Exploiting stellar explosion induced by the QCD phase transition in large-scale neutrino detectors

Anna M. Suliga

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with T. Pitik, D. Heimsoth, and B. Balantekin

Berkeley
UNIVERSITY OF CALIFORNIA

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

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N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

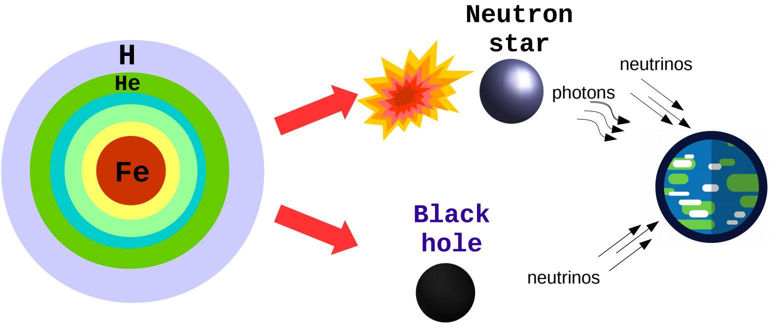
NSF

Introduction and Motivation

Why are neutrinos important for a core-collapse supernova?

Neutrinos:

- $\sim 10^{58}$ of them emitted from a single core collapse
- only they (+ GW) can reveal the deep interior conditions
- only they (+ GW) are emitted from the collapse to a black hole



Earth image: Kurzgesagt

Why core-collapse supernovae are good physics probes?

Advantages

- extreme physical conditions not accessible on Earth: very high densities, long baselines etc.
- within our reach to detect (SK, JUNO, XENON, PandaX...)

What can we learn with a variety of detectors?

- explosion mechanism — Bethe & Wilson (1985), Fischer et al. (2011)...
- yields of heavy elements — Woosley et al. (1994), Surman & McLaughlin (2003)...
- compact object formation — Warren et al. (2019), Li, Beacom et al. (2020)...
- neutrino mixing — Balantekin & Fuller (2013), Tamborra & Shalgar (2020)...
- non-standard physics — **Suliga** et al. (2019), (2020) **Suliga** & Tamborra (2020) ...

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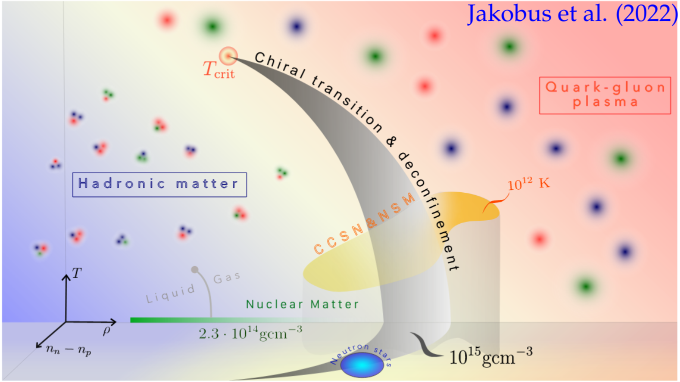
QCD phase diagram



- Does the protocompact star contain non-leptonic degrees of freedom other than neutrons and protons?
- How to identify the presence of quark matter in astrophysical objects?

Where the quark matter can appear in atrophysical objects?

- quark matter in accreting neutron stars
  Lin et al. (2006), Abdikamalov et al. (2008), Espino, Paschalidis (2021), ...
- in protoneutron stars after the CCSN explosion
  Pons et al. (2001), Keranen et al. (2004)
- in protocompact stars during early postbounce phase
  Takahara et al. (1988), Sagert et al. (2008), Fischer, Sagert et al. (2011) ...

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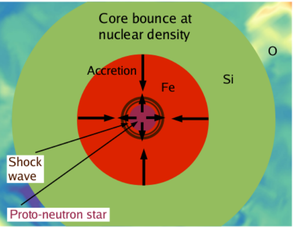
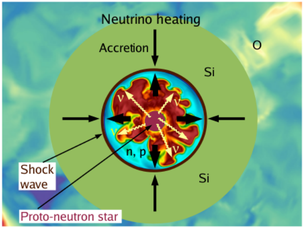
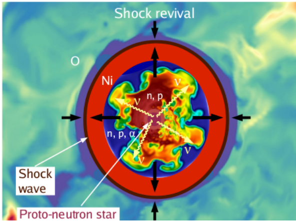
Different phases of core-collapse supernova explosion

- Infall phase, ν_e burst ~ 40 ms
- Accretion phase, ~ 100 ms
- Cooling phase, ~ 10 s

H. T. Janka (2017)







What drives the supernova supernova explosions?

- neutrino heating Colgate & White (1966), Bethe & Wilson (1985)
- magneto-rotational mechanism LeBlanc and Wilson (1970), Takiwaki et al. (2009)
- particles beyond the Standard Model Fuller et al. (2008), **Suliga** et al. (2020) ...
- phase transition to quark matter Sagert et al. (2008)...

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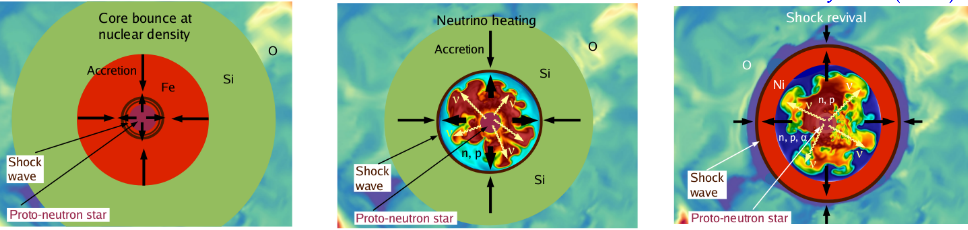

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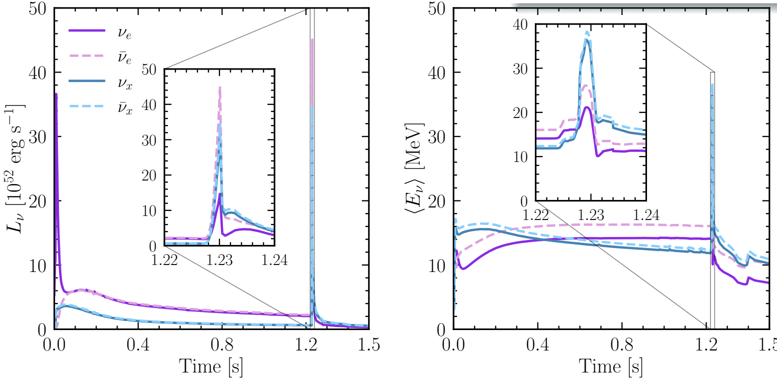
Numerical modeling

Neutrino Emission Properties from the QHPT CCSN

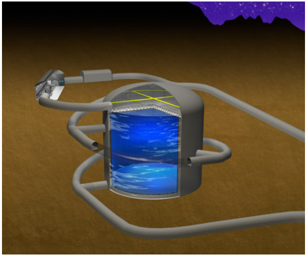
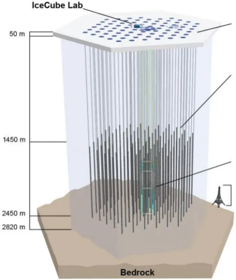
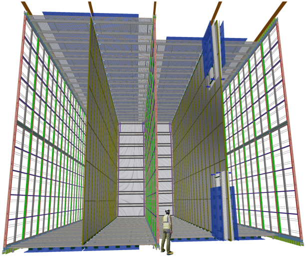
1D SN model Fischer et al. (2017)



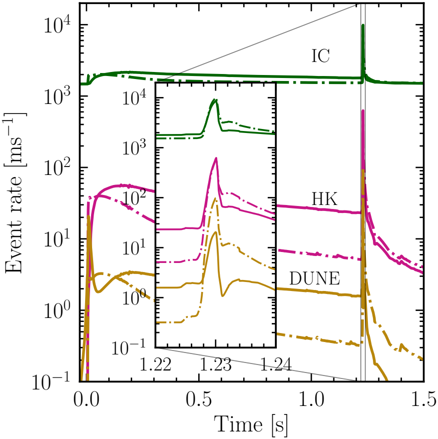
- second sharp neutrino burts dominated by $\bar{\nu}_e$
- non-exploding models can explode

Astrophysical neutrino detection

Large scale neutrino detectors

Hyper-Kamiokande (2027)	Ice-Cube Observatory	DUNE (2030)
		
fiducial volume	**fiducial volume**	**fiducial volume**
217 kton	3500 kton	40 kton
main detection channel	**main detection channel**	**main detection channel**
$\bar{\nu}_e + \mathrm{p} \to e^+ + \mathrm{n}$	$\bar{\nu}_e + \mathrm{p} \to e^+ + \mathrm{n}$	$\nu_e + \mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$

Neutrino Event Rates



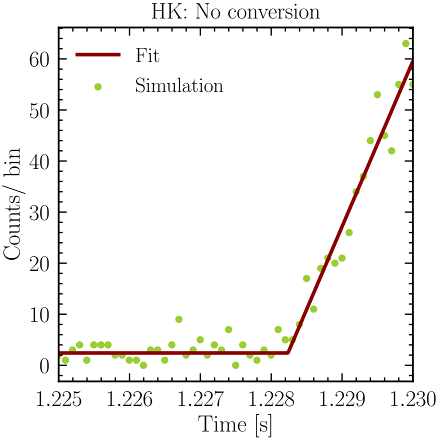
Impact of neutrino conversions

- Event rate in the antineutrino detectors comparable for both conversion scenarios
- Event rate in the neutrino detector larger for the full conversion case

$$R(t) = N_t \int_{E_\nu^{\min}}^{\infty} dE_\nu \int_{E_{\rm th}}^{E_{\max}} dE\ \varepsilon \sigma_i(E, E_\nu)\ F_{\nu_\beta}(E_\nu, t)$$

Main Results

Timing the Neutrino Signal



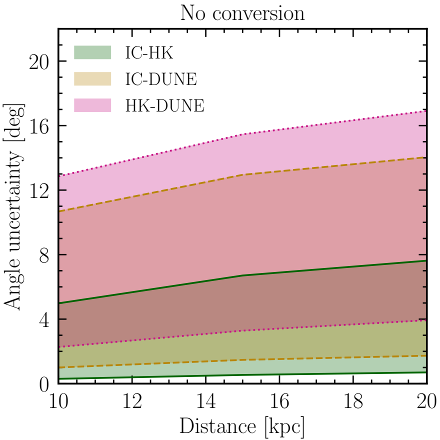
Detectors	No conversion	Full conversion
	B_{ij} [ms]	
IC-HK	-0.32 ± 0.10	-0.32 ± 0.10
IC-DUNE	-0.11 ± 0.48	-0.27 ± 0.20
HK-DUNE	0.22 ± 0.50	0.05 ± 0.22
	$\delta(\theta_{ij})$ (min, max) [deg]	
IC-HK	$(0.30, 5.00)$	$(0.29, 4.90)$
IC-DUNE	$(1.00, 10.67)$	$(0.41, 6.90)$
HK-DUNE	$(2.27, 12.85)$	$(1.00, 8.54)$
	95% C.L. upper limit on m_ν [eV]	
IC	$0.16^{+0.03}_{-0.04}$	$0.21^{+0.05}_{-0.05}$
HK	$0.22^{+0.05}_{-0.06}$	$0.30^{+0.07}_{-0.09}$
DUNE	$0.80^{+0.21}_{-0.29}$	$0.58^{+0.14}_{-0.19}$

$$\Delta t_{ij}^{\text{true}} = \frac{(\mathbf{r}_i - \mathbf{r}_j)\cdot \mathbf{n}}{c} = \frac{D_{ij}\cos\theta}{c}$$

$$R_{\text{exp}} = \begin{cases} R_*, & \text{if } t < t_0 \\ R_* + a(t - t_0), & \text{otherwise} \end{cases},$$

$$\Delta t_{ij}^{\text{measured}} = \Delta t_{ij}^{\text{true}} + B_{ij}$$

Determination of the uncertainty of the CCSN localization



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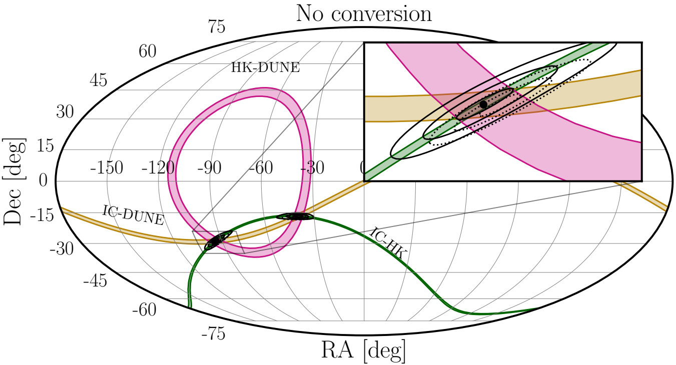
$$\delta(\theta_{ij}) \approx \begin{cases} \delta(\cos\theta_{ij})/\sin\theta_{ij} & \text{if } \sin\theta_{ij} > \sqrt{\delta(\cos\theta_{ij})} \\ \sqrt{2\delta(\cos\theta_{ij})}, & \text{for } \theta_{ij} \ll \delta(\cos\theta_{ij}) \end{cases} .$$

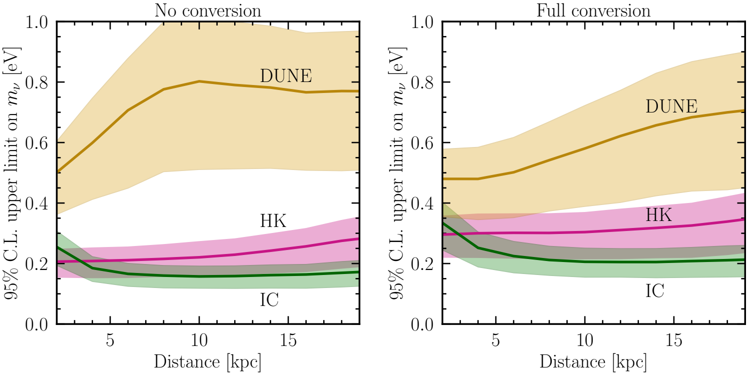
Determination of the CCSN localization



- improvement by 4.5-10 times compared to neutronization burst
- comparable results for black hole forming supernovae
- not far off from elastic scattering on electrons

Sensitivity to the Absolute Neutrino Mass

$$\Delta t \approx 5.15 \left(\frac{D}{10\ \mathrm{kpc}}\right)\left(\frac{m_\nu}{1\ \mathrm{eV}}\right)^2\left(\frac{10\ \mathrm{MeV}}{E_\nu}\right)^2\ \mathrm{ms}$$



- up to ∼ 10x improvement compared to neutronization burst
- more stringent limits than from the laboratory experiments (0.8 eV)

Summary and Conclusions

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- QCP phase transition in the collapsing star can:
  - produce second core bounce
  - result in release of a second sharp neutrino burst
  - lead to *r*-process elements production
- Detection of the phase transition induced neutrino burst:
  - indicates the QCD phase transition in supernova
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  - sets competitive limits on the neutrino mass

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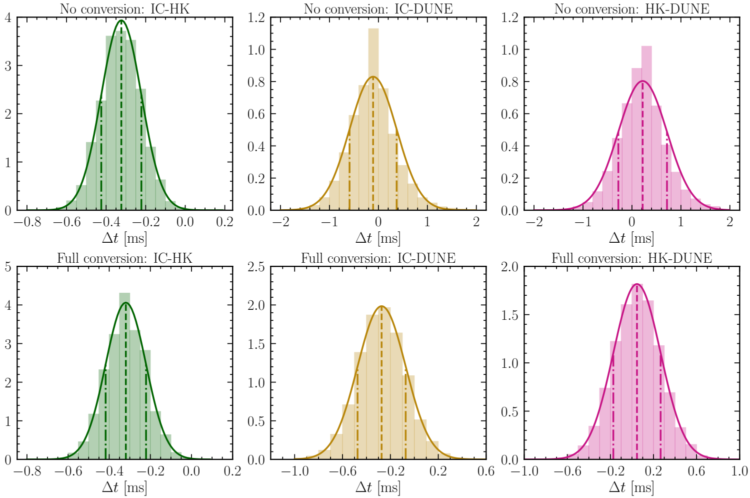
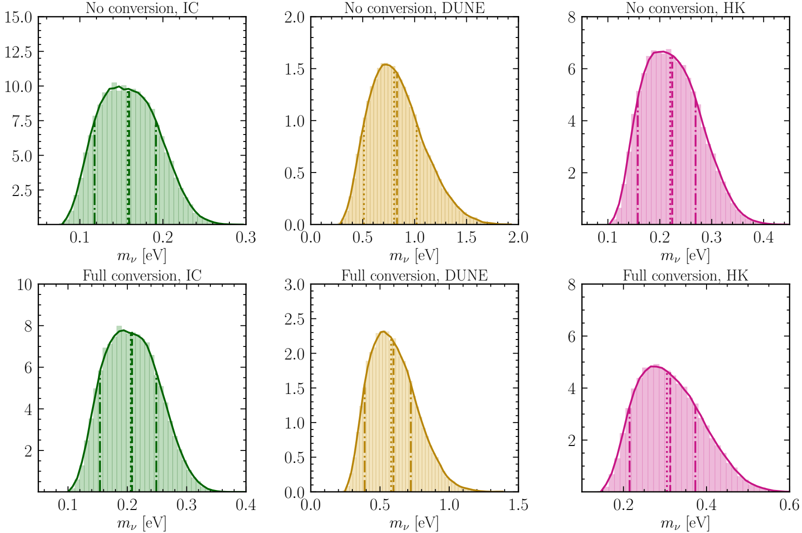
Thank you for the attention!

Backup

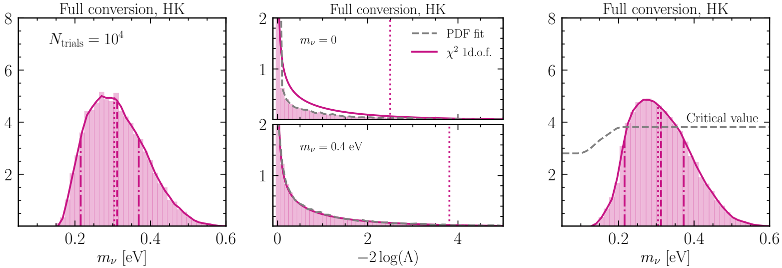
Histograms: Timing the neutrino signal



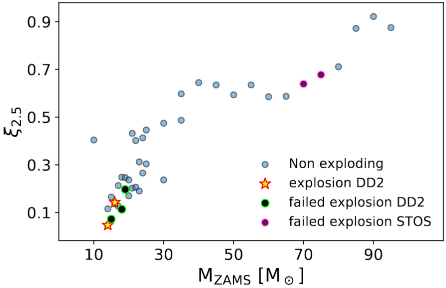
Histograms: neutrino mass limit



Relaxing Wilk's theorem approximation



The Role of the QCD Phase Transition in CCSNe



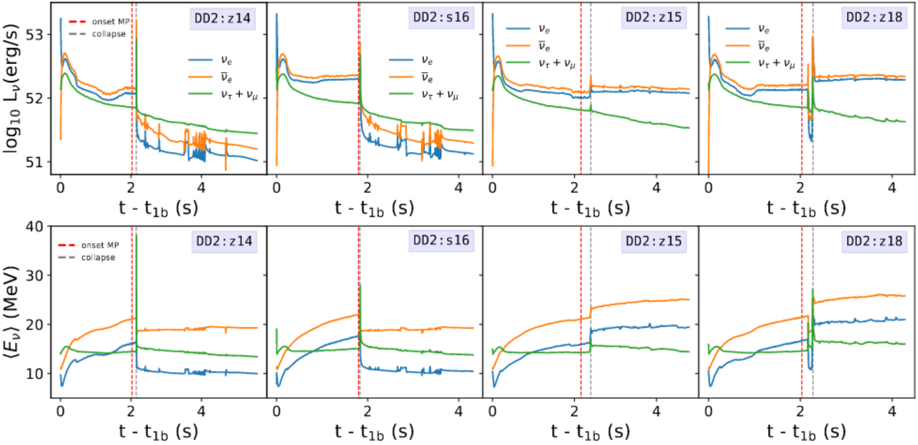
Compactness parameter

$$\xi_M = \frac{M/M_\odot}{r(M)/1000\ \mathrm{km}}$$

- Three equations of state: DD2F (1st order PT, Gibbs), STOS-B145 (1st order PT, Maxwellian), and CMF (smooth crossover)
- Sucessful explosions only for 2 models in DD2F
- Failed explosions in DD2F and STOS-B145

Pia Jakobus et al. (2022)

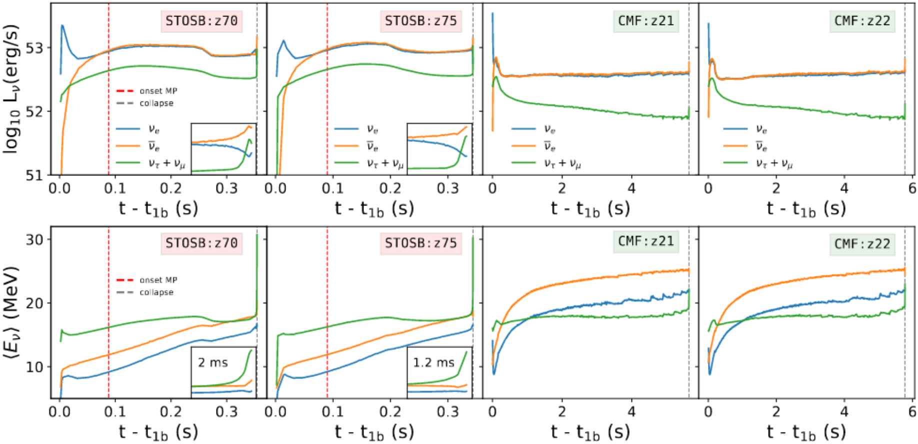
Neutino signals: DD2F



- Low explosion energies $\sim 10^{50}$ erg
- Majority of models have second bounce 37/40
- Failed explosions only for zero metallicity

Pia Jakobus et al. (2022)

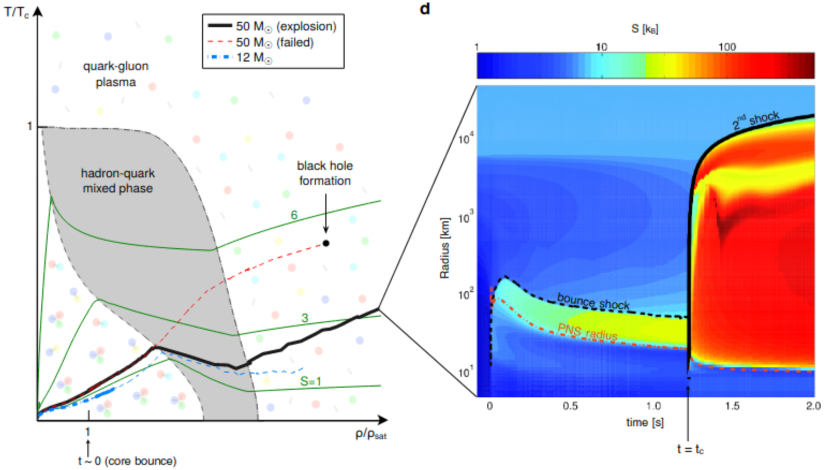
Neutino signals: STOS-B145, CMF



- Relatively small increase in luminosity during 2nd bounce
- No models successfuly explode
- No 2nd bounces in the CMF models

Pia Jakobus et al. (2022)

Quark deconfinement as a supernova explosion engine for massive blue supergiant stars



Fisher et al. (2017)