Neutrino-Driven Convection and Neutrino-Driven Explosions

by
Jeremiah W. Murphy
(Princeton U.)

Collaborators:
Adam Burrows (Princeton U.), Josh Dolence (Princeton U.)
& Casey Meakin (LANL)

1D simulations (Rad-hydro)

Wilson '85
Bethe & Wilson '85
Liebendoerfer et al. '01
Rampp & Janka '02
Buras et al. '03
Thompson et al. '03
Liebendoer et al. '05
Kitaura et al. '06
Burrows et al. '07

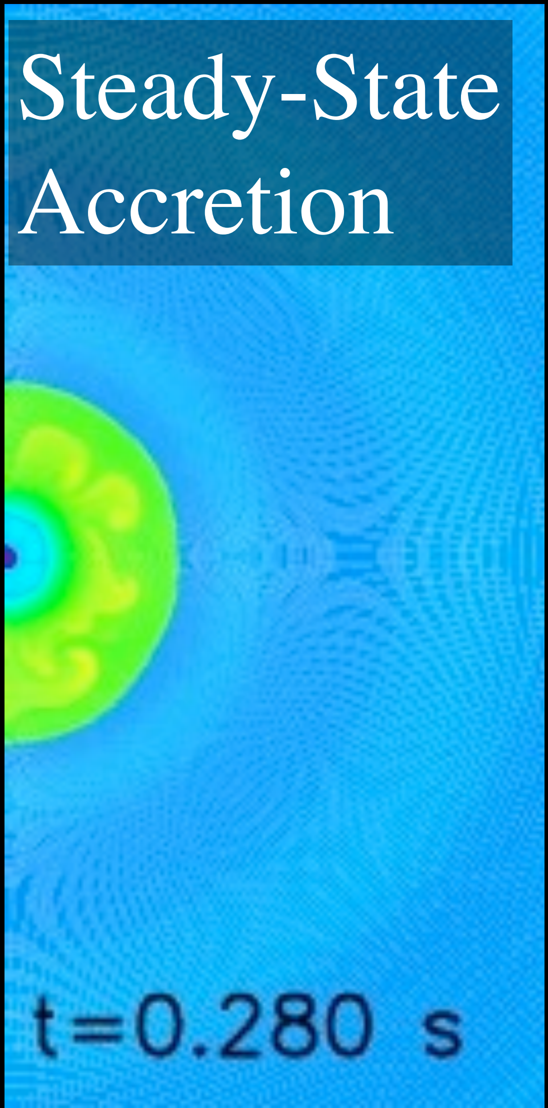
} Neutrino mechanism suggested (Wilson '85; Bethe & Wilson '85)

} (Liebendoerfer et al. '01 – Burrows et al. '07):

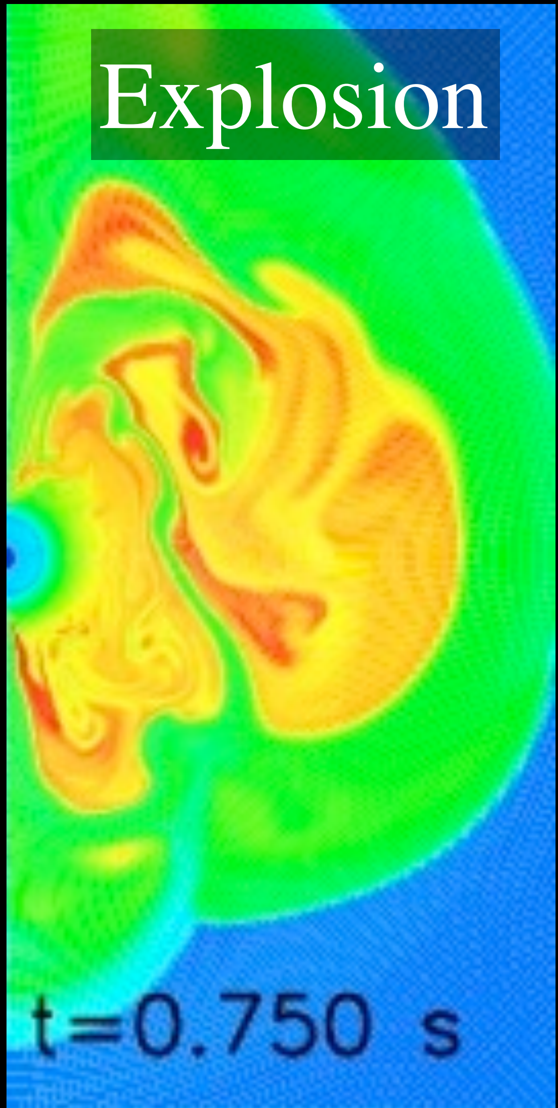
No Explosions
(Except lowest masses)

Spherical symmetry!
No GW emission?

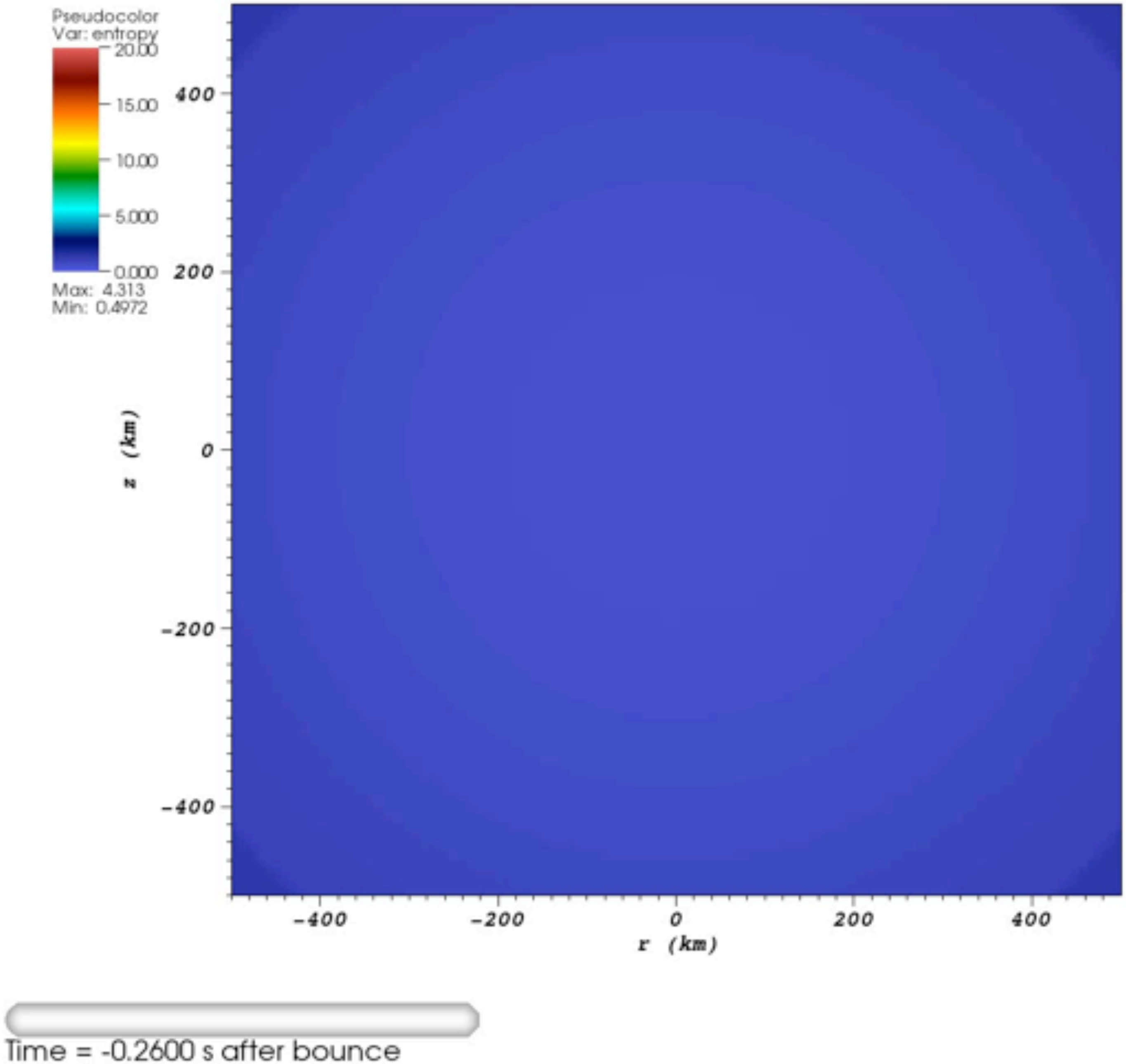
Fundamental Question of Core-Collapse Theory



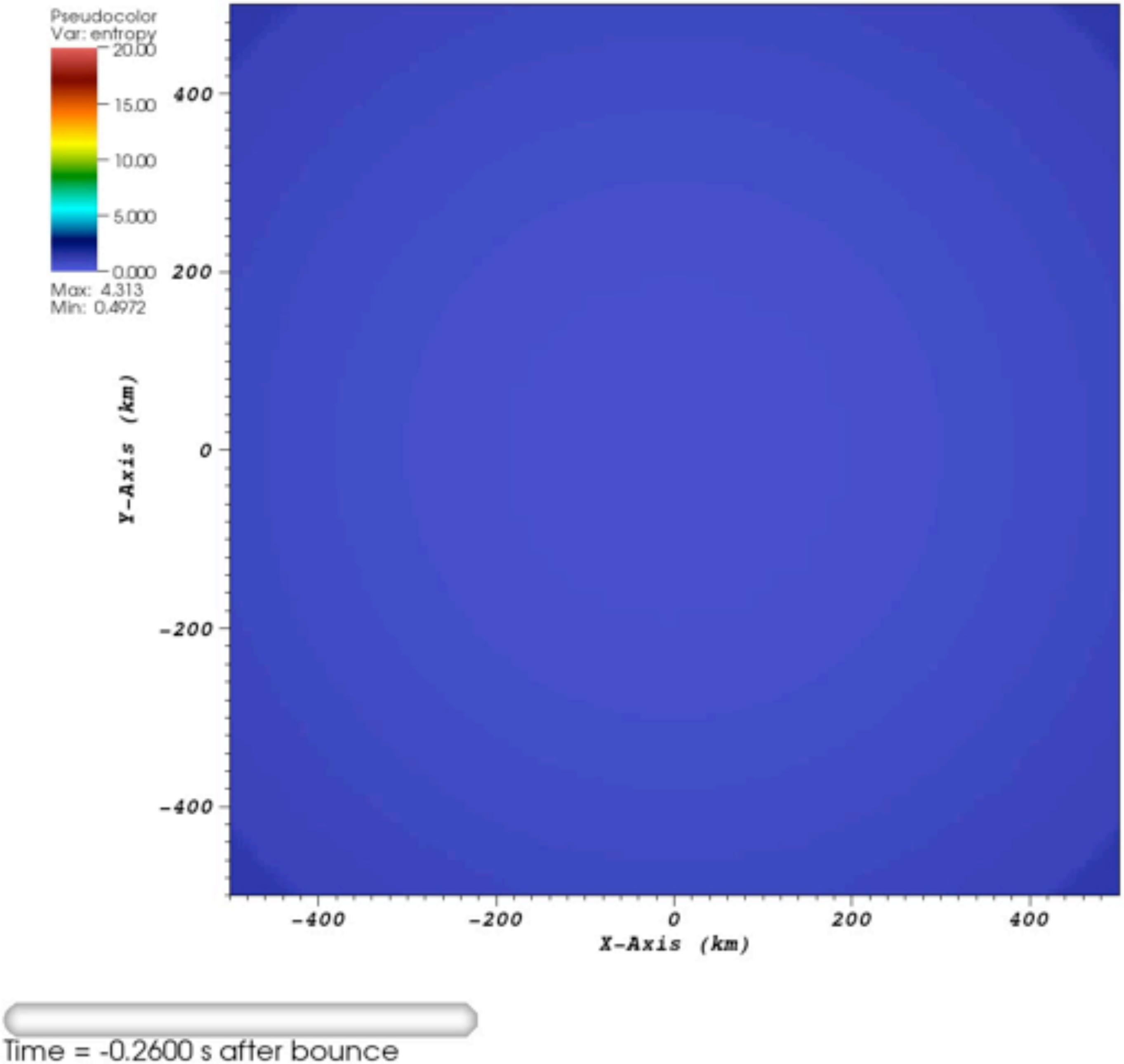
?



Relax 1D assumption?



Pseudocolor
Var: entropy
20.00
15.00
10.00
5.000
0.000
Max: 4.313
Min: 0.4972
400
200
0
-200
-400
z (km)
-400
-200
0
200
400
r (km)
Time = -0.2600 s after bounce


Pseudocolor
Var: entropy
20.00
15.00
10.00
5.000
0.000
Max: 4.313
Min: 0.4972
Y-Axis (km)
400
200
0
-200
-400
X-Axis (km)
-400
-200
0
200
400
Time = -0.2600 s after bounce

Multi-D makes it easier to explode

Neutrino Mechanism:

- •Neutrino-heated convection
- •Standing Accretion Shock Instability (SASI)
- •Explosions? Maybe

Acoustic Mechanism:

- •Explosions but caveats.

Magnetic Jets:

- •Only for very rapid rotations
- •Collapsar?

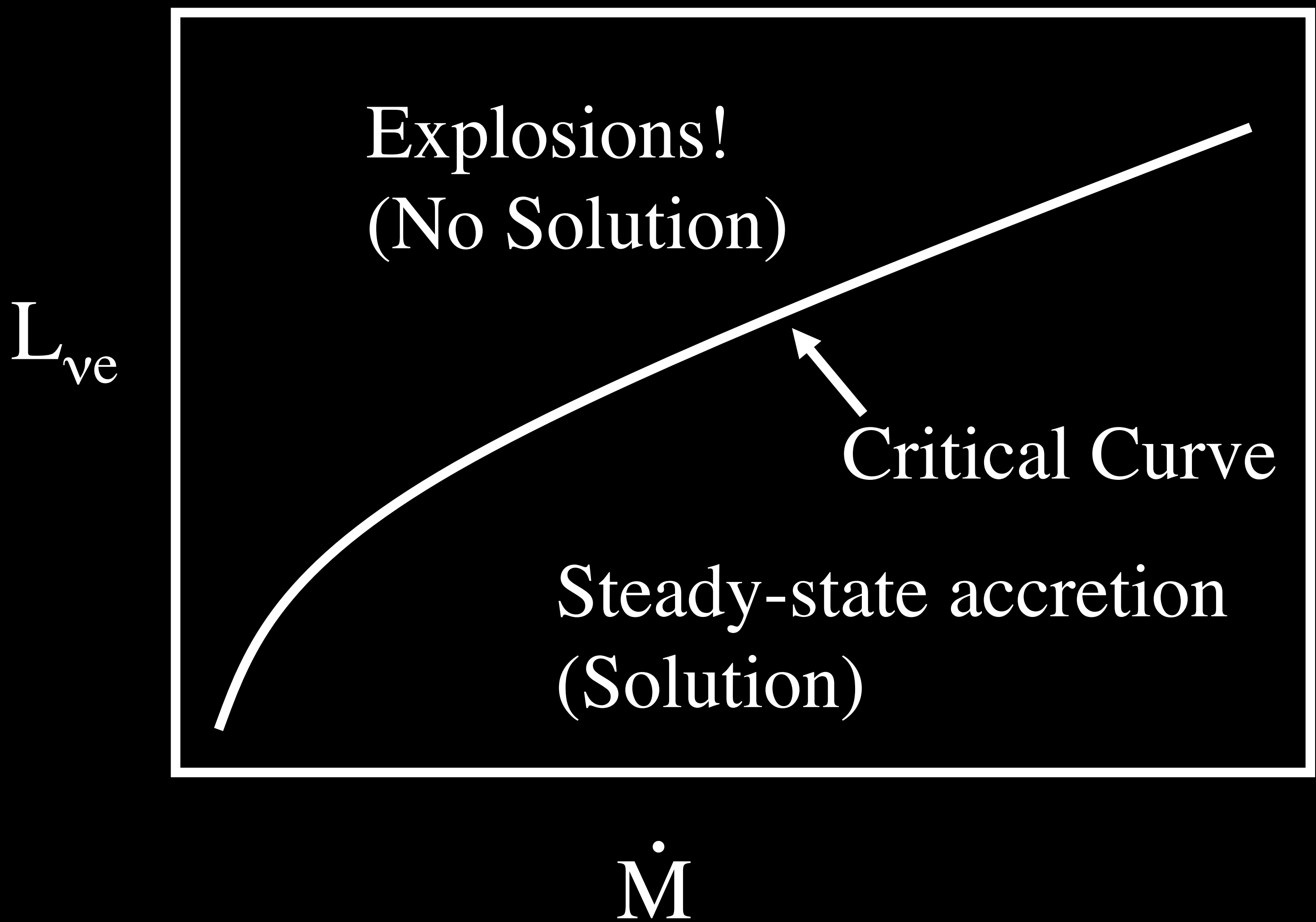
Why is it easier to explode in 2D compared to 1D?

Two Paths to the Solution

- Detailed 3D radiation-hydrodynamic simulations
(“Accurate” energies, NS masses, nucleo., etc.)

- Parameterizations that capture essential physics
(Tease out fundamental mechanisms)

Burrows & Goshy ‘93
Steady-state solution (ODE)

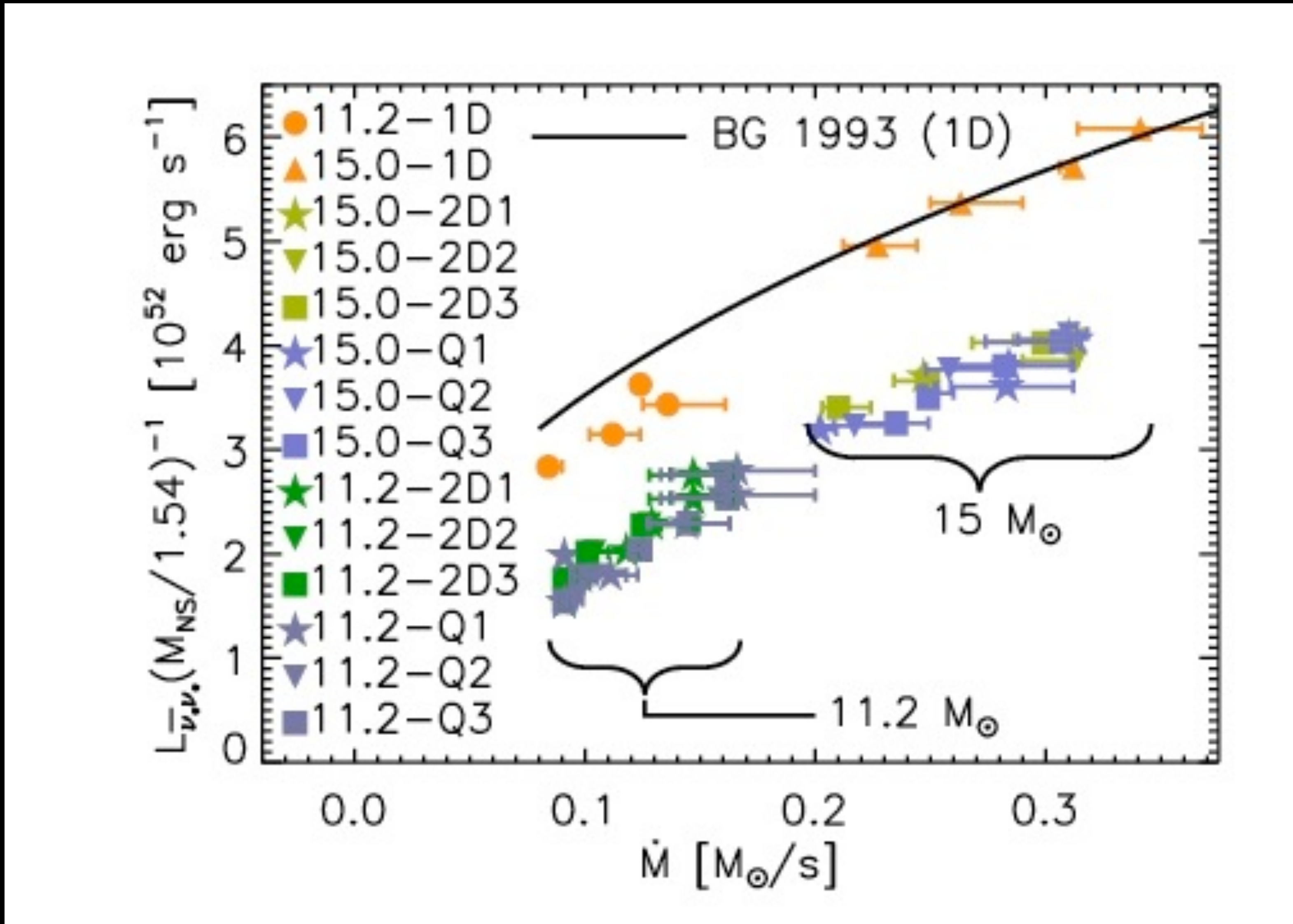


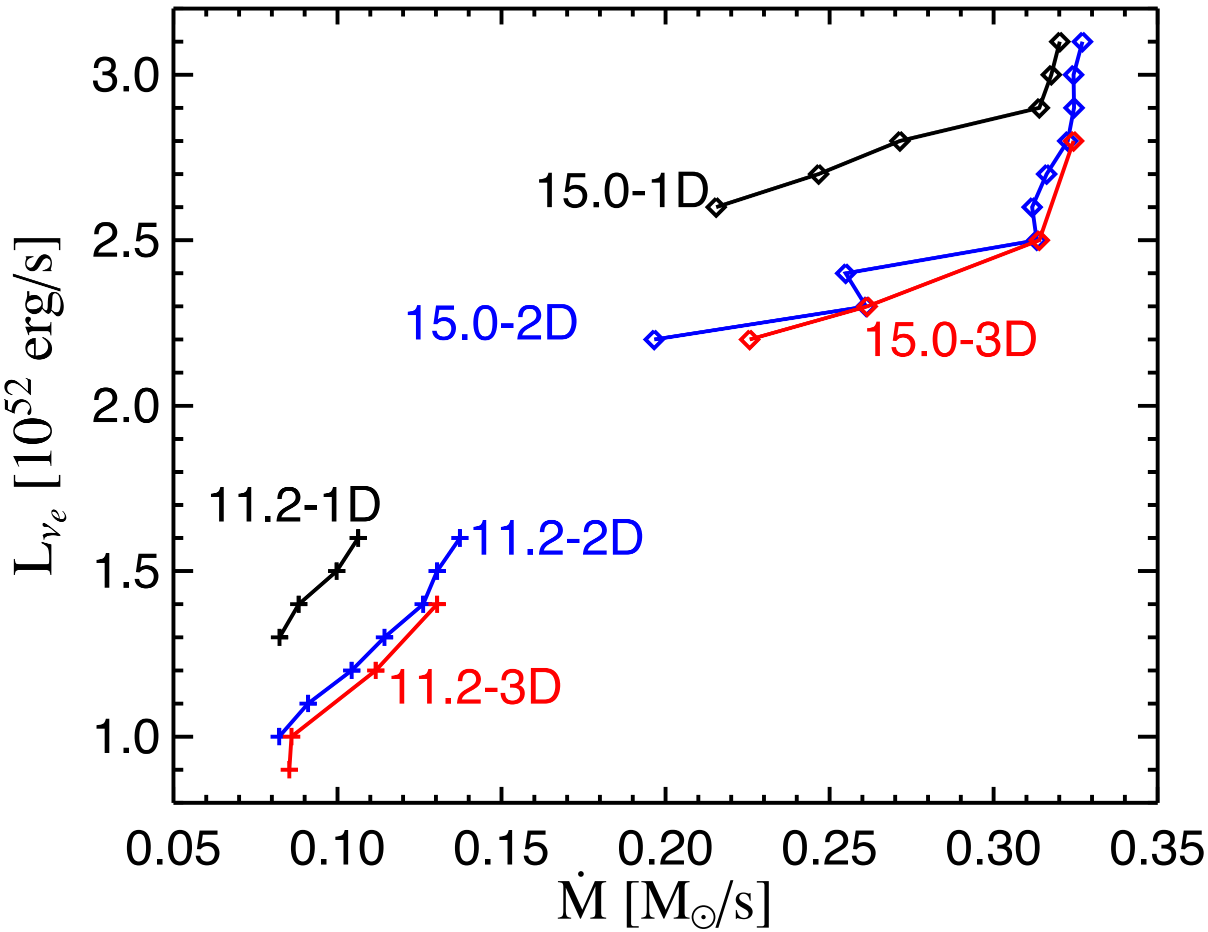
Is a critical luminosity relevant in hydrodynamic simulations?

- 1D
- 2D Convection and SASI?

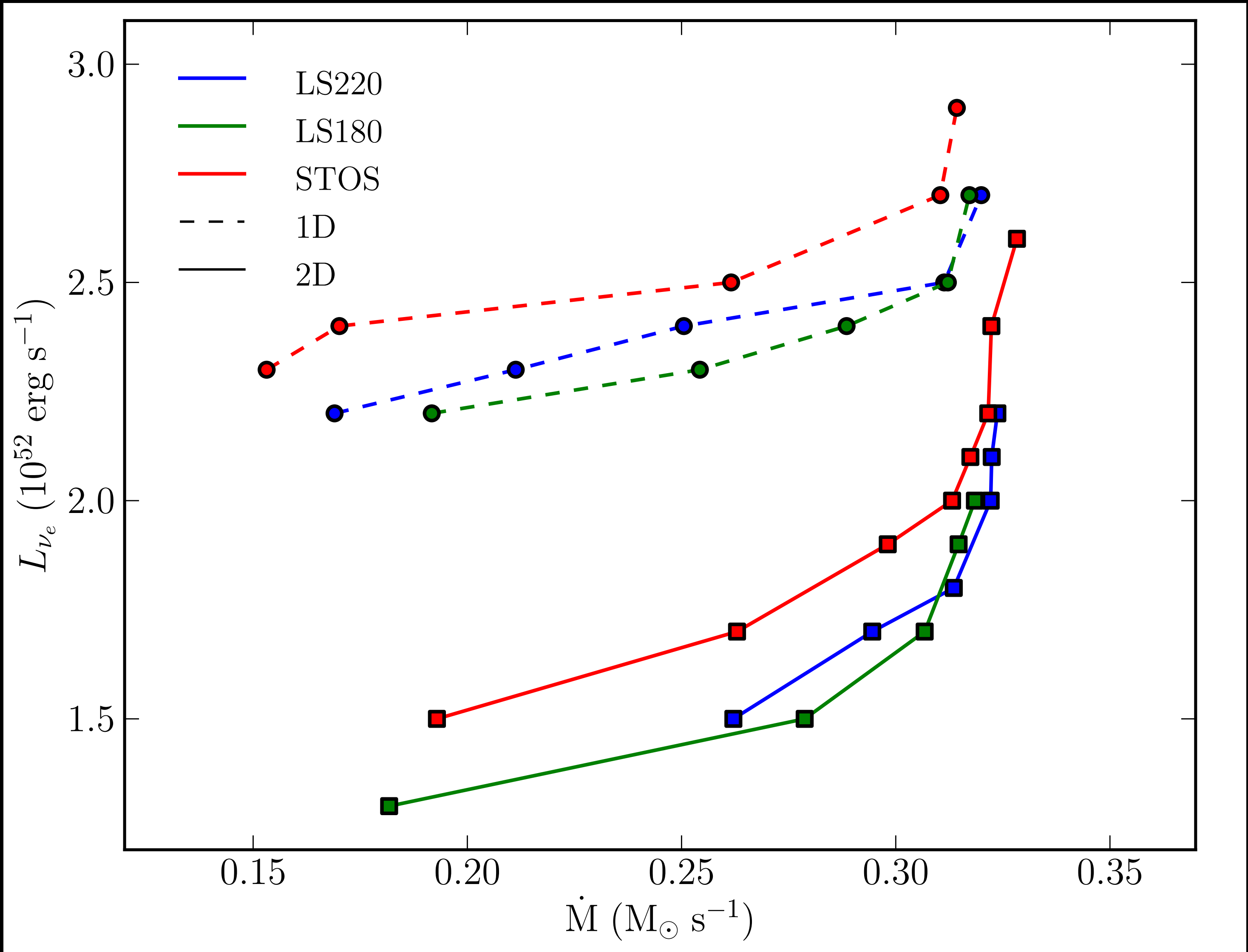
How do the critical luminosities differ between 1D and 2D?

Murphy & Burrows '08





Hanke et al 2011



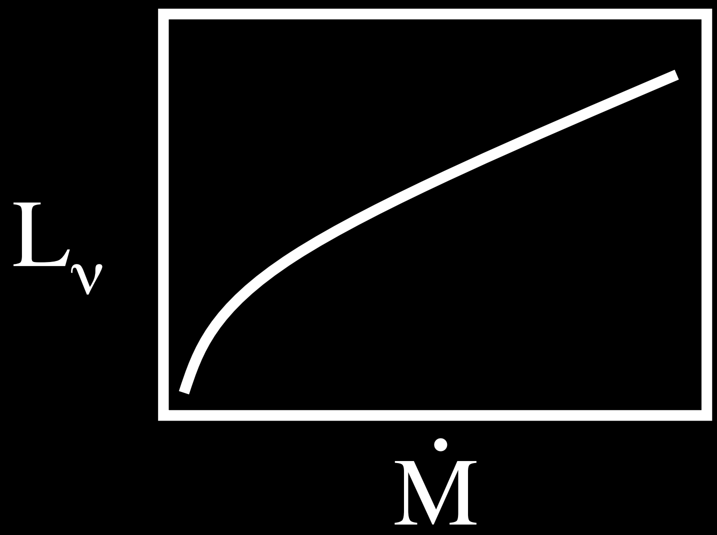
LS220
LS180
STOS
1D
2D
3.0
2.5
2.0
1.5
L_{ν_e} (10^{52} erg s^{-1})
0.15
0.20
0.25
0.30
0.35
$\dot{M}$ ($M_\odot$ s^{-1})

Couch 2012

2D & 3D critical luminosity lower than 1D

Turbulence plays an important role!

A Theoretical Framework for Successful Explosions

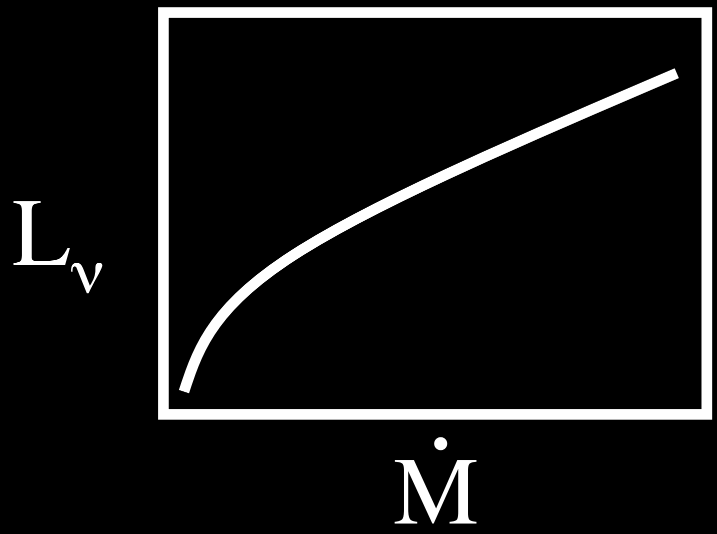


+

Turbulence Model

Murphy & Meakin 2011

A Theoretical Framework for Successful Explosions



+

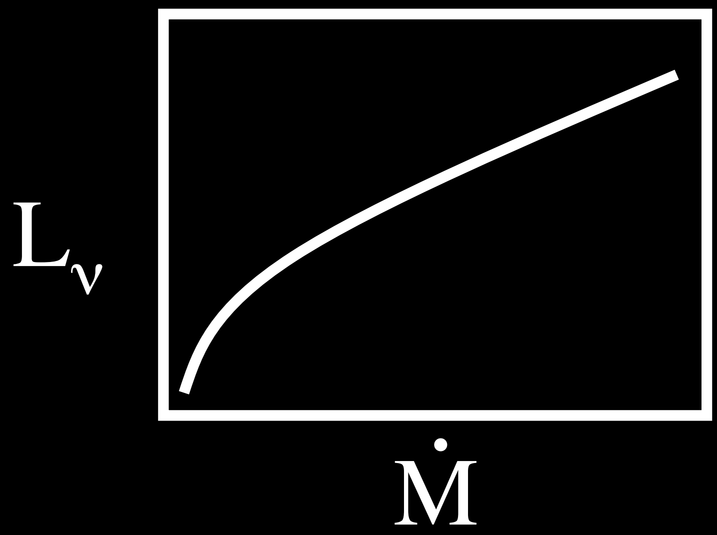
Turbulence Model

↕

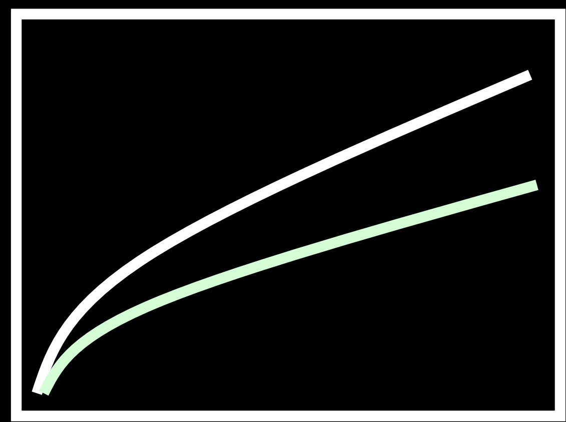
Calibrate with 3D Simulations

Murphy et al. 2012, in prep

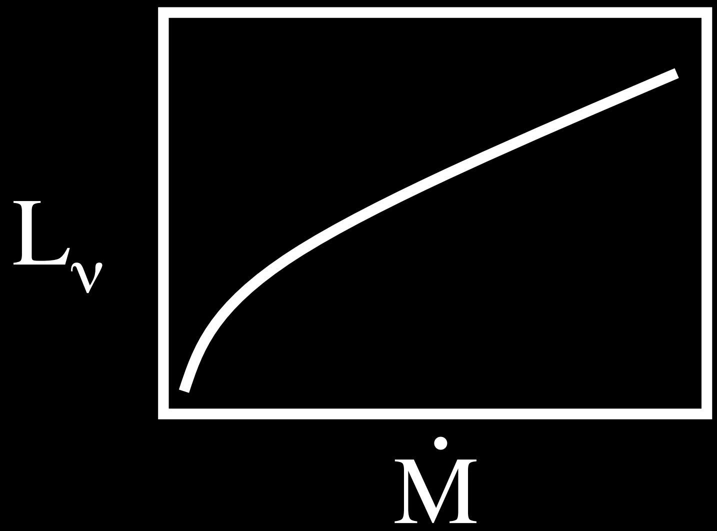
A Theoretical Framework for Successful Explosions



+ Turbulence Model



A Theoretical Framework for Successful Explosions



+

Turbulence Model

↓

1D Rad-hydro simulations

Realistic and quantitative explosions

Systematic exploration

What dominates the turbulence?
Convection, SASI... both?

Compare nonlinear theories for convection and SASI with post shock flow

SASI nonlinear theory

?

Compare nonlinear theories for convection and SASI with post shock flow

A Nonlinear Theory for Convection

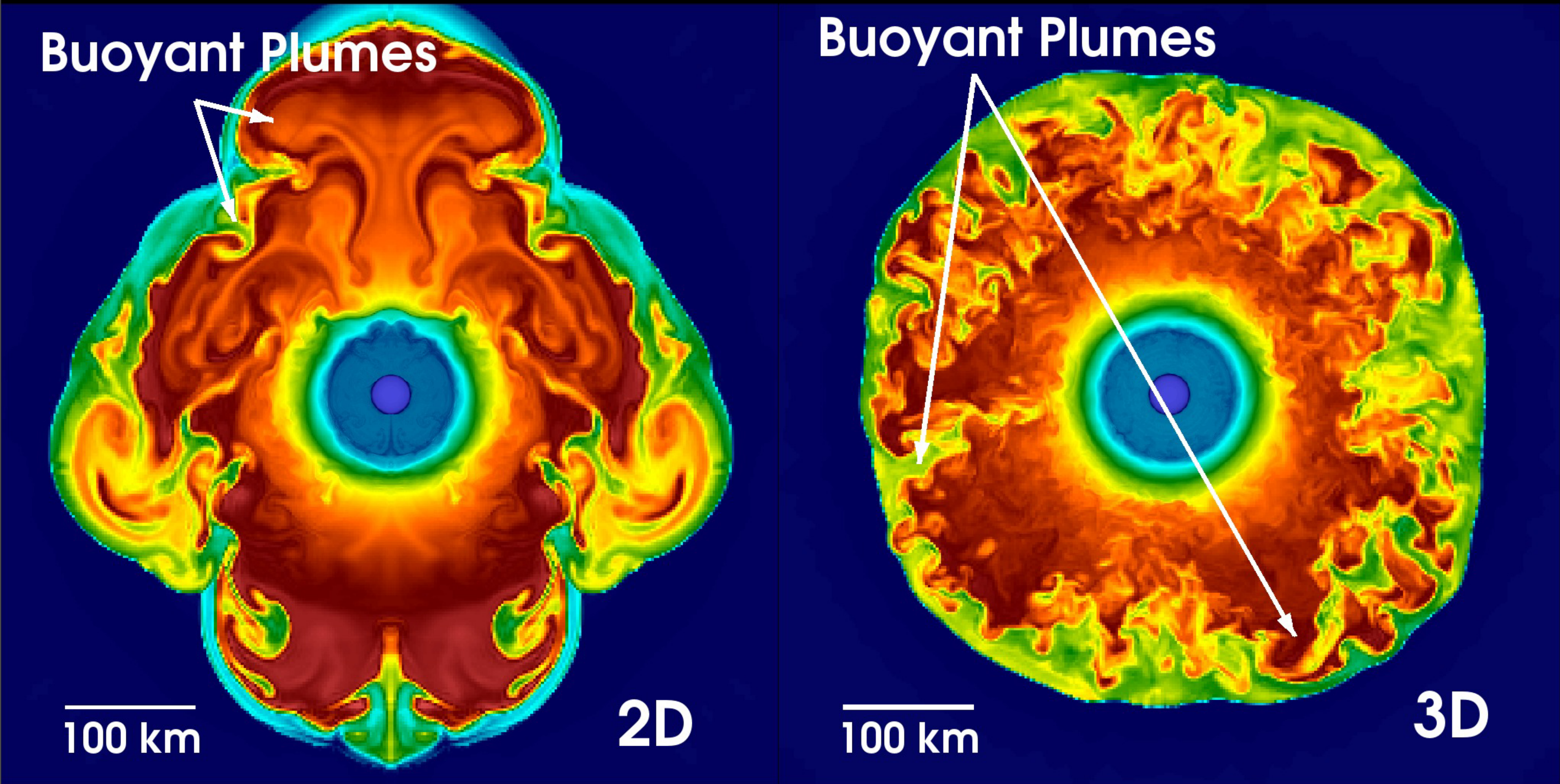
Murphy & Meakin 2012

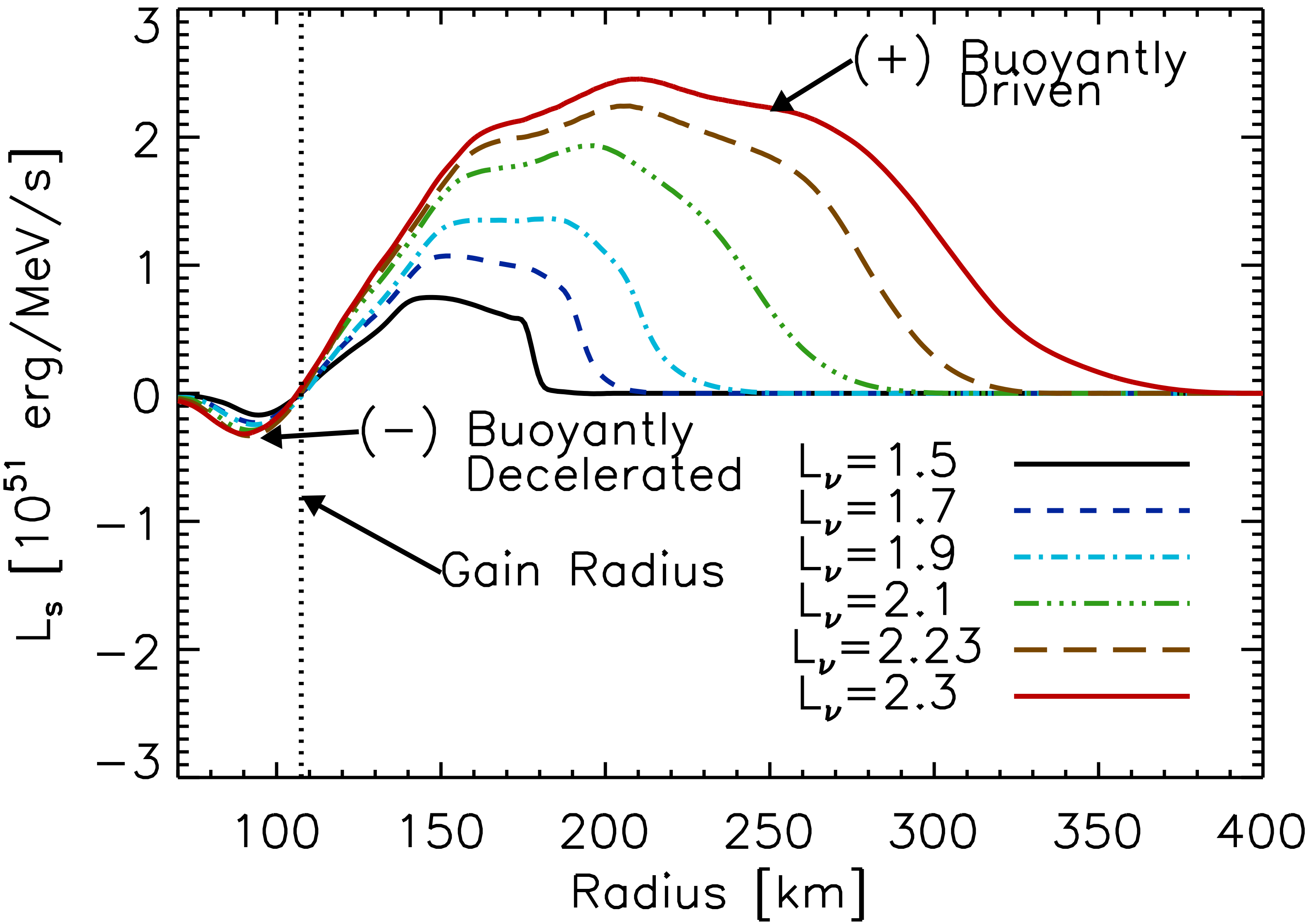
Compare nonlinear theories for convection and SASI with post shock flow

A Nonlinear Theory for Convection

Murphy & Meakin 2012

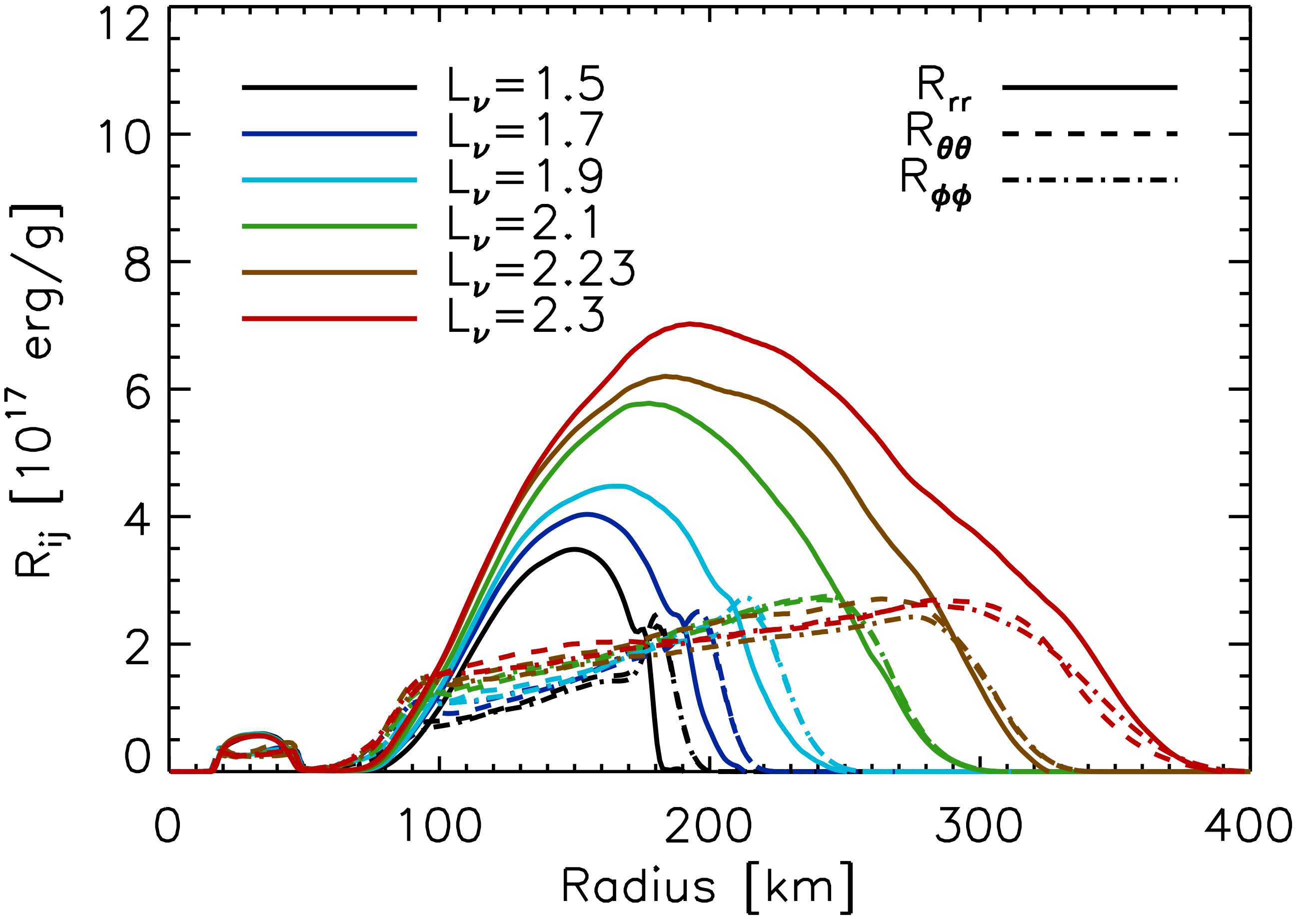
We can test this fledgling theory with 3D simulations


Buoyant Plumes
100 km
2D
Buoyant Plumes
100 km
3D



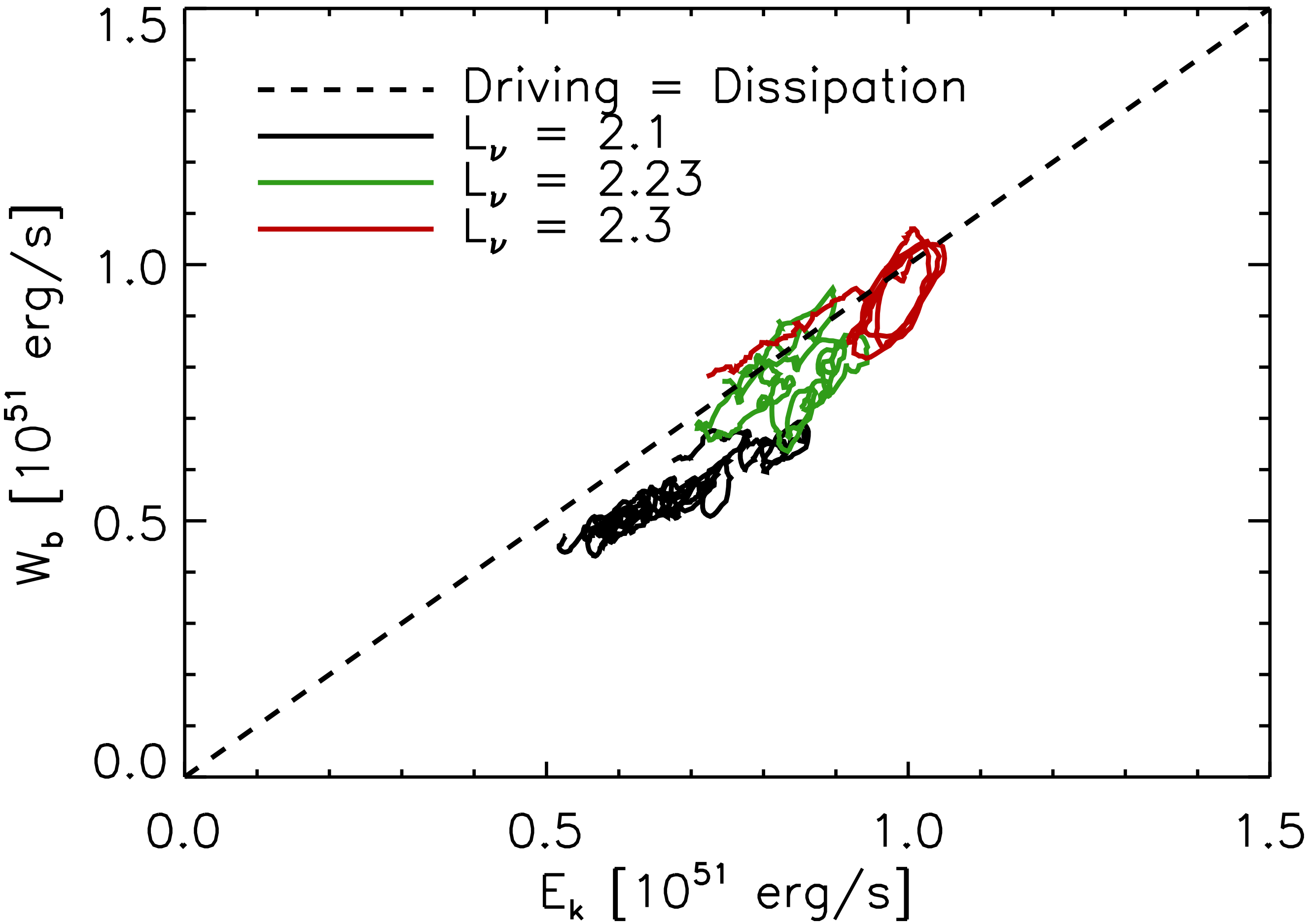
$$L_s = \langle \rho v' s' \rangle 4\pi r^2$$

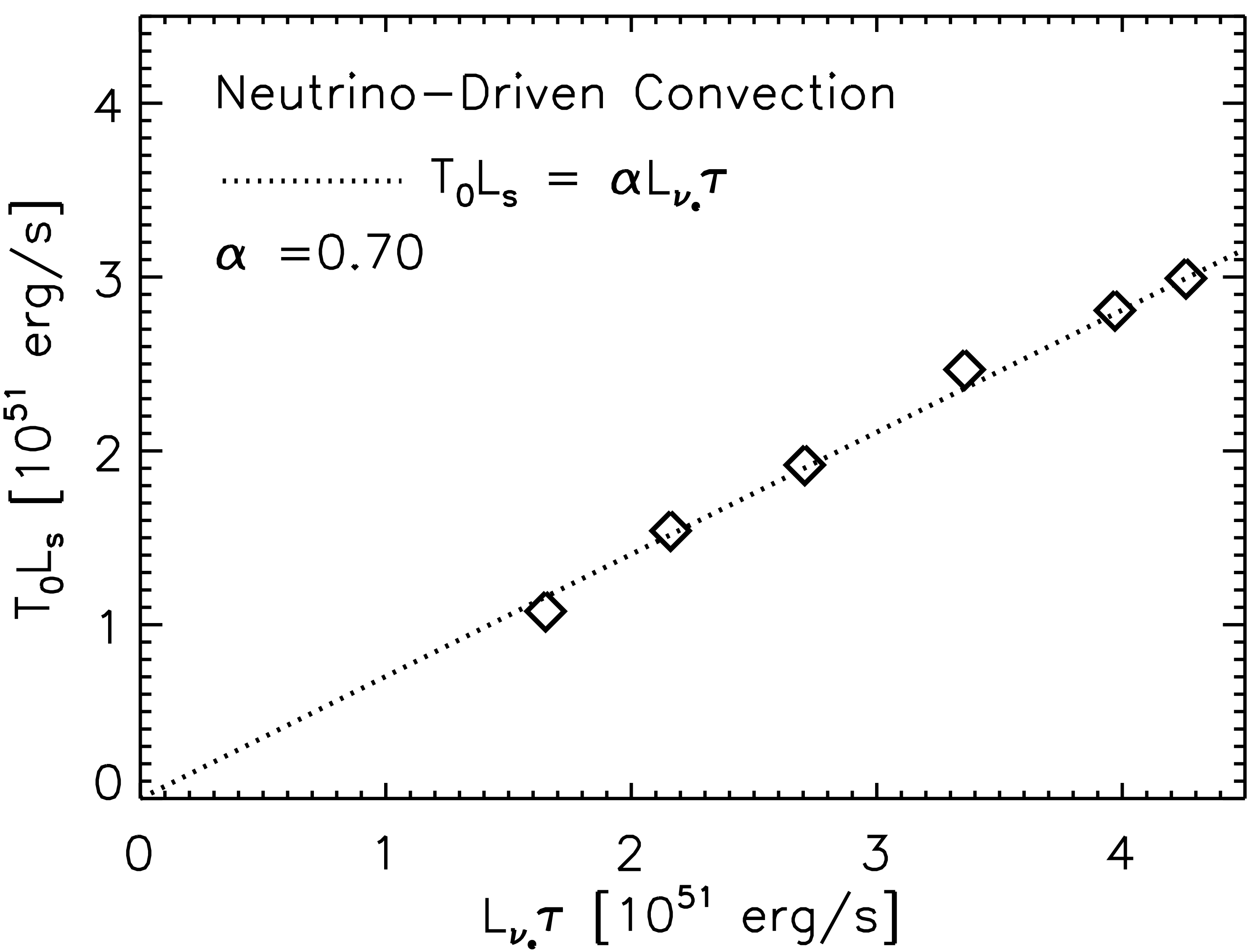
$$R_{ij} = \left\langle v'_i v'_j \right\rangle$$



$$R_{rr} \approx R_{\theta\theta} + R_{\phi\phi} \qquad R_{\theta\theta} \approx R_{\phi\phi}$$

$$\int \langle \rho' v' \rangle \, g \, dV = \int \frac{\rho (v_r')^3}{L} dV$$





Neutrino-Driven Convection
$T_0L_s = \alpha L_{\nu_e}\tau$
α =0.70
T_0L_s [10^{51} erg/s]
$L_{\nu_e}\tau$ [10^{51} erg/s]
0
1
2
3
4

Nonlinear Convection is Consistent with Post Shock Flow

1. Consistent buoyancy flux profile
2. Consistent Reynolds stresses
3. Buoyant driving balances dissipation
4. Analytic scaling between buoyant flux and neutrino driving

Nonlinear Convection is Consistent with Post Shock Flow

But what about the SASI?

A theory for neutrino-driven explosions

A turbulence model for CCSNe

Post shock flow is consistent with nonlinear convection theory