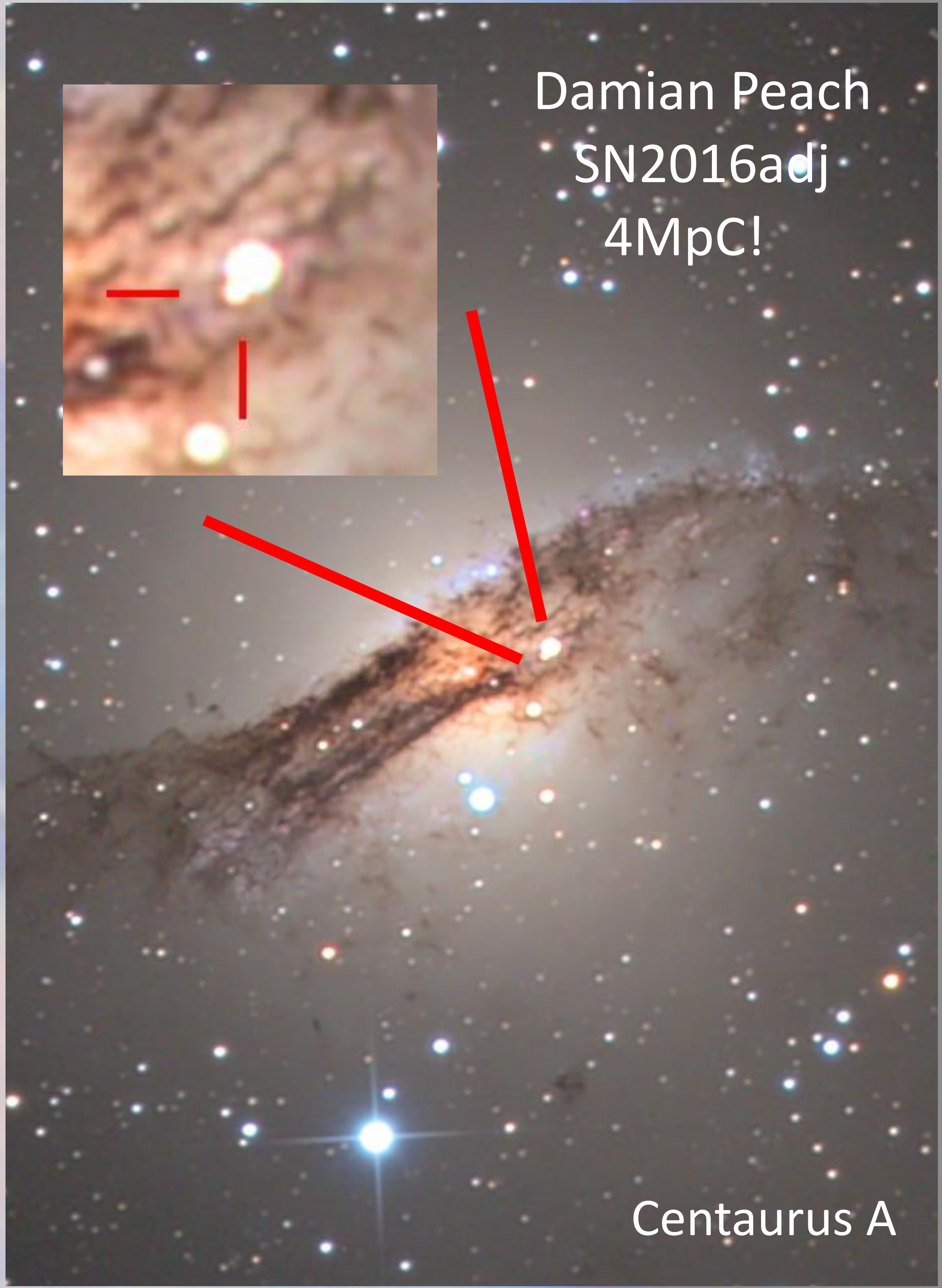
Outline

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

Evan O’Connor
Stockholm University

Core Collapse Supernovae

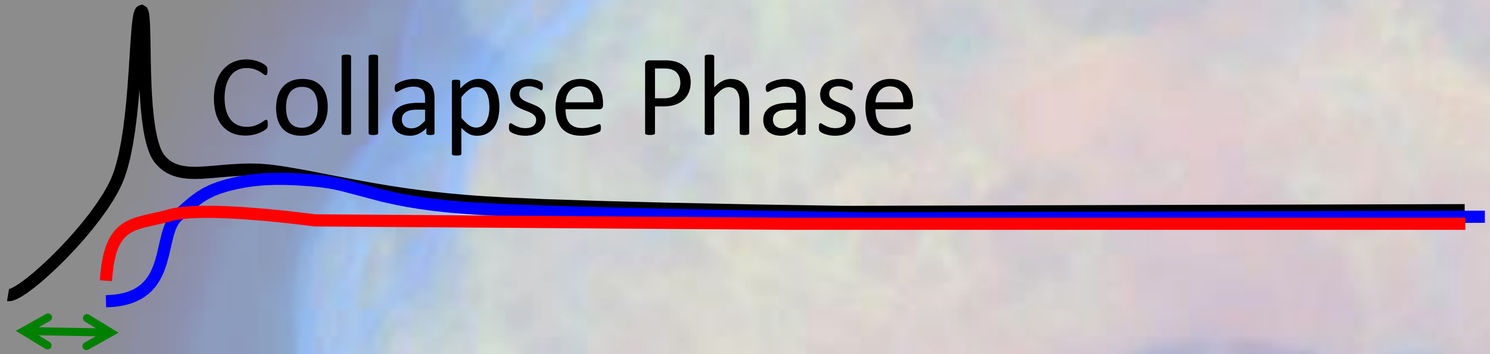
- CCSNe are one of the brightest astrophysical phenomena in the modern universe.
- They are an important site for nucleosynthesis and the mechanism for unbinding elemental products of stellar evolution and spreading them throughout the galaxy. They help trigger star formation, and are the source both 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!



Damian Peach
SN2016adj
4MpC!

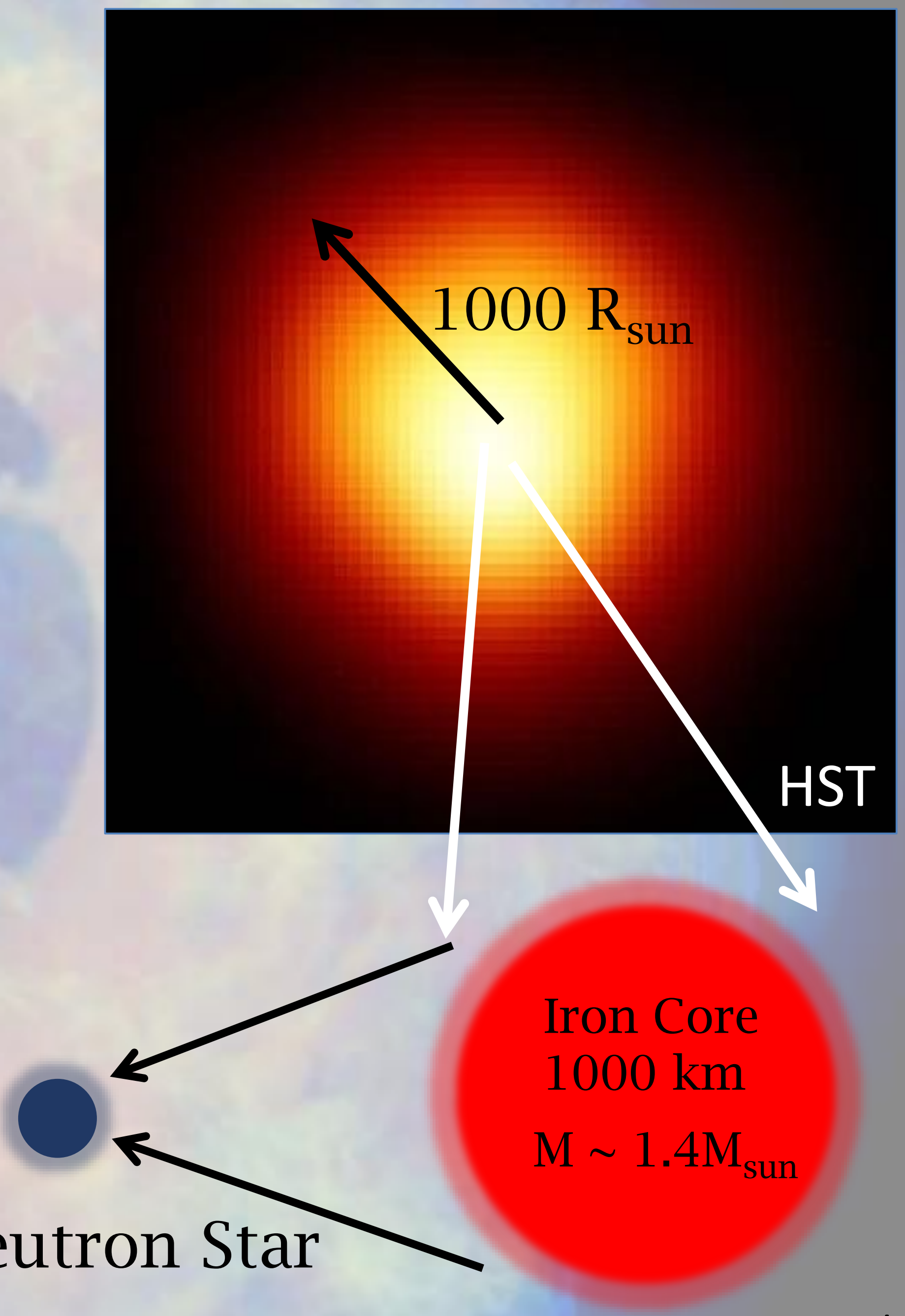
Centaurus A

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

$$-\frac{3}{5}\left[\frac{GM^2}{1000\mathrm{km}}-\frac{GM^2}{12\mathrm{km}}\right]\sim 300\times10^{51}\mathrm{ergs}$$



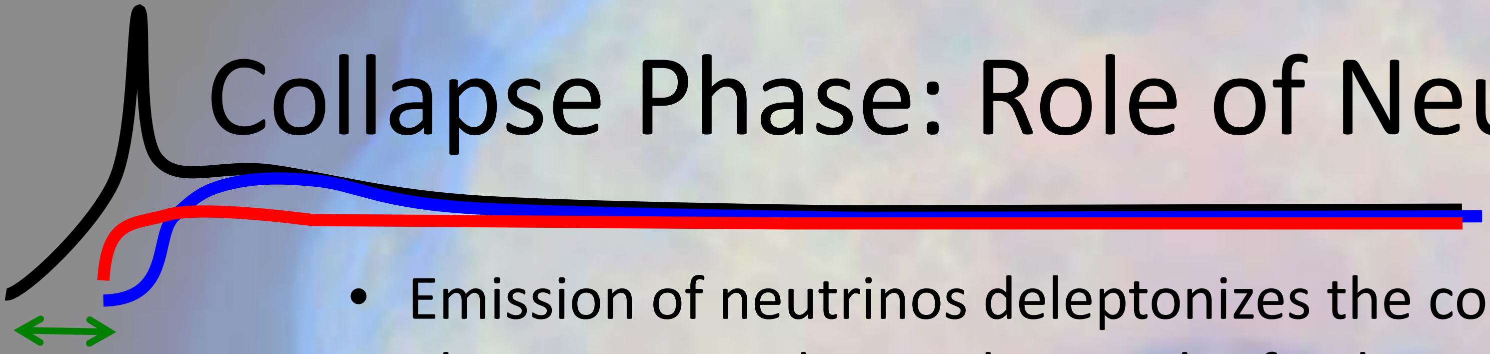
1000 R_{sun}

HST

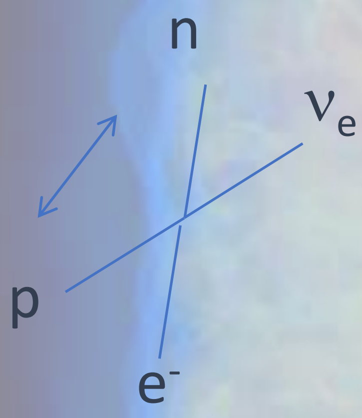
Iron Core
1000 km
M ~ $1.4M_{sun}$

Protoneutron Star
~30km

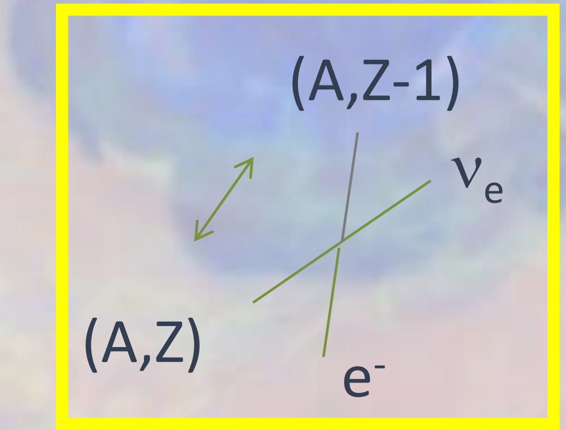
Collapse Phase: Role of Neutrinos



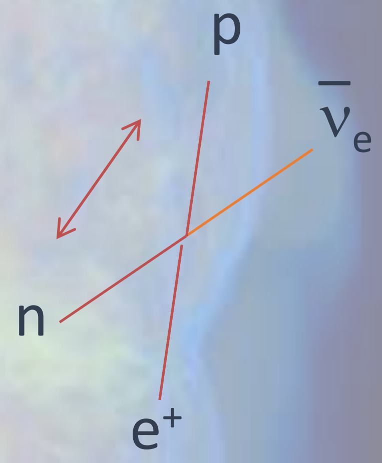
- Emission of neutrinos deleptonizes the core and accelerates collapse
- The emission ultimately sets the final Ye of the core and therefore its mass at bounce
  - Heavy-lepton neutrino production is highly suppressed because temperature is so low



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

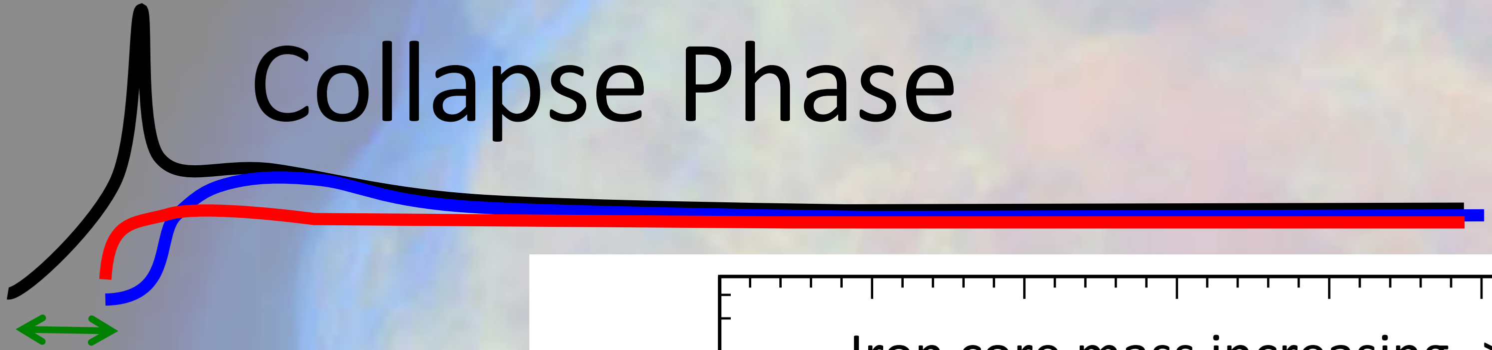


Electron capture on heavy nuclei. Abundance is very high, cross section is somewhat suppressed because of energetic cost of converting proton to neutron in a nucleus.

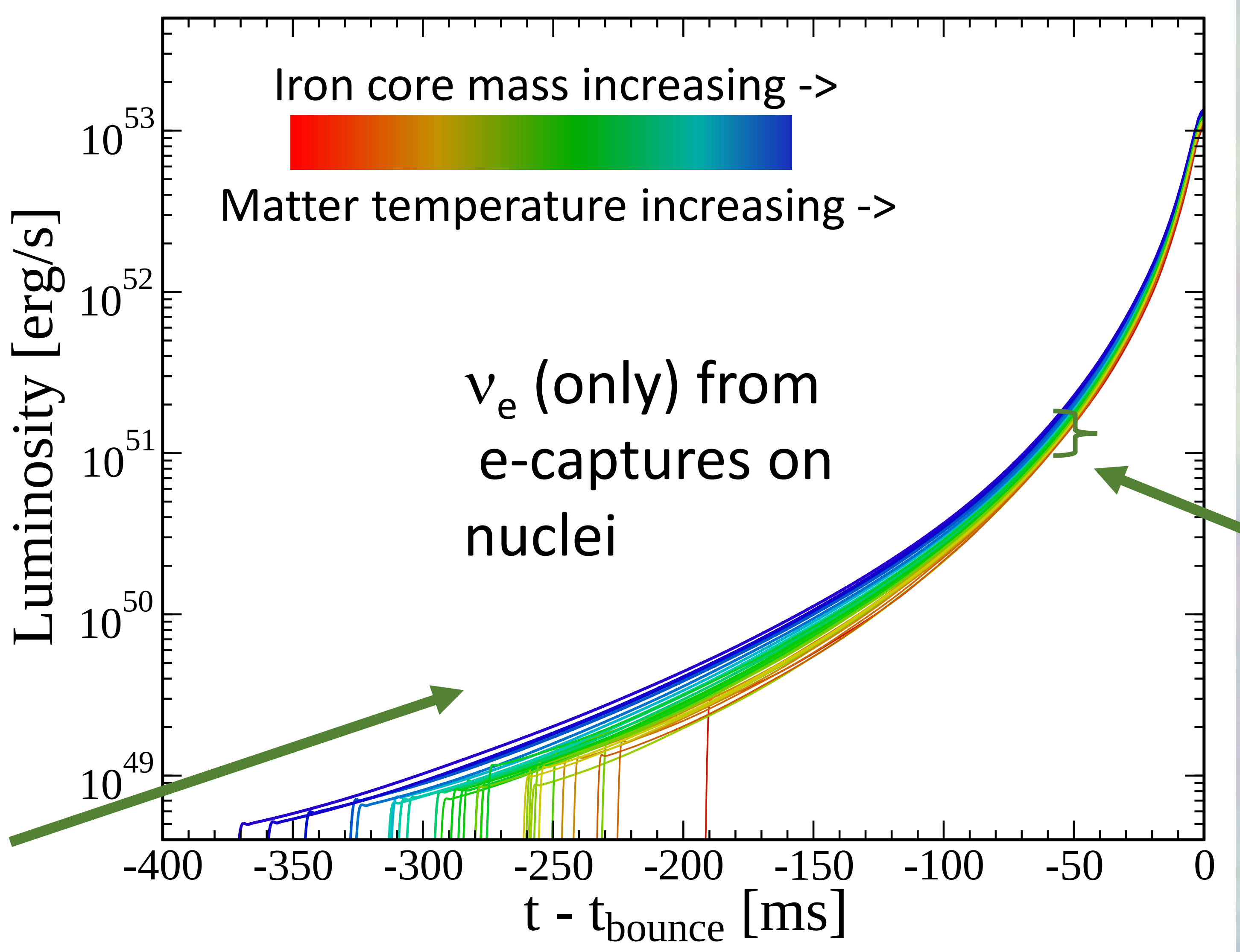


Positron capture on free neutrons. Suppressed because positron density is very low due to high electron chemical potential

Collapse Phase



32 Progenitors from Woosley & Heger (2007)

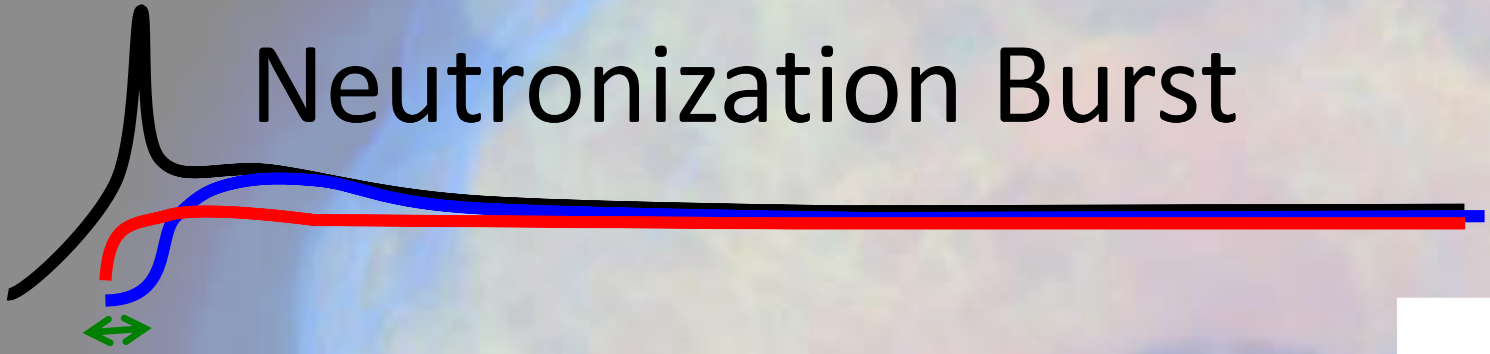


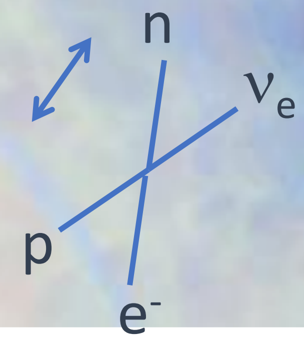
Little progenitor dependence

Low luminosity (and <E>) Difficult to detect

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

Neutronization Burst

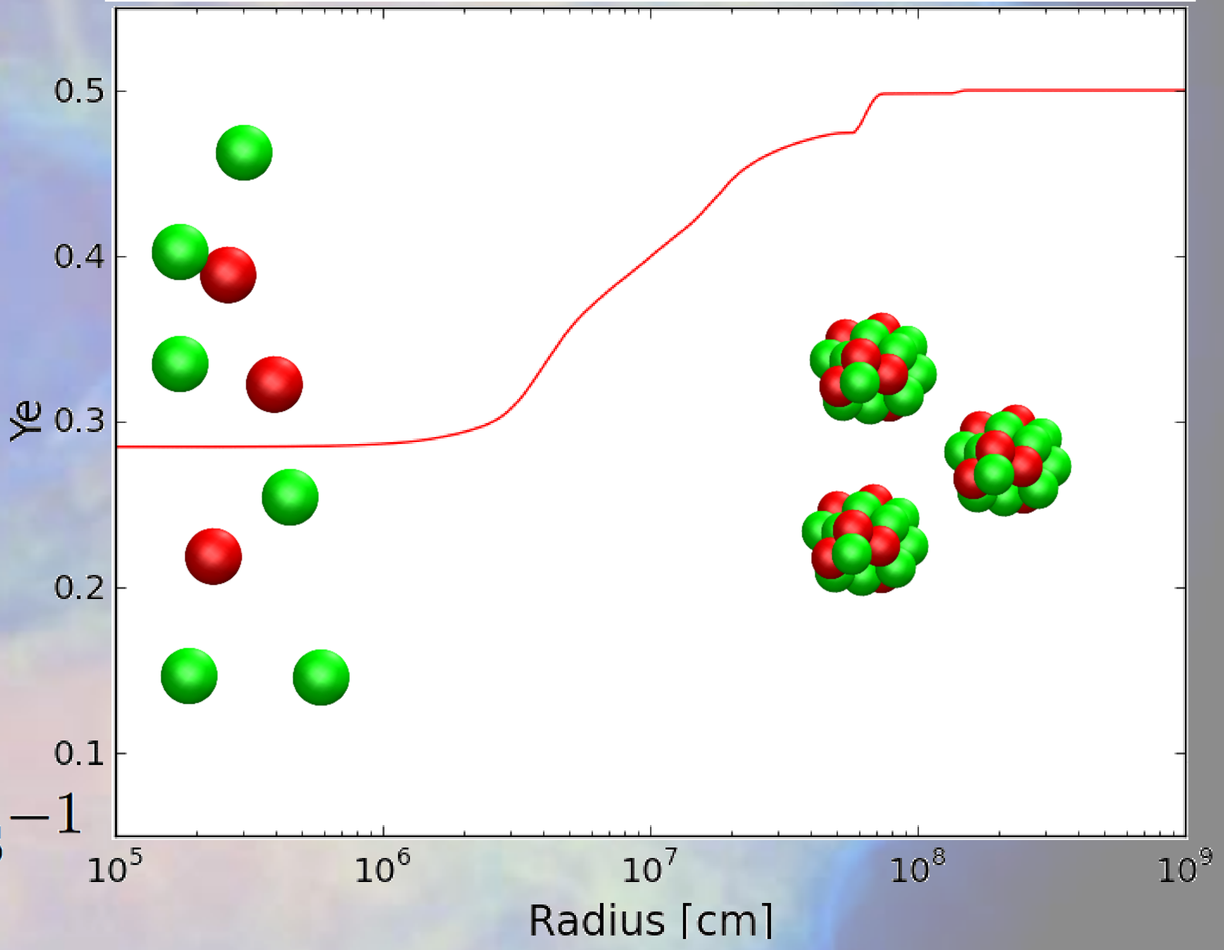


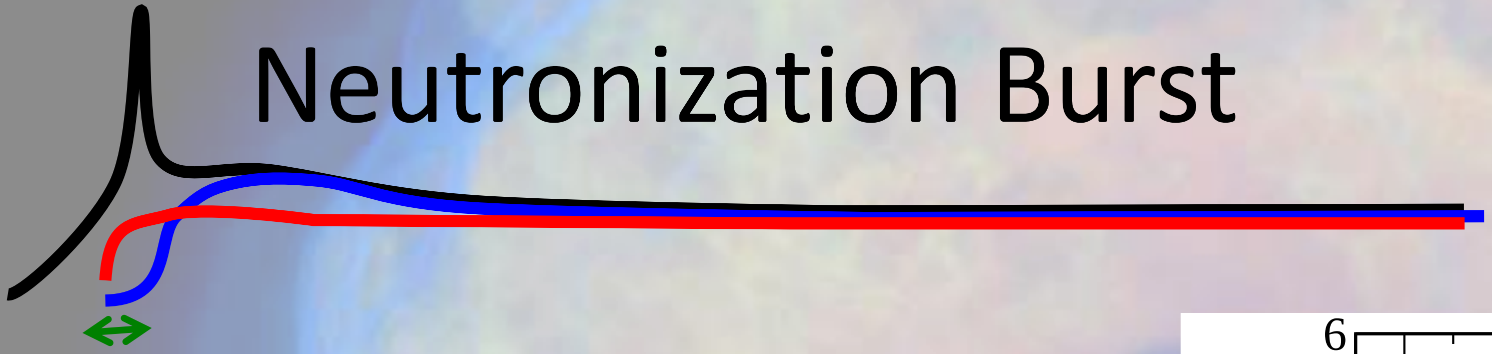


- When the matter reaches nuclear density and the supernova shock forms, it liberates the nucleons from the nuclei
- Recently freed and no longer supressed, protons now rapidly capture electrons, producing a burst of ν_e

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

10ms duration, starting just before bounce



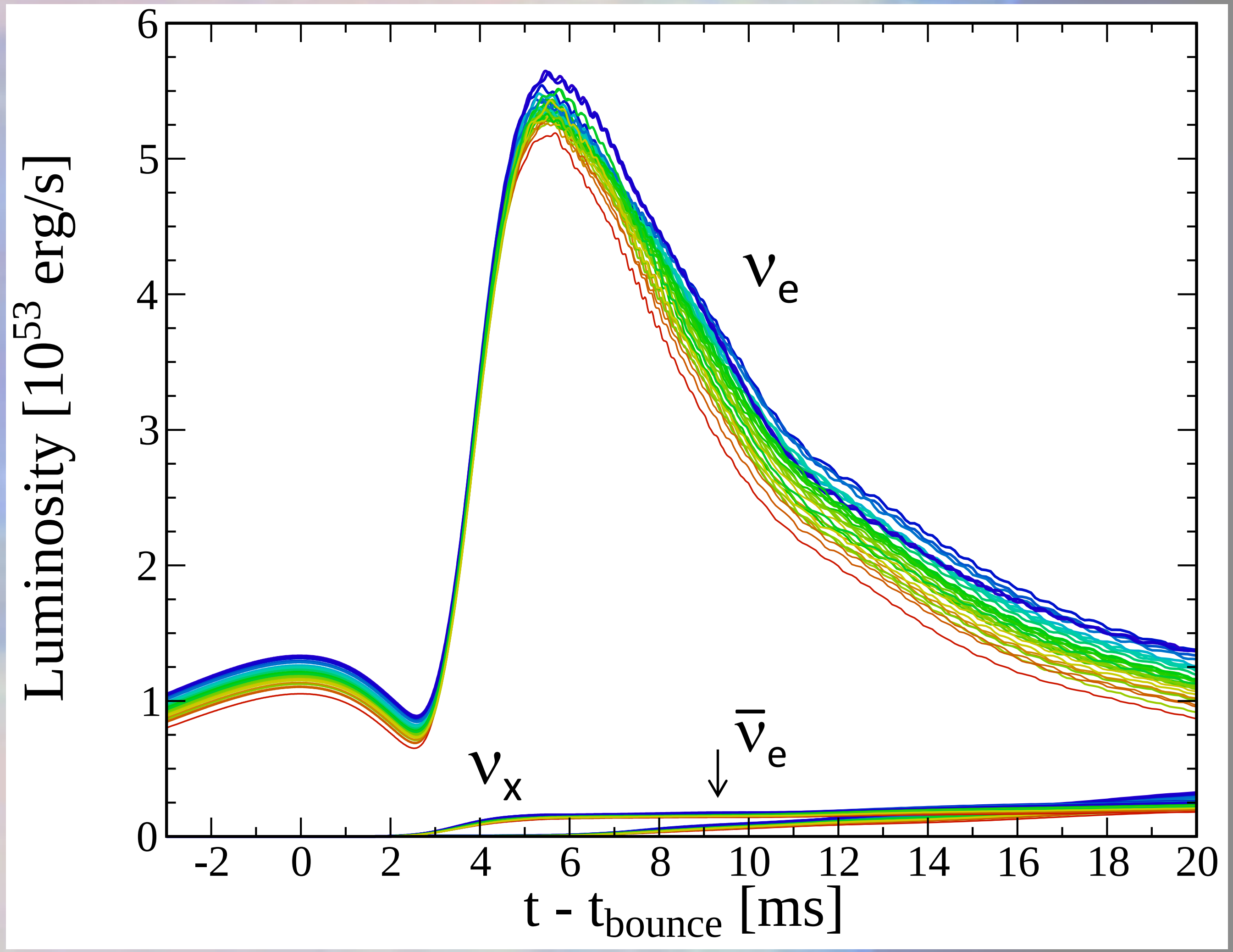


Neutronization Burst

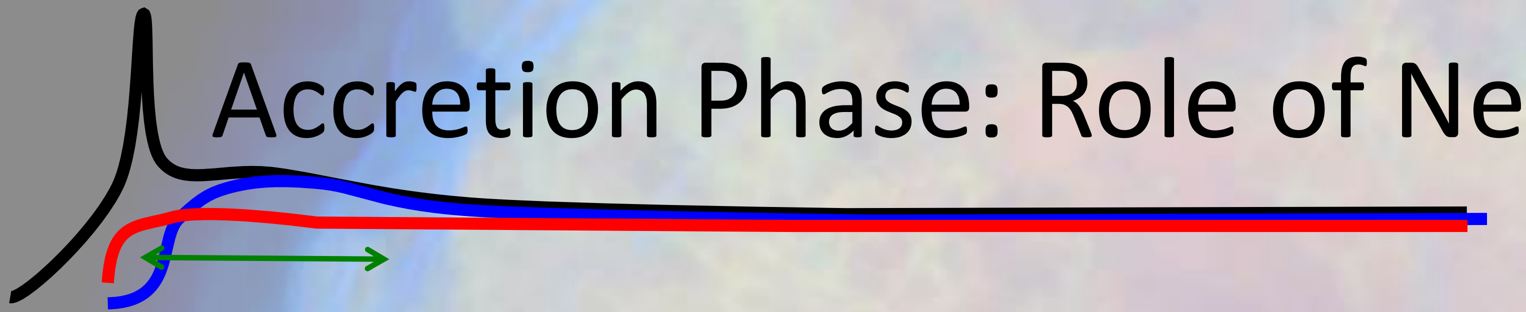
Iron core mass increasing ->

Matter temperature increasing ->

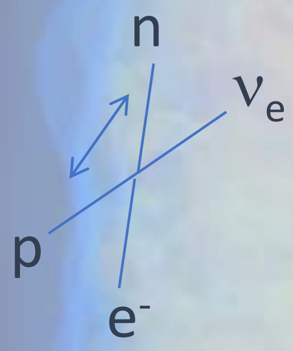
- ν_e's take a bit of time (few ms) before the density at the shock is low enough for the ν's to escape
- anti-ν_e and ν_x neutrinos luminosity is low. anti-ν_e are suppressed because high electron degeneracy, ν_x because T is low
- Little progenitor dependence, universal nature of collapse



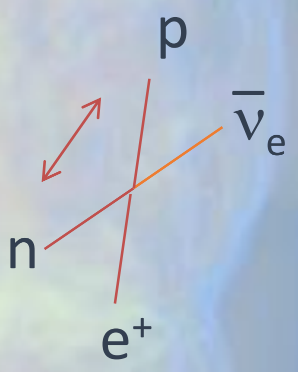
Accretion Phase: Role of Neutrinos



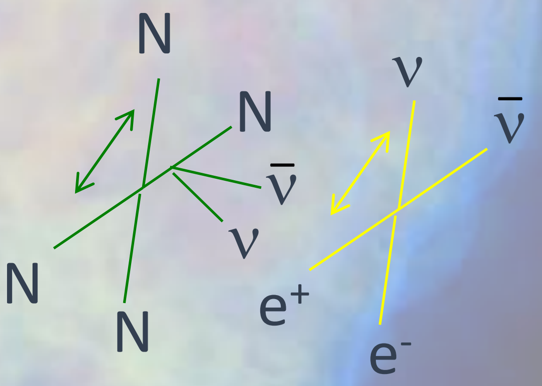
- After the burst, ν_e and anti-ν_e emission is powered by accretion
- Infalling matter is shock heated and then is cooled via neutrino emission



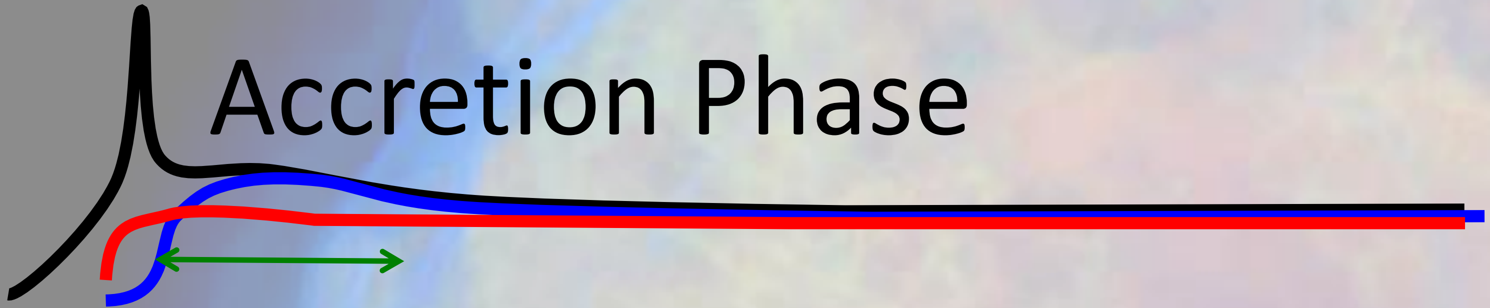
  - Charged current processes dominant production
  - Thermal production processes dominate at high densities where neutrinos are trapped for seconds



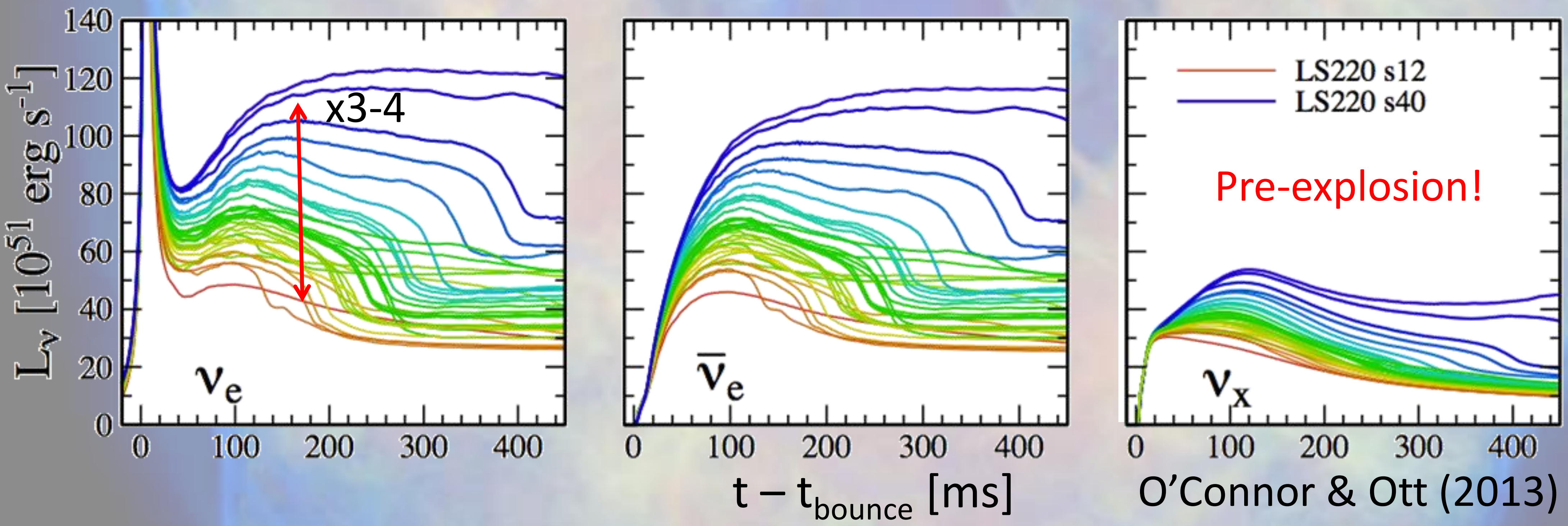
- After ~10-20ms, positron production no longer inhibited
- Thermal emission is dominant production process for heavy lepton neutrinos as T is too low for charged-current processes with μ's and τ's



Accretion Phase



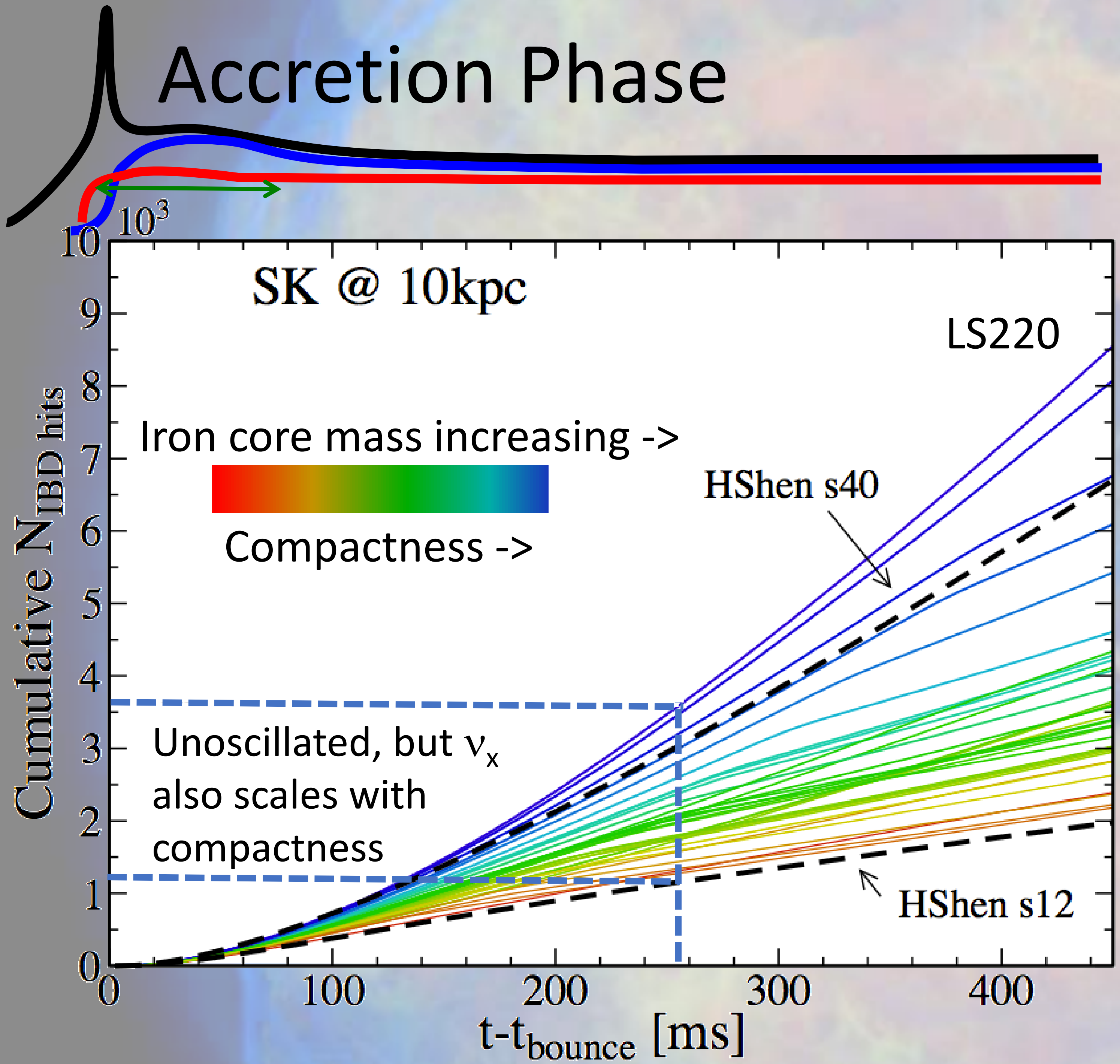
- The accretion phase introduces first progenitor dependence of luminosities
  - High ‘compactness’: higher mass accretion -> more binding energy released -> higher luminosities
- Detection will reveal progenitor properties and constrain stellar evolution



Pre-explosion!

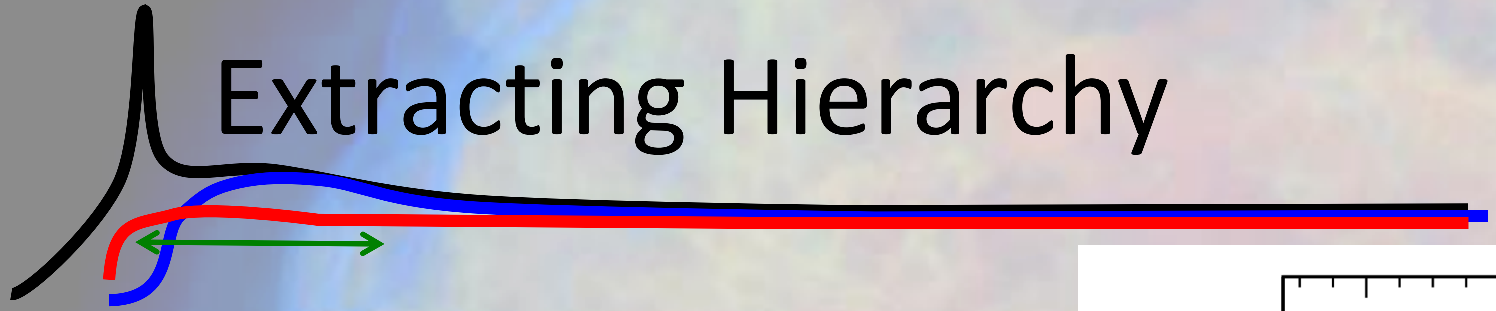
O’Connor & Ott (2013)

Accretion Phase

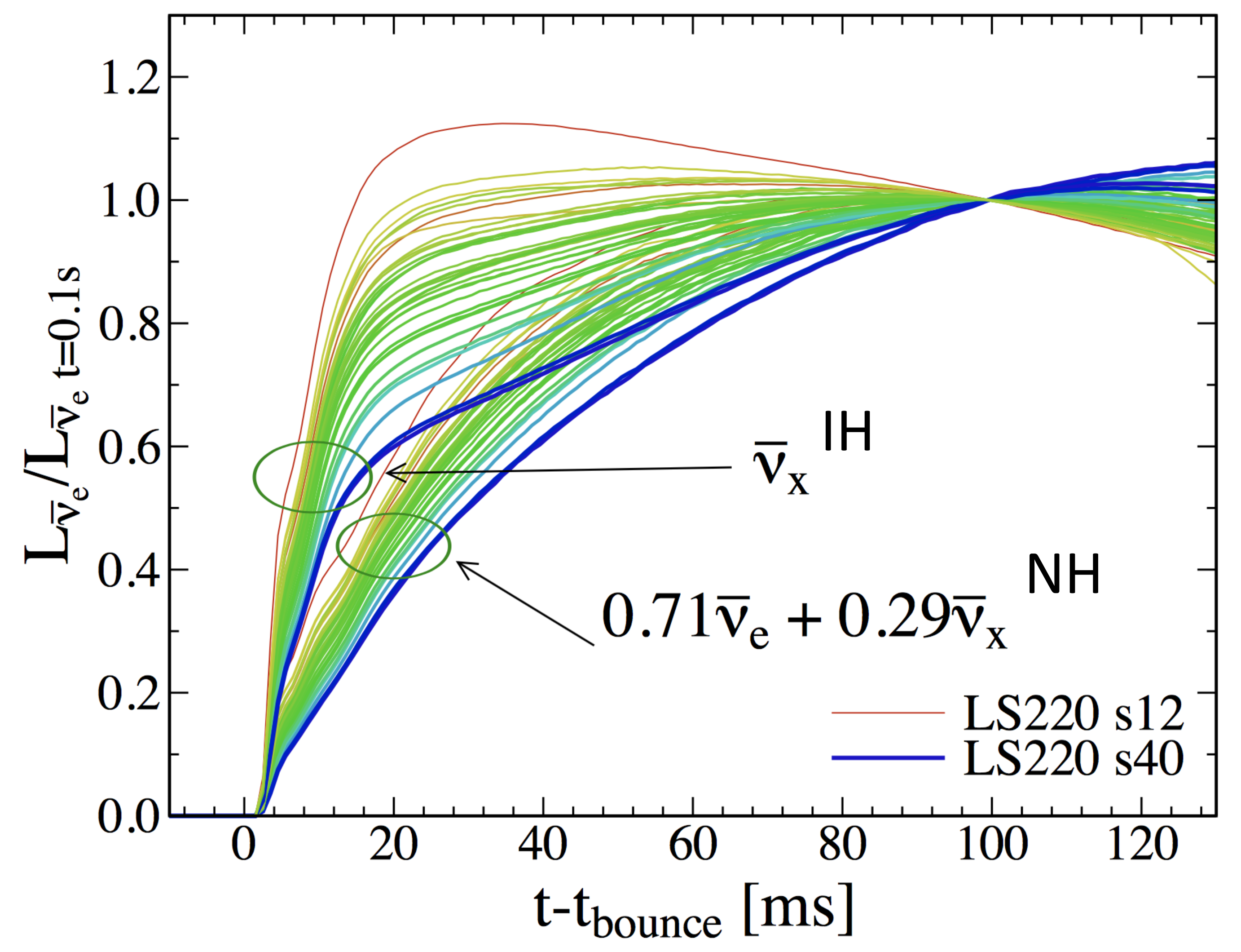


- We use `SNOwGLoBES` (Beck et al. 2011) to reconstruct the number of interactions in a Super-K-like ν detector for a 10 kpc supernova
- Higher luminosities give higher interaction rates
- Small EOS dependence
- The early postbounce preexplosion ν signal will tell us information on the structure of the progenitor star!

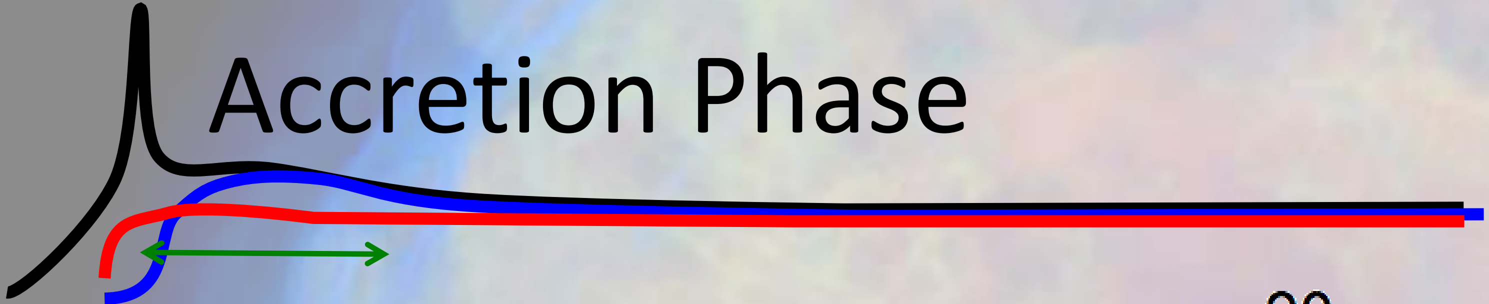
Extracting Hierarchy



- 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,
- caveat: collective oscillations, could also use neutronization burst



Accretion Phase

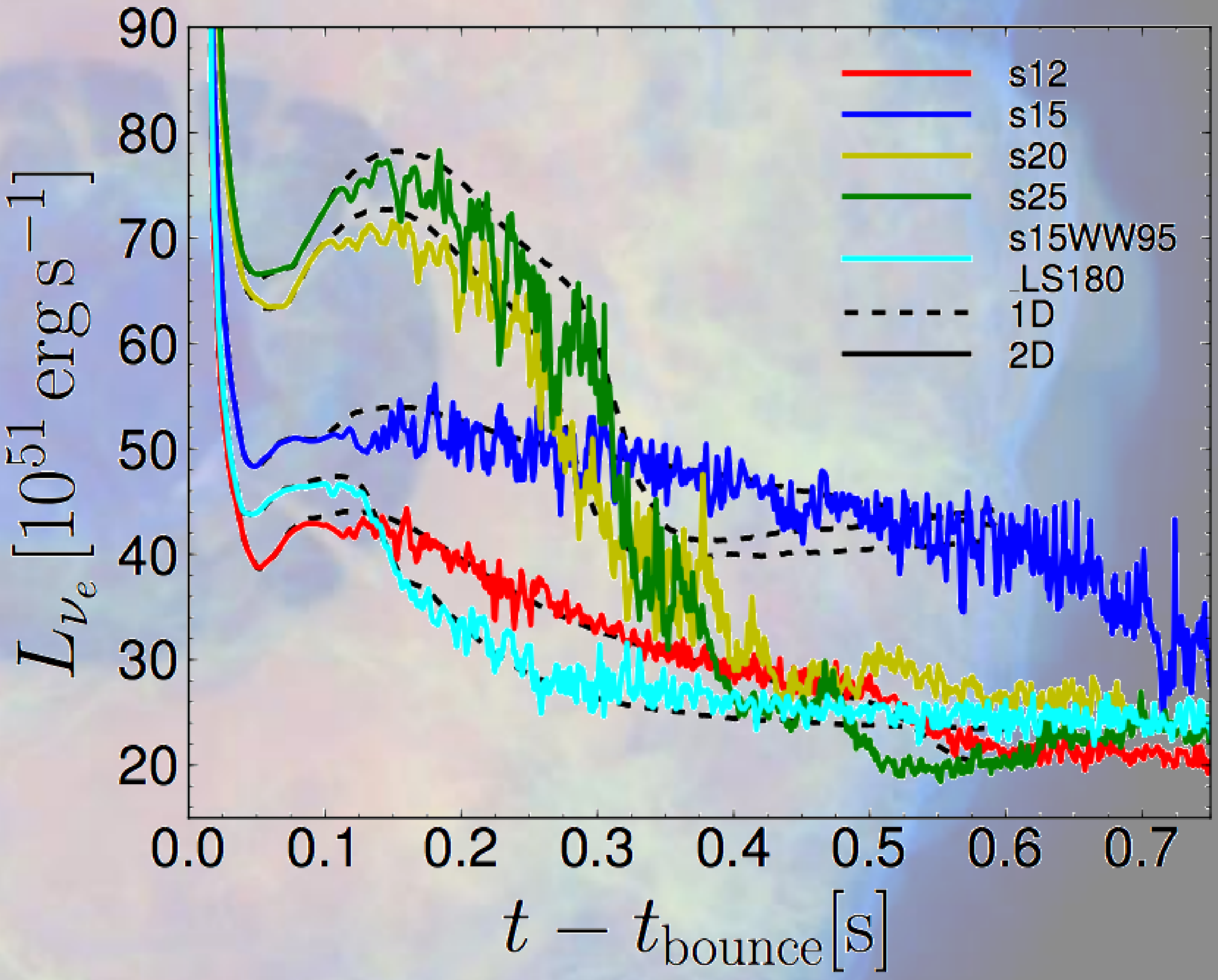


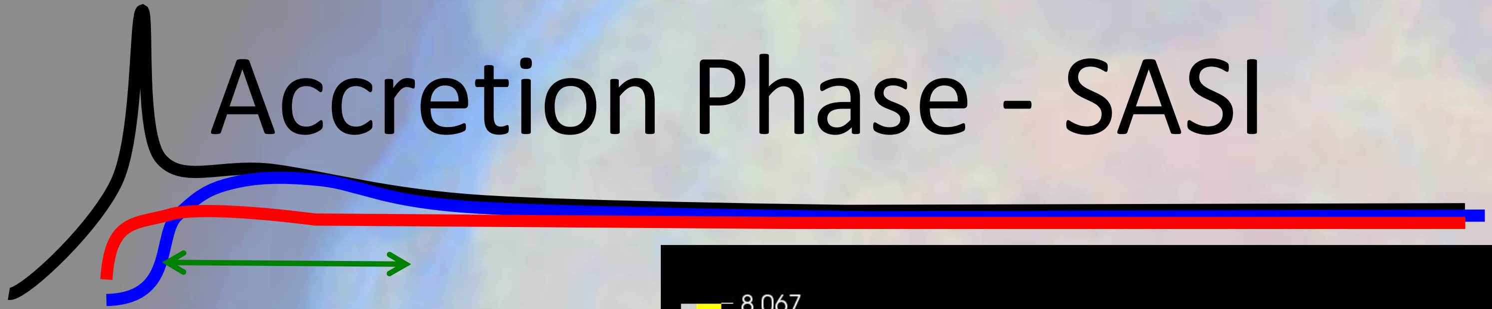
- Many groups consistently predict successful explosions in 2D simulations of core-collapse supernovae, 3D are harder, but promising

Points:

- Prior to explosion, similar to 1D
- After explosion luminosity drops
- Hydrodynamic instabilities present

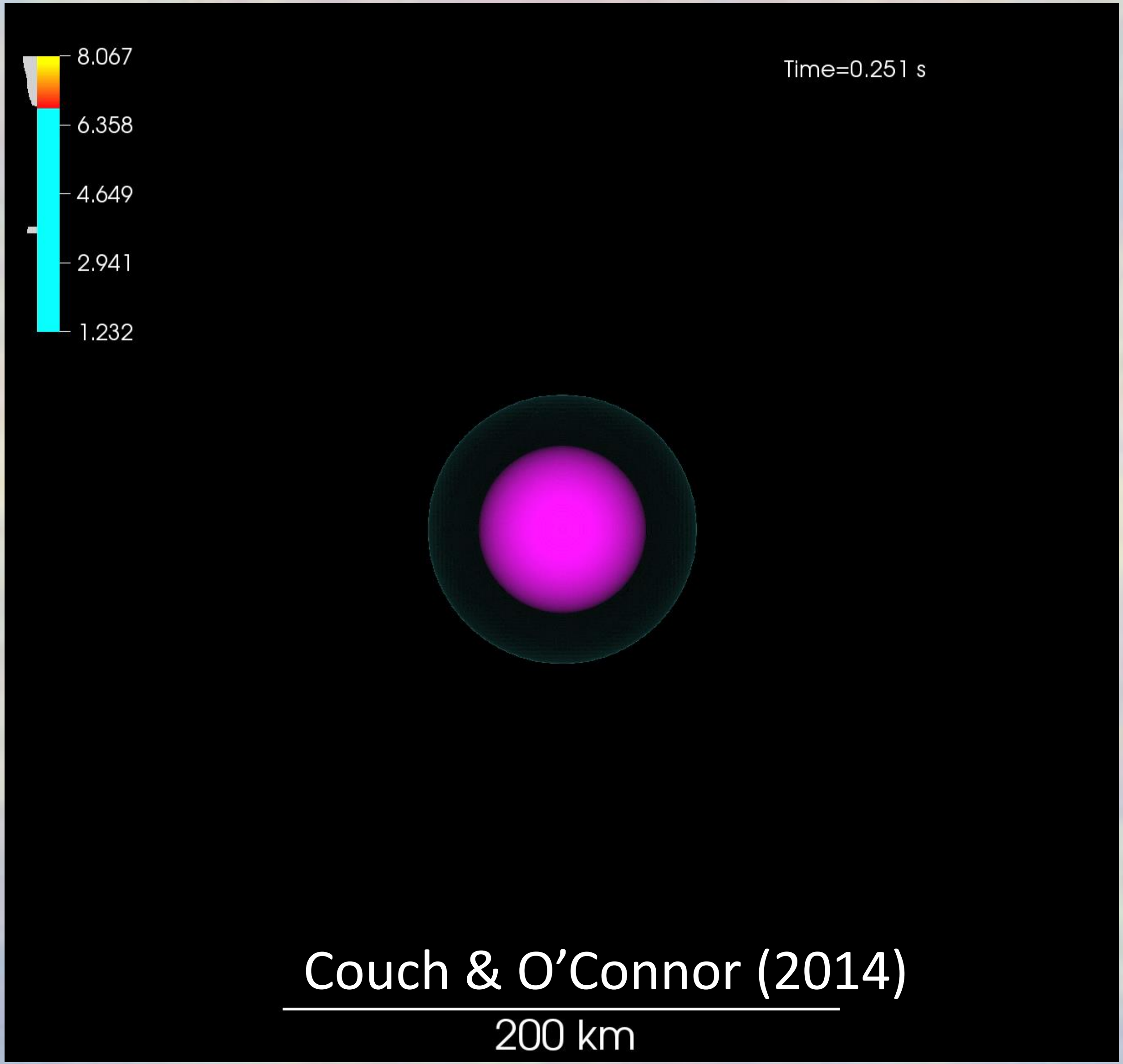
O’Connor & Couch (2015)





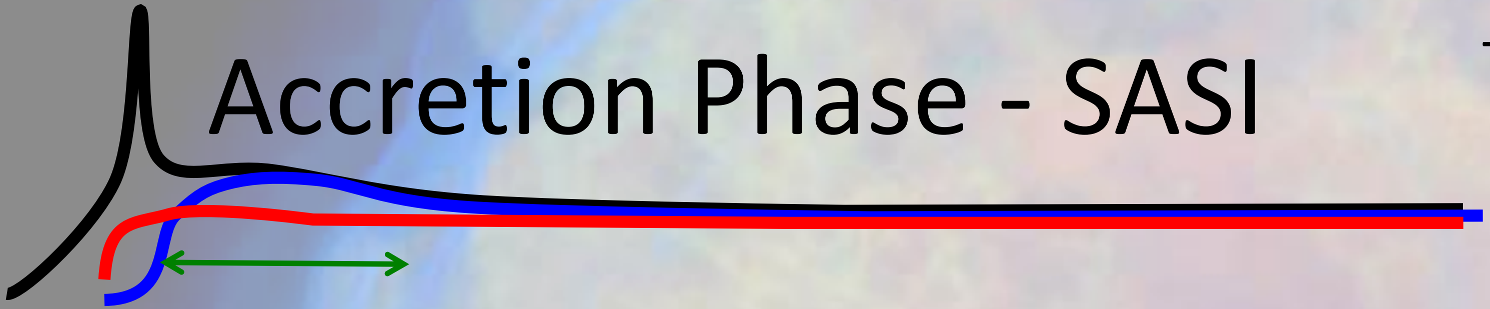
Accretion Phase - SASI

- SASI – Standing/Stationary Accretion Shock Instability

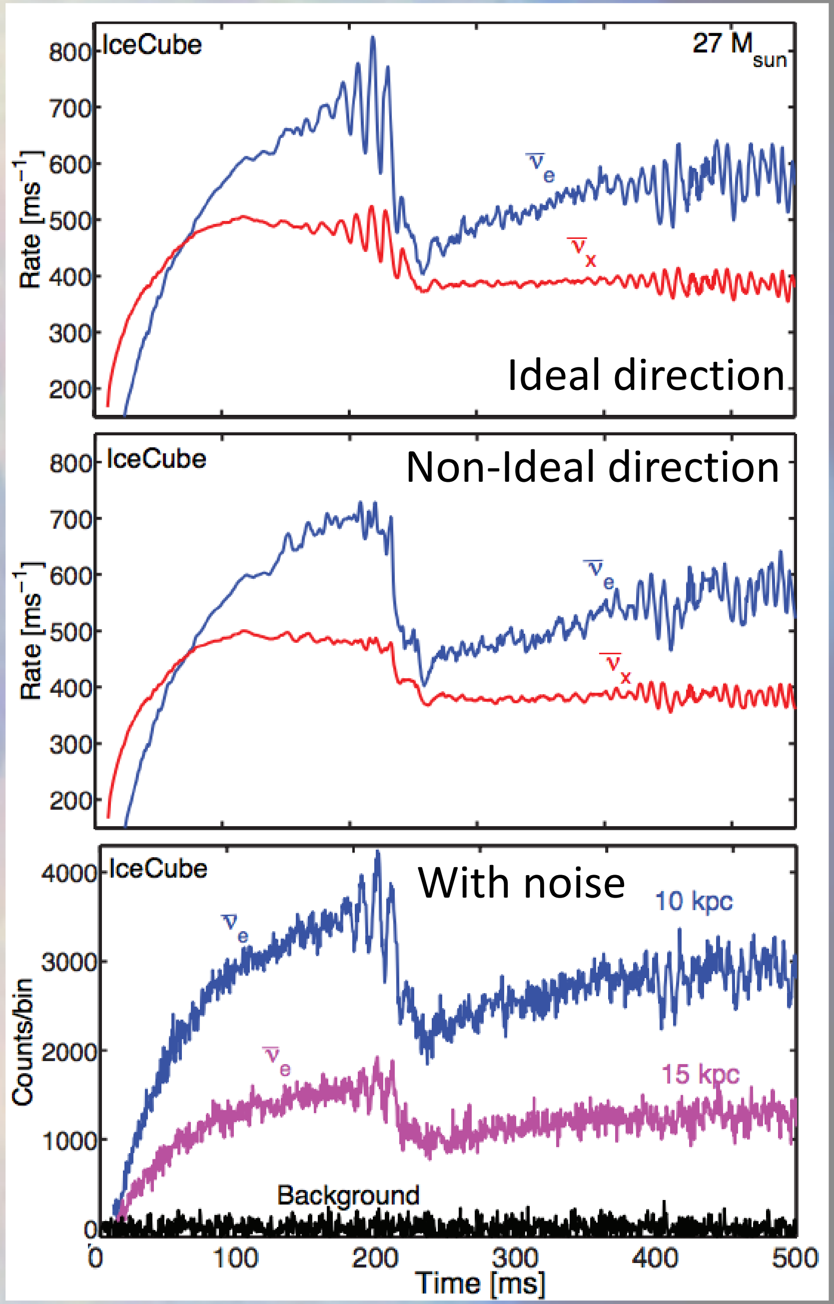


Couch & O’Connor (2014)

Accretion Phase - SASI

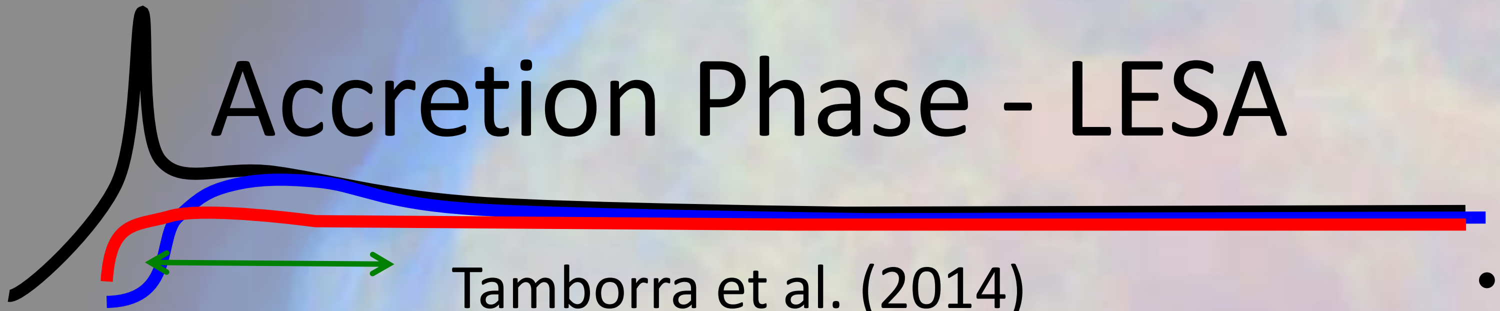


Tamborra et al. (2013); Mirizzi et al. (2015)

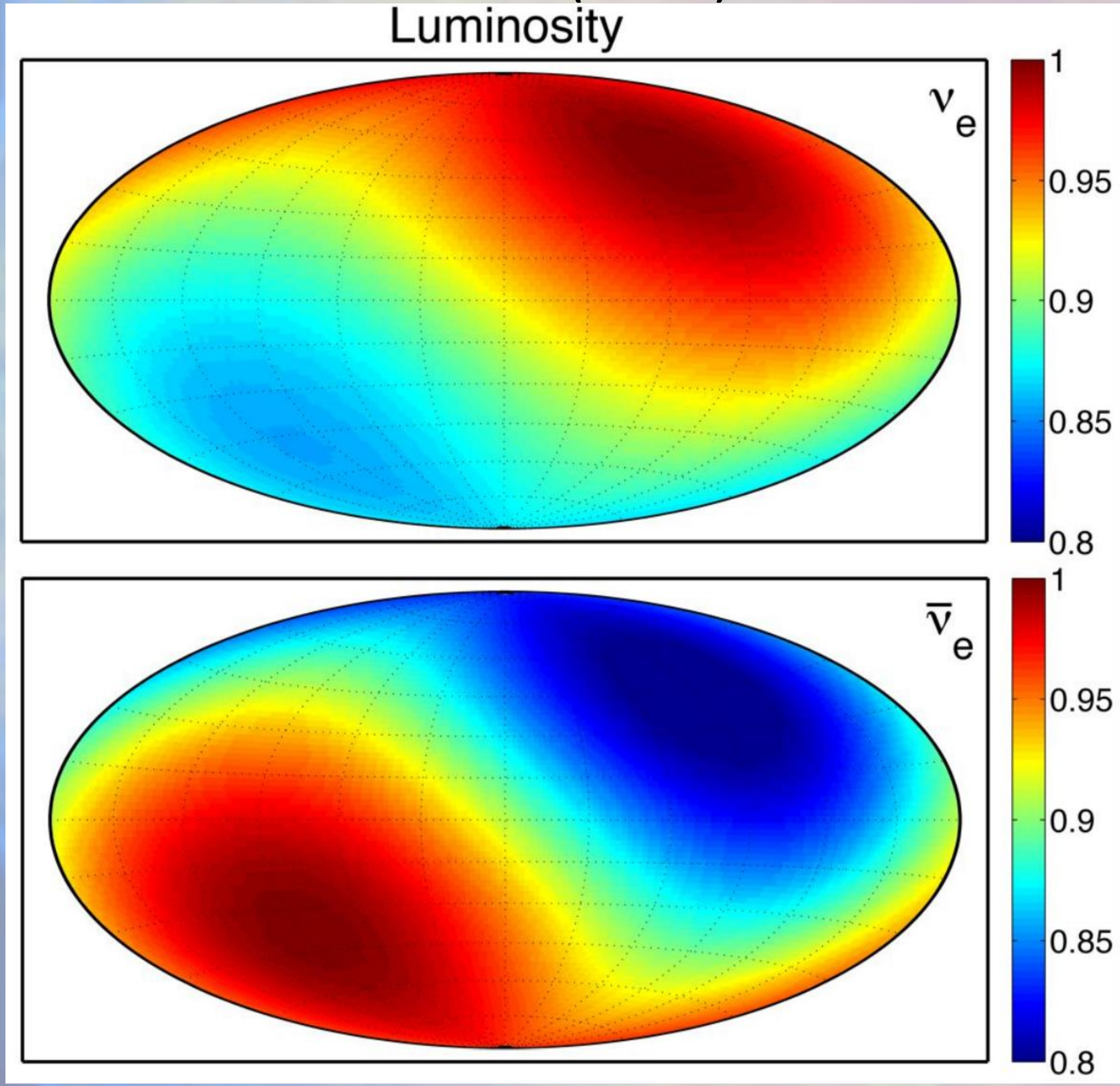


- Convection and SASI impact signal at lower order, can even be coherent/periodic, but do not systematically shift luminosity/energy
- Observable in HyperK and IceCube, perhaps not Dune. Timescales too short: ~10ms

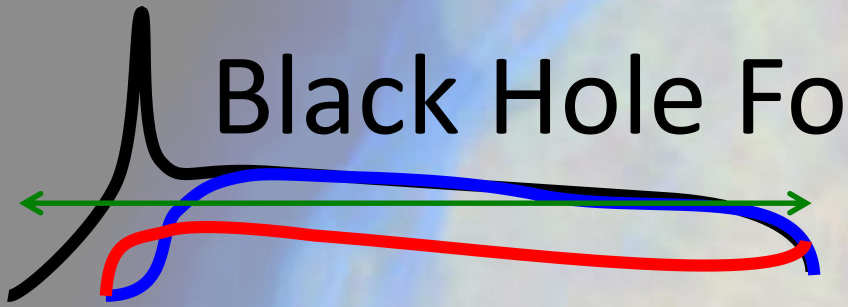
Accretion Phase - LESA



Tamborra et al. (2014)


Luminosity

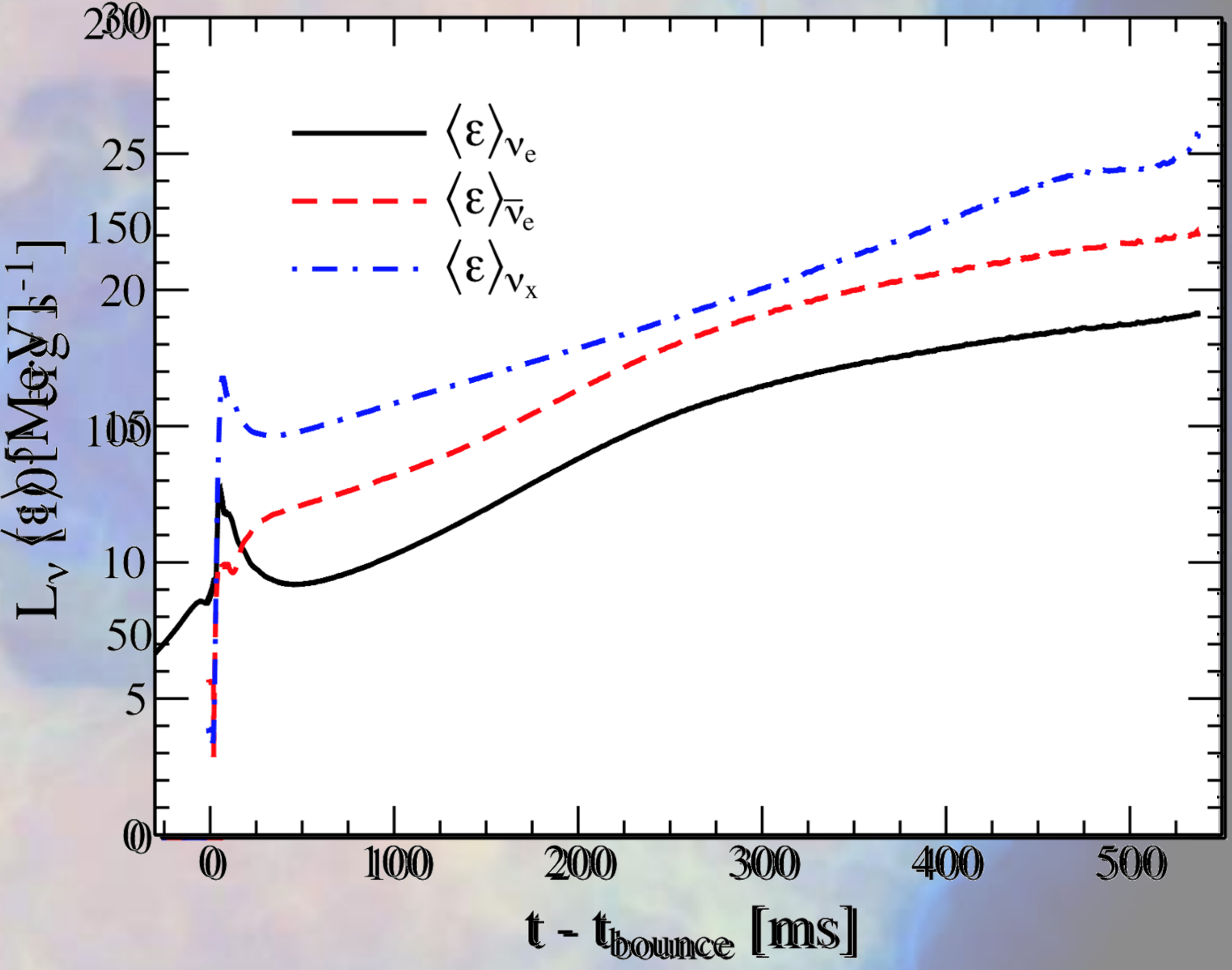
- Lepton number Emission Self-sustained Asymmetry - LESA
- Discovered in 3D simulations
  - Develops within 150ms of bounce
  - Creates a dipole in lepton number
  - Results in observer-angle dependent luminosity variations ~ 20%
- Stills need confirmation
- Measurements of both neutrino and antineutrino luminosities important



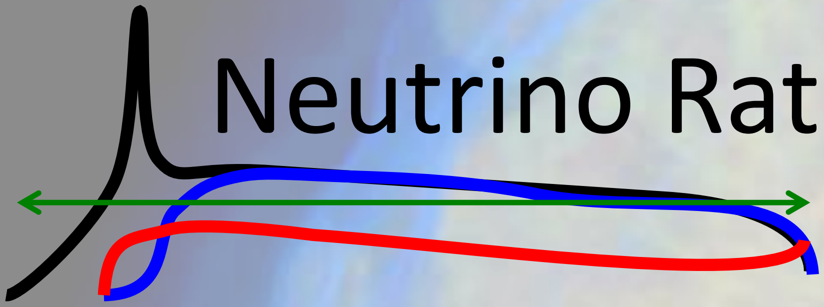
Black Hole Formation

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

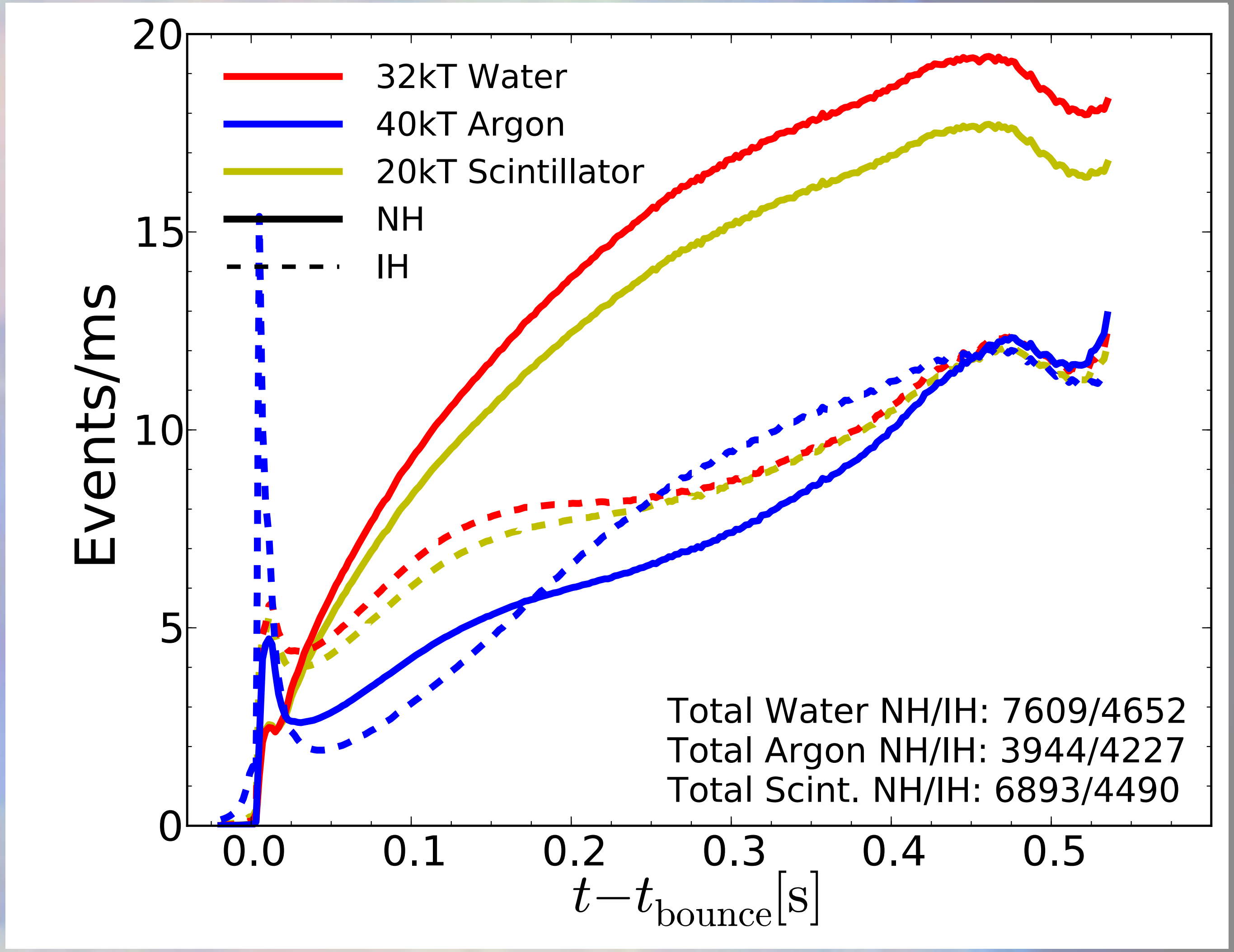
O’Connor (2015)



Neutrino Rates



- 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



Total Water NH/IH: 7609/4652
Total Argon NH/IH: 3944/4227
Total Scint. NH/IH: 6893/4490

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

Dighe & Smirnov (2000)

NH

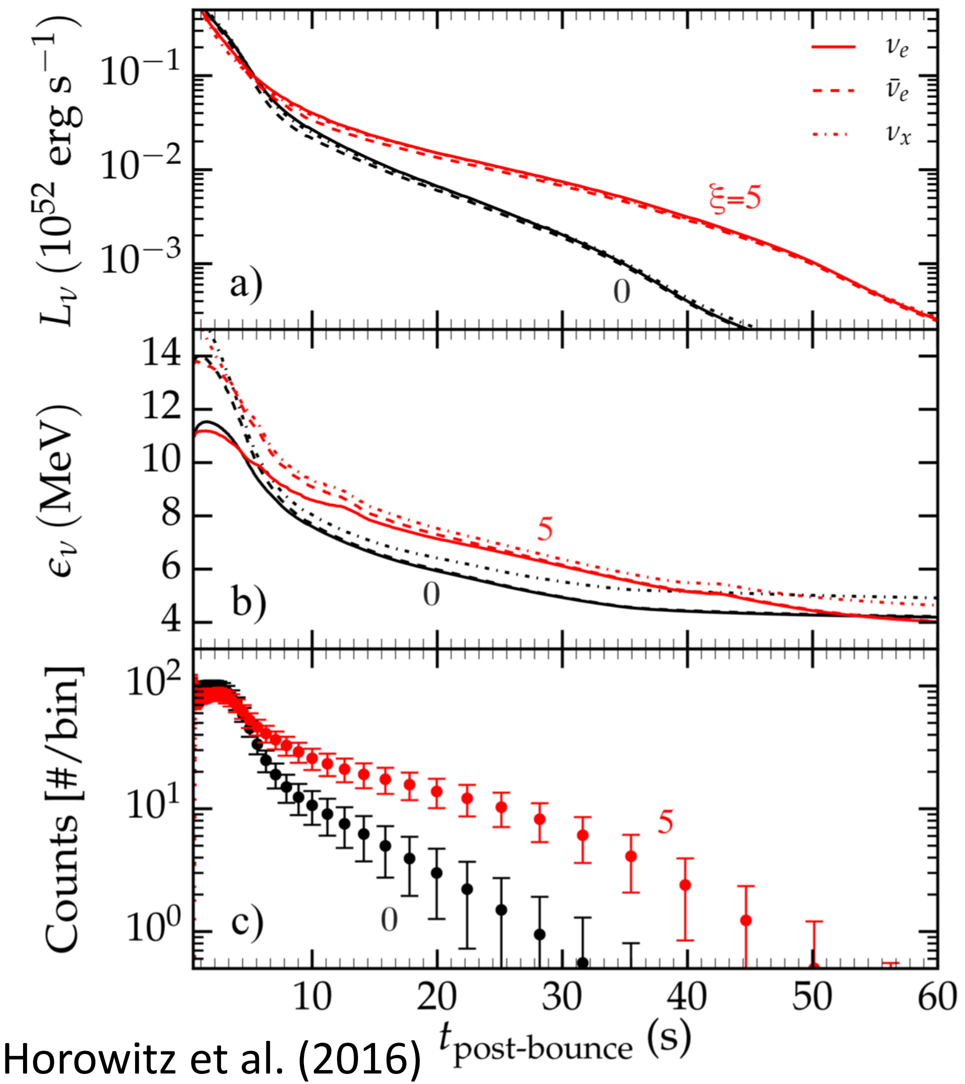
$$\begin{aligned} N_{\nu_e} &= N^0_{\nu_x} \\ N_{\bar{\nu}_e} &= \cos^2\theta_\odot N^0_{\bar{\nu}_e} + \sin^2\theta_\odot N^0_{\nu_x} \\ 4N_{\nu_x} &= \cos^2\theta_\odot N^0_{\nu_x} + \sin^2\theta_\odot N^0_{\bar{\nu}_e} + N^0_{\nu_e} + 2N^0_{\nu_x} \end{aligned}$$

IH

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

Cooling Phase

See Shirley Lee’s talk on Friday

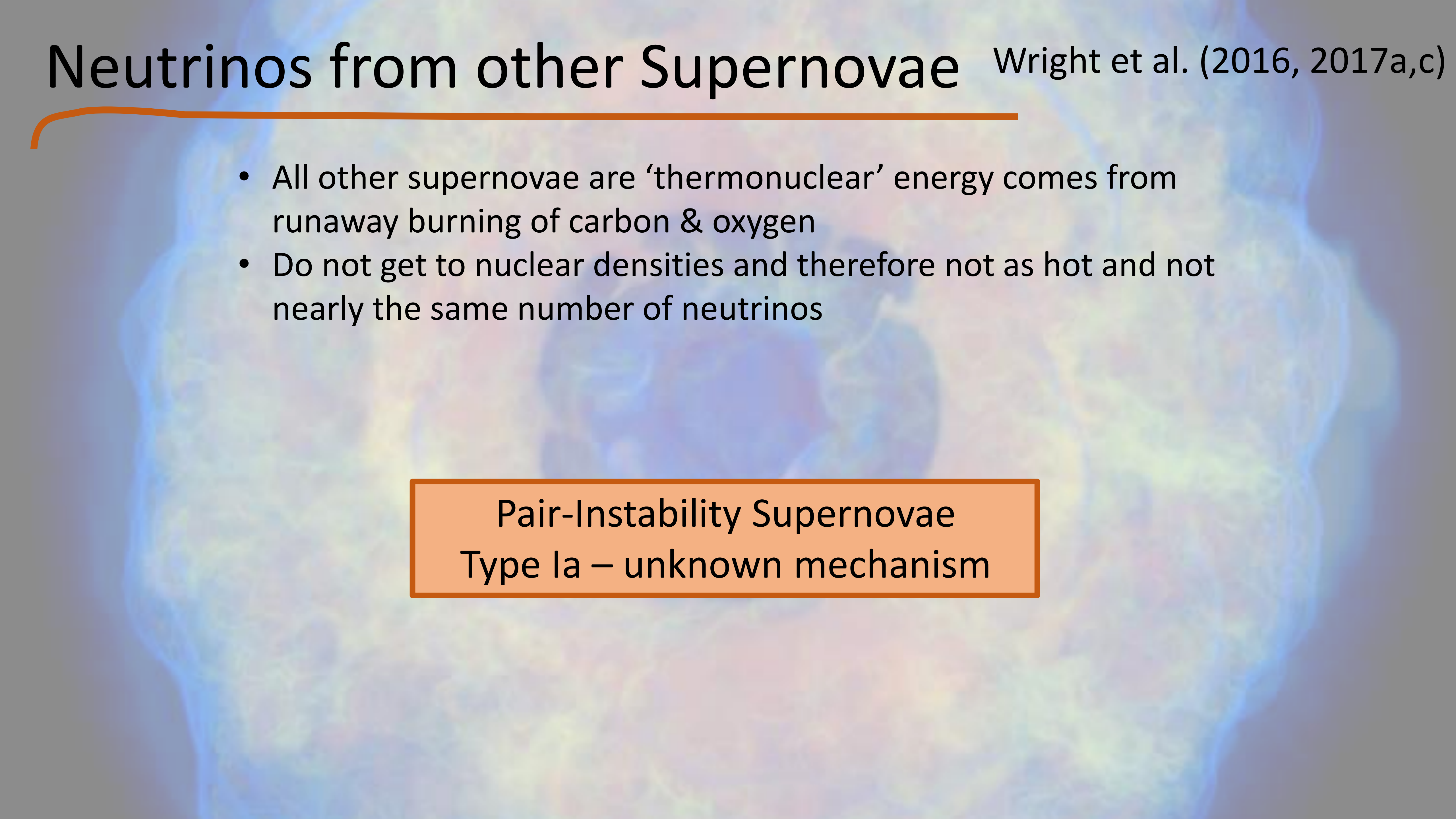


Horowitz et al. (2016)

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

Neutrinos from other Supernovae

Wright et al. (2016, 2017a,c)



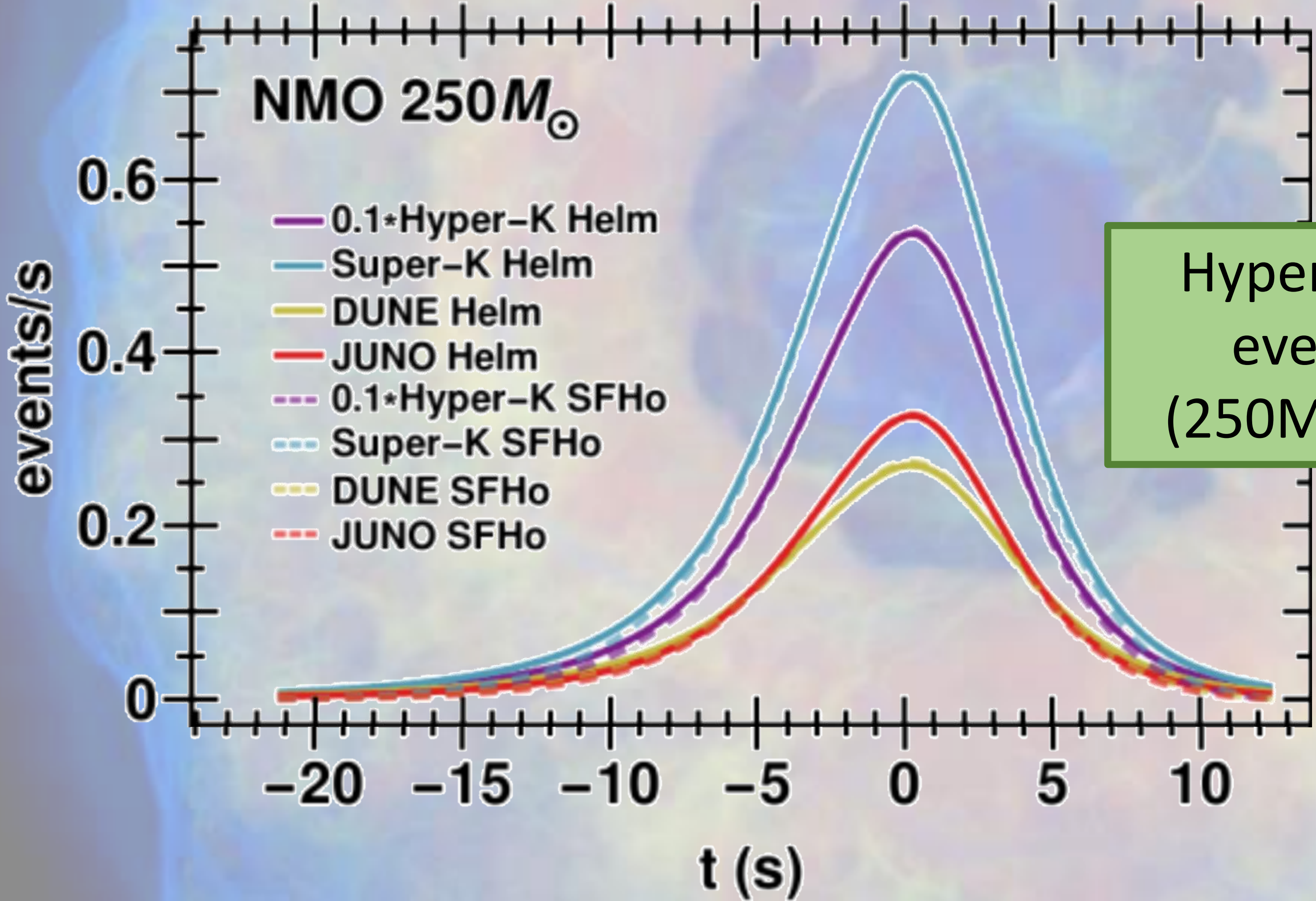
- All other supernovae are ‘thermonuclear’ energy comes from runaway burning of carbon & oxygen
- Do not get to nuclear densities and therefore not as hot and not nearly the same number of neutrinos

Pair-Instability Supernovae
Type Ia – unknown mechanism

Neutrinos from other Supernovae

Wright et al. (2016, 2017a,c)

Pair-Instability Supernovae

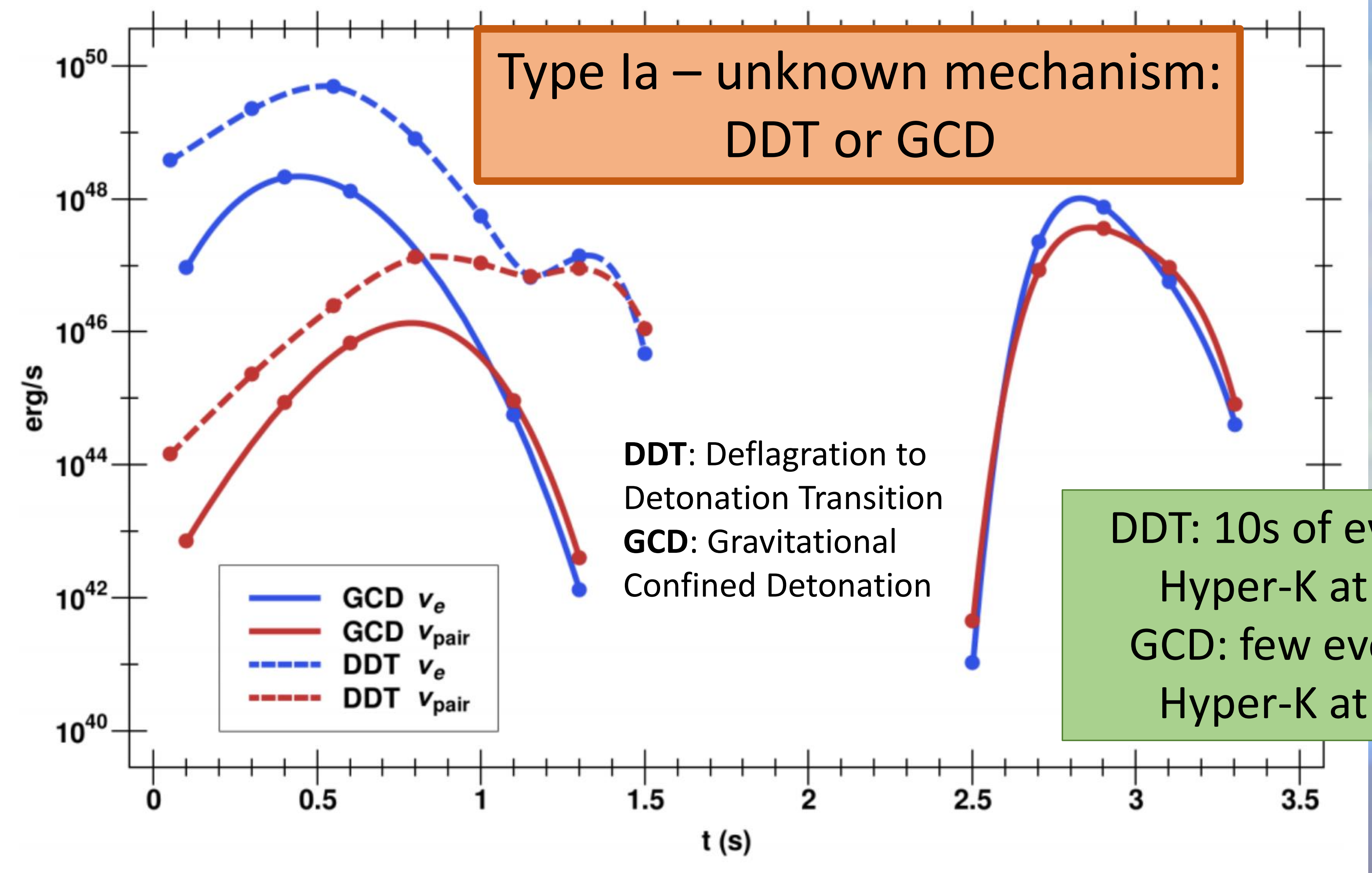


Hyper-K: 50 NH (40 IH) events for massive ($250M_{sun}$) PISN at 10kpc

Caveat: <u>Very Low Energy</u> requires low threshold: 2MeV -> 50% efficiency

Neutrinos from other Supernovae

Wright et al. (2016, 2017a,c)



Type Ia – unknown mechanism:
DDT or GCD

DDT: Deflagration to Detonation Transition
GCD: Gravitational Confined Detonation

DDT: 10s of events in Hyper-K at 1kpc
GCD: few events in Hyper-K at 1kpc

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!