A Unifying Explosion Condition for Core-Collapse Supernovae

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Theory

↓

How do massive stars end their lives?

↑

Which stars actually explode?

Theory

How do massive stars end their lives?

Which stars actually explode?

Constraining the Progenitor Masses of 100 Core-Collapse Supernova Remnants

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David A. Rubin

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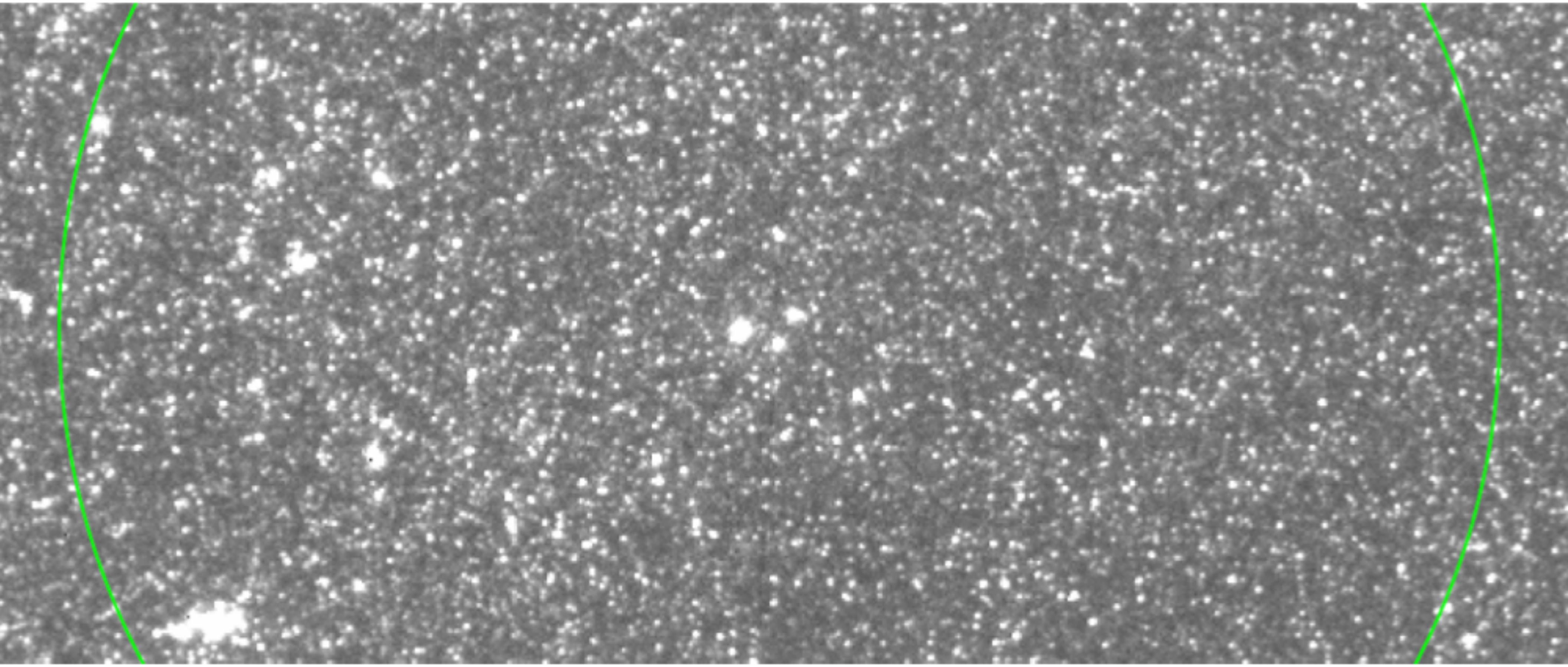
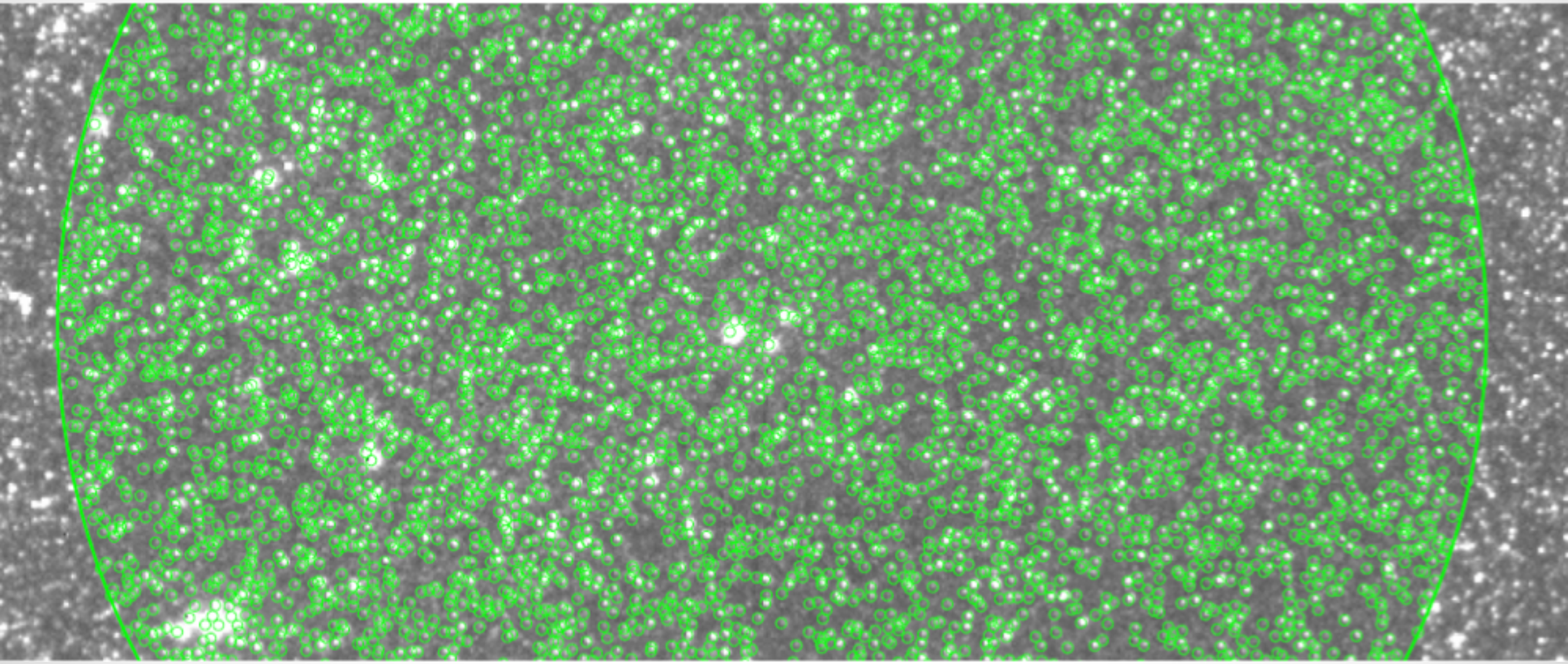
An Alternate Technique: Age date the Stellar Population

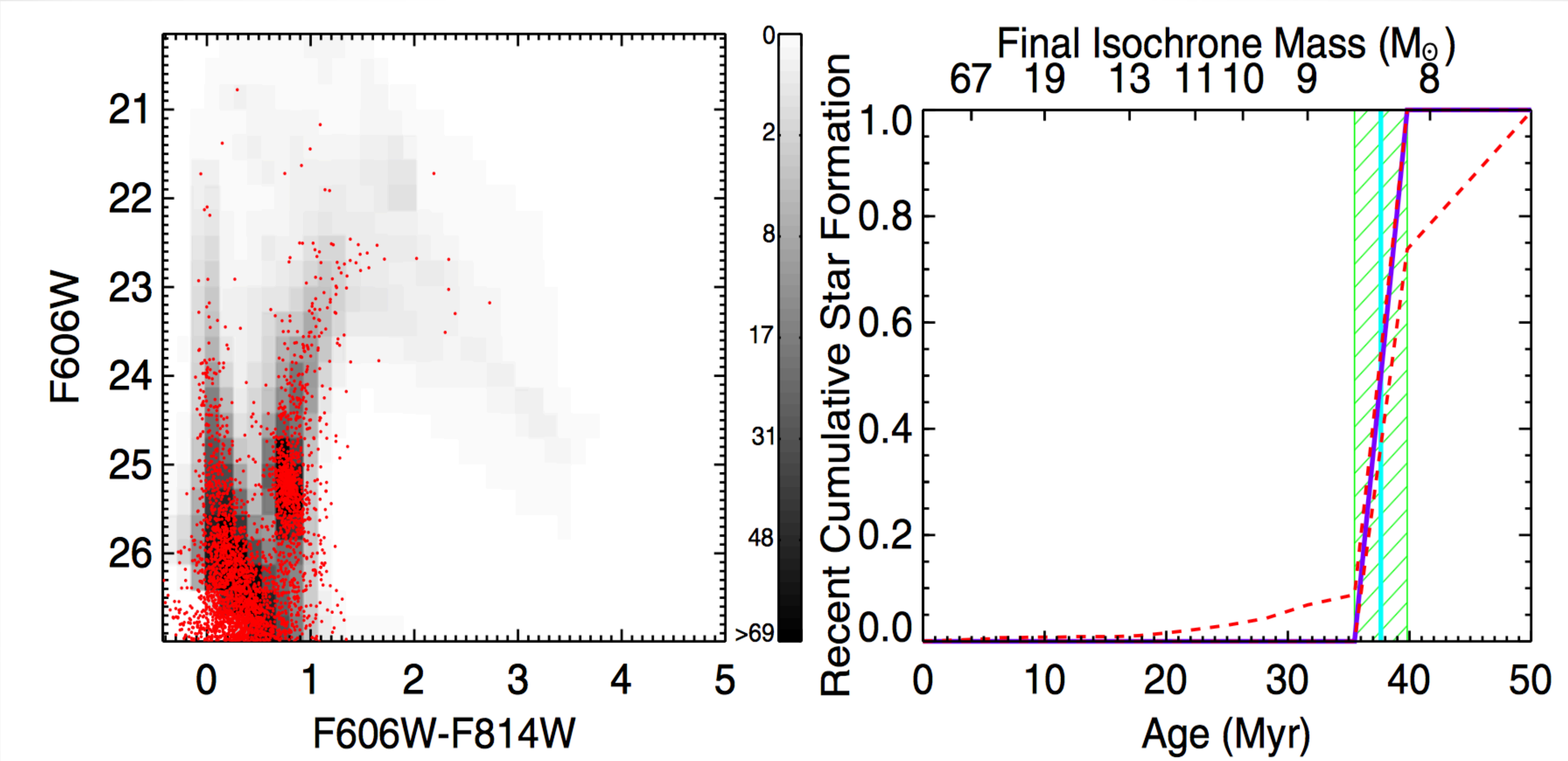


Gogarten et al. 2009

An Alternate Technique: Age date the Stellar Population



Gogarten et al. 2009

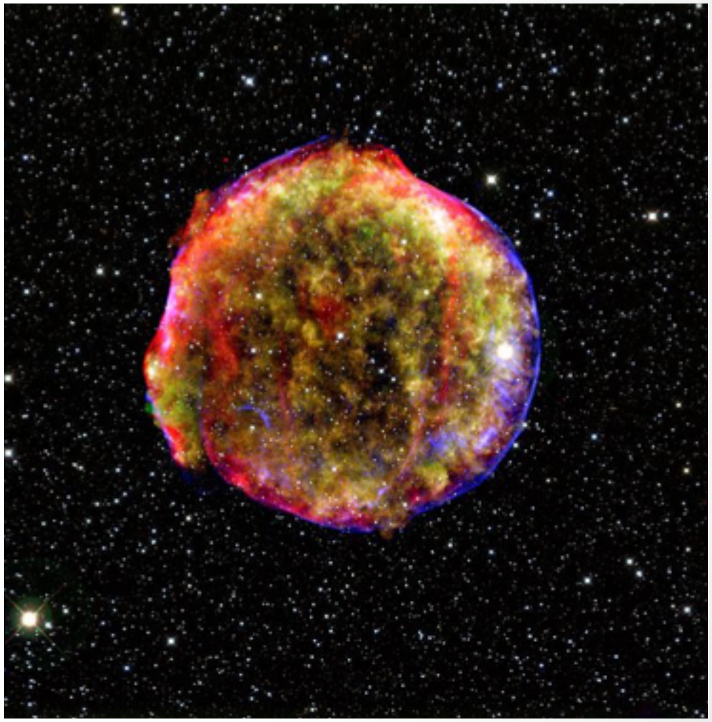


Jennings et. al. 2014

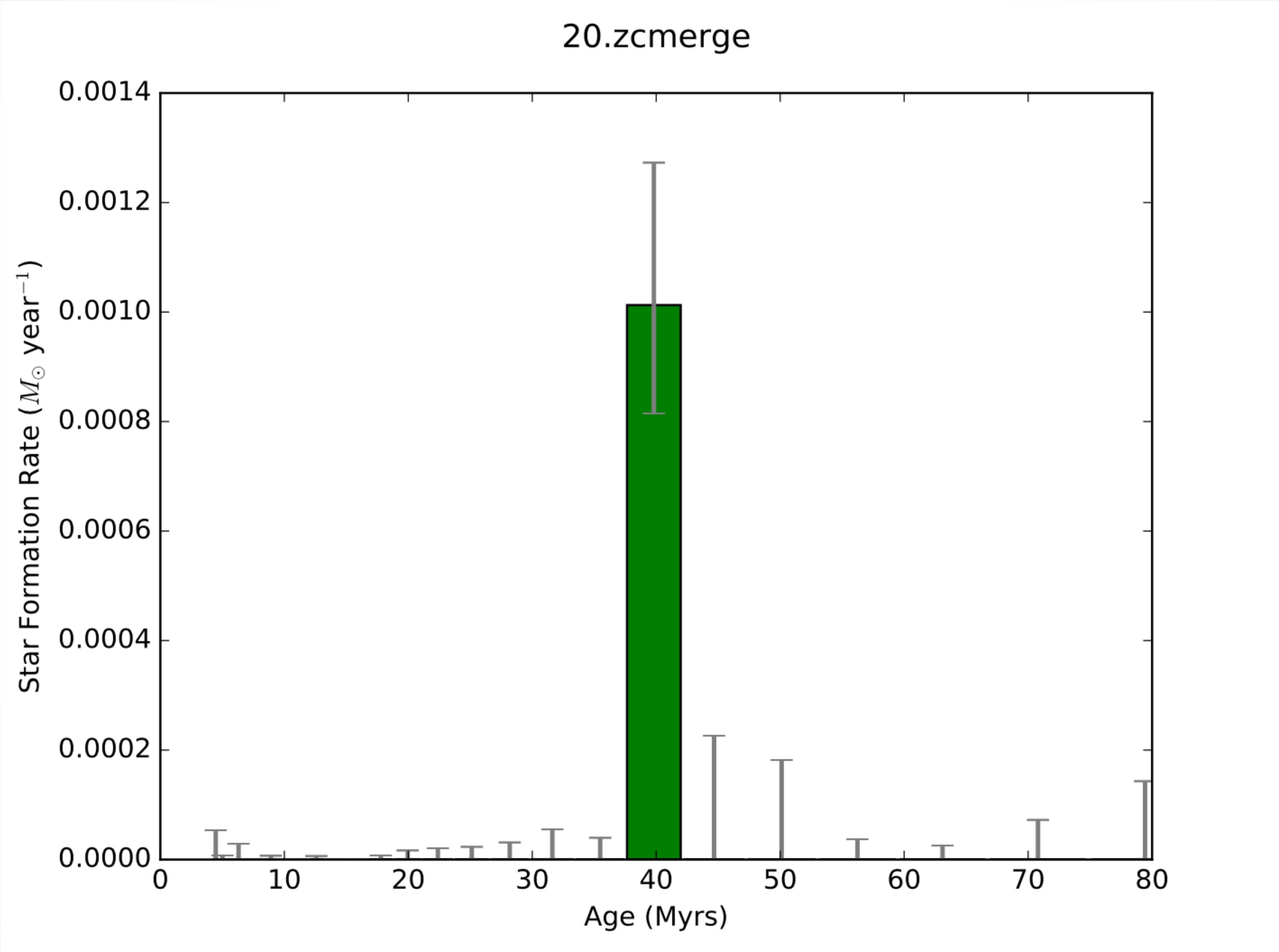
Supernova Remnants as SN Tracers

- Detectable for ~ 10^4 yrs
- Lots of SNRs in nearby galaxies with archival data
  - ✓ ~100 in M31
  - ✓ Up to 65 in M33

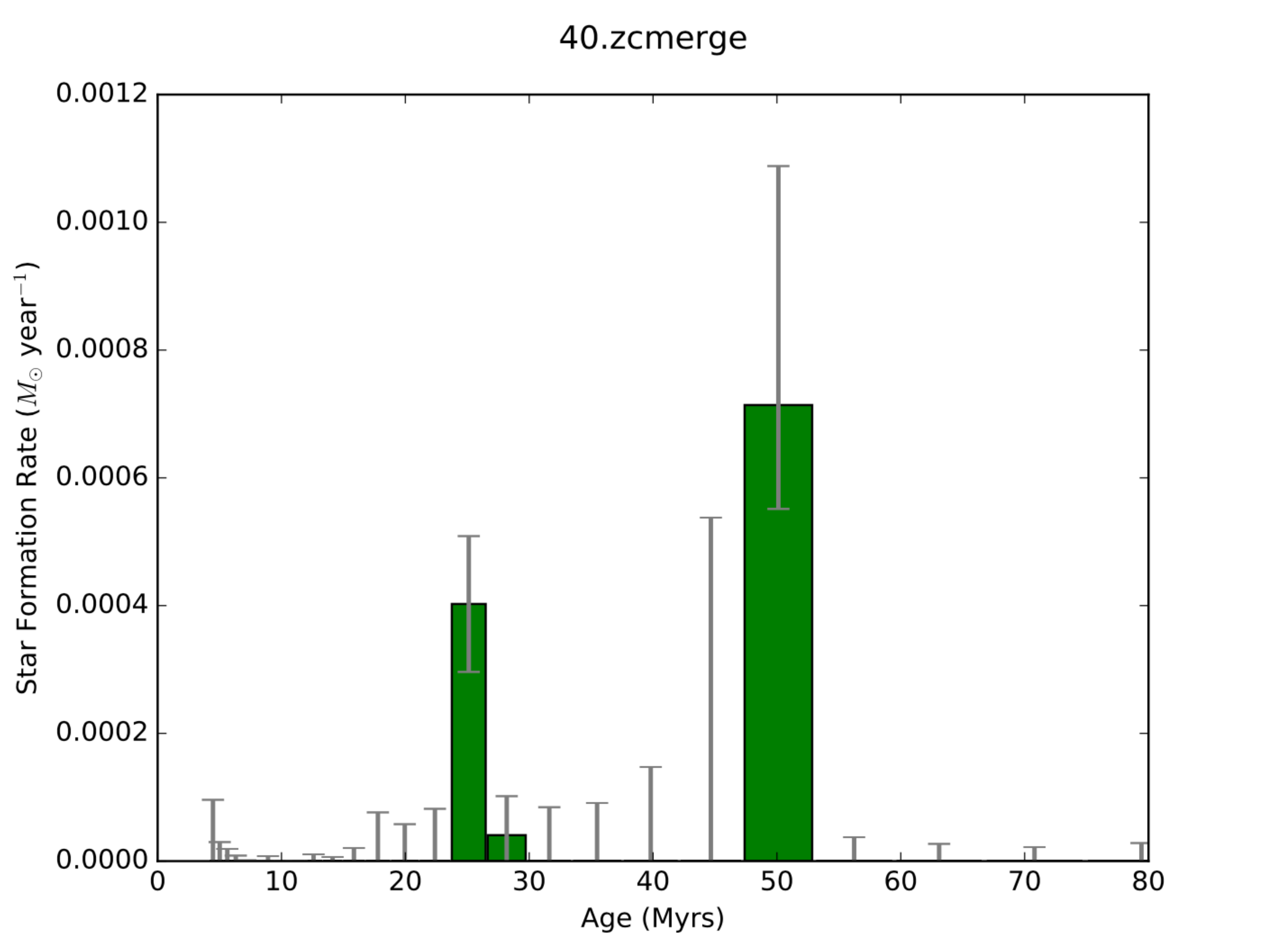
➢Increase the number of progenitors by a factor of 10

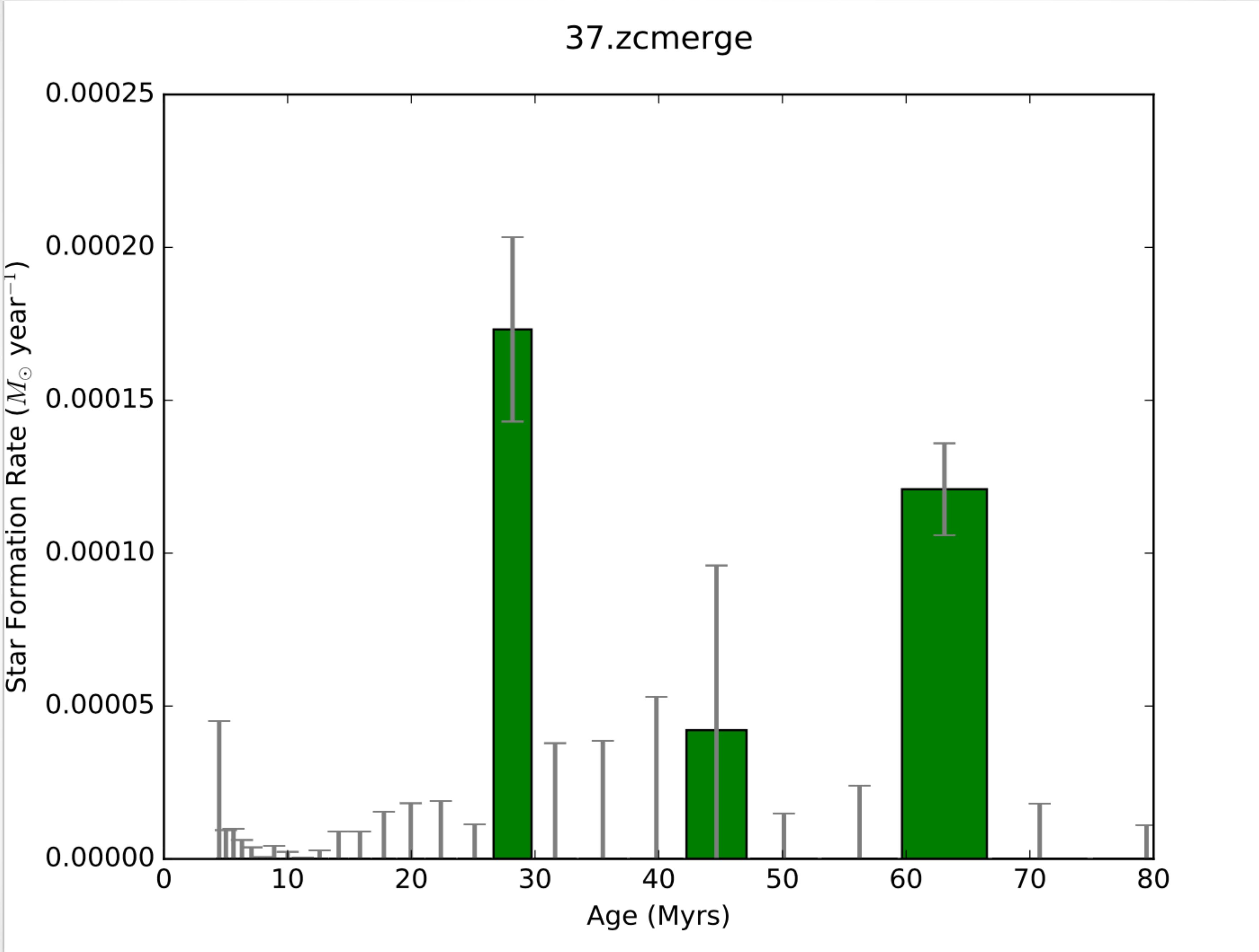


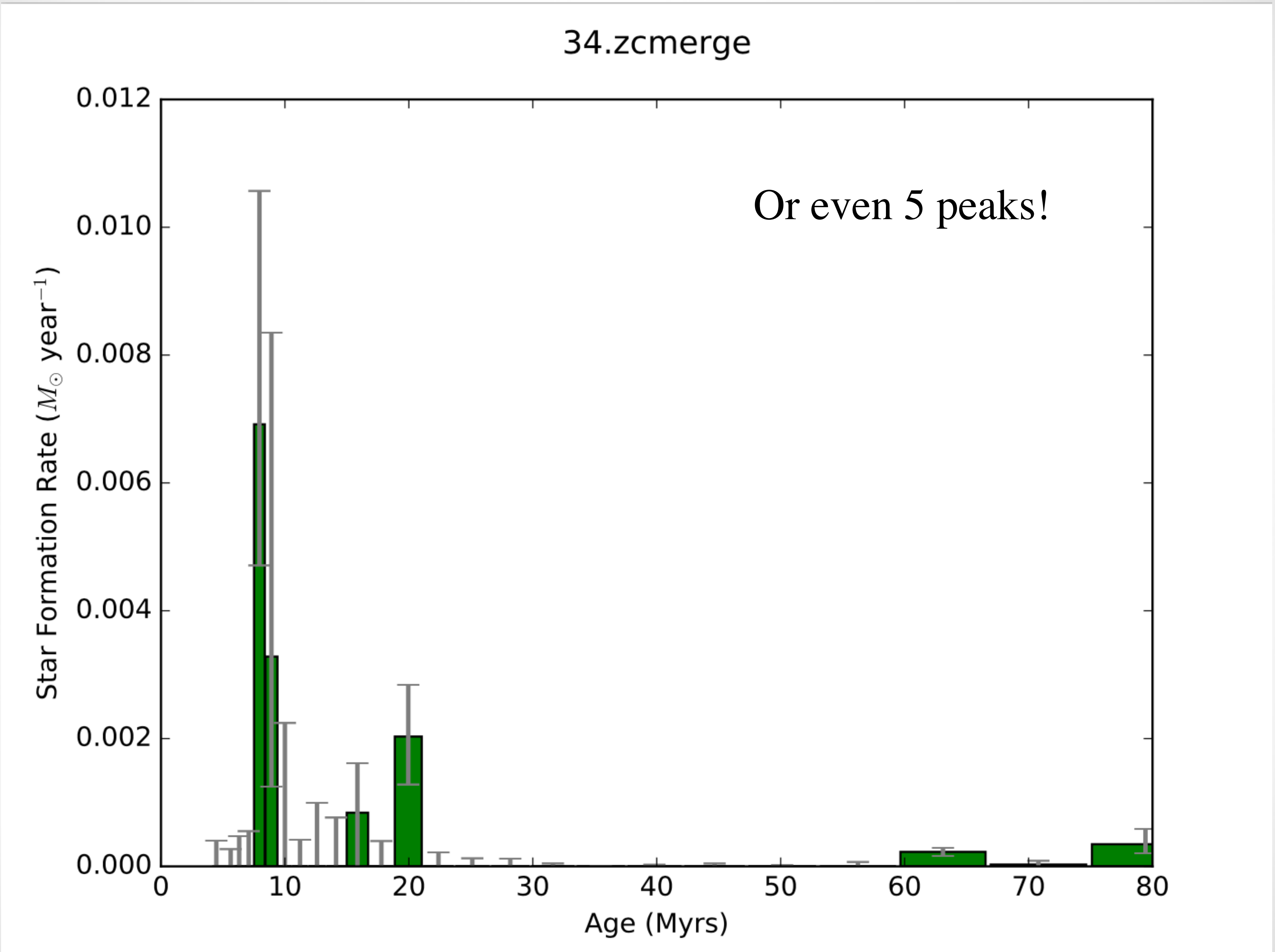
SFH and Ages of SNRs



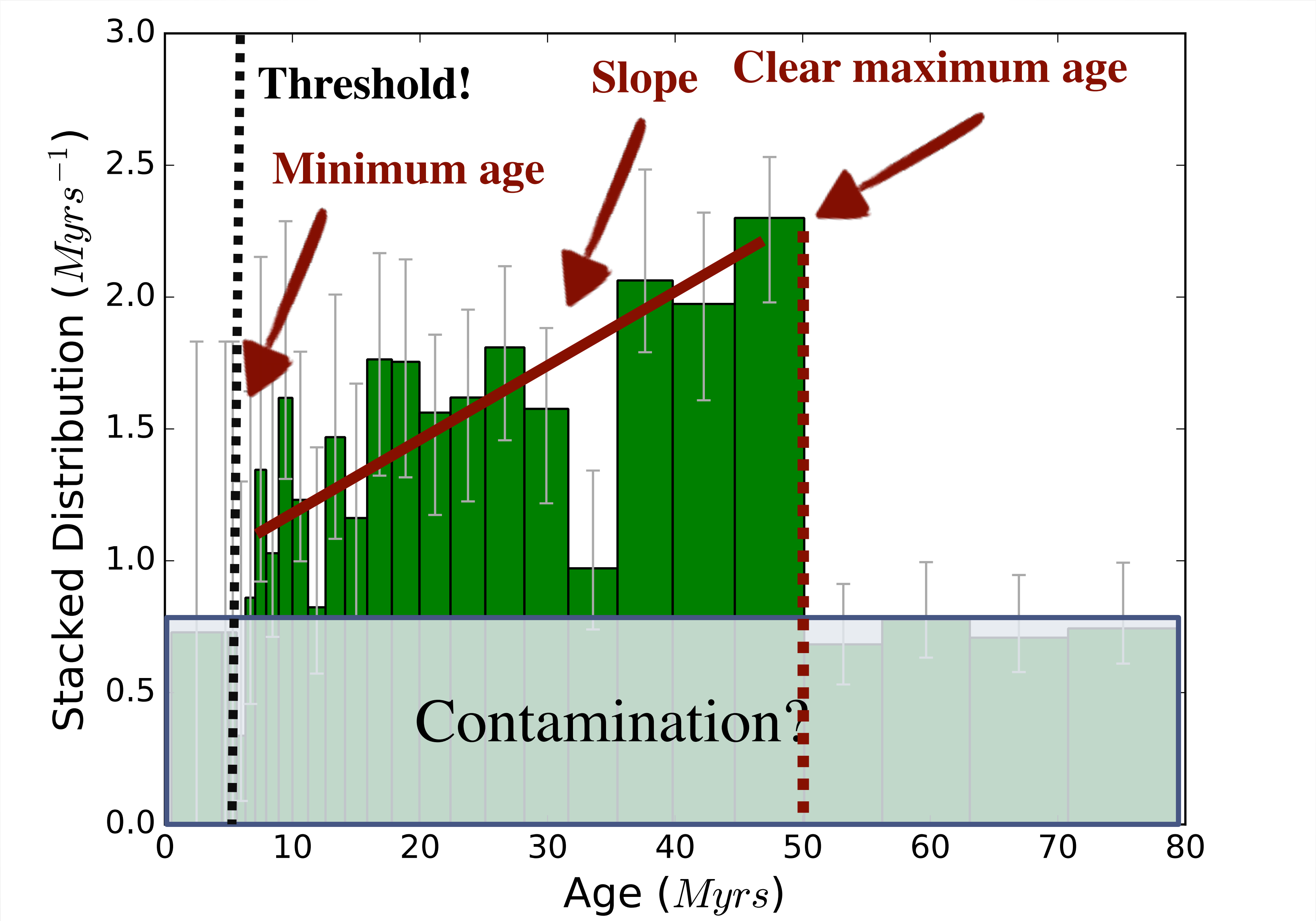
But sometimes….



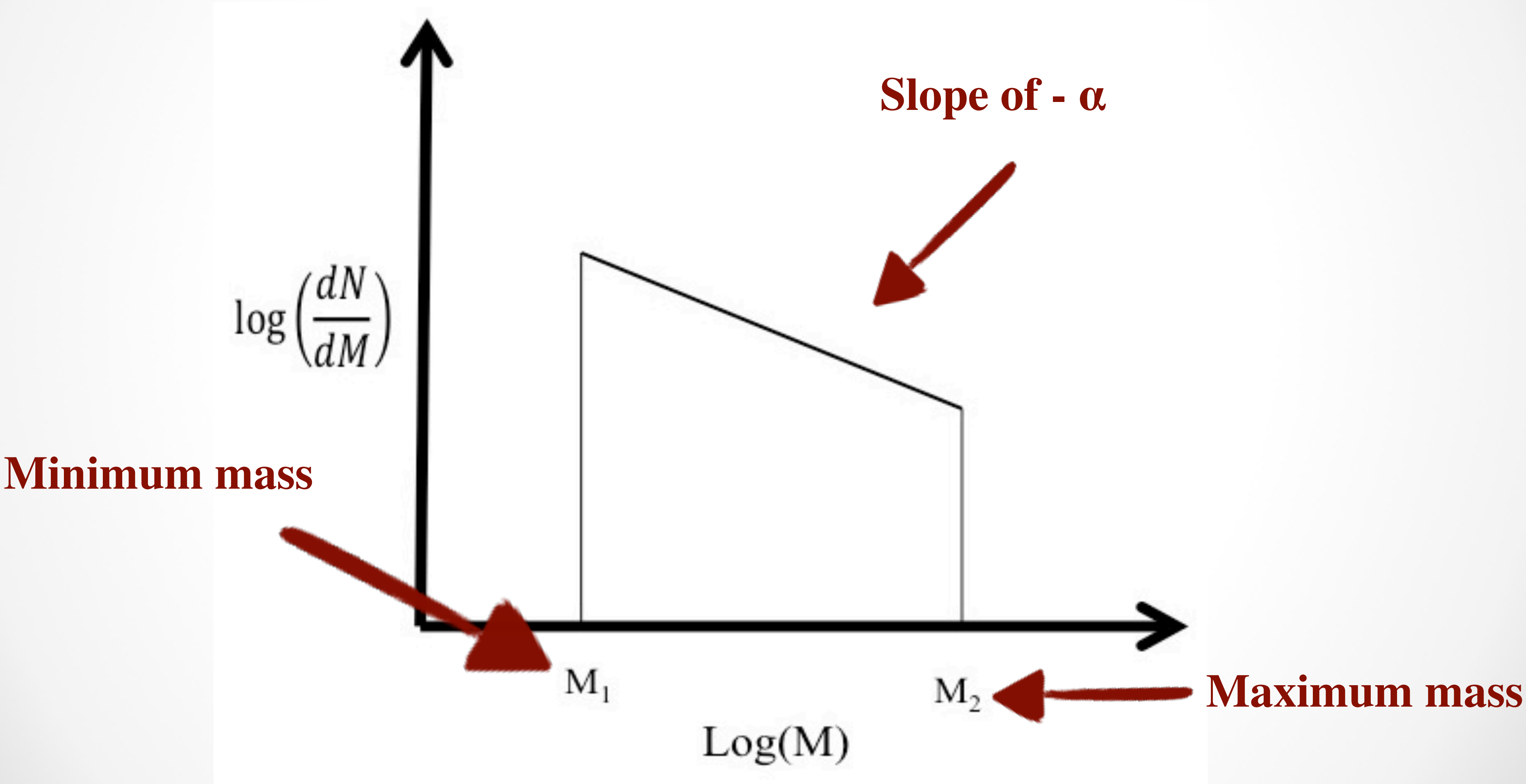

37.zcmerge
Star Formation Rate ($M_\odot$ year^{-1})
0.00025
0.00020
0.00015
0.00010
0.00005
0.00000
0
10
20
30
40
50
60
70
80
Age (Myrs)

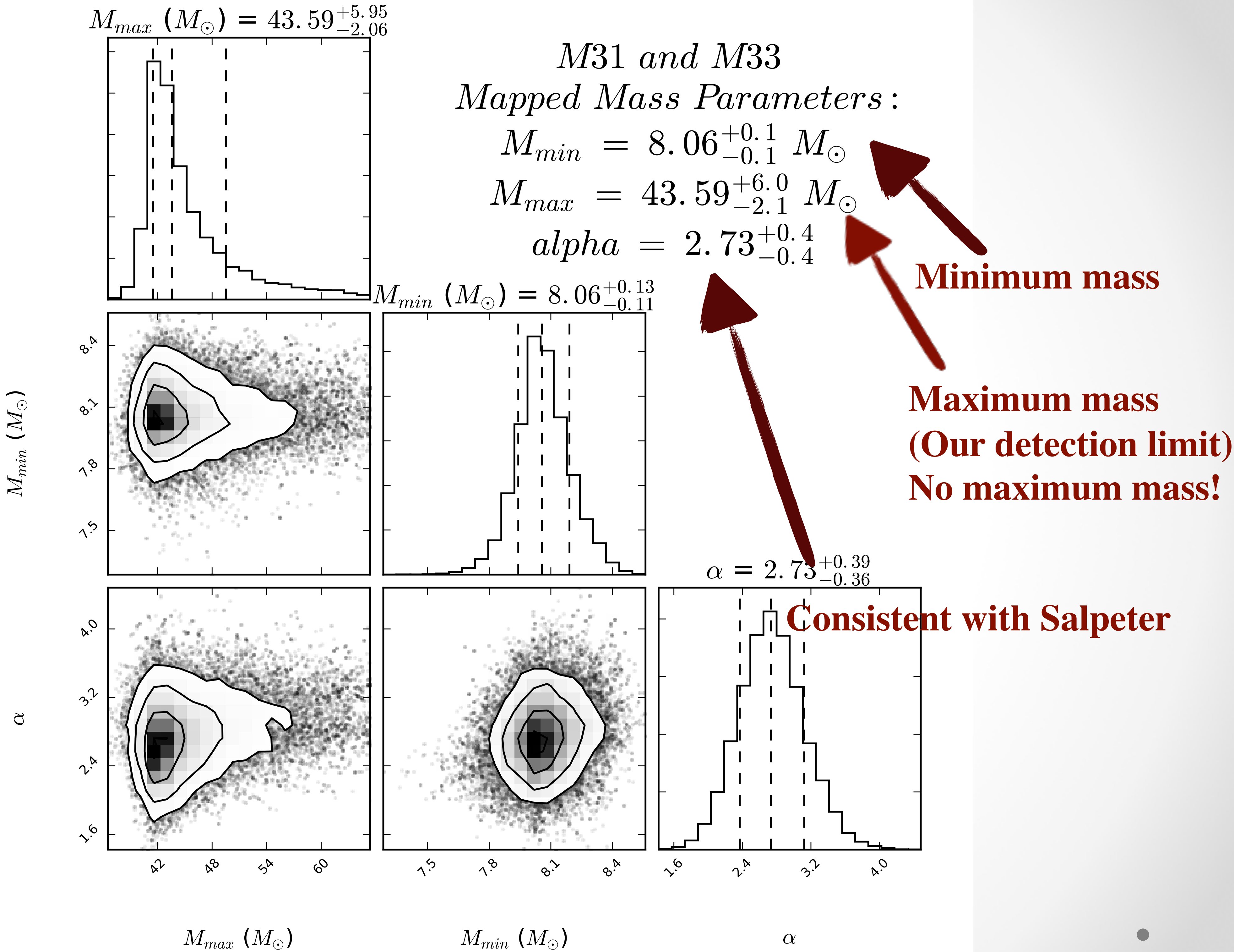

34.zcmerge
Or even 5 peaks!
Star Formation Rate ($M_\odot$ year^{-1})
Age (Myrs)
0.000
0.002
0.004
0.006
0.008
0.010
0.012
0
10
20
30
40
50
60
70
80

Stacked Distribution of 100 SNRs

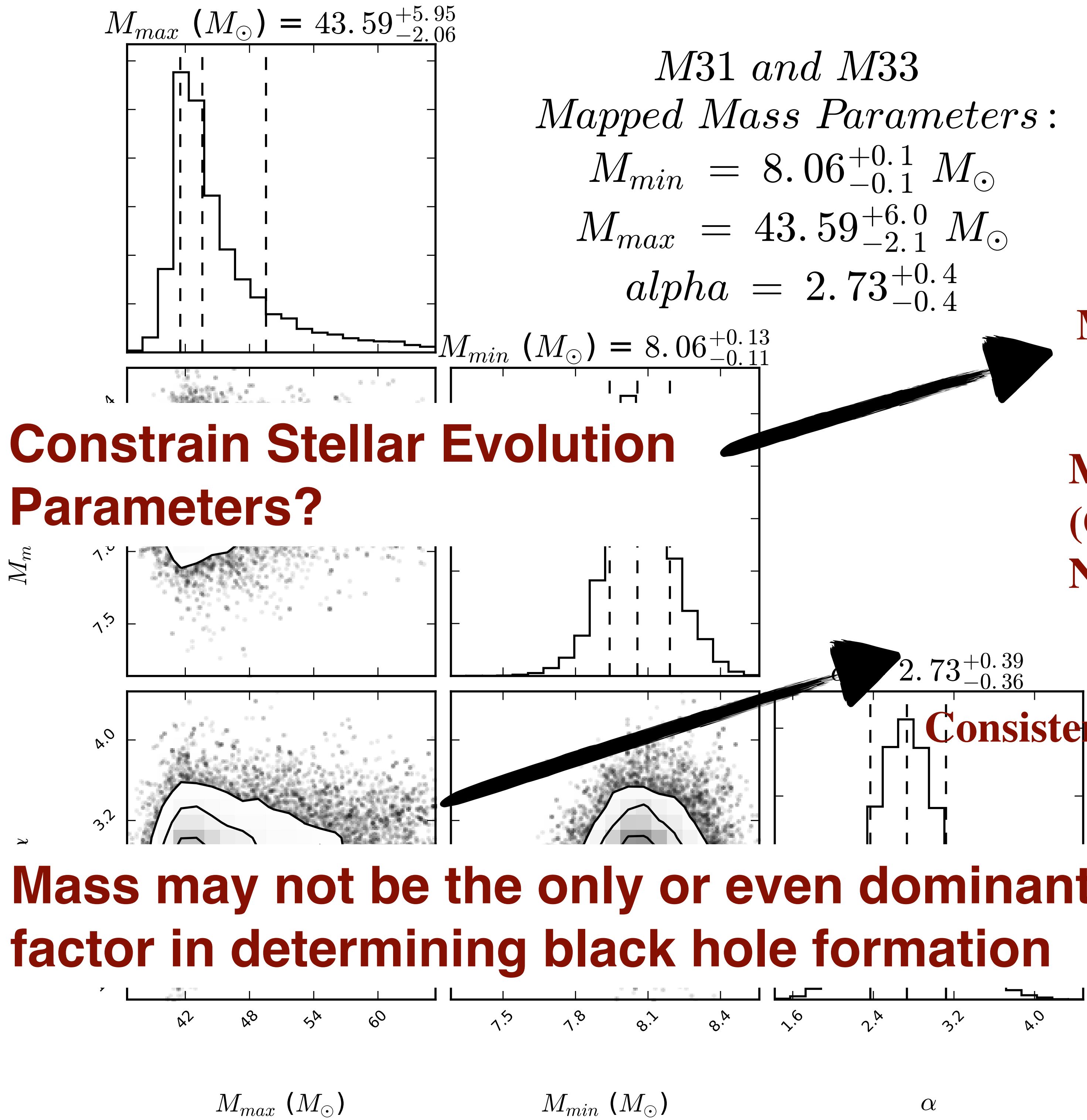


Progenitor Mass Model:





$M_{max}\ (M_\odot) = 43.59^{+5.95}_{-2.06}$
M31 and M33
Mapped Mass Parameters:
$M_{min} = 8.06^{+0.1}_{-0.1}\ M_\odot$
$M_{max} = 43.59^{+6.0}_{-2.1}\ M_\odot$
$alpha = 2.73^{+0.4}_{-0.4}$
Minimum mass
$M_{min}\ (M_\odot) = 8.06^{+0.13}_{-0.11}$
Maximum mass
(Our detection limit)
No maximum mass!
$\alpha = 2.73^{+0.39}_{-0.36}$
Consistent with Salpeter
$M_{min}\ (M_\odot)$
α
$M_{max}\ (M_\odot)$
$M_{min}\ (M_\odot)$
α



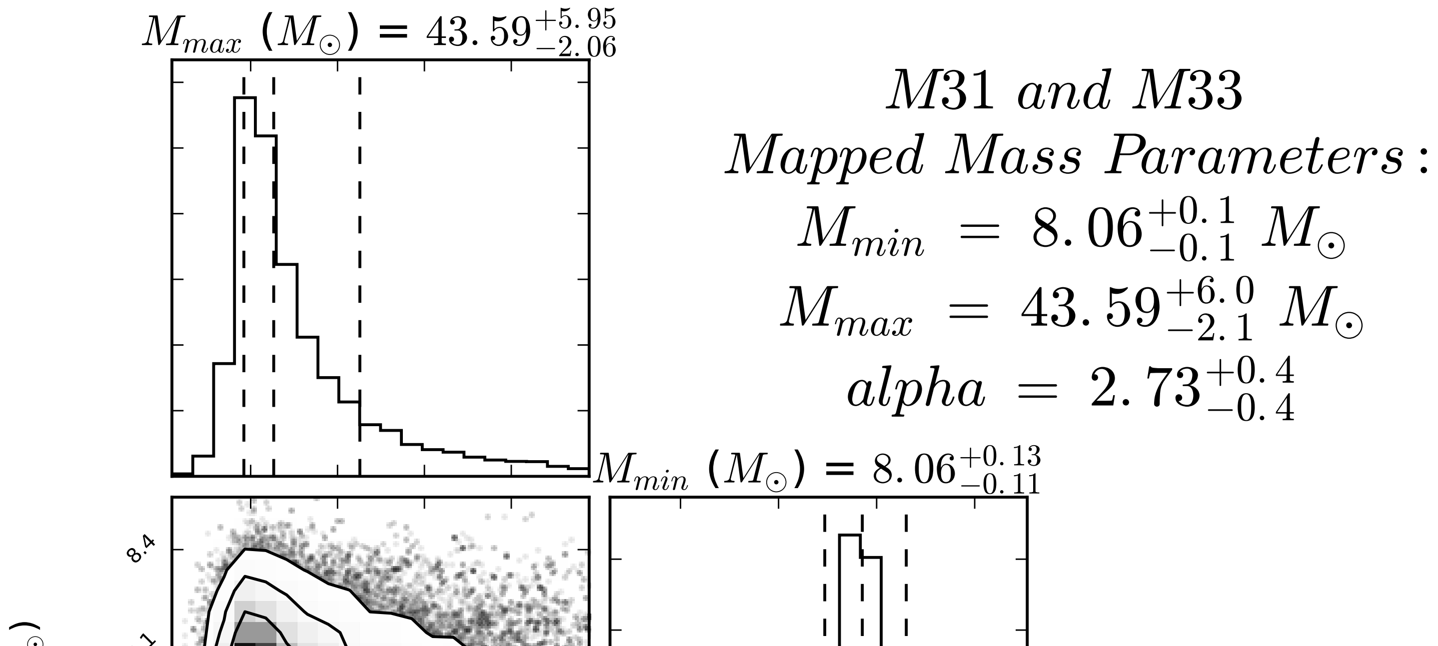
Minimum mass

Constrain Stellar Evolution Parameters?

Maximum mass
(Our detection limit)
No maximum mass!

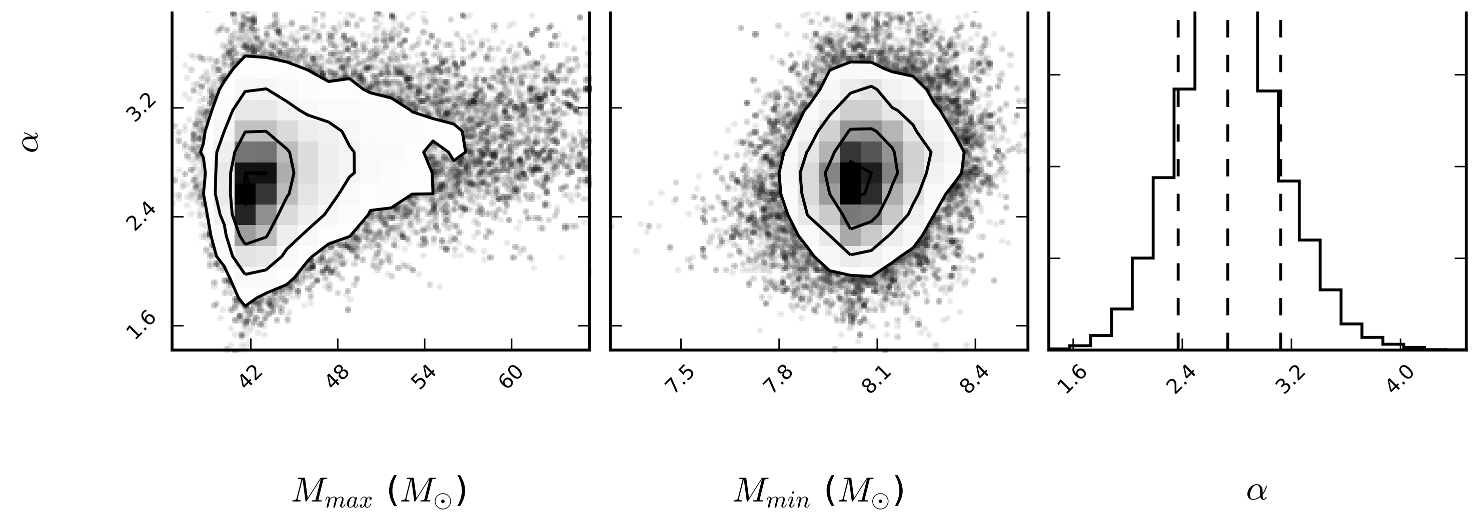
Consistent with Salpeter

Mass may not be the only or even dominant factor in determining black hole formation



Caveats:

- **SNR Catalogs are biased tracers of CCSNe**
- **Still exploring best models for Bayesian inference**
- **We assumed single-star evolution**



Coming Soon…Hundreds more SNR progenitor masses from M83

Theory

How do massive stars end their lives?

Which stars actually explode?

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Numerical simulations are important

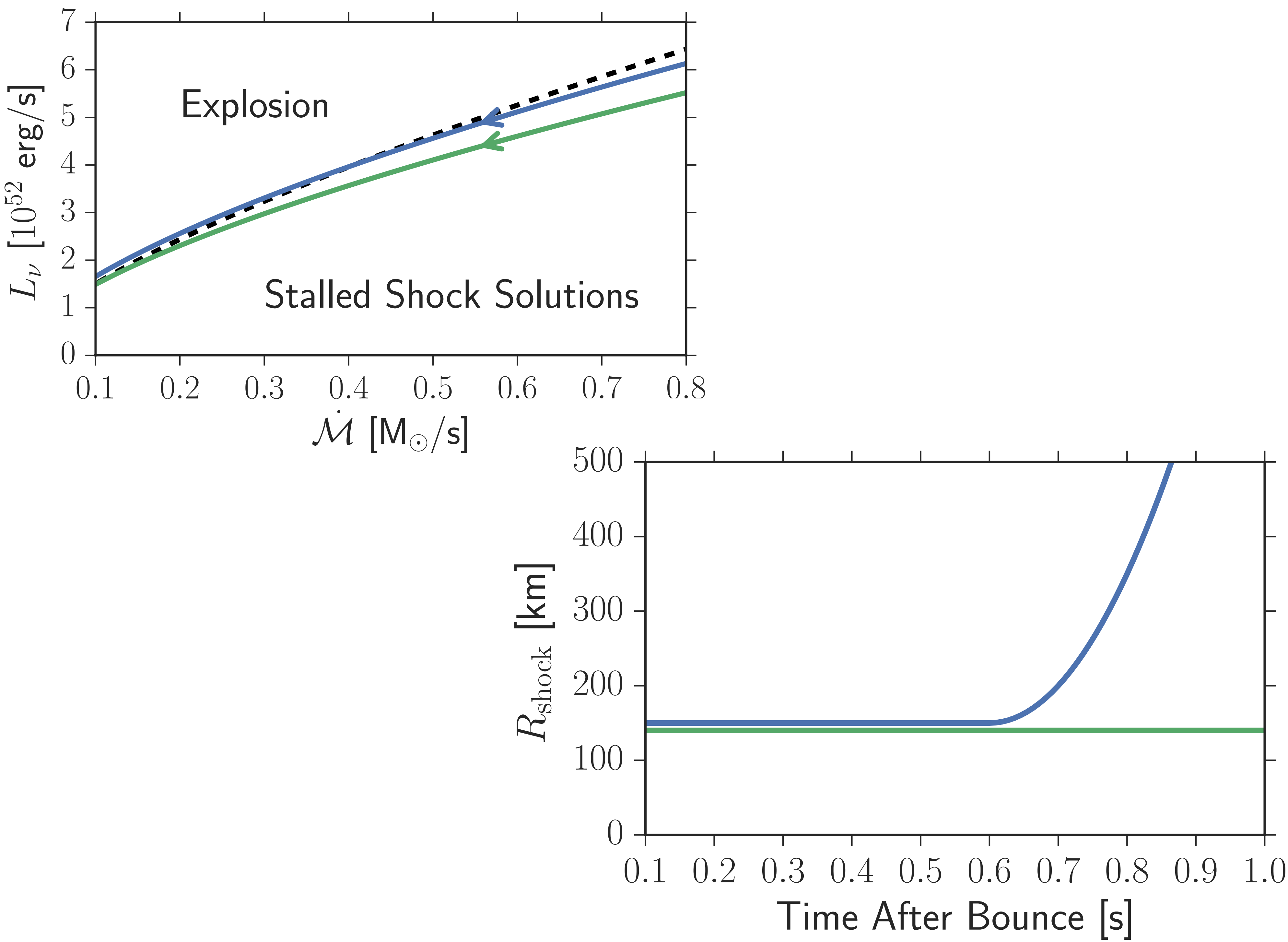
…,but we need to augment this tool with another approach

Analytic Explosion Conditions

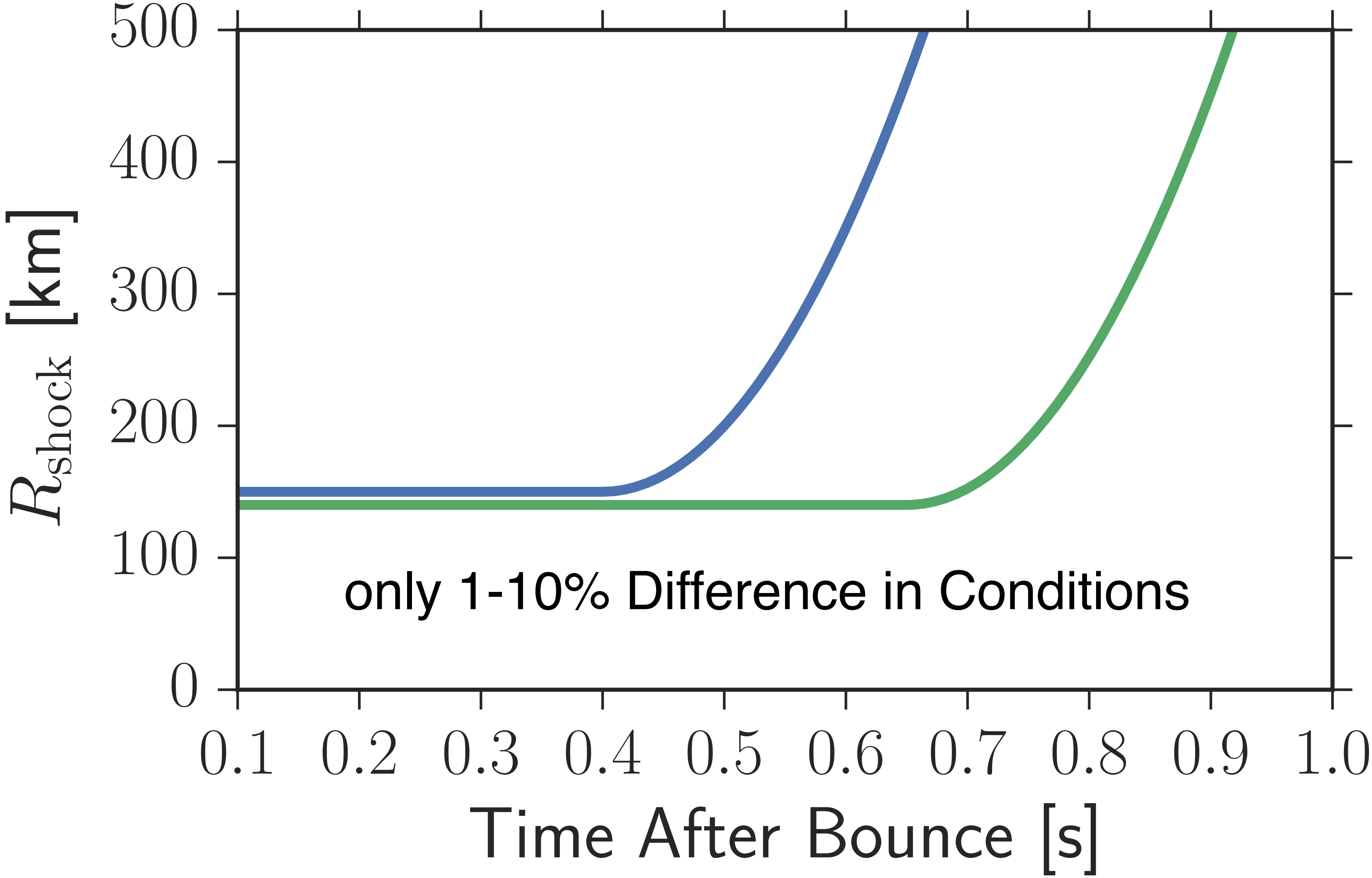
Some progress

- A deep understanding of why stars explode
- Better quantify why some simulations explode and others fail.
- Predict which stars will explode and which won't

Physics	Measured Effect	My Best Guess	Refs.
Neutrino-driven Convections	30%		Murphy & Burrows 2008, Mabanta & Murphy 2017
Progenitor Structure		$\mathcal{O}(1)$	Sukhbold et al. 2016
SASI		$\lesssim$ 30%	Hanke et al. 2013, Fernández et al. 2014, Fernández 2015
GR		~ 10%	Marek et al. 2009, Müller 2012, Roberts et al. 2016
EOS		~ 10%	Couch 2012
many-body corrections to ν-nucleon scattering		~ 5%	Horowitz et al. 2017, Burrows et al. 2106
Progenitor Perturbations		~ 1-10%	Couch 2013, Müller & Janka 2015
ν-transport		3-50 %	Richers et al. 2017



Explosion
Stalled Shock Solutions
L_ν [10^{52} erg/s]
$\dot{\mathcal{M}}$ [$M_\odot$/s]
0
1
2
3
4
5
6
7
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
$R_{\rm shock}$ [km]
0
100
200
300
400
500
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Time After Bounce [s]



500
400
300
200
100
0
$R_{\rm shock}$ [km]
only 1-10% Difference in Conditions
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Time After Bounce [s]

Analytic Explosion Conditions

- A deep understanding of why stars explode
- Better quantify why some simulations explode and others fail.
- Predict which stars will explode and which won't

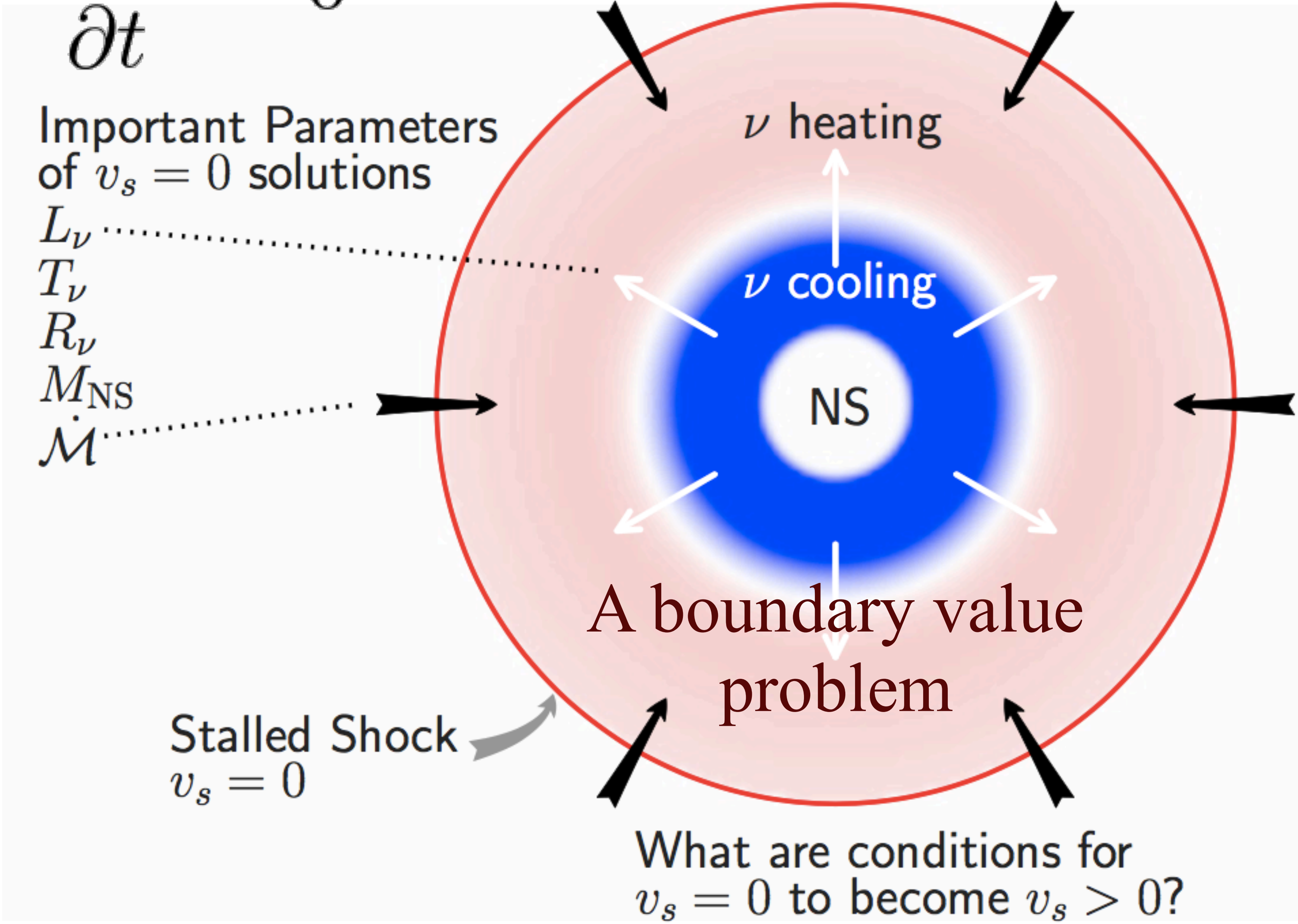
Toward Analytic Explosion Conditions

- Empirical
  - O'conor & Ott 2011, Ertl 2016
- Heuristic
  - e.g. Heating and advection time scales
- First Principles (kind of…)
  - Burrows & Goshy 1993, Pejcha & Thompson 2012, Müller 2016, Murphy & Dolence 2017

Toward Analytic Explosion Conditions

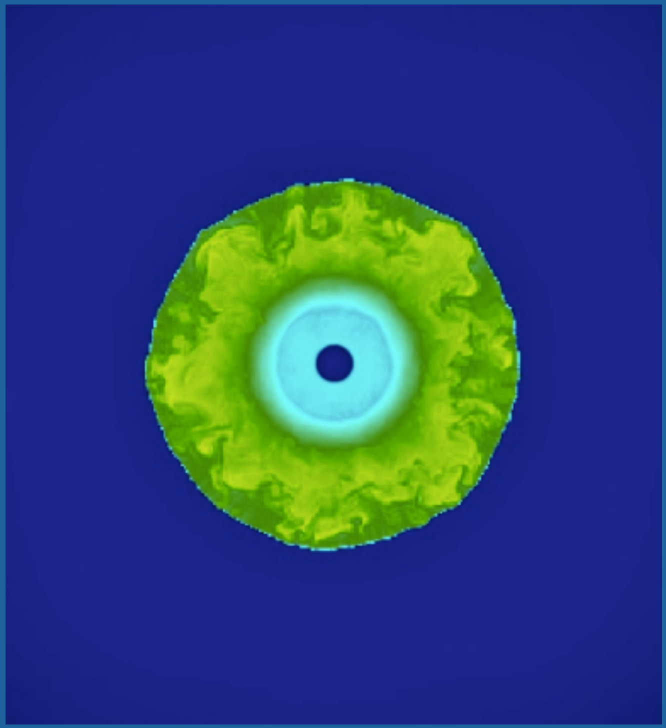
Murphy & Dolence 2017
Mabanta & Murphy 2017

$$\frac{\partial(.)}{\partial t} = 0$$



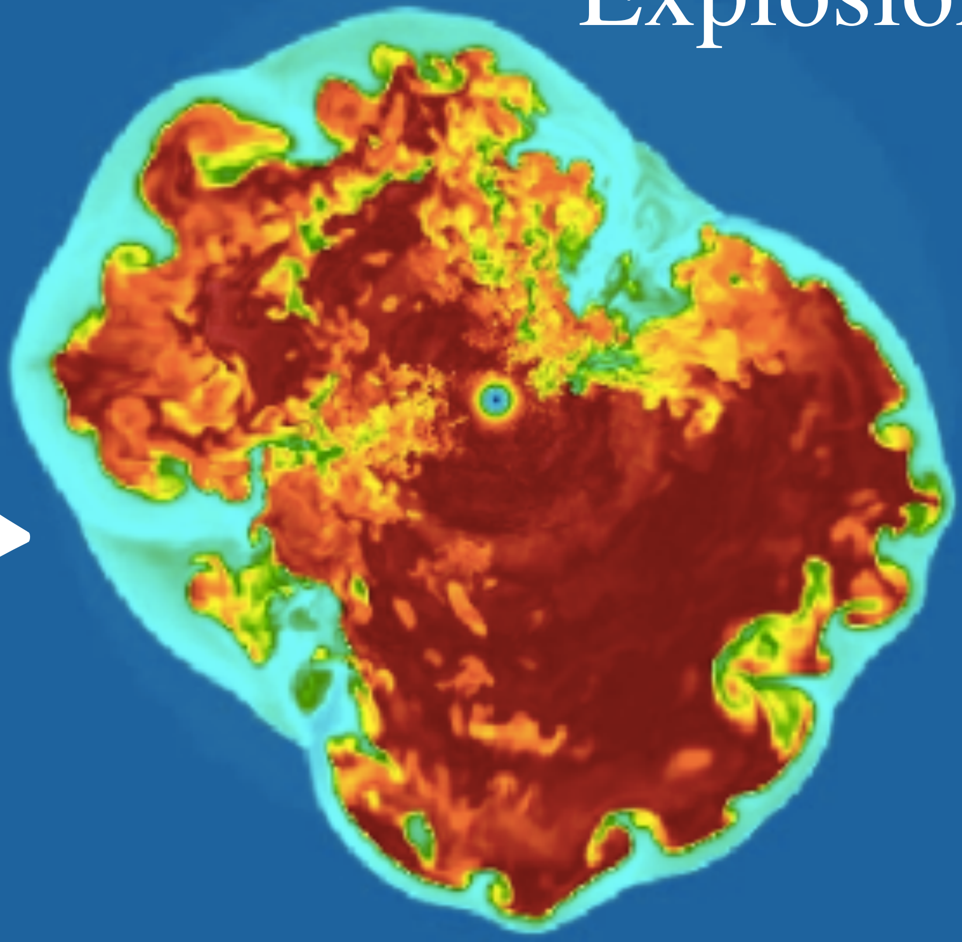
Fundamental Question of Core-Collapse Theory

Stalled Shock



?

Explosion

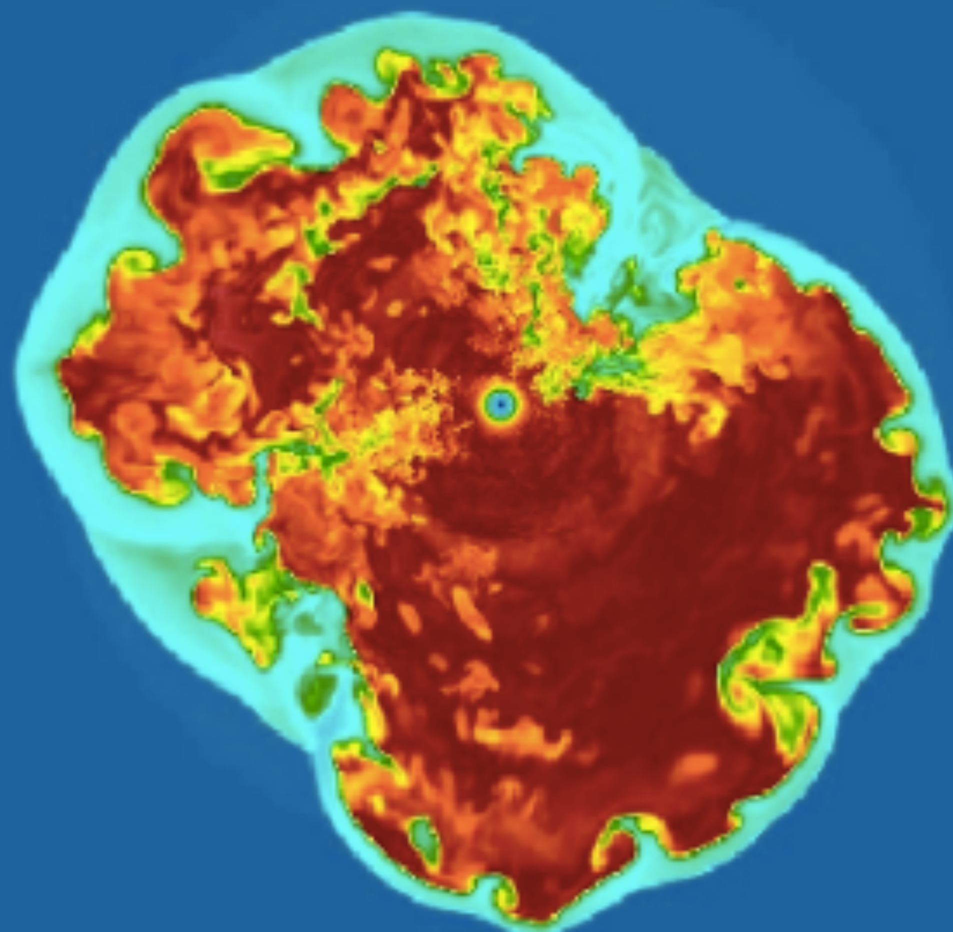


Murphy et al. 2013

Primary Result of Last Three Decades

1D simulations rarely explode, yet multi-D simulations often do.

Why?

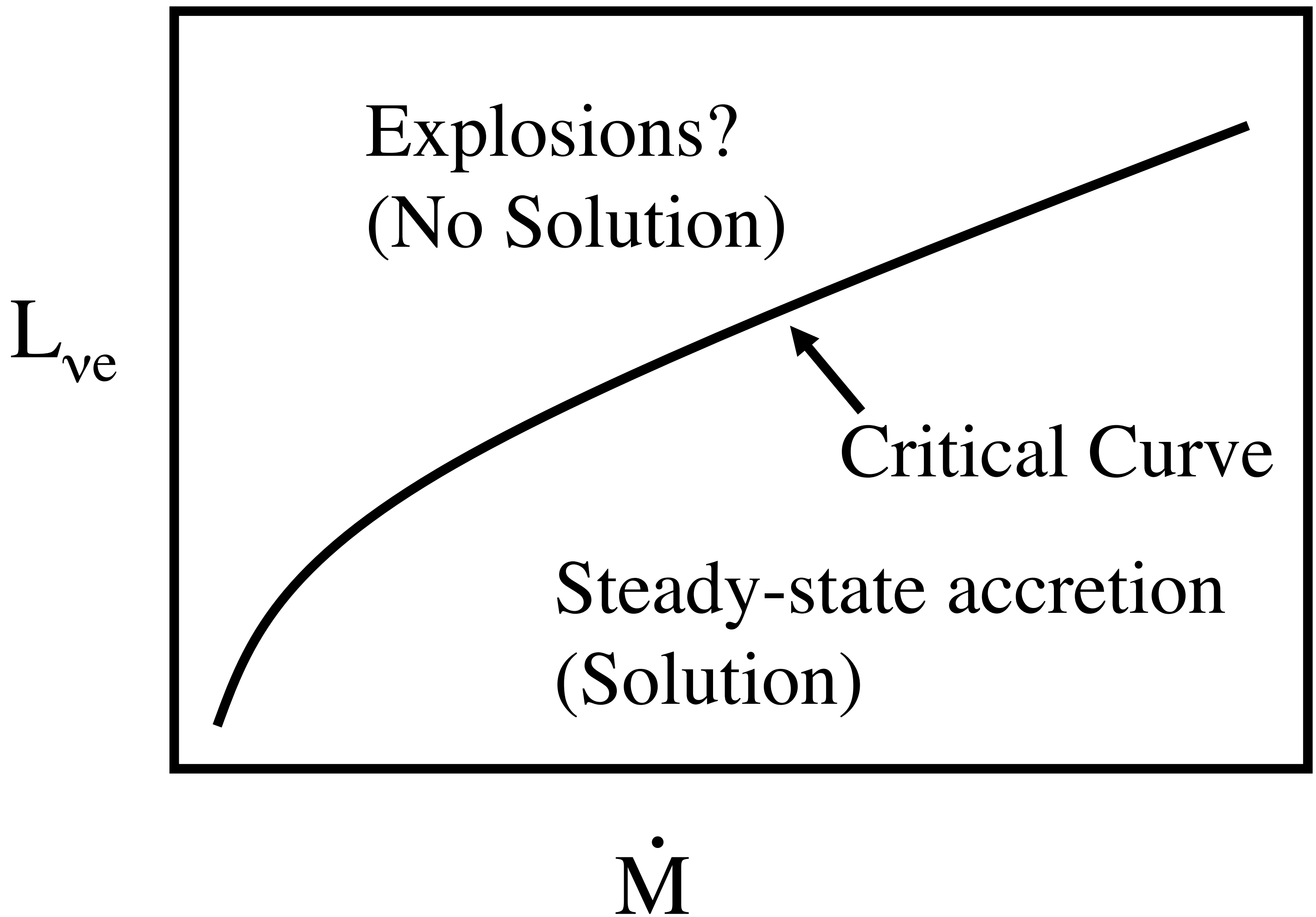


Murphy et al. 2013

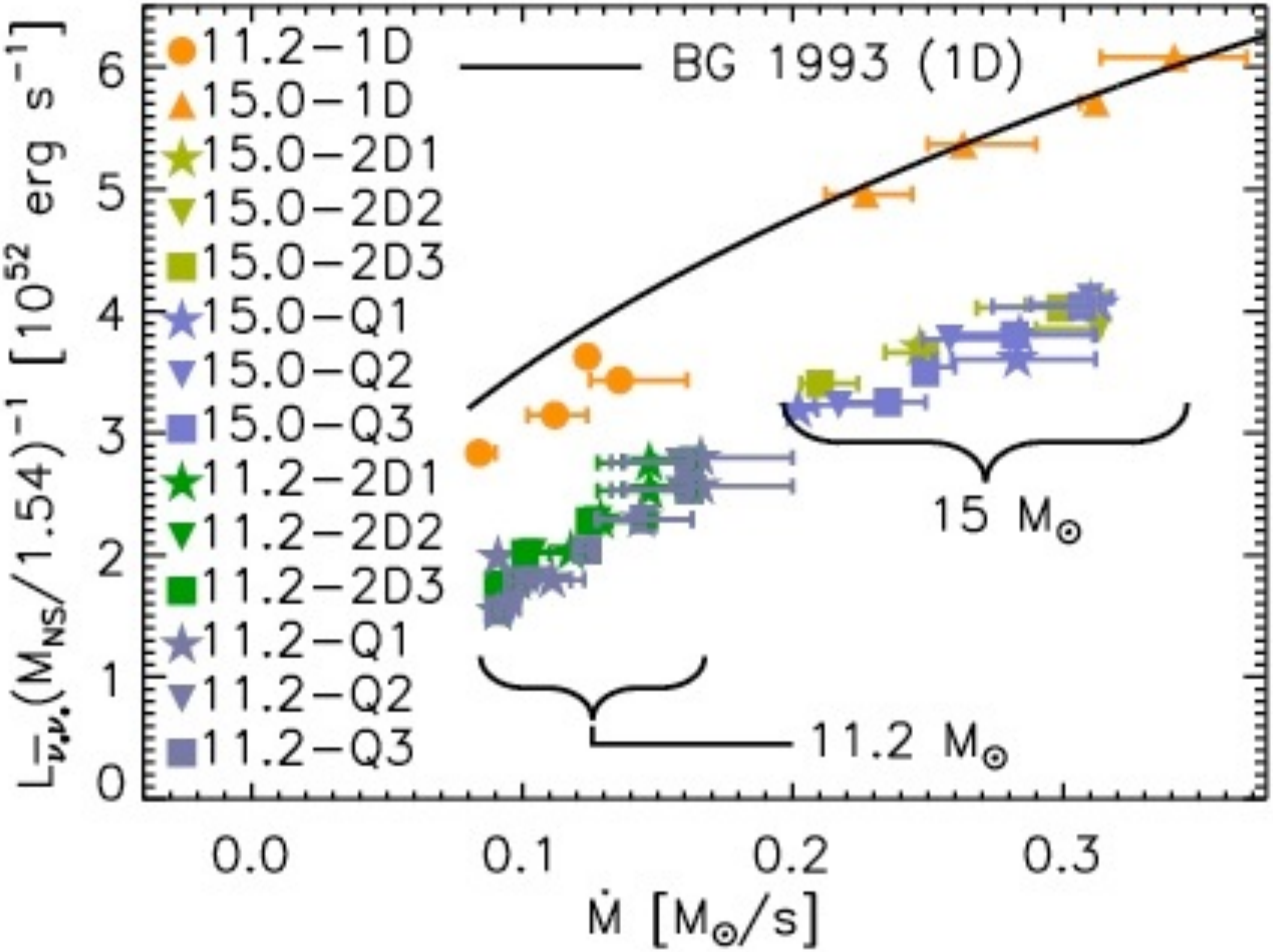
Let’s assume that the delayed-neutrino mechanism works

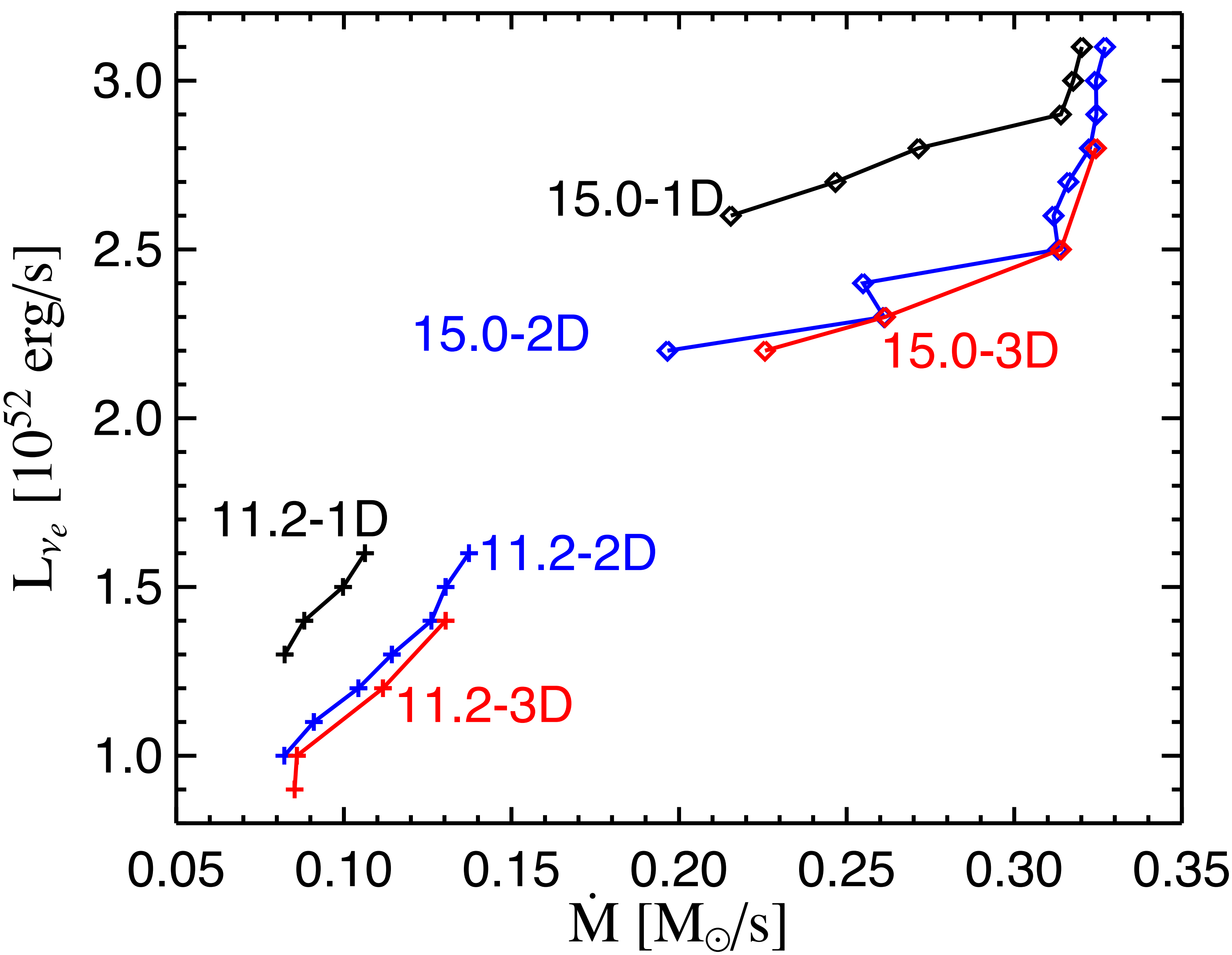
What are the conditions for explosion?

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



Murphy & Burrows '08



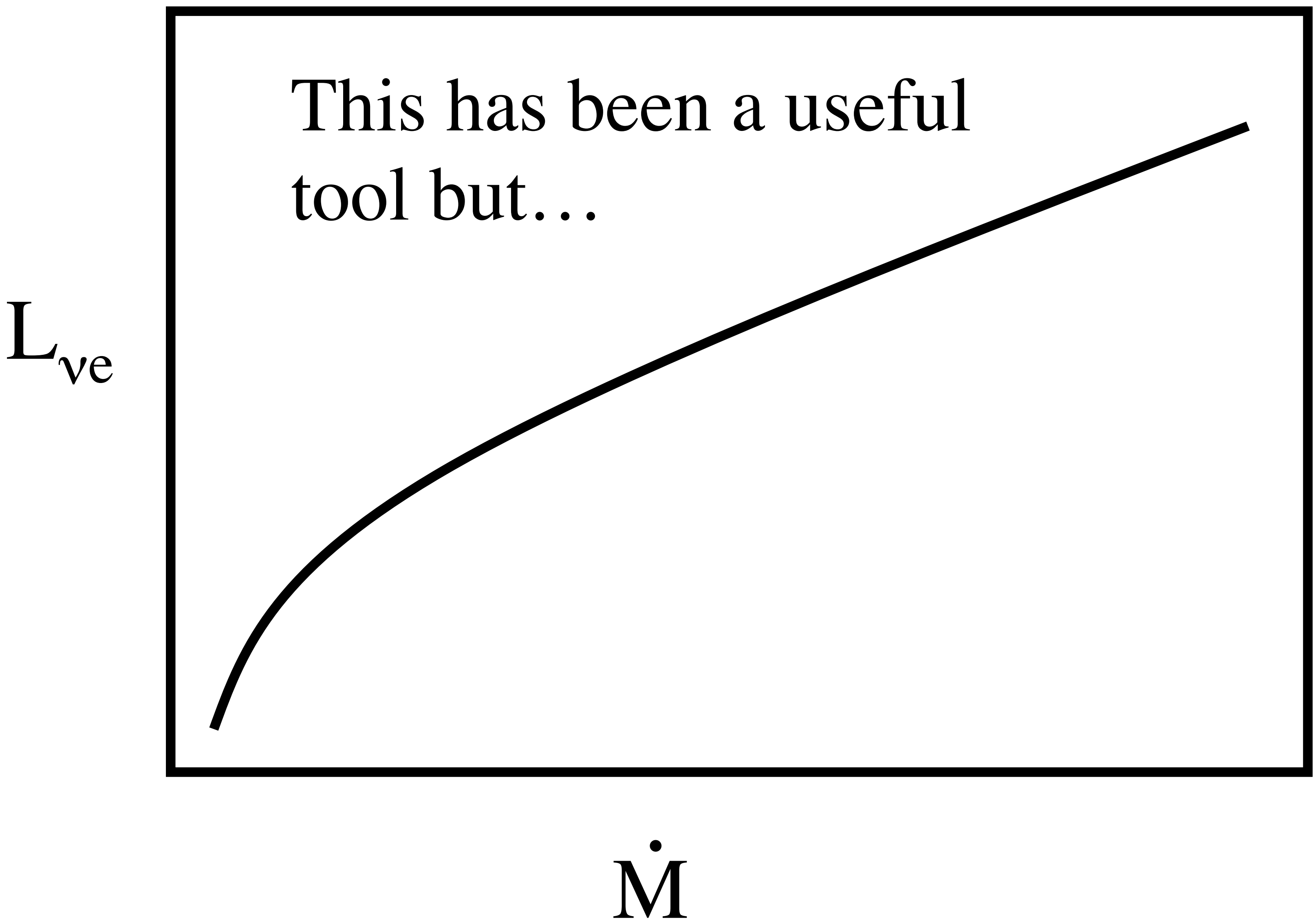


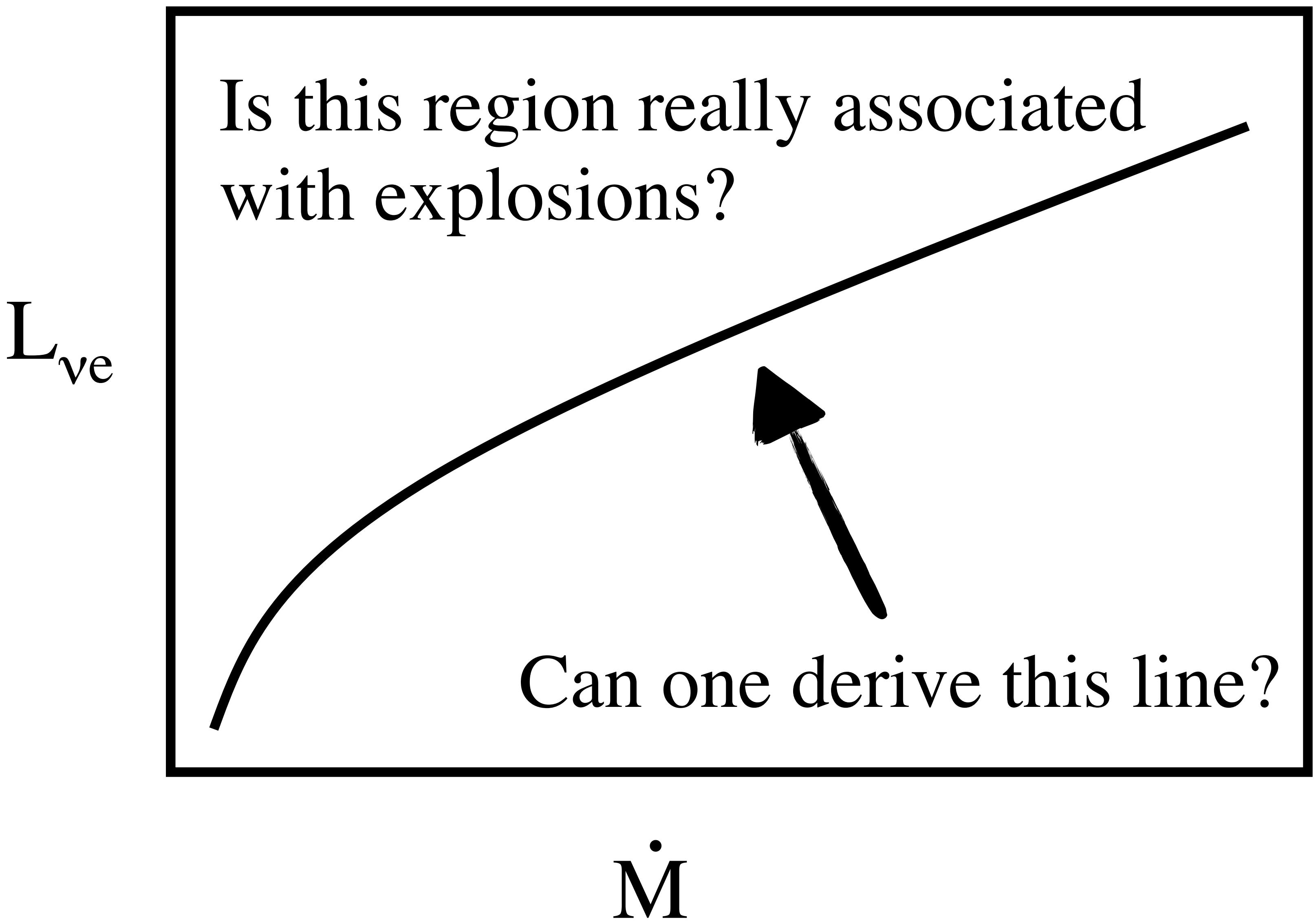
Hanke et al 2011

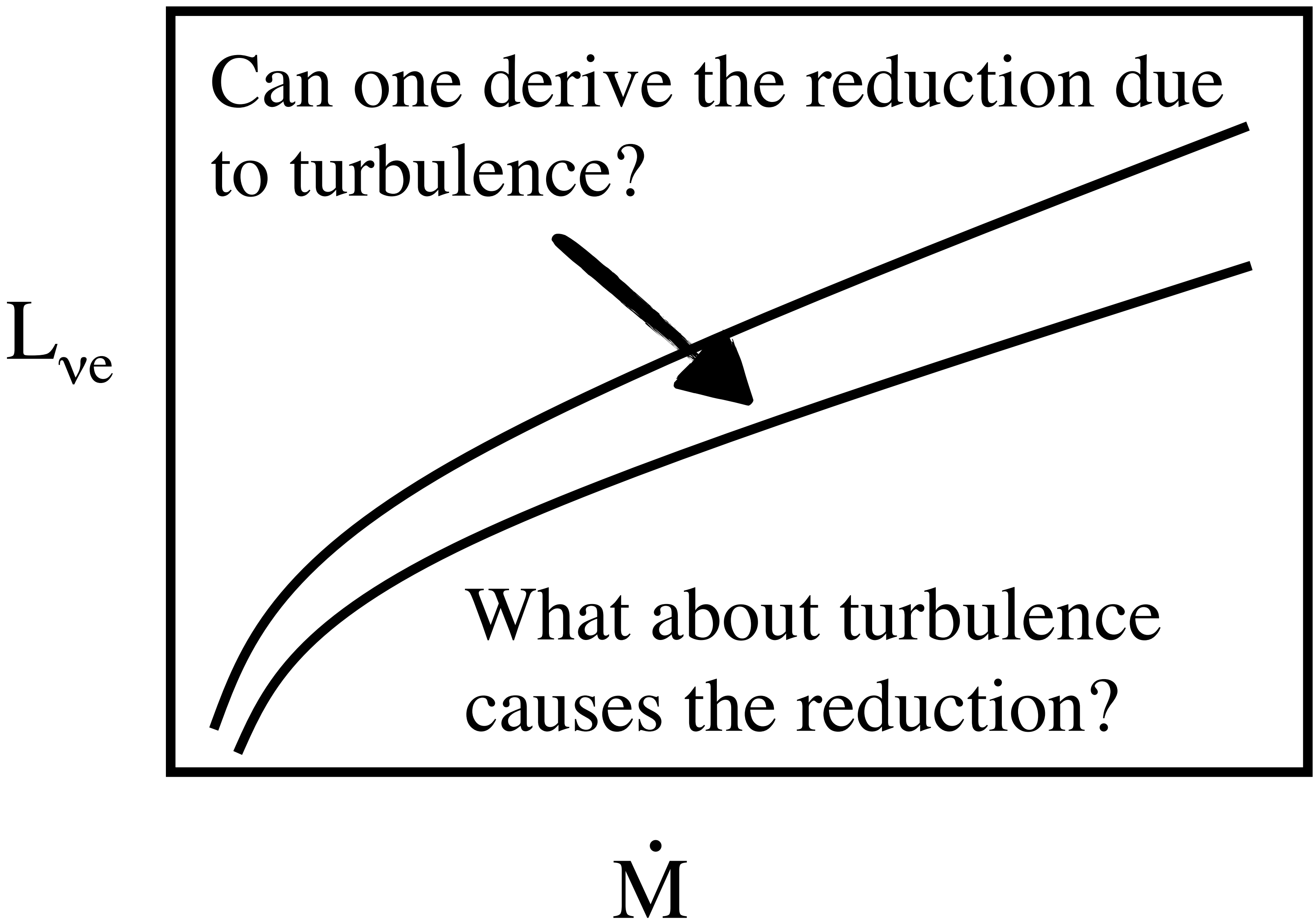
2D & 3D critical luminosity lower than 1D

Turbulence plays an important role, but how was not clear.

Murphy & Burrows 2008
Murphy & Meakin 2012
Burrows, Dolence, and Murphy 2012
Murphy, Burrows, and Dolence 2013
Dolence, Burrows, and Murphy 2013
Couch & Ott 2015
Radice et al. 2015

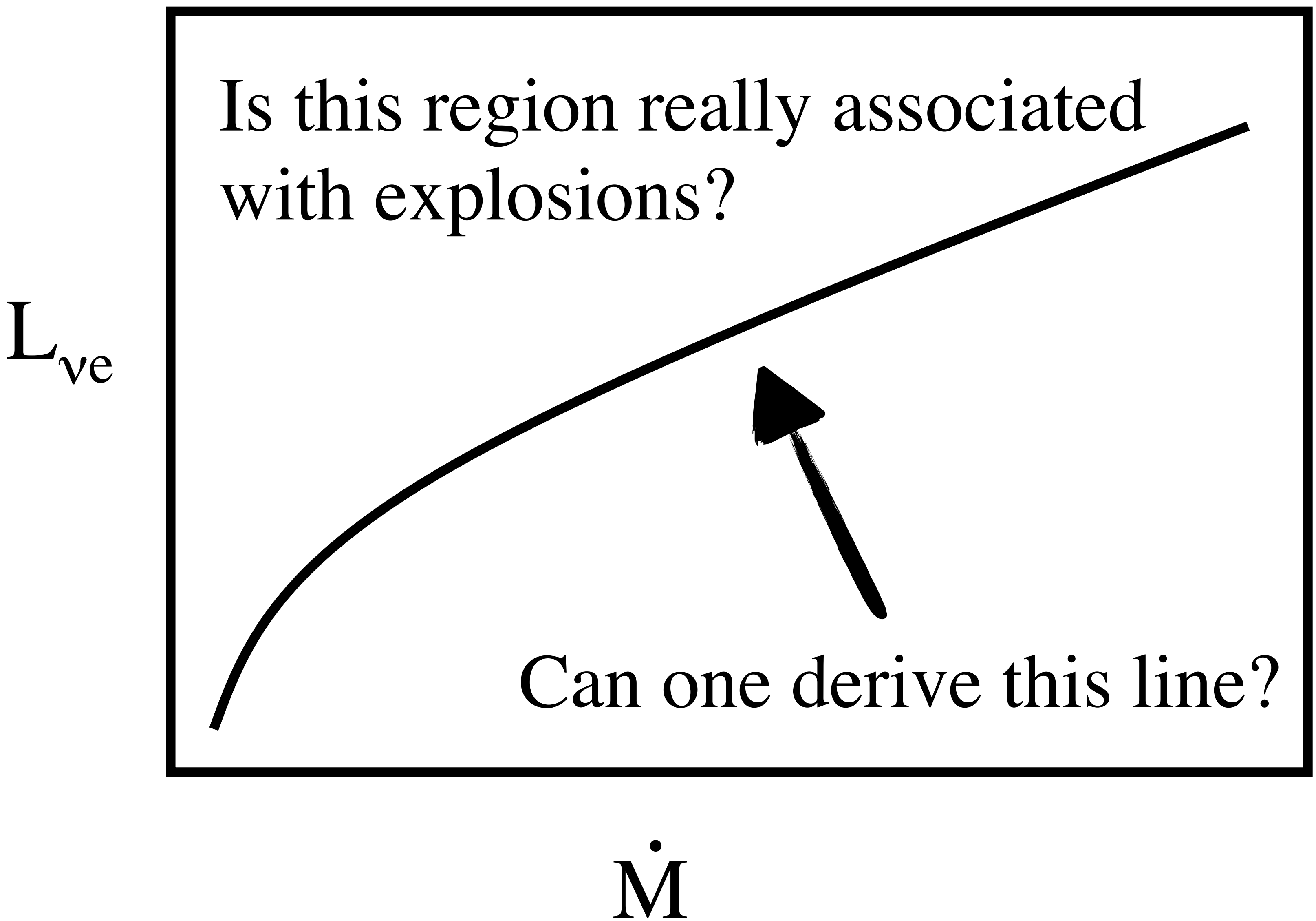

This has been a useful tool but…
$L_{\nu e}$
$\dot{M}$


Is this region really associated with explosions?
$L_{\nu e}$
Can one derive this line?
$\dot{M}$



Can one derive the reduction due to turbulence?
$L_{\nu e}$
What about turbulence causes the reduction?
$\dot{M}$

First…

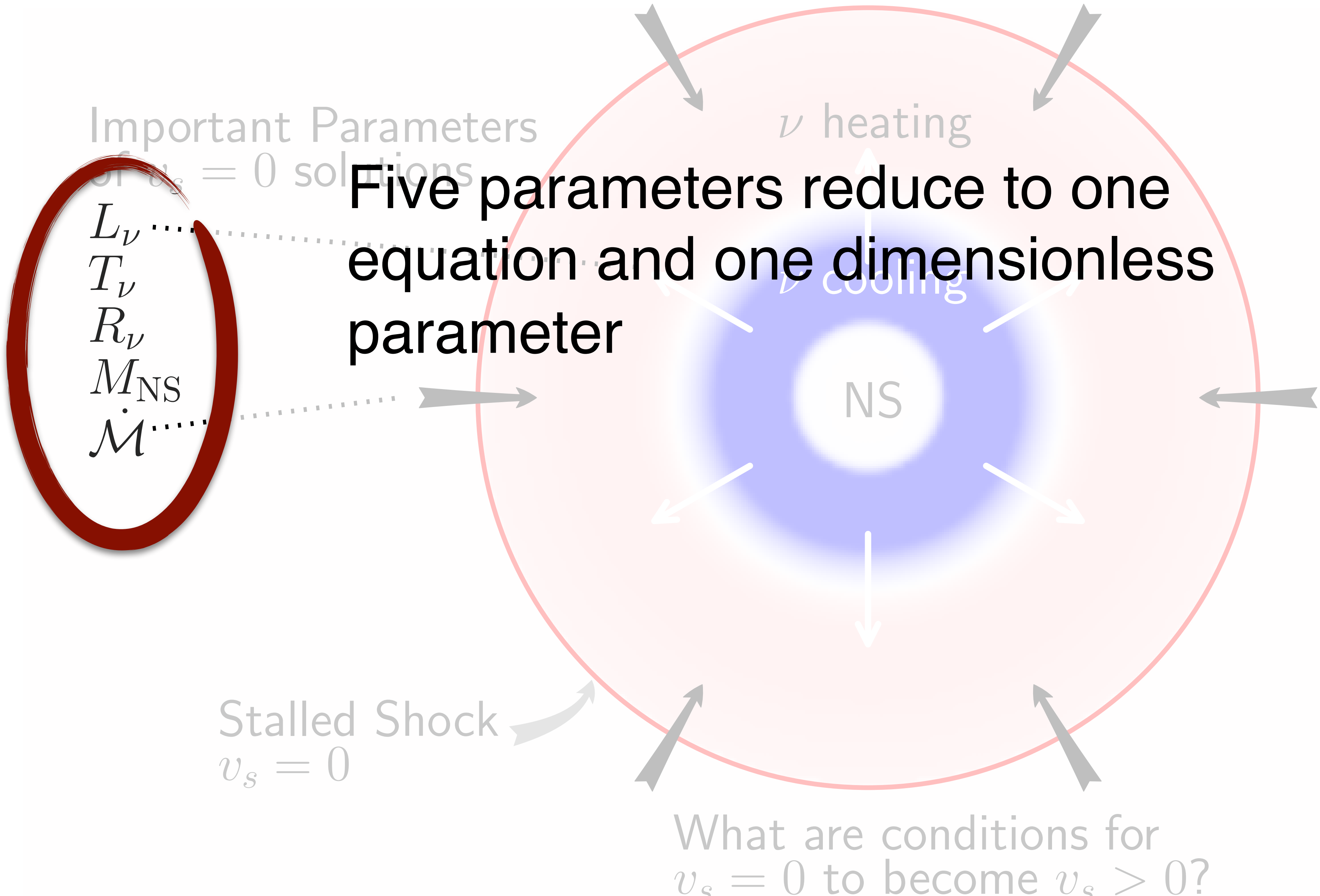


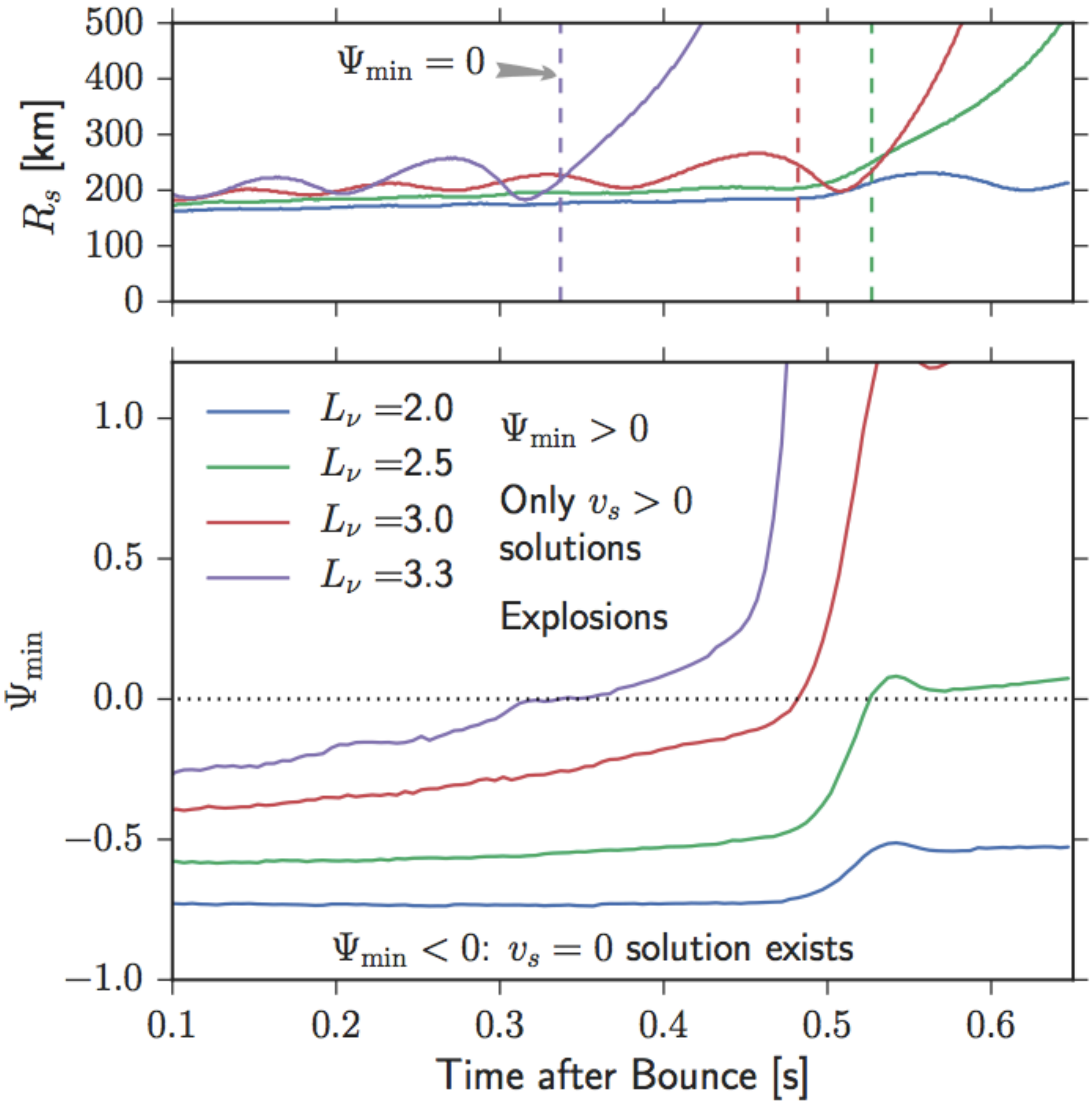
Is this region really associated with explosions?
Can one derive this line?
$L_{\nu e}$
$\dot{M}$

An Integral Condition for Explosion

(Murphy & Dolence 2017)

Five parameters reduce to one equation and one dimensionless parameter





$\Psi_{\rm min} = 0$
R_s [km]
500
400
300
200
100
0
L_ν =2.0
L_ν =2.5
L_ν =3.0
L_ν =3.3
$\Psi_{\rm min} > 0$
Only $v_s > 0$ solutions
Explosions
$\Psi_{\rm min} < 0$: $v_s = 0$ solution exists
$\Psi_{\rm min}$
1.0
0.5
0.0
−0.5
−1.0
0.1
0.2
0.3
0.4
0.5
0.6
Time after Bounce [s]

So what is $\Psi_{\min}$?

Let's start with two assumptions:

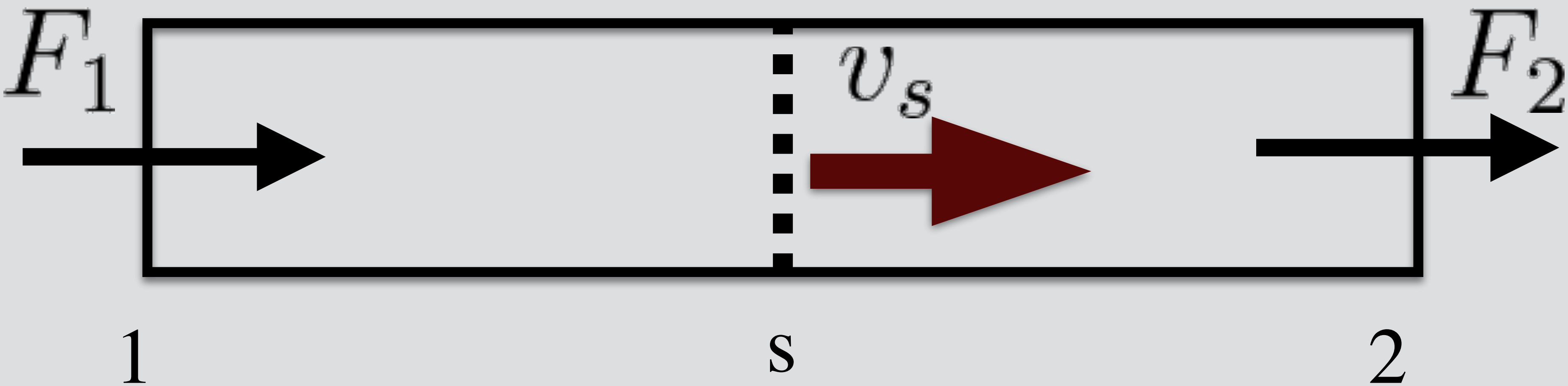
1. $v_s \geq 0$ is the condition for explosion
2. Integral condition will be illuminating

$$\frac{d^2x}{dt^2} = \frac{f}{m} \quad \text{or} \quad \frac{1}{2}v^2 + \phi = \text{const.}$$

Will use $v_s \geq 0$ to derive an integral condition for explosion.

Governing Conservation Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot F = S$$



Integrate conservation equations…
an expression that relates integral condition to boundaries

In steady state…

$$A_s(\rho_1 - \rho_2)v_s = F_1 A_1 - F_2 A_2 + \int S\, dV$$

$$v_s \geq 0$$

Integral terms in momentum equation

∇P

ρg

ρv^2

ram pressure

$$\Psi = \frac{r_{\mathrm{NS}}^2 P_{\mathrm{NS}} + 2\int P r\, dr - \int G M \rho\, dr - r_s^2 \rho_+ v_+^2}{r_s^2 \rho_+ v_+^2}$$

A measure of post shock pressure pushing against ram pressure of inflating star

Integral terms with boundary terms gives…

$$\frac{v_s}{v_+} = -1 + \sqrt{1 + \Psi \frac{\beta}{\beta - 1}}$$

$$v_s \geq 0 \rightarrow \Psi \geq 0$$

Integral terms in momentum equation

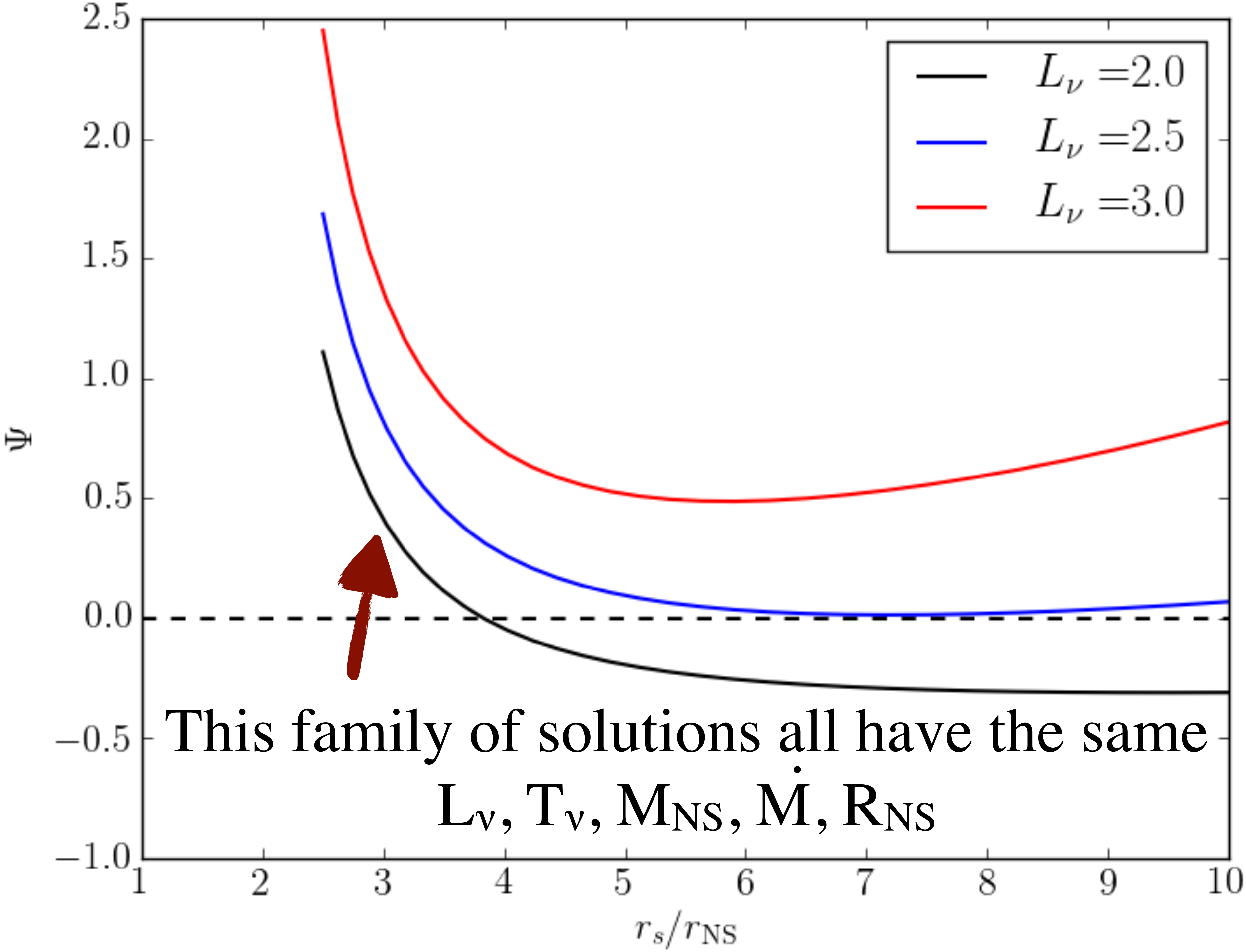
∇P

ρg

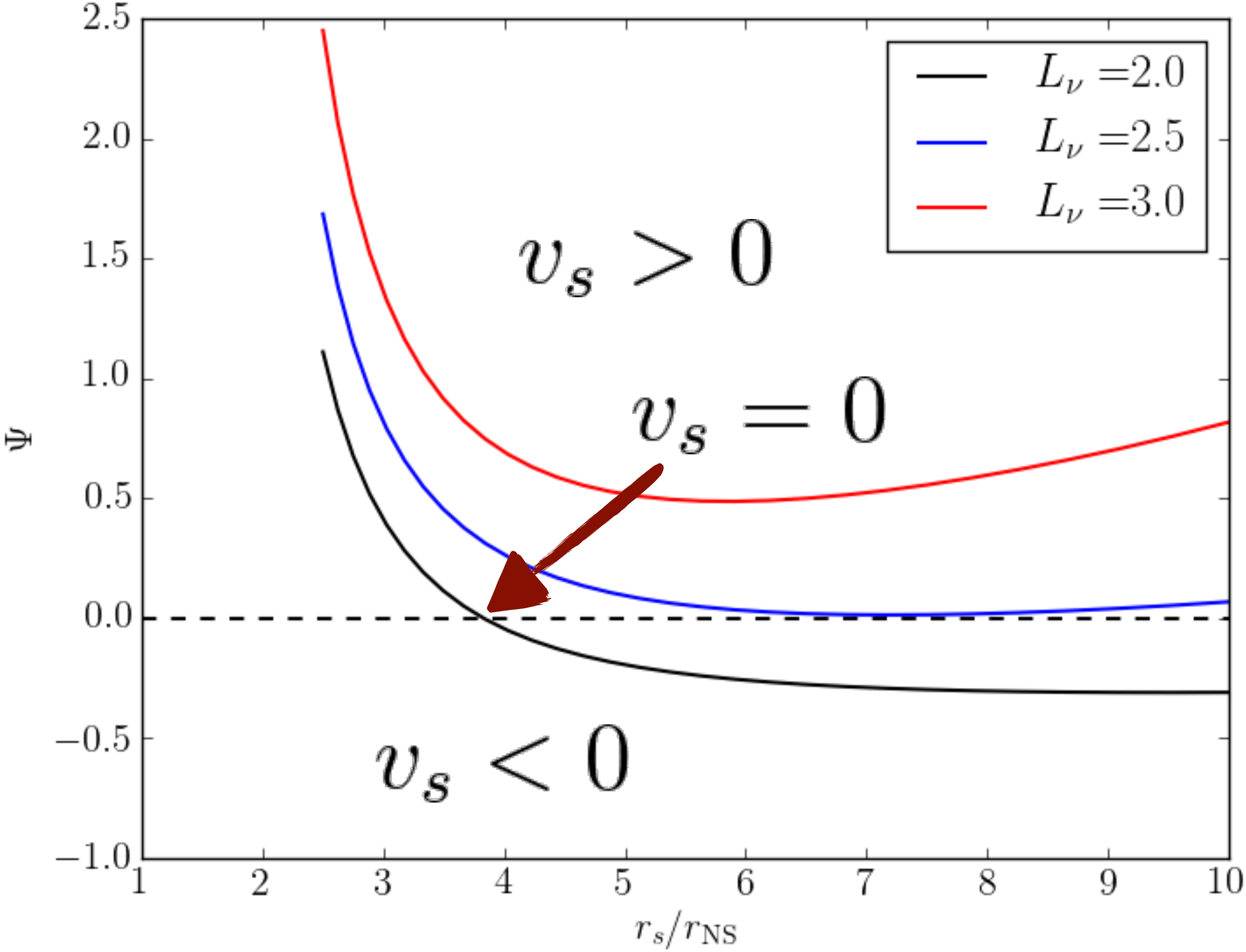
ρv^2
ram pressure

$$\Psi = \frac{r_{\mathrm{NS}}^2 P_{\mathrm{NS}} + 2\int P r\, dr - \int G M \rho\, dr - r_s^2 \rho_+ v_+^2}{r_s^2 \rho_+ v_+^2}$$

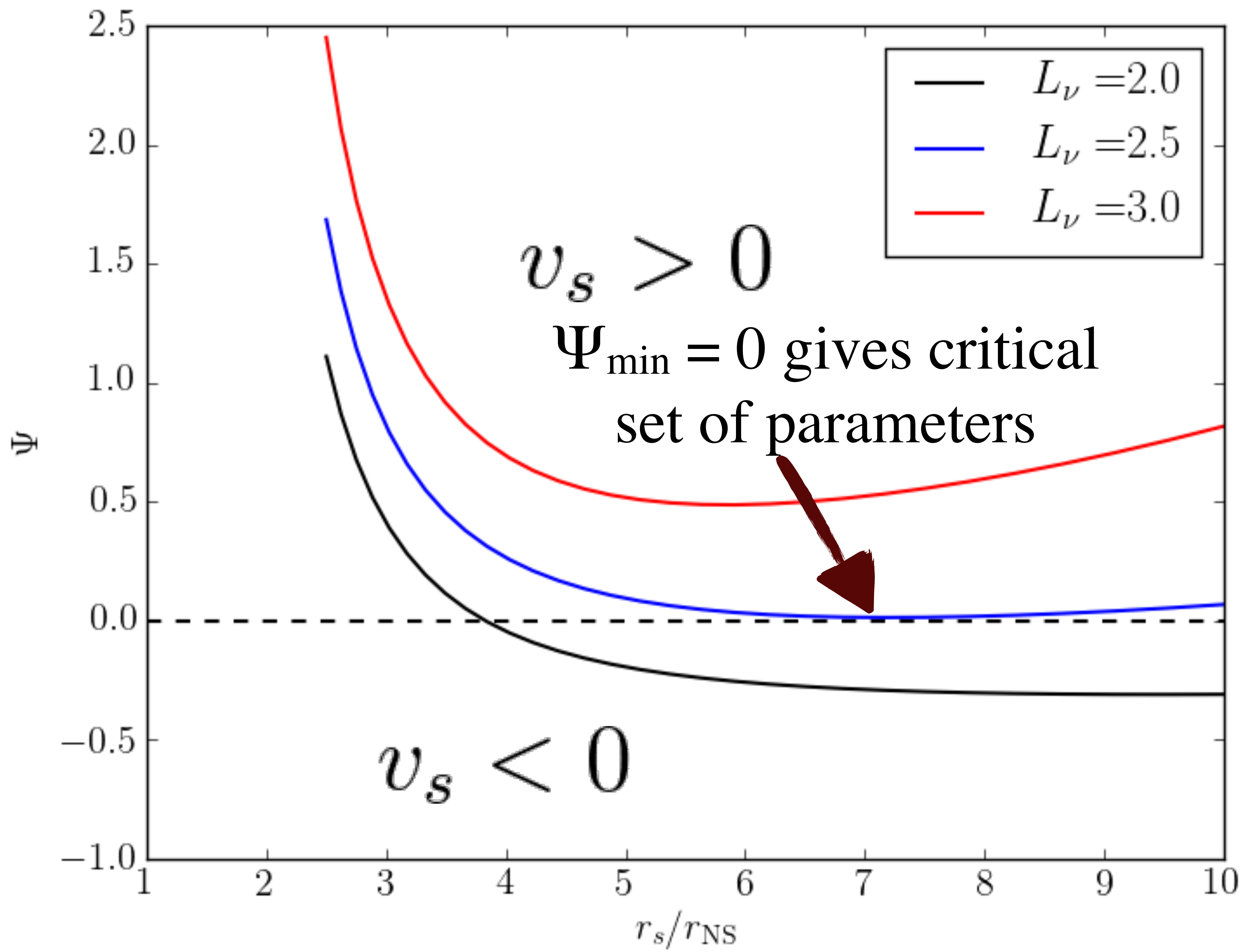
Need solutions to these terms.
Semi-analytic…similar to Burrows & Goshy.



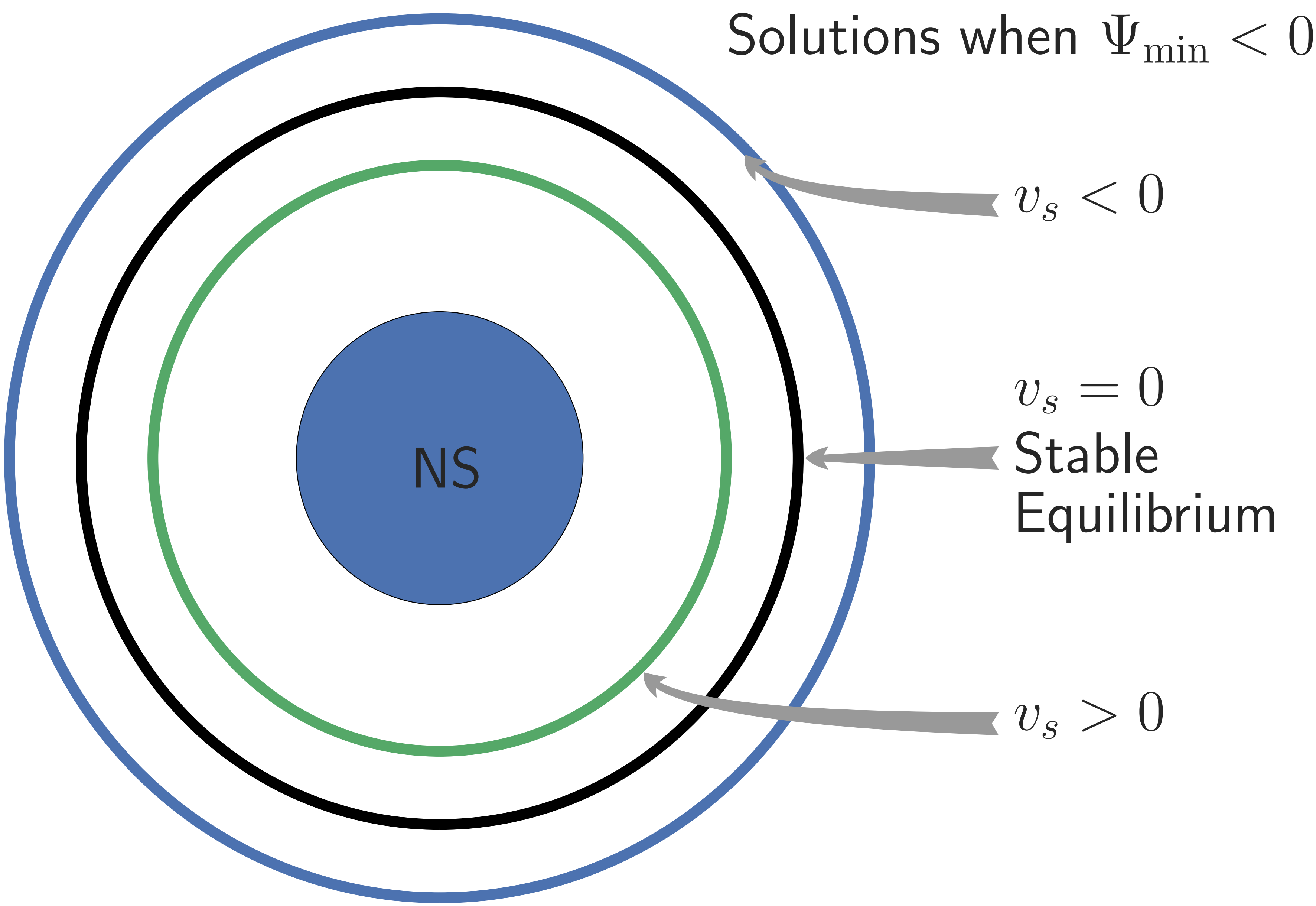
$L_\nu = 2.0$
$L_\nu = 2.5$
$L_\nu = 3.0$
Ψ
r_s/r_{NS}
This family of solutions all have the same
L_ν, T_ν, M_{NS}, $\dot{M}$, R_{NS}



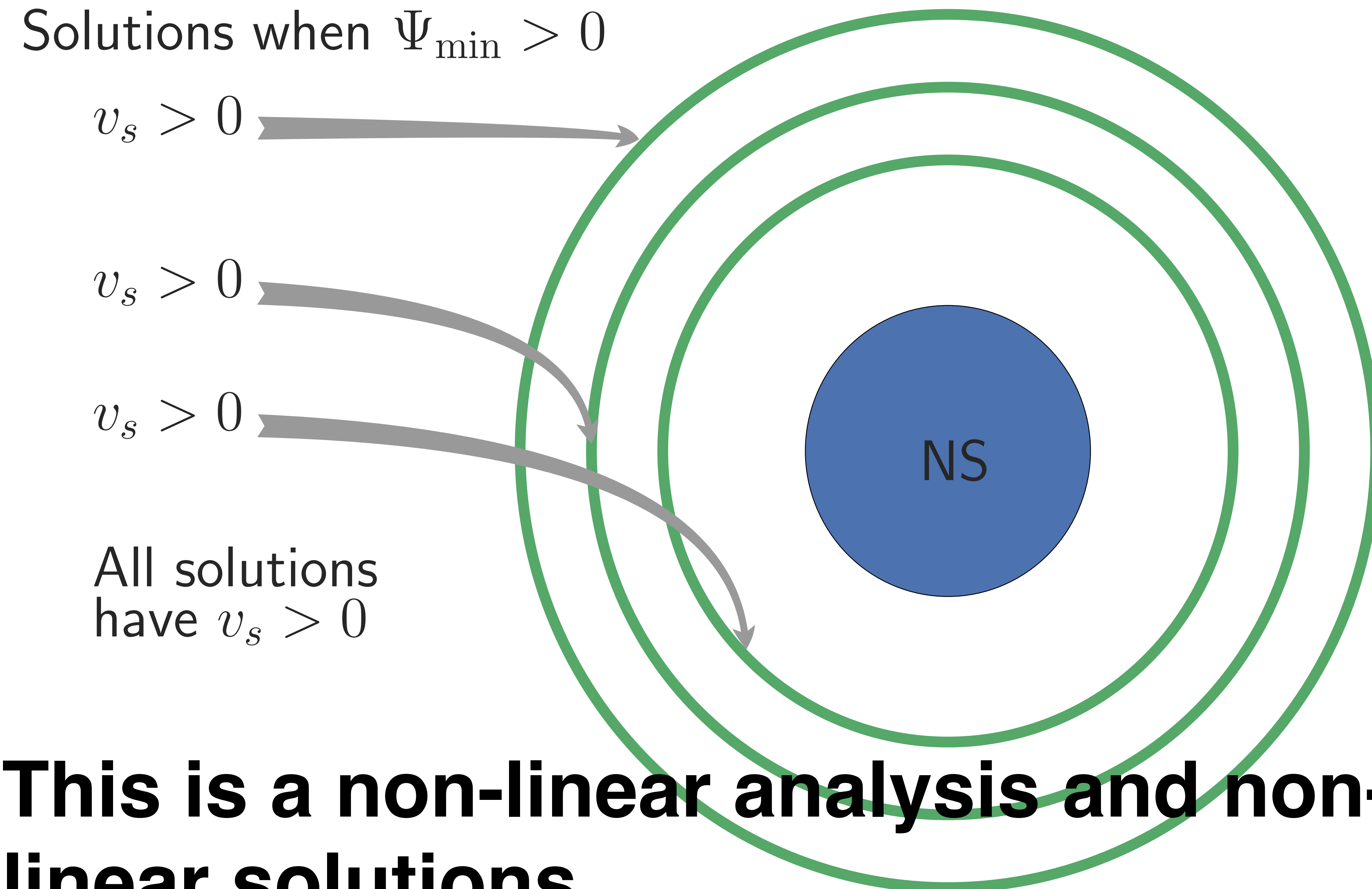
L_ν =2.0
L_ν =2.5
L_ν =3.0
$v_s > 0$
$v_s = 0$
$v_s < 0$
Ψ
$r_s/r_{\rm NS}$
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
1
2
3
4
5
6
7
8
9
10



$L_\nu = 2.0$
$L_\nu = 2.5$
$L_\nu = 3.0$
$v_s > 0$
$\Psi_{min} = 0$ gives critical set of parameters
$v_s < 0$
Ψ
r_s / r_{NS}
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
1
2
3
4
5
6
7
8
9
10

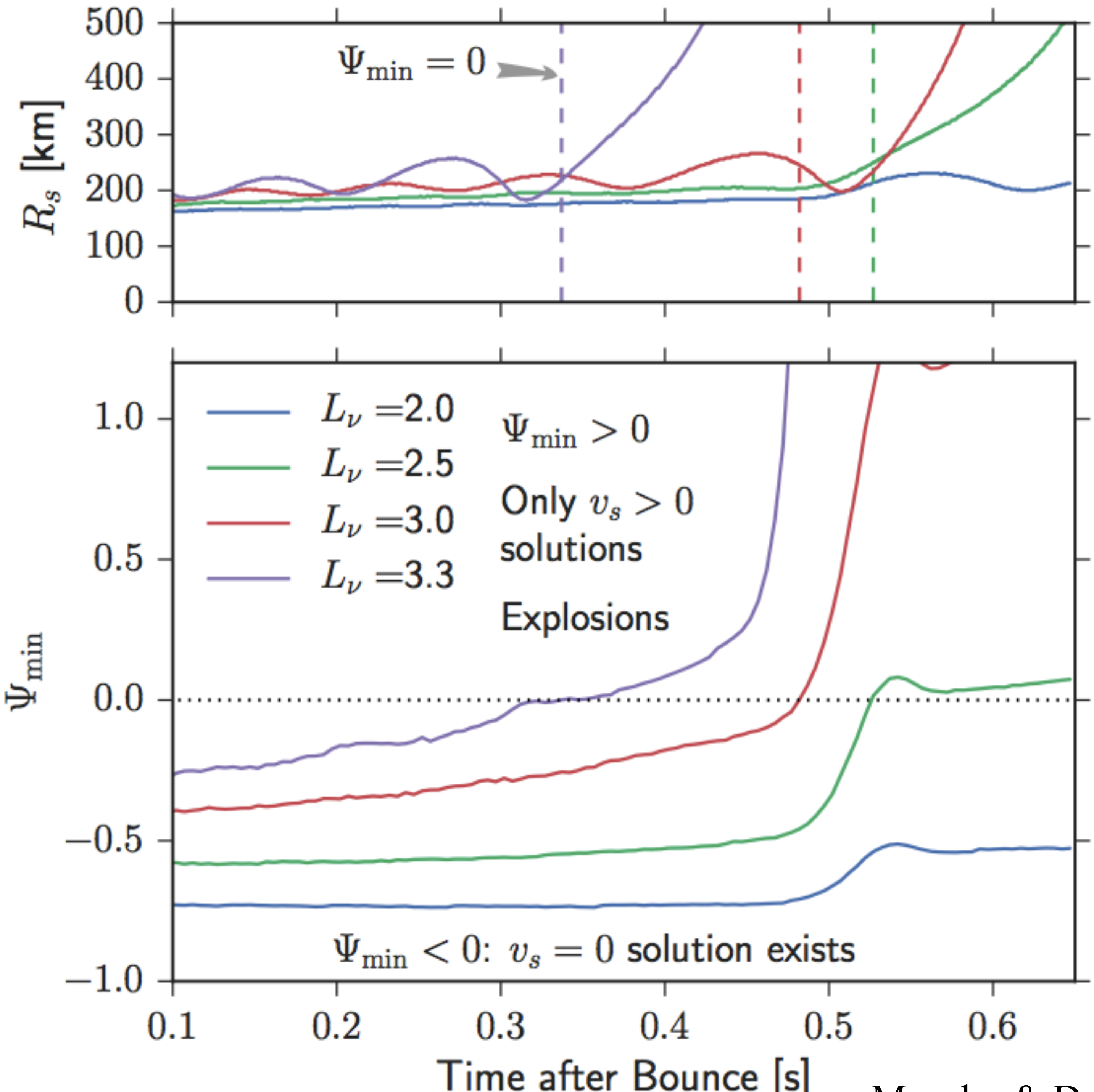


Solutions when $\Psi_{\min} < 0$
$v_s < 0$
$v_s = 0$
Stable
Equilibrium
$v_s > 0$
NS



This is a non-linear analysis and non-linear solutions

Use Ψ_{min} to evaluate nearness-to-explosion in 1D simulations

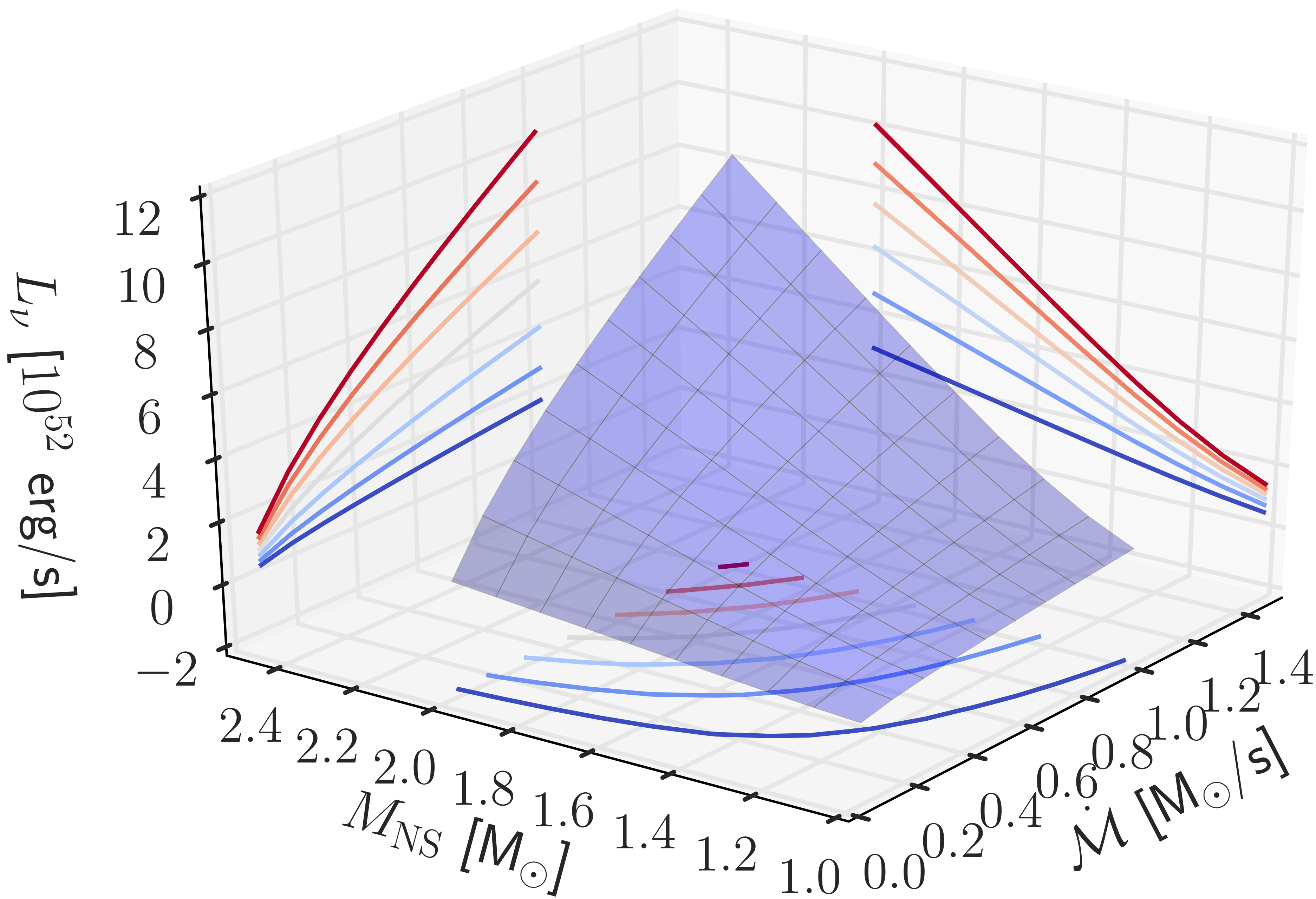


Murphy & Dolence 2017

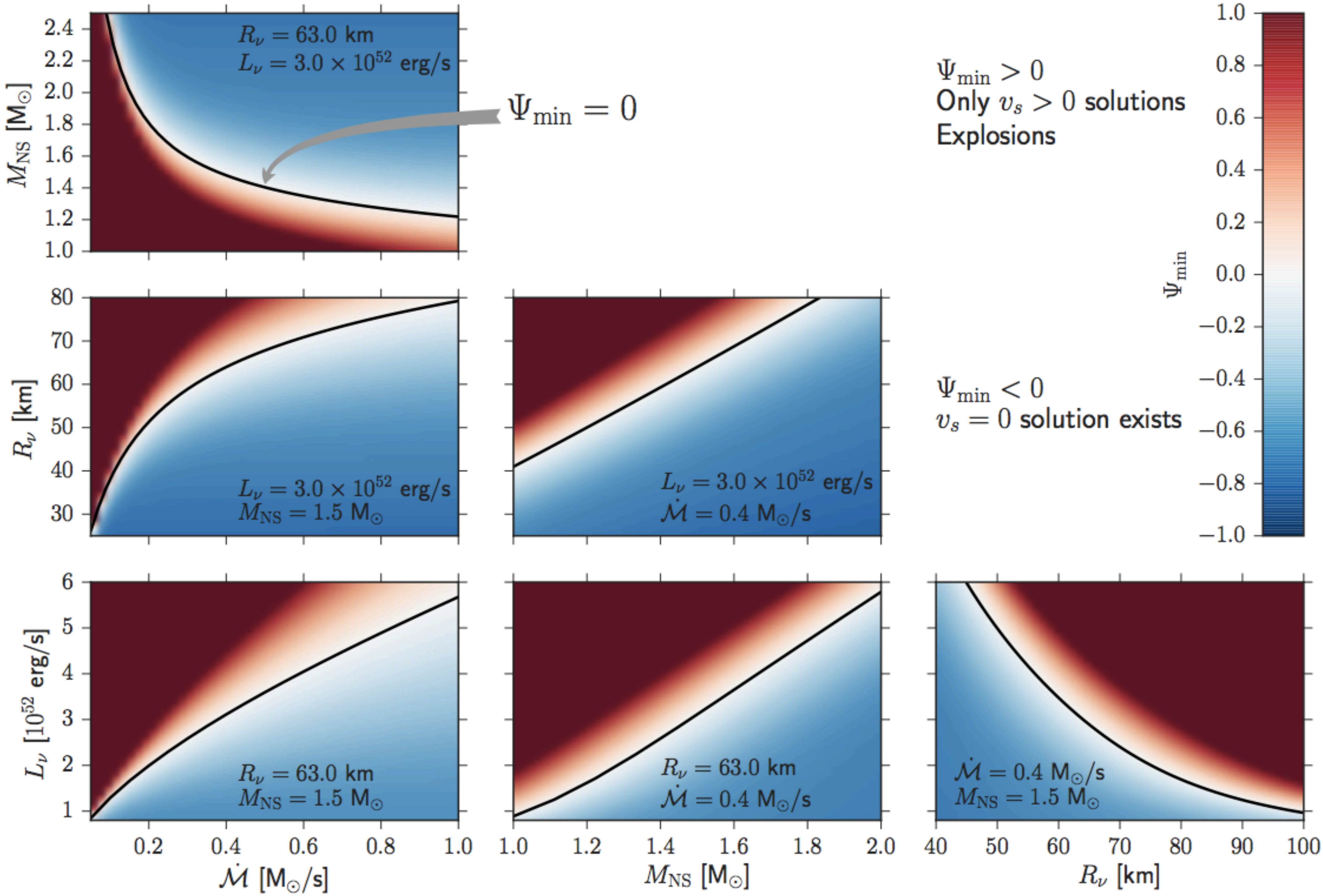
$\Psi_{min} = 0$ defines a hyper-surface in a five dimensional space $(L_\nu, T_\nu, R_{NS}, M_{NS}, \dot{M})$

below this hyper-surface $v_s = 0$ solutions

above this hyper-surface $v_s > 0$ (explosions)

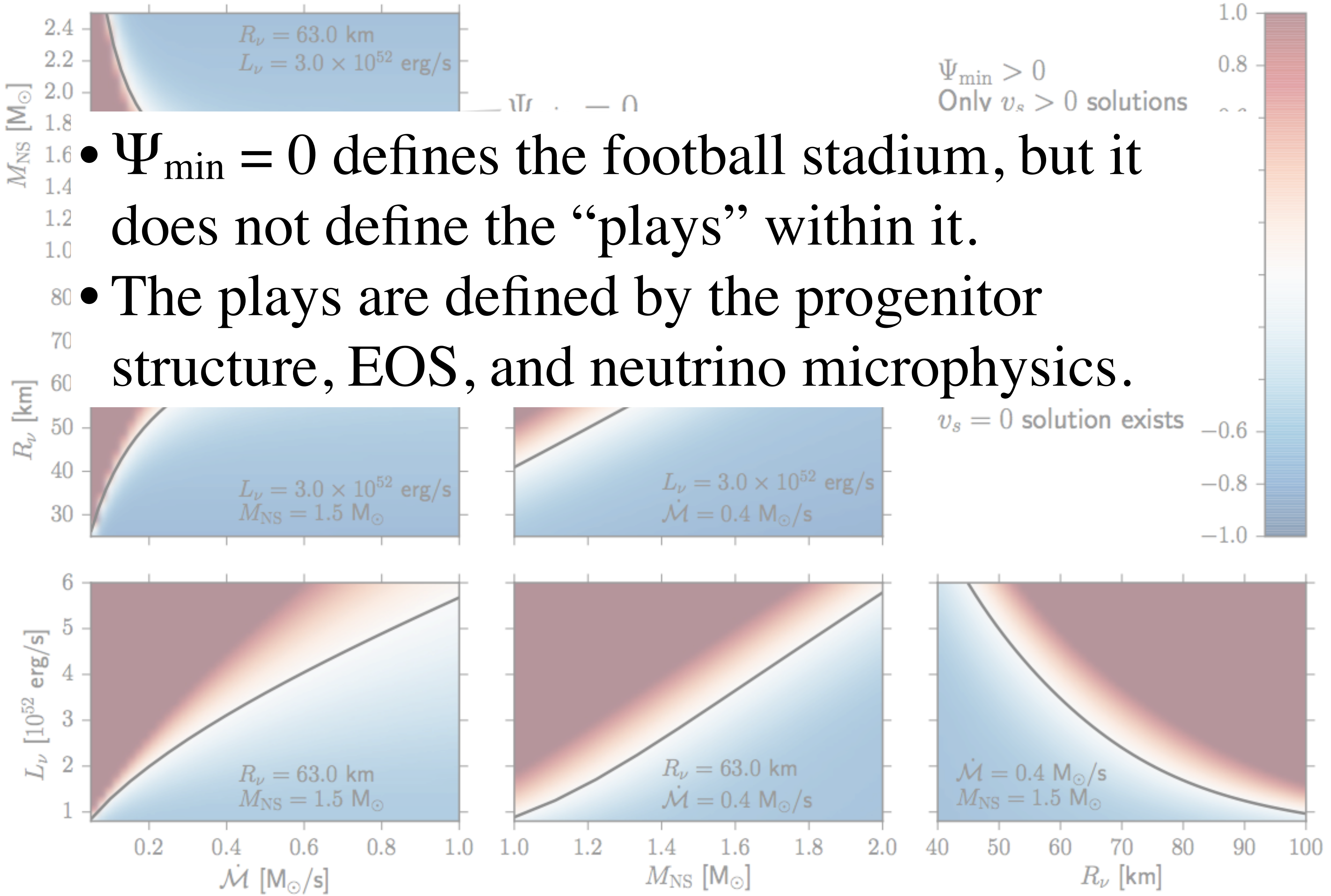


L_ν [10^{52} erg/s]
−2
0
2
4
6
8
10
12
M_{NS} [M$_\odot$]
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
$\dot{\mathcal{M}}$ [M$_\odot$/s]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4

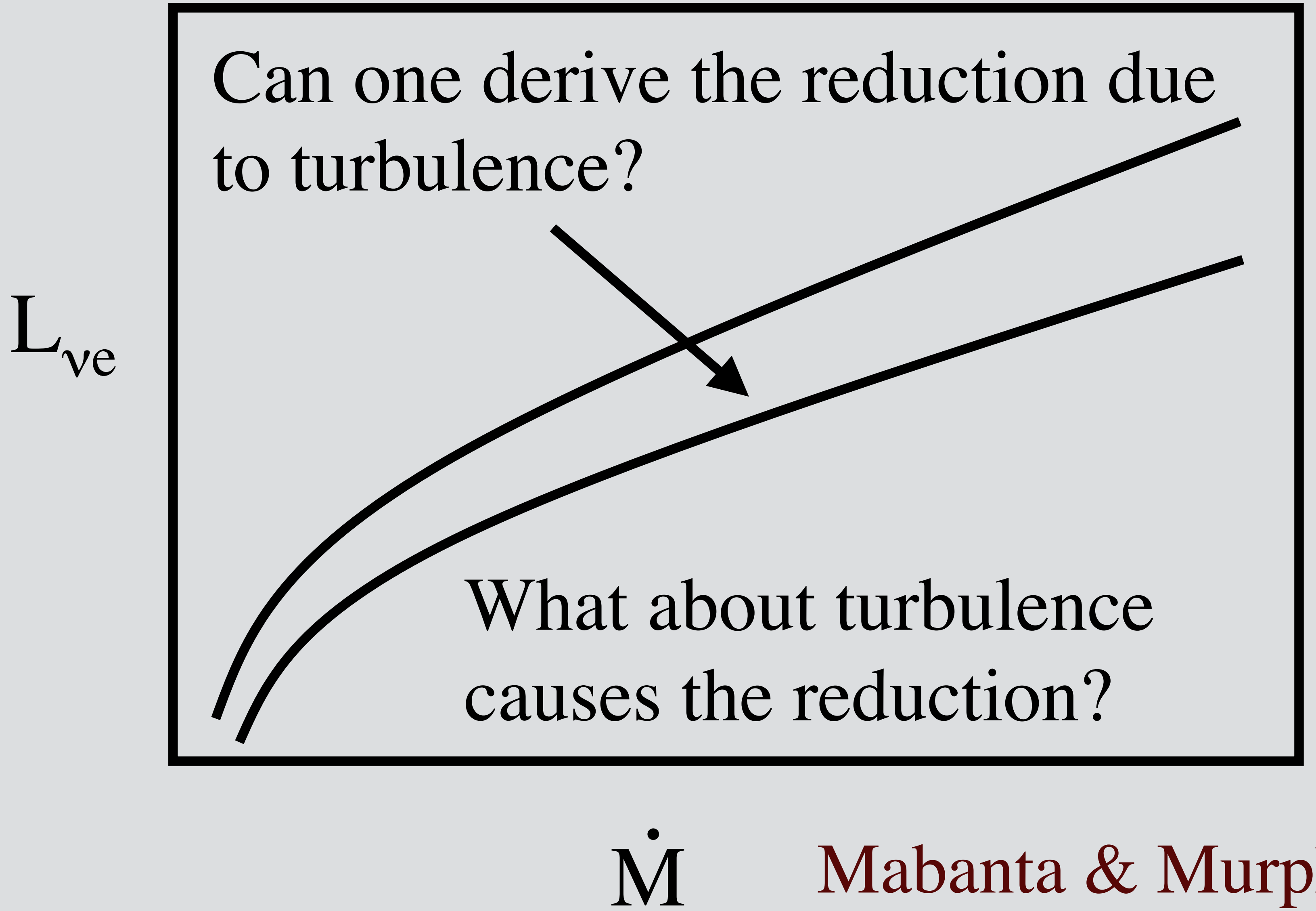


$R_\nu = 63.0$ km
$L_\nu = 3.0 \times 10^{52}$ erg/s
$\Psi_{\rm min} = 0$
$\Psi_{\rm min} > 0$
Only $v_s > 0$ solutions
Explosions
$\Psi_{\rm min} < 0$
$v_s = 0$ solution exists
$\Psi_{\rm min}$
$M_{\rm NS}$ [M$_\odot$]
R_ν [km]
L_ν [10^{52} erg/s]
$L_\nu = 3.0 \times 10^{52}$ erg/s
$M_{\rm NS} = 1.5$ M$_\odot$
$\dot{\mathcal{M}} = 0.4$ M$_\odot$/s
$\dot{\mathcal{M}}$ [M$_\odot$/s]
R_ν [km]

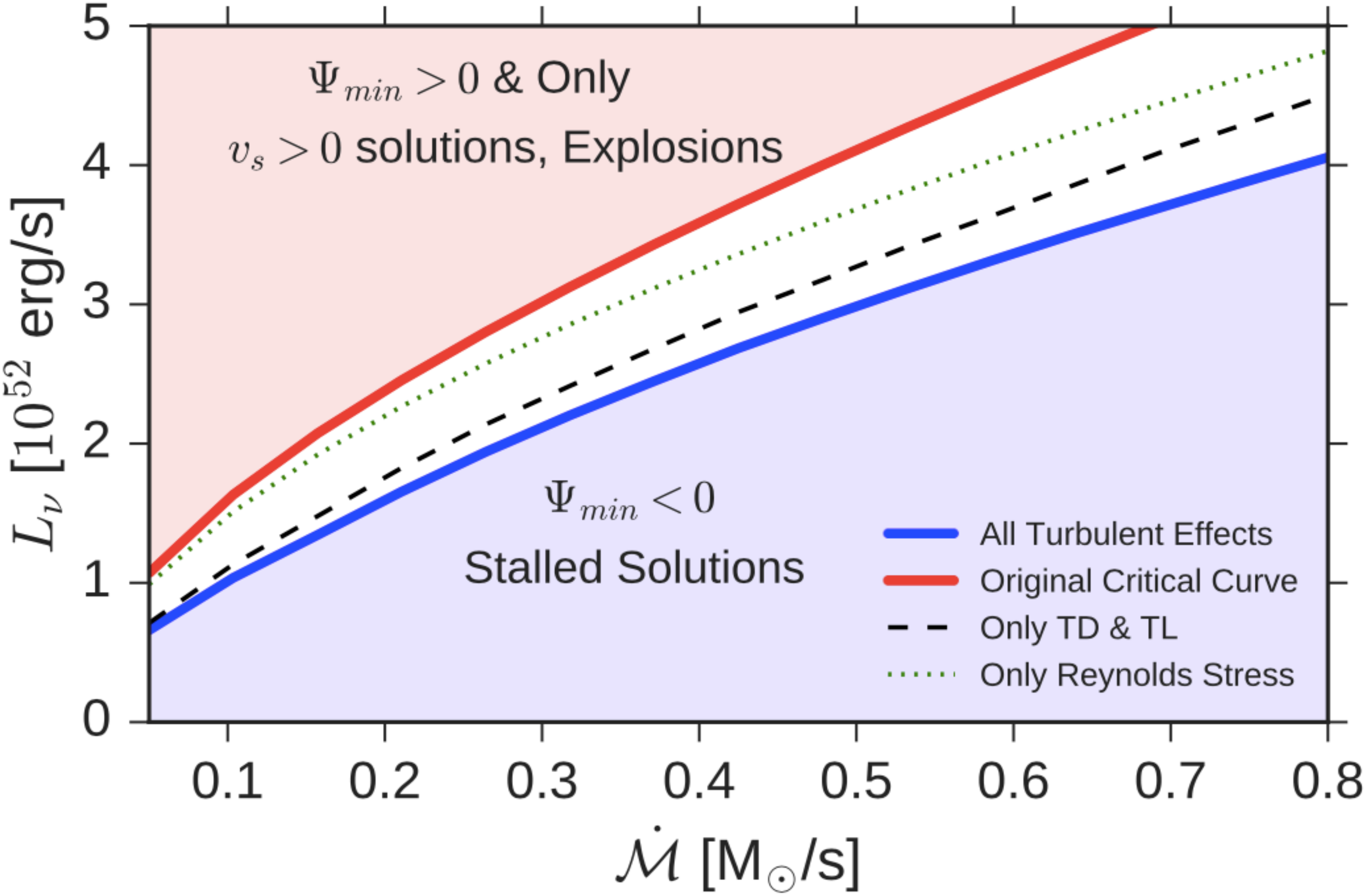
- $\Psi_{\rm min} = 0$ defines the football stadium, but it does not define the “plays” within it.
- The plays are defined by the progenitor structure, EOS, and neutrino microphysics.



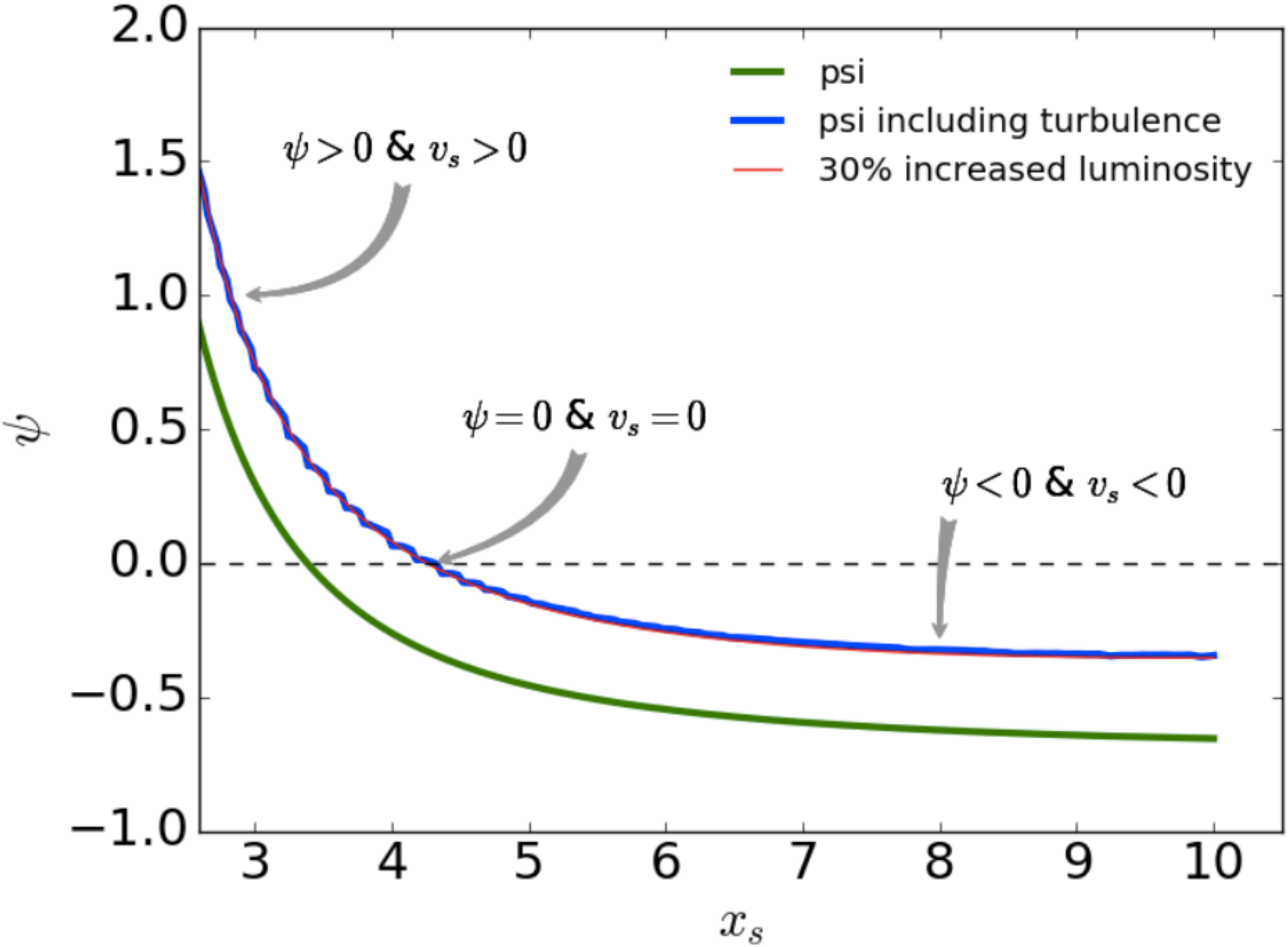
Now, let's use this condition to understand how turbulence affects this condition

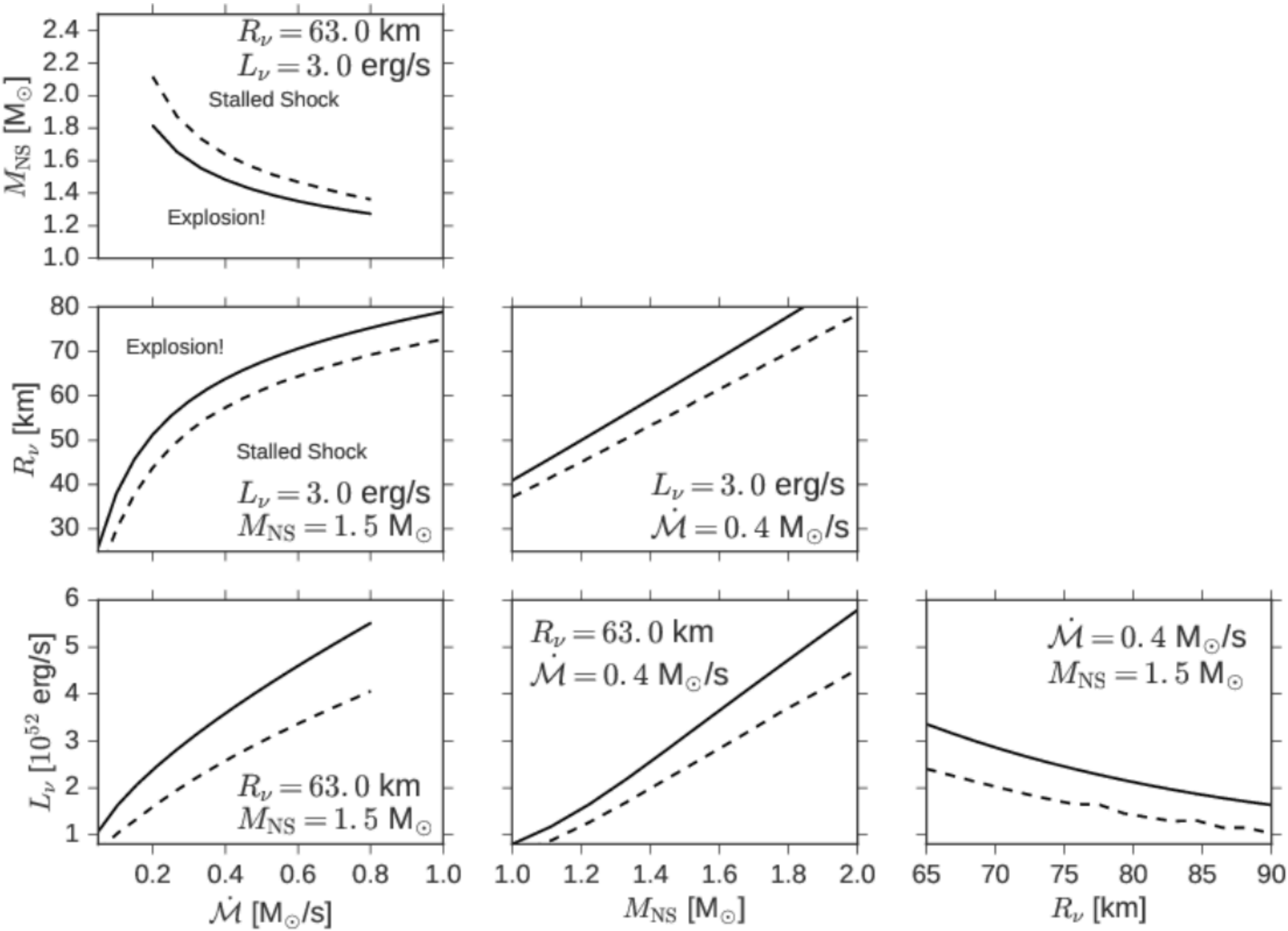


Mabanta & Murphy 2017



$\Psi_{min} > 0$ & Only
$v_s > 0$ solutions, Explosions
$\Psi_{min} < 0$
Stalled Solutions
All Turbulent Effects
Original Critical Curve
Only TD & TL
Only Reynolds Stress
L_ν [10^{52} erg/s]
$\dot{\mathcal{M}}$ [$M_\odot$/s]
0
1
2
3
4
5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8


psi
psi including turbulence
30% increased luminosity
$\psi > 0$ & $v_s > 0$
$\psi = 0$ & $v_s = 0$
$\psi < 0$ & $v_s < 0$
ψ
x_s
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
3
4
5
6
7
8
9
10

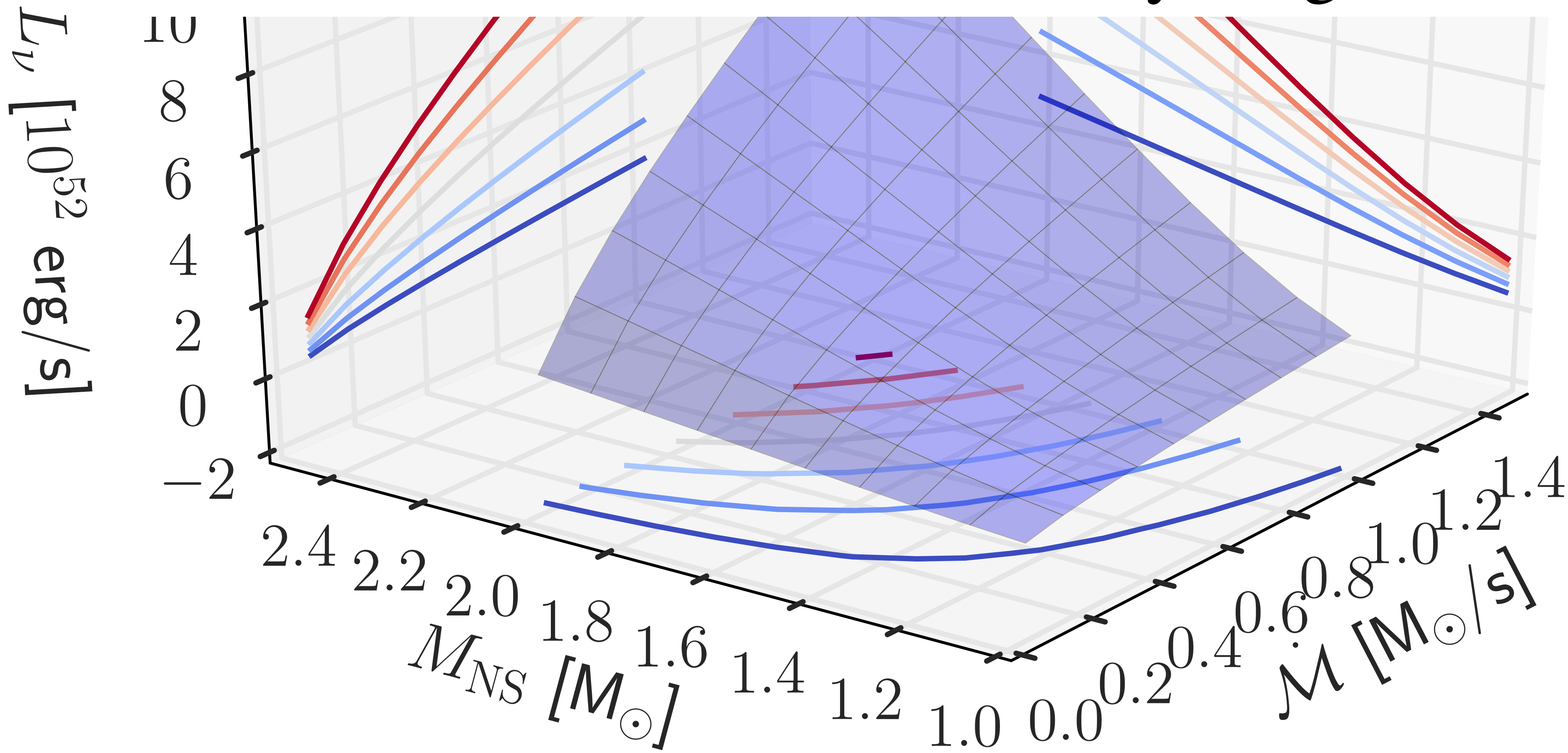


$R_\nu = 63.0$ km
$L_\nu = 3.0$ erg/s
Stalled Shock
Explosion!
$M_{\rm NS}$ [$M_\odot$]
Explosion!
Stalled Shock
$L_\nu = 3.0$ erg/s
$M_{\rm NS} = 1.5$ $M_\odot$
R_ν [km]
$L_\nu = 3.0$ erg/s
$\dot{\mathcal{M}} = 0.4$ $M_\odot$/s
$R_\nu = 63.0$ km
$\dot{\mathcal{M}} = 0.4$ $M_\odot$/s
$\dot{\mathcal{M}} = 0.4$ $M_\odot$/s
$M_{\rm NS} = 1.5$ $M_\odot$
$R_\nu = 63.0$ km
$M_{\rm NS} = 1.5$ $M_\odot$
L_ν [10^{52} erg/s]
$\dot{\mathcal{M}}$ [$M_\odot$/s]
$M_{\rm NS}$ [$M_\odot$]
R_ν [km]

Next Steps

Quantify distance to Ψ_{min}=0 surface

Metrics, Geodesics, Constrained by Progenitor Path



Next Steps

$\Psi_{min}\ (L_\nu, T_\nu, R_{NS}, M_{NS}, \dot{M}) = 0$ defines a hyper-surface in a five dimensional space.

Found this curve semi-analytically.

With a few simple assumptions, we can ***derive*** this curve analytically. Murphy, Mabanta, & Dolence, in prep.

Physics	Measured Effect	My Best Guess	Refs.
Neutrino-driven Convections	30%		Murphy & Burrows 2008, Mabanta & Murphy 2017
Progenitor Structure		$\mathcal{O}(1)$	Sukhbold et al. 2016
SASI		$\lesssim$ 30%	Hanke et al. 2013, Fernández et al. 2014, Fernández 2015
GR		~ 10%	Marek et al. 2009, Müller 2012, Roberts et al. 2016
EOS		~ 10%	Couch 2012
many-body corrections to ν-nucleon scattering		~ 5%	Horowitz et al. 2017, Burrows et al. 2106
Progenitor Perturbations		~ 1-10%	Couch 2013, Müller & Janka 2015
ν-transport		3-50 %	Richers et al. 2017

<u>Summary of our results:</u>

- Critical hyper surface
- Step closer to showing that solutions above critical condition are explosive
- Nearness-to-explosion for Simulations
- Use it to explain reduction in critical condition
- Let’s try quantify the other important effects