Quarks and Compact Stars 2019
26-28 Sept. 2019 @ Hanwha Resort, Busan

Thermal Evolution of Quark-Hadron Hybrid Stars with Nucleon Superfluidity and Quark Superconductivity

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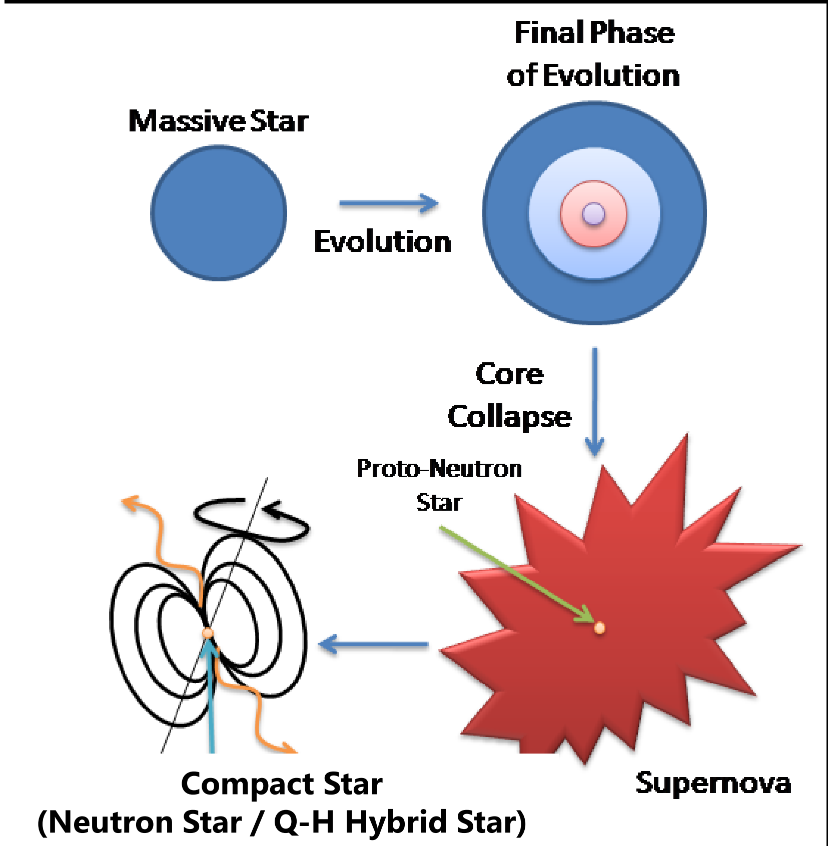
INTRODUCTION

THERMAL HISTORY OF COMPACT STARS



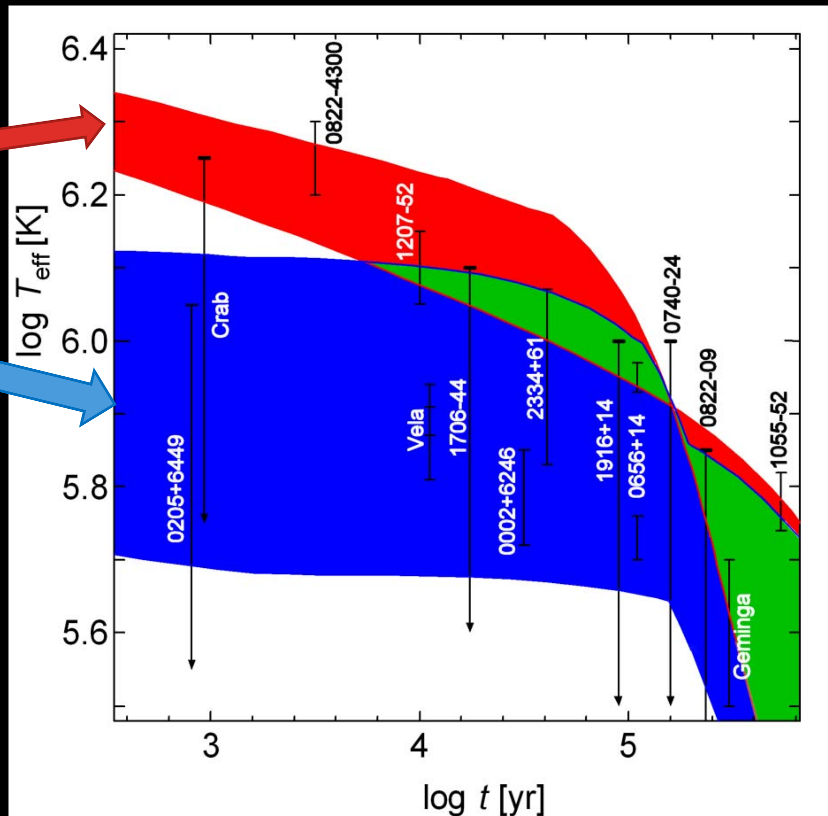
- Compact stars are born from supernovae explosions.
  - Born at high temperature (~10^{10} K)
- No internal heat source
  - Emitting thermal energy by neutrinos
  - Isolated compact star only cools down.
    - t < 10^5 yr: Neutrinos
    - t > 10^5 yr: Photon (X-ray)

COOLING OF COMPACT STARS

- Cooling process corresponds the internal matter state
  - Normal nuclear matter (Standard Cooling)
  - π condensation
  - K condensation
  - Hyperon mixing
  - Quark matter
  - Superfluidity

  etc…

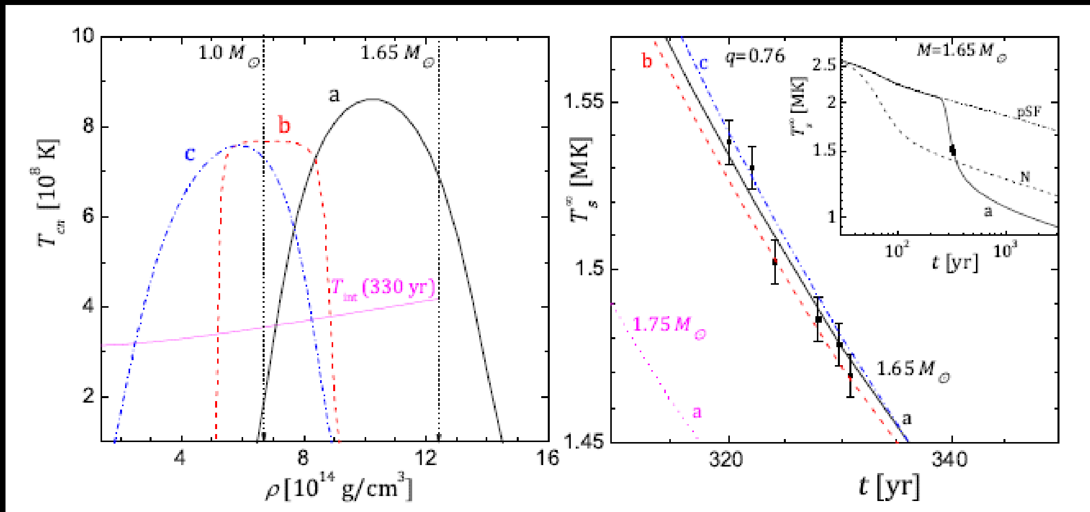
  (π condensation, K condensation, Hyperon mixing, Quark matter: Exotic Cooling)
- Exotic phase appears at higher density, and it cools star rapidly.



TN+, PoS (NIC-IX) 153, 2006

SUPERFLUIDITY

- Superfluidity has 2 effects on neutrino emissivities of compact stars
  - Normal→Super Transition: ν-emission (PBF/Strong Cooling)
  - After Transition: Suppression of ν-emissivity (Weak Cooling)
- n-$^3P_2$
  - Density dependence of critical temperature affects to cooling curves



Shternin et al. 2011

OBSERVATIONS OF COMPACT STARS

- **PSR J1614-2230**, **PSR J0348-0432**, **MSP J0704+6620**
  (Demorest+ 2010, Antoniadis+ 2013, Cromartie+ 2019)
  - **$2M_\odot$** compact stars in binary systems (Companion: WD)
  - The EoS must support the maximum mass $2M_\odot$
- **Central Source of Cassiopeia A** (Cas A, CXOU J232327.9+584842)
  (Ho & Heinke 2009)
  - **Isolated** compact star
  - **Young** (~330 yr) & **Heavy** (1.5-2.4 $M_\odot$) Compact Star, **Hot** for its age
  - Rapid cooling in these 20 years? (Heinke & Ho 2010, Posselt+ 2013)
- **PSR J0205+6449** (3C58) (Slane+ 2002), **Vela Pulsar** (Pavlov+ 2001)
  - **Isolated** compact stars
  - **Cold** for their ages, unknown masses
- **SAX J1808.4–3658** (Campana+ 2002)
  - Compact star in LMXB
  - **Lower surface temperature** for accretion rate -> **Exotic cooling process**

MOTIVATION

Cas A

- Hot, young and heavy
- Isolated compact star with known mass range

3C58 / Vela

- Cold compact stars
  - Older than Cas A
  - Lower temperature
- Isolated compact stars
  (mass range unknown)

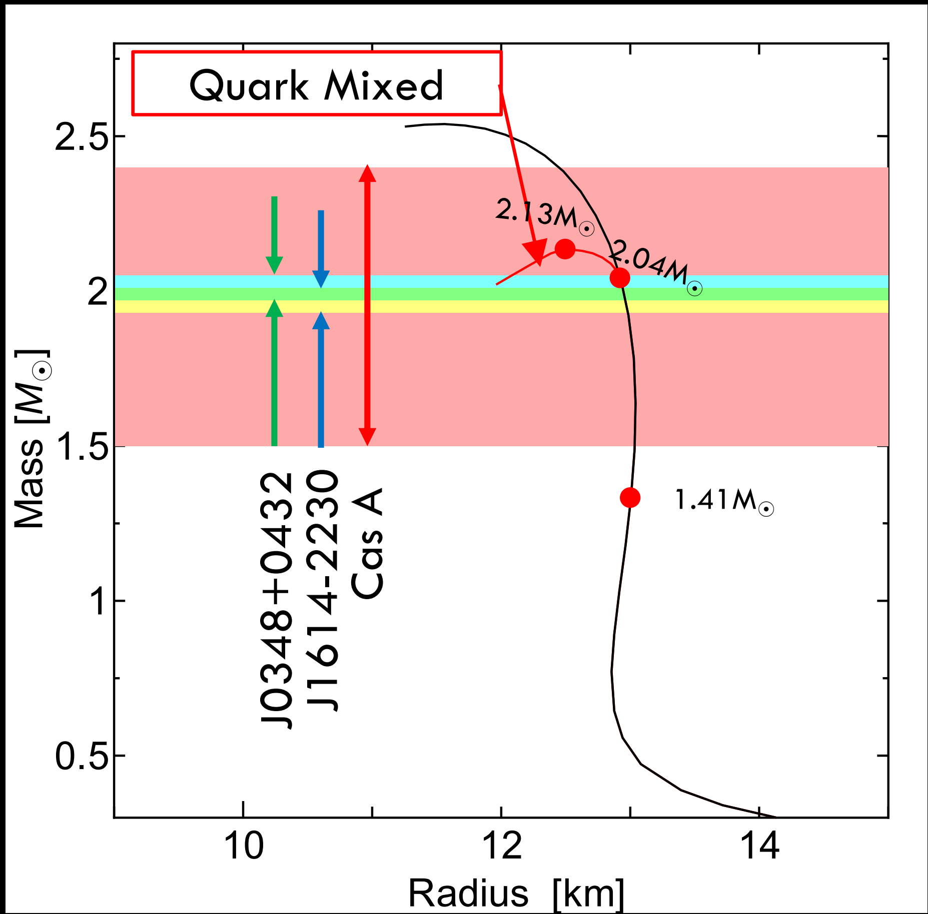
Should be explained by a **single model**

Cas A is heavy, and has an exotic phase, but not cooled down
⇒ **Colour Superconductivity in quark phase** (TN+,2013)

CALCULATION SETUP

MODELS

- Quark-Hadron Hybrid Star EoS
  - Satisfies $2M_\odot$
  - Brueckner-Hartree-Fock (HM) + Dyson-Schwinger (QM)
  - Mixed phase between HM-QM
    (Yasutake+ 2016)
- Surface Composition: ^{56}Fe
- Cooling Process
  - Modified URCA + Bremsstrahlung
  - n-Super($^1S_0$, $^3P_2$), p-Super($^1S_0$)
  - Hadronic Direct URCA ($y_p > 1/9$)
  - Quark Cooling with Colour Superconductivity (CSC)
- Parameters
  - Mass
  - Critical Temperature model of neutron $^3P_2$ superfluidity
  - CSC paring



QUARK PHASE

Quark matter at high density

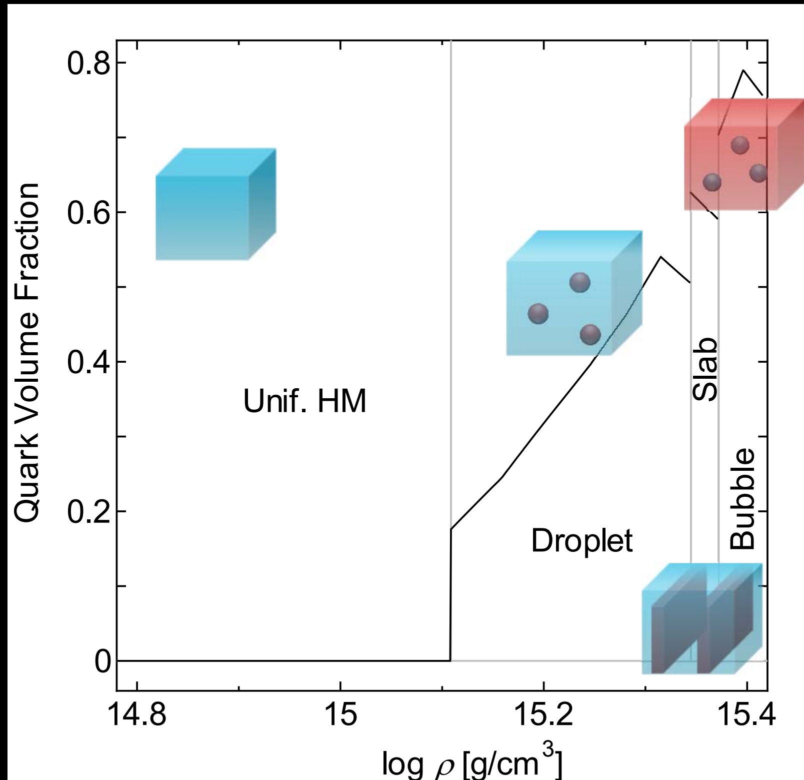
- Colour super conductivity (CSC)

CSC state has similar effect to nucleon superfluidity

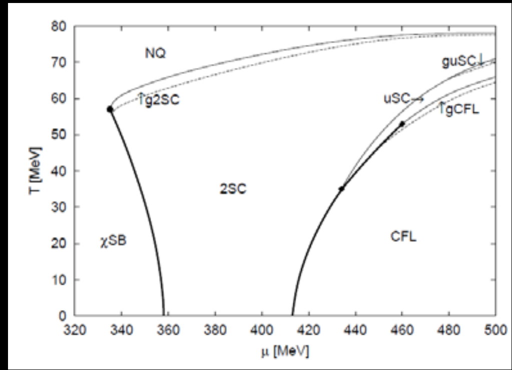
- Assuming $\Delta \geq 10$ MeV
- Suppression of neutrino emissivity

$$\propto \exp\left(-\Delta/k_{\mathrm{B}}T\right)$$

- Quark-Hadron Mixed Phase Between hadronic phase
  - No uniform QM appears in this model

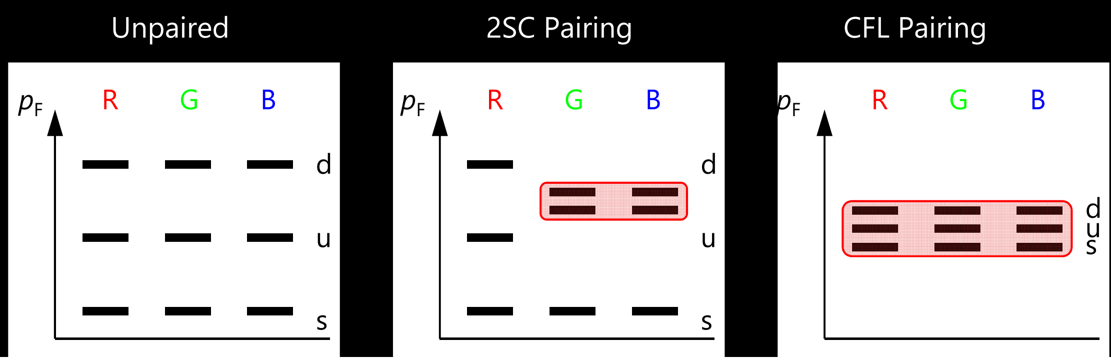


PAIRING OF QUARKS



Rüster et al. (2006)

- CSC quarks paring pattern
  - Due to the degrees of freedom of colour and flavour
- **CFL Phase** (Colour Flavour Locking・High density)
  - All colours & flavours make pairs below the gap
  - **All quarks becomes superconductor → Suppression of neutrino emission**
- **2SC Phase** (Two-Flavour Superconductivity・Low density)
  - **2 colours**, 2 flavours make pairs (e.g. ud-ud, ud&s remain as normal)
  - **Remaining Normal quarks (~1/3)** ->**Strong neutrino emission**



QUARK PHASE

- **Large gap**: $\Delta \geq 10$ MeV
- Once quark phase appears, quarks are in **CSC**.
- Models
  - **CFL**: CSC pairing is CFL, no 2SC phase appears
  - **2SC**: CSC paring is 2SC, no CFL phase appears
- No transition during the cooling

- Quark-Hadron mixed phase
  - Neutrino emissivities are multiplied by the volume fraction of each phase (hadron/quark)

NUCLEON SUPERFLUIDITY

- Superfluidity

  Neutron: $^{1}S_0$, $^{3}P_2$ Proton: $^{1}S_0$

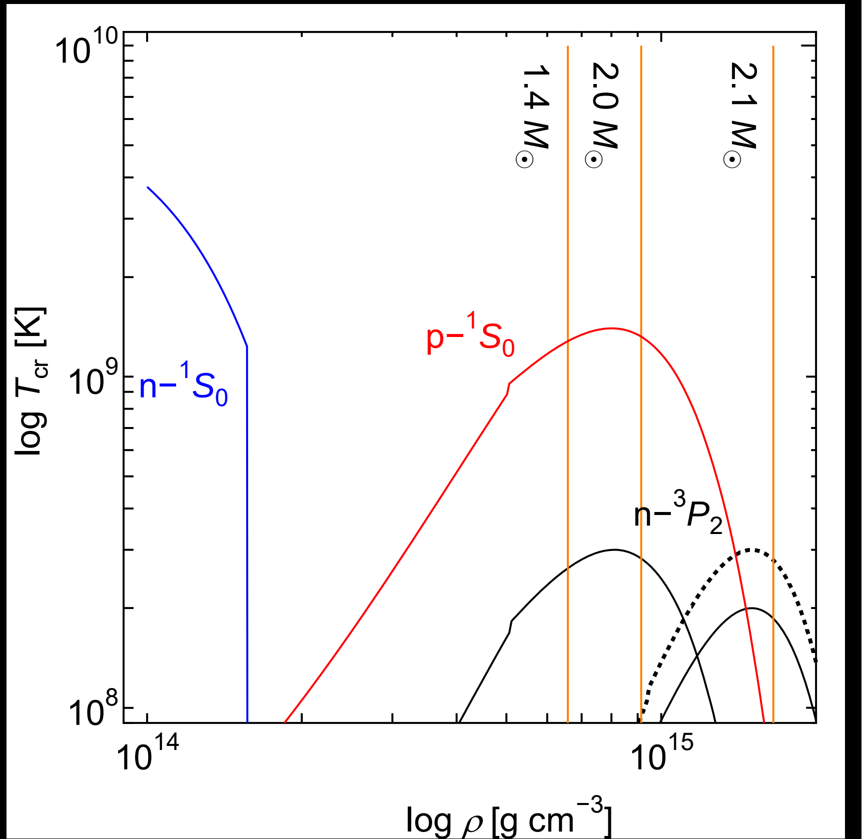
- Critical Temperature(T_{cr})
  - Parameterized density dependence

- Effects on Cooling

  At the transition: **Strong cooling (Pair Breaking and Formation)**

  (Page+ 2004)

  After transition: **Suppress other neutrino emission processes**



Orange lines denote the central densities of each calculation models.

COOLING PROCESSES

Hadronic Phase

Bremsstrahlung	with n/p-super
Modified URCA	with n/p-super
PBF (Superfluid)	
Direct URCA ($y_p > 1/9$)	with n/p-super

Quark Phase

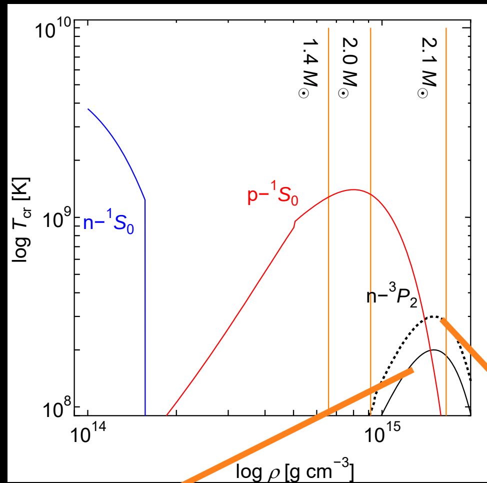
Quark β-decay	with Q-super ($\Delta \geq 10$ MeV)

Works in the high dense region (Q-H Mixed)

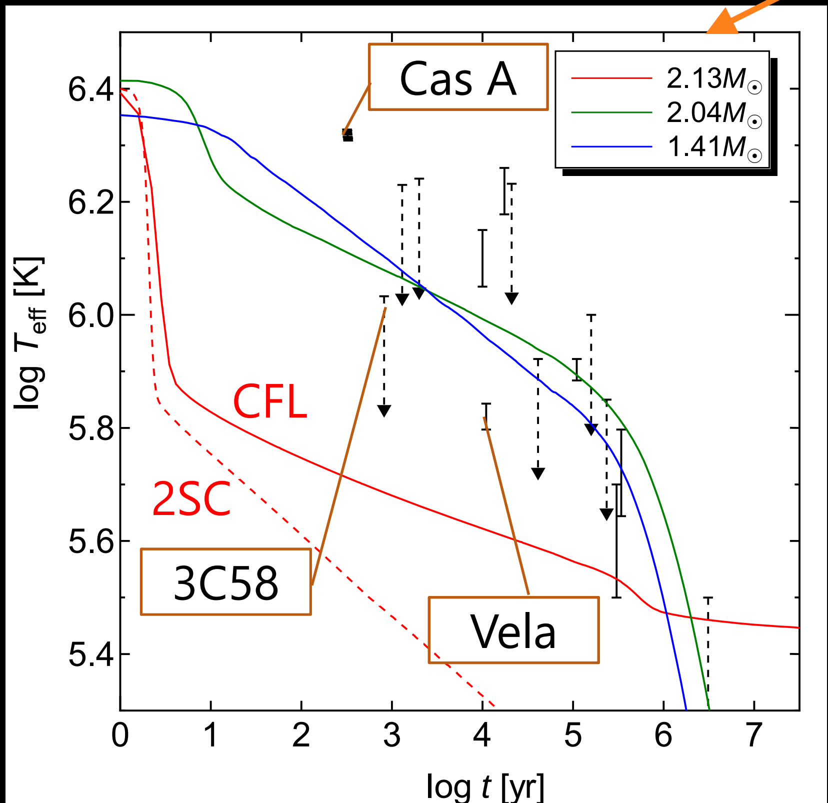
Density

RESULTS & DISCUSSIONS

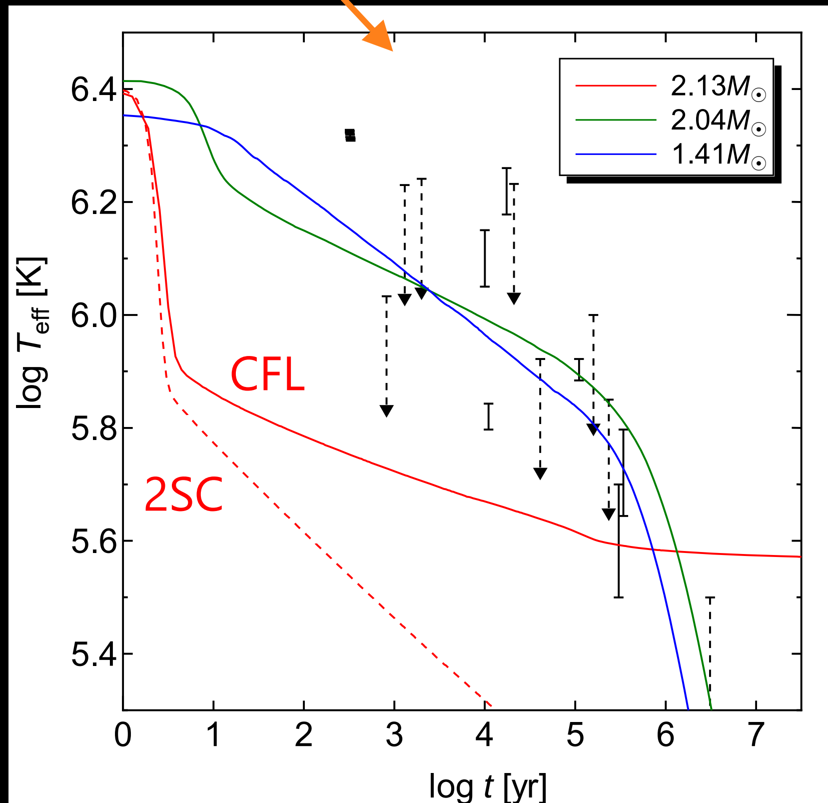
RESULTS-1



1.4 $M_\odot$
2.0 $M_\odot$
2.1 $M_\odot$
p-$^1S_0$
n-$^1S_0$
n-$^3P_2$
log T_{cr} [K]
log ρ [g cm^{-3}]

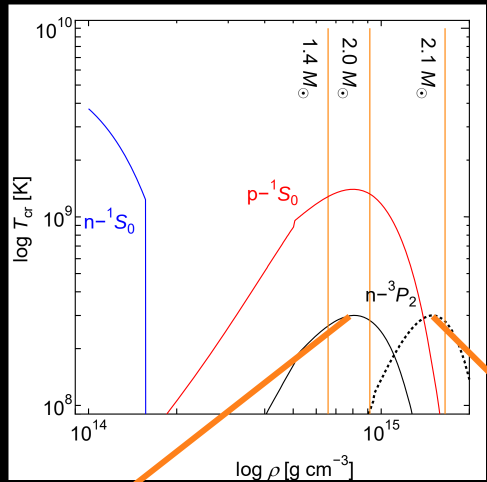


Cas A
3C58
Vela
CFL
2SC
2.13$M_\odot$
2.04$M_\odot$
1.41$M_\odot$
log T_{eff} [K]
log t [yr]

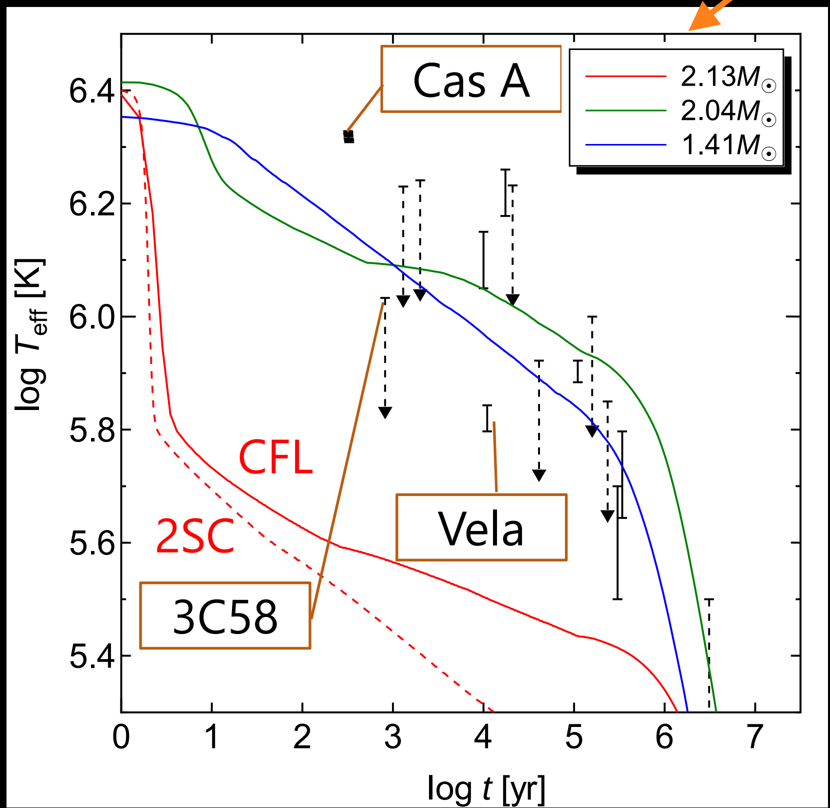


CFL
2SC
2.13$M_\odot$
2.04$M_\odot$
1.41$M_\odot$
log T_{eff} [K]
log t [yr]

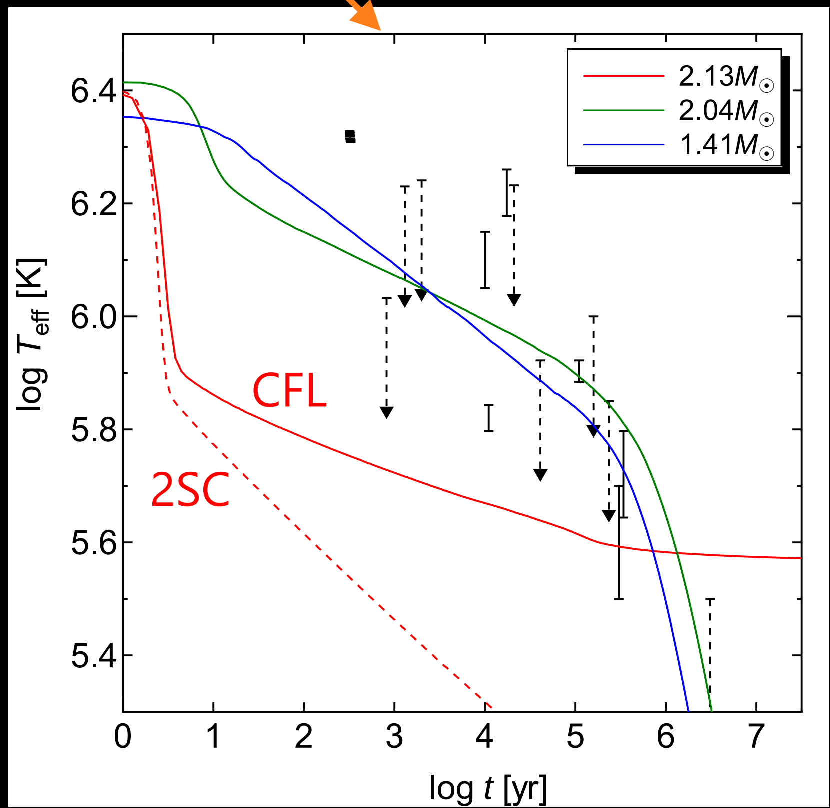
RESULTS-2



10^{10}
10^{9}
10^{8}
log T_{cr} [K]
1.4 $M_\odot$
2.0 $M_\odot$
2.1 $M_\odot$
n−$^1S_0$
p−$^1S_0$
n−$^3P_2$
10^{14}
10^{15}
log ρ [g cm^{-3}]



Cas A
2.13$M_\odot$
2.04$M_\odot$
1.41$M_\odot$
CFL
2SC
Vela
3C58
log T_{eff} [K]
6.4
6.2
6.0
5.8
5.6
5.4
0
1
2
3
4
5
6
7
log t [yr]



2.13$M_\odot$
2.04$M_\odot$
1.41$M_\odot$
CFL
2SC
log T_{eff} [K]
6.4
6.2
6.0
5.8
5.6
5.4
0
1
2
3
4
5
6
7
log t [yr]

SUMMARY

We examined cooling of compact stars with quark colour superconductivity

Difference of Quark paring affects the cooling profiles of compact stars

- **Heavy star with 2SC**
  - **Very fast cooling**, dropping the temperature below observations
  - Neutron $^3P_2$ superfluidity does **NOT** affect to the cooling profile
  - Dominant cooling process: **Quark β-decay**
- **Heavy star with CFL**
  - **Fast cooling but slower than 2SC**
  - Cooling curves are affected by **neutron $^3P_2$ superfluidity**
  - Dominant cooling process: **Hadronic Direct URCA**

- Cold stars can be explained by two way
  - With 2SC phase: Cooled by **Quark β-decay**
  - With CFL phase: Cooled by **Direct URCA with neutron superfluidity**

FUTURE PROSPECTS

- Tuning of surface composition & neutron superfluidity
  - To fit Cas A or other warm stars
- Other exotic states, CSC paring
  - Hyperon-mixed, Meson-condensation
  - 2SC+X colour superconductivity (Grigorian+ 2005, Fujimoto+ 2019)
  - FFLO superfluidity
- Direct URCA problem
  - EoS with small symmetry energy *S* does not allow Direct URCA (Togashi+ 2017, Dohi+ 2019)
- Further Observation
  - GW signals from binaries of double NS / BH-NS
  - Temperature of young & isolated neutron stars (SN1987A??)