Cooling of the Cassiopeia A neutron star and the effect of diffusive nuclear burning

Wynn C.G. Ho
Haverford College, USA and University of Southampton, UK

Marcella J.P. Wijngaarden
University of Southampton, UK

Philip Chang
University of Wisconsin-Milwaukee, USA
Craig O. Heinke
University of Alberta, Canada
Dany Page, Mikhail Beznogov
Universidad Nacional Autonoma de Mexico, Mexico
Daniel J. Patnaude
Smithsonian Astrophysical Observatory, USA

HAVERFORD COLLEGE

Wijngaarden et al, MNRAS, in press (arXiv:1901.01012)

UNIVERSITY OF Southampton

Xiamen-CUSTIPEN Workshop, Xiamen – 3–7 January 2019

Outline

- Introduction to neutron star cooling theory
  - superfluidity and superconductivity
  - envelope composition and T_s–T_b
- Diffusive nuclear burning (DNB)
  - envelope and atmosphere evolution
- Observations of cooling of neutron star in Cassiopeia A
- Summary

HAVERFORD COLLEGE

UNIVERSITY OF Southampton

Introduction to cooling theory

- Stages of thermal evolution
  1) relaxation to isothermal interior

     $t_{relax} \sim (C / K)\, L^2 \sim 10 - 100$ yr

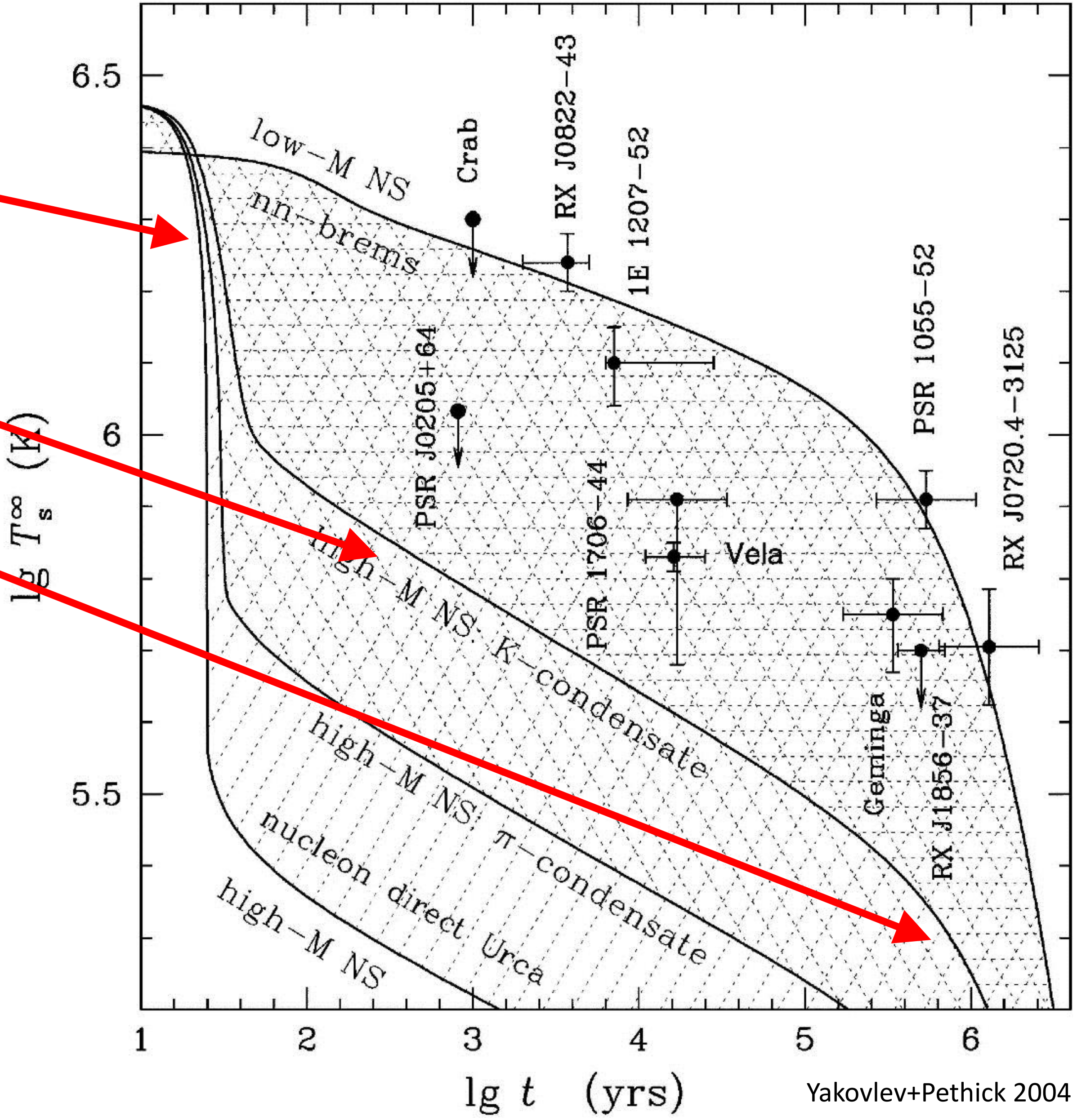
  2) early cooling by neutrinos

     $dT/dt \approx -\varepsilon_\nu / C$

  3) after 10^5–10^6 yr, photon cooling

- Microphysics
  - neutrino emissivity ε_ν
  - heat capacity C
  - thermal conductivity K

- Other effects
  - superfluid/superconductor
  - envelope composition $K \propto Z^{-1}$ and T_s–T_b
  - magnetic field



Yakovlev+Pethick 2004

Effect of envelope composition

- Stages of thermal evolution
  1) relaxation to isothermal interior

     $t_{relax} \sim (C / K)\, L^2 \sim 10 - 100$ yr

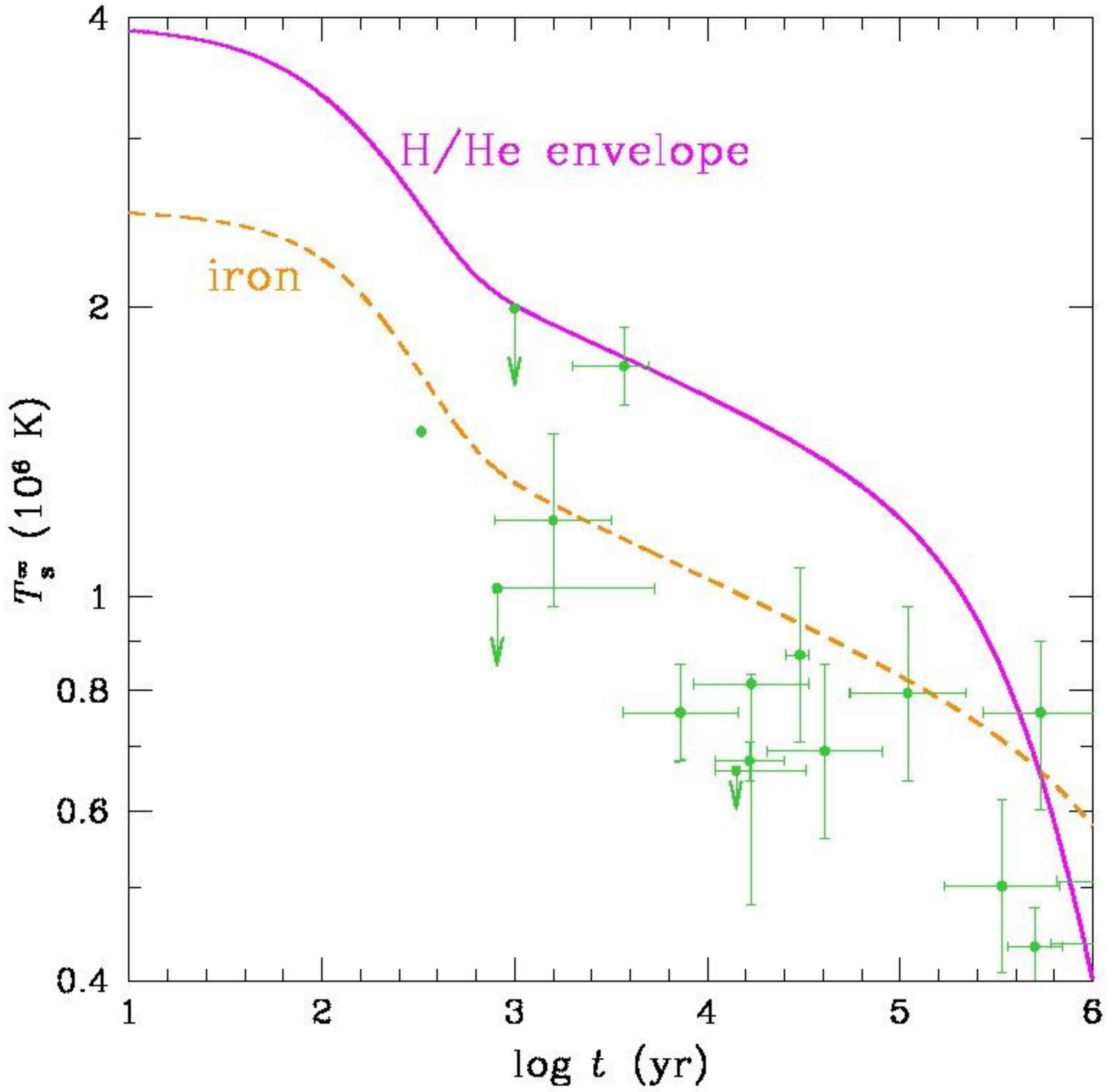
  2) early cooling by neutrinos

     $dT/dt \approx -\varepsilon_\nu / C$

  3) after 10^5–10^6 yr, photon cooling

- Microphysics
  - neutrino emissivity ε_ν
  - heat capacity C
  - thermal conductivity K

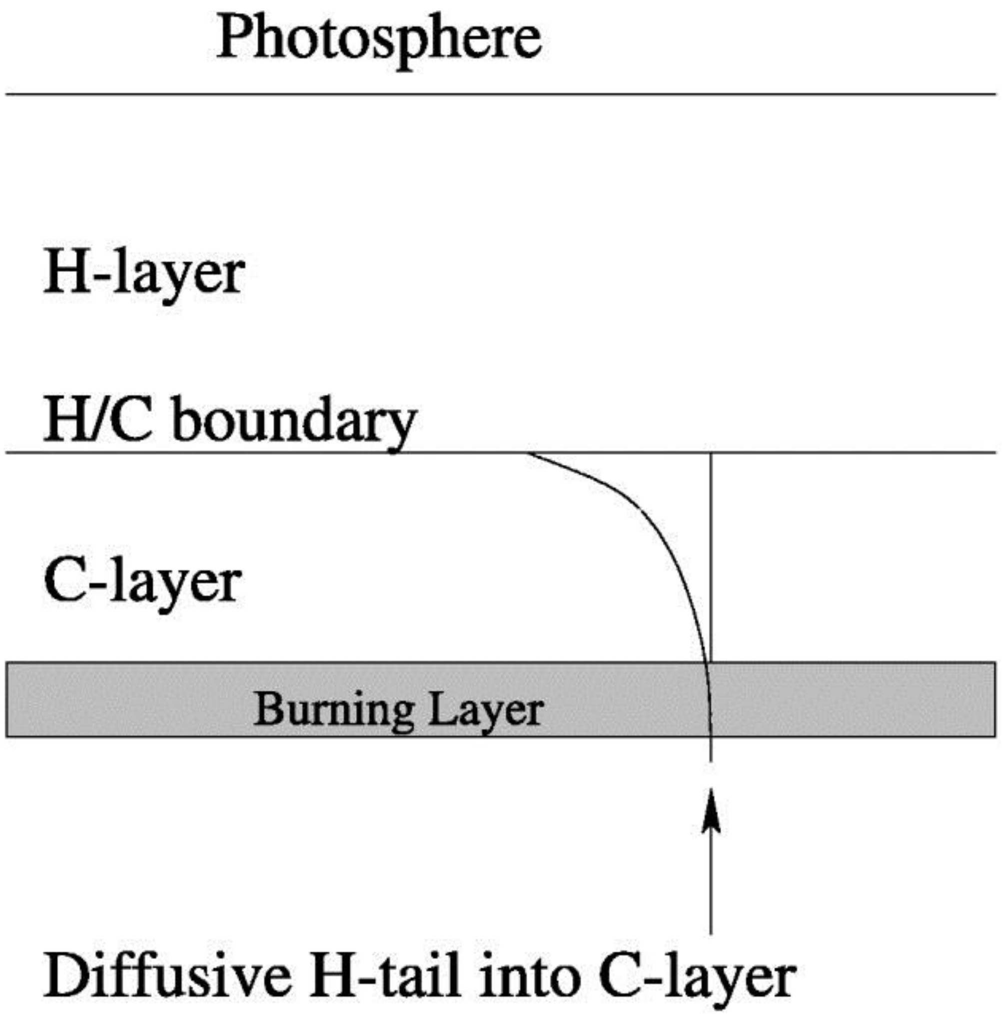
- Other effects
  - superfluid/superconductor
  - envelope composition $K \propto Z^{-1}$ and T_s–T_b
  - magnetic field



Diffusive nuclear burning (DNB)

- Previous envelopes and T_s–T_b are static (time-independent)
  - iron (Gudmundsson+1982,1983)
  - light elements (Potekhin+1997,2003;Yakovlev,WH+2011)
  - H–He, He–C, C–Fe mixtures (Beznogov+2016)

- DNB causes evolving envelope and atmosphere (Rosen1964; Chang+Bildsten2003,2004; Chang+2004,2010)



Chang+Bildsten 2003

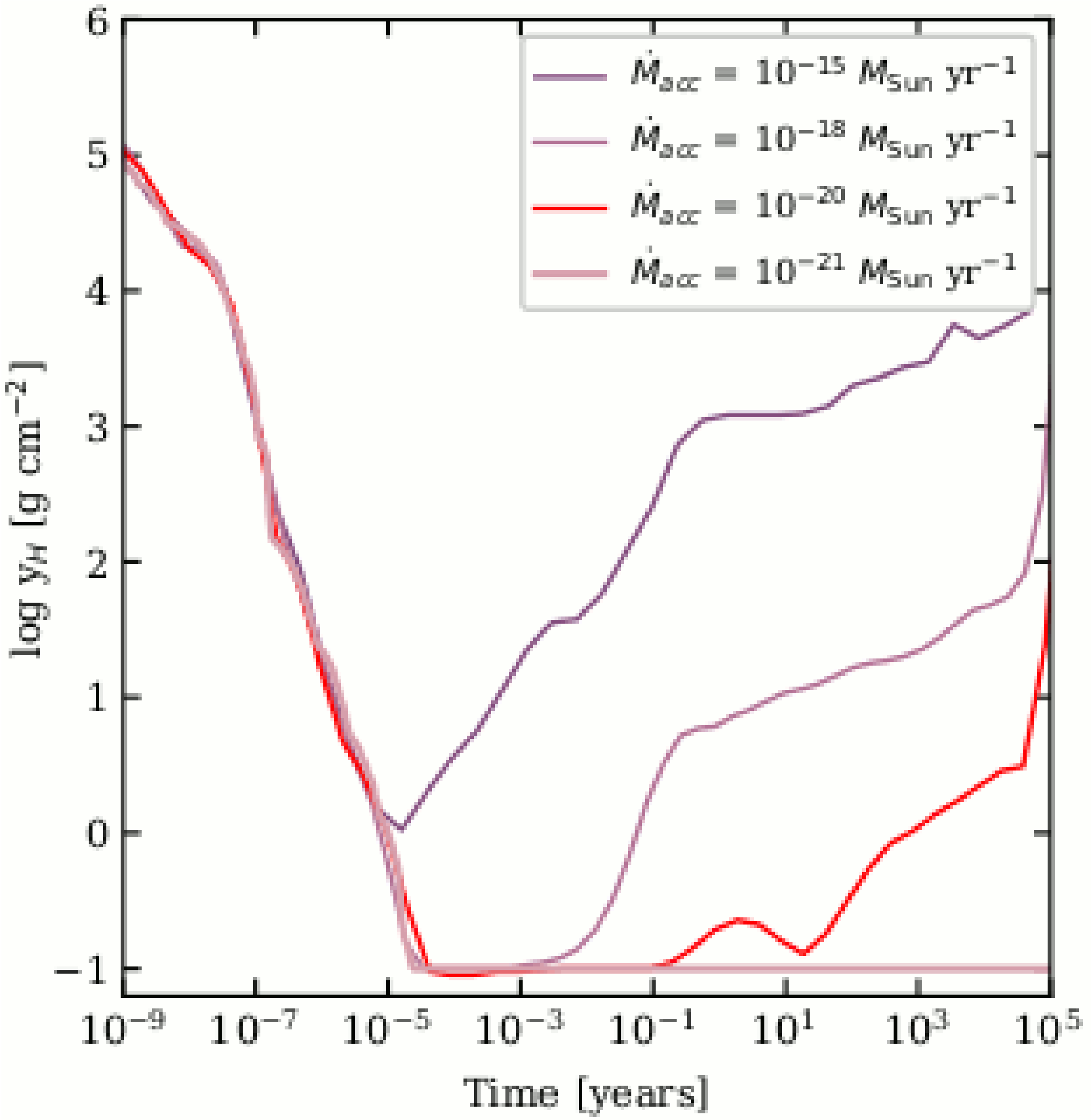
Effect of DNB on envelope and atmosphere

- Previous envelopes and T_s–T_b are static (time-independent)
  - iron (Gudmundsson+1982,1983)
  - light elements (Potekhin+1997,2003;Yakovlev,WH+2011)
  - H–He, He–C, C–Fe mixtures (Beznogov+2016)

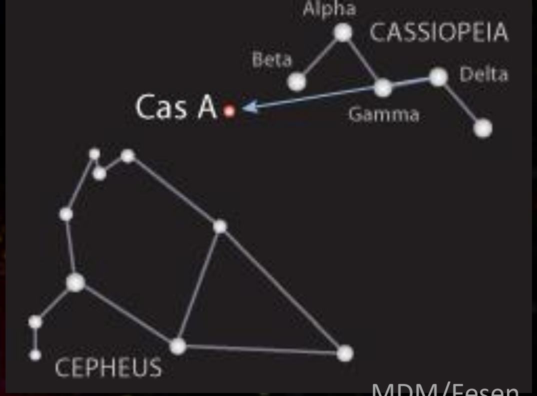
- DNB causes evolving envelope and atmosphere (Rosen1964; Chang+Bildsten2003,2004; Chang+2004,2010)

- Wijngaarden,WH+2019:
  - T_s–T_b for H–He, He–C (and H–C)
  - cooling simulations with DNB and weak accretion

    $dM_{acc}/dt = 10^{-15}\ M_{Sun}/yr$ (n_{ism}=1 cm^{-3}, v=20 km/s)
  - DNB relevance to Cassiopeia A and other young NSs
  - new *Chandra* data of Cas A



Neutron star in Cassiopeia A supernova remnant



MDM/Fesen

- ≈1681: supernova (Fesen+2006; age ≈ **337yr**)
- 1999: central **non-pulsed** X-ray source discovered by *Chandra*
- 2009: identified as neutron star, **youngest** known (WH+Heinke, with C atm)
- 2010: **rapid cooling** detected (Heinke+WH)
- 2011: rapid cooling due to **superfluid-superconductor** (Shternin,WH+;Page+)

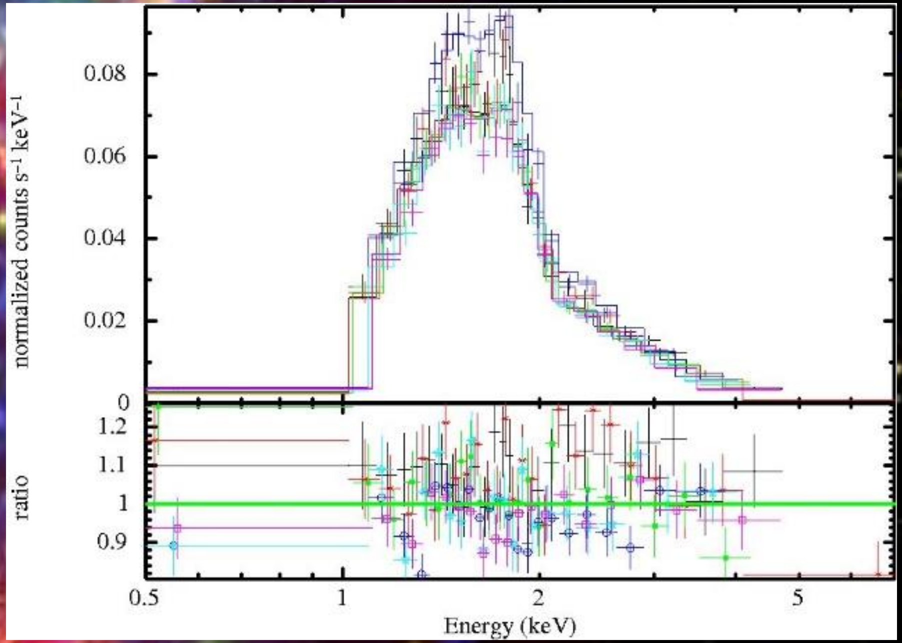
o cooling from 2006 and 2012 subarrary data (Posselt+)

st reported T_s from graded data (WH+)

4% or <3.3% from 2015 subarray data (Posselt+Pavlov)

raded data

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



Mass and radius of Cassiopeia A neutron star

- ≈1681: supernova (Fesen+2006; age ≈ **337yr**)
- 1999: central **non-pulsed** X-ray source discovered by *Chandra*
- 2009: identified as neutron star, **youngest** known (WH+Heinke, with C atm)
- 2010: **rapid cooling** detected (Heinke+WH)
- 2011: rapid cooling due to **superfluid-superconductor** (Shternin,WH+;Page+)

o cooling from 2006 and 2012 subarray data (Posselt+)

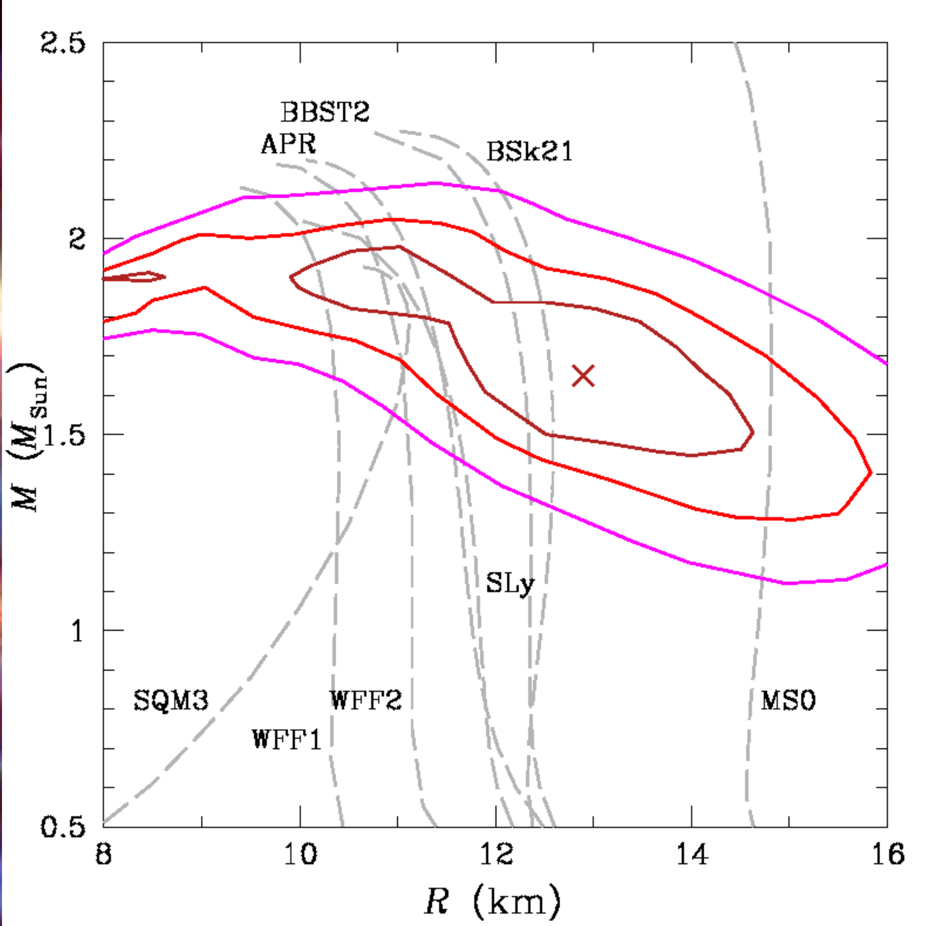
st reported T_s from graded data (WH+)

rate <2.4% or <3.3% from 2015 subarray data (Posselt+Pavlov)

- 2019: 4 new T_s from graded data

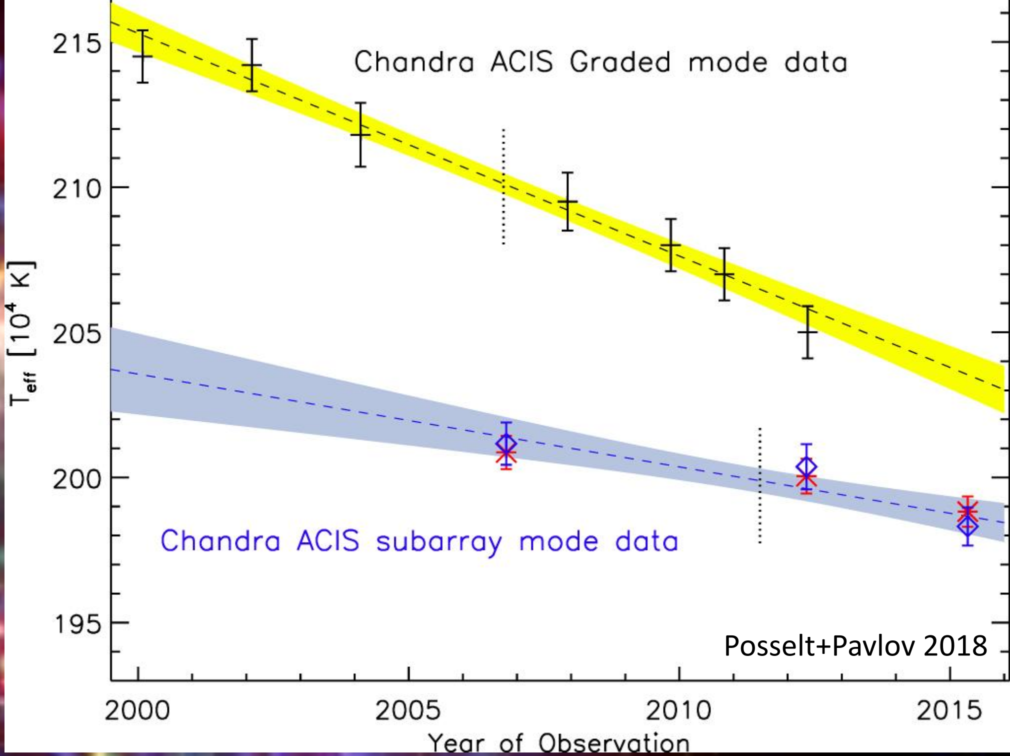
Chandra graded

- 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



Cooling of Cassiopeia A neutron star?

- ~1681 ... 2006; age ~ 337yr)
- 1999: central non-pulsed X-ray source discovered by *Chandra*
- 2009: identified as neutron star, **youngest** known (WH+Heinke, with C atm)
- 2010: **rapid cooling** detected (Heinke+WH)
- 2011: rapid cooling due to **superfluid-superconductor** (Shternin,WH+;Page+)
- 2013: no cooling from 2006 and 2012 subarrary data (Posselt+)
- 2015: last reported T_s from graded data (WH+)
- 2018: cooling rate **<2.4%** or **<3.3%** from 2015 subarray data (Posselt+Pavlov)
- ... 4 new T_s from graded data



Chandra graded

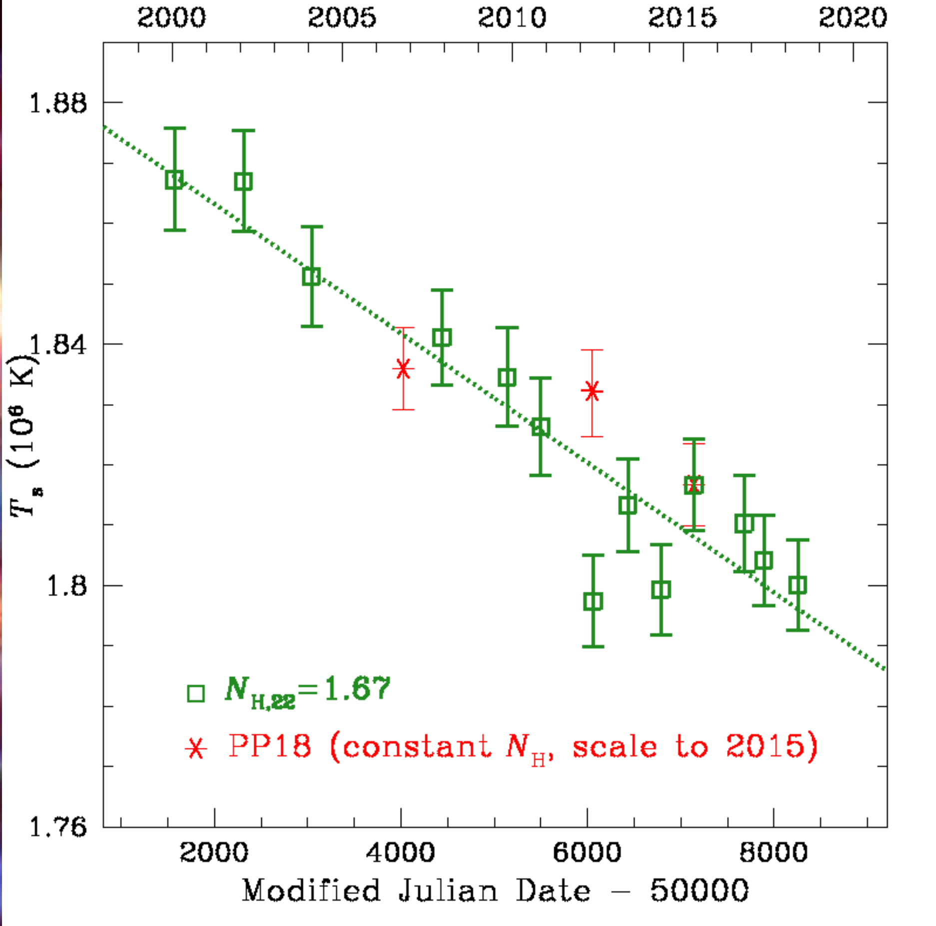
- 2000 Jan
- 2002 Feb
- 2004 Feb
- 2007 Dec
- 2009 Nov
- 2010 Nov
- 2012 May
- 2013 May
- 2014 May
- 2015 Apr
- 2016 Oct
- 2017 May
- 2018 May

Cooling of Cassiopeia A neutron star!

- ~1681 [illegible] (Fesen+2006; age ~ **337yr**)
- 1999: central non-pulsed X-ray source discovered by *Chandra*
- 2009: identified as neutron star, **youngest** known (WH+Heinke, with C atm)
- 2010: **rapid cooling** detected (Heinke+WH)
- 2011: rapid cooling due to **superfluid-superconductor** (Shternin,WH+;Page+)
- 2013: no cooling from 2006 and 2012 subarrary data (Posselt+)
- 2015: last reported T_s from graded data (WH+)
- 2018: cooling rate **<2.4%** or <3.3% from 2015 subarray data (Posselt+Pavlov)
- 2019: 4 new T_s from graded data, cooling **2.1±0.2%** or 2.7±0.3%

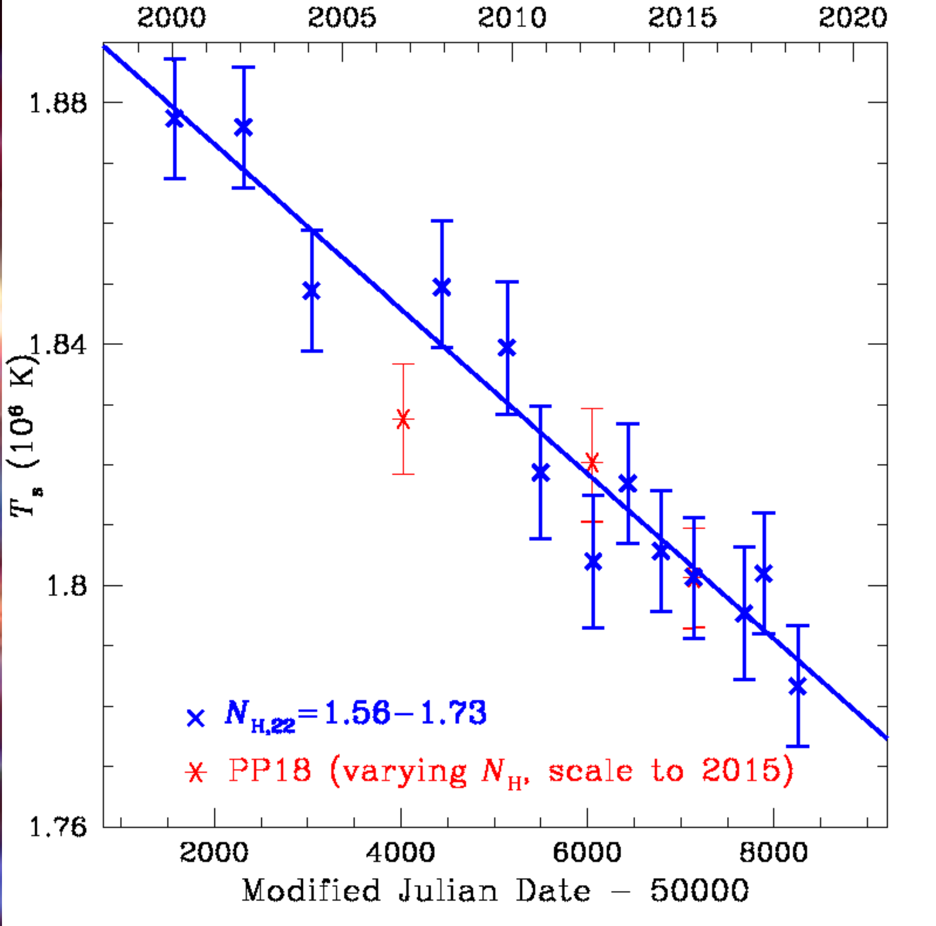
Chandra graded

- 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



Cooling of Cassiopeia A neutron star!

- ~1681 [illegible] 2006; age ≈ 337yr)
- 1999: central non-pulsed X-ray source discovered by *Chandra*
- 2009: identified as neutron star, **youngest** known (WH+Heinke, with C atm)
- 2010: **rapid cooling** detected (Heinke+WH)
- 2011: rapid cooling due to **superfluid-superconductor** (Shternin,WH+;Page+)
- 2013: no cooling from 2006 and 2012 subarrary data (Posselt+)
- 2015: last reported T_s from graded data (WH+)
- 2018: cooling rate <2.4% or **<3.3%** from 2015 subarray data (Posselt+Pavlov)
- 2019: 4 new T_s from graded data, cooling 2.1±0.2% or **2.7±0.3%**

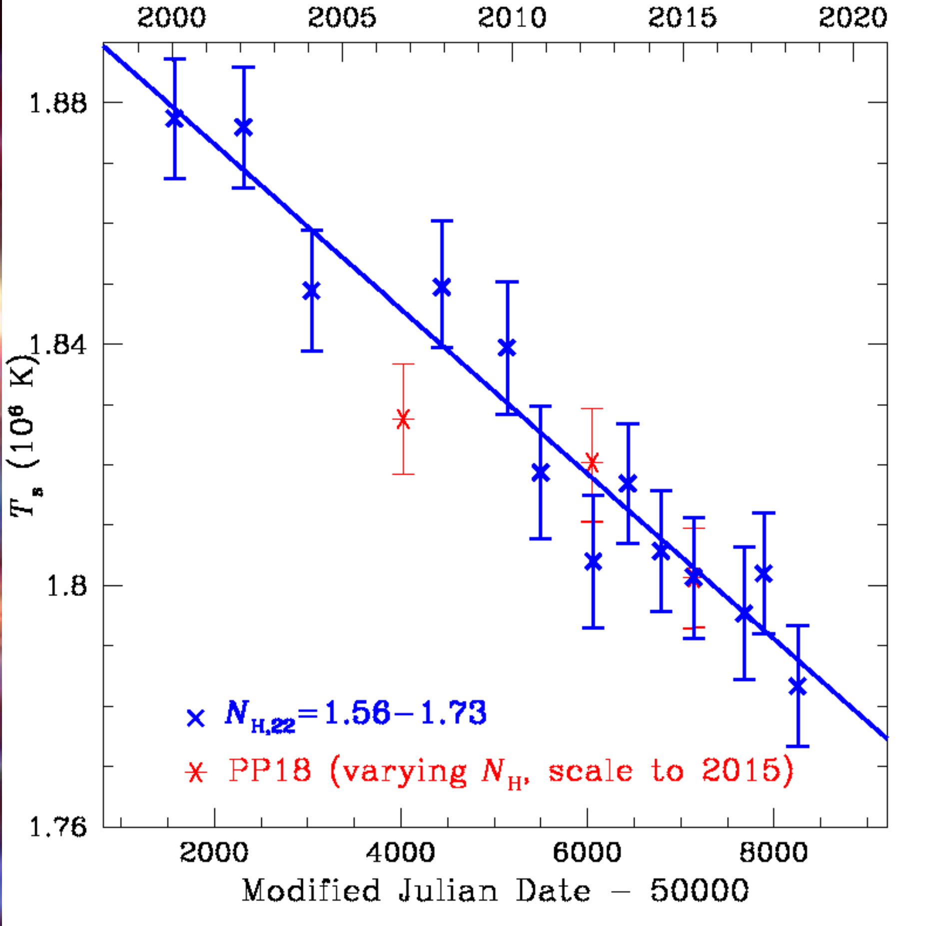


Chandra graded

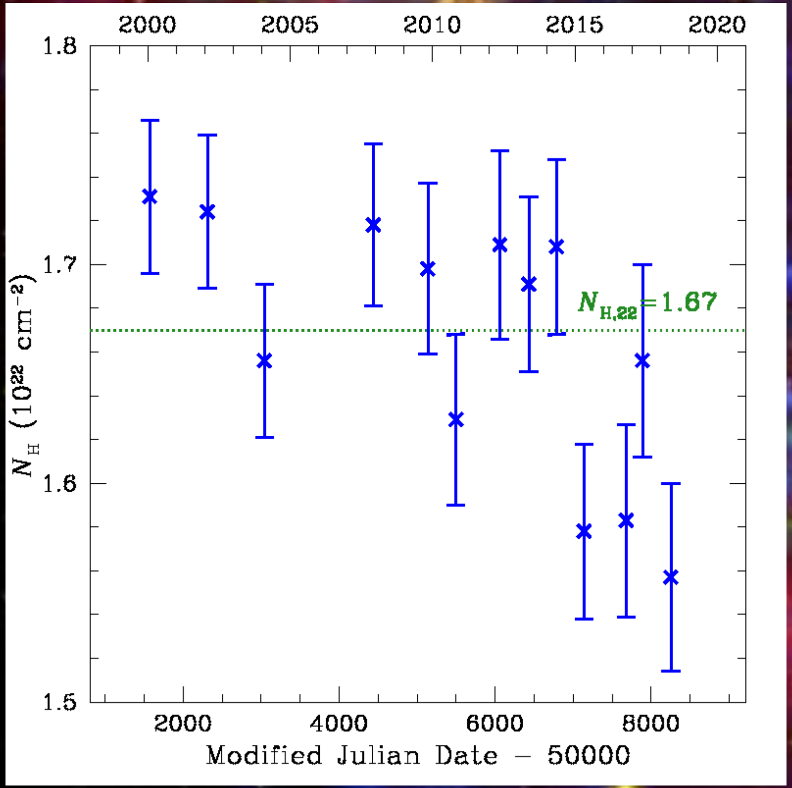
- 2000 Jan
- 2002 Feb
- 2004 Feb
- 2007 Dec
- 2009 Nov
- 2010 Nov
- 2012 May
- 2013 May
- 2014 May
- 2015 Apr
- 2016 Oct
- 2017 May
- 2018 May

Cooling of Cassiopeia A neutron star!

- ~1681 … sen+2006; age ~ 337yr)
- 1999: central non-pulsed X-ray source discovered by *Chandra*
- 2009: identified as neutron star, **youngest** known (WH+Heinke, with C atm)
- 2010: rapid **cooling** detected (Heinke+WH)
- 2011: rapid cooling due to **superfluid-superconductor** (Shternin,WH+;Page+)
- 2013: no cooling from 2006 and 2012 subarrary data (Posselt+)
- 2015: last reported T_s from graded data (WH+)
- 2018: cooling rate <2.4% or **<3.3%** from 2015 subarray data (Posselt+Pavlov)
- 2019: 4 new T_s from graded data, cooling 2.1±0.2% or **2.7±0.3%**



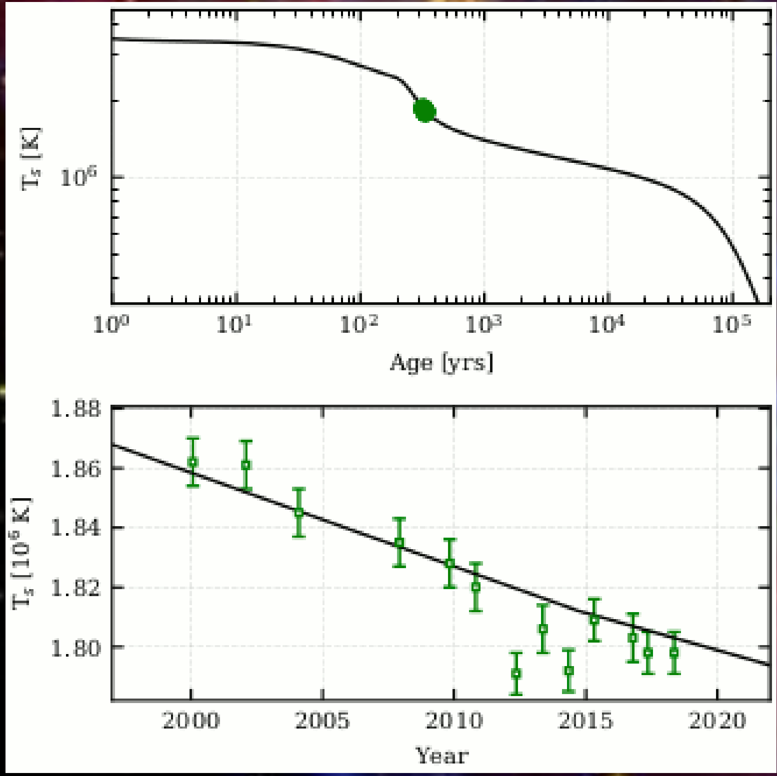
Chandra graded
- 2000 Jan
- 2002 Feb
- 2004 Feb
- 2007 Dec
- 2009 Nov
- 2010 Nov
- 2012 May
- 2013 May
- 2014 May
- 2015 Apr
- 2016 Oct
- 2017 May
- 2018 May

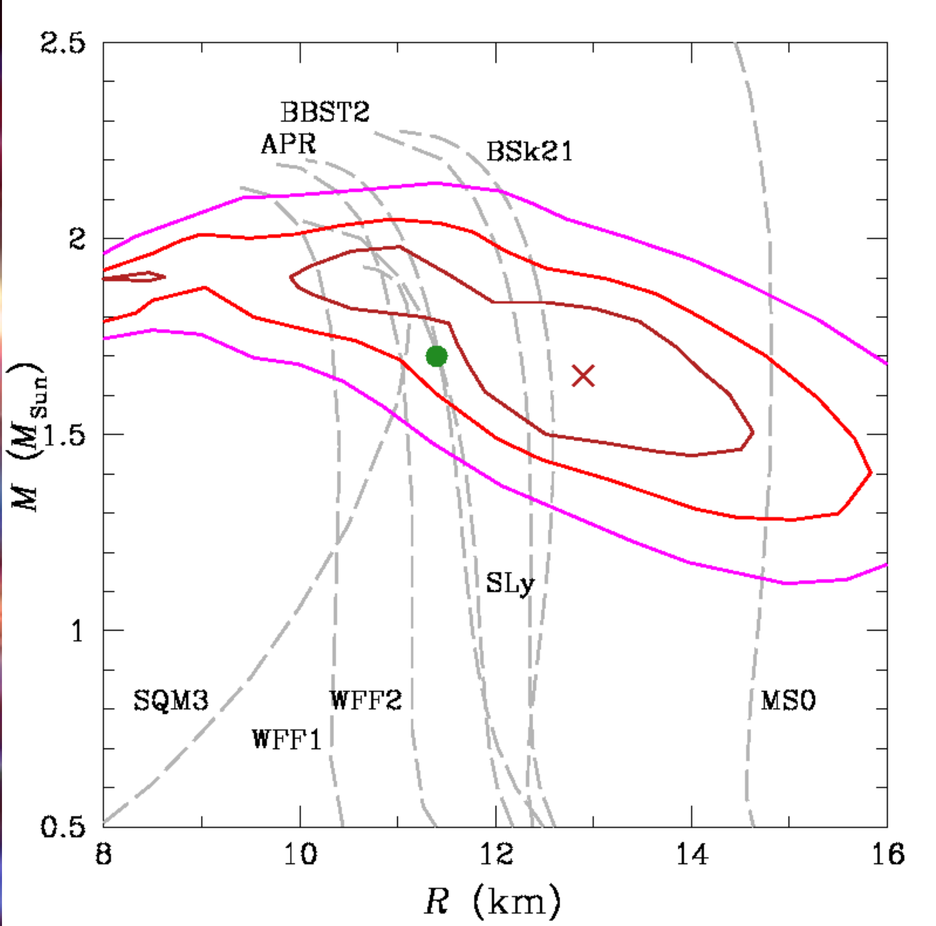


Cooling of Cassiopeia A neutron star!

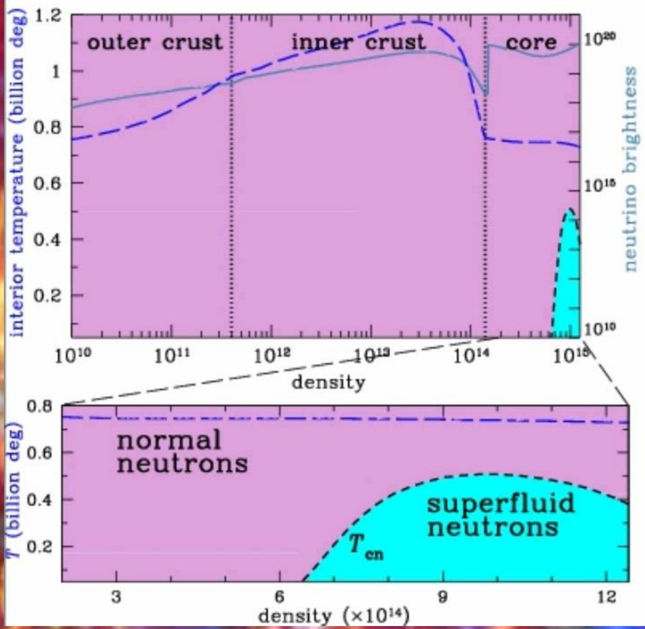
- ~1681 [illegible] +2006; age ~ 337yr)
- 1999: central [illegible] X-ray source discovered by *Chandra*
- 2009: identified as neutron star, **youngest** known (WH+Heinke, with C atm)
- 2010: **rapid cooling** detected (Heinke+WH)
- 2011: rapid cooling due to **superfluid-superconductor** (Shternin,WH+;Page+)
- 2013: no cooling from 2006 and 2012 subarrary data (Posselt+)
- 2015: last reported T_s from graded data (WH+)
- 2018: cooling rate <2.4% or **<3.3%** from 2015 subarray data (Posselt+Pavlov)
- 2019: 4 new T_s from graded data, cooling 2.1±0.2% or **2.7±0.3%**

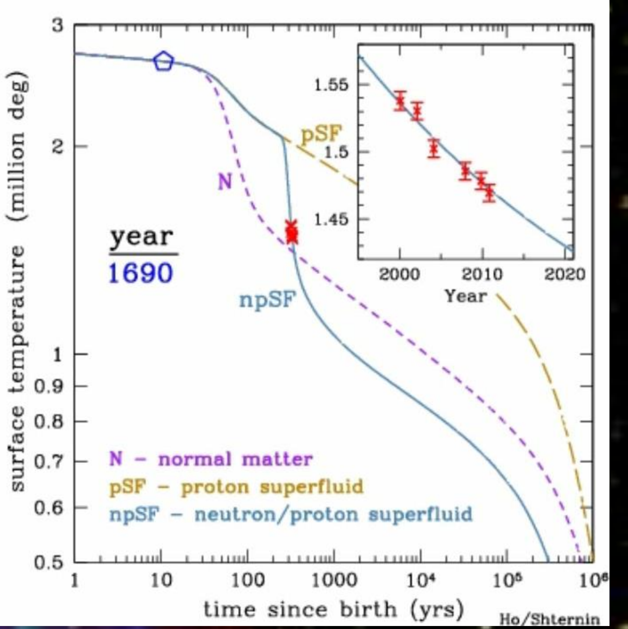
Chandra graded
- 2000 Jan
- 2002 Feb
- 2004 Feb
- 2007 Dec
- 2009 Nov
- 2010 Nov
- 2012 May
- 2013 May
- 2014 May
- 2015 Apr
- 2016 Oct
- 2017 May
- 2018 May





Summary





- **Nuclear physics (eg EOS, superfluidity/superconductivity) from comparisons of neutron star cooling theory with observations**

- Wijngaarden+2019:
  - **diffusive nuclear burning causes envelope and atmosphere composition changes with time**
  - **Cassiopeia A neutron star cooling at ≈2 or 3% per decade**

- Searches for gravitational waves from Cassiopeia A
  - informed by spin period, mass, radius, temperature, magnetic field