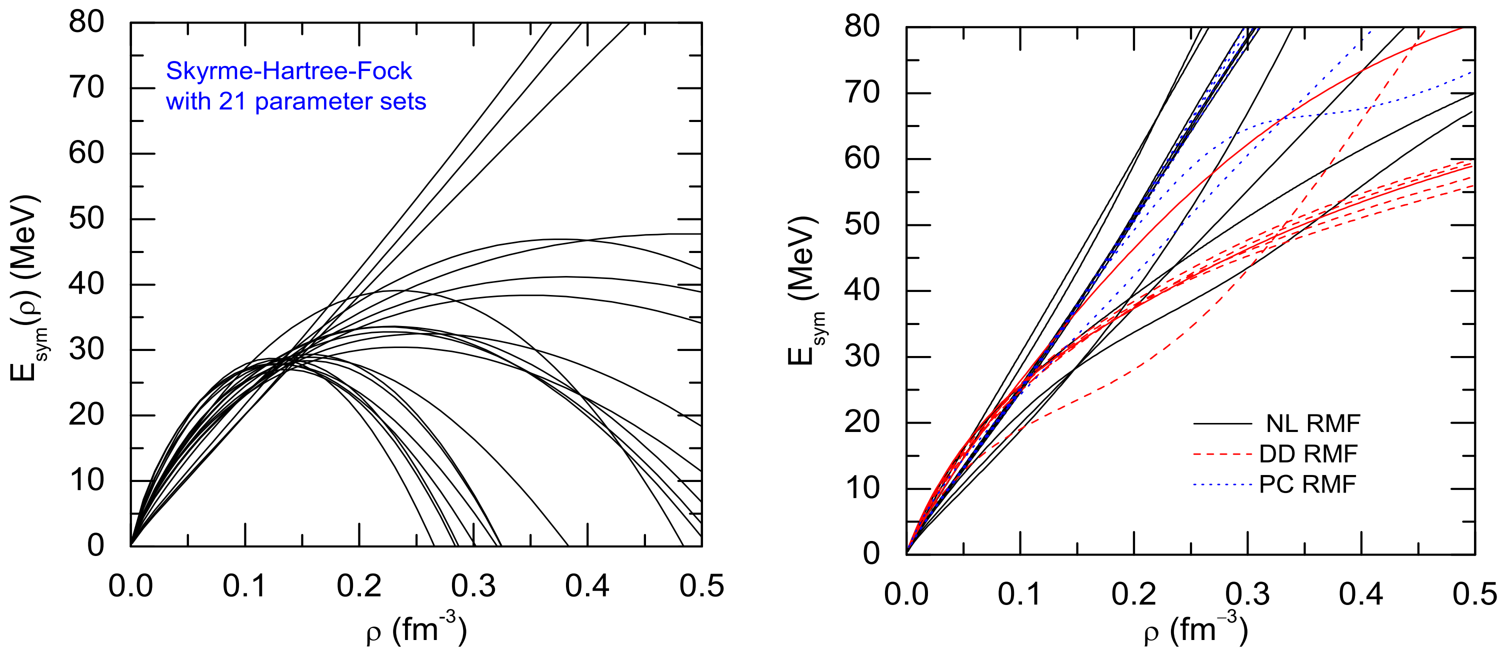
The cooling of the Cas A neutron star as a probe of the symmetry energy and nuclear pasta

W.G. Newton, K. Murphy, J. Hooker, Bao-An Li

Texas A&M-Commerce

Symmetry energy



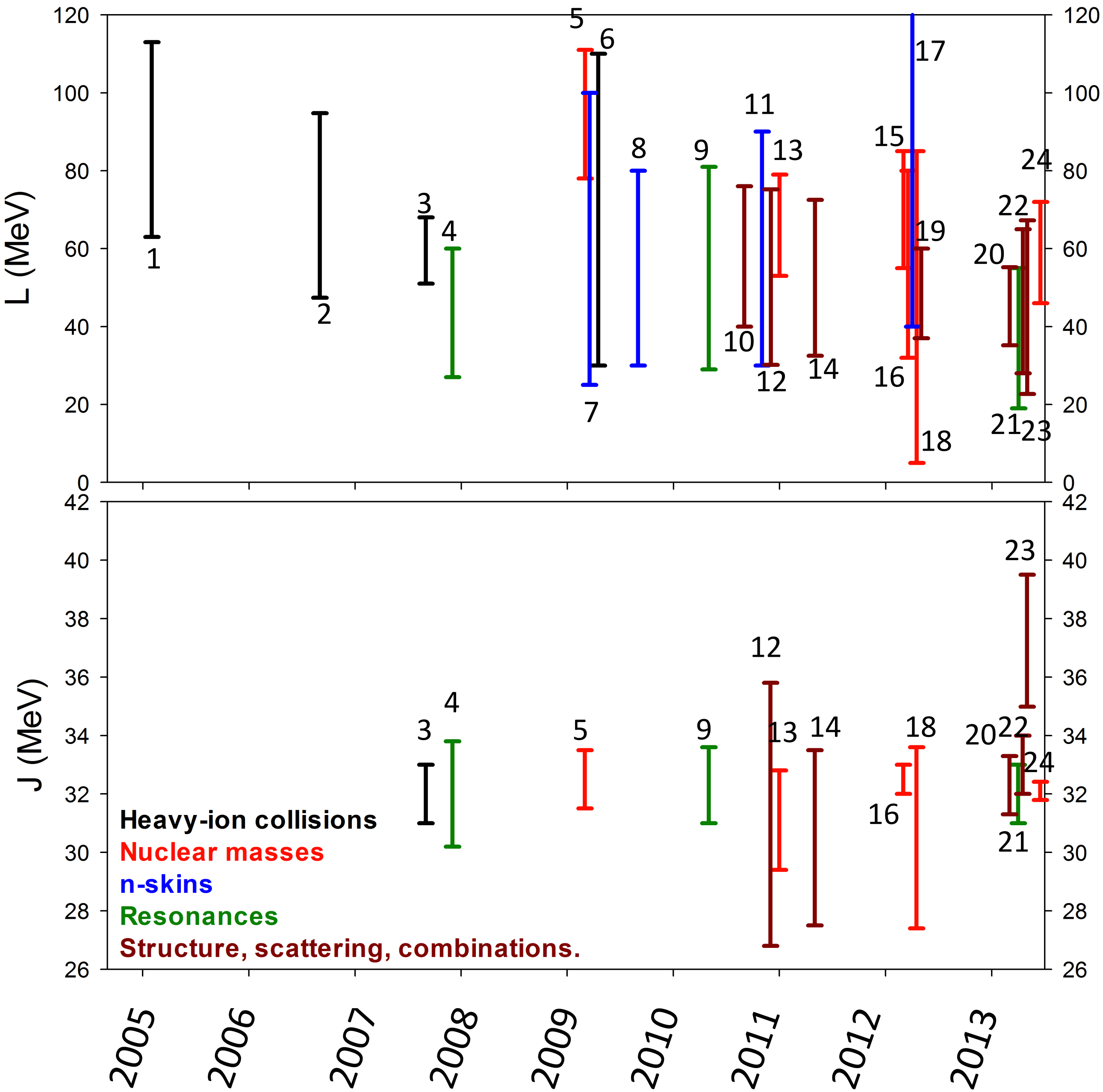
Li, Chen, Ko, Phys. Rep. 464 (2008)

$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots \qquad \delta = 1 - 2x$$

$$S(n) = J + L\chi + \frac{K_{\mathrm{sym}}}{2}\chi^2 + \ldots \qquad \chi = \frac{n-n_0}{3n_0}$$

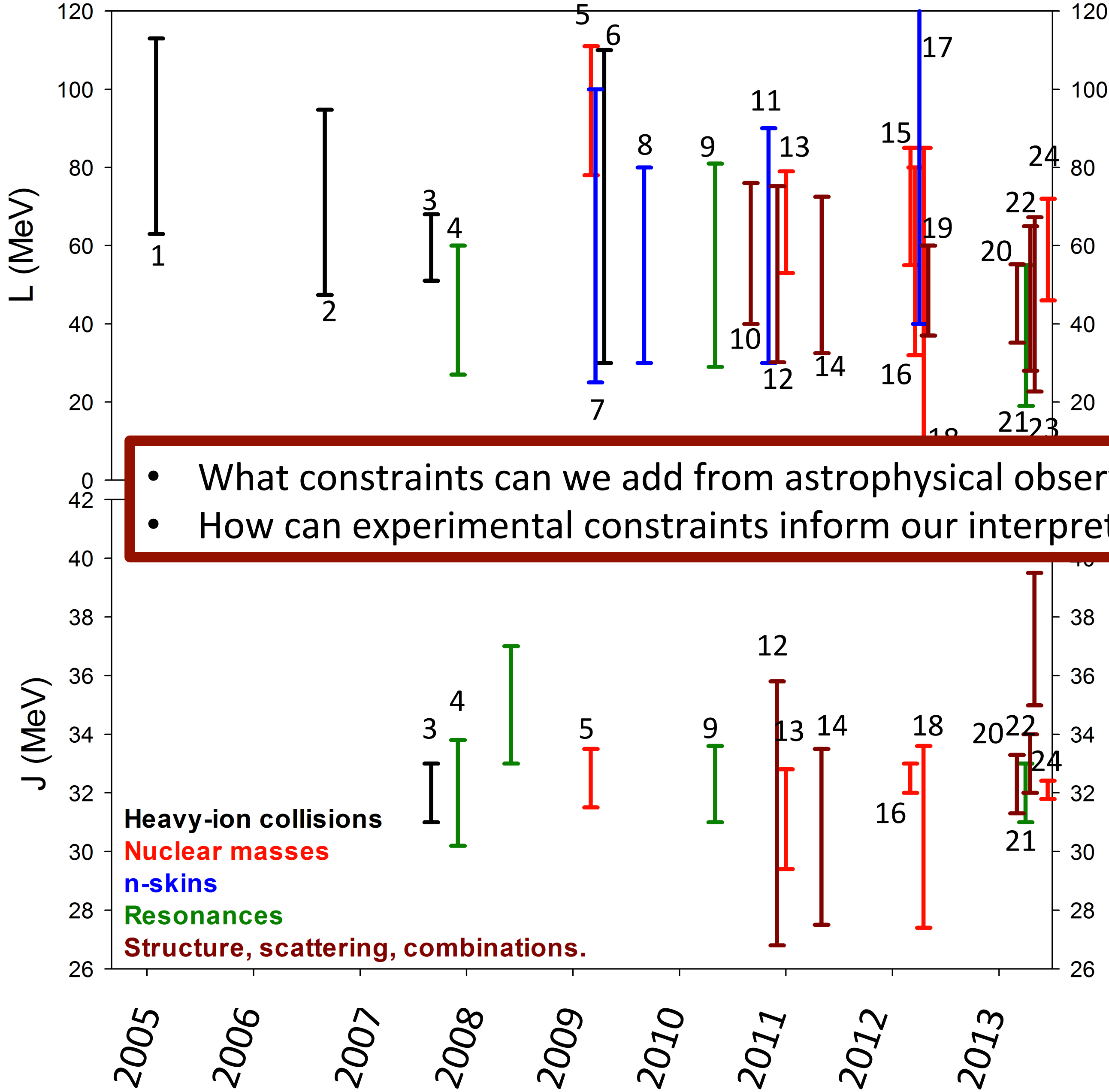
Other notations are available

Motivation: symmetry energy sensitive observables



1. Chen,Ko,Li; PRL94
2. Famiano et al; PRL97
3. Shetty et al; PRC76
4. Klimkiewicz et al; PRC76
5. Danielewicz, Lee; NPhys A818
6. Tsang et al; PRL102
7. Centelles et al; PRL102
8. Warda et al; PRC80
9. Carbone et al; PRC81
10. Chen, Ko, Li, Xu; PRC82
11. Zenihiro et al; PRC82
12. Xu, Li, Chen; PRC82
13. Liu et al; PRC82
14. Chen; PRC83
15. Möller et al; PRL108
16. Lattimer, Lim; arxiv:1203.4286
17. Abrahamyan et al, PRL108
18. Dong et al; PRC85
19. Piekarewicz et al; PRC85
20. Zhang, Chen; arxiv:1302.5327
21. Roca-Maza et al. PRC87
22. Wang, Ou, Liu, PRC87
23. Li et al. PLB721
24. Agrawal et al, arxiv:1305:5336

Motivation: symmetry energy sensitive observables



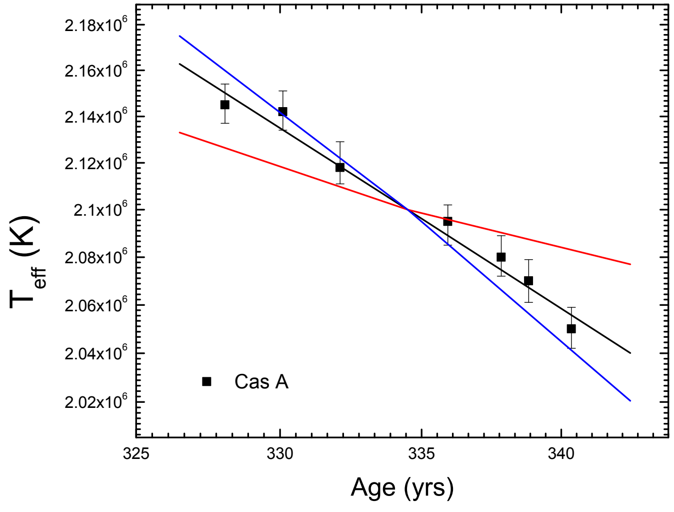
- What constraints can we add from astrophysical observation?
- How can experimental constraints inform our interpretation of observations?

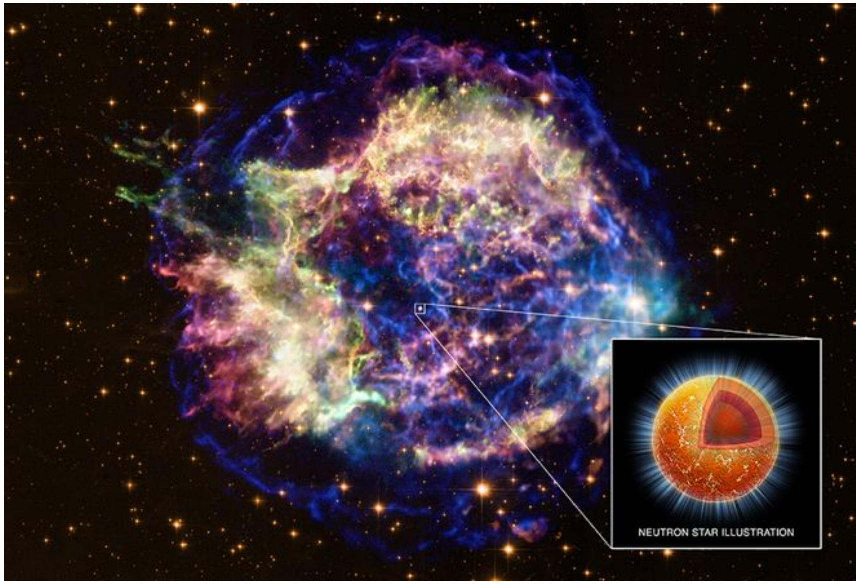
1. Chen,Ko,Li; PRL94
2. Famiano et al; PRL97
3. Shetty et al; PRC76
4. Klimkiewicz et al; PRC76
5. Danielewicz, Lee; NPhys A818
6. Tsang et al; PRL102
7. Centelles et al; PRL102
8. Warda et al; PRC80
9. Carbone et al; PRC81
10. Chen, Ko, Li, Xu; PRC82
11. Zenihiro et al; PRC82
15. Möller et al; PRL108
16. Lattimer, Lim; arxiv:1203.4286
17. Abrahamyan et al, PRL108
18. Dong et al; PRC85
19. Piekarewicz et al; PRC85
20. Zhang, Chen; arxiv:1302.5327
21. Roca-Maza et al. PRC87
22. Wang, Ou, Liu, PRC87
23. Li et al. PLB721
24. Agrawal et al, arxiv:1305:5336

Cooling of Cas A NS

- Cas A NS: birth date 1680 ± 20yr (Fesen et al 2006)
- Thermal emission best fit* using a Carbon atmosphere model (Ho & Heinke 2009)
  ➔ $\langle T_{eff} \rangle \approx 2.1 \times 10^6$ K.
- Subsequent analysis of Chandra data taken over the previous decade ➔ evidence for rapid decrease in surface temperature by ≈ 4% (Heinke & Ho 2010).
- Detailed analysis of Chandra all X-ray detectors and modes ➔ 2-5.5% temperature decline over the same time interval (Elshamouty et al. 2013).
- Definitive measurements difficult (surrounding bright and variable supernova remnant)

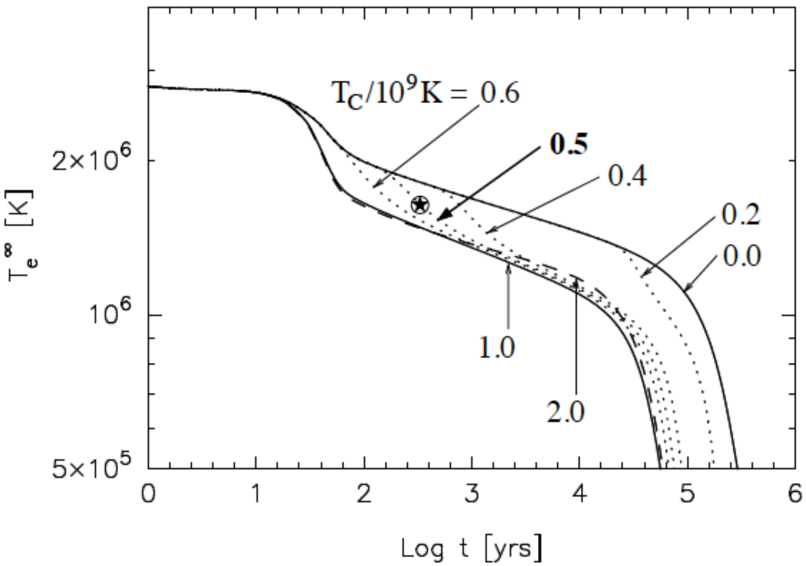
* "best" means most consistent with an emitting area of order the total neutron star surface



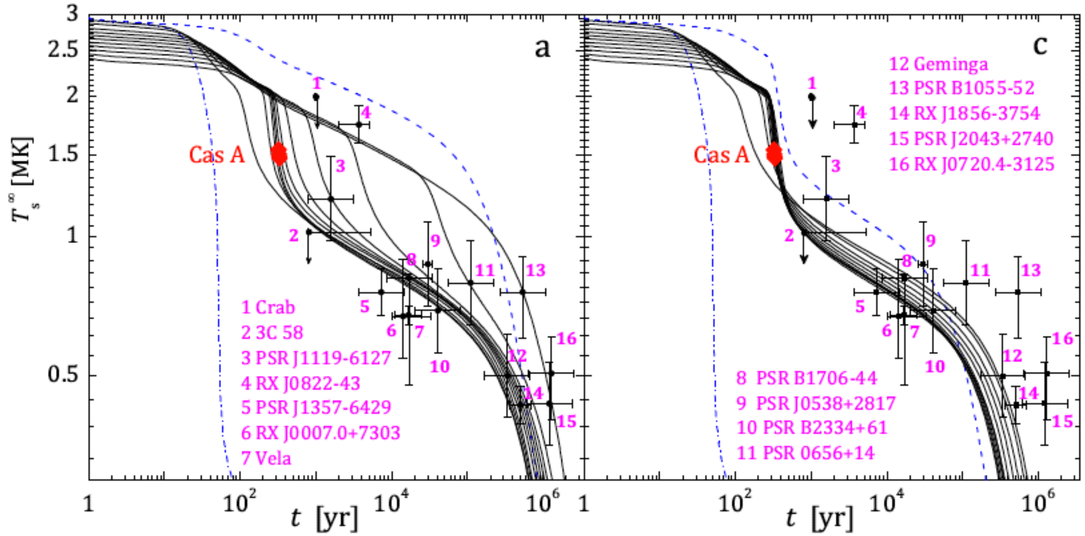


Cooling of Cas A NS: Evidence for an astrophysical superfluid transition?

Page et al 2011

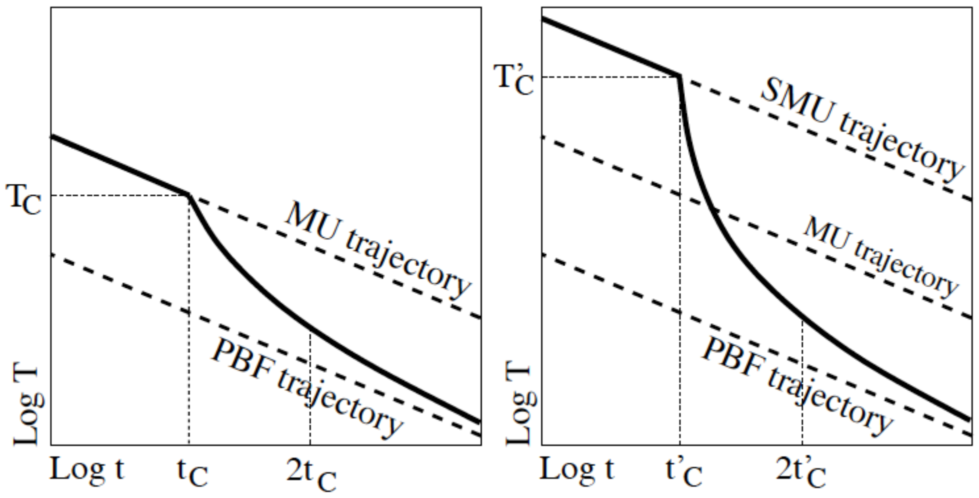


Shternin et a 2011



- Minimal cooling paradigm (MCP) (Page et al 2004) (only nucleonic components; fast ν-emission processes (dUrca) excluded):
- Rapid cooling of the Cas A NS (CANS) from enhanced neutrino emission from neutron $^3P_2$ Cooper pair breaking and formation (PBF) in the core (superfluid phase transition)
- Alternatives: medium modifications to standard ν-emission processes, quark phases… (Blaschke et al. 2012; Sedrakian 2013)

Cooling of Cas A NS: Evidence for an astrophysical superfluid transition?



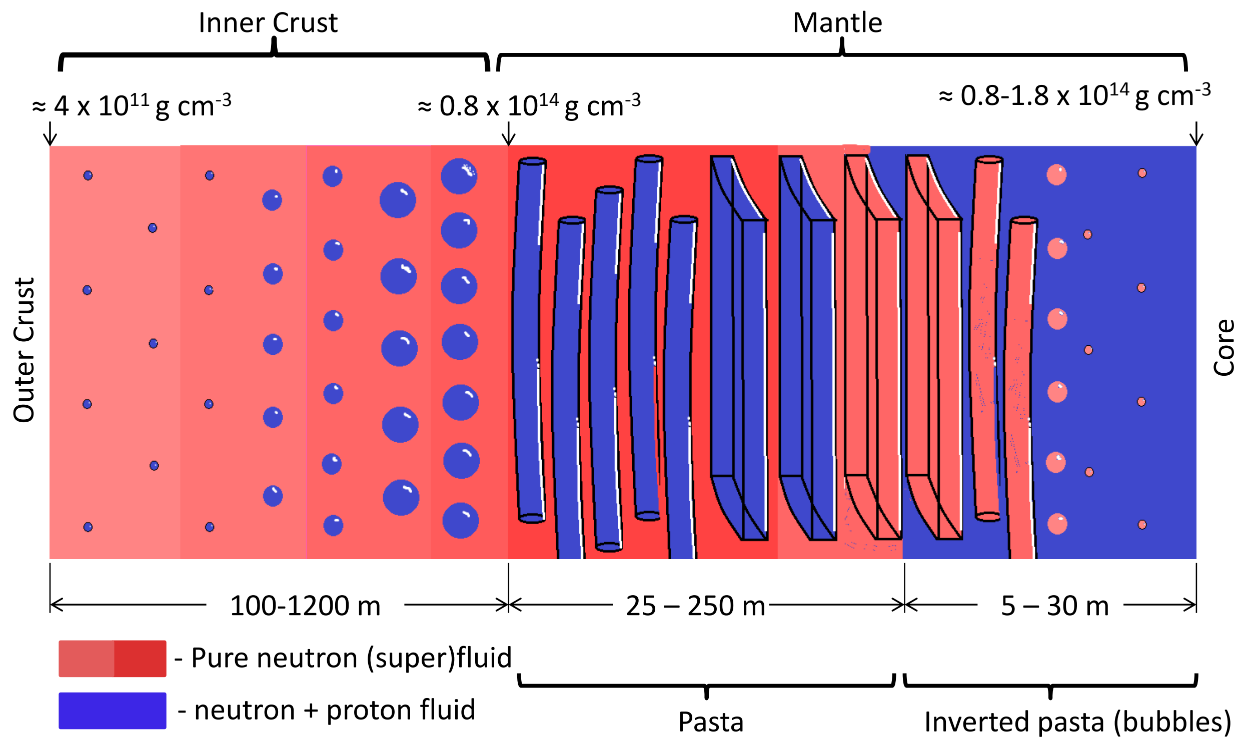
- Max. of critical temperature T_c^{max} controls age at which star enters PBF cooling phase
- Core temperature at onset of PBF cooling phase, T_{PBF}, controls subsequent cooling *rate* > make steeper by suppressing mUrca process with proton superconductivity throughout core.

Cooling of Cas A NS: Parameter Space in Minimal Cooling Scenario

In the Minimal Cooling Paradigm, three additional parameters affect the cooling trajectories of the NSs (Page et al.2004):

- The equation of state (EOS) of nuclear matter (NM).
- The mass of light elements in the atmosphere ΔM_{light} parameterized as η= log (ΔM_{light}) (best fit $-13 < \eta < -8$ (Yakovlev et al. 2011))
  - More light elements means higher thermal conductivity and lower core temperature for a given $T_{\rm eff}$.
- The mass of Cas ANS ≈ 1.25 – $2M_{SUN}$ with a most likely value of $1.65M_{SUN}$ Yakovlev et al. 2011).

ν-emission in Nuclear pasta: Bubble cooling processes

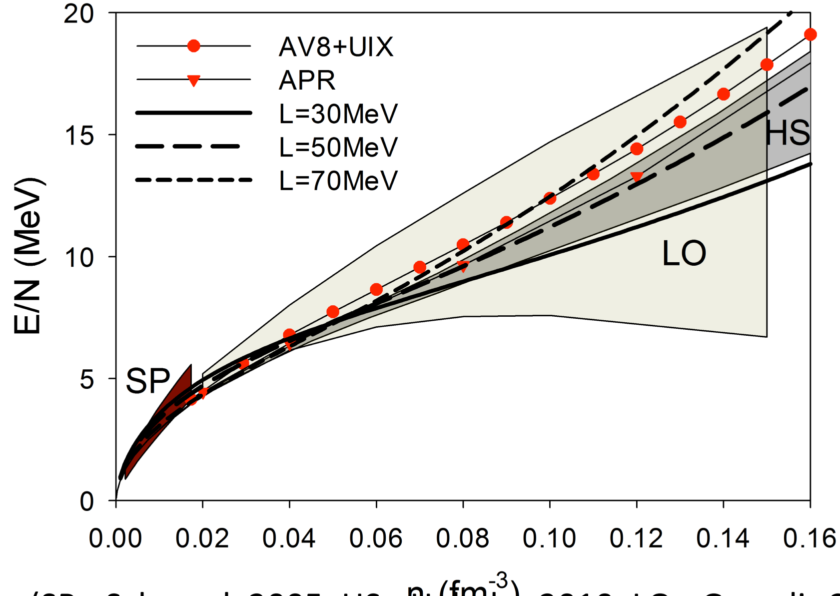


- Neutron scattering off of bubble phases of pasta can lead to:
  dUrca (Gusakov et al. 2004)
  neutrino and anti-neutrino pair emission (Leinson 1993)
- Luminosity comparable with Modified Urca at core temperatures around onset of PBF cooling phase

$$L_\nu^{BCP} \sim 10^{40} T_9^6 \qquad L_\nu^{MU} \sim 10^{40} T_9^8$$

$$T_9 = T_{\rm core}/10^9 {\rm K}$$

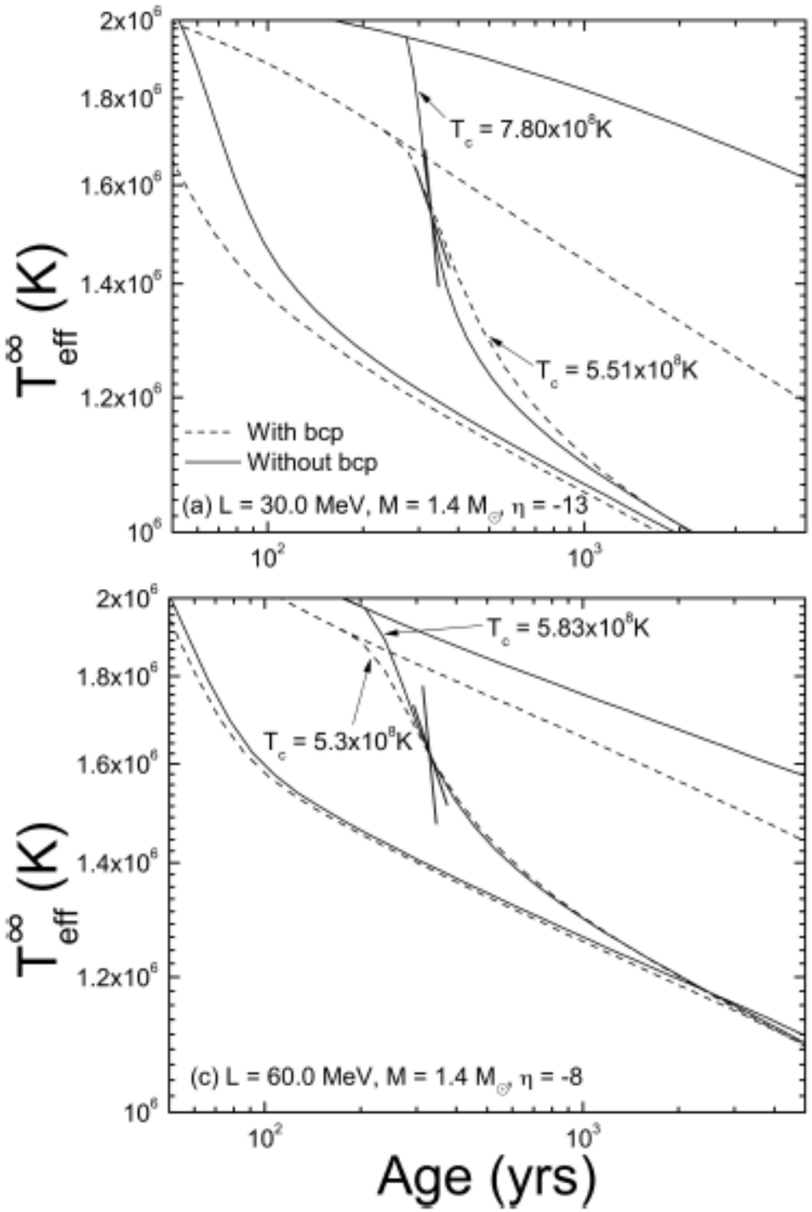
Model



(SP - Schwenk 2005, HS - Hebeler 2010, LO - Gezerlis 2013, AV8+UIX - Gandolfi 2010, APR - Akmal 1998)

- NS Crust and core EOSs and compositions calculated consistently using SkIUFSU Skyrme model (Fattoyev et al. 2012) which is fit to nuclear properties and ab-initio pure neutron matter calculations.
- Two Skyrme parameters are adjusted to vary the symmetry energy J and its density slope L at n_0. EOSs were created with L between 30MeV and 80MeV.
- With a fixed stellar mass, as L increases, the stellar radius and crust thickness increases and the fraction of the crust by mass composed of the bubble phases decreases (Newton et al. 2013).
- Cooling trajectories calculated using Dany Page's public code NSCool

Results



Even the lowest cooling rate (2%) inferred by Elshamouty et al is relatively rapid, favoring a relatively high core temperature and:

- Smaller value of L (smaller radii)
- Smaller stellar masses M
- Smaller η
- Less cooling from BCPs.

Results

$M(M_\odot)$	η=-8; BCP	η=-13; BCP	η=-8; no BCP	η=-13; no BCP
1.25	$\lesssim 45$	-	$\lesssim 70$	$\lesssim 55$
1.40	-	$\lesssim 35$	$\lesssim 55$	$\lesssim 55$
1.60	-	$\approx$ 35-45	-	$\approx$ 35-55
1.80	-	-	-	-

Ranges of L for which model cooling trajectories fall within the inferred rate from Elshamouty et al 2013

With ν-emission processes from bubble phases of pasta, only a soft symmetry energy L < 45 MeV matches the inferred cooling rate.

Conclusions

- Within minimal cooling paradigm, and using the inferred Cas A NS cooling rate from Elshamouty et al (2013), L < 70 MeV
- *With the addition of enhanced cooling from ν-emission processes in pasta phases* L < 45 MeV – i.e. cooling from the pasta phases can have an observable effect

CAVEATS

- Carbon atmosphere model preferred largely because it results in emitting area of order neutron star size.
- Enhanced superfluidity in crust would suppress ν-emission processes in pasta phases (gap parameter space not explored here).
- Posselt et al; arxiv:1311.0888 – Chandra Cas A data consistent with *no cooling* in past decade!