Convection-Aided Explosions in 1D CCSN Simulations

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Fifty-One Ergs
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1851

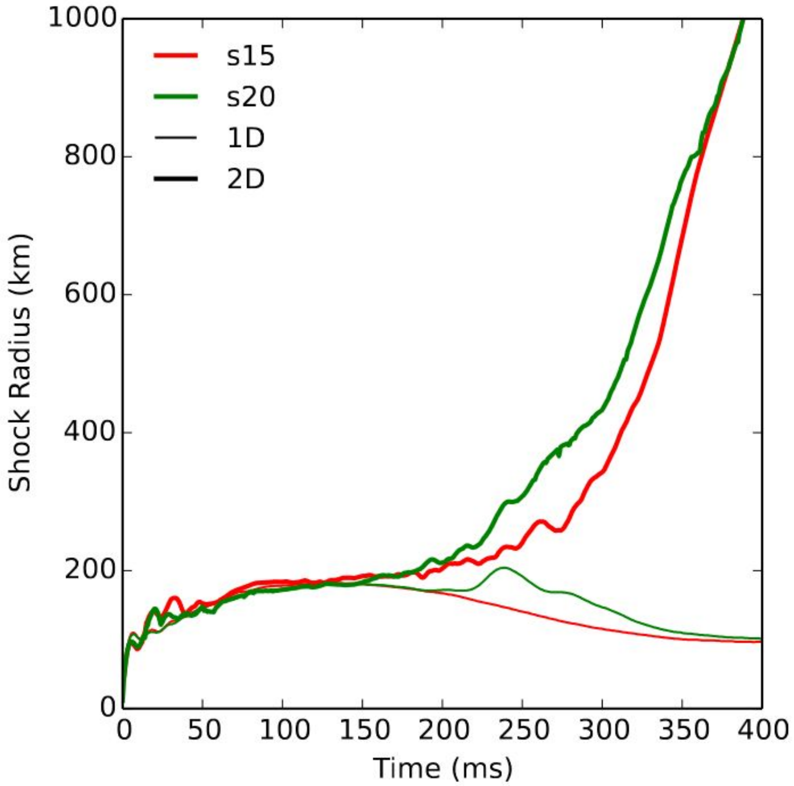
The fundamental questions are:

Why do multi-D simulations explode while 1-D do not?

How do massive stars explode?

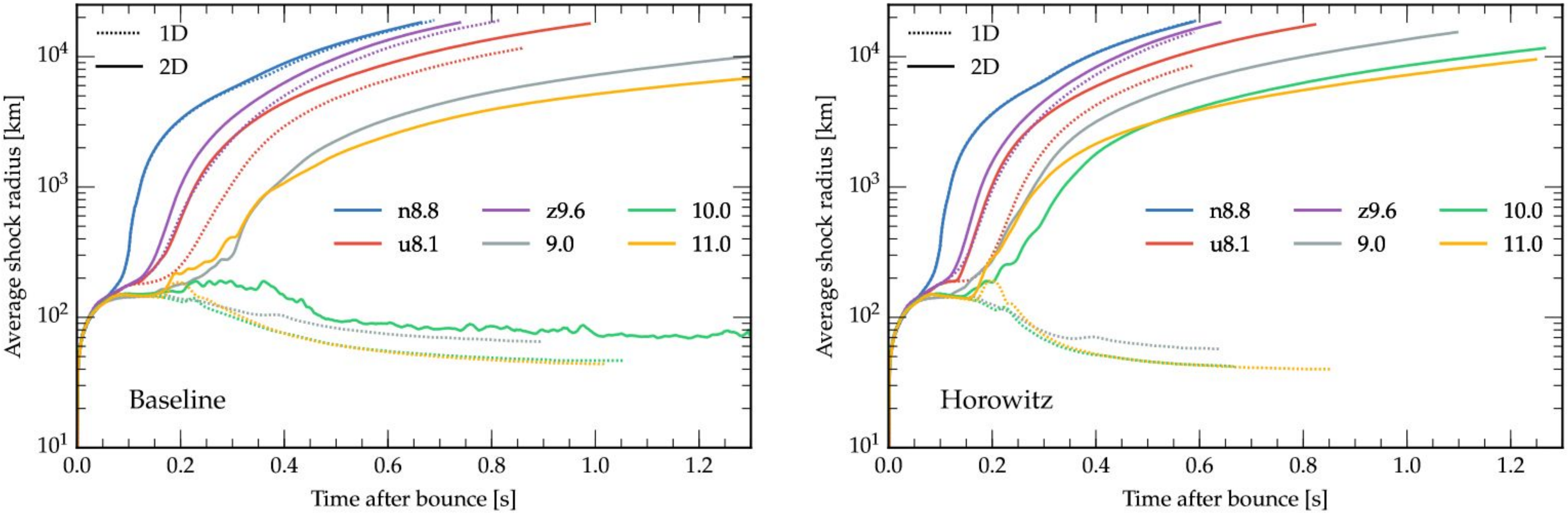
Can we predict which stars explode?

Most 1-D simulations do not explode, yet many multi-D do



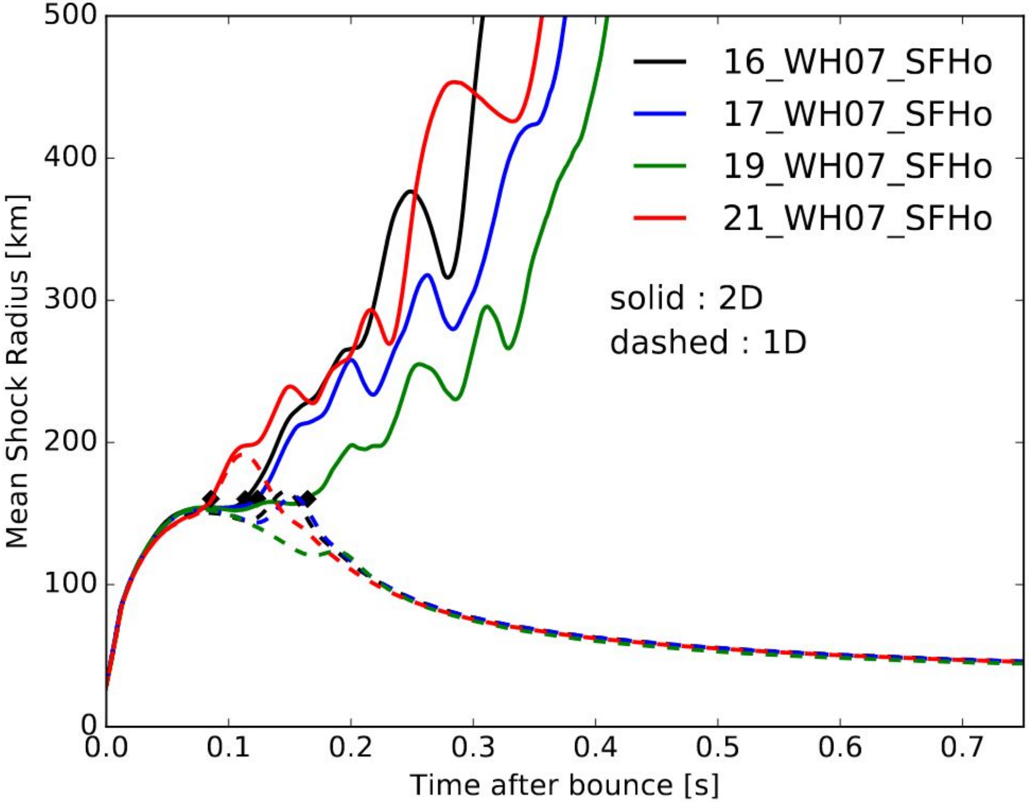
Pan+ (2015)

again...



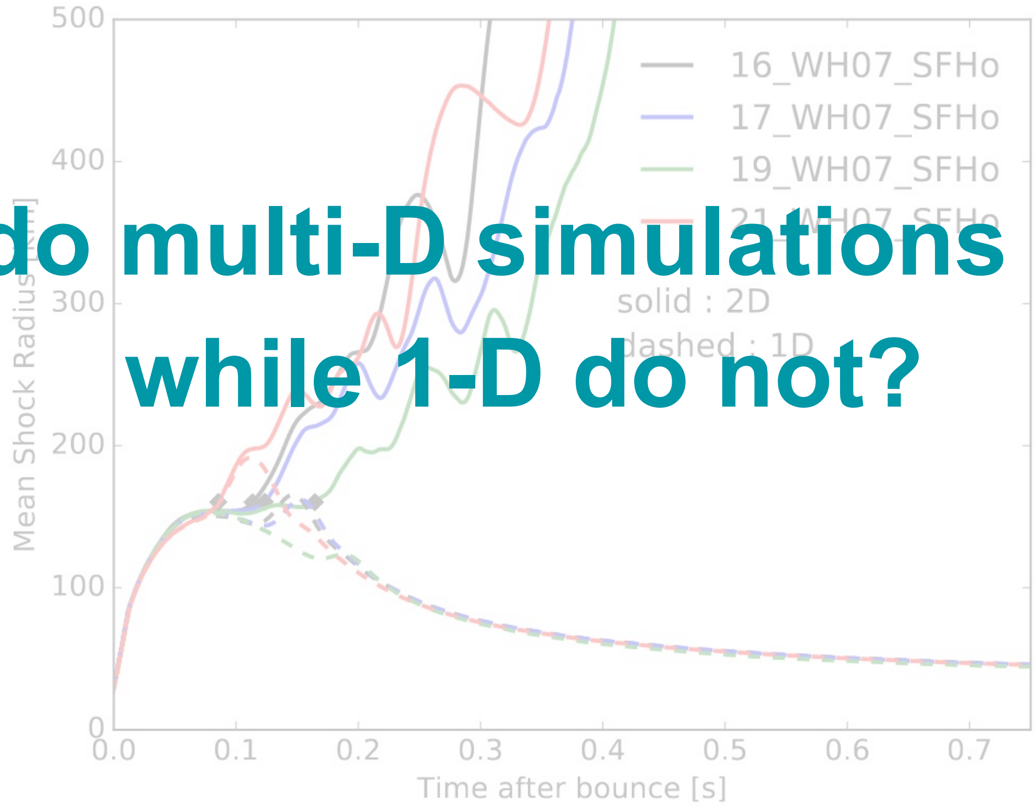
Radice+ (2017)

...and again!



Vartanyan+ (2018)

...and again!



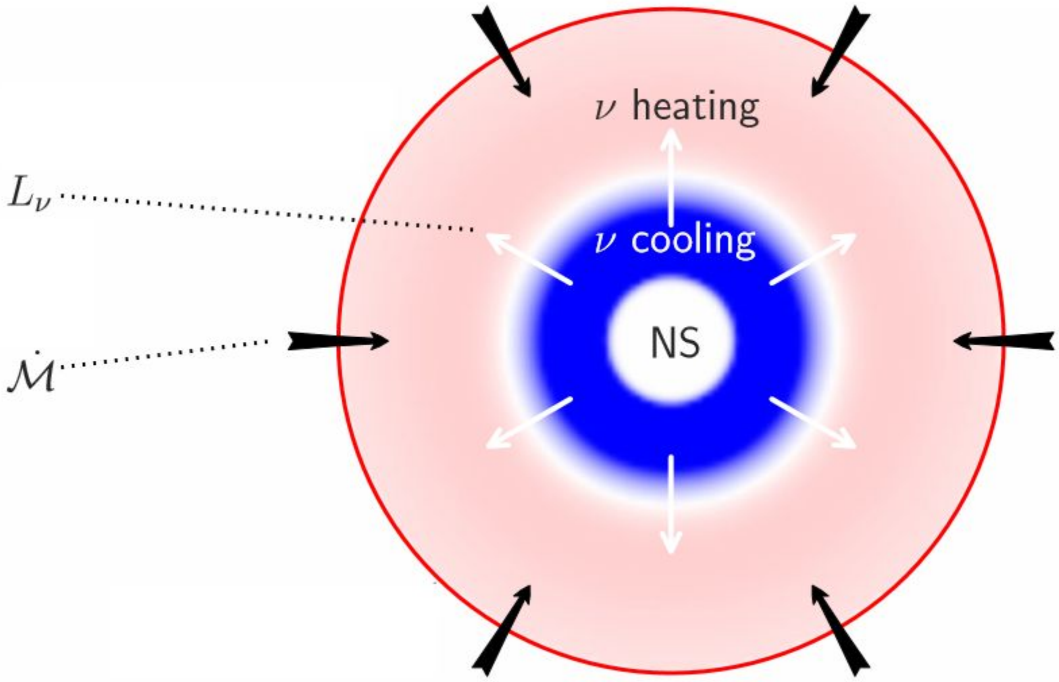
Why do multi-D simulations explode while 1-D do not?

Vartanyan+ (2018)

We need a way to define a critical condition for explosion

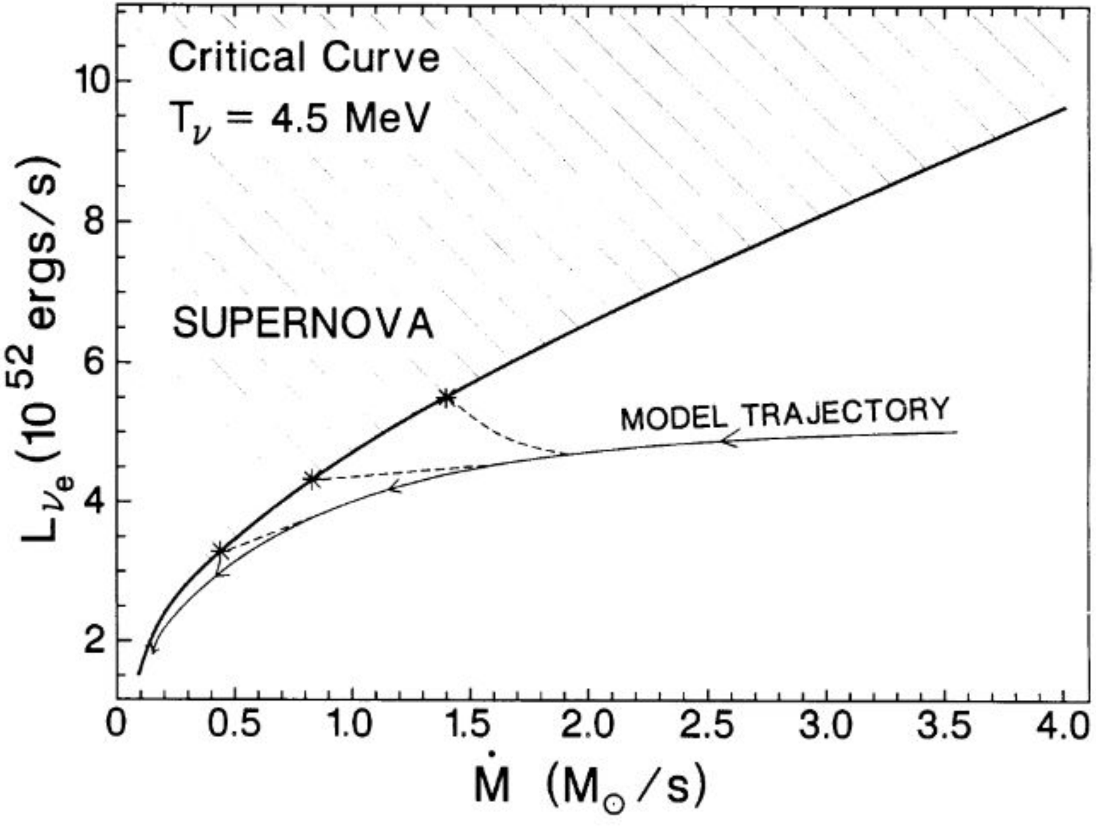
What does it take to revive the stalled shock?

- Bethe and Wilson (1985) hypothesized that neutrino heating alone revitalized the shock



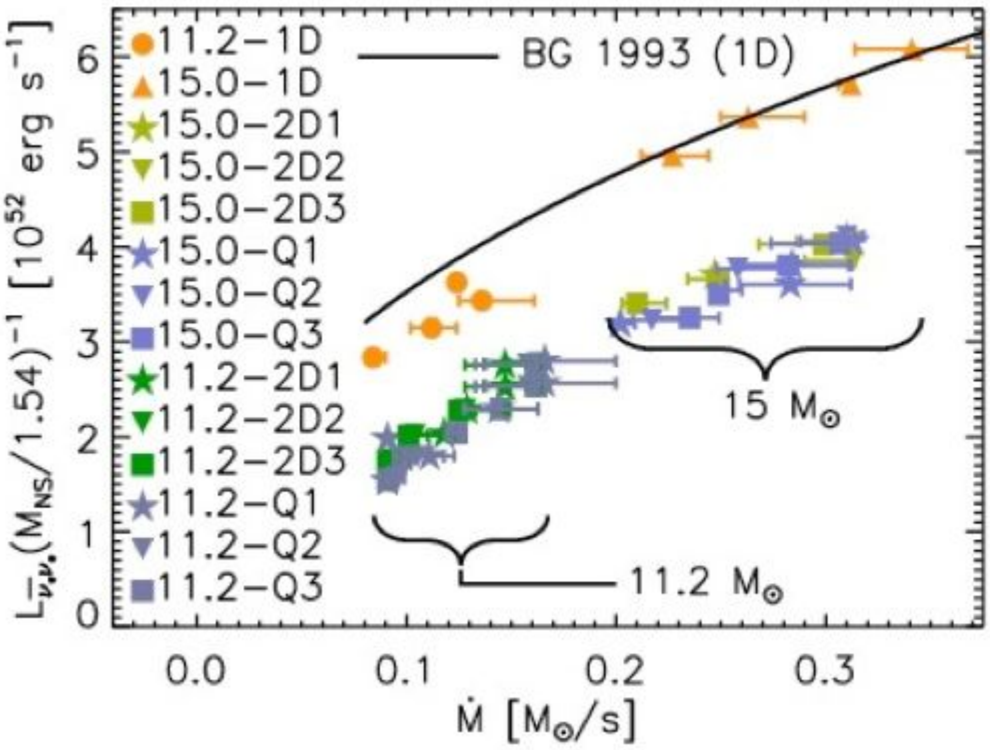
Murphy & Dolence (2017)

Burrows and Goshy Suggested a Critical Curve



Burrows & Goshy (1993)

Critical Curve is Reduced by ~30% in multi-D



Murphy & Burrows (2008)

Simulations suggested, but did not prove, that turbulence is the dominant factor that aids explosion

Start With Continuity Equations

$$\frac{d\rho}{dt} = -\rho \nabla \cdot \boldsymbol{v},$$

$$\rho \frac{d\boldsymbol{v}}{dt} = -\rho \nabla \Phi - \nabla P,$$

$$\rho \frac{d\varepsilon}{dt} = -P \nabla \cdot \boldsymbol{v} + \mathcal{H} - \mathcal{C},$$

Equations With Turbulence

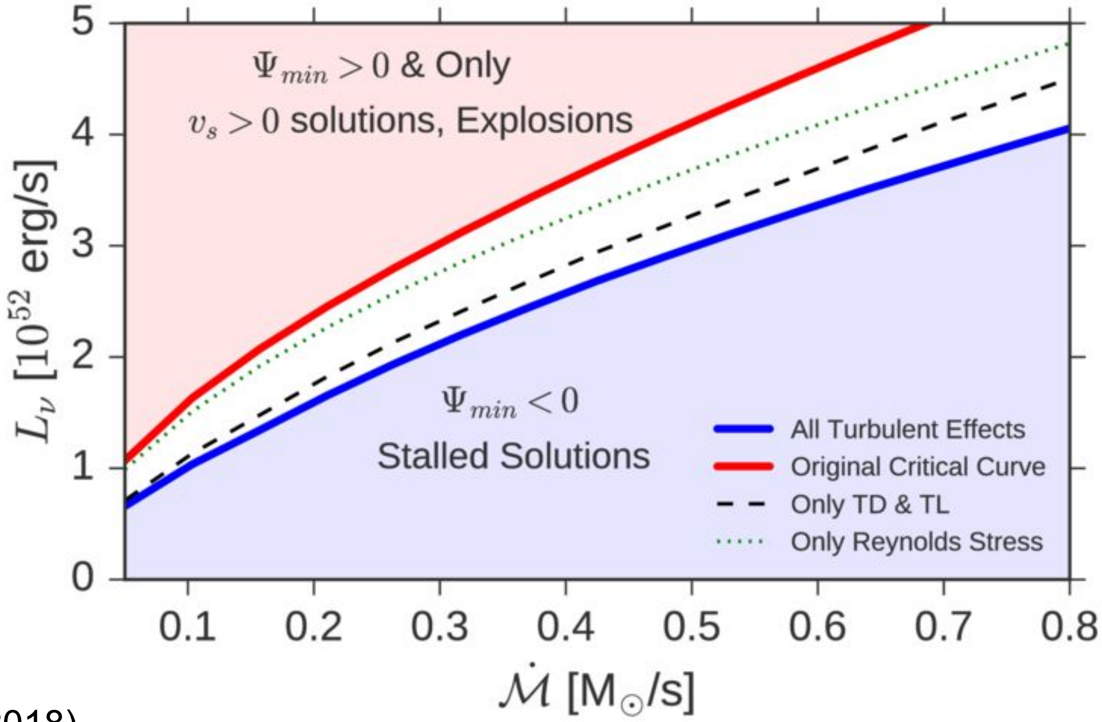
$$\nabla \cdot (\rho_0 \vec{u}_0 + \langle \rho' \vec{u}' \rangle) = 0$$

$$\langle \rho \vec{u} \rangle \cdot \nabla \vec{u}_0 = -\nabla P_0 + \rho_0 \vec{g} - \nabla \cdot \langle \rho \mathbf{R} \rangle$$

$$\langle \rho u \rangle \cdot \nabla e_0 + \langle P_0 \nabla \cdot u_0 \rangle + \langle P' \nabla \cdot u' \rangle = -\nabla \cdot \langle F_e \rangle + \rho_0 q + \rho_0 \epsilon_k$$

By Reynolds decomposing our equations we can peer into the various components involved in creating a successful supernova explosion

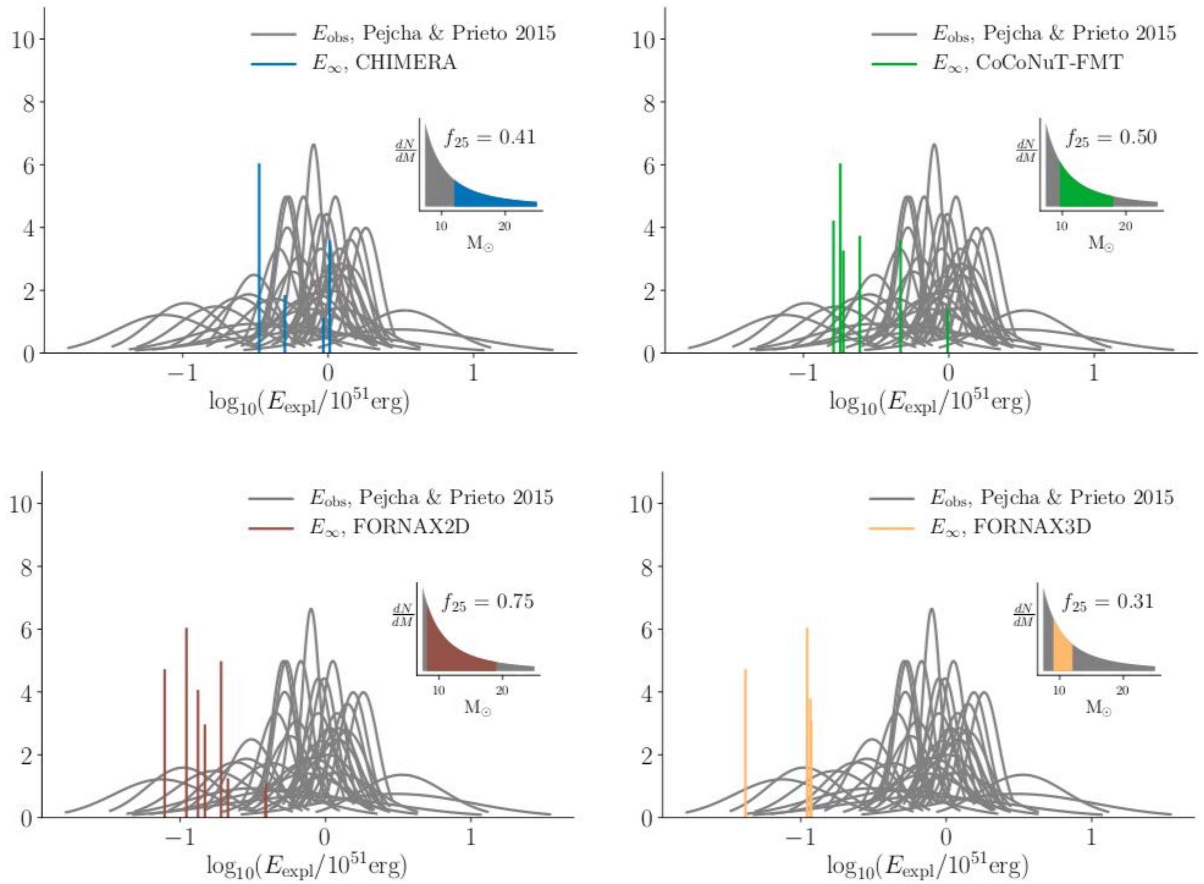
How Turbulence Affects the Critical Curve



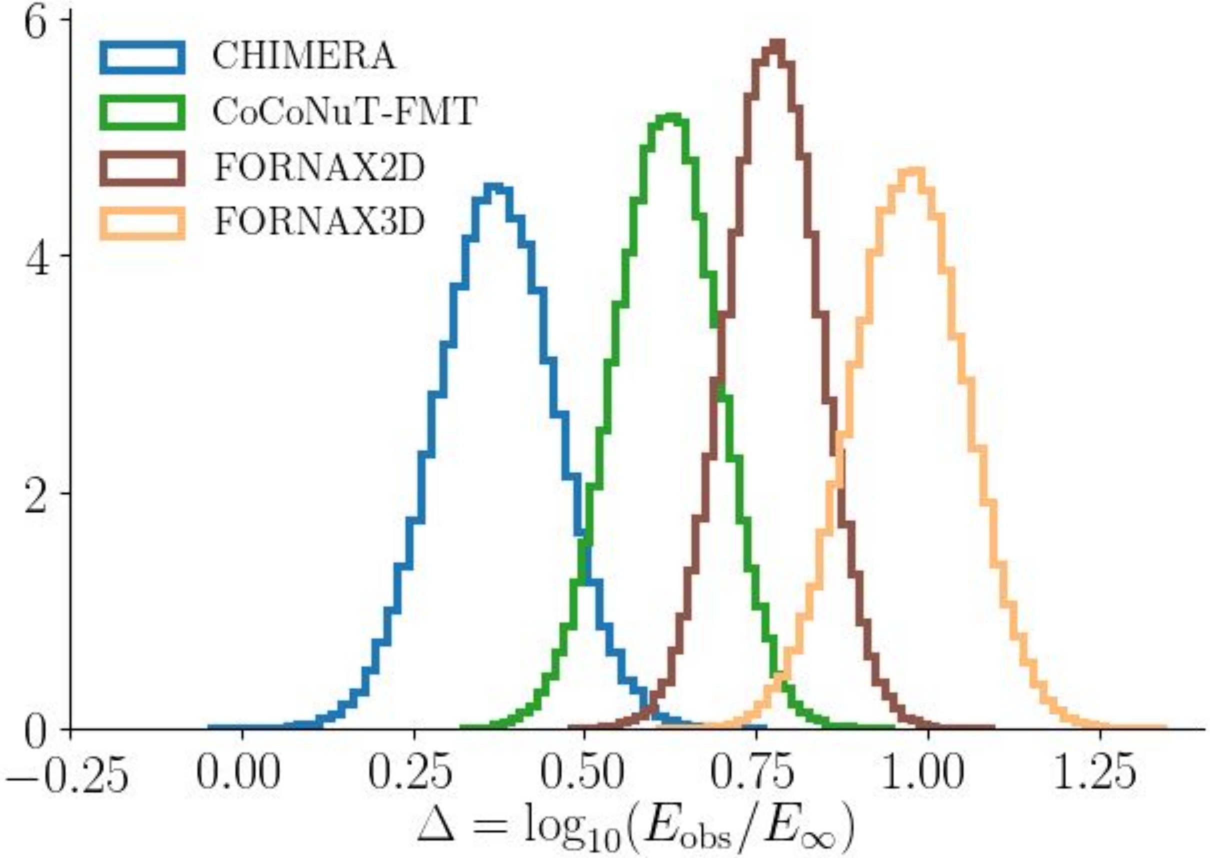
Mabanta & Murphy (2018)

Multi-Dimensional simulations are important, but they are computationally expensive, and they may not accurately represent nature

For Example: Murphy, Mabanta, & Dolence (2019)



For Example: Murphy, Mabanta, & Dolence (2019)

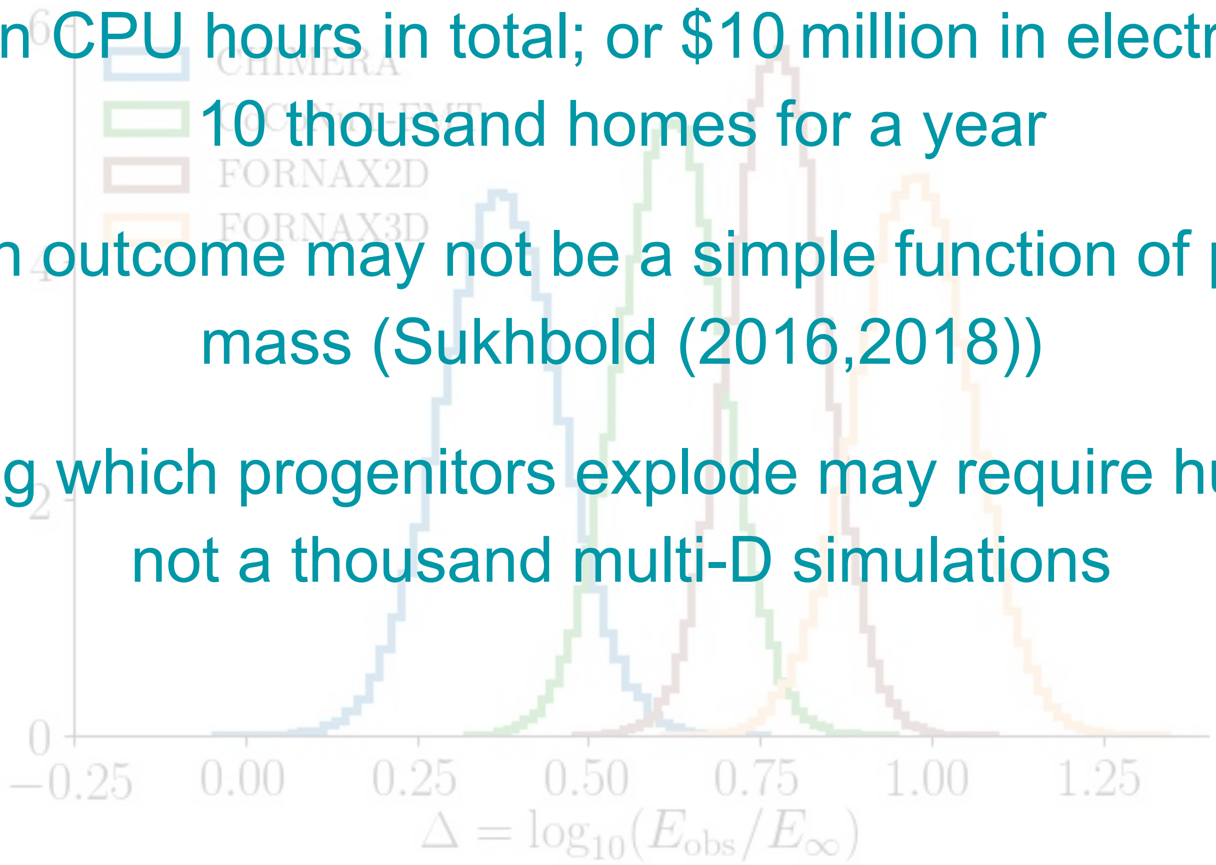


For Example, Murphy, Mabanta, & Dolence (2019)

100 million CPU hours in total; or $10 million in electricity bills = 10 thousand homes for a year

Explosion outcome may not be a simple function of progenitor mass (Sukhbold (2016,2018))

Predicting which progenitors explode may require hundreds if not a thousand multi-D simulations

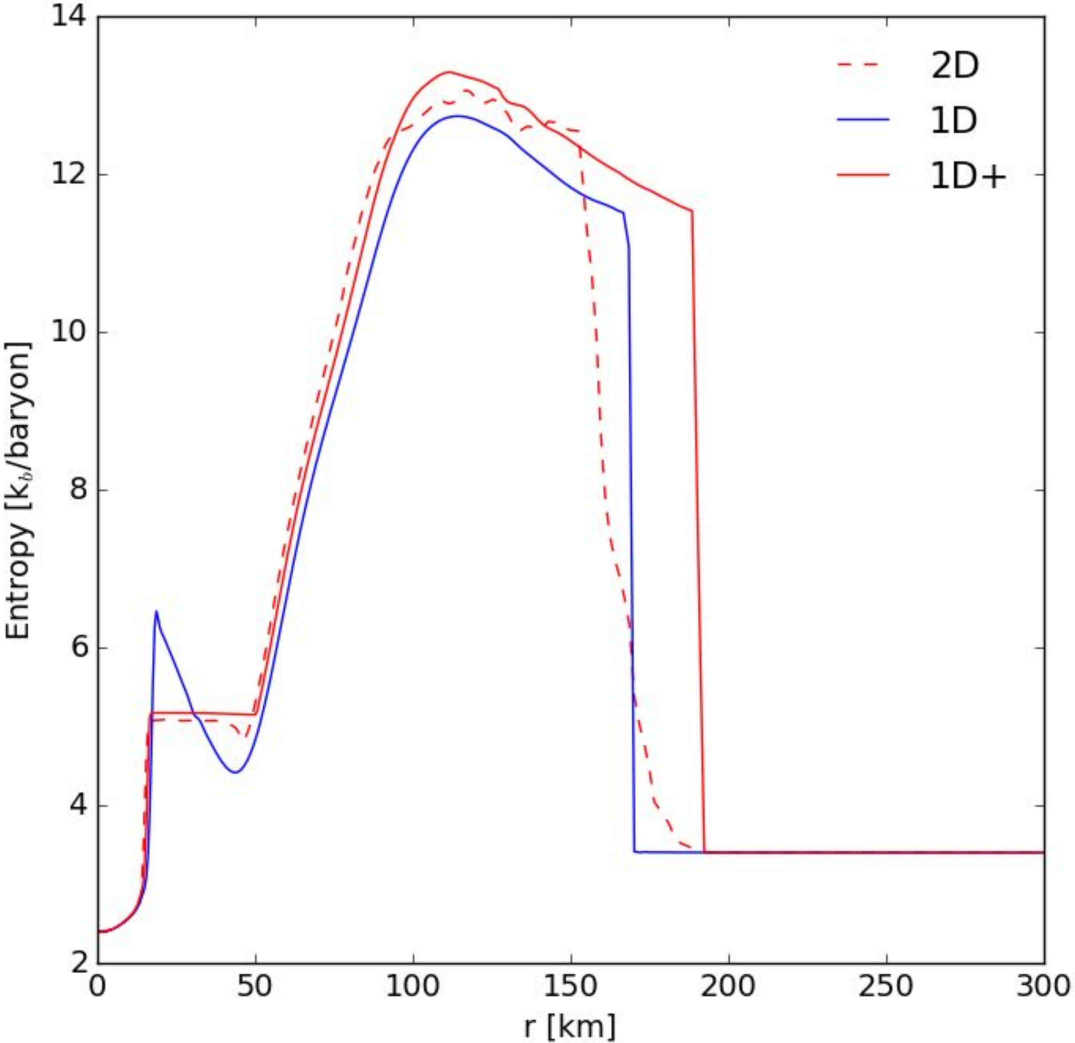


We need another way to systematically explore which progenitors explode and explore other physics that may be important

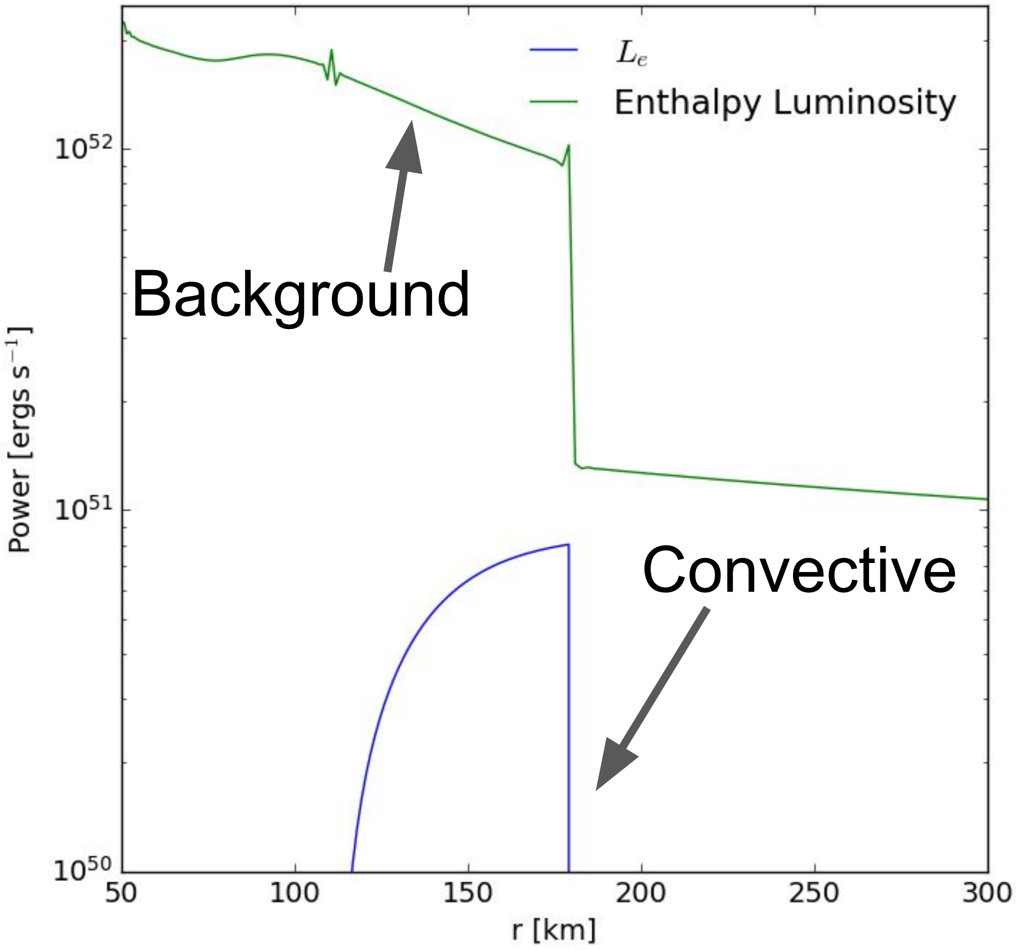
Now that we understand how convection aids explosion, we include our analytic convection model in 1D simulations (we call these 1D+)

Using FORNAX, we performed tests of 1D+

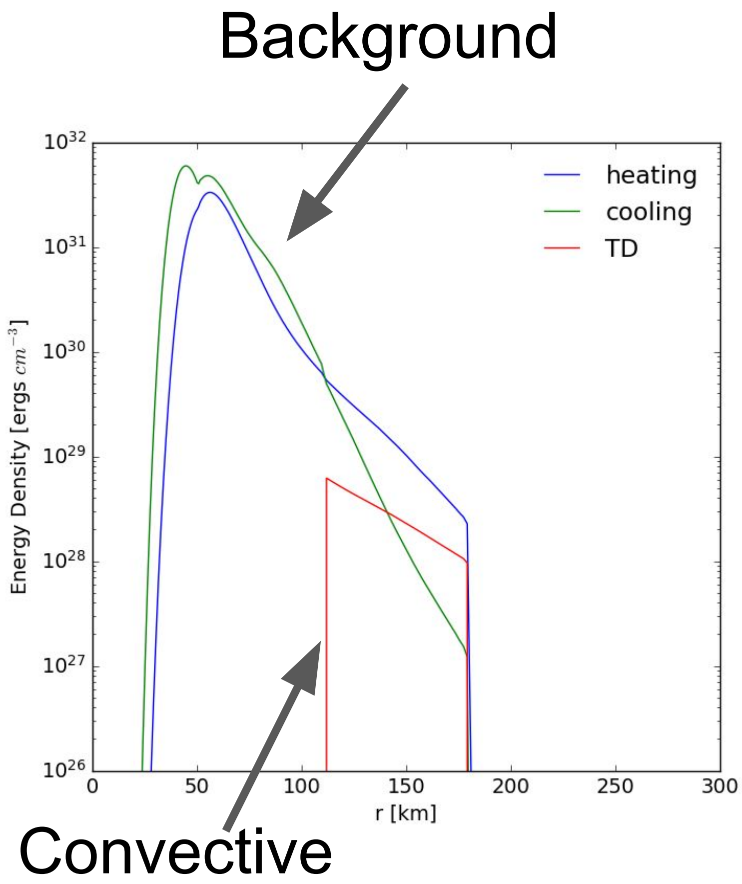
(Mabanta, Murphy, & Dolence 2019)

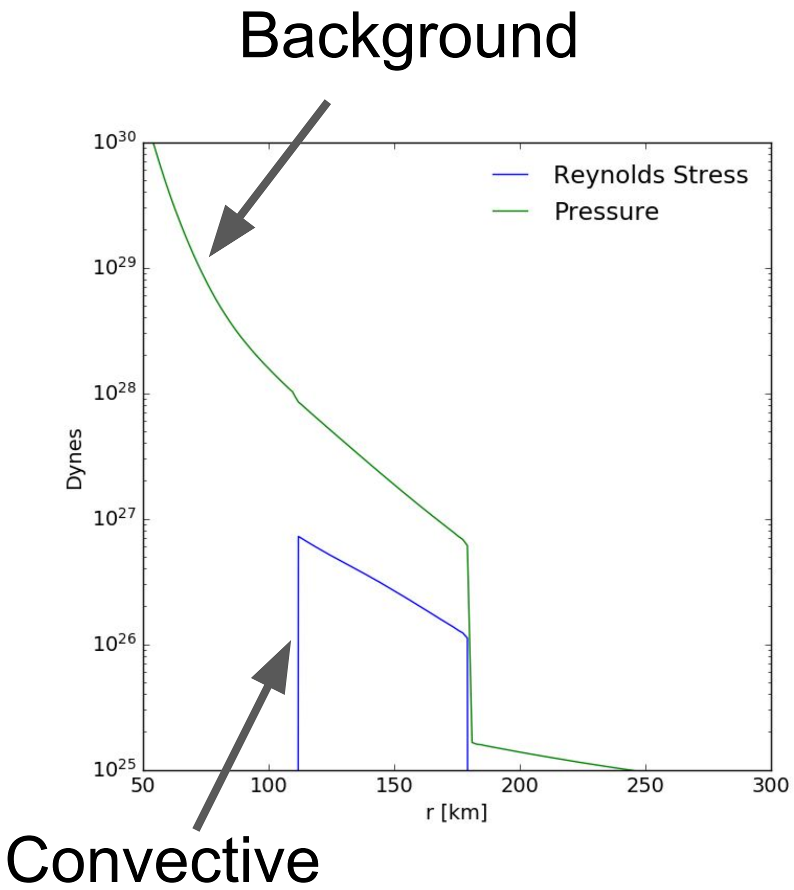


Mabanta, Murphy, & Dolence (2019)



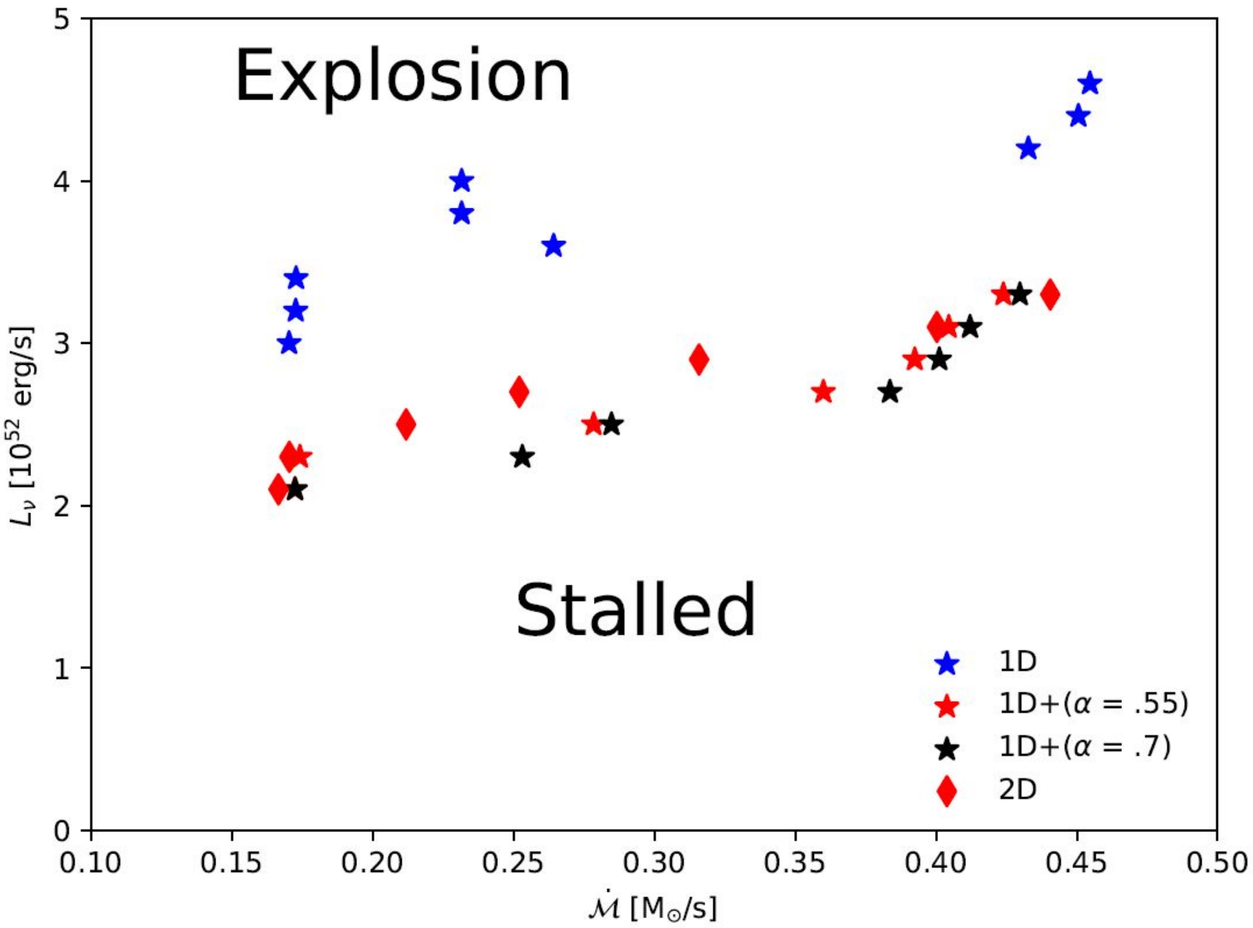
Mabanta, Murphy, & Dolence
(2019)



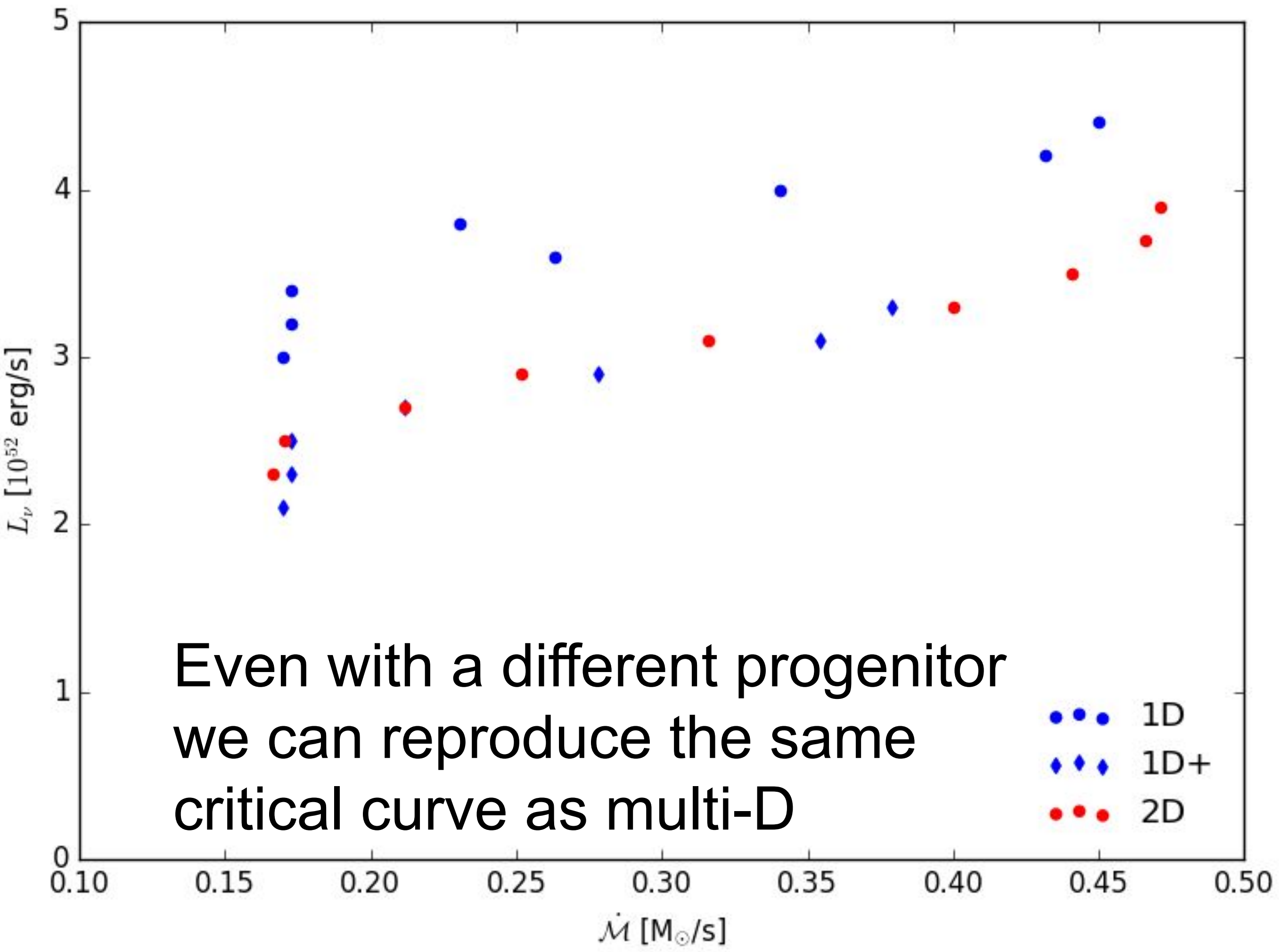


Mabanta, Murphy, & Dolence (2019)

1D+ reproduces the explosion condition of two-dimensional simulations in 1% of the time



Mabanta, Murphy, & Dolence (2019)



Mabanta, Murphy, & Dolence (2019)

Future Work

- Test 1D+ with detailed neutrino transport
- Compare 1D+ to 3D simulations; 1D+ will likely be 10^5 times faster than 3D simulations
- Use this new turbulence model to systematically explore the thousands of progenitor models

- We developed an analytic model for convection
- Used it to explain how convection aids explosions
- Incorporate it into 1D simulations (1D+)