Nucleosynthesis and Evolution of Neutron Stars @YITP, Kyoto
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Compact star cooling with quark-hadron continuity

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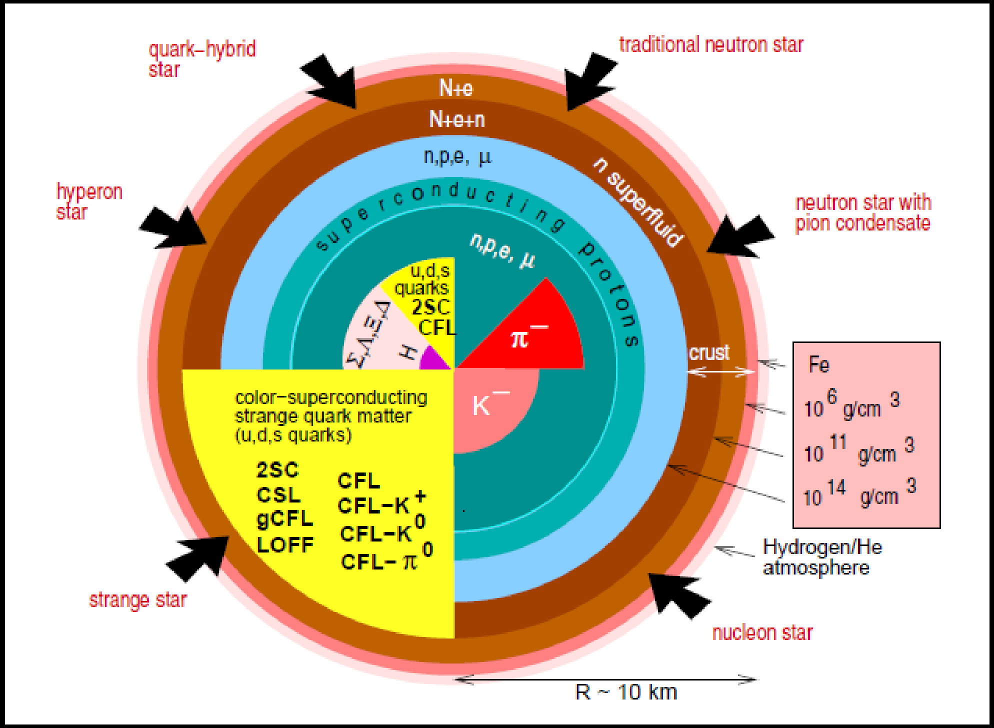
Introduction - Neutron Star Interior

- Interior of NS is **higher density than Nuclear Density**
  - Deconfinement of Quarks
  - Hyperon Mixing
  - Meson Condensation
  - Nucleon Superfluidity

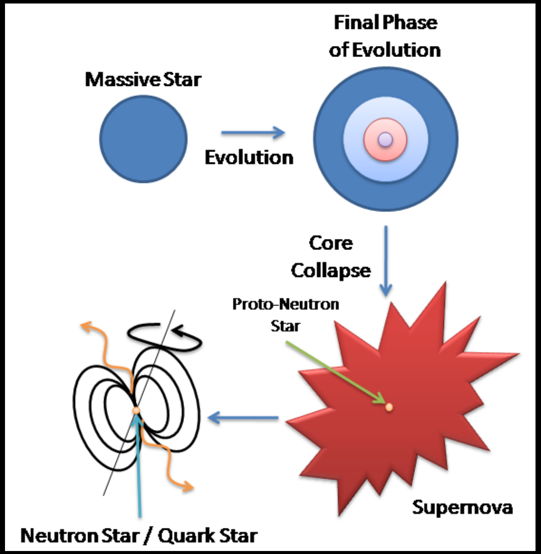
- Observations
  - M-R Relation ・Temperature
- Other Simulations
  - Stellar Evolution ・Supernova



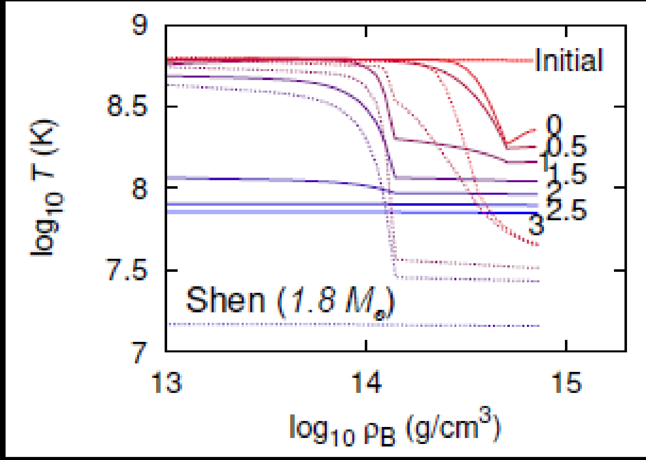
F. Weber, Prog. Part. Nucl. Phys. 54, 193 (2005)

Introduction - Thermal History of Neutron Stars

- NSs are born during supernovae explosions
  - Very high temperature at beginning (~10^{10} K)
- Isolated NSs has **no heat source inside of stars**
  - Thermal energy released by neutrinos.
  - NSs just cool down
    - $t < 10^5$ yr: Neutrino Emission
    - $t > 10^5$ yr: Photon Emission (X-ray)



1. Core cools down. Outside remains quite warm.
2. After the isothermal (~100yr) → Surface temperature starts to drop down.
3. Photon emission overtakes the neutrino emission.



Dohi et al. PTEP 2019, 113E01 (2019)

Introduction - Cooling of Neutron Stars

Cooling processes strongly depends on the Internal State of NSs.

- **Normal nuclear matter**
- π condensation
- K condensation
- **Quark matter**
- **Superfluidity**

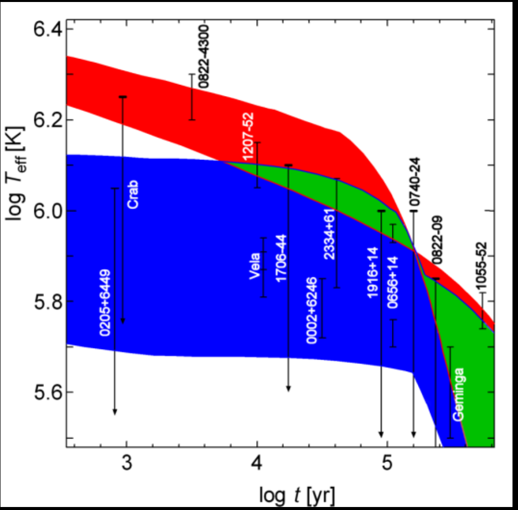
  etc…

→ **Neutrino Emission**

Exotic phase appears at high density region, and **cools down entire star**

Central density exceeds the threshold density = Heavy Stars

(TN+ 2006)



Comparing observations of isolated NSs and cooling simulations

⇒ Restrictions on high-density conditions

Cooling calculation with quark matter: Quark Hadron Continuity

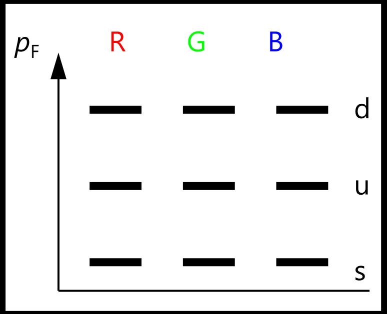
Introduction - Neutrino Cooling

- **Dominant cooling process at early stage** (t < 10^5 yr)
  - **Slow cooling processes** (~10^{19} erg cm^{-3} s^{-1})
    - Modified URCA, Bremsstrahlung
    - Occurring in ALL NSs, Not requiring any EXOTIC phases / particles
  - **Fast cooling processes** (~10^{25} erg cm^{-3} s^{-1})
    - Direct URCA, Meson condensation, Hyperon mixing, Quark β-decay
    - Conditions for appearance (Densities / Proton fraction / Particles)
    - Too strong for observed NSs, Requiring superfluid suppression to match observations
  - **Superfluidity** (Hadron) / **Superconductivity** (Quark)
    - Suppresses involving neutrino emission process
    - Emitting neutrinos at the transition (PBF)

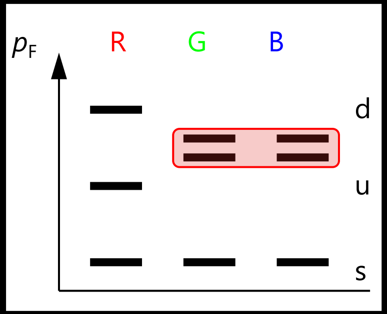
Quark Cooling

- Quark Matter at High-density region
  - **Normal quarks: Strong neutrino emission by Quark β-decay**
  - **Colour Superconductivity (CSC): Strongly Suppression of the neutrino emission**
- CSC
  - CFL phase: All colours / flavours make pairs, Appears at ultrahigh density
    Strong ν emission is suppressed
  - 2SC phase: Two of colours / flavours make pairs, Appears at lower density than CFL
    1/3 of unpaired quarks remains as normal → Strong ν emission

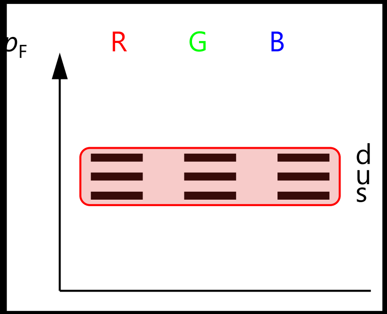
Unpaired

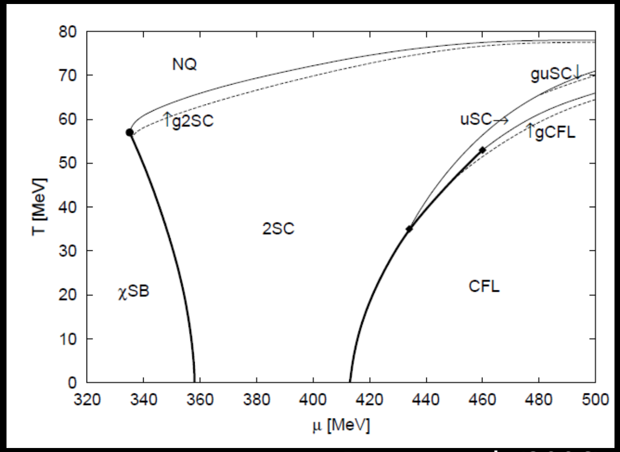


2SC Pairing



CFL Pairing





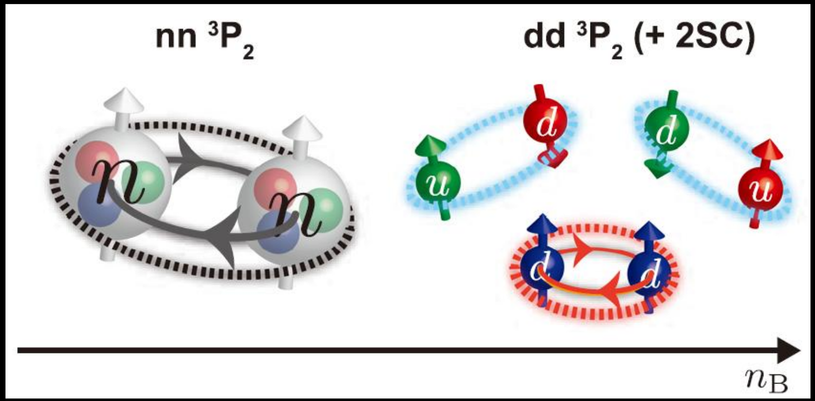
Rüster et al. (2006)

Quark-Hadron Continuity

Once 2SC phase appears in the core of NS, the entire star cools drastically.

Considering continuous transition of Neutron $^3P_2$ → Quark $^3P_2$+2SC
(Fujimoto+ PRD 101, 094009, (2020))

- Neutron $^3P_2$ is carried over by unpaired d-quarks in 2SC phase

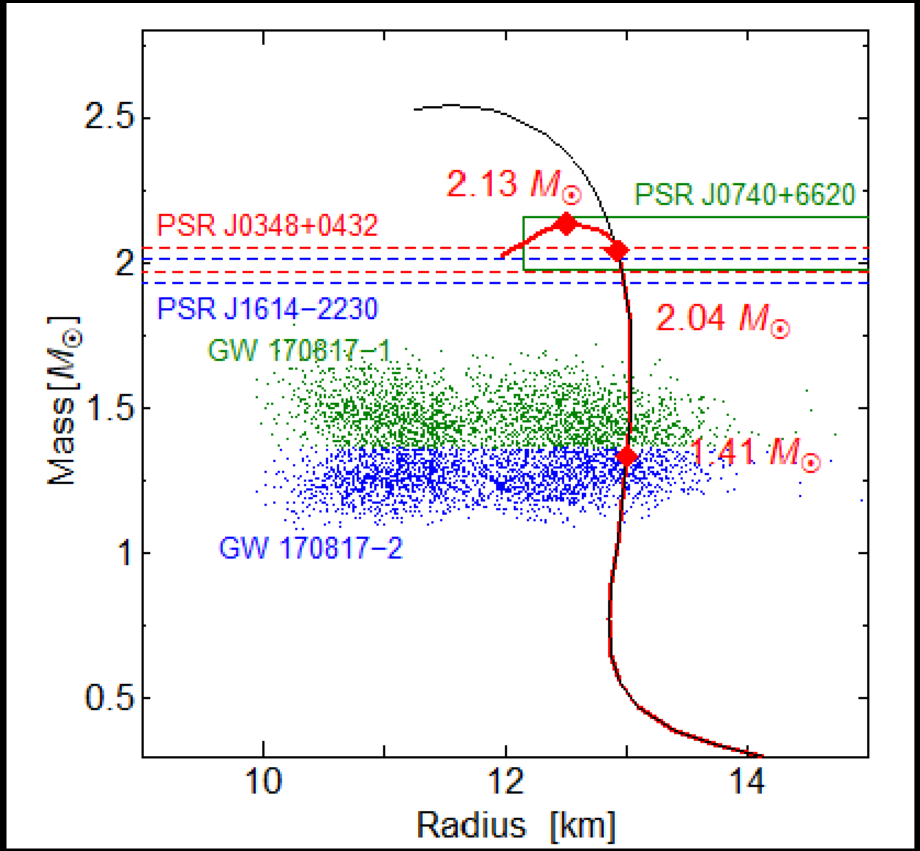


- **All quarks make pairs.**
- **Strong quark cooling in 2SC suppressed.(2SC+<dd>)**

- We demonstrate the effect of 2SC+<dd> pairing on the NSs cooling.

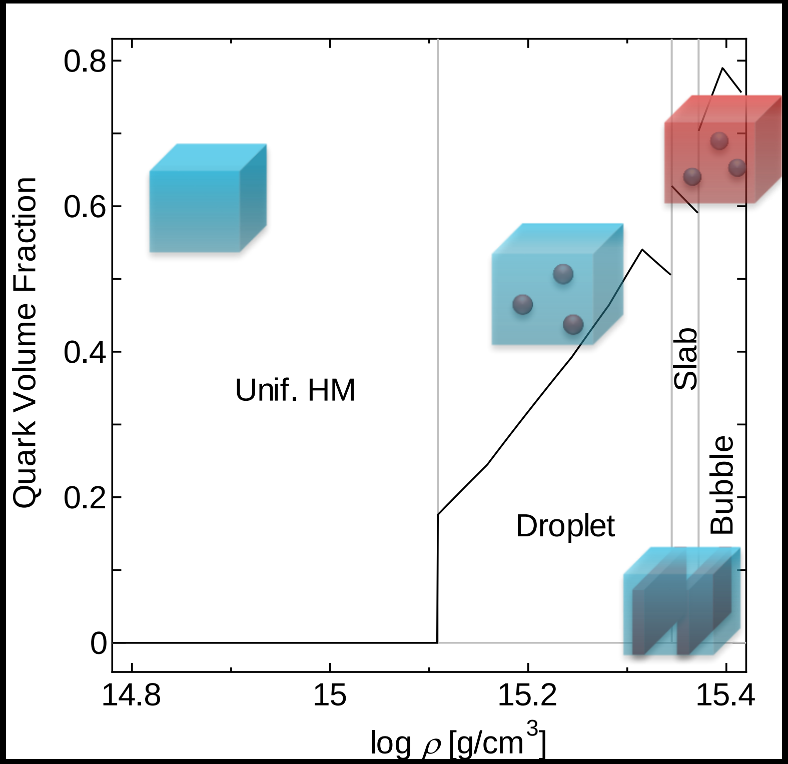
Calculation Setup - Models

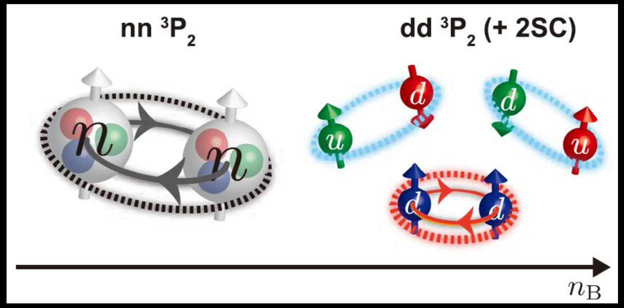
- Quark-Hadron EoS which reaches $2M_{\odot}$
  - Brueckner-Hartree-Fock (HM) + Dyson-Schwinger (QM)
  - Mixed-phase between HM and QM (Yasutake+ 2016)
    - – Mixed-phase at the maximum mass
- Cooling Processes
  - Modified URCA + Bremsstrahlung
  - n-Super($^1S_0$, $^3P_2$), p-Super($^1S_0$)
  - **Direct URCA (y_p>1/9)**
  - **Quark Cooling** with Colour Superconductivity (CSC)
- Parameters
  - **Mass**
  - **Density Dependence of n, d- $^3P_2$ Superfluid Critical Temp.**
  - **Pairing of CSC** (CFL / 2SC / 2SC+<dd>)
  - Surface Composition (^{56}Fe, ^{4}He)



Calculation Setup - Quarks

- Quark Matter at High-dense region
  - Quark-Hadron transition: 1st order transition with mixed phase
- CSC
  - CFL phase: ν emission strongly suppressed
  - 2SC phase: ν emission suppressed by 1/3
  - 2SC+<dd> phase: 2SC cooling suppressed as neutron's $^3P_2$
- Assumption
  - **Critical temperature of Neutron $^3P_2$ is carried by d-quark's $^3P_2$**
  - Δ of 2SC/CFL: Few tens of MeV
  - No strange quarks



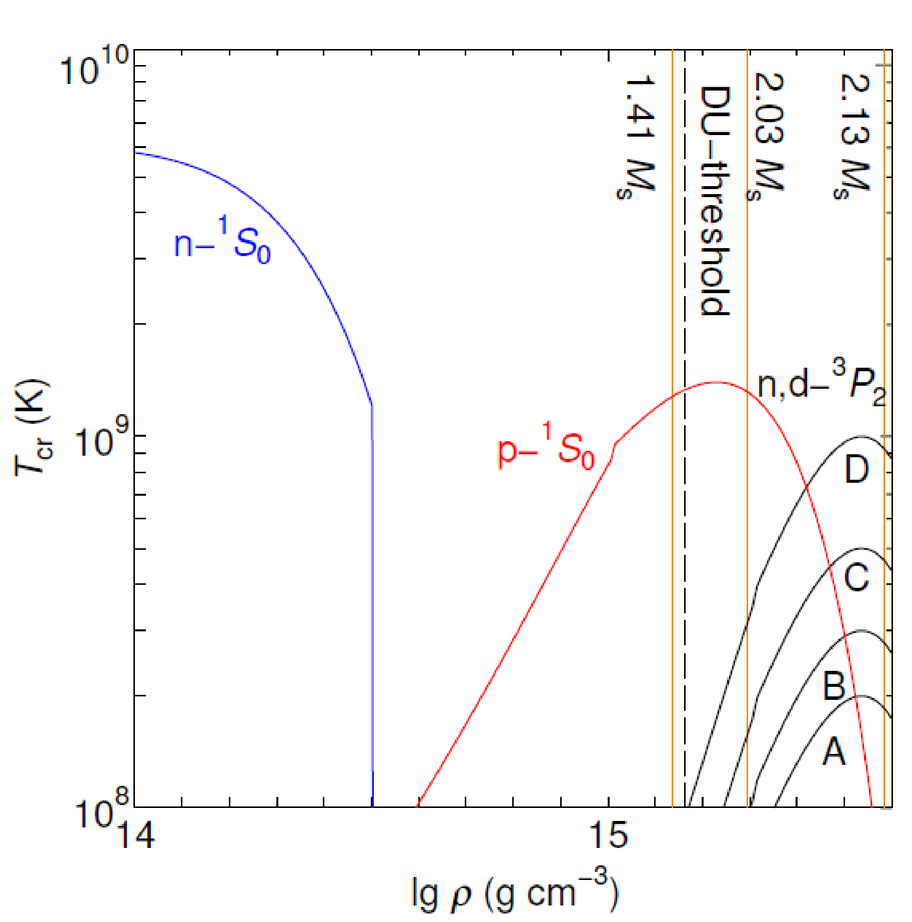


Calculation Setup - Nucleon Superfluidity

- Superfluidity of n and p
  Neutron: $^1S_0$, $^3P_2$ Proton: $^1S_0$
- Critical Temperature (T_{cr})
  - Functionalizing the temperature dependence

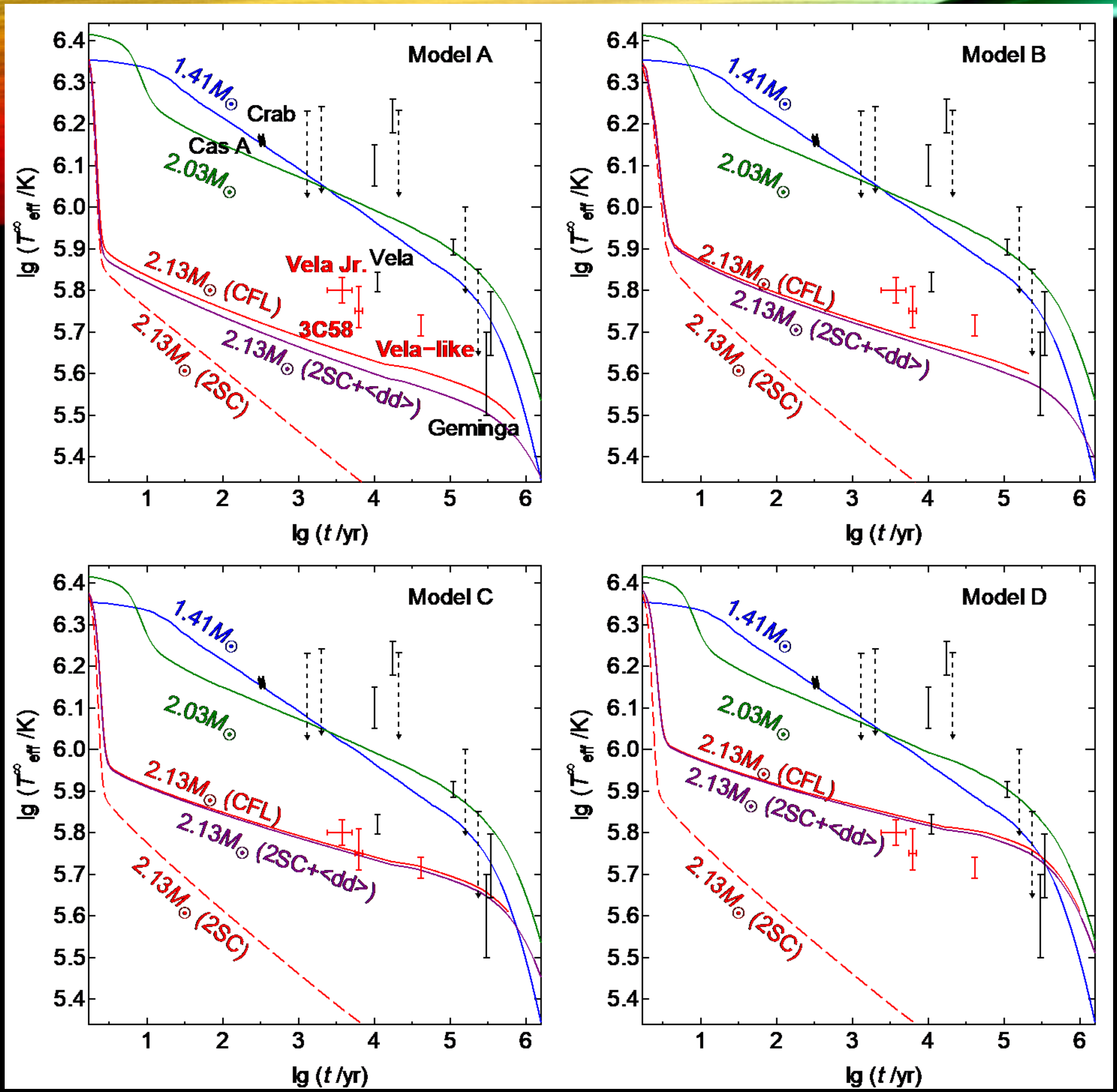
  Effects on Cooling
  Transiting to super: **Strong cooling (PBF)**
  (Page+ 2004)
  After the transition: **Suppression of other ν emission**

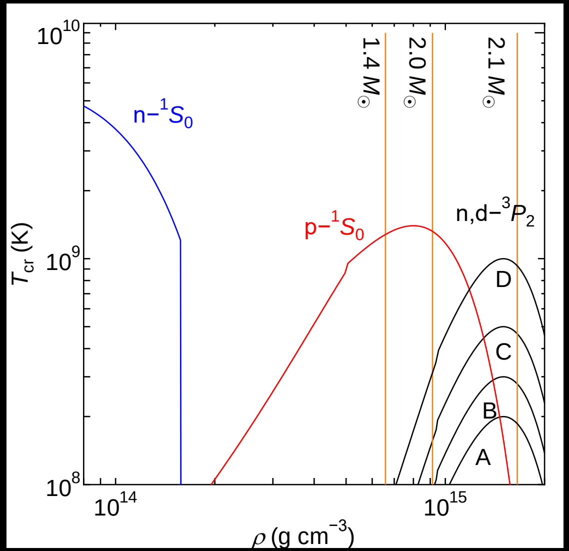
- T_{cr} of n- $^3P_2$ is connected to 2SC+<dd>
- Varying n, d- $^3P_2$ model and calculating



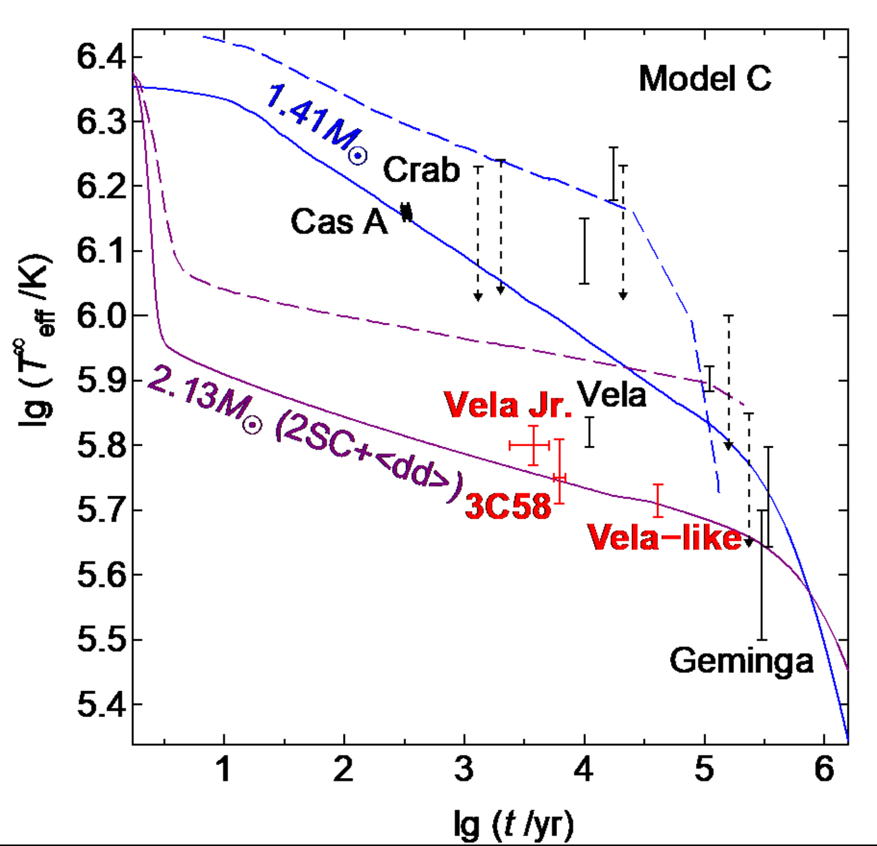
Results 1

- Superfluid model change the cooling curve tendency
- Cooling curves are changed by the CSC paring and n/d- $^3P_2$ superfluidity





Results 2



- Considering light element envelopes
  - ~10^{-9} $M_{\odot}$
  - ^{4}He (Dashed line)
  - Models are 1.41 $M_{\odot}$ and 2.13 $M_{\odot}$.
- Lines cover higher region $t<10^5$ yr than ^{56}Fe
  - **Good for warmer stars**
  - 2SC+<dd> line (Model C) matches with Vela, 3C58 & Vela-like pulsars.

Summary

We simulated compact star cooling with colour superconducting quark matter.

- Too strong cooling with 2SC → NS becomes too cold ✗
  - Appearing density ✓
- Mild cooling with CFL (Depends on n- $^3P_2$ critical temperature) → Good for cold NSs ✓
  - Appearing density is much higher ✗
- **Mild cooling (similar CFL) with 2SC+<dd>** (Depends on n, d $^3P_2$ critical temperature) → **Good for colds NSs** ✓
  - Appearing density ✓

- If quark core appears in NS, 2SC+<dd> is suitable for the CSC paring.
- (Future) Unified treatment of quark matter (i.e. Crossover)