CURRENT STATUS OF NEUTRON STAR THERMAL EVOLUTION AND RELATED PROBLEMS

Sachiko Tsuruta

Physics Department,
Montana State University

Kiken Conference, Kyoto, Japan, September 1 2012

I. INTRODUCTION

BRIEF HISTORY

Neutron star (NS) cooling:

First suggested by A.G.W. Cameron, in ApJ 1959

First calculated by ST, in Columbia PhD thesis, using the isothermal method:

Conclusion: NS can be observed for about a million years after supernova (SN explosion); ~a million degrees at ~ a million years

First calculated by K. Nomoto and ST, ApJ 1987, etc., by the exact method, include heating

Since then many calculations by ST group, Page group, Yakovlev's group, etc.

Standard Cooling: **modified URCA** neutrino emissivity, etc.

Non-standard Cooling: faster cooling, with `exotic' processes such as direct URCA processes involving nucleons, pions, hyperons, kaons, quarks, etc.

- Note: All non-standard cooling - too fast to be consistent with the observational detection data of e.g. Vela pulsar, etc.,without superfluid suppression, e.g., (*1).

(*1) Tsuruta, S., 2010 ASAL(Ap. And Space Sci. Lib), 357, Springer lecture series (AIP), ed. W. Becker, pp 289-318

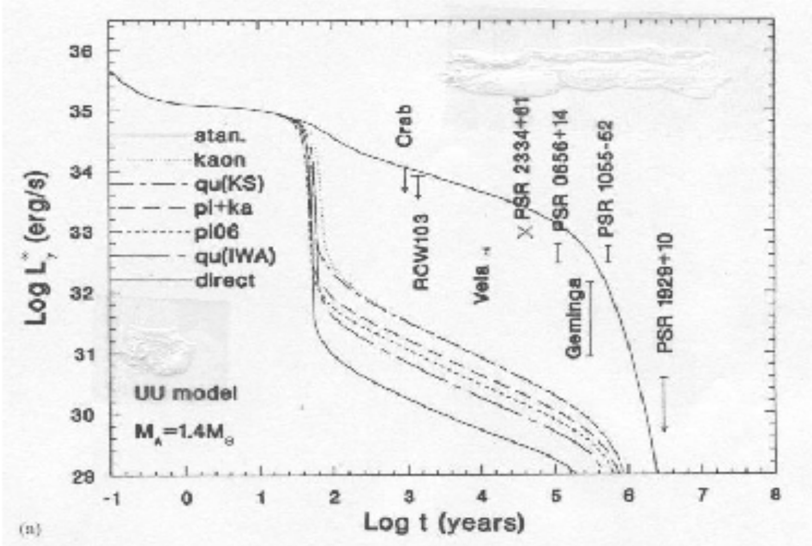


Fig. 6. NS standard and non-standard cooling curves, taken from [21]. See the text for the details.

T72 constructed by Takatsuka (1972) [40], AO constructed by Amundsen and Ostgard (1985) [41], and HGRR constructed by Hoffberg et al. (1970) [42], respectively. The other models, NPC, ETA, E1 and E2 were constructed by Takatsuka and Tmagaki (1980)(1982) [37].

The major effect of superfluidity on cooling is that when the interior temperature T becomes below T_{cr}, all neutrino processes involving the superfluid particles decrease roughly as:

$$L_\nu(super) = L_\nu(normal)R(T/T_{cr}), \tag{20}$$

where $L_\nu(super)$ and $L_\nu(normal)$ are neutrino luminosity with and without superfluid particles, respectively, and $R(T/T_{cr})$ is the reduction factor, i.e., the luminosity is suppressed by this factor in the presence of superfluidity. Roughly it reduces as $\exp(-a_c T_{cr}/T)$ (for $T << T_{cr}$, where a_c is a constant), although the precise dependence is somewhat more complicated[10]. The net effect is that in the presence of superfluidity a star cools more slowly due to suppression of neutrino cooling, which raises surface temperature during the neutrino cooling era. The suppression is larger for stronger superfluidity, meaning a larger energy gap and hence higher T_{cr}. This effect on cooling is

[10] Specific heat C_v also decreases similarly with superfluidity.

- **Superfluid Suppression**:

- Fast cooling can be suppressed in the presence of superfluid particles: When particles are in a superfluid state, neutrino emissivity, specific heat, involving these particles can be suppressed when $T << T_{crit}$,.

- where T_{crit} is superfluid critical temperature, which depends on superfluid energy gap, and T is the internal temperature of the star
- T_{crit} depends on density

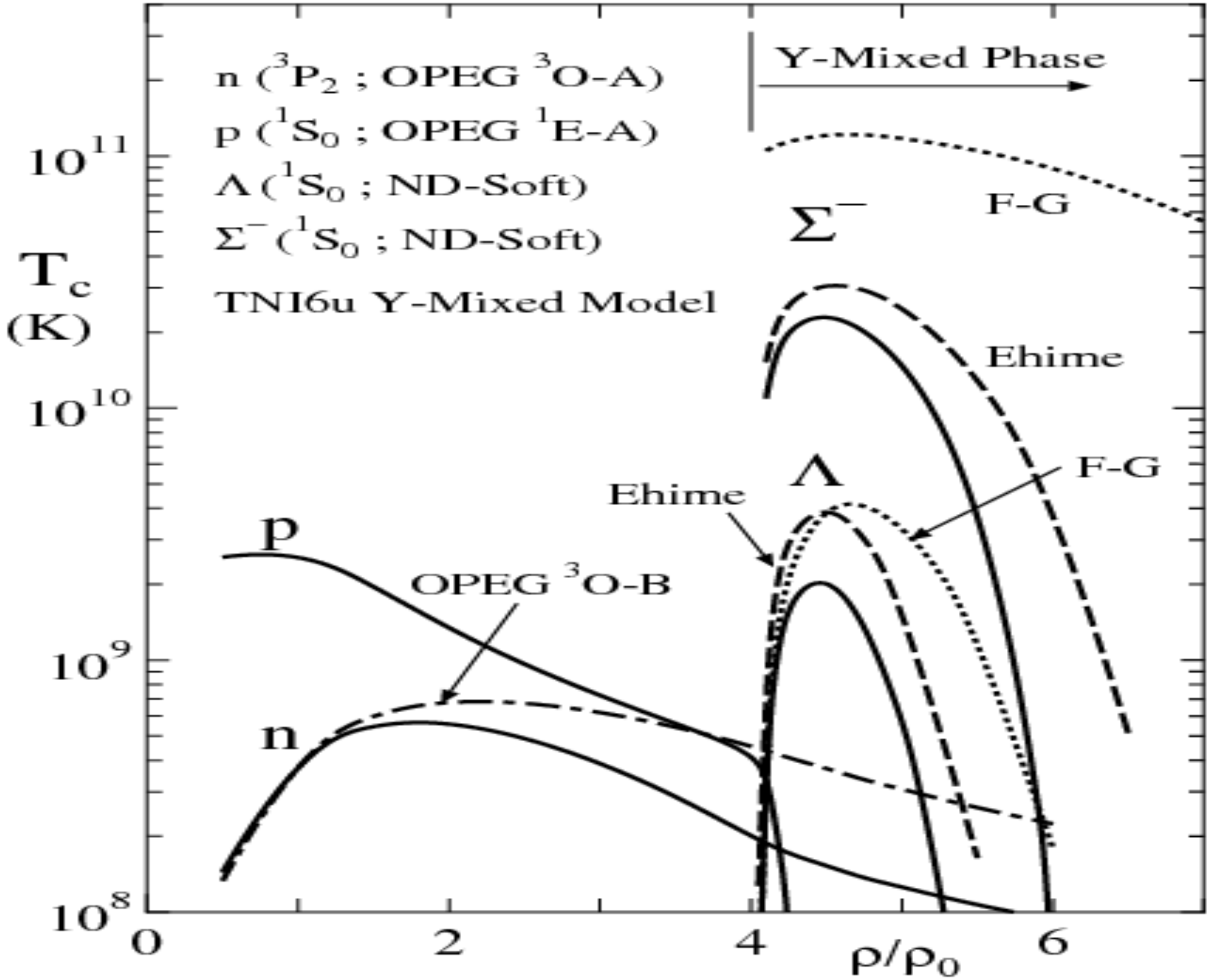


Fig. 2.— Various superfluid models, shown as the superfluid critical temperature T_c versus matter density ρ (in units of nuclear density) relation. For hyperon-mixed neutron matter, we show three representative models, ND-Soft (solid curves), Ehime (dashed curves) and FG (Funabashi-Gifu type A) (dotted curves) for Σ^- and Λ hyperons as marked (in the higher density range of $\rho \geq 4\rho_0$, where ρ_0 is nuclear density). TNI6u EOS parameters are used.

- **Data: Temperature (photon luminosity) vs age Mainly from ROSAT, Chandra and XMM**

- Nucleon direct Urca operates when proton concentration is high → fastest cooling

  → if coldest star found --. May need this process.
- Among fast cooling, superfluid suppression does not work for nucleon direct Urca (and kaon condensates)(*2).

→Both cool too fast for Vela pulsar.

In hyperon-mixed core, proton concentration increases with density → nucleon direct Urca opens for highest mass hyperon stars

→ Offer fastest cooling → coolest stars

- **Frictional heating due to vortex creep, in inner crust (Anderson, Alpar, Pine; Umeda, Tsuruta, Nomoto 1995, etc .):**

- In the inner crust, the friction between superfluid neutrons and crustal heavy nuclei cause heating(*2).

- The heavy ion crust spins down as the pulsar spins down, but superfluid neutrons do not. That causes friction. Superfluid neutron vortex is pinned to the crustal material, but when the difference in spinning speed exceeds some critical value, the vortex is unpinned and flows outward, causing friction and heating. The heating depends on strength of pinning – from this theory, can estimate maximum vortex creep heating allowed from theory.

-

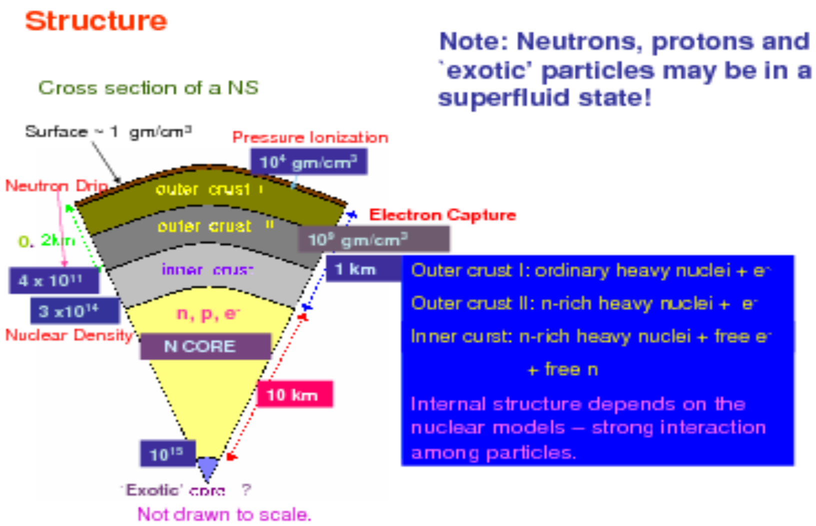


Fig. 5. A cross section of an NS showing the structure and composition of different parts of the star - not drawn to scale. See the text for the details.

exceeds thermal energy kT [5]. With densities from terrestrial values up to $\rho_p \sim 10^4$ gm cm^{-3} ordinary terrestrial matter exists. Calculations show that the equilibrium composition peaks at iron [5]. Therefore, in this range the most abundant element is predicted to be ordinary $^{56}Fe_{26}$ atoms, and hence we expect the atmosphere and the outermost layers just beneath the surface consist of ordinary heavy atoms peaking at $^{56}Fe_{26}$. At ρ_p, the density is so large that the pressure ionization, where atoms are ionized by pressure due to high density (rather than temperature), takes place. This is where the outer crust I (see Figure 5), consisting of ordinary heavy ions and free electrons, starts. With further increase of density another critical point is reached where free electrons become so abundant that they are captured by nuclei. It takes place at density $\rho_e \sim 10^9$ gm cm^{-3}. A captured electron combines with a proton and becomes a neutron within a nucleus. In this way neutron-rich nuclei are formed. This is where the outer crust II (Figure 5) starts. Here the mater consists of neutron-rich heavy nuclei and free electrons. With further increase of density, another critical point is reached when there are so many neutrons in a nucleus that some neutrons drip out of the nucleus. This point is called the 'neutron-drip' point, with the critical density $\rho_n \sim 4 \text{ x } 10^{11}$ gm cm^{-3}. At this density the inner crust starts which consists of free neutrons, electrons and neutron-rich heavy nuclei. Finally when density approaches the nuclear

- **Cooper Pair Cooling**

- It affects neutrino emissivity involving superfluid neutrons in a very complicated way – for a certain choice of the energy gap it can be significantly enhanced- bringing the cooling curve down.

- Proton superfluidity (superconductivity) can affect cooling also.

- But effects of Cooper pair cooling on hyperon and pion cooling cases are minor.

Basic Equations:

General relativistic equations of hydrostatic equilibrium and thermodynamics (energy balance and energy transport), used exact evolutionary code (see (*1))

(a)Earlier Calculations:

Pion Cooling (Cooling of neutron stars (NS) with core with pion condensates):

Used superfluid gap models constructed by the Kyoto-Iwate group (Tamagaki, Takatsuka, etc.) in the 1980s

Umeda, Nomoto, Tsuruta, Muto and Tatsumi 1994 (ApJ. 431, 309),

Tsuruta, Teter, Takatsuka, Tatsumi, Tamagski 2002 (ApJ 571, L143),

ST: Physics Reports in 1998 (*2), etc.

Some results shown last night by Tatsumi san, etc.)

(b) Recent Calculations:

(ii) Hyperon Cooling (with hyperon-mixed core):

Tsuruta, Sadino, Kobelski, Teter, Lirbmann Takatsukas, Nomoto, Umeda 2009 (ApJ, 691, 621), and various review papers, conference proceedings

Equation of State(EOS)(*7):

Hyperon matter, for $\rho > \rho_{crit} = 4\ \rho_N$

(a) TNI2U(soft)

(b) TNI6U(medium stiffness)

(c) TNI3U (stiff)

PionCondensates, for $\rho > \rho_{crit} = 3\rho_{N}$.

TNI3P(stiff), TNI7p(very stiff)

Neutron matter with density

$\rho < \rho_{crit}$ (critical superfluid density)
(where ρ_N is nuclear density = 2.8 x 10^{14}gm/cm$^{3)}$;

EOS(*7):

(i) (a)TNI6(medium stiffness)

(b) TNI3(stiff)

© TNI7(very stiff)

Below ~ nuclear density, regular crusts and atmospheres –

EOS - same as in Tsuruta 1998 (T98)(*2)

(*2) Tsuruta, S., Physics Reports, 292, 1 1998

Neutrino Emissivity:

Standard Cooling: **Modified URCA** (both nucleons in the core and heavy ions in the crust), **Cooper Pair,** nucleon bremsstrahlung, plasmon neutrino, photo neutrino, pair neutrino emissivity, etc.(*2)

Non Standard Cooling:

(i) **Λ and Σ Hyperon direct URCA** emissivity, including Cooper pair emissivity (*2)(*3)

(ii) Pion direct URCA emissivity(*5)

Heating: Vortex creep heating(*2)

- (*3) Tsuruta et al. 2009, ApJ., 691, 621
- (*5) Tamagaki and Takatsuka, Progress, 115, 245, 2006;
- Takatsuka, Nishizaki, Tamagaki 2008 (TNT08)
-

Superfluidity:(depends on density)

Neutron superfluidity:

OPEG-B(*7)

Hyperon superfluidity: Modified Ehime(*7)

Pion superfluidity:

Modified Tamagaki/Takatsuka(*5)

Proton superfluidity: CCY(*2)

Opacity/Conductivity: Standard, as adoptred in Ref: (*2)

Atmosphere: Blackbody ~ Fe atmosphere

- (*7) Takatsuka , Nishizaki, Yamamoto, Tamagaki 2006, Prog. Theor. Phys. 115, 355; Nishizaki, Yamamoto, Takatsuka 2002, Prog. Theor. Physics 108, 703; Tamagaki, Takatsuka 2007, Prog. Theor. Physics, 117, 5, etc., and referenes therein

II. RESULTS AND DISCUSSION:

A. Isolated Pulsars

Hyperon-Mixed Stars

(a)TNI6U(soft) Model

$1.3M_{\odot}$ star: neutron star,

- **standard cooling** since central density

$\rho_c < \rho_{crit}$

(.....) Both neutron and proton **superfluids, with heating**

(-----) **No heating**

For hot pulsar PSR 1055, $1.3M_{\odot}$ neutron star (no hyperons) o.k. if heating included!

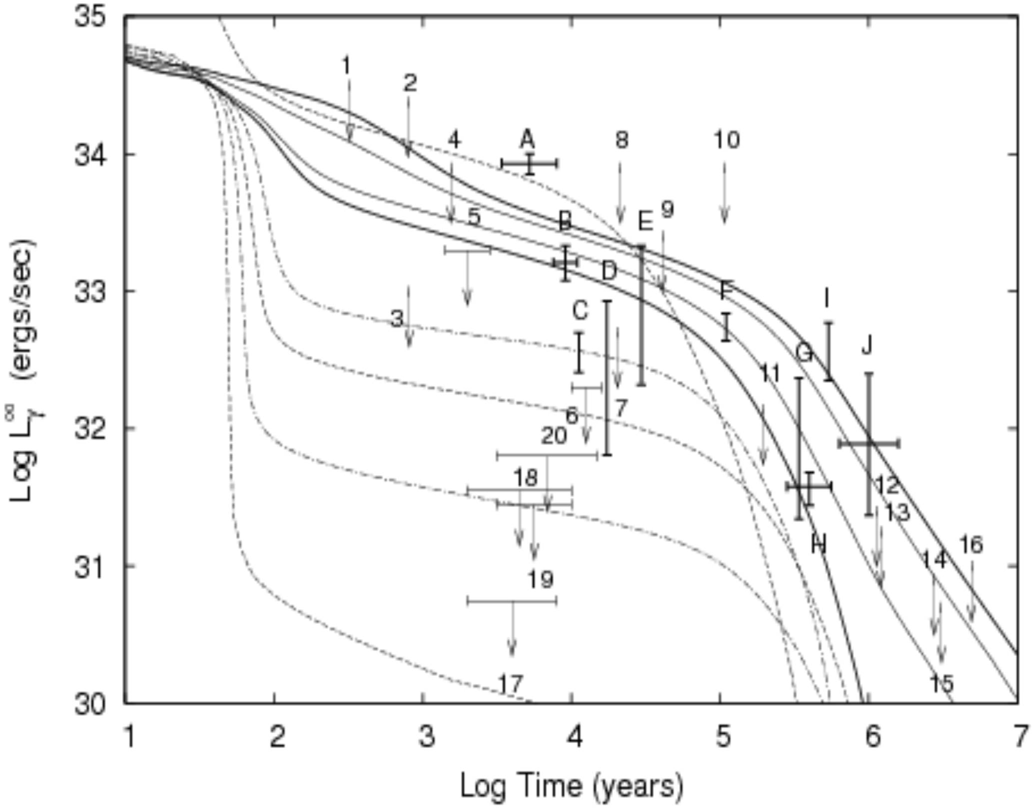


Fig. 3.— Thermal evolution of NSs with TNI6u-EOS, of medium stiffness. The upper four solid curves refer to stars with gravitational mass M = 1.26M$_\odot$, with the maximum vortex creep heating with the heating parameter K = 10^{37} ergs $m^{-3/2}s^2$ (highest thick solid curve), moderate heating with K = 5 x 10^{36} ergs $m^{-3/2}$ s^2 and 10^{36} ergs $m^{-3/2}s^2$ (middle two thin solid curves), and no heating (lower thick solid curve), respectively, in the decreasing order. The uppermost dashed curve shows a model which is the same as the lowest thick solid curve (a 1.26M$_\odot$ star with no heating) but with the envelope contaminated with Hydrogen. The

Figure:

Medium EOS TNI6u, and hyperon cooling/heating,

but qualitatively similar results for pion cooling also.

All isolated NS temperature data consistent with the model

CONCLUSION

- **By changing stellar mass, both hotter and cooler pulsar data are consistent with current thermal evolution theories when heating is taken into account.**
- **Constituent 'exotic' particles (pions, etc.) for non-standard cooling must be in the superfluid state, if cooler data are detections – Vela pulsar, etc!**
- **Heating needed for PSR 1055 data.**

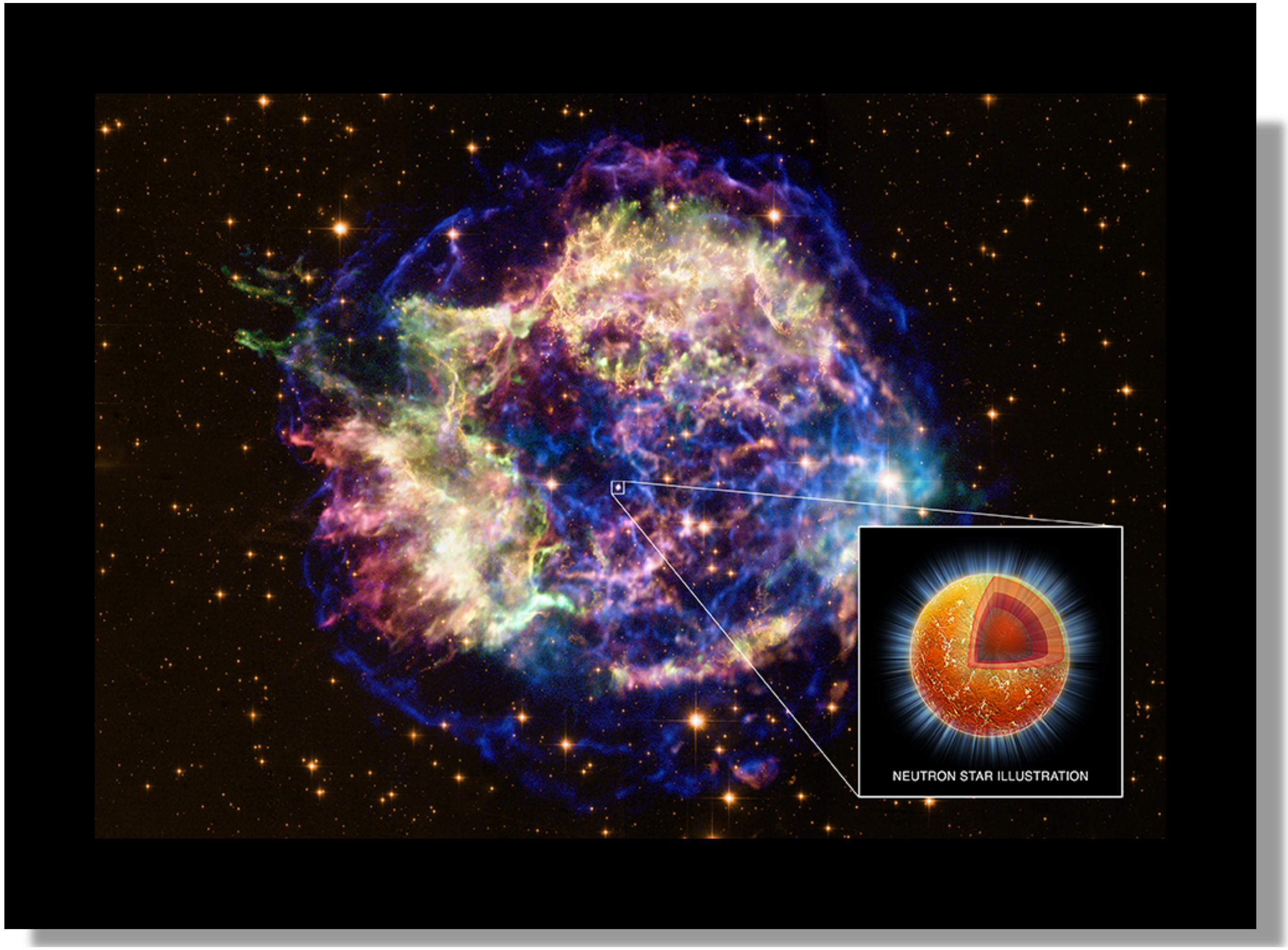
If cool data (e.g., Vela, 3C58) are detections(*), NUCLEON direct URCA cooling NOT consistent with observation →too cold!

(*) LMXB case to be shown soon, for further support!

Then, we DO need `exotic' core particles, such as pion condensates or quarks.

Hyperon option in trouble, if Nagara effect applies

RALTEST DEVELOPMENTS:
Fast Cooling of Supernova Remnant Cassiopeia-A Neutron Star



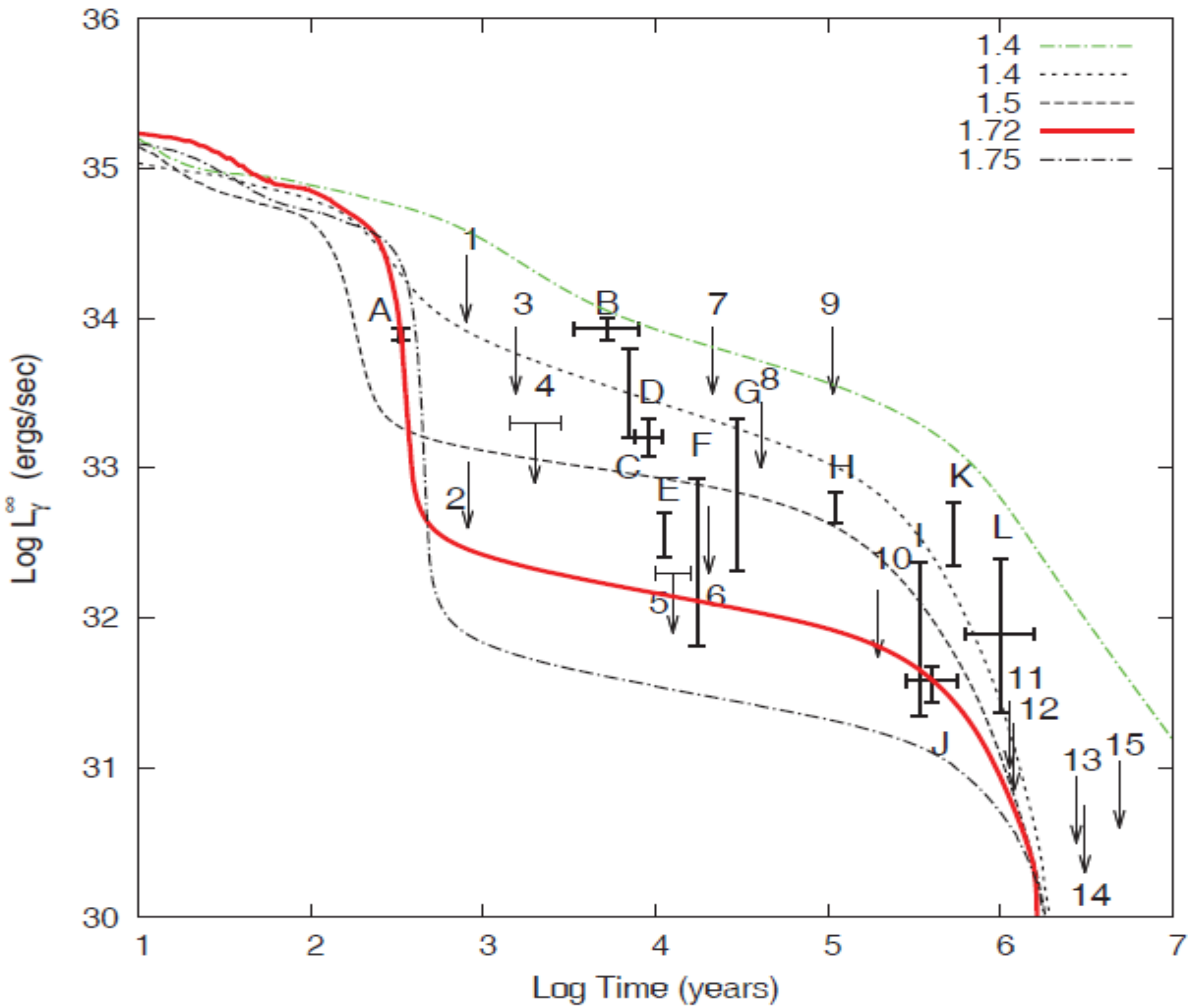
BACKGROUND

- 11,000 Light years away
- Strongest radio source
- Probably about 330 years old
  - though no confirmed actual supernova observation
- Unknown progenitor
  - Possibly a very massive star

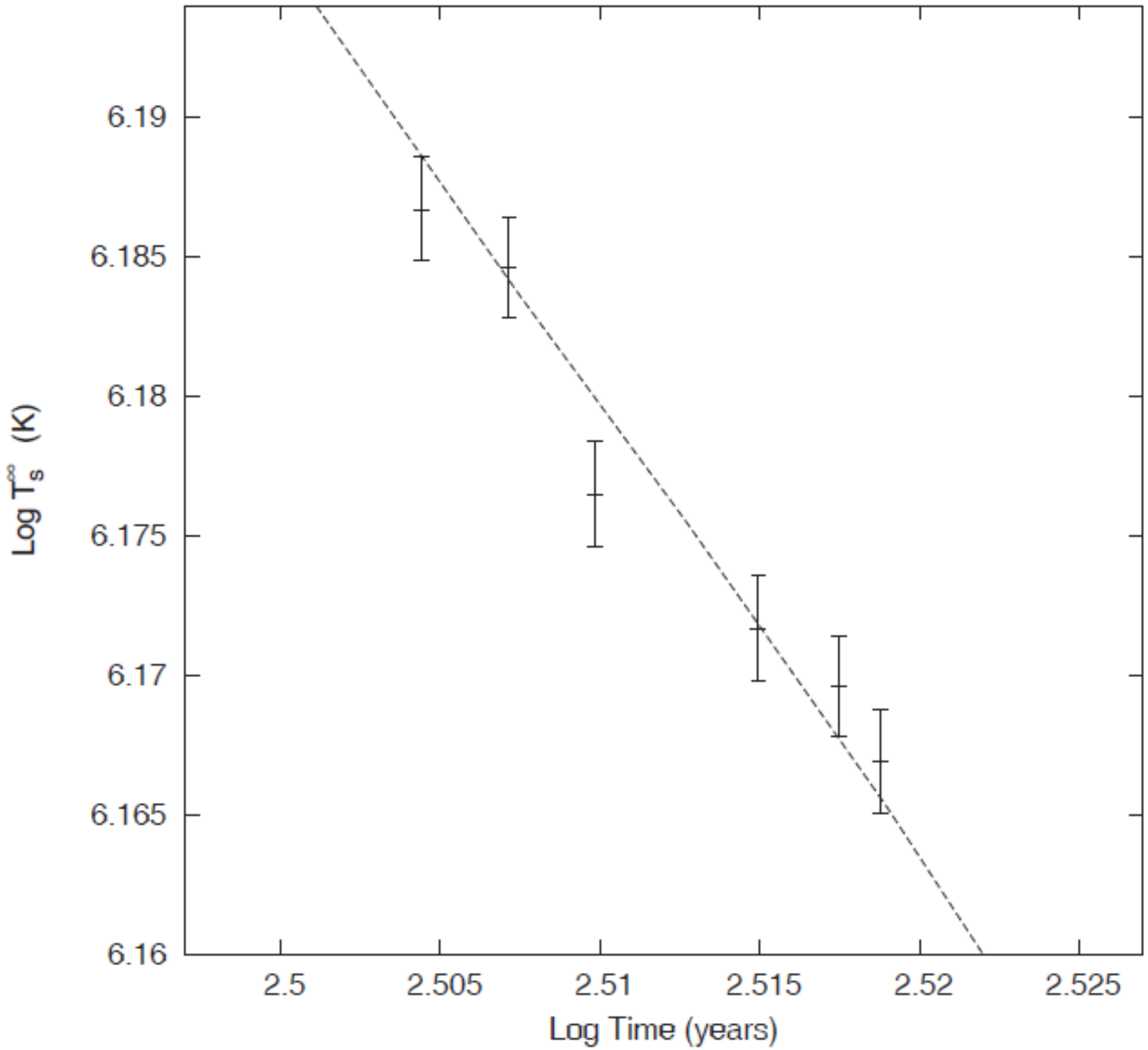
- New observations: Detection, not just upper limit! Moreover, cooling fast!

Ho, Heike, etc., 2010, 2012

Our Latest Results



Close up at Cas A NS



Latest Pion Condensate Model

New results (Unver, Tsuruta, et al, in prearation 2012)

Pion condensates at $\rho > \rho_{crit} = 3\rho_N$

New Very Stiff EOS: TNI7, with maximum mass 2M(solar) - similar to $2\pi\Delta$ of TNT08, with UTBR (Universal Three-Body Repulsion)

Cas A NS: Mass 1.72M(solar); Radius 13.5km

New superfluid model for pion condensate, by Tamagaki and Takatsuka 2006 (in PTP)

Fast cooling: THERMAL RELAXATION

- Newest report: AAS meeting talk 2012 – many authors including Hoand Heinke – slope may not be so sharp:
- Implication: R ~ 13km, o.k.

- Some references suggest radii narrow within R ~ 11 – 12.9 km - claimed from both nuclear experiments and astrophysical observations: e.g., Steiner, Lattimer, Brown 2010, 2011(*8) – really?
- Our tentative interpretation: even if true, 13km close enough, within various reasonable uncertainties – so, o.k.

CONCLUSION

Our Model: Cas A NS fast cooling is due to Thermal Relaxation.

Due to stiff EOS with larger radius

Hint from PS Model with R~15-16km

→Relaxation time t ~ a few x 1000 years (T98)

→ Can be tested if R is found -

R ~ 13km ok?

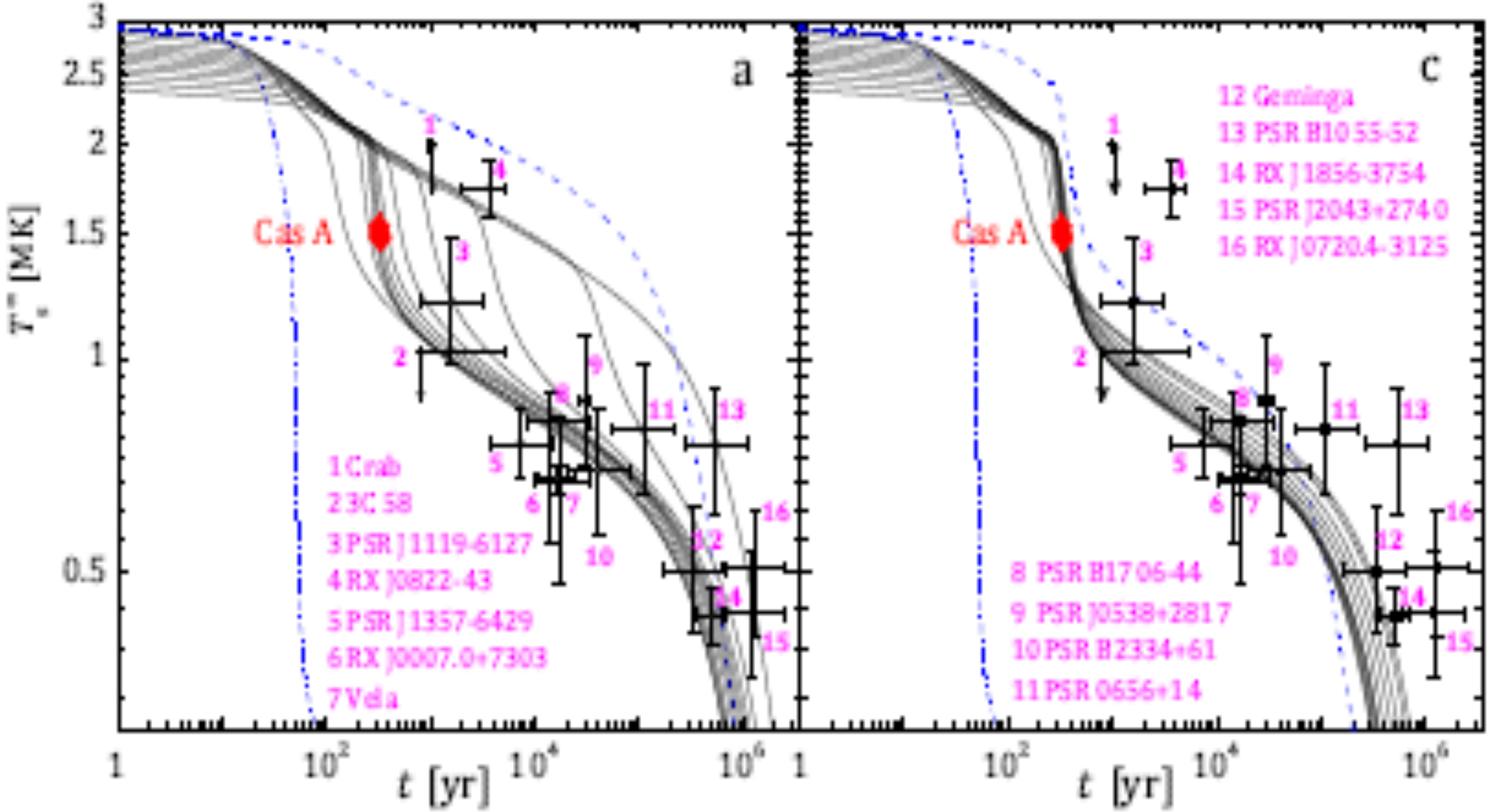
→Motivated by trouble with Yakovlev, Lattimer, Page etc models – which claim Cas A NS fast cooling is a proof of NS superfluid in core

- Recent observations favor large mass, up to about 2M(solar) - Need stiff EOS.
- Most convincing data: Shapiro effect of j1614-2230 – binary nearly edge-on

  (Demorest et al 2010)

→ Our choice of TNI7 (very stiff EOS)

Why core neutron superfluid model for Cas A NS in troube?



B.Model a ok, not model c, but for model a need stange neutron superfluid model

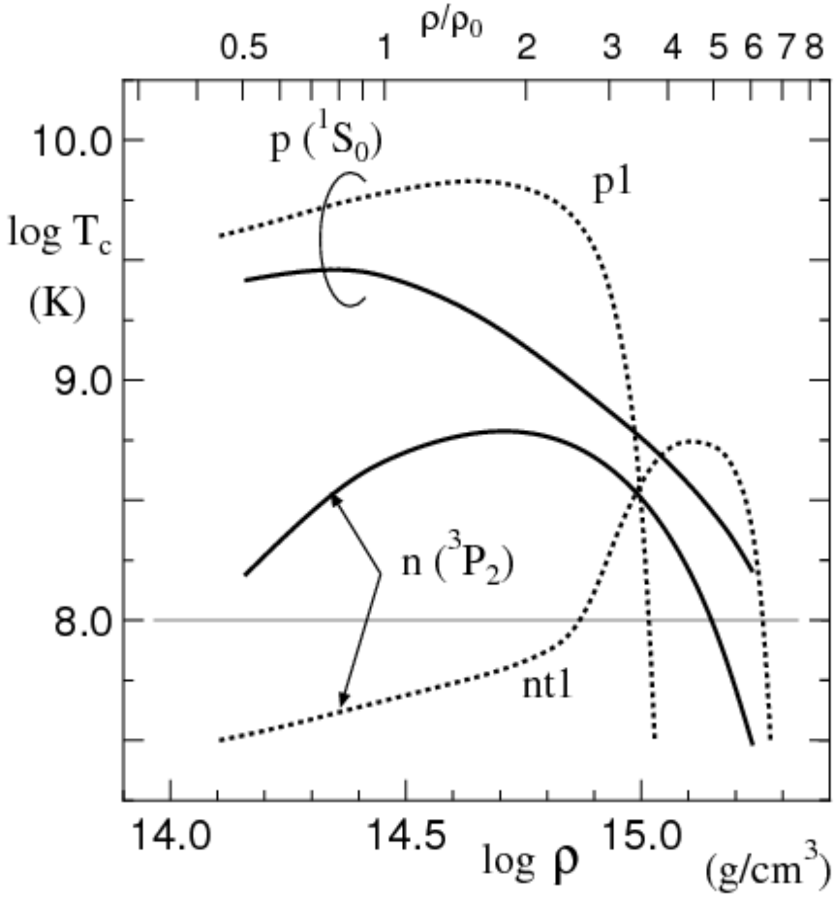


Fig. 7.— Critical temperature T_c for neutron $^3P_2$-superfluidity in the standard NS matter composed of n, p, e^- and μ^-, as a function of total baryon number density ρ. It was calculated by including the ρ-dependence of neutron effective mass and neutron fraction, for TNI6-EOS and useing realistic pairing interactions. Solid and dashed curves refer to

B. SXT in LMXB

- BeppoSAX, RXTE, XMM-Newton –
  X-ray burst observations

- Idea:
- Soft X-ray transients (SXT) in low-mass X-ray binaries (LMXB): in quiescence states provide strong constraints on thermal evolution theories (cooling and heating) of neutron stars (e.g., (*4), (*6)(*8)(*9)(*10))

- (*4) Yakovlev et al. 2003, A&A, astroph/0310259
- (*6) Brown, F., Bildsten, L and Rutledge, R.E., 1998, ApJ 504, L95
- (*8) Heinke et al. 2007, ApJ 660, 1424
- (*10) Tsuruta, S., et al. 2009, in preperation

Neutron Star Mini Nova

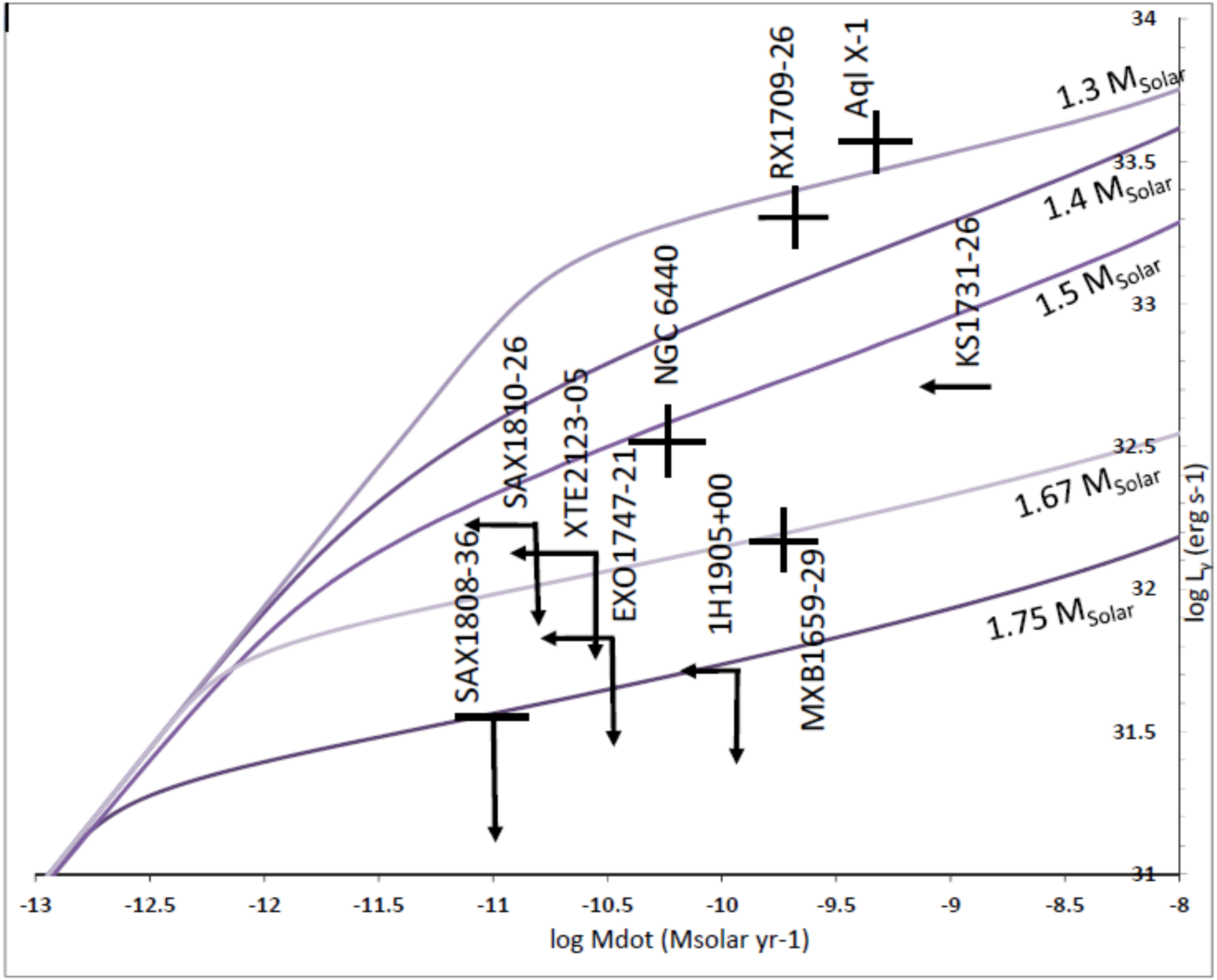
- Accretion until critical density.
- Energy is produced by pycnonuclear reactions.
- Energy is spread over the neutron star via thermal conduction.
- Deep crustal heating.
- Photon emissions from the surface, neutrinos from the interior.
- Usually followed by quiescent period.

- L_{dh}(the deep nuclear heating power) = fn of Q, dM/dt.
- dM/dt = accretion rate averaged over the quiescent period (months to years)
- Q = the total amount of heat released per one accreted nucleon = ~ 1.45 Mev and 1.12 Mev (*9)
- $L_{dh}^{\infty} = L_{\nu}^{\infty}(T_{in}) + L_{\gamma}^{\infty}(T_{eff})$,

$$L_{dh}\left(\langle \dot{M} \rangle\right) = Q_{tot}\langle \dot{M} \rangle / m_u \approx 6.03 \times 10^{33} \langle \dot{M}_{-10} \rangle \frac{Q_{tot}}{\mathrm{MeV}} \mathrm{erg.s}^{-1}$$

- Here L_{dh}^{∞}, L_{ν}^{∞} and L_{γ}^{∞}, are the deep heating power, neutrino luminosity and photon luminosity observed at infinity. T_{in} and T_{eff} are the internal and surface temperature(*4)
- (*9) Haensel and Zdunik, A and A, 1990,227, 117; 2003, 404, 133,

Photon Luminosity vs mass accretion rate



CONCLUSION

I. Cooler Stars: Important new results

From thermal evolution (cooling/heating) curves of isolated neutron stars, only Vela data require the presence of `exotic' particles such as pions, quarks, etc. But, from LMXB SXT data from XMM-Newton,, more data require the exotic particles, e.g., MXB1659-29, NGC 6440

II Cold Stars:

For coldest stars, pion, hyperon, nucleon direct Urca o.k.

III Cas A NS:

Our current model presented here explains new Cas A data excellently, including fast cooling.

COMMENT: If $\rho_{crit} = 2\rho_N$ our model still works.

- **Tentative prediction from current theory and observation - possibility**

- Lowest mass stars – neutron stars:
  → standard cooling
- Low mass stars – stars with pion condensates:
  → nonstandard pion direct Urca cooling
- Medium mass stars – hyperon-mixed stars:
  → hyperon direct Urca cooling
- Massive stars – pion stars, quark stars?

But depend on EOS

• Questions, e.g.

- Do we need nonstandard cooling?
- Do we need `exotic' particles such as pion condensates, or quarks?
- What is the composition of the core, envelope and surface/atmosphere?
- What is the effect of magnetic fields on surface temperature?
- With Nagara event, hyperon cooling may be in trouble.
- What is NS radii, EOS?

(*8) REFERENCES for NS Radii, e.g.

- Astrophysics:
- Steiner, Lattimer, Brown ApJ 2010; arXiv: 1205.6871v1, 2012; Leahy, Morsink, Chou ApJ 2011; and references therein; etc.

- Nuclear experiment/theory: Gandofi, Carlson, Reddy arXiv: 1101.1921v2, 2012; Dutra, et al. 2012 Physical Review C; Tsang et al. Physical Review 2012; Sagert et al arXiv: 1111.6058v1 2011; Lattimerand Lim arXiv: 1203.4286v1, 2012, etc.