Relativistic burning on neutron stars

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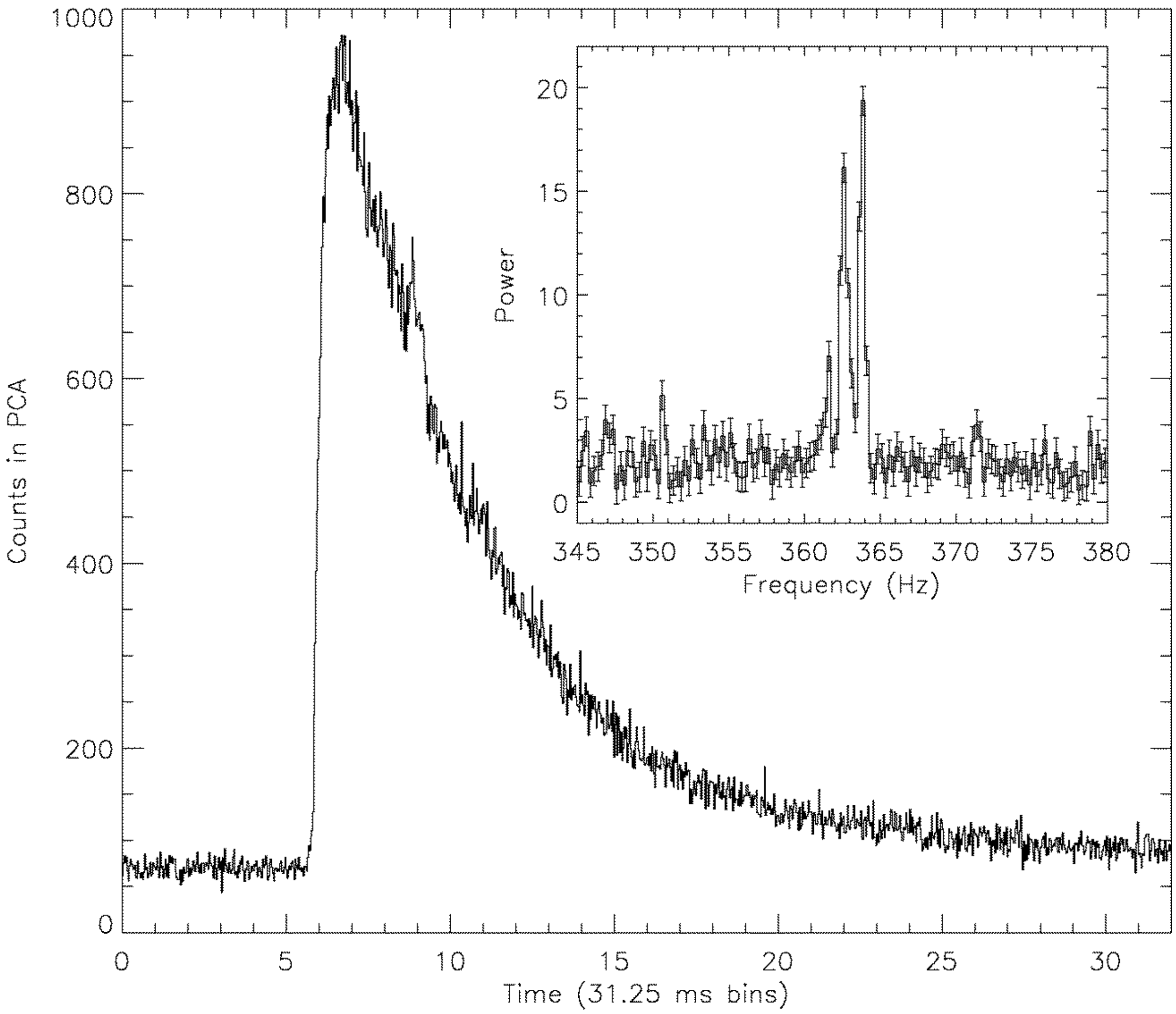
Overview

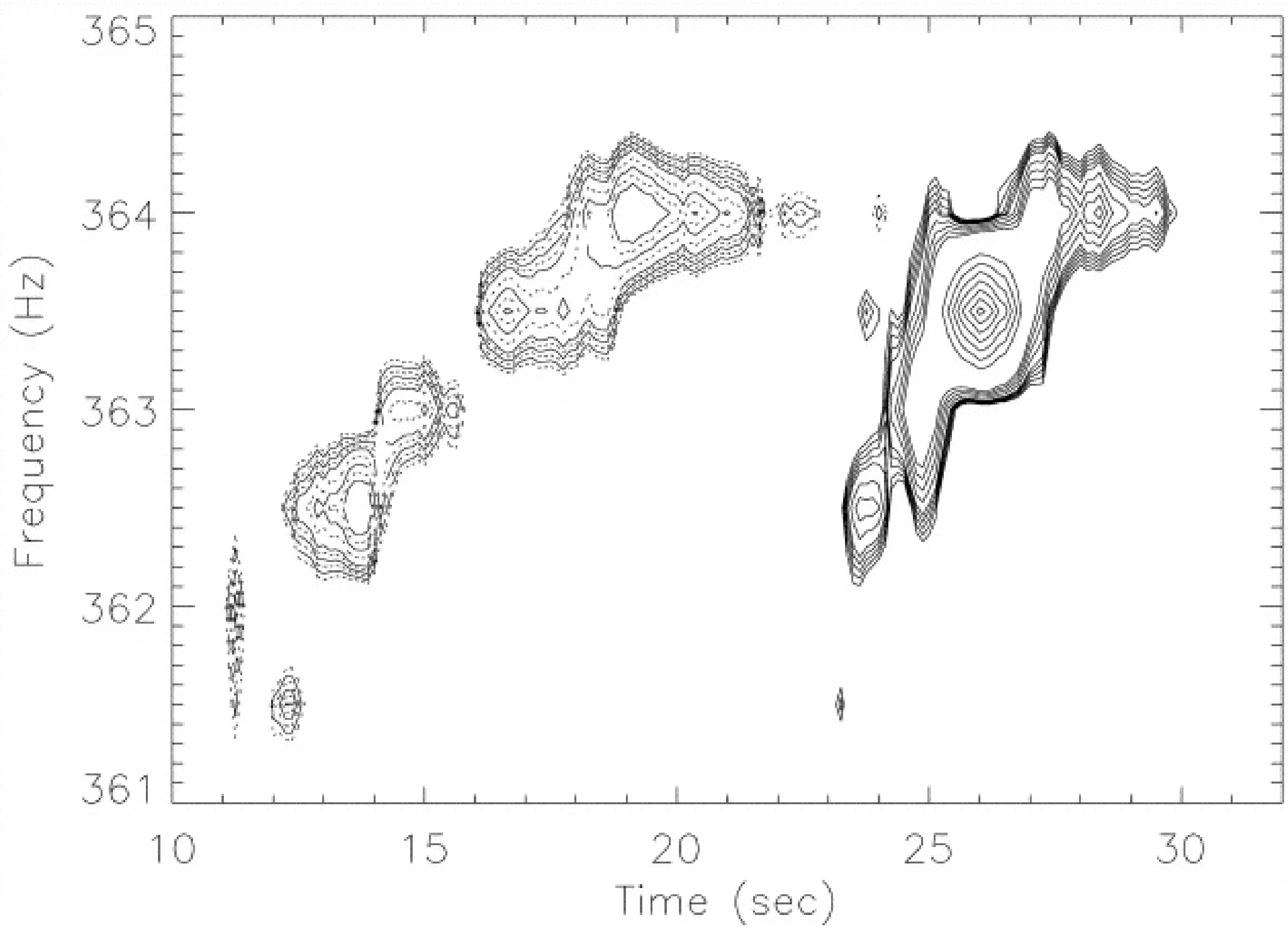
- X-ray bursts
- Relativistic low Mach number approximation
- Simulations
- Relativistic reactive Riemann problem
- Conclusions & future plans

What is a Type I X-ray burst?

- Accreting neutron stars in low mass X-ray binaries develop liquid surface layer
- About 10 - 50 m thick, primarily H & He
- Continuous accretion
  $\longrightarrow$ ocean temperature & density increase
  $\longrightarrow$ ignition
- Could use to determine neutron star radius



Burst from 4U 1728-34 (Strohmayer+ 1996)



Dynamic power spectrum from 4U 1728-34 (Strohmayer+ 1998)

Previous work

- Many existing models for X-ray burst physics, e.g.
  - **Burst oscillations**:
    - Coriolis force (Spitkovsky+ 02),
    - surface oscillations (Berkhout & Levin 08, Heyl 04, Lee & Strohmayer 05) or
    - magnetic field (Cavecchi 13)
  - **Frequency drifts**:
    - horizontal spreading of the flame (Strohmayer+ 97) or
    - conservation of angular momentum (Cumming 00, Strohmayer+ 97)
  - **Ignition latitude**:
    - equator (Spitkovsky+ 02) or
    - poles (Bhattacharyya & Strohmayer 05, 06)
- Still many questions

What about GR?

- Strong gravity known to be important for NS physics
- NSs in LMXBs mostly fast rotators ($\gtrsim 200$ Hz)
- Spitkovsky+ 02 - Coriolis force drives spreading of flame front
- Could *frame dragging* be important?
- Relativistic turbulence? (Radice & Rezzolla 13)

Modelling bursts

- Flame speed $\ll$ sound speed
- Motivates sound proof model
- We use ***Low Mach Number*** approximation:

$$M = \frac{v}{c_s} \ll 1$$

$$p \to p_0(r) + \pi(\vec{x}, t), \qquad \pi = O(M^2)$$

- Previously used for Newtonian case (MAESTRO, Almgren+ 07) - we have extended to GR

Low Mach approximation

- Newtonian momentum equation

$$\frac{\partial \vec{u}}{\partial t} + \vec{u} \cdot \vec{\nabla} \vec{u} + \vec{\nabla} p = -\rho \, |g| \vec{e}_r$$

- Relativistic 3-covariant form

$$(\partial_t - \mathscr{L}_\beta) v_i + \alpha v^{k \, (3)} \nabla_k v_i + \frac{^{(3)}\nabla_i p}{H W^2} = \text{Source terms}$$

- Relativistic low Mach, $v_i = \bar{v}_i + V_i$

$$(\partial_t - \mathscr{L}_\beta) V_i + \alpha V^{k \, (3)} \nabla_k V_i + \frac{\beta_0}{H} {}^{(3)}\nabla_i \left(\frac{\pi}{\beta_0} \right) = - \frac{\varrho - \bar{\varrho}}{H} {}^{(3)}\nabla_i$$

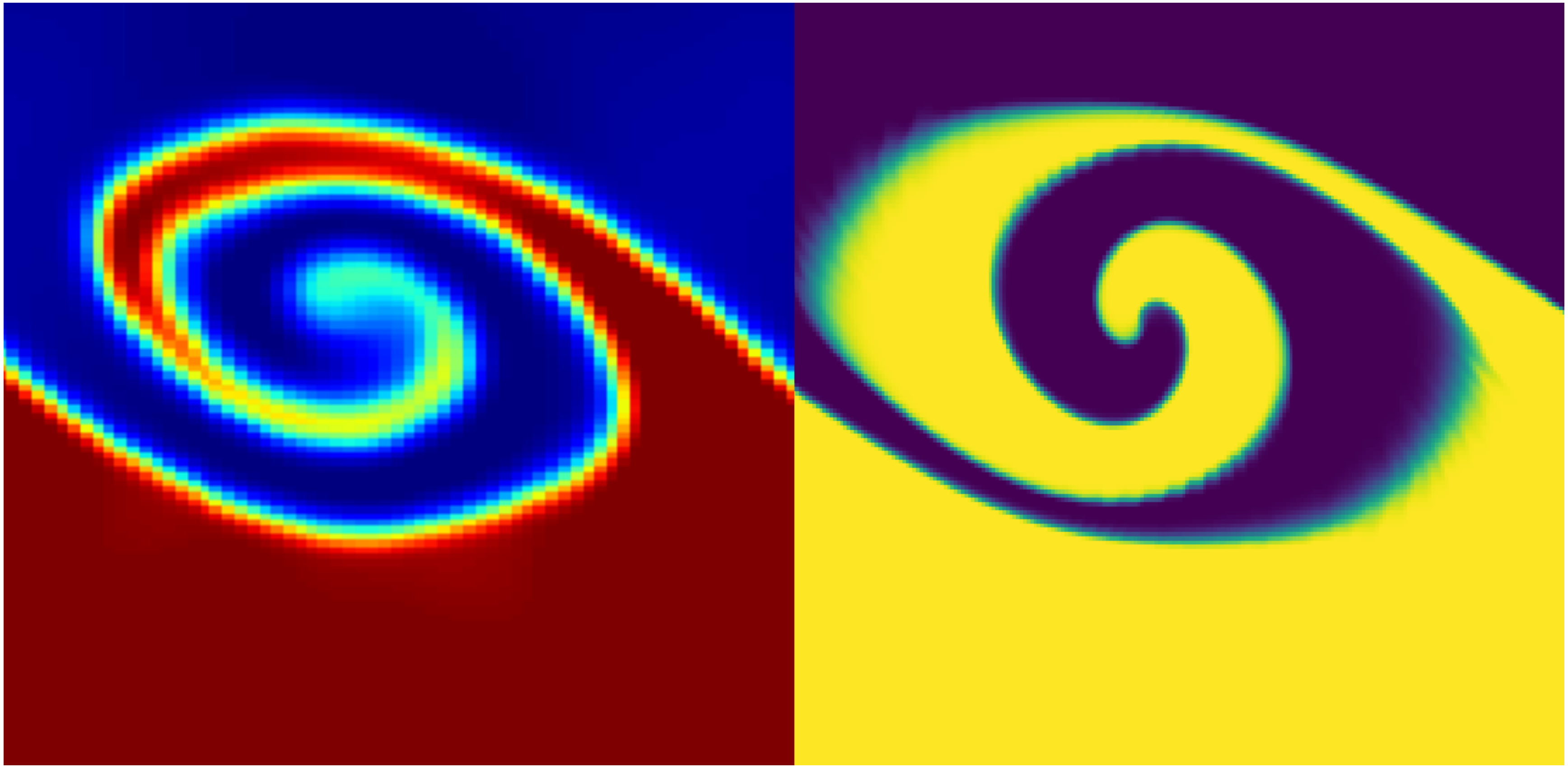
Burning

- Model 2-species system
- Burning an instantaneous 1-step reaction
- Based on triple-α He $\longrightarrow$ C (Cumming & Bildsten 00)

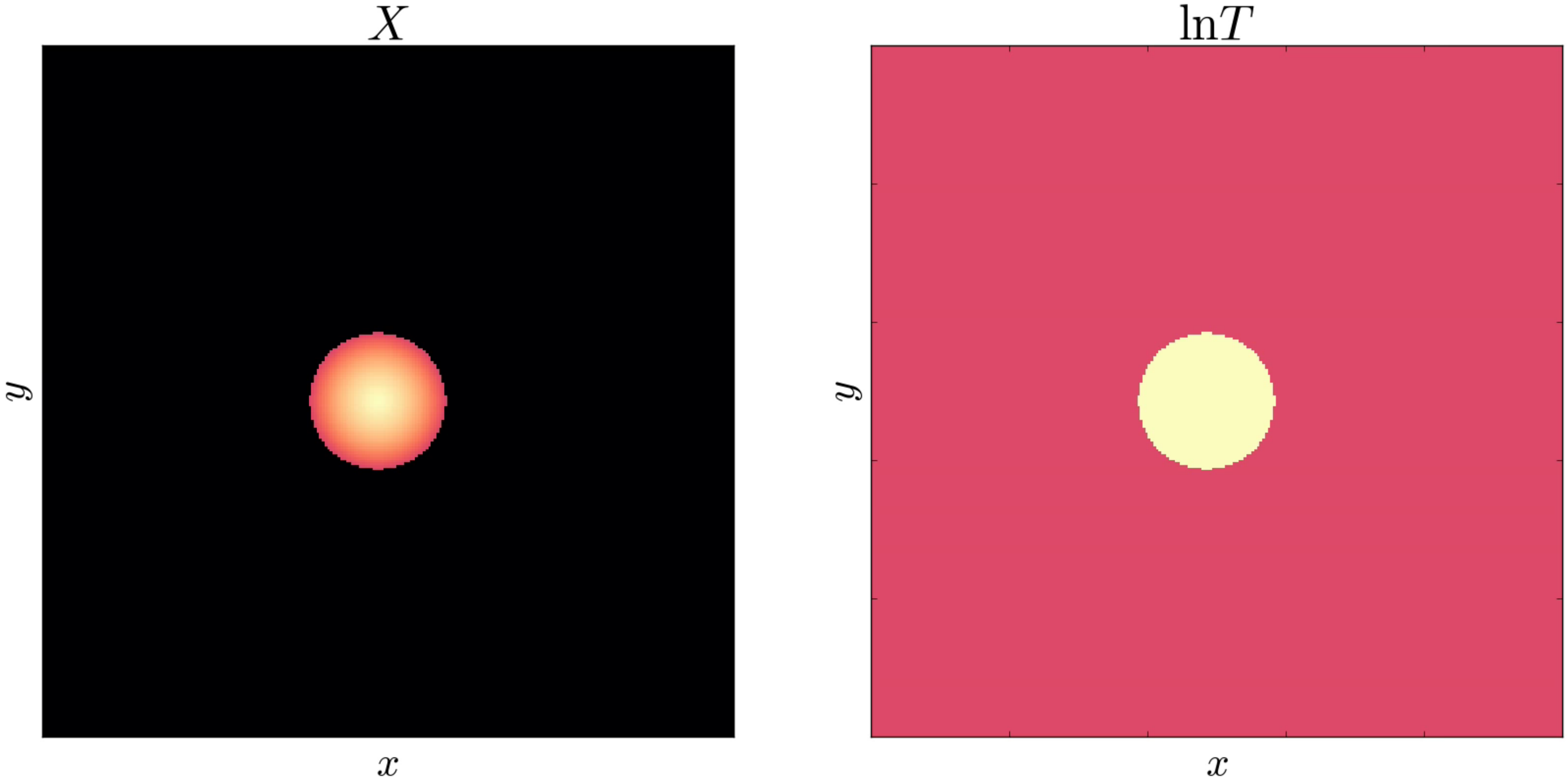
$$Q \propto \rho^2 \left(\frac{Y}{T}\right)^3 e^{-\alpha/T}$$

- In future will use multi-species reaction network with many species

Compressible vs Low Mach



Hubber, Falle & Goodwin 13



n: 0, t = 0.00000

Relativistic reactive Riemann problem

- On scale of whole NS, treat flame as ***discontinuity***
- Model propagation by solving Riemann problem (RP) for relativistic deflagrations
- In relativistic systems, ***RP is 2d*** (Radice & Rezzolla 13): coupling of tangential velocity due to Lorentz factor, e.g.

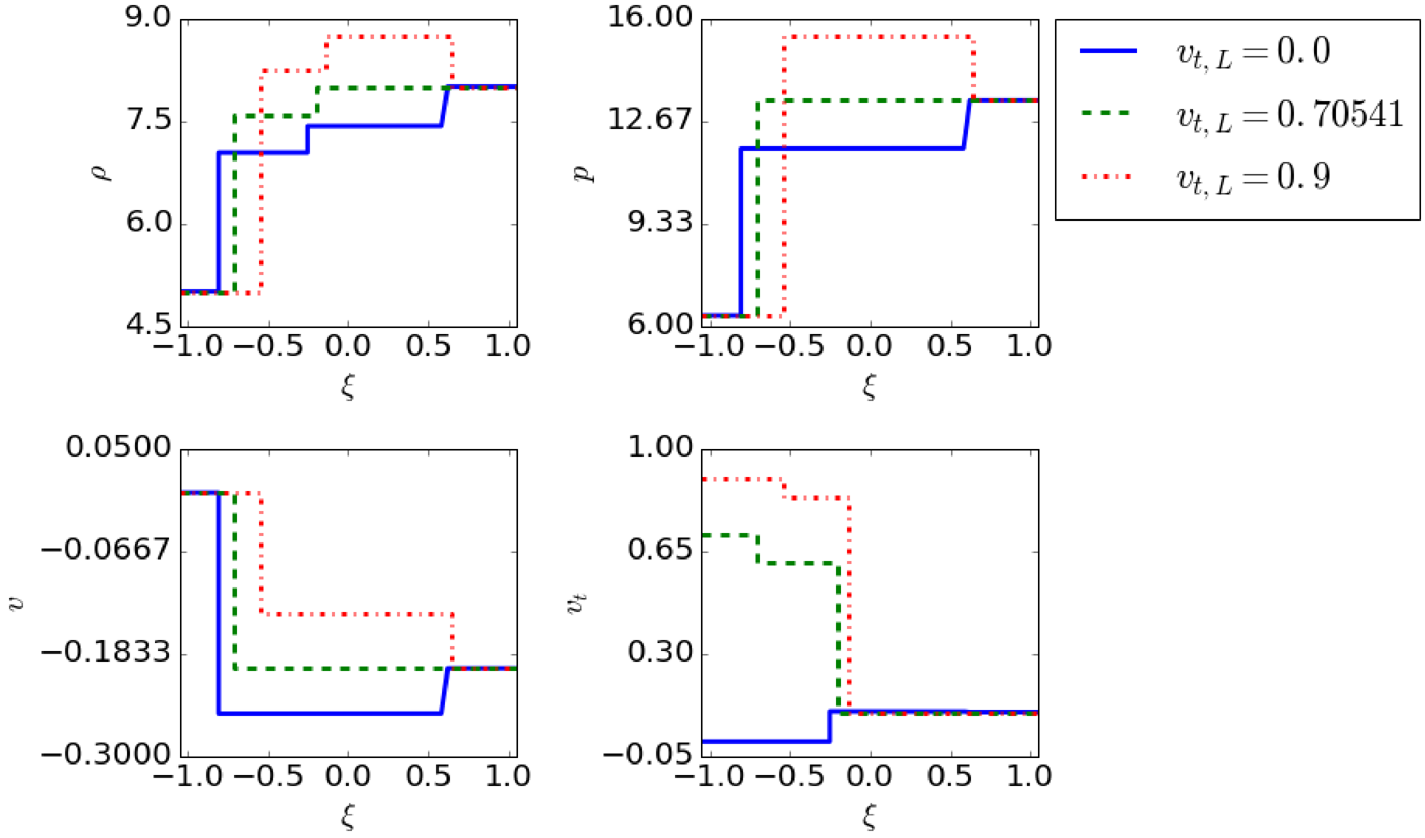
$$[[\rho(V_s - v^x)]] = 0 \quad \rightarrow \quad [[\rho W(V_s - v^x)W_s]] = 0$$

- Could this be ***important for X-ray bursts***?

R3D2

- Developed `r3d2` - python based **R**elativistic **R**eactive **R**iemann (exact) solver for **D**eflagrations and **D**etonations (Harpole & Hawke 16)
- Found tangential velocities ***can*** change wave pattern, but only if:
  - initial system is already near transition point, or
  - tangential velocity is *very* relativistic

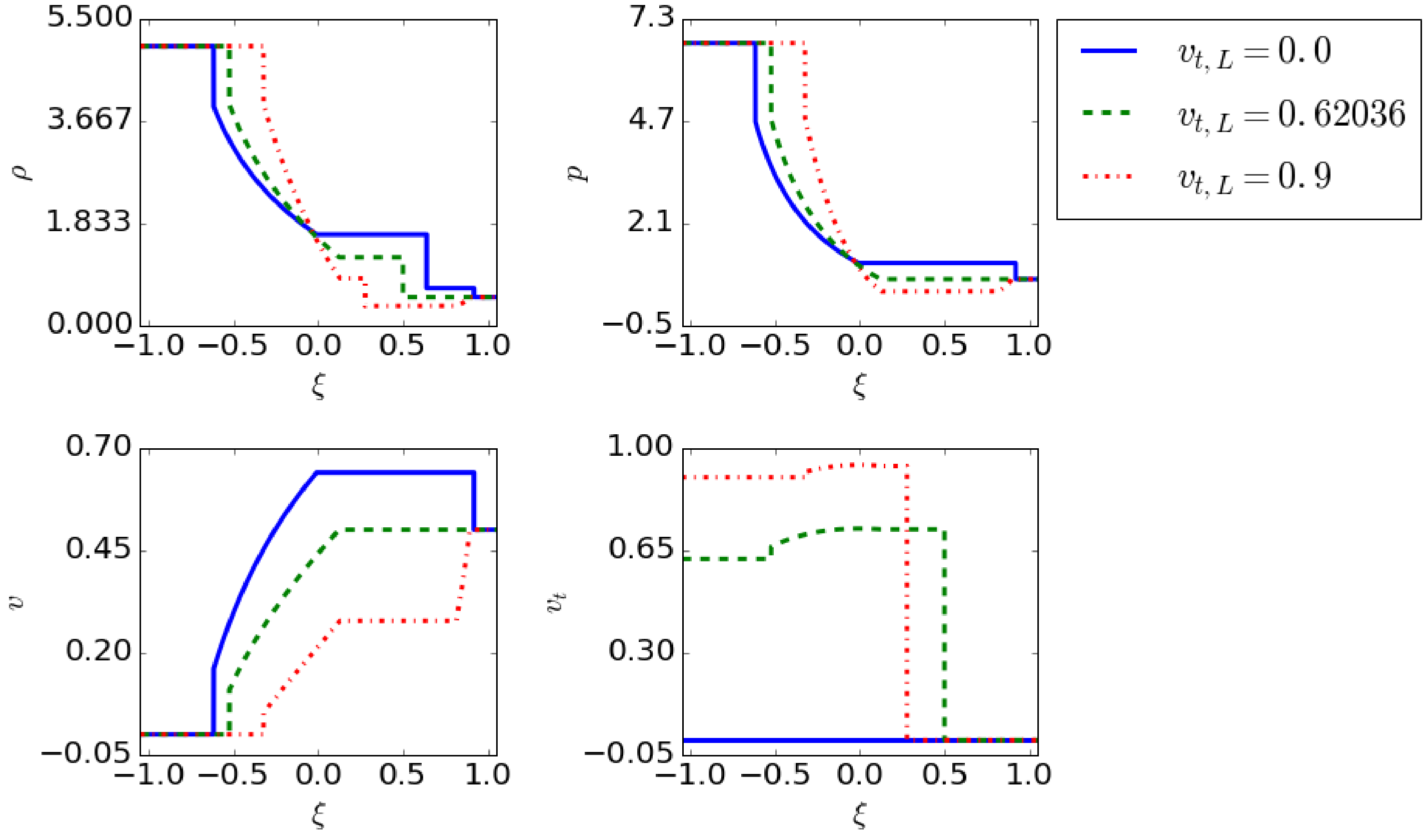
Varying v_t



$$(\rho, v_x, \varepsilon)_L = (5, 0, 2.0), (\rho, v_x, v_t, \varepsilon)_R = (8, -0.2, 0.1, 2.5)$$

$$SDT_{\leftarrow} CR_{\rightarrow} \rightarrow SDT_{\leftarrow} CS_{\rightarrow}$$

Varying v_t



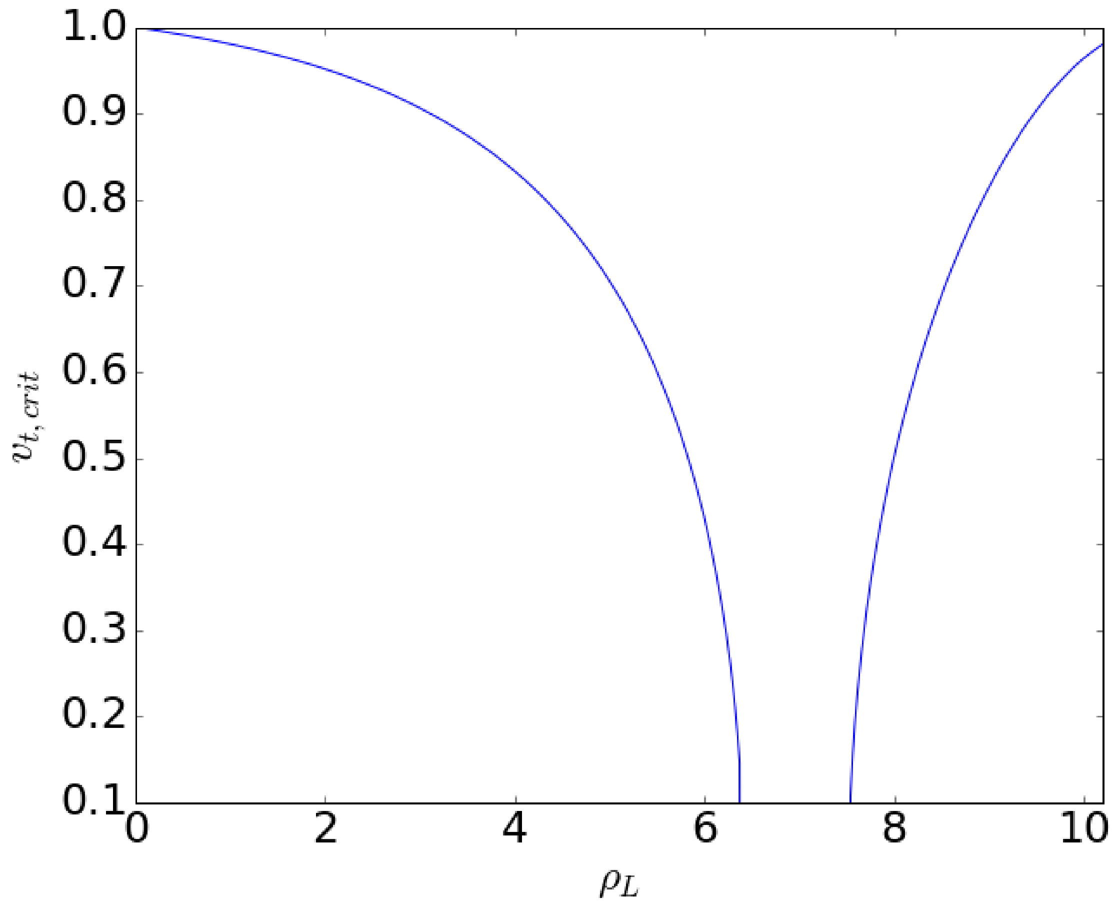
$$(\rho, v_x, \varepsilon)_L = (5, 0, 2.1), (\rho, v_x, v_t, \varepsilon)_R = (0.5, 0.5, 0.0, 2.0)$$

$$(CJDF_{\leftarrow}R_{\leftarrow})CS_{\rightarrow} \rightarrow (CJDF_{\leftarrow}R_{\leftarrow})CR_{\rightarrow}$$

Rarefaction to shock transition

- Transition occurs when pressure in central 'star' states are equal to pressure of one of the initial states, such that:
$$p^* = p_S, \qquad v_x^* = (v_x)_S, \qquad \rho_S^* = \rho_S$$
- Use this to find critical tangential velocity at which transition occurs

Critical v_t



$$(v_x, \varepsilon)_L = (0, 2.0), (\rho, v_x, v_t, \varepsilon)_R = (8, -0.2, 0.1, 2.5)$$

Conclusions & future plans

- We are modelling relativistic burning on neutron stars
- Using a relativistic extension to the ***Low Mach approximation***
- Have modelled weak planar gravitational field & reactions
- Investigated relativistic deflagrations and detonations using `r3d2`
- Next steps: physical parameters, spherical coordinates, 3d, rotation