Supernova explosion of massive stars driven by hadron-quark phase transition and its signature

- Fischer, Bastian, MRW, Baklanov, Sorokina, Blinnikov, Typel, Klähn, Blaschke, Nature Astron. 2 (2018) 12, 980, arXiv:1712.08788
- Fischer, MRW, Wehmeyer, Bastian, Martínez-Pinedo, Thielemann, ApJ 894 (2020) 9, arXiv:2003.00972

Meng-Ru Wu (Institute of Physics, Academia Sinica)

QCD Theory Seminar JP, KEK–YITP–Keio, 06/22/2020

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NCTS

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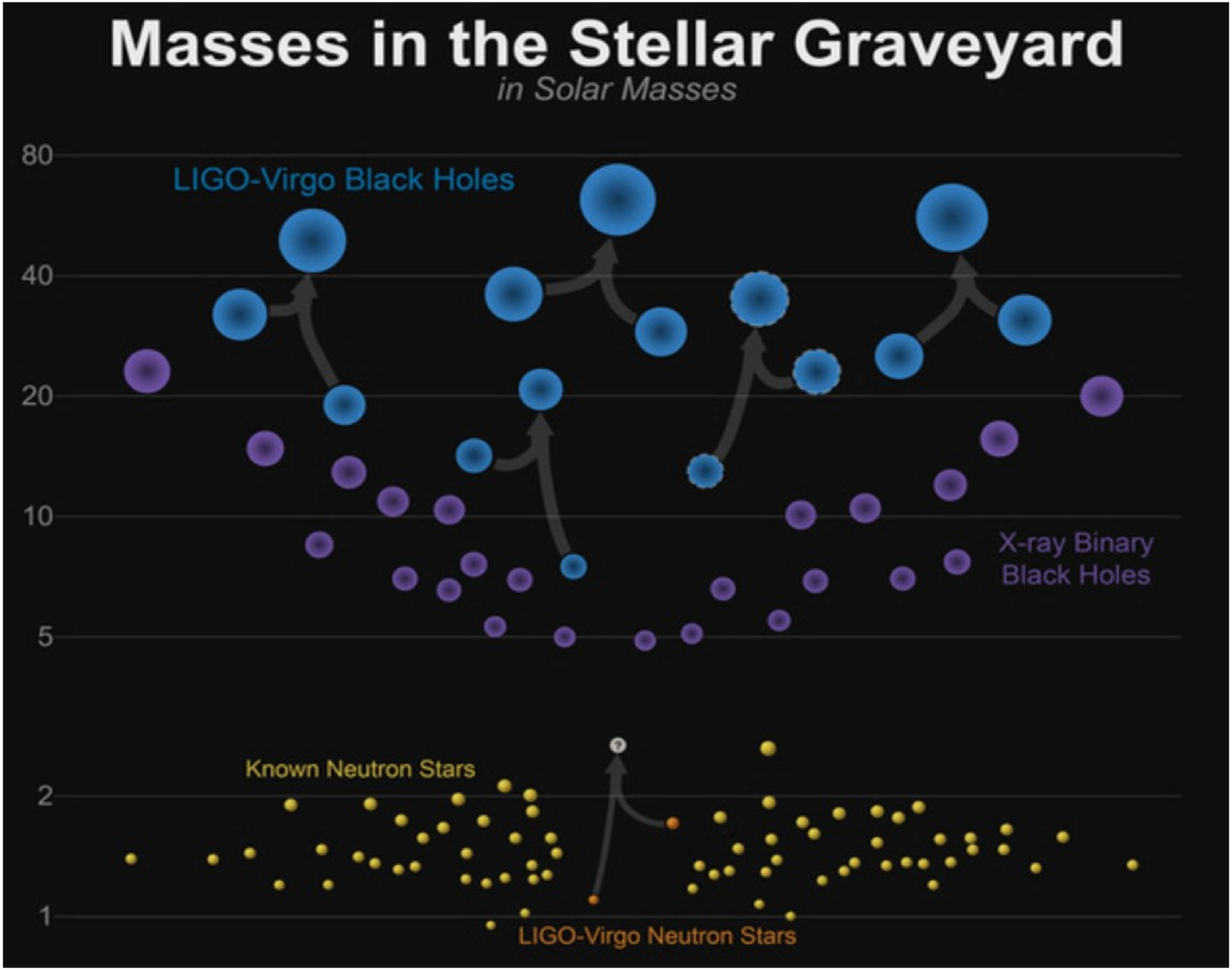
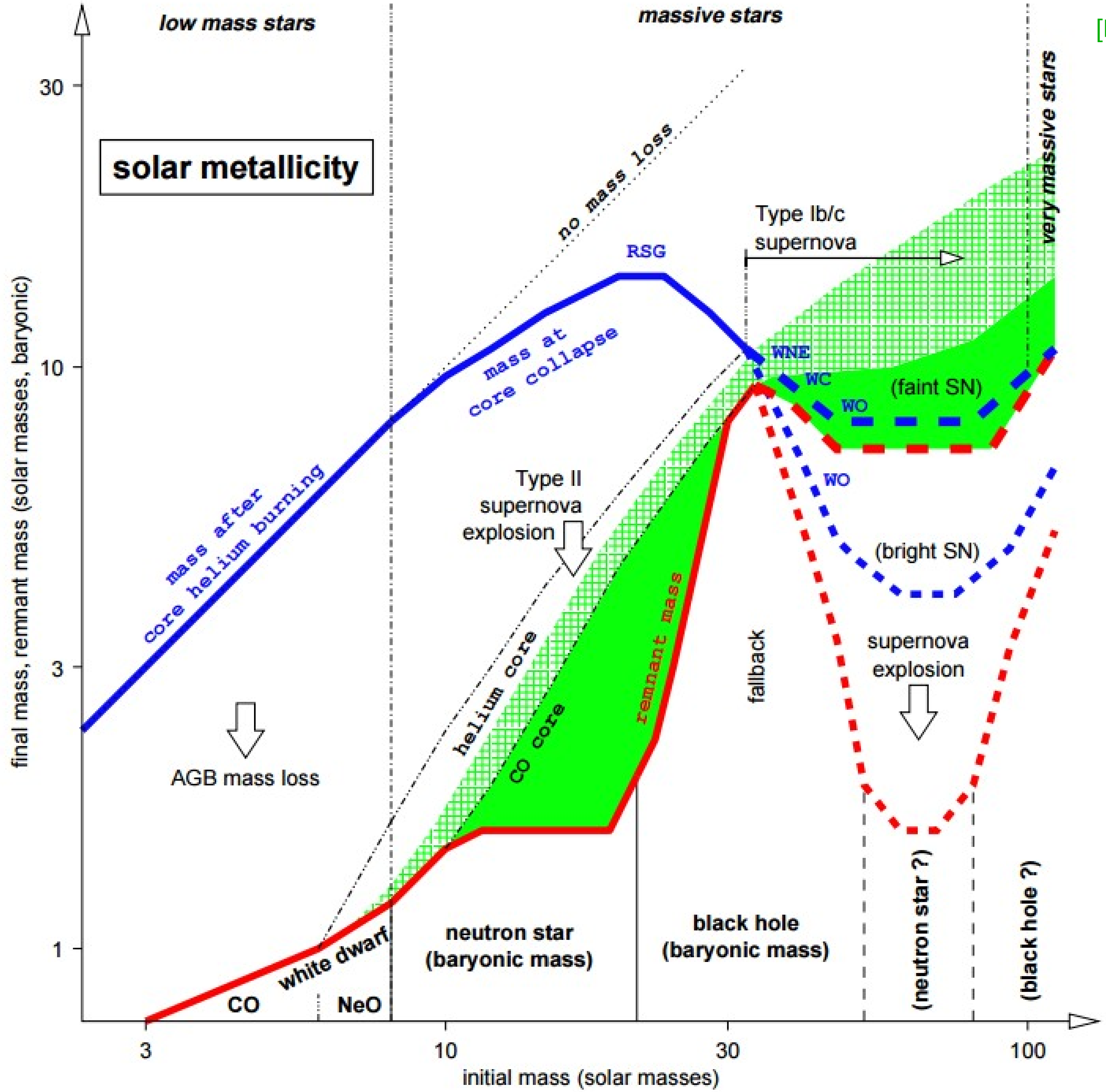
Outline

- Introduction
- Equation of state including a quark-hadron phase-transition (QHPT)
- Supernova explosion of massive stars due to QHPT
- Heavy element production by QHPT supernovae
- Summary



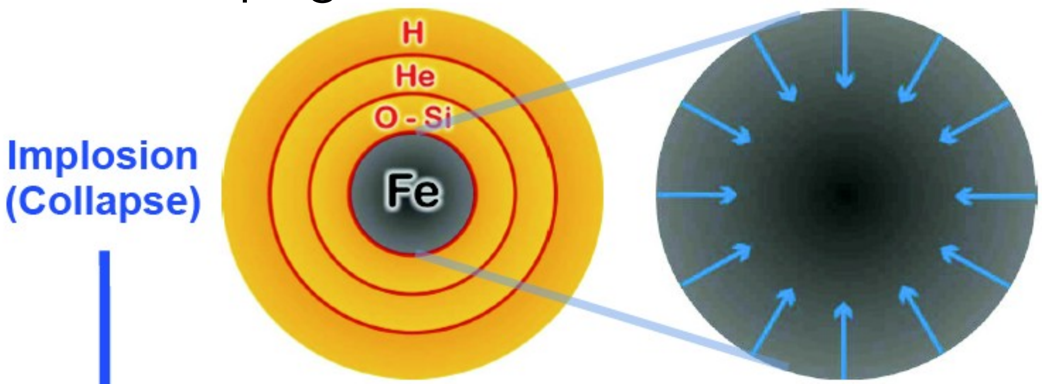
Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary
Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars


low mass stars
massive stars
solar metallicity
no mass loss
RSG
mass at
core collapse
mass after
core helium burning
Type Ib/c
supernova
very massive stars
WNE
WC
WO
(faint SN)
WO
(bright SN)
Type II
supernova
explosion
helium core
CO core
remnant mass
fallback
supernova
explosion
AGB mass loss
white dwarf
CO
NeO
neutron star
(baryonic mass)
black hole
(baryonic mass)
(neutron star ?)
(black hole ?)
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
30
10
3
1
3
10
30
100

[Heger+ 2002]

Supernova explosion: turning implosion into explosion

progenitor star



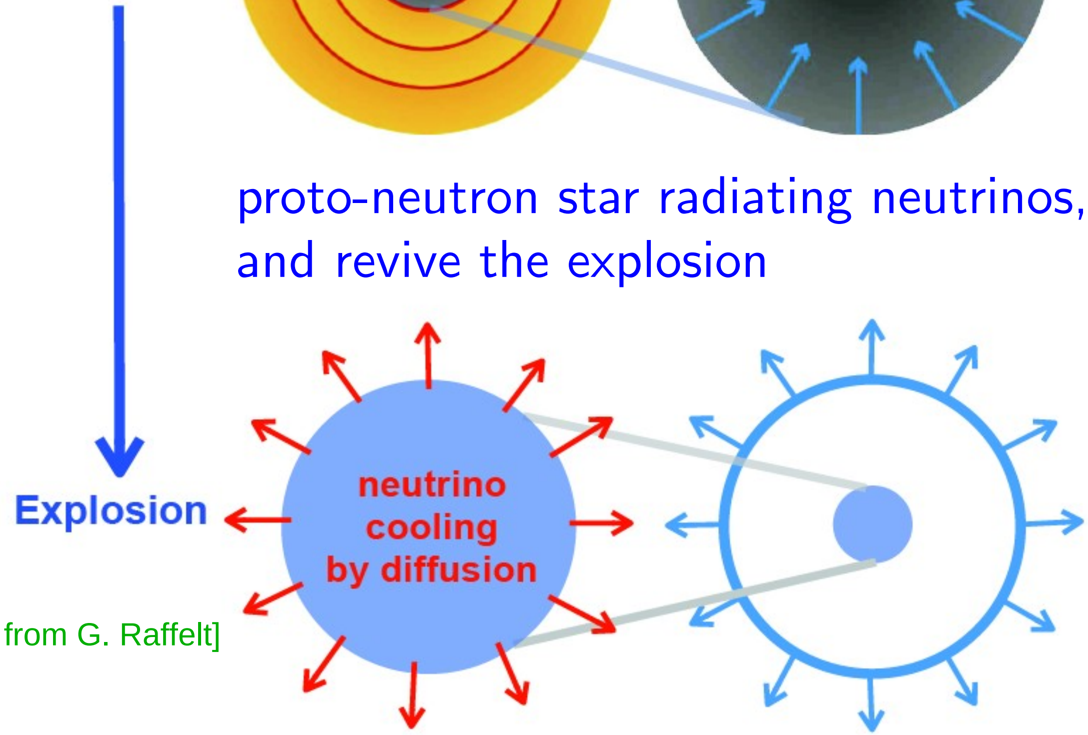
$M_{\mathrm{Fe,core}} \approx 1.4 M_{\odot}$

$R_{\mathrm{Fe,core}} \approx 3000$ km

$\rho_c \approx 10^9$ g cm^{-3}

$T_c \approx 10^{10}$ K~ 1 MeV

proto-neutron star radiating neutrinos, heat the stalled shock and revive the explosion



[Figure from G. Raffelt]

$M_{\mathrm{PNS}} \approx 1.4 M_{\odot}$

$R_{\mathrm{PNS}} \approx 15$–$50$ km

$\rho_c \approx 3 \times 10^{14}$ g cm^{-3}

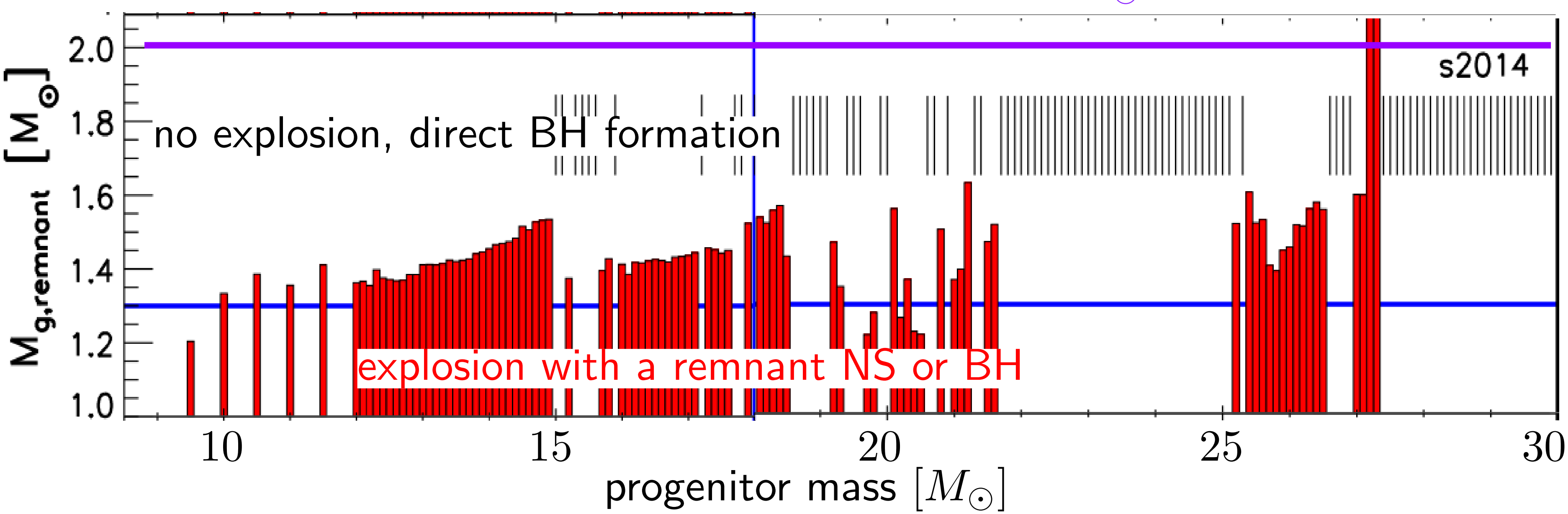
$T_c \approx 30$ MeV

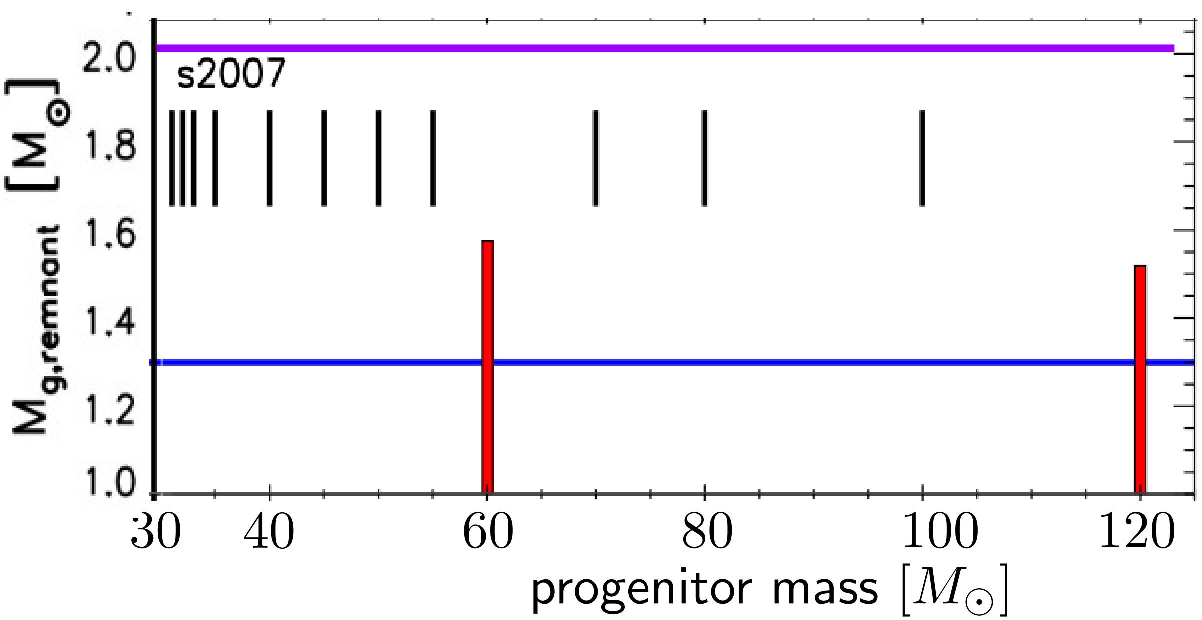
energy release:

$E_\gamma \sim 10^{49}$ erg, $E_{GW} \sim 10^{46}$ erg, $E_{\mathrm{kinetic}} \sim 10^{51}$ erg, $E_\nu \sim 10^{53}$ erg.

observed most massive NS of $\approx 2M_\odot$

[Ertl+ 2016]





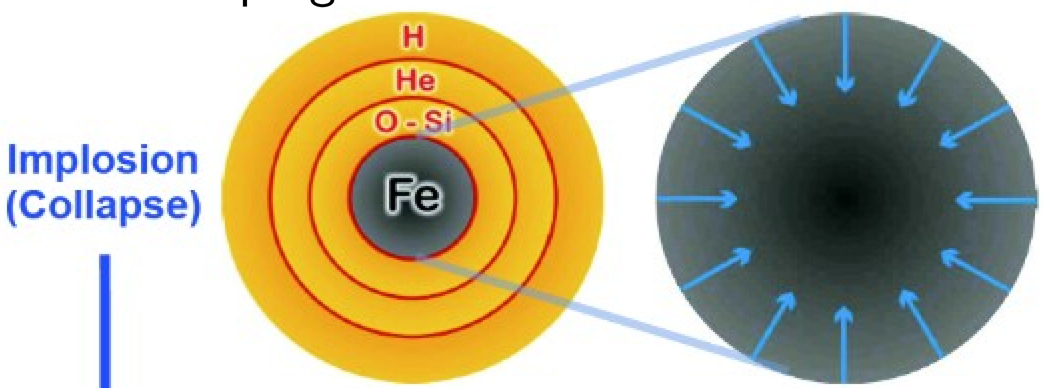
**assuming ν-driven explosion:

- no $2M_\odot$ NS formed

- hard to explode massive stars

Alternative case...

progenitor star



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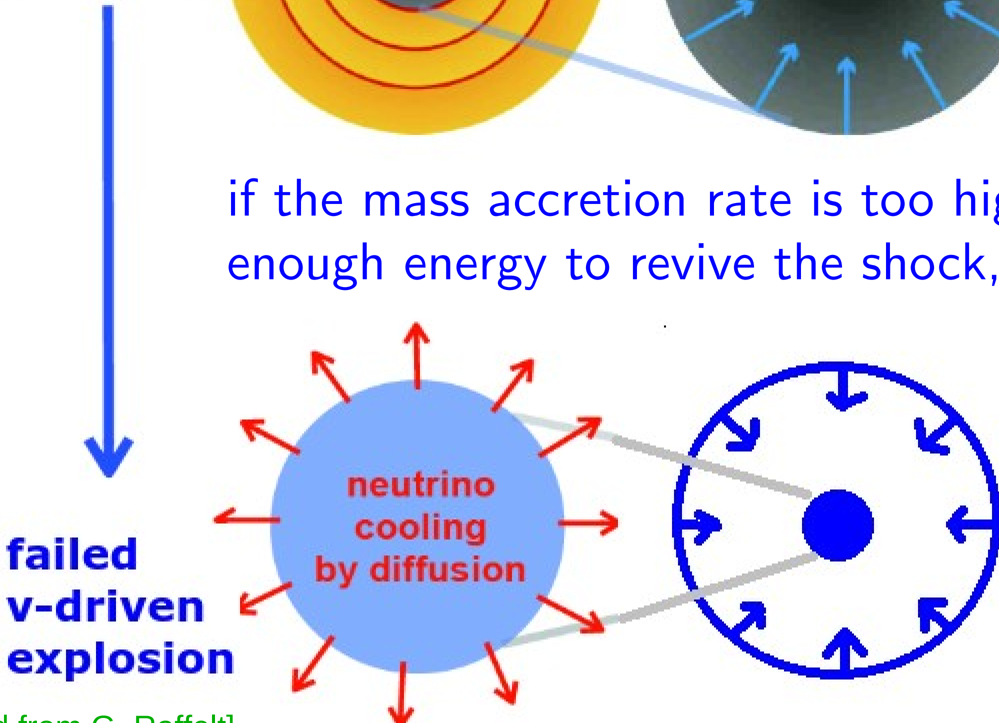
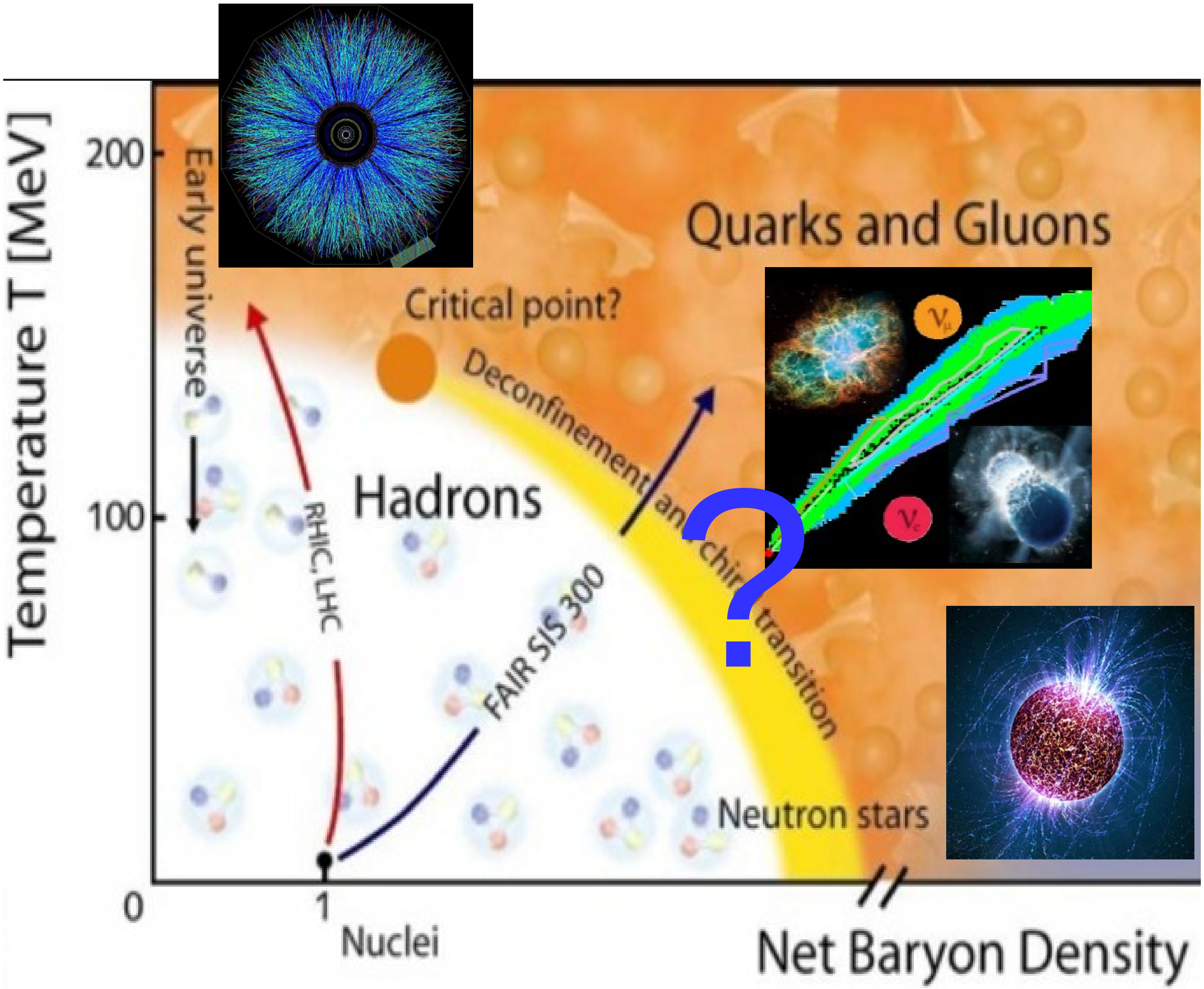
if the mass accretion rate is too high, neutrinos failed to deposit enough energy to revive the shock, accretion can continue...



to a black hole?

or something else?

[Modified from G. Raffelt]


Temperature T [MeV]
200
100
0
1
Nuclei
Net Baryon Density
Early universe
RHIC, LHC
FAIR SIS 300
Quarks and Gluons
Critical point?
Hadrons
Deconfinement and chiral transition
Neutron stars
?

Equation of state including a quark-hadron phase-transition

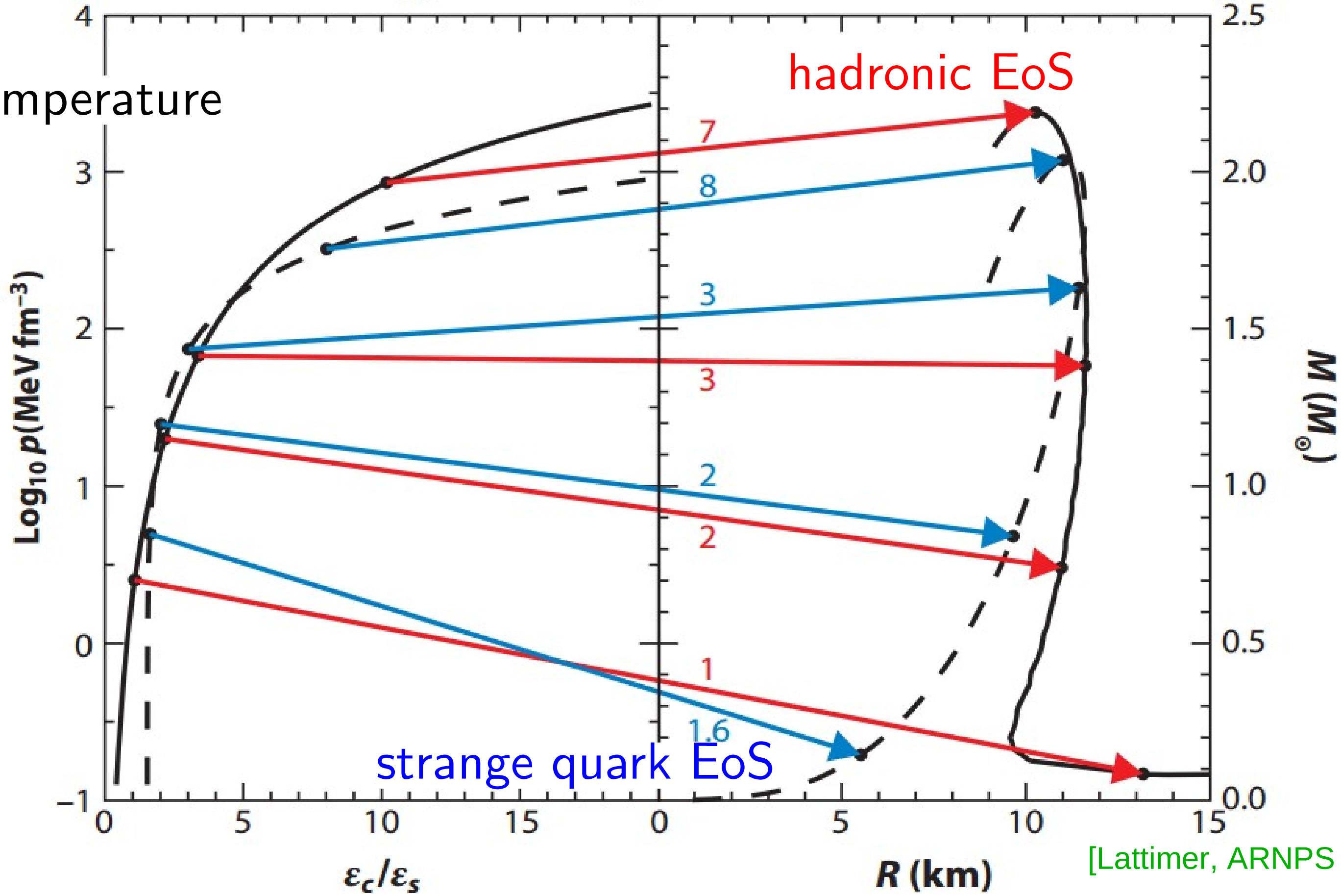
Nuclear equation of state & neutron star

Hydrostatic equilibrium:

$$\frac{dp}{dr} = -\frac{G}{c^2}\frac{(p+\varepsilon)(m+4\pi r^3 p/c^2)}{r(r-2Gm/c^2)},$$
$$\frac{dm}{dr} = 4\pi r^2 \frac{\varepsilon}{c^2},$$

(TOV equation)

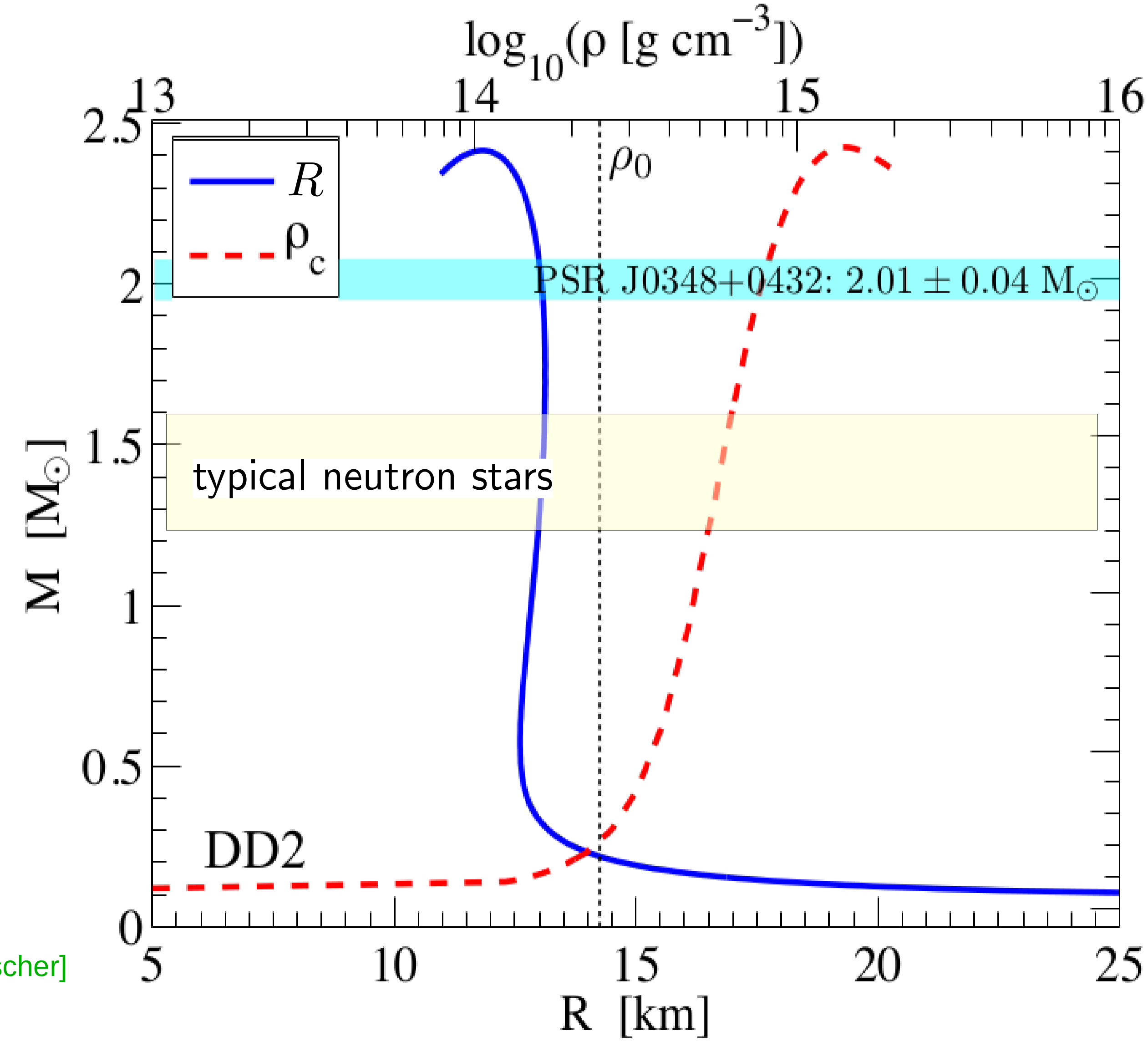
**zero temperature



[Lattimer, ARNPS 62 (2012) 485]

each pressure-energy density relation gives one neutron star mass-radius relation

Nuclear equation of state & neutron star



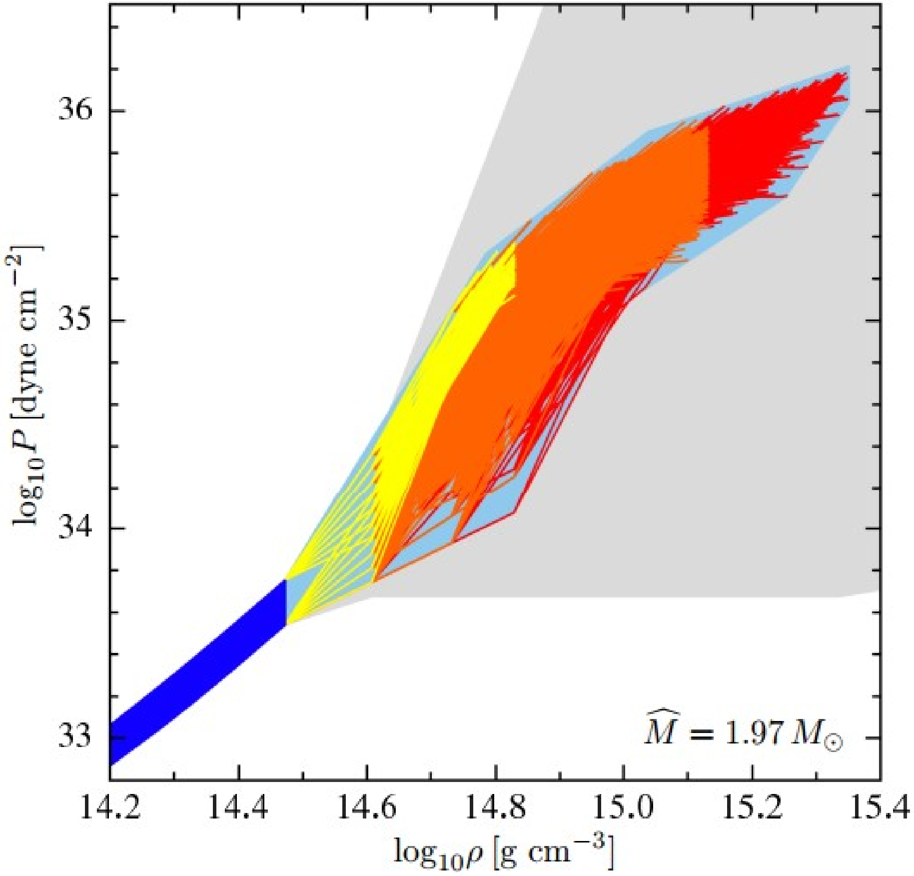
[from T. Fischer]

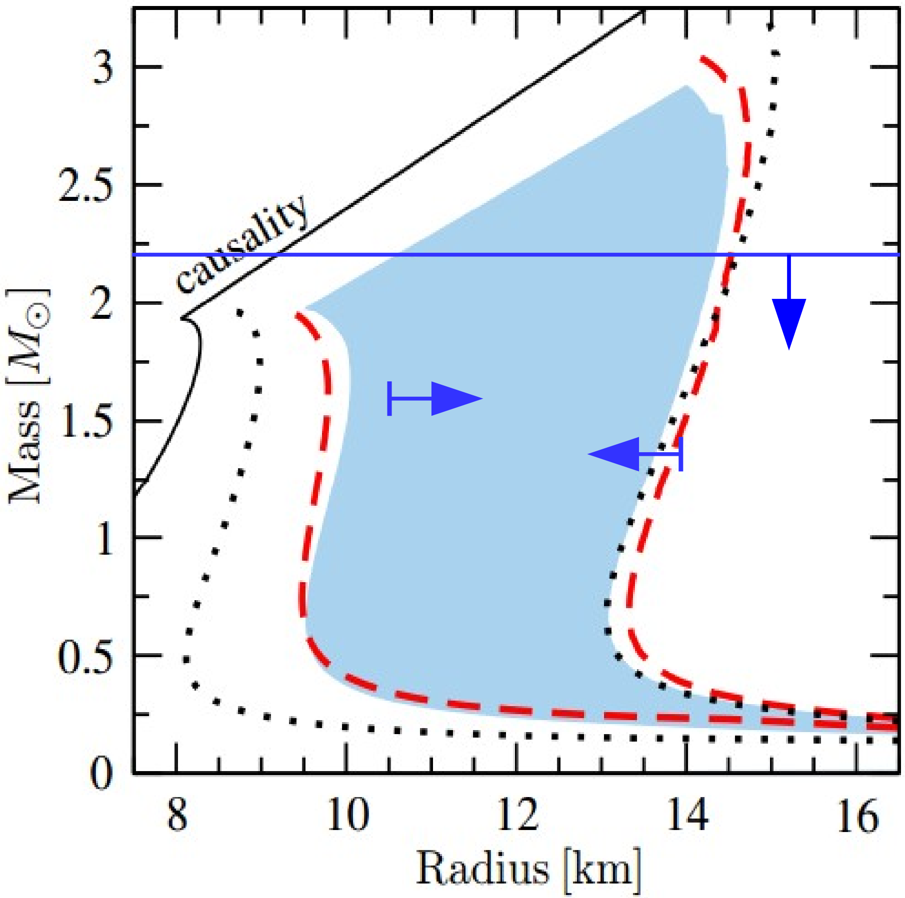
typical $1.35\ M_\odot$ NS has central mass density $\lesssim 5 \times 10^{14}$ g/cm^3, a heavier NS may reach higher density

Nuclear equation of state & neutron star

current constraint based on extrapolation from chiral effective field theory + the existence of $2\ M_\odot$ NS + causality

[Hebeler+ 2013]





**bounds from GW170817

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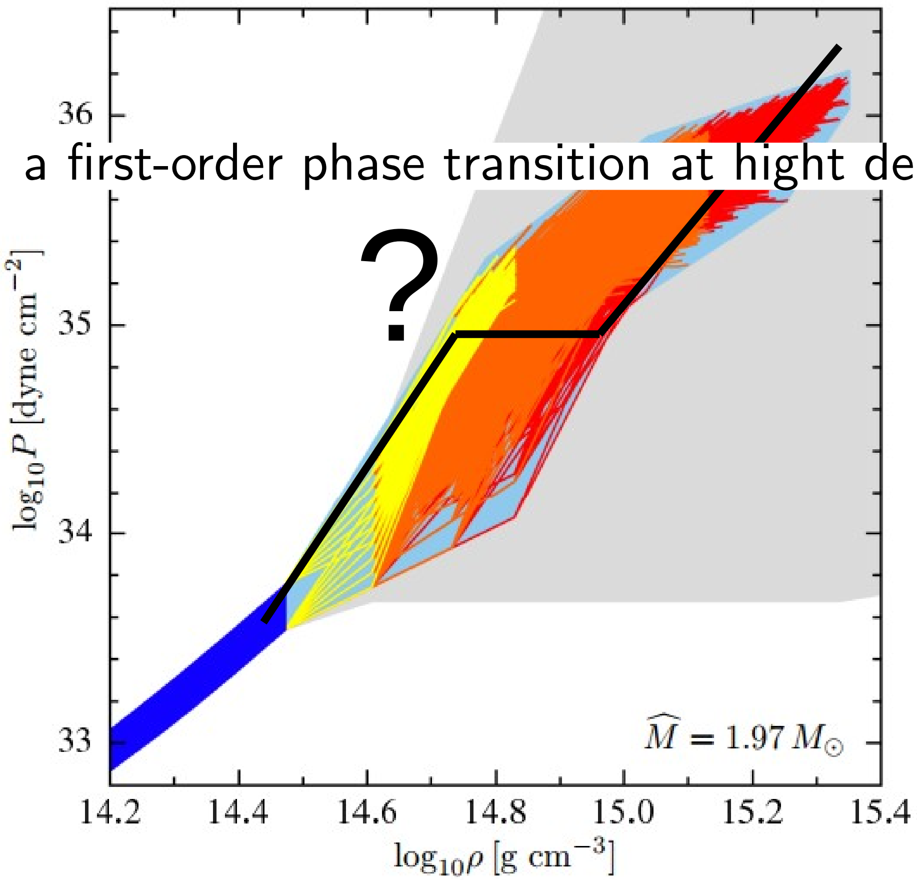
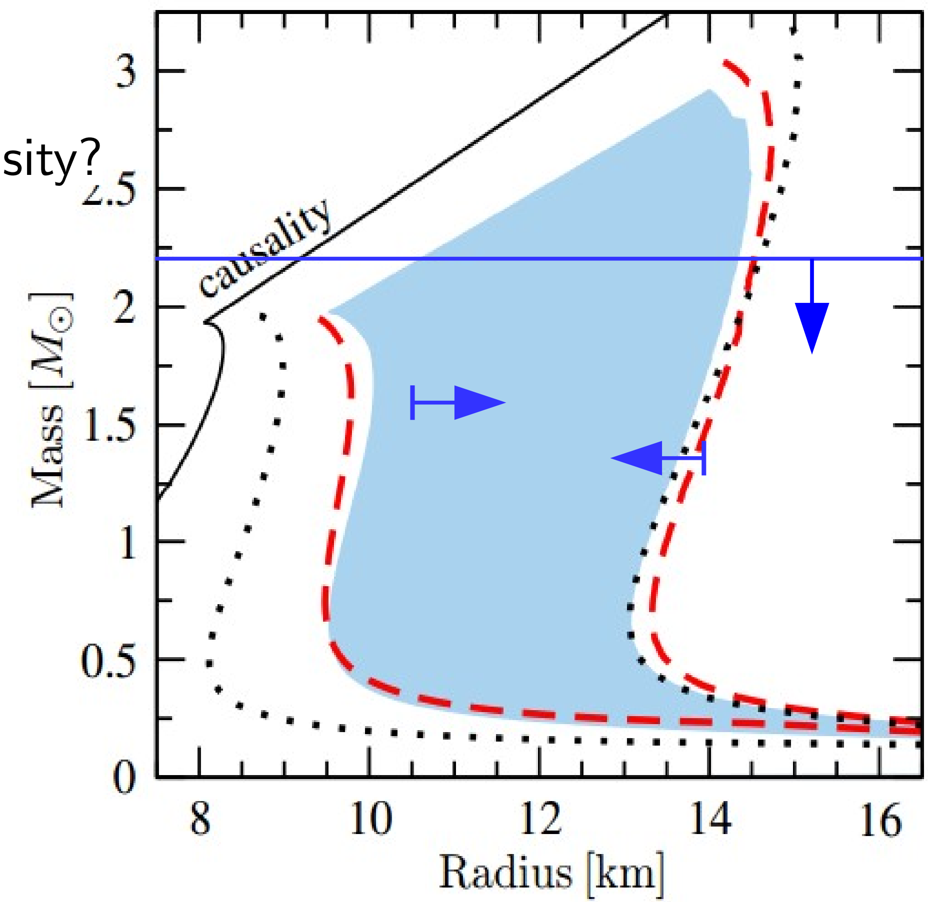


a first-order phase transition at hight density?

[Hebeler+ 2013]



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Constructing hadron-quark phase transition

Effective Lagrangian with couplings determined by experiments or with prescribed interaction potentials

$\rightarrow$ compute the mean-field potential and effective mass for the single-particle or the quasiparticle

$\rightarrow$ derive the resulting thermodynamic properties

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hadronic EoS (DD2): [Typel+ 2009]

- relativistic mean-field model, effective meson-exchange interactions
- couplings fixed by low energy nuclear experiments, satisify all known constraints

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quark matter EoS: [Kaltenborn+ 2017]

- relativistic mean-field model with effective quark interaction potential

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{free}} - U(\bar{q}q, \bar{q}\gamma_0 q), \quad \mathcal{L}_{\text{free}} = \bar{q}\left(-\gamma_0 \frac{\partial}{\partial \tau} + i\vec{\gamma}\cdot\vec{\nabla} - \hat{m}\right)q,$$

$$U(\bar{q}q, \bar{q}\gamma_0 q) = U(n_s, n_v) + (\bar{q}q - n_s)\Sigma_s + (\bar{q}\gamma_0 q - n_v)\Sigma_v + \cdots,$$

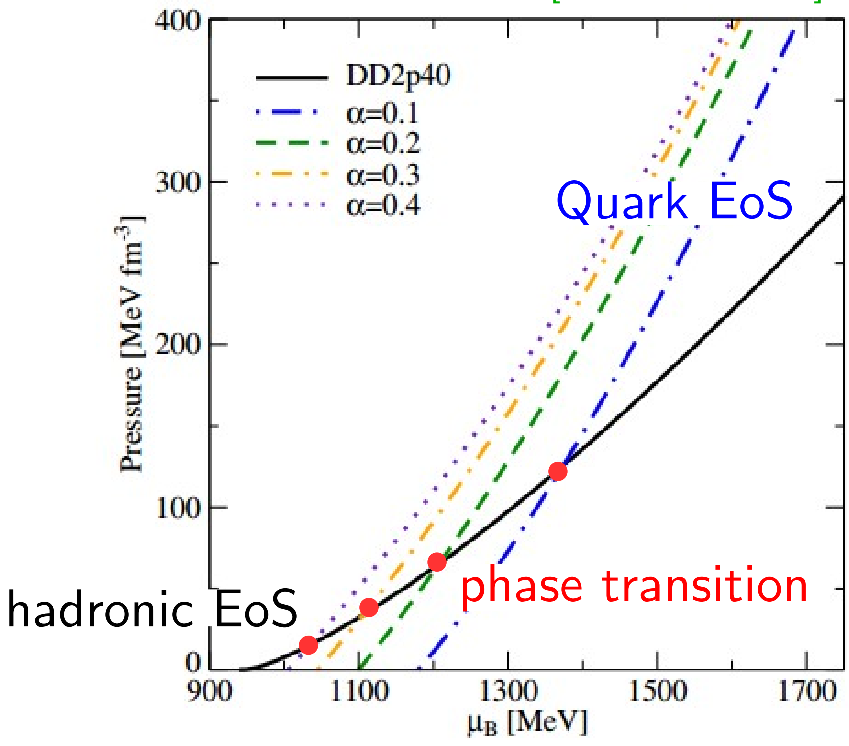
$$U(n_s, n_v) = \underline{D(n_v)n_s^{2/3}} + \underline{an_v^2 + \frac{bn_v^4}{1 + cn_v^2}}. \quad D(n_v) = \underline{D_0 e^{-\alpha(n_v - n_{\text{sat}})^2}} \text{ for } n_v > n_{sat}$$

confinement potential — high density repulsion — high density deconfinement

Constructing hadron-quark phase transition

for a given chemical potential, an EoS with higher pressure is selected to minimize the thermodynamic potential

[Kaltenborn+ 2017]

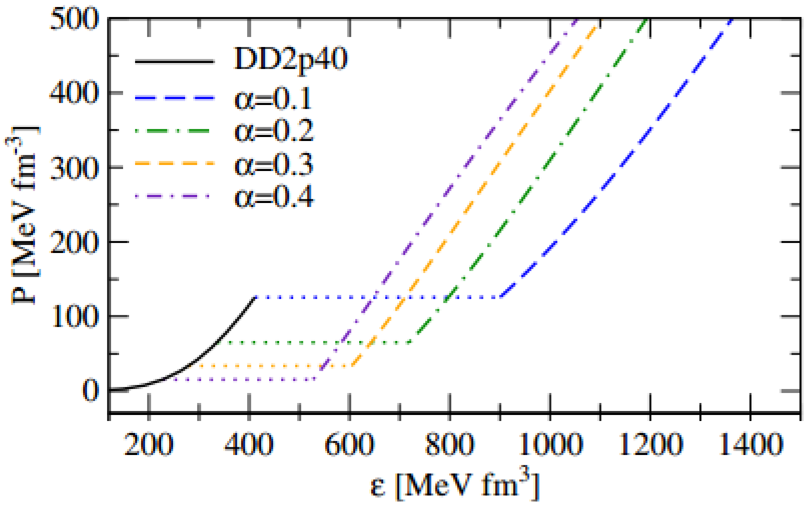


$$a = -2 \text{ MeV fm}^3 \quad c = 0.036 \text{ fm}^6$$
$$b = 2.0 \text{ MeV fm}^9 \quad D_0 = (240 \text{ MeV})^2$$

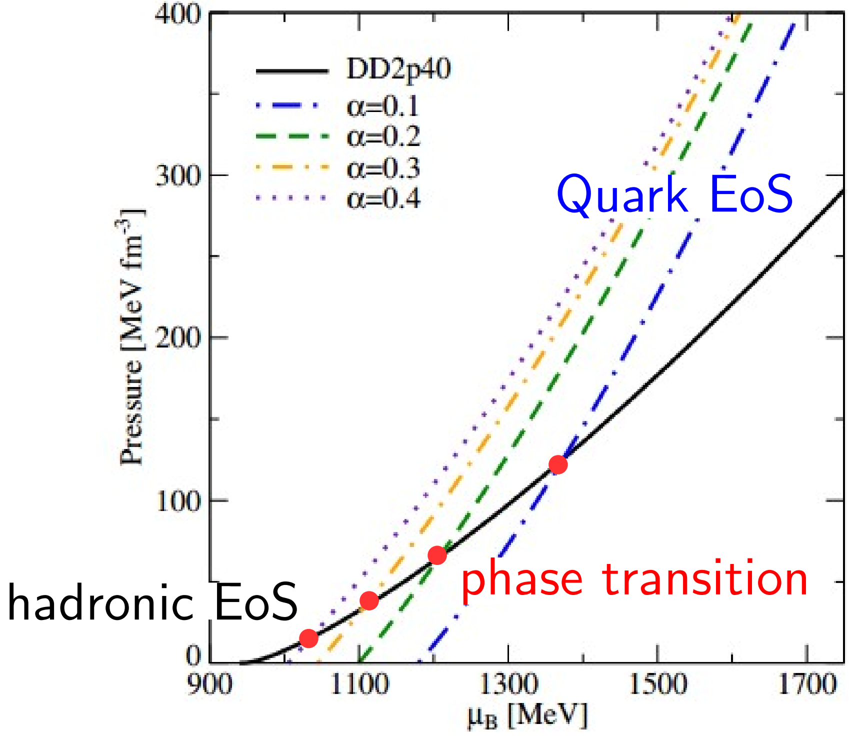
Constructing hadron-quark phase transition

for a given chemical potential, an EoS with higher pressure is selected to minimize the thermodynamic potential

resulting $P(\rho)$ relation:



[Kaltenborn+ 2017]



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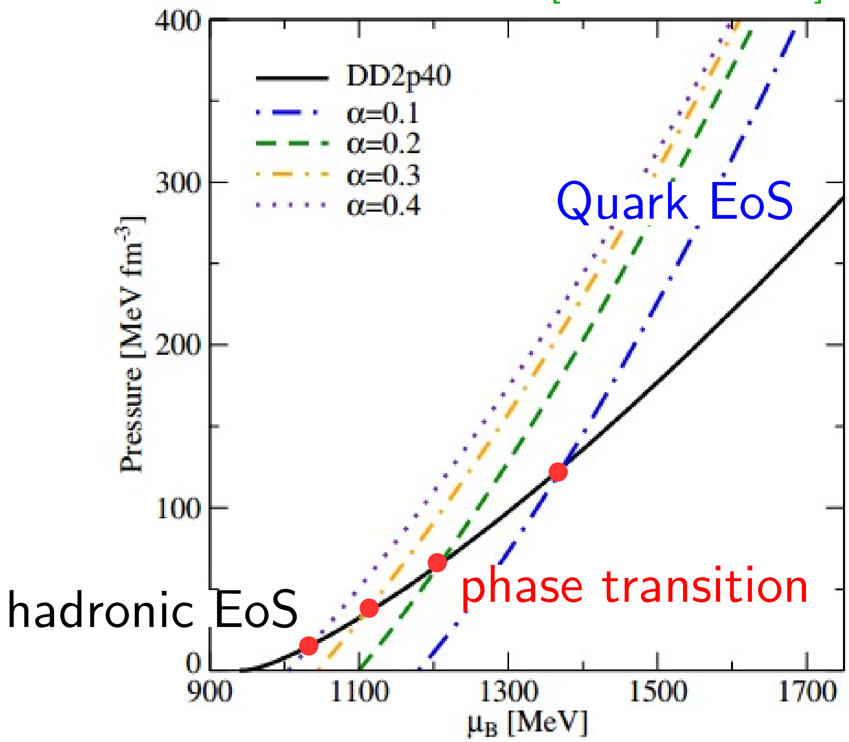

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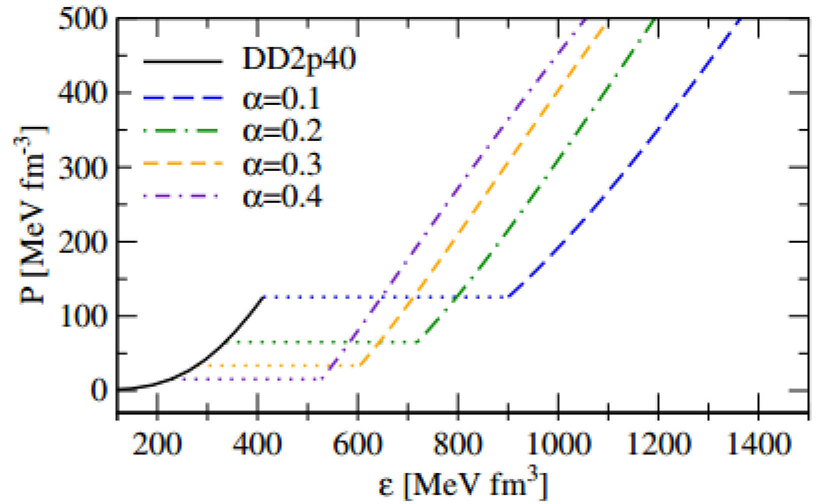

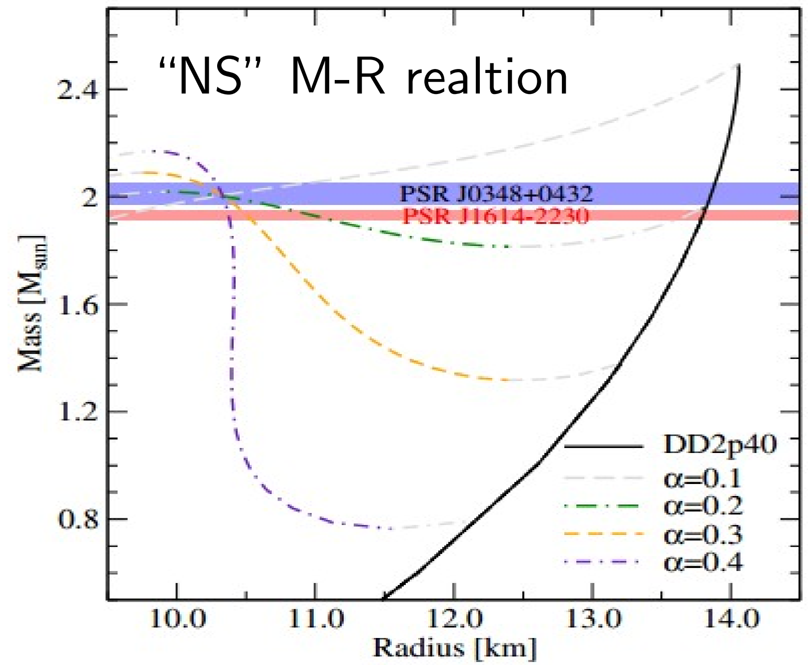

$a = -2$ MeV fm^3 $c = 0.036$ fm^6

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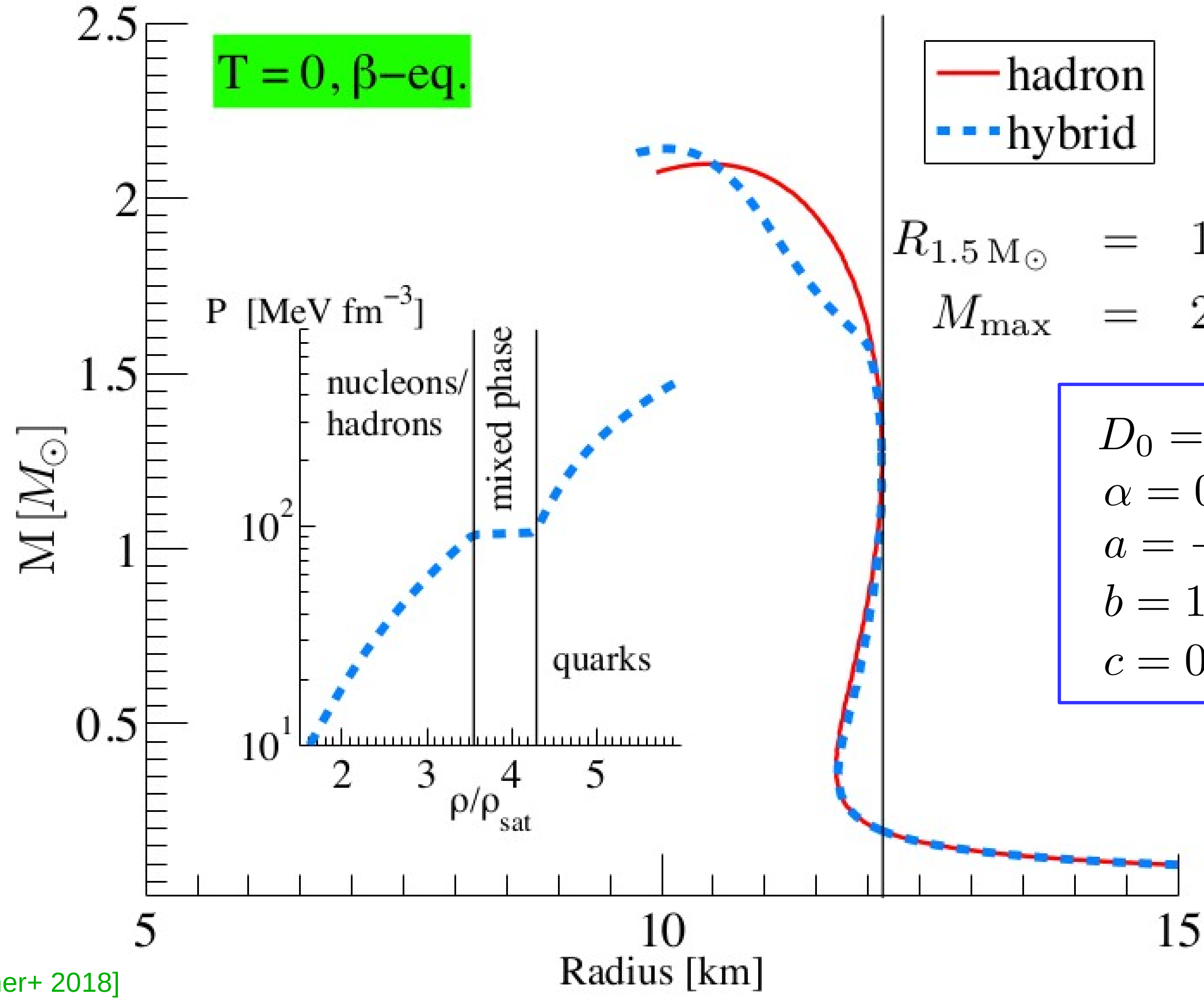
Constructing hadron-quark phase transition

A hybrid EoS that satisfies all known constraints



$R_{1.5\,M_\odot} = 12.2$ km

$M_{max} = 2.15\ M_\odot$

$D_0 = (265\text{ MeV})^2$
$\alpha = 0.39\text{ fm}^6$
$a = -4\text{ MeV fm}^3$
$b = 1.6\text{ MeV fm}^9$
$c = 0.025\text{ fm}^6$

[Fischer+ 2018]

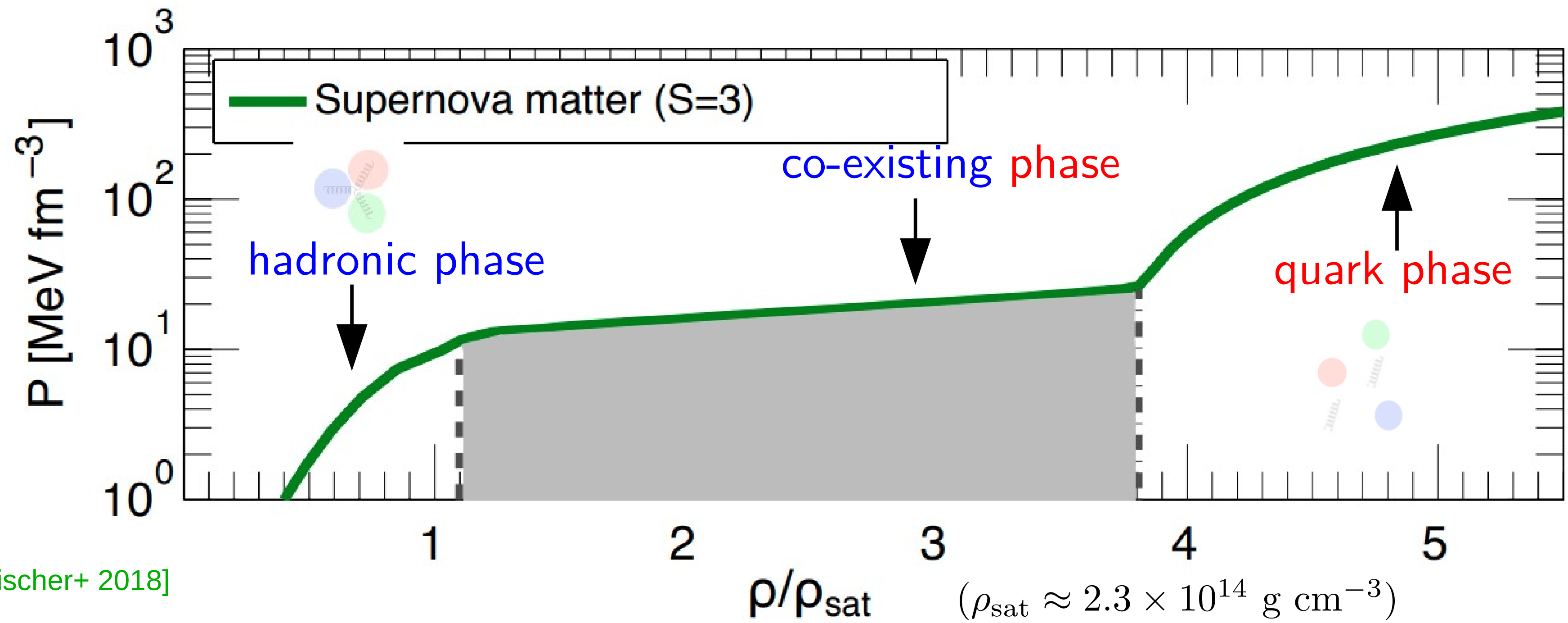
Supernova explosion of massive stars due to QHPT

Supernova explosion with hadron-quark phase transition?

Prevalent supernova theory predicts that most of the CCSNe are powered via the neutrino-driven mechanism aided by multi-dimensional fluid motion.

Other possibilities:

- magneto-rotational supernovae [Winteler+ 2012, Moesta+ 2014,...]
- collapse-induced thermonuclear burning [Kushnir+ 2015]
- quark-hadron phase transition [Takahara+ 1988, Sagert+ 2009, Fischer+ 2018]

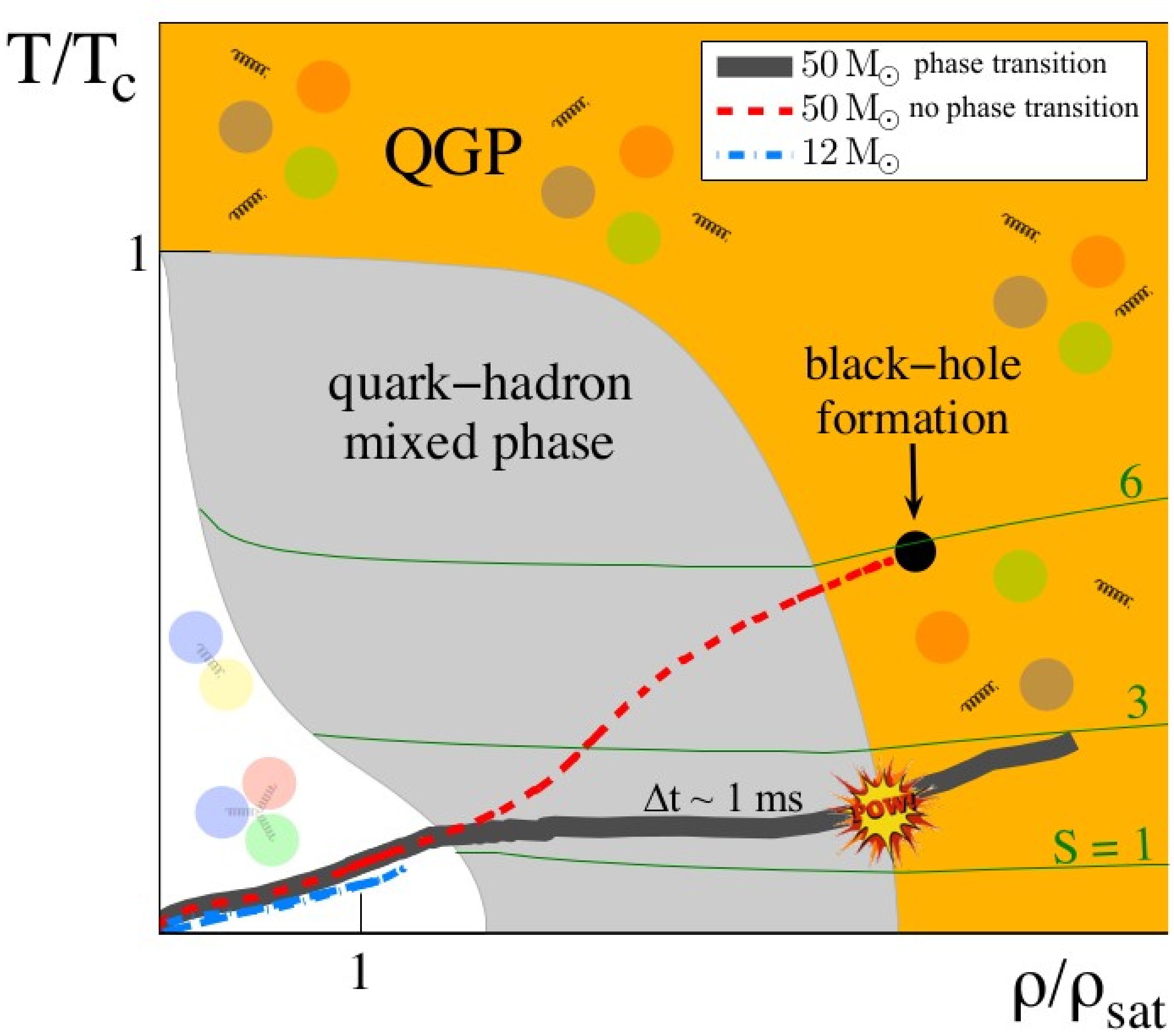


[Fischer+ 2018]

$(\rho_{\rm sat} \approx 2.3 \times 10^{14}$ g cm$^{-3})$

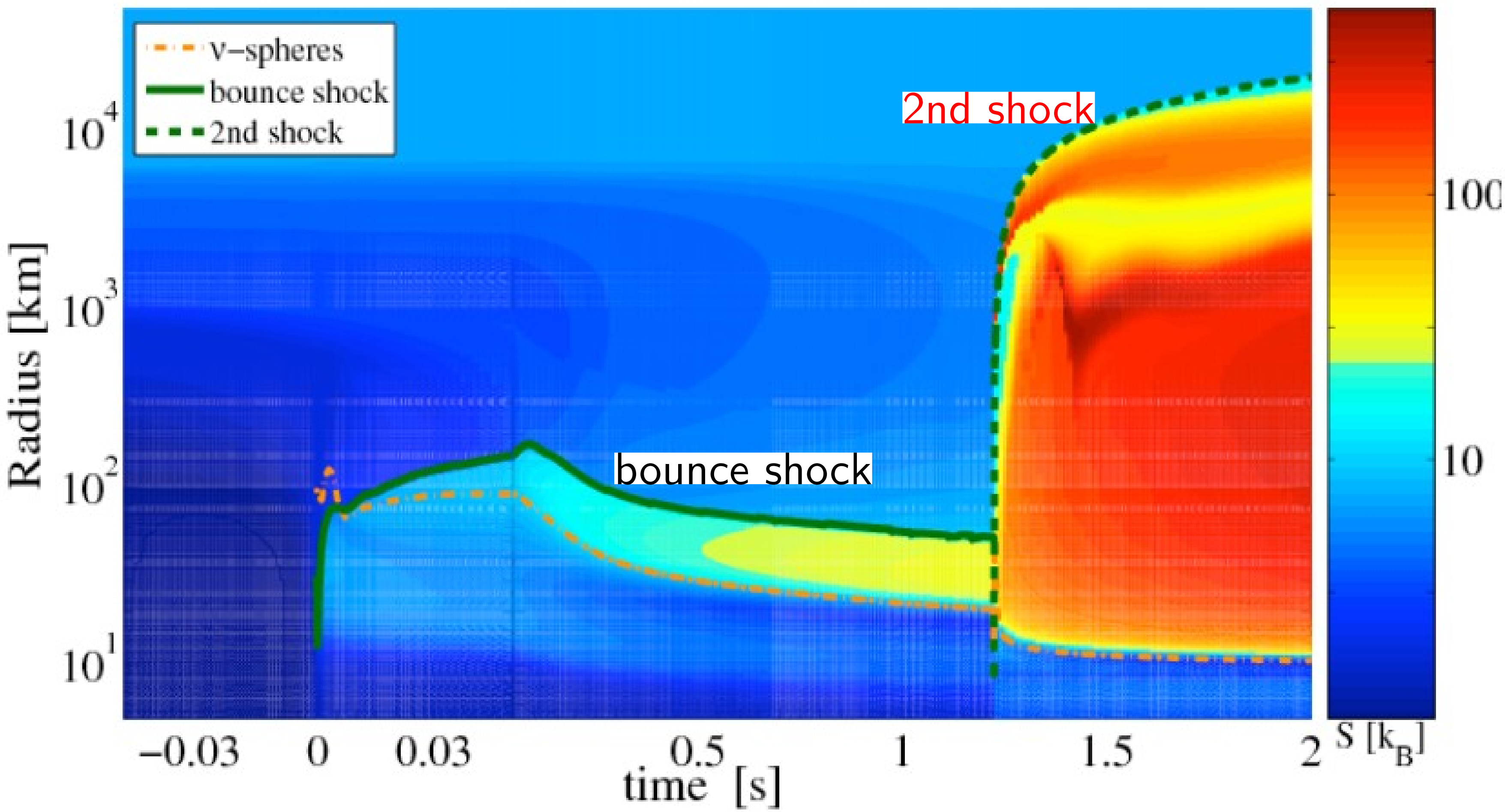
Supernova explosion with hadron-quark phase transition?

[Fischer+ 2018]



Supernova explosion with hadron-quark phase transition?

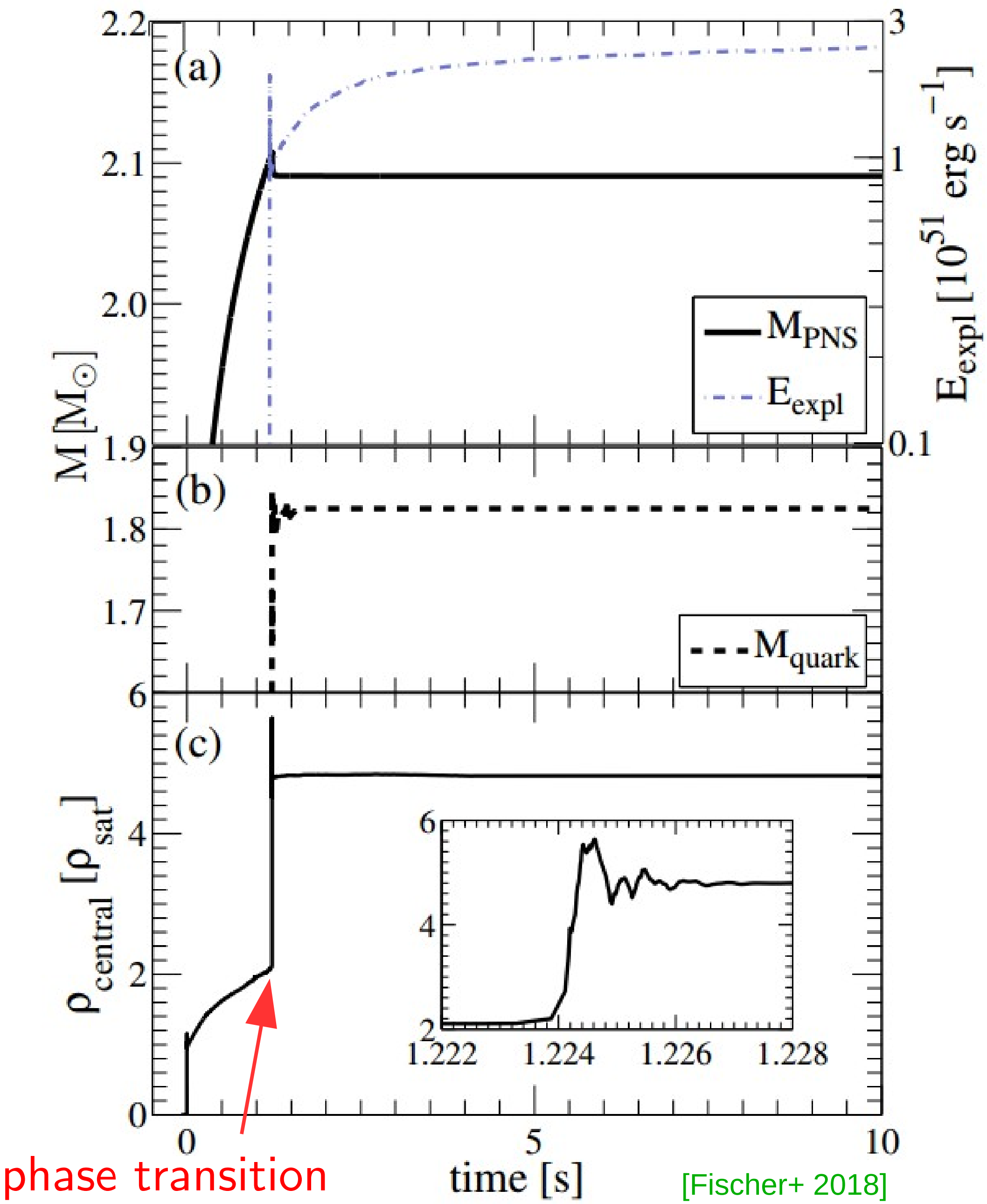
[Fischer+ 2018]



when a 1st order phase transition occurs, the PNS goes through a second collapse, until the central density reaches the quark matter density

→ a second shock wave is generated due to the core stiffens after the transition

Supernova explosion with hadron-quark phase transition?



[Fischer+ 2018]

- very strong shock due to the short dynamical timescale ~ 1 ms

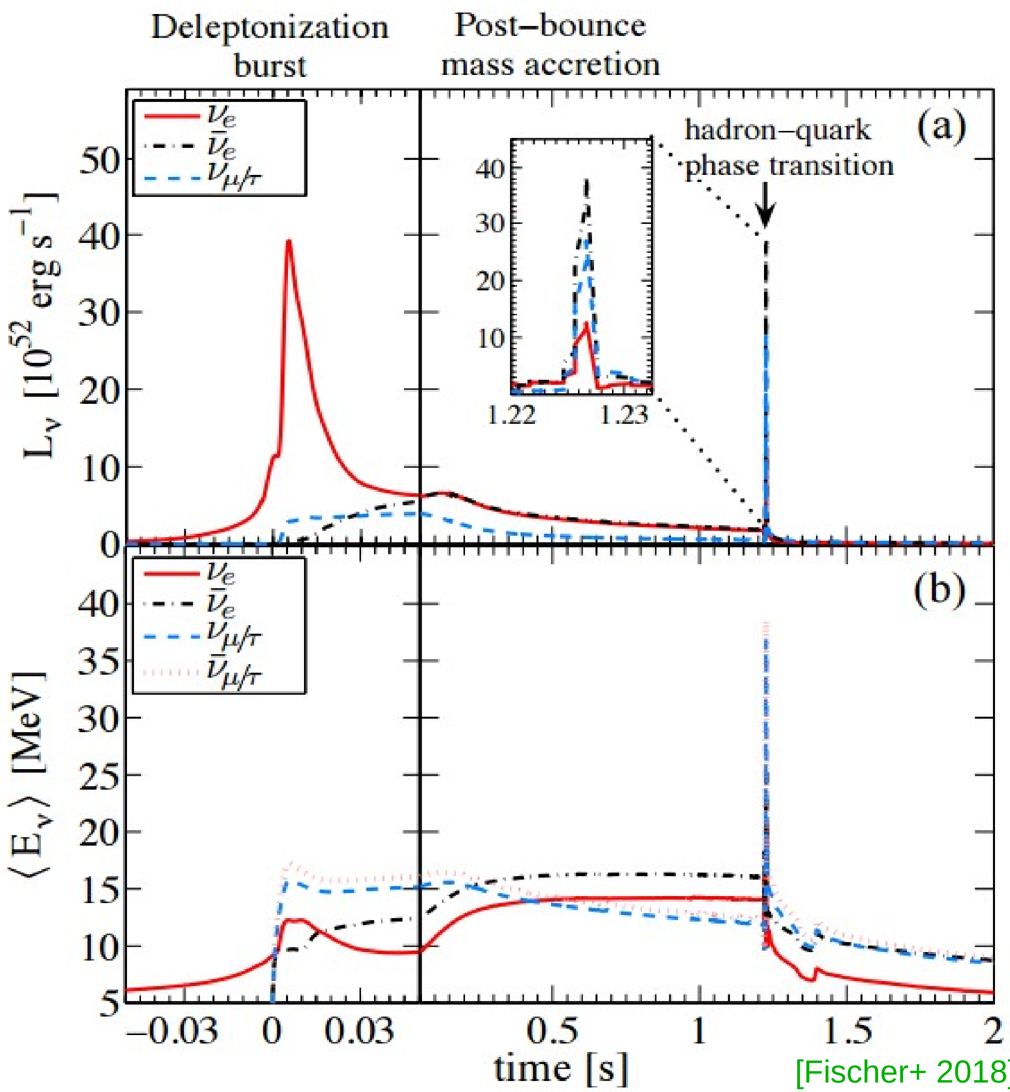
- large explosion energy $\sim 3 \times 10^{51}$ erg

- results in a $\sim 2\ M_\odot$ hybrid star containing $\sim 1.8\ M_\odot$ quark core

$\rightarrow$ origin of the observed heavy "neutron stars"?

Observational signatures?

As the shockwave swipes throgh the outer part of the PNS, it releases a millisecond neutrino burst in ALL flavors:



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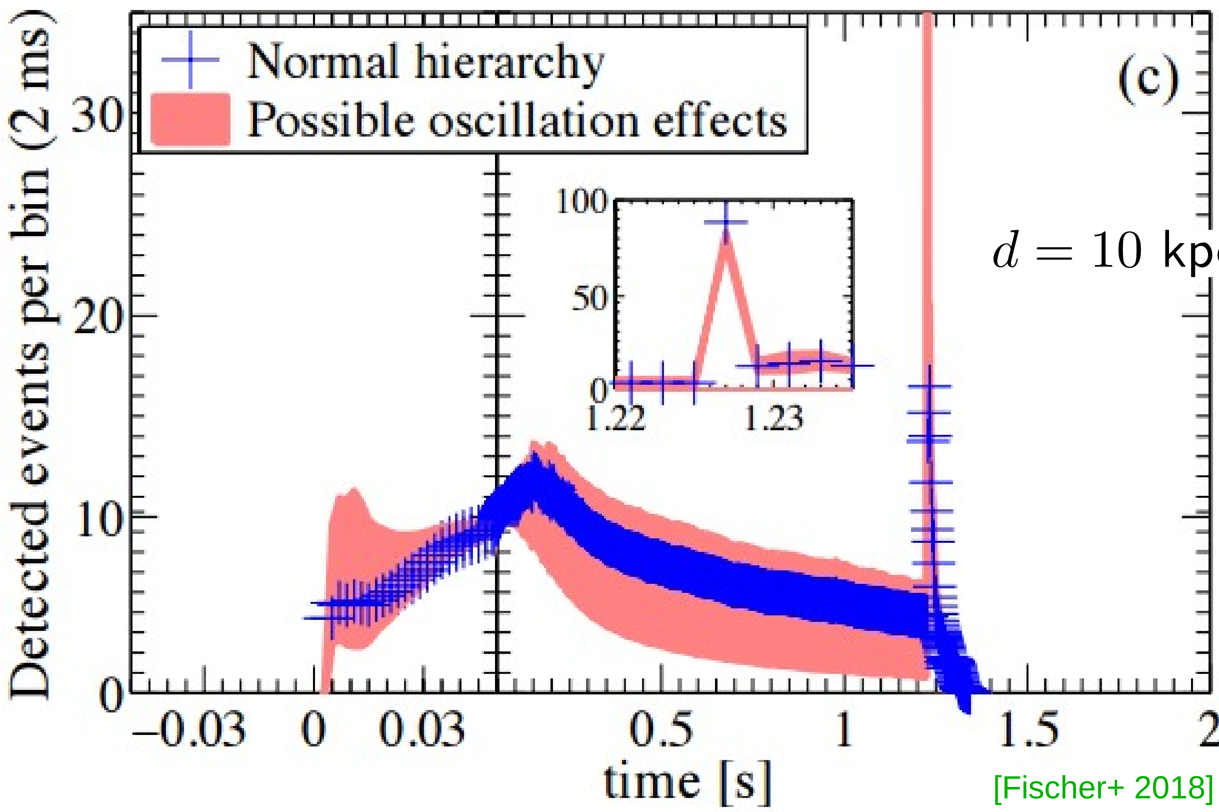


$d = 10$ kpc, Super-K

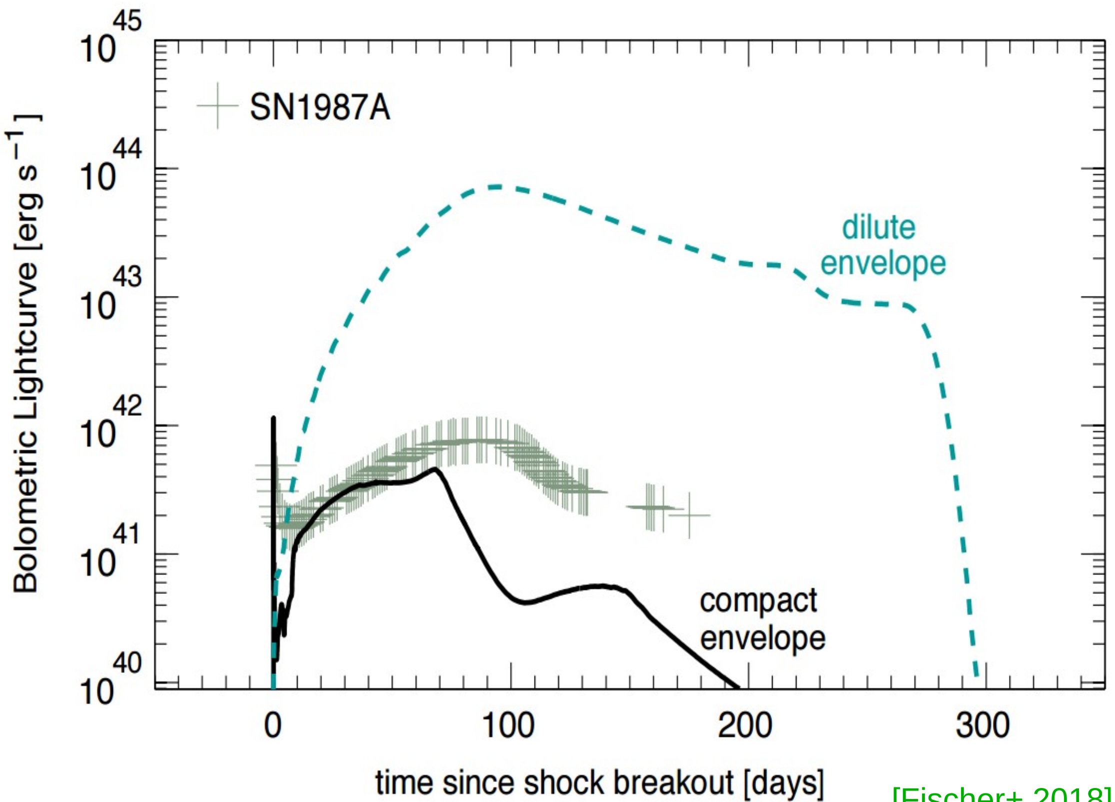
[Fischer+ 2018]

Can be detected for a Milky Way event with kiloton neutrino detectors, independent of how flavor oscillations happen

Observational signatures?

- the resulting EM lightcurve depends on how the progenitor envelopes were dispelled during the stellar evolution

- At least as bright as SN1987A, can possibly produce a hypernova or superluminous supernova if there is large mass loss right before the explosion



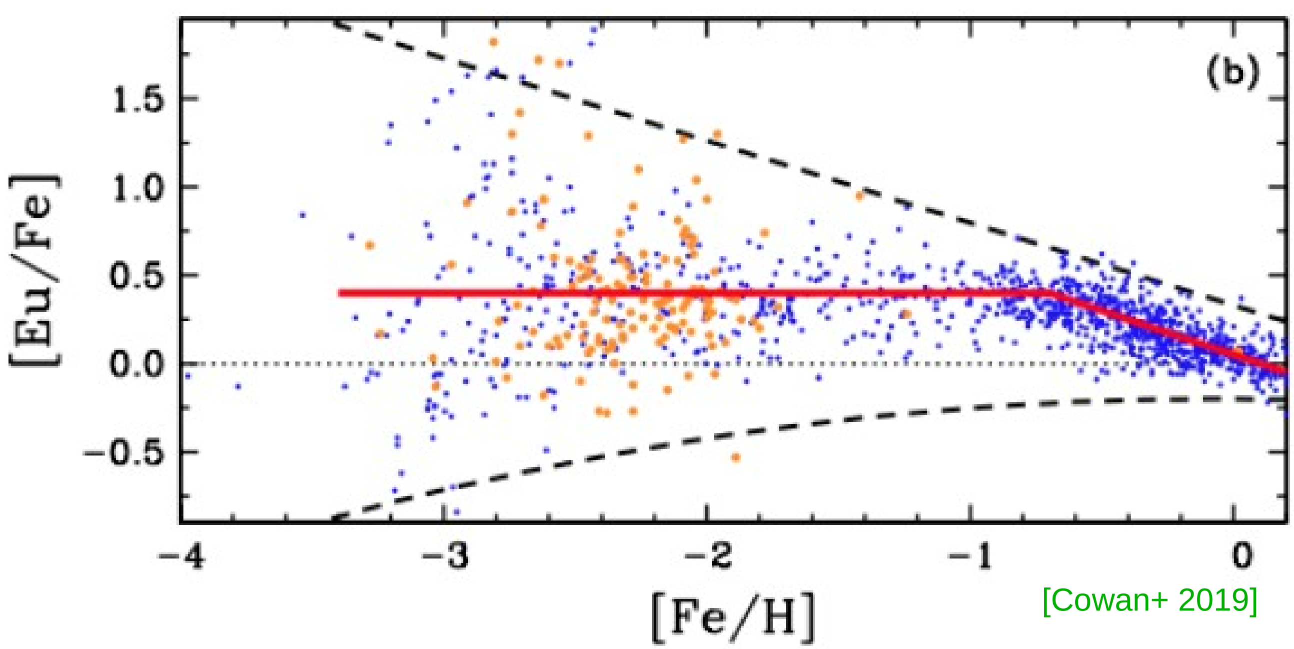
[Fischer+ 2018]

Heavy element production by QHPT supernovae

Do we need massive stars as r-process sources?

The discovery of binary neutron star merger event 170817 suggested that the mergers are likely sources producing r-process nuclei heavier than iron.

However, r-process element production associated with massive stars may still be needed to address the enrichment of r-elements (e.g., Eu) at low metalicity, the observed diversity in abundance patterns of metal-poor stars, the decreasing trend of [Eu/Fe] at high metalicity, and the potential association of ^{244}Pu with ^{60}Fe from deep see measurement



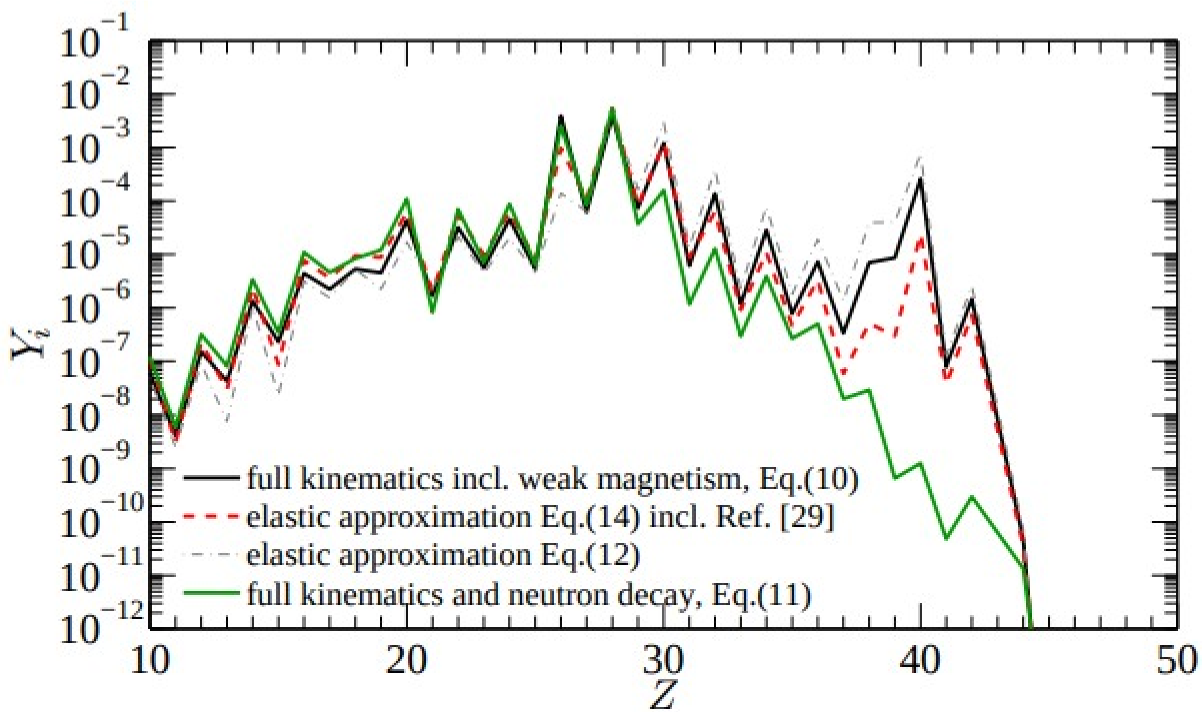
[Cowan+ 2019]

Do we need massive stars as r-process sources?

The conditions in the neutrino-driven wind from typical proto-neutron stars born after supernova explosion only allow the production of elements up to $Z \sim 40$, due to: [Wanajo+, Martinez-Pinedo+, Arcones+, ...]

(i) too high $Y_e \equiv n_e / n_{\rm nucleon} \sim 0.45 - 0.55$

(ii) too low entropy $\lesssim 100\ k_B$ per nucleon



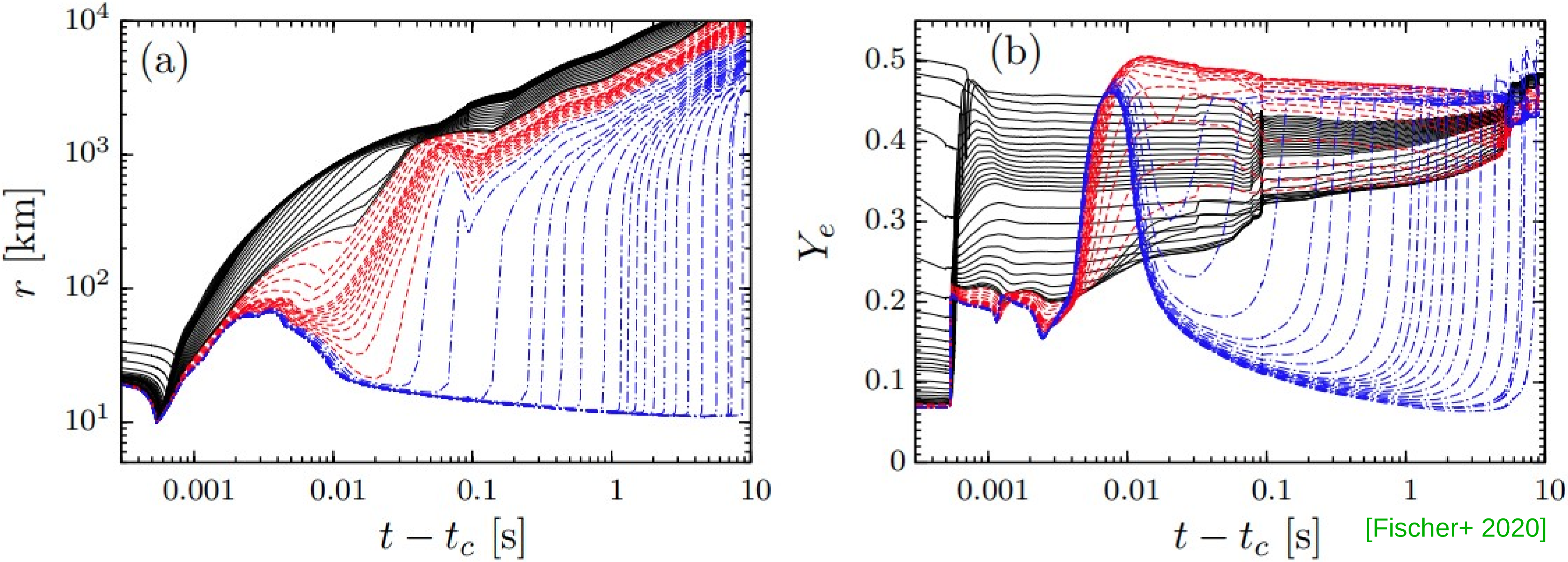
[Fischer+ 2020]

Remnant property from phase-transition SNe (PTSNe)

The QHPT-SN can produce conditions more favorable for the r-process:

(i) a strong second shock:

$\rightarrow$ faster expanding ejecta with lower Y_e at early times



[Fischer+ 2020]

($40M_\odot$ model)

direct, intermediate, and ν-driven

Remnant property from phase-transition SNe (PTSNe)

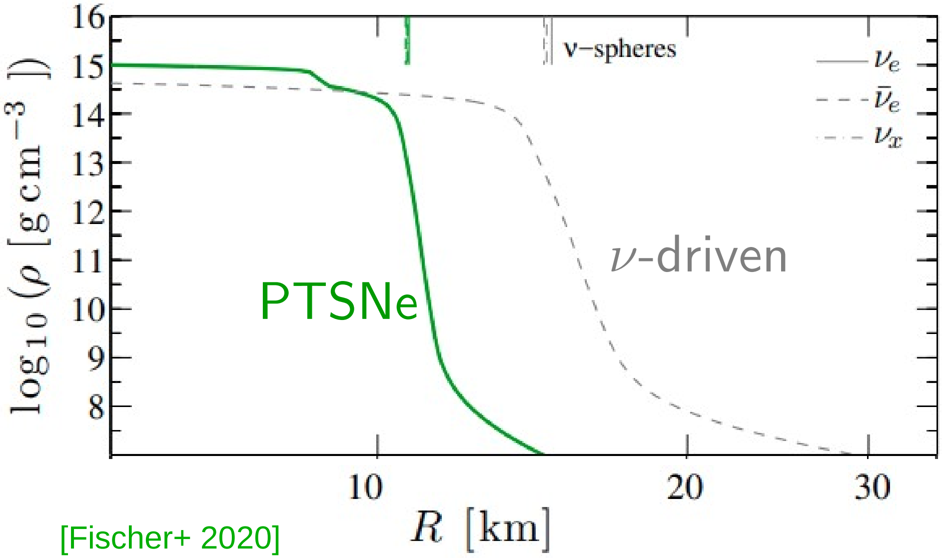
The QHPT-SN can produce conditions more favorable for the r-process:

(i) a strong second shock:

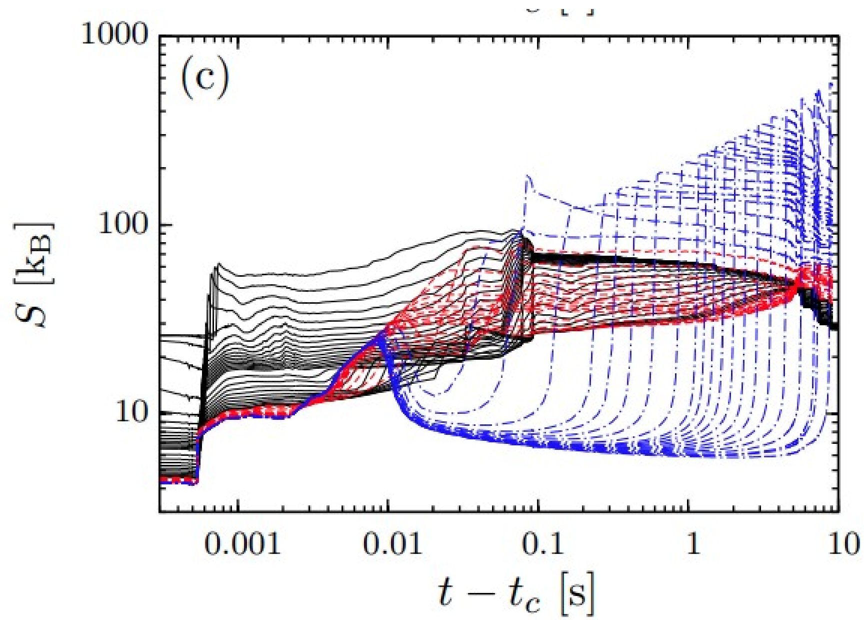
$\rightarrow$ faster expanding ejecta with lower Y_e at early times

(ii) a more compact proto-neutron star:

$\rightarrow$ a higher entropy in the neutrino-driven wind ($S \propto M/R$)



[Fischer+ 2020]



($40M_\odot$ model)

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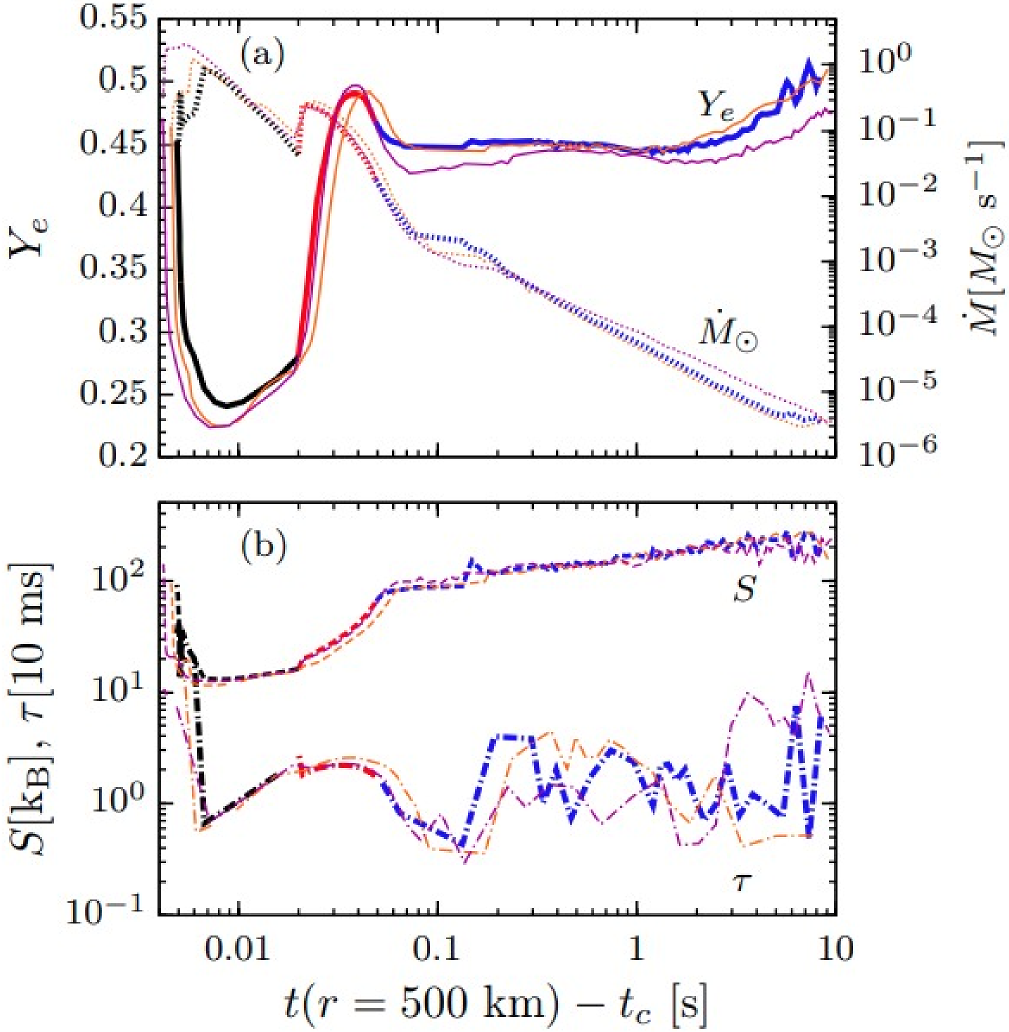
Ejecta & nucleosynthesis in PTSNe



direct ejecta: low Y_e & entropy

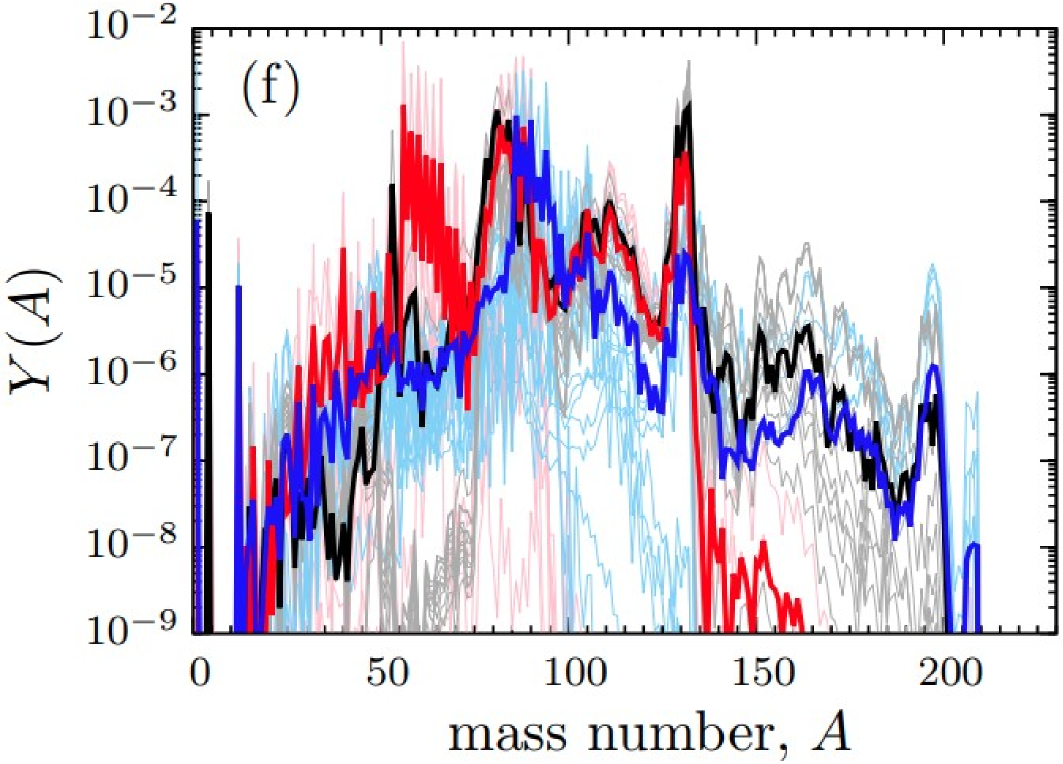
intermediate

ν-driven wind: high Y_e & entropy

similar results obtained for different progenitor masses

($35M_\odot$, $40M_\odot$, $50M_\odot$)

Ejecta & nucleosynthesis in PTSNe



direct ejecta: low Y_e & entropy

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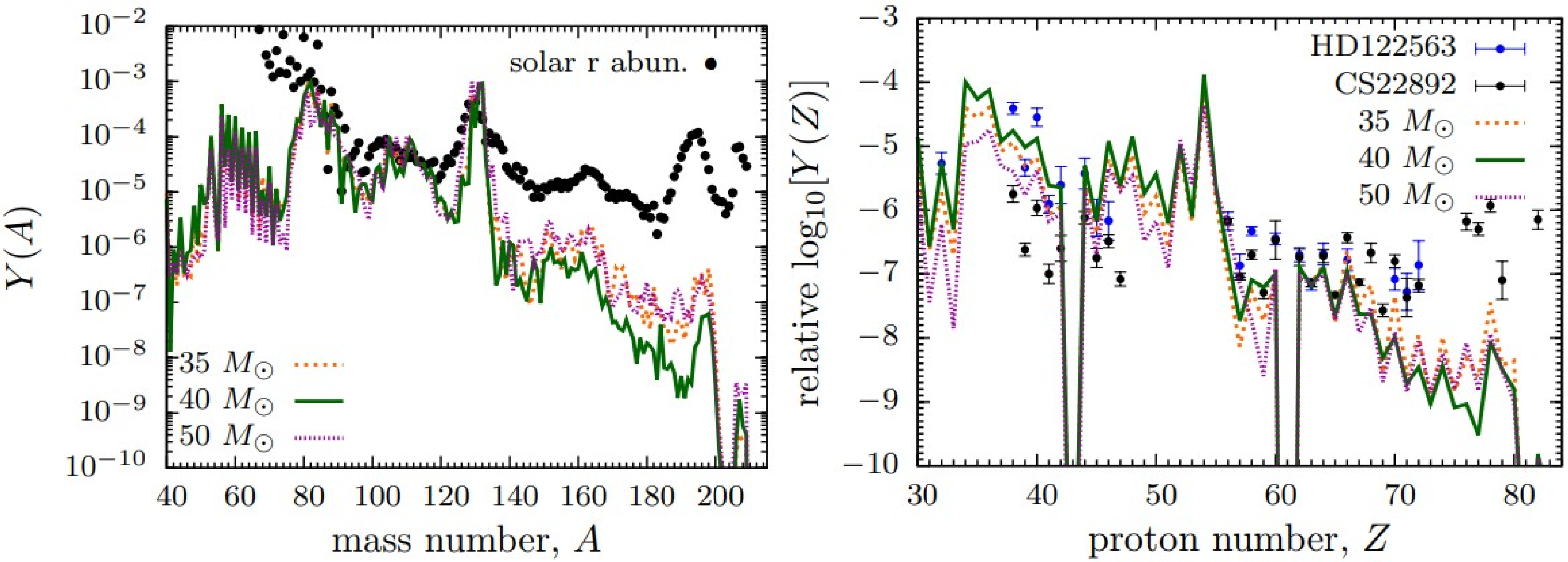
($35M_\odot$, $40M_\odot$, $50M_\odot$)

Integrated nucleosynthesis yields

The integrated nucleosynthesis yields from all components produce reduced amount of third-peak nuclei relative to the second-peak, when compared to the Solar r abundances.

However, the yields may possibly account for the metal-poor stars that show the "weak" r-process patterns



[Fischer+ 2020]

(The produced ratio of ^{244}Pu to ^{60}Fe are also boradly consistent with very recent deep-sea measurement)

Summary

- A hadron-quark phase transition may be possible at supra-nuclear density.
- This may happen during the collapse of massive stars of $\sim 40 - 50 M_\odot$ failed to be powered by ν-driven mechanism, and can result in a strong explosion, leave behind a $\sim 2\ M_\odot$ hybrid star.
- Such an explosion will produce a millisecond neutrino burst detectable if happened in the Milky Way.
- It can potentially power a variety of supernova lightcurves, ranging from $\sim$ of SN1987a to superluminous SNe, depending on the pre-supernova mass ejection history.
- It can generate the condition suitable for the r-process nucleosynthesis as a potential source to explain some metal-poor star abundances.