Neutron Stars

Lecture 2:
Evolution and Cooling

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NS 1987A
in
SN 1987A

The Supernova 1987A

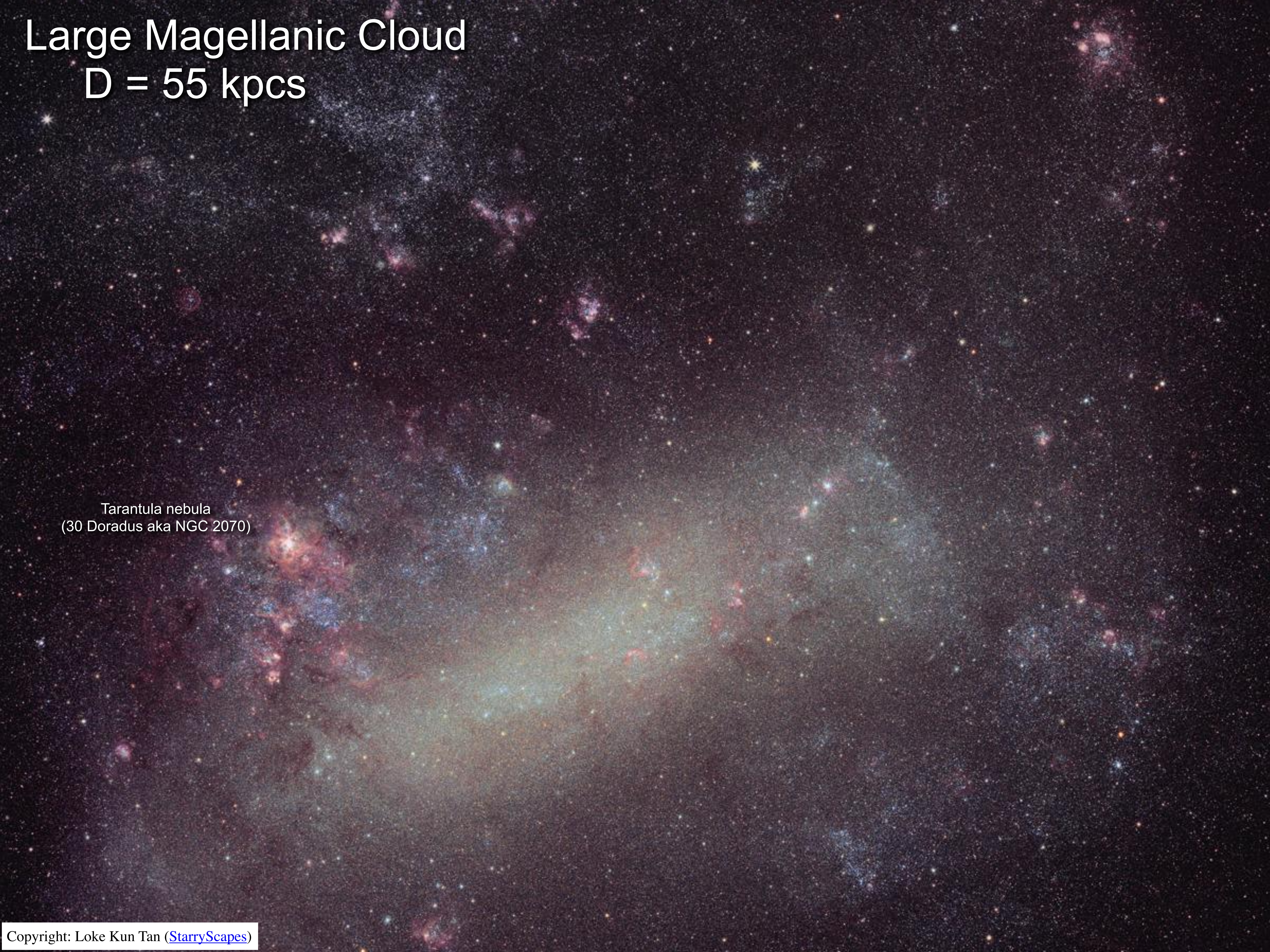
The Event: 23rd February, 1987

Discovery: Ian Shelton, in La Campanas (Chile), processing an image sees a “spot” …

Reaches (in March ‘87) magnitude 3:
$L \sim 10^8 L_\odot$ for several months

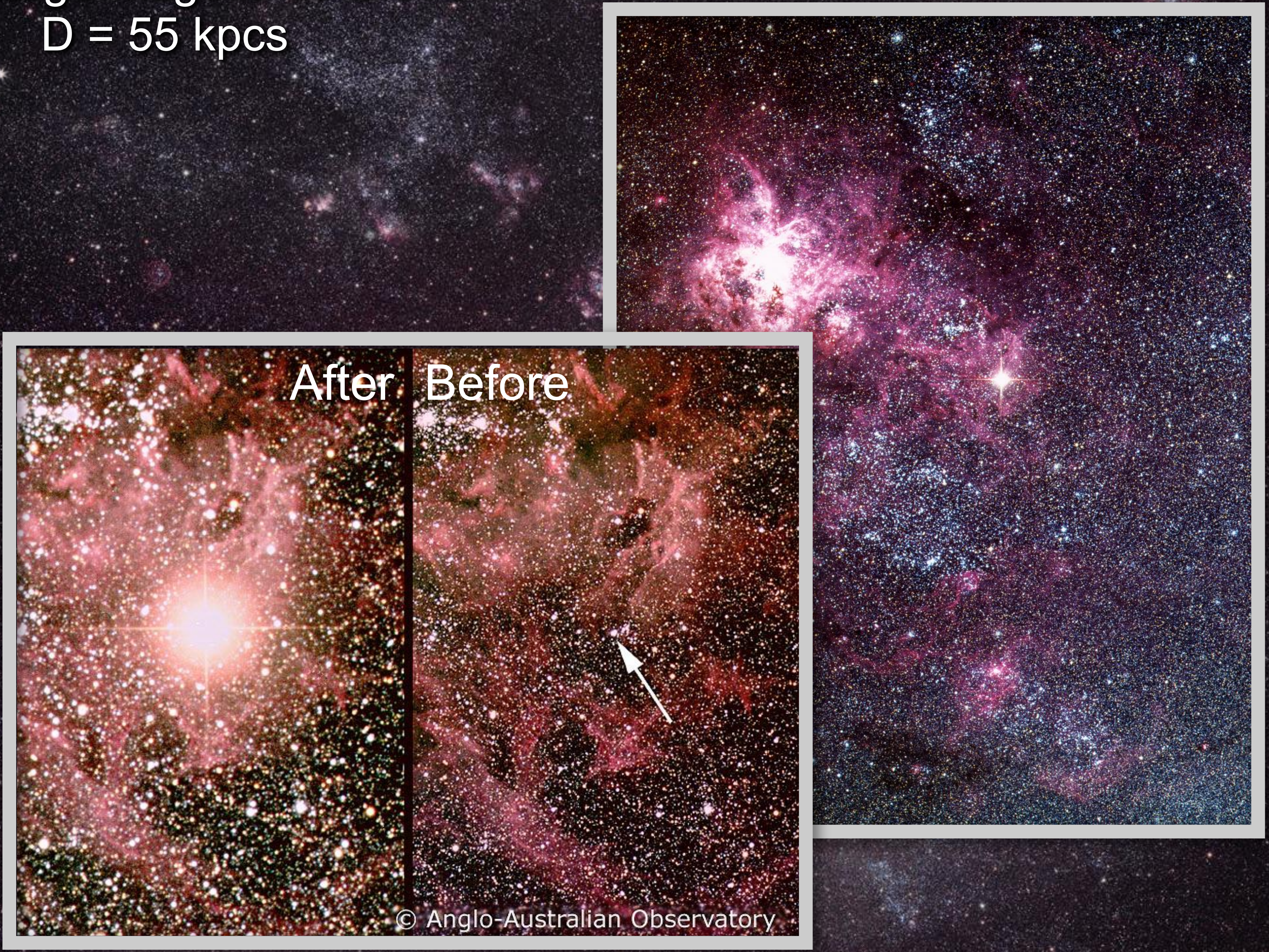
The first supernova visible by eye since Kepler (1604) . . .

. . . or Flamsteed, 1680?


Large Magellanic Cloud
D = 55 kpcs
Tarantula nebula
(30 Doradus aka NGC 2070)

Large Magellanic Cloud
D = 55 kpcs

# Large Magellanic Cloud
D = 55 kpcs



The Neutrinos from SN 1987A

VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst in Coincidence with Supernova 1987A in the Large Magellanic Cloud

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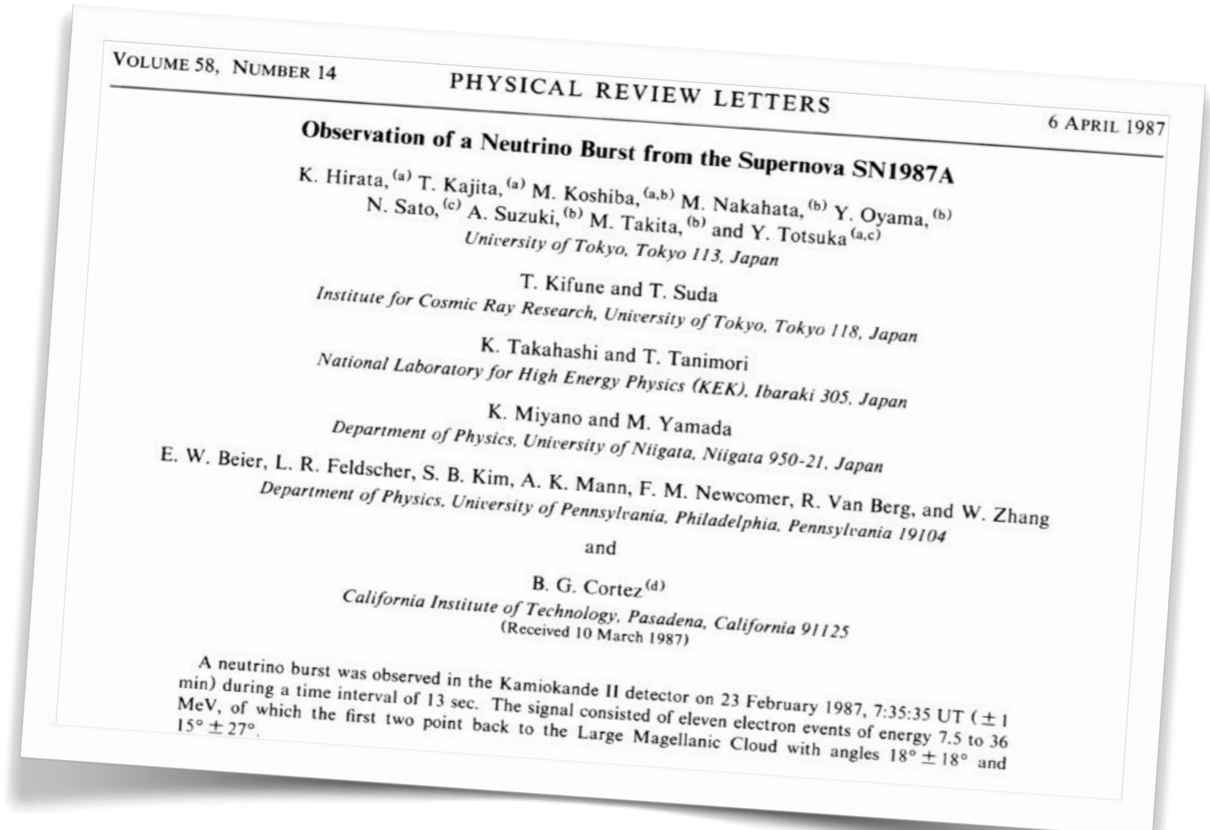
(Received 13 March 1987)

A burst of eight neutrino events preceding the optical detection of the supernova in the Large Magellanic Cloud has been observed in a large underground water Cherenkov detector. The events span an interval of 6 s and have visible energies in the range 20–40 MeV.



VOLUME 58, NUMBER 14 PHYSICAL REVIEW LETTERS 6 APRIL 1987

Observation of a Neutrino Burst from the Supernova SN1987A

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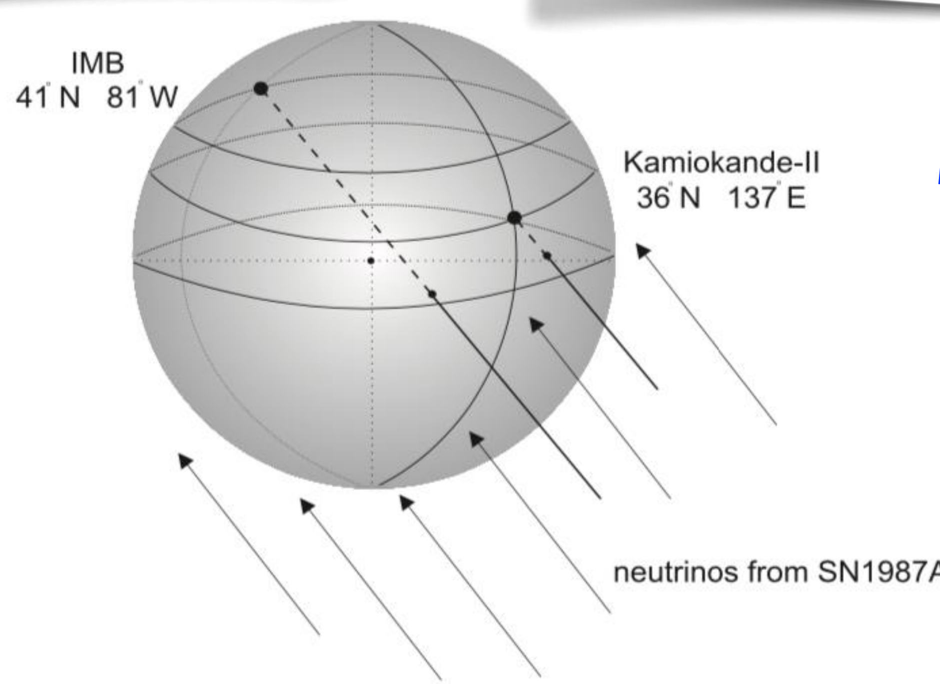
(Received 10 March 1987)

A neutrino burst was observed in the Kamiokande II detector on 23 February 1987, 7:35:35 UT (±1 min) during a time interval of 13 sec. The signal consisted of eleven electron events of energy 7.5 to 36 MeV, of which the first two point back to the Large Magellanic Cloud with angles 18° ± 18° and 15° ± 27°.

IMB recorded
8 neutrinos
20-40 MeV
over 6 sec.



Kamiokande II
recorded 12 neutrinos

Fig. 1. The sketch of the positions of Kamiokande-II and IMB detectors at the time of the arrival of SN1987A neutrinos.

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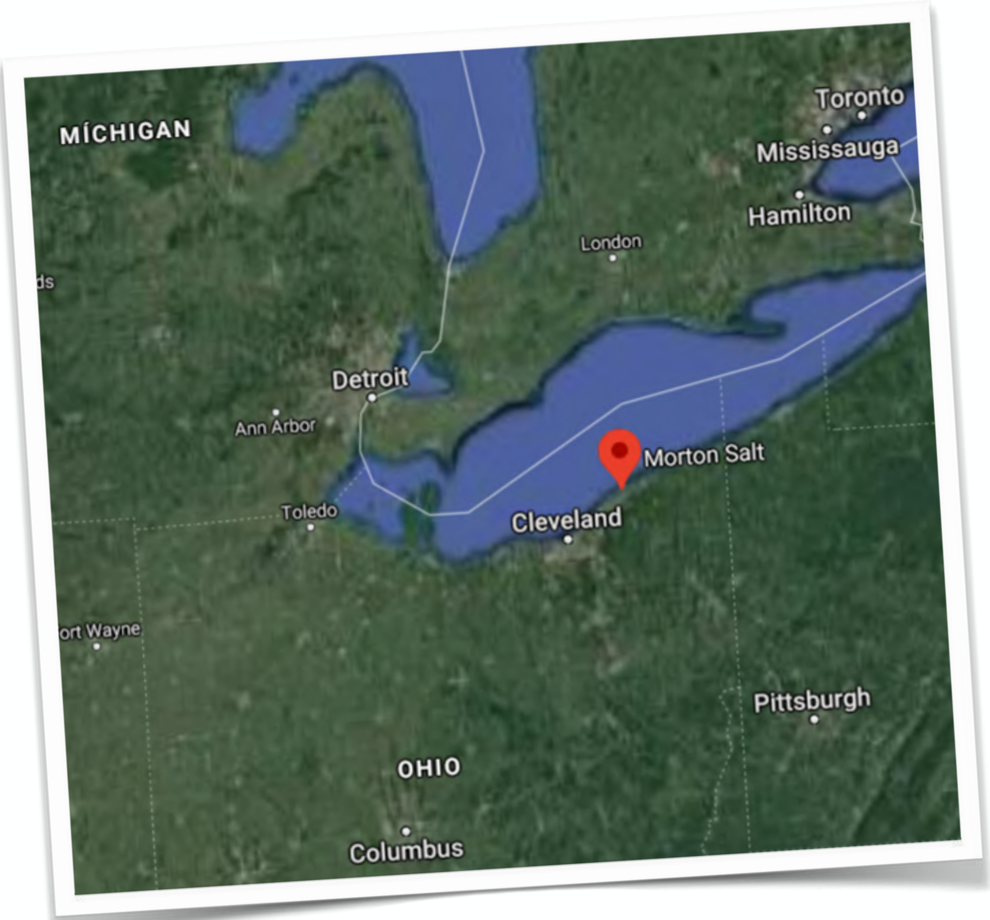
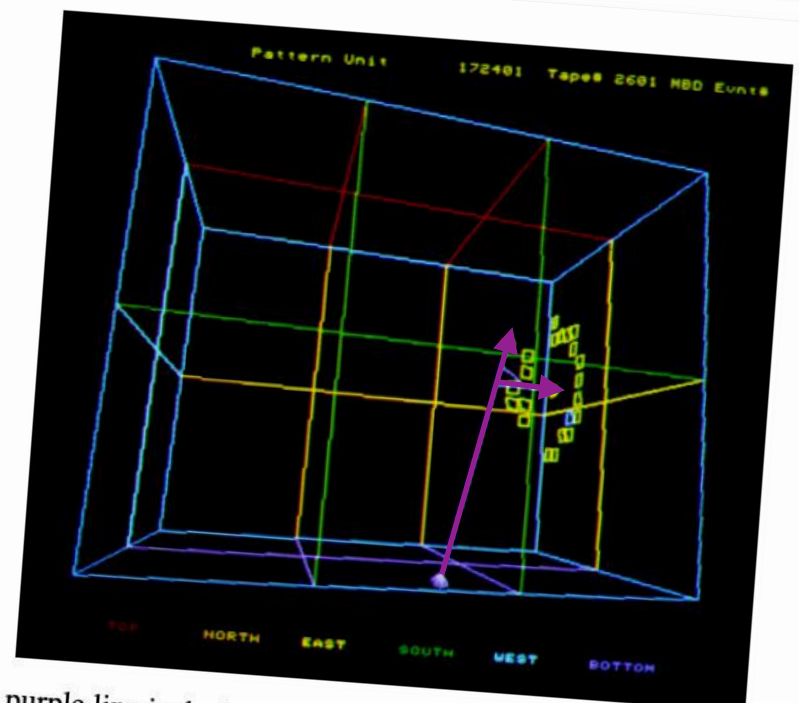
IMB Detector

In Fairport Harbor, nearby Cleveland (Ohio, USA), in a salt mine, 600 meters underground





In this view the long purple line is the known neutrino direction coming from the Large Magellenic Cloud. The short purple line going right is the positron direction and the yellow squares show where its Cherenkov cone hit the north and east walls.

Detector: cubical tank filled with ~7,000 m^3 of ultra pure water covered by 2,048 PMTs.

For SN neutrinos: $\overline{\nu}_e + p \longrightarrow e^+ + n$

For Solar neutrinos: $\nu_e + e^- \longrightarrow \nu_e + e^-$

$$\sigma_{\overline{\nu}_e p} \sim 100\, \sigma_{\nu_e e^-}$$

http://www-personal.umich.edu/~jcv/imb/imb.html

The Neutrinos from SN 1987A

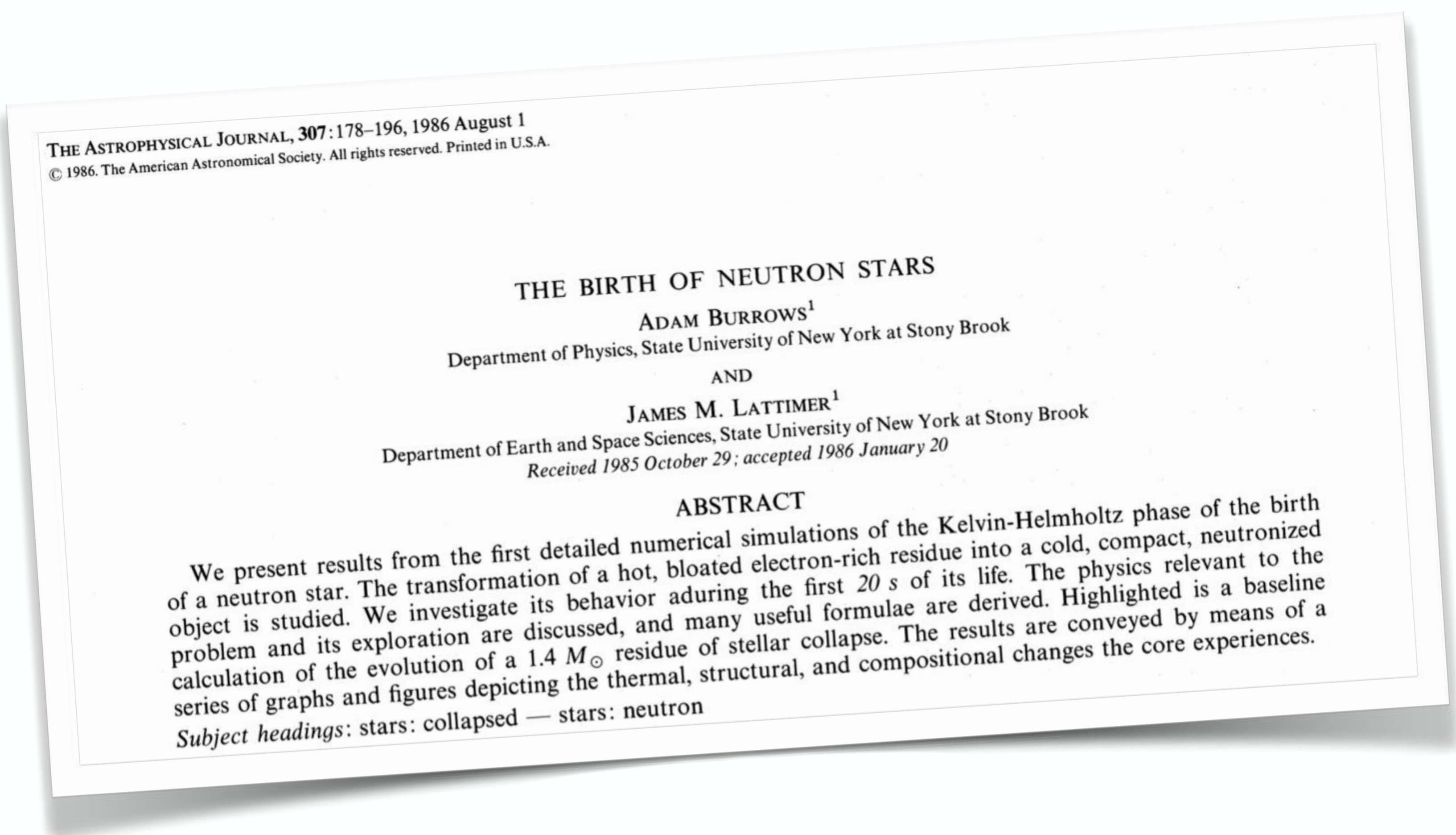
$$E_G \simeq \frac{GM^2}{R} \approx 4 \times 10^{53} \text{ erg}$$

$$\frac{E_G}{N} \simeq 10^{-4} \text{ erg} \simeq 60 \text{ MeV} \Longrightarrow T \approx 6 \times 10^{11} \text{ K}$$

$$M \simeq 1.6 M_\odot \Longrightarrow N \approx 3 \times 10^{57} \text{ part.}$$

Detected neutrinos: E ~ 10 MeV ⇒ ~ 2×10^{58} neutrinos emitted

At a distance of 55 kpcs: 10^{11} neutrinos per cm^2 passed by !


THE ASTROPHYSICAL JOURNAL, 307:178–196, 1986 August 1
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THE BIRTH OF NEUTRON STARS

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Received 1985 October 29; accepted 1986 January 20

ABSTRACT

We present results from the first detailed numerical simulations of the Kelvin-Helmholtz phase of the birth of a neutron star. The transformation of a hot, bloated electron-rich residue into a cold, compact, neutronized object is studied. We investigate its behavior aduring the first *20 s* of its life. The physics relevant to the problem and its exploration are discussed, and many useful formulae are derived. Highlighted is a baseline calculation of the evolution of a 1.4 $M_\odot$ residue of stellar collapse. The results are conveyed by means of a series of graphs and figures depicting the thermal, structural, and compositional changes the core experiences.

Subject headings: stars: collapsed — stars: neutron

The Proto-Neutron Star Phase: First Min.

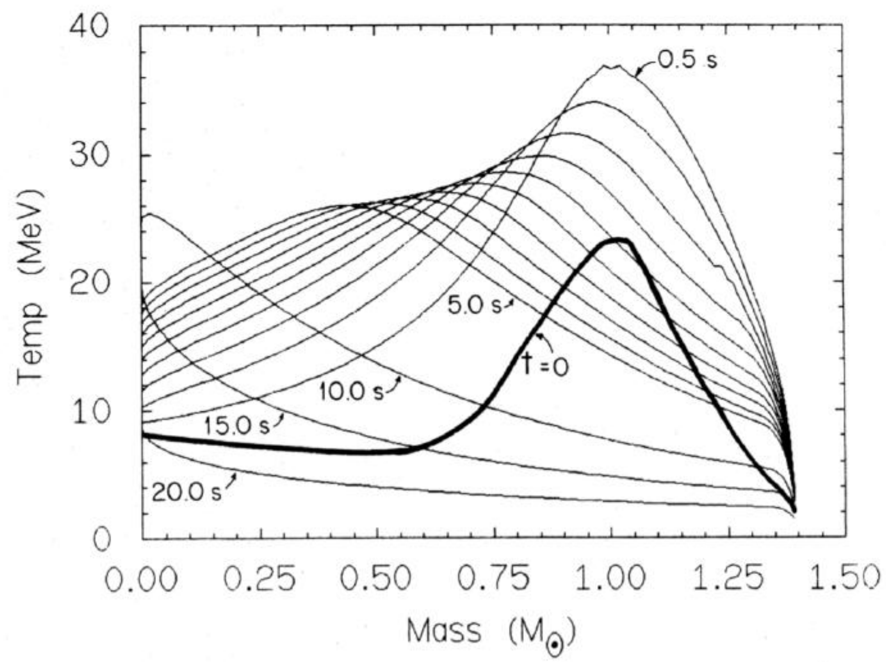


FIG. 1.—Temperature vs. enclosed baryon mass profiles at various times for the baseline simulation (see text). Snapshots are taken every 0.5 s for 5.0 s, and then every 5.0 s until 20.0 s is reached. Temperature is given in MeV, and baryon mass in solar masses. The $t = 0$ profile is the bold line.

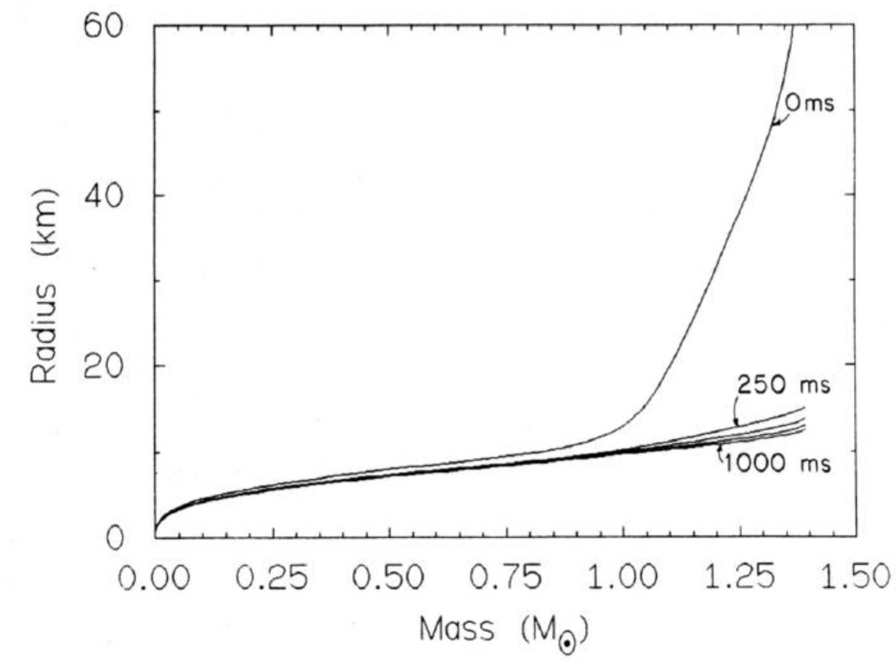


FIG. 5.—Radius vs. baryon mass. Radius is the coordinate radius and is in kilometers. Dumps are every 250 ms for 1.0 s.

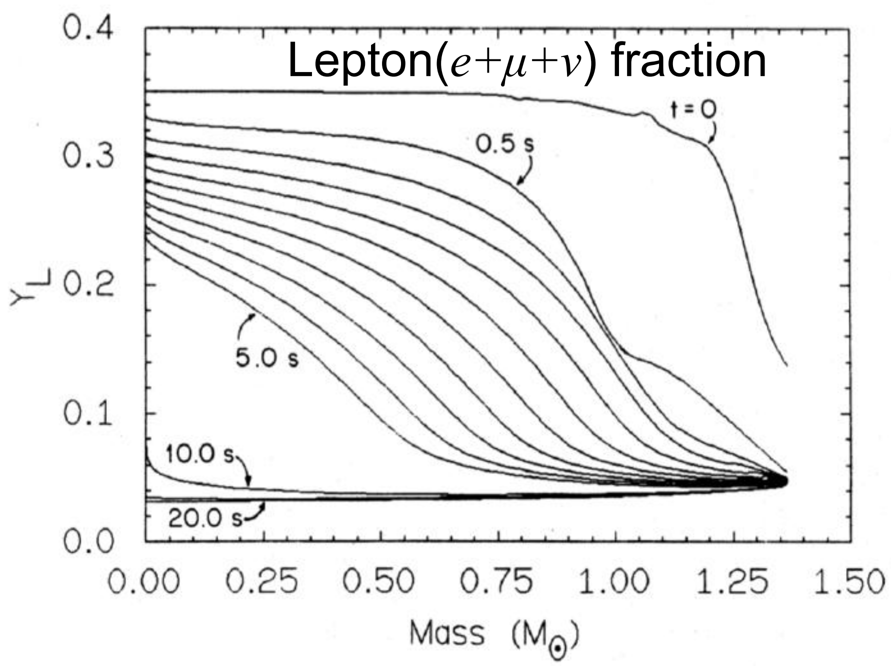


FIG. 7.—Lepton fraction, Y_L $(= Y_e + Y_\nu)$, vs baryon mass. Snapshots are at intervals given in Fig. 1 legend. Notice that $0.0 < t < 10.0$ s.

$$\nu_i + n \rightarrow \nu_i + n$$
$$\nu_i + p \rightarrow \nu_i + p$$
$$\nu_i + A \rightarrow \nu_i + A$$

$$\nu_e + n \rightarrow e^- + p$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

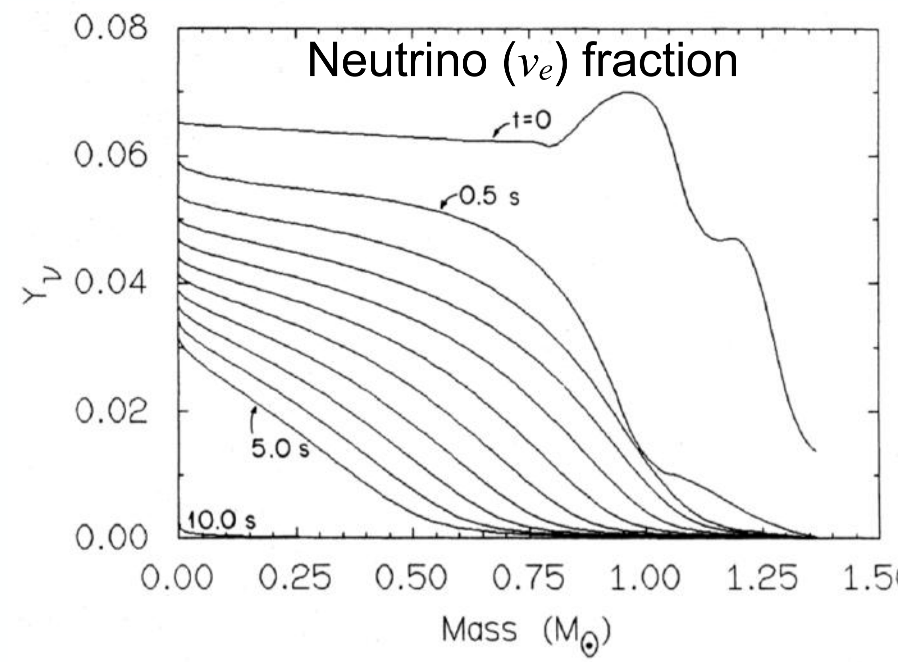


FIG. 8.—Same as Fig. 7, but Y_ν vs. baryon mass. The quantity Y_ν is the electron-neutrino fraction.

After 20 seconds neutrinos have left and we have a 5% lepton (e+μ) fraction:
$n_p = n_e + n_\mu$ gives a 4% proton and 96% neutron fractions: it is now a neutron star

The birth of neutron stars
Burrows, A.; Lattimer, J. M.
1986ApJ...307..178B

Expected Mass of NS 1987A

From the detected neutrinos: if about 1/6 of the total binding energy was radiated as the observed electron anti-neutrinos then

$$E_{bind} = (2.9 \pm 1.2) \times 10^{53} \text{ ergs}$$

and its gravitational mass is

$$M = (1.38 \pm 0.43)\, M_\odot$$

Analysis of the Neutrino Events from Supernova 1987A
Lattimer, James M.; Yahil, A.
1989ApJ...340..426L

Explosion models of Utrobin et al (2019) for state-of-the-art progenitor models of SN 1987A indicate the baryonic mass, M_B, of its compact remnant to be $(1.35 - 1.66)\, M_\odot$.

Results of Ertl et al. (2020) predict $(1.48 - 1.56)\, M_\odot$ for single-star progenitors and

$(1.38 - 1.75)\, M_\odot$ for binary progenitors.

Together these give a gravitational mass

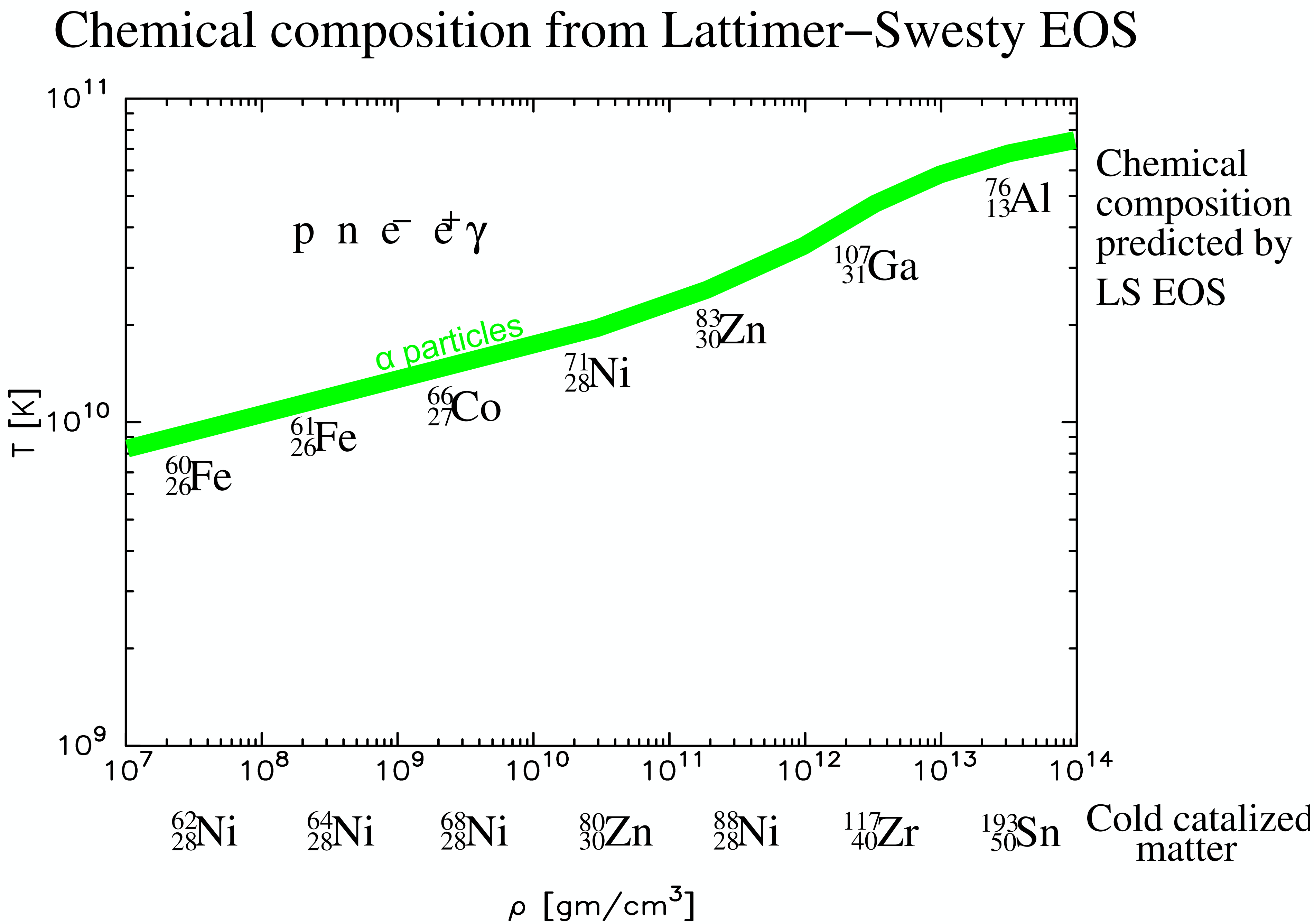
$$M \simeq (1.22 - 1.62)\, M_\odot$$

This expected mass range is well below the measured masses of several pulsars and thus makes it very unlikely that the compact remnant of SN 1987A be a black-hole.

Three-dimensional mixing and light curves: constraints on the progenitor of supernova 1987A
Utrobin, V. P.; Wongwathanarat, A.; Janka, H. -Th.; Müller, E.; Ertl, T.; Woosley, S. E.
2019A&A...624A.116U

The Explosion of Helium Stars Evolved with Mass Loss
Ertl, T.; Woosley, S. E.; Sukhbold, Tuguldur; Janka, H. -T.
2020ApJ...890...51E

Formation of Nuclei in the Neutron Star Crust



Swesty, Lattimer & Myra, ApJ 425 (1994), p. 195–204

Phases of Neutron Star Cooling

- Proto-Neutron Star: ~30 seconds:
  Matter from the collapsed iron core: x_p = 40%.
  Neutrinos are trapped, once they have left x_p = 5% and we have a "Neutron Star".
  "Exotic matter" (hyperons, quarks, ...) will form at the end of this phase: needs low x_p.

- Neo-Neutron Star: ~1 year:
  Rapid cooling of outer layers by neutrino emission.
  Eddington luminosity for about an hour.
  Ends with T_{eff} ~ 2-4x10^6 K.

- Young Neutron Star: ~50 years:
  Early plateau: crust relaxation phase whose heat flows into the core.
  Crust neutrino emission is not very efficient.
  At its end the interior is isothermal and T_{eff} reflects the core temperature.

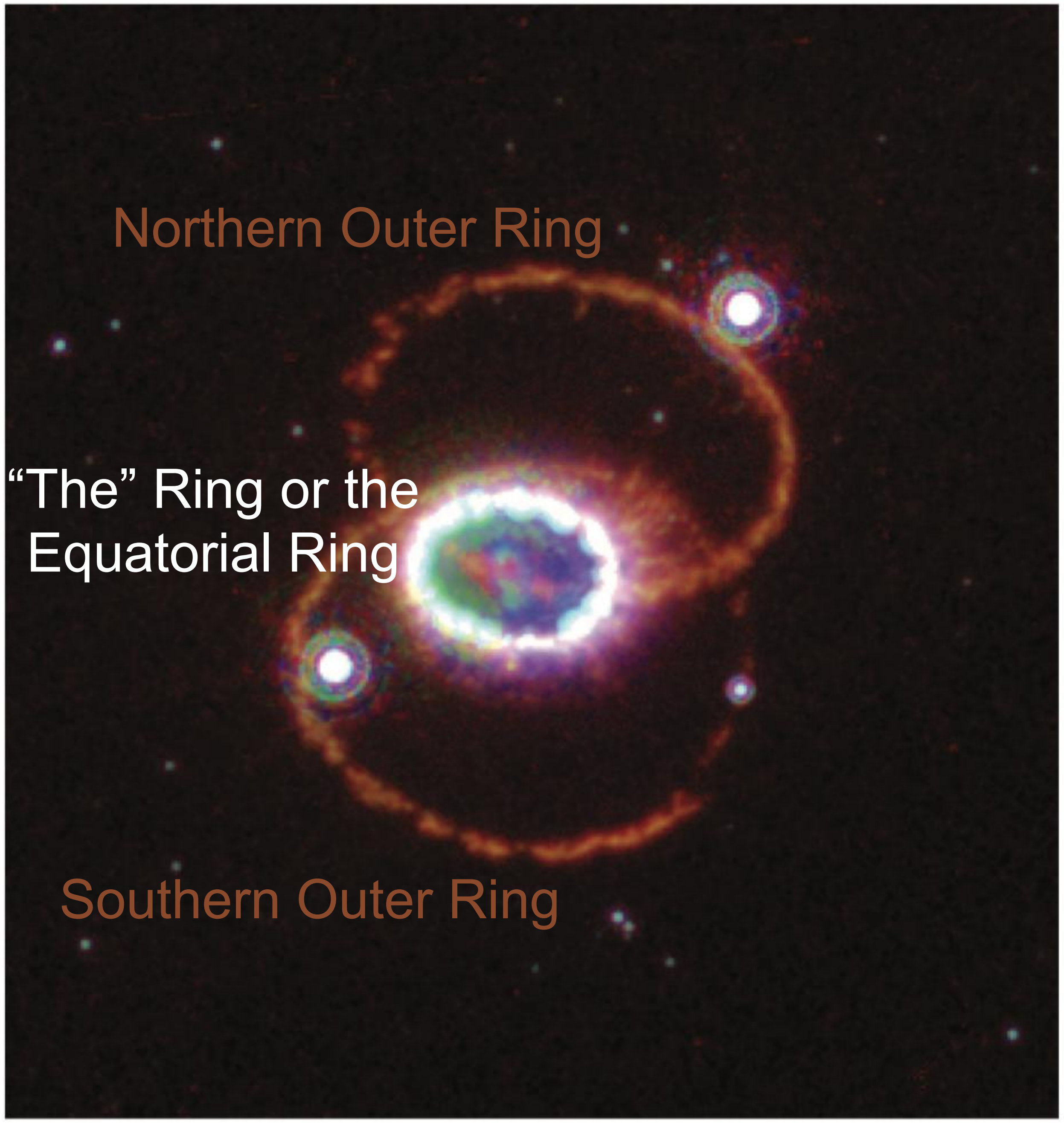
- Neutrino Cooling Phase: ~10^5 years:
  Evolution of the isothermal star is driven by core neutrino emission.

- Photon Cooling Phase: ~10^6 years:
  Evolution of the isothermal star is driven by surface photon emission.

- Dark Phase: >> 10^6 years :
  Star possibly kept not too cold by internal heating (mag. field decay, friction from differential rotation, baryonic/dark matter accretion, ...)

The Remnant of SN 1987A

The SN 1987A "Remnant"

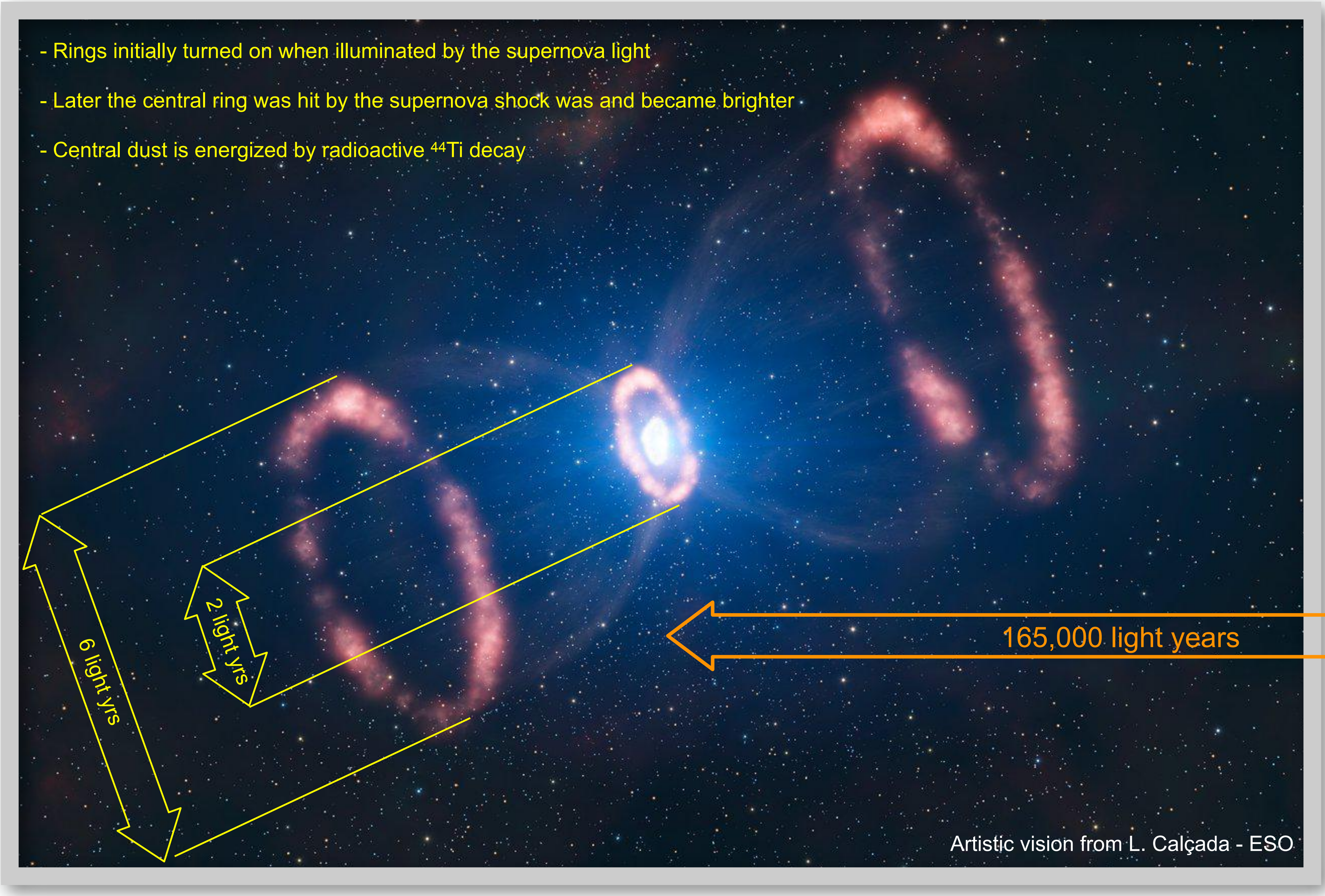


The Remnant of Supernova 1987A
McCray, Richard; Fransson, Claes
2016ARA&A..54...19M

Figure 1

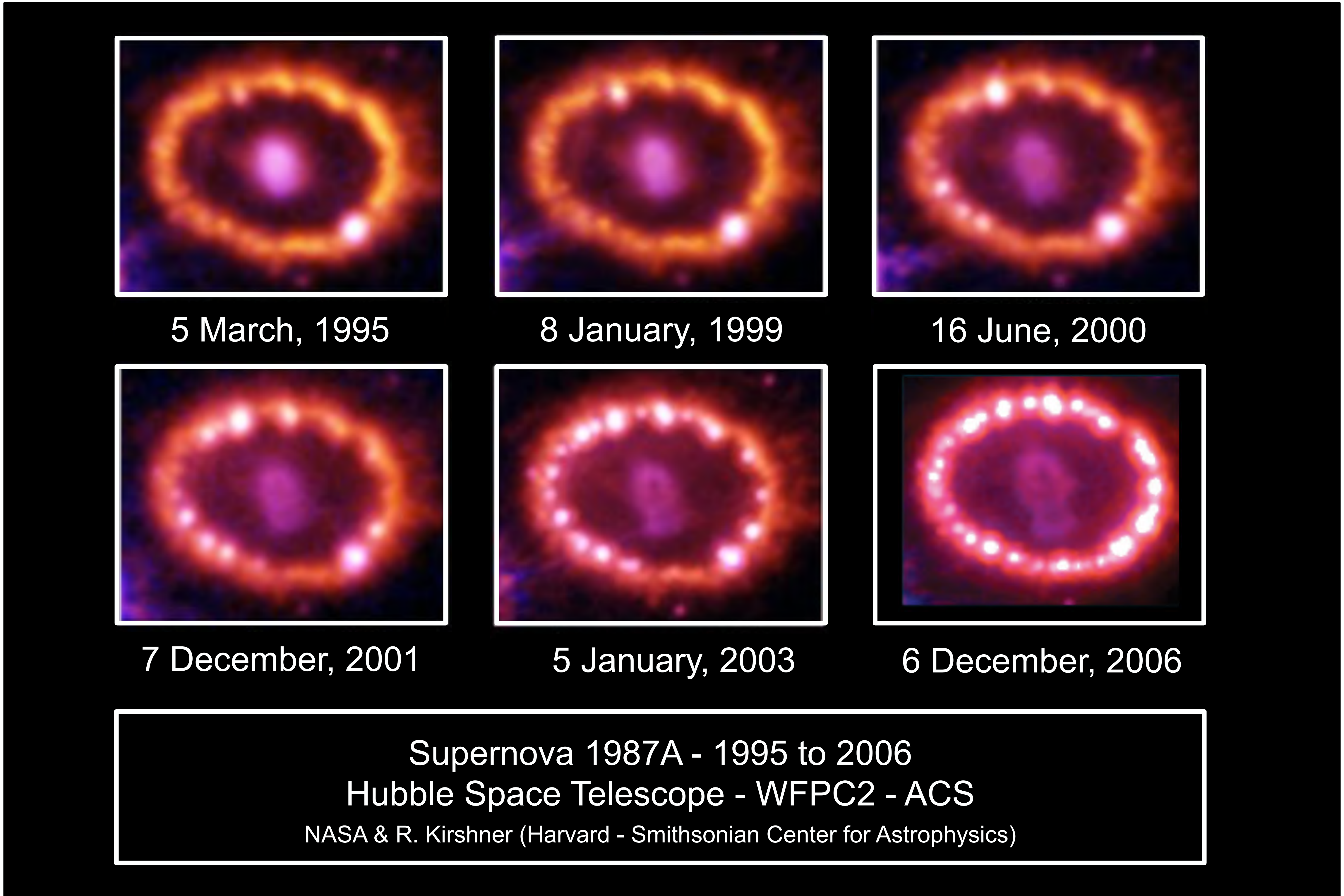
Composite image of SN 1987A in Hα taken with the *Hubble Space Telescope* (HST). Images from three epochs have been stretched and combined to enhance different components. Red, as seen by HST/WFPC2 in 1994–1997; blue, as seen by HST/ACS in 2001–2004; and green, as seen by HST/WFPC3 in 2009–2014. Courtesy of Peter Challis.

The Three Rings of SN 1987A



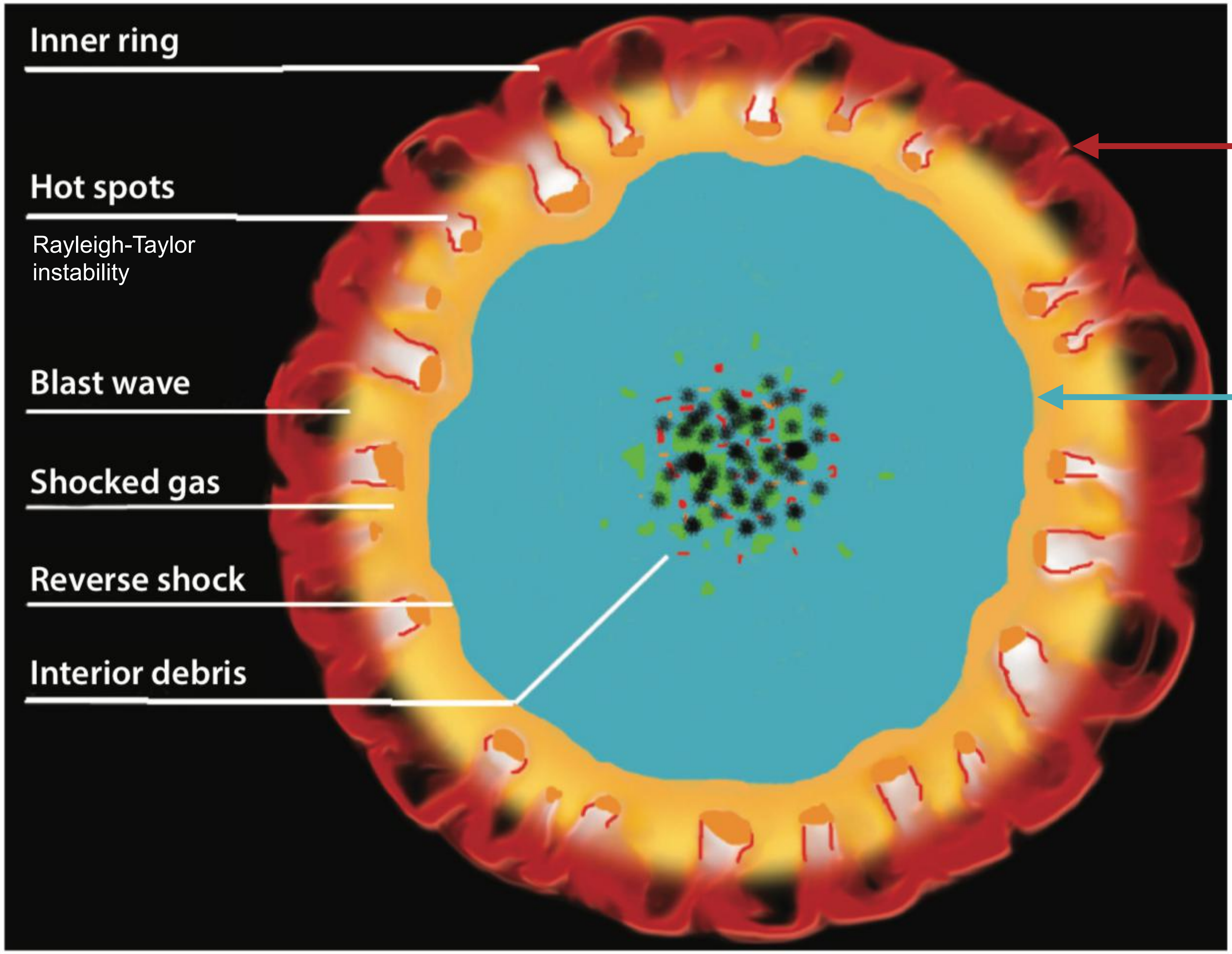
https://www.eso.org/public/news/eso1032/

SN Shock Wave Reaches the Inner Ring



https://www.spacetelescope.org/images/heic1704b/

“The” Ring and the SN Material



Material ejected by the progenitor star wind long before the SN explosion

H/He envelope ejected by the SN

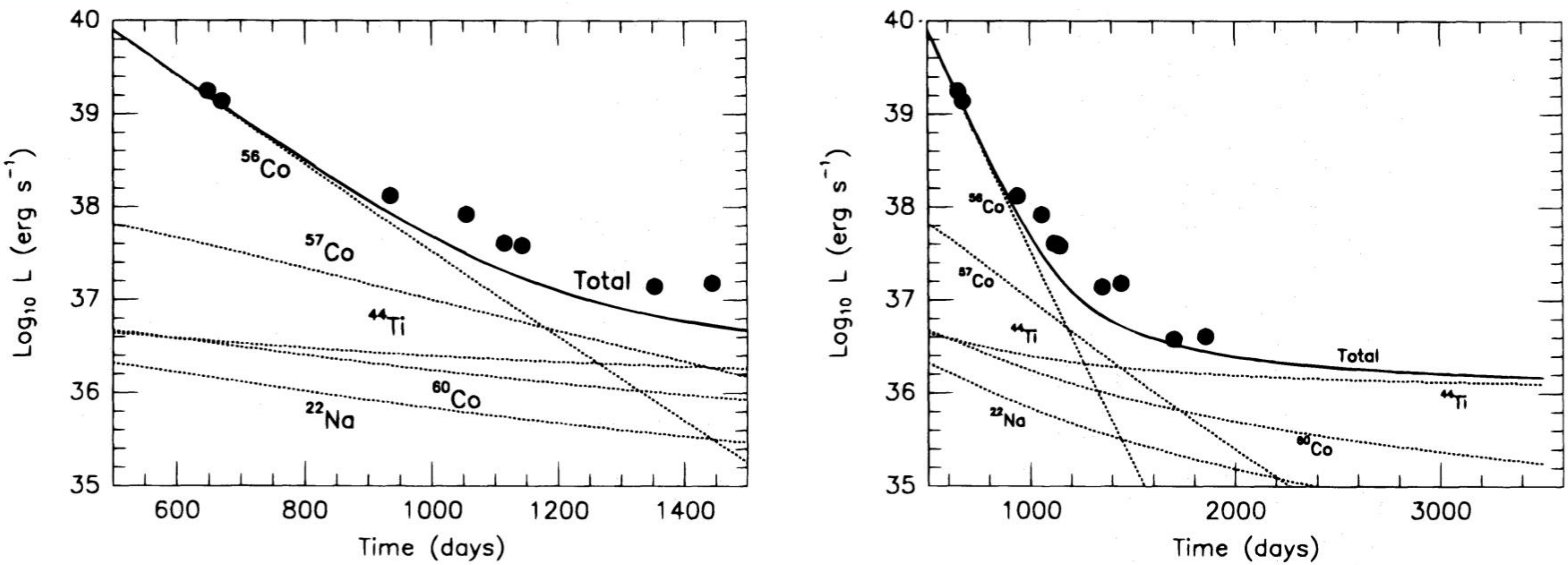
“Interior debris”, C/O/Mg/Si/ …/Ti/Ni/Fe/…: heavy elements from the interior of the star, products of the star’s nucleosynthesis

Figure 10

Diagram illustrating the interaction of the supernova debris with the equatorial ring.

The Remnant of Supernova 1987A
McCray, Richard; Fransson, Claes
2016ARA&A..54...19M

Bolometric Light-Curve of SN 1987A



^{44}Ti decay: electron capture $\quad ^{44}\mathrm{Ti} + e^- \longrightarrow ^{44}\mathrm{Sc}^* + \nu_e \quad \tau_0 \simeq 85\,\mathrm{yr}$

^{44}Sc de-excitation: two photons $\quad ^{44}\mathrm{Sc}^* \longrightarrow ^{44}\mathrm{Sc} + \gamma(67.85\,\mathrm{keV}) + \gamma(78.38\,\mathrm{keV})$

^{44}Sc decay: β^+-decay $\quad ^{44}\mathrm{Sc} \longrightarrow ^{44}\mathrm{Ca}^* + e^+ + \overline{\nu}_e \quad \tau_0 \simeq 5.7\,\mathrm{hr}$

^{44}Ca de-excitation: one photons $\quad ^{44}\mathrm{Ca}^* \longrightarrow ^{44}\mathrm{Ca} + \gamma(1.157\,\mathrm{MeV})$

e^+-e^- annihilation: two photons of 0.511 MeV

The Production of ^{44}Ti and ^{60}Co in Supernovae
Timmes, F. X.; Woosley, S. E.; Hartmann, D. H.; Hoffman, R. D.
1996ApJ...464..332T

A Compact Source
in
SN 1987A

Dust in the Inner Part of SN 1987A

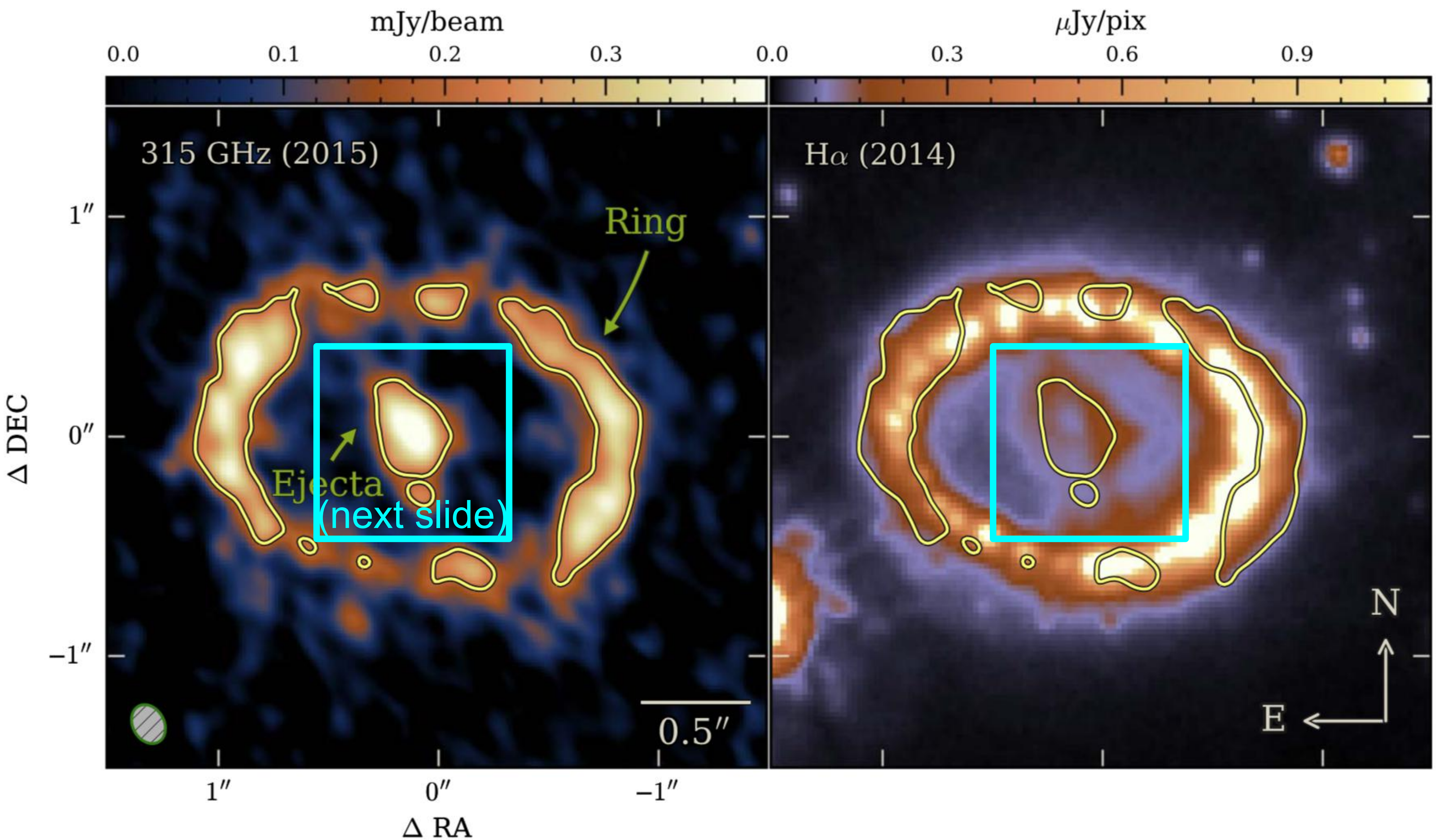
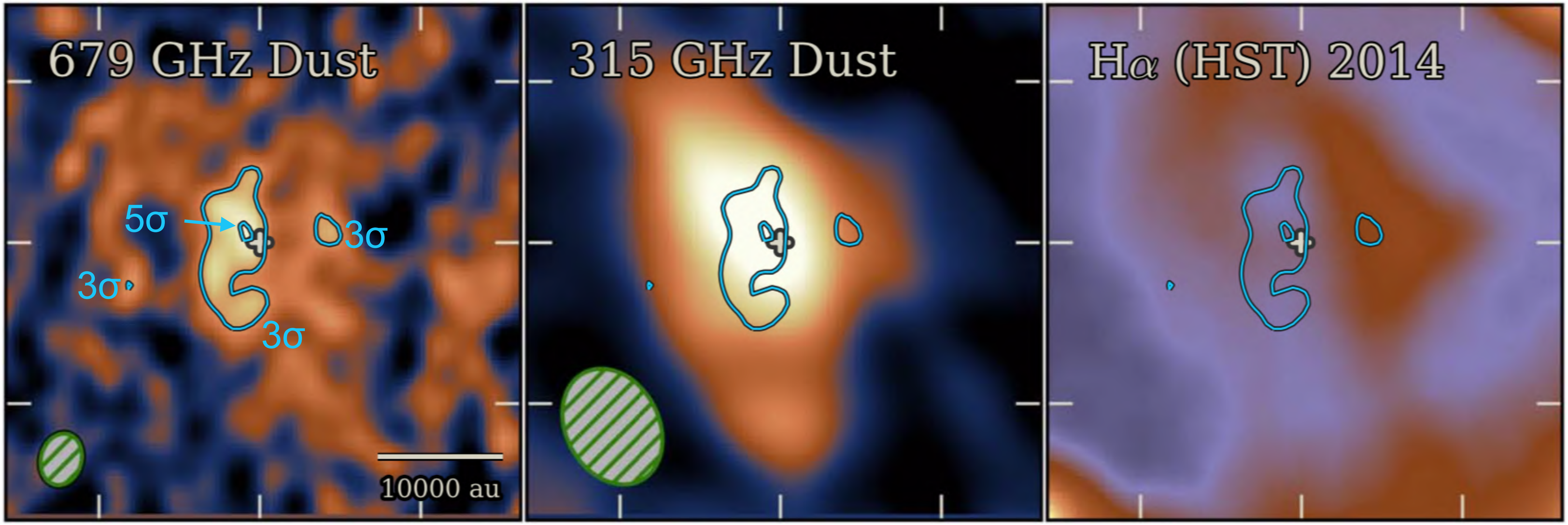


Figure 2. ALMA 315 GHz (with beam) and 2014 *HST* F625W band image (Fransson et al. 2015), which includes Hα. The yellow contours display 315 GHz emission at 0.2 mJy beam^{-1}. The 315 GHz continuum in the inner ejecta originates from thermal dust emission, while in the ring it is due to synchrotron emission. The 18 mas uncertainty on the relative alignment due to Band 7 astrometric error (12 mas) and *HST* image registration based on fitting the ring (6 mas) is of order 1 pixel in these images.

High angular resolution ALMA images of dust and molecules in the SN 1987A ejecta
Cigan, Phil et al. 2019ApJ...886...51C

The Discovery: a “Blob” in the Debris’ Dust



The blob is a 5σ detection, slightly offset from the center of the debris (center of explosion).
Inner debris are energized by ^{44}Ti decay (half life 60 yrs), T_{dust} ~ 17-22 K
“The Blob”: T_{dust} ~ 33 K difficult to explain by just higher debris density: **needs extra energy**

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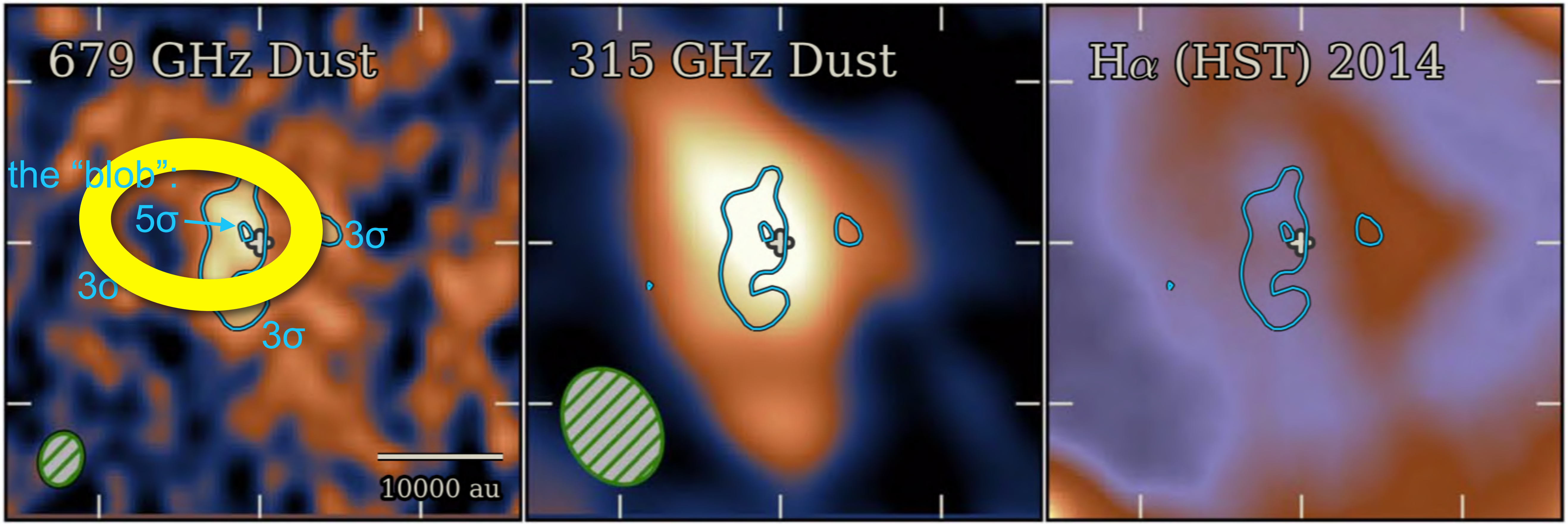

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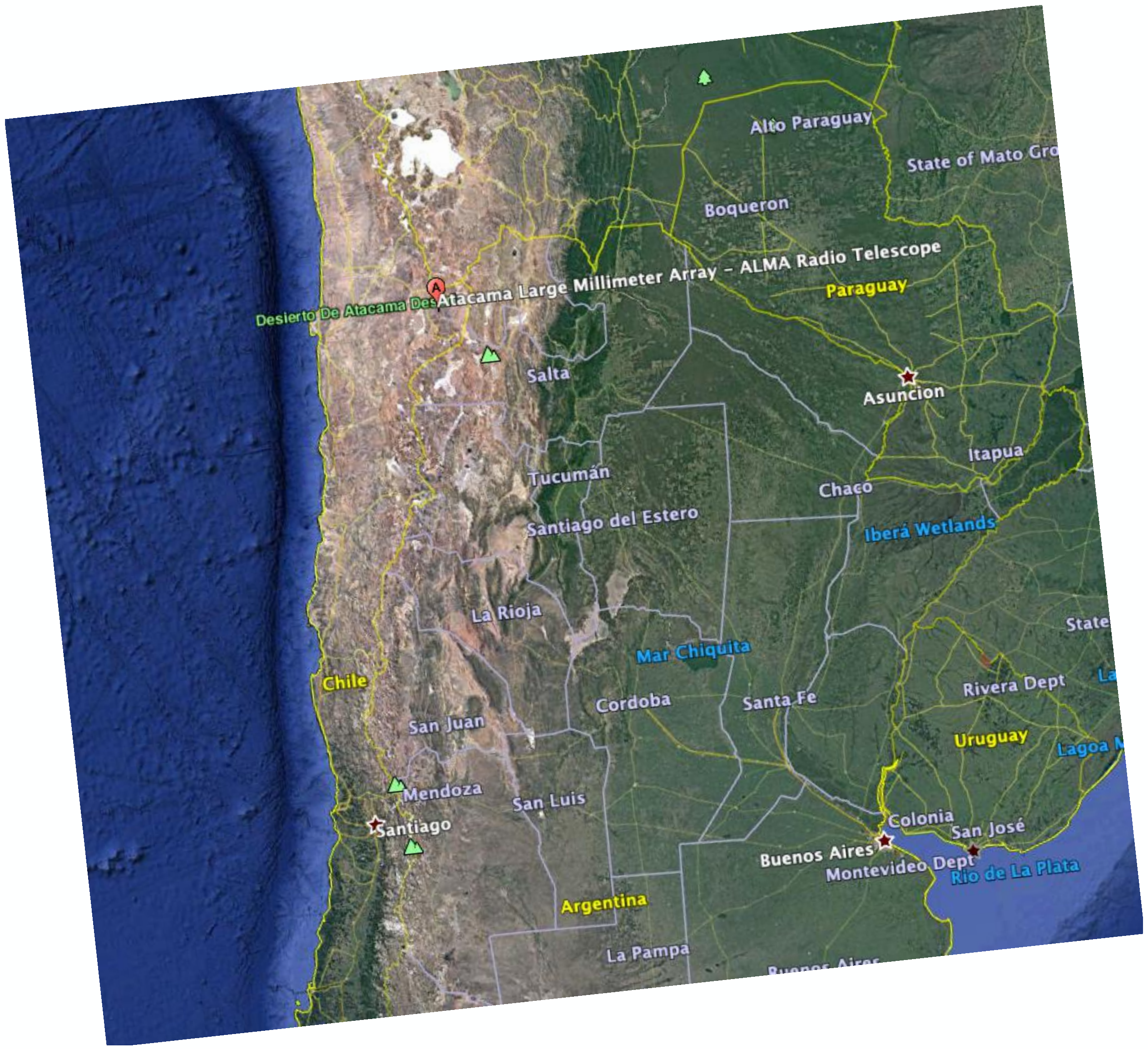
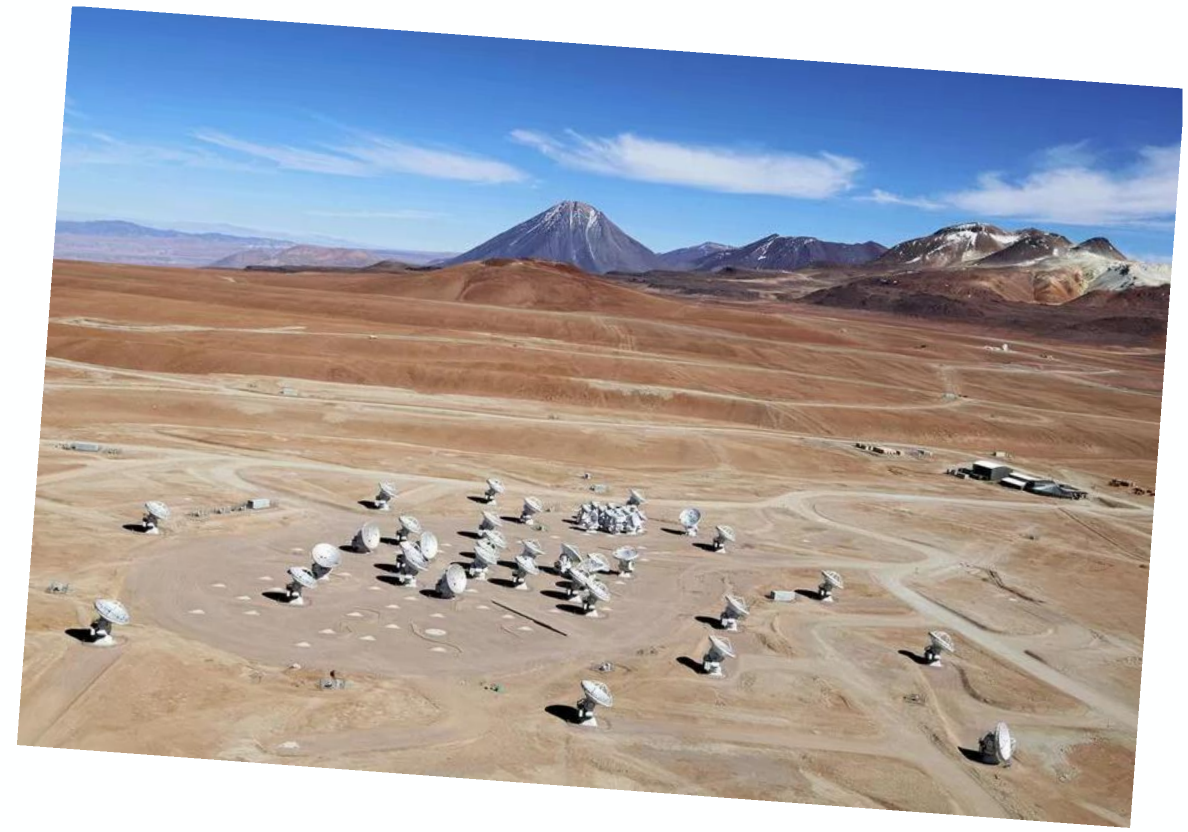
Inner debris are energized by ^{44}Ti decay (half life 60 yrs), T_{dust} ~ 17-22 K
“The Blob”: T_{dust} ~ 33 K difficult to explain by just higher debris density: **needs extra energy**

Energy injection by the Central Compact Object: 40-90 $L_\odot$ ~ 1.5-3.5×10^{35} erg s^{-1}

High angular resolution ALMA images of dust and molecules in the SN 1987A ejecta
Cigan, Phil et al. 2019ApJ...886...51C

The ALMA Observatory





Located in the Atacama desert (altitud: 5,000 m)
66 antenas (54 of 12m and 12 of 7m diameter)
movable with maximum separation of 16 km.
Observes from 0.32 mm to 3.2mm (100 to 1000 GHz).
Cost: US$1,4 billions, began operating in 2011.

Each antena weighs 115 tons

The Astrophysical Journal, 886:51 (27pp), 2019 November 20
https://doi.org/10.3847/1538-4357/ab4b46

High Angular Resolution ALMA Images of Dust and Molecules in the SN 1987A Ejecta

Phil Cigan[1], Mikako Matsuura[1], Haley L. Gomez[1], Remy Indebetouw[2], Fran Abellán[3], Michael Gabler[4], Anita Richards[5], Dennis Alp[6], Timothy A. Davis[1], Hans-Thomas Janka[4], Jason Spyromilio[7], M. J. Barlow[8], David Burrows[9], Eli Dwek[10], Claes Fransson[11], Bryan Gaensler[12], Josefin Larsson[6], P. Bouchet[13,14], Peter Lundqvist[11], J. M. Marcaide[3], C.-Y. Ng[15], Sangwook Park[16], Pat Roche[17], Jacco Th. van Loon[18], J. C. Wheeler[19], and Giovanna Zanardo[20]

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Abstract

We present high angular resolution (∼80 mas) ALMA continuum images of the SN 1987A system, together with CO $J = 2 \rightarrow 1$, $J = 6 \rightarrow 5$, and SiO $J = 5 \rightarrow 4$ to $J = 7 \rightarrow 6$ images, which clearly resolve the ejecta (dust continuum and molecules) and ring (synchrotron continuum) components. Dust in the ejecta is asymmetric and clumpy, and overall the dust fills the spatial void seen in Hα images, filling that region with material from heavier elements. The dust clumps generally fill the space where CO $J = 6 \rightarrow 5$ is fainter, tentatively indicating that these dust clumps and CO are locationally and chemically linked. In these regions, carbonaceous dust grains might have formed after dissociation of CO. The dust grains would have cooled by radiation, and subsequent collisions of grains with gas would also cool the gas, suppressing the CO $J = 6 \rightarrow 5$ intensity. The data show a dust peak spatially coincident with the molecular hole seen in previous ALMA CO $J = 2 \rightarrow 1$ and SiO $J = 5 \rightarrow 4$ images. That dust peak, combined with CO and SiO line spectra, suggests that the dust and gas could be at higher temperatures than the surrounding material, though higher density cannot be totally excluded. One of the possibilities is that a compact source provides additional heat at that location. Fits to the far-infrared–millimeter spectral energy distribution give ejecta dust temperatures of 18–23 K. We revise the ejecta dust mass to $M_{\rm dust} = 0.2$–$0.4\ M_\odot$ for carbon or silicate grains, or a maximum of $<0.7\ M_\odot$ for a mixture of grain species, using the predicted nucleosynthesis yields as an upper limit.

Unified Astronomy Thesaurus concepts: Interstellar dust (836); Supernovae (1668); Interstellar molecules (849)

THE ASTROPHYSICAL JOURNAL, 886:51 (27pp), 2019 November 20

https://doi.org/10.3847/1538-4357/ab4b46

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THE ASTROPHYSICAL JOURNAL, 898:125 (15pp), 2020 August 1

https://doi.org/10.3847/1538-4357/ab93c2

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NS 1987A in SN 1987A

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Cooling of Neutron Stars

The
Neo-Neutron Star
Phase (1 year)

Phases of Neutron Star Cooling

- Proto-Neutron Star: ~30 seconds:
  Matter from the collapsed iron core: x_p = 40%.
  Neutrinos are trapped, once they have left x_p = 5% and we have a "Neutron Star".
  "Exotic matter" (hyperons, quarks, ...) will form at the end of this phase: needs low x_p.

- Neo-Neutron Star: ~1 year:
  Rapid cooling of outer layers by neutrino emission.
  Eddington luminosity for about an hour.
  Ends with T_{eff} ~ 2-4x10^6 K.

- Young Neutron Star: ~50 years:
  Early plateau: crust relaxation phase whose heat flows into the core.
  Crust neutrino emission is not very efficient.
  At its end the interior is isothermal and T_{eff} reflects the core temperature.

- Neutrino Cooling Phase: ~10^5 years:
  Evolution of the isothermal star is driven by core neutrino emission.

- Photon Cooling Phase: ~10^6 years:
  Evolution of the isothermal star is driven by surface photon emission.

- Dark Phase: >> 10^6 years :
  Star possibly kept not too cold by internal heating (mag. field decay, friction from differential rotation, baryonic/dark matter accretion, ...)

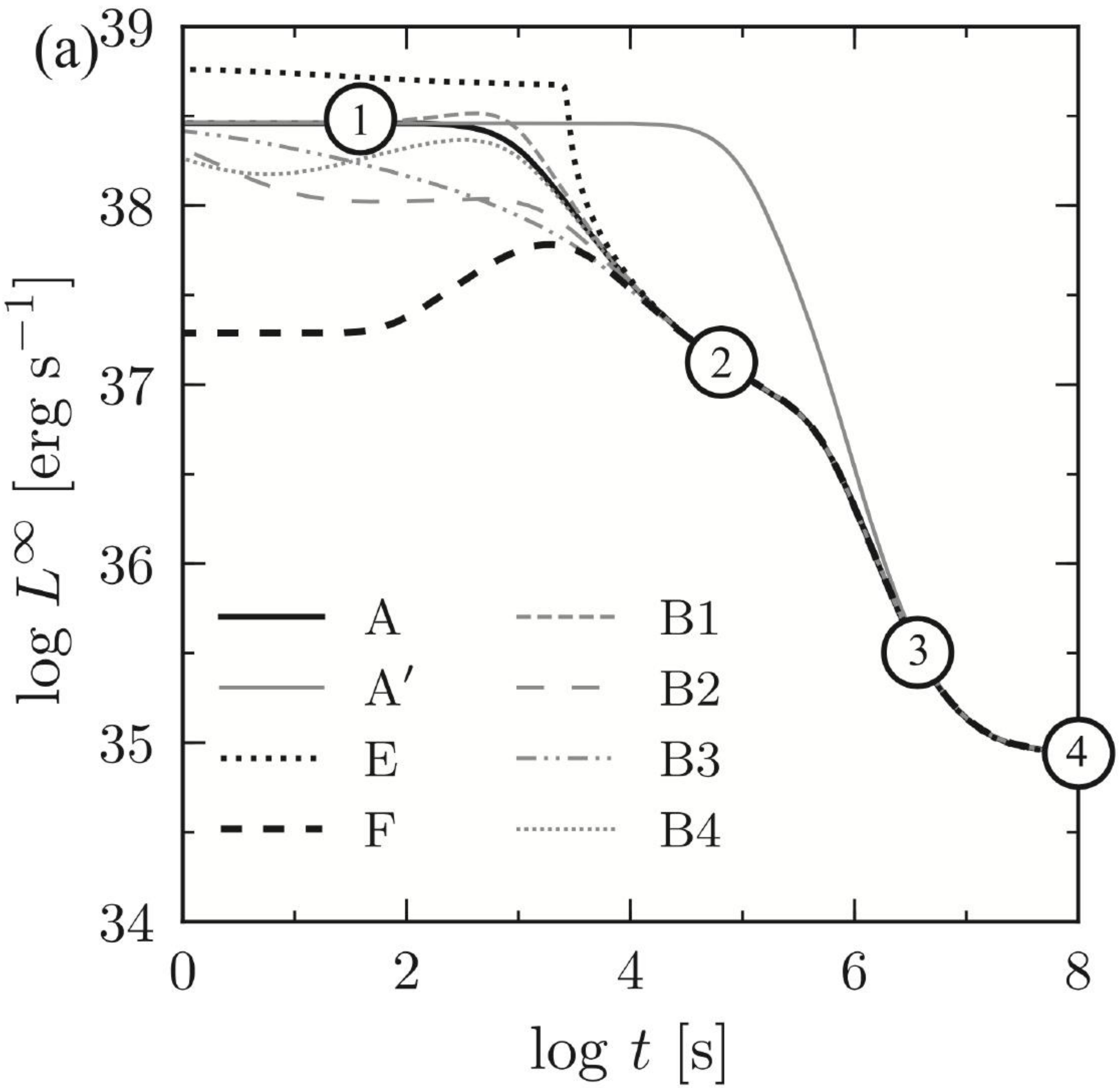
Luminosity Evolution

1: Eddington phase: relaxation from initial condition ~ 1hour

2: Cooling by pair neutrinos

3: Cooling by plasma neutrinos

4: Early plateau: young NS phase



[Thermal Evolution of Neo-neutron Stars. I. Envelopes, Eddington Luminosity Phase, and Implications for GW170817](#)
Beznogov, Mikhail V.; Page, Dany; Ramirez-Ruiz, Enrico
2020ApJ...888...97B

Neutrino (Pair) Emission in the Crust

Pair annihilation:

$$e^+ + e^- \longrightarrow \nu_x + \overline{\nu}_x$$

Plasmon decay::

$$\Gamma \longrightarrow \nu_x + \overline{\nu}_x$$

e-ion bremsstrahlung:

$$e^- + N \longrightarrow e^- + N + \nu_x + \overline{\nu}_x$$

Photo-neutrino emission:

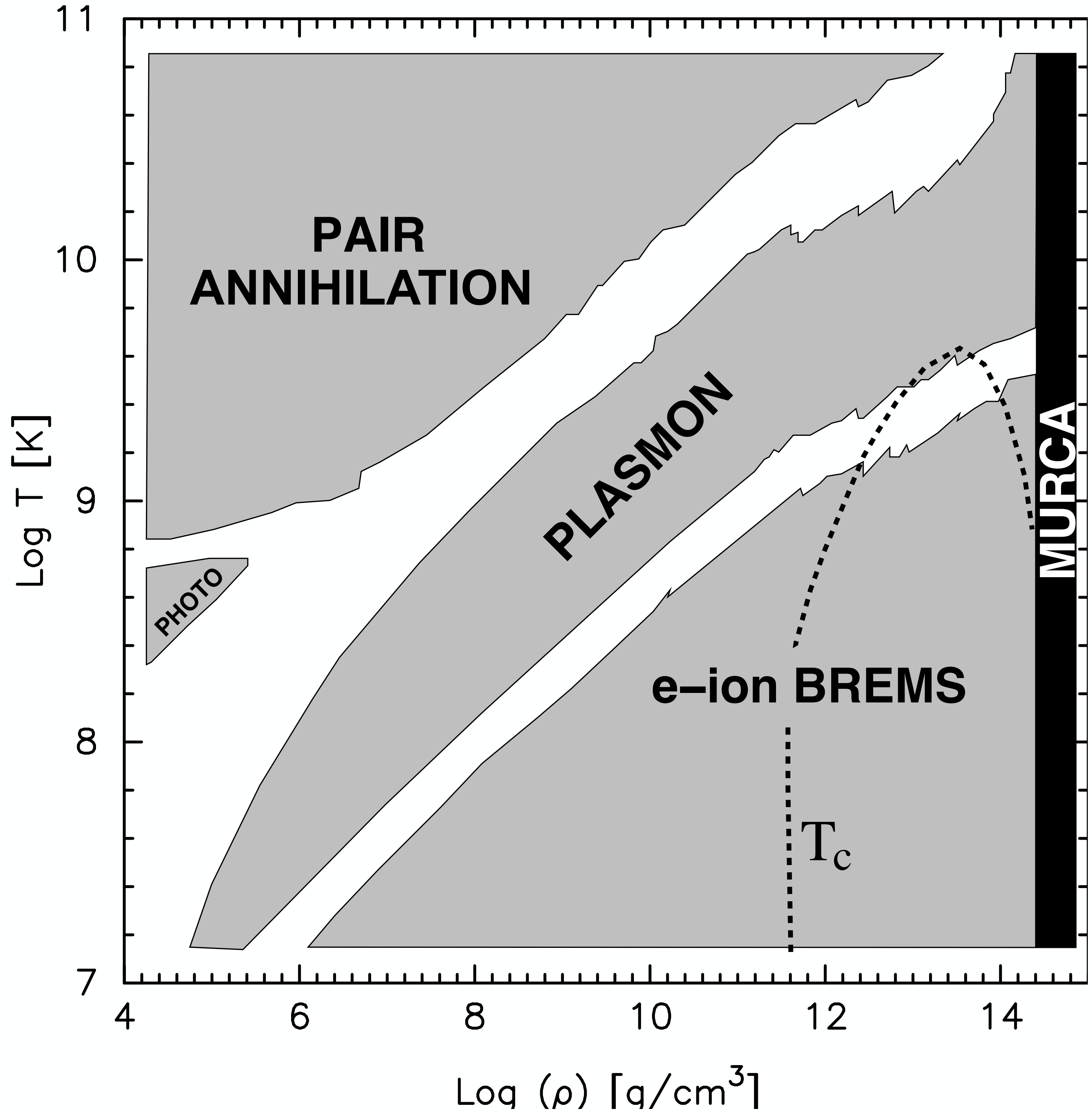
$$e^- + \gamma \longrightarrow e^- + \nu_x + \overline{\nu}_x$$

Synchrotron radiation:

$$e^- \xrightarrow{B} e^- + \nu_x + \overline{\nu}_x$$

Cooper pair formation:

$$n + n \longrightarrow \langle nn \rangle + \nu_x + \overline{\nu}_x$$



Early Cooling of the Envelope

Background color: pressure
(contour lines are isobars)

P independent of density:
pair plasma

Outermost layer contracts
at constant pressure:
from pair plasma to
degenerate matter

P independent of temperature:
degenerate matter

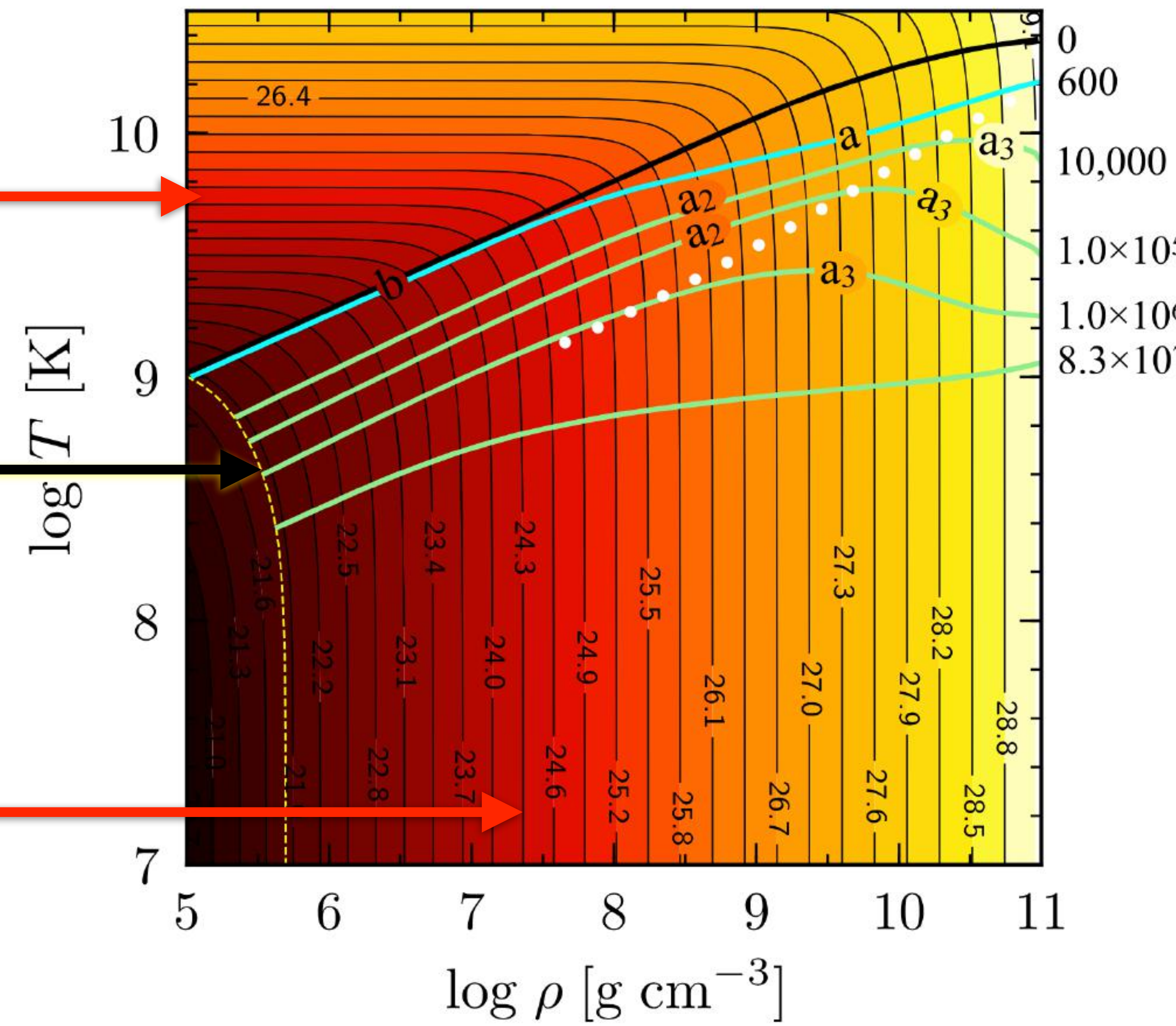


Figure 7. Selected local temperature profiles of model A. Ages, in seconds, are indicated on the right margin. Background color shows the pressure, and contours are isobars labeled with the decimal logarithm of pressure (in dyn cm^{-2}). The dashed (yellow) contour corresponds to the initial P_b and the thick dotted (white) line reproduces the one from Figure 17.

- Layers "a" cool by neutrinos:
  "a_2" by pair neutrinos
  "a_3" by plasmon neutrinos
  (separated by white dotted line)
- Layers "b" follow cooling of deeper ones
- Later cooling is driven by
  deeper layers once thermal
  time scale of envelope ~ age

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Luminosity Evolution

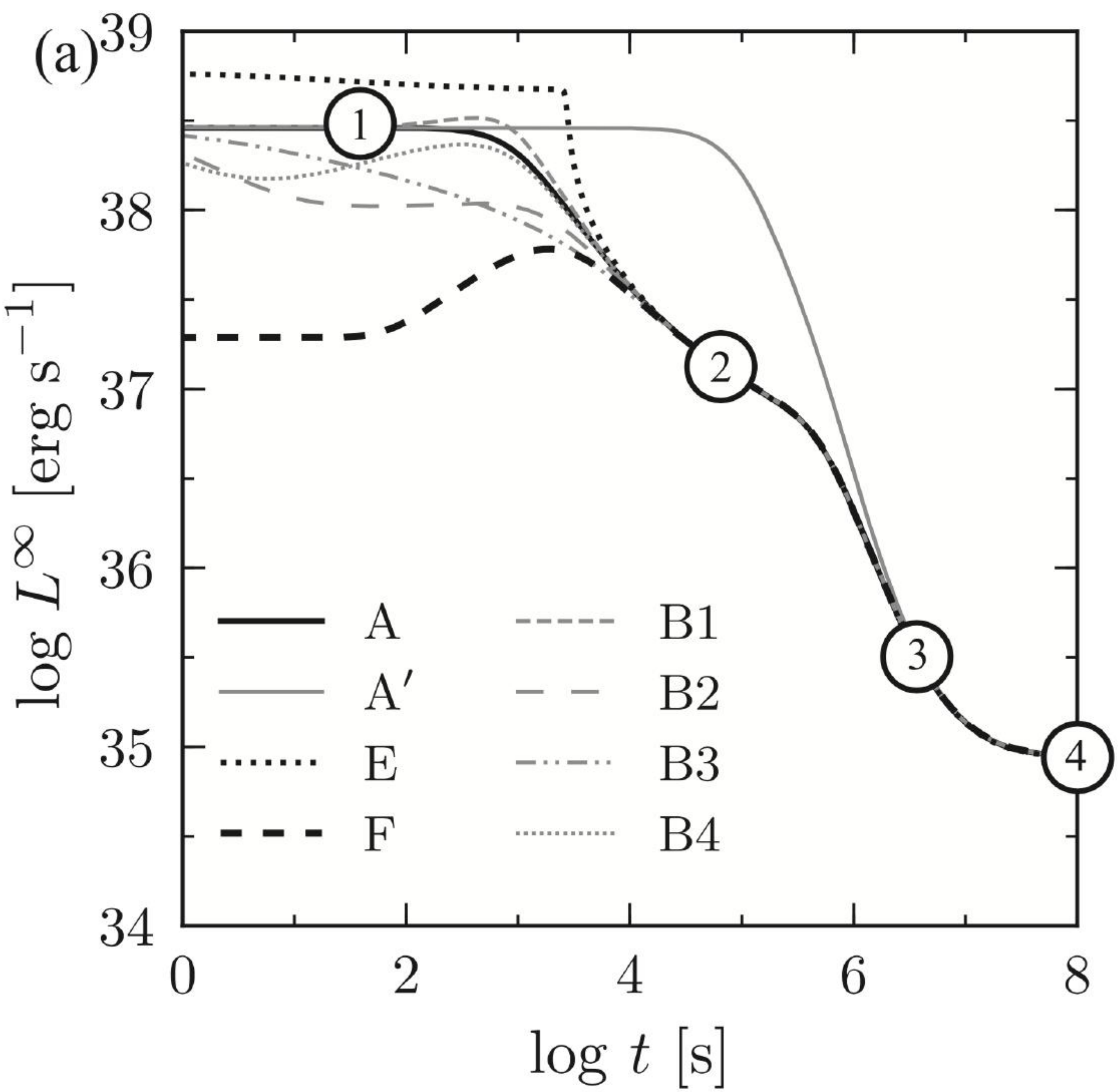
1: Eddington phase: relaxation from initial condition ~ 1hour

2: Cooling by pair neutrinos

3: Cooling by plasma neutrinos

4: Early plateau: young NS phase

At stage 4: L ~ 10^{35} erg/s ~ luminosity of the blob in SN 1987A !!!



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Long Term Cooling
of
Neutron Stars

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  Star possibly kept not too cold by internal heating (mag. field decay, friction from differential rotation, baryonic/dark matter accretion, ...)

Neutrino Processes

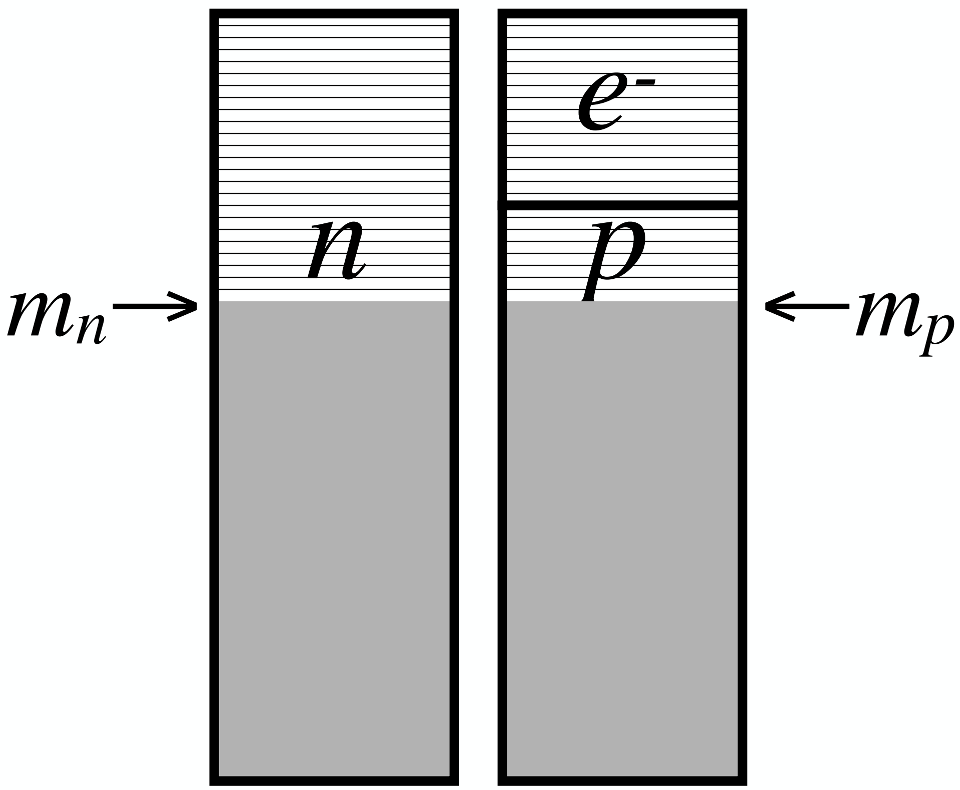
The Direct Urca Process

Basic mechanism: β and inverse β decays:

$$n \longrightarrow p + e^- + \overline{\nu}_e \quad \text{and} \quad p + e^- \longrightarrow n + \nu_e$$

Energy conservation:

$E_{Fn} = E_{Fp} + E_{Fe}$



Momentum conservation:

"Triangle rule": $p_{Fn} < p_{Fp} + p_{Fe}$

$$n_i = \frac{k_{F\,i}^3}{3\pi^2} \Rightarrow n_n^{1/3} \leq n_p^{1/3} + n_e^{1/3} = 2n_p^{1/3}$$

$$x_p \equiv \frac{n_p}{n_n + n_p} \geq \frac{1}{9} \approx 11\%$$

The Modified Urca Process

Direct Urca process: $$\begin{cases} n & \longrightarrow & p + e^- + \overline{\nu}_e \\ p + e^- & \longrightarrow & n + \nu_e \end{cases}$$

DUrca needs x_p > 11%: possible only at high densities

Modified Urca process: $$\begin{cases} n + n' & \longrightarrow & p + n' + e^- + \overline{\nu}_e \\ p + n' + e^- & \longrightarrow & n + n' + \nu_e \end{cases}$$

The “spectator” neutron n´ gives or take the needed extra momentum: possible at any density

$$\epsilon_{\mathrm{DUrca}} \simeq 10^{27} \cdot T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1}$$

$$\epsilon_{\mathrm{MUrca}} \simeq 10^{21} \cdot T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}$$

← One cubic meter of matter at T=10^9 K emits 10^{33} erg s^{-1} ~ $L_\odot$

The Murca-Bremsstrahlung Family & Durca

Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca cycle (neutron branch)	$n + n \to n + p + e^- + \bar{\nu}_e$ $n + p + e^- \to n + n + \nu_e$	$\sim 2\times 10^{21}\, R\, T_9^8$	Slow
Modified Urca cycle (proton branch)	$p + n \to p + p + e^- + \bar{\nu}_e$ $p + p + e^- \to p + n + \nu_e$	$\sim 10^{21}\, R\, T_9^8$	Slow
Bremsstrahlung	$n + n \to n + n + \nu + \bar{\nu}$ $n + p \to n + p + \nu + \bar{\nu}$ $p + p \to p + p + \nu + \bar{\nu}$	$\sim 10^{19}\, R\, T_9^8$	Slow
Direct Urca cycle	$n \to p + e^- + \bar{\nu}_e$ $p + e^- \to n + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast

The Murca-Bremsstrahlung Family & Durca

Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca cycle (neutron branch)	$n + n \to n + p + e^- + \bar{\nu}_e$ $n + p + e^- \to n + n + \nu_e$	$\sim 2{\times}10^{21}\ R\ T_9^8$	Slow
Modified Urca cycle [illegible]	$p + n \to p + p + e^- + \bar{\nu}_e$ [illegible] $+ n + \nu$ [illegible]	$\sim 10^{21}\ R\ T_9^8$	Slow
[illegible]	[illegible] $+ \bar{\nu}$ [illegible] $\nu + \bar{\nu}$ [illegible]	$\sim 10^{19}\ R\ T_9^8$	Slow
Direct Urca cycle	$n \to p + e^- + \bar{\nu}_e$ $p + e^- \to n + \nu_e$	$\sim 10^{27}\ R\ T_9^6$	Fast

$$\left(\frac{T}{E_F}\right) = 10^{-3}\left(\frac{T/10^9\mathrm{K}}{E_F/100\mathrm{MeV}}\right)$$

URCA =
"Un-Recorded
Cooling
Agent" !

Neutrino Emission from Hyperons

Hyperons, as Λ and Σ⁻, can be produced through reactions as, e.g.

$$\begin{cases} p + e^- & \longrightarrow & \Lambda + \nu_e \\ \Lambda & \longrightarrow & p + e^- + \overline{\nu}_e \end{cases}$$

$$\begin{cases} n + e^- & \longrightarrow & \Sigma^- + \nu_e \\ \Sigma^- & \longrightarrow & n + e^- + \overline{\nu}_e \end{cases}$$

Energy conservation requires: $\mu_\Lambda = \mu_n$ and $\mu_{\Sigma^-} = \mu_n + \mu_e$

Momentum conservation: very easily satisfied for Λ and not very difficult to satisfy for Σ^-

Hyperons will result in DUrca processes if they can be present

Neutino Emission from Deconfined Quarks

2 DUrca processes are possibles (energy and momentum are easily conserved):

$$\begin{cases} u + e^- & \longrightarrow & d + \nu_e \\ d & \longrightarrow & u + e^- + \overline{\nu}_e \end{cases} \qquad \begin{cases} u + e^- & \longrightarrow & s + \nu_e \\ s & \longrightarrow & u + e^- + \overline{\nu}_e \end{cases}$$

In $d \longrightarrow u + e^- + \overline{\nu}_e$ the matrix element (squared)

$$|M_{fi}|^2 = 32 G_F^2 \cos^2\theta_C (p_1 \cdot p_2)(p_3 \cdot p_4)$$

vanishes if $\mu_q = c p_{Fq}$ ⇒ need α_c correction: $\mu_q = \left(1 + \frac{8\alpha_c}{3\pi}\right) c p_{Fq}$

$$\epsilon^{\mathrm{ud-DUrca}} = \frac{914}{315} \frac{G_F^2 \cos^2\theta_C}{\hbar^{10} c^9} \alpha_c \, \mu_u \mu_d \mu_e (k_B T)^6$$

Deconfined Quarks will result in DUrca processes if they can be present

A sample of neutrino emission processes

Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca cycle (neutron branch)	$n+n \to n+p+e^- + \bar{\nu}_e$ $n+p+e^- \to n+n+\nu_e$	$\sim 2 \times 10^{21}\, R\, T_9^8$	Slow
Modified Urca cycle (proton branch)	$p+n \to p+p+e^- + \bar{\nu}_e$ $p+p+e^- \to p+n+\nu_e$	$\sim 10^{21}\, R\, T_9^8$	Slow
Bremsstrahlung	$n+n \to n+n+\nu+\bar{\nu}$ $n+p \to n+p+\nu+\bar{\nu}$ $p+p \to p+p+\nu+\bar{\nu}$	$\sim 10^{19}\, R\, T_9^8$	Slow
Cooper pair formations	$n+n \to [nn]+\nu+\bar{\nu}$ $p+p \to [pp]+\nu+\bar{\nu}$	$\sim 5 \times 10^{21}\, R\, T_9^7$ $\sim 5 \times 10^{19}\, R\, T_9^7$	Medium
Direct Urca cycle (nucleons)	$n \to p+e^- + \bar{\nu}_e$ $p+e^- \to n+\nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (Λ hyperons)	$\Lambda \to p+e^- + \bar{\nu}_e$ $p+e^- \to \Lambda+\nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (Σ^- hyperons)	$\Sigma^- \to n+e^- + \bar{\nu}_e$ $n+e^- \to \Sigma^- +\nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
π^- condensate	$n+ <\pi^-> \to n+e^- + \bar{\nu}_e$	$\sim 10^{26}\, R\, T_9^6$	Fast
K^- condensate	$n+ <K^-> \to n+e^- + \bar{\nu}_e$	$\sim 10^{25}\, R\, T_9^6$	Fast
Direct Urca cycle (u-d quarks)	$d \to u+e^- + \bar{\nu}_e$ $u+e^- \to d+\nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (u-s quarks)	$s \to u+e^- + \bar{\nu}_e$ $u+e^- \to s+\nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast

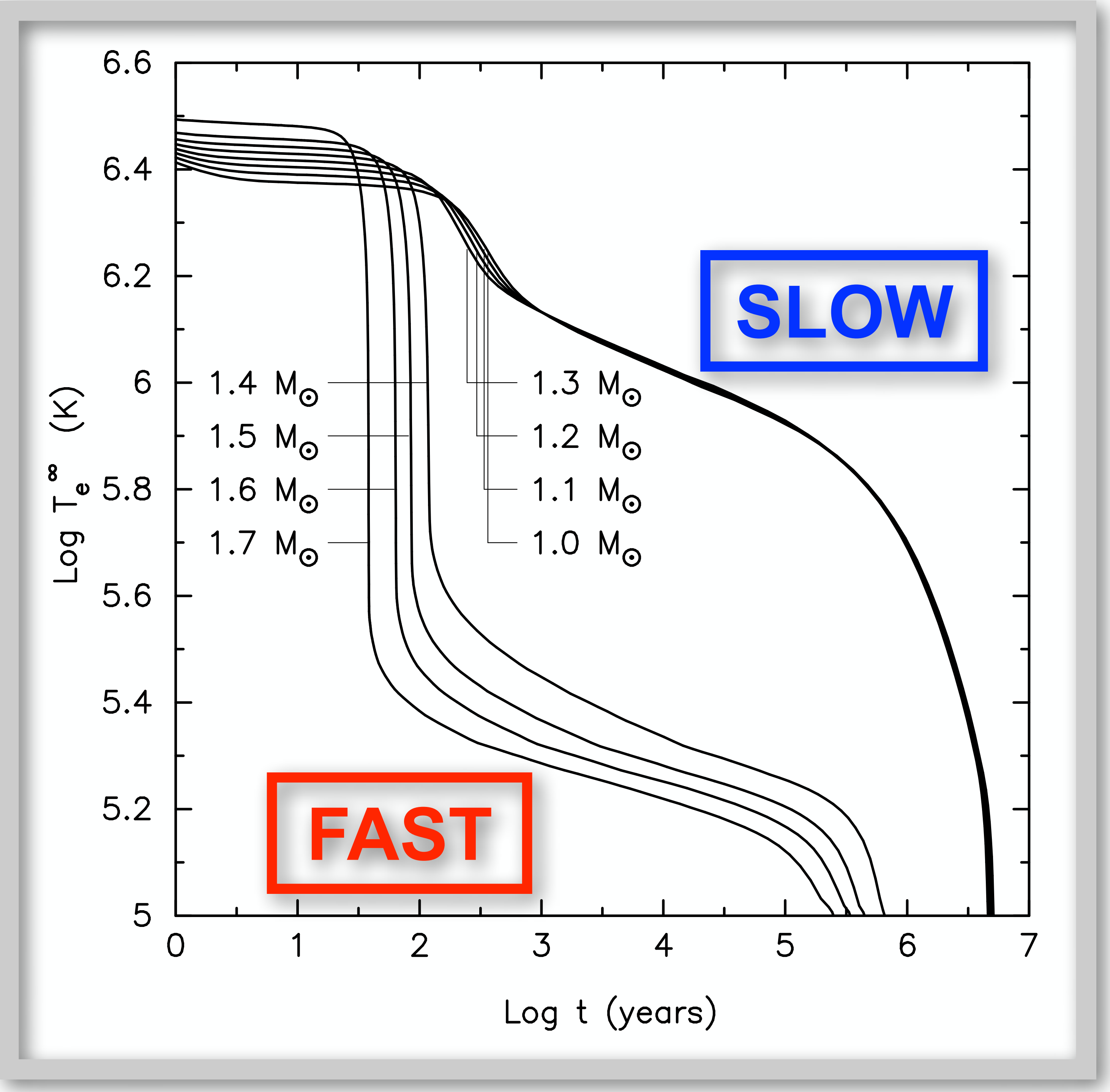
A sample of neutrino emission processes

Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca cycle (neutron branch)	$n+n \to n+p+e^- + \bar\nu_e$ $n+p+e^- \to n+n+\nu_e$	$\sim 2\times 10^{21}\, R\, T_9^8$	Slow
Modified Urca cycle (proton branch)	$p+n \to p+p+e^- + \bar\nu_e$ $p+p+e^- \to p+n+\nu_e$		Slow
Bremsstrahlung	$n+n \to n+n+\nu+$ ... $n+p \to n+$ ... $p+p \to$ ...		Slow
Cooper pair formations	n ...	... $R\, T_9^7$	Medium
Direct Urca cycle (nucleons)		$\sim 10^{27}\, R\, T_9^6$	Fast
Dir...	... $+\nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
D... (Σ ...	... $n+e^- + \bar\nu_e$ $n+e^- \to \Sigma^- + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
π^- c...	$n + <\pi^-> \to n+e^- + \bar\nu_e$	$\sim 10^{26}\, R\, T_9^6$	Fast
K^- c...	$n + <K^-> \to n+e^- + \bar\nu_e$	$\sim 10^{25}\, R\, T_9^6$	Fast
Direct Urca cycle (u-d quarks)	$d \to u+e^- + \bar\nu_e$ $u+e^- \to d+\nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (u-s quarks)	$s \to u+e^- + \bar\nu_e$ $u+e^- \to s+\nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast

Anything beyond just neutrons and protons (and only a small amount of them) results in enhanced neutrino emission

Naive
Neutron Star Cooling

Direct vs Modified Urca Cooling



Models based on the PAL EOS:

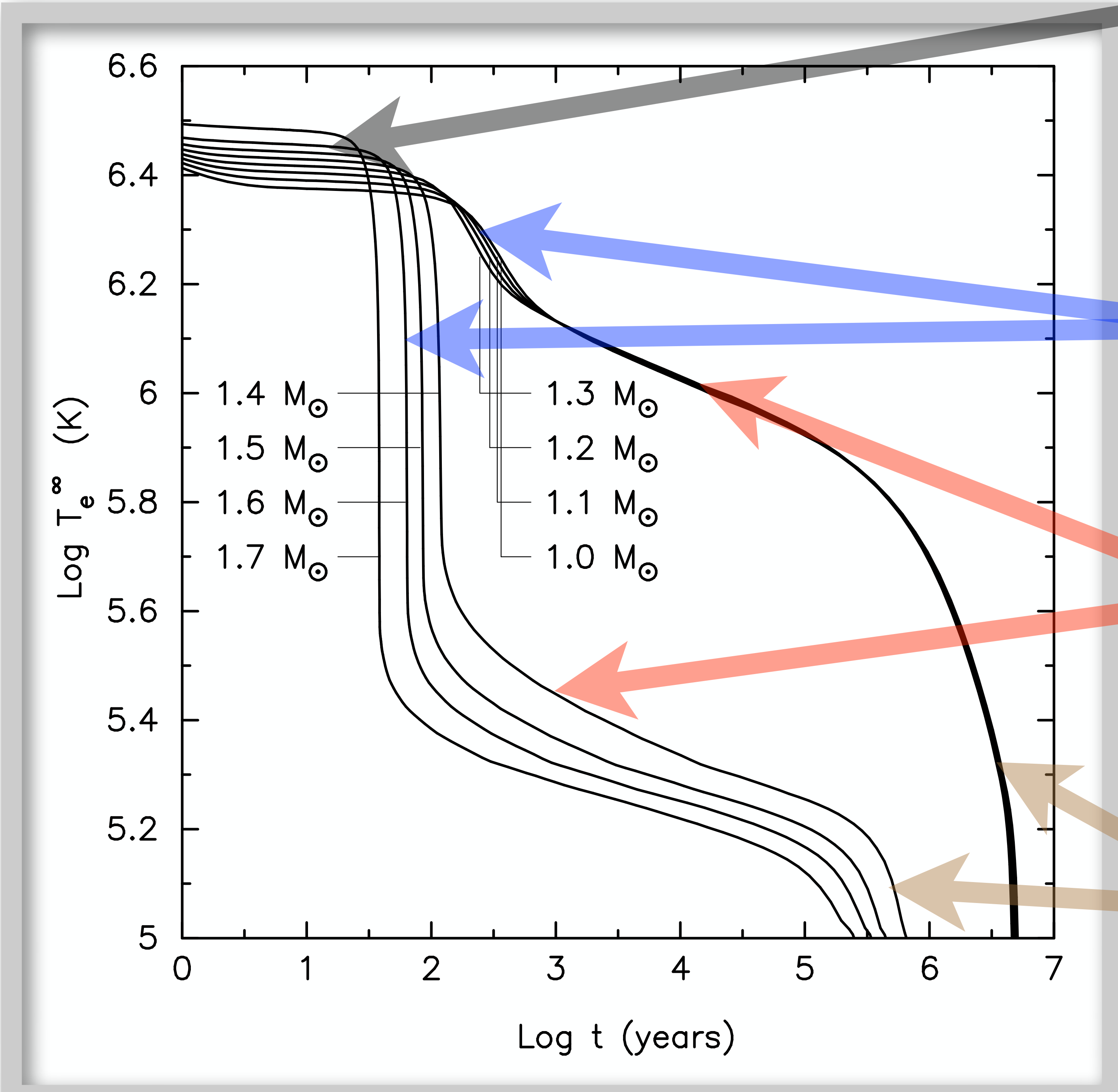
adjusted (by hand) so that DURCA becomes allowed (triangle rule !) at M > 1.35 M_{Sun}.

This value is arbitrary:
we DO NOT know the value of this critical mass, and hopefully observations will, some day, tell us what it is !

GR models, solving numerically the energy balance and heat transport equations, with lots of microphysics involved.

"The Cooling of Neutron Stars by the Direct Urca Process", Page & Applegate, ApJ 394, L17 (1992)

Successive Phases of Cooling



Early Time:
T_e controled by
ν emission
in the crust

Crust relaxation:
crustal heat flows
into the core.

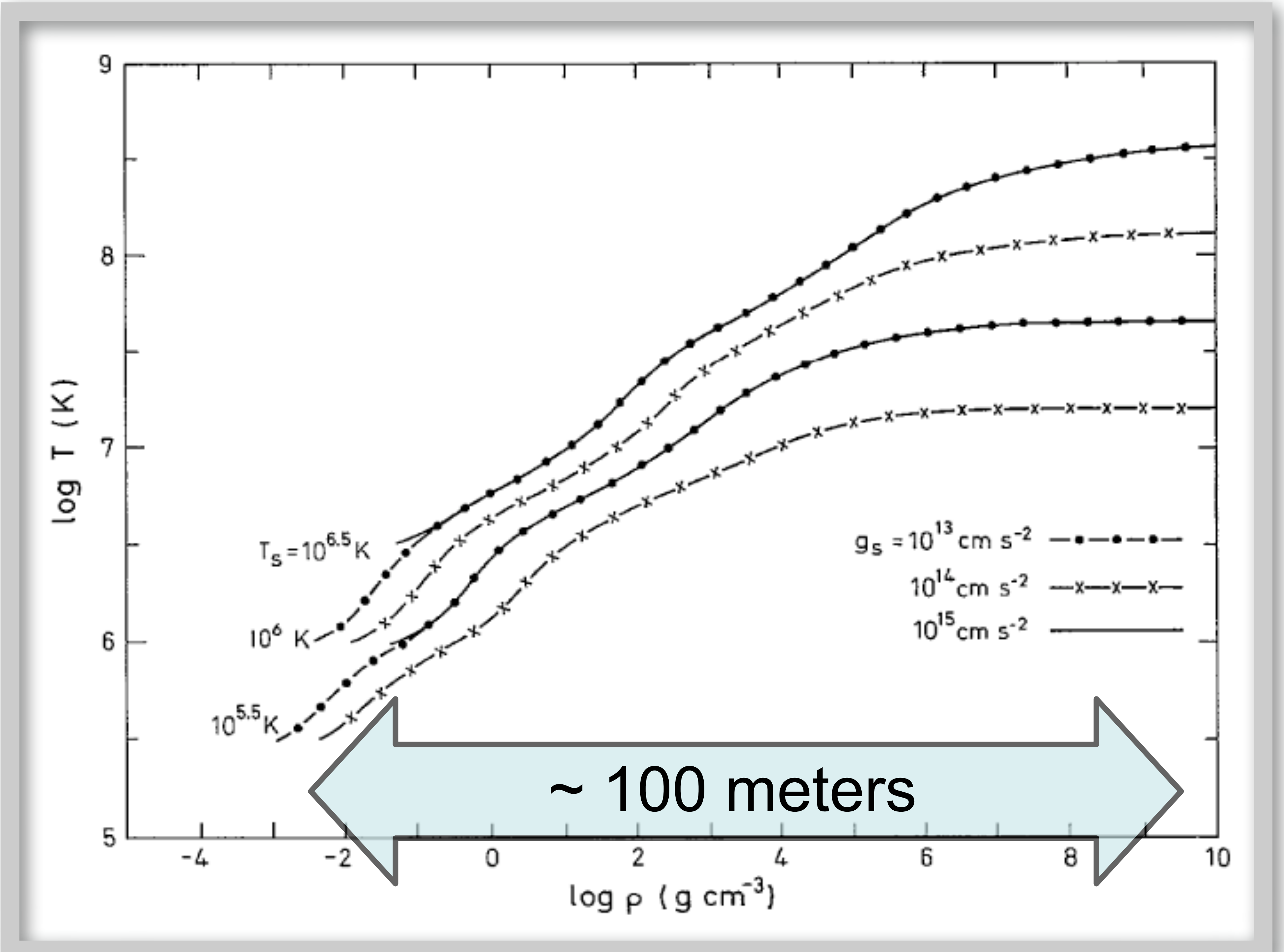
Isothermal Star:
T_e controled by
ν emission
from the core

Isothermal Star:
T_e driven by
photon emission
from the surface

"The Cooling of Neutron Stars by the Direct Urca Process", Page & Applegate, ApJ 394, L17 (1992)

Surface Thermal Emission: The envelope

Neutron Star Envelopes



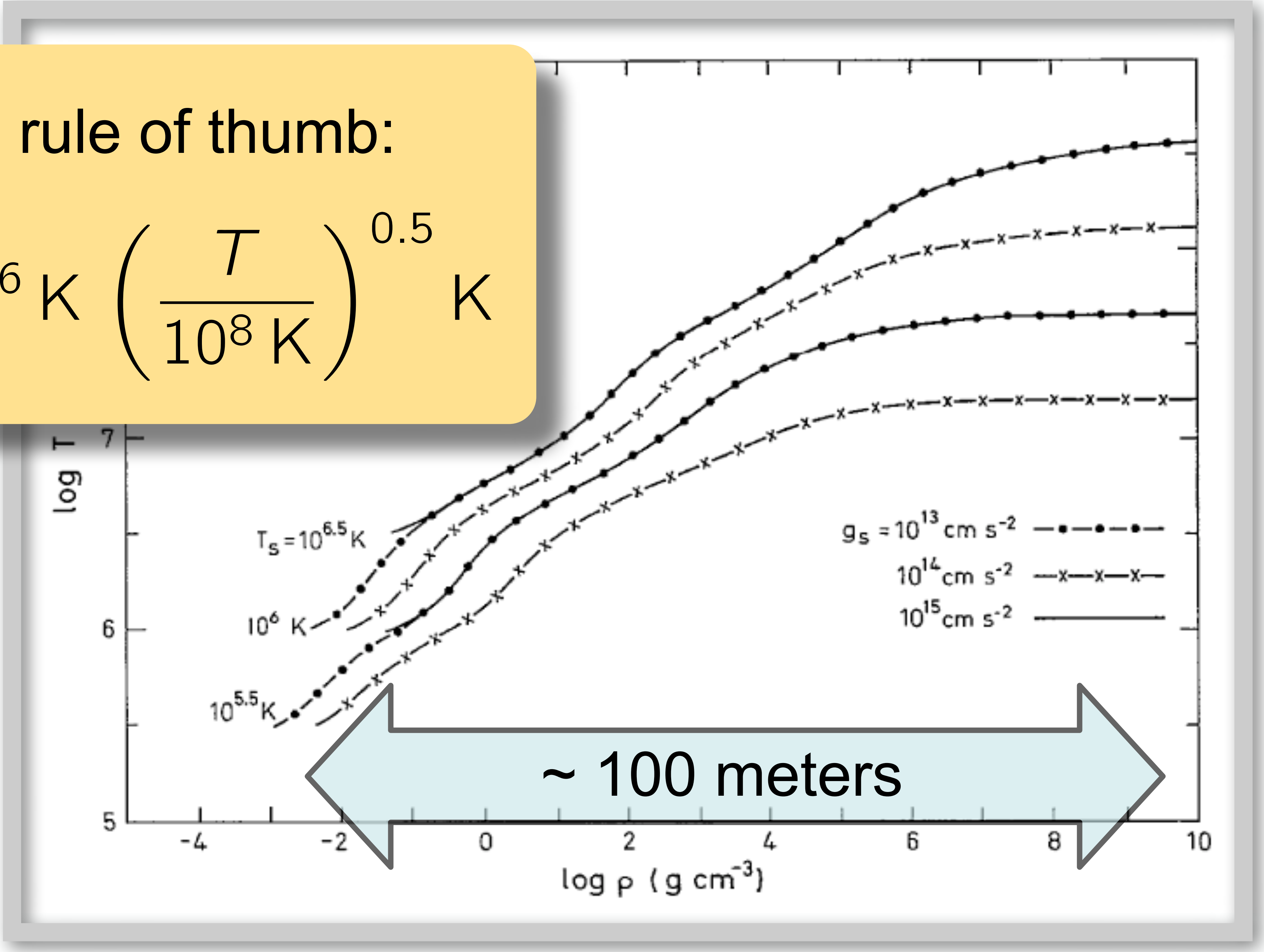
Neutron star envelopes
Gudmundsson, E. H.; Pethick, C. J.; Epstein, R. I.
1982ApJ...259L..19G

Structure of neutron star envelopes
Gudmundsson, E. H.; Pethick, C. J.; Epstein, R. I.
1983ApJ...272..286G

Neutron Star Envelopes

As a rule of thumb:

$$T_e \approx 10^6\,\mathrm{K}\left(\frac{T}{10^8\,\mathrm{K}}\right)^{0.5}\,\mathrm{K}$$



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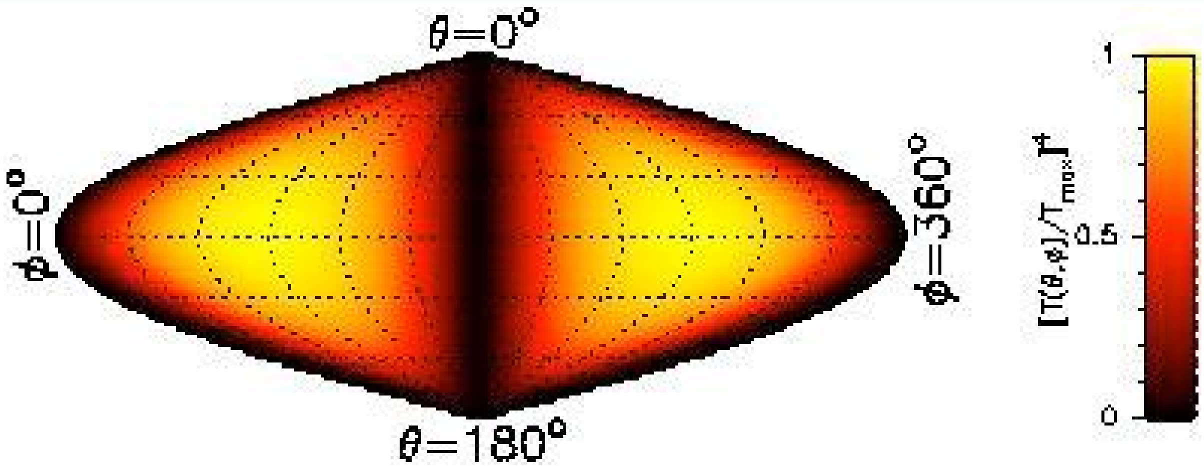
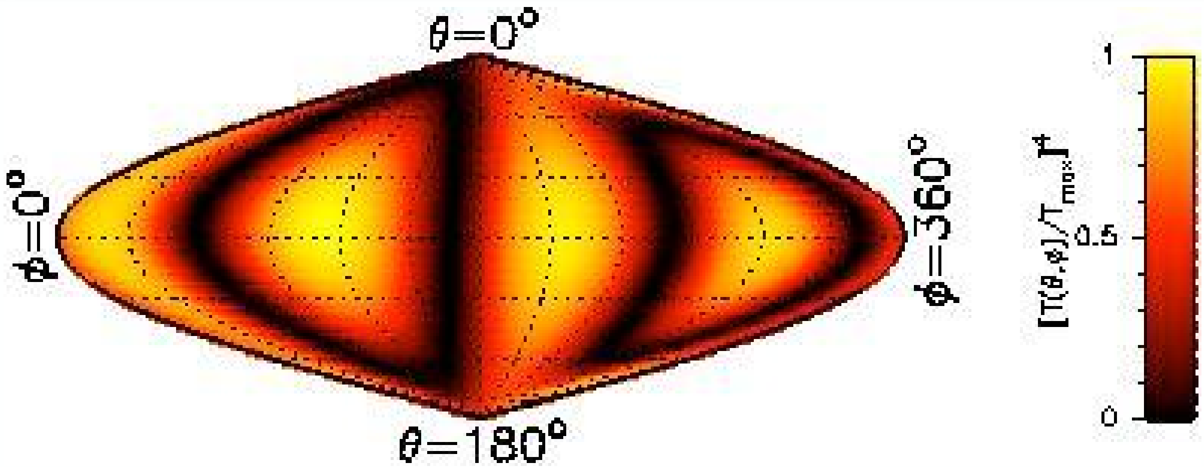
Neutron Star Envelope: Magnetic Fields



Purely dipolar field
(oriented on the equatorial plane to make a prettier picture !)

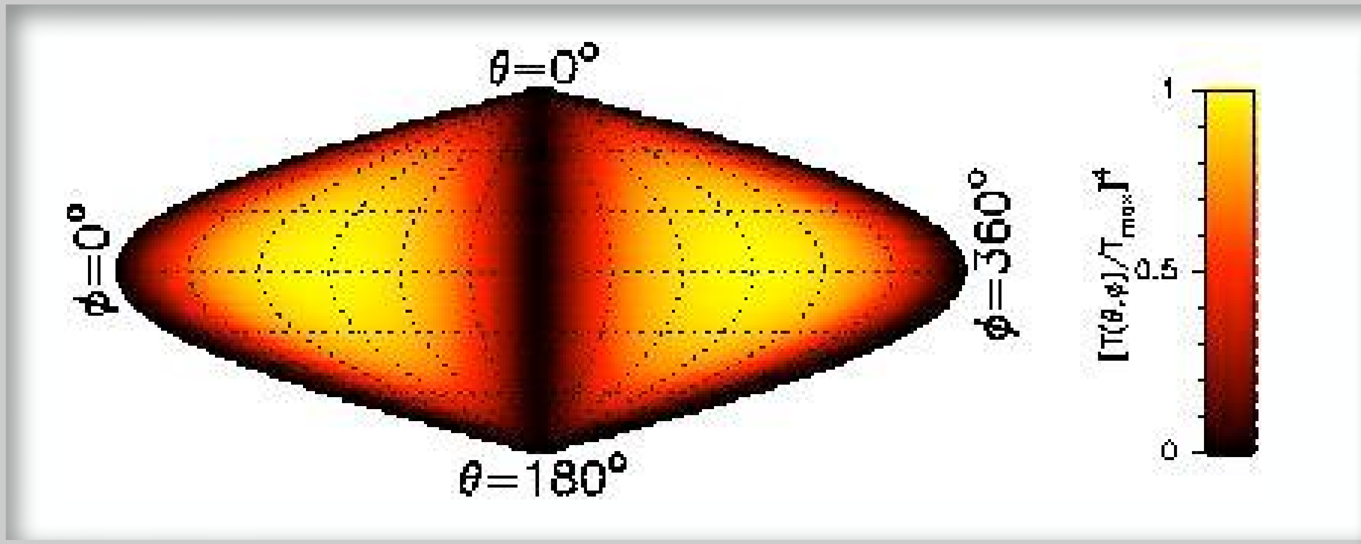


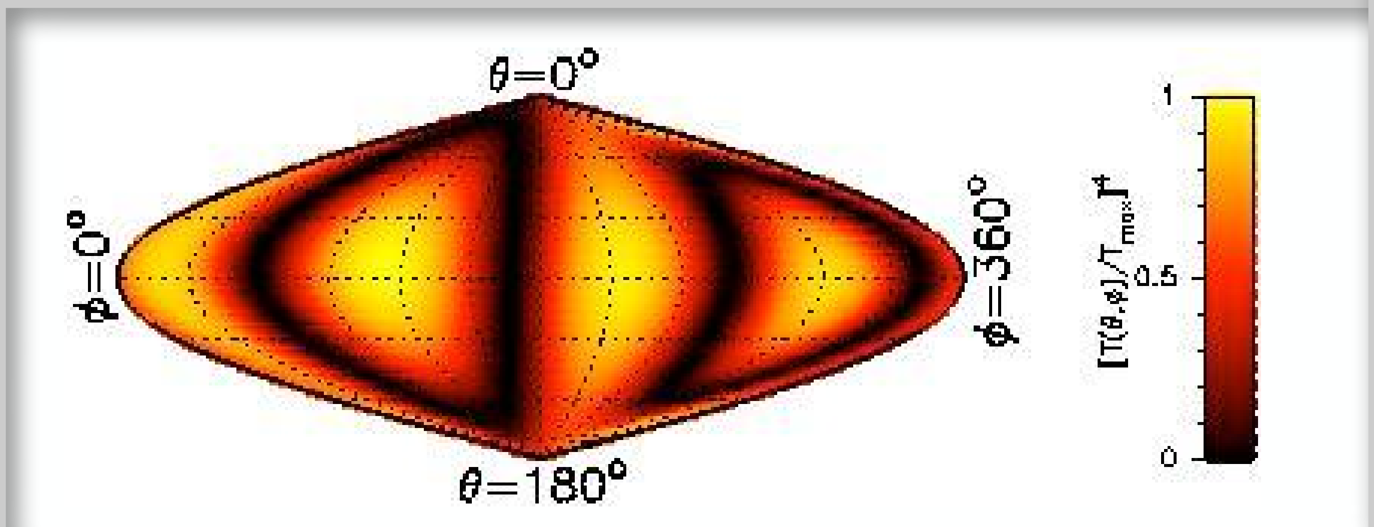
Dipolar + quadrupolar field

Surface temperature of a magnetized neutron star and interpretation of the ROSAT data. I. Dipolar fields
Page, D.
1995ApJ...442..273P

Surface temperature of a magnetized neutron star and interpretation of the ROSAT data. II.
Page, D.; Sarmiento, A.
1996ApJ...473.1067P

Neutron Star Envelope: Magnetic Fields





The star's effective temperature is then easily calculated:

$$L = \iint \sigma_B T_s(\theta,\phi)^4 dS \;=\; 4\pi R^2 \sigma T_e^4$$

$$(dS \;=\; R^2 \cdot d\Omega)$$

$$T_e^4 = \frac{1}{4\pi} \iint T_s(\theta,\phi)^4 \, d\Omega$$

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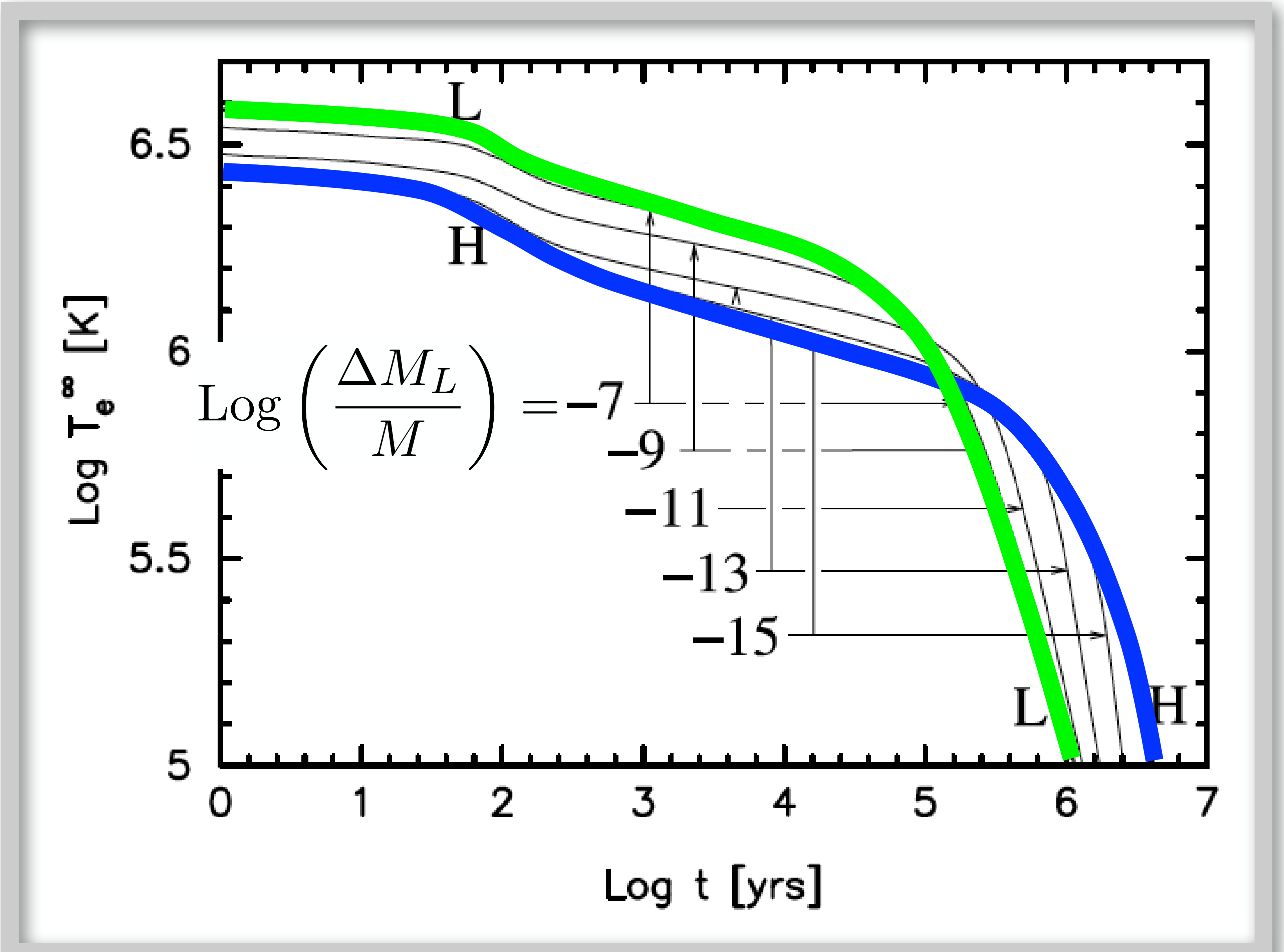
Effects of Light Elements Envelopes



Pairing: Superfluidity & Superconductivity

Brief History of Superconductivity & Superconductivity

- 1911: Heike Kamerlingh Onnes discovers superconductivity
- 1937: Pyotr Kapitsa discovers superfluidity of ^{4}He
- 1940: Lev Landau proposes his theory of superfluidity
- 1954: F. London proposes a simple explanation of superconductivity
- 1956: Leon Cooper ‘discovers’ the Cooper pairs
- 1957: J. Bardeen, L.N. Cooper, & J.R. Schrieffer present the `BCS´ theory of superconductivity.
- 1958: A. Bohr, B.R. Mottelson, & D. Pines argue that neutrons and protons in nuclei form Cooper pairs
- 1959: A. Migdal suggests that neutrons in neutron stars may be superfluid
- 1960´s: theoretical work on possibility of ^{3}He superfluidity *à la* BCS
- 1972: D.D. Osheroff, R.C. Richardson, & D. Lee discover ^{3}He superfluidity
- 1967: J. Bell & A. Hewish discover pulsars (= neutron stars)
- → numerous theoretical works on neutron/proton superfluidity/superconductivity in neutron stars ...

Bosons versus Fermions

Fermions obey the Pauli exclusion principle:
only one particle per wave function

Bosons do not:
many particles can be described by the same wave function

Bose-Einstein Condensation (**BEC**):
when $T<T_c$ most particles occupy the ground state

De Broglie wave length: $\lambda_{dB}^2 = \frac{2\pi\hbar^2}{mk_B T}$

Thermal energy $\frac{p^2}{2m} \approx k_B T$ Heisenberg: $\Delta p \cdot \Delta x \sim \hbar$ $\Delta p \approx p \Longrightarrow (\Delta x)^2 \sim \frac{\hbar^2}{2mk_B T}$

Bose-Einstein Condensation when λ_{dB} > interparticle distance

Bosons versus Fermions

Fermions obey the Pauli exclusion principle:
only one particle per wave function

Bosons do not:
many ... ve function

Bose-Eins...
wh... state

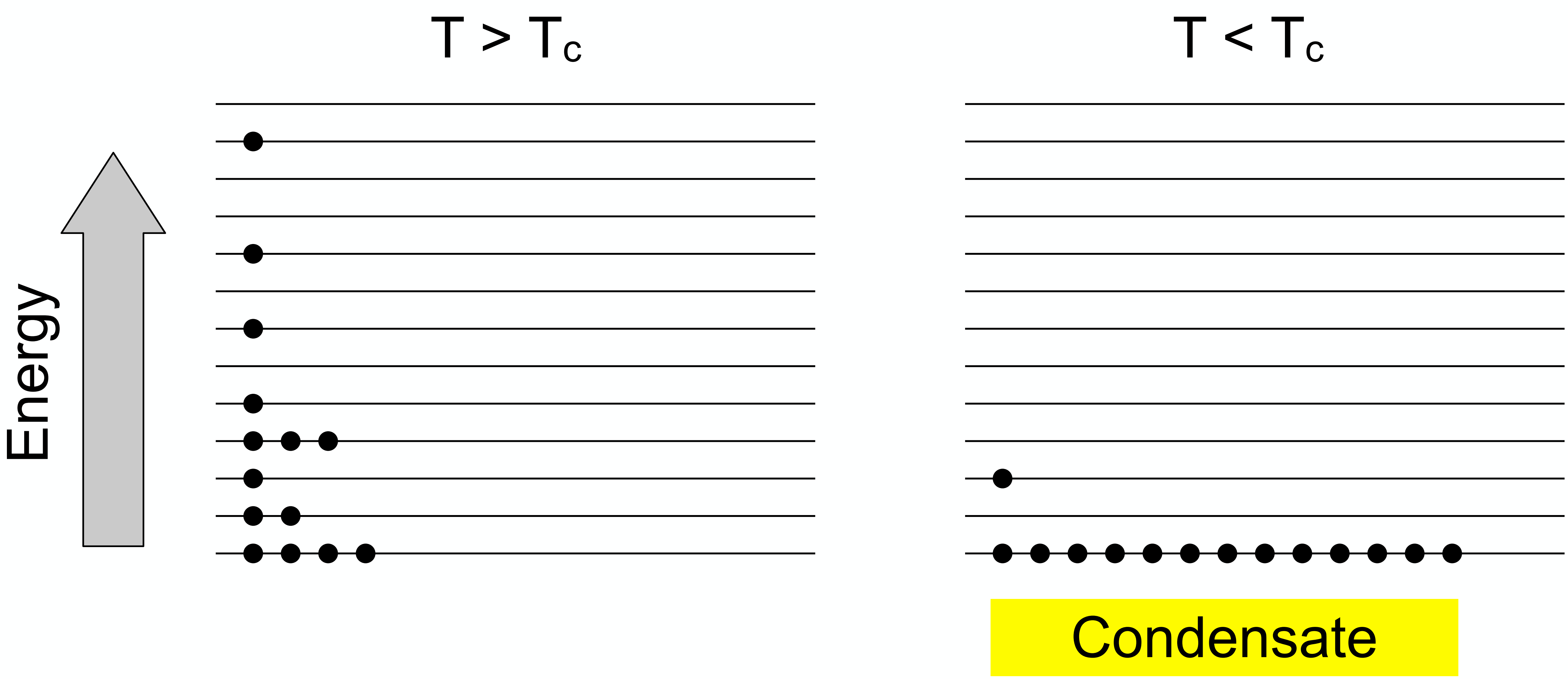
Superfluidity of ^{4}He is some kind of Bose-Einstein condensation

De Broglie wave length: $\lambda_{dB}^2 = \frac{2\pi\hbar^2}{mk_BT}$

Thermal energy $\frac{p^2}{2m} \approx k_B T$ Heisenberg: $\Delta p \cdot \Delta x \sim \hbar$ $\Delta p \approx p \Longrightarrow (\Delta x)^2 \sim \frac{\hbar^2}{2mk_BT}$

Bose-Einstein Condensation when λ_{dB} > interparticle distance

Bosons Energy Levels and BEC



BEC versus BCS

Superfluidity/superconductivity o fermions:
fermionic condensation

BCS Theory (Bardeen-Cooper-Schrieffer):

1 - fermions form Cooper pairs (=bosons)
2 - and then the pairs can condense

Fermion Superfluidity/Superconductivity

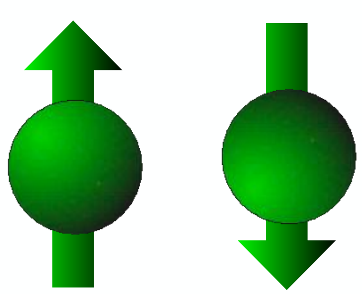
Superfluidity/superconductivity o fermions:
fermionic condensation

BCS Theory (Bardeen-Cooper-Schrieffer):
1 - fermions form Cooper pairs (=bosons)
2 - and then the pairs can condense

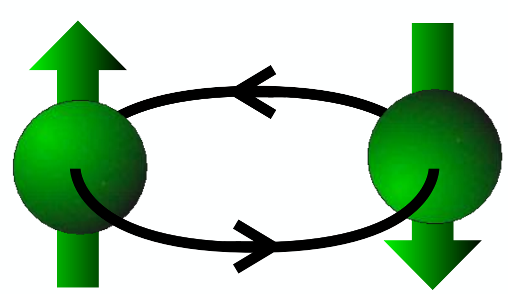
Cooper pairs spin-angular momentum

spin singlet pairs

L = 0

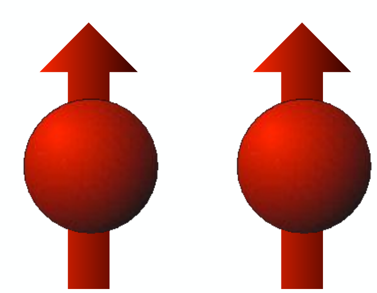


L > 0

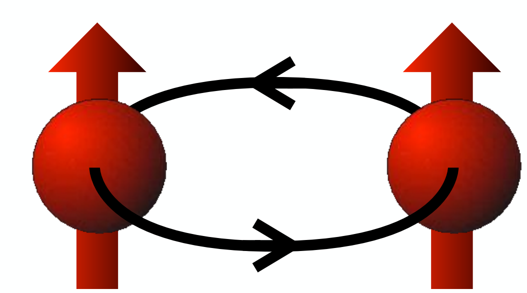


spin triplet pairs

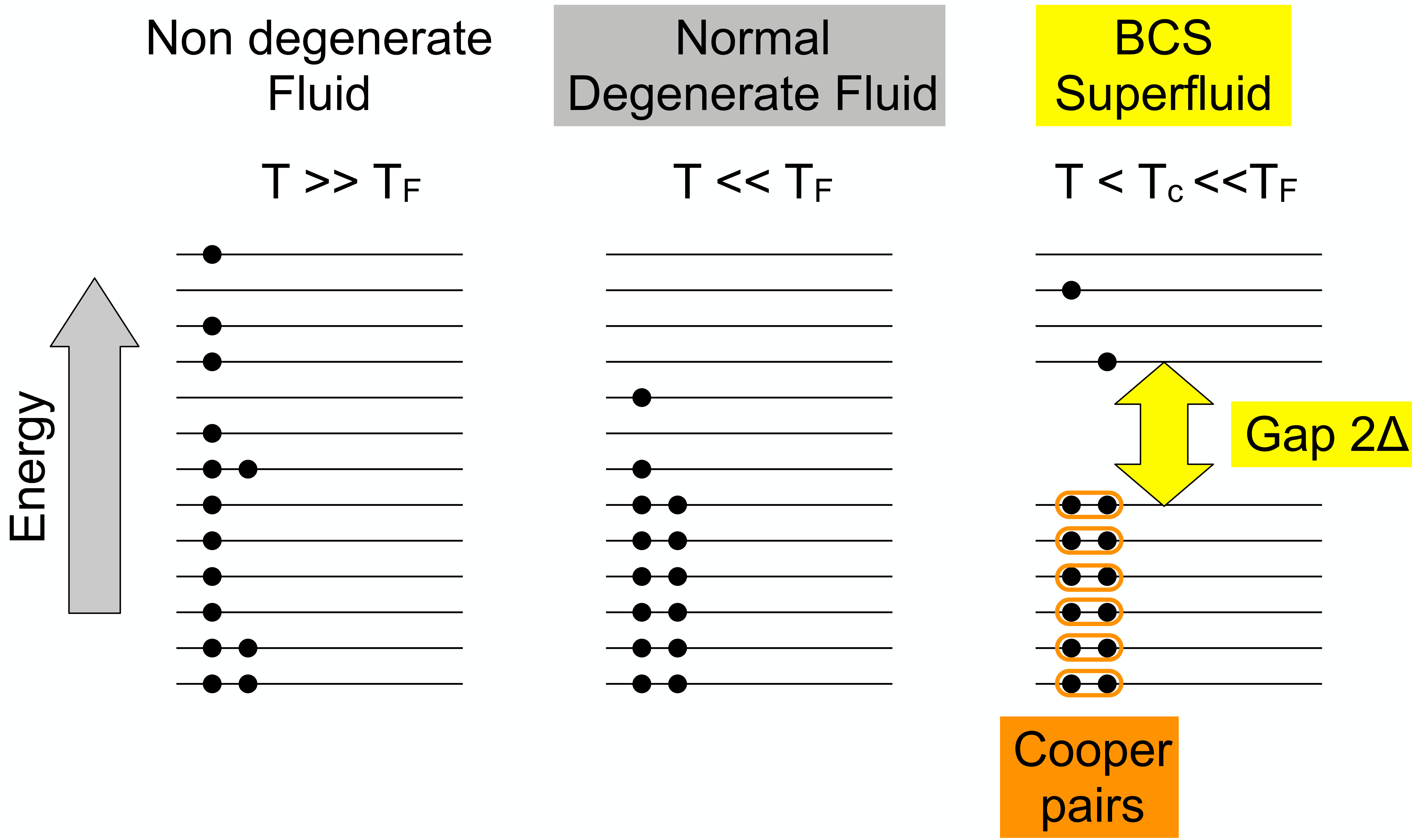
L = 0



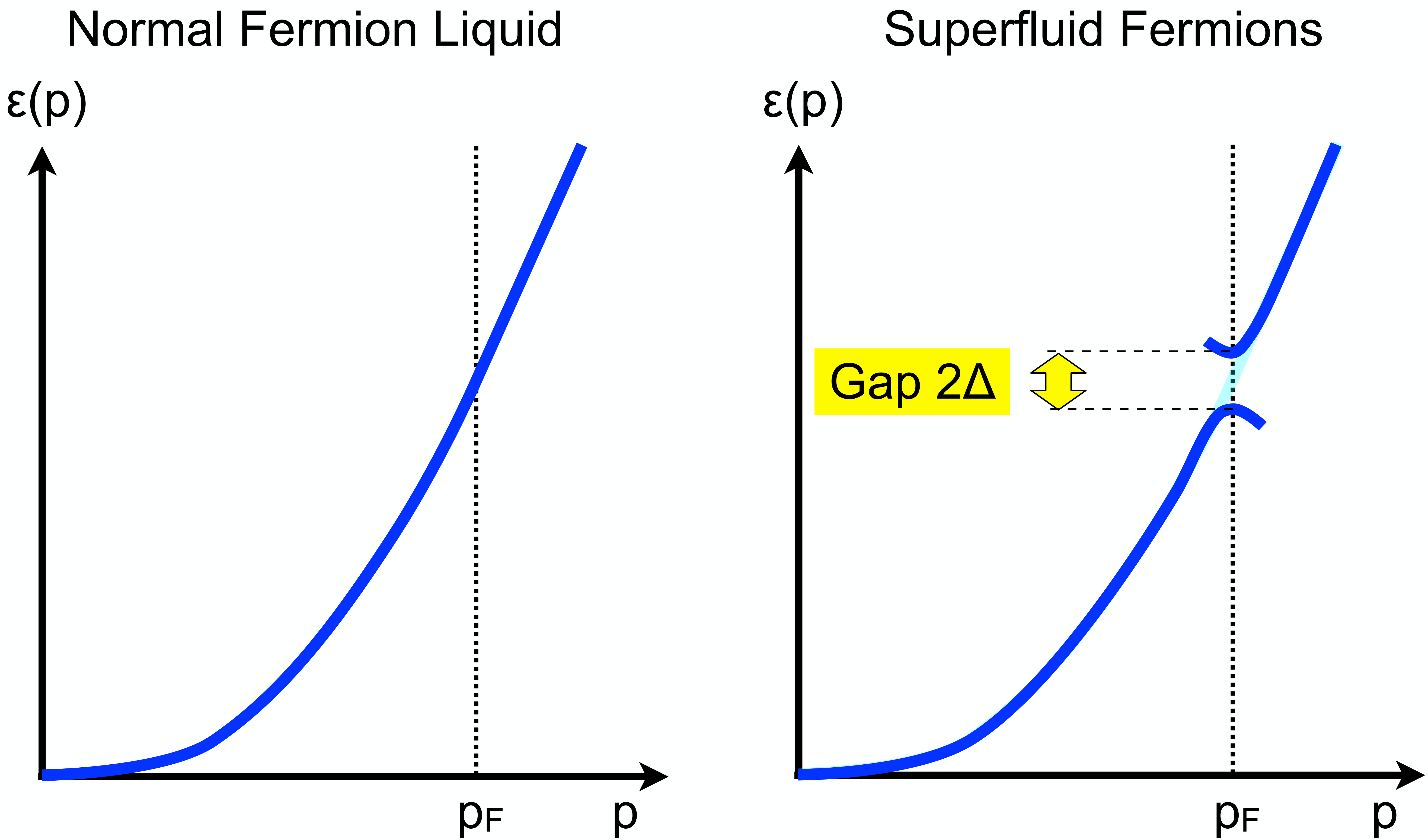
L > 0



Fermions Energy Levels and BCS



Single-Particle Excitations Spectra



First vs Second Order Phase Transition

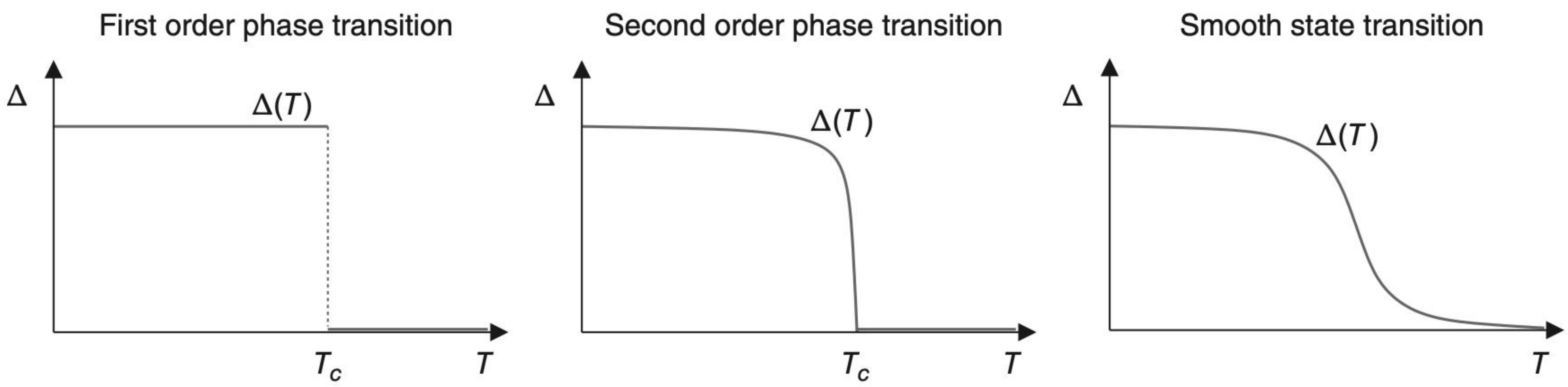


Fig. 21.6 Temperature evolution of the state of a system parametrized by an "order" parameter, $\Delta(T)$.

First order phase transition : everything happens at T_c, latent heat is released.

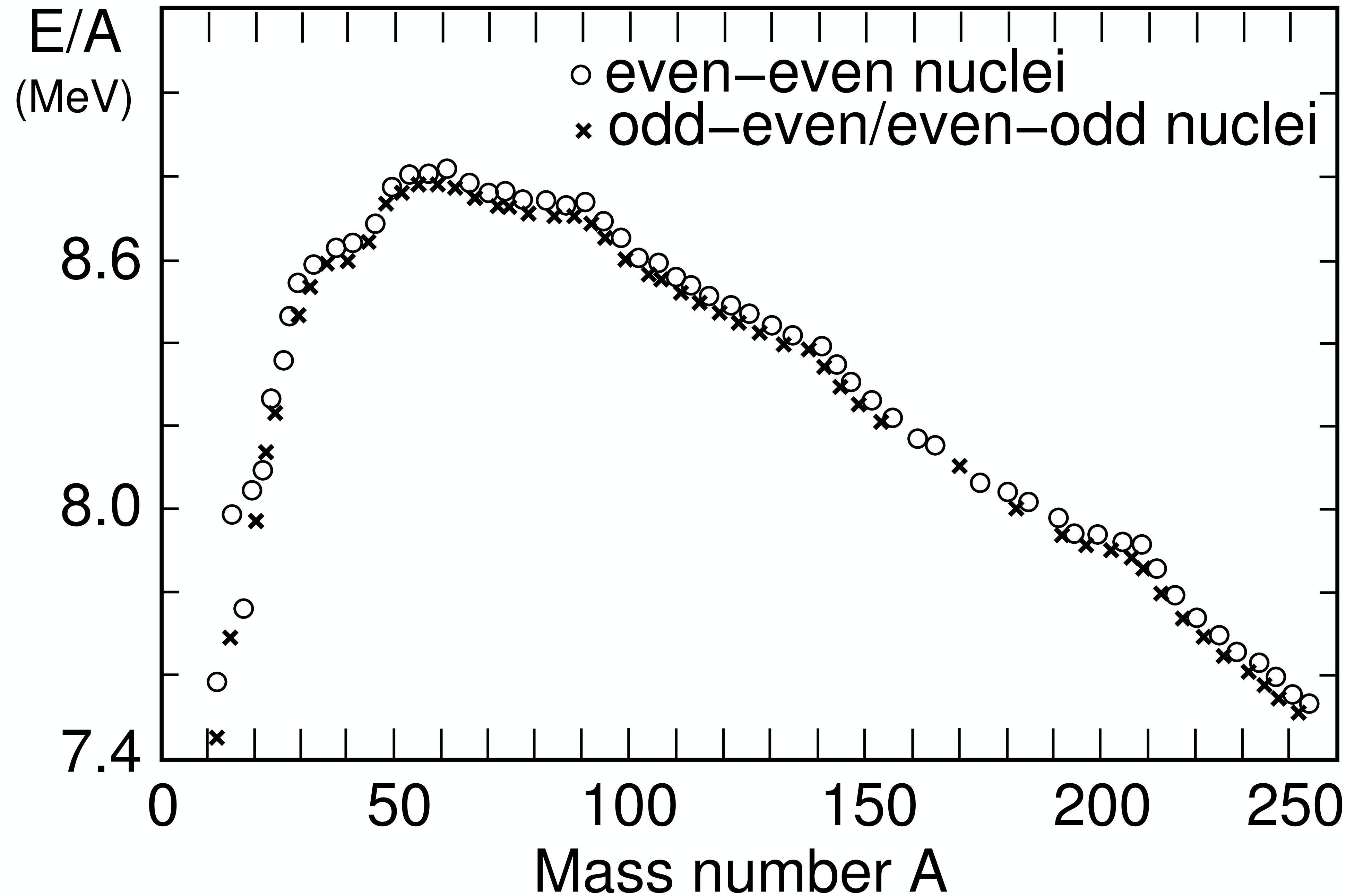
Second order phase transition: transition is initiated at Tc and keeps going on as T decreases.

Smooth state transition: no collective effects, no critical temperature

Pairing in Nuclei

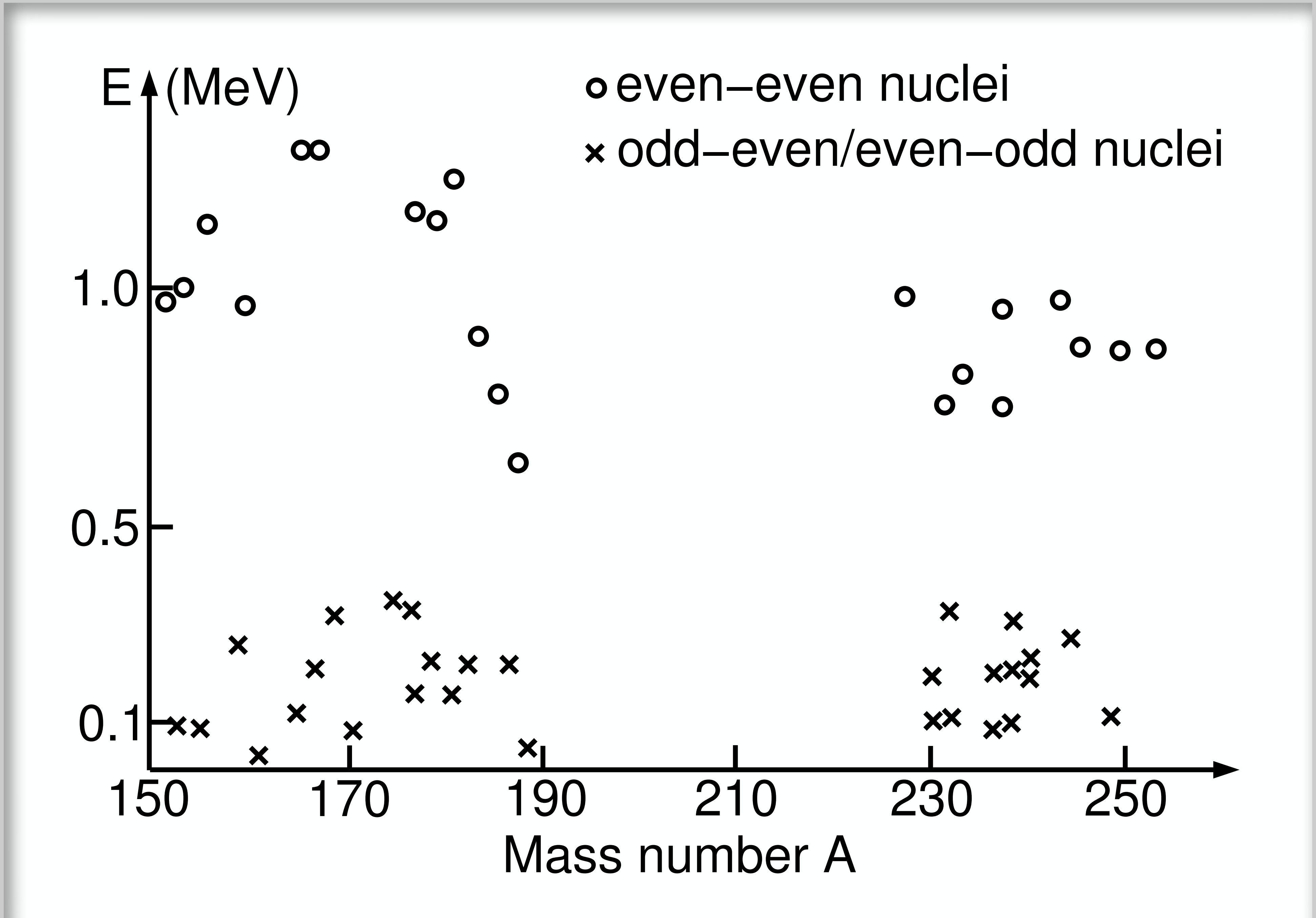
Nuclear Binding Energy

Binding energy per nucleon of the most beta-stable isobars



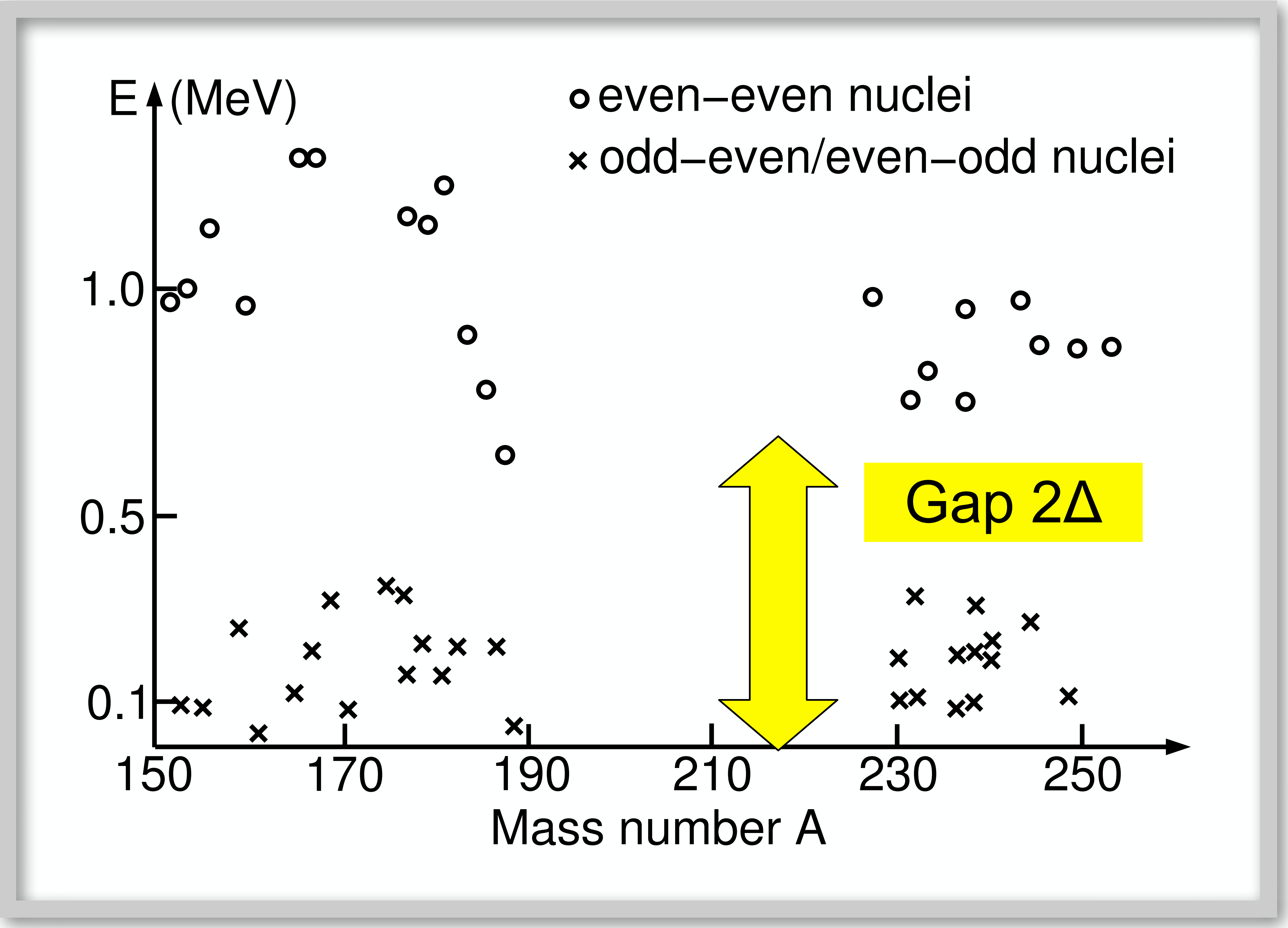
odd-odd nuclei: ^{2}H (1,1), ^{6}Li (3,3), ^{10}B (5,5) and ^{14}N (7,7)

Lowest Excitation Levels in Nuclei



Possible Analogy between the Excitation Spectra of Nuclei and Those of the Superconducting Metallic State
Bohr, A.; Mottelson, B. R.; Pines, D. (1958), Phys. Rev. 110, p.936

Lowest Excitation Levels in Nuclei



Possible Analogy between the Excitation Spectra of Nuclei and Those of the Superconducting Metallic State
Bohr, A.; Mottelson, B. R.; Pines, D. (1958), Phys. Rev. 110, p.936

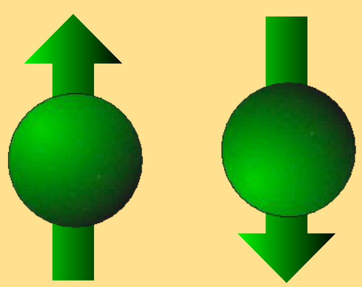
Pairing in Neutron Stars

Pairing of Nucleons

spin singlet pairs

S=0 L=0 J=0

At low k_F:



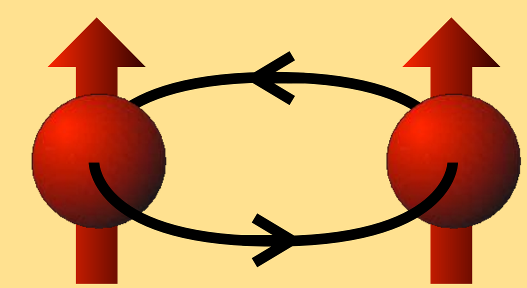
$^1S_0$ pairing

spin triplet pairs

S=1 L=1 J=2

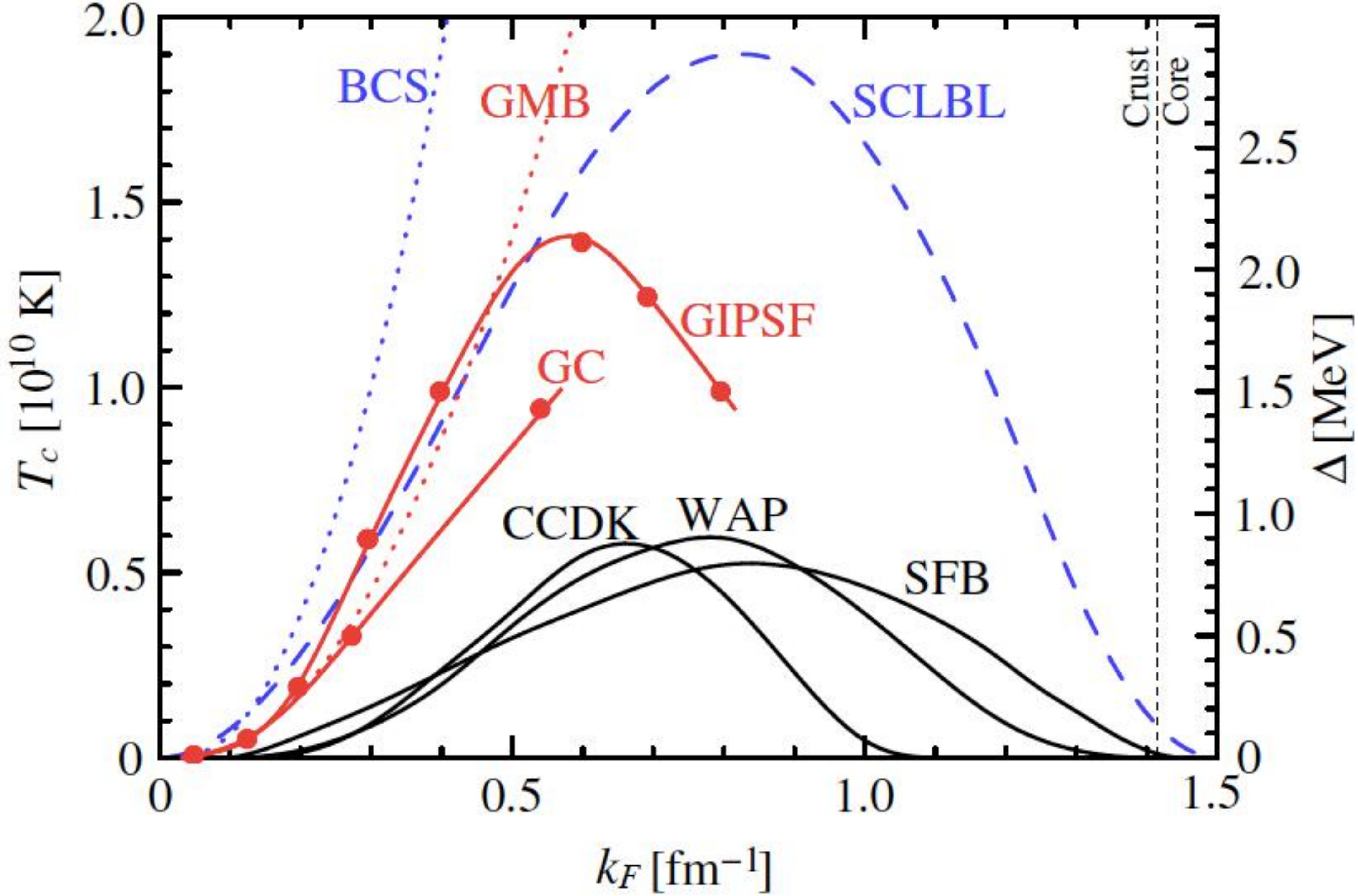
At high k_F:

$^3P_2$ pairing

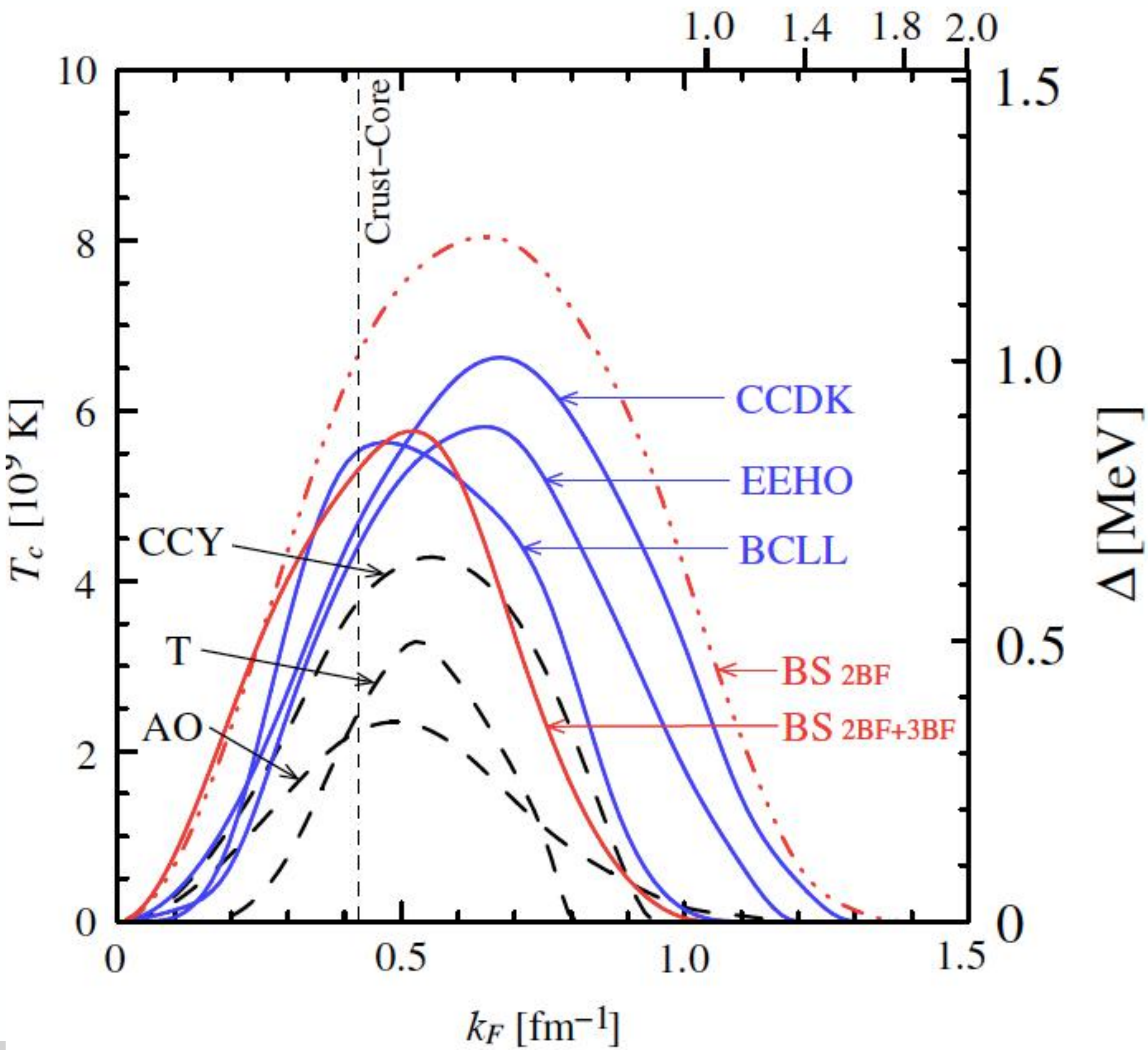


Superfluid State in Neutron Star Matter. I Generalized Bogoliubov Transformation and Existence of $^3P_2$ Gap at High Density
Tamagaki, R., 1970PThPh..44..905T

Prediction for Neutron $^1S_0$ Pairing



Prediction for Proton $^1S_0$ Pairing

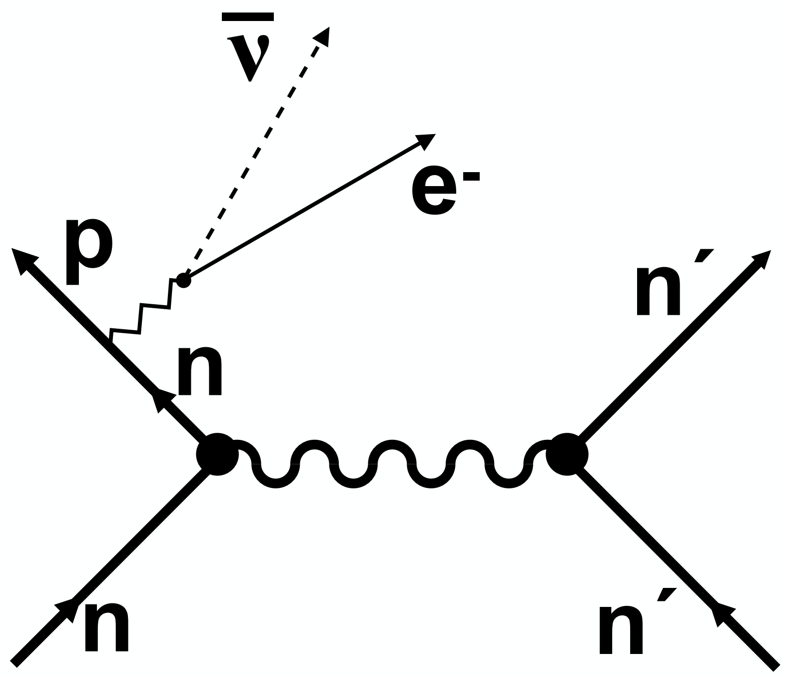


A sample of neutrino emission processes

Name	Process	Emissivity (erg cm^{-3} s^{-1})	
Modified Urca cycle (neutron branch)	$n + n \to n + p + e^- + \bar{\nu}_e$ $n + p + e^- \to n + n + \nu_e$	$\sim 2{\times}10^{21}\, R\, T_9^8$	Slow
Modified Urca cycle (proton branch)	$p + n \to p + p + e^- + \bar{\nu}_e$ $p + p + e^- \to p + n + \nu_e$	$\sim 10^{21}\, R\, T_9^8$	Slow
Bremsstrahlung	$n + n \to n + n + \nu + \bar{\nu}$ $n + p \to n + p + \nu + \bar{\nu}$ $p + p \to p + p + \nu + \bar{\nu}$	$\sim 10^{19}\, R\, T_9^8$	Slow
Cooper pair formations	$n + n \to [nn] + \nu + \bar{\nu}$ $p + p \to [pp] + \nu + \bar{\nu}$	$\sim 5{\times}10^{21}\, R\, T_9^7$ $\sim 5{\times}10^{19}\, R\, T_9^7$	Medium
Direct Urca cycle (nucleons)	$n \to p + e^- + \bar{\nu}_e$ $p + e^- \to n + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (Λ hyperons)	$\Lambda \to p + e^- + \bar{\nu}_e$ $p + e^- \to \Lambda + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (Σ^- hyperons)	$\Sigma^- \to n + e^- + \bar{\nu}_e$ $n + e^- \to \Sigma^- + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
π^- condensate	$n + <\pi^-> \to n + e^- + \bar{\nu}_e$	$\sim 10^{26}\, R\, T_9^6$	Fast
K^- condensate	$n + <K^-> \to n + e^- + \bar{\nu}_e$	$\sim 10^{25}\, R\, T_9^6$	Fast
Direct Urca cycle (u-d quarks)	$d \to u + e^- + \bar{\nu}_e$ $u + e^- \to d + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast
Direct Urca cycle (u-s quarks)	$s \to u + e^- + \bar{\nu}_e$ $u + e^- \to s + \nu_e$	$\sim 10^{27}\, R\, T_9^6$	Fast

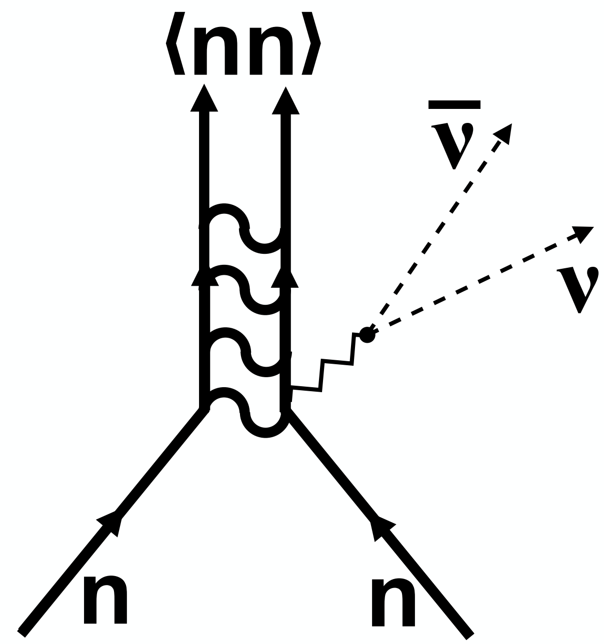
The Three Basic Neutrino Processes

SLOW



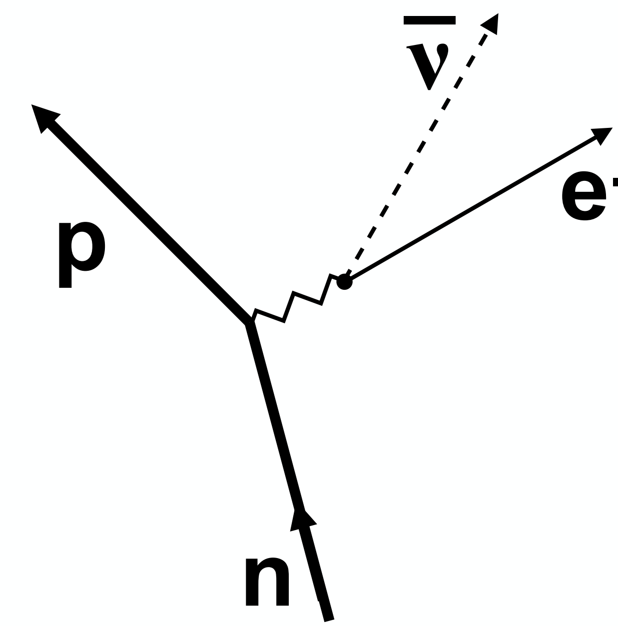
Modified Urca

MEDIUM



Cooper pair formation ("PBF")

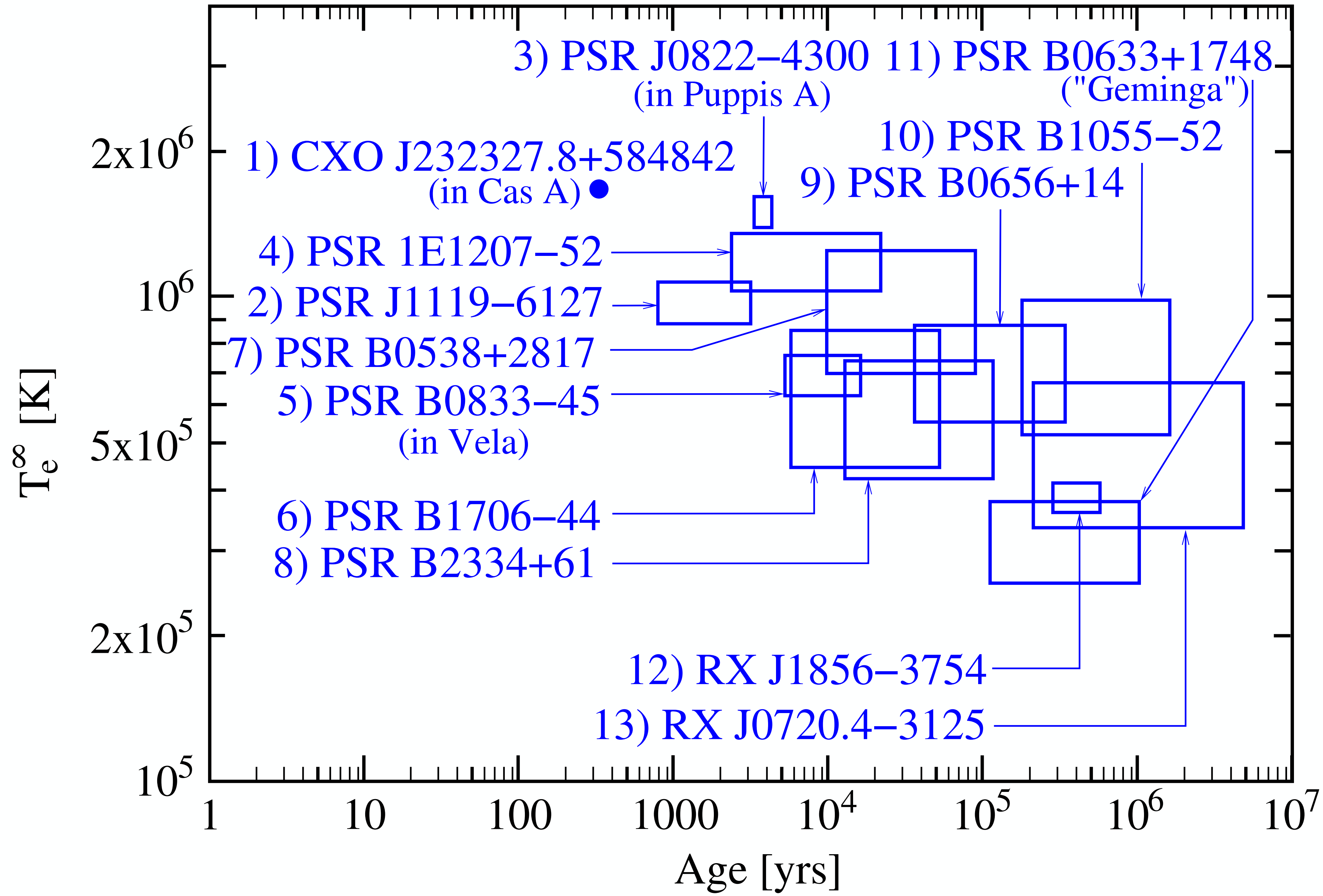
FAST



Direct Urca

Data for
Neutron Star Cooling

Isolated Cooling Neutron Stars I



Neutron stars with clearly detected thermal emission

One Example: PSR 0656+14

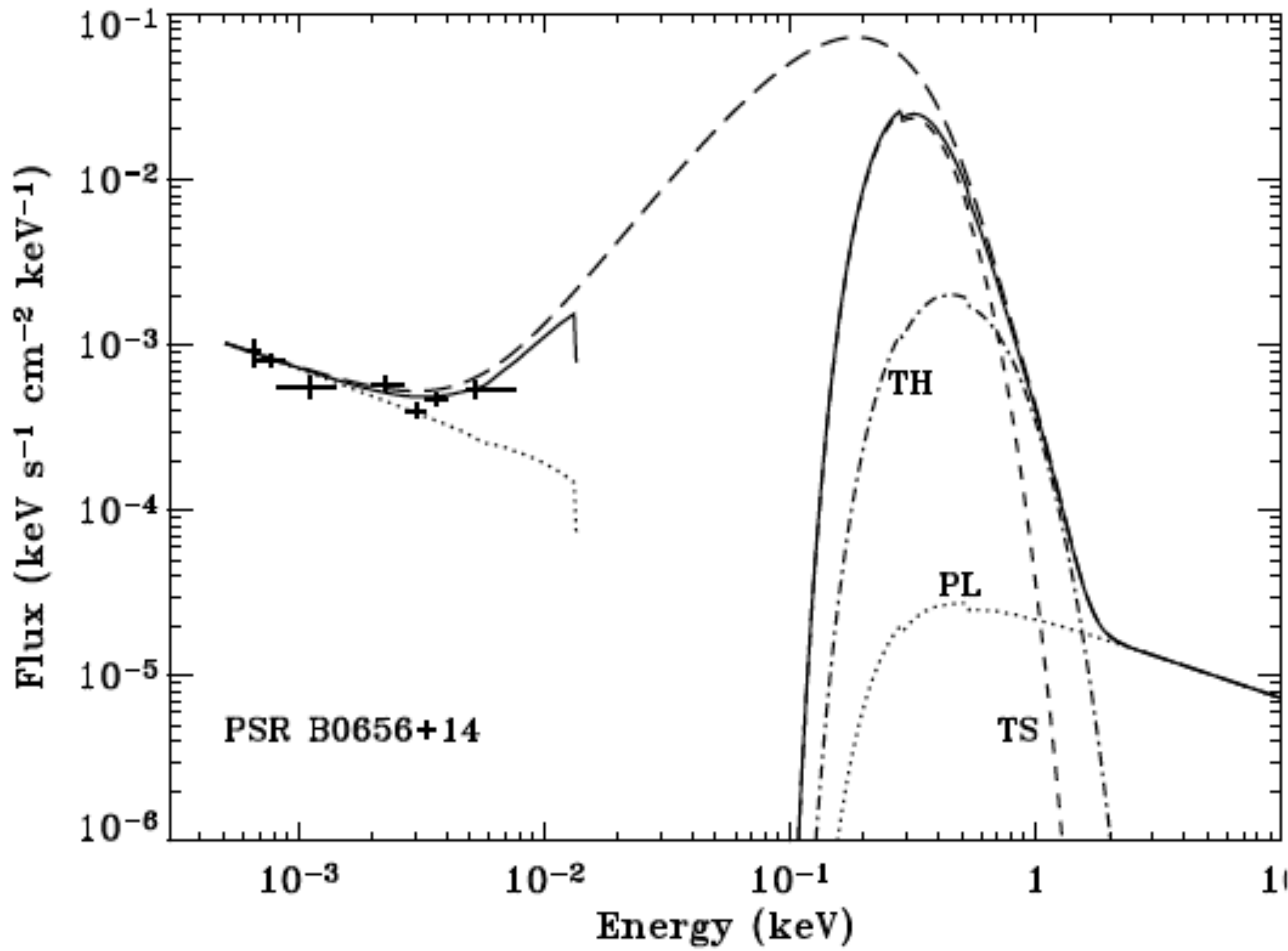
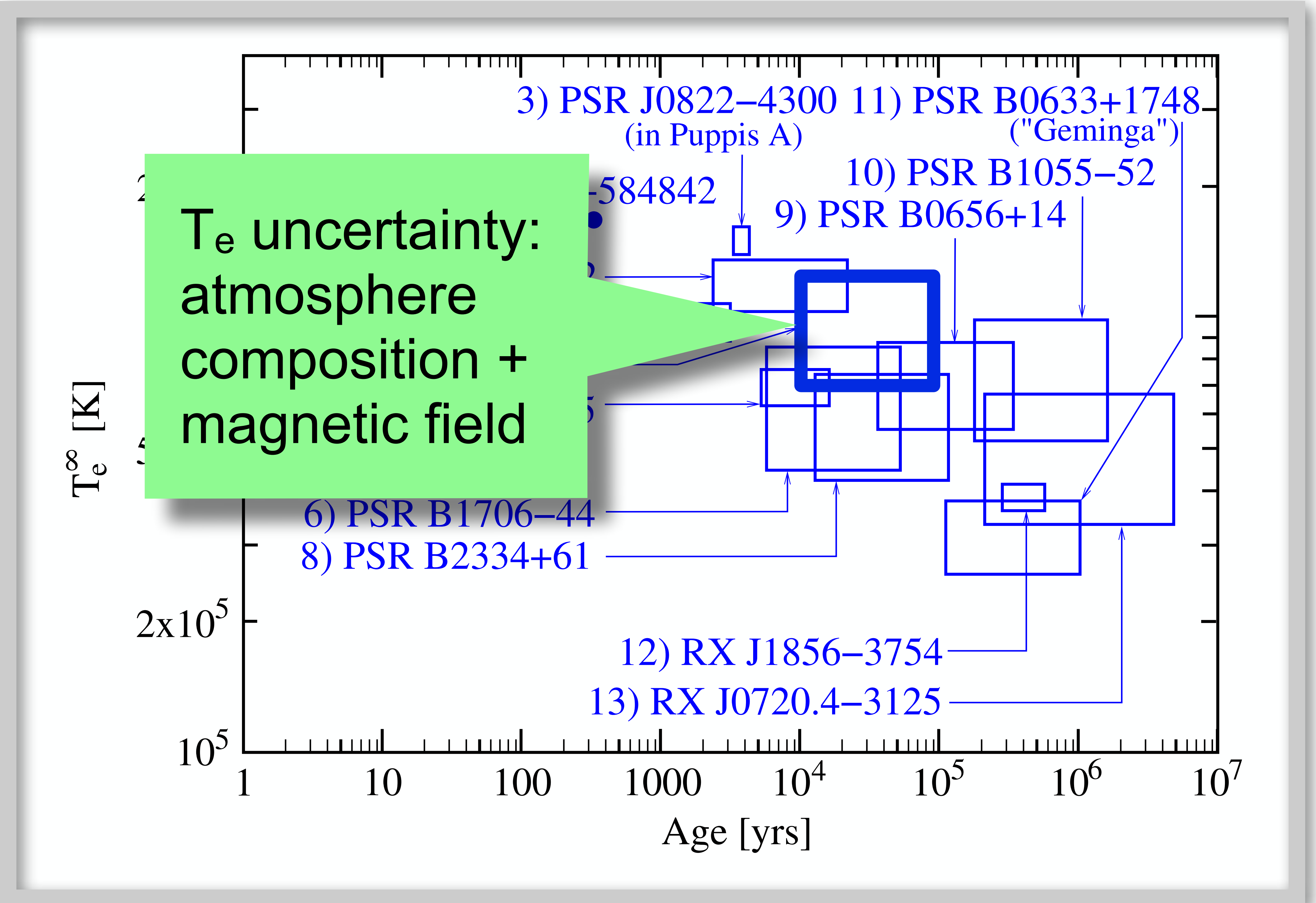


Fig. 9. Broadband spectrum of PSR B0656+14 for a three-component model (TS+TH+PL; see § 4.4) extrapolated in optical. The solid and long-dashed curves show the absorbed and unabsorbed spectra, respectively. Crosses indicate the IR-optical fluxes.

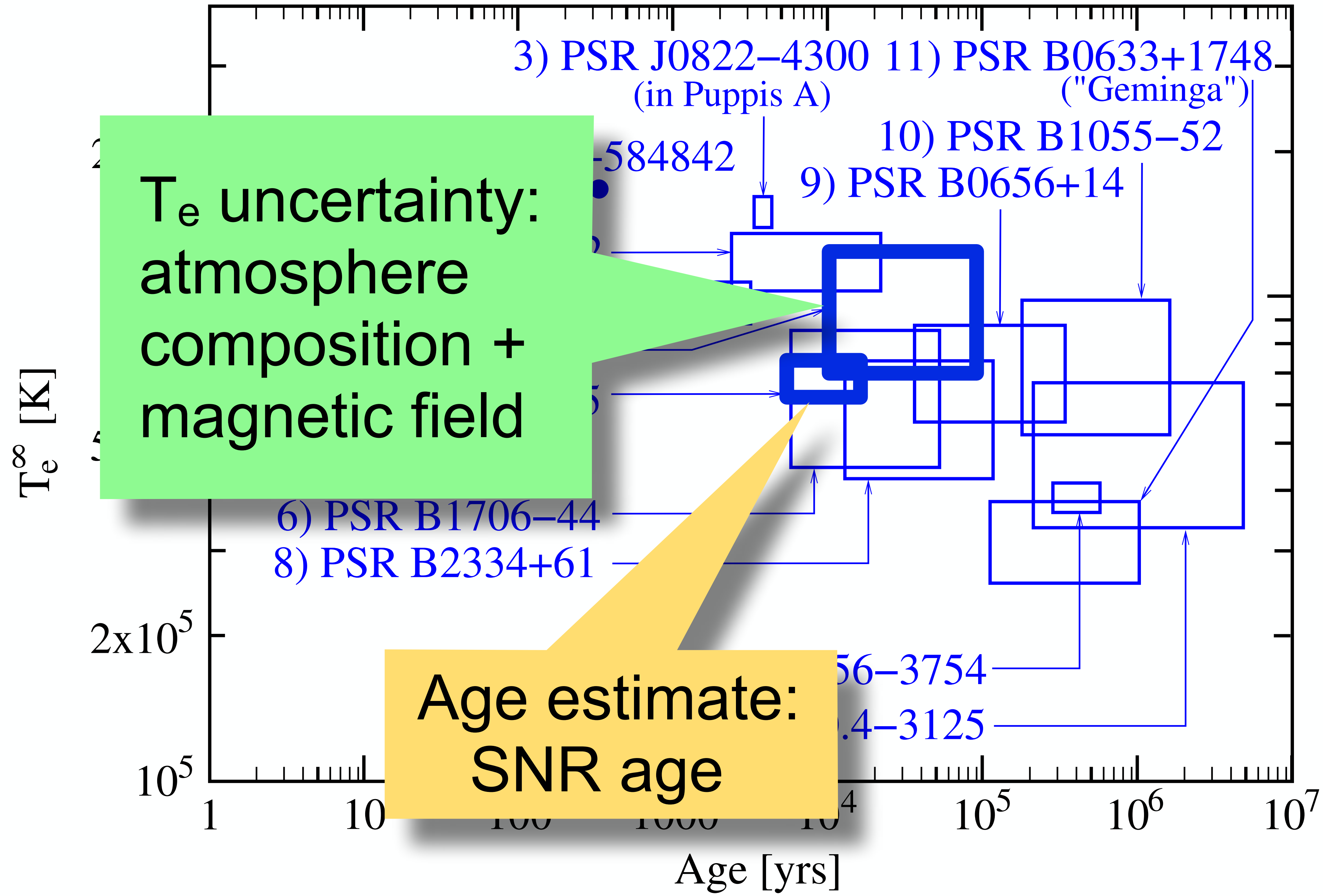
Thermal emission from isolated neutron stars: theoretical and observational aspects
V. E. Zavlin
in "Neutron Stars and Pulsars", Ed. W. Becker, Astrophysics and Space Library, vol. 357, p. 181 (2008).

Isolated Cooling Neutron Stars I



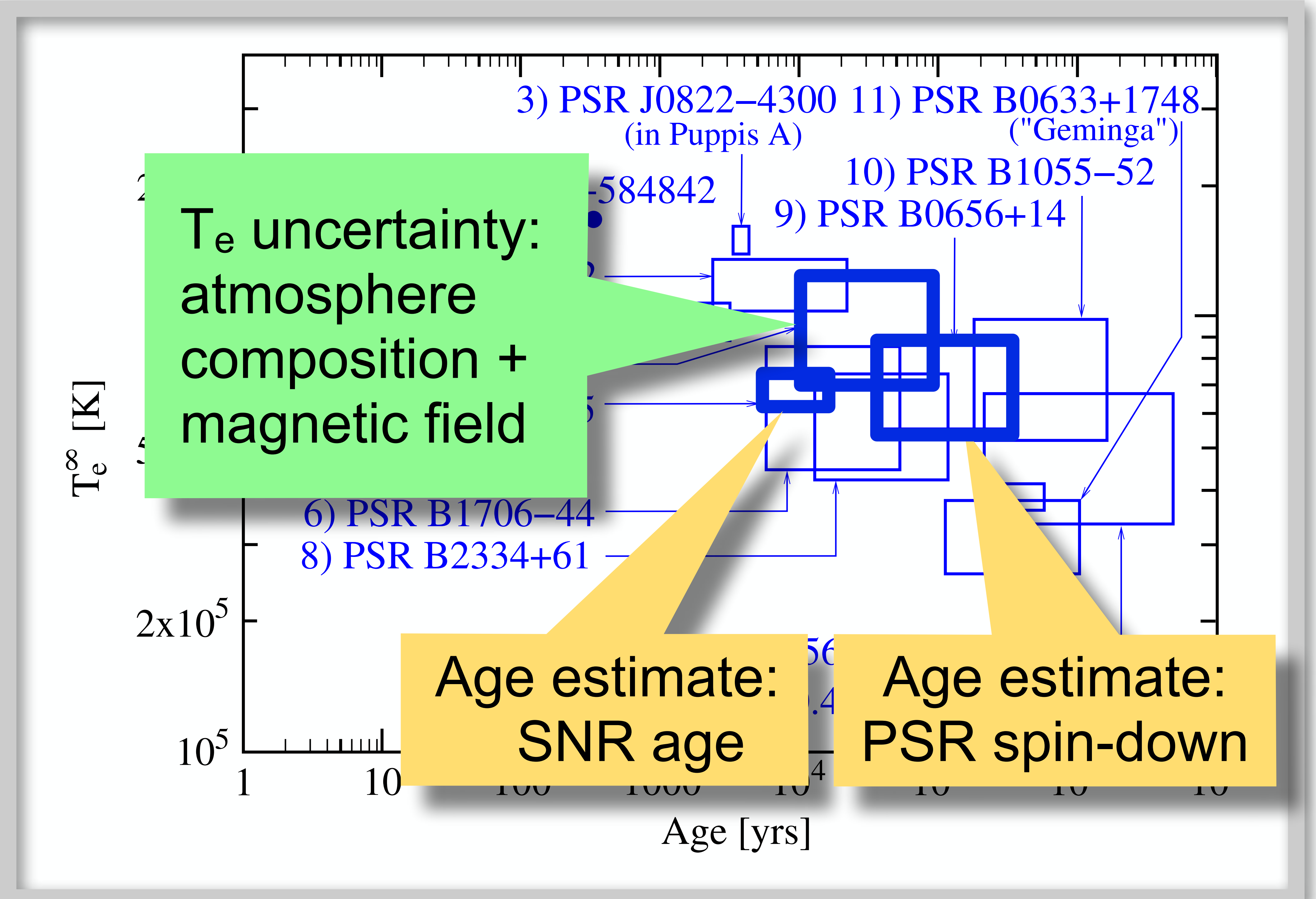
Neutron stars with clearly detected thermal emission

Isolated Cooling Neutron Stars I



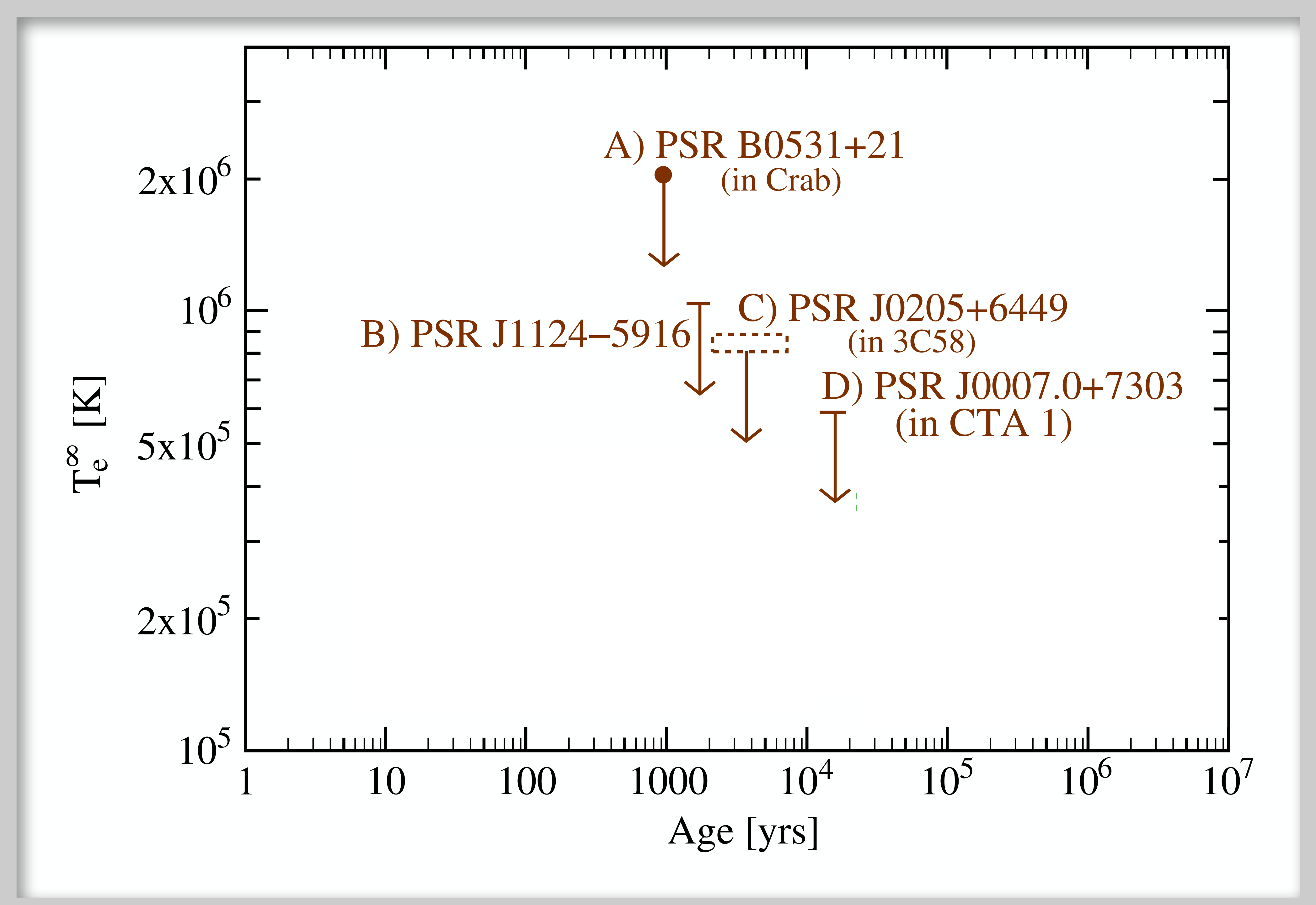
Neutron stars with clearly detected thermal emission

Isolated Isolated Cooling Neutron Stars I



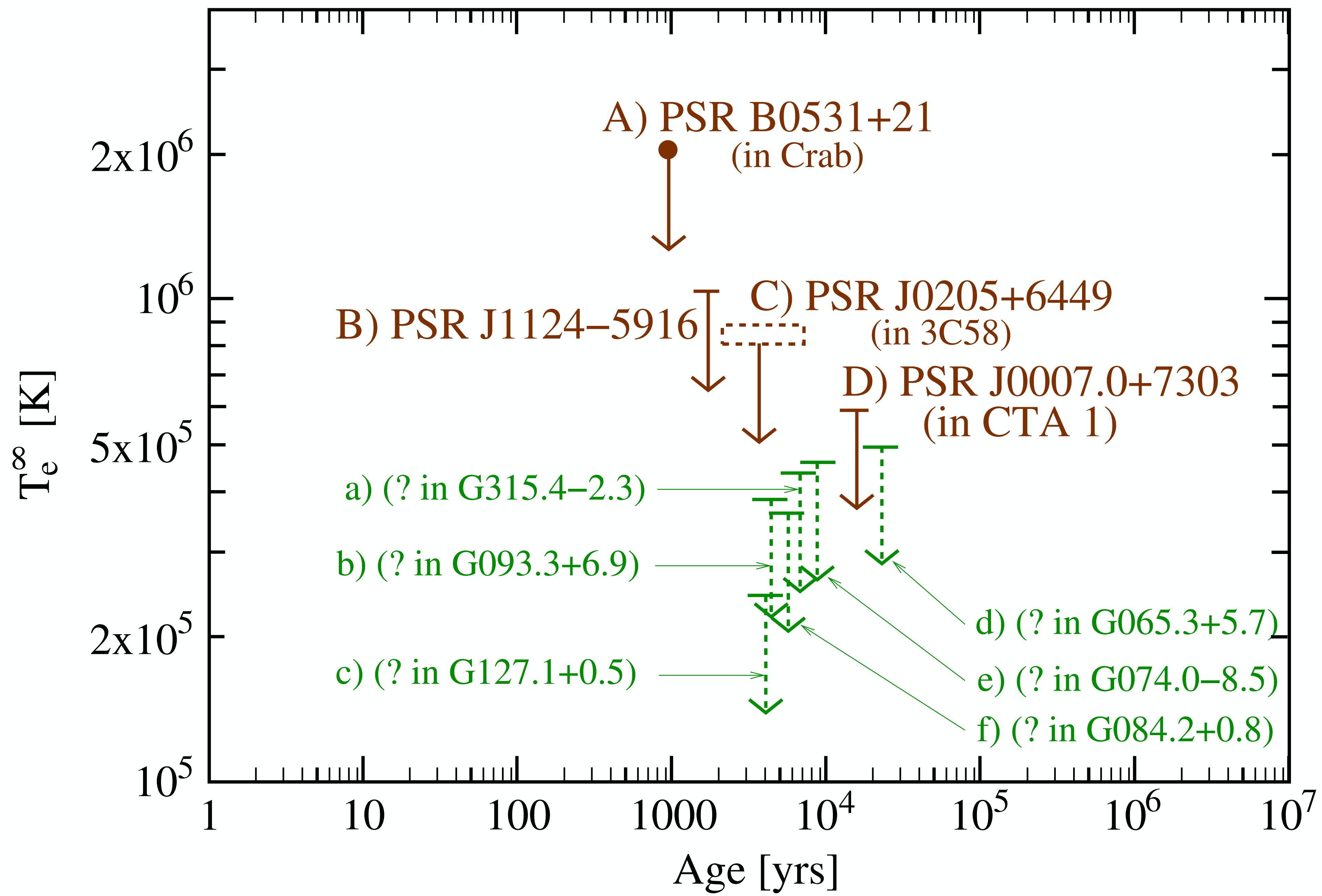
Neutron stars with clearly detected thermal emission

Isolated Cooling Neutron Stars II



Detected neutron stars with undetected thermal emission

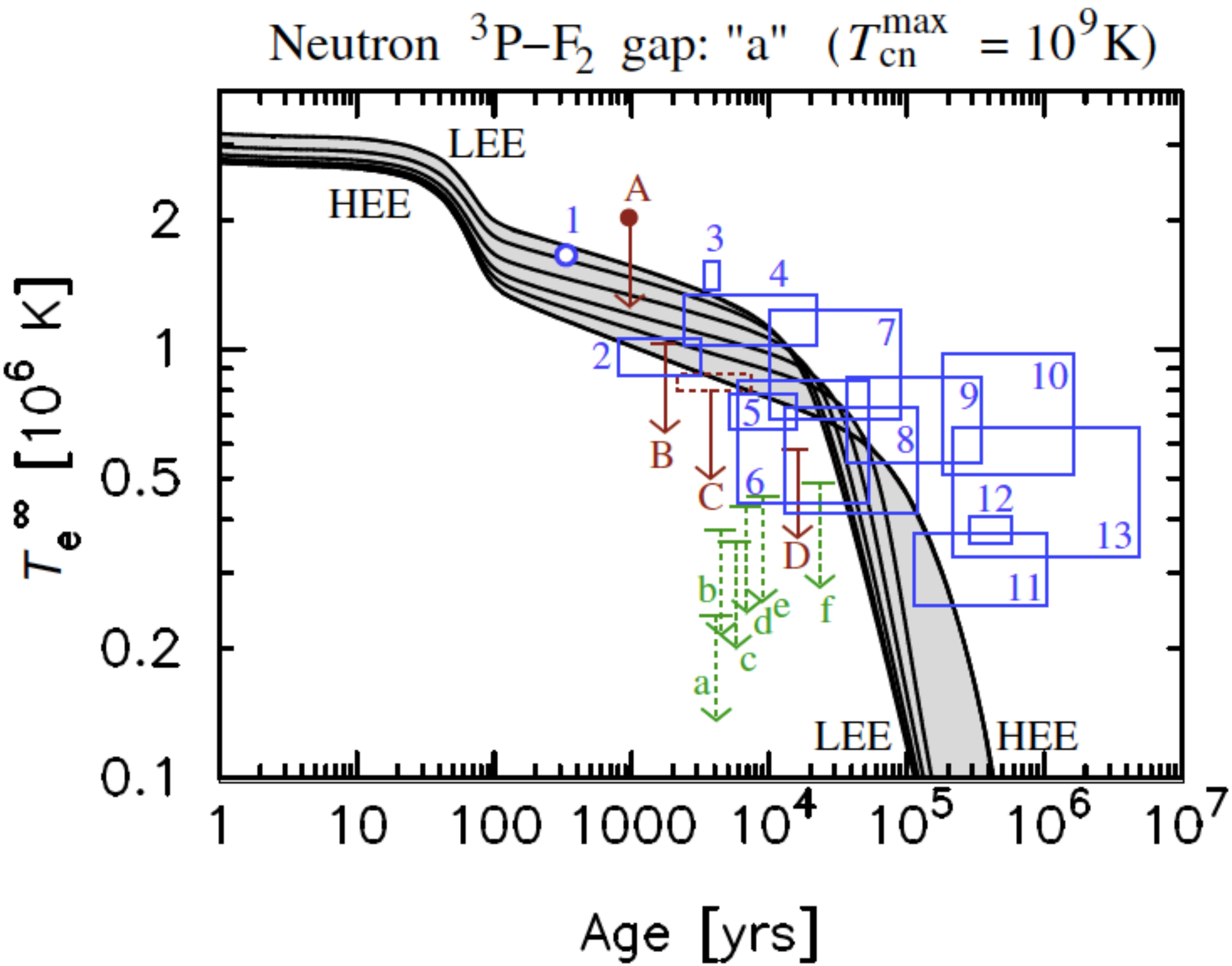
Isolated Cooling Neutron Stars ?



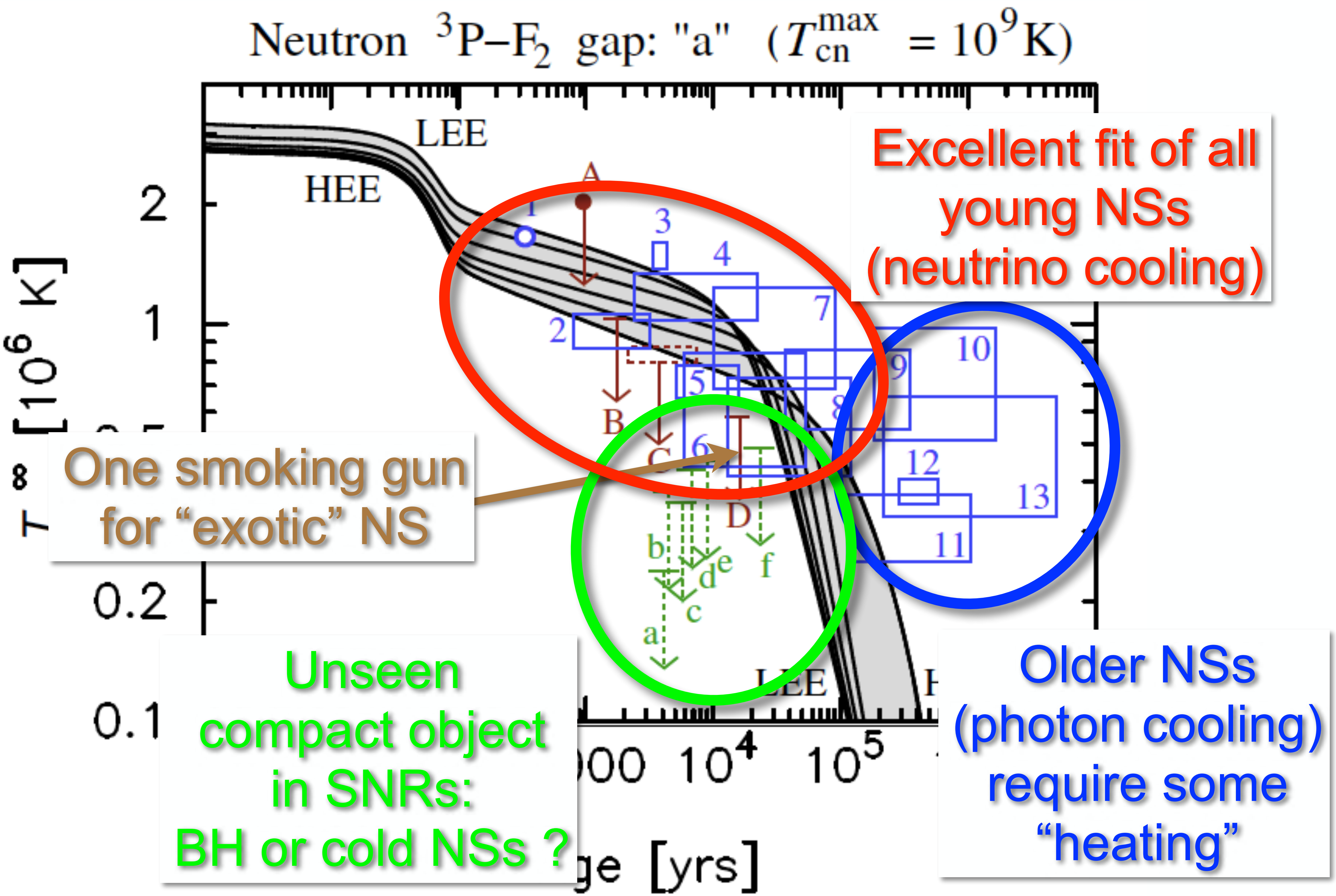
Upper limits on undetected neutron stars

Minimal Cooling

Minimal Cooling with Medium n $^3P_2$ Gap



Minimal Cooling with Medium n $^3P_2$ Gap



Minimal Cooling: Conclusions

- Minimal Cooling: excludes, a priori, any “exotic” inner core with fast neutrino emission.
- Benchmark model: any NS too cold for minima cooling is a serious candidate for the presence of “exotic” matter.

Minimal Cooling vs Data:
- IF the neutron $^3P_2$ pairing critical T_c has the right value all but ONE detected young NS are compatible with minimal
- IF NOT, then about 50% of detected young NSs show evidence of fast neutrino emission

Minimal Cooling: Conclusions

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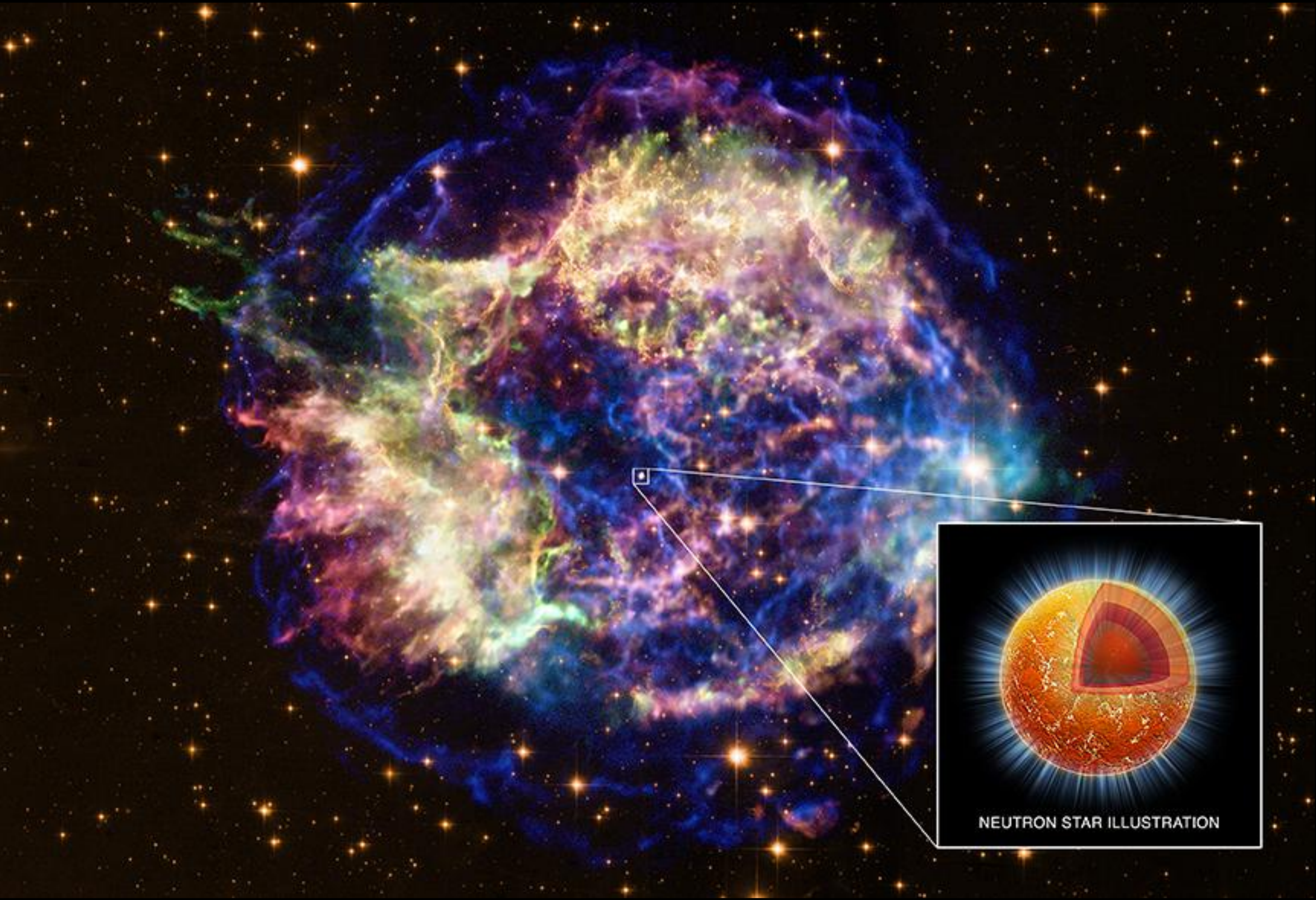
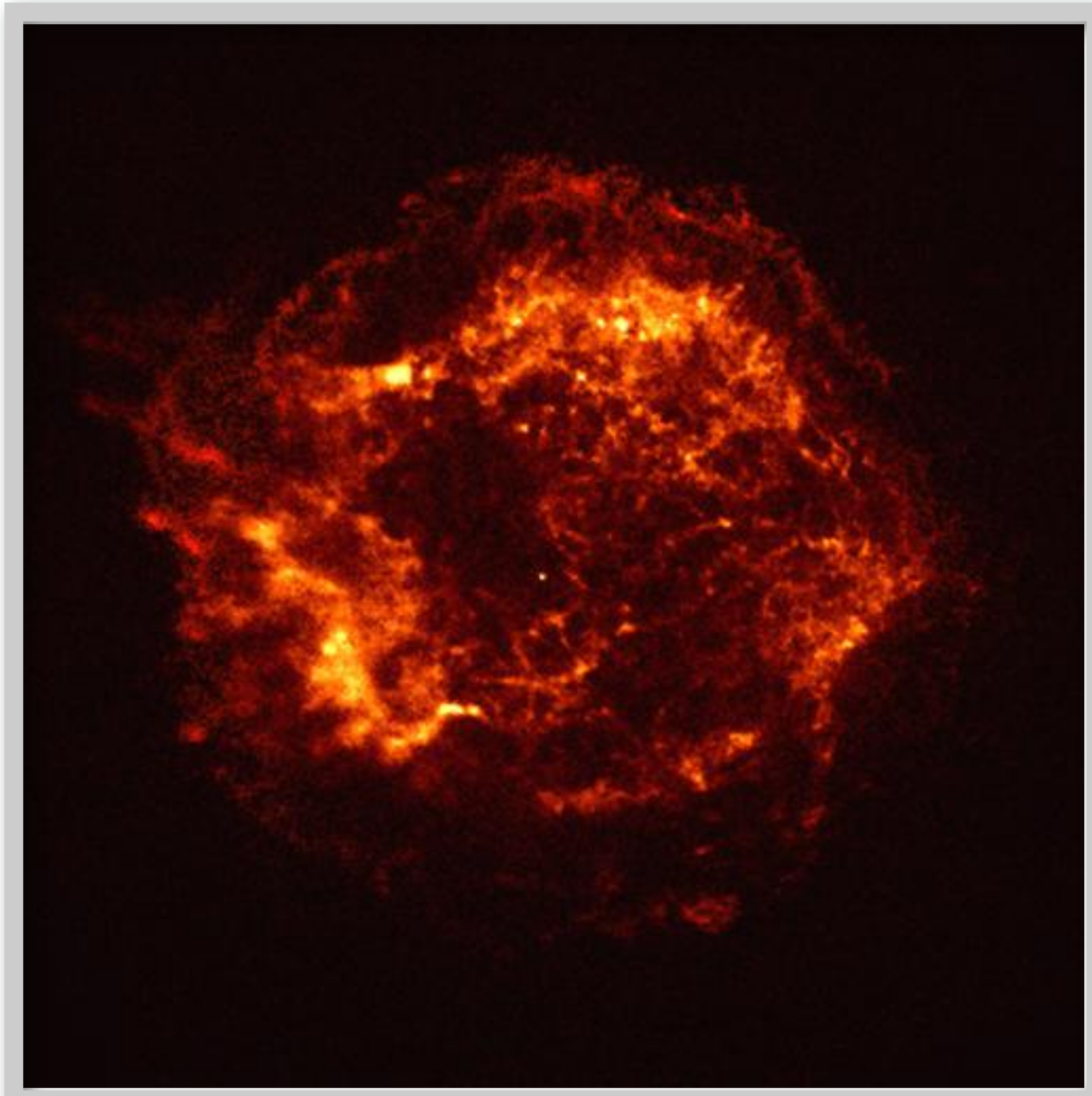
Minimal Cooling vs Data:
- IF the neutron $^3P_2$ pairing critical T_c has the right value all but ONE detected young NS are compatible with minimal
- IF NOT, then about 50% of detected young NSs show evidence of fast neutrino emission

Minimal vs “exotic”: do we have evidence for “exotic”:
MAYBE or MAYBE NOT
It depends on the values of neutron $^3P_2$ T_c that are unknown
(Still bad)

Minimal Cooling and Cas A


NEUTRON STAR ILLUSTRATION

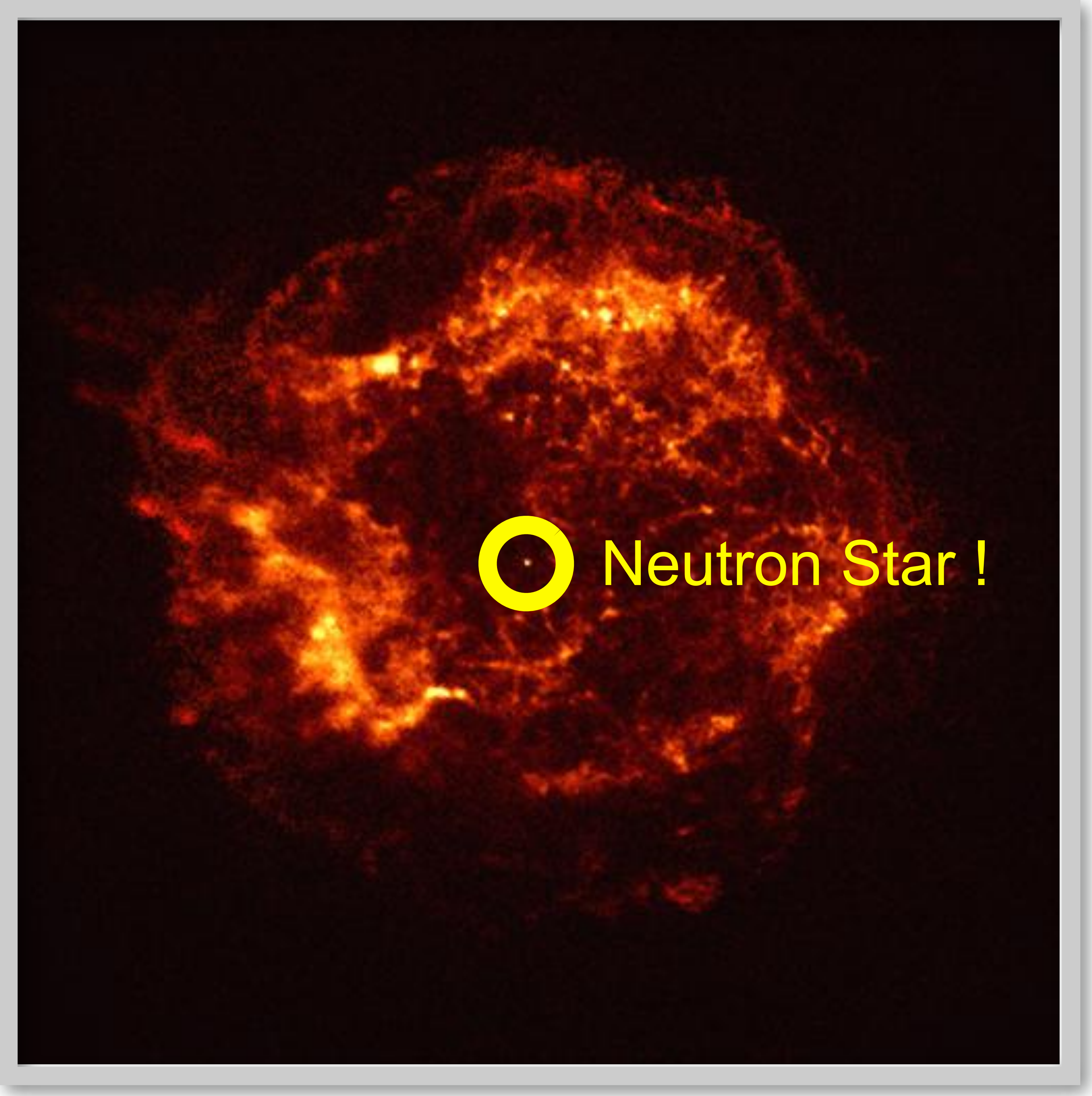
Chandra's First Light: Cassiopeia A



August 1999

Chandra's First Light: Cassiopeia A

August 1999



SNR Expansion and Age:

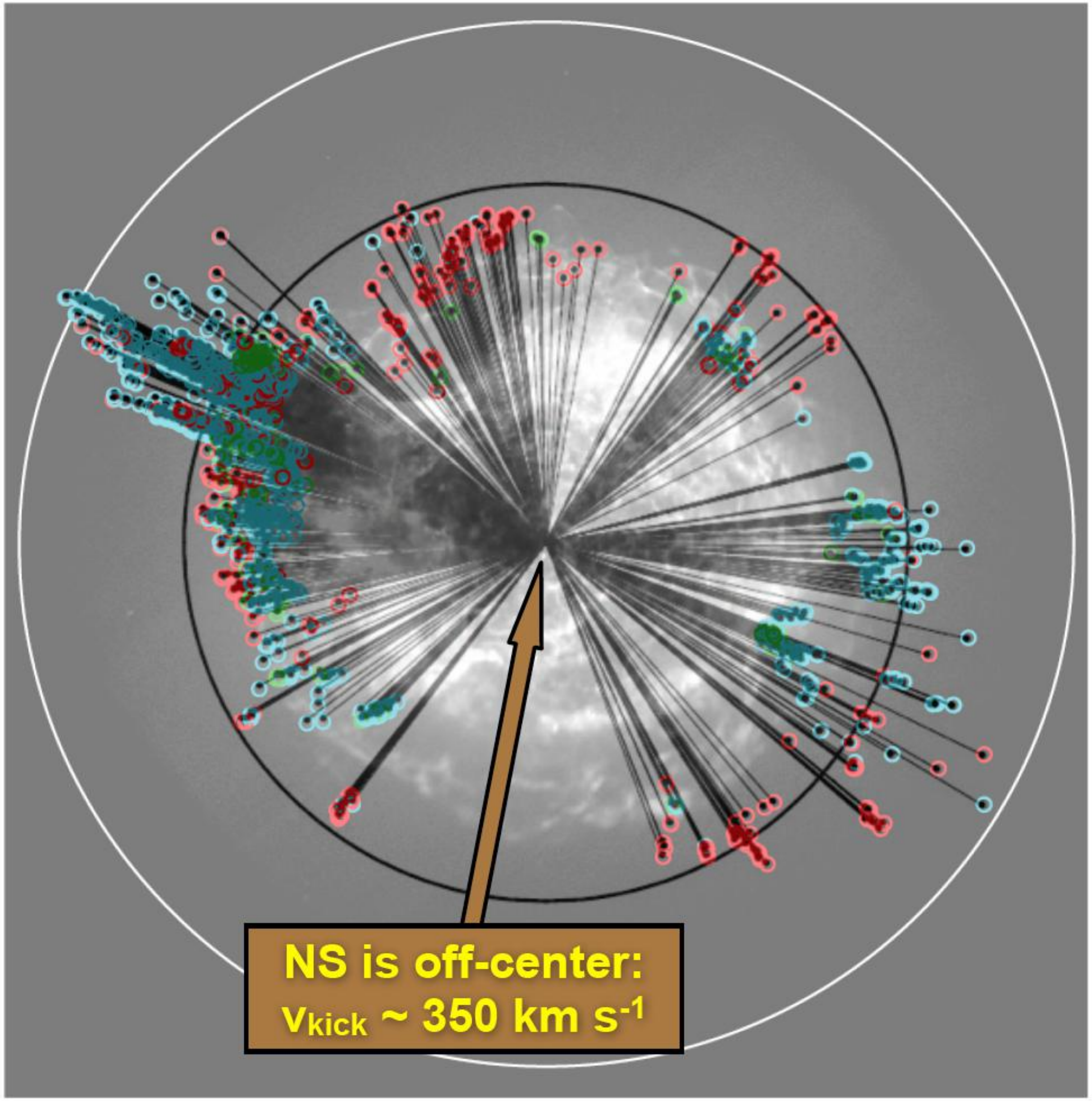
Chandra image + Hubble knots:
NII OII SII emission lines

March to December 2004:
knots expansion clearly seen.

COE (Center Of Expansion)

Supernova explosion time:

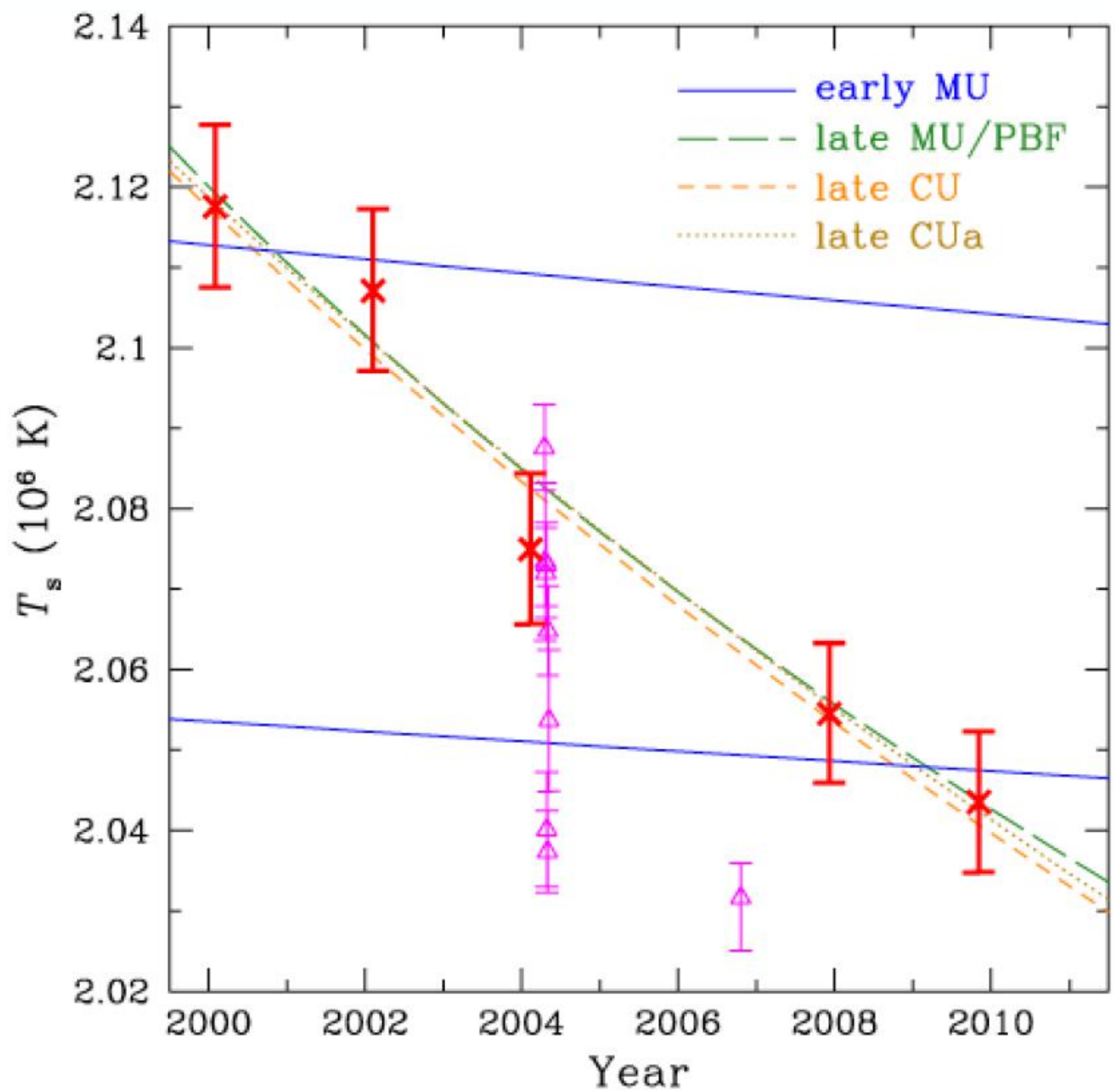
- 1825 outer ejecta knots give
  AD **1662 ± 27**
- 72 bright compact knots give
  AD **1672 ± 18**



The Expansion Asymmetry and Age of the Cassiopeia A Supernova Remnant Fesen, R. A. et al. 2006ApJ...645..283F

Rapid Cooling of Cas A

4% decrease in T_e
20% decrease in L_γ



[Direct Observation of the Cooling of the Cassiopeia A Neutron Star](#)
Heinke, Craig O.; Ho, Wynn C. G. [2010ApJ...719L.167H](#)

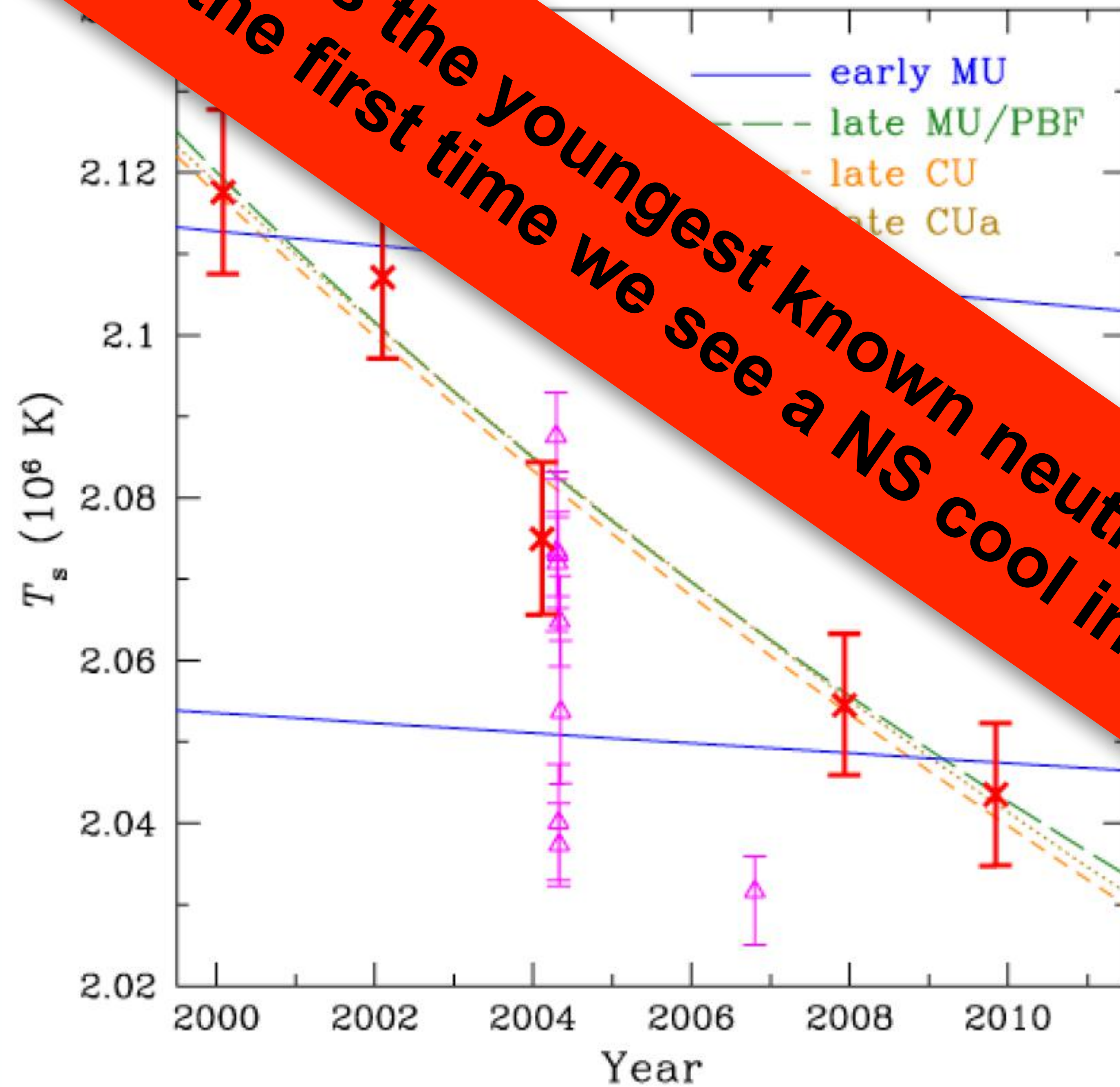
d Cooling of Cas A

It is the youngest known neutron star

It is the first time we see a NS cool in real time !

4% decrease in T_e

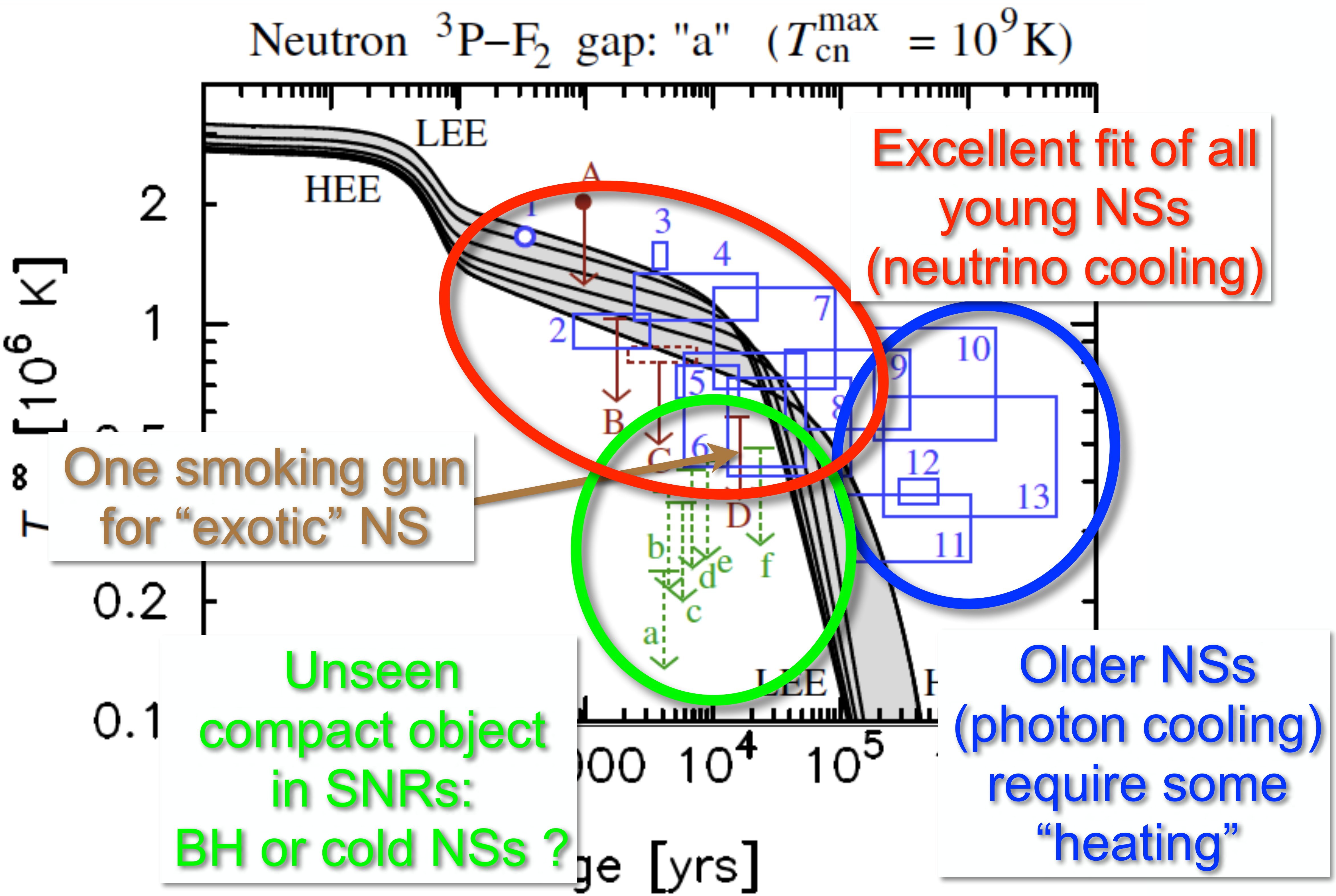
20% decrease in L_γ



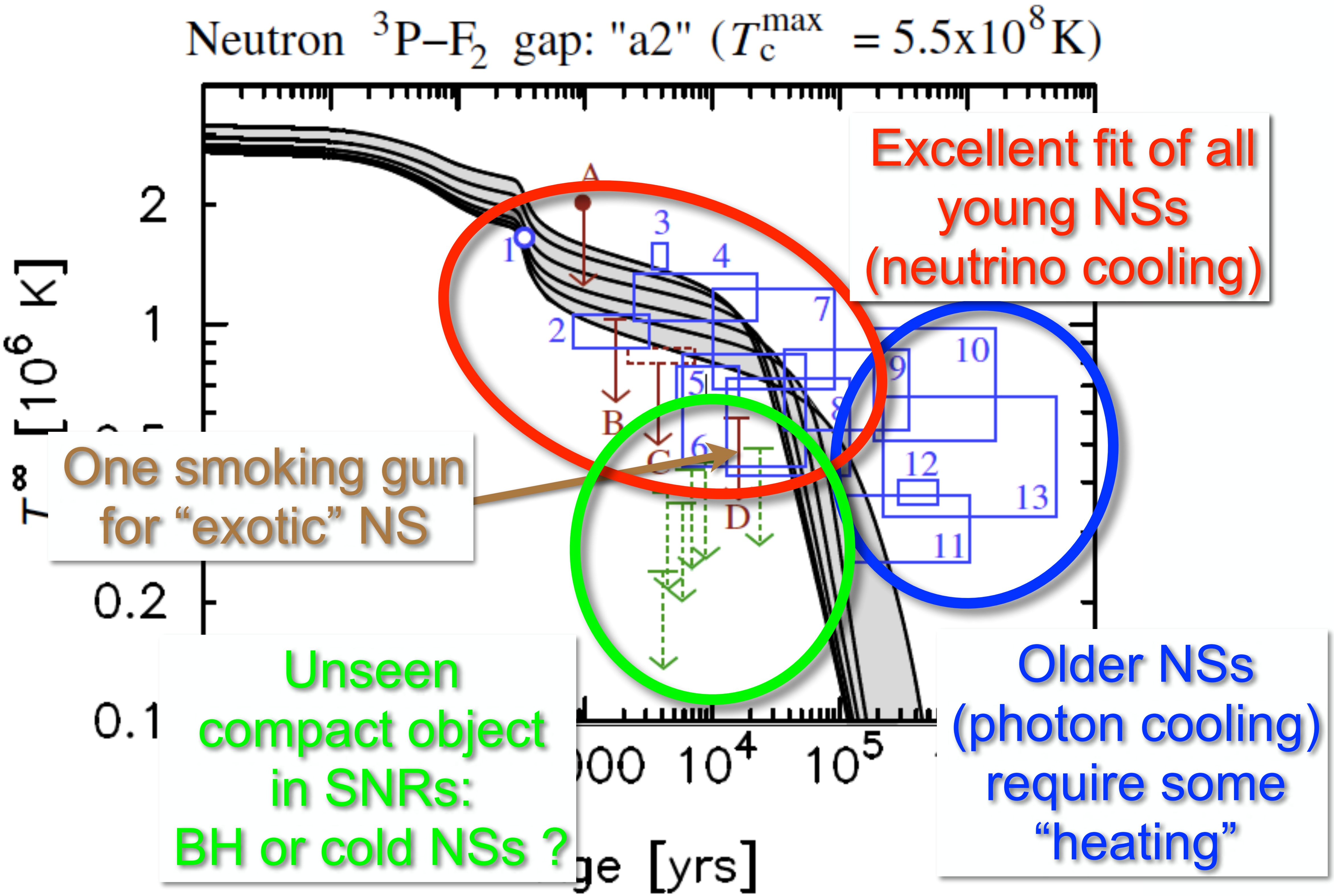
Direct Observation of the Cooling of the Cassiopeia A Neutron Star

Heinke, Craig O.; Ho, Wynn C. G. 2010ApJ...719L.167H

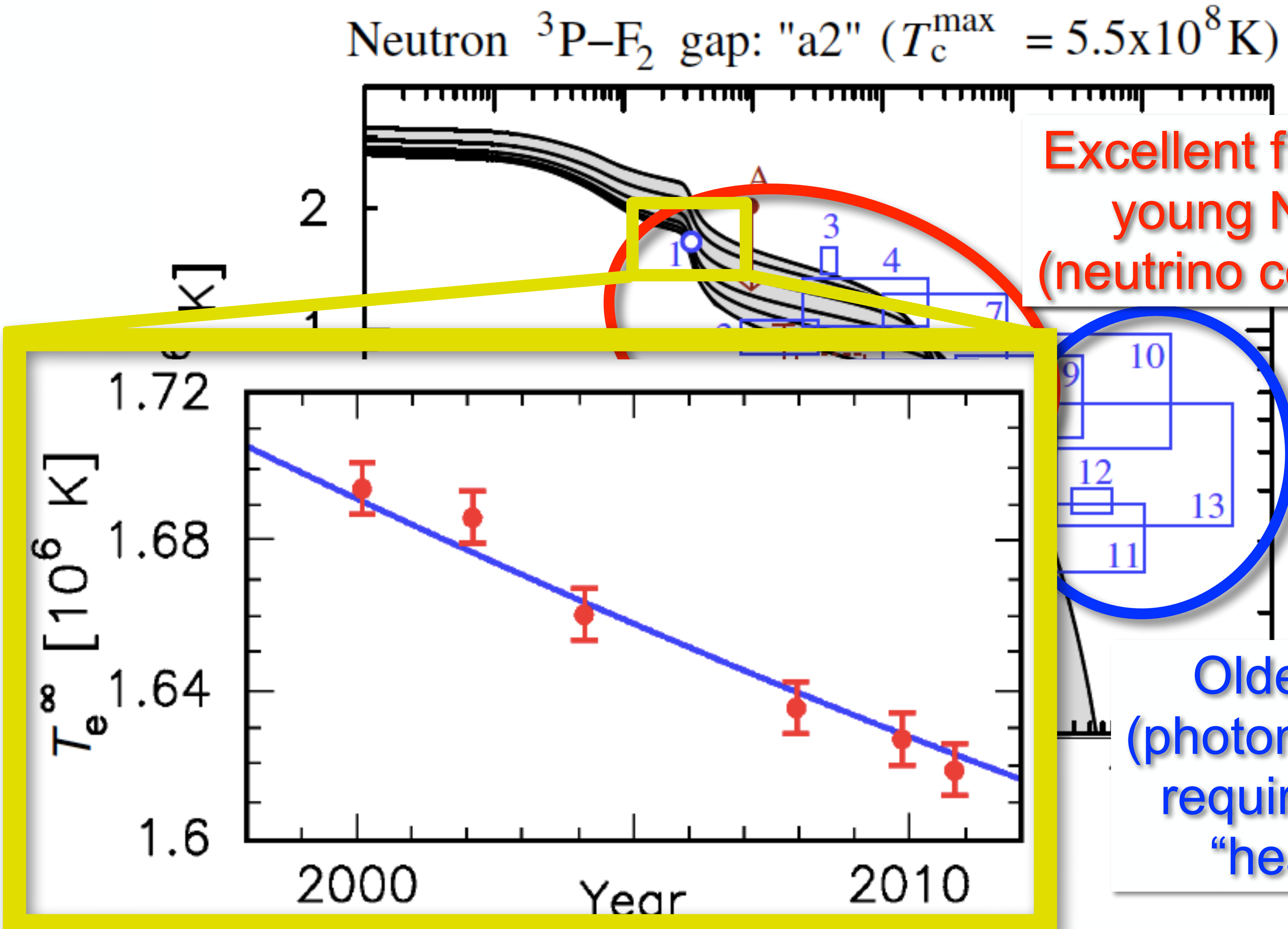
Minimal Cooling with Medium n $^3P_2$ Gap



Minimal Cooling and “Cas A”



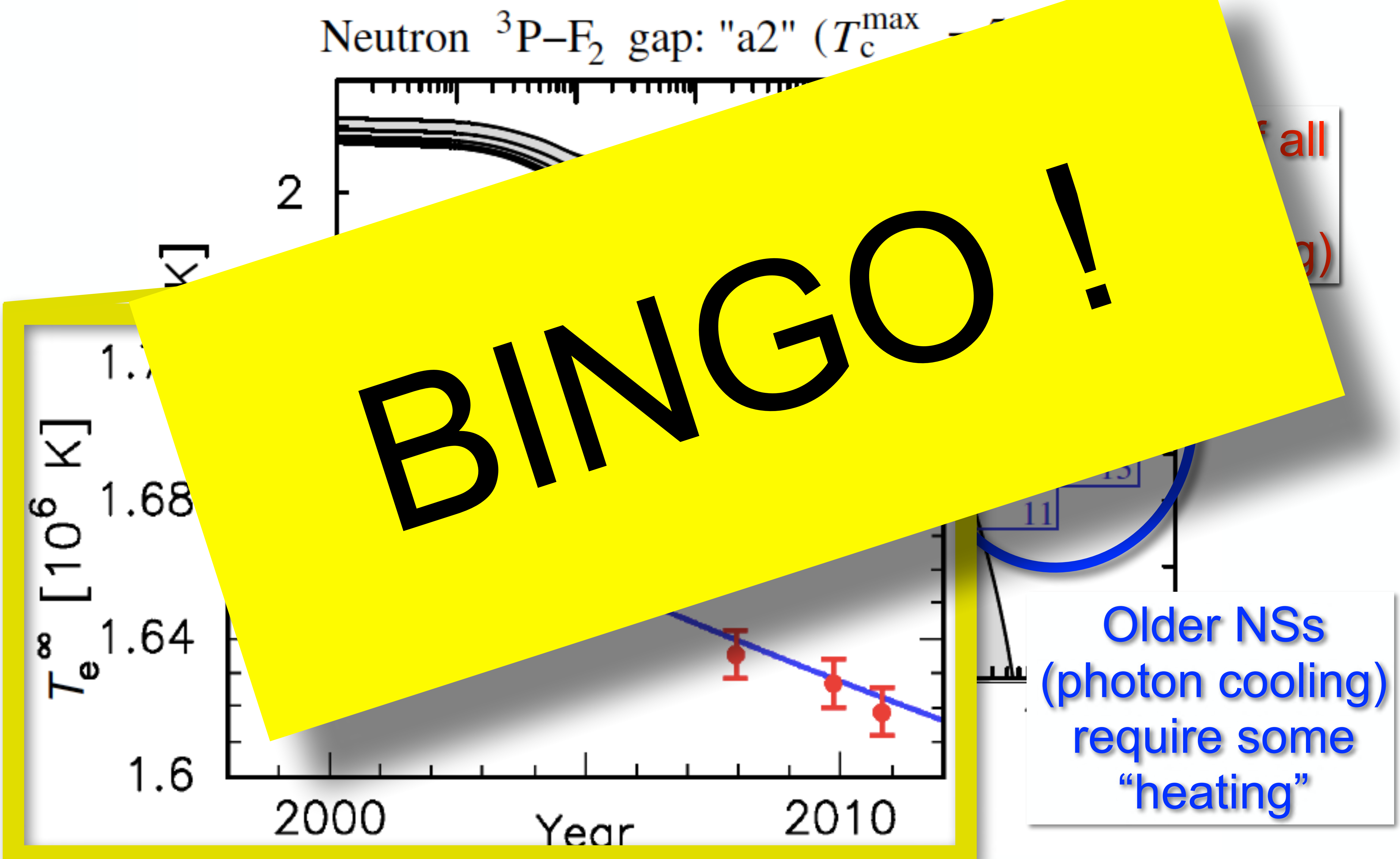
Minimal Cooling and "Cas A"



Excellent fit of all young NSs (neutrino cooling)

Older NSs (photon cooling) require some "heating"

Minimal Cooling and "Cas A"



Older NSs (photon cooling) require some "heating"

The first direct evidence that superfluidity and superconductivity occur at supranuclear densities within neutron stars.

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

Peter S. Shternin[1]★, Dmitry G. Yakovlev[1], Craig O. Heinke[2], Wynn C. G. Ho[3]†, Daniel J. Patnaude[4]
[1]*Ioffe Physical Technical Institute, Politekhnicheskaya 26, 194021 St. Petersburg, Russia*
[2]*Department of Physics, University of Alberta, Room 238 CEB, 11322-89 Avenue, Edmonton, AB, T6G 2G7, Canada*
[3]*School of Mathematics, University of Southampton, Southampton, SO17 1BJ, United Kingdom*
[4]*Smithsonian Astrophysical Observatory, Cambridge, MA 02138, USA*

Month. Not. R. Astron. Soc. Lett. **412** (2011), p. 108

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

Dany Page,[1] Madappa Prakash,[2] James M. Lattimer,[3] and Andrew W. Steiner[4]
[1]*Instituto de Astronomía, Universidad Nacional Autónoma de México, Mexico D.F. 04510, Mexico*
[2]*Department of Physics and Astronomy, Ohio University, Athens, Ohio 45701-2979, USA*
[3]*Department of Physics and Astronomy, State University of New York at Stony Brook, Stony Brook, New York 11794-3800, USA*
[4]*Joint Institute for Nuclear Astrophysics, National Superconducting Cyclotron Laboratory and, Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA*

Phys. Rev. Lett. 106 (2011), p. 08101

The
Crust Relaxation
Phase (50 years):
NS 1987A (again)

Phases of Neutron Star Cooling

- Proto-Neutron Star: ~30 seconds:
  Matter from the collapsed iron core: x_p = 40%.
  Neutrinos are trapped, once they have left x_p = 5% and we have a "Neutron Star".
  "Exotic matter" (hyperons, quarks, ...) will form at the end of this phase: needs low x_p.

- Neo-Neutron Star: ~1 year:
  Rapid cooling of outer layers by neutrino emission.
  Eddington luminosity for about an hour.
  Ends with T_{eff} ~ 2-4x10^6 K.

- Young Neutron Star: ~50 years:
  Early plateau: crust relaxation phase whose heat flows into the core.
  Crust neutrino emission is not very efficient.
  At its end the interior is isothermal and T_{eff} reflects the core temperature.

- Neutrino Cooling Phase: ~10^5 years:
  Evolution of the isothermal star is driven by core neutrino emission.

- Photon Cooling Phase: ~10^6 years:
  Evolution of the isothermal star is driven by surface photon emission.

- Dark Phase: >> 10^6 years :
  Star possibly kept not too cold by internal heating (mag. field decay, friction from differential rotation, baryonic/dark matter accretion, ...)

Luminosity Evolution

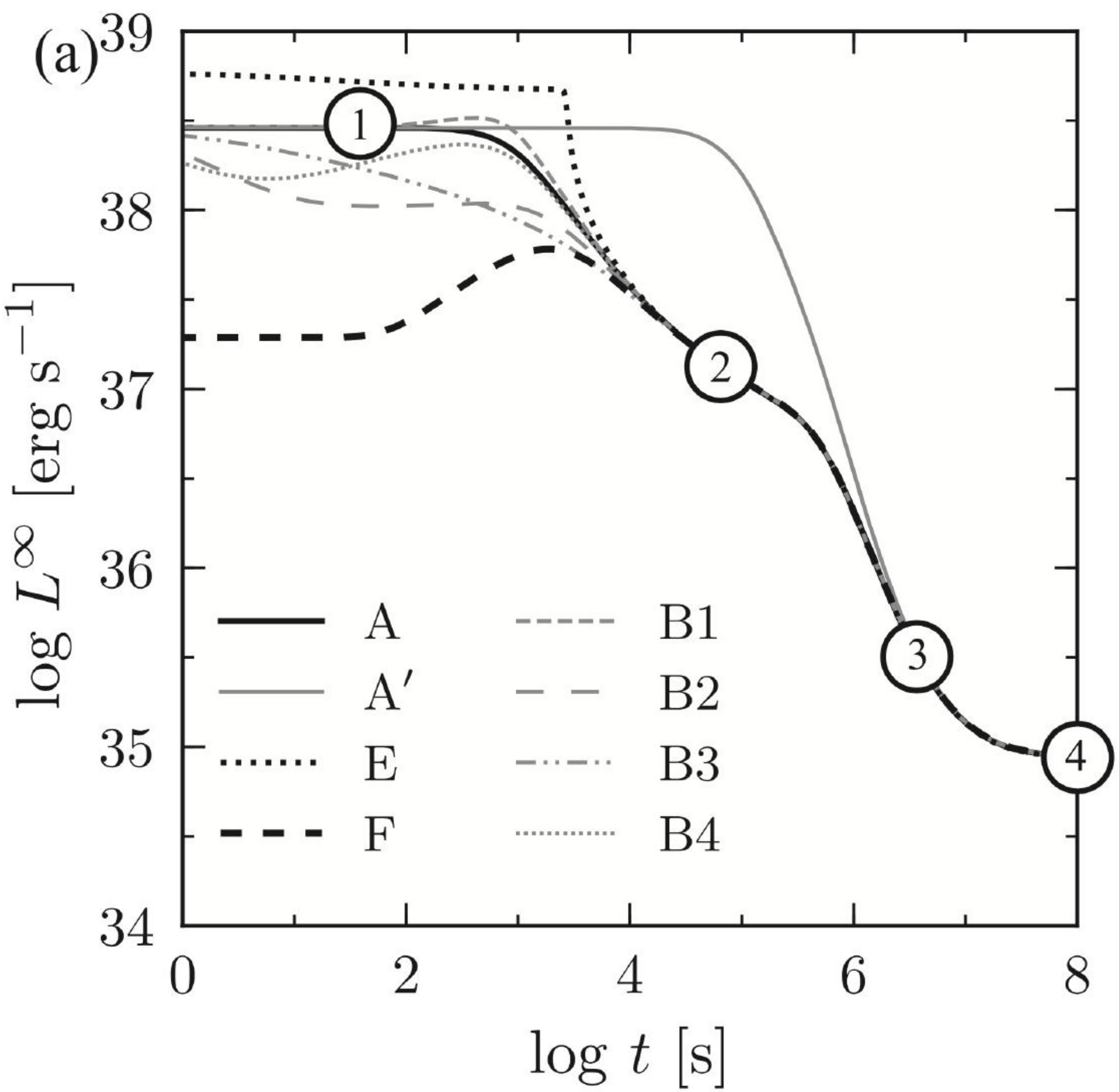
1: Eddington phase: relaxation from initial condition ~ 1hour

2: Cooling by pair neutrinos

3: Cooling by plasma neutrinos

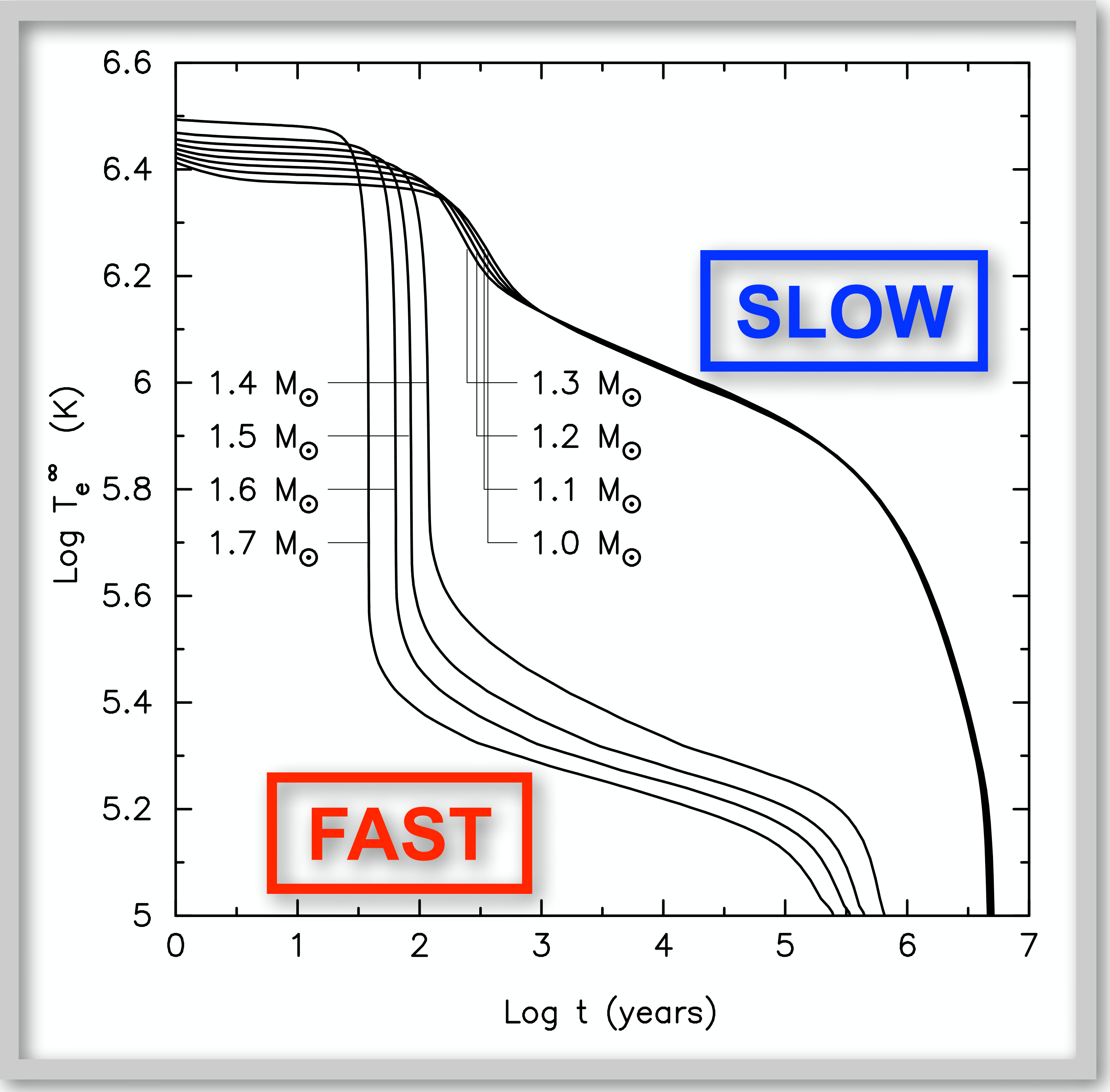
4: Early plateau: young NS phase

At stage 4: L ~ 10^{35} erg/s ~ luminosity of the blob in SN 1987A !!!



Thermal Evolution of Neo-neutron Stars. I. Envelopes, Eddington Luminosity Phase, and Implications for GW170817
Beznogov, Mikhail V.; Page, Dany; Ramirez-Ruiz, Enrico
2020ApJ...888...97B

Direct vs Modified Urca Cooling



Models based on the PAL EOS:

adjusted (by hand) so that DURCA becomes allowed (triangle rule !) at M > 1.35 M_{Sun}.

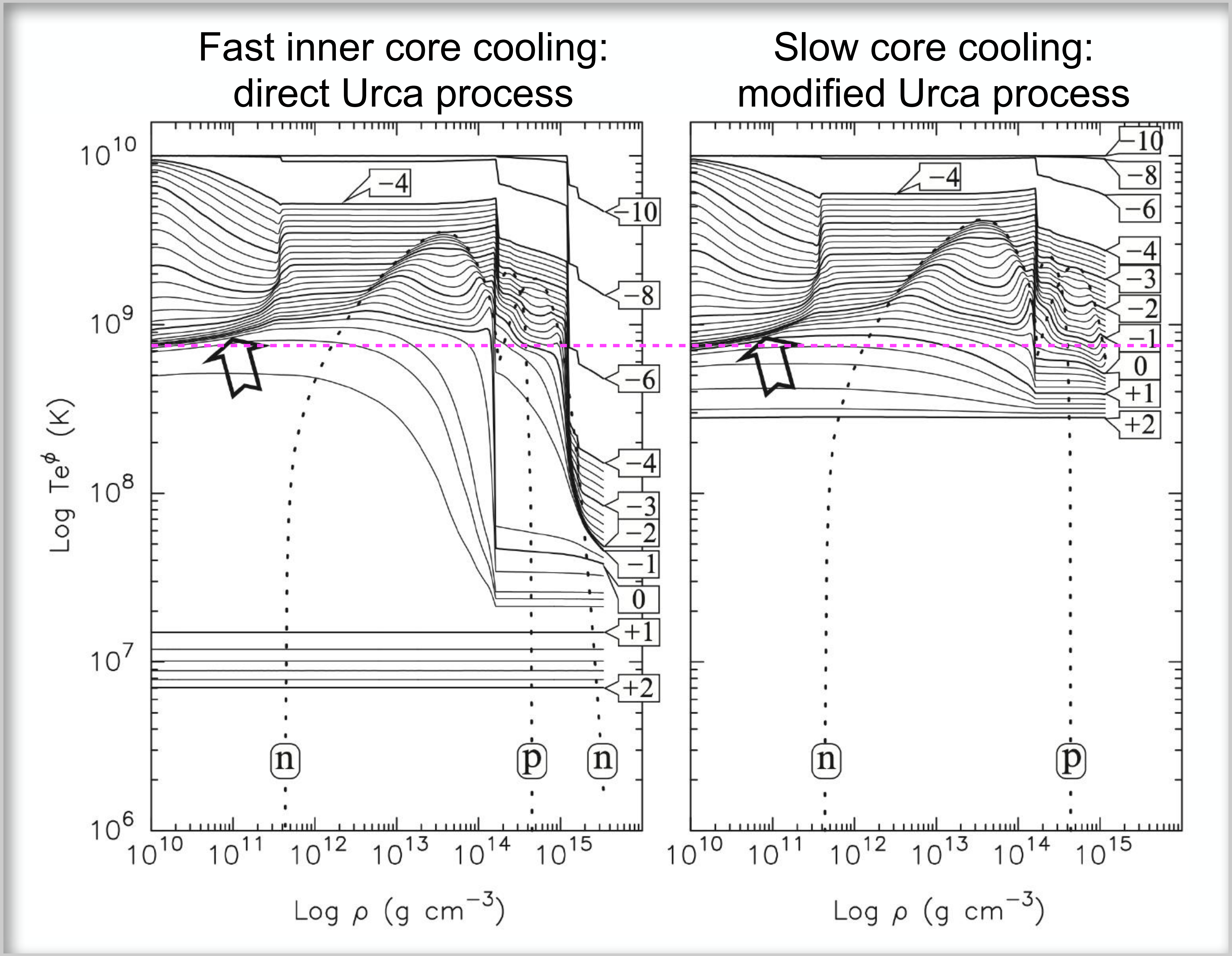
This value is arbitrary:
we DO NOT know the value of this critical mass, and hopefully observations will, some day, tell us what it is !

GR models, solving numerically the energy balance and heat transport equations, with lots of microphysics involved.

"The Cooling of Neutron Stars by the Direct Urca Process", Page & Applegate, ApJ 394, L17 (1992)

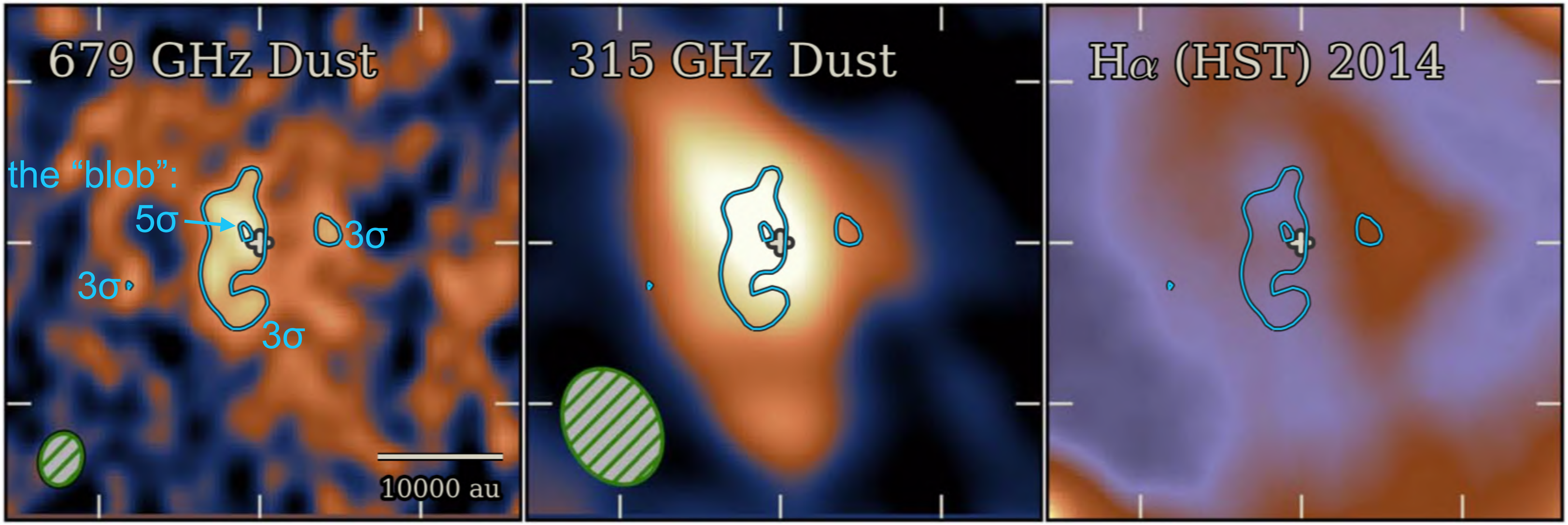
Early Plateau

The cooling of the outer crust slow down when plasma neutrinos shut off: early plateau



[Neutron Star Cooling I](#)
Page, D.
Heraeus Seminar contribution
[2009ASSL..357..247P](#)

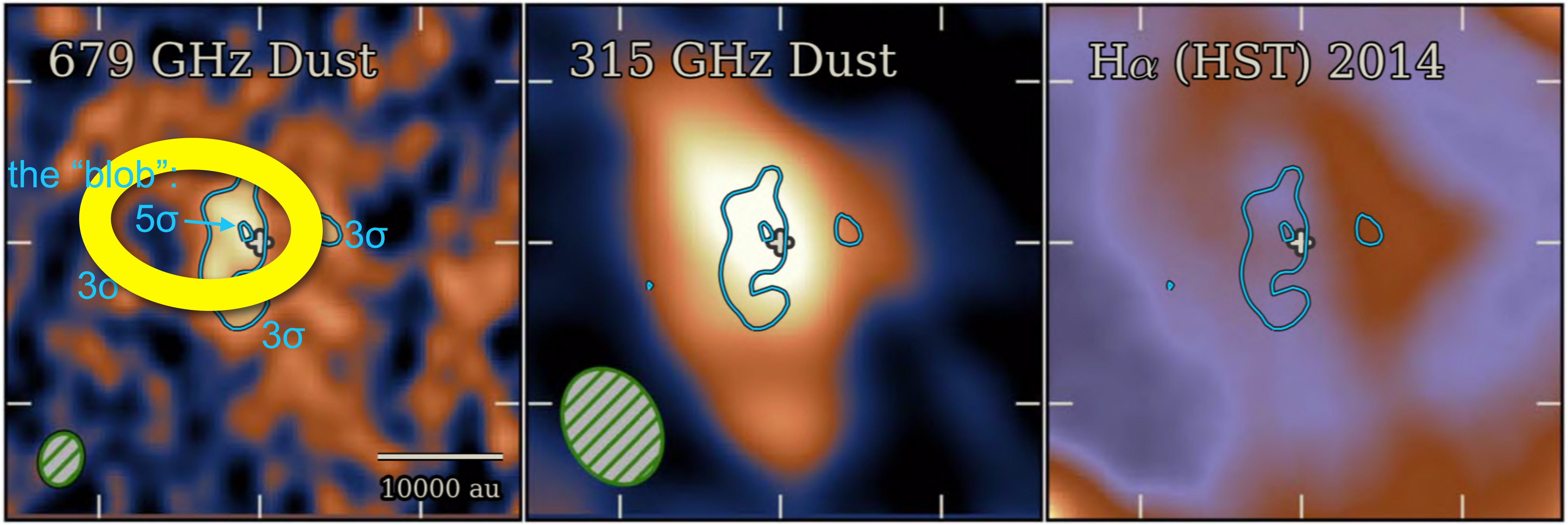
The Discovery: a “Blob” in the Debris’ Dust



The blob is a 5σ detection, slightly offset from the center of the debris (center of explosion).
Inner debris are energized by ^{44}Ti decay (half life 60 yrs), T_{dust} ~ 17-22 K
“The Blob”: T_{dust} ~ 33 K difficult to explain by just higher debris density: **needs extra energy**

High angular resolution ALMA images of dust and molecules in the SN 1987A ejecta
Cigan, Phil et al. 2019ApJ...886...51C

The Discovery: a "Blob" in the Debris' Dust



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"The Blob": T_{dust} ~ 33 K difficult to explain by just higher debris density: **needs extra energy**

Energy injection by the Central Compact Object: 40-90 $L_\odot$ ~ 1.5-3.5×10^{35} erg s^{-1}

High angular resolution ALMA images of dust and molecules in the SN 1987A ejecta
Cigan, Phil et al. 2019ApJ...886...51C

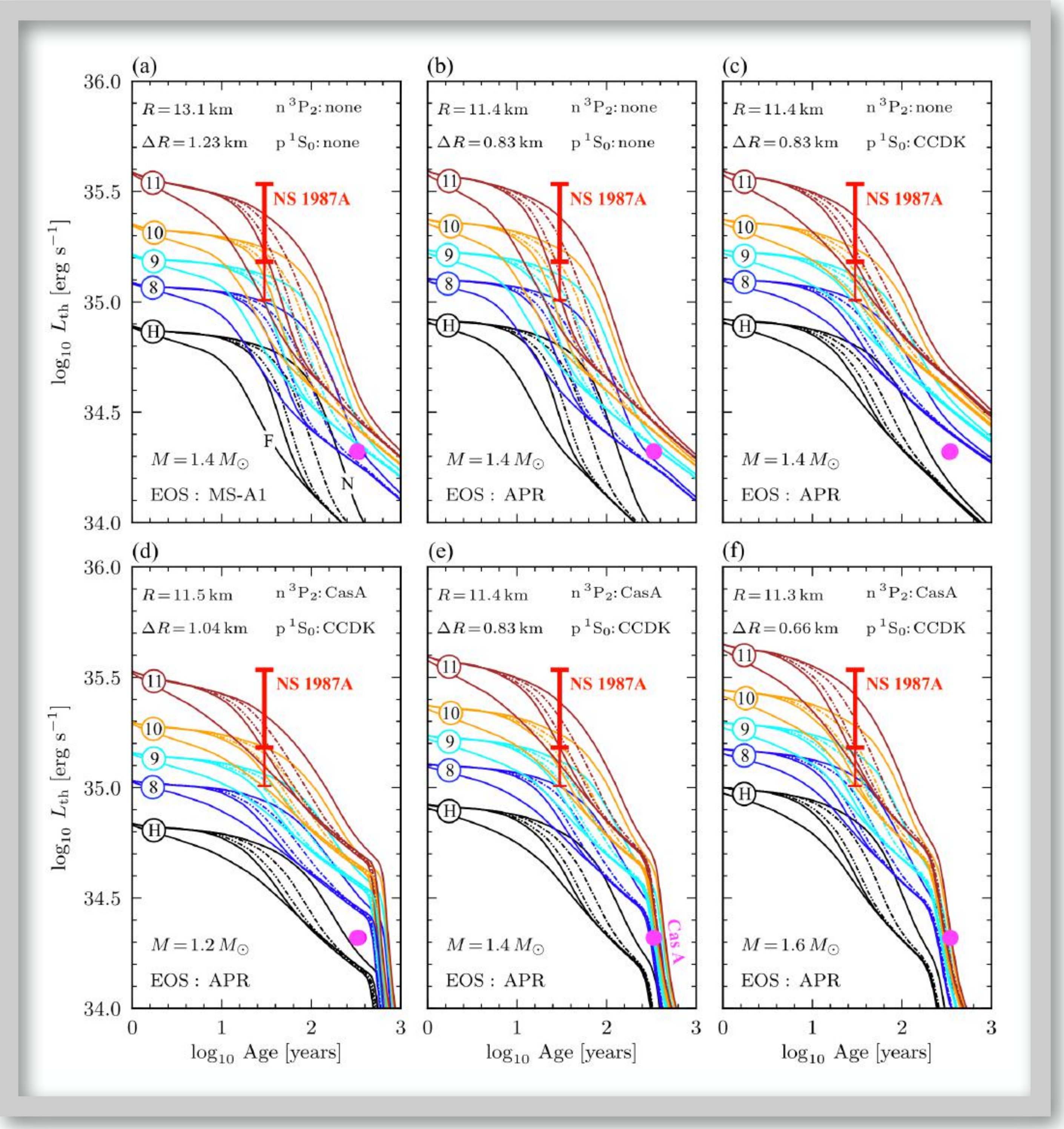
NS 1987A and the Plateau Phase

NS 1987A:
luminosity inferred from the "blob" luminosity.

Each panel corresponds to different assumptions about the core: EOS, mass, pairing.

Within panels:
each color corresponds to a different thickness of the light elements layer.

Within each color:
each line corresponds to different assumptions about neutron $^1S_0$ superfluidity in the inner crust.



NS 1987A in SN1987A
Page, Dany; Beznogov, Mikhail V.; Garibay, Iván; Lattimer, James M.; Prakash, Madappa; Janka, Hans-Thomas
2020ApJ...898..125P


"That's all Folks!"