The Effects of Neutrino Oscillations on Core-Collapse Supernova Explosions

Charles Stapleford

North Carolina State University

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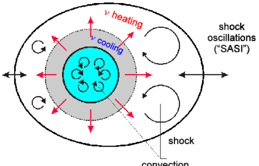
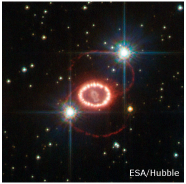
Together with
Carla Fröhlich & James Kneller

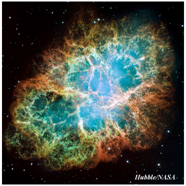
Core Collapse Supernovae (CCSN)

- How does the shock get revived after stalling to cause the explosion?
- The neutrino mechanism: scattering and absorption in the gain region



Müller (2016)


ESA/Hubble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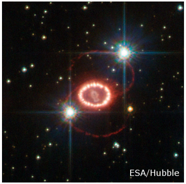

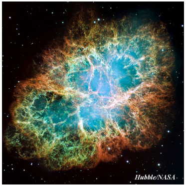

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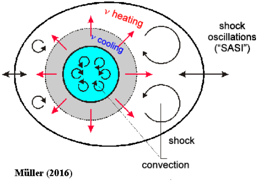
- Requires careful multi-flavor neutrino transport



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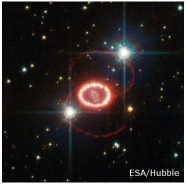

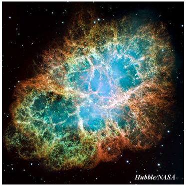

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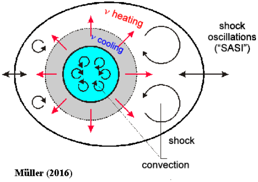

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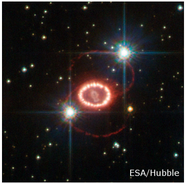

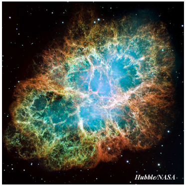

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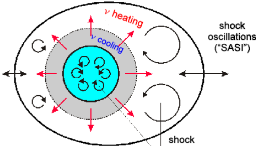

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- Requires careful multi-flavor neutrino transport
- Neutrino flavors interact differently:
  - ν_e - strongest interactions - lower mean energy
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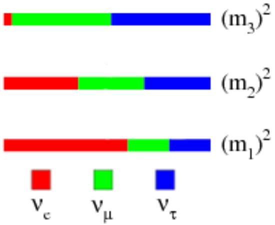
- Mixing the flavors could affect the heating
- **There is a need for self-consistent neutrino flavor oscillations in supernova simulations**

Neutrino Oscillations

- Oscillations occur because the ν mass states are not the same as ν flavor states
- Neutrinos keep the same energy & momentum, only changing flavor



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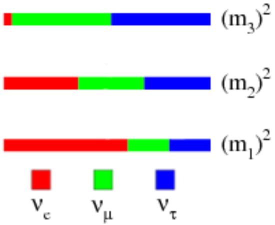
- Supernovae are environments where a variety of different oscillation phenomenon can occur:
  - Collective neutrino oscillations(CνO) *Duan+ (2006)*
  - Flavor evolution through shocks and turbulence *Patton+ (2013) Xu+ (2014)*
  - Fast-flavor conversions *Sawyer+ (2005) Dasgupta+ (2015)*
  - Potential nonstandard interactions *Esteban-Pretel+ (2007) Stapleford+ (2016)*

Yang+ (2018)



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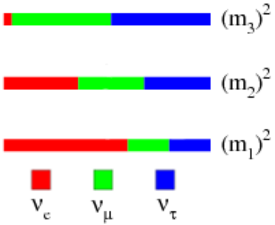
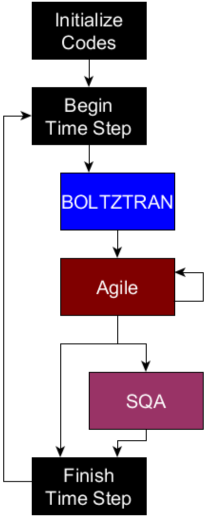


- Conditions exist for possible flavor mixing behind the shock

The Effects of Oscillations

- Some approximate treatment of CνO has been done to examine the effects on heating
  - Manual spectral swap was found to produce explosions if some critical heating rate was reached *Suwa+ (2011)*
  - Numerical post-processing found that the CνO mostly occurs beyond the shock where it can not aid heating *Dasgupta+ (2012)*
  - Assuming maximal flavor mixing found that CνO most effective for small M_{PNS}, $\dot{M}$ and large R_ν *Pejcha+ (2012)*
- We wish to improve upon these findings by dynamically coupling full oscillation calculations directly to the neutrino transport

Our Codes



Agile-BOLTZTRAN

- 1-D Lagrangian GR Hydrodynamics
- $\mathcal{O}\left(\frac{v}{c}\right)$ Boltzmann Equation $(\nu_e, \bar{\nu}_e, \nu_x, \bar{\nu}_x)$
- Lattimer-Swesty EOS
- Implicit time evolution
- Adaptive Grid
- Transport Processes
  - $\nu_e + n \rightleftharpoons e^- + p$
  - $\nu_e + N(Z, A) \rightleftharpoons e^- + N(Z+1, A)$
  - $\nu_e + e^- \to \nu_e + e^-$
  - “Isoenergetic” Scattering
  - Pair-production & Annihilation

Mezzacappa+ (1993) Liebendörfer+ (2001)

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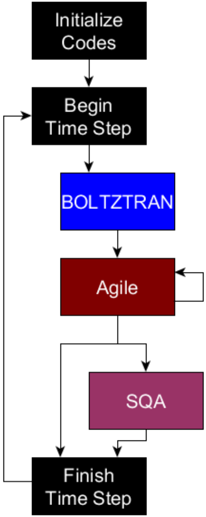


Sqa

- Multi-energy, single-angle, free-streaming, oscillation code for 6 flavors $(\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau)$
- Solves Schrödinger Equation for evolution operator in a quasi-adiabatic basis:

$$\frac{\partial S}{\partial x} = -\frac{i}{\hbar c} HS \qquad \rho(x) = S\rho(o)S^\dagger$$

- $H = H_{VAC} + V_{MSW} + V_{SI}$ with GR corrections
- Limit how often Sqa is called:
  - Only run after bounce & behind shock
  - Run only as required, not every time step

Galais+ (2011) Yang+ (2017)

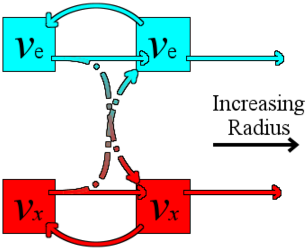
Integrating Oscillations

- Oscillations are introduced as a source term in the transport
- Transition probabilities converted into an effective opacity:

$$\sigma_{i,k} = \frac{P_{i,k}^{\alpha\rightarrow\beta} c}{r_i - r_{i-1}}$$

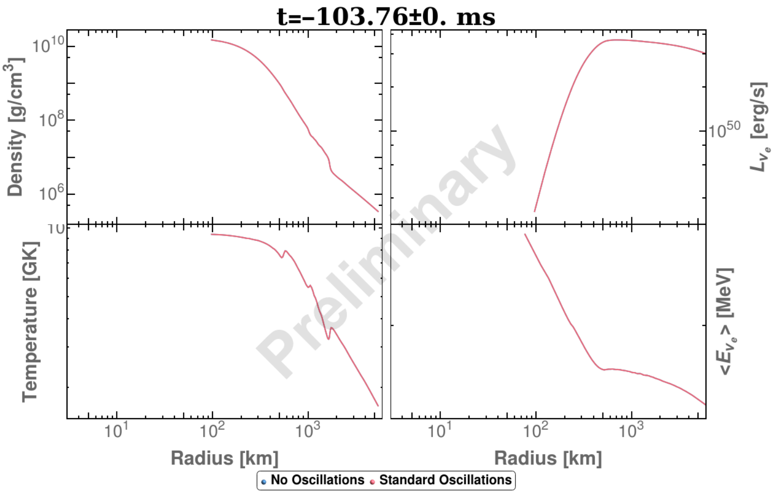
- Link absorption in one flavor to emission in the other:

$$\frac{df_\alpha}{dt} = \sigma_{i,k}(f_\beta - f_\alpha) \qquad \frac{df_\beta}{dt} = \sigma_{i,k}(f_\alpha - f_\beta)$$

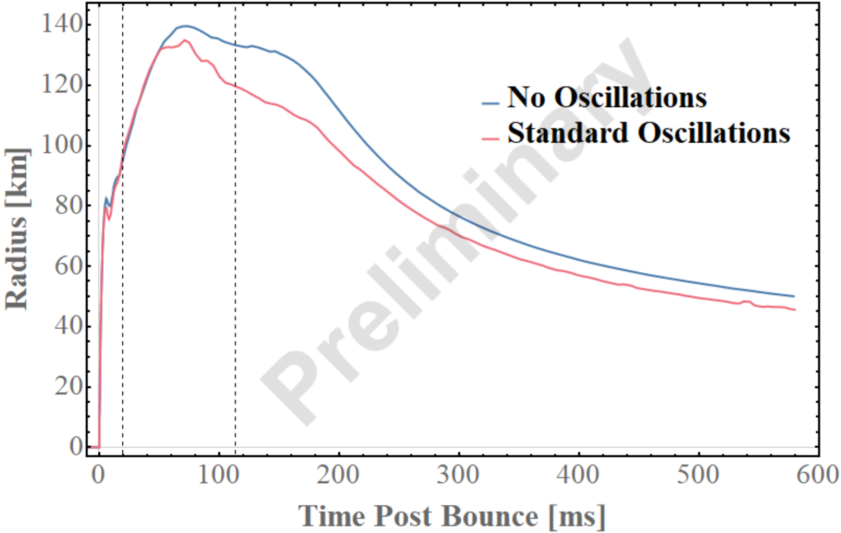


- $\sigma_{i,k}$ constant between calls to Sqa

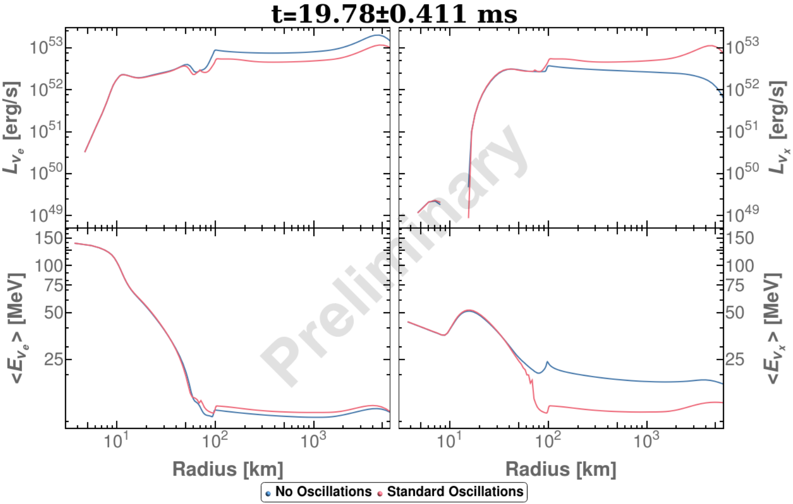
Our Simulation



Shock Radius



Just after Bounce



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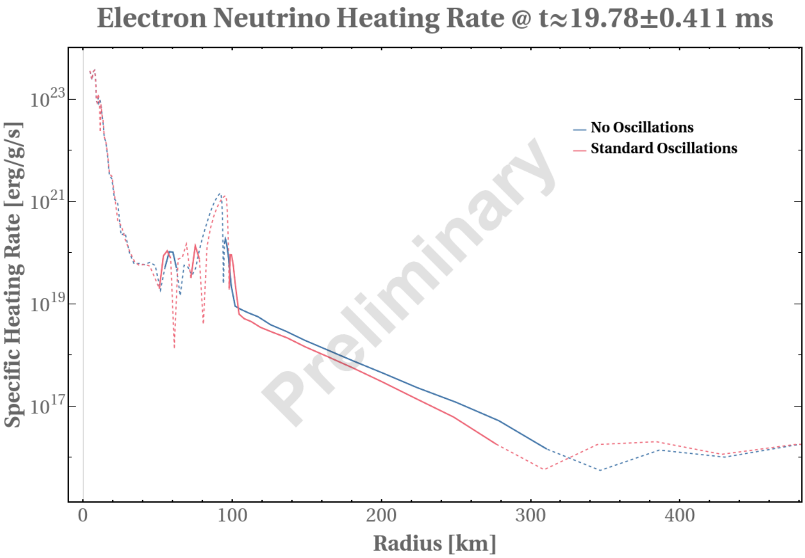
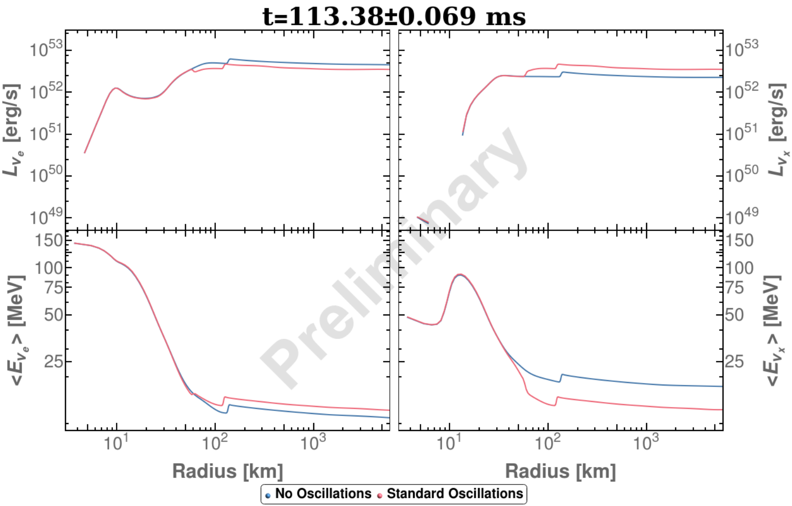


Stalled Shock



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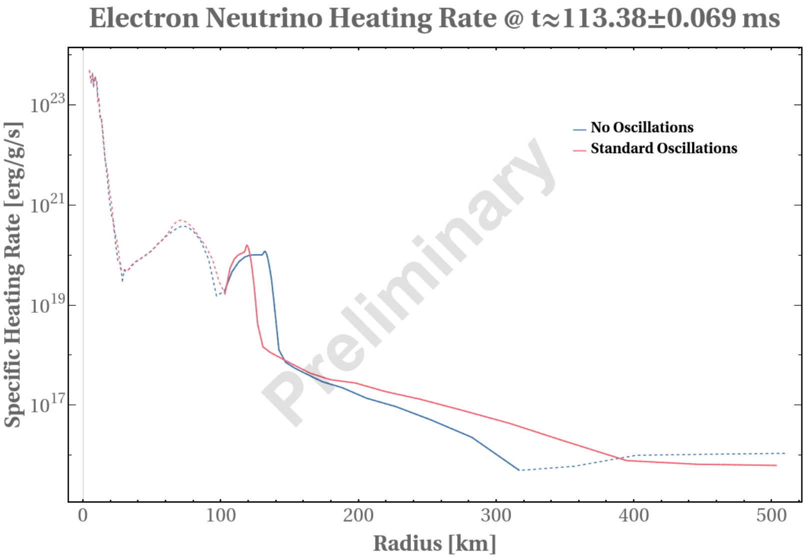
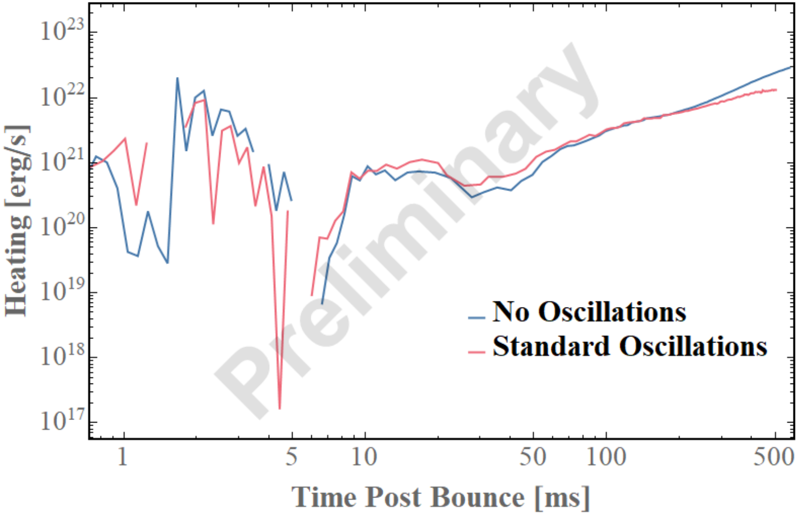


Mass Integrated Heating Rate



Conclusions & Outlook

- Neutrinos are very important in supernovae, but self-consistent effects of oscillations had not previously been studied
- We have developed a code that self-consistently couples neutrino oscillation calculations with neutrino transport and supernova hydrodynamics for the first time
- Neutrino oscillations do impact the dynamics of the simulations, but do not cause the explosion to occur
- In the future we wish to include additional effects such as fast-flavor conversion and nonstandard interactions

Thank You