

# Discussion

## Astrophysical signatures of / bounds on axions

Alessandro Mirizzi

globular clusters,  
red giants, supernova

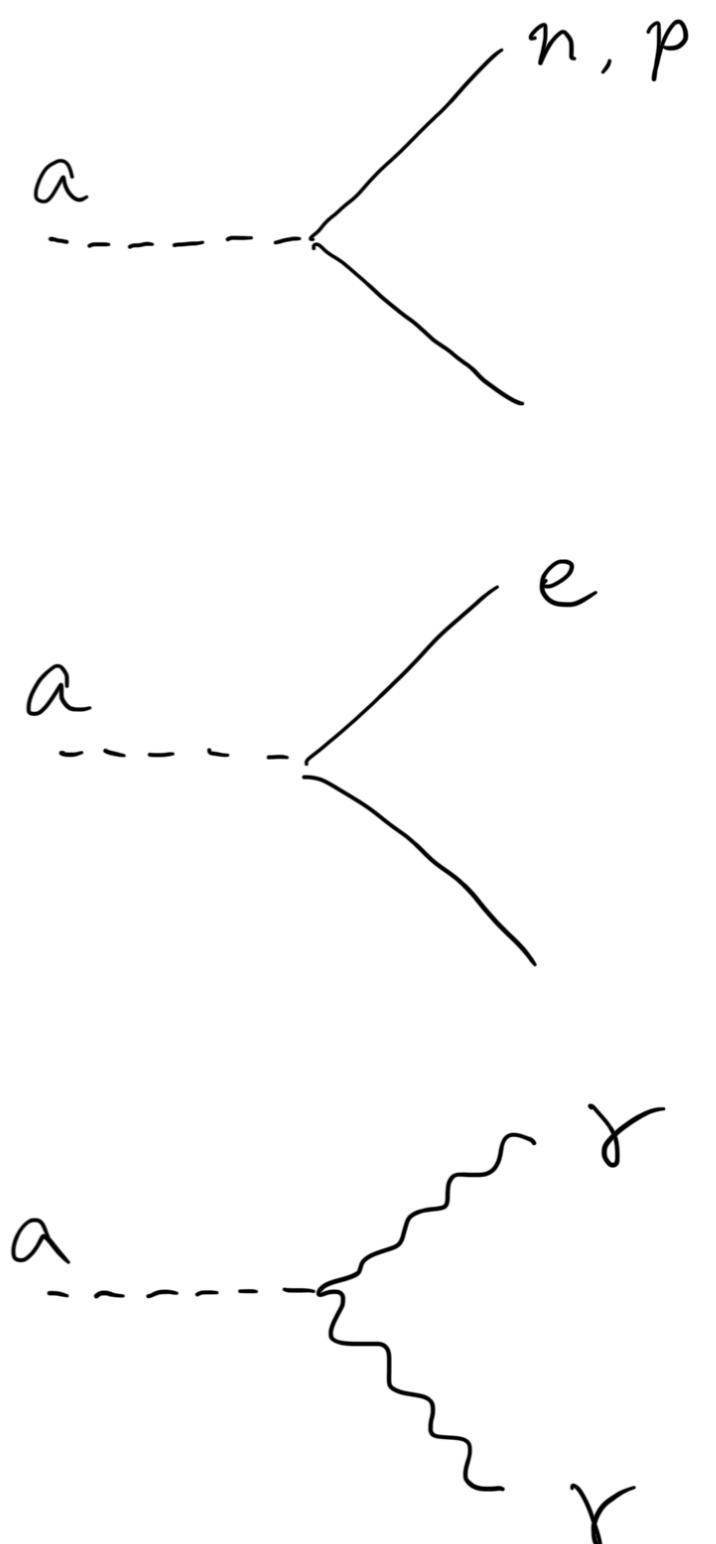
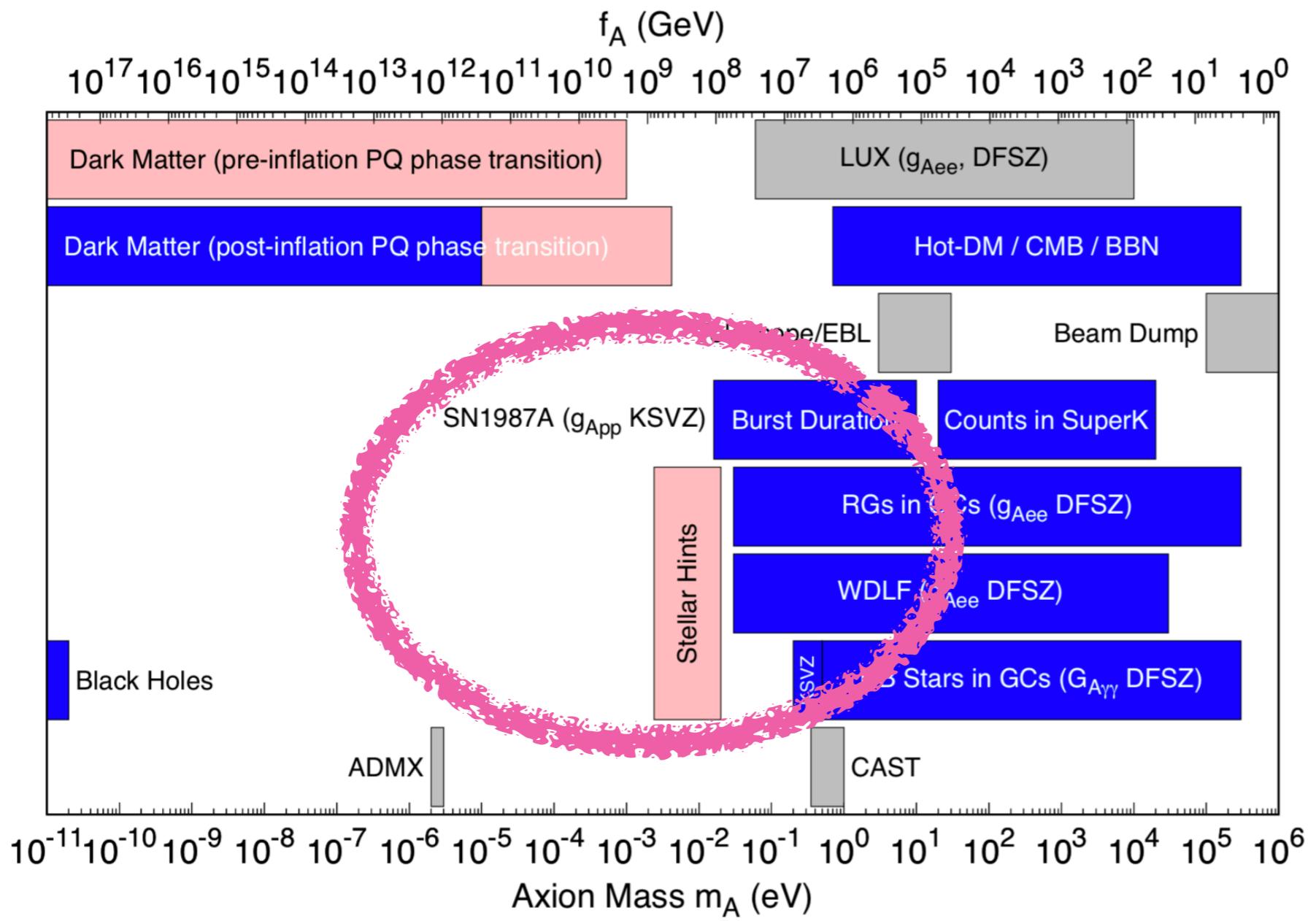
Kfir Blum Supernova

Koichi Hamaguchi Neutron Star

Axions in the Lab and in the Cosmos

@CERN, July 19, 2019

$$\mathcal{O}(10^8) \text{ GeV} < f_a < \mathcal{O}(10^{12}) \text{ GeV}$$





# A Limit on Axion from the Cooling Neutron Star in Cassiopeia A

Koichi Hamaguchi (University of Tokyo)

Axions in the Lab and in the Cosmos @CERN, July 19, 2019

Based on

K. Hamaguchi, N. Nagata, K. Yanagi, J. Zheng, [[arXiv:1806.07151](https://arxiv.org/abs/1806.07151)]

Phys.Rev. D98 (2018) 103015

# Plan

1. Cas A NS Cooling
2. Cas A NS Cooling with axion
3. Summary

# Plan

1. Cas A NS Cooling
  - 1.1. Cas A
  - 1.2. Cas A NS
  - 1.3. Cas A NS Cooling (observation)
  - 1.4. Cas A NS Cooling (theory)

2. Cas A NS Cooling with axion

3. Summary

# Cassiopeia A

- What? Supernova remnant (SNR)

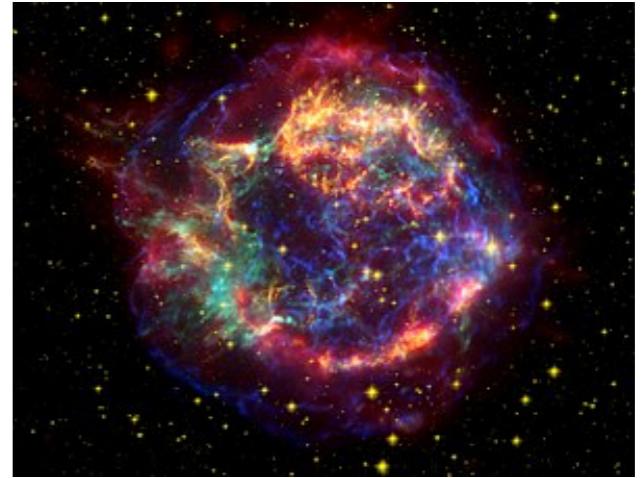


image from Wikipedia

# Cassiopeia A

- What? Supernova remnant (SNR)

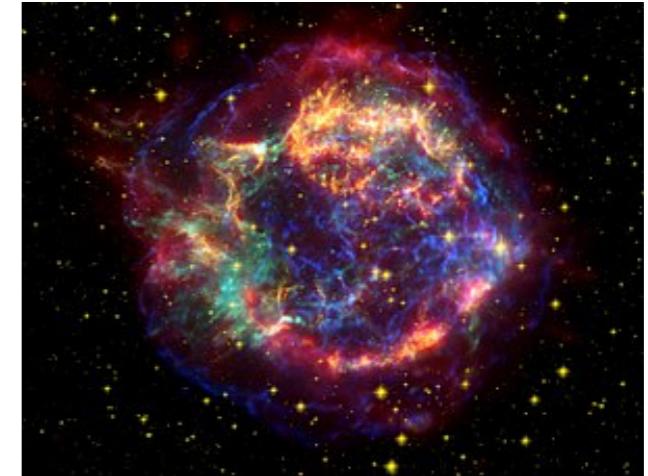
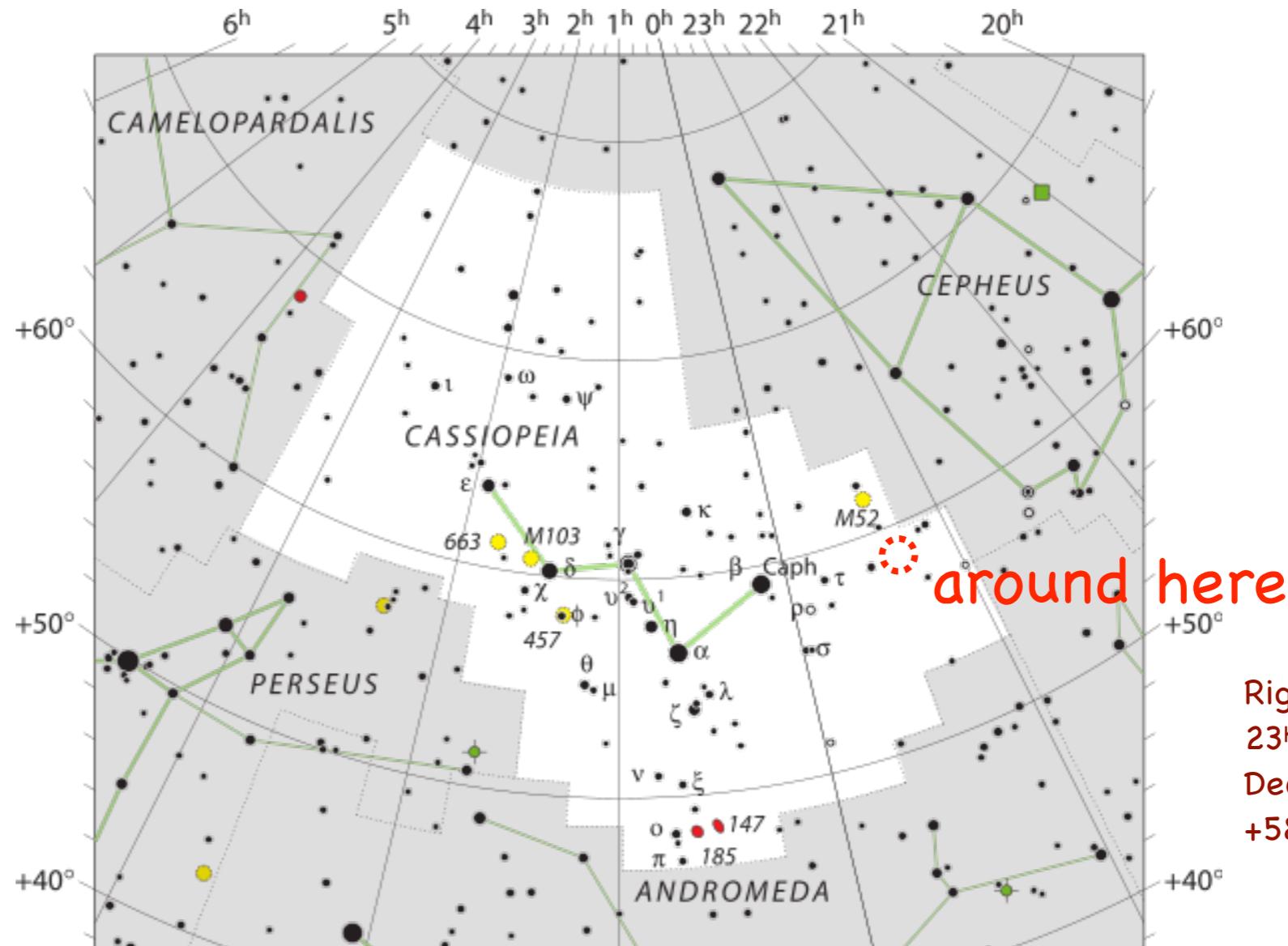


image from Wikipedia

- Where?

In the constellation Cassiopeia.

$3.4^{+0.3}_{-0.1}$  kpc away [J.E.Reed et.al. '95], within the Milky Way.



# Cassiopeia A

- What? Supernova remnant (SNR)

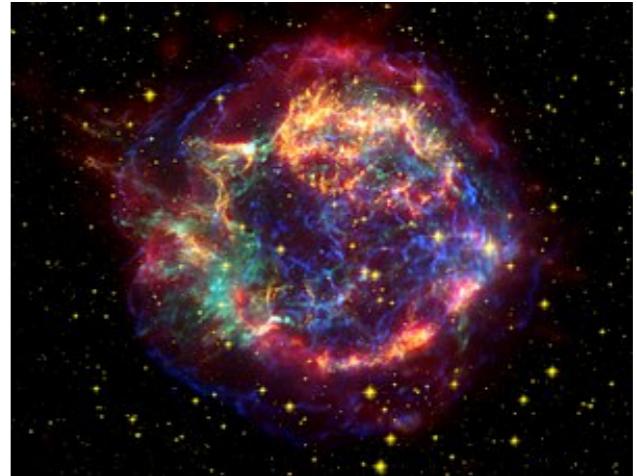


image from Wikipedia

- Where?

In the constellation Cassiopeia.

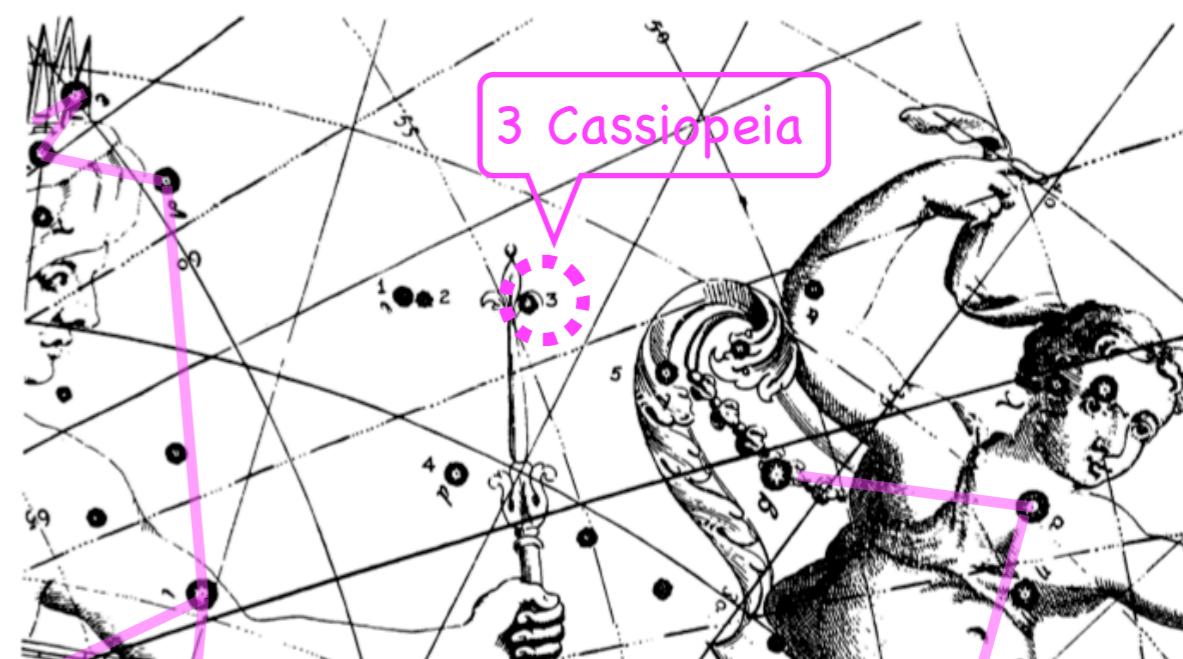
$3.4^{+0.3}_{-0.1}$  kpc away [J.E.Reed et.al. '95], within the Milky Way.

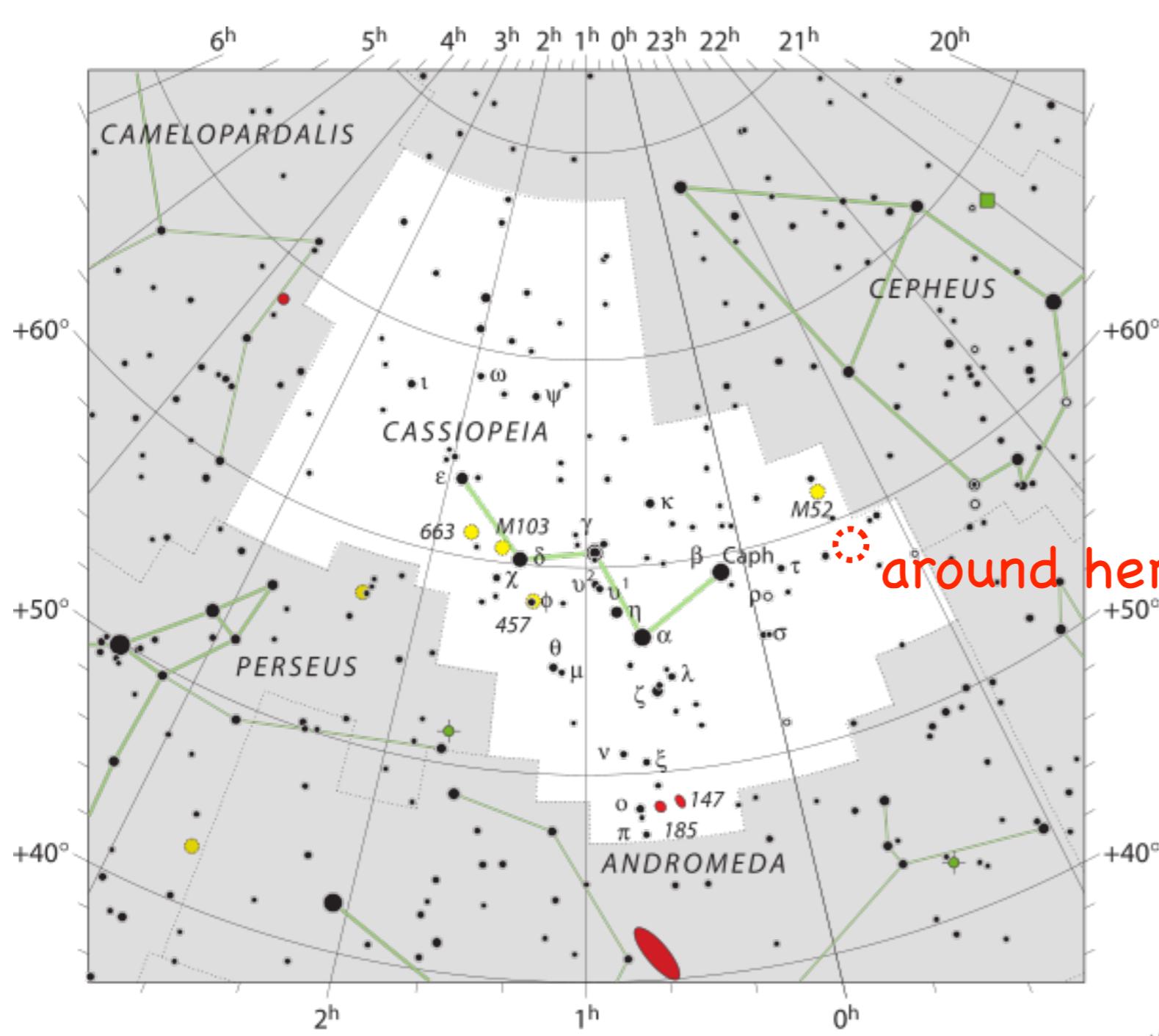
- When?

Explosion (light reached Earth) about **340 years ago**.

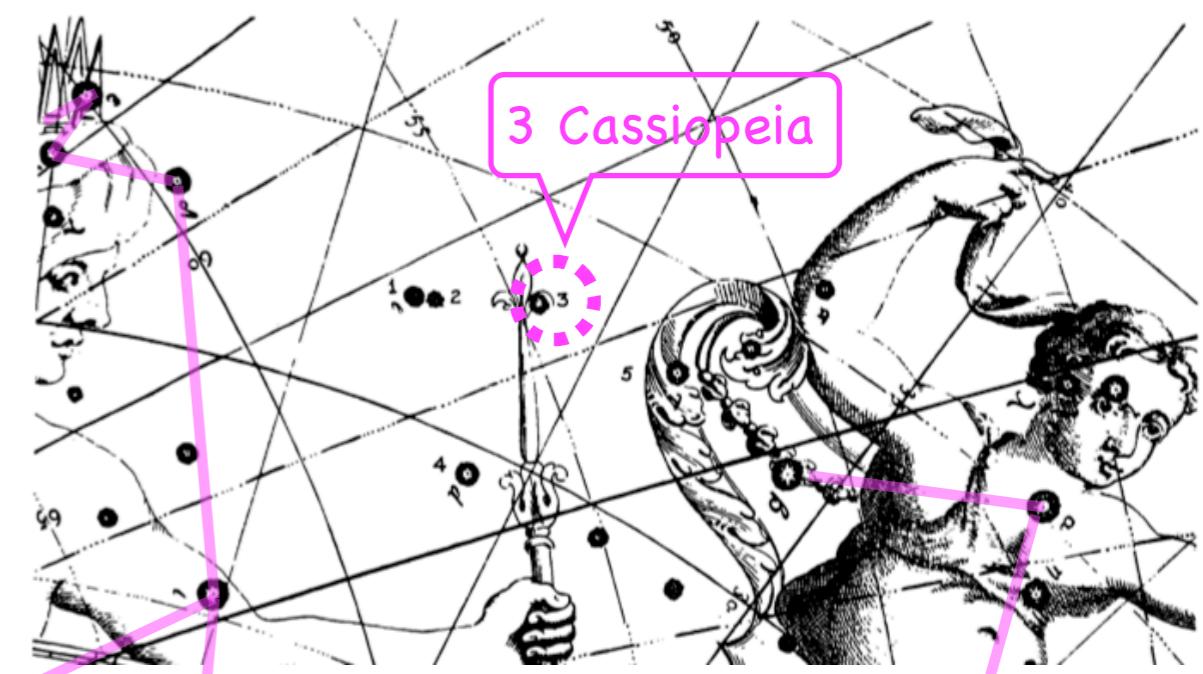
- Remnant expansion suggests explosion dates of **1681 ± 19**. [R.A.Fesen, et.al., '06]
- Cas A may be identical to the star **3 Cassiopeia**, which was recorded by J. Flamsteed on **August 16, 1680** and has been missed since then.

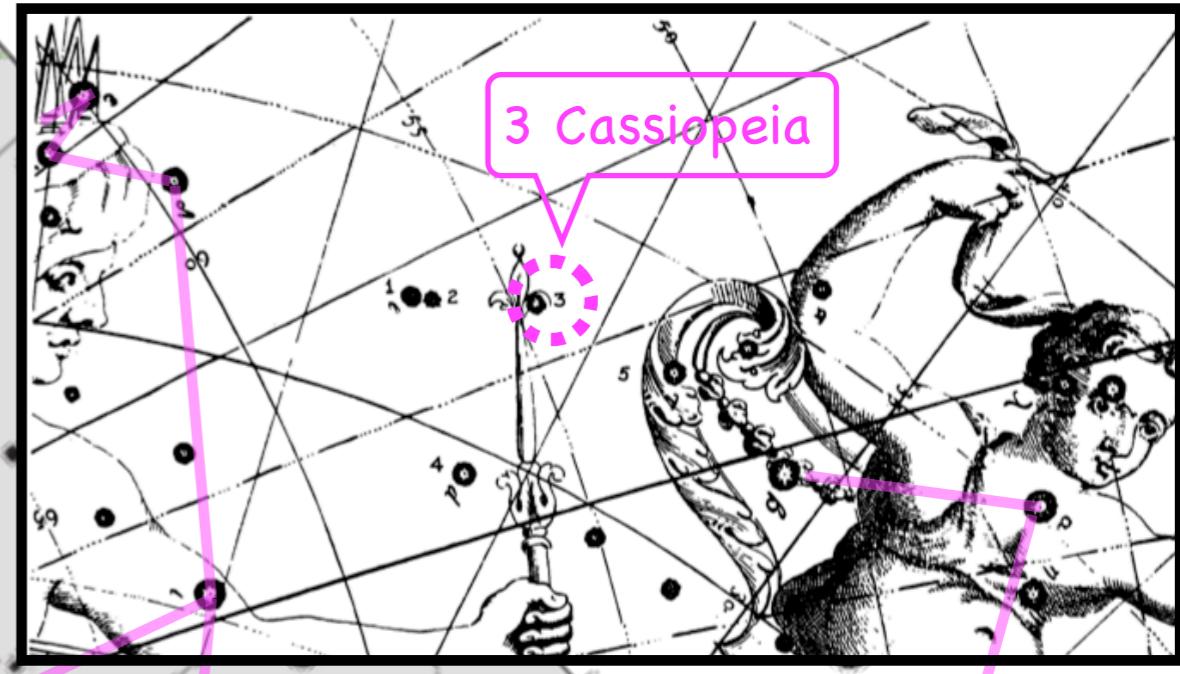
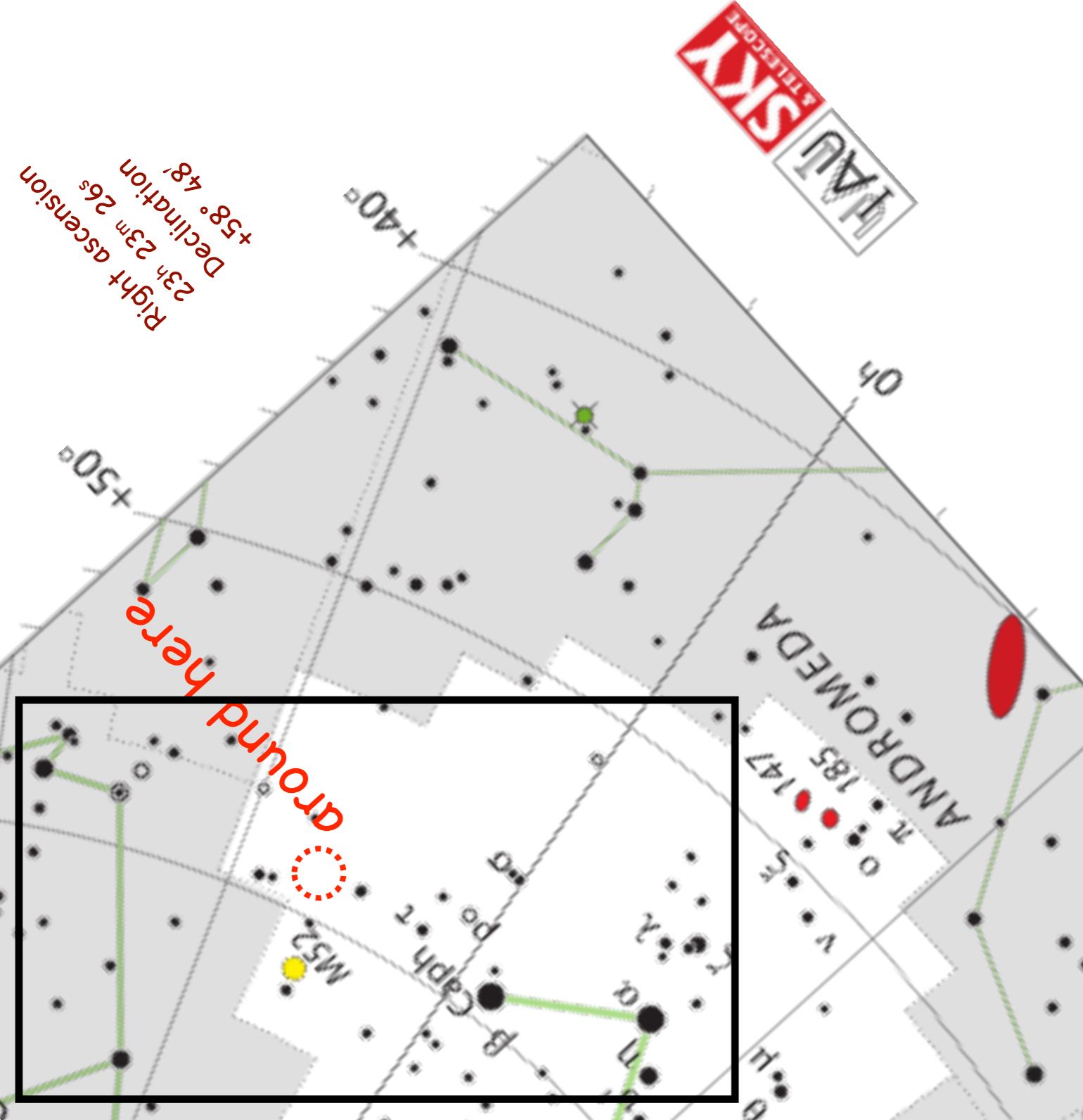
[W. B. Ashworth, Jr. (1980); K. W. Kamper (1980); D. W. Hughes (1980).]



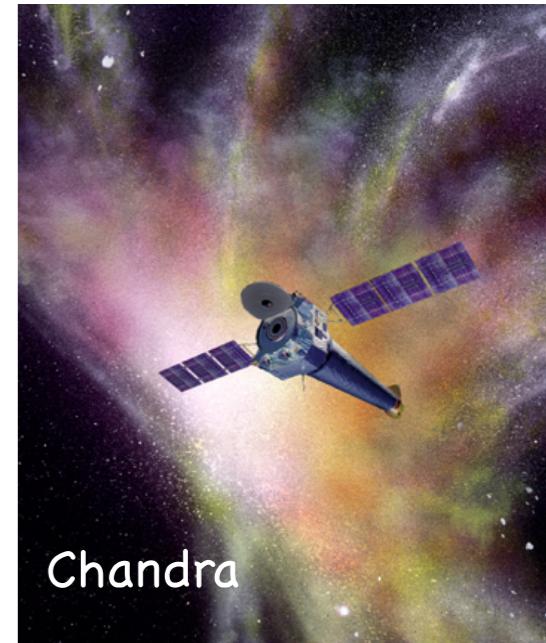
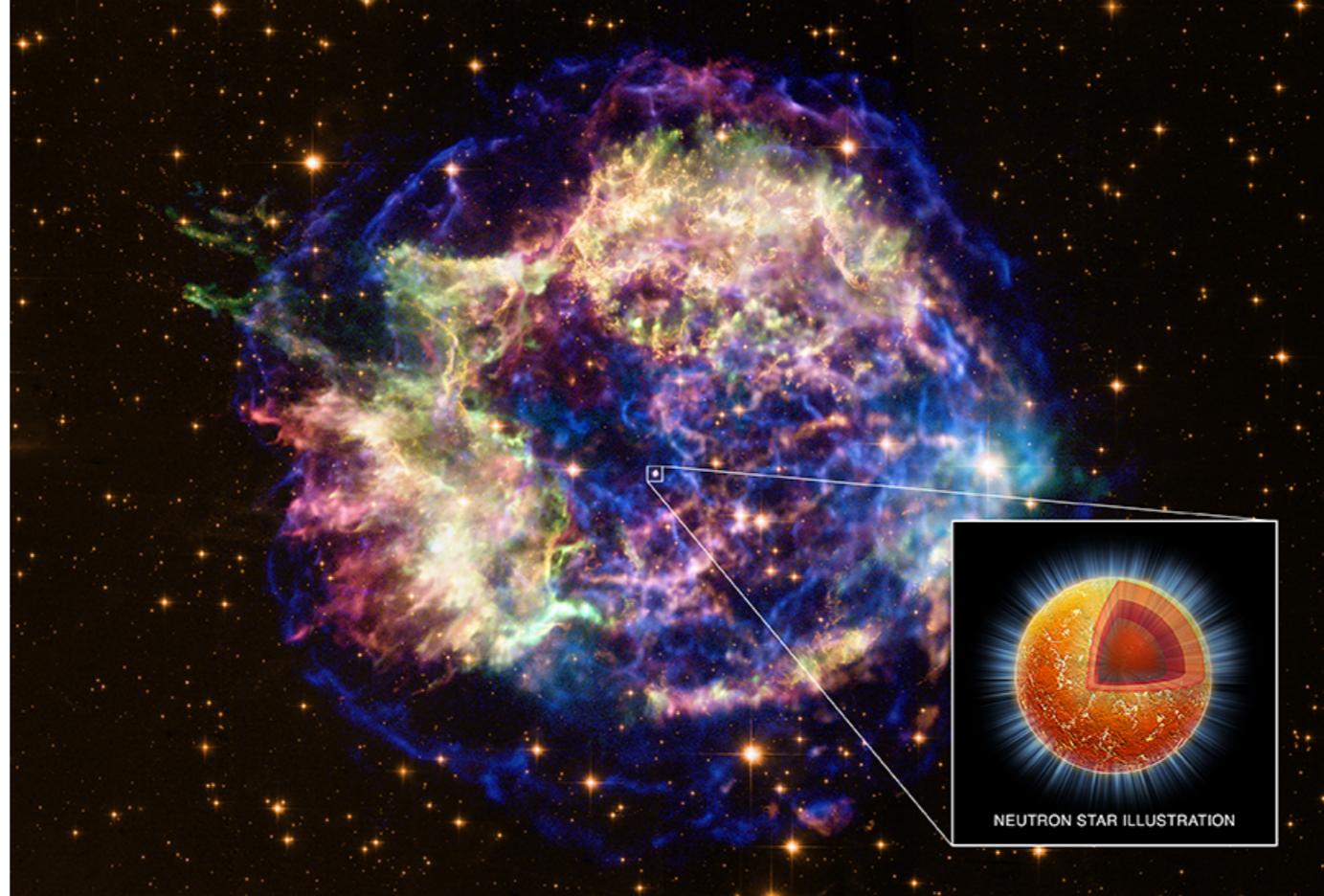


around here





# Cas A Neutron Star



Chandra

images from Chandra's webpage

- In 1999, Chandra found a point source at the center of Cas A.
- X-ray spectrum is consistent with a **thermal emission** of **Neutron Star** with a carbon atmosphere, mass  $M = (1.4 \pm 0.3)$   $M_{\odot}$ , and radius  $R = (11-13)$  km.

[W.C.G.Ho, C.O.Heinke, '09], [W.C.G.Ho, K.G.Elshamouty, C.O.Heinke, A.Y.Potekhin, '14].

# Cas A NS Cooling

- The **Cooling** is observed!

Cas A NS is the only isolated NS whose cooling has been observed in real time.

**Temperature decreases by (3-4)% in 10 years.**

THE ASTROPHYSICAL JOURNAL LETTERS, 719:L167–L171, 2010 August 20  
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doi:10.1088/2041-8205/719/2/L167

## DIRECT OBSERVATION OF THE COOLING OF THE CASSIOPEIA A NEUTRON STAR

CRAIG O. HEINKE<sup>1</sup> AND WYNN C. G. HO<sup>2</sup>

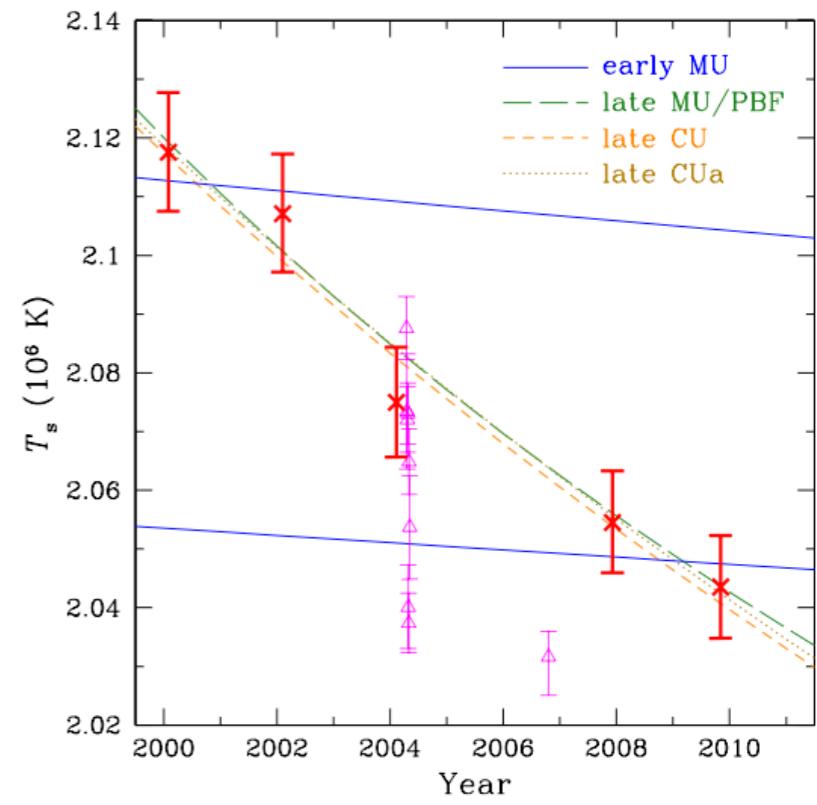
<sup>1</sup> Department of Physics, University of Alberta, Room 238 CEB, Edmonton, AB T6G 2G7, Canada; heinke@ualberta.ca

<sup>2</sup> School of Mathematics, University of Southampton, Southampton SO17 1BJ, UK; wynnho@slac.stanford.edu

Received 2010 April 14; accepted 2010 July 8; published 2010 August 2

## ABSTRACT

The cooling rate of young neutron stars (NSs) gives direct insight into their internal makeup. Although the temperatures of several young NSs have been measured, until now a young NS has never been observed to decrease in temperature over time. We fit nine years of archival *Chandra* ACIS spectra of the likely NS in the ∼330 yr old Cassiopeia A supernova remnant with our non-magnetic carbon atmosphere model. Our fits show a relative decline in the surface temperature by 4% ( $5.4\sigma$ , from  $(2.12 \pm 0.01) \times 10^6$  K in 2000 to  $(2.04 \pm 0.01) \times 10^6$  K in 2009) and the observed flux by 21%. Using a simple model for NS cooling, we show that this temperature decline could indicate that the NS became isothermal sometime between 1965 and 1980, and constrains some combinations of neutrino emission mechanisms and envelope compositions. However, the NS is likely to have become isothermal soon after



**NOTE: (the interpretations of) the observational data may not be conclusive...**

Elshamouty et.al., 1306.3387, Posselt et.al. 1311.0888, Posselt, Pavlov, 1808.00531.

# Cas A NS Cooling

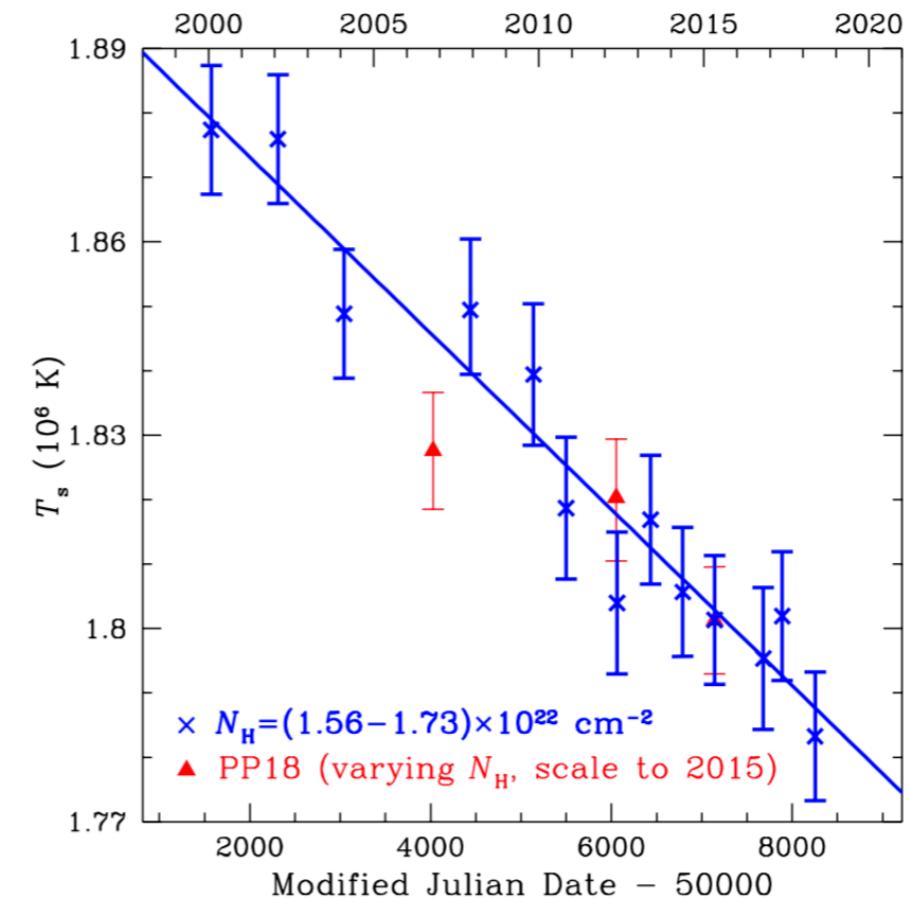
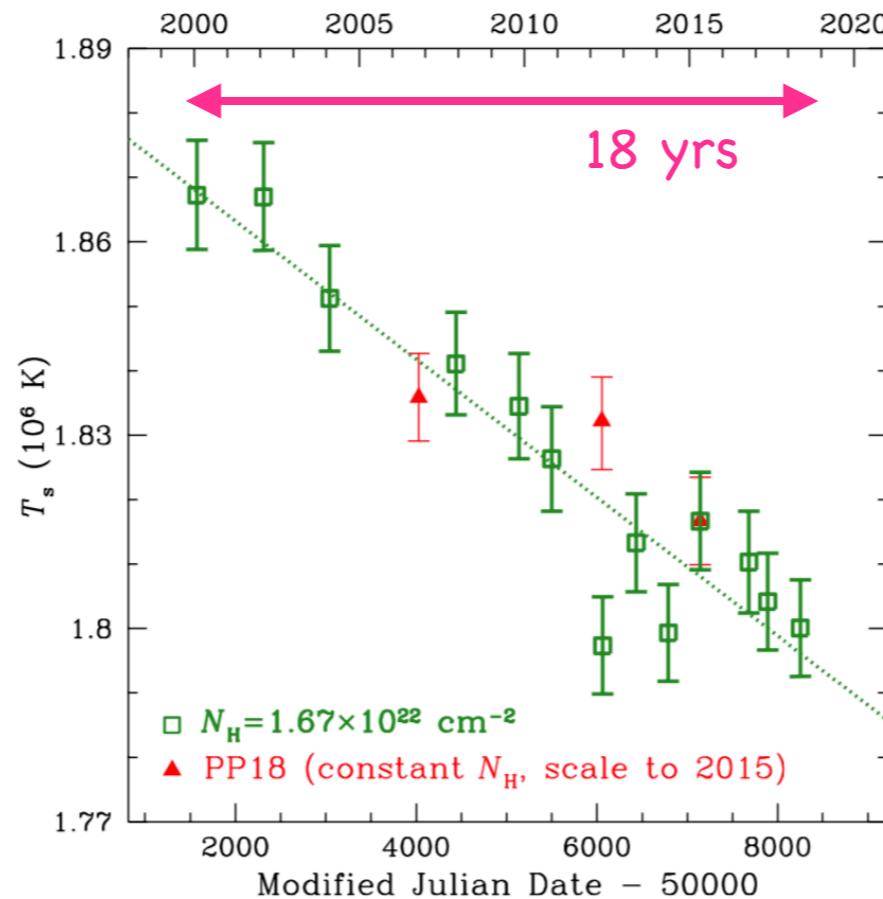
- The **Cooling** is observed!

Cas A NS is the only isolated NS whose cooling has been observed in real time.

**Temperature decreases by (3-4)% in 10 years.**

## More Recent data

W.C.G.Ho, et.al. 1904.07505



# Plan

## 1. Cas A NS Cooling

1.1. Cas A

1.2. Cas A NS

1.3 Cas A NS Cooling (observation)

1.4 Cas A NS Cooling (theory)

## 2. Cas A NS Cooling with axion

## 3. Summary



# Cas A NS Cooling (theory)

- The observed Cas A NS cooling can be explained within the standard NS cooling scenario.
- Neutron **superfluidity** plays a key role.  
(also proton **superconductivity**)

D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].  
P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].

# Cas A NS Cooling (theory)

## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu - L_\gamma$$

Photon emission luminosity. ( $dE_\gamma/dt$ )

Neutrino emission luminosity. ( $dE_\nu/dt$ )

Heat Capacity of the NS.  
 $C = dE_{\text{thermal}}/dT$

$$L_\gamma = 4\pi R^2 \sigma_{\text{SB}} T_s^4$$

※ assuming isothermal state  $T(r) \propto e^{-\phi(r)}$  for simplicity.  
In the numerical calculation, we followed  $T(r,t)$ .

# Cas A NS Cooling (theory)

## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu - L_\gamma$$

↑  
Neutrino emission  
luminosity. ( $dE_\nu/dt$ )

Photon emission  
luminosity. ( $dE_\gamma/dt$ )

Photon emission  
luminosity. ( $dE_\gamma/dt$ )

$$L_\gamma = 4\pi R^2 \sigma_{\text{SB}} T_s^4$$

$$L_\gamma \ll L_\nu \quad \text{for } t \lesssim 10^6 \text{ years}$$

Negligible for Cas A NS.  $t \simeq 300$  years

Heat Capacity of the NS.

$$C = dE_{\text{thermal}}/dT$$

# Cas A NS Cooling (theory)

## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu$$

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Neutrino emission  
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Heat Capacity of the NS.

$$C = dE_{\text{thermal}}/dT$$

# Cas A NS Cooling (theory)

## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu$$

- Direct Urca
- Modified Urca
- Bremsstrahlung
- PBF

# Cas A NS Cooling (theory)

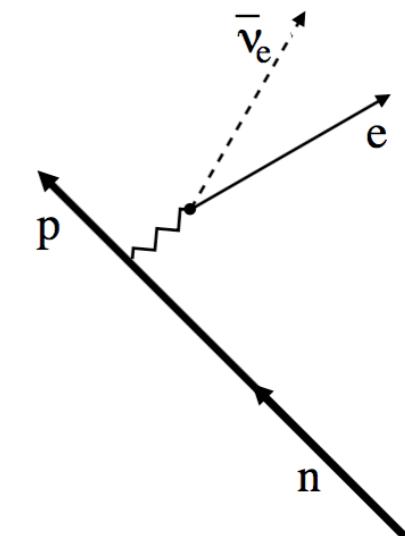
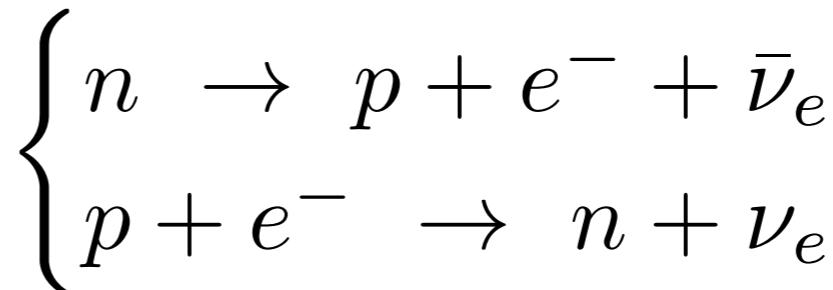
## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu$$

~~• Direct Urca~~

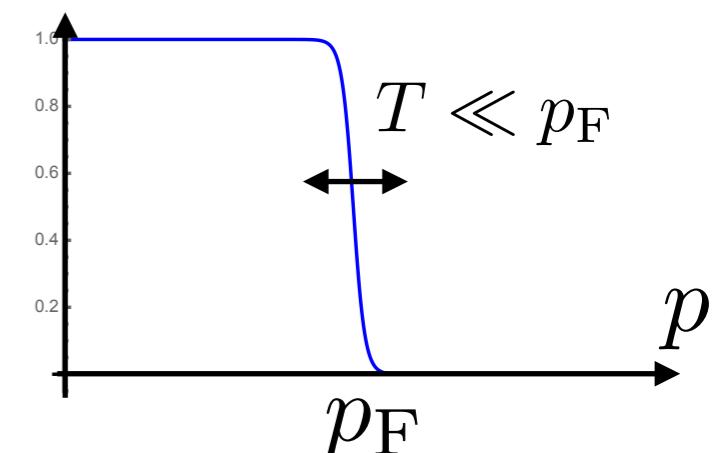
- Modified Urca
- Bremsstrahlung
- PBF

$\beta$  decay and its inverse:



- It requires  $p_p + p_e > p_n$ , which works only in very heavy NS and **unlikely** for Cas A NS.
- Even if it happens, the temperature would be  $T \ll T(\text{obs.})$  at  $\sim 300$  yrs, and **cannot explain the data**.

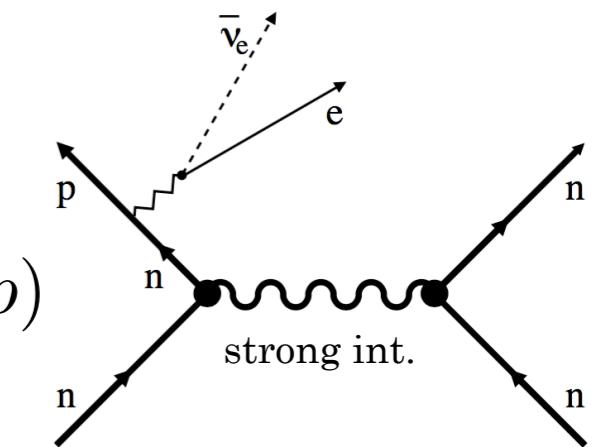
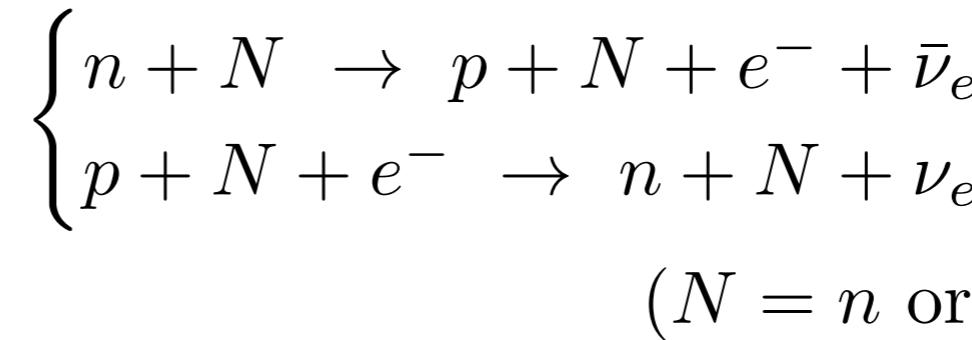
※ Neutron, proton, electron are all Fermi degenerate.



# Cas A NS Cooling (theory)

## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu$$



- **Dominant process** (before the onset of Cooper pairing)

- $L_\nu^{\text{MU}} \propto T^8$

$$L_\nu^{\text{MU}} \sim \underbrace{\int d^3 p_n}_{T} \underbrace{\int d^3 p_N}_{T} \cdot \underbrace{\int d^3 p_p}_{T} \underbrace{\int d^3 p_N}_{T} \underbrace{\int d^3 p_e}_{T} \cdot \underbrace{\int d^3 p_\nu \delta^4(p_i - p_f) E_\nu}_{T^3}$$

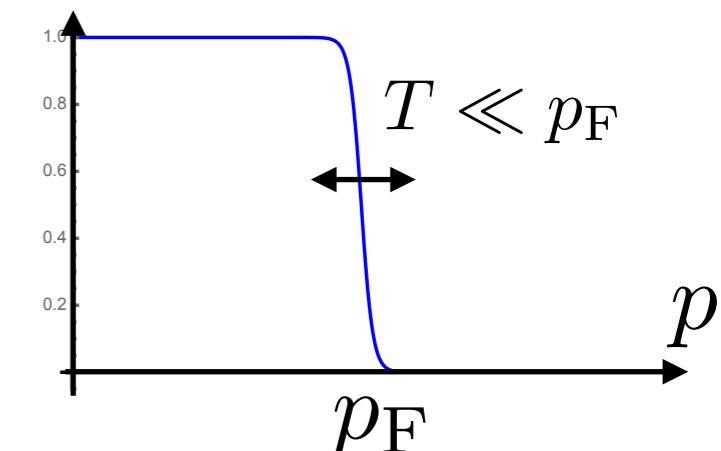
• **Direct Urca**

• **Modified Urca**

• Bremsstrahlung

• PBF

⊗ Neutron, proton, electron  
are all Fermi degenerate.



# Cas A NS Cooling (theory)

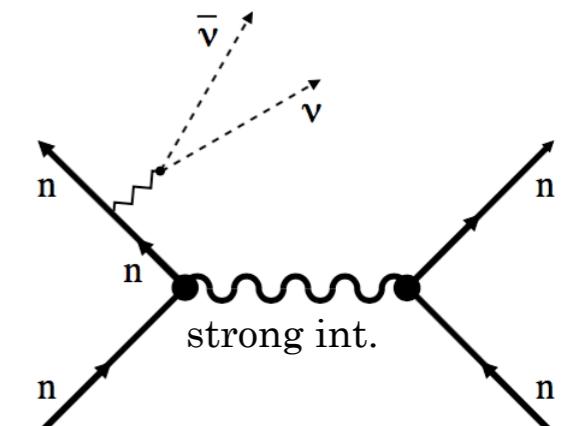
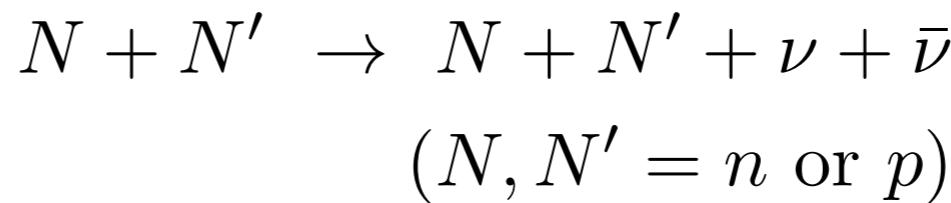
## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu$$

- ~~Direct Urca~~
- Modified Urca

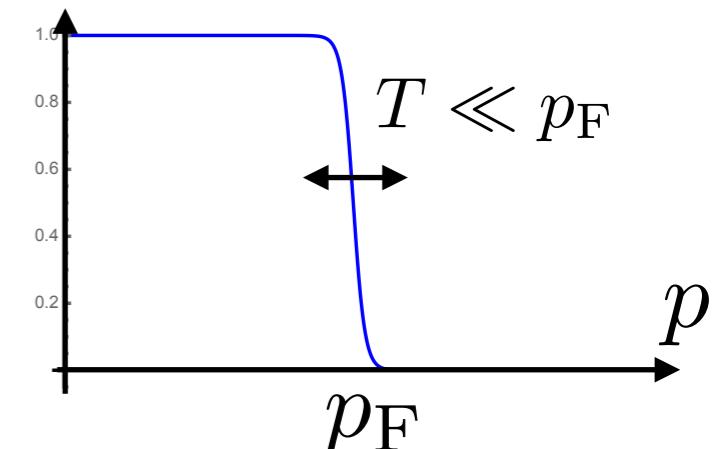
### Bremsstrahlung

- PBF



- similarly,  $L_\nu^{\text{Brems}} \propto T^8$
- but **subdominant**,  $L_\nu^{\text{Brems}} \sim \mathcal{O}(0.01)L_\nu^{\text{MU}}$

⊗ Neutron, proton, electron  
are all Fermi degenerate.



# Cas A NS Cooling (theory)

## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu$$

- ~~Direct Urca~~
- Modified Urca
- Bremsstrahlung
- (PBF)
  - We neglect it for the moment.  
(more on this later)

# Cas A NS Cooling (theory)

## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu \propto T^8$$

$\alpha T$

$$\implies T \propto t^{-1/6}$$

For Cas A NS observation,

$$\begin{cases} t \simeq 330 \text{ yrs} \\ \Delta t \simeq 10 \text{ yrs} \end{cases}$$

$$\implies \left. \frac{\Delta T}{T} \right|_{10 \text{ yrs}} \sim -\frac{1}{6} \cdot \frac{\Delta t}{t} \sim 0.5\%$$

surface temperature

- ~~Direct Urca~~
- Modified Urca
- Bremsstrahlung
- (PBF)

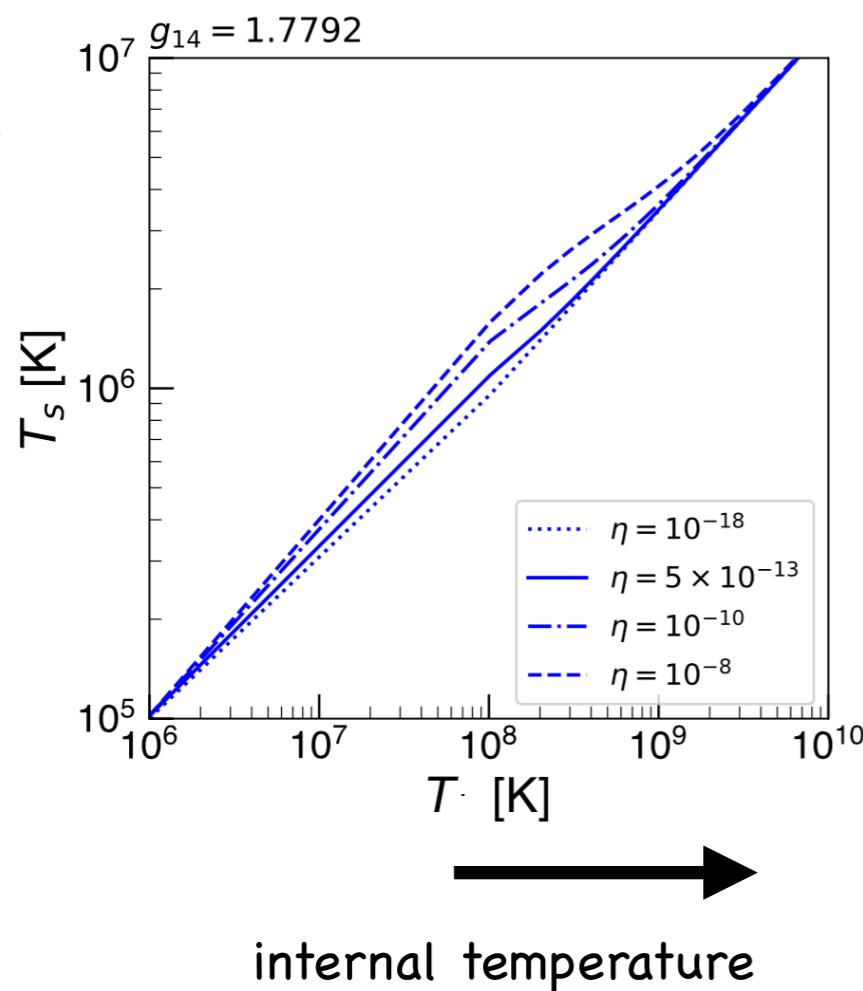
$$\implies \left. \frac{\Delta T_s}{T_s} \right|_{10 \text{ yrs}} \sim 0.3\% !!$$

# Cas A NS Cooling (theory)

NS surface is insulated from the hot interior by its envelope.

surface temperature (observed)

$$T_s \sim T^\alpha \quad (\alpha \sim 0.5)$$



$$\eta = g_{14}^2 \Delta M / M$$

$\Delta M$  : mass of light elements

$g_{14}$  : surface gravity in units of  $10^{14} \text{ cm/s}^2$

→

$$T \propto t^{-1/6}$$

For Cas A NS observation,

$$\begin{cases} t \simeq 330 \text{ yrs} \\ \Delta t \simeq 10 \text{ yrs} \end{cases}$$

$$\Rightarrow \left. \frac{\Delta T}{T} \right|_{10 \text{ yrs}} \sim -\frac{1}{6} \cdot \frac{\Delta t}{t} \sim 0.5\%$$

surface temperature

→

$$\left. \frac{\Delta T_s}{T_s} \right|_{10 \text{ yrs}} \sim 0.3\% !!$$

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surface temperature

- ~~Direct Urca~~
- **Modified Urca**
- **Bremsstrahlung**
- (PBF)

$$\implies \left. \frac{\Delta T_s}{T_s} \right|_{10 \text{ yrs}} \sim 0.3\% !!$$

**much smaller than the observation,  $\Delta T_s/T_s \sim (3-4)\%$ .**

# Cas A NS Cooling (theory)

## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu$$

- ~~Direct Urca~~
- Modified Urca
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- PBF

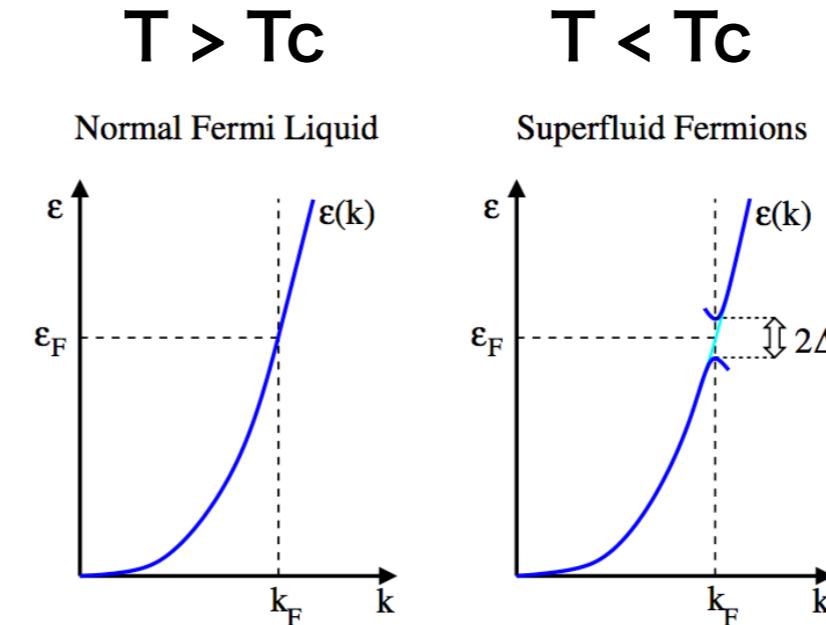
# Cas A NS Cooling (theory)

## NS temperature evolution

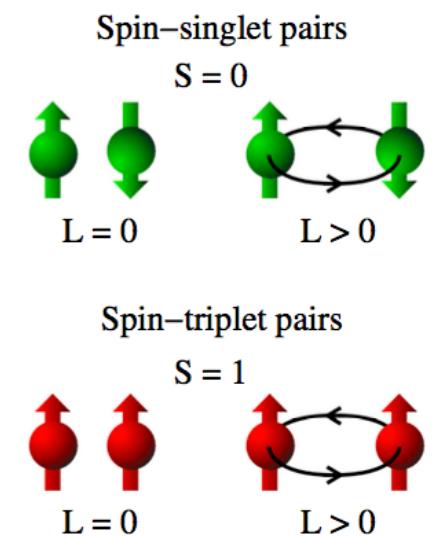
$$C \frac{dT}{dt} = -L_\nu$$

- Direct Urca
- Modified Urca
- Bremsstrahlung
- PBF

- At  $T < T_c$ , Cooper pairing occurs.



neutron singlet ( $^1S_0$ )  
neutron triplet ( $^3P_2$ )  
proton singlet ( $^1S_0$ )



- M.Urca and Brems. are suppressed then.
- On the other hand, a new process,  
**Cooper pair breaking and formation (PBF),**  
is enhanced.

# Cas A NS Cooling (theory)

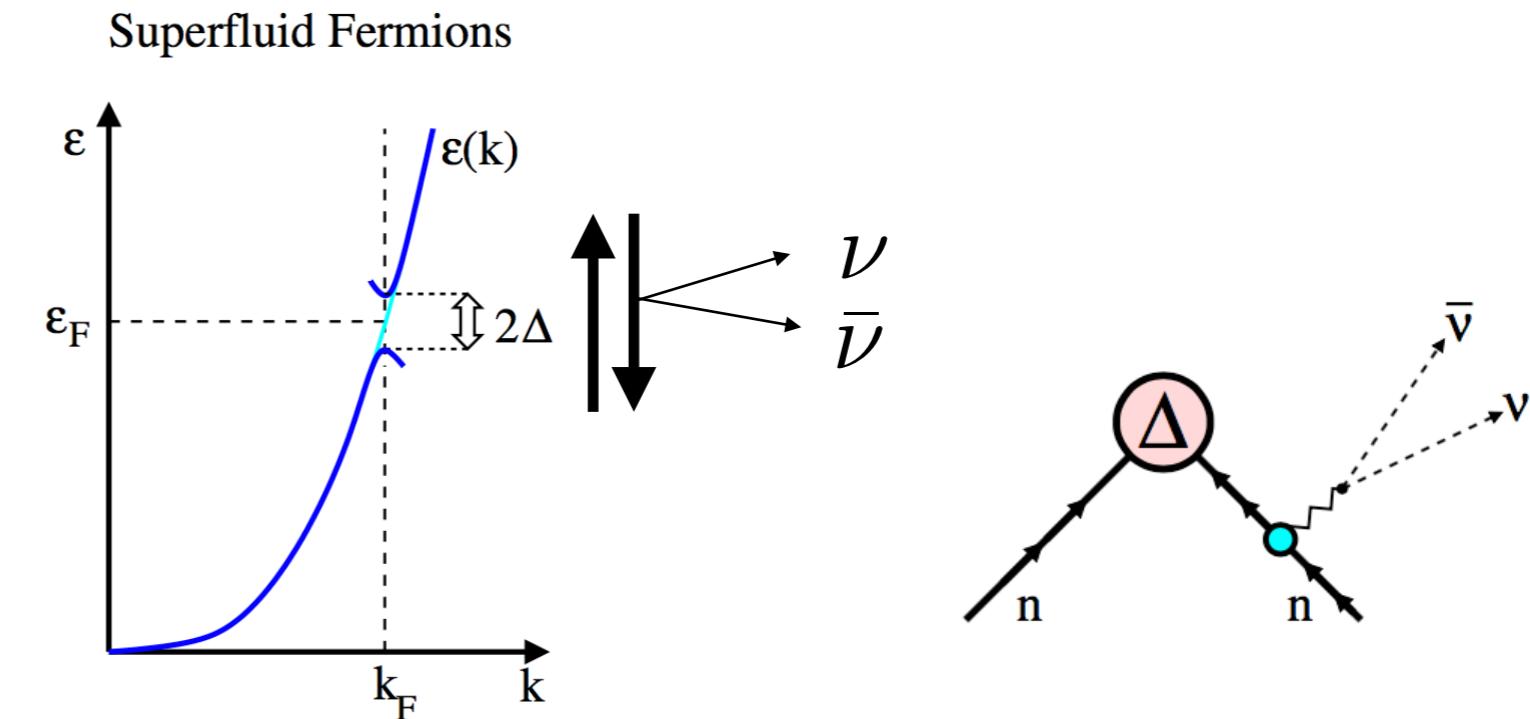
## NS temperature evolution

$$C \frac{dT}{dt} = -L_\nu$$

- ~~Direct Urca~~
- Modified Urca
- Bremsstrahlung

**PBF**

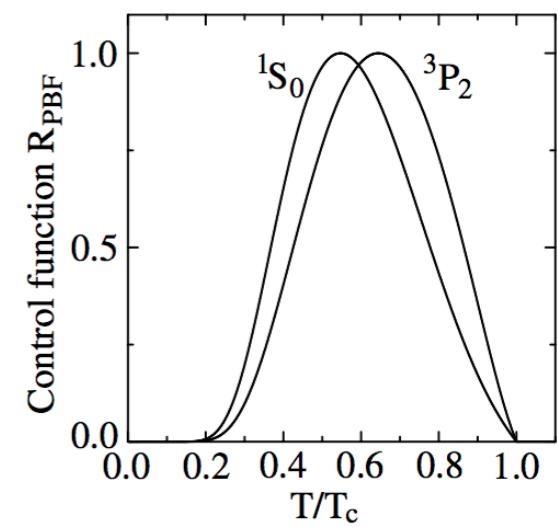
### Cooper pair breaking and formation (PBF)



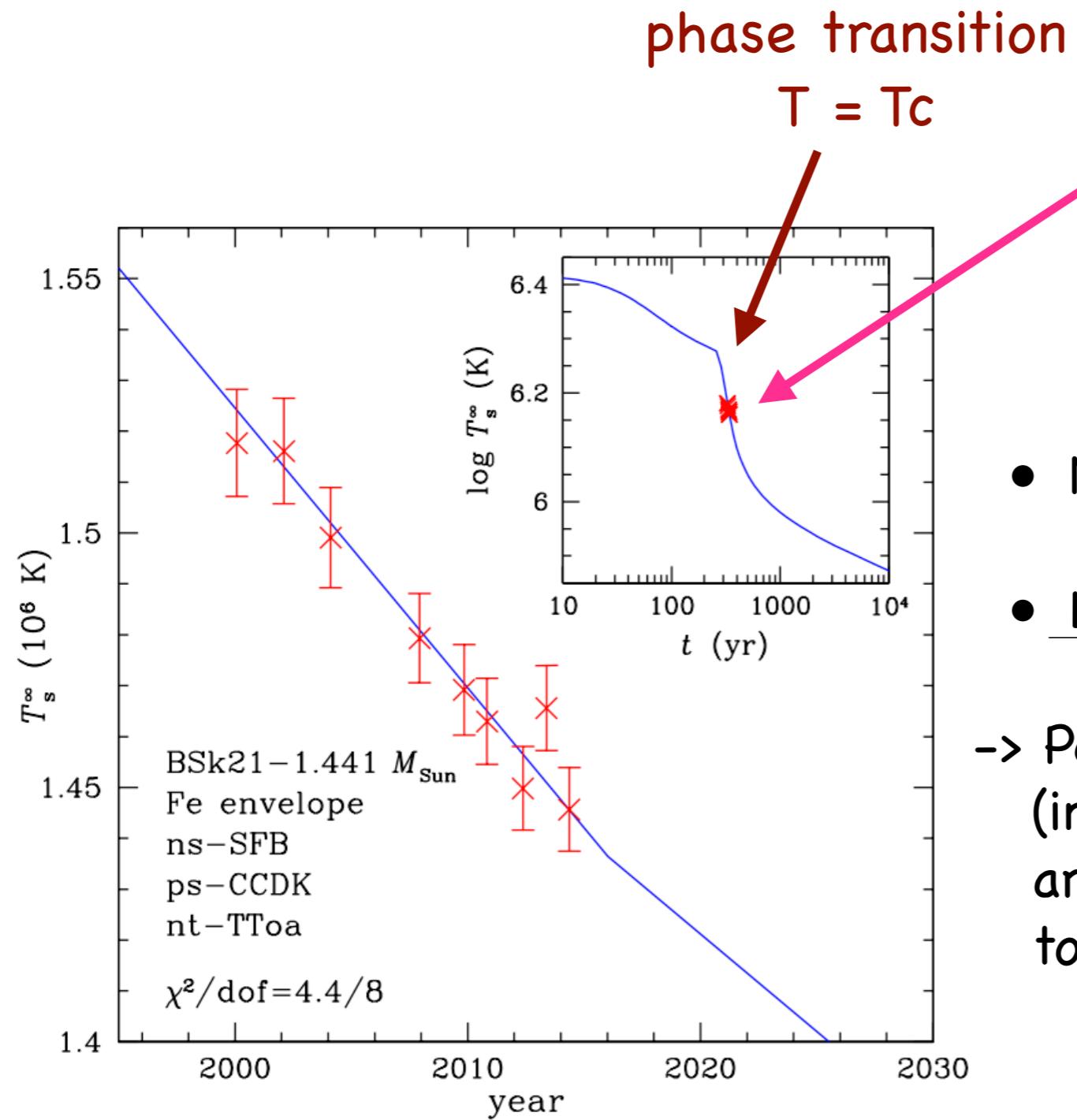
Effective only in a short period

- At  $T > T_c$ , no paring.
- At  $T \ll T_c$ , no pair breaking.

It triggers a sudden cooling at around  $T = T_c$ .

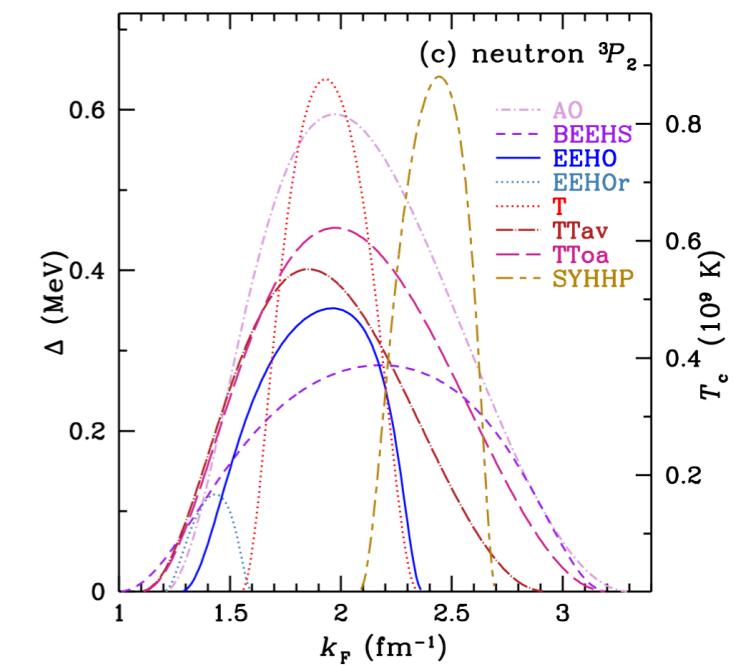


# Cas A NS Cooling (theory)



sudden, rapid cooling  
by PBF process.

- Neutron triplet ( $n-{}^3P_2$ ) PBF is dominant.
  - Large uncertainty in  $n-{}^3P_2$  gap.
- > Parameters (in particular,  $T_c$ ) are adjusted to fit the data.



# Cas A NS Cooling (theory)

- The observed Cas A NS cooling can be explained within the standard NS Cooling.
- Neutron **superfluidity** (and proton **superconductivity**) play key roles.

D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].

P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].

PRL 106, 081101 (2011)

 Selected for a Viewpoint in Physics  
PHYSICAL REVIEW LETTERS

week ending  
25 FEBRUARY 2011



## Rapid Cooling of the Neutron Star in Cassiopeia A Triggered by Neutron Superfluidity in Dense Matter

Dany Page,<sup>1</sup> Madappa Prakash,<sup>2</sup> James M. Lattimer,<sup>3</sup> and Andrew W. Steiner<sup>4</sup>

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<sup>2</sup>*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701-2979, USA*

<sup>3</sup>*Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794-3800, USA*

<sup>4</sup>*Joint Institute for Nuclear Astrophysics, National Superconducting Cyclotron Laboratory and, Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

(Received 29 November 2010; published 22 February 2011)

We propose that the observed cooling of the neutron star in Cassiopeia A is due to enhanced neutrino emission from the recent onset of the breaking and formation of neutron Cooper pairs in the  $^3P_2$  channel. We find that the critical temperature for this superfluid transition is  $\approx 0.5 \times 10^9$  K. The observed rapidity of the cooling implies that protons were already in a superconducting state with a larger critical temperature. This is the first direct evidence that superfluidity and superconductivity occur at supranuclear densities within neutron stars. Our prediction that this cooling will continue for several decades at the present rate can be tested by continuous monitoring of this neutron star.

# Cas A NS Cooling (theory)

- The observed Cas A NS cooling can be explained within the standard NS Cooling.
- Neutron **superfluidity** (and proton **superconductivity**) play key roles.

D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].

P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].



## Cooling neutron star in the Cassiopeia A supernova remnant: evidence for superfluidity in the core

Peter S. Shternin,<sup>1,2</sup>★ Dmitry G. Yakovlev,<sup>1</sup> Craig O. Heinke<sup>3</sup> and Daniel J. Patnaude<sup>4</sup>

<sup>1</sup>Ioffe Physical Technical Institute, Politekhnicheskaya 26, 194021 St Petersburg, Russia

<sup>2</sup>St Petersburg State Polytechnical University, Politekhnicheskaya 29, 195251 St Petersburg, Russia

<sup>3</sup>Department of Physics, University of Alberta, Room 238 CEB, 11322-89 Avenue, Edmonton, AB T6G 2J1, Canada

<sup>4</sup>School of Mathematics, University of Southampton, Southampton SO17 1BJ, UK

<sup>5</sup>Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA

### ABSTRACT

According to recent results of Ho & Heinke, the Cassiopeia A supernova remnant contains a young ( $\approx 330$ -yr-old) neutron star (NS) which has carbon atmosphere and shows notable decline of the effective surface temperature. We report a new (2010 November) *Chandra* observation which confirms the previously reported decline rate. The decline is naturally explained if neutrons have recently become superfluid (in triplet state) in the NS core, producing a splash of neutrino emission due to Cooper pair formation (CPF) process that currently accelerates the cooling. This scenario puts stringent constraints on poorly known properties of NS cores: on density dependence of the temperature  $T_{\text{cn}}(\rho)$  for the onset of neutron superfluidity [ $T_{\text{cn}}(\rho)$  should have a wide peak with maximum  $\approx (7\text{--}9) \times 10^8$  K]; on the reduction factor  $q$  of CPF process by collective effects in superfluid matter ( $q > 0.4$ ) and on the intensity of neutrino emission before the onset of neutron superfluidity (30–100 times weaker than the standard modified Urca process). This is serious evidence for nucleon superfluidity in NS cores that comes from observations of cooling NSs.

### ABSTRACT

According to recent results of Ho & Heinke, the Cassiopeia A supernova remnant contains a young ( $\approx 330$ -yr-old) neutron star (NS) which has carbon atmosphere and shows notable decline of the effective surface temperature. We report a new (2010 November) *Chandra* observation which confirms the previously reported decline rate. The decline is naturally explained if neutrons have recently become superfluid (in triplet state) in the NS core, producing a splash of neutrino emission due to Cooper pair formation (CPF) process that currently accelerates the cooling. This scenario puts stringent constraints on poorly known properties of NS cores: on density dependence of the temperature  $T_{\text{cn}}(\rho)$  for the onset of neutron superfluidity [ $T_{\text{cn}}(\rho)$  should have a wide peak with maximum  $\approx (7\text{--}9) \times 10^8$  K]; on the reduction factor  $q$  of CPF process by collective effects in superfluid matter ( $q > 0.4$ ) and on the intensity of neutrino emission before the onset of neutron superfluidity (30–100 times weaker than the standard modified Urca process). This is serious evidence for nucleon superfluidity in NS cores that comes from observations of cooling NSs.

# Plan

## 1. Cas A NS Cooling

1.1. Cas A

1.2. Cas A NS

1.3 Cas A NS Cooling (observation)

1.4 Cas A NS Cooling (theory)

## 2. Cas A NS Cooling with axion

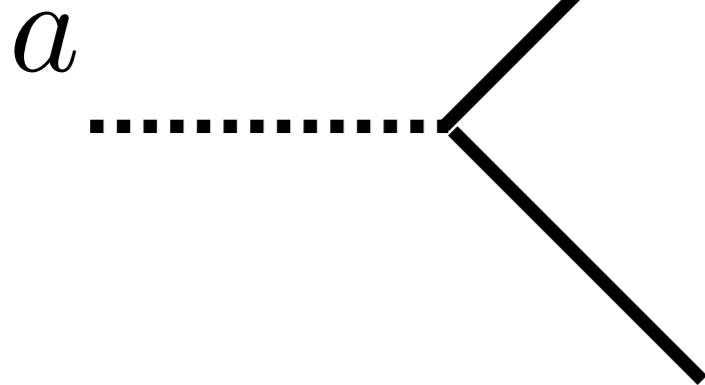
## 3. Summary

# Cas A NS Cooling with axion

$$C \frac{dT}{dt} = -L_\nu - L_a$$

axion emission

$$N = p, n$$



$$\mathcal{L}_{\text{int}} = \sum_{N=p,n} \frac{C_N}{2f_a} \bar{N} \gamma^\mu \gamma_5 N \partial_\mu a$$

KSVZ:  $\begin{cases} C_p = -0.47(3) \\ C_n = -0.02(3) \end{cases}$

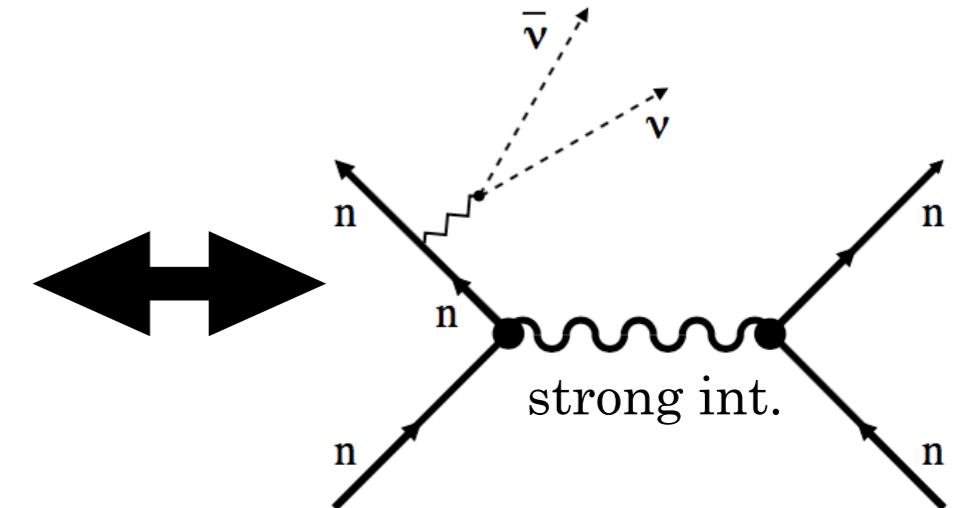
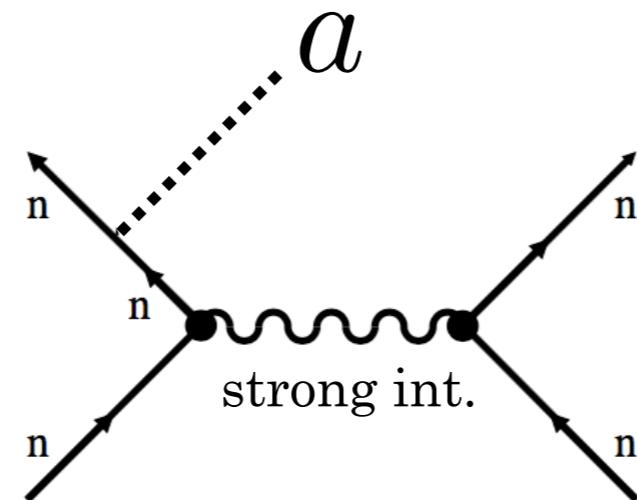
DFSZ:  $\begin{cases} C_p = -0.182(25) - 0.435 \sin^2 \beta \\ C_n = -0.160(25) - 0.414 \sin^2 \beta \end{cases}$

# Cas A NS Cooling with axion

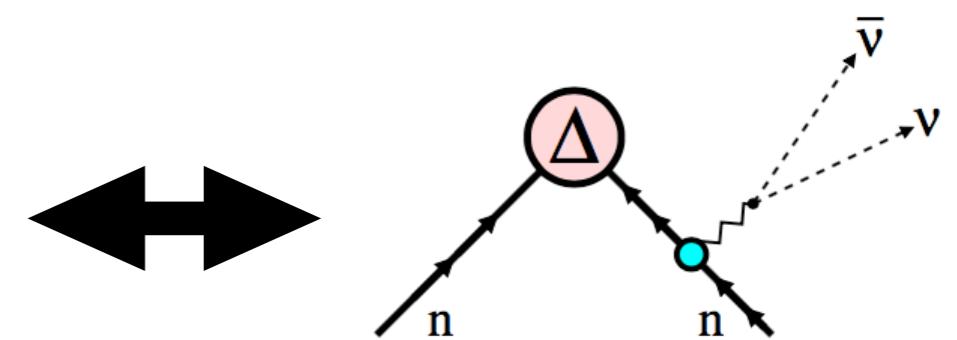
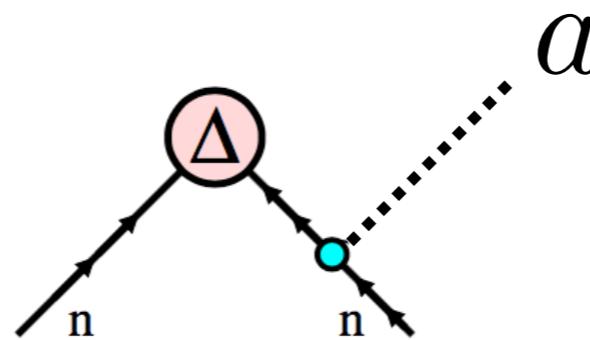
$$C \frac{dT}{dt} = -L_\nu - L_a$$

axion emission

Bremsstrahlung  
axion emission



PBF  
axion emission



Brems.: N. Iwamoto, Phys. Rev. Lett. 53, 1198 (1984); N. Iwamoto,'89, '01.

PBF: A. Sedrakian, 1512.07828 [PRD]; J. Keller, A. Sedrakian,'12.

# Cas A NS Cooling with axion

$$C \frac{dT}{dt} = -L_\nu - L_a$$

axion emission

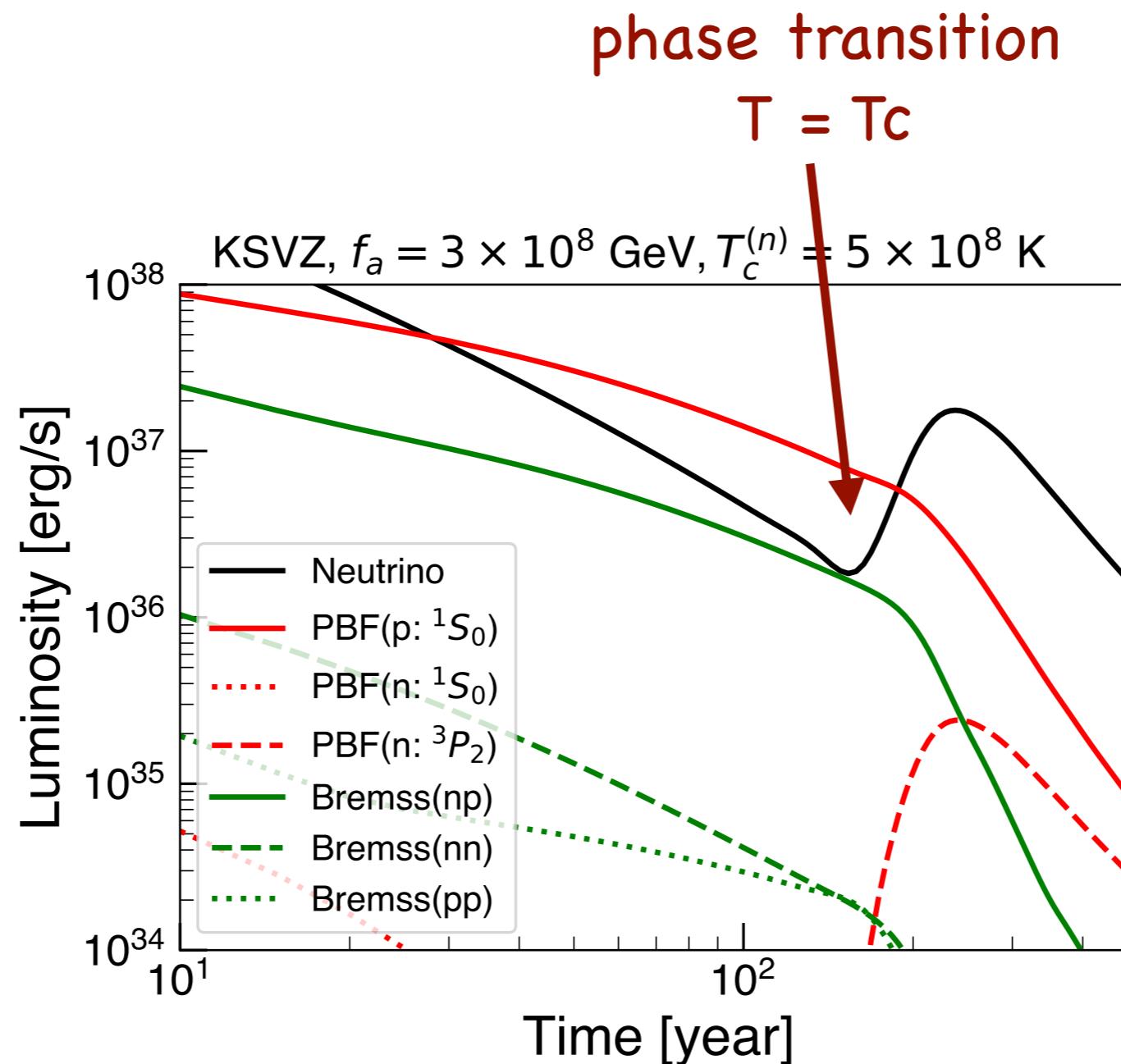
## What we did:

- followed NS cooling with axion emission (Brems. and PBF).  
by modifying a public code NSCool.
- APR EoS.
- NS mass  $M = 1.4 \text{ Msun}$ .
- gap models:
  - ▶  $n^{-1}S_0$  gap: SFB (doesn't matter)
  - ▶  $p^{-1}S_0$  gap: CCDK (doesn't matter as far as large enough)
  - ▶  $n^{-3}P_2$  gap: gap height  $\Delta \propto T_c$  and width: free parameter.

# Cas A NS Cooling with axion

## Results

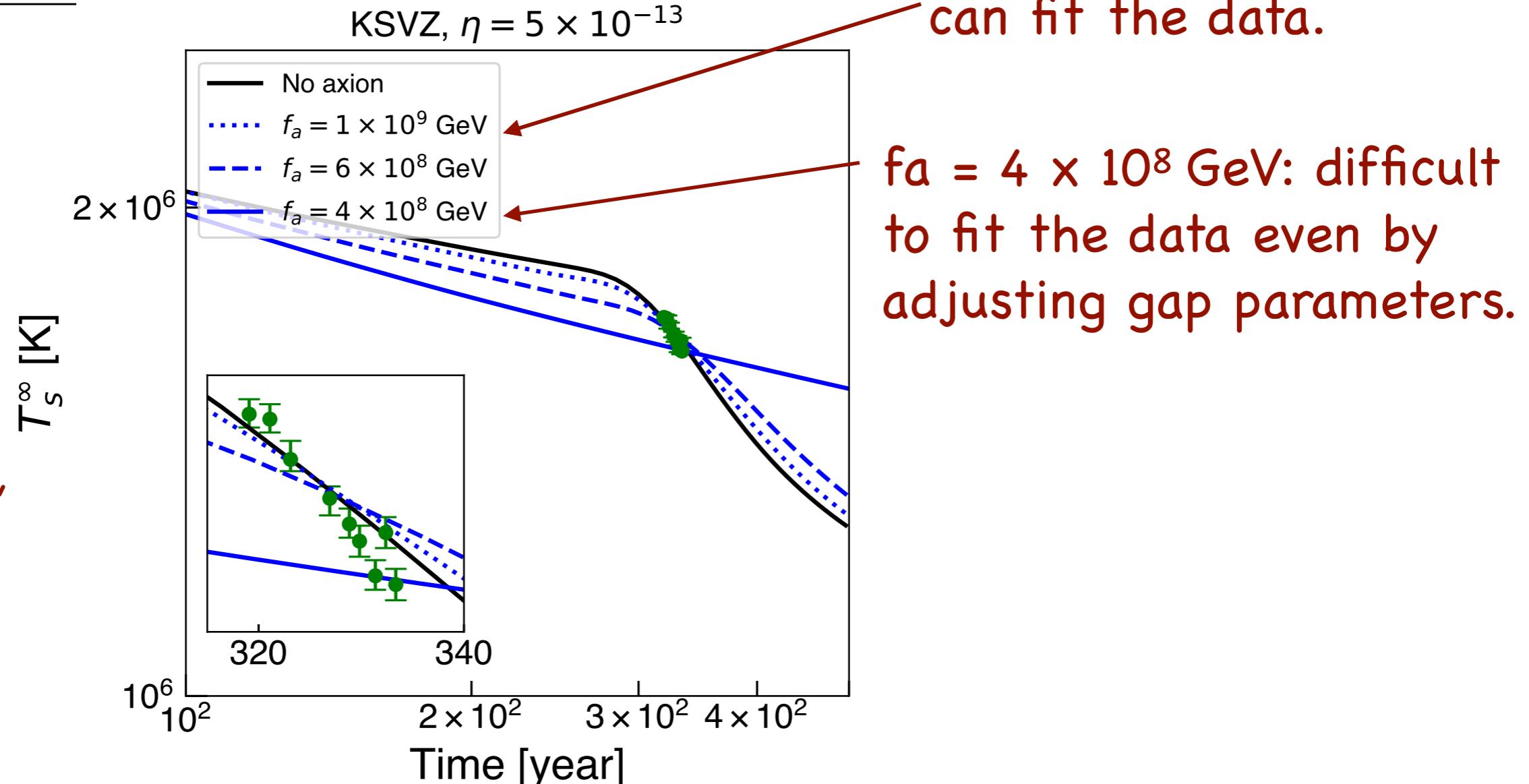
K. Hamaguchi,  
N. Nagata,  
K. Yanagi,  
J. Zheng,  
1806.07151



Axion emission can be as strong as neutrino emission.

# Cas A NS Cooling with axion

## Results



obtained a new bound:  $f_a \gtrsim 5 \times 10^8 \text{ GeV}$  (KS VZ)

(for an envelope with a thin carbon layer)

cf. SN1987A bound:  $f_a \gtrsim 4 \times 10^8 \text{ GeV}$

# Summary

A rapid cooling of Cas A Neutron Star (NS) has been observed.

It can be explained within the standard NS cooling scenario. (i.e., without physics beyond the Standard Model)

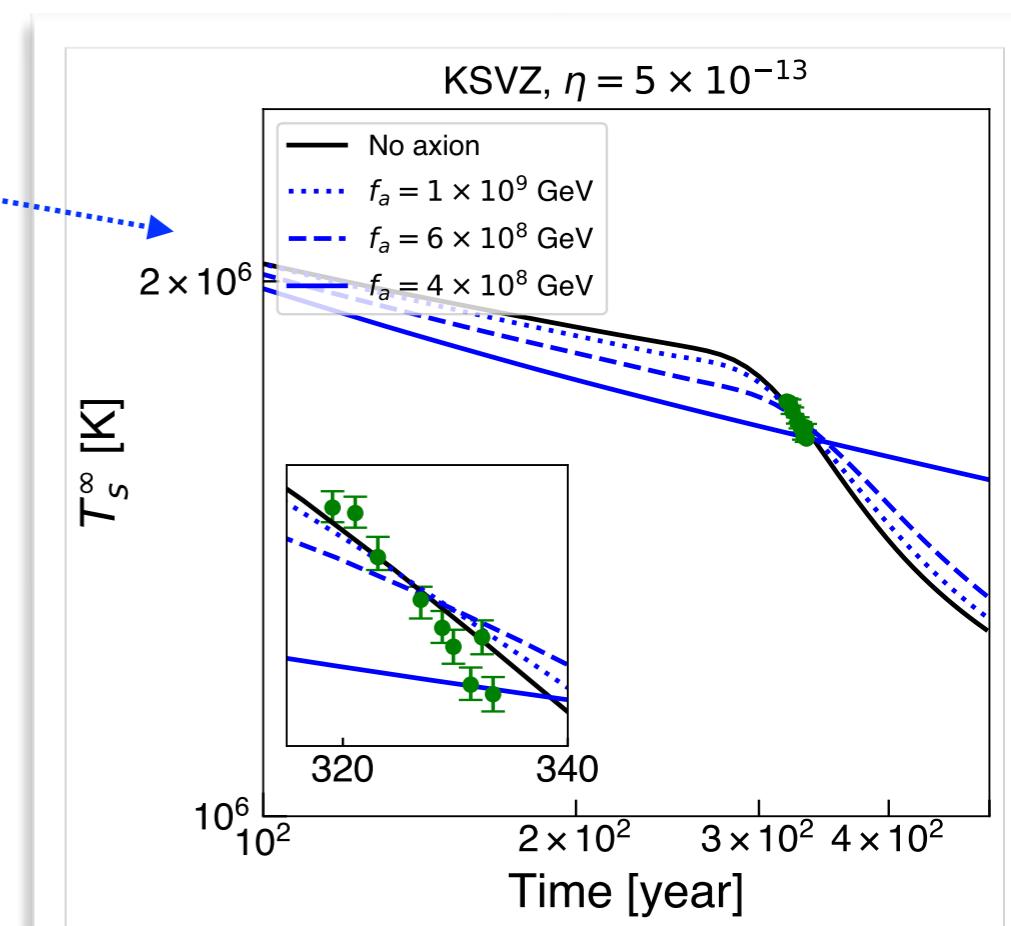
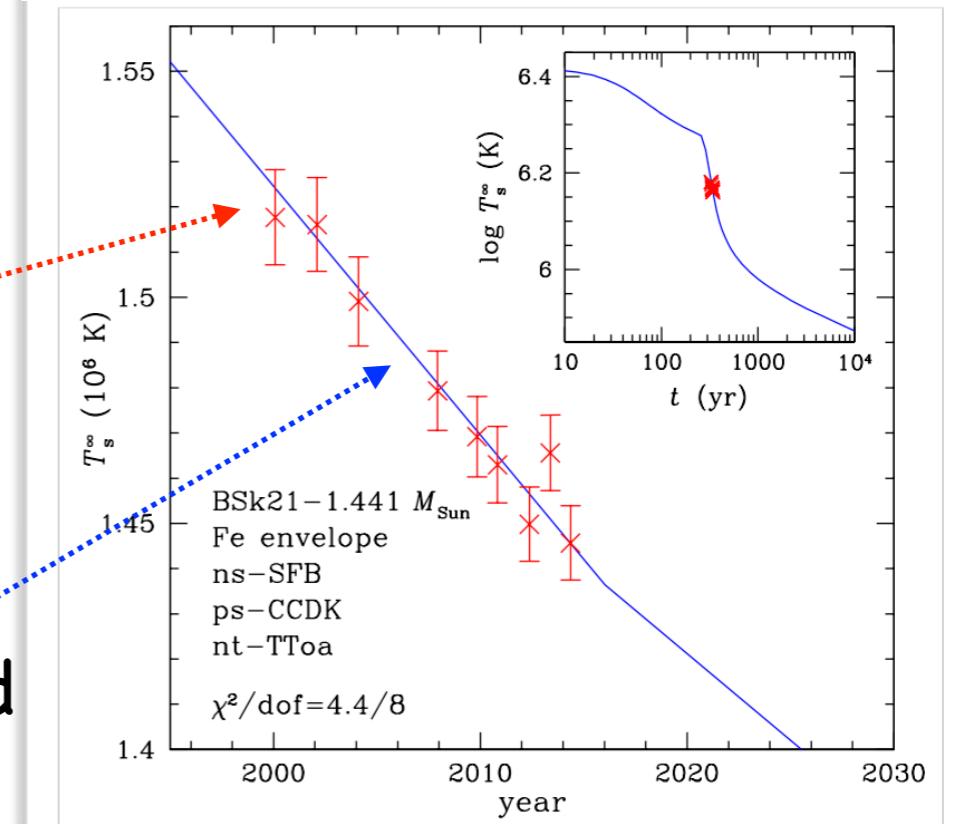


If there is an extra cooling, such as an axion emission, the cooling is modified.

We studied the Cas A NS cooling with an axion emission, and obtained a new bound on the axion decay constant,

$f_a > O(10^8)$  GeV.

(comparable to the existing SN1987A bound)

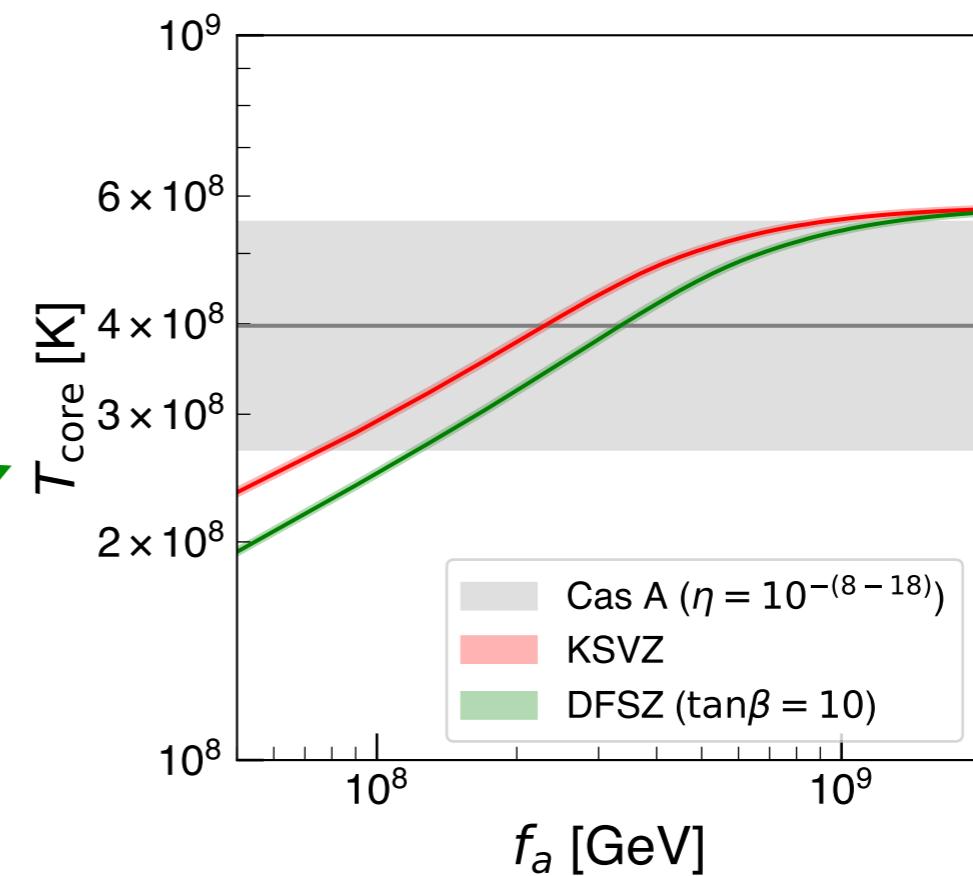
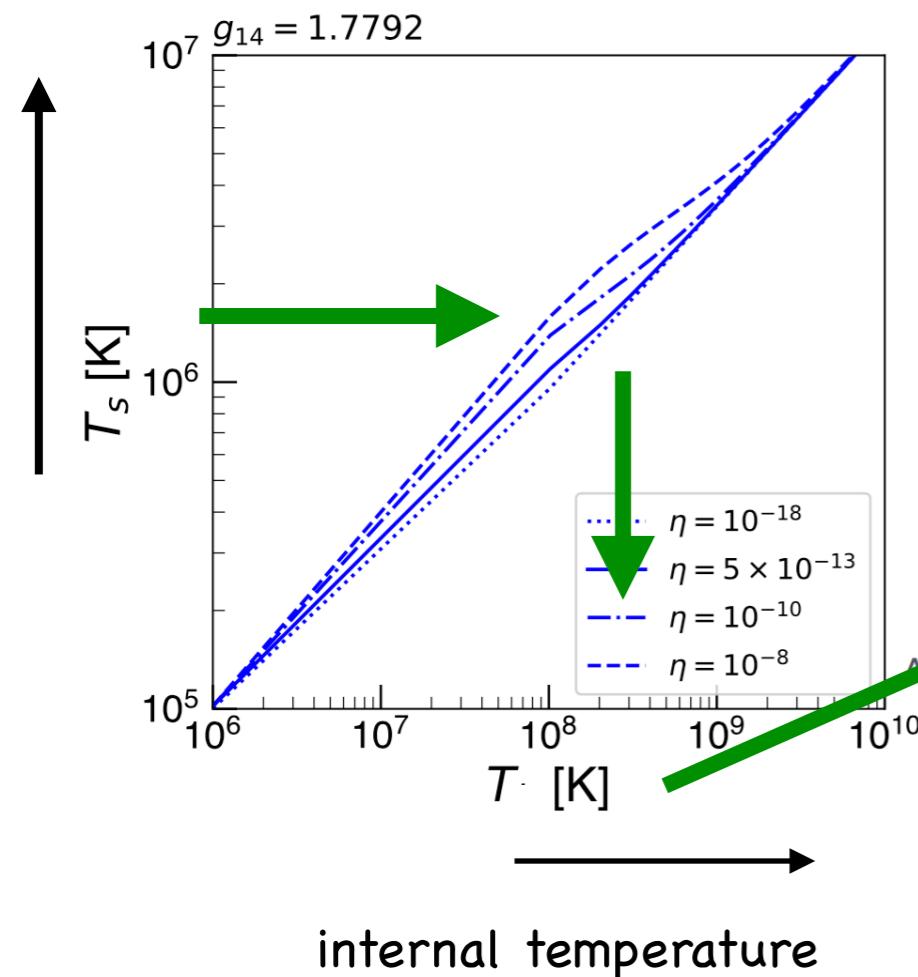


# Backup

# Cas A NS Cooling with axion

Remark: uncertainty from envelope

surface  
temperature  
(observed)



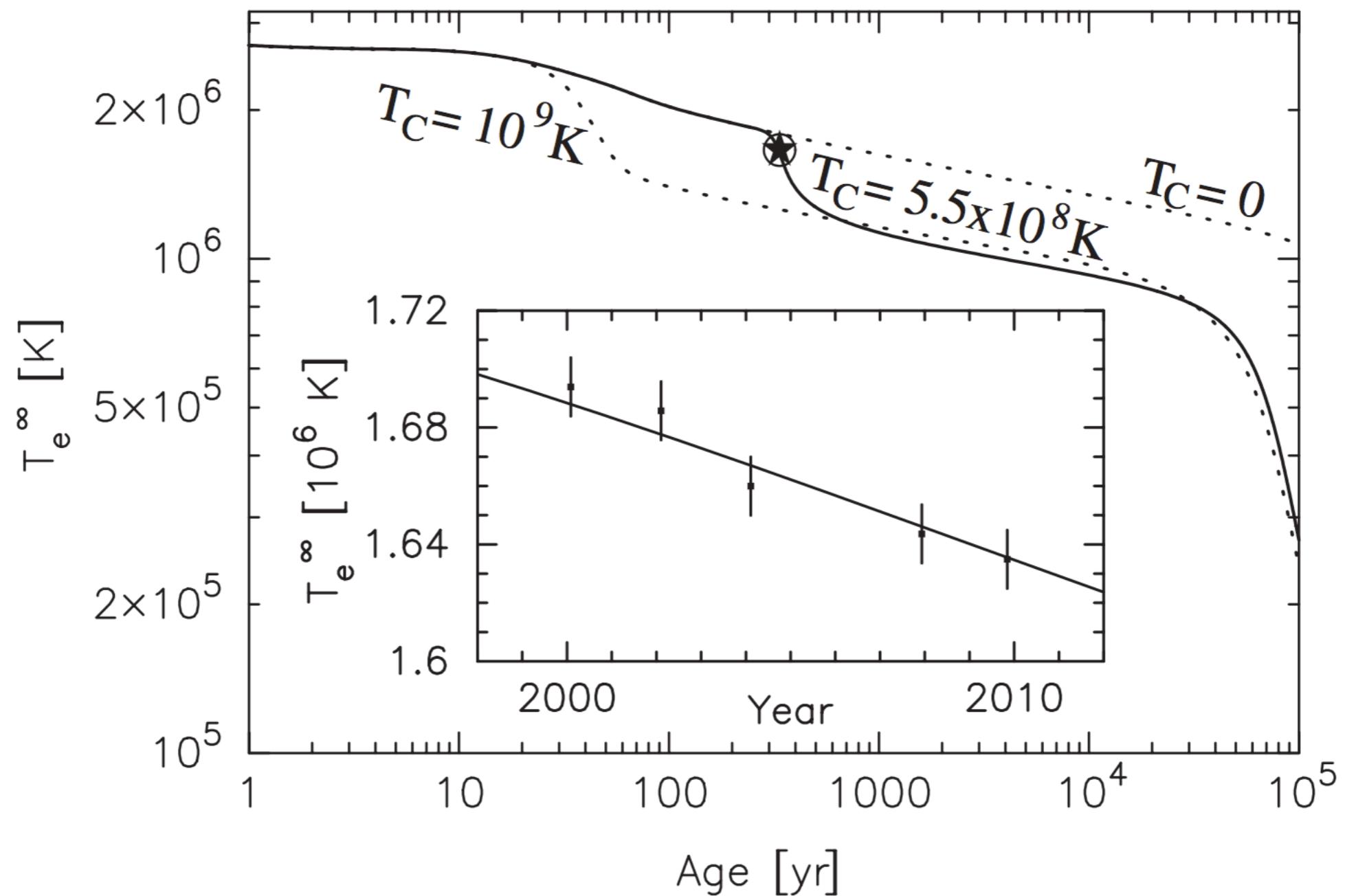
$\implies O(1)$  uncertainty in  $f_a$  bound.

# Alternative scenario to explain Cas A cooling

- longer thermal relaxation timescale in the crust or core
- etc

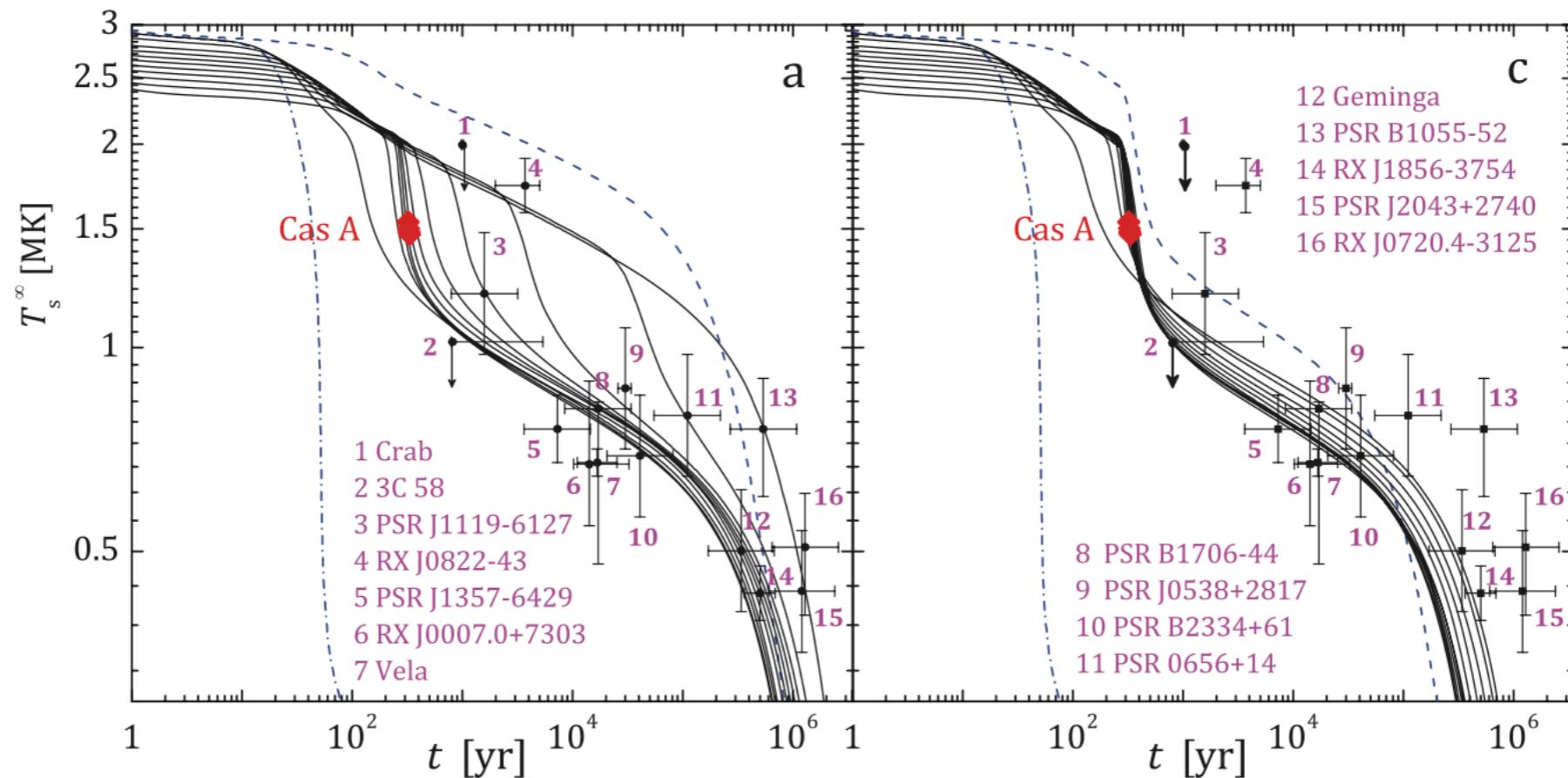
S.-H. Yang, C.-M. Pi, and X.-P. Zheng, arXiv:1103.1092;  
R. Negreiros, S. Schramm, and F. Weber, arXiv:1103.3870;  
D. Blaschke, H. Grigorian, D. N. Voskresensky, and F. Weber, arXiv:1108.4125;  
T. Noda, M.-A. Hashimoto, N. Yasutake, T. Maruyama, T. Tatsumi, and M. Fujimoto, arXiv:1109.1080;  
A. Sedrakian, arXiv:1303.5380;  
D. Blaschke, H. Grigorian, and D. N. Voskresensky, arXiv:1308.4093;  
A. Bonanno, M. Baldo, G. F. Burgio, and V. Urpin, arXiv:1311.2153;  
L. B. Leinson, arXiv:1411.6833;  
G. Taranto, G. F. Burgio, and H. J. Schulze, arXiv:1511.04243;  
T. Noda, N. Yasutake, M.-a. Hashimoto, T. Maruyama, T. Tatsumi, and M. Y. Fujimoto, arXiv:1512.05468;  
H. Grigorian, D. N. Voskresensky, and D. Blaschke, arXiv:1603.02634.

# Minimal Cooling vs Cas A NS



D. Page, M. Prakash, J. M. Lattimer, A. W. Steiner, 1011.6142 [Phys.Rev.Lett.].

# Other NS temperature observations



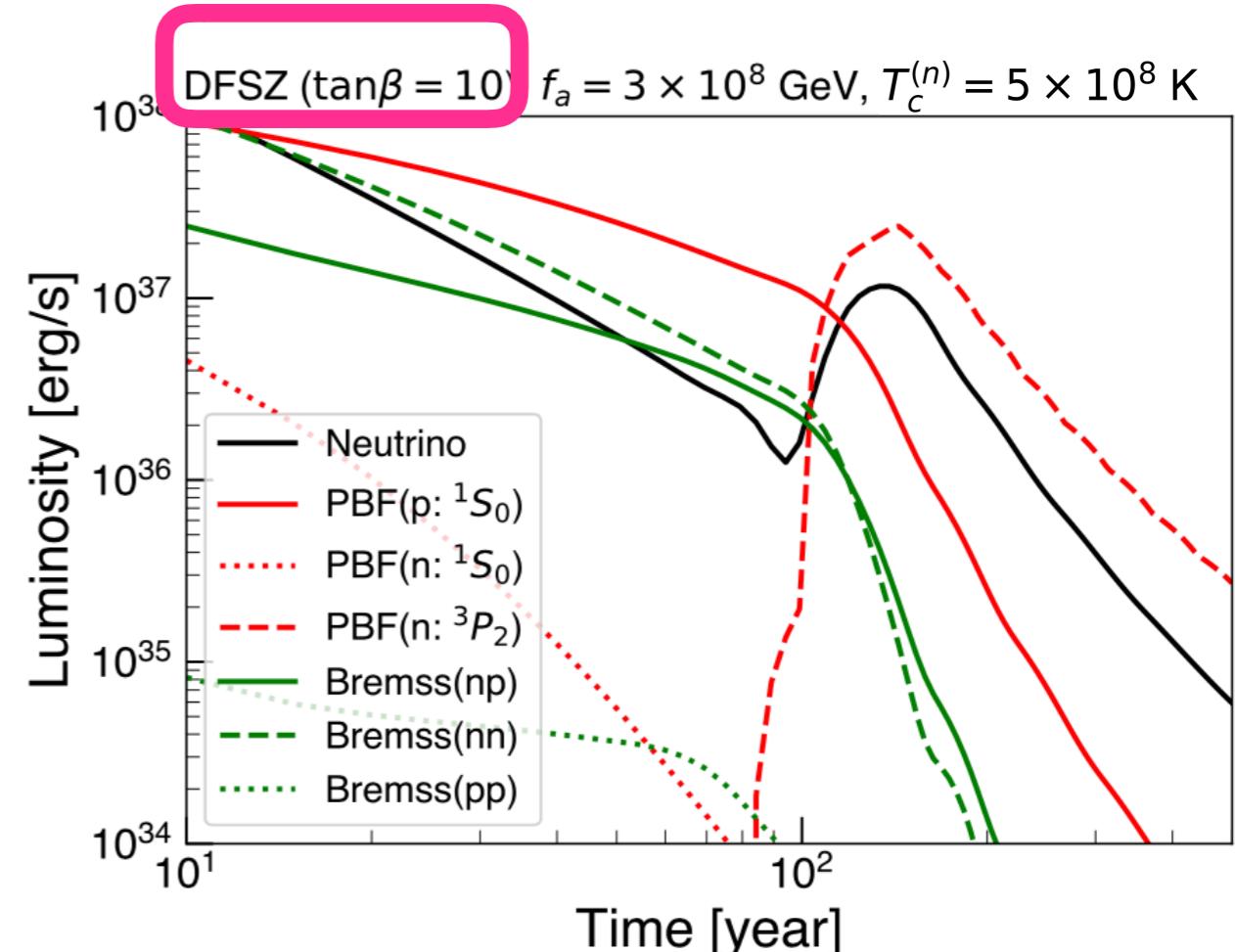
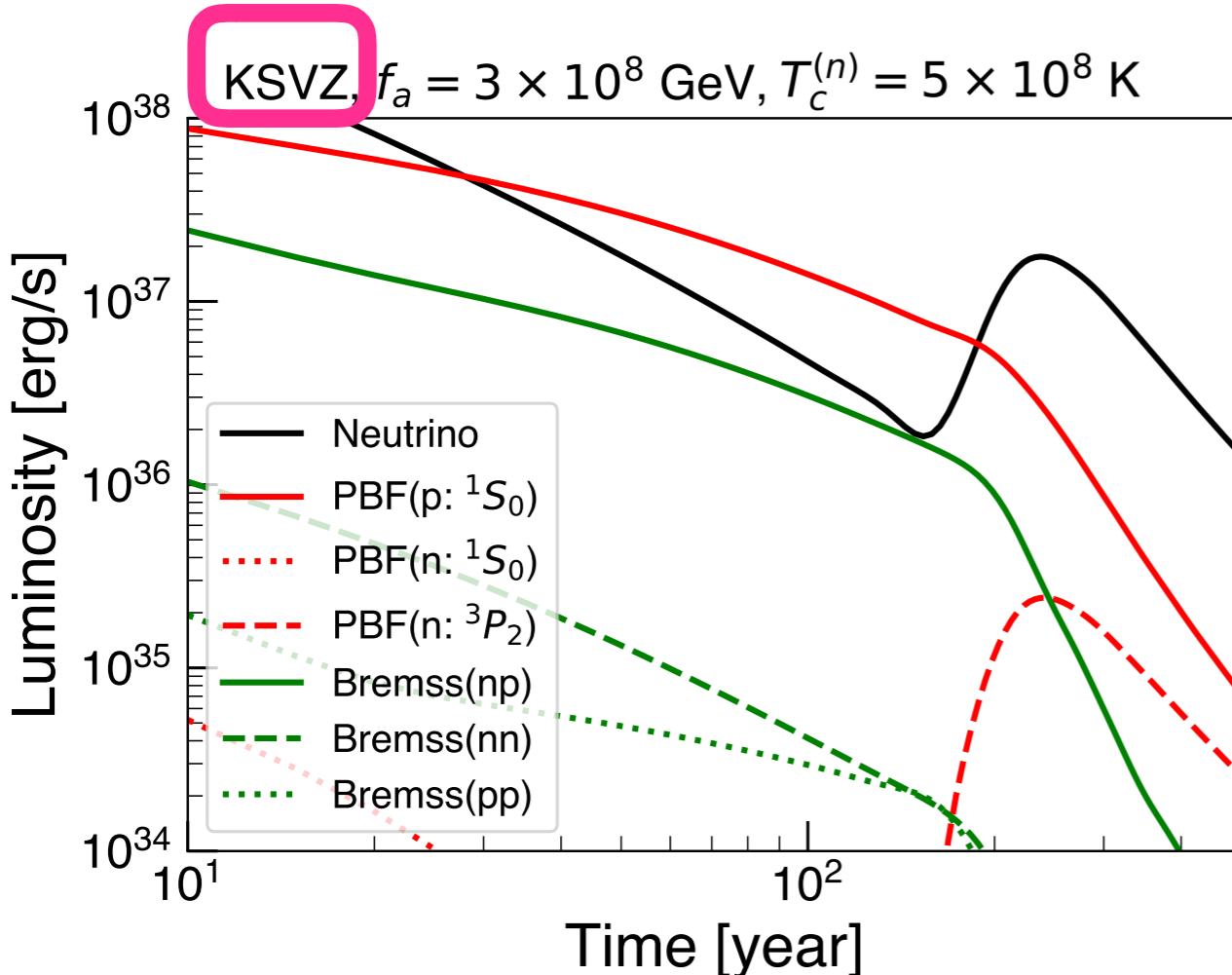
**Figure 2.** Sequences of (solid) cooling curves for NSs of masses from  $1 M_{\odot}$  to  $M_{\max}$  (through  $0.1 M_{\odot}$ ) with strong proton superfluidity and moderate neutron superfluidity (a) (left-hand panel) or (c) (right-hand panel) in the core ( $q = 0.76$ ) compared with observations of isolated NSs. Dashed lines refer to warmest stars of these types –  $1 M_{\odot}$  stars with the carbon surface layer of mass  $10^{-8} M_{\odot}$ . Dot-dashed lines refer to coolest  $M_{\max}$  stars without proton superfluidity in the inner core.

P. S. Shternin, D. G. Yakovlev, C. O. Heinke, W. C. G. Ho, D. J. Patnaude, 1012.0045 [MNRAS].

# KSVZ and DFSZ

$$\text{KSVZ: } \begin{cases} C_p = -0.47(3) \\ C_n = -0.02(3) \end{cases}$$

$$\text{DFSZ: } \begin{cases} C_p = -0.182(25) - 0.435 \sin^2 \beta \\ C_n = -0.160(25) - 0.414 \sin^2 \beta \end{cases}$$



$f_a \gtrsim 5 \times 10^8 \text{ GeV (KSVZ)}$   
 $f_a \gtrsim 7 \times 10^8 \text{ GeV (DFSZ, } \tan\beta = 10\text{)}$

(larger uncertainty from envelope for DFSZ)

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