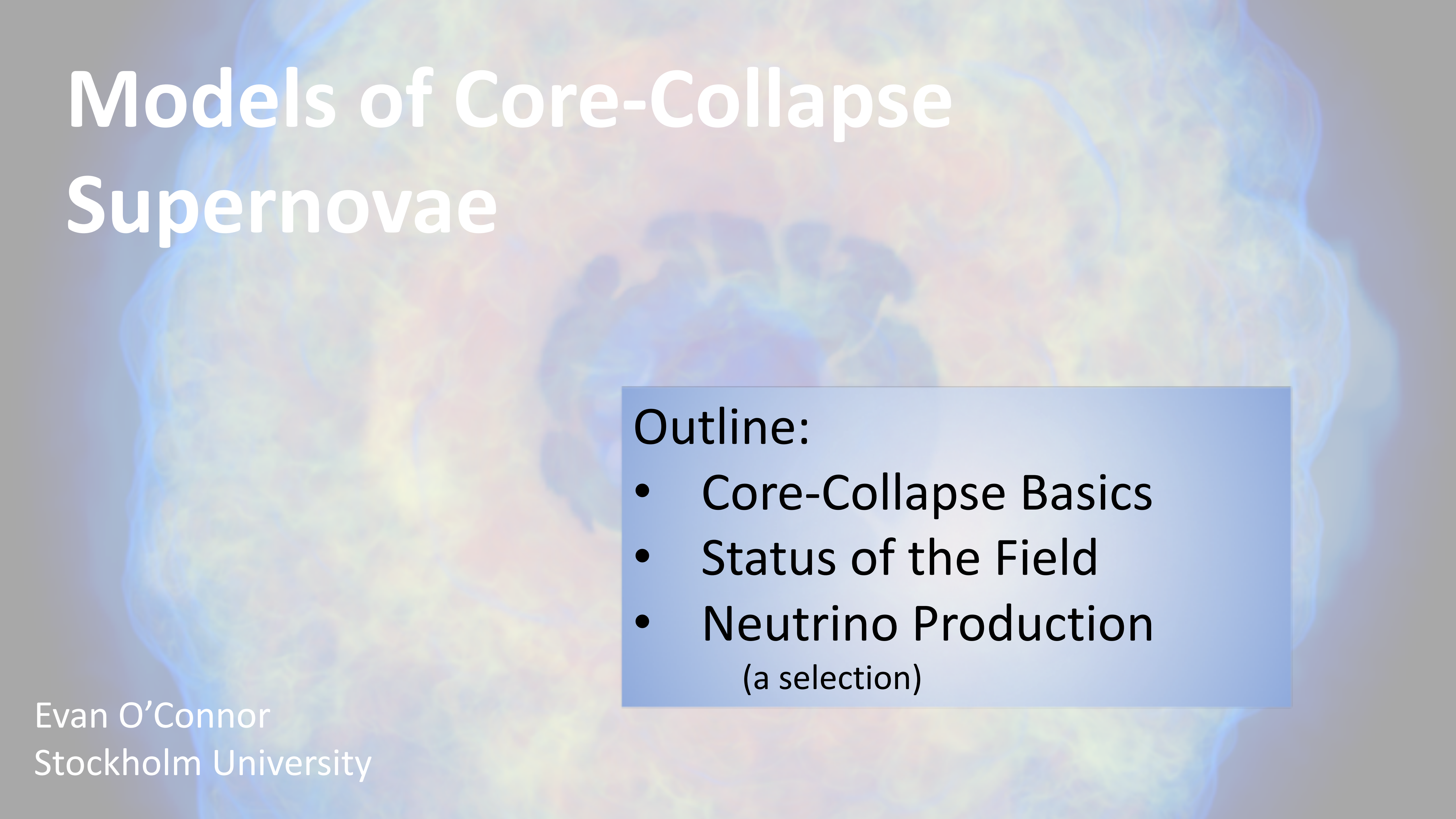
Models of Core-Collapse Supernovae



Outline:
- Core-Collapse Basics
- Status of the Field
- Neutrino Production

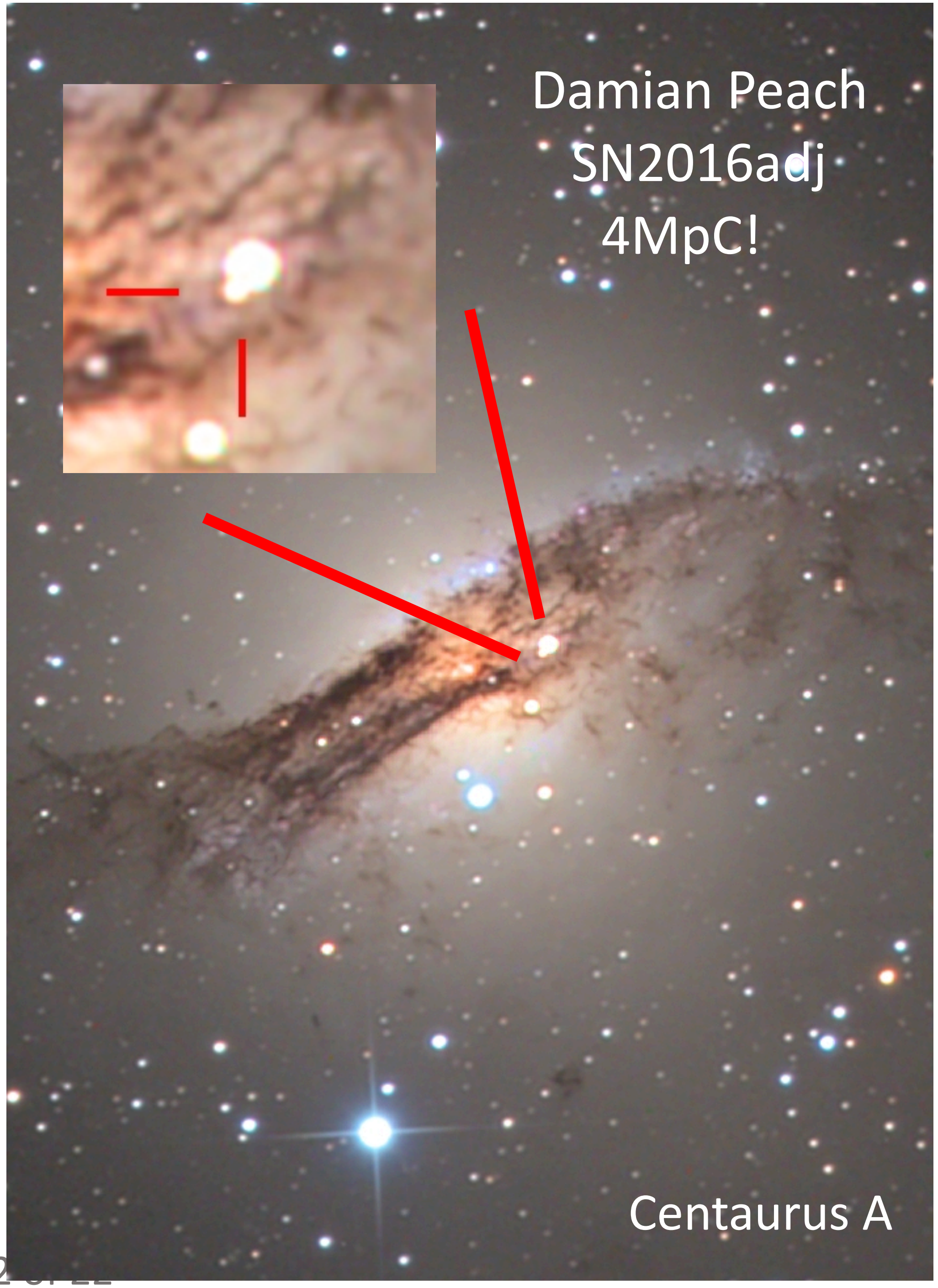
(a selection)

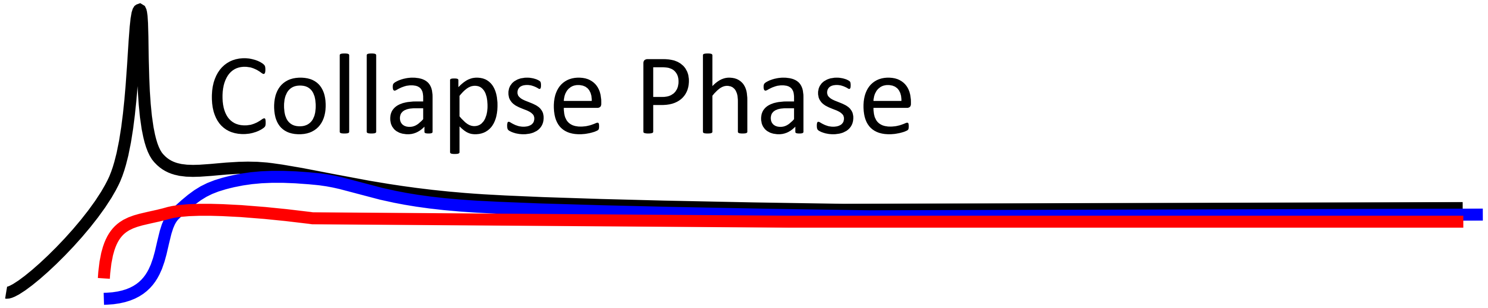
Evan O'Connor
Stockholm University

Core Collapse Supernovae

- CCSNe are some of the brightest astrophysical phenomena in the modern universe.
- Astrophysical importance:
  - nucleosynthesis
  - trigger and regulate star formation
  - source of neutron stars and black holes.
- Unique and fantastic laboratory for studying high density/temperature and neutron rich conditions.

  -> Need to observe central engine
  - Neutrinos!
  - Gravitational Waves!

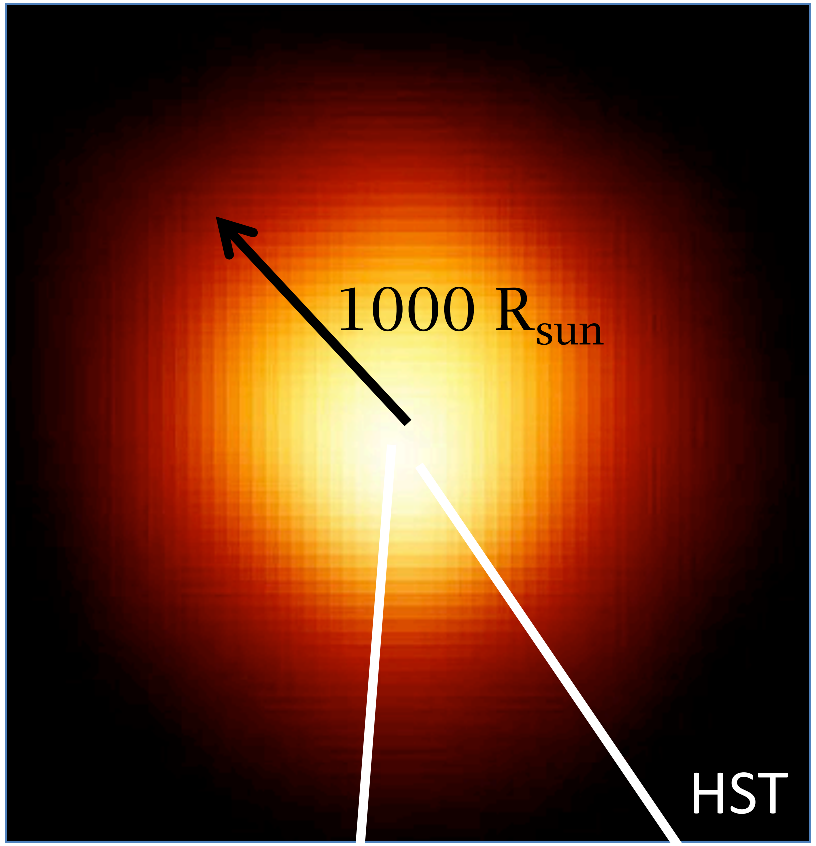


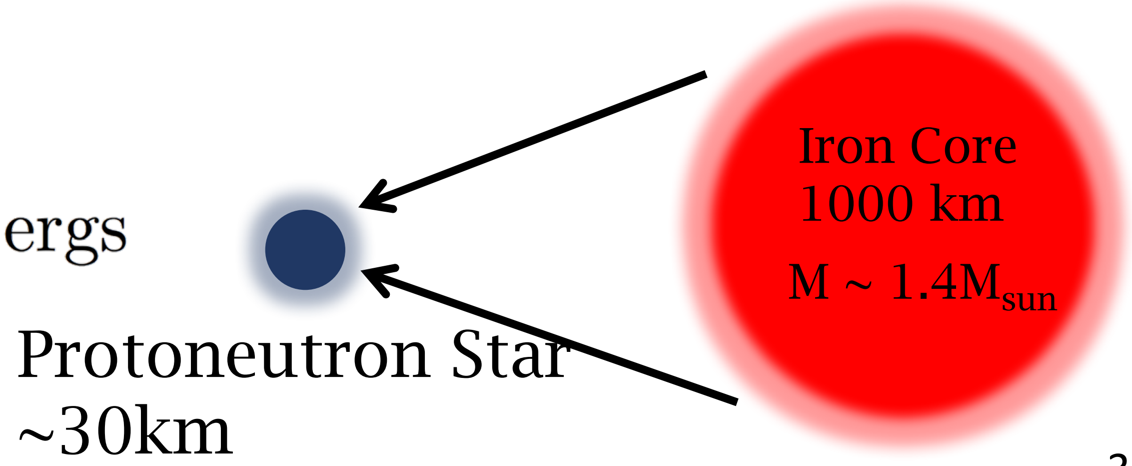


Collapse Phase

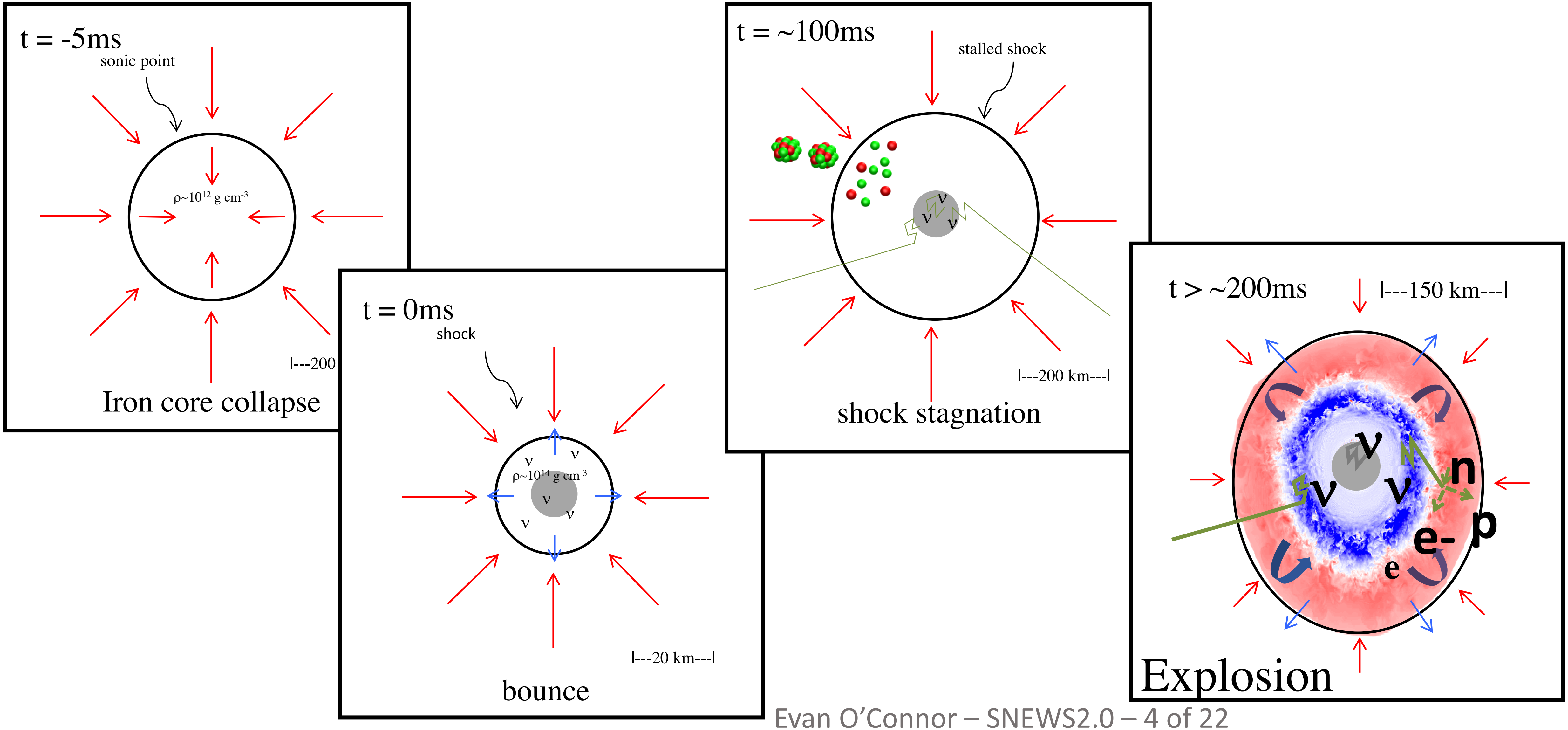
- Most massive stars core collapse during the red supergiant phase
- CCSNe are triggered by the collapse of the iron core (~1000km, or 1/10^6 of the star's radius)
- Collapse ensues because electron degeneracy pressure can no longer support the core against gravity

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





CCSNe: The Stages



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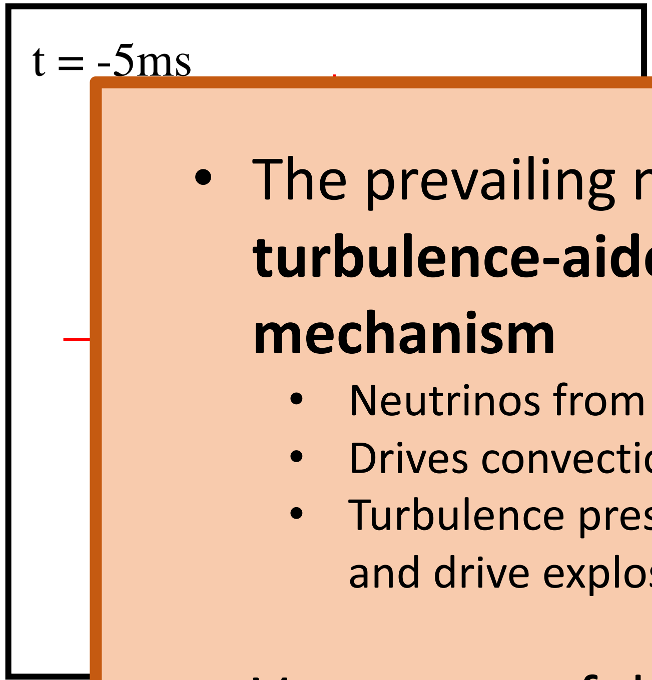
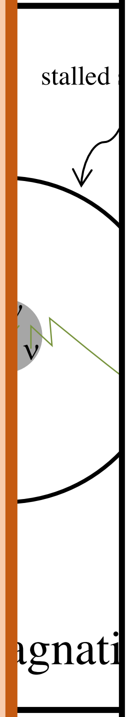
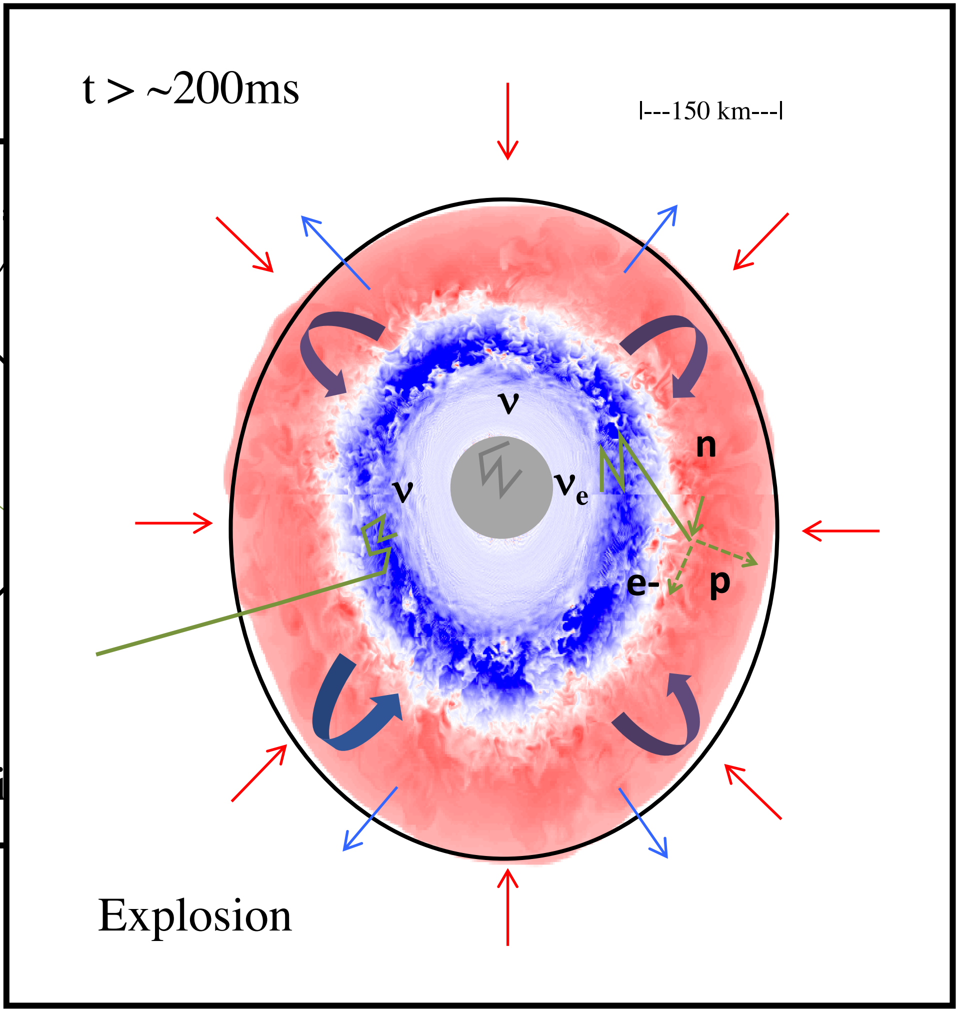


- The prevailing mechanism is the **turbulence-aided neutrino mechanism**
    - Neutrinos from core heat outer layers
    - Drives convection
    - Turbulence pressure support aids heating and drive explosion
- Very successful in 2D*, many successful explosions
- Success in 3D too: fewer simulations





The Core-Collapse Supernova Problem

Understanding the transition from an imploding iron core to an exploding star has been a persistent and difficult problem in astrophysics.

Requires:

3D - (Magneto)hydrodynamics

General Relativity

Nuclear Reactions

Progenitors

Nuclear Equation of State

Neutrino Transport & Interactions

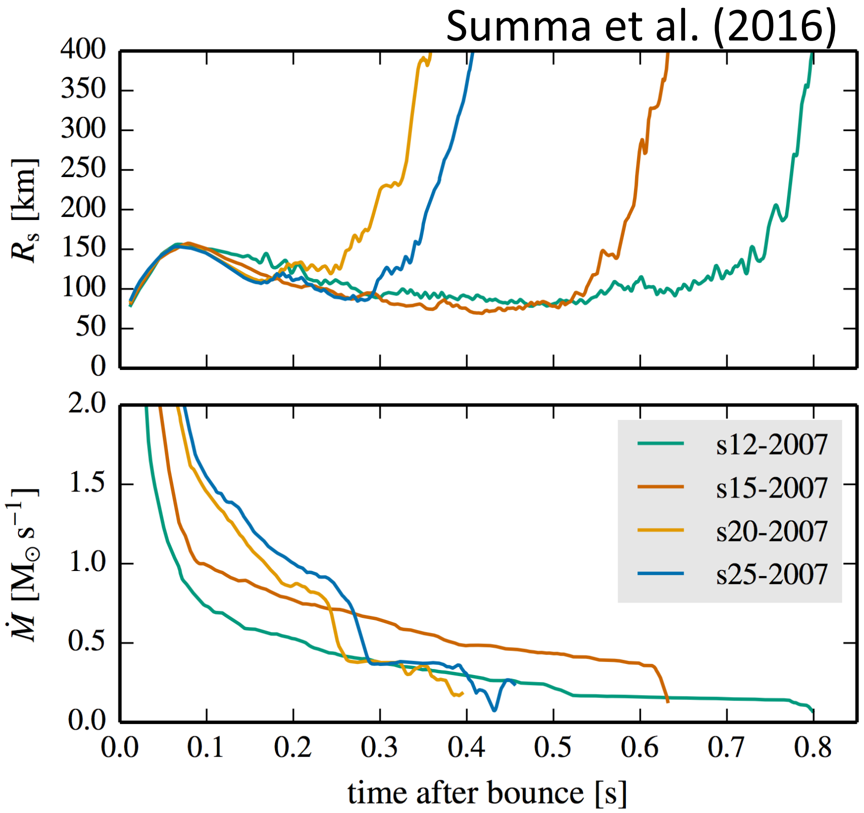
Computational Physics

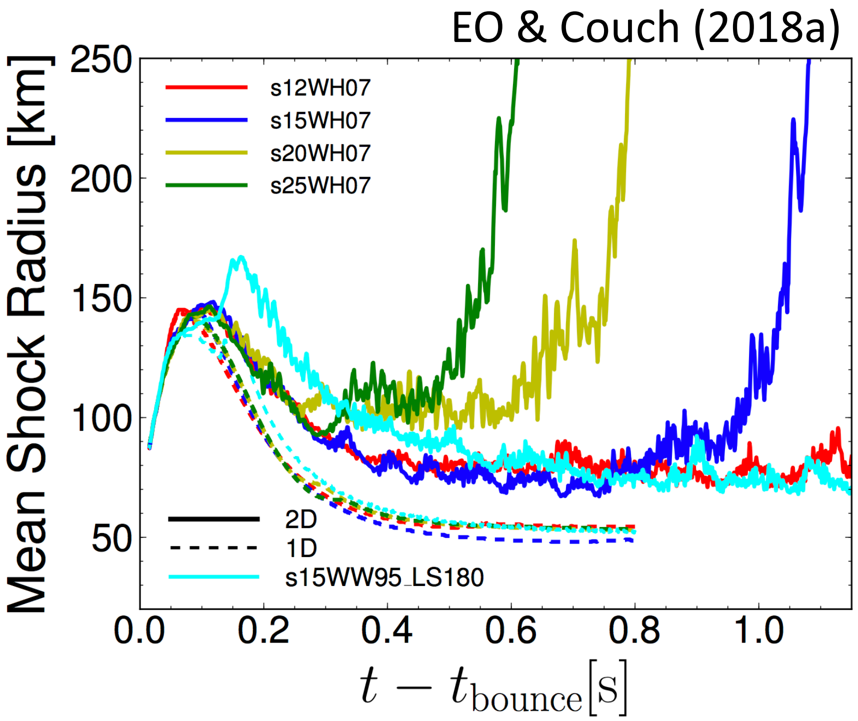
movie

EO & Couch (2018b)

Explosion Successes in multiD – 2D

Woosley & Heger (2007) progenitors

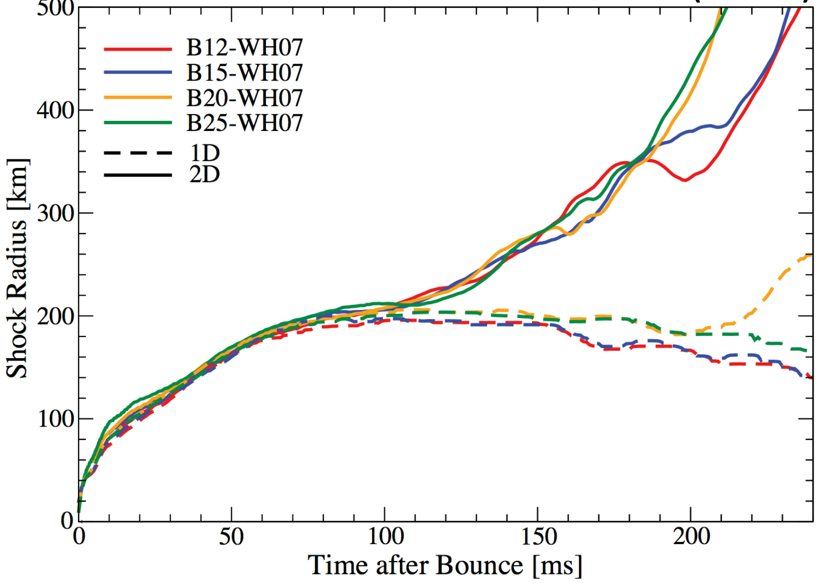

Summa et al. (2016)


EO & Couch (2018a)

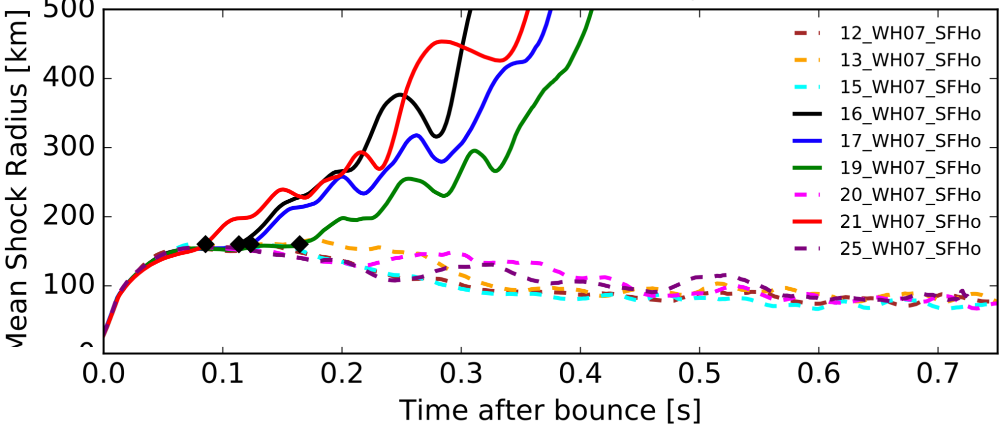
Explosion Successes in multiD – 2D

Woosley & Heger
(2007) progenitors

Bruenn et al. (2013)



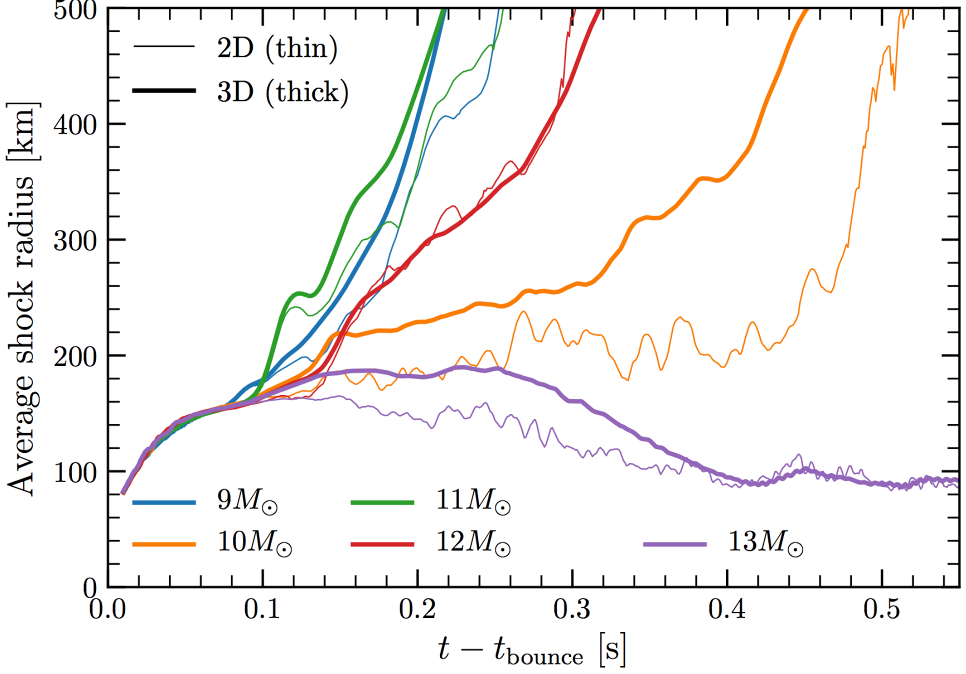
Vartanyan et al. (2018)



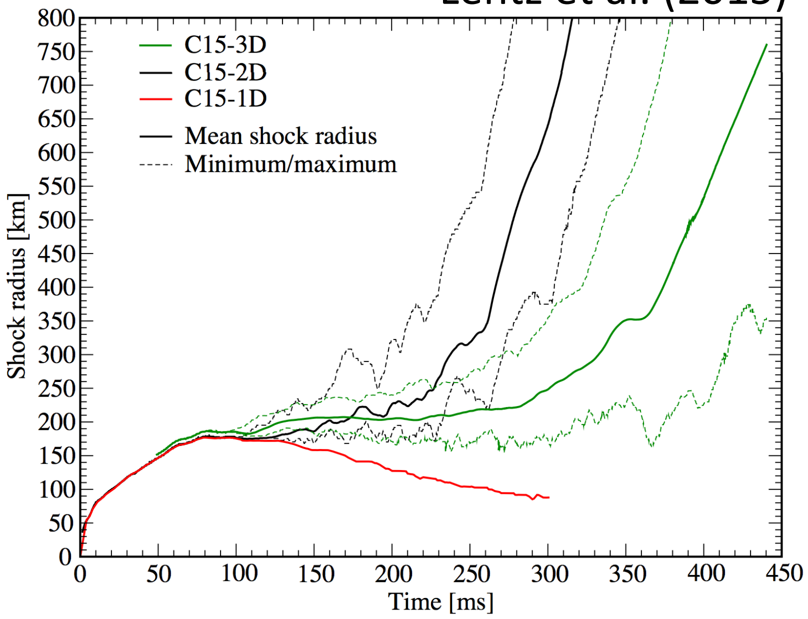
Explosion Successes in multiD – 3D

Woosley & Heger
(2007) progenitors

Burrows et al. (2019)



Lentz et al. (2015)



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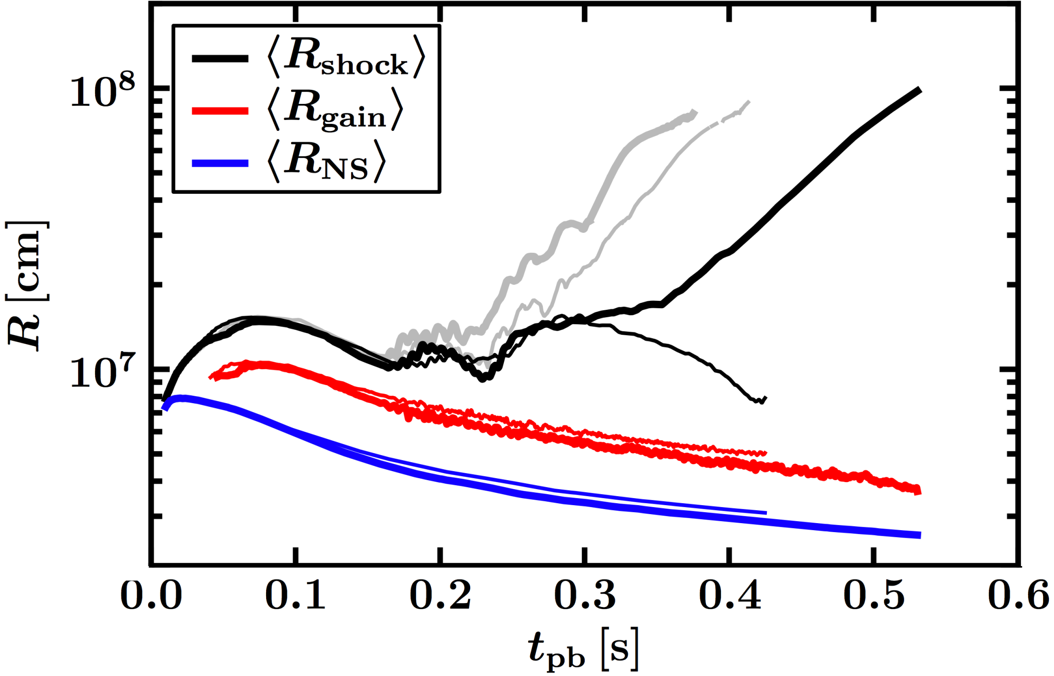
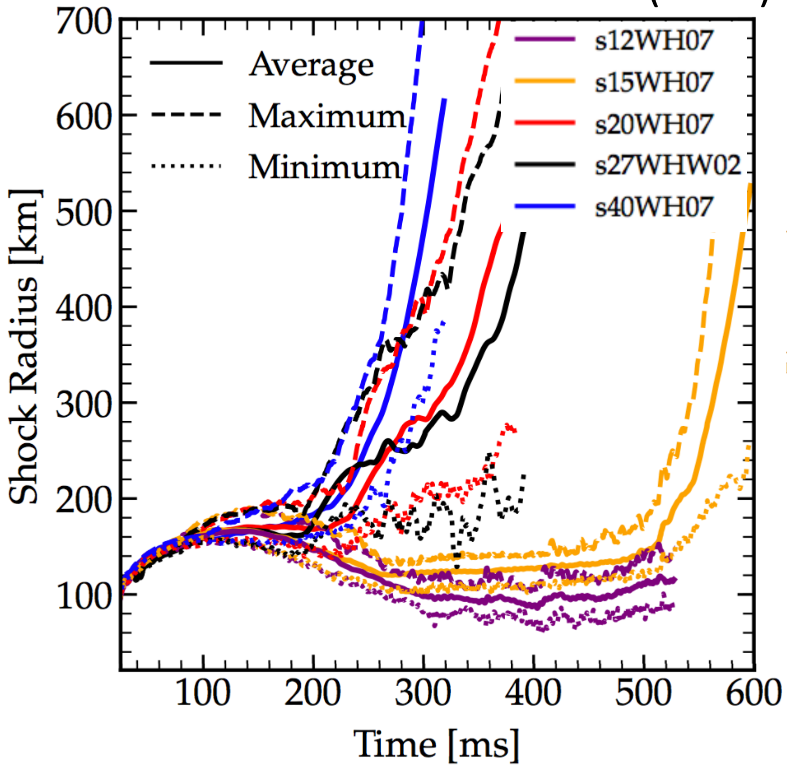
Melson et al. (2015b)

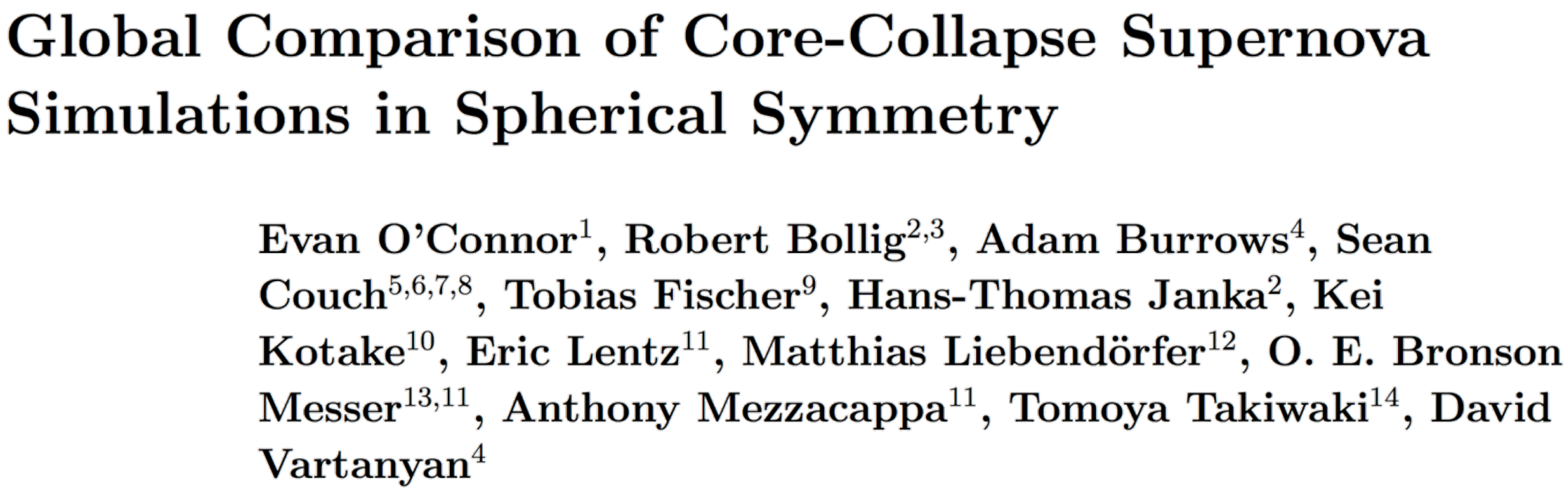


Ott et al. (2018)



Global effort towards agreement

- Want to demonstrate the community's ability to simulate SN
- Comparison of 6 core-collapse supernova codes
- *Very carefully* control input physics and initial conditions to ensure fair comparison

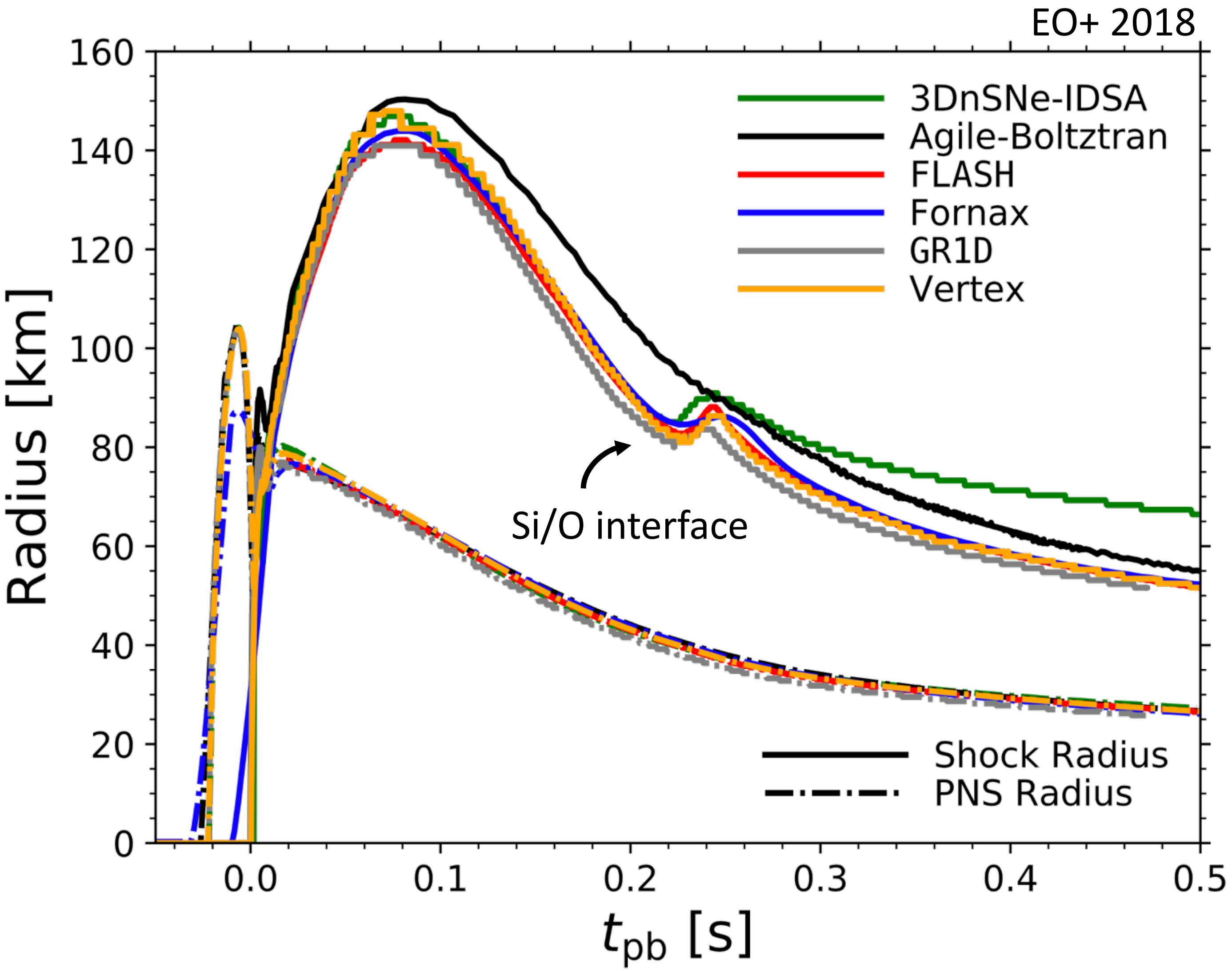


Global Comparison of Core-Collapse Supernova Simulations in Spherical Symmetry

Evan O'Connor[1], Robert Bollig[2,3], Adam Burrows[4], Sean Couch[5,6,7,8], Tobias Fischer[9], Hans-Thomas Janka[2], Kei Kotake[10], Eric Lentz[11], Matthias Liebendörfer[12], O. E. Bronson Messer[13,11], Anthony Mezzacappa[11], Tomoya Takiwaki[14], David Vartanyan[4]

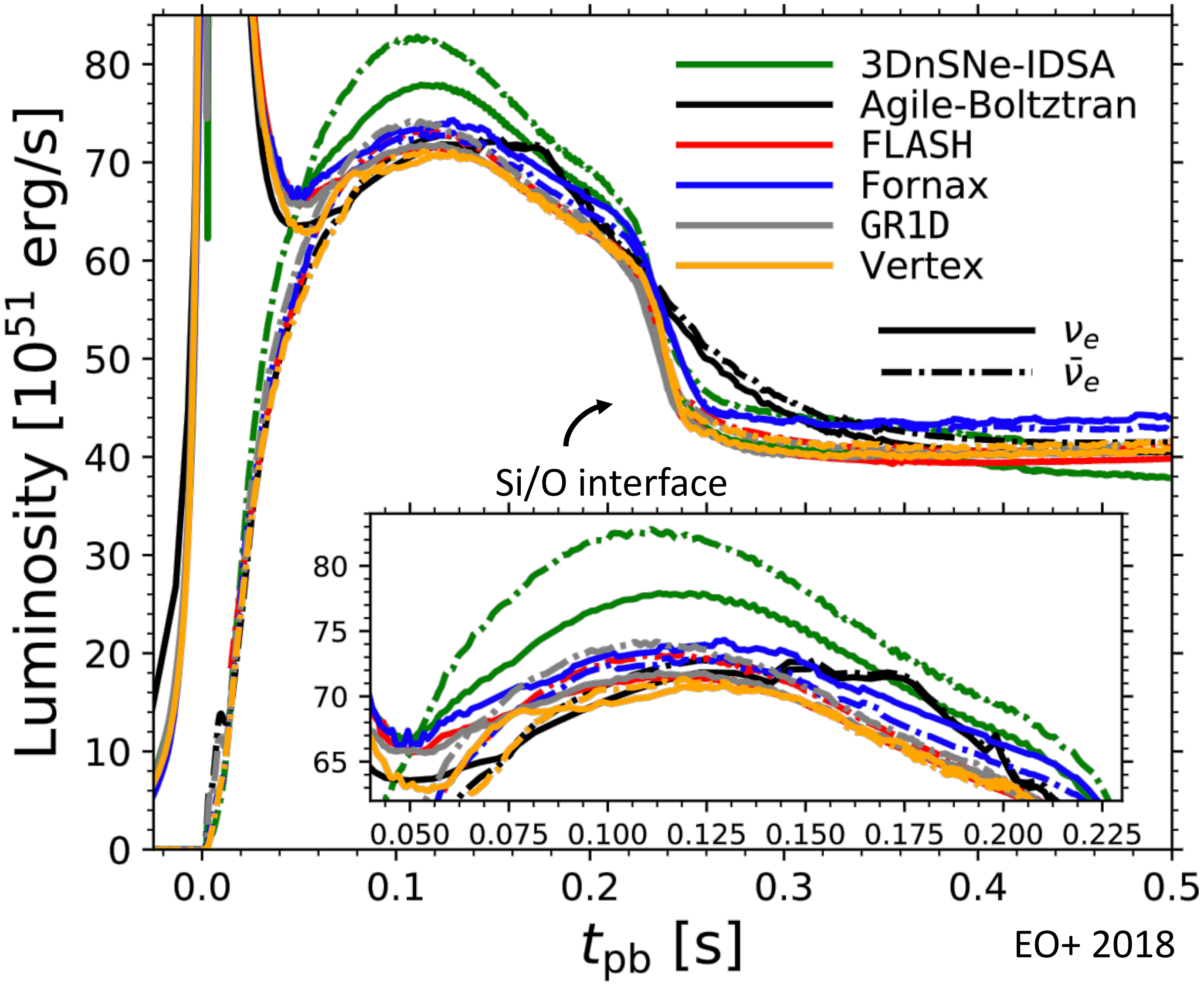
Journal of Physics: G 45 10 2018

Excellent Agreement in 1D


EO+ 2018

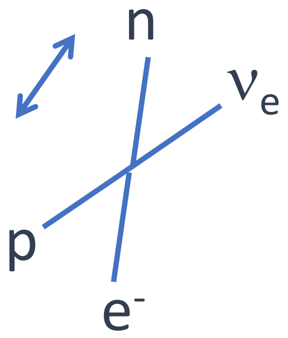
Si/O interface

Excellent Agreement in 1D



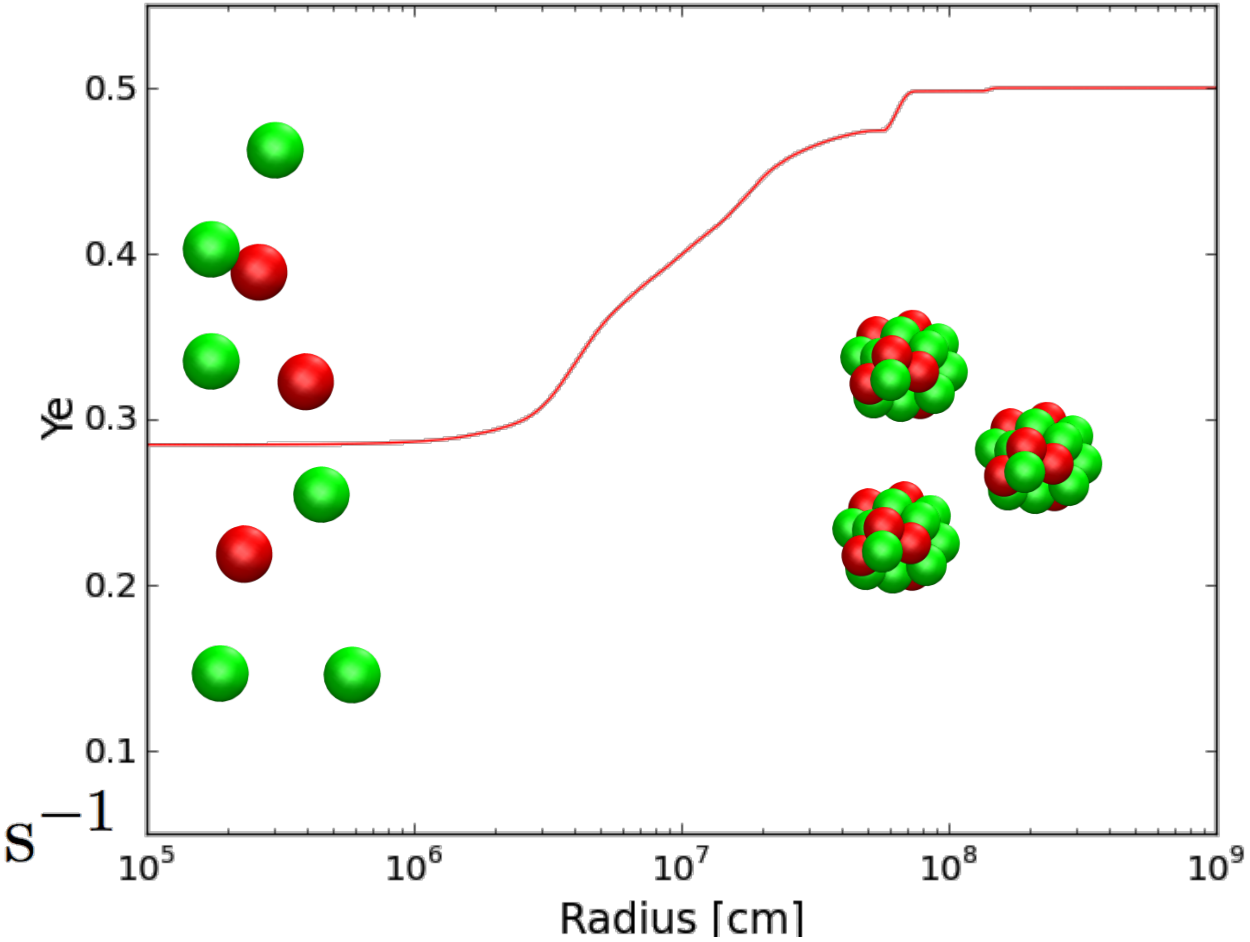
EO+ 2018

Neutronization Burst



10ms duration, starting just before bounce

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



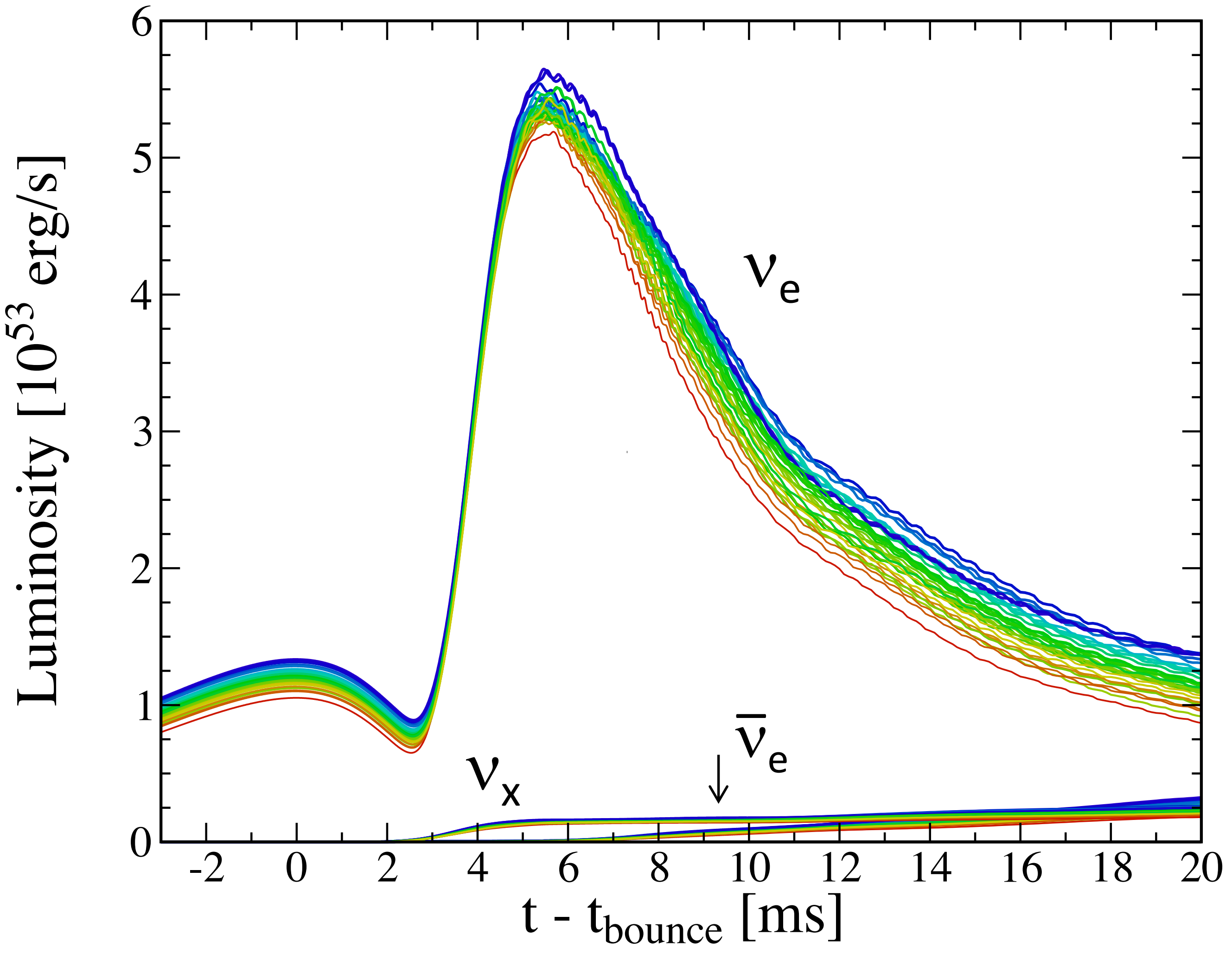
$$\frac{1}{2}\frac{M_\odot}{m_N}\times 0.2\times\frac{10\,\mathrm{MeV}}{5\,\mathrm{ms}}\sim 4\times 10^{53}\,\mathrm{erg\,s^{-1}}$$

Neutronization Burst

Iron core mass increasing ->

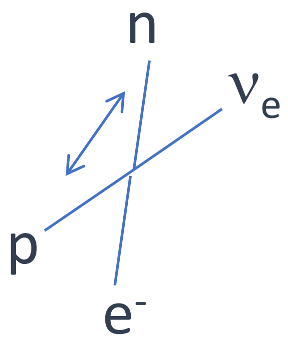
Matter temperature increasing ->

- 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

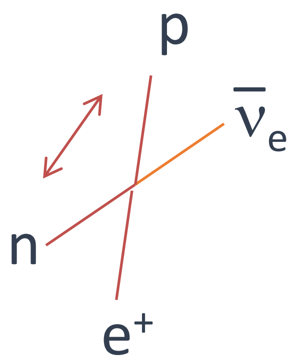


Accretion Phase: Role of Neutrinos

- 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

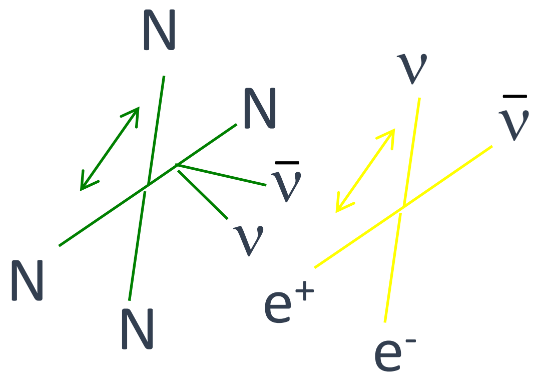


- Charged current processes
- Thermal production processes

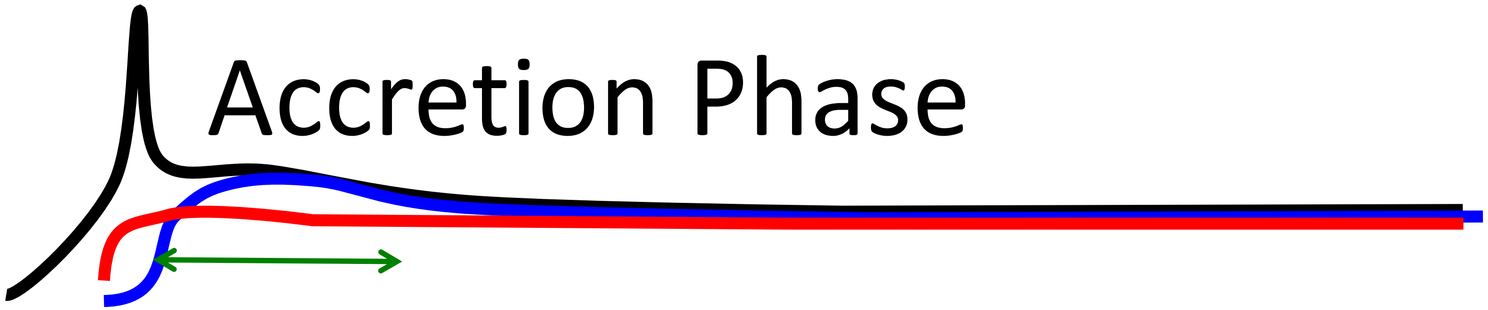


- After ~10-20ms, positron production no longer inhibited

- 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

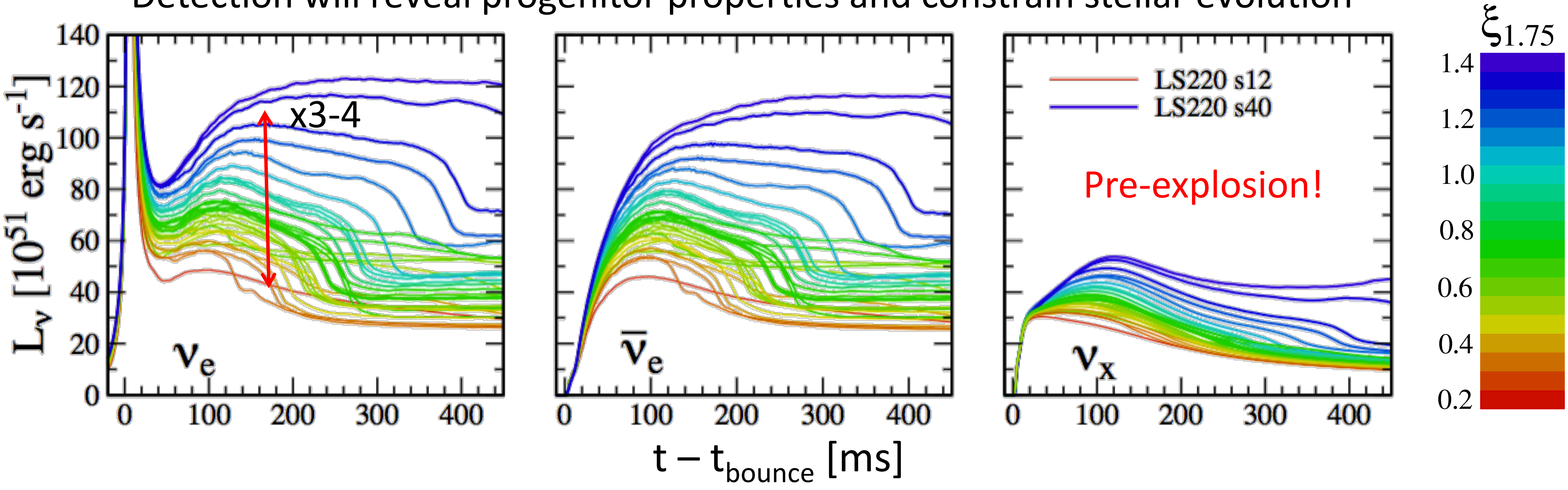


Accretion Phase



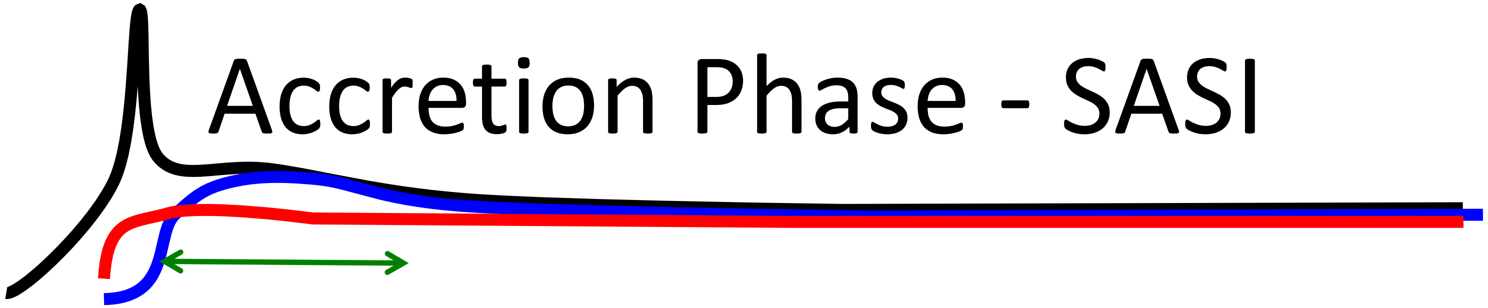
- The accretion phase introduces first progenitor dependence of luminosities
  - High ‘compactness’: higher mass accretion -> more binding energy released -> higher luminosities

- Detection will reveal progenitor properties and constrain stellar evolution



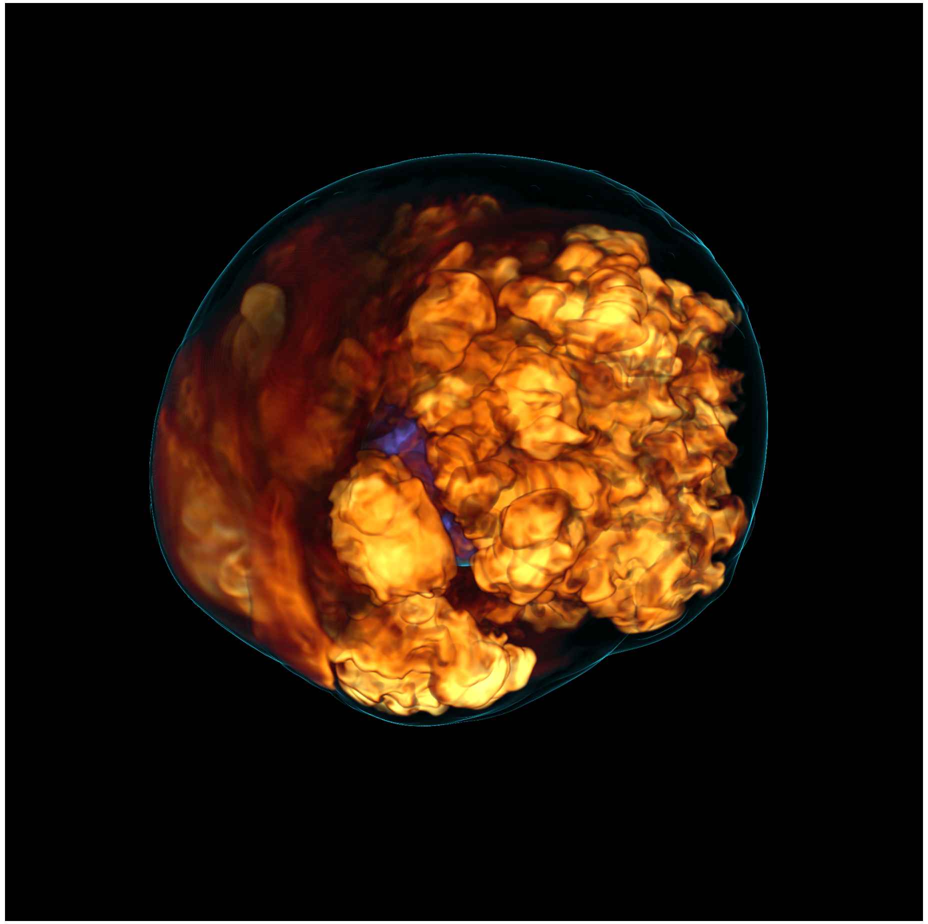
x3-4

Pre-explosion!

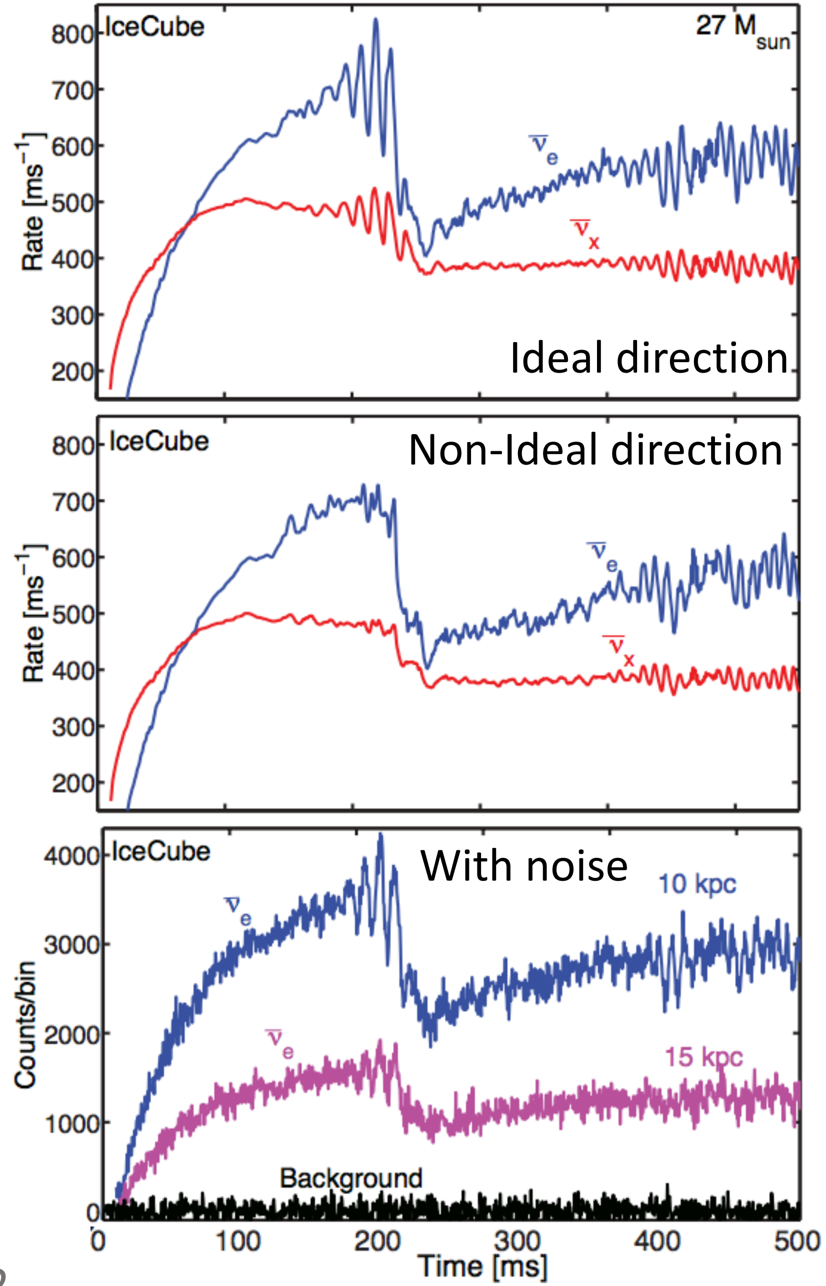


Accretion Phase - SASI

- Standing Accretion Shock Instability (SASI) can impact signal, periodic variations.
- Observable in HyperK and IceCube, perhaps not Dune. Timescales too short: ~10ms



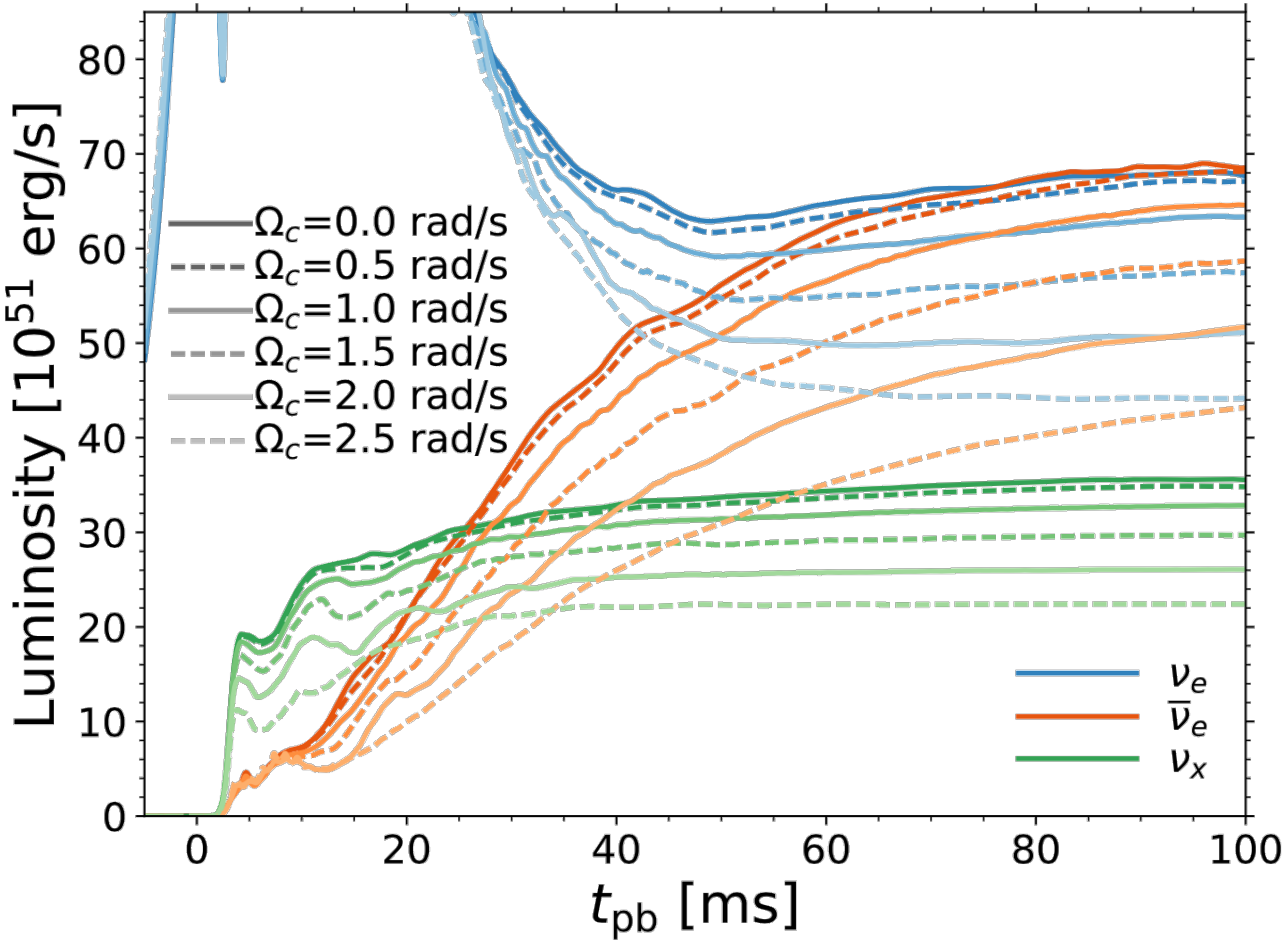
Tamborra et al. (2013); Mirizzi et al. (2015)

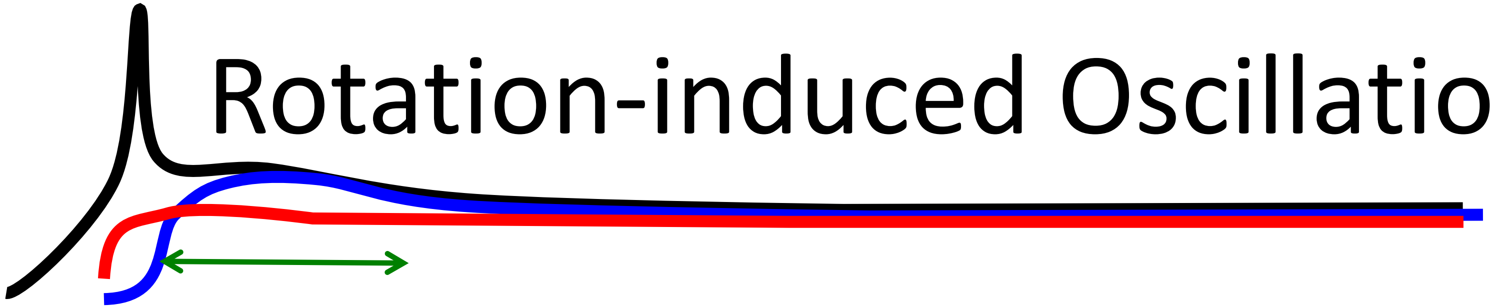


Rotation in Core-Collapse Supernovae

- Rotation impacts neutrinos
    - Less energy released, lower luminosities initially
- Rotating collapse excites the newly formed protoneutron star
    - Correlated signal in GWs and neutrinos

Westernacher-Schneider+ (2019 *in prep*)

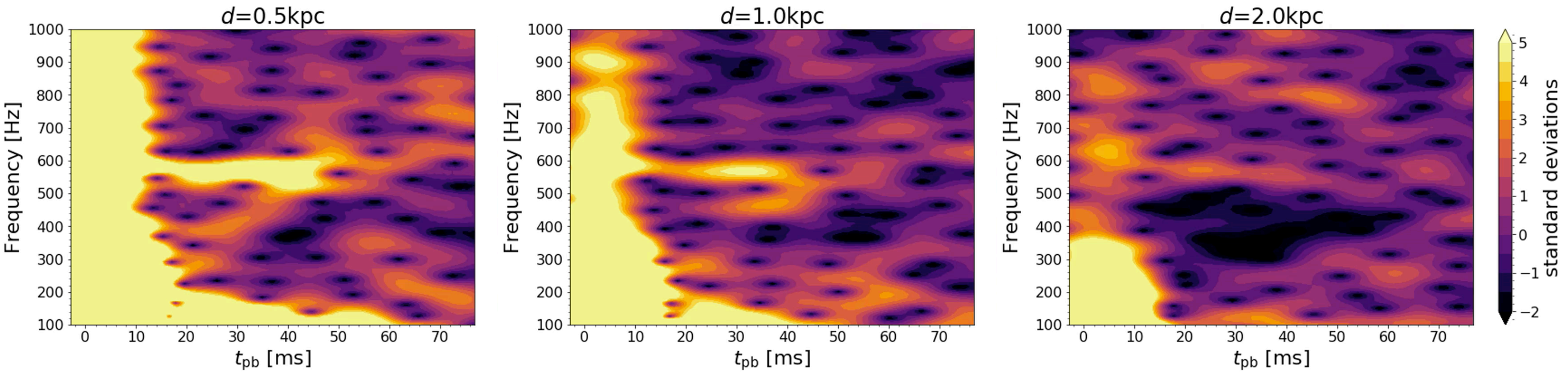




Rotation-induced Oscillations in neutrinos

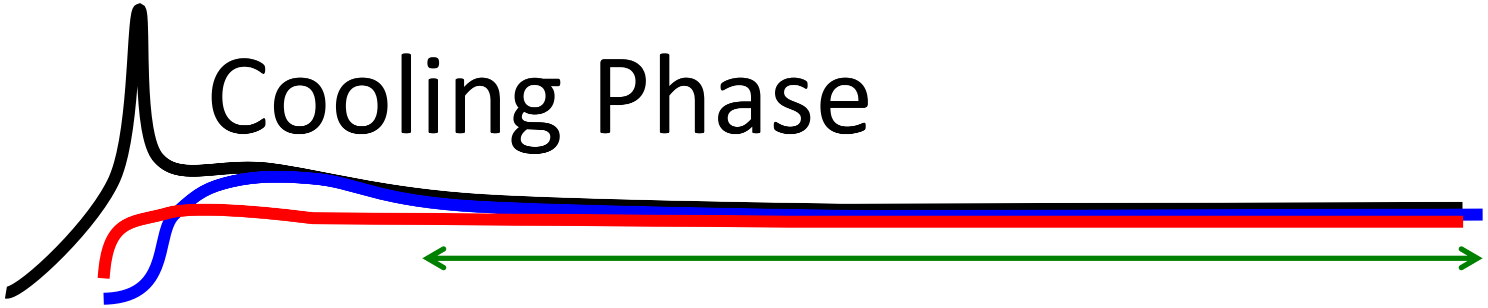
- Must be close to see such small signal. In IceCube: ~1kpc

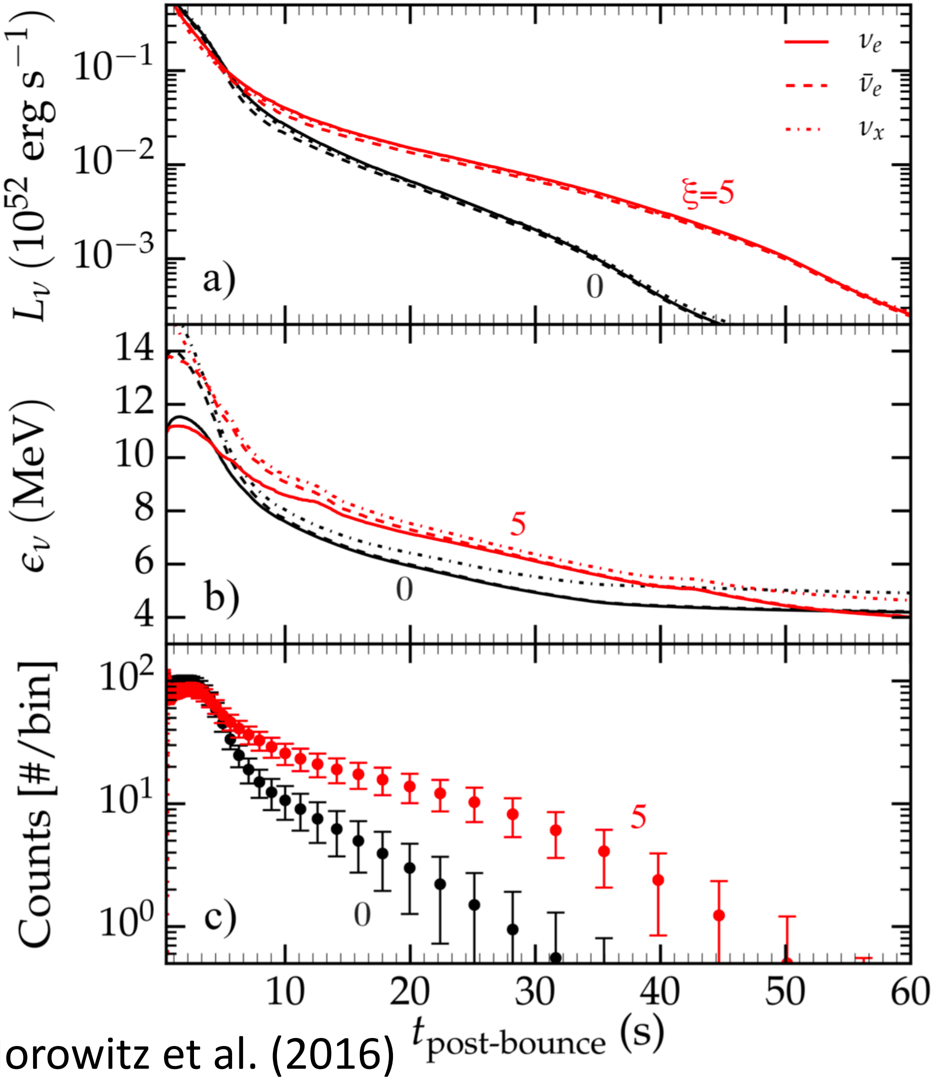
Westernacher-Schneider+ (2019 *in prep*)



*Realizations take into account statistical noise and detector background noise

Cooling Phase





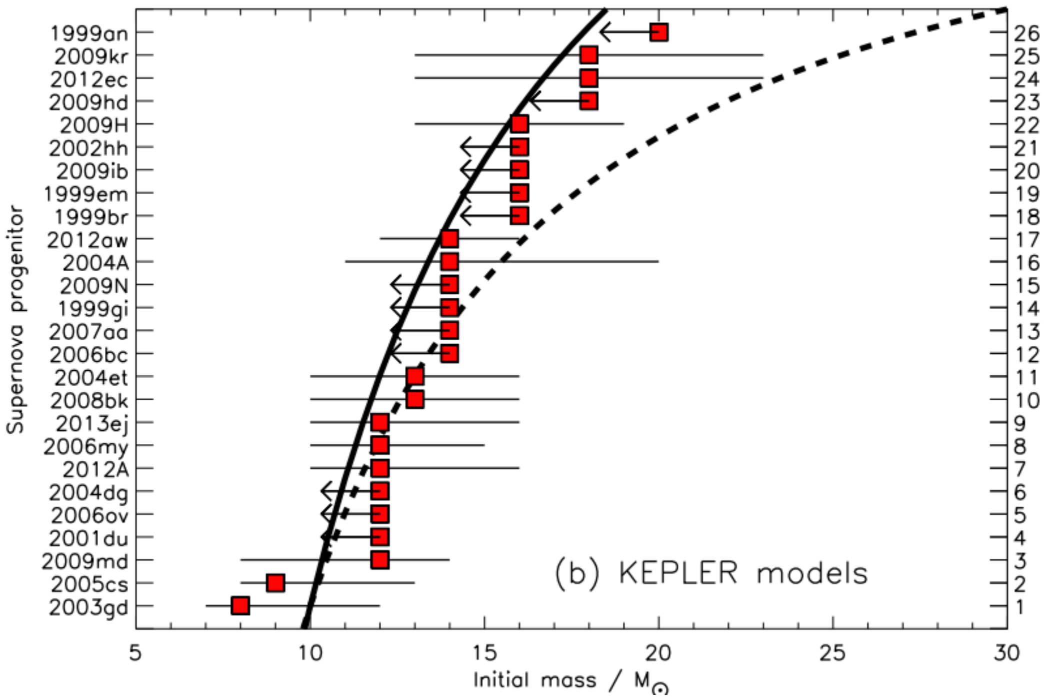
Horowitz et al. (2016)

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

Not all core collapses will succeed

- Progenitors of Type II-P CCSNe suggest a maximum mass of ~16.5 +/- 1.5 M_{sun} – but RSG extend to 25 M_{sun}
- Stellar mass black holes exist!
- We have seen preliminary evidence that massive stars disappear, perhaps following a failed supernovae

Smartt (2015)



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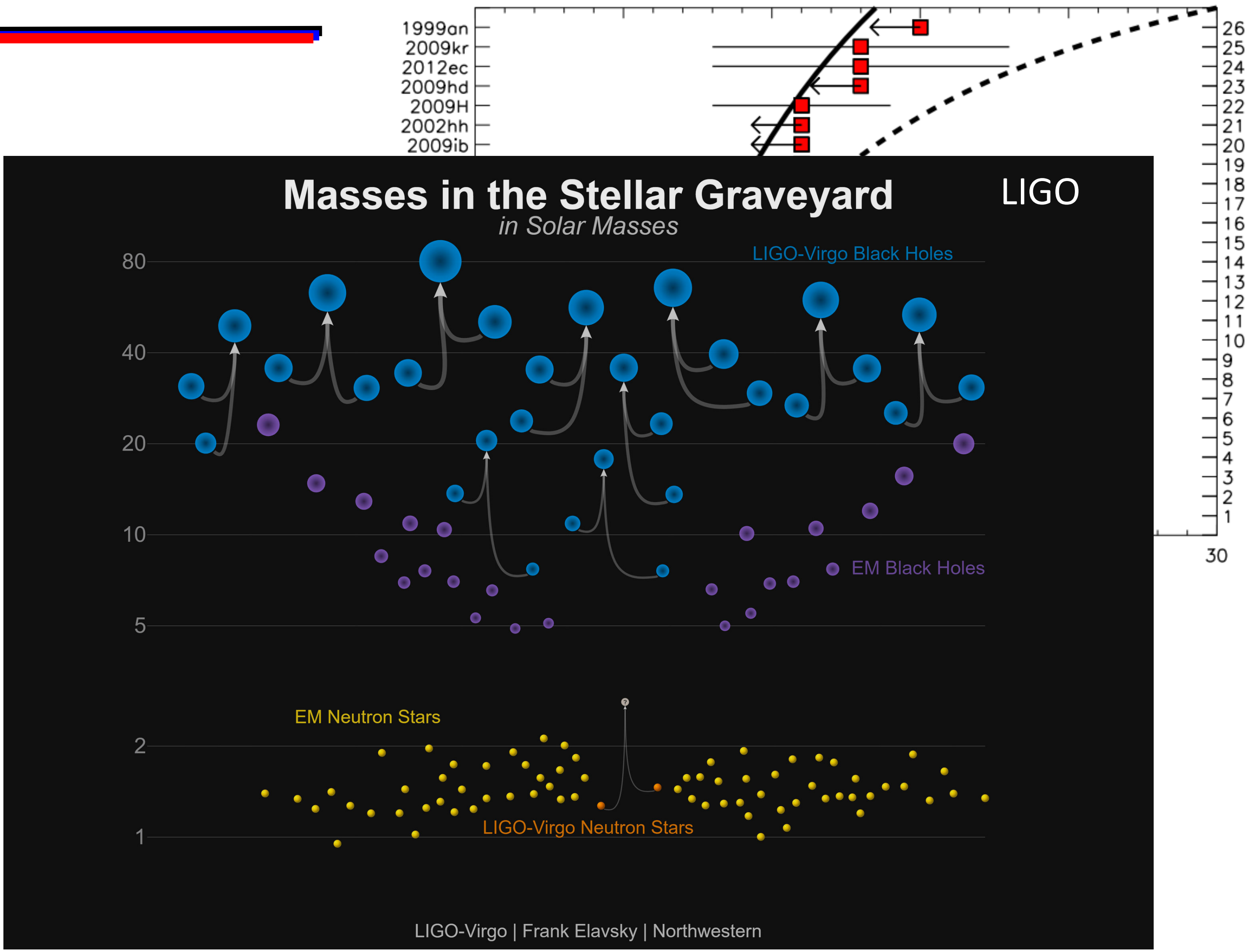
LIGO



LIGO-Virgo | Frank Elavsky | Northwestern

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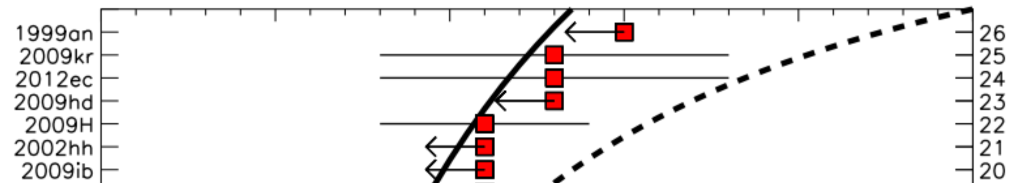

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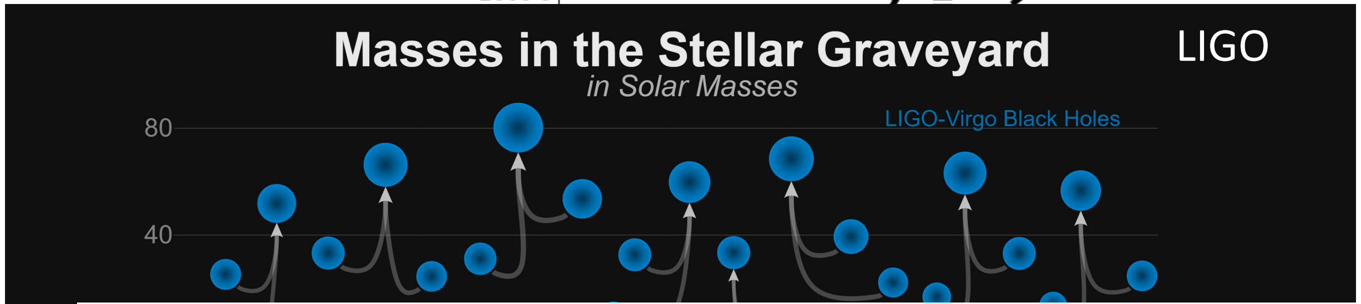
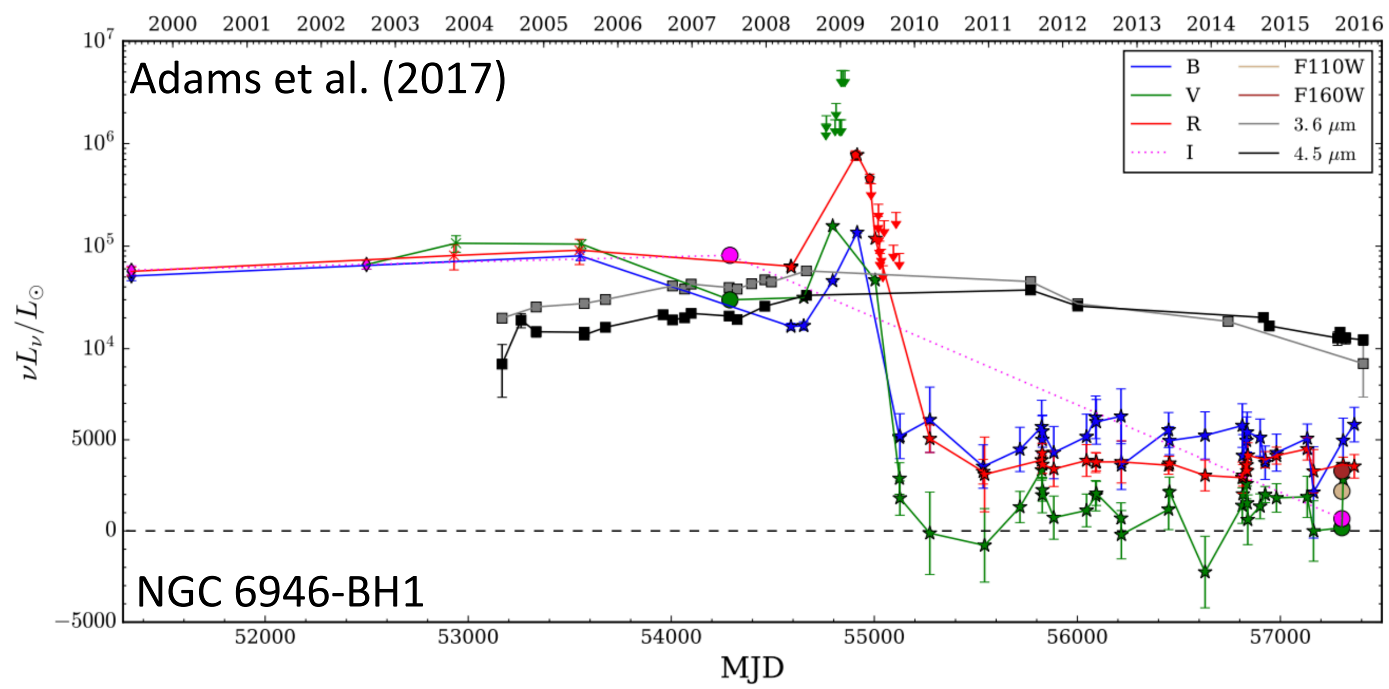
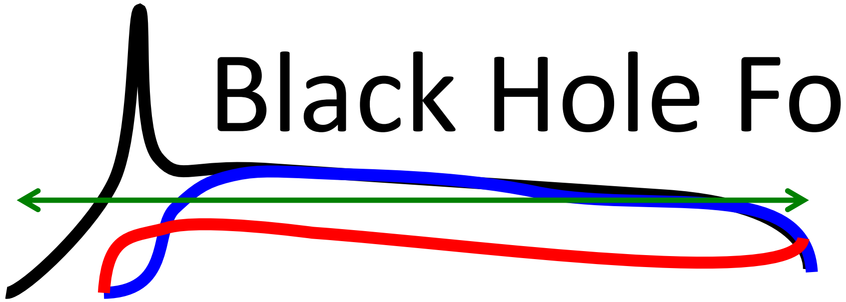


Adams et al. (2017)

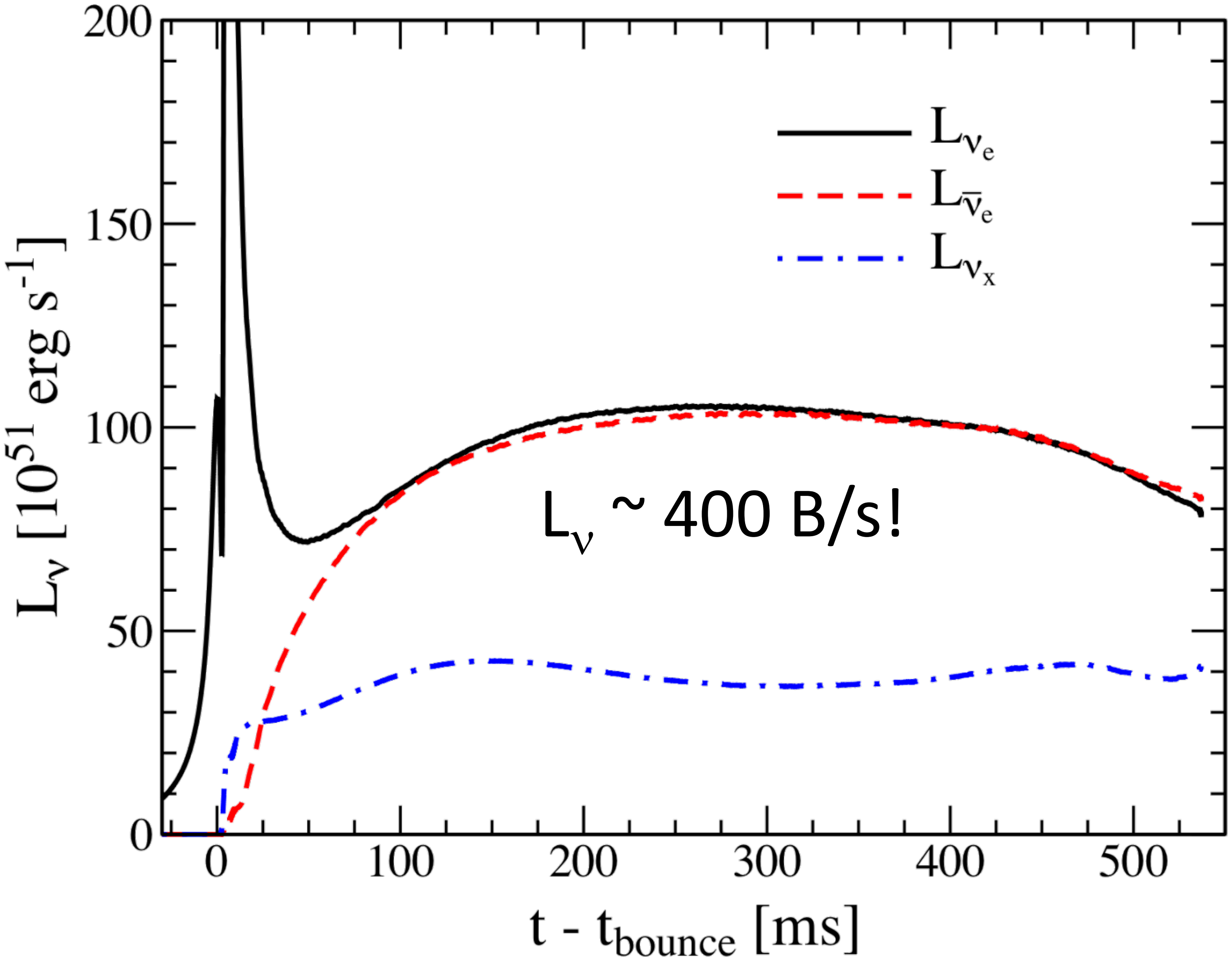




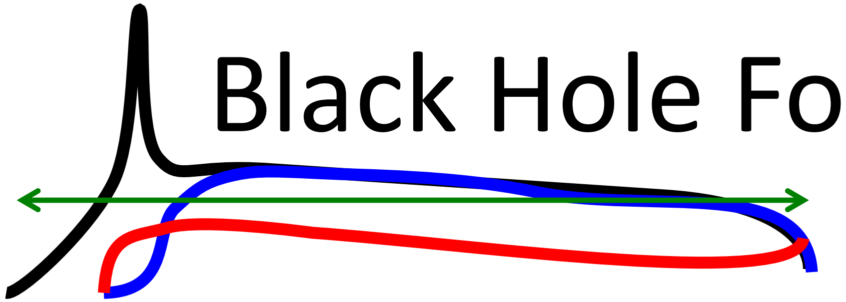
Black Hole Formation

- Failure rate could be ~15%
- Smoking gun signature is prompt shutoff of neutrinos
- Would give detailed information regarding progenitor and nuclear EOS

O’Connor (2015)



L_ν ~ 400 B/s!



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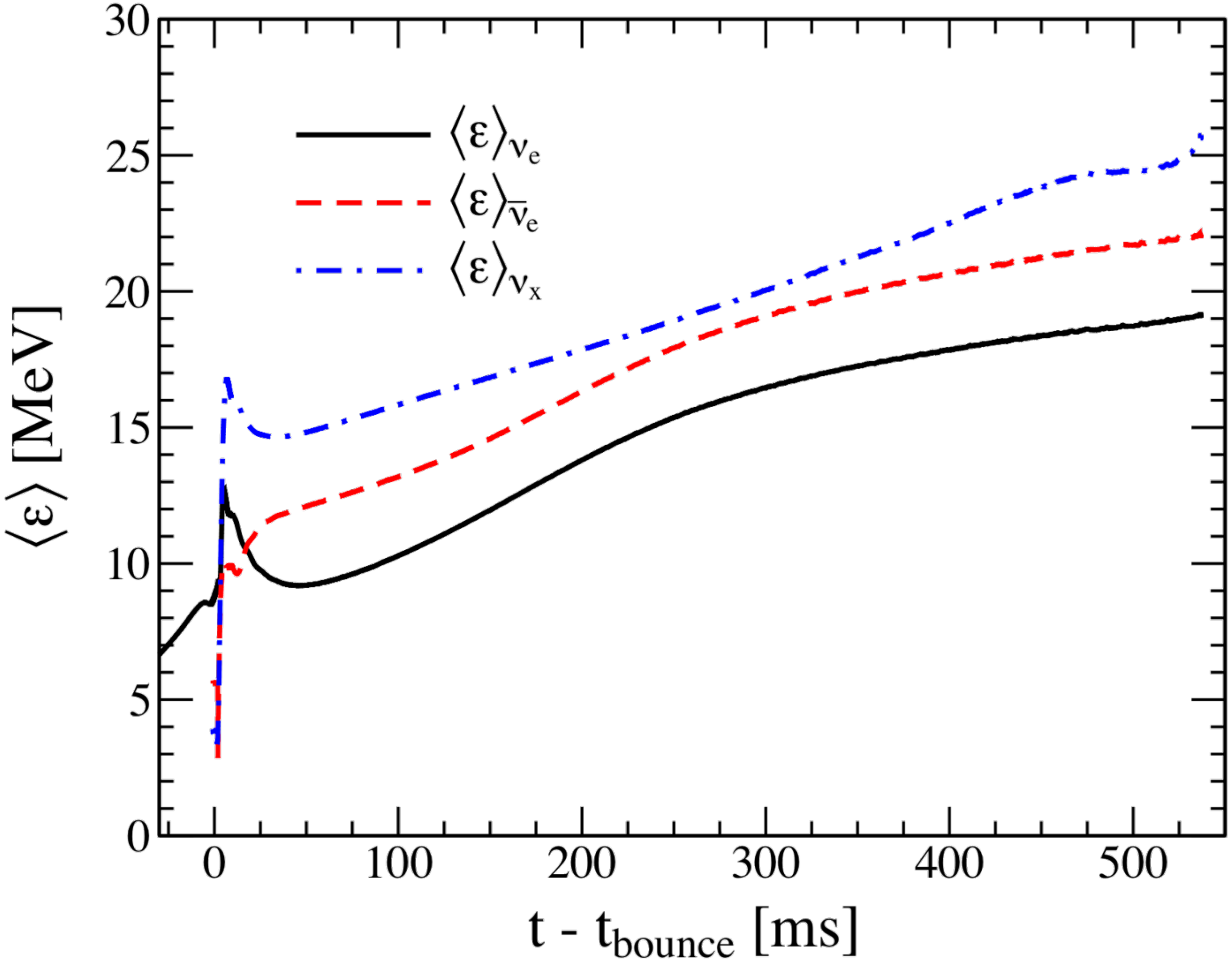

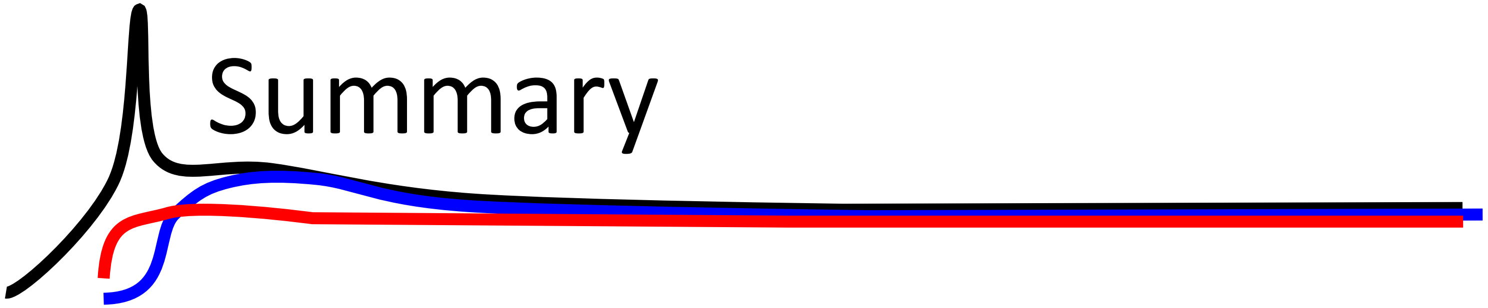

Summary

- Core Collapse models in multiD explode via the turbulence-aided neutrino mechanism, *across codes and progenitors*

- Models predict several interesting neutrino-signal-related phenomena
    - Neutronization Burst (Universal)
    - Neutrino mass ordering likely discernible from signal
    - Accretion Luminosity (probes progenitor)
    - SASI predicts large time variations in signal
    - Rotation predicts correlated neutrino and GW signals
    - Equation of State sets cooling curve over ~5-100s
    - Failed supernovae predict sharp cutoff on neutrinos