Cooling of the Cassiopeia A neutron star and superfluid implications

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Ho et al, Monthly Notices of the Royal Astronomical Society, 506, 5015 (2021)
Shternin et al, Monthly Notices of the Royal Astronomical Society, 506, 709 (2021)

N3AS seminar – 2022 January 25

Outline

- Observations of cooling of the neutron star in Cassiopeia A (Cas A)

- Introduction to neutron star cooling theory
  - superfluidity and superconductivity
  - application to Cassiopeia A

- Summary

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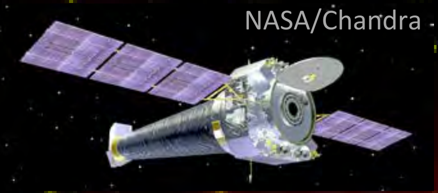
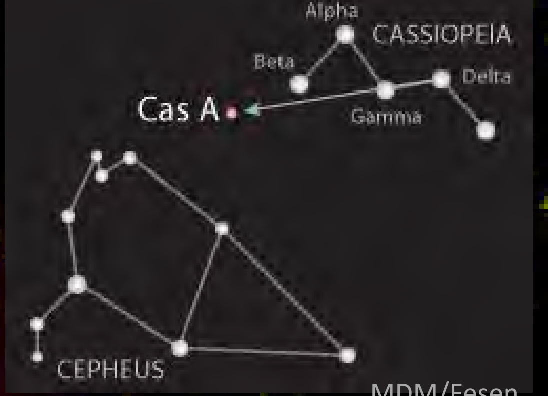
Cassiopeia A supernova remnant and neutron star

NASA/Chandra





MDM/Fesen

Chandra graded

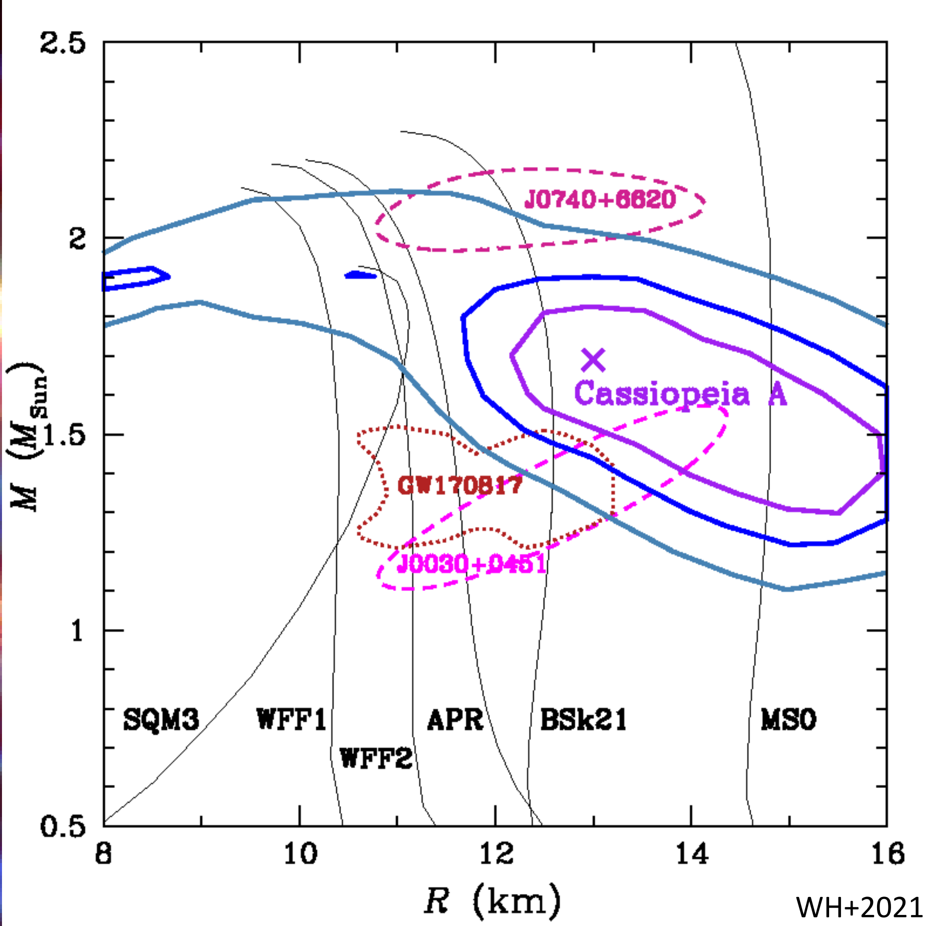
- 2000 Jan
- 2002 Feb
- 2004 Feb
- 2007 Dec
- 2009 Nov
- 2010 Nov

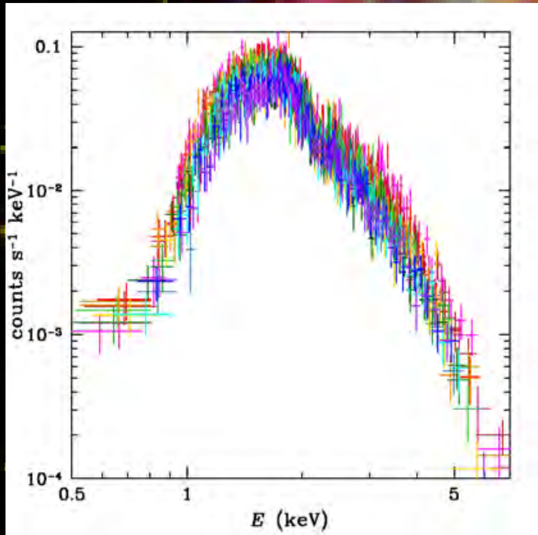
- ≈1681: supernova (age ≈ **340 yr**; Fesen+2006)
- 1999: **non-pulsed** X-ray source discovered in *Chandra* first light (Tananbaum)
- 2009: identified as neutron star, **youngest** known (WH+Heinke)
- 2010: **rapid cooling** measured (Heinke+WH)
- 2011: rapid cooling due to **superfluid-superconductor** (Shternin,WH+; Page,Prakash,Lattimer,Steiner)

Mass and radius of Cassiopeia A neutron star

Chandra graded

- 2000 Jan
- 2002 Feb
- 2004 Feb
- 2007 Dec
- 2009 Nov
- 2010 Nov
- 2012 May
- 2013 May
- 2014 May
- 2015 Apr
- 2016 Oct
- 2017 May
- 2018 May
- 2019 May





Fit X-ray spectra with model spectrum:

- interstellar absorption N_H
- neutron star atmosphere *T*, *d*, *M*, *R*

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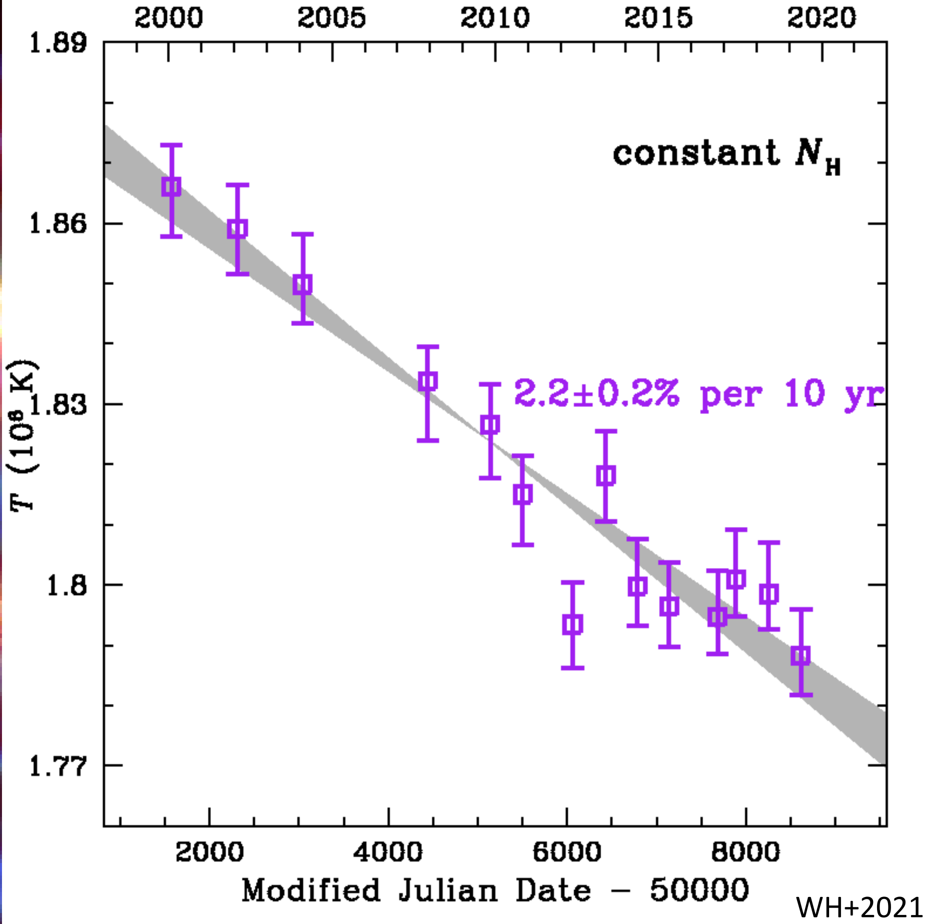

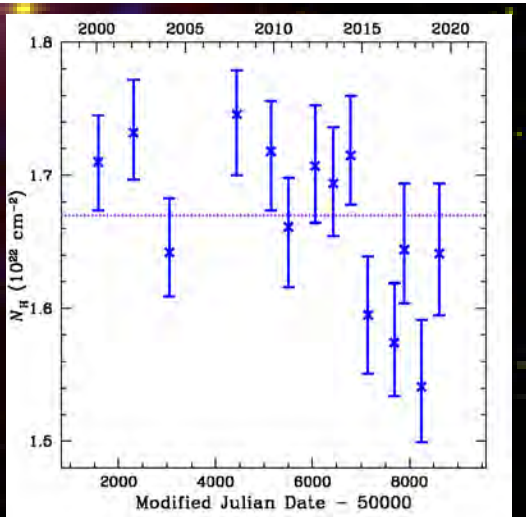

- 14 T_s over 19 years: cooling rate **2.2 ± 0.2%** or 2.8 ± 0.3% per decade
- interstellar absorption **N_H = constant**
- neutron star atmosphere *T*, *d*, *M*, *R*

Cooling of Cassiopeia A neutron star

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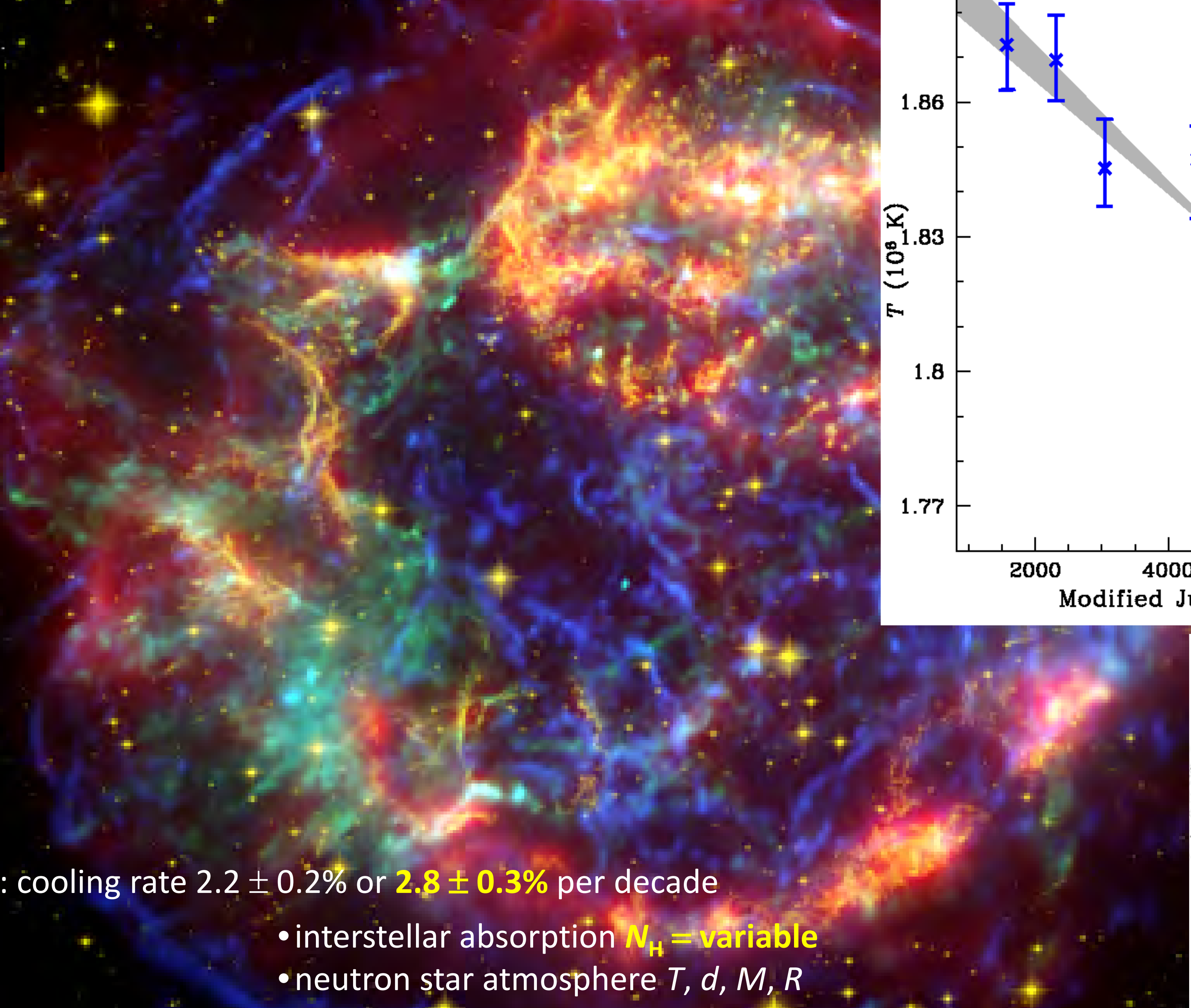
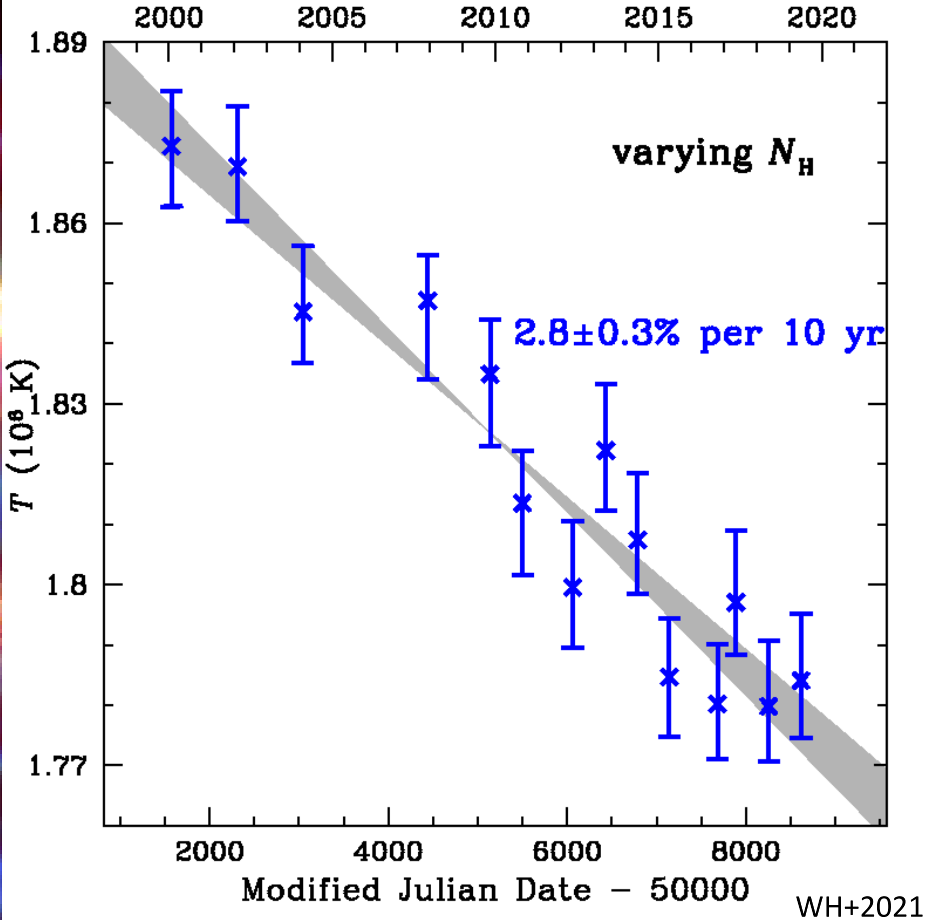
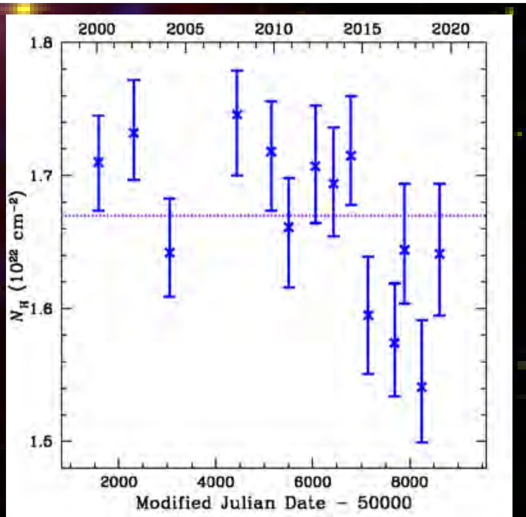


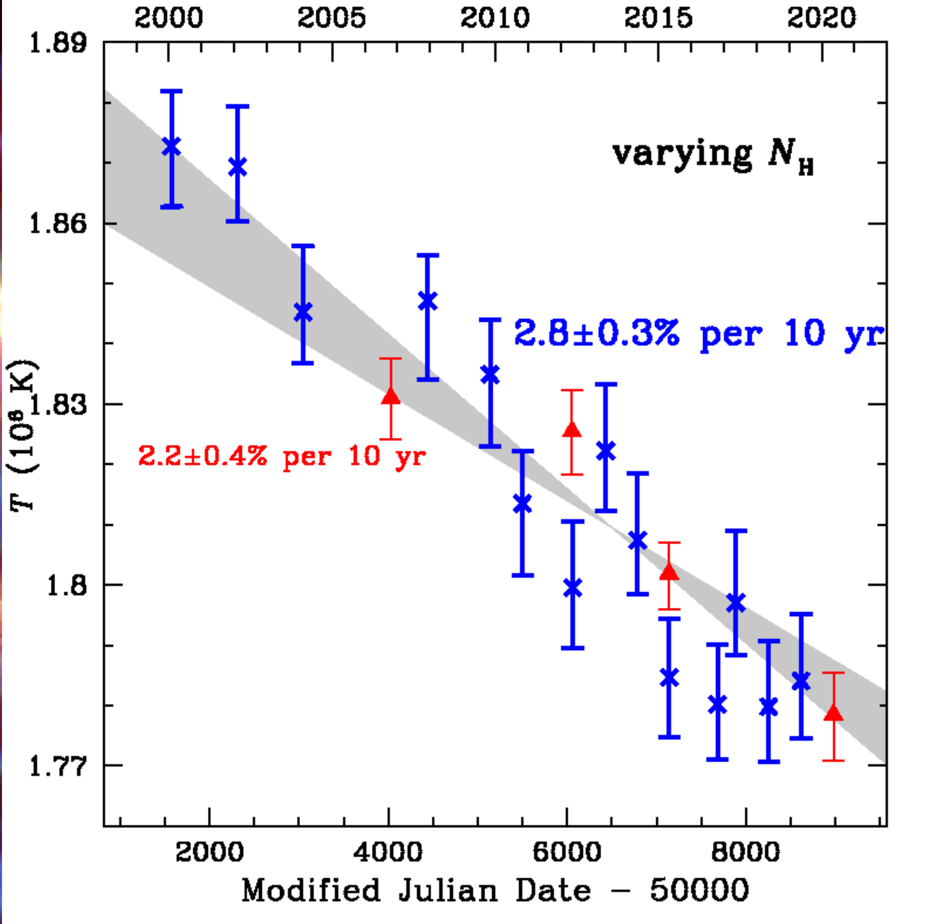


WH+2021



- 14 T_s over 19 years: cooling rate 2.2 ± 0.2% or **2.8 ± 0.3%** per decade
  - interstellar absorption **N_H = variable**
  - neutron star atmosphere *T*, *d*, *M*, *R*

Cooling of Cassiopeia A neutron star



Chandra graded

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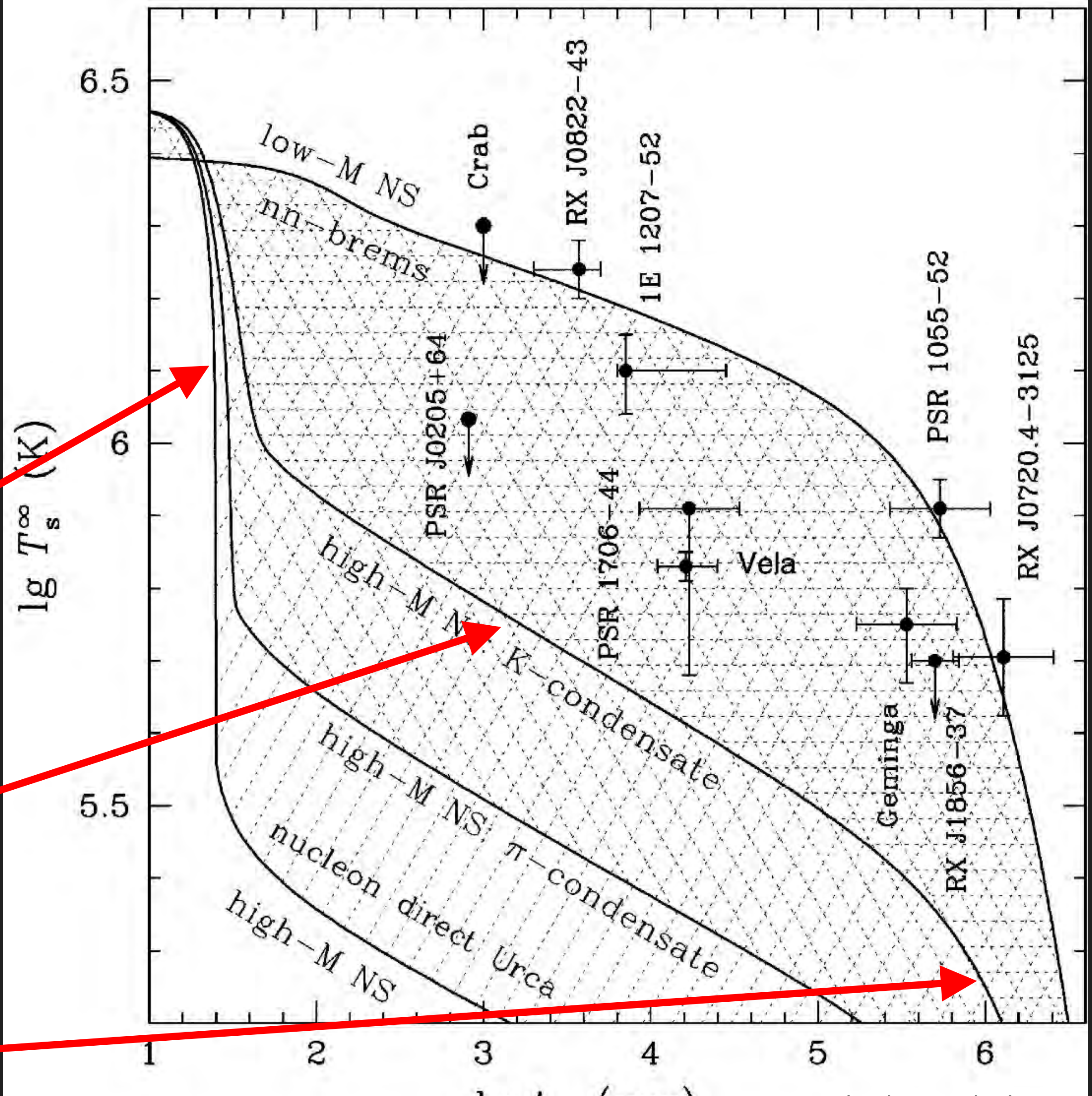
Chandra subarray

- 2006 Oct
- 2012 May
- 2015 Apr
- 2020 May

- 14 T_s over 19 years: cooling rate $2.2 \pm 0.2\%$ or **$2.8 \pm 0.3\%$** per decade
- 3 T_s over 9 years: $< 2.4\%$ or $< 3.3\%$ [Posselt+Pavlov 2018]
- 4 T_s over 14 years: $1.2 \pm 0.3\%$ or $2.2 \pm 0.4\%$

Introduction to neutron star cooling theory

- Microphysics of neutron star cooling
  - heat capacity C
  - thermal conductivity K
  - (neutrino) emissivity ε_ν
- Effects on microphysics
  - proton fraction
  - particle species
  - superfluidity and superconductivity [eg WH+2015; Beloin,Han+2017,2018]
- Stages of thermal evolution
  1) relaxation to isothermal interior
     $t_{relax} \sim (C / K)\, L^2 \sim 10 - 100$ yr
  2) early cooling when hot by neutrinos
     $dT/dt \approx -\varepsilon_\nu / C$
  3) after 10^5–10^6 yr, photon cooling



Yakovlev+Pethick 2004

Superfluidity and superconductivity in neutron stars

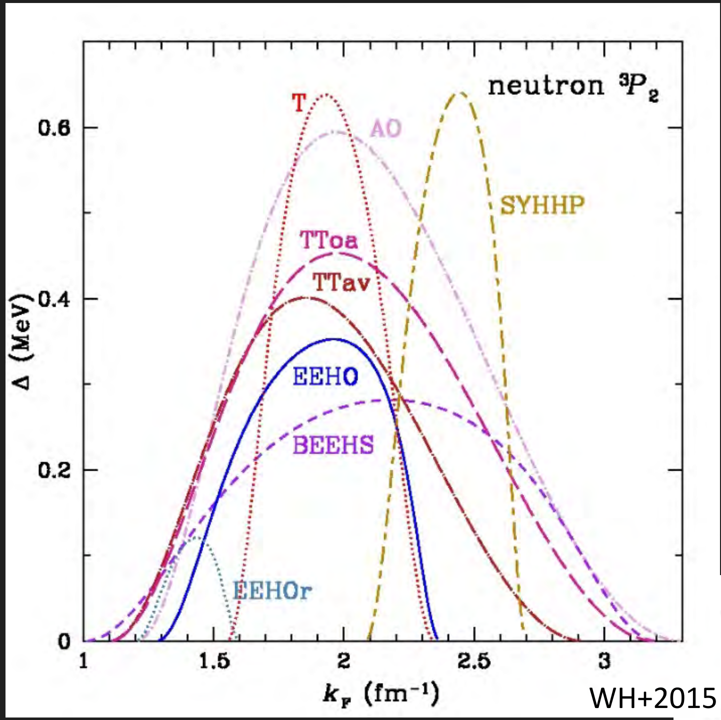
- Matter becomes sf/sc (Cooper paired) when $T < T_c(\Delta)$
  [eg works by Carlson, Gandolfi, Gezerlis, Reddy]

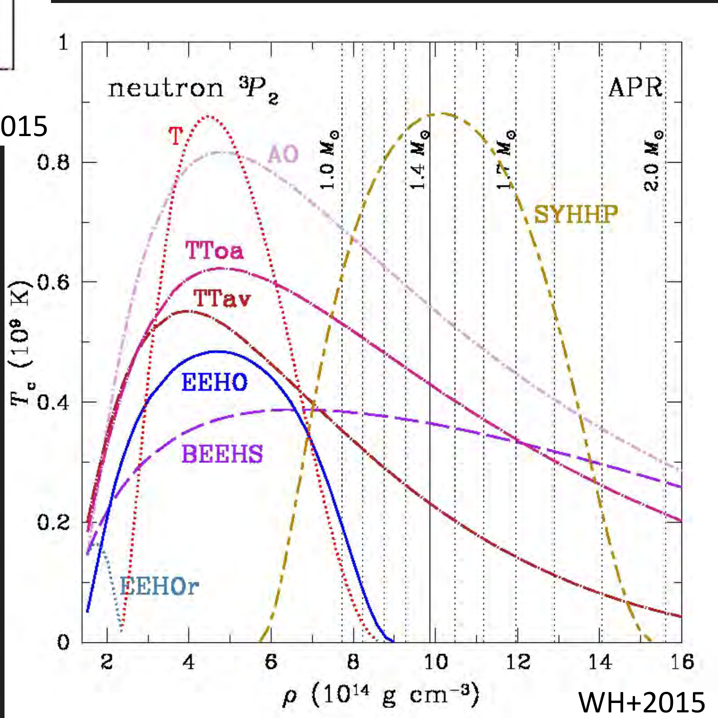
- Pairing energy $\Delta(k_F)$ where $k_F \propto n^{1/3}$
  from nuclear theory

- 3 pairing types in neutron stars:
  - o core – proton singlet $^1S_0$
  - o core – neutron triplet $^3P_2$-$^3F_2$
  - o inner crust-core – neutron singlet $^1S_0$

- Cooling effects of superfluid/superconductor:
  1) suppress (sf/sc) nucleon processes
  2) extra neutrino emission channel CPF, $n+n\rightarrow\nu+\underline{\nu}$

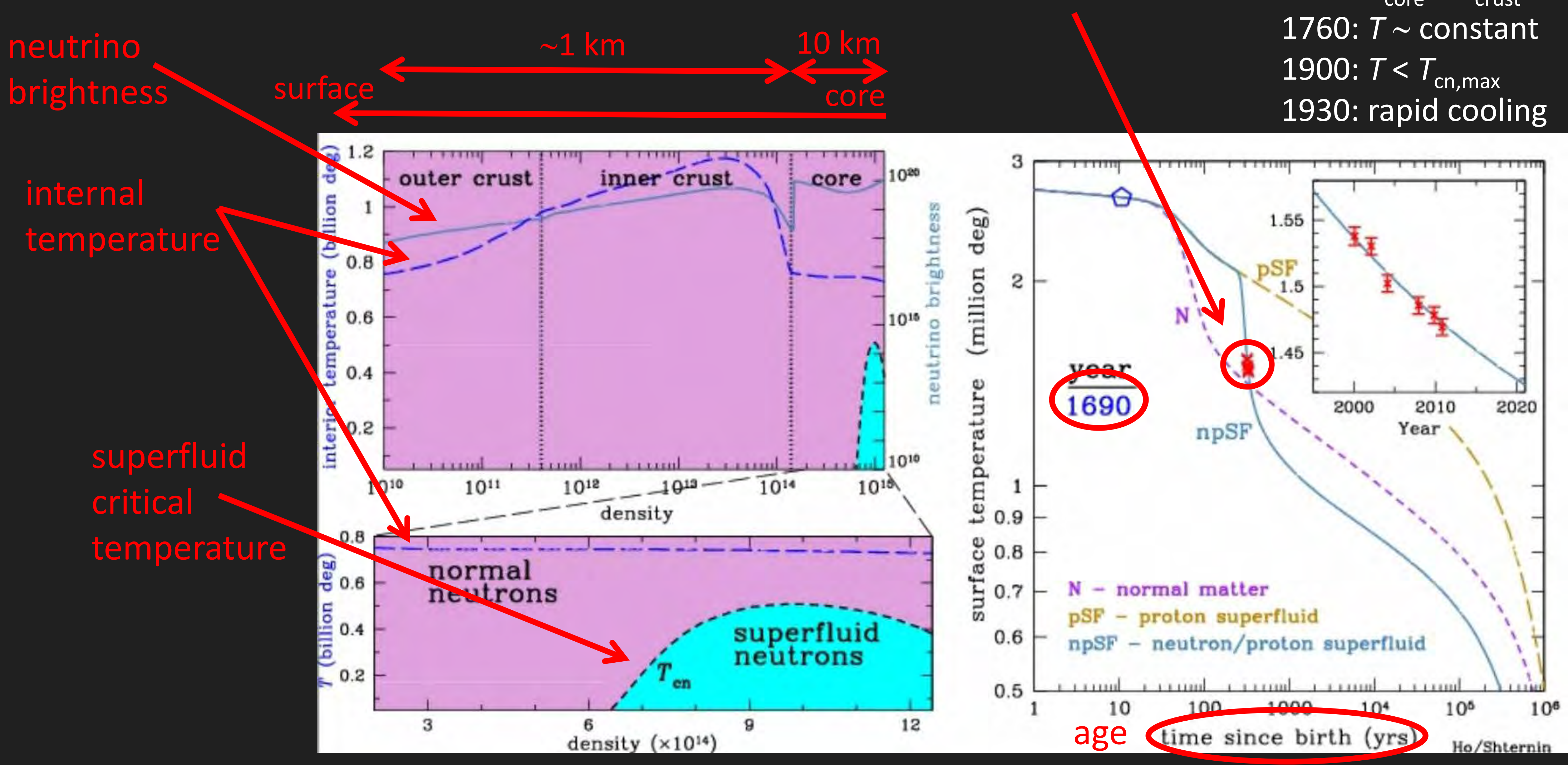
  - o proton singlet in core – slower cooling (1)
  - o neutron triplet in core – faster cooling (2)
  - o neutron singlet in crust – faster cooling (2)





Cassiopeia A on superfluidity and superconductivity

Milestones:
1680: supernova
1690: $T_{core} < T_{crust}$
1760: $T \sim$ constant
1900: $T < T_{cn,max}$
1930: rapid cooling



Cassiopeia A on superfluidity and superconductivity

Milestones:
1680: supernova
1690: $T_{core} < T_{crust}$
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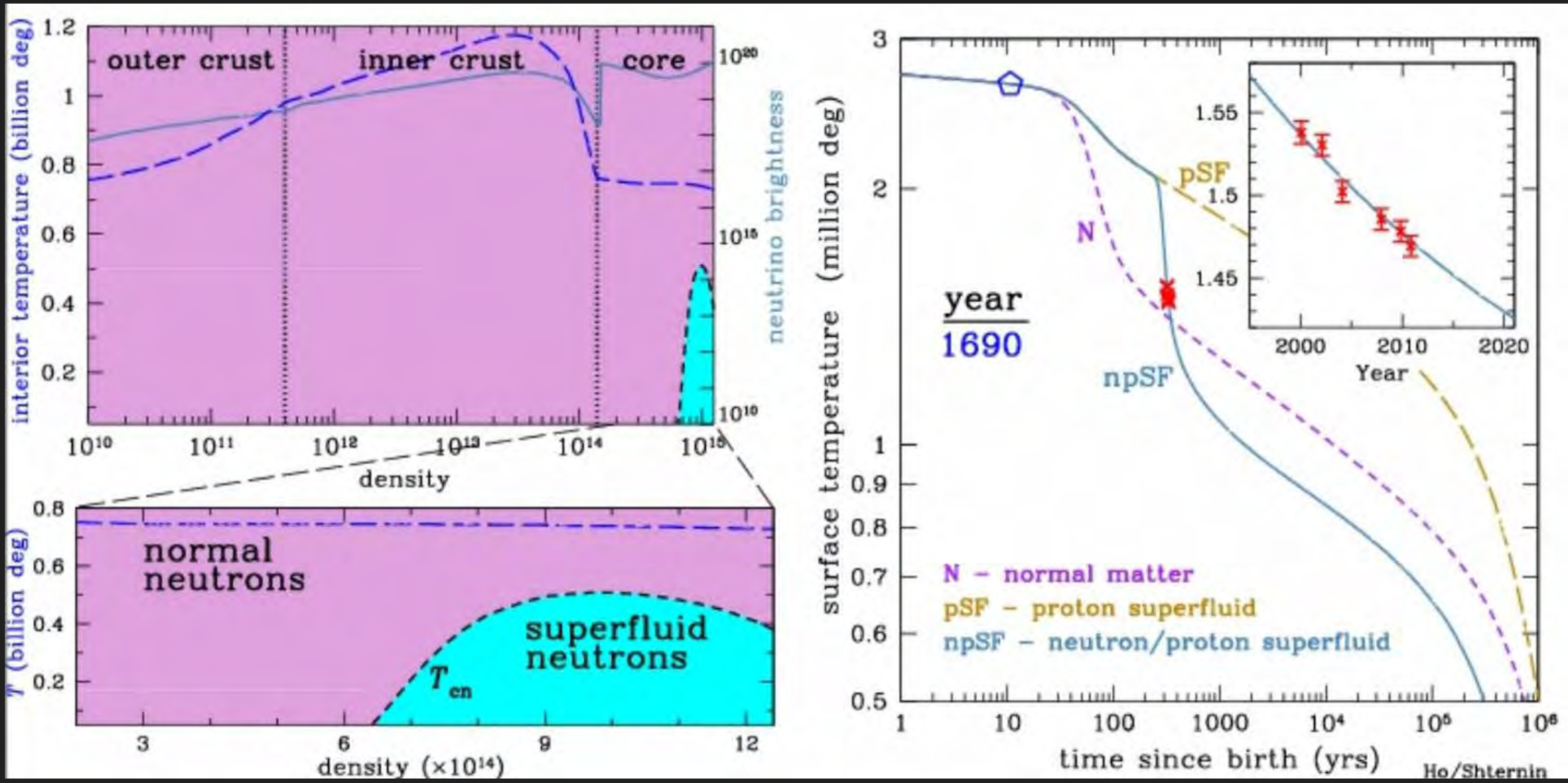
1930: rapid cooling

~1 km
10 km
surface
core



- Effects of superfluid/superconductor:
  1) suppress (sf/sc) nucleon processes
  2) extra neutrino emission channel
  [see Shternin,WH+2021 for new constraints]

  - proton singlet in core – slower
  - neutron triplet in core – faster
  - neutron singlet in crust – faster

Summary

- Comparison of **cooling theory with observations** reveals nuclear/particle physics
  - o Cassiopeia A cooling at ≈ **2–3% per decade**
  - o insights into superfluidity and superconductivity

- Gravitational wave searches of Cassiopeia A
  [eg Papa+2020;Abbott+2021]

- **Go beyond neutron star mass–radius**