Constraints on Core-Collapse Supernova Theory

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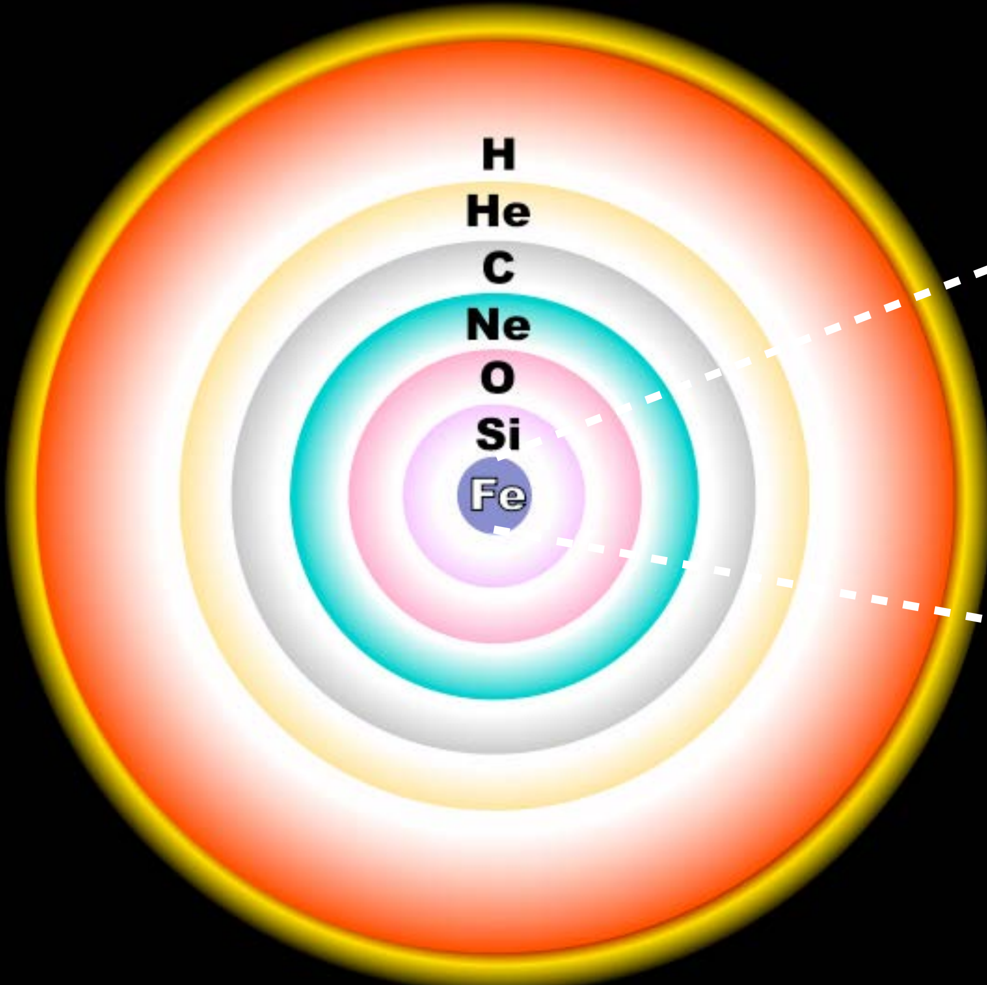
Quintin
Mabanta
Mariangelly
Díaz-Rodriguez

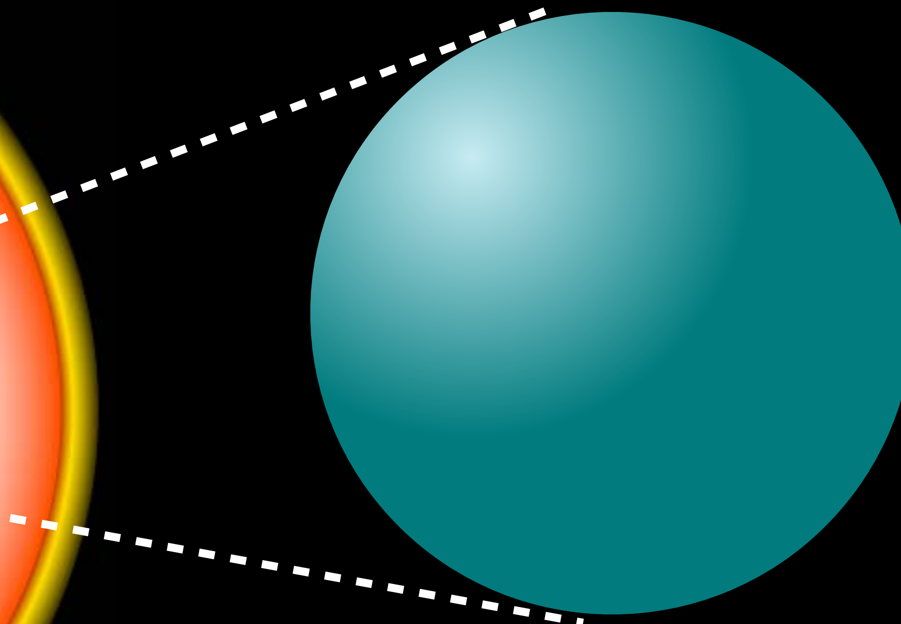
Theory…conditions for explosion, predictions

How do massive stars explode?

Which stars actually explode?

Before we talk about constraints, let's give some context (theory)





$1.4\ M_\odot$, R ~3000 km

T_{dyn} ~ 150 ms

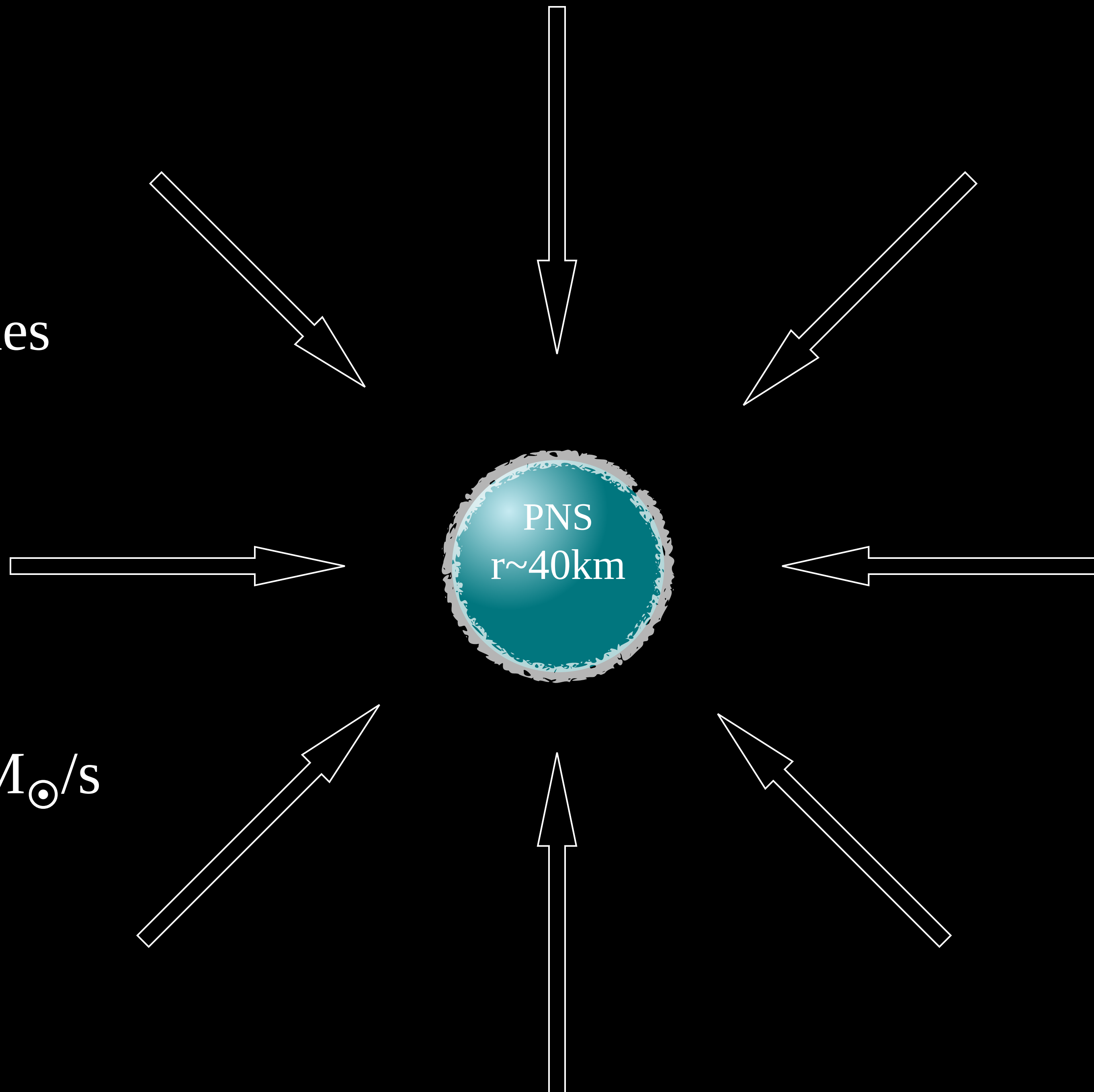
PNS, Final R~ 40 km

Progenitor Stars

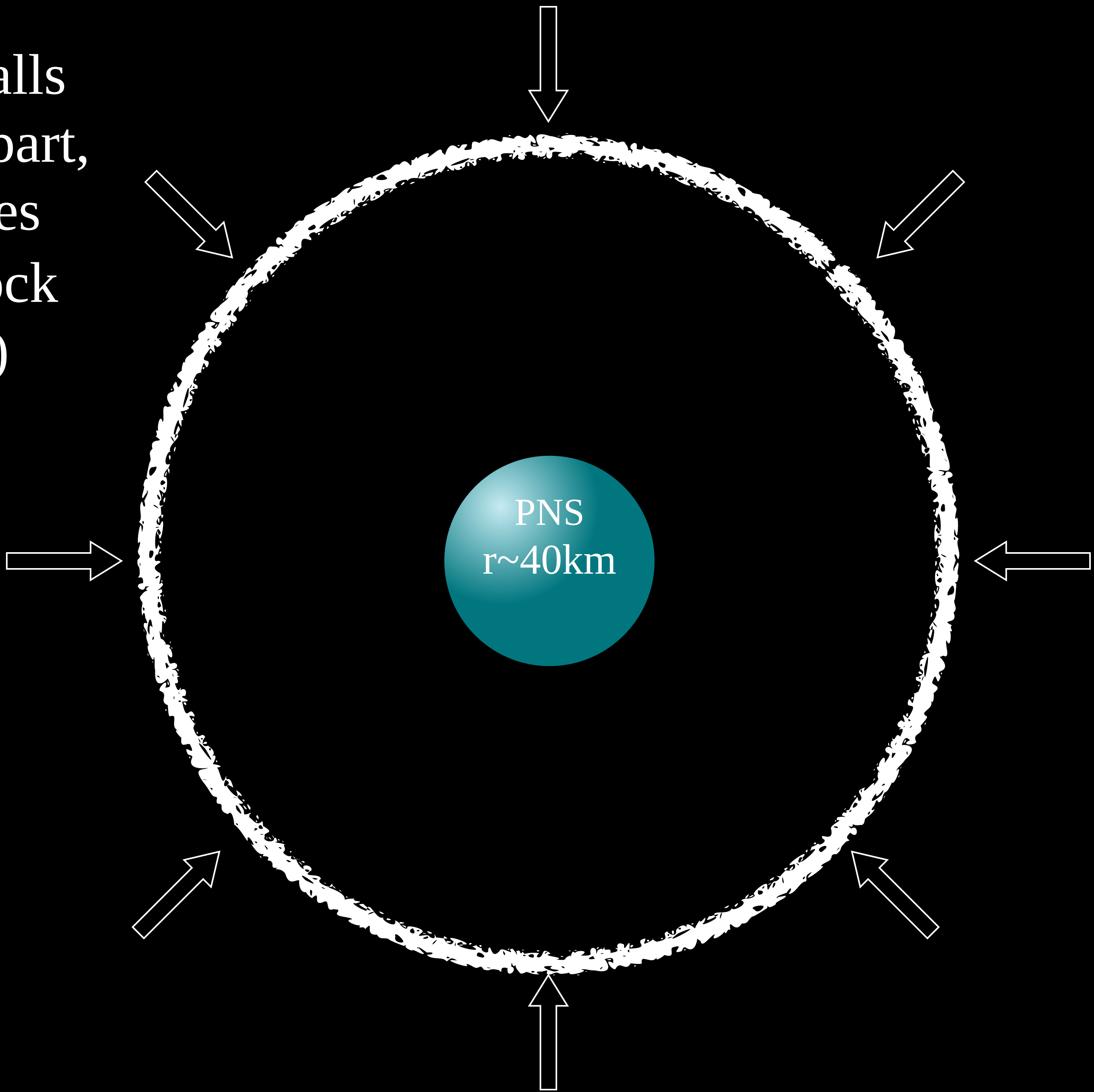
$7.3 +/- 0.1\ M_\odot < M <$ ~$60\text{-}100\ M_\odot$

Bounce launches
shock wave

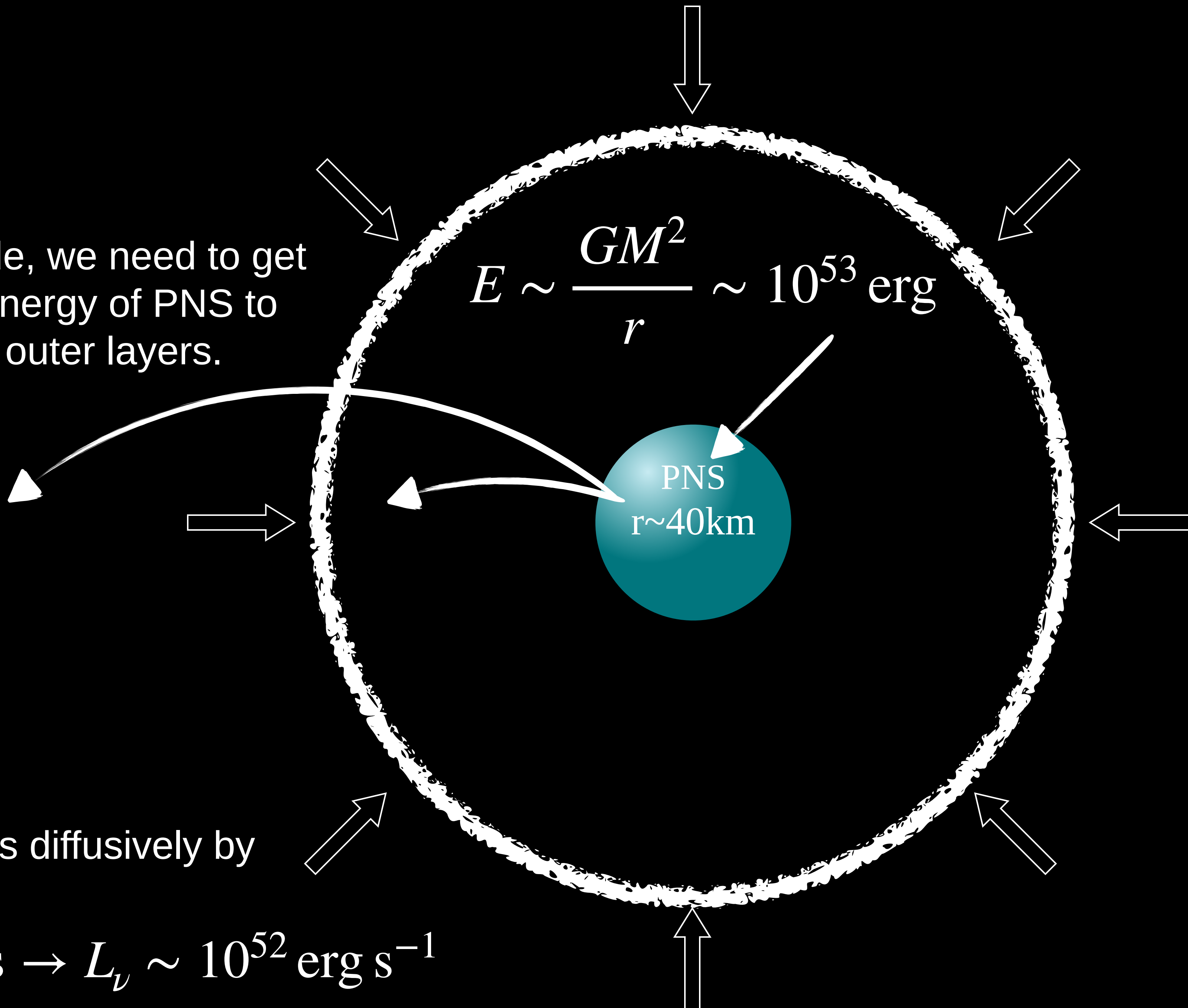
~0.1 to ~10 $M_\odot$/s



The Shock Stalls
Nuclei break apart,
e^- cap, ν losses
Accretion shock
(r ~200 km)



To explode, we need to get thermal energy of PNS to couple to outer layers.



PNS cools diffusively by neutrinos

$$\tau \sim 10\,\mathrm{s} \rightarrow L_\nu \sim 10^{52}\,\mathrm{erg\,s^{-1}}$$

Neutrino Transport

$$p + \bar{\nu}_e \leftrightharpoons n + e^+$$

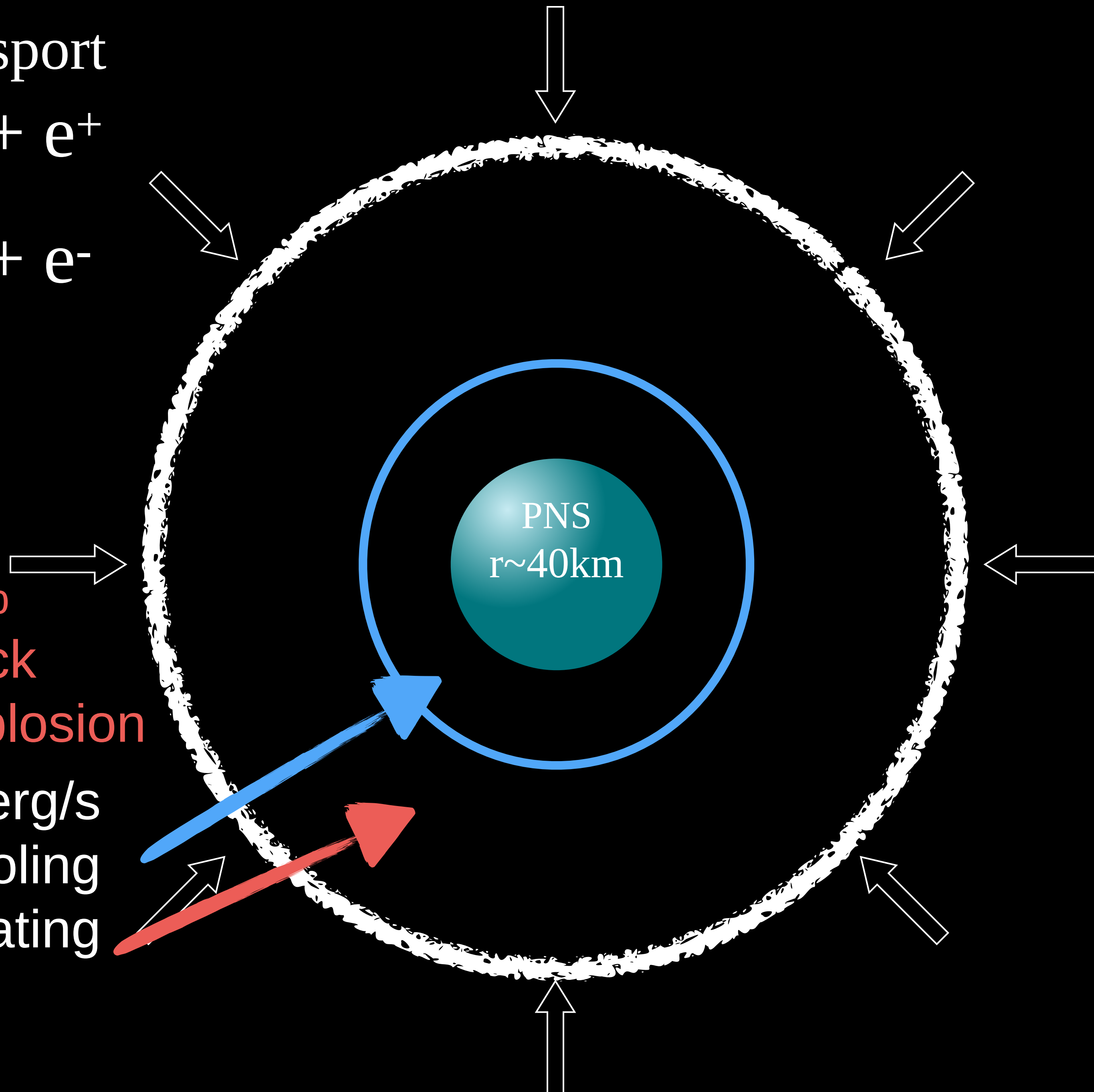
$$n + \nu_e \leftrightharpoons p + e^-$$

Re-capture 10%
just behind shock
to re-launch explosion

L_ν ~ few x 10^{52} erg/s

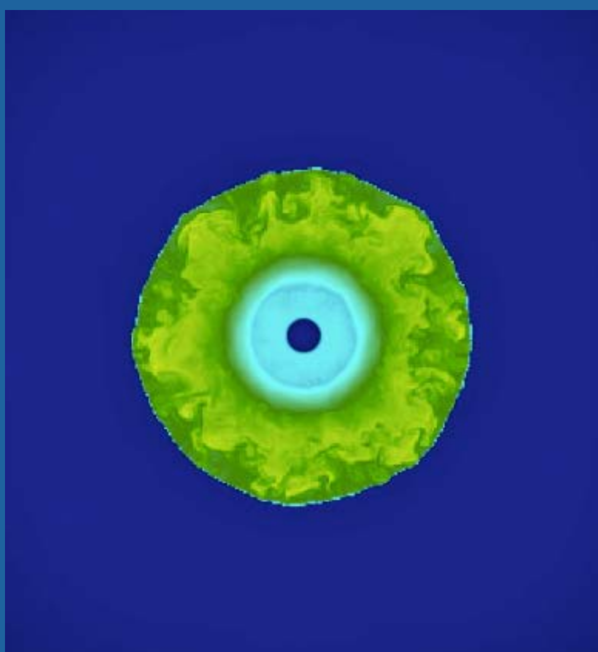
cooling

heating



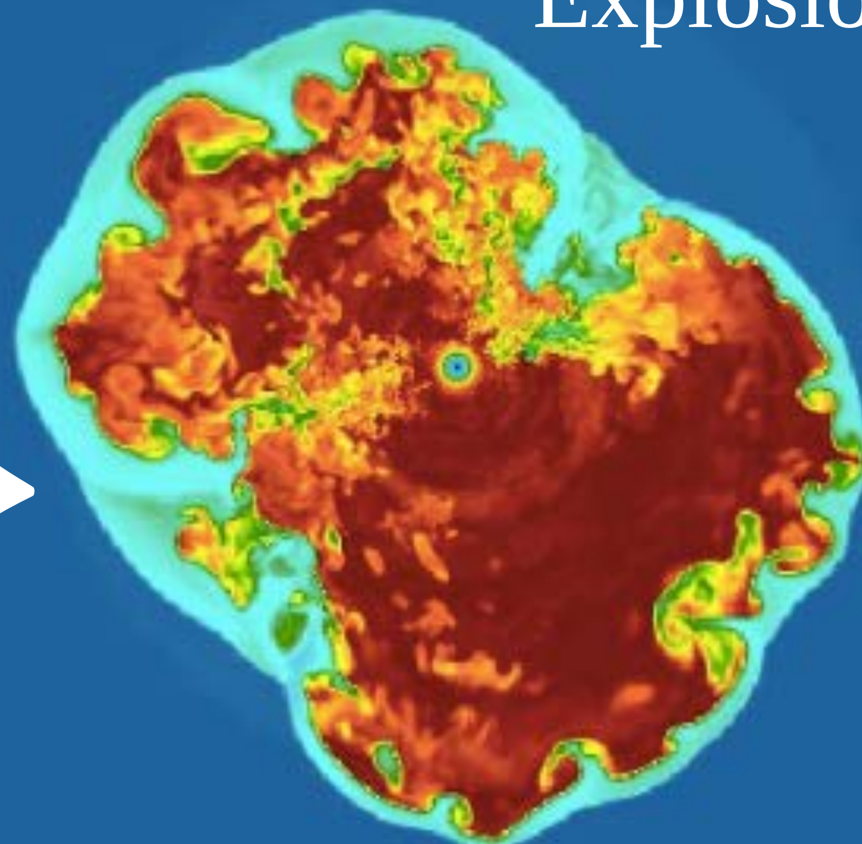
Fundamental Question of Core-Collapse Theory

Stalled Shock



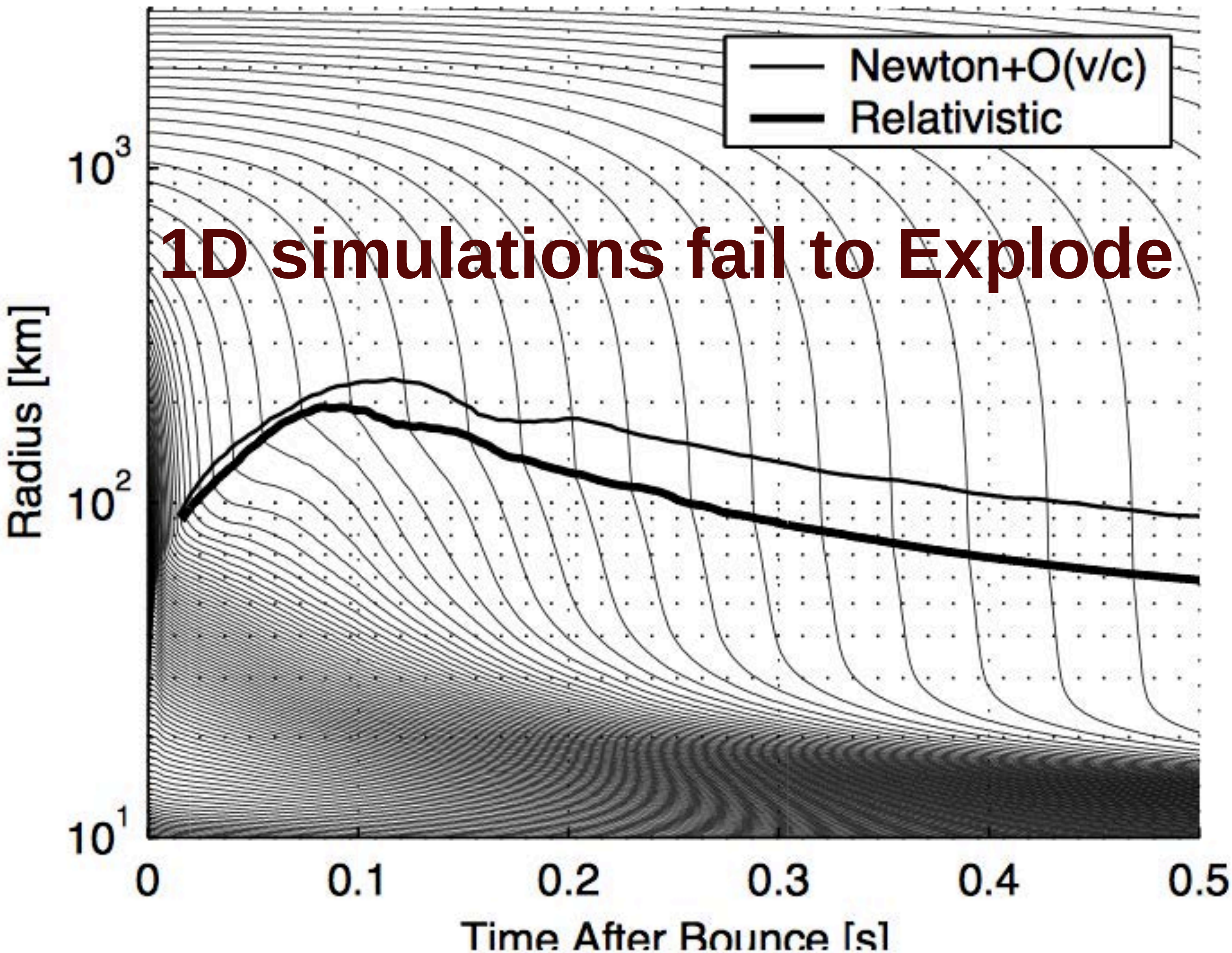
?

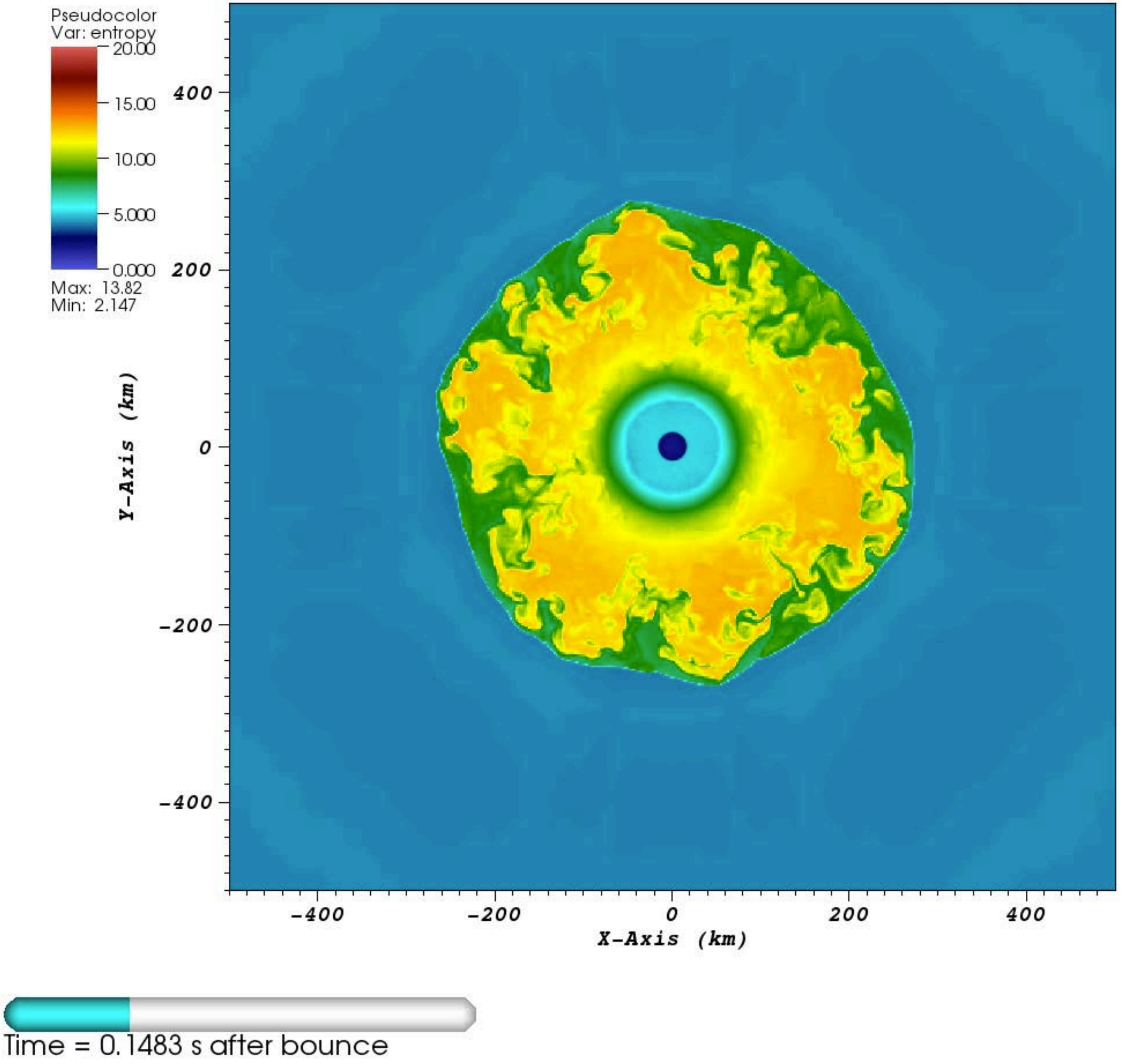
Explosion



Liebendörfer et al. 2001

1D simulations fail to Explode

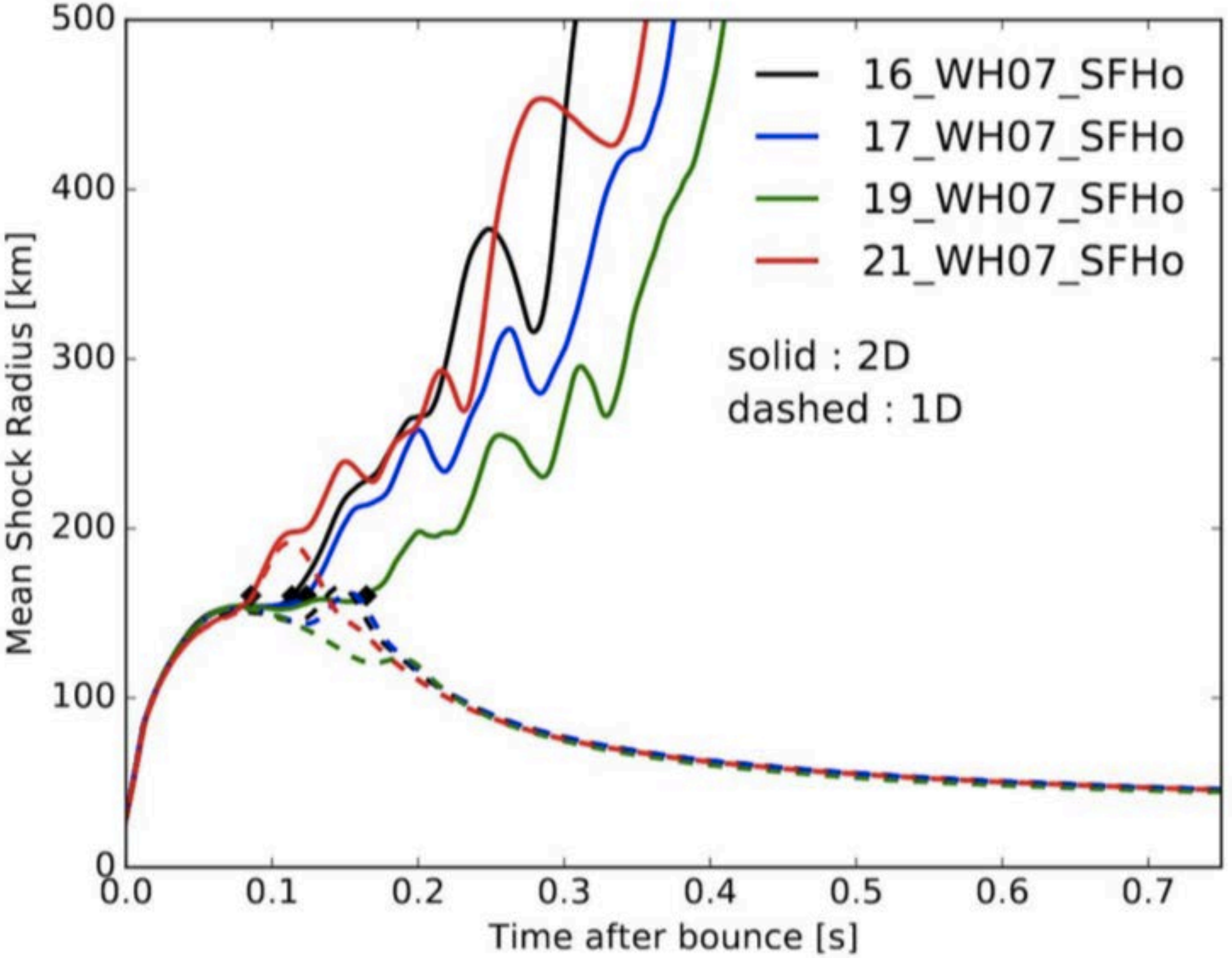




Multi-dimensional Instabilities

- Convection
- Standing Accretion Shock Instability (SASI)

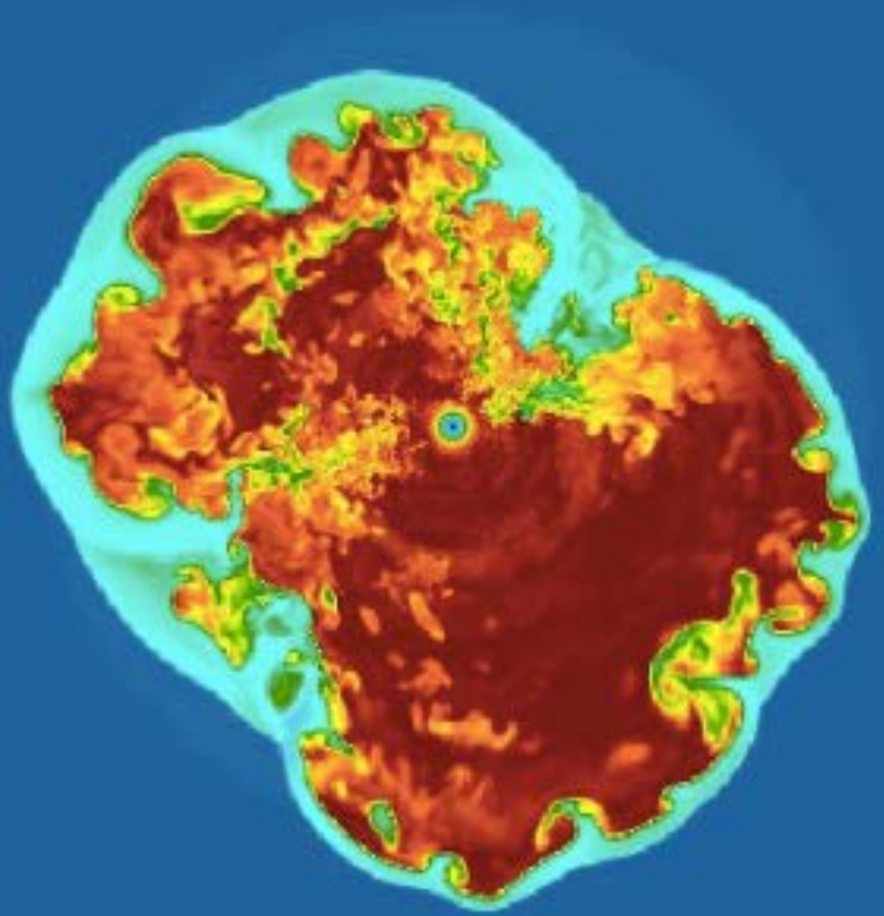
Most 1-D simulations do not explode, yet many multi-D do.



Vartanyan et al. 2018

Primary Result of Last Three Decades

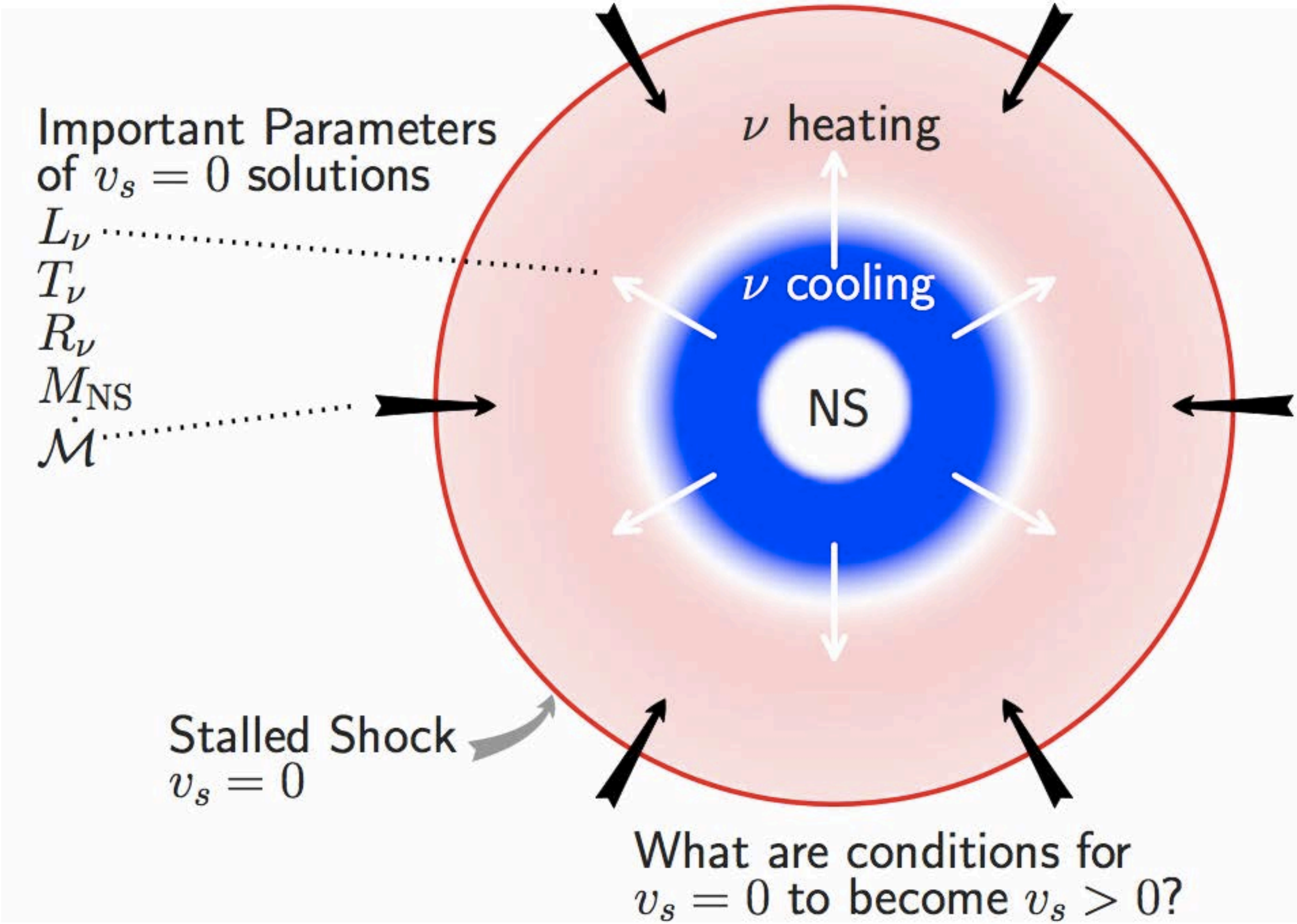
1D simulations rarely explode, yet multi-D simulations sometimes do…but not always



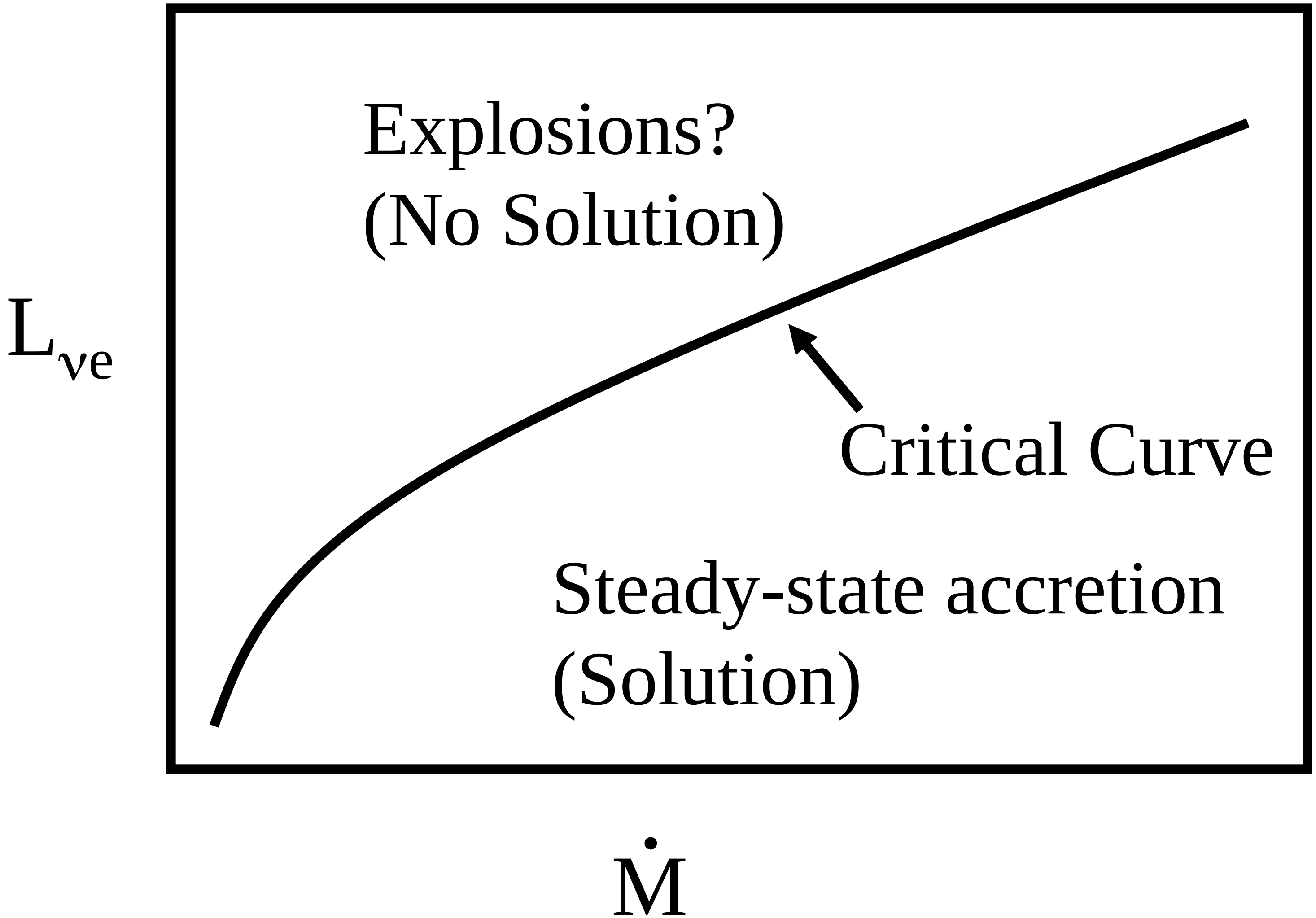
Why?

Which progenitors explode?

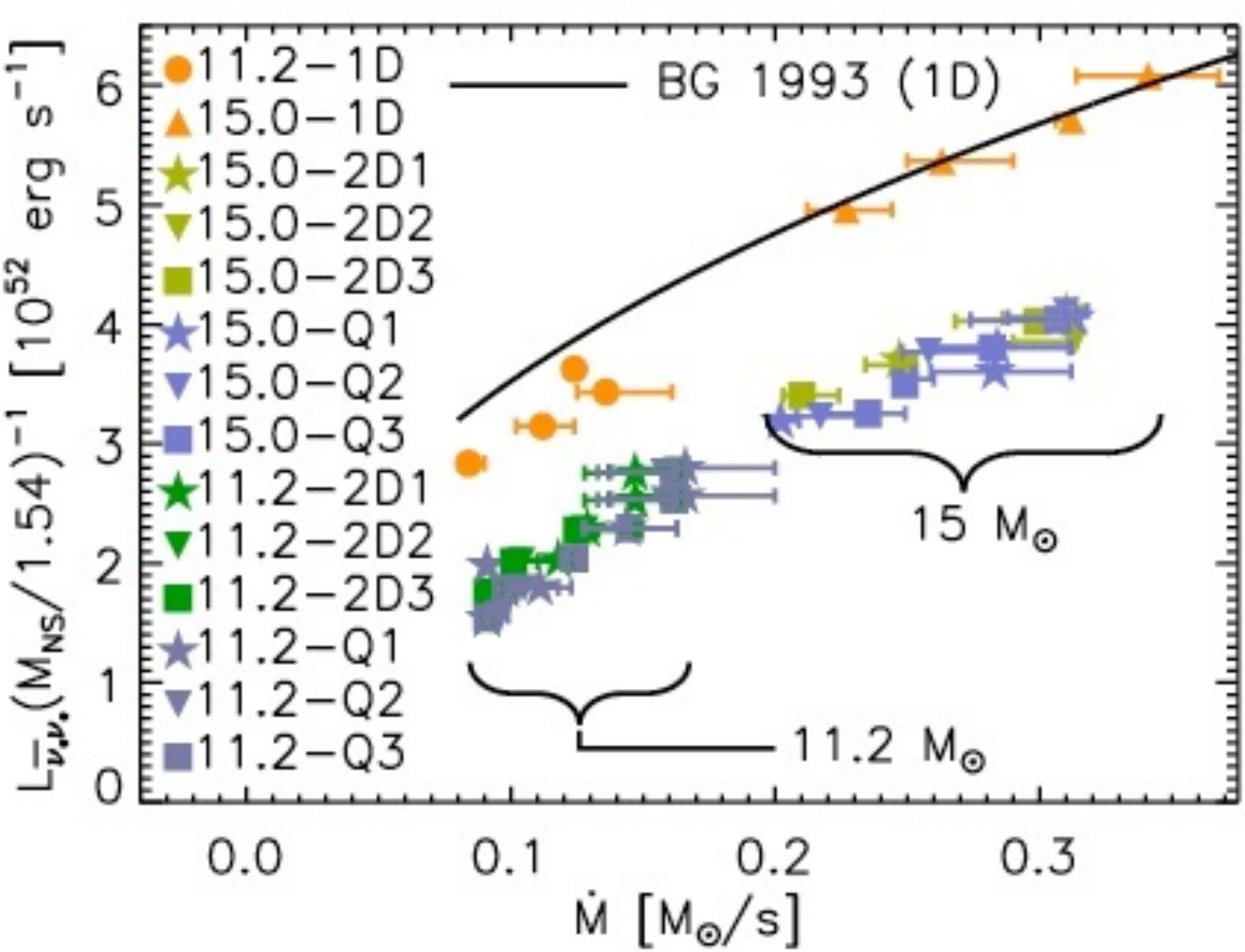
Murphy & Dolence 2017



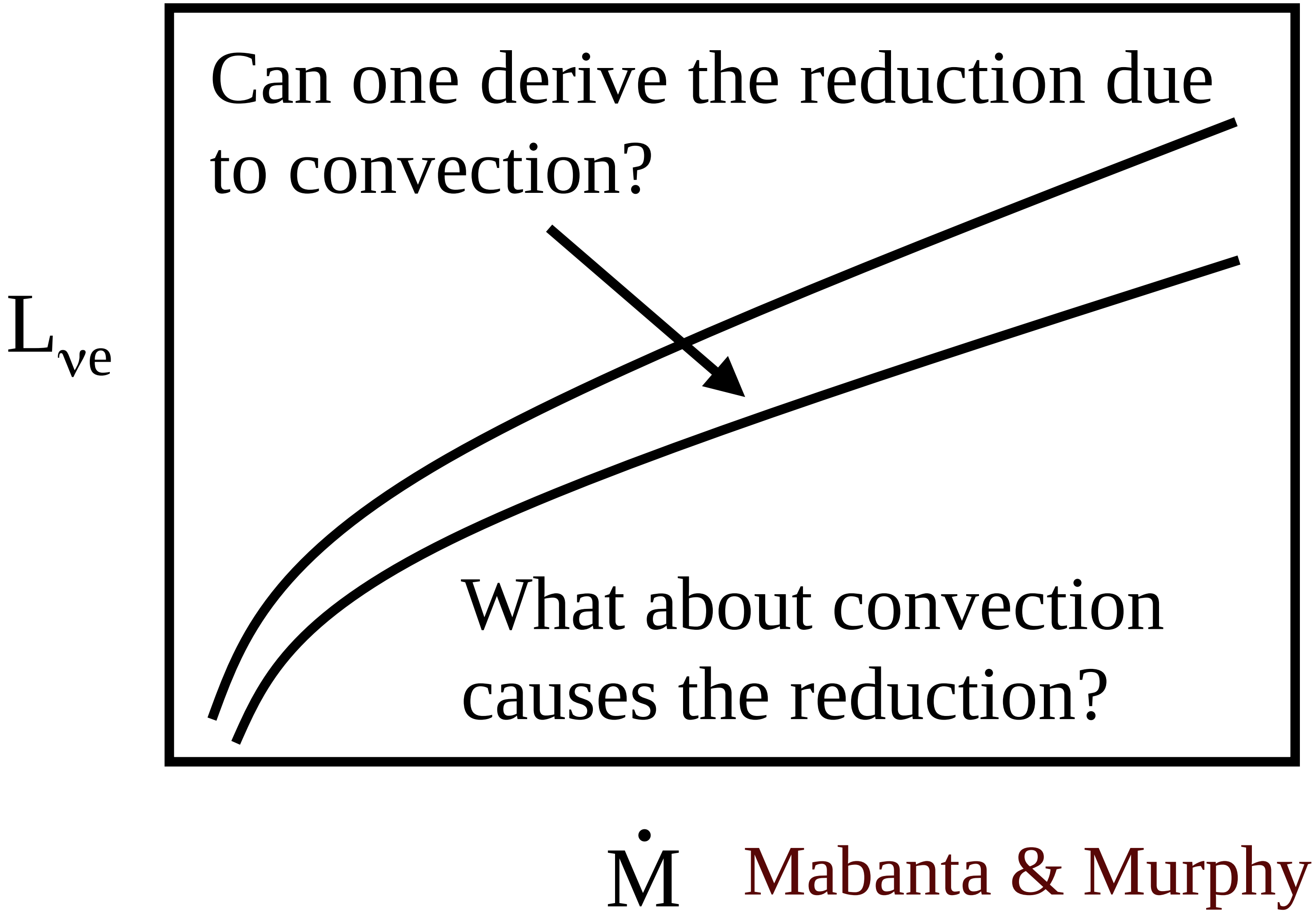
Burrows & Goshy '93
Steady-state solution (ODE)



Murphy & Burrows '08



Many years of multi-D simulations suggest (but did not prove) that convection and turbulence aid explosion.



Mabanta & Murphy 2018

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 Convection

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

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

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

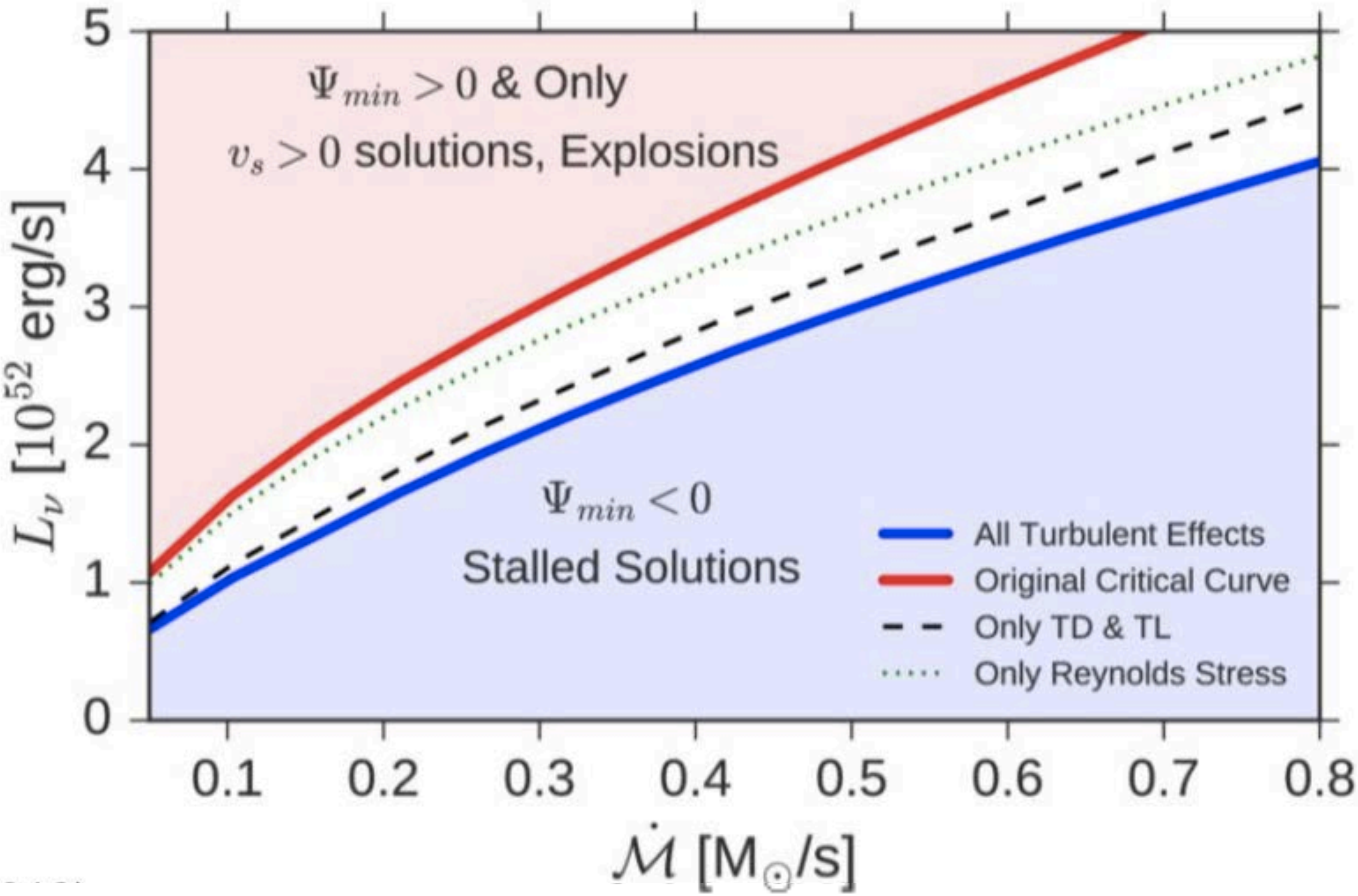
Close with a Convection Model

Investigate which terms are important

How Turbulence Enables Core-collapse Supernova Explosions

Quintin A. Mabanta and Jeremiah W. Murphy
Florida State University, USA; qam13b@my.fsu.edu, jwmurphy@fsu.edu

ApJ, 2018



Constraint #1:

A Comparison of Explosion Energies for Simulated and Observed Core-Collapse Supernovae

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[2] *Los Alamos National Laboratory*

2019

There are now ~20 multi-dimensional simulations that explode

Bruenn et al. 2016

Code: CHIMERA (2D)

The Astrophysical Journal, 818:123 (39pp), 2016 February 20 Bruenn et al.

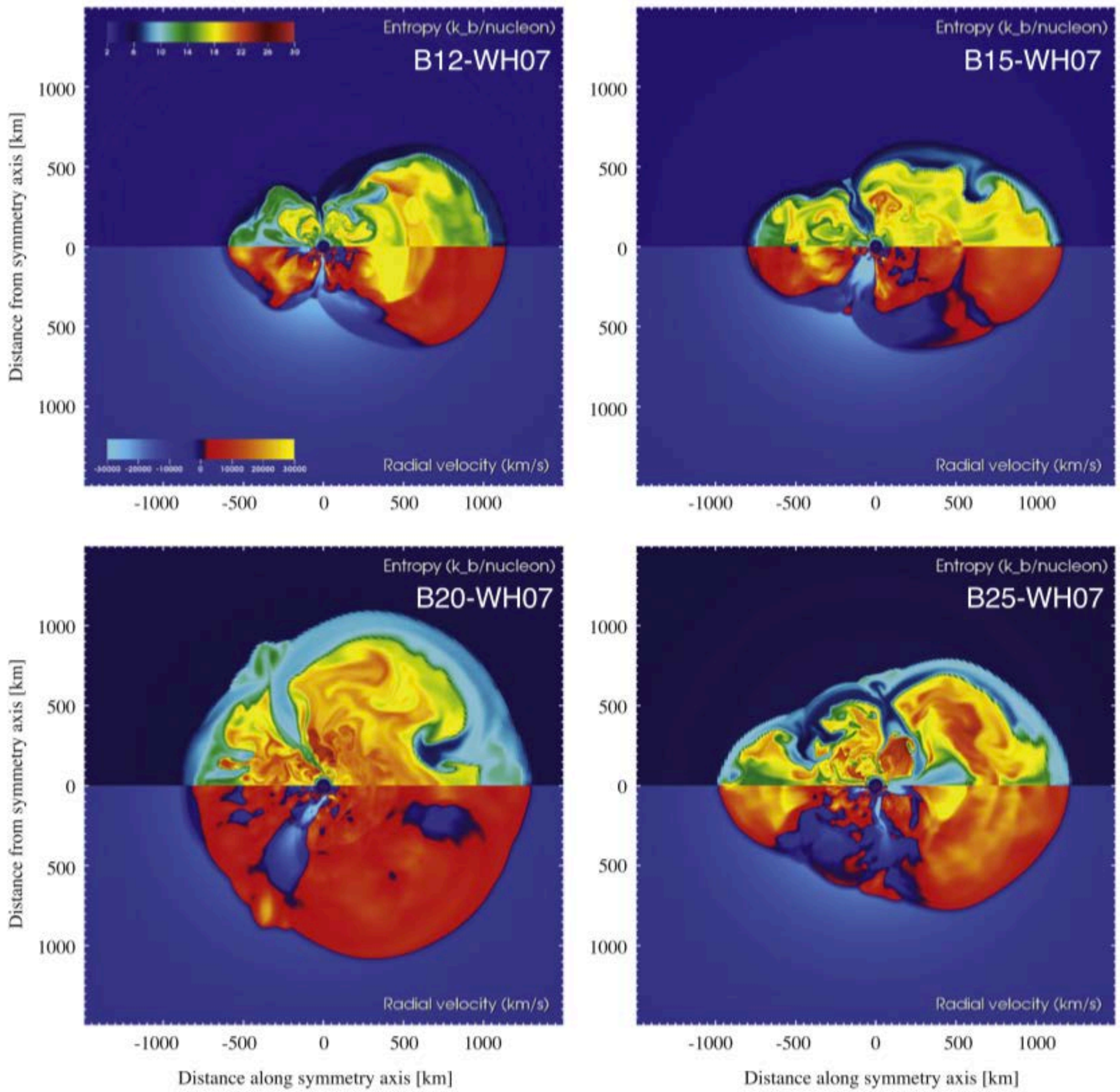
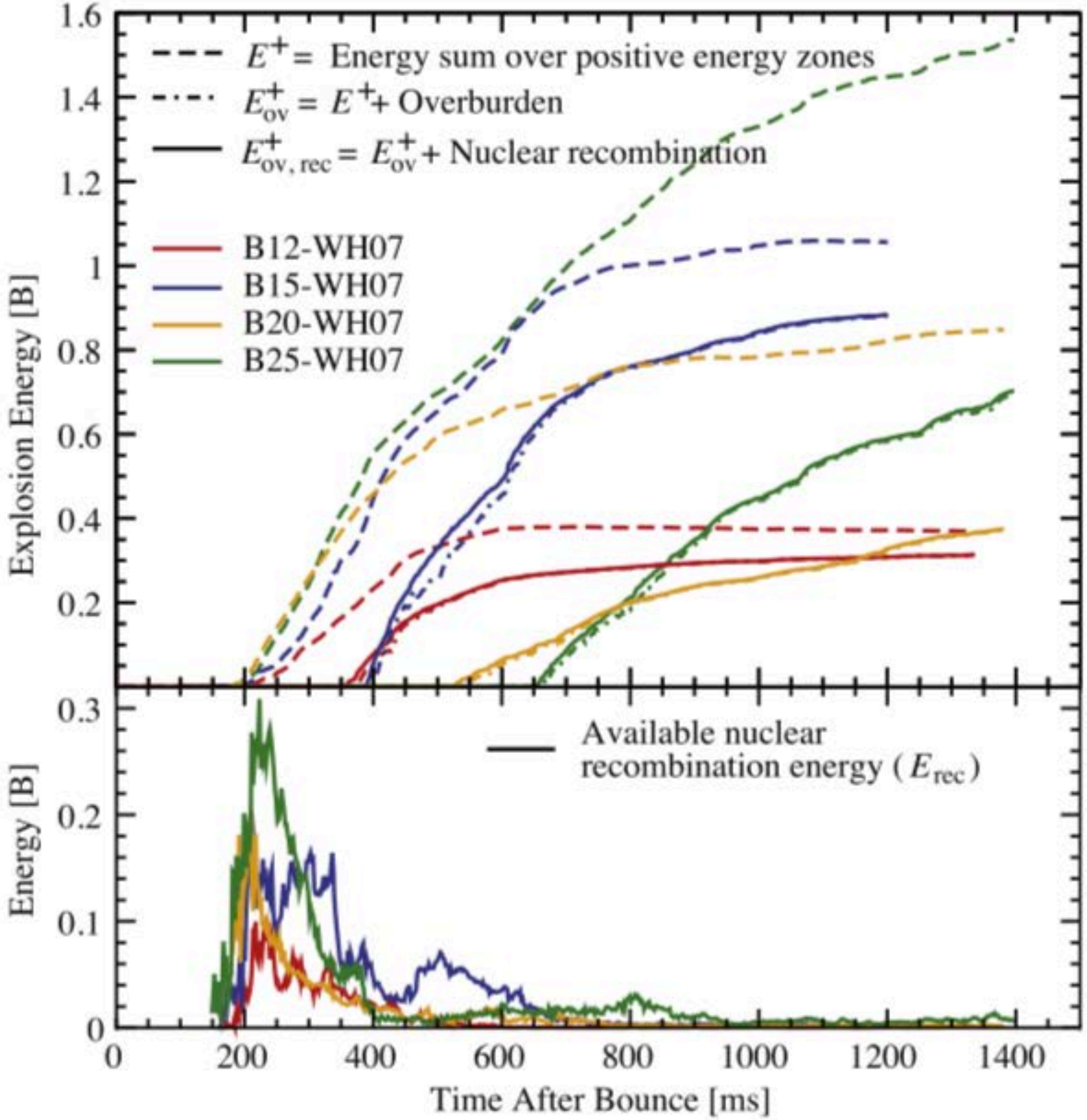


Figure 24. Profiles of entropy (upper portion of frames) and radial velocity (lower portion of frames) for all four models at 250 ms after bounce. Plotted as in Figure 3 with the entropy scale extended.

Bruenn et al. 2016

Code: CHIMERA (2D)



Müller et al. 2019

Code: CoCoNuT-FMT (3D)

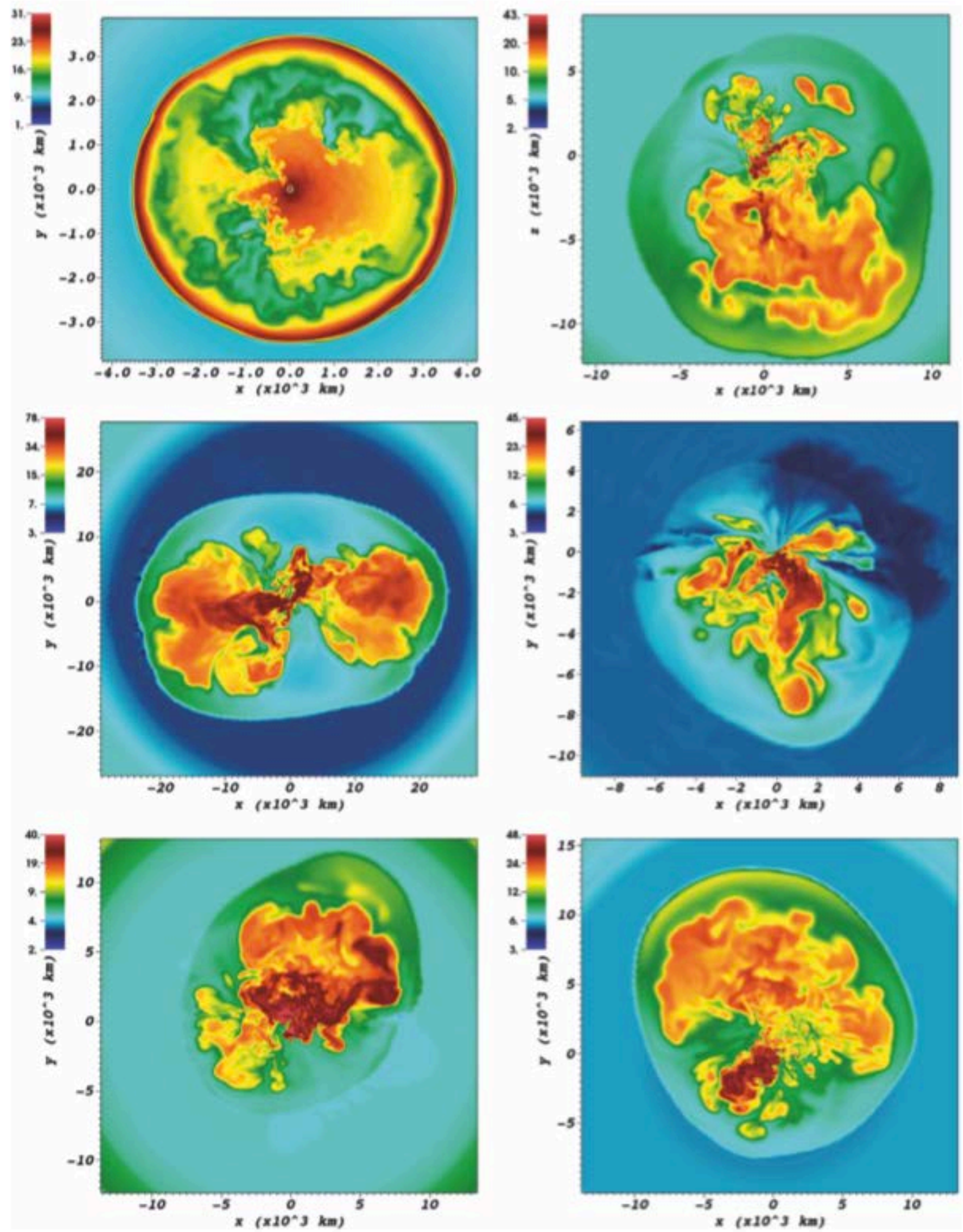
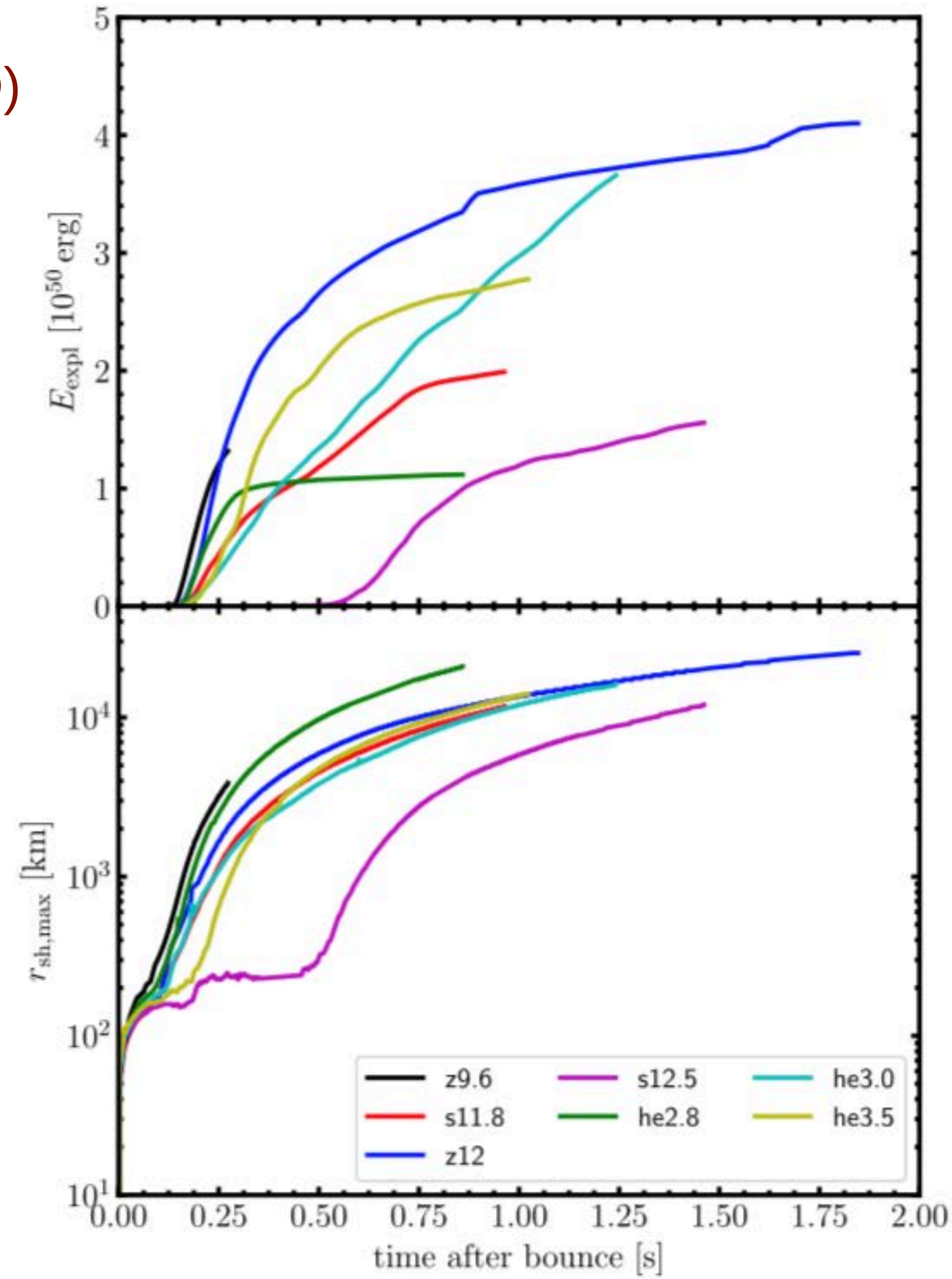


Figure 4. Entropy s in units of k_b/nucleon on 2D slices at the end of the simulations for models z9.6 (top left), s11.8 (top right), z12 (middle left), s12.5 (middle right), he3 (bottom left), and he3.5 (bottom right). The axis of the spherical polar grid is aligned with the x-axis of the plots. Note that there is no visible ...nment of the flow structures with the axis of the spherical polar grid in models s11.8, s12.5, he3, and he3.5. The explosion are predominantly unipolar, with ... exception of z12, and to some degree z9.6 at early times.

Müller et al. 2019

Code: CoCoNuT-FMT (3D)



Burrows et al. 2019

Code: FORNAX (2D & 3D)

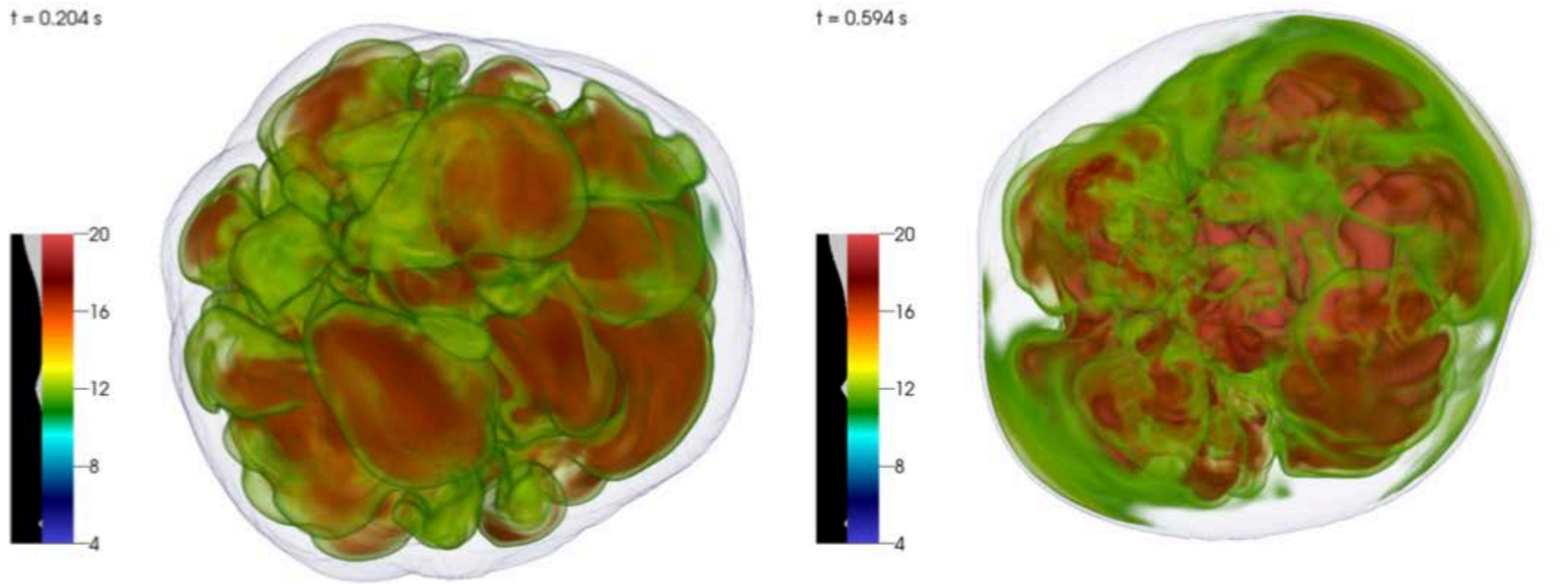
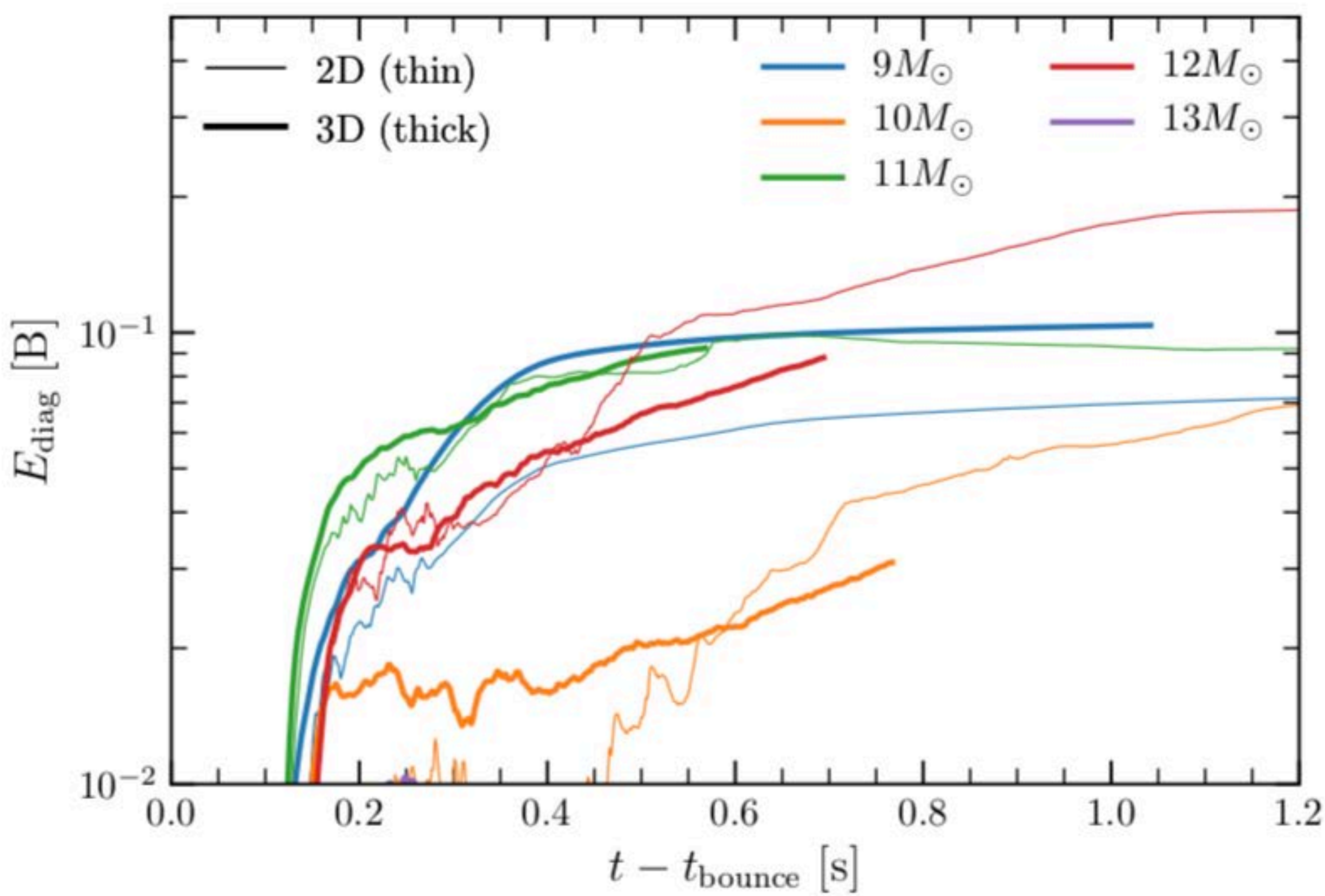


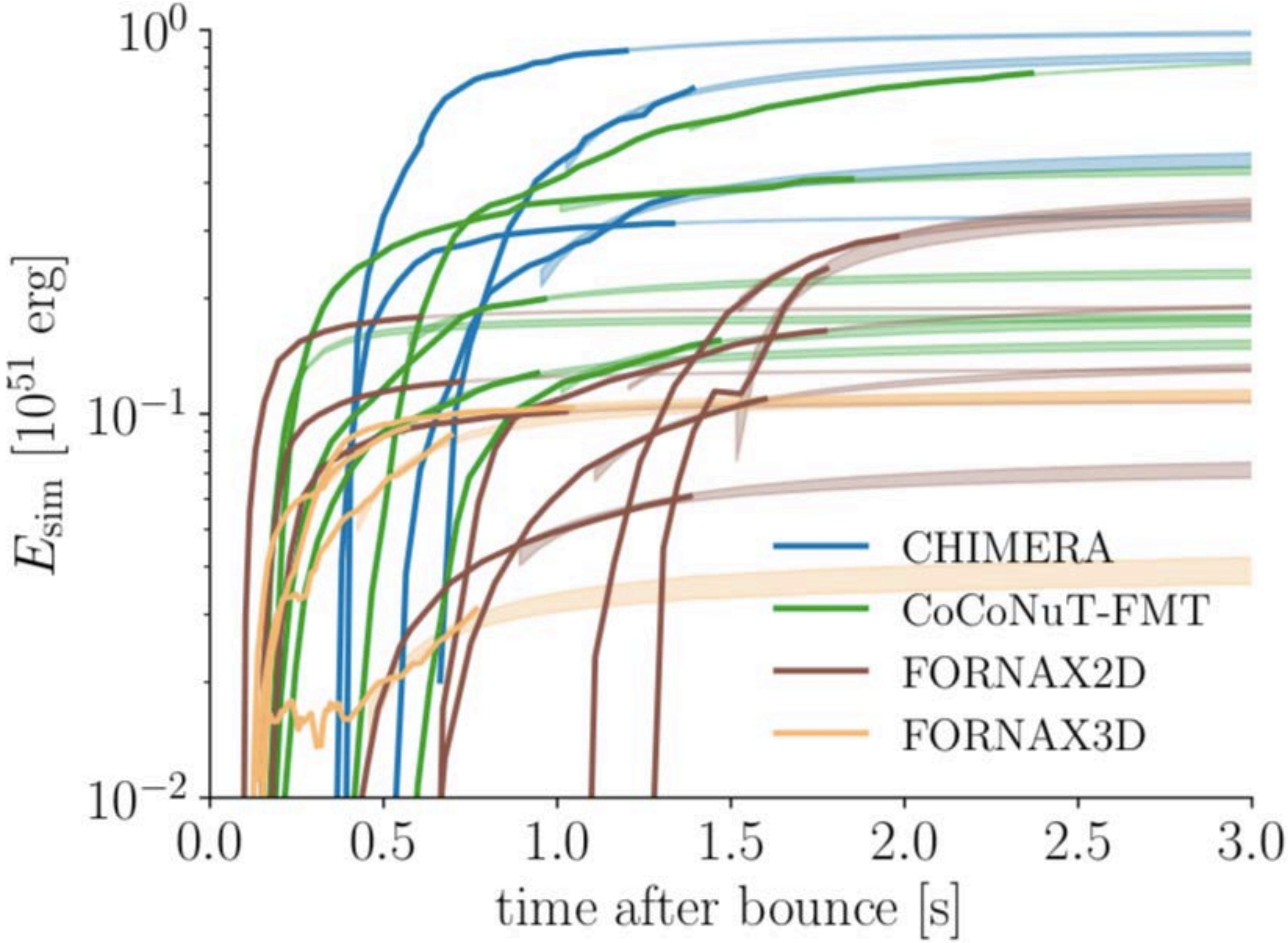
Figure 9. Three representative stills during the post-bounce 3D evolution of the exploding 9-$M_{\odot}$ model. Time proceeds from left to right and the spatial scale expands as a function of time. The outer blue shroud is the shock wave. The representation is a volume rendering of the entropy at the post-bounce time given in each top-left corner (in seconds) and the associated color map given in the bottom-left corner. The entropy units are per baryon per Boltzmann's constant. High entropies in the shocked mantle are more conducive to explosion, but entropy alone does not determine a predilection towards explosion. The physical scales are 400 km (left) and 6000 km (right). Note that, as with the following figures, the last time depicted here is not the last time of the simulation (see Table 1). See the text for a discussion of this and related plots.

Burrows et al. 2019

Code: FORNAX (2D & 3D)



A simple model for explosion to extrapolate to E_∞



Inferring explosion properties from SN IIP light curves

Goldberg et al. 2019

Observed Parameters: $L_{50}, t_p, M_{\rm Ni}$

Model Parameters:

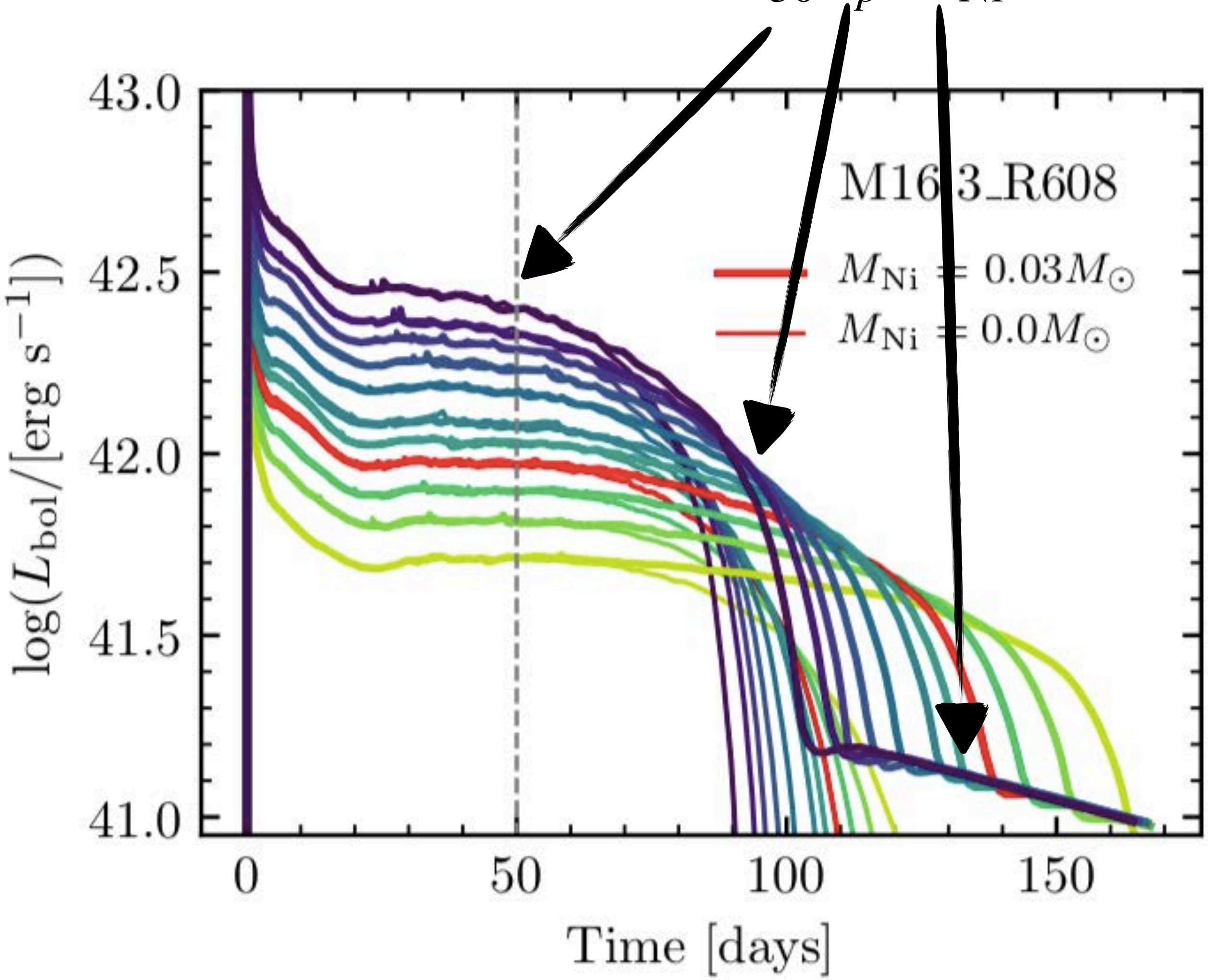
$E_{\rm exp}, M_{\rm ej}, R_\star, M_{\rm Ni}$

4th Observation?

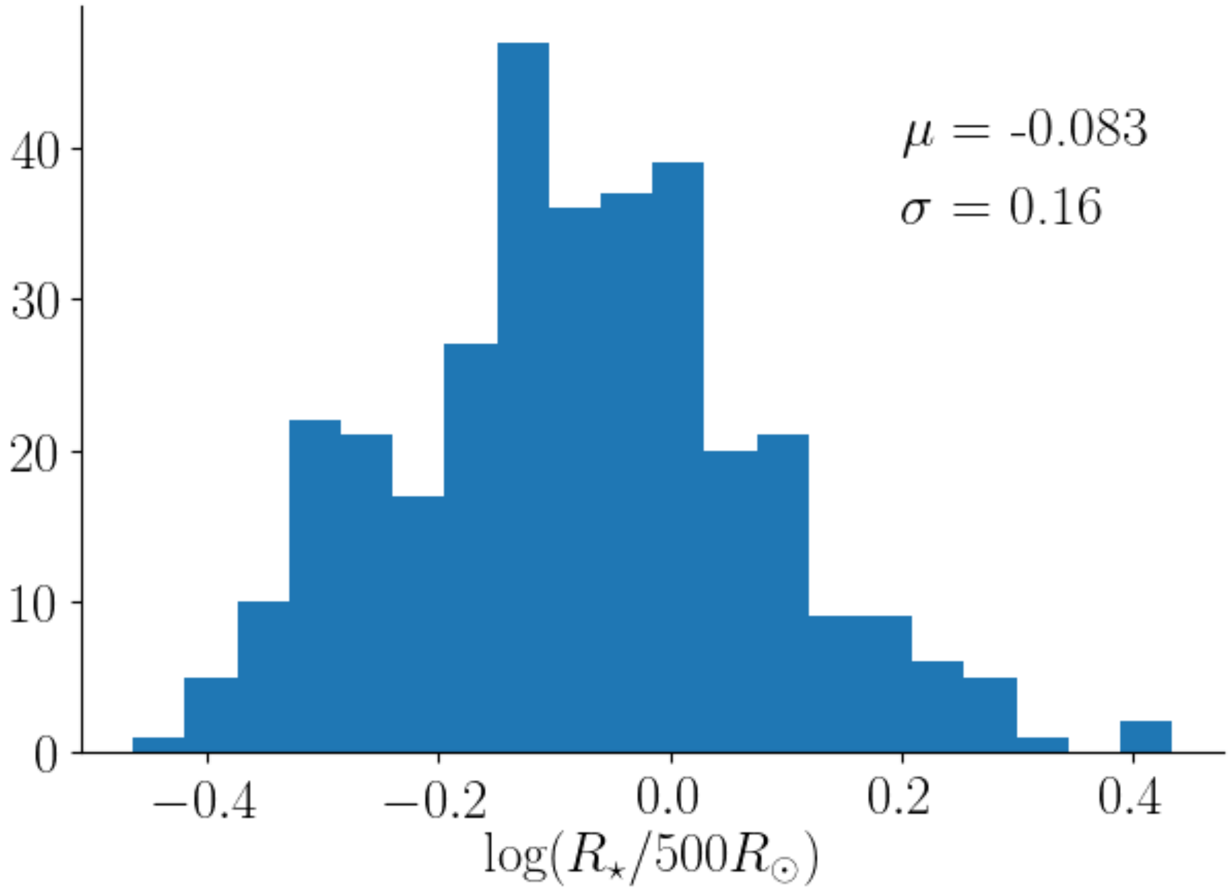
~~Spectra → v_{50}~~

$L_{50} \propto v_{50}^2$

Need to constrain $R_\star$



The degeneracy in $R_\star$ is not a big problem, because RSGs have similar sizes



Use this distribution of RSG sizes as a prior in an inference of explosion energies.

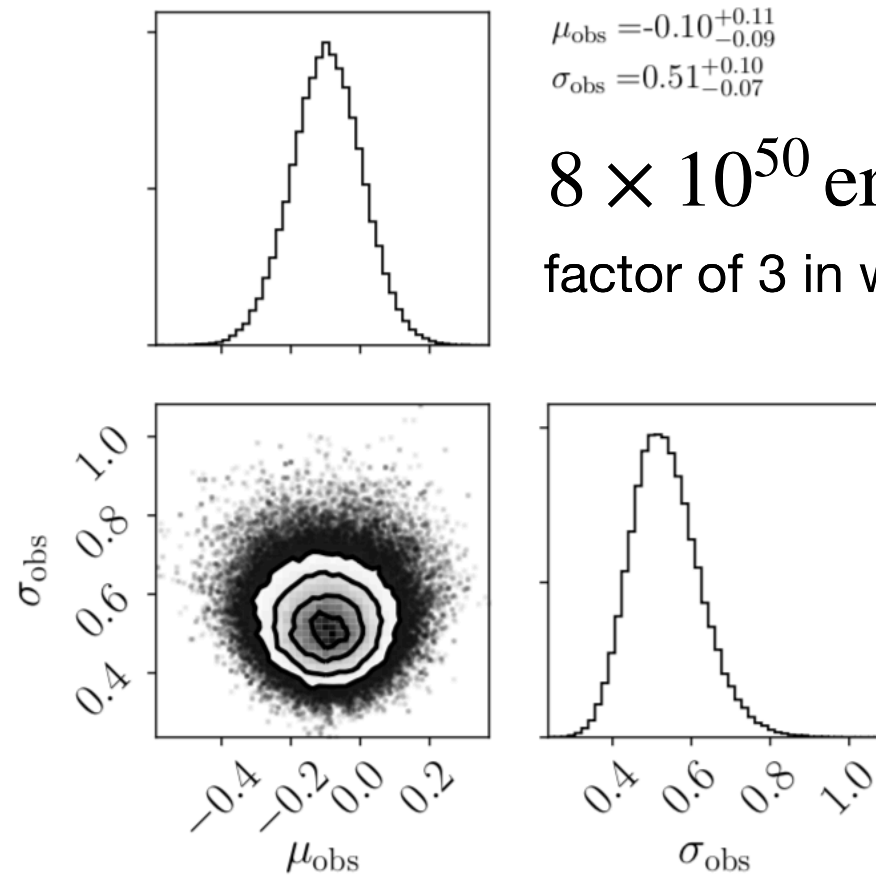
Name	$\epsilon = \log_{10}(E_{obs}/10^{51})$	σ_ϵ
SN 1980K	-1.38	0.30
SN 1992H	1.20	0.32
SN 1995ad	0.97	0.36
SN 1996W	0.26	0.33
SN 1999em	0.08	0.30
SN 2001dc	-1.65	0.33
SN 2002hh	-0.11	0.31
SN 2004A	-0.17	0.31
SN 2004dj	-0.53	0.32
SN 2004et	0.11	0.30
SN 2005cs	-0.72	0.31
SN 2006bp	0.45	0.30
SN 2007od	1.52	0.31
SN 2008bk	-0.53	0.52
SN 2008in	-0.11	0.63
SN 2009bw	0.19	0.30
SN 2009dd	-0.43	0.40
SN 2009js	0.72	0.38
SN 2009N	-0.34	0.30
SN 2012A	-0.52	0.30
SN 2012aw	0.49	0.30
SN 1992ba	-0.01	0.47
SN 2002gw	0.03	0.38
SN 2003B	-0.40	0.59
SN 2003bn	-0.13	0.34
SN 2003E	-0.05	0.39
SN 2003ef	0.43	0.38
SN 2003fb	-0.35	0.43
SN 2003hd	-0.11	0.34
SN 2003hn	-0.49	0.35
SN 2003ho	-0.94	0.33
SN 2003T	-0.33	0.32
SN 2009ib	-0.26	0.32
SN 2012ec	-0.08	0.31
SN 2013ab	0.26	0.42
SN 2013ej	-0.28	0.34
SN 2013fs	-0.19	0.32
SN 2014G	-0.35	0.33
ASSASSN-14gm	0.09	0.34
ASSASSN-14ha	-0.38	0.38

40 SN IIP

Pejcha & Prieto 2015

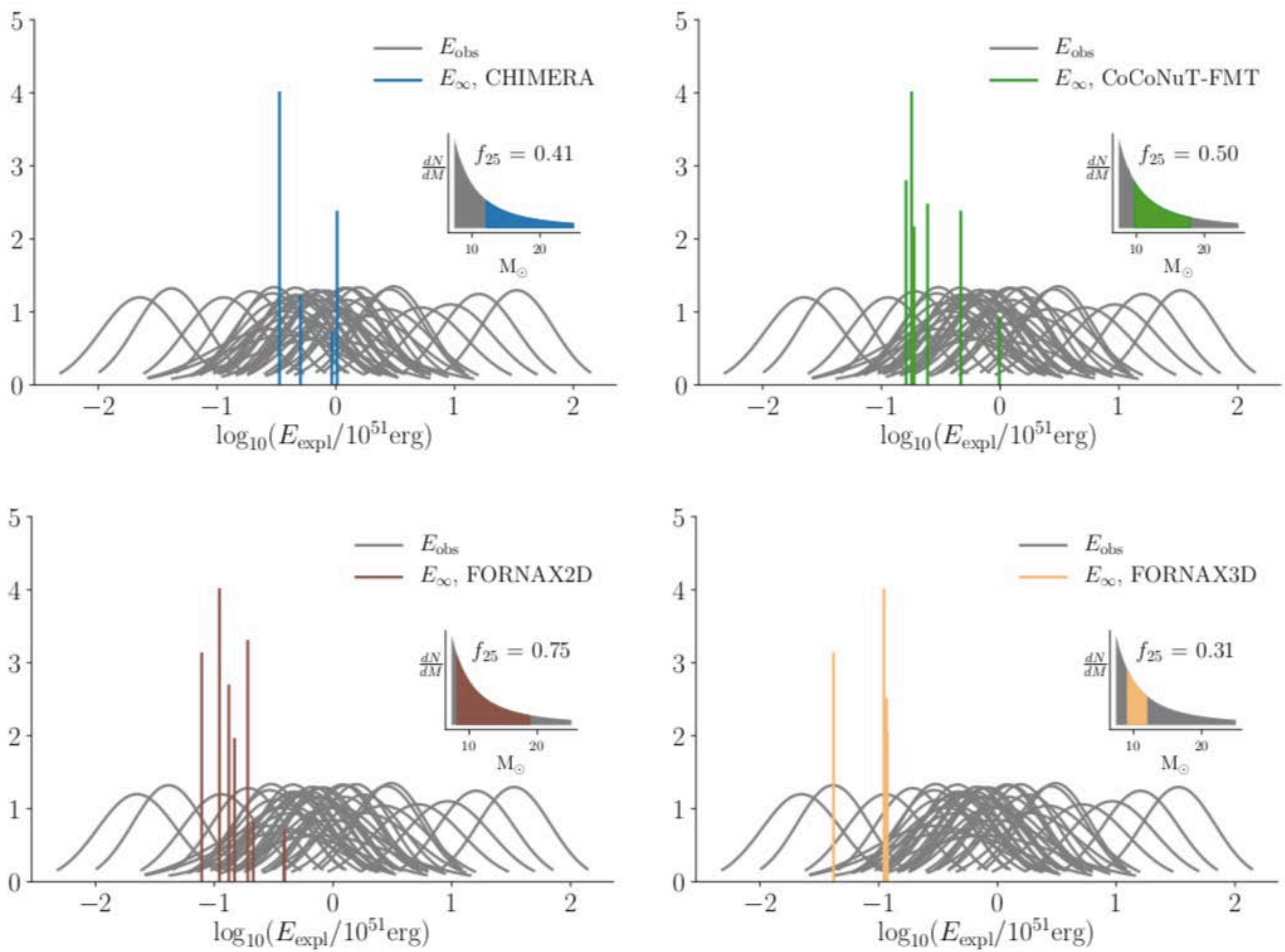
Müller et al. 2017

Use Goldberg et al. 2019 inference equations

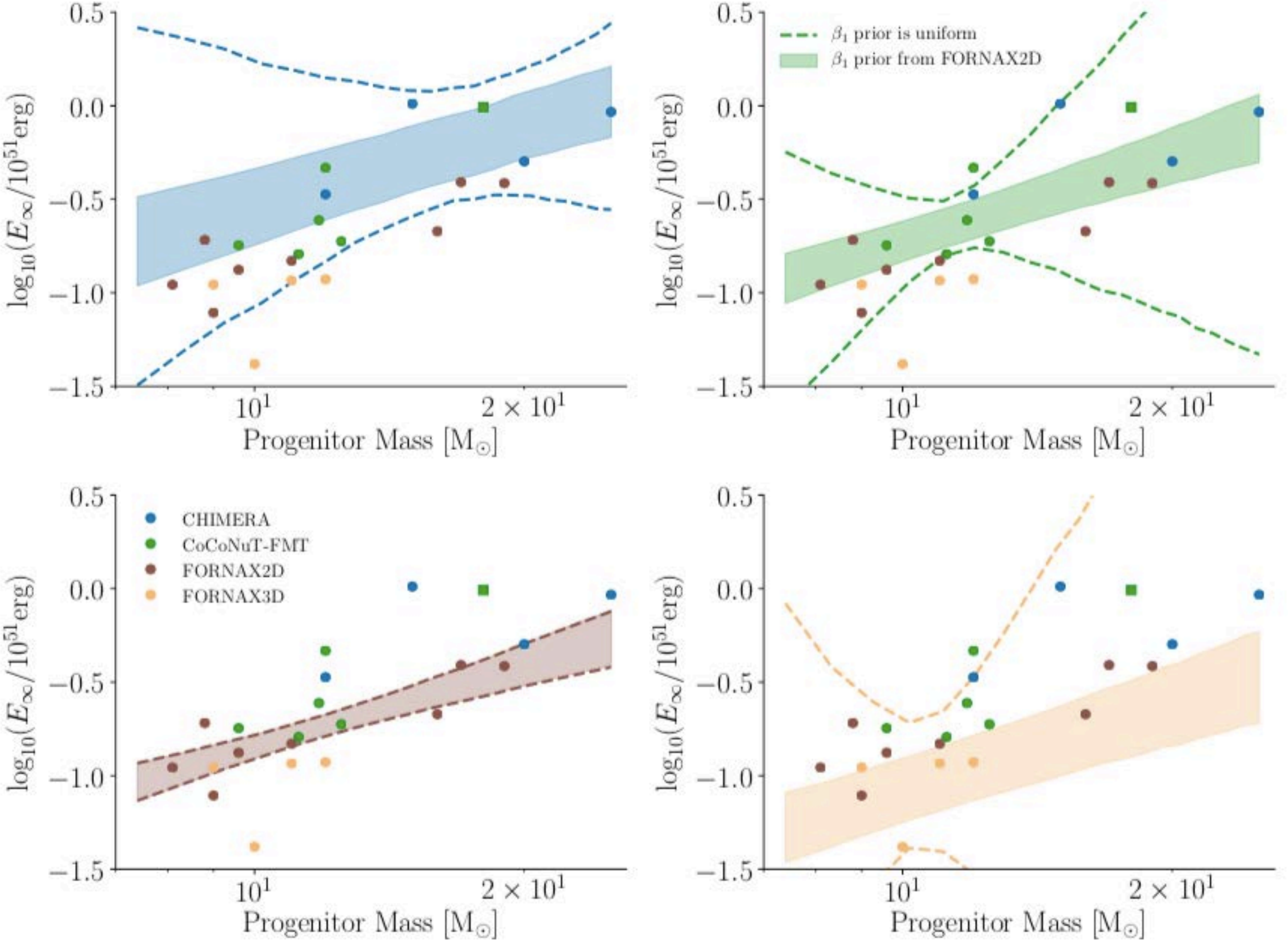


8×10^{50} erg

factor of 3 in width

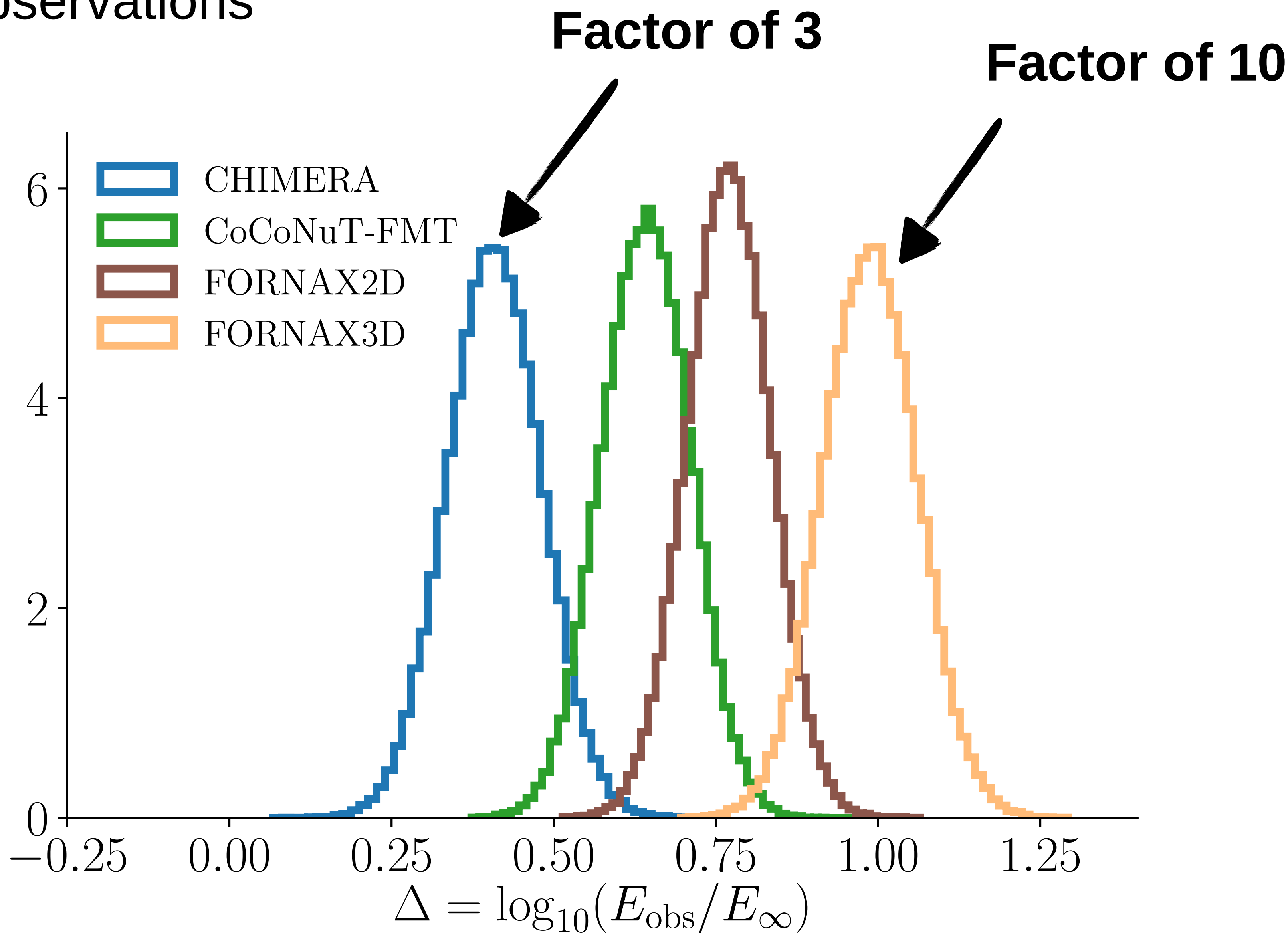


E_{obs}
E_∞, CHIMERA
$f_{25} = 0.41$
E_∞, CoCoNuT-FMT
$f_{25} = 0.50$
E_∞, FORNAX2D
$f_{25} = 0.75$
E_∞, FORNAX3D
$f_{25} = 0.31$
$\frac{dN}{dM}$
$M_\odot$
$\log_{10}(E_{expl}/10^{51}erg)$



β_1 prior is uniform
β_1 prior from FORNAX2D
CHIMERA
CoCoNuT-FMT
FORNAX2D
FORNAX3D
$\log_{10}(E_\infty/10^{51}\mathrm{erg})$
Progenitor Mass [$\mathrm{M}_\odot$]
0.5
0.0
−0.5
−1.0
−1.5
10^1
2×10^1

Posterior distributions for differences in simulations and observations



Numerical simulations are important

…,but 18 Million cpu-hr/run
months on 16256 cores*
~ $1 million/run
~Power 1,000 homes for a year.
…to systematically explore
progenitors and physics will take
100s of years.

*Vartanyan 2018

Numerical simulations are important, but need another way to systematically explore which progenitors explode?

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

Mabanta, Murphy & Dolence 2019

Equations with Convection

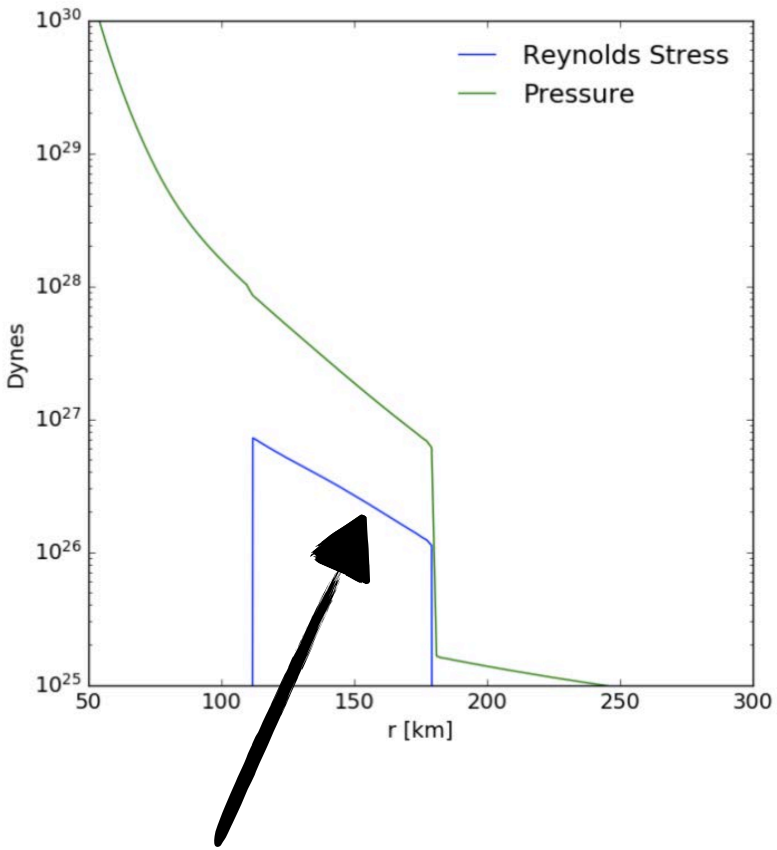
$$\nabla \cdot (\rho_0 \vec{u}_0 + \langle \rho' \vec{u}' \rangle) = 0$$

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

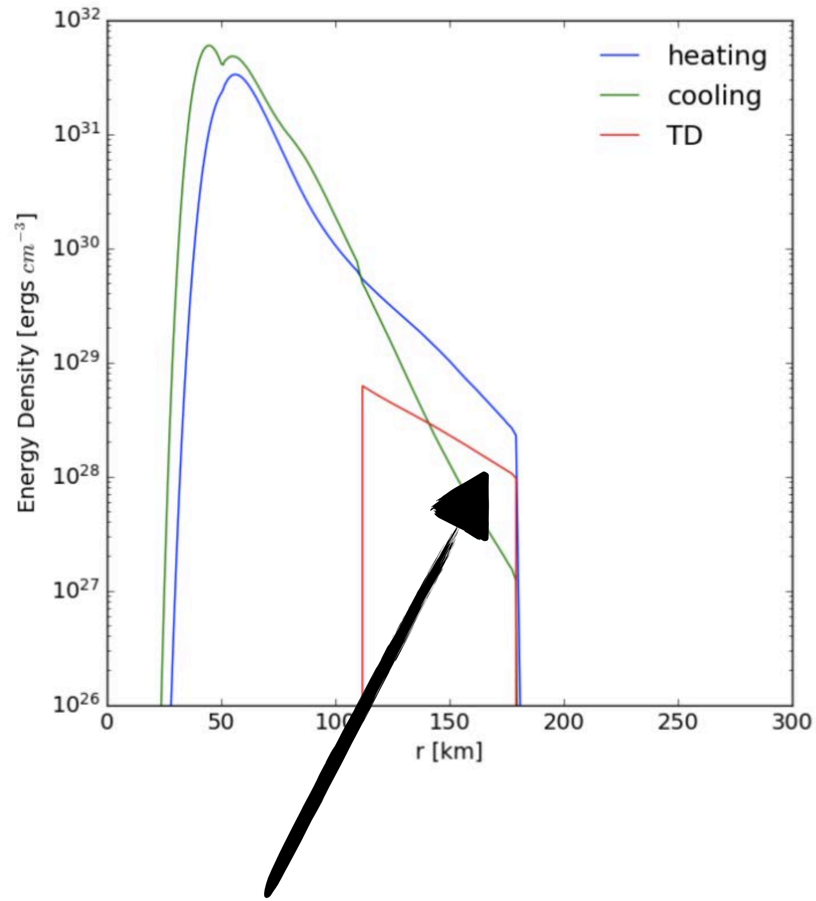
$$\langle \rho u \rangle \cdot \nabla e_0 + \langle P_0 \nabla \cdot u_0 \rangle + \langle P' \nabla \cdot u' \rangle = -\nabla \cdot \langle F_e \rangle + \rho_0 q + \rho_0 \epsilon_k$$

Reynolds Decompose
Close with a Convection Model
Investigate which terms are important

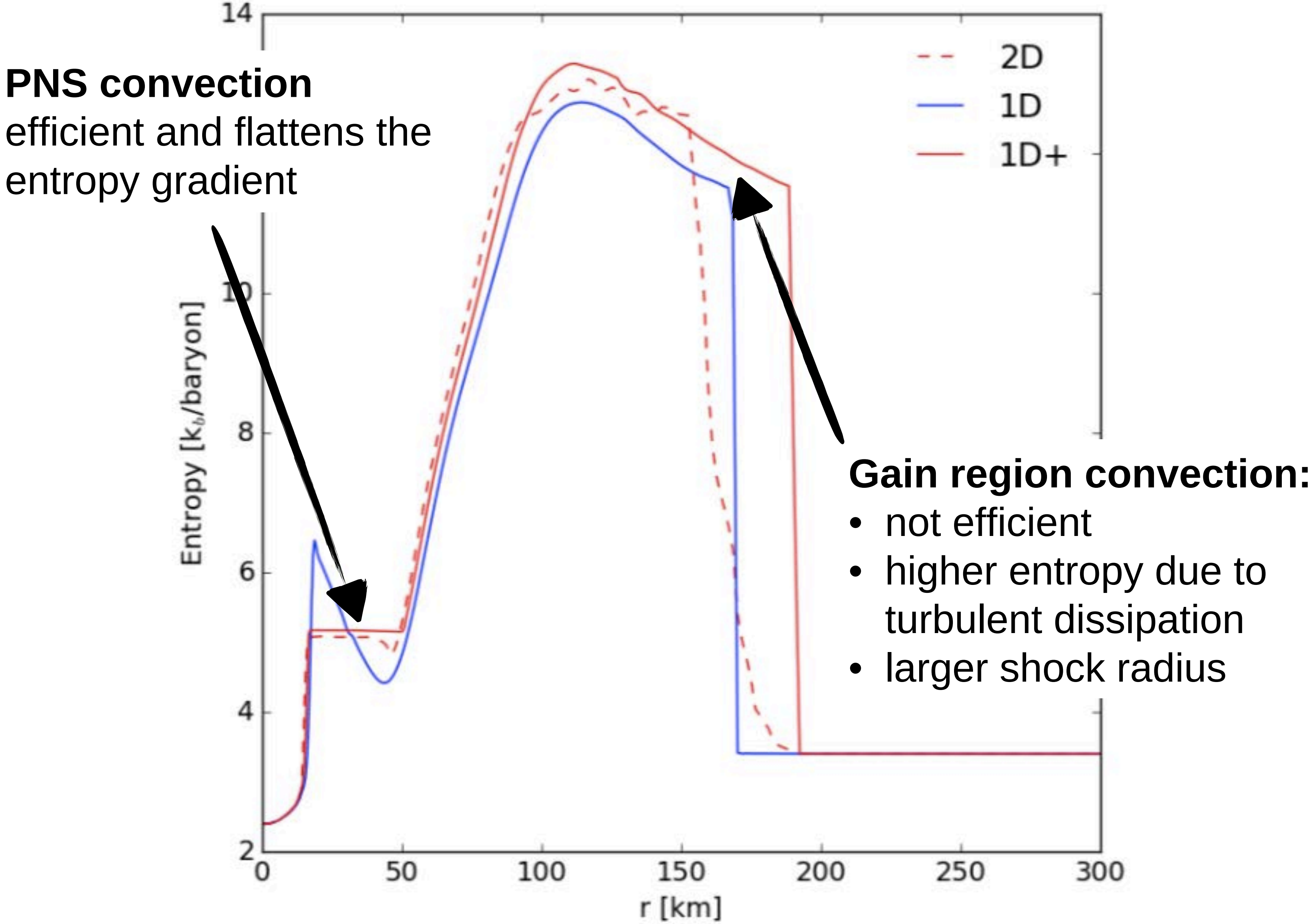
Include convection model in 1D simulations (1D+)

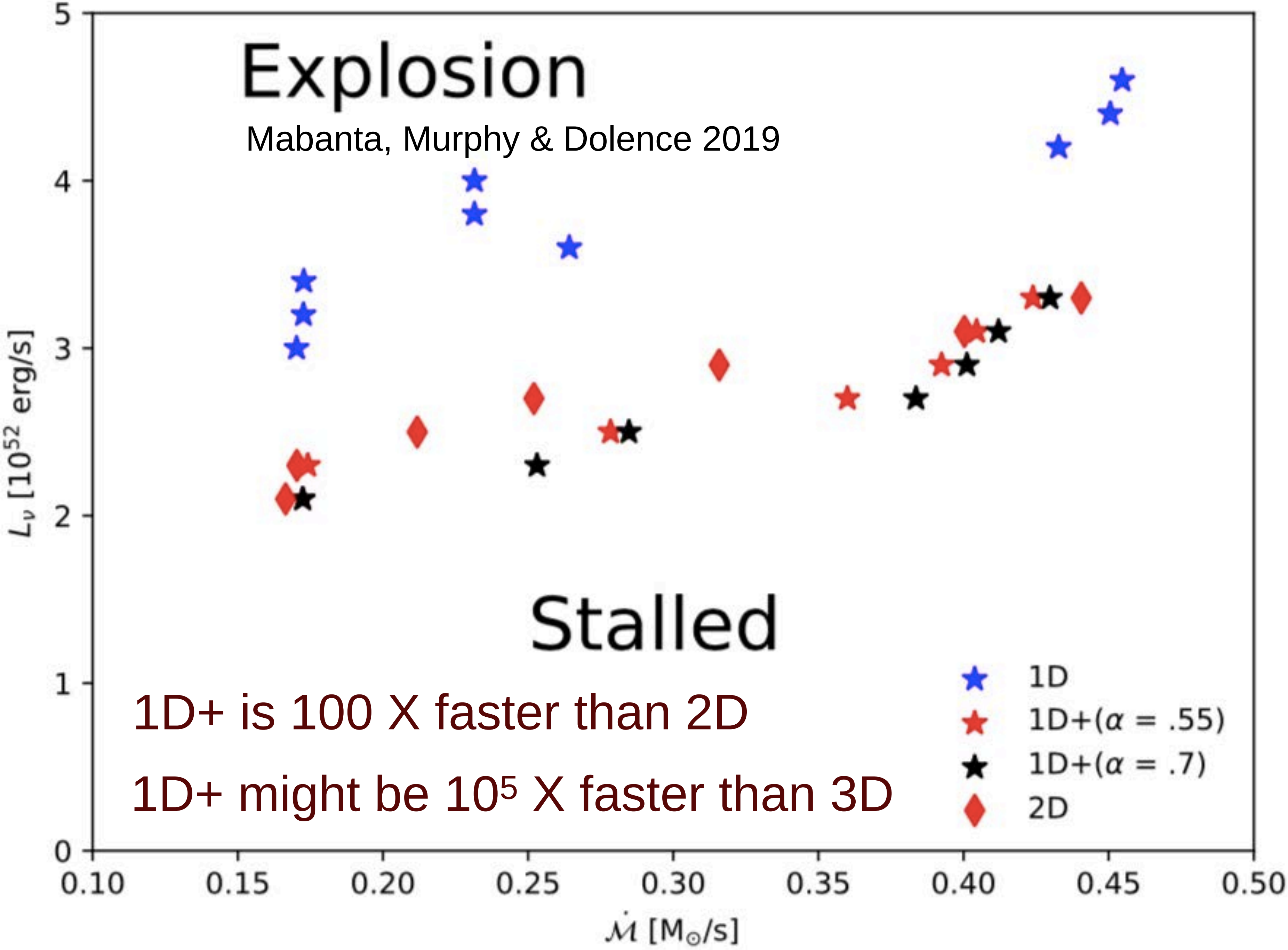


Turbulent ram pressure is about 10% of thermal pressure



Turbulent dissipation is about 50% of neutrino heating.


PNS convection
efficient and flattens the entropy gradient
Gain region convection:
• not efficient
• higher entropy due to turbulent dissipation
• larger shock radius
2D
1D
1D+
Entropy [k_b/baryon]
r [km]
14
10
8
6
4
2
0
50
100
150
200
250
300


Explosion
Mabanta, Murphy & Dolence 2019
Stalled
1D+ is 100 X faster than 2D
1D+ might be 10^5 X faster than 3D
1D
1D+(α = .55)
1D+(α = .7)
2D
L_ν [10^{52} erg/s]
$\dot{\mathcal{M}}$ [$M_\odot$/s]
0
1
2
3
4
5
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50

Constraint 2: Progenitor Mass Distribution for Core Collapse SNRs

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David Rubin
William Blair
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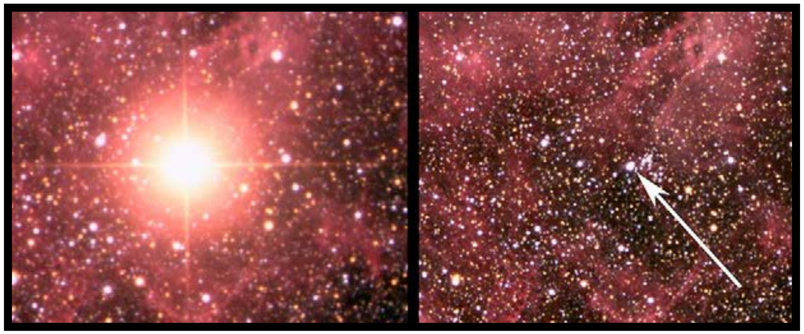
One way to identify SN progenitor masses:

Pre-SN imaging:



Benefit: Image of the star that actually exploded

But, direct progenitor imaging is **rare**:

✳ 30 direct detections and 38 upper limits (Van Dyk 2017)

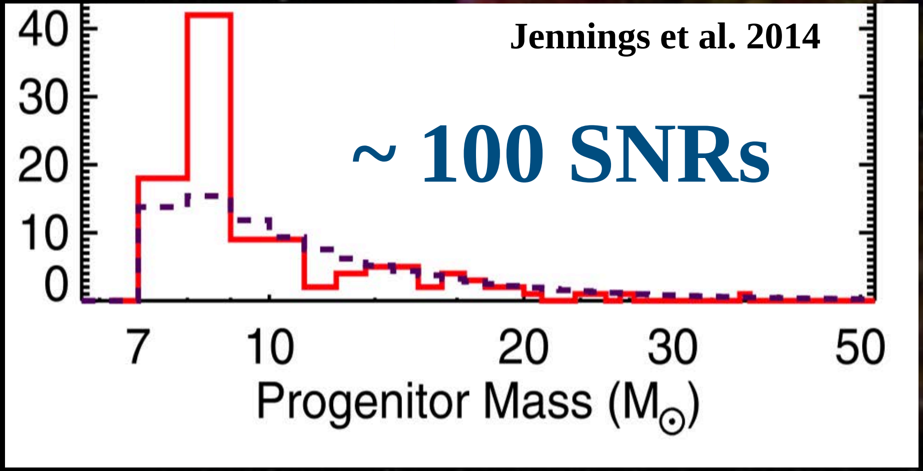
rate of $SN_{\mathrm{DT}} = 2/yr$

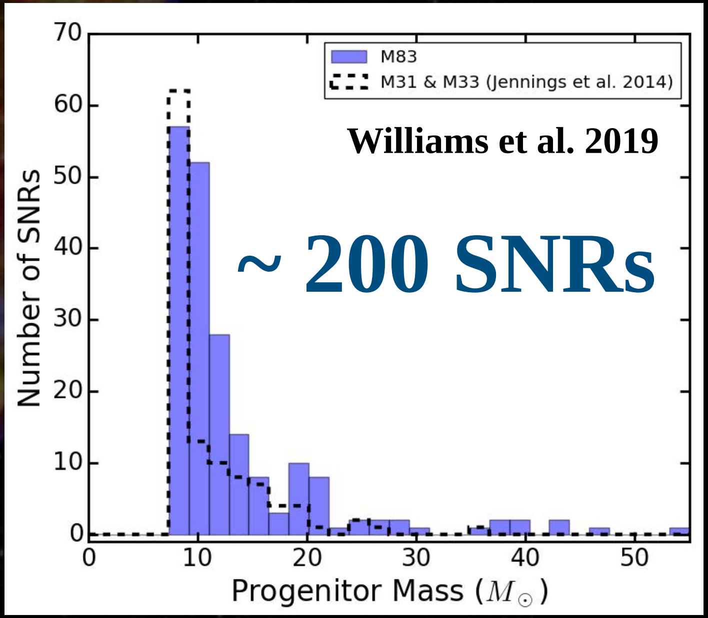
To get to 100 SN progenitors we have to wait until 2049

We need a technique to verify theory and direct imaging, and one that will give us **hundreds** of progenitor masses

Supernova Remnants as SN tracers

- The SN rate is ~ 2 SN / century / galaxy
- SNRs are detectable for ~10,000 years.
- We can expect to have ~200 progenitor mass estimates per galaxy





(Badenes et al. 2009; Jennings et al. 2012, 2014; Williams et al. 2018; Díaz-Rodríguez et al. 2018; Murphy et al. 2018; Lopez et al. 2019, etc)

Goal: Age date thousands of SNRs

$$\tau \sim \frac{f M_\star c^2}{L_\star}$$

$$L_\star \propto M^{3.5}$$

$$\tau \propto \frac{1}{M^{2.5}}$$

$$\tau \propto \frac{1}{L_\star^{5/7}}$$

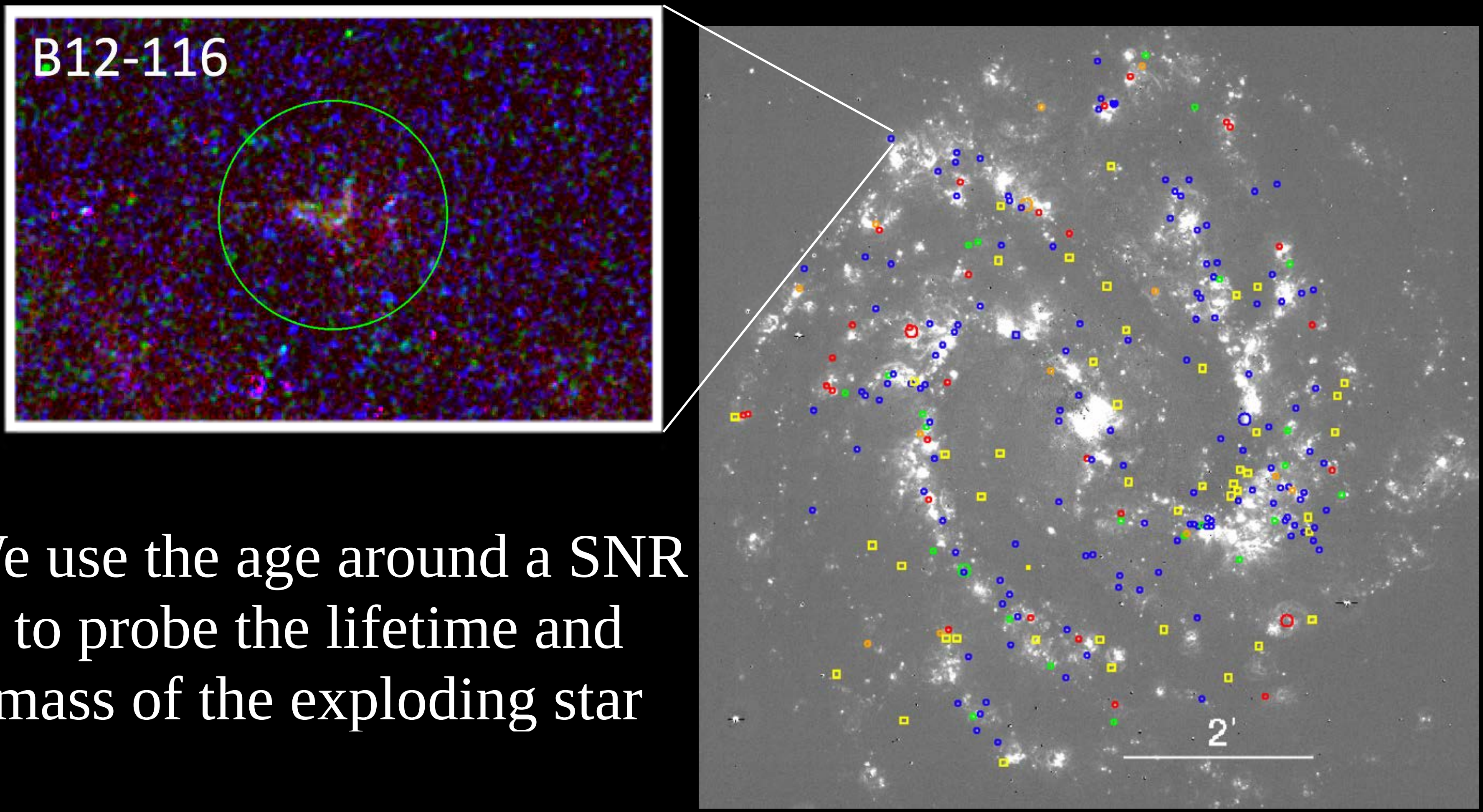
$$1M_\odot \qquad \tau = 10^{10}\,\mathrm{yr}$$

$$7.5M_\odot \qquad \tau = 4.5 \times 10^{7}\,\mathrm{yr}$$

$$15M_\odot \qquad \tau = 1.5 \times 10^{7}\,\mathrm{yr}$$

$$50M_\odot \qquad \tau = 5 \times 10^{6}\,\mathrm{yr}$$

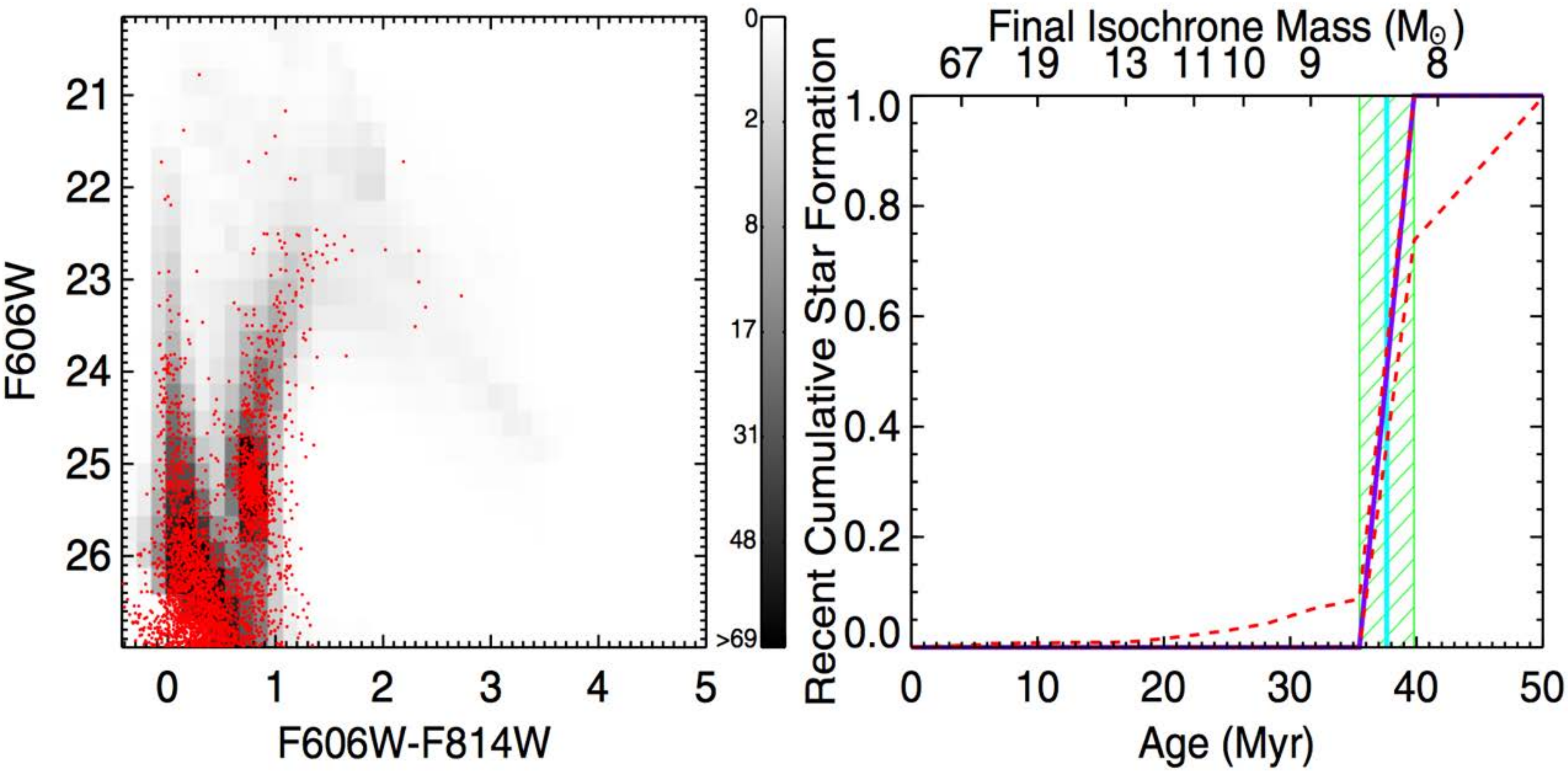
An Alternate Technique: Age date the Stellar Population



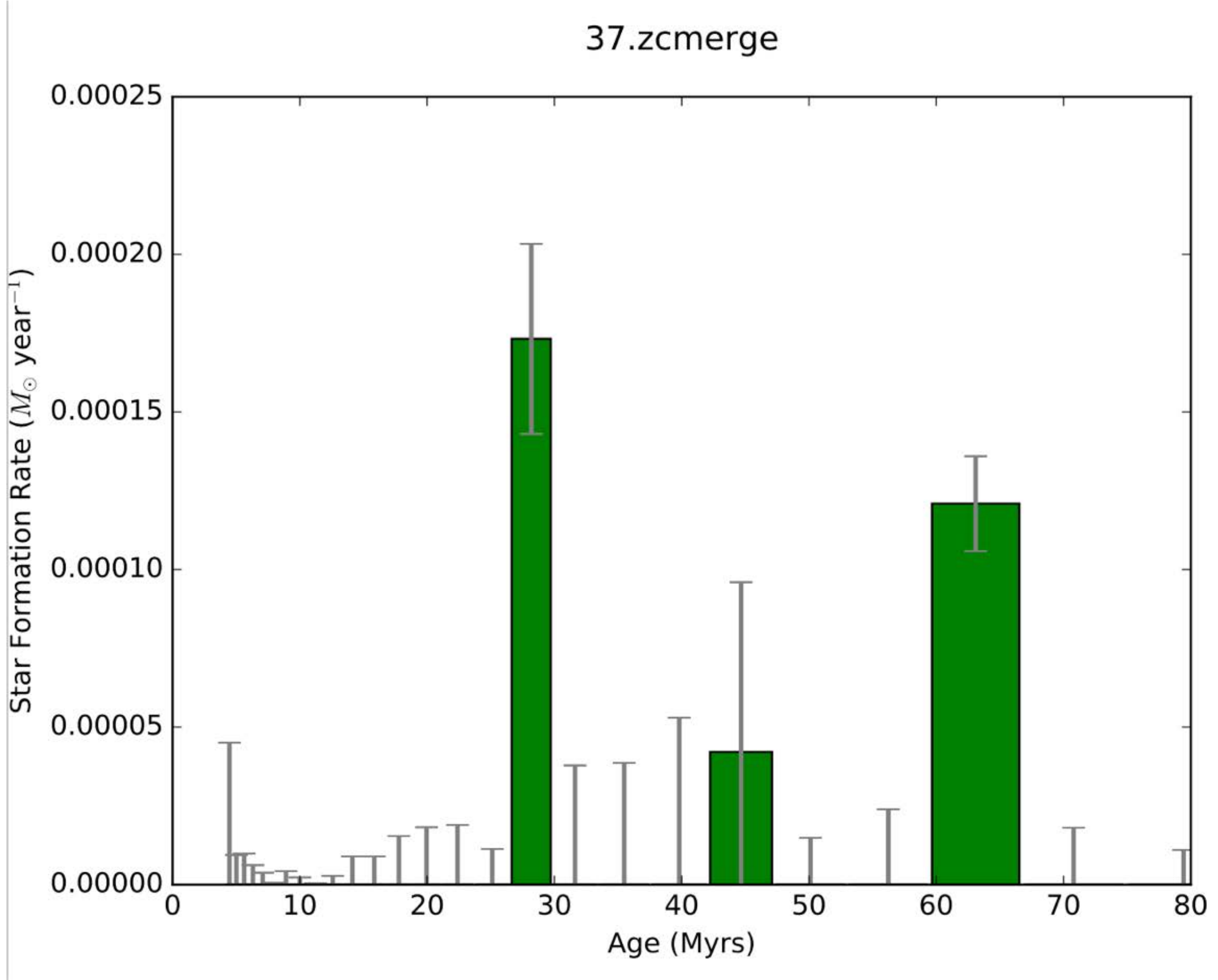
We use the age around a SNR to probe the lifetime and mass of the exploding star

Williams et al. 2019, Blair et al. 2012

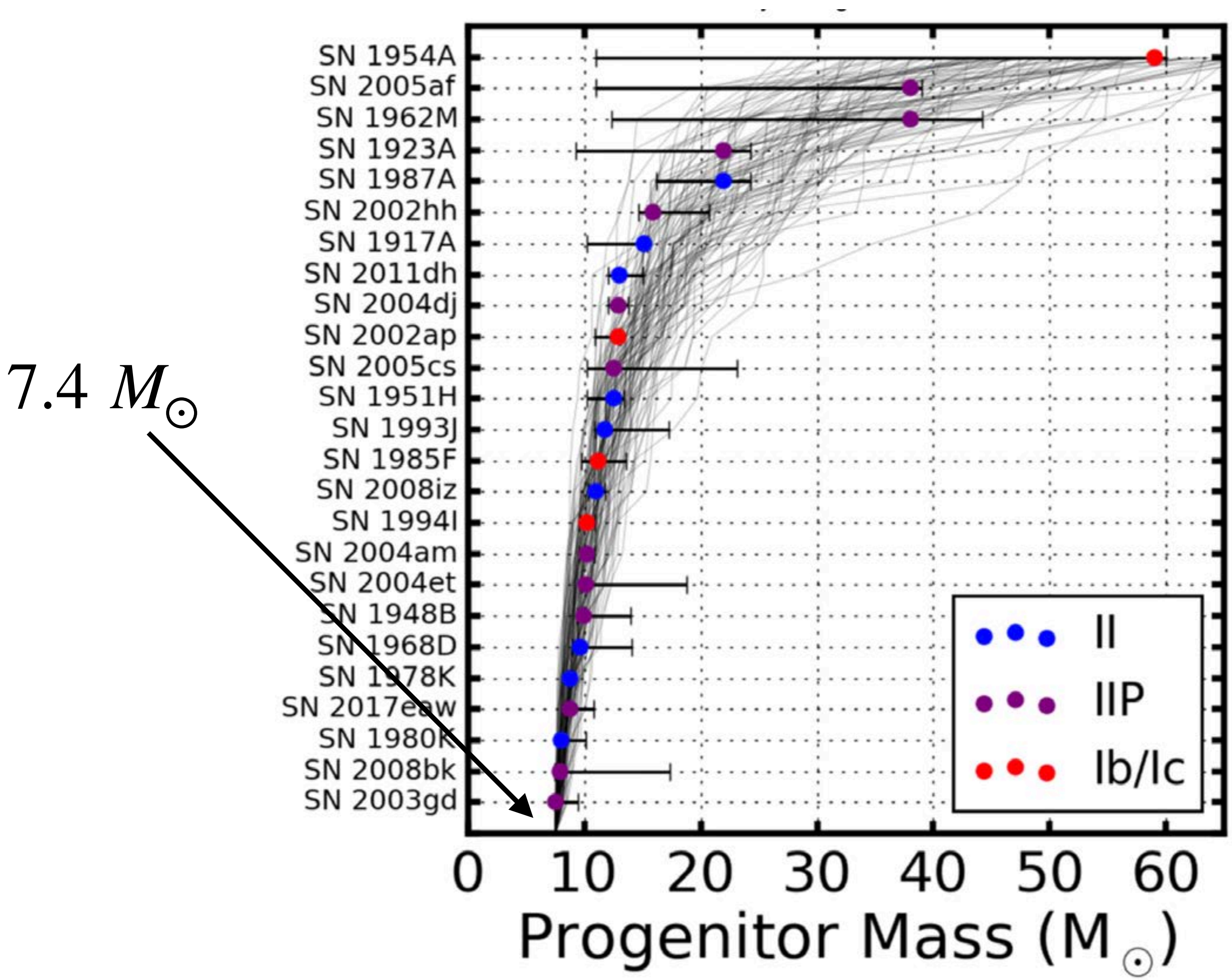
Jennings et al. 2014



However, sometimes….

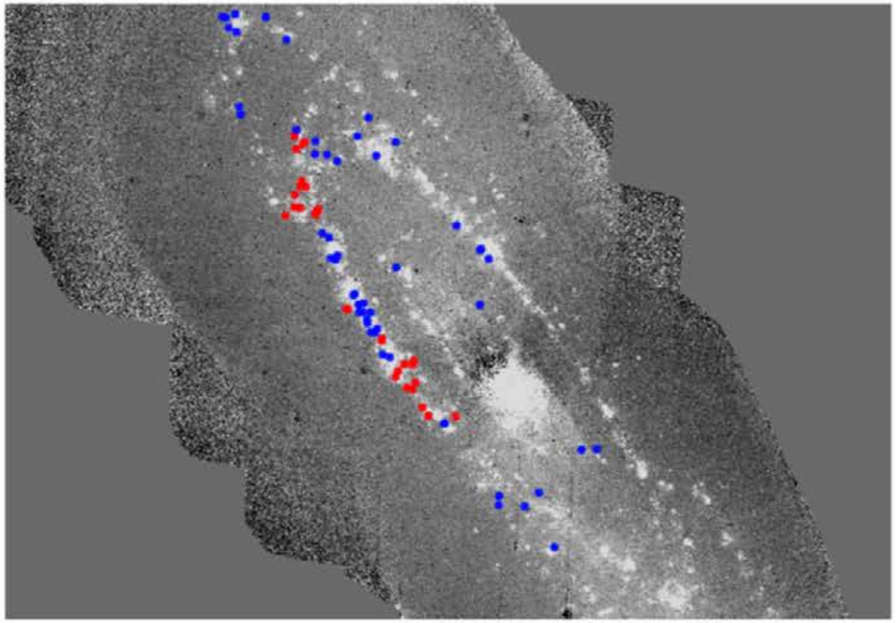


Williams et al. 2018

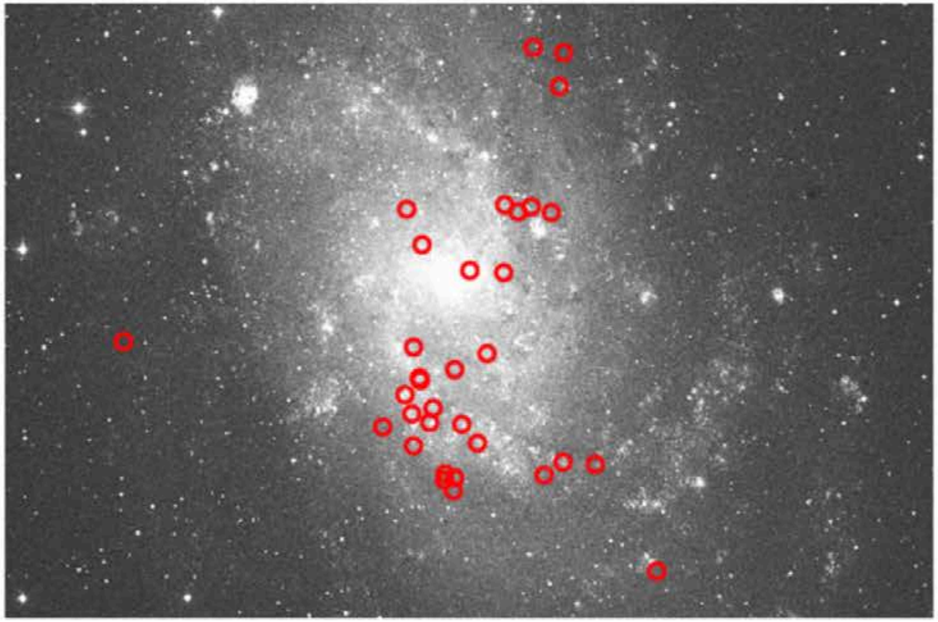


Age dating 115 SNRs in M31 and M33

(Jennings et al. 2012,2014 ; Díaz-Rodríguez et al. 2018)



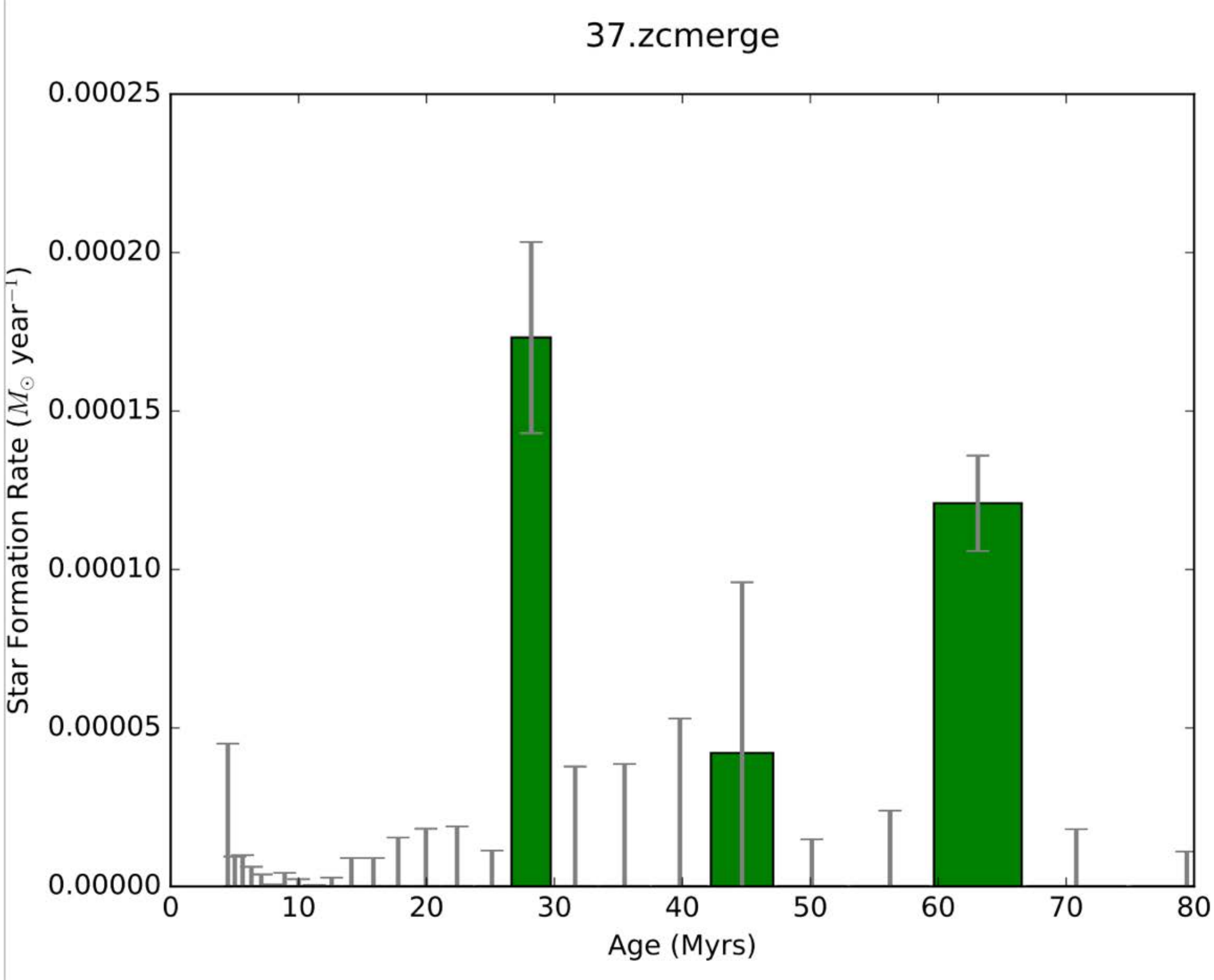
M31



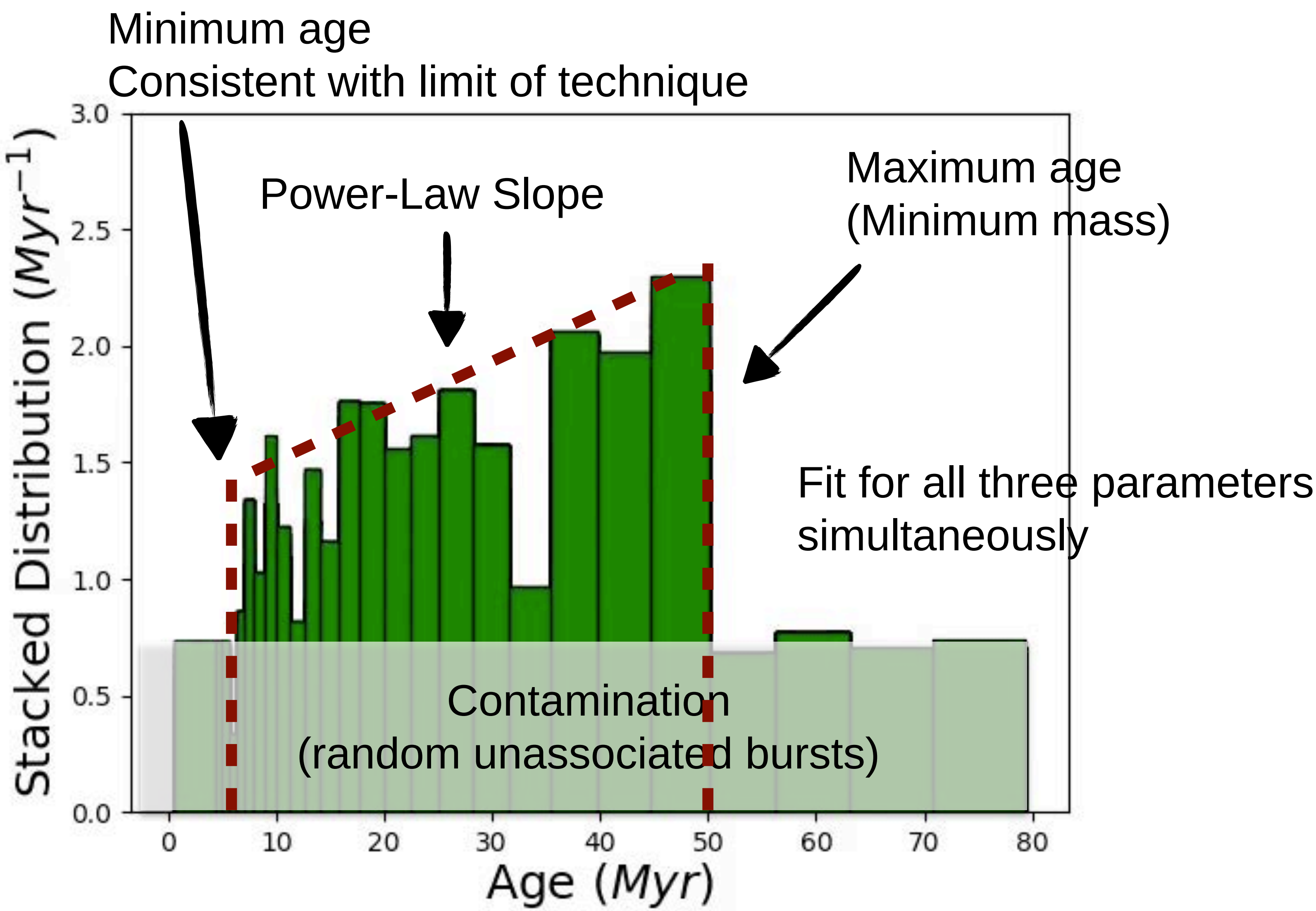
M33

- 94 of these SNRs have SFHs that are consistent with young massive stars.
- The rest have no SF within the last 80 Myr. Likely SN Ia.

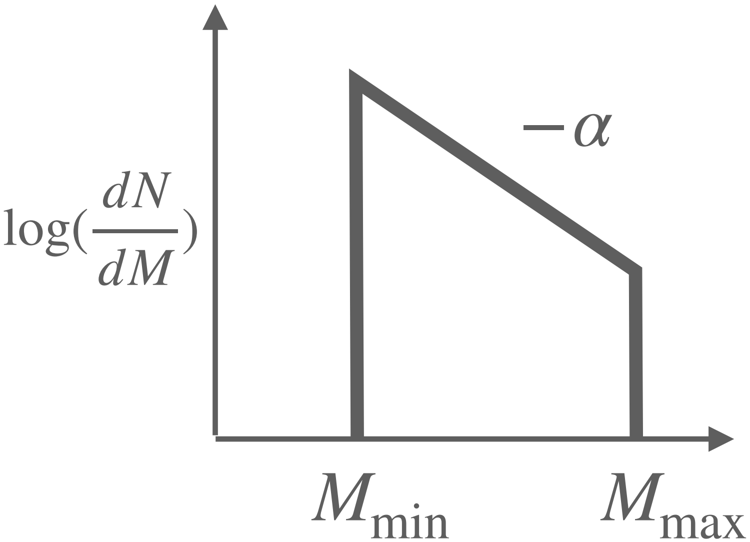
An individual SFH…Let's stack these and look for global trends

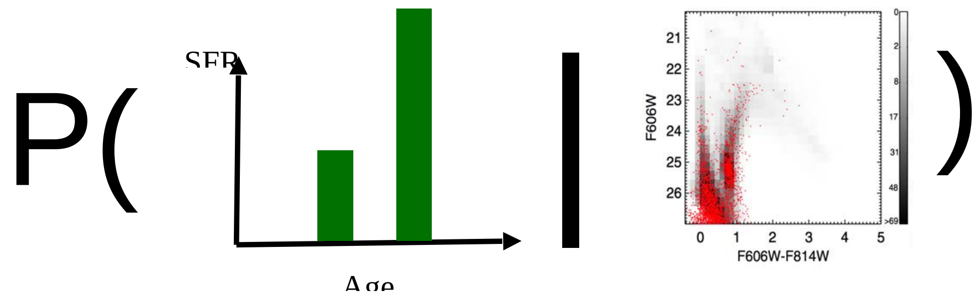


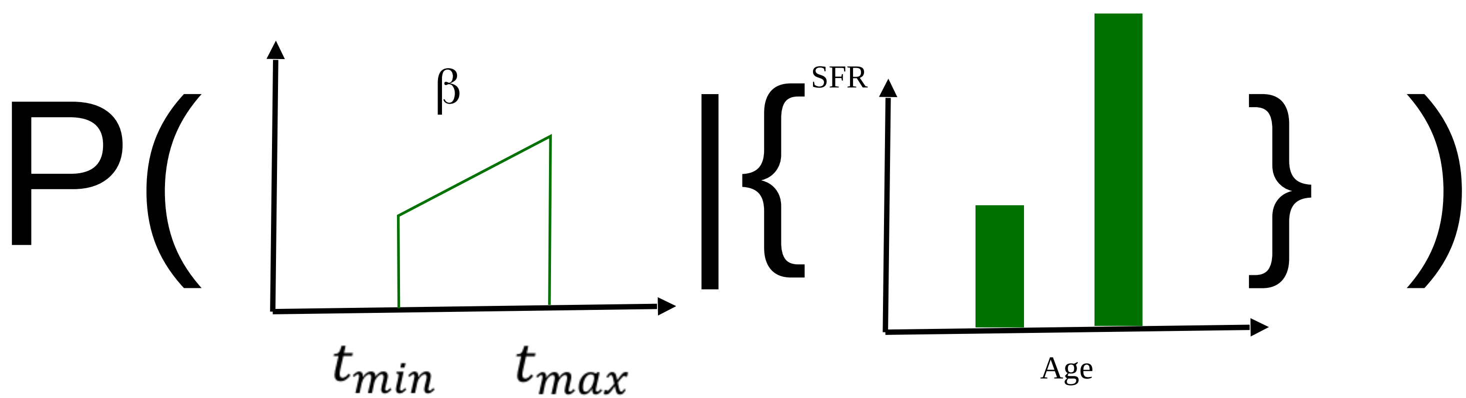
Stacking 94 Age Distributions



A Simple Model: Progenitor Mass Distribution for 100 SNRs in M31 and M33

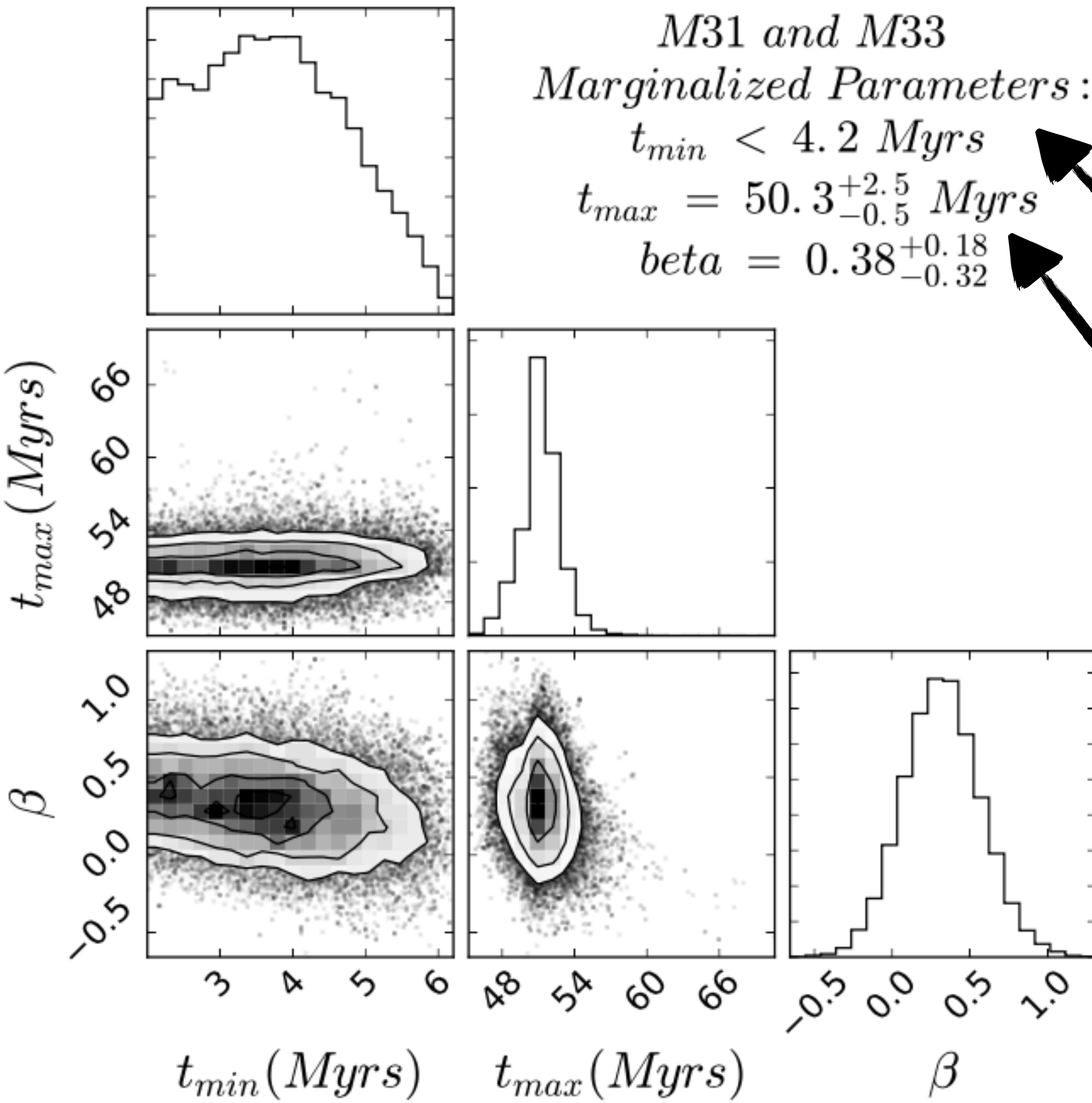






Díaz-Rodriguez et al. 2018

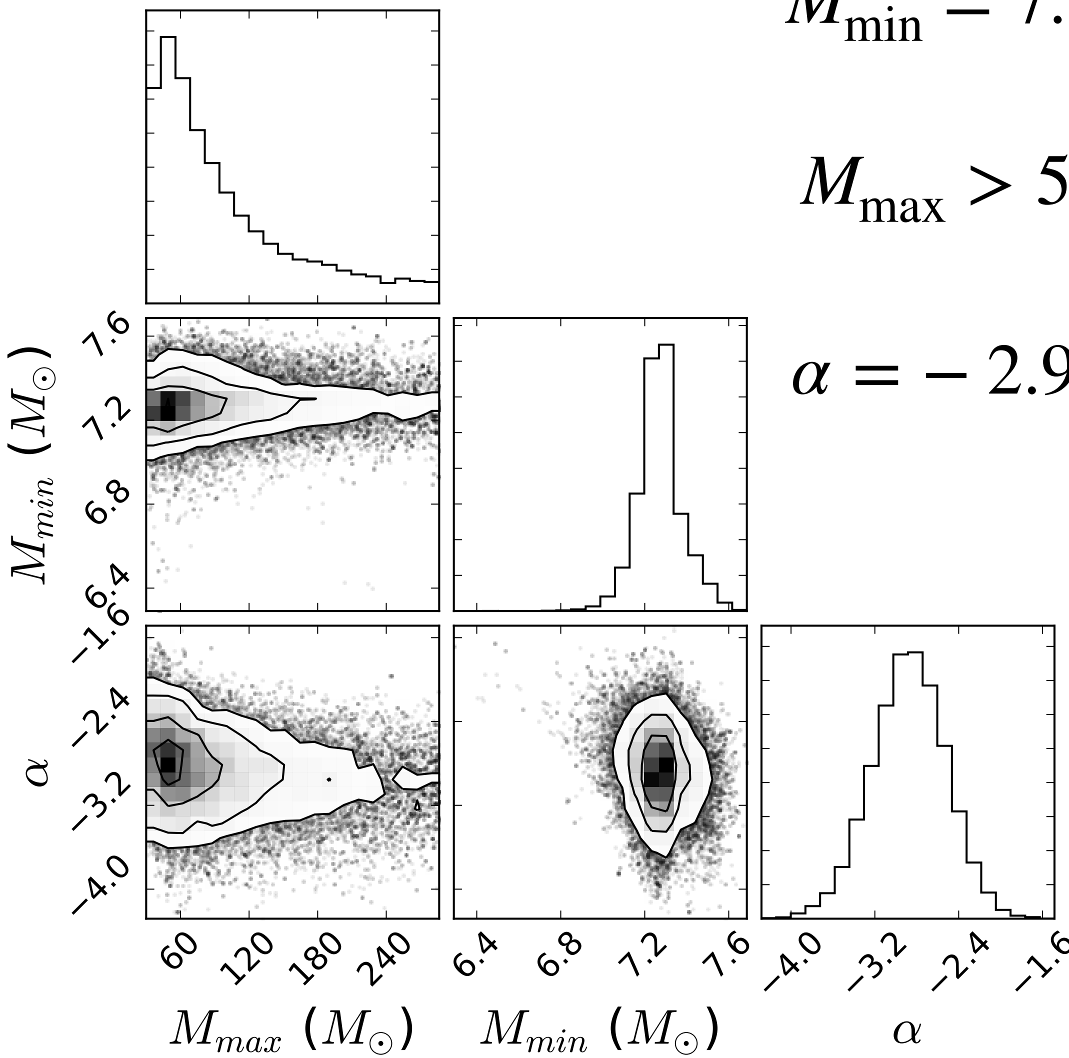
Díaz-Rodríguez et al. 2018



Detection limit.

Consistent with the fact that single star progenitors for CCSNe are believed to be < 50 Myr

Díaz-Rodríguez et al. 2018



$$M_{\rm min} = 7.33^{+0.02}_{-0.16}\ M_\odot$$

$$M_{\rm max} > 59\ M_\odot$$

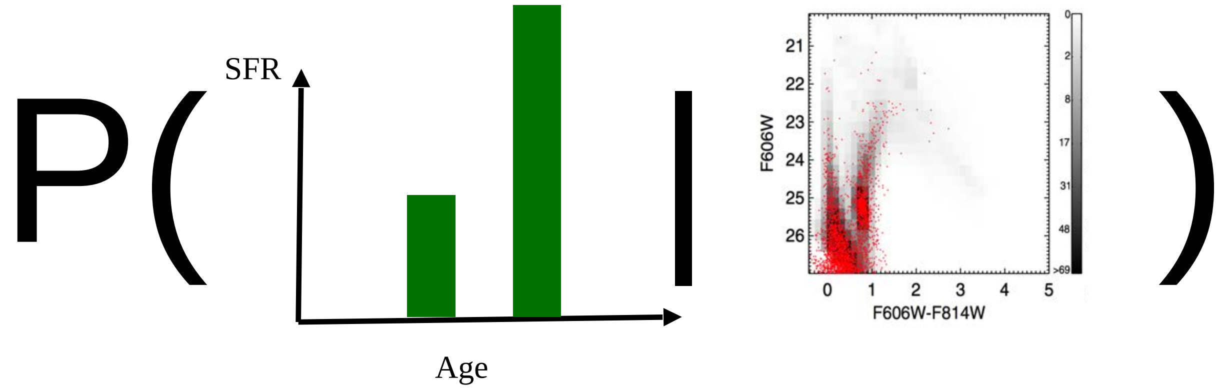
Consistent with theory, tighter constraints

$$\alpha = -\,2.96^{+0.45}_{-0.25}$$

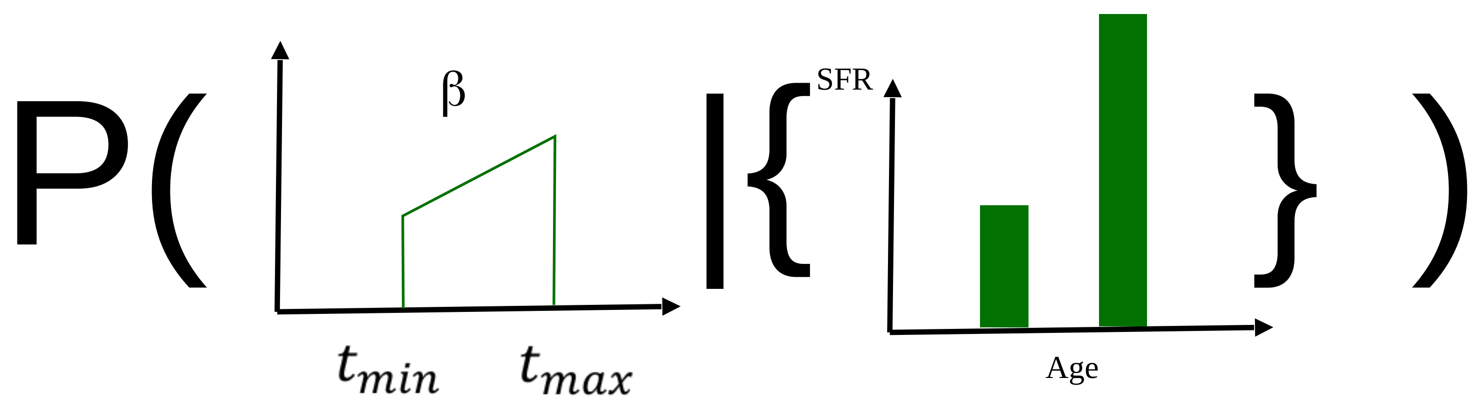
Is there another parameter besides mass that determines BH formation?

Massive stars are exploding less frequently or there is a bias.

Improving our uncertainty estimates

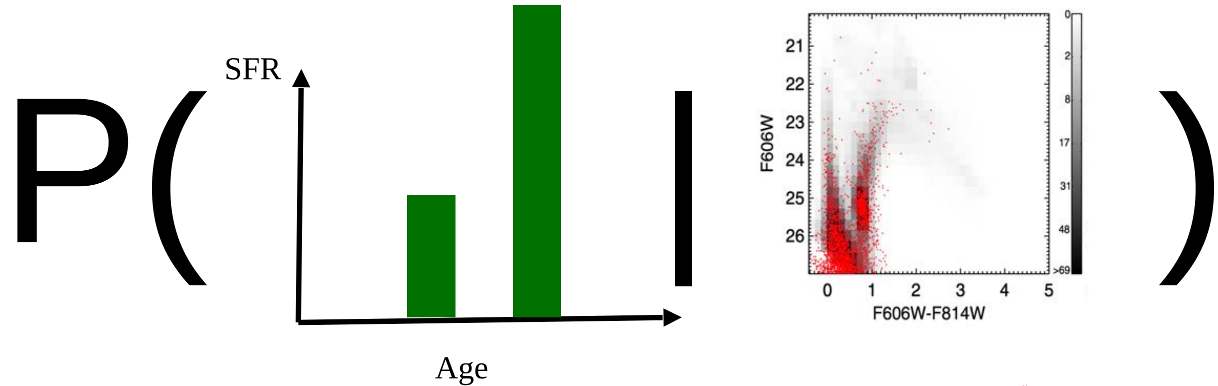


Match, Dolphin A. 2013

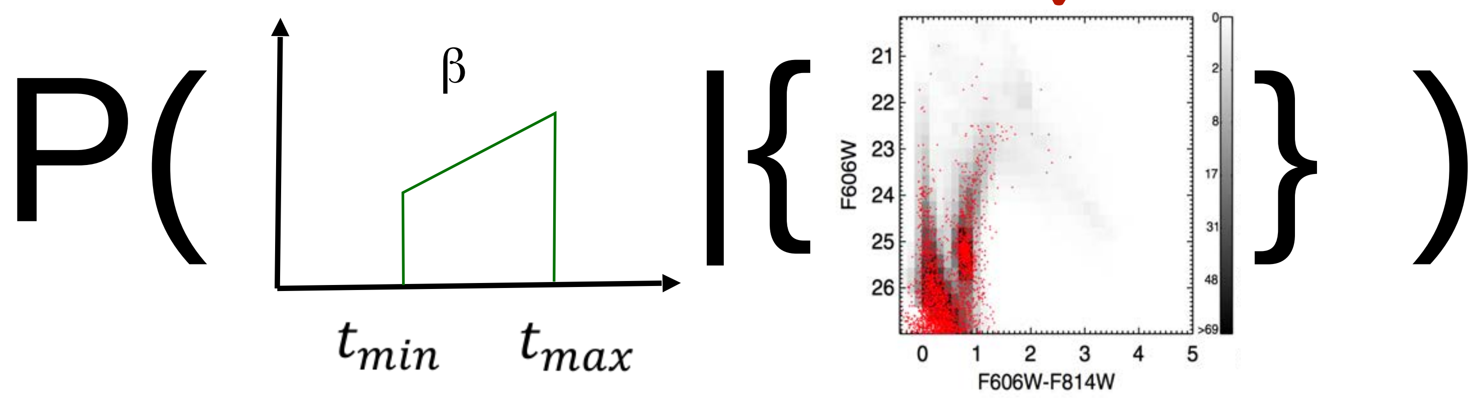


Díaz-Rodriguez et al. 2018

Improving our uncertainty estimates

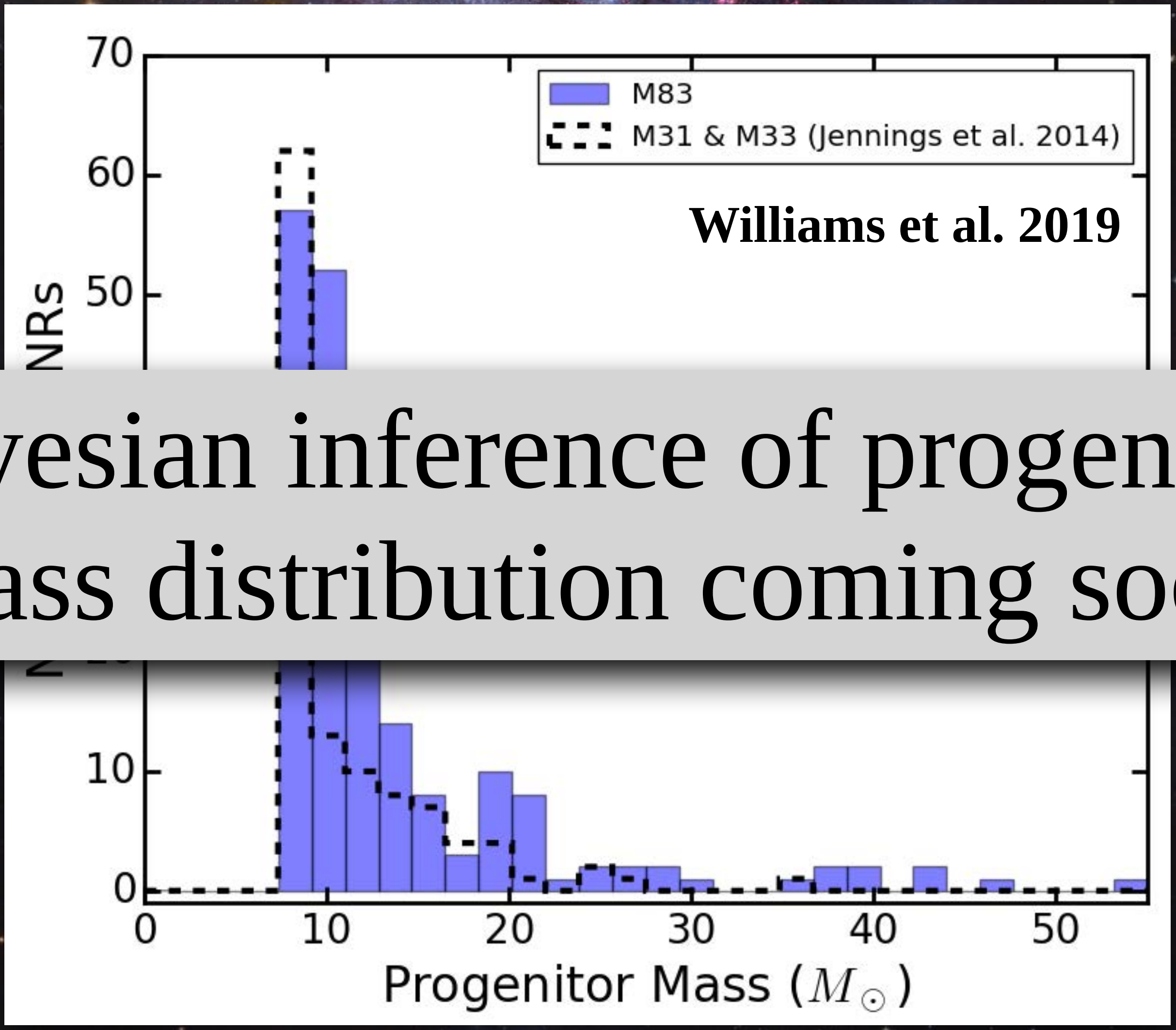


Match, Dolphin A. 2013



Díaz-Rodriguez et al. 2019

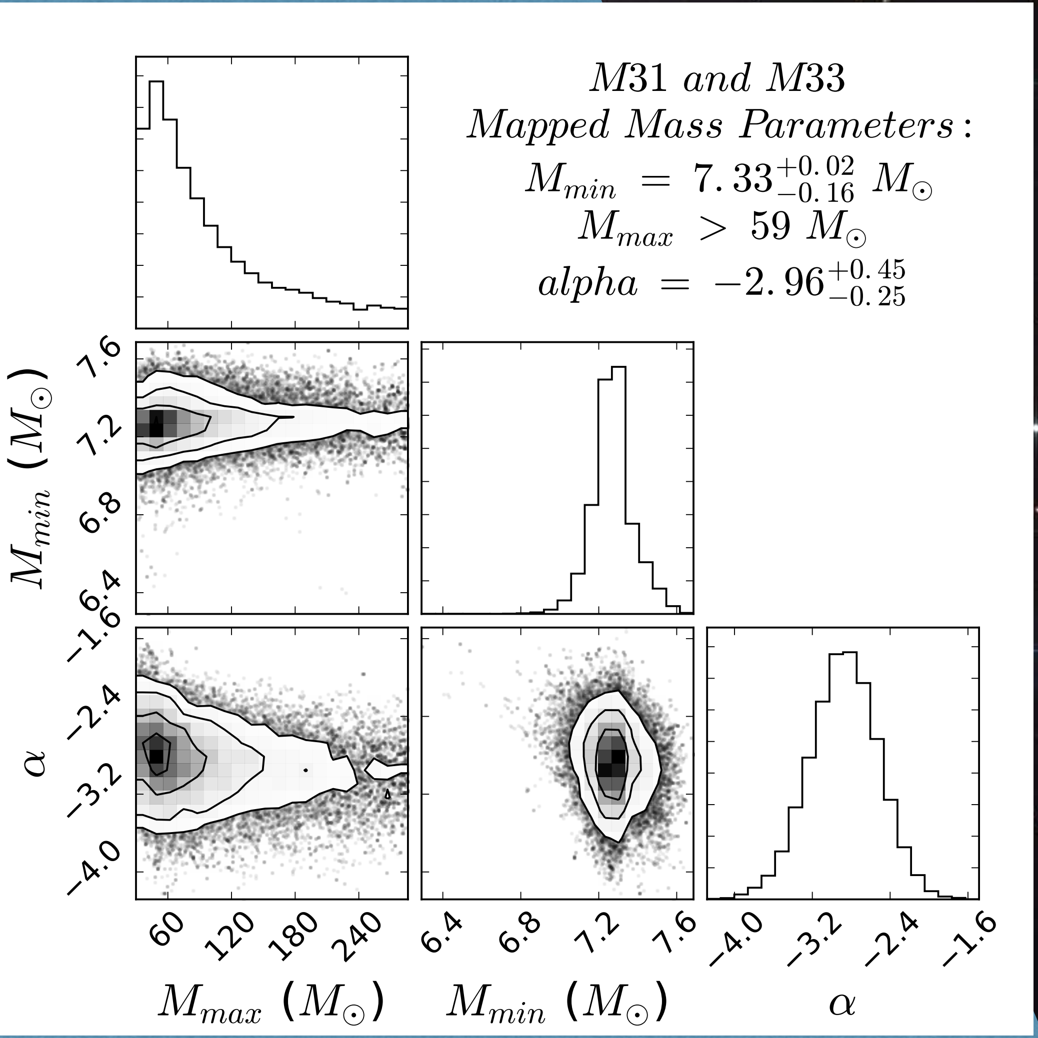
~200 more SNR progenitor masses from M83



Bayesian inference of progenitor mass distribution coming soon

Summary

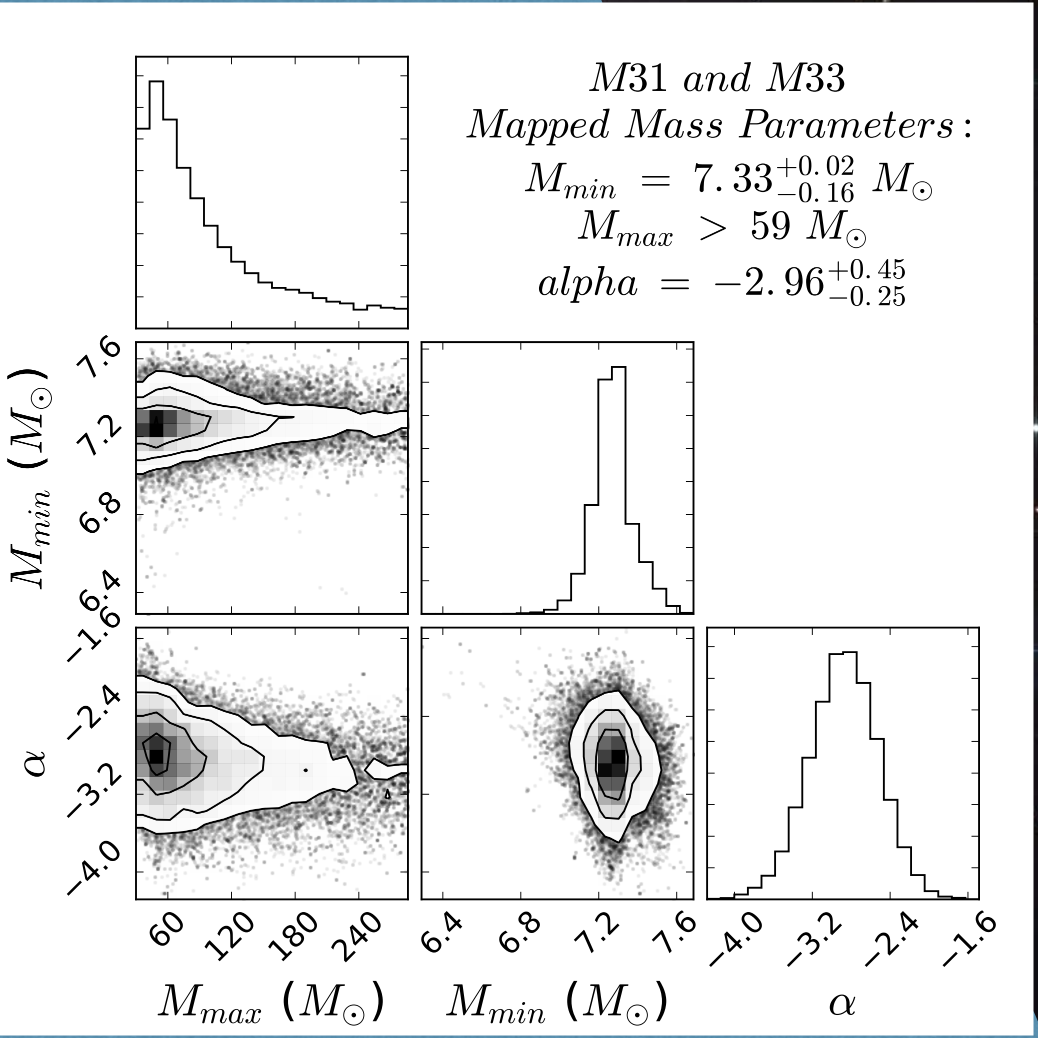
- Infer progenitor mass distribution using about a hundred SNRs.
- Very soon we will infer the distribution for 200 more.
- Our goal is a thousand or more



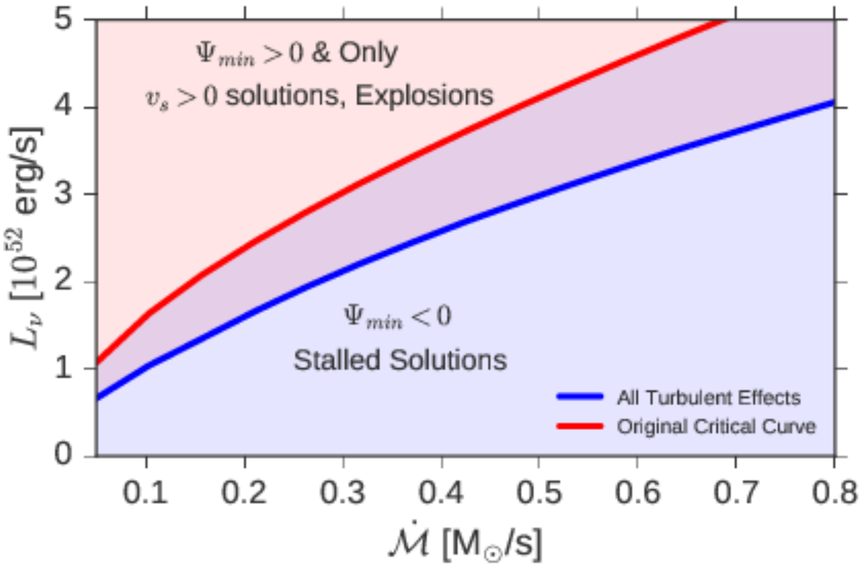
(Díaz-Rodríguez et al. 2018)

Requests for SNR Community

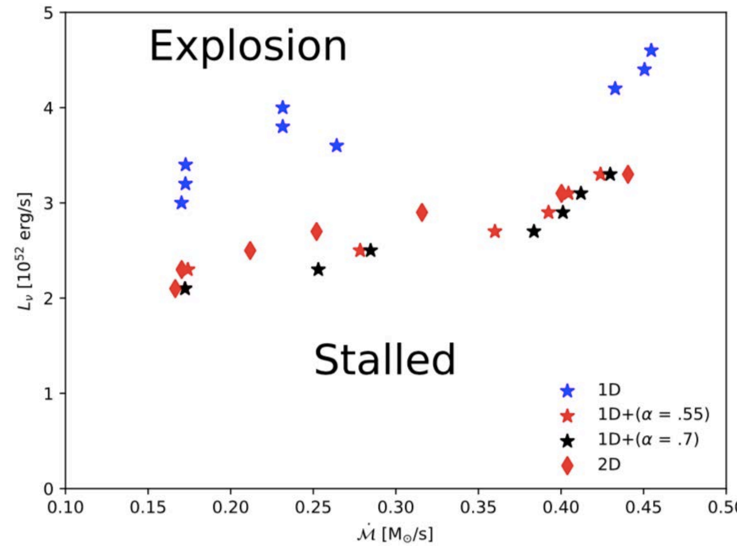
- SNR catalogs for all nearby galaxies. It would be nice to have thousands of SNRs
- Quantify the bias of SNR catalogs
- Is there a bias against for observing SNRs in young star forming regions?



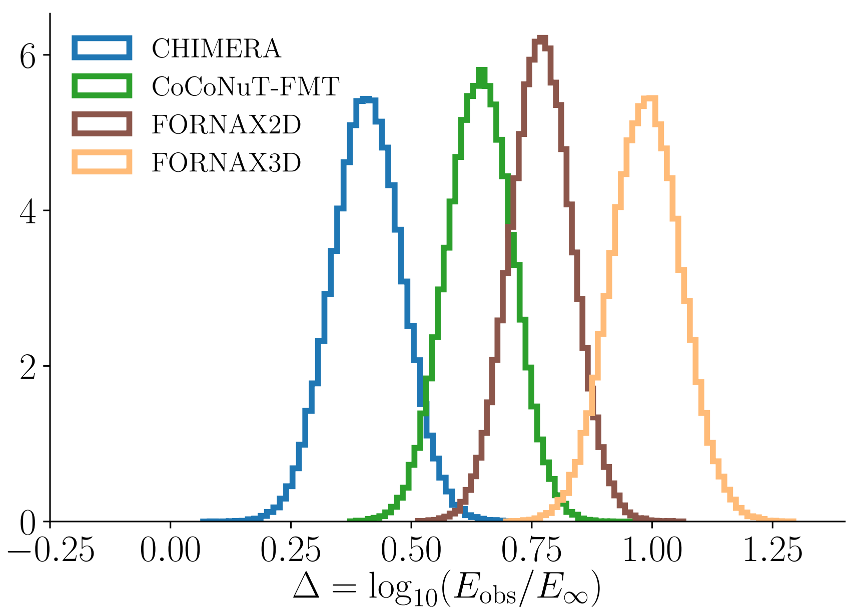
(Díaz-Rodríguez et al. 2018)



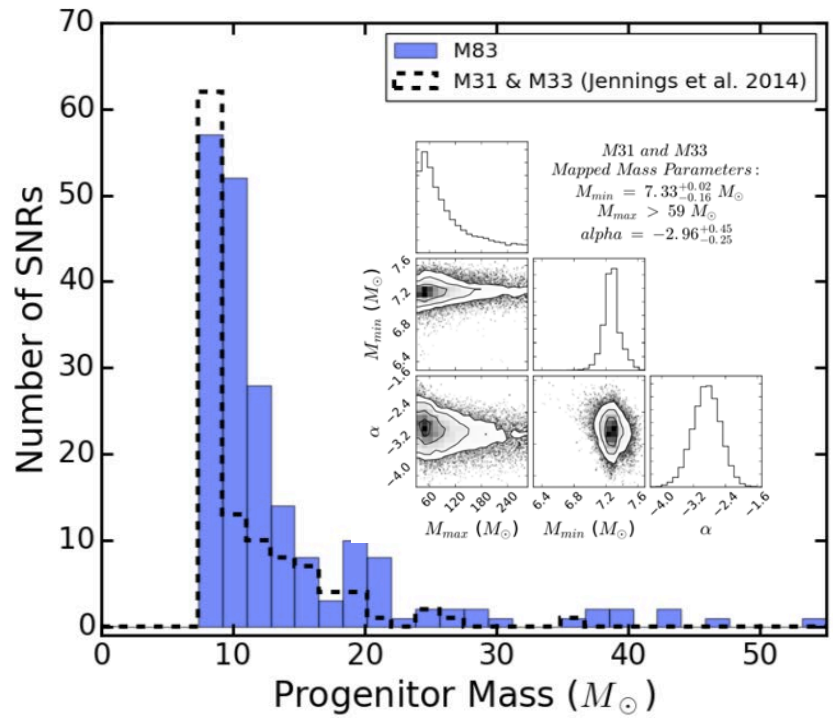
$\Psi_{min} > 0$ & Only
$v_s > 0$ solutions, Explosions
$\Psi_{min} < 0$
Stalled Solutions
All Turbulent Effects
Original Critical Curve
L_ν [10^{52} erg/s]
$\dot{M}$ [$M_\odot$/s]
0
1
2
3
4
5
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8



Explosion
Stalled
1D
1D+(α = .55)
1D+(α = .7)
2D
L_ν [10^{52} erg/s]
$\dot{M}$ [$M_\odot$/s]
0
1
2
3
4
5
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.45
0.50



CHIMERA
CoCoNuT-FMT
FORNAX2D
FORNAX3D
$\Delta = \log_{10}(E_{\rm obs}/E_\infty)$
0
2
4
6
−0.25
0.00
0.25
0.50
0.75
1.00
1.25



M83
M31 & M33 (Jennings et al. 2014)
M31 and M33
Mapped Mass Parameters:
$M_{min} = 7.33^{+0.02}_{-0.16}\ M_\odot$
$M_{max} > 59\ M_\odot$
$alpha = -2.96^{+0.45}_{-0.25}$
M_{min} ($M_\odot$)
α
M_{max} ($M_\odot$)
Number of SNRs
Progenitor Mass ($M_\odot$)
0
10
20
30
40
50
60
70