Explosions of Massive Stars

by
Jeremiah W. Murphy
(Florida State University)

A Theory for Core-Collapse Supernova Explosions

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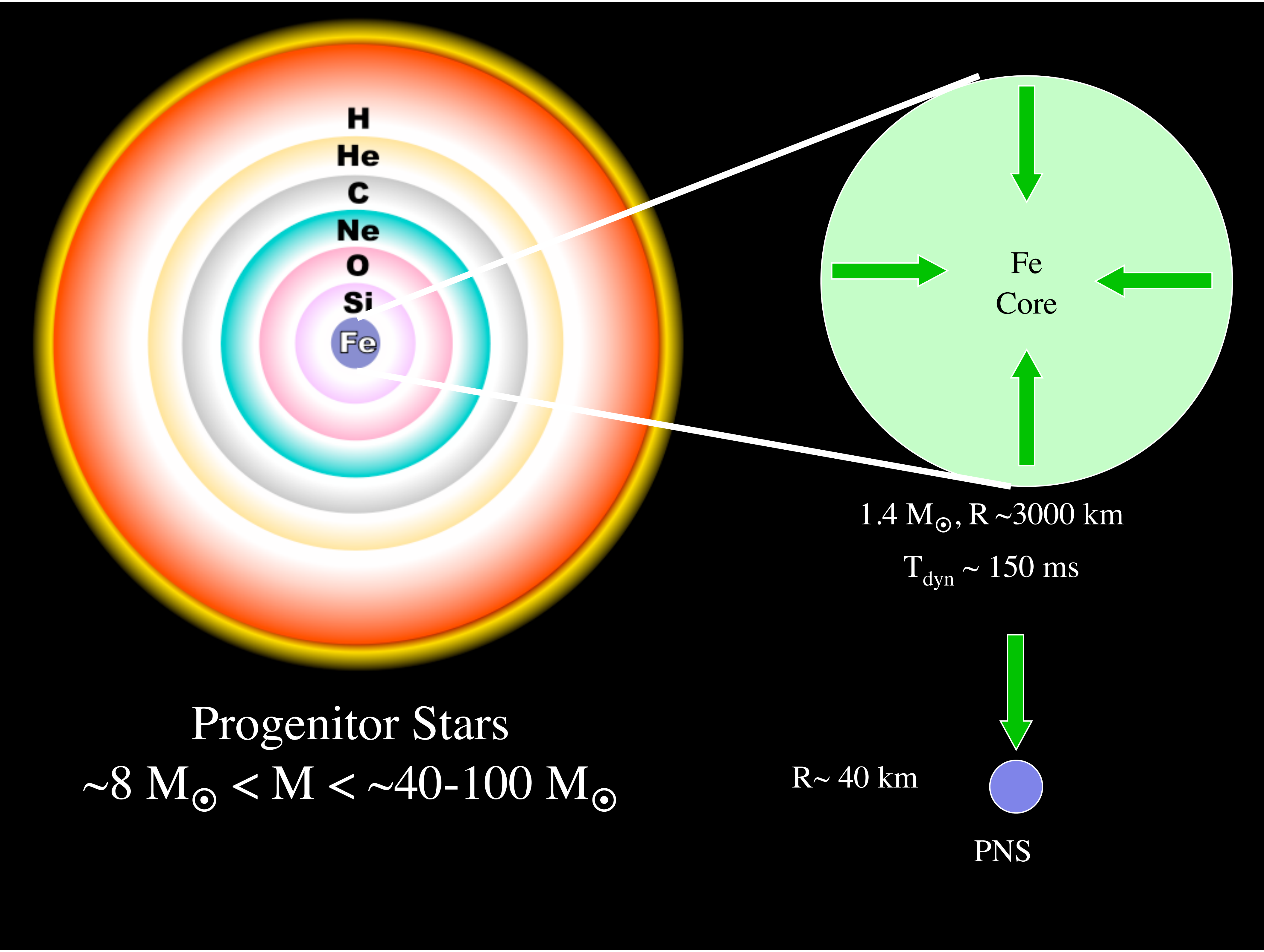
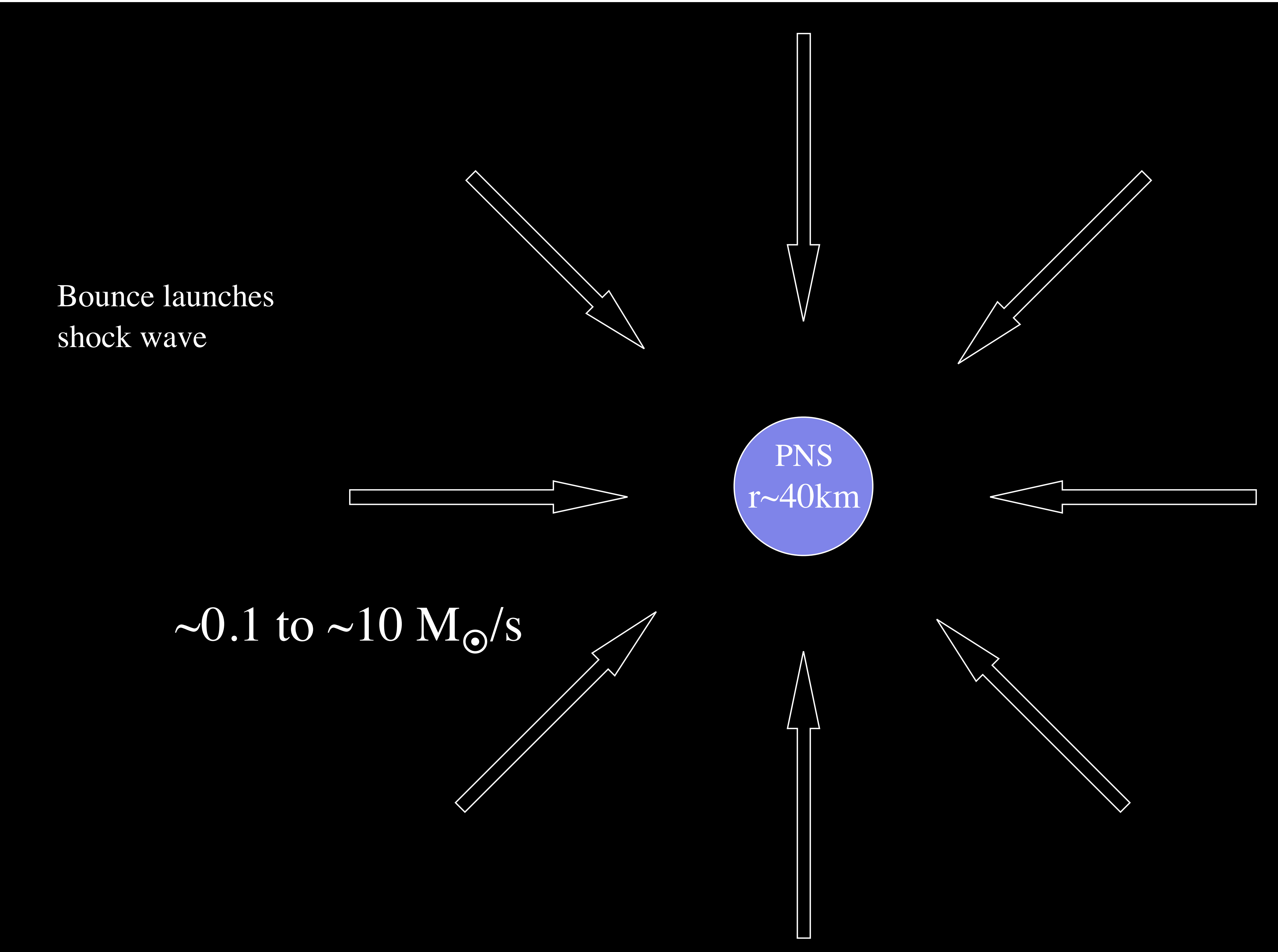
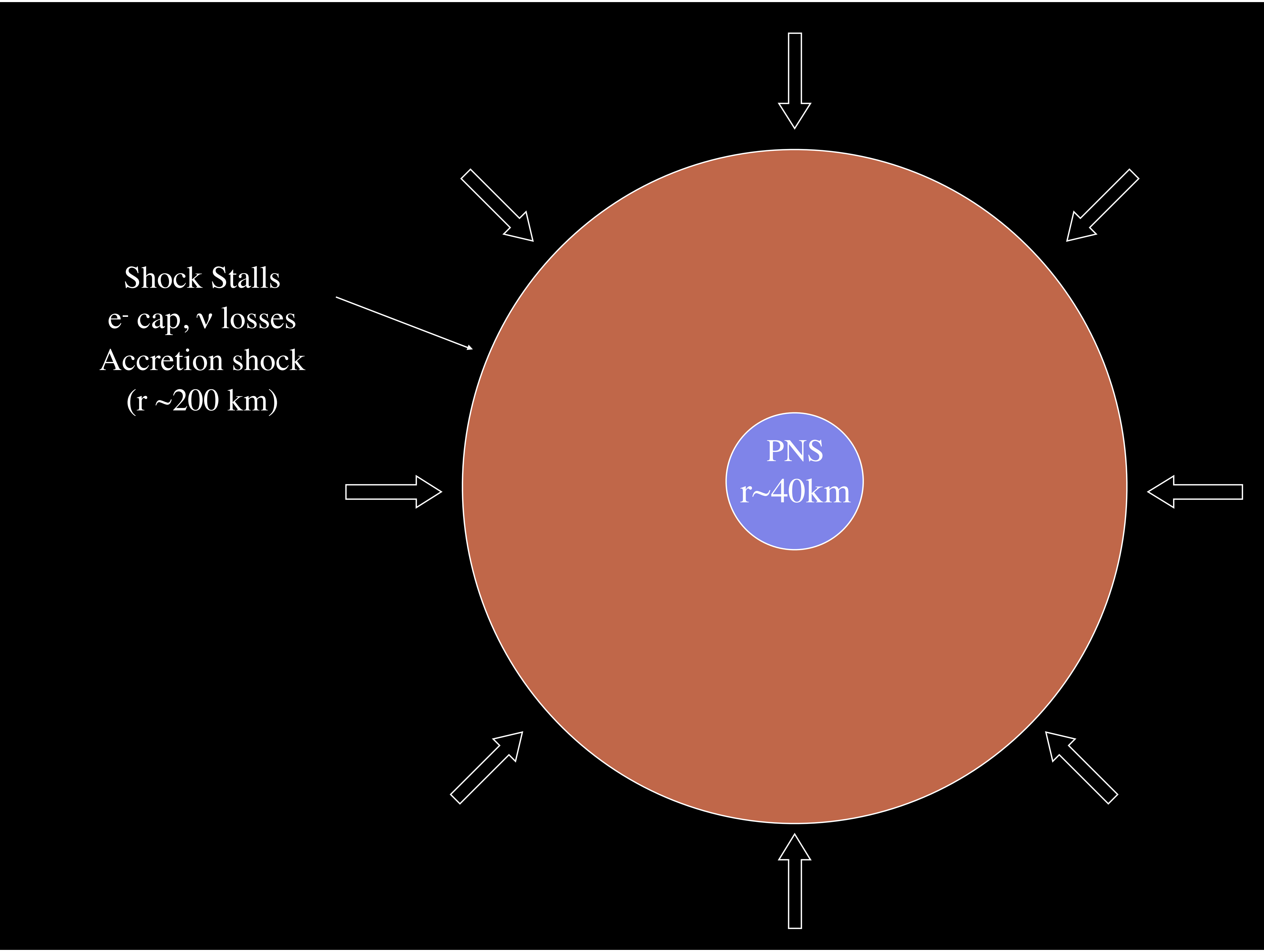
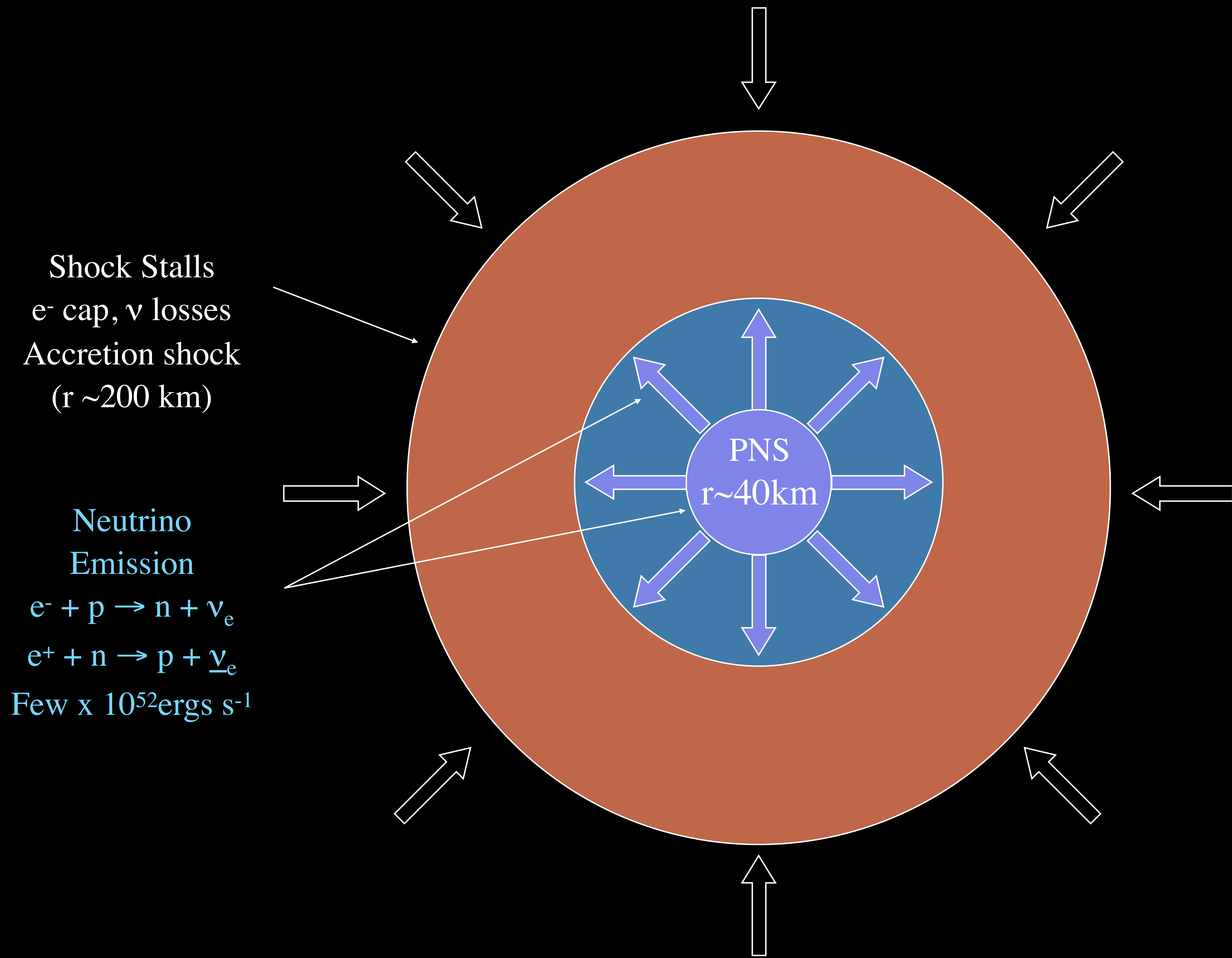
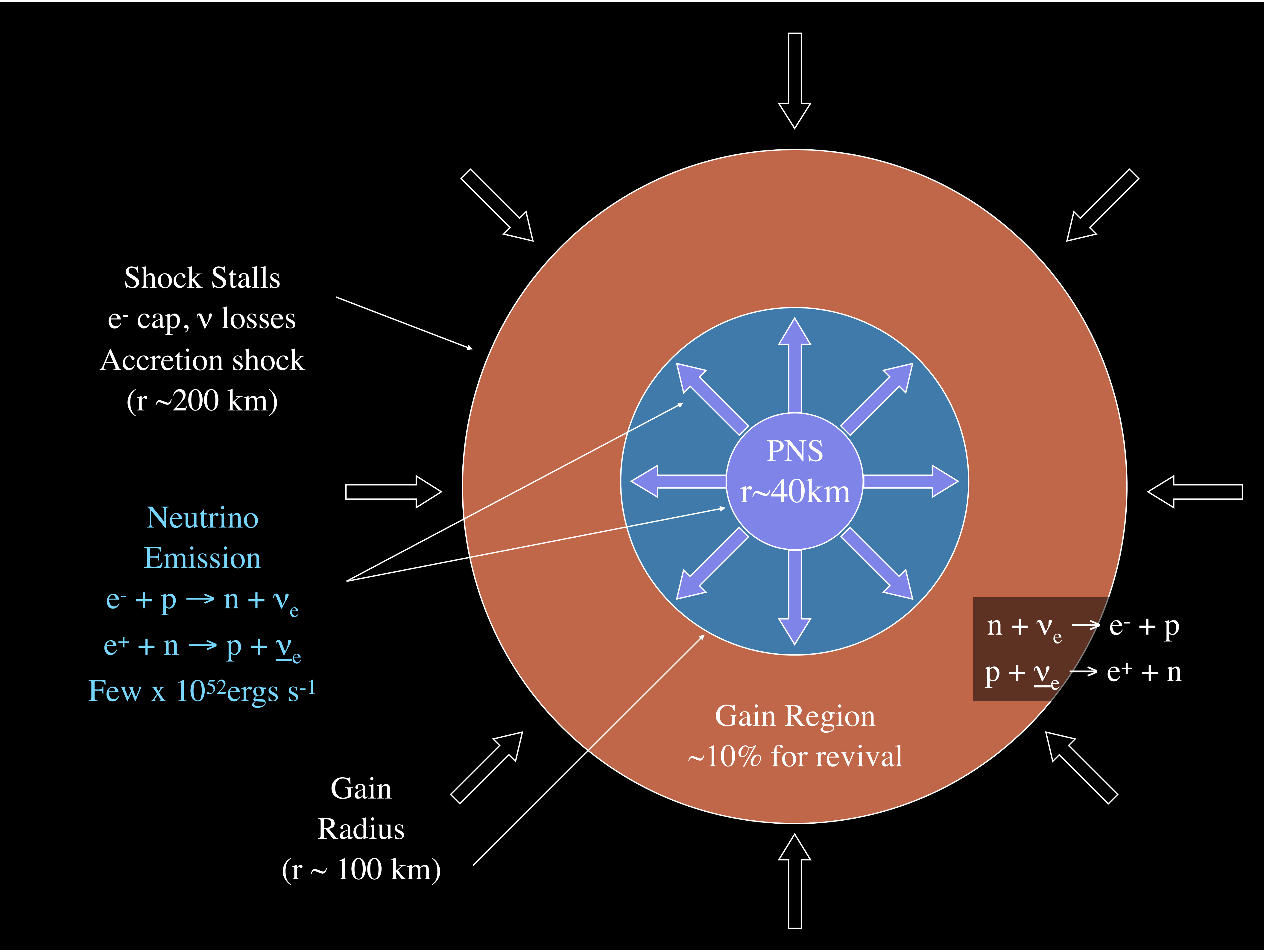
What is the mechanism of explosion?


H
He
C
Ne
O
Si
Fe
Fe
Core
1.4 $M_\odot$, R ~3000 km
T_{dyn} ~ 150 ms
R~ 40 km
PNS
Progenitor Stars
~8 $M_\odot$ < M < ~40-100 $M_\odot$

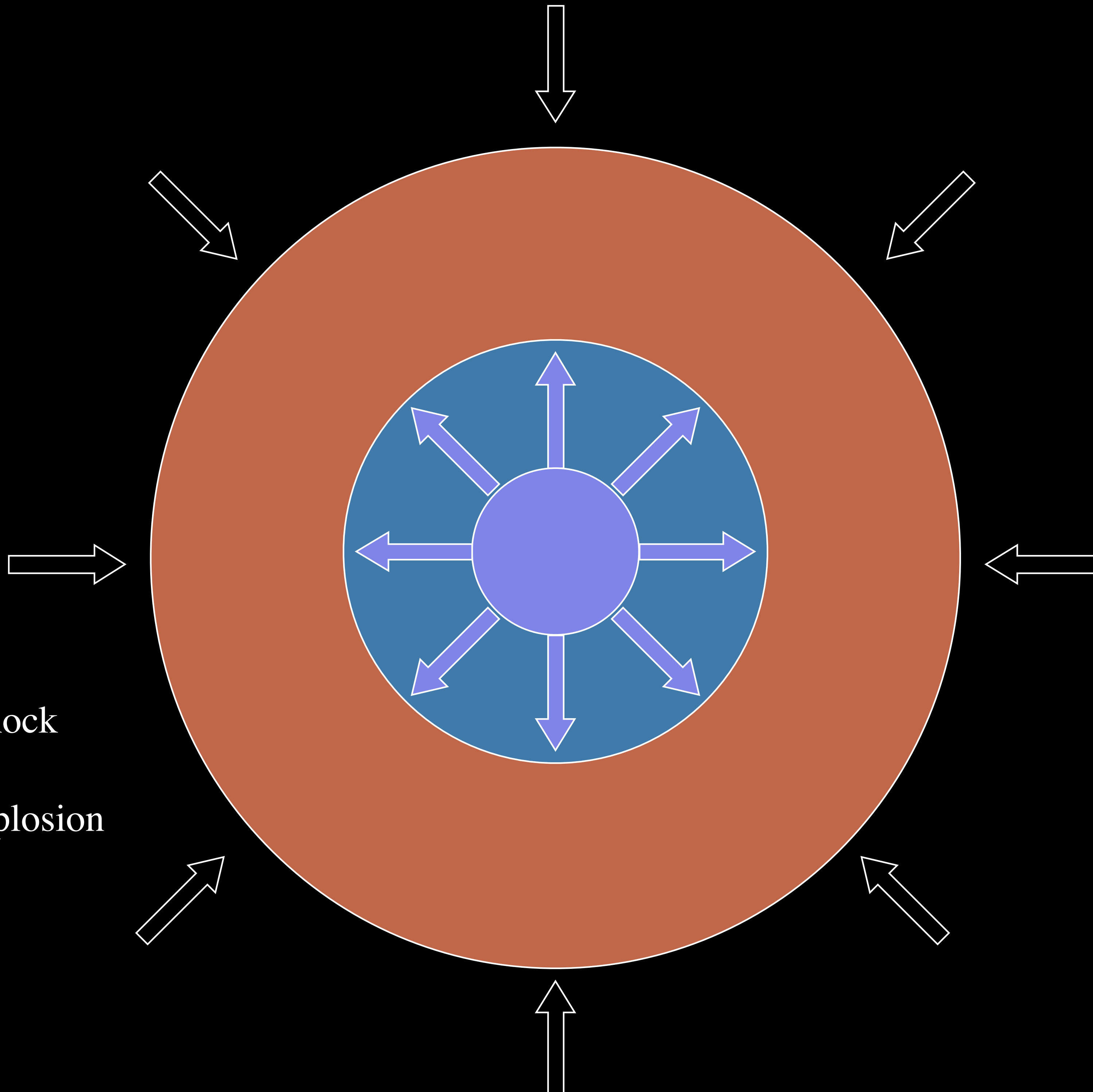

Bounce launches
shock wave
~0.1 to ~10 M⊙/s
PNS
r~40km


Shock Stalls
e^- cap, ν losses
Accretion shock
(r ~200 km)
PNS
r~40km


Shock Stalls
e^- cap, ν losses
Accretion shock
(r ~200 km)
Neutrino
Emission
$e^- + p \rightarrow n + \nu_e$
$e^+ + n \rightarrow p + \underline{\nu}_e$
Few x 10^{52}ergs s^{-1}
PNS
r~40km



Shock Stalls
e^- cap, ν losses
Accretion shock
(r ~200 km)
PNS
r~40km
Neutrino
Emission
$e^- + p \rightarrow n + \nu_e$
$e^+ + n \rightarrow p + \underline{\nu}_e$
Few x 10^{52}ergs s^{-1}
$n + \nu_e \rightarrow e^- + p$
$p + \underline{\nu}_e \rightarrow e^+ + n$
Gain Region
~10% for revival
Gain
Radius
(r ~ 100 km)



Subsonic below shock

Global solution to explosion

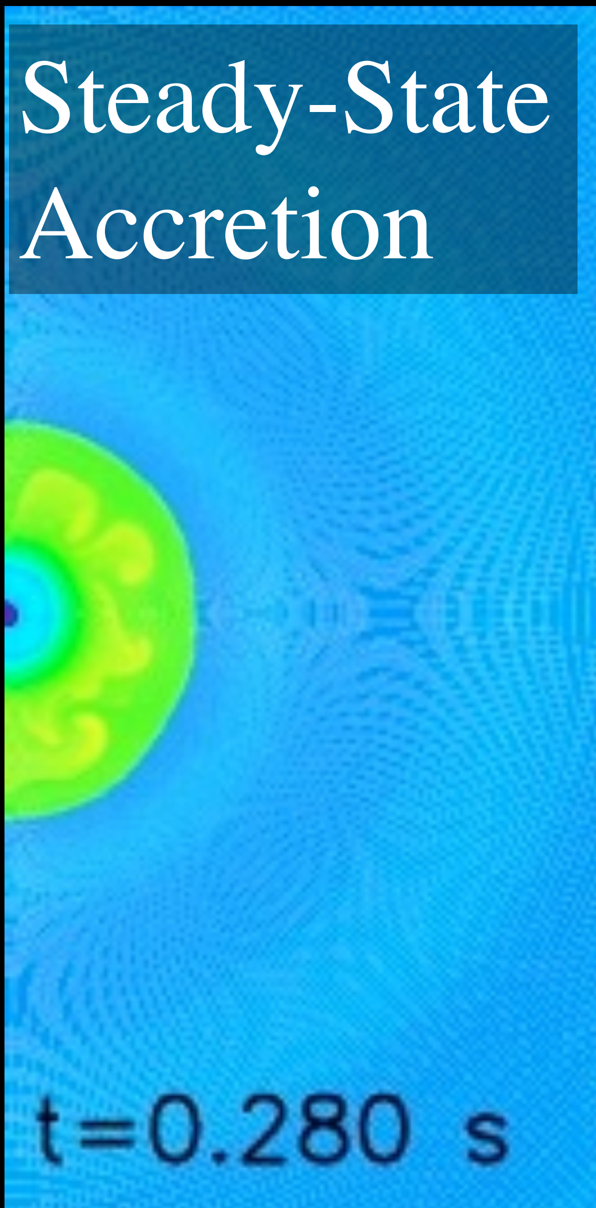
1D simulations (Rad-hydro)

Wilson '85
Bethe & Wilson '85
} Neutrino mechanism suggested

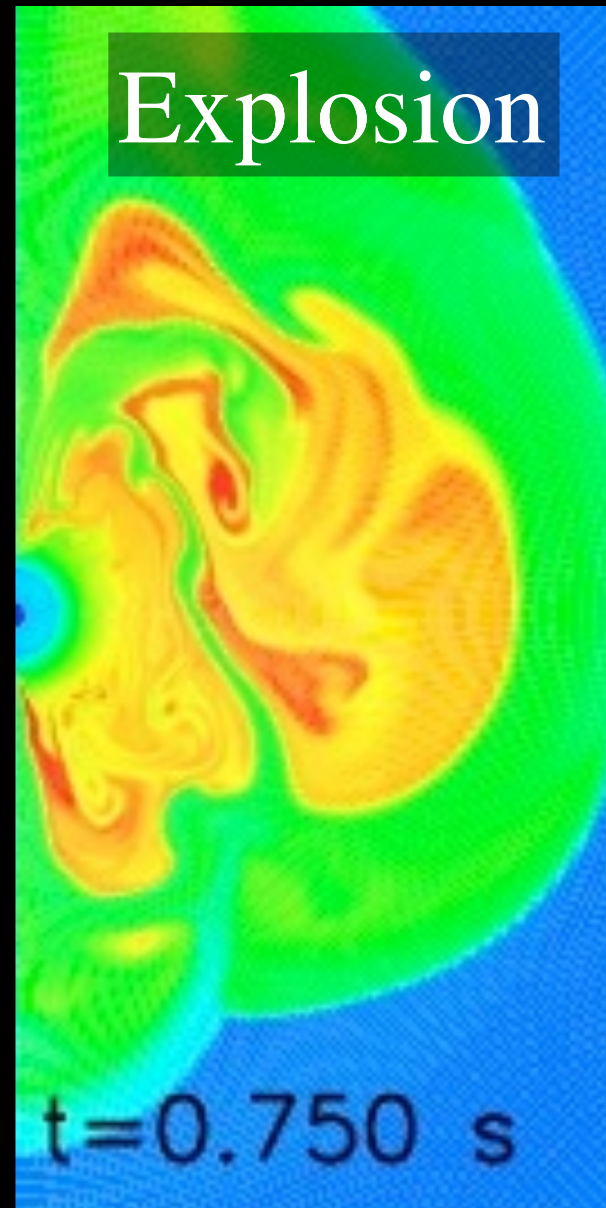
Liebendoerfer et al. '01
Rampp & Janka '02
Buras et al. '03
Thompson et al. '03
Liebendoer et al. '05
Kitaura et al. '06
Burrows et al. '07
} No Explosions
(Except lowest masses)

An Important Unsolved Astrophysical Problem?

Fundamental Question of Core-Collapse Theory

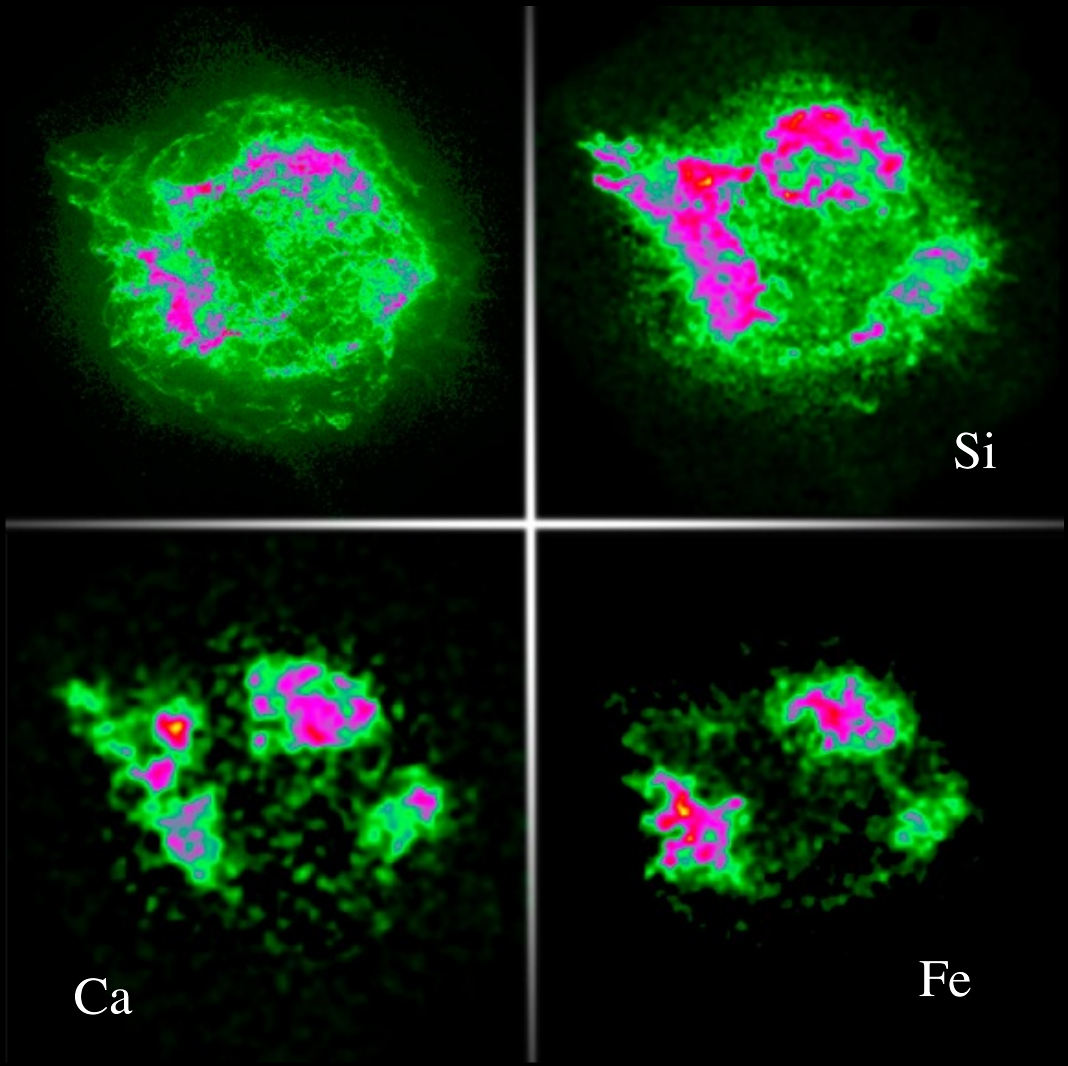


?



Important Observational Clues

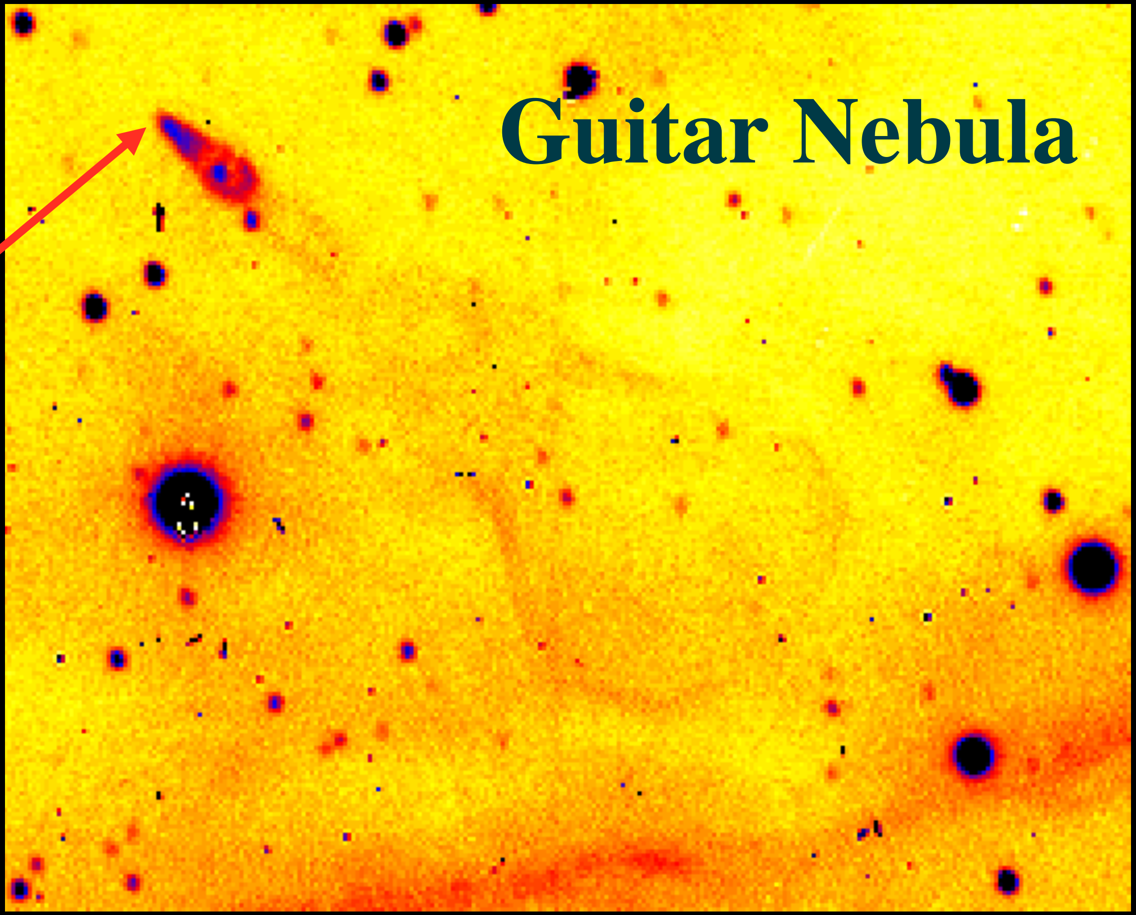
Asymmetry in Ejecta



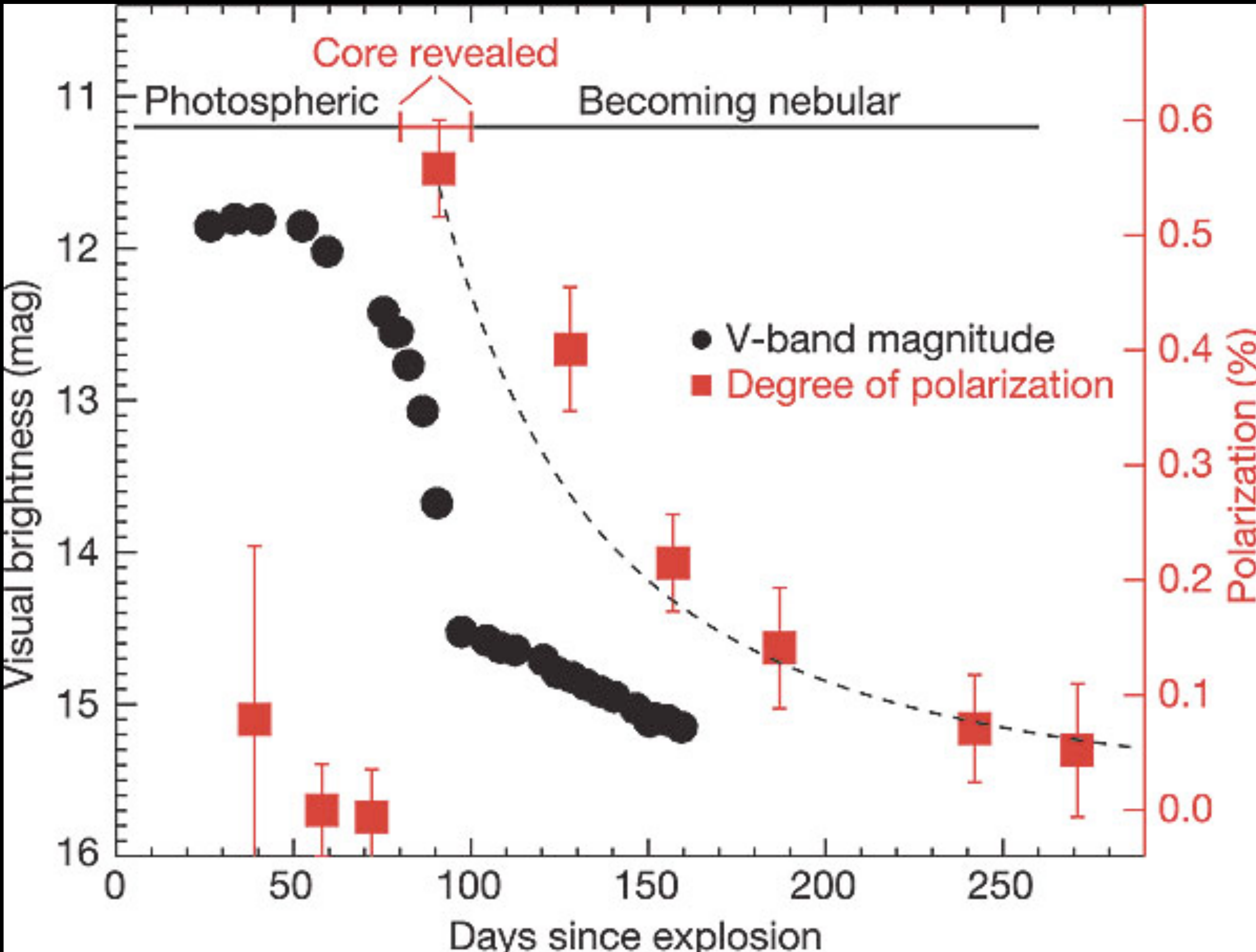
Cas A SN Remnant: Chandra

Pulsar Recoil: A Generic Feature

Pulsar Kicks:
Pulsar B2224+65
and Bow Shock
$V \geq 1000$ km s^{-1}



Cordes, Romani, Lundgren '93



Leonard et al. '06, Nature

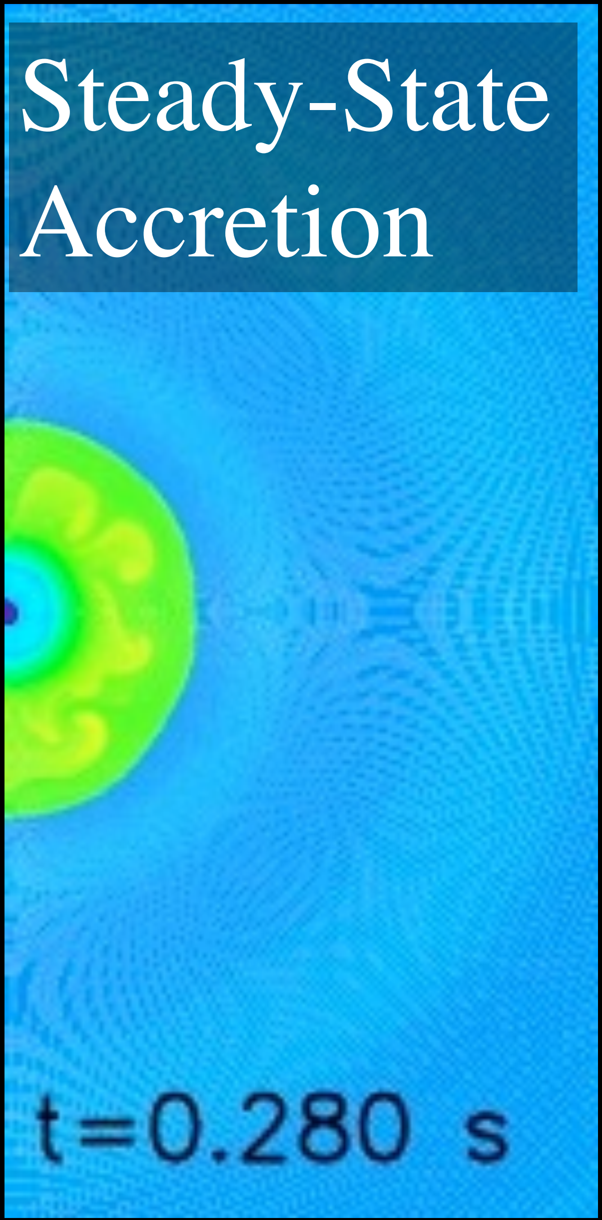
Asymmetry in SN 1987A

Supernova 1987A • November 28, 2003
Hubble Space Telescope • ACS

NASA and R. Kirshner (Harvard-Smithsonian Center for Astrophysics) STScI-PRC04-09a

- Early X- and y- ray detection
  Dotani et al. ‘87; Matz et al. ‘88
- Mixing Pinto & Woosley ‘88
- Infrared, gamma-ray, and Hydrogen lines: Erickson et al. ‘88; Barthelmy et al. ‘89; Hoflich ‘88
- Early Polarization
  Jeffery et al. ‘91
- Supernova ejecta

Fundamental Question of Core-Collapse Theory



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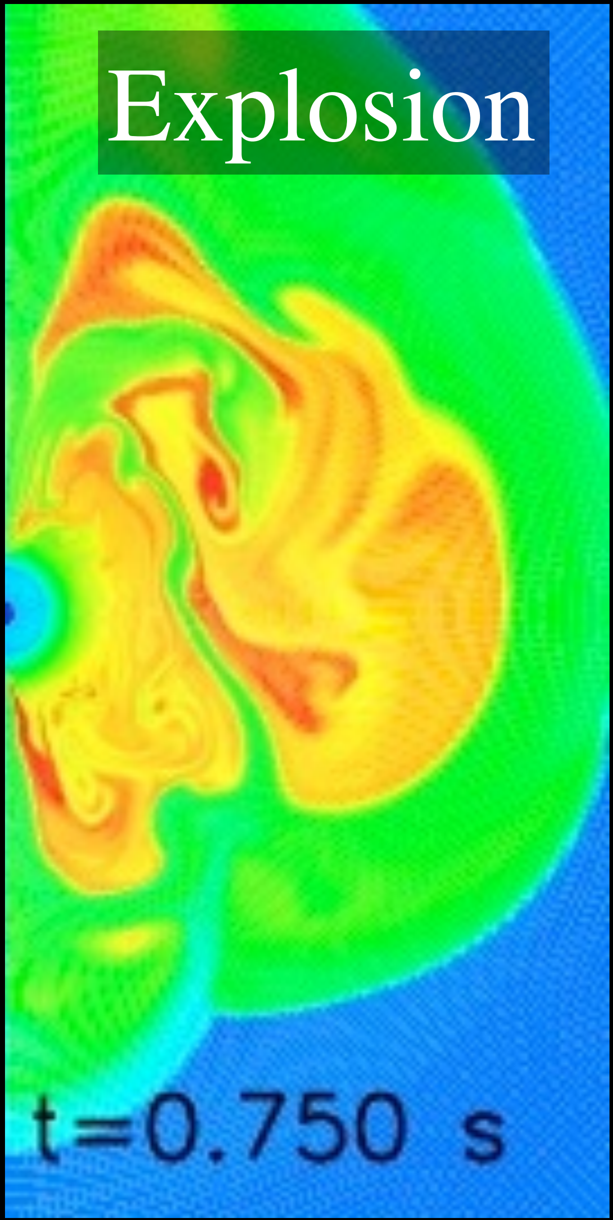
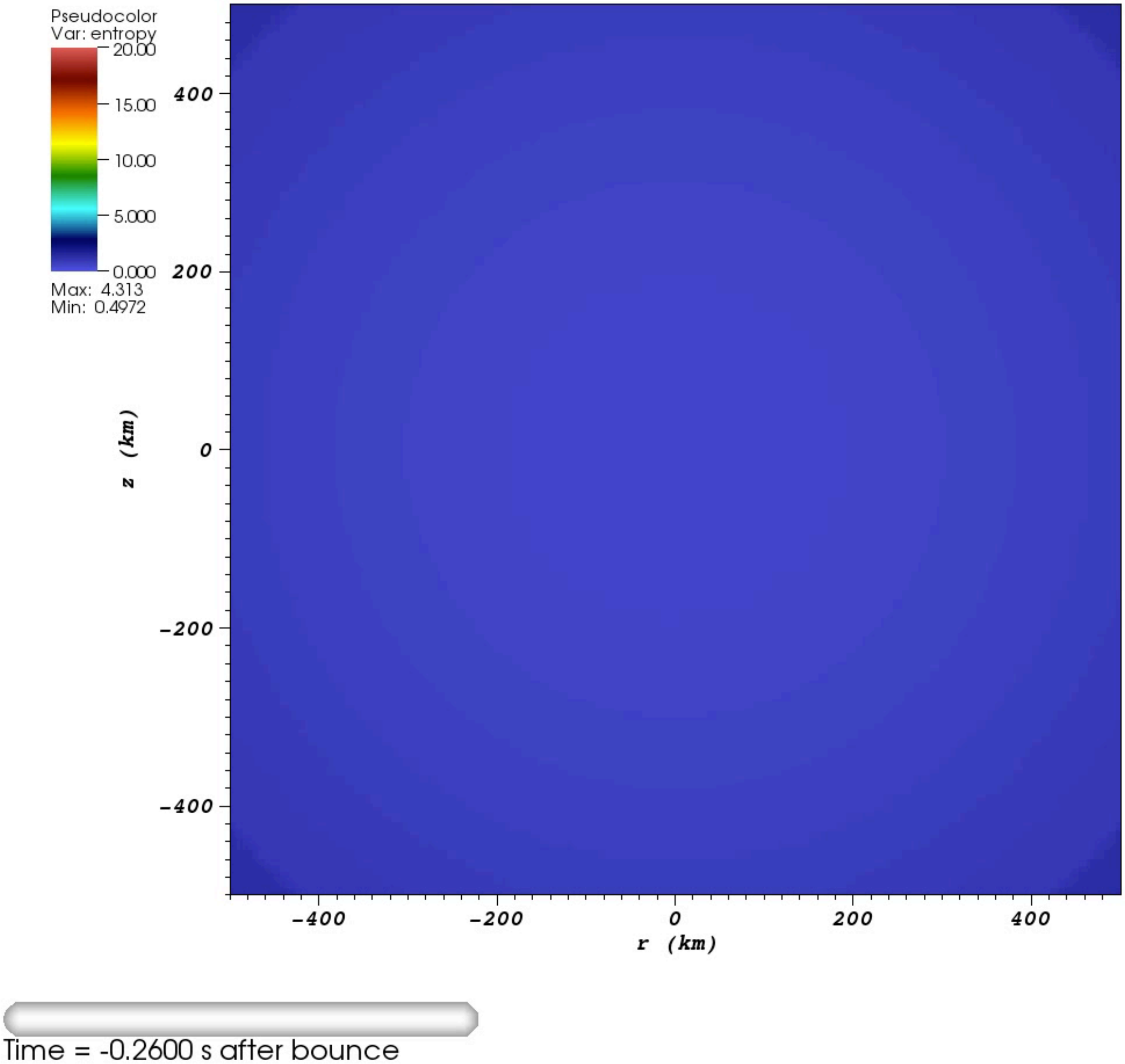
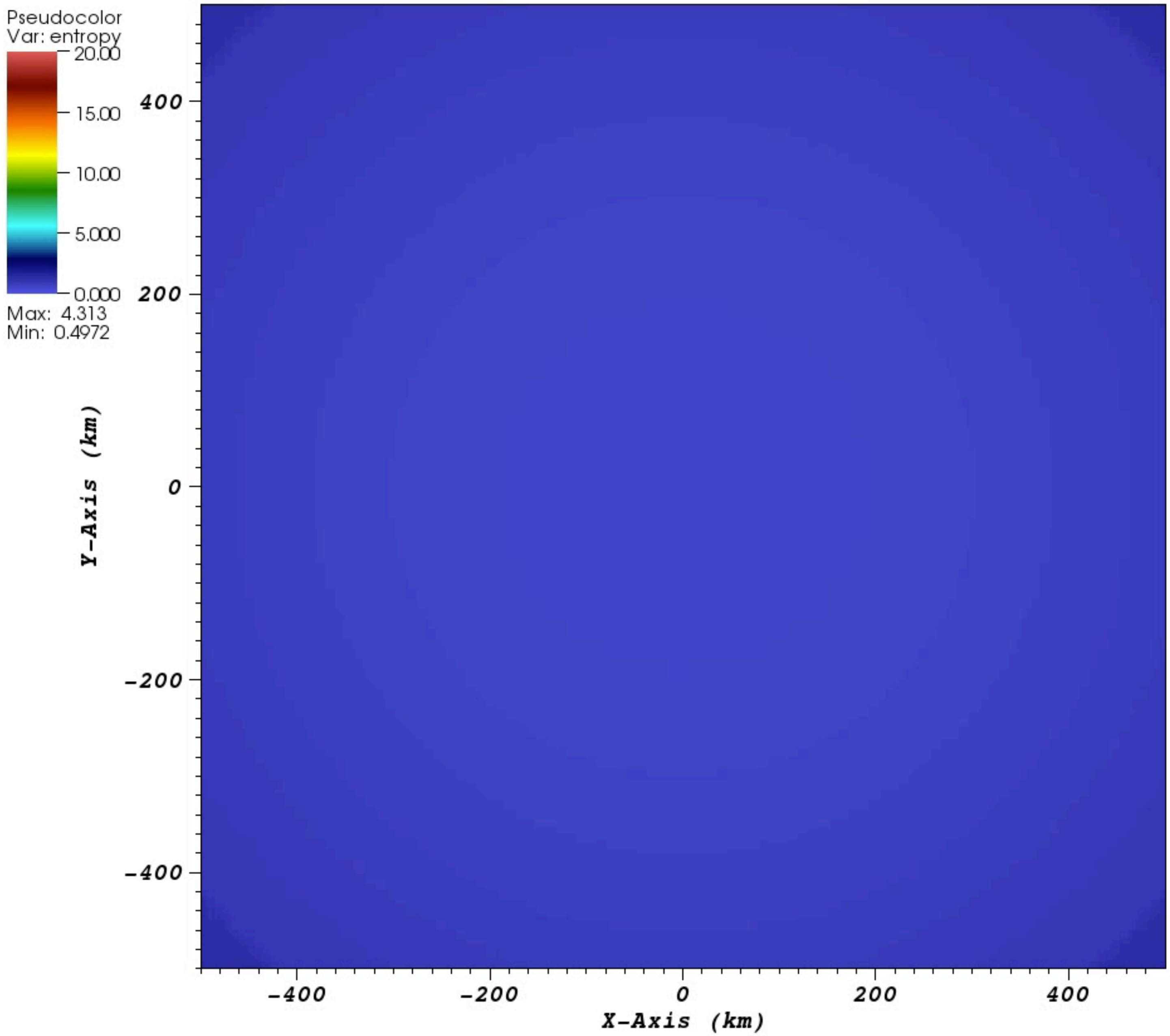


Relax 1D assumption?


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



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?

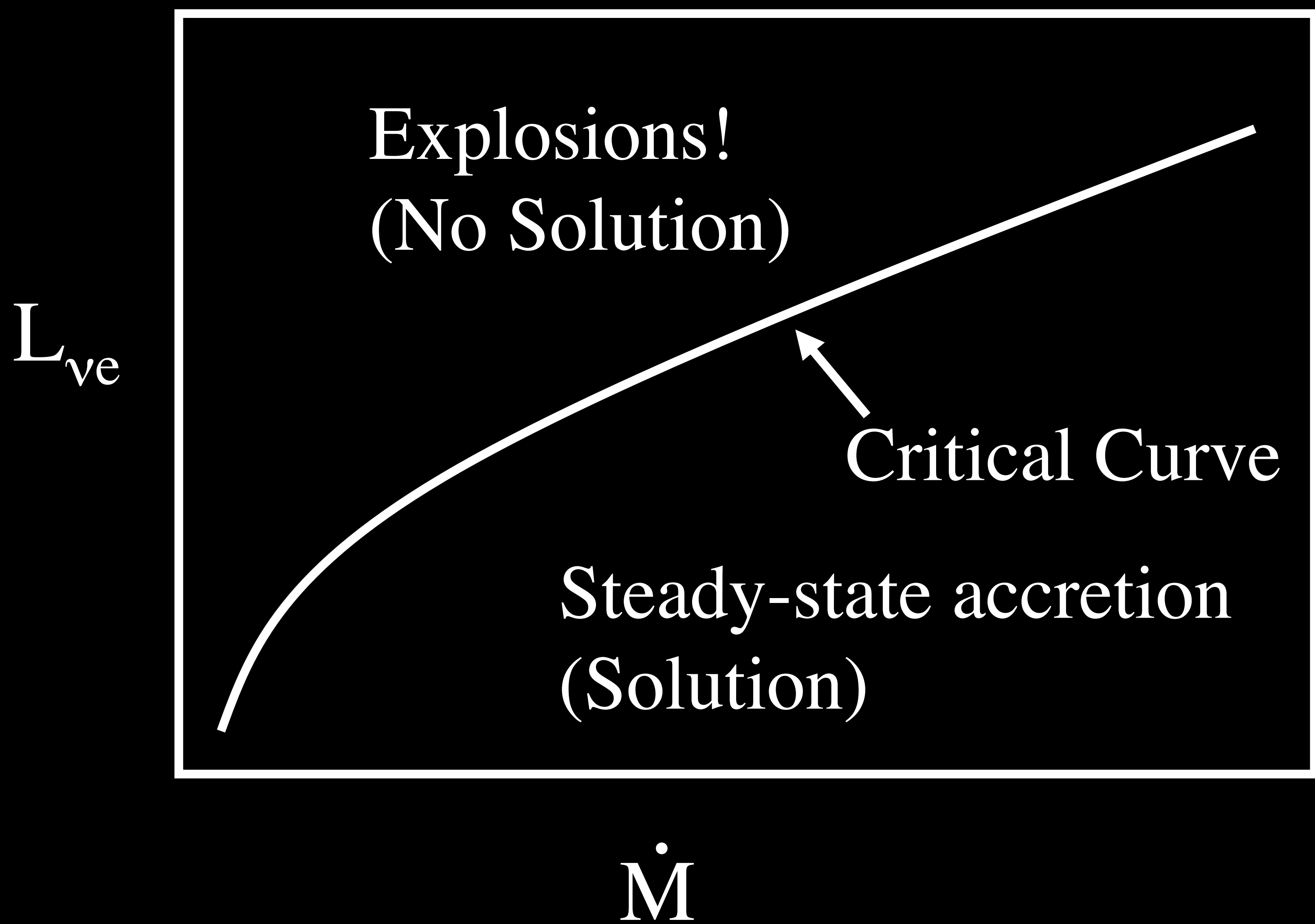
Why is it easier to explode in 2D compared to 1D?

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)

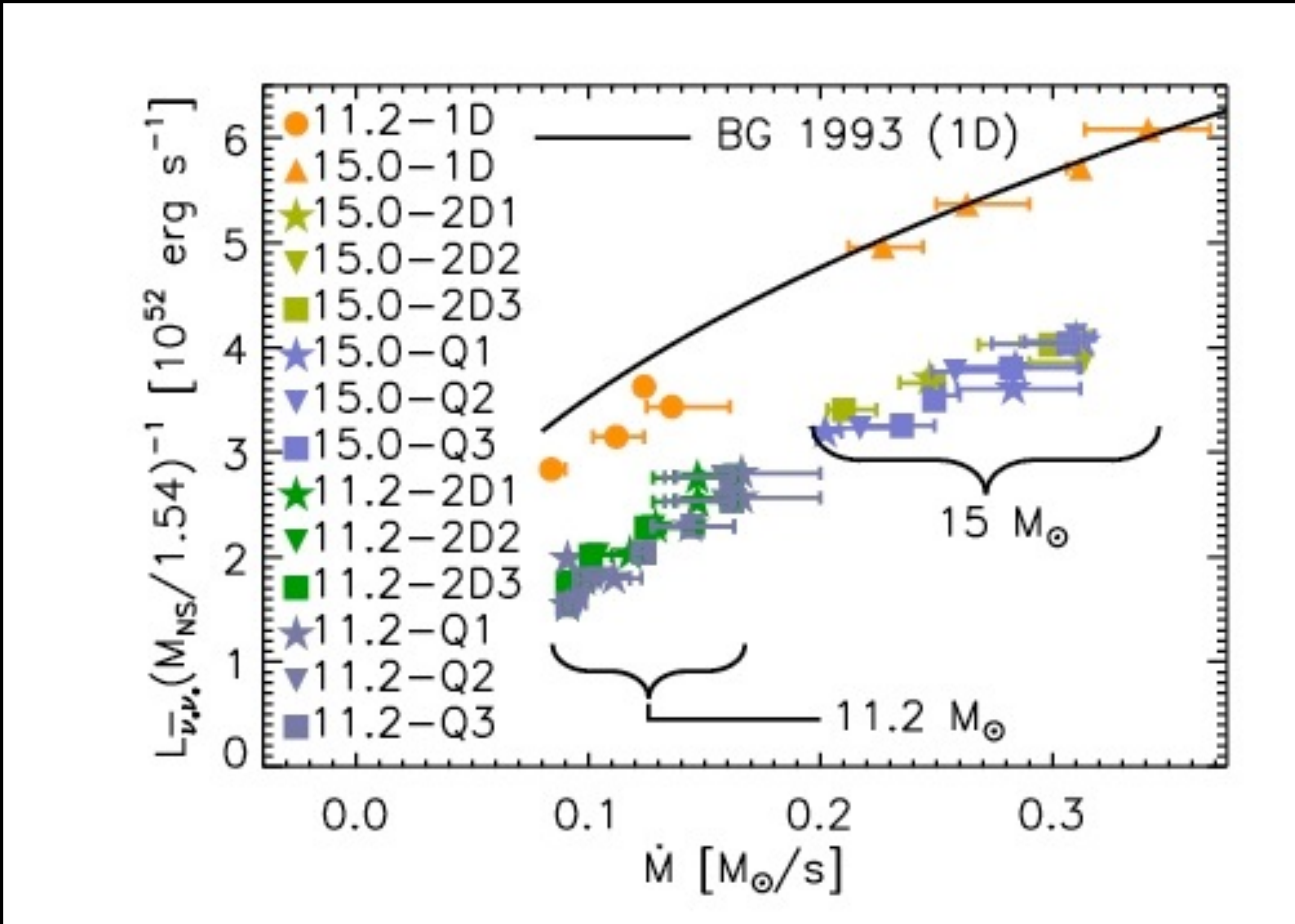


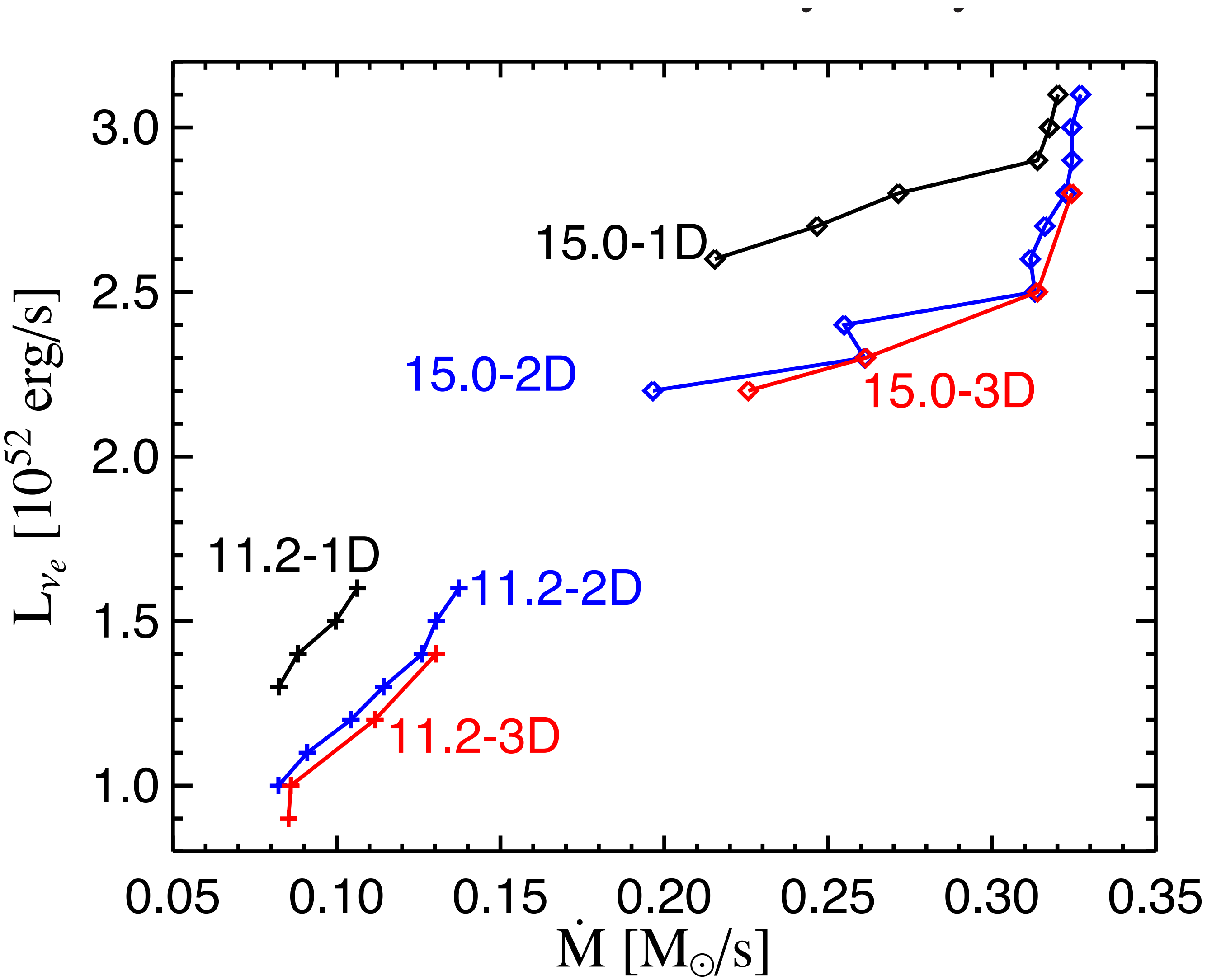
Is a critical luminosity relevant in hydrodynamic simulations?

- 1D
- 2D Convection and SASI?

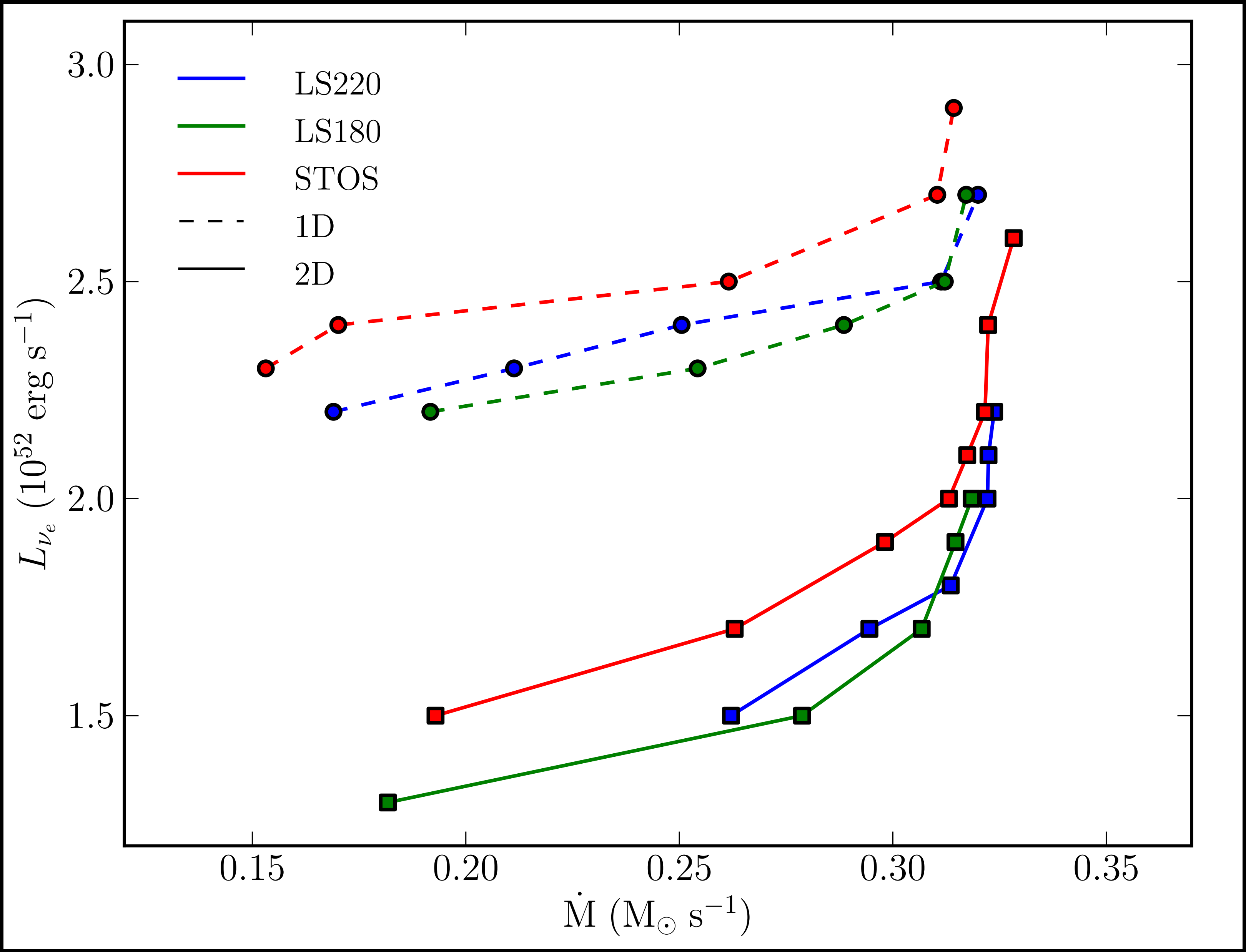
How do the critical luminosities differ between 1D and 2D?

Murphy & Burrows ‘08





Hanke et al 2011



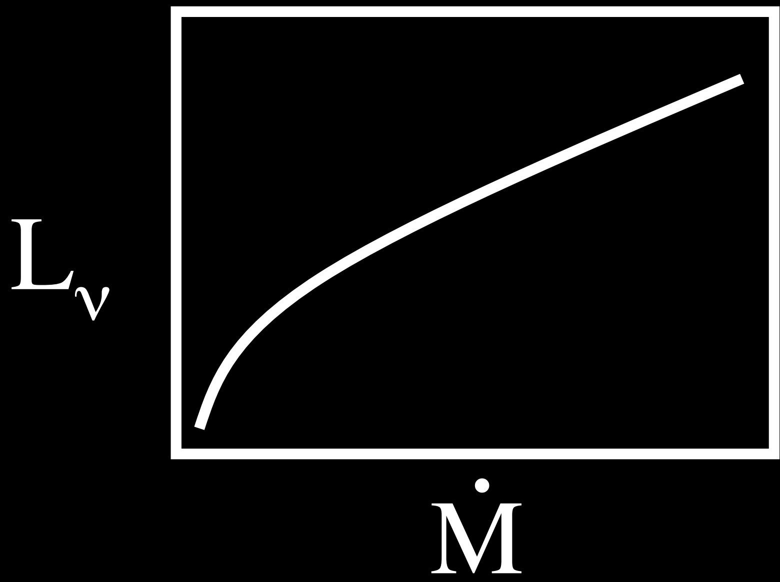
LS220
LS180
STOS
1D
2D
3.0
2.5
2.0
1.5
0.15
0.20
0.25
0.30
0.35
L_{ν_e} (10^{52} erg s^{-1})
$\dot{M}$ ($M_\odot$ s^{-1})

Couch 2012

2D & 3D critical luminosity lower than 1D

Turbulence plays an important role!

A Theoretical Framework for Successful Explosions

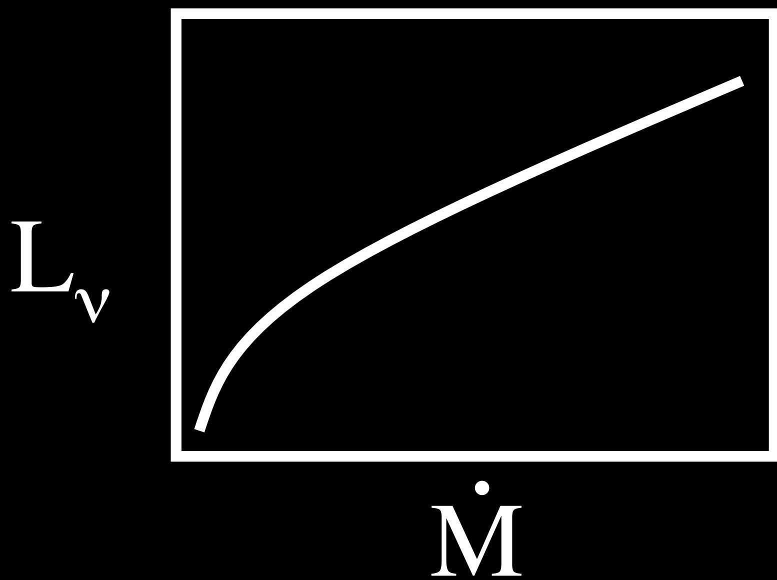


+

Turbulence Model

Murphy & Meakin 2011

A Theoretical Framework for Successful Explosions



+

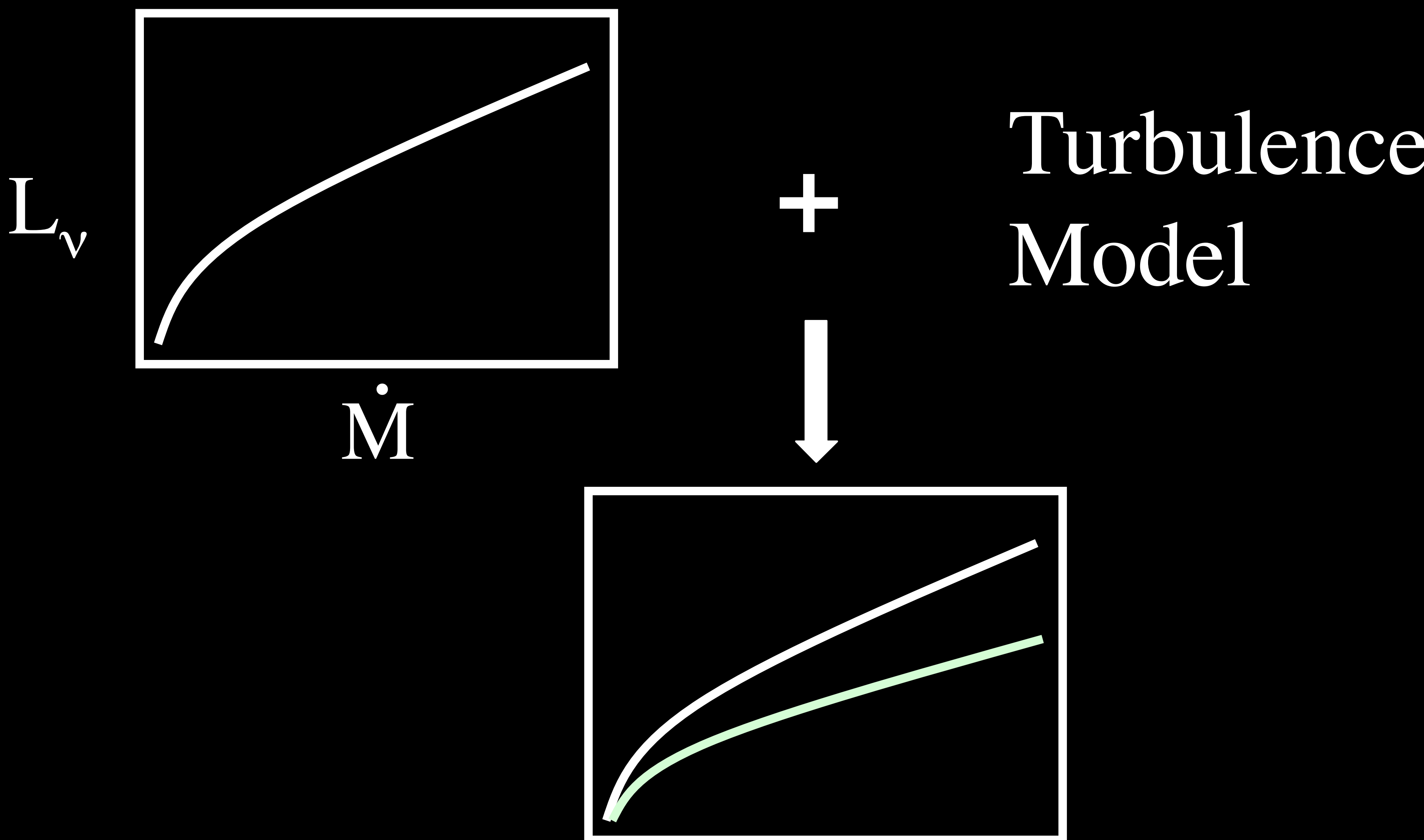
Turbulence Model

↕

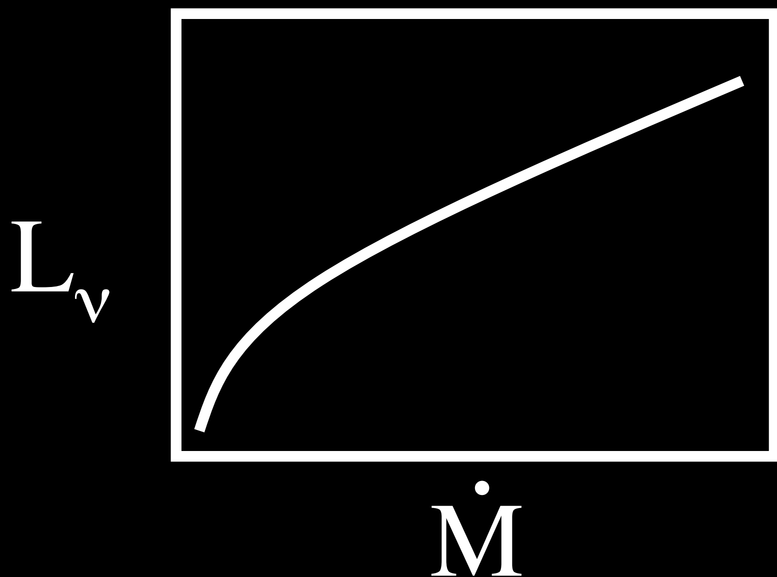
Calibrate with 3D Simulations

Murphy et al. 2013, in prep

A Theoretical Framework for Successful Explosions



A Theoretical Framework for Successful Explosions



+ Turbulence Model

↓

1D Rad-hydro simulations

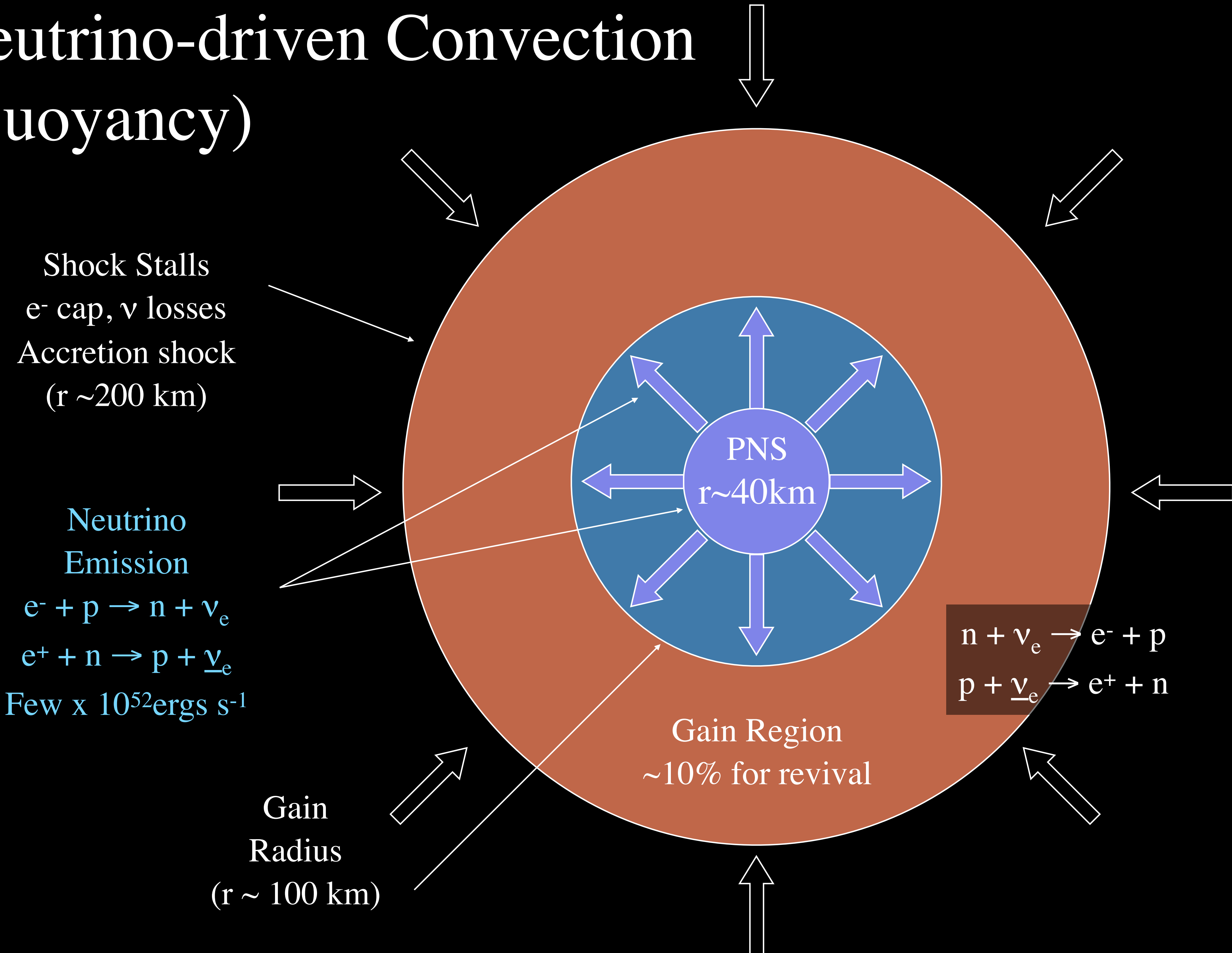
Realistic and quantitative explosions

Systematic exploration

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

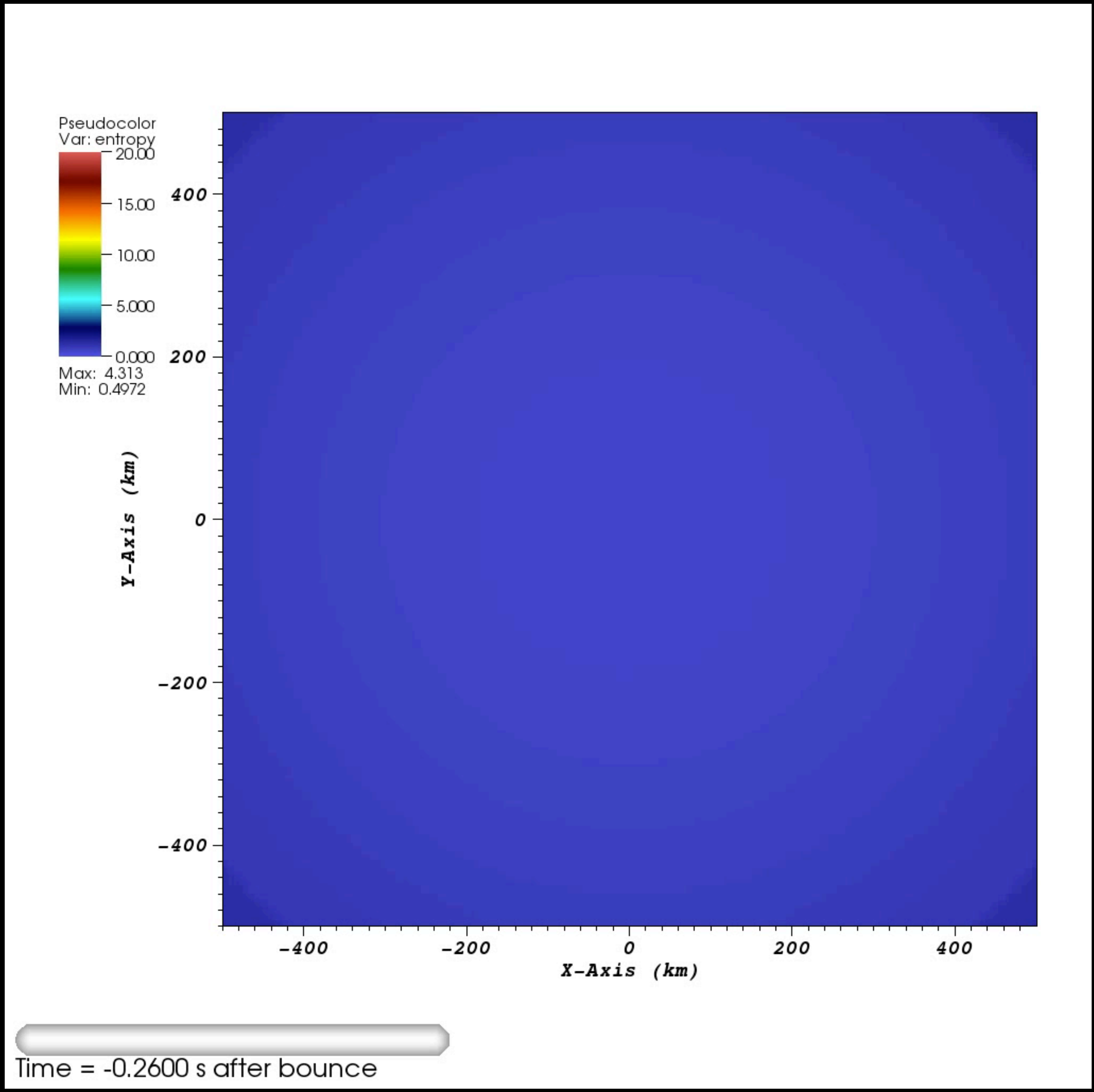
Neutrino-driven Convection
(Buoyancy)

Neutrino-driven Convection (Buoyancy)



Neutrino-driven Convection (Long Recognized)

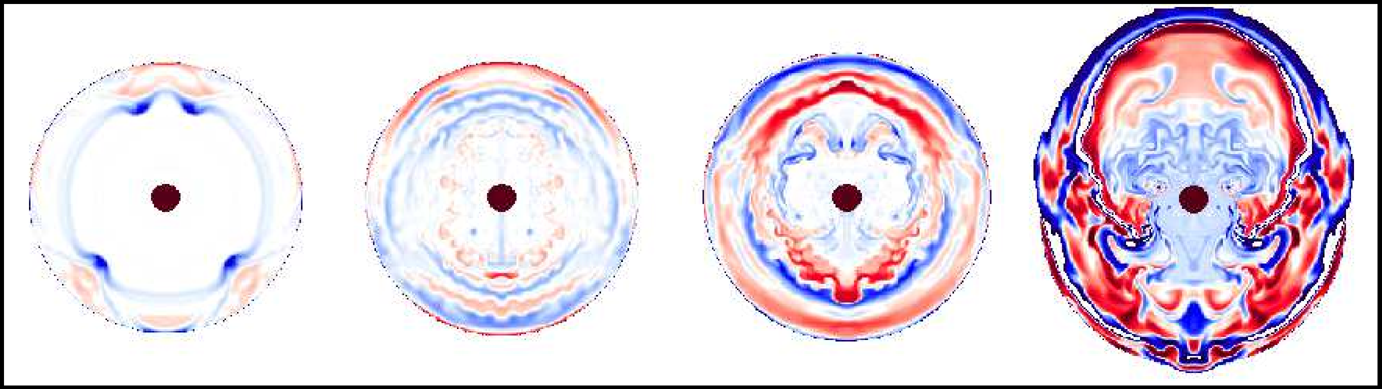
Bethe ’90
Herant et al. ’92
Benz et al. ’94
Burrows et al. ’95
Janka & Mueller ’96
...
Murphy & Meakin 2012
Murphy et al. 2012

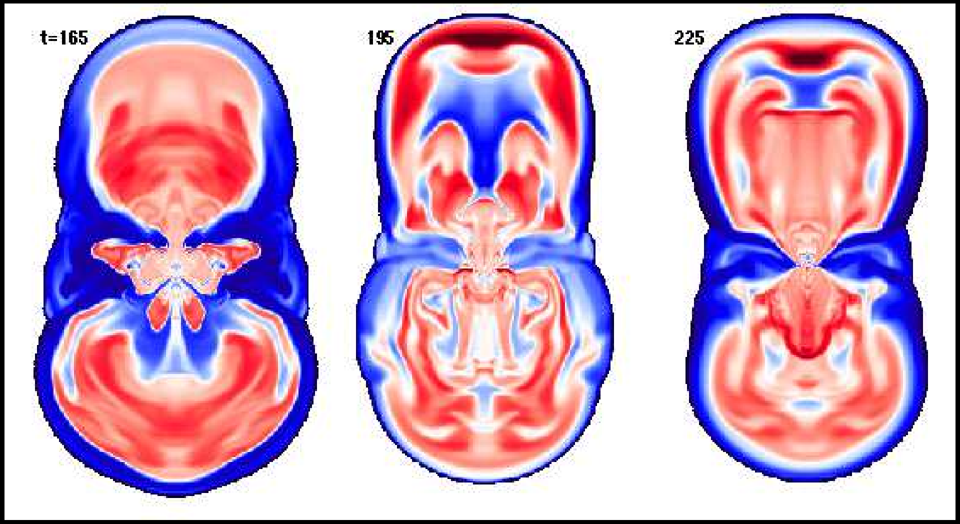


Standing Accretion Shock Instability (SASI)

Standing Accretion Shock Instability (SASI)

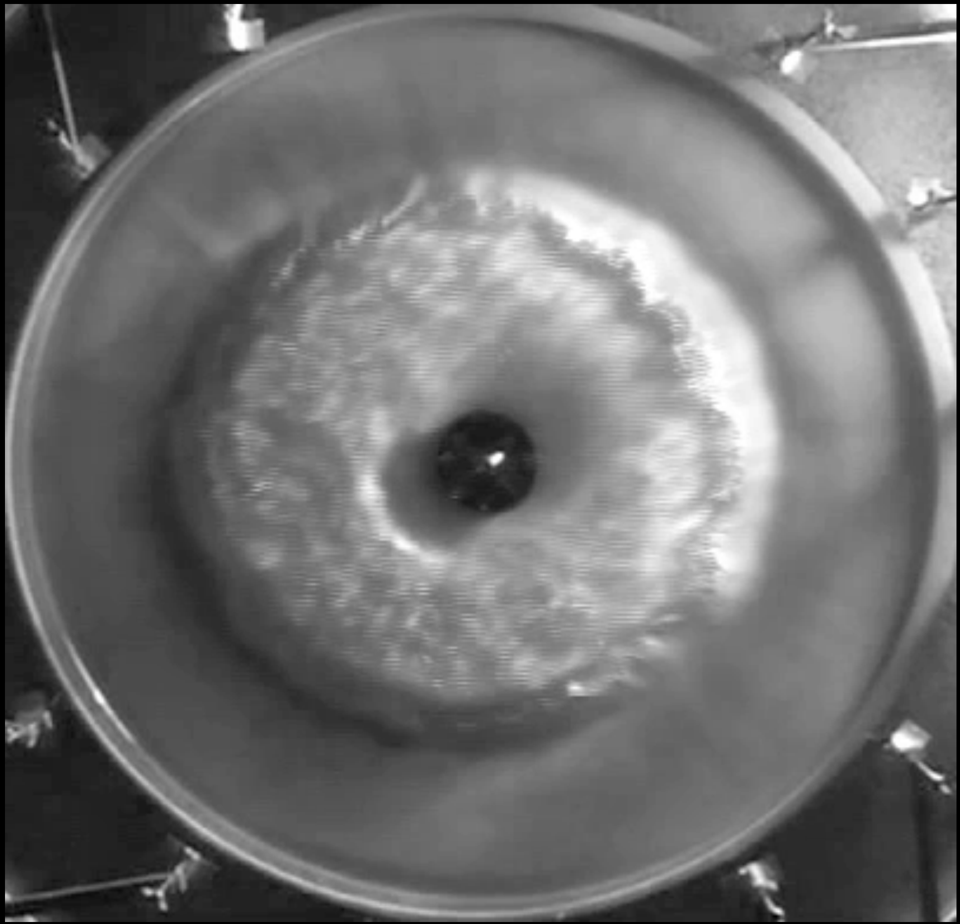
Blondin et al. '03





Standing Accretion Shock Instability (An Advective Acoustic Cycle)

Foglizzo et al. 2012



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

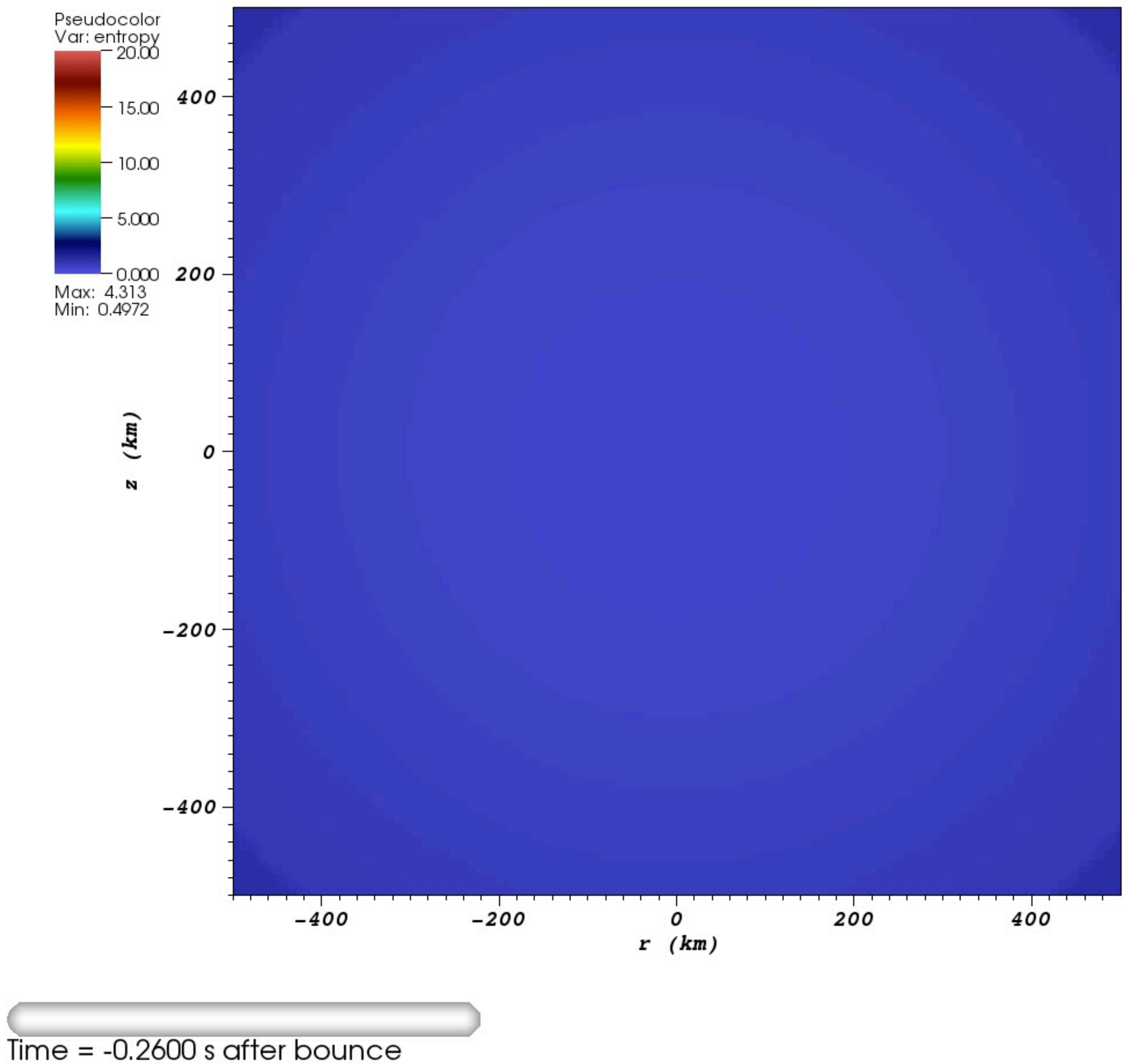
Murphy & Meakin 2012
Murphy, Dolence, Burrows 2013

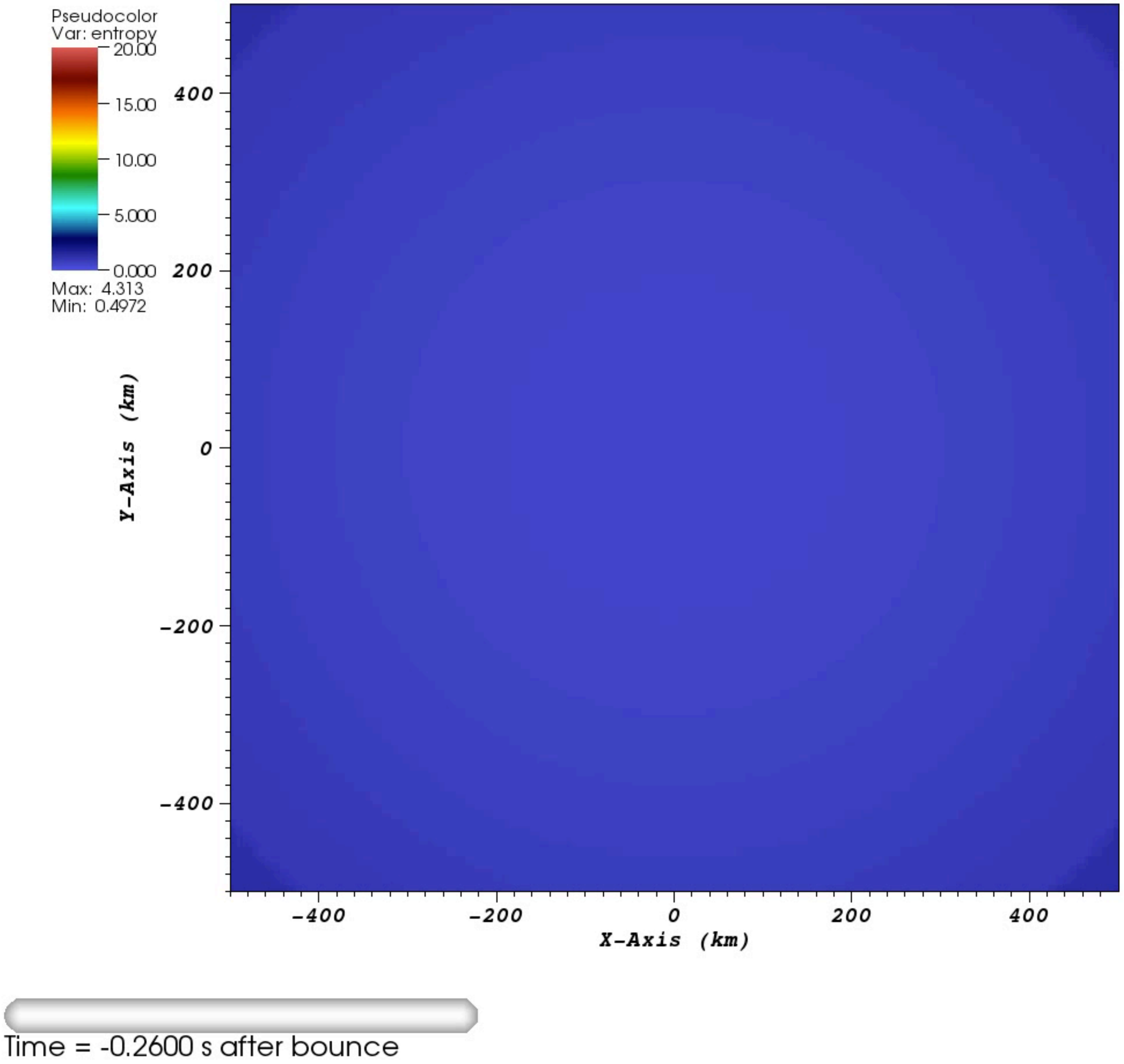
Compare nonlinear theories for convection and SASI with post shock flow

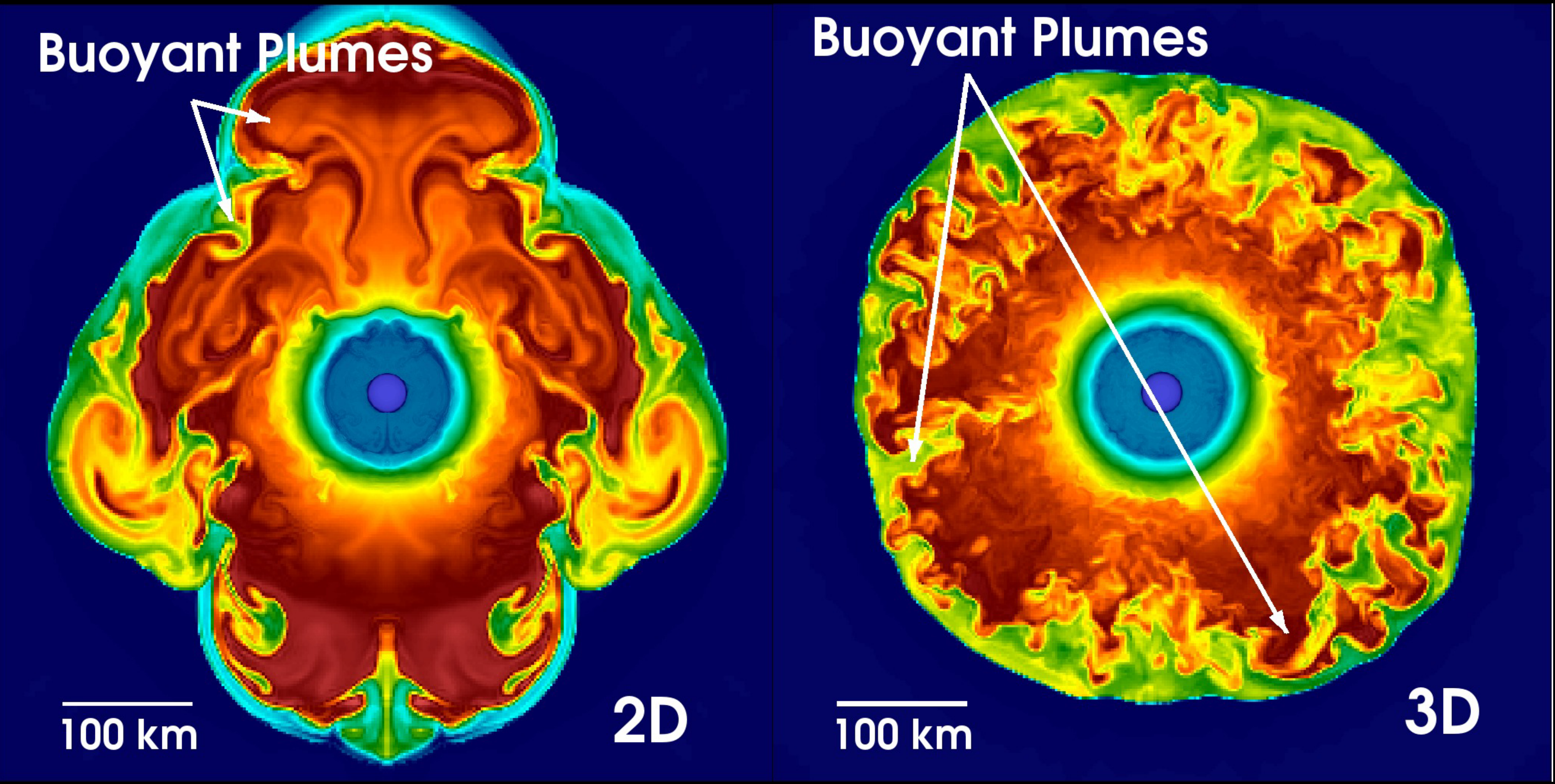
A Nonlinear Theory for Convection

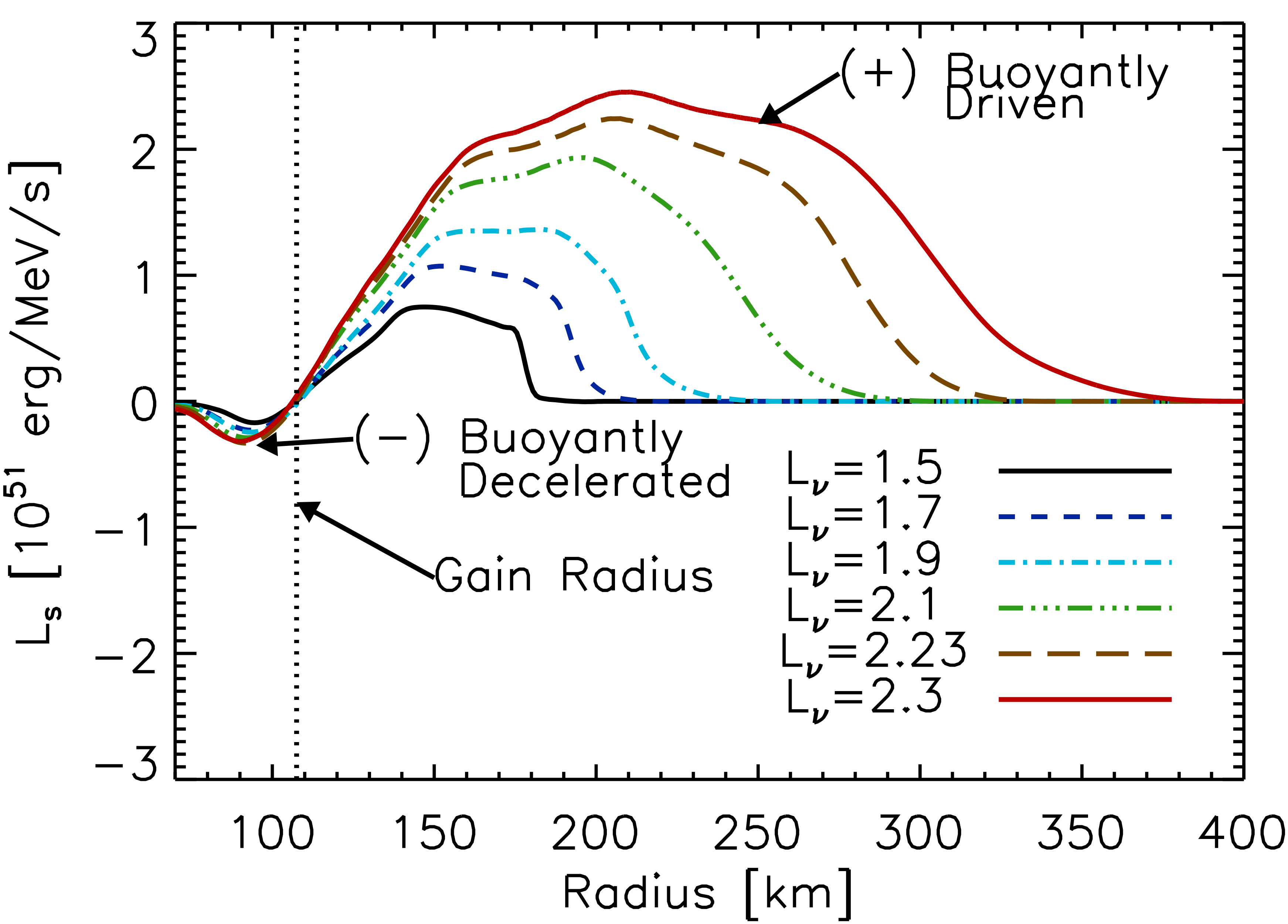
Murphy & Meakin 2012
Murphy, Dolence, Burrows 2013

We can test this fledgling theory with 3D simulations


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

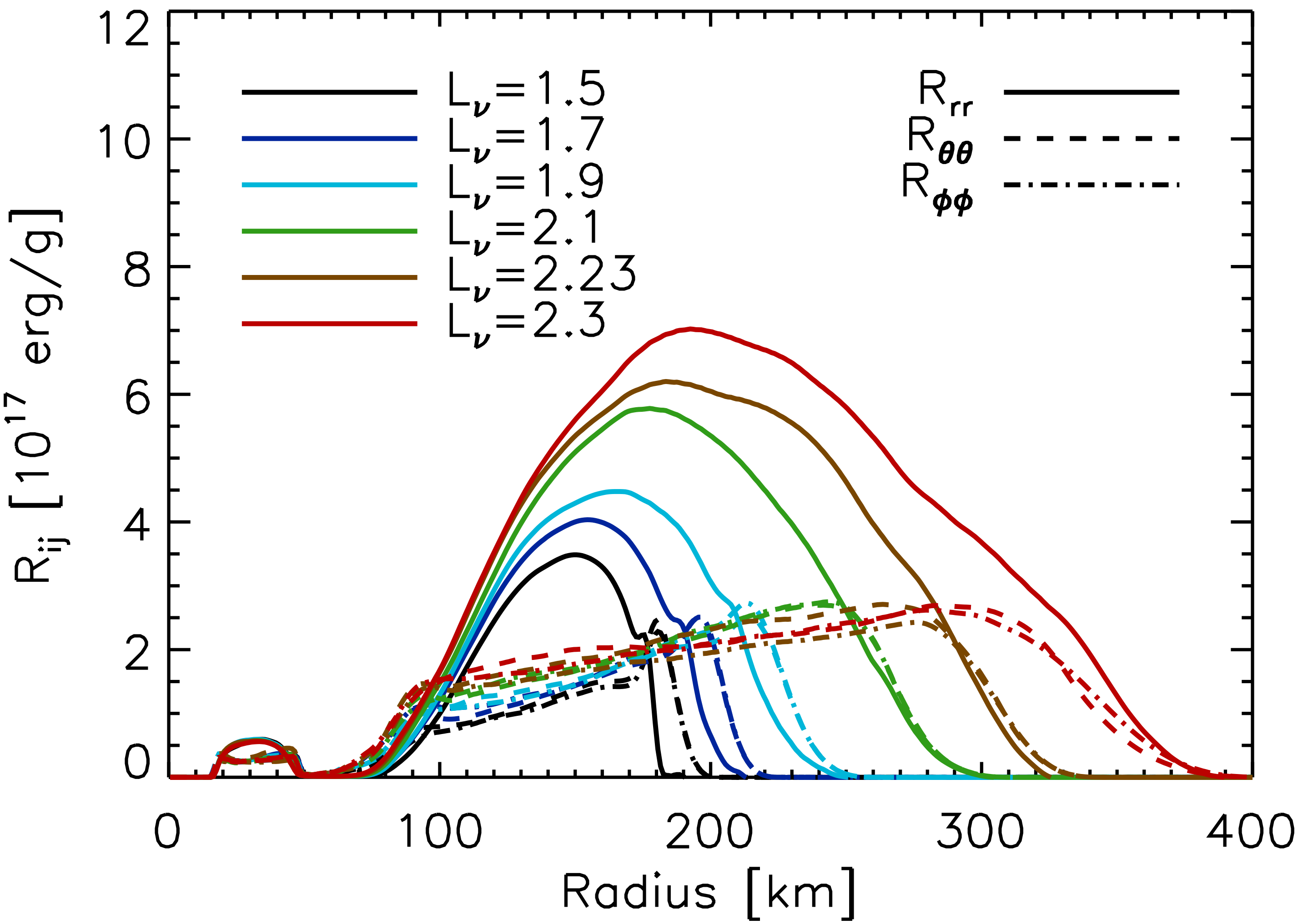

Pseudocolor
Var: entropy
20.00
15.00
10.00
5.000
0.000
Max: 4.313
Min: 0.4972
400
200
0
-200
-400
Y-Axis (km)
-400
-200
0
200
400
X-Axis (km)
Time = -0.2600 s after bounce


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



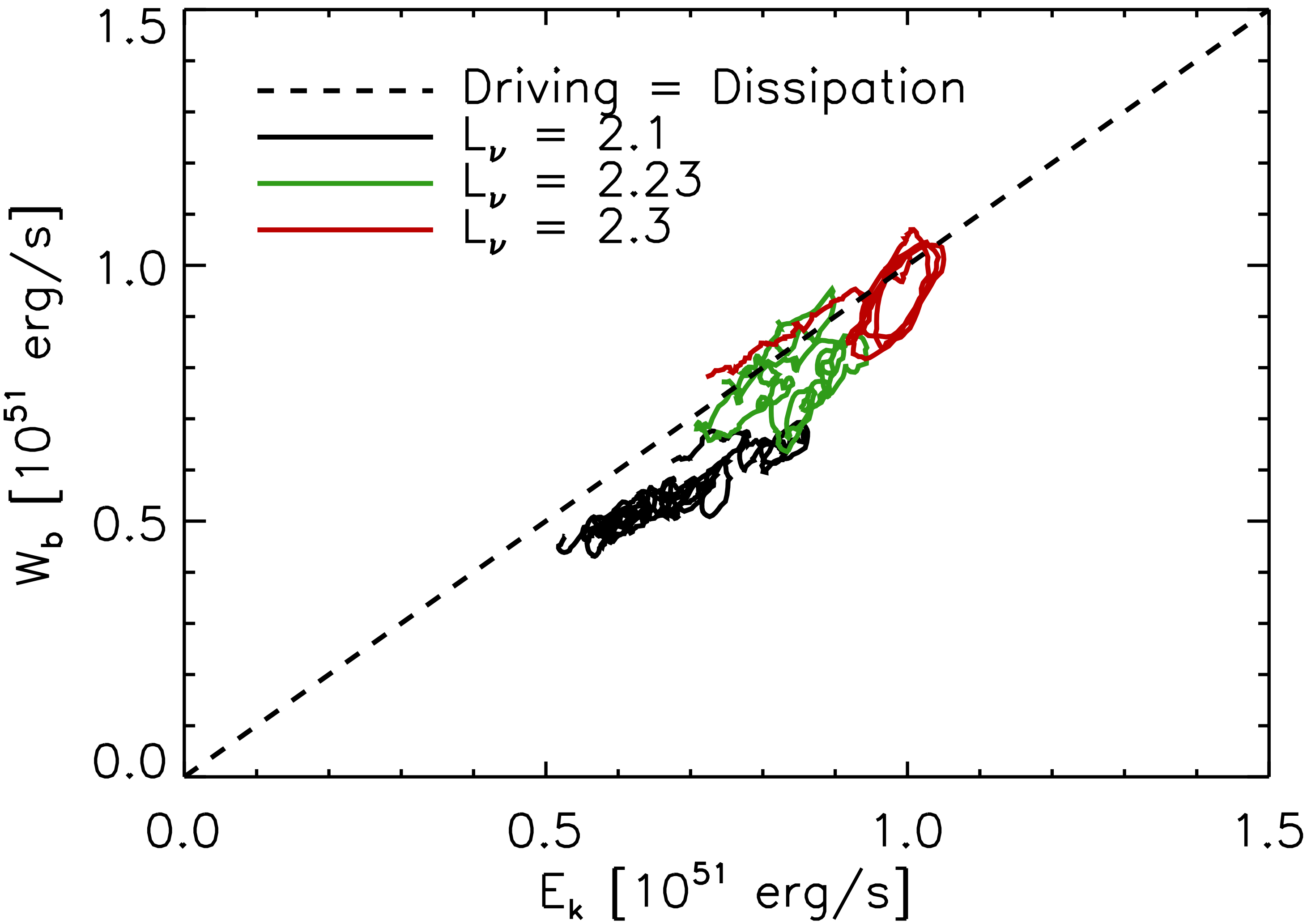
$$L_s = \langle \rho v' s' \rangle 4\pi r^2$$

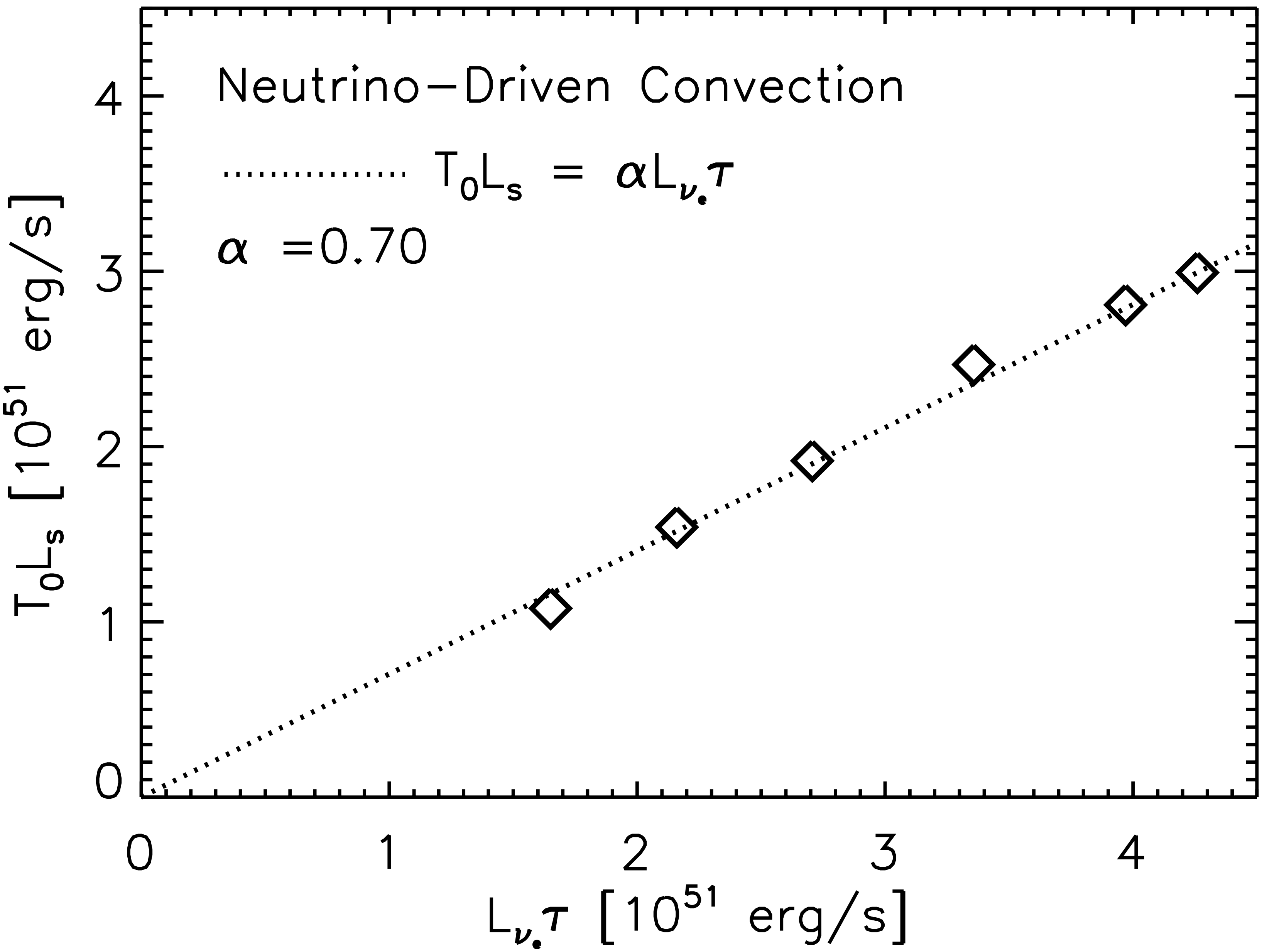
$$R_{ij} = \left\langle v_i' v_j' \right\rangle$$



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

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





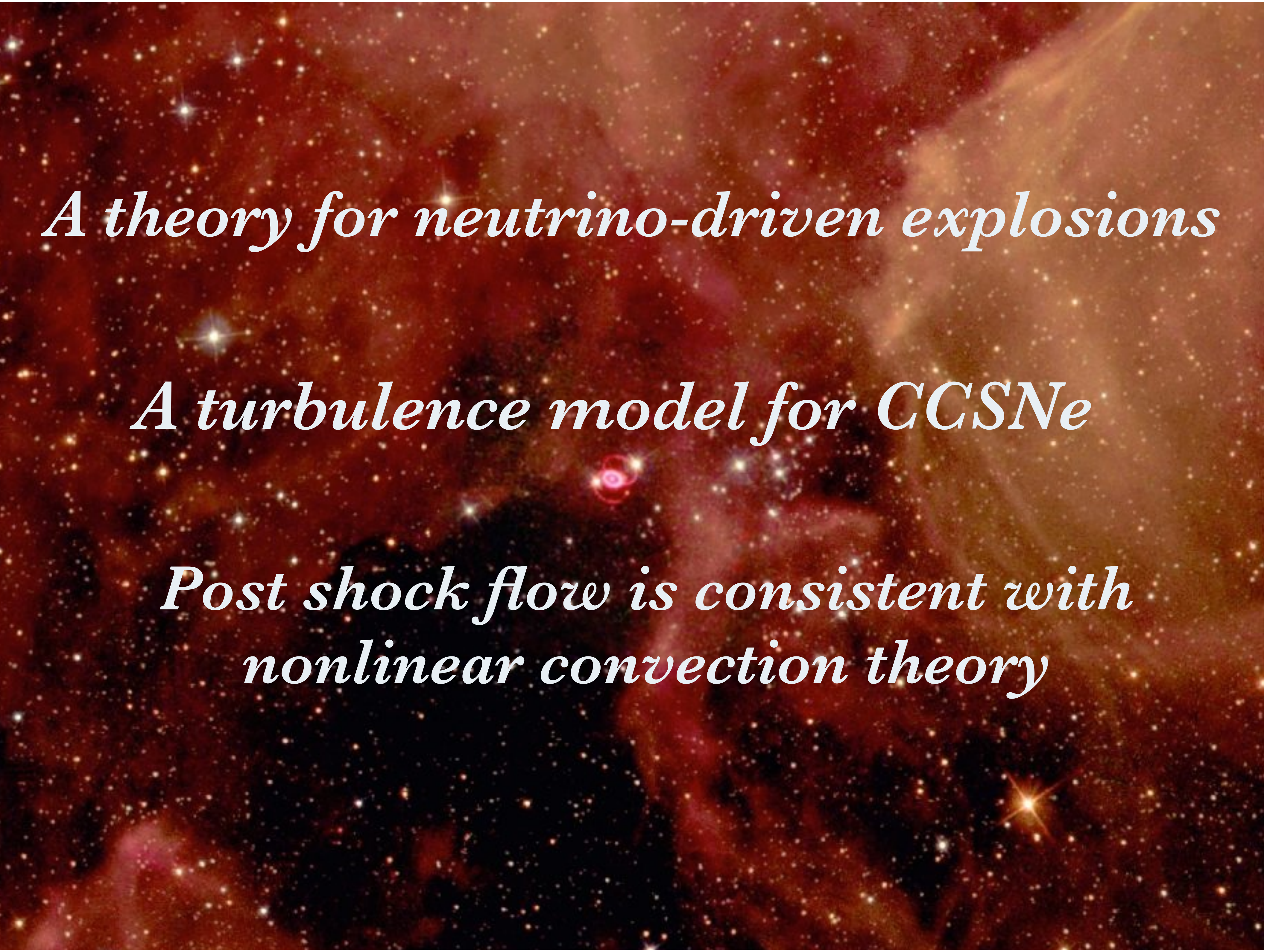
Neutrino-Driven Convection
$T_0 L_s = \alpha L_{\nu_e} \tau$
α =0.70
$T_0 L_s$ [10^{51} erg/s]
$L_{\nu_e} \tau$ [10^{51} erg/s]
0
1
2
3
4
0
1
2
3
4

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?

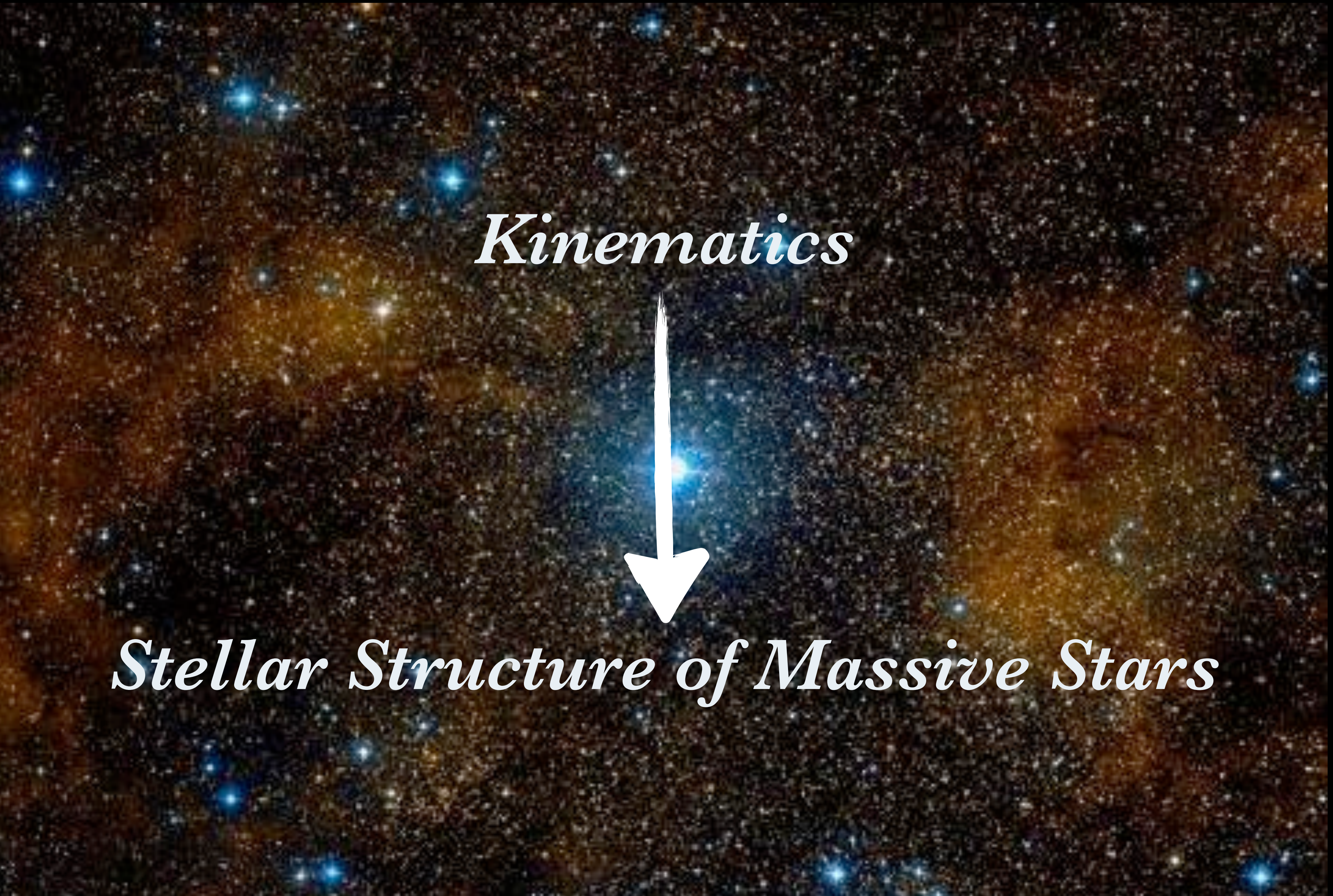


A theory for neutrino-driven explosions

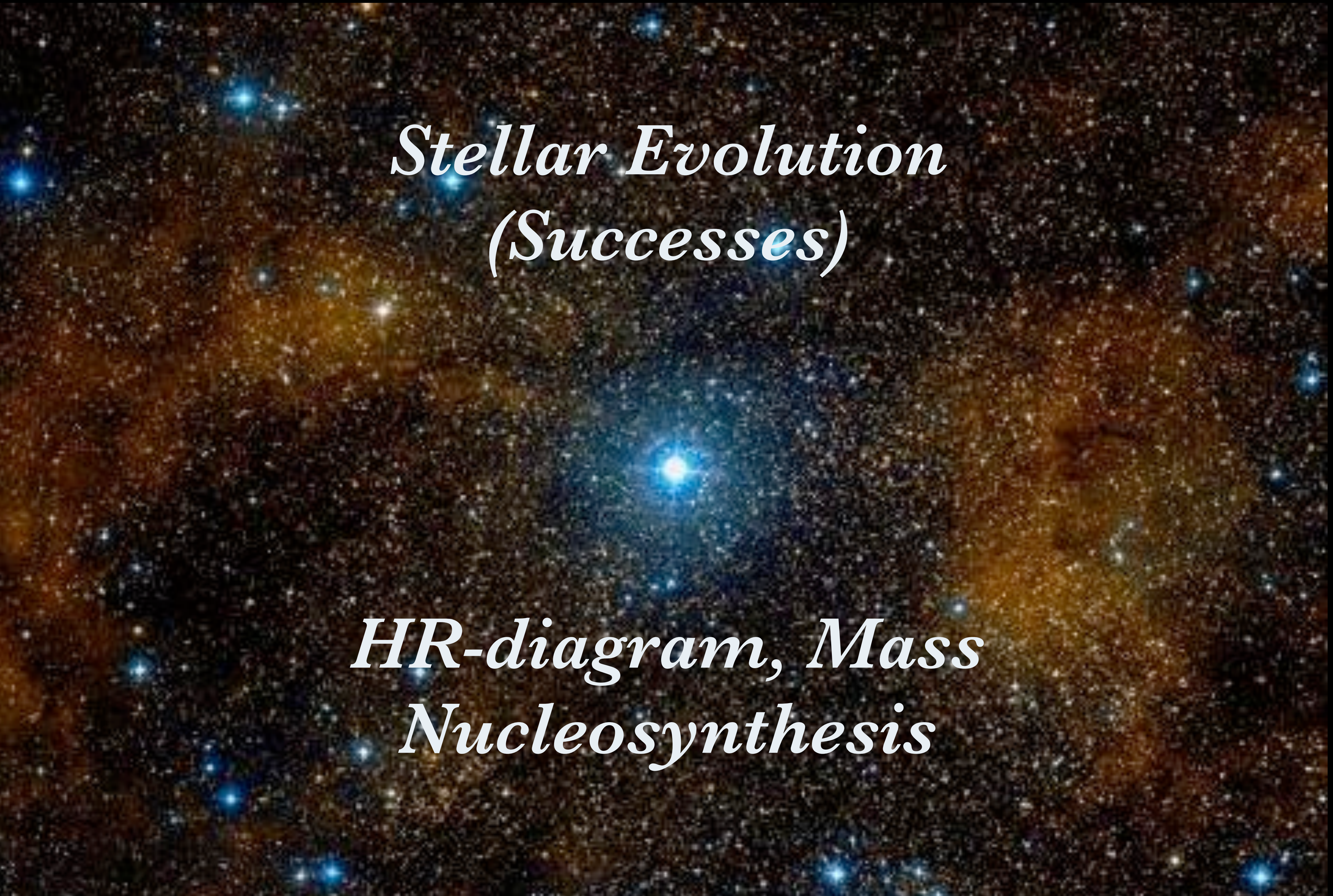
A turbulence model for CCSNe

Post shock flow is consistent with nonlinear convection theory

Constrain Giant Eruptions from Massive Stars


Kinematics
Stellar Structure of Massive Stars

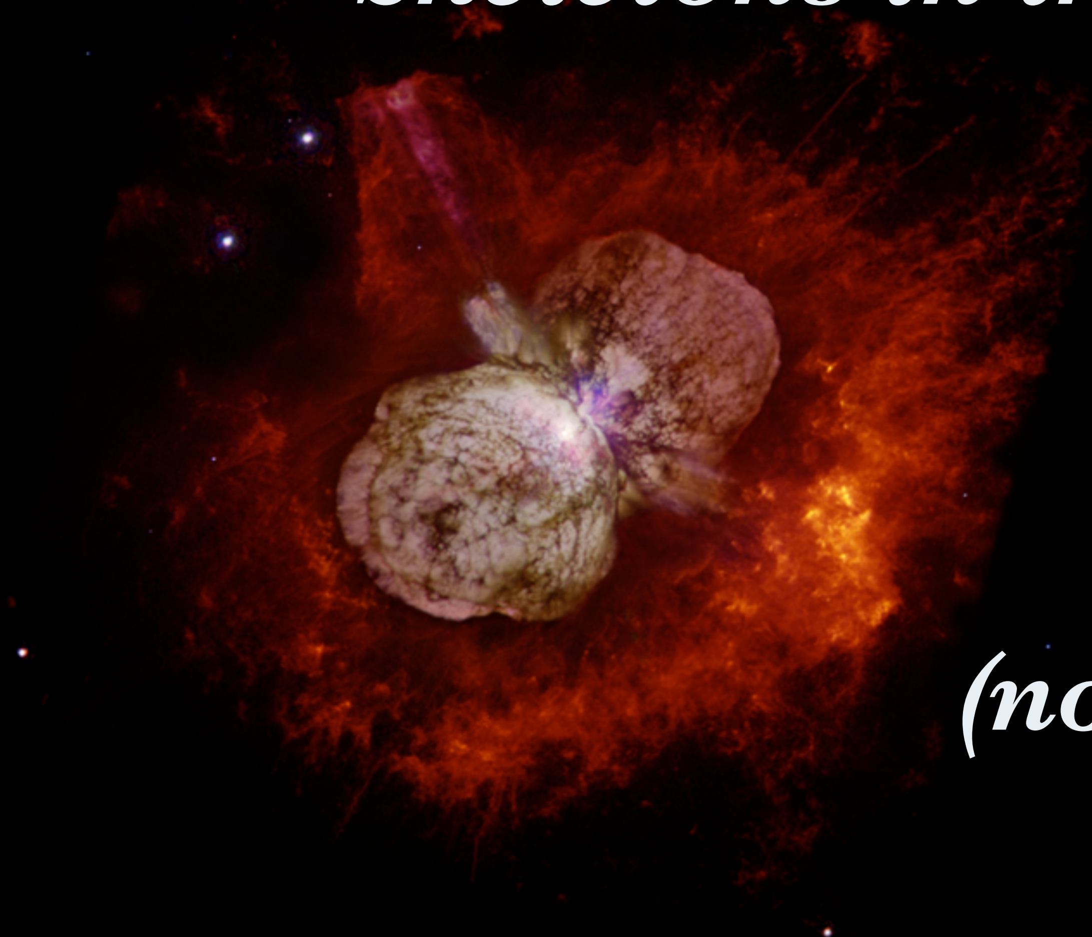
Stellar Evolution (Successes)



HR-diagram, Mass Nucleosynthesis

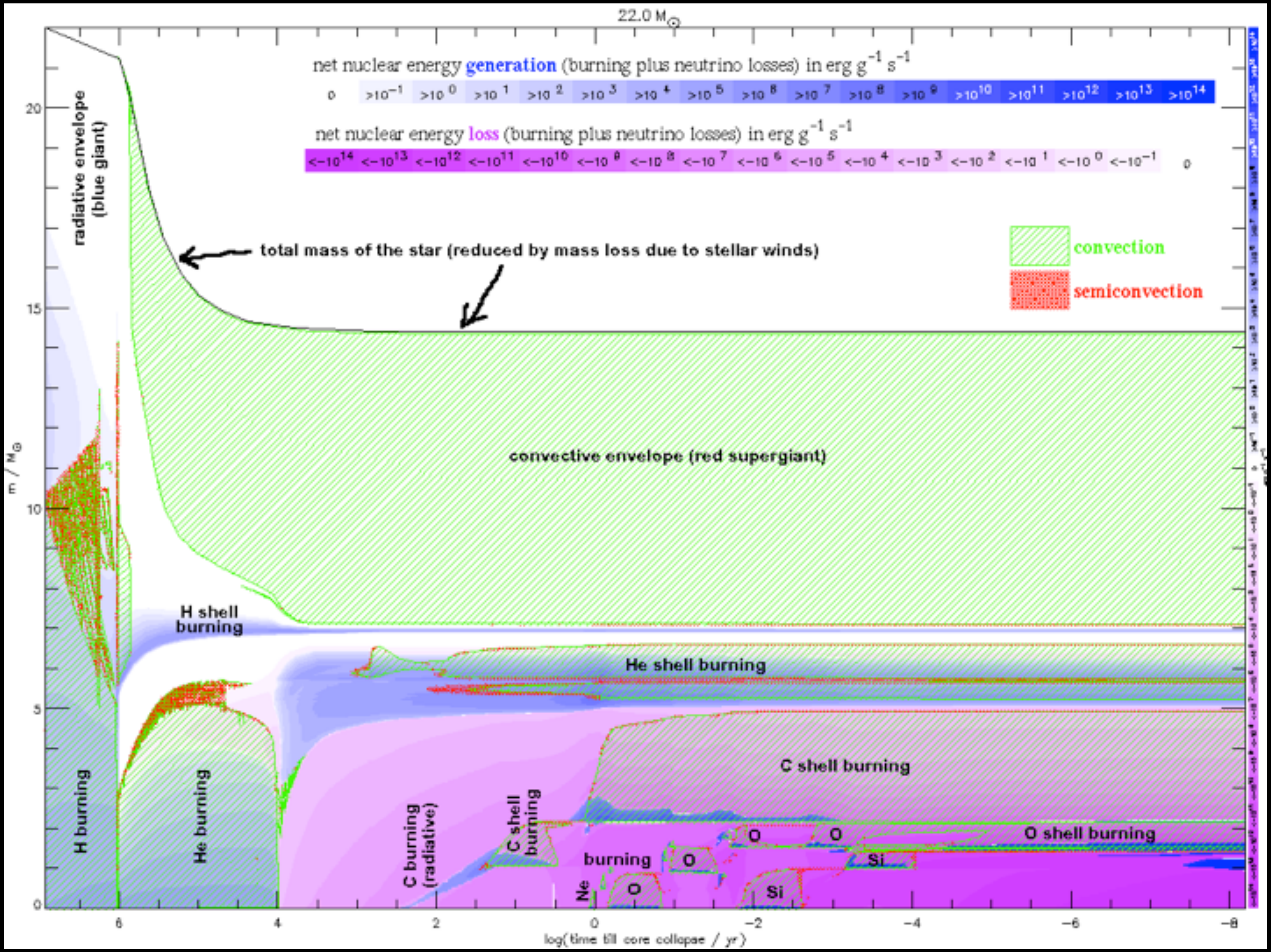
Skeletons in the Closet

Skeletons in the Closet



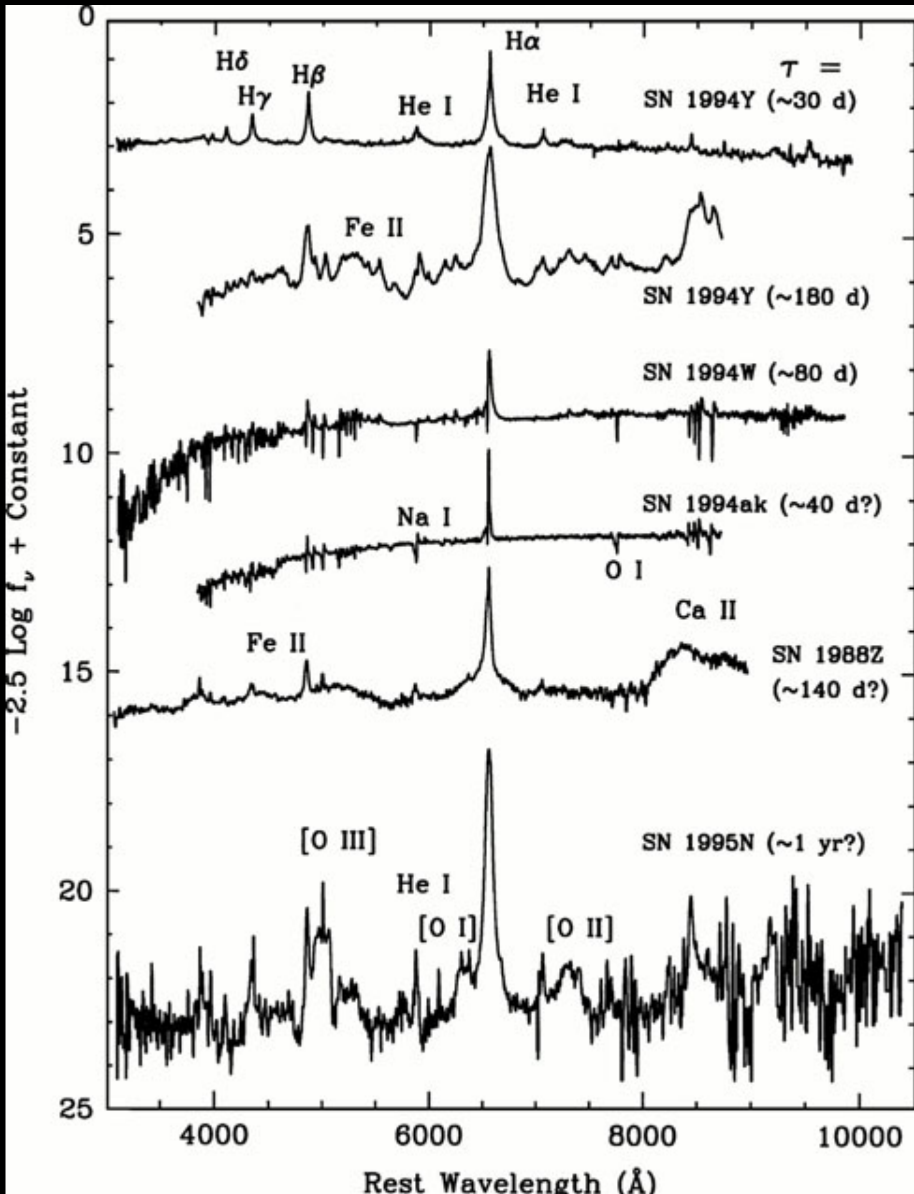
Mass Loss
Convection
Rotation
(not mere details)

Mass Loss



Credit: Alex Heger

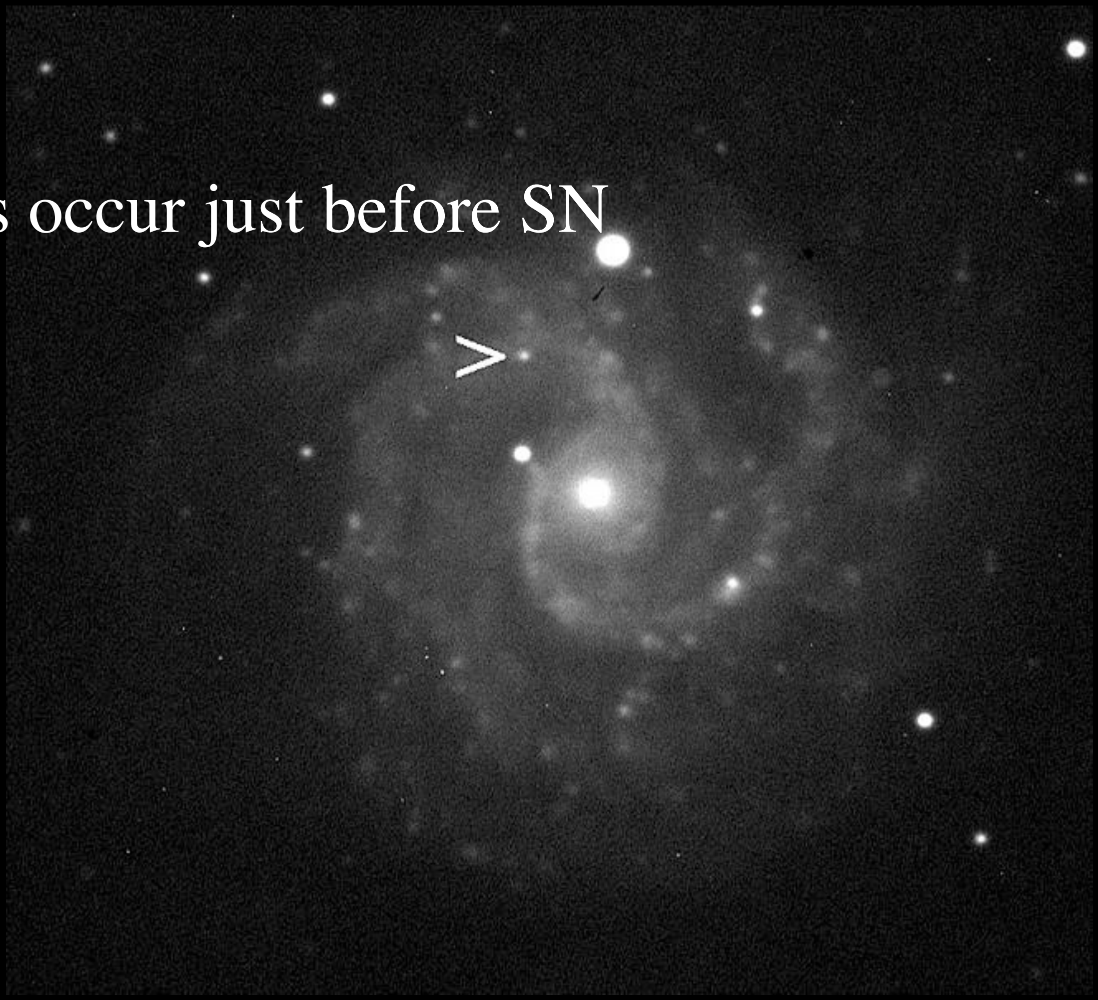
Episodic Mass Loss



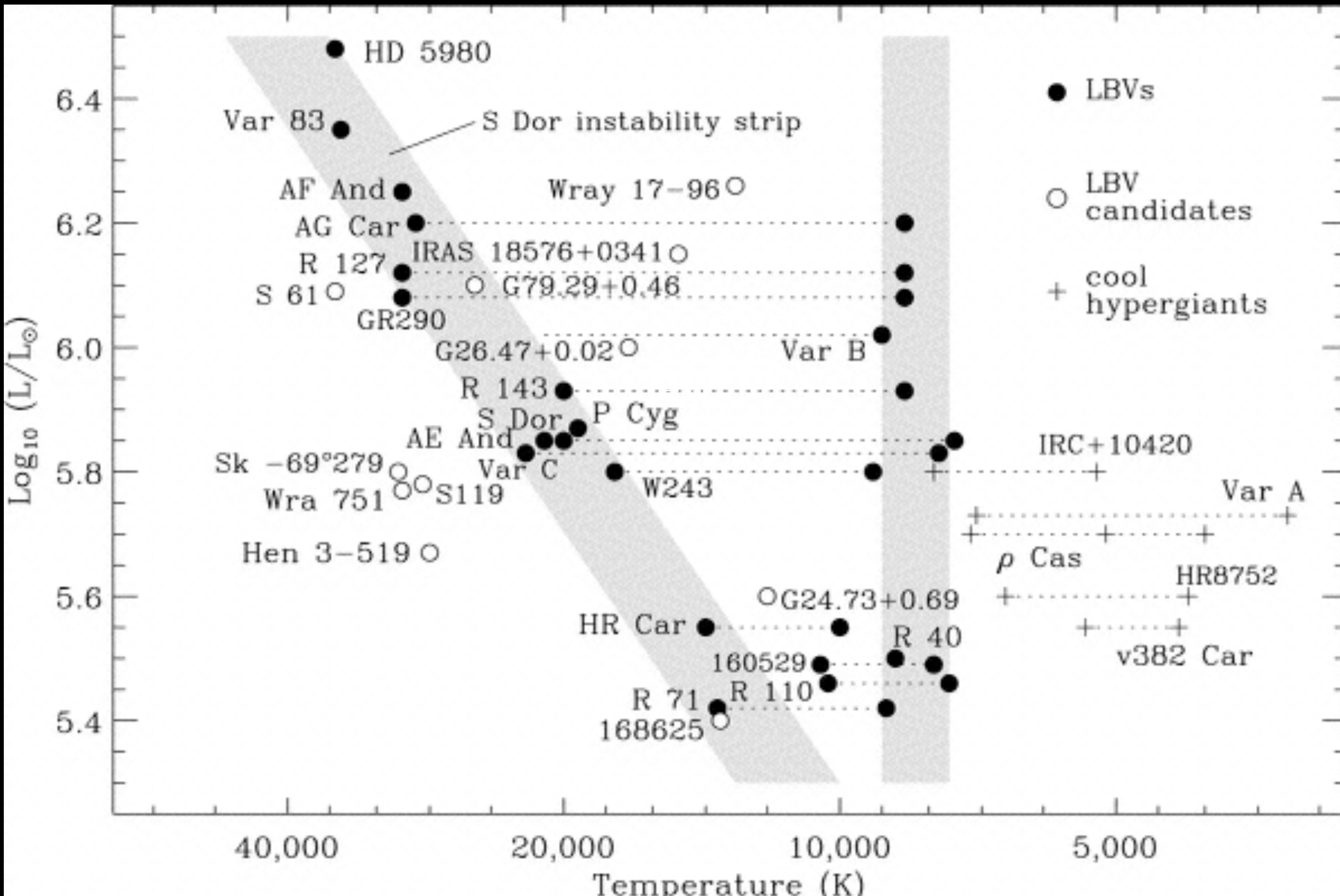
SN IIn
Evidence of episodic mass loss before explosion

Episodic Mass Loss

SN Impostors
Some SN Impostors occur just before SN

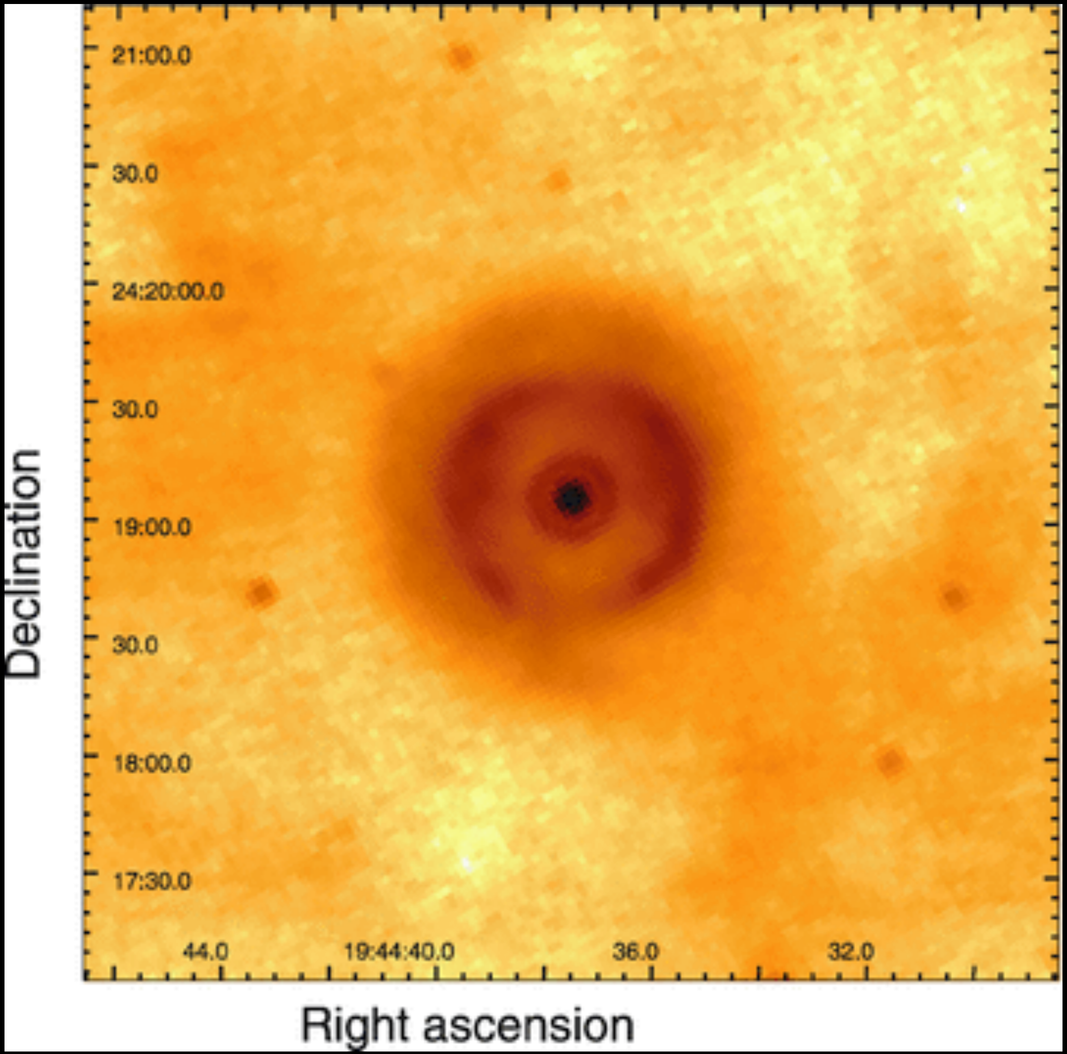


Episodic Mass Loss



Episodic Mass Loss

LBV Dust Shells
Represent a giant eruption
Massive amounts of mass loss



Is episodic mass loss a dominant mode of mass loss?

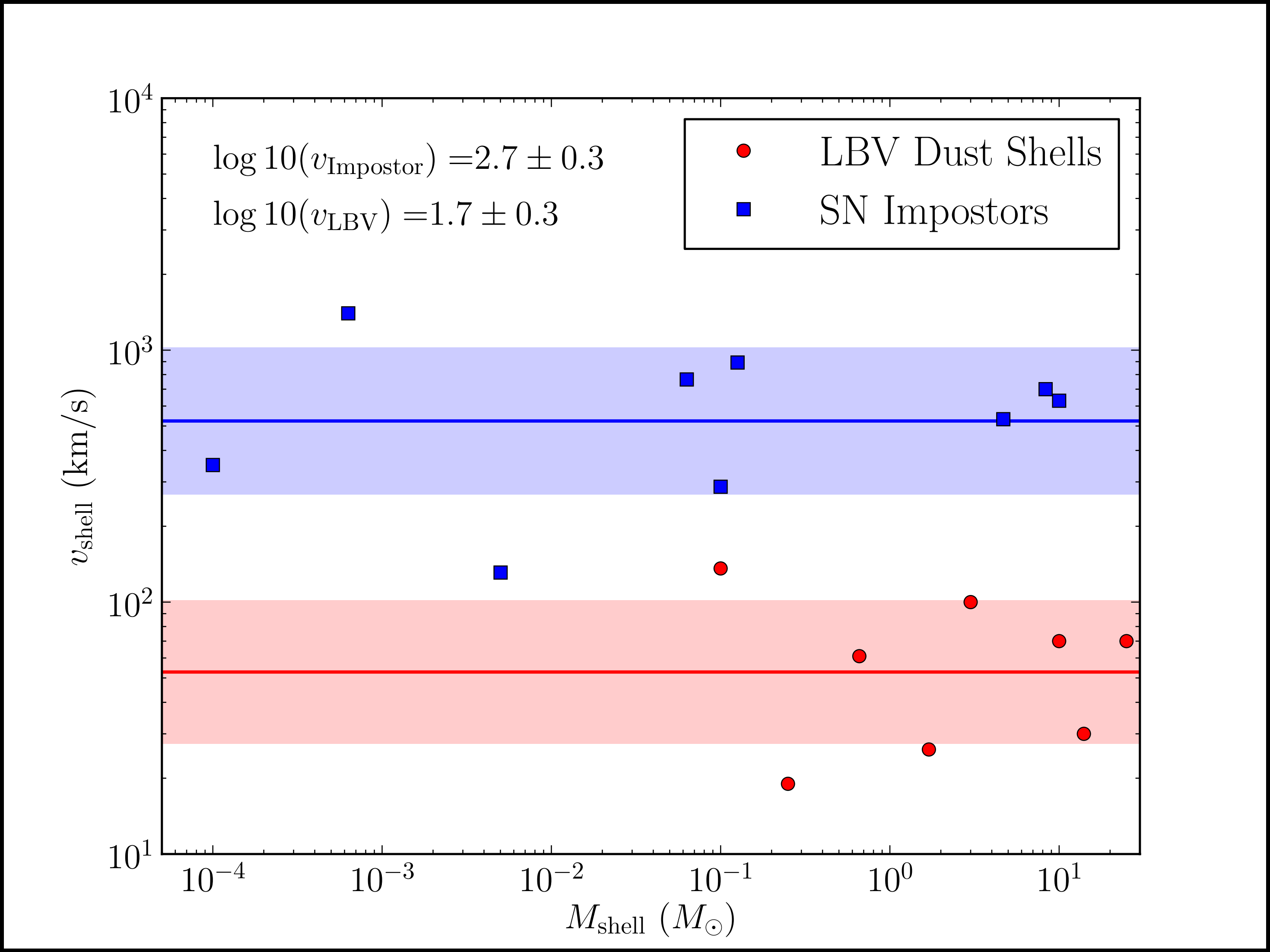
What causes Giant Eruptions?

We don't know what's going on inside!

Stellar Structure?
Evolutionary State?

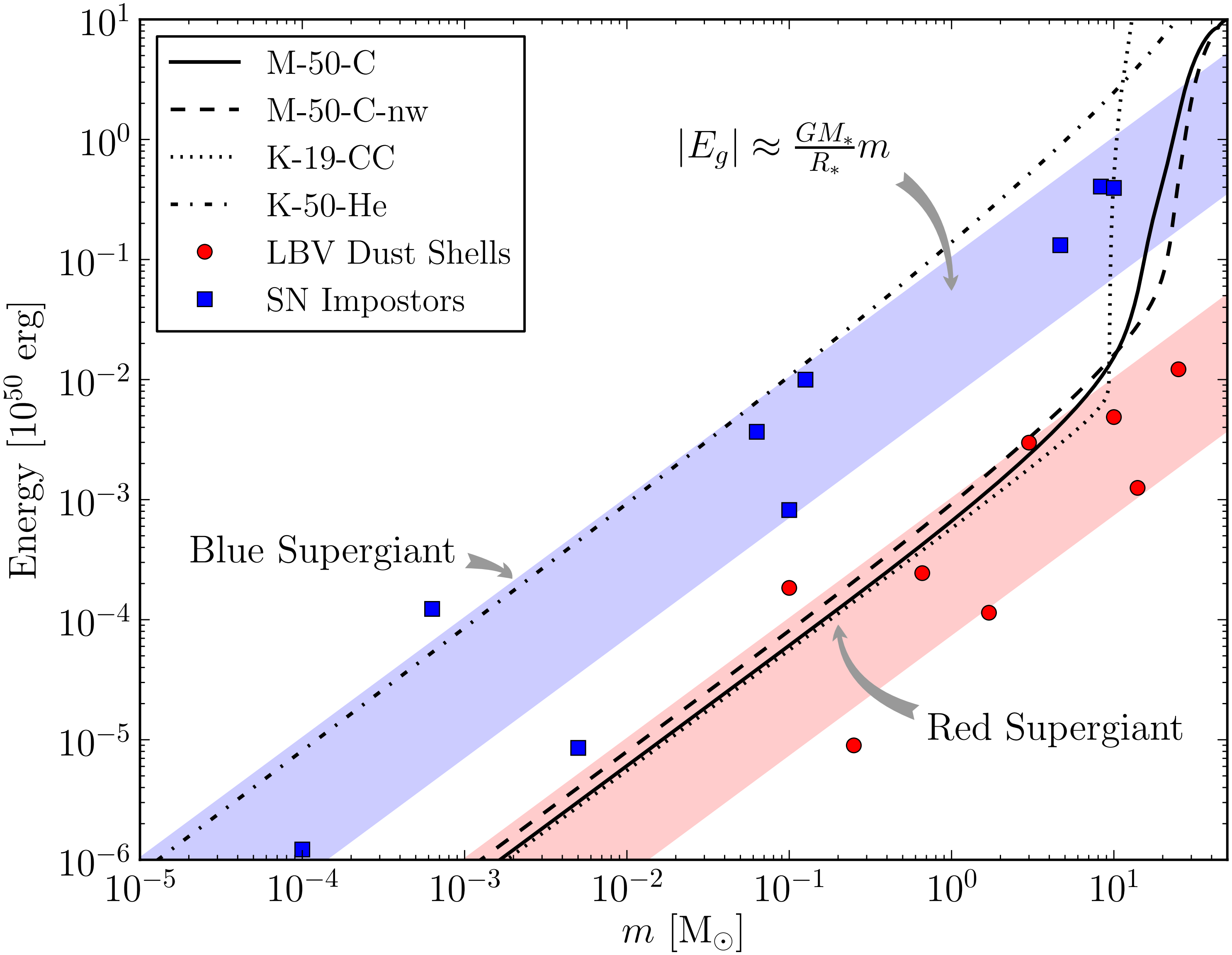
The Data

(Kochanek 2011 & Kochanek 2012)

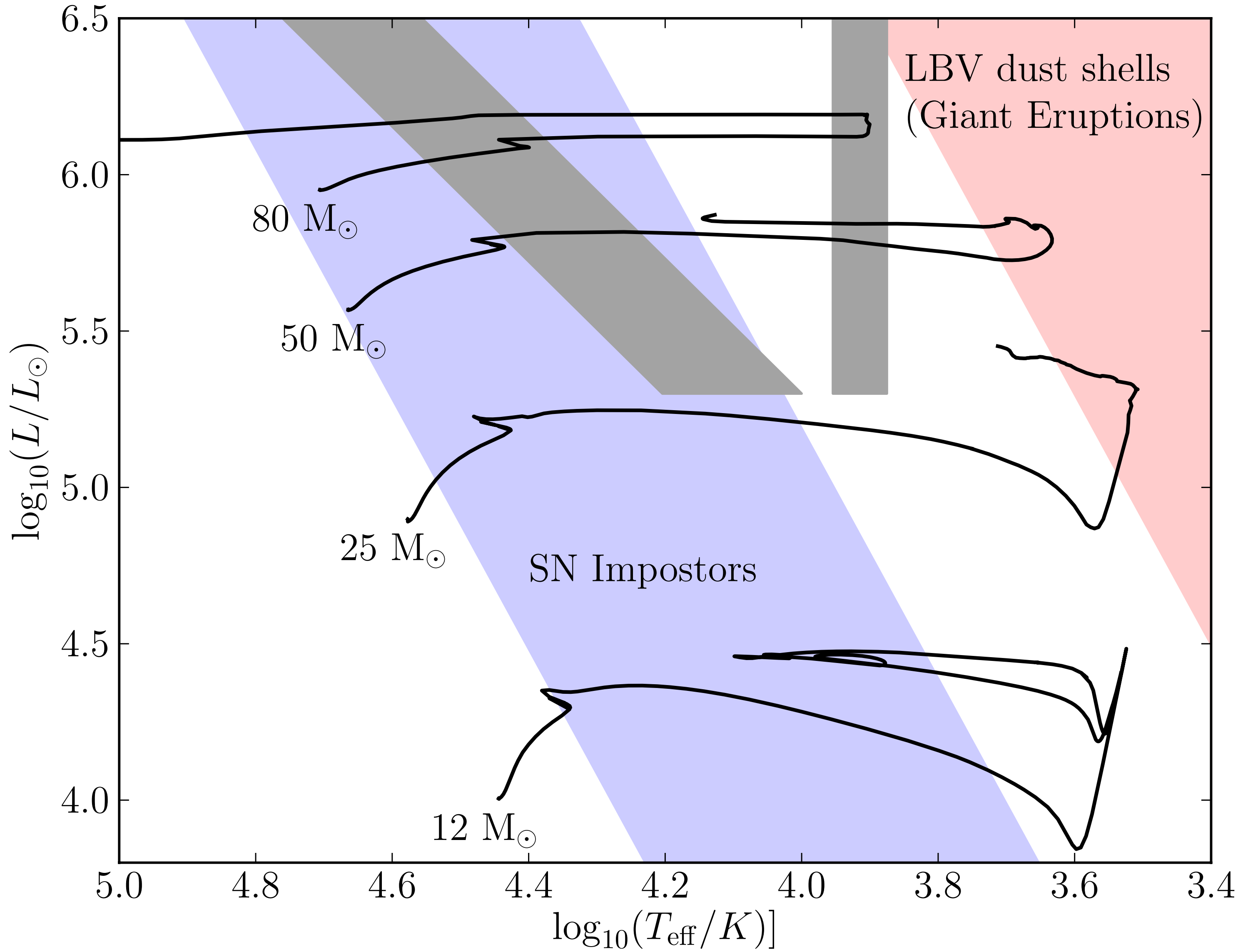


A Natural Energy Scale

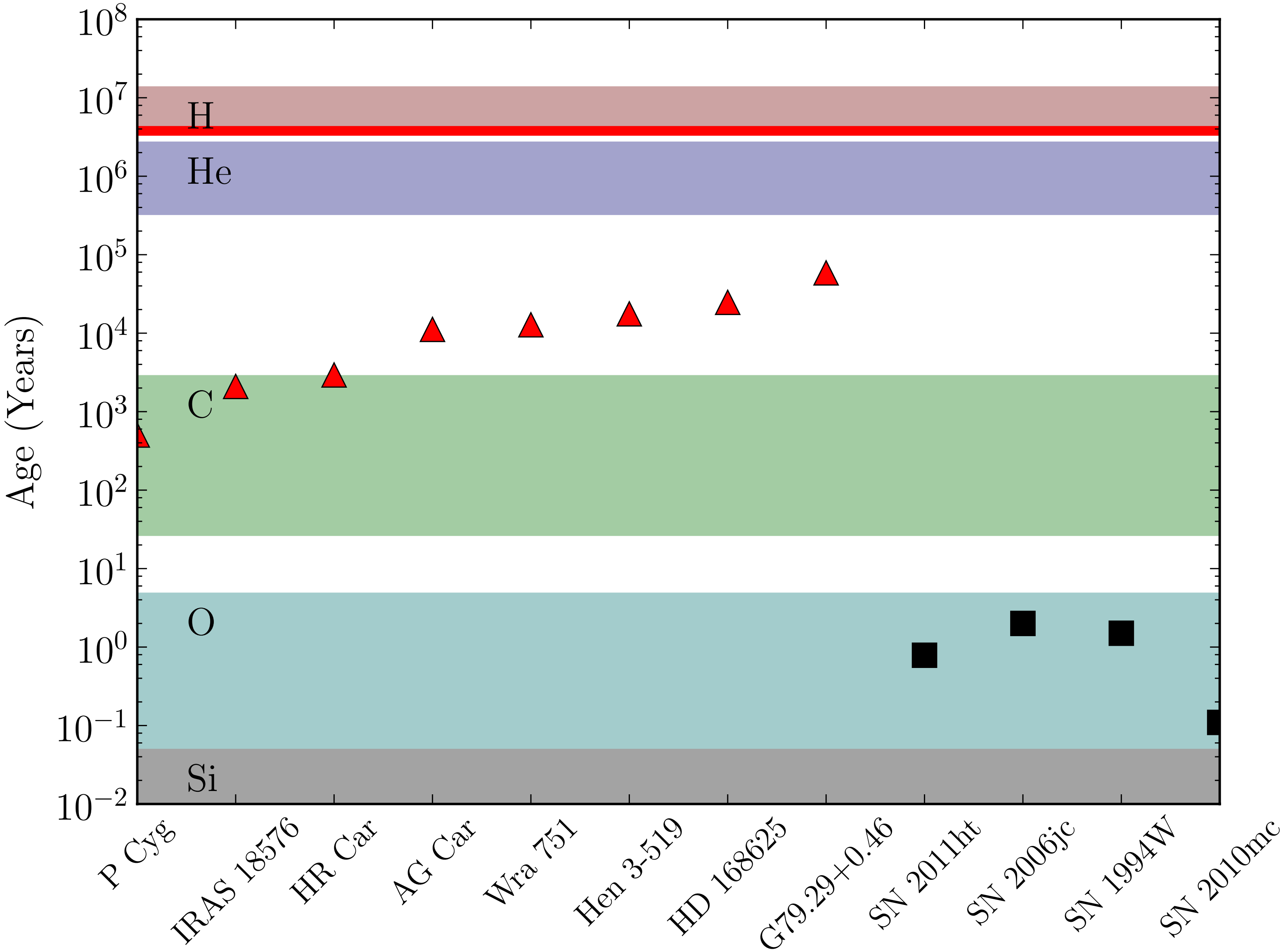
$$|E_g| = \int_0^m \frac{GM}{r}\,dm$$



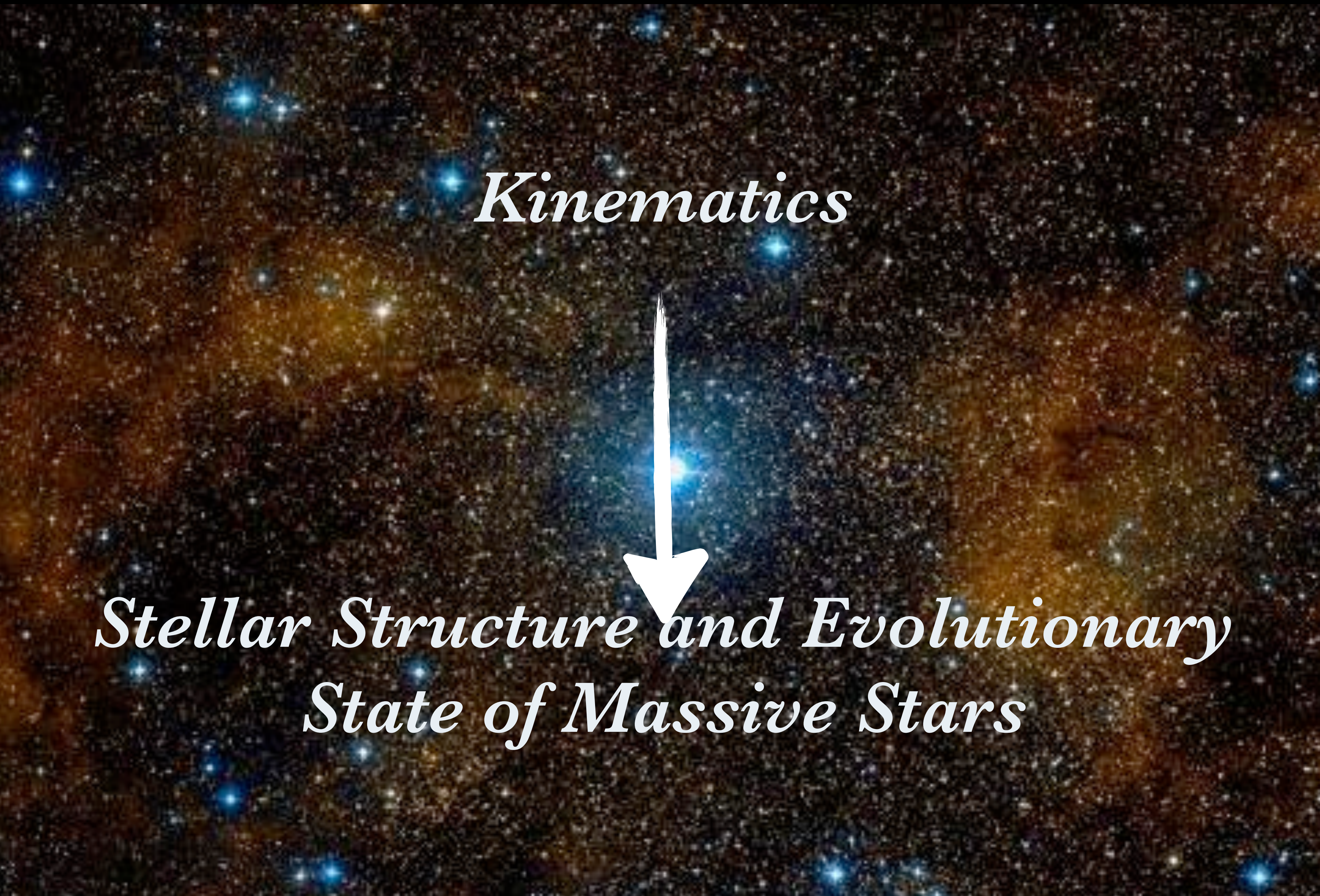
Energy $[10^{50}$ erg$]$
m $[\mathrm{M}_\odot]$
M-50-C
M-50-C-nw
K-19-CC
K-50-He
LBV Dust Shells
SN Impostors
$|E_g| \approx \frac{GM_*}{R_*} m$
Blue Supergiant
Red Supergiant
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



LBV dust shells
(Giant Eruptions)
80 M$_\odot$
50 M$_\odot$
25 M$_\odot$
12 M$_\odot$
SN Impostors
6.5
6.0
5.5
5.0
4.5
4.0
$\log_{10}(L/L_\odot)$
5.0
4.8
4.6
4.4
4.2
4.0
3.8
3.6
3.4
$\log_{10}(T_{\rm eff}/K)]$



Age (Years)
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
H
He
C
O
Si
P Cyg
IRAS 18576
HR Car
AG Car
Wra 751
Hen 3-519
HD 168625
G79.29+0.46
SN 2011ht
SN 2006jc
SN 1994W
SN 2010mc


Kinematics
Stellar Structure and Evolutionary
State of Massive Stars