X-ray Observations of CCOs

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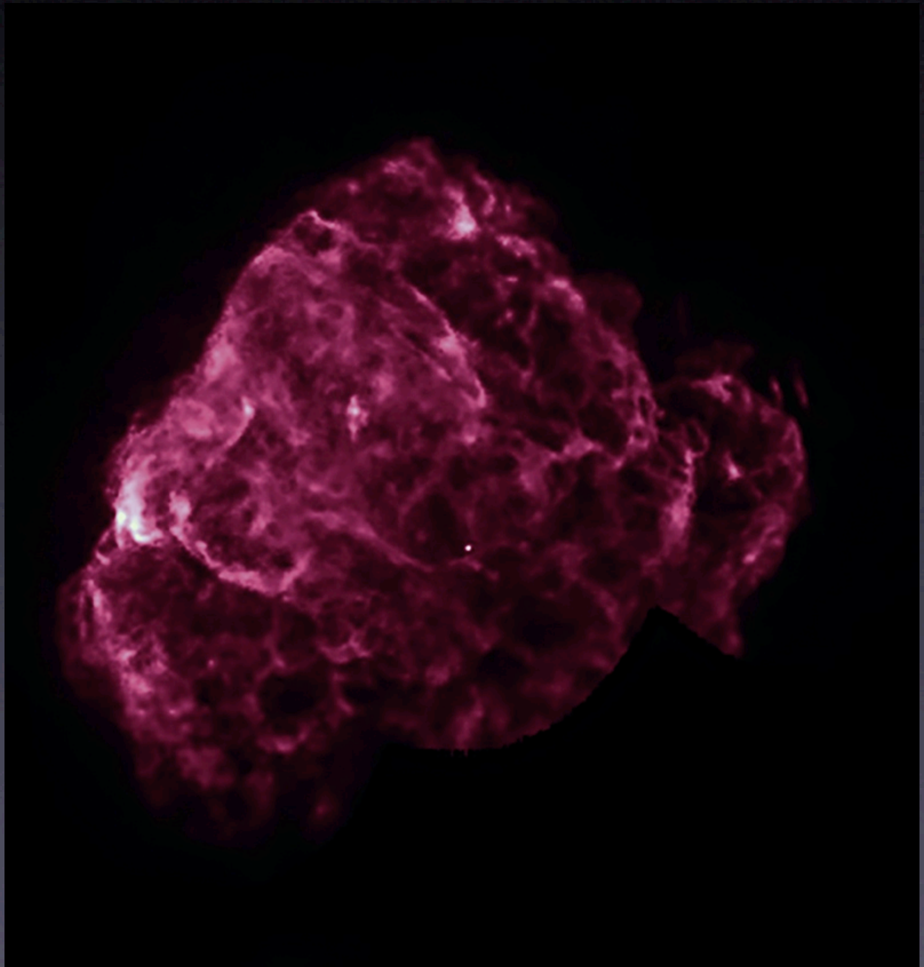
Central Compact Objects (CCOs)

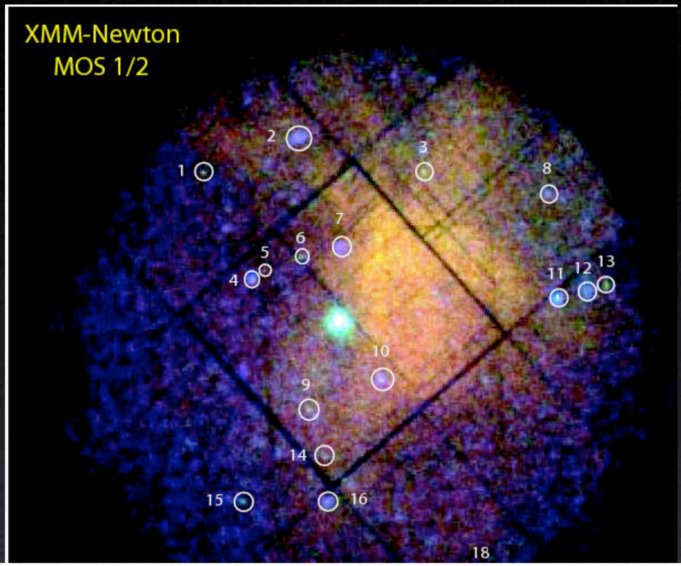
- 10 CCOs: X-ray point sources inside supernova remnants (omit RCW 103)
- Thermal BB-like spectra, long-term variability <5% (Pavlov+03)
- Young NSs, not radio pulsars

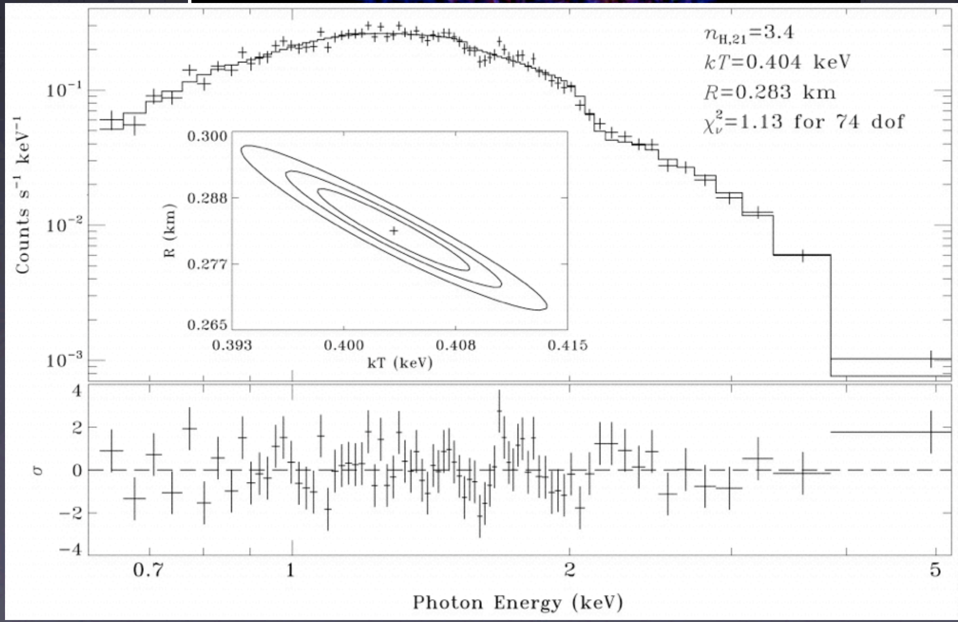


Puppis A, ROSAT

Thermal X-ray Emission

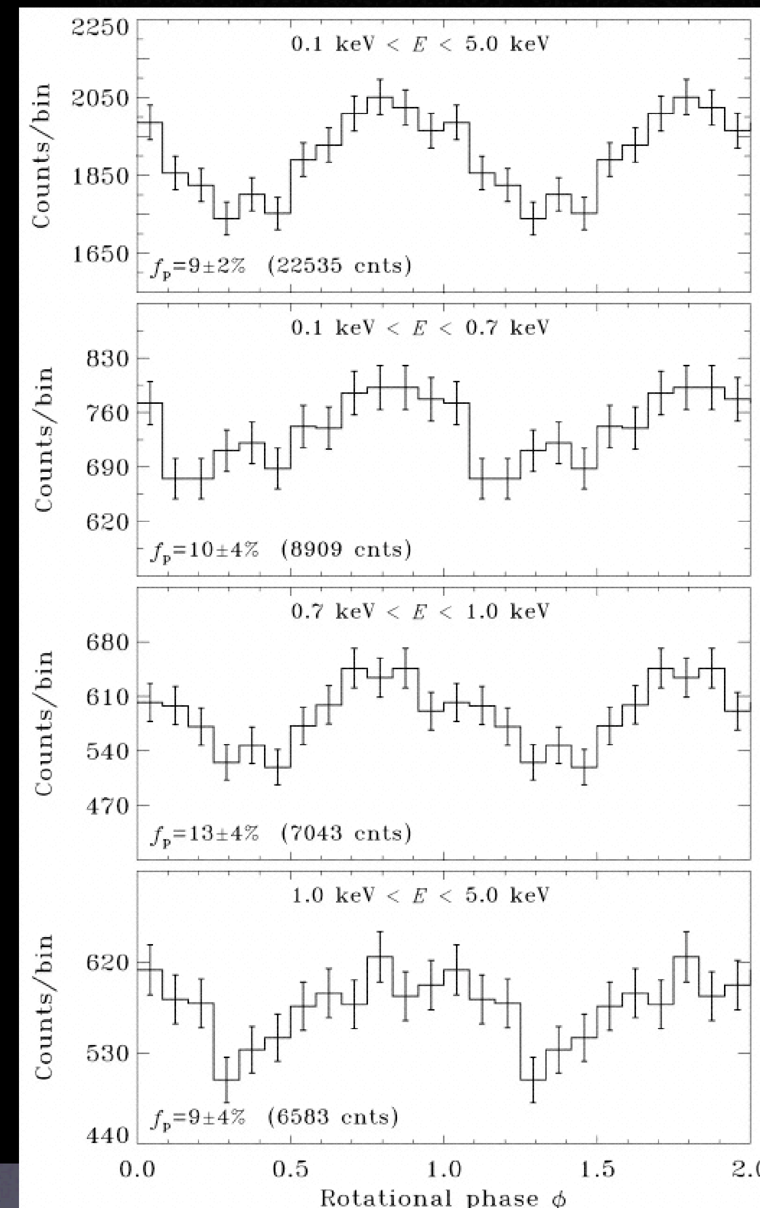
- CCOs show thermal, BB-like X-ray emission, kT~0.1-0.4 keV, L_X~10^{33}-10^{34} ergs/s
- No optical, radio, IR counterparts
- Seem to be quiet NSs





Vela Jr. CCO spectrum, Kargaltsev+02

1E1207.4-5209

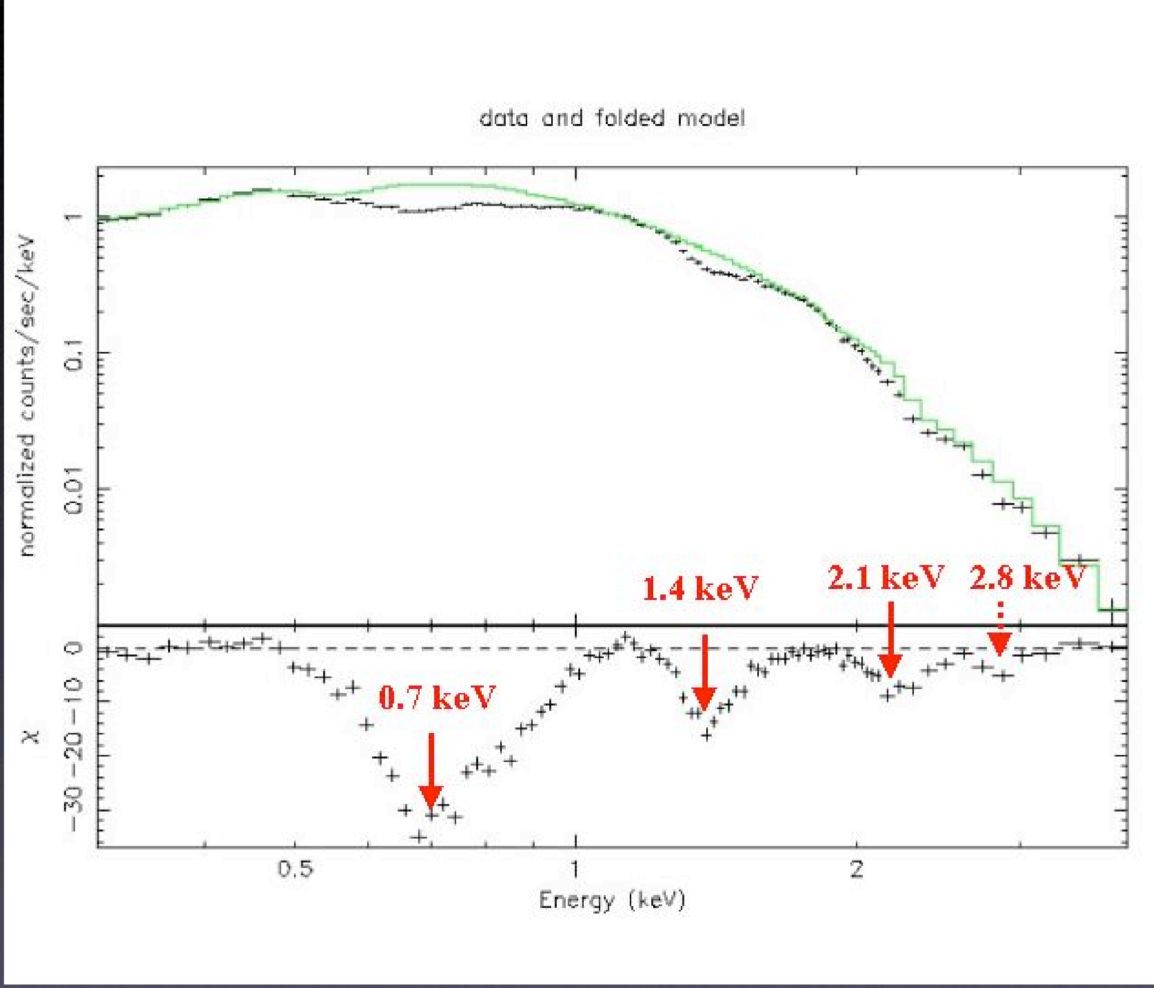


0.424 s X-ray pulsations,
7% pulsed fraction

Zavlin+00

1E1207 spectrum

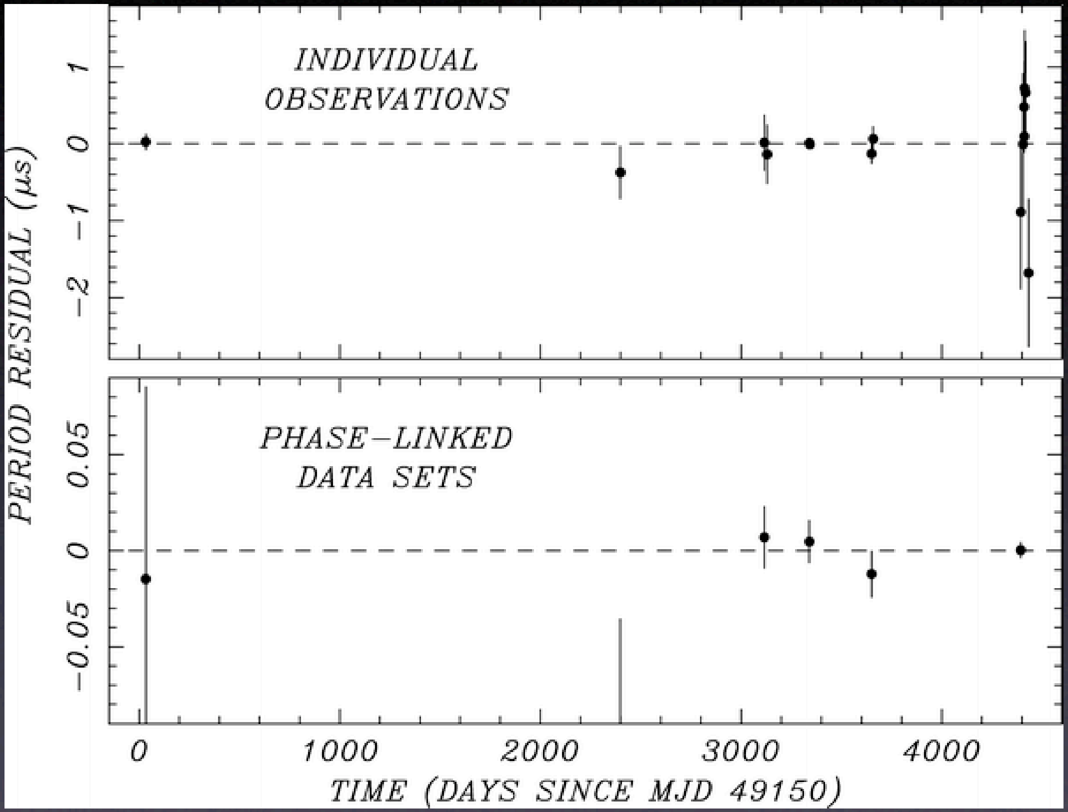
- 2-4 absorption lines (Zavlin+01, Bignami+03)
- Pulsations principally affect lines
- Cyclotron lines?
  Electron: B=8e10 G
  Proton: B=6e14 G
- Harmonics resonances in magnetic free-free opacity (Suleimanov+10)



Bignami+03

P change in 1E1207

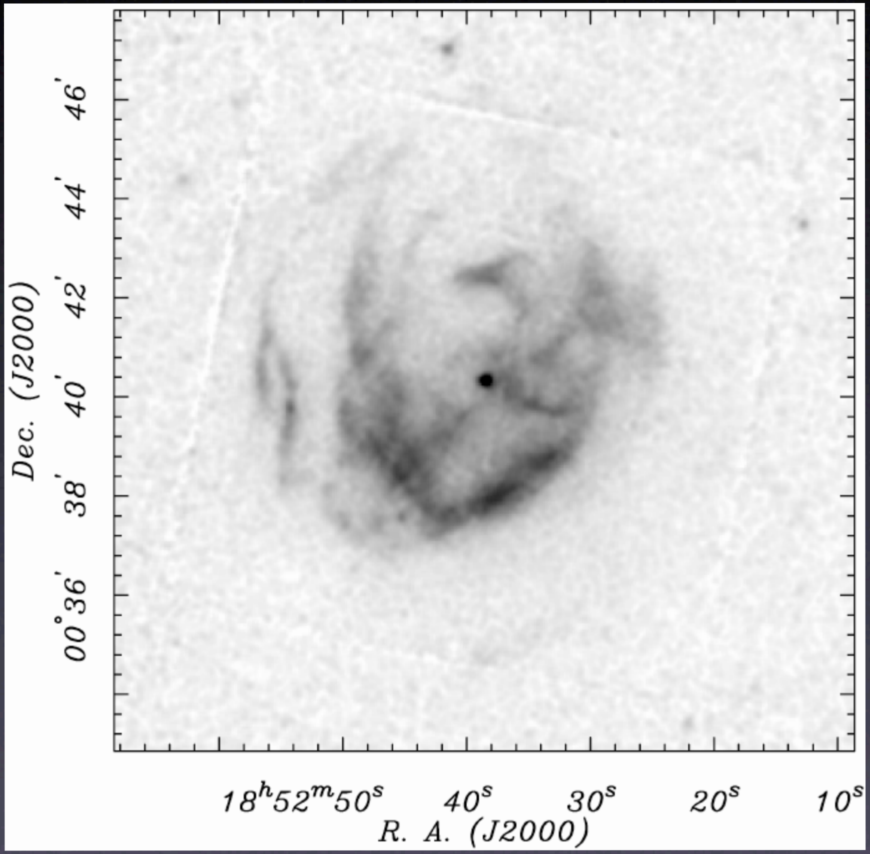
Gotthelf & Halpern 07:
No P changes (1993-2005),
$dP/dt < 10^{-16}$

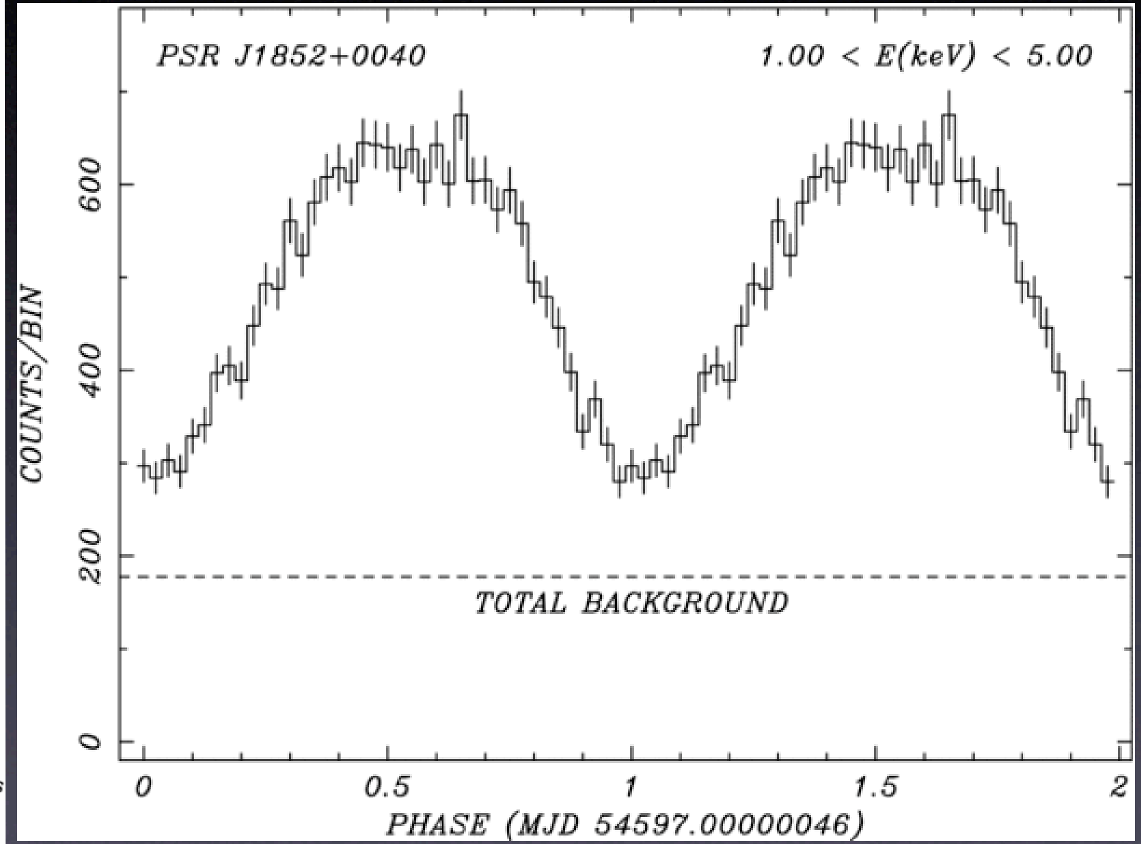


Halpern+11: Timing data give B=9.9e10 G or 2.4e11 G.
Lower similar to e^- cyclotron line inference (8e10 G)

Kes 79: 64% Pulsed Fraction

Only CCO with >12% pulsed fraction

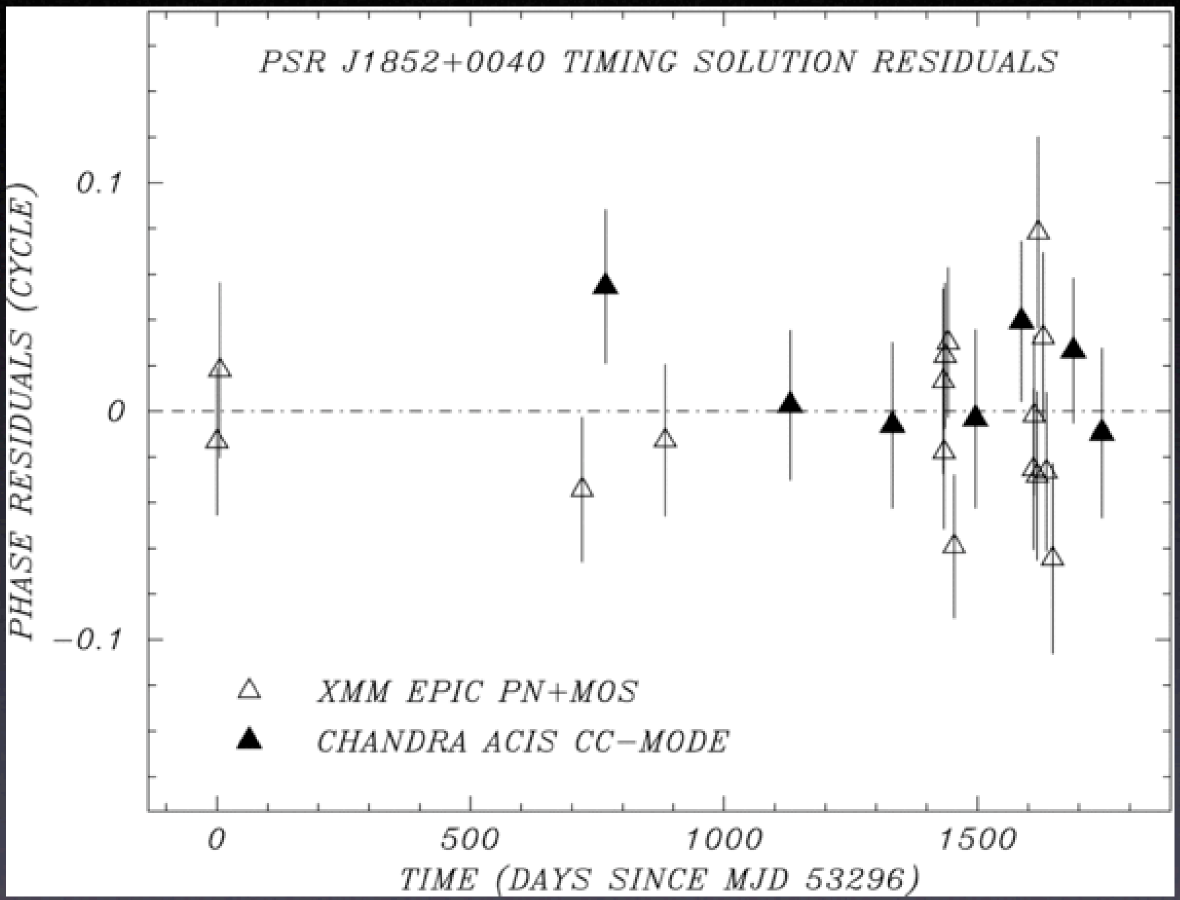




Kes 79, Gotthelf+05

Pulse profile, Halpern+10
0.105s

Kes 79: First Pdot



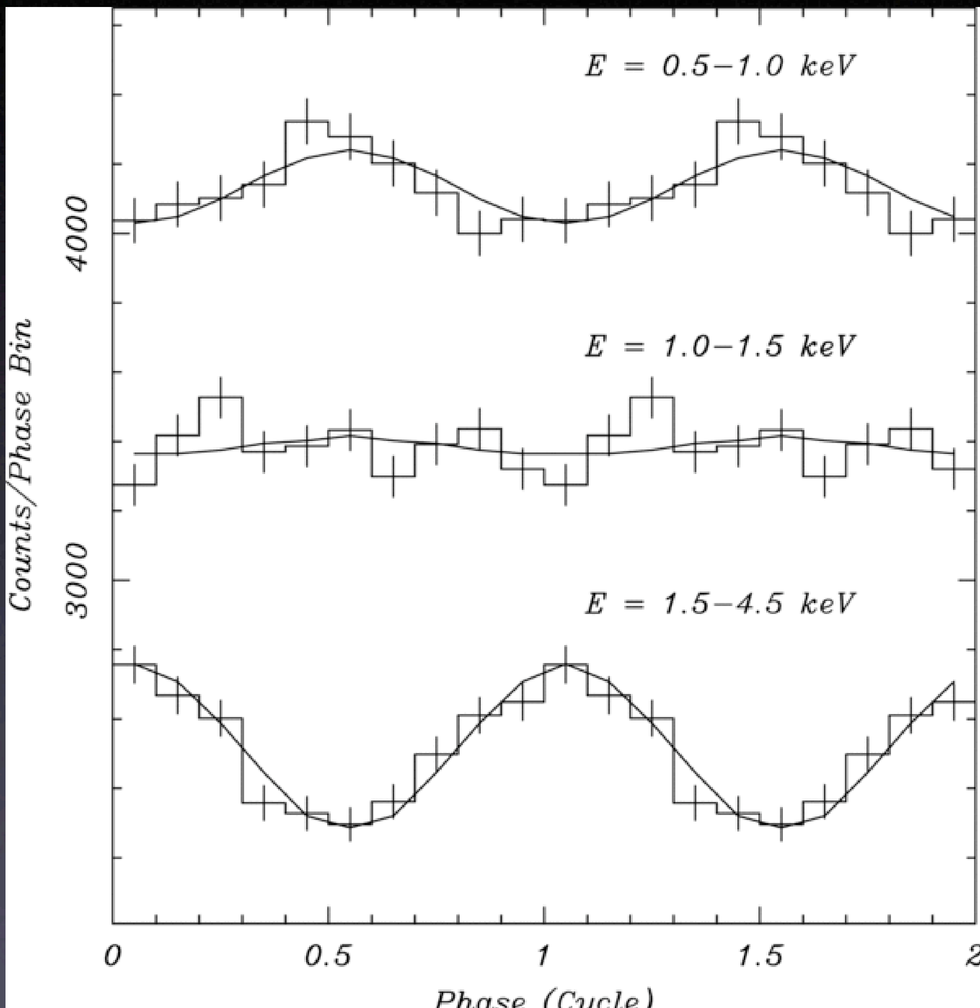
Kes 79 ephemeris, Halpern+10

Halpern+10 phase-connected epochs to get Pdot=8.7e-18, B=3.1e10 G

Difficult problem: highly pulsed emission & low B field???

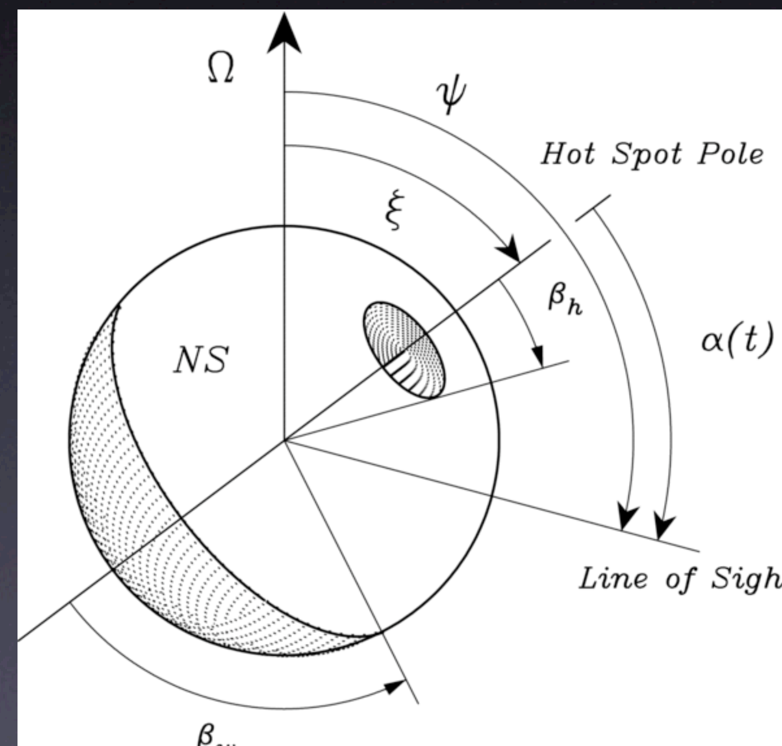
Spots where buried toroidal B field emerging? (Lai's talk)

Puppis A: Two spots



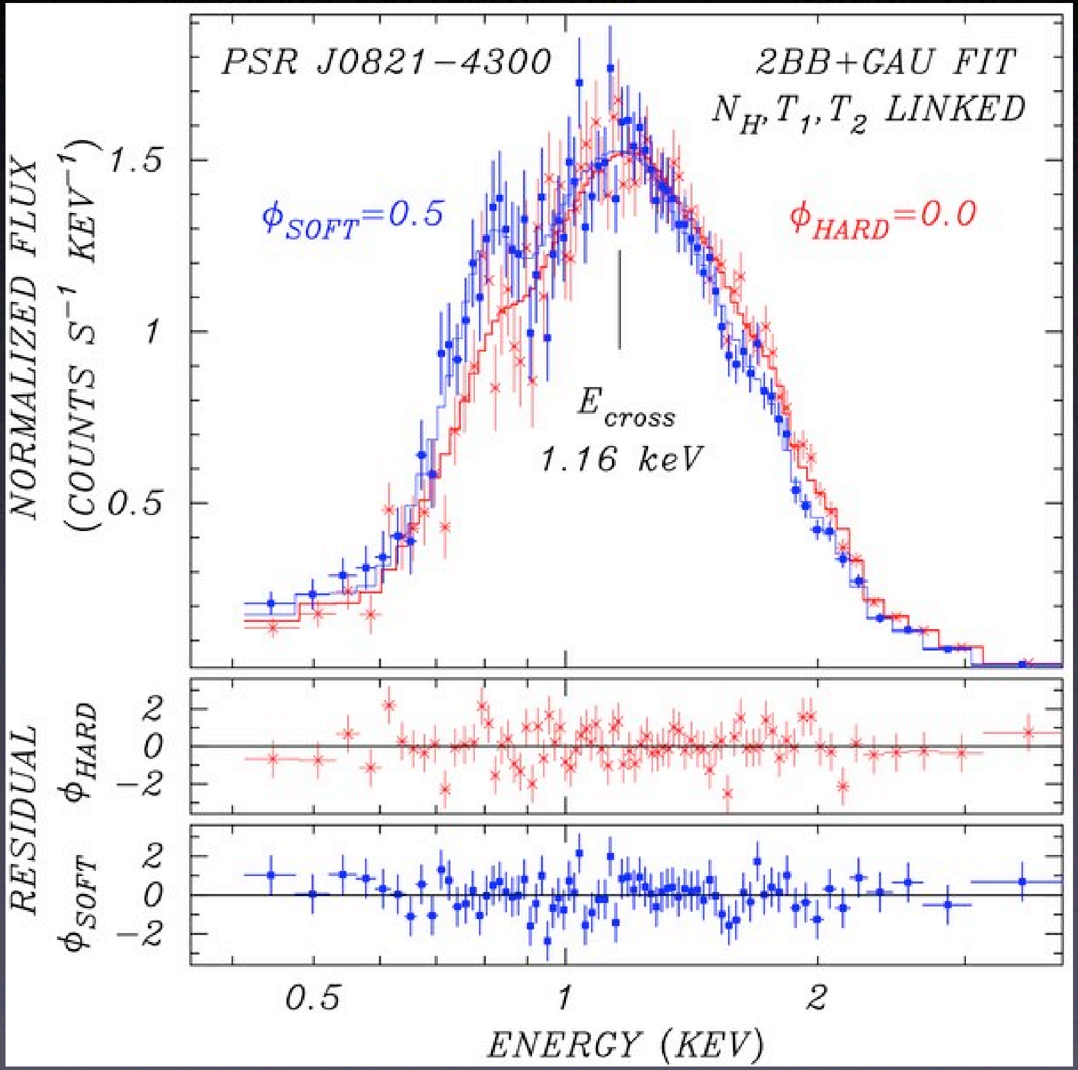
Lightcurves, Gotthelf+10

No overall modulation; pulsations at low, high energies; two spots?



Spot model, Gotthelf+10

Puppis A spectrum



Spectrum, Gotthelf+09

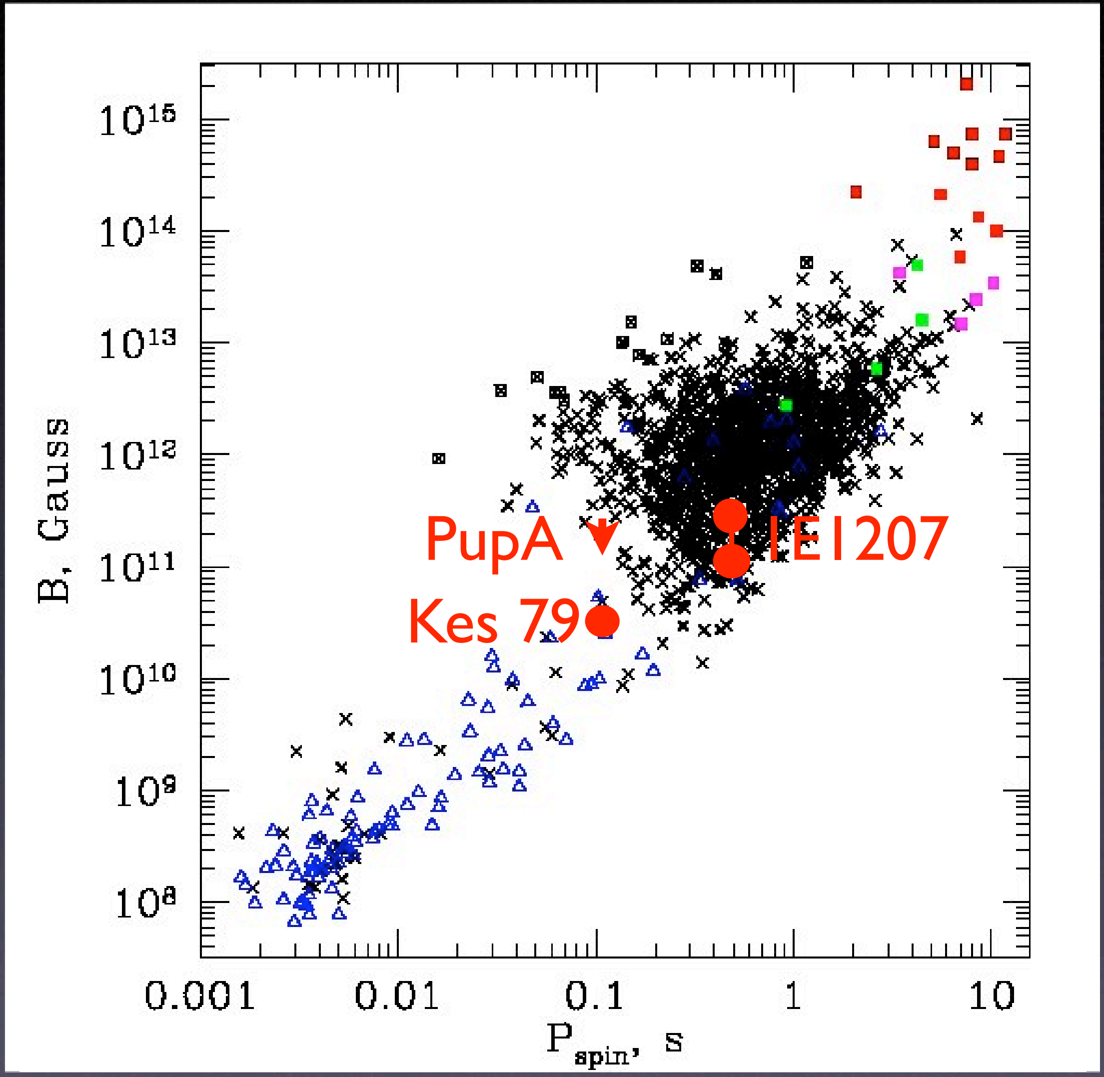
X-ray spectrum thermal, with feature near 1 keV

Gotthelf+09 fit by two blackbodies, & gaussian line 0.8 keV

(Could be absorption line, ~0.9 keV, as in 1E1207)

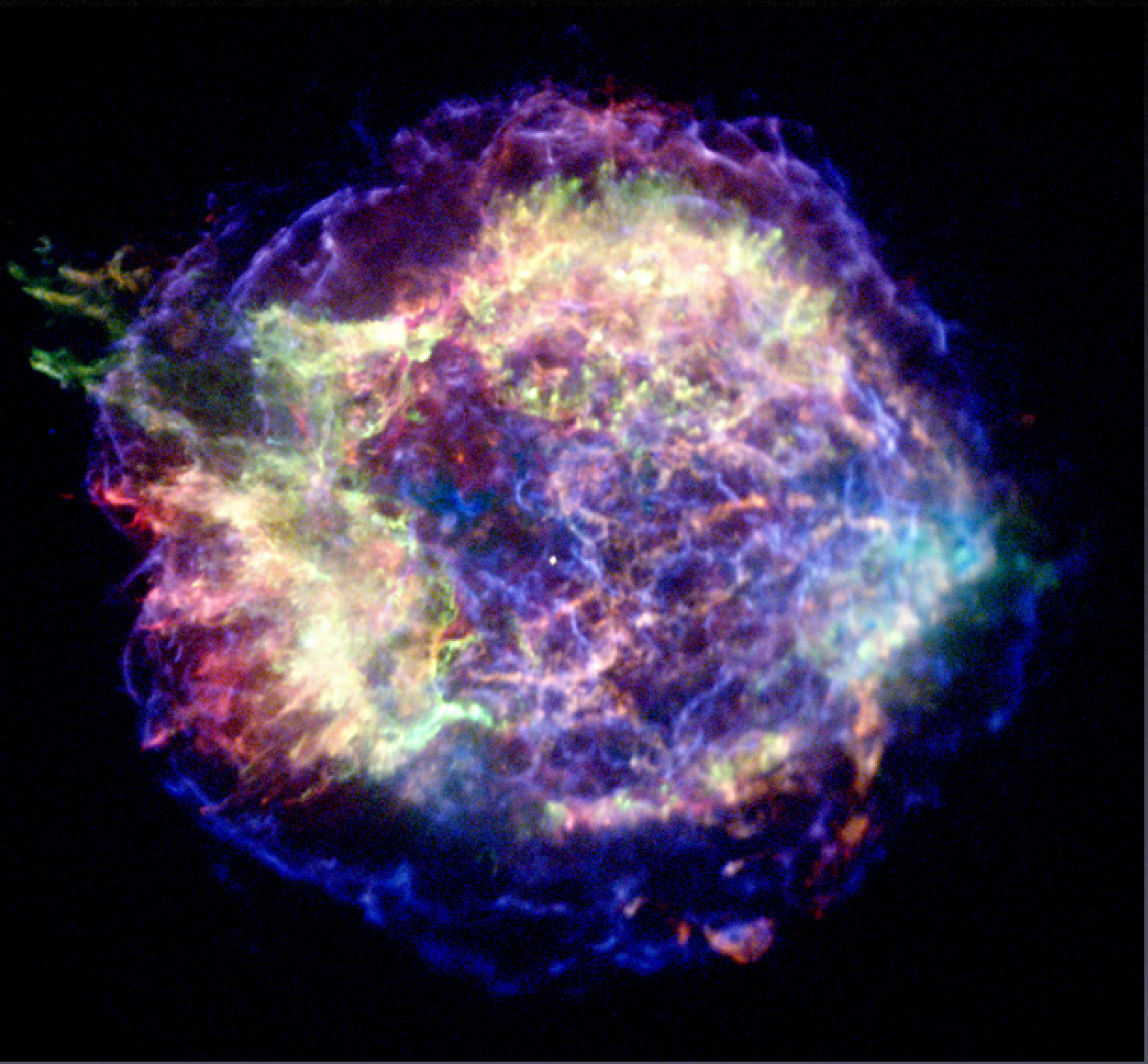
Low-B neutron stars

- 3 CCOs with P, dP/dt, thus B constraints
- Born with lower B fields, ~longer P than normal pulsars
- Large fraction of NS in young SNRs
- Do CCO B fields emerge, turn on as pulsars? (Ho 2011)



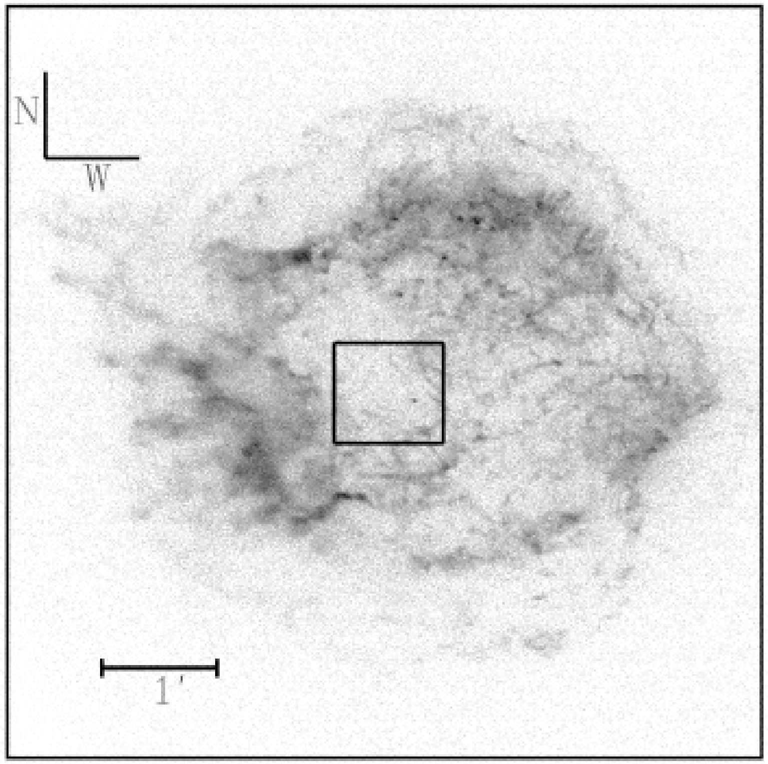
Pulsars, ATNF; blue Δ, binary; squares, other; red CCOs marked

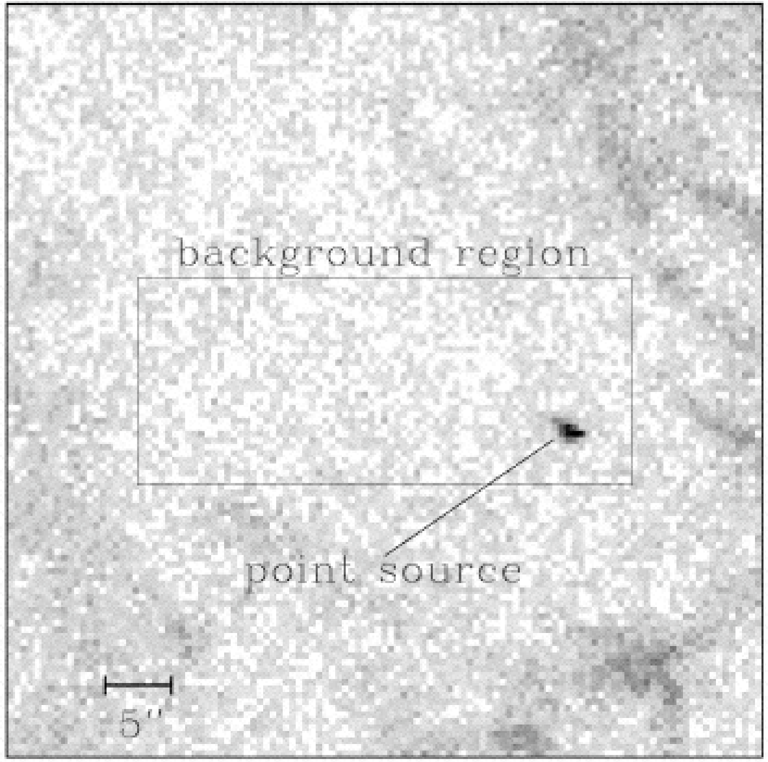
Cassiopeia A CCO



Chandra discovery 1999

Youngest known supernova remnant with central NS

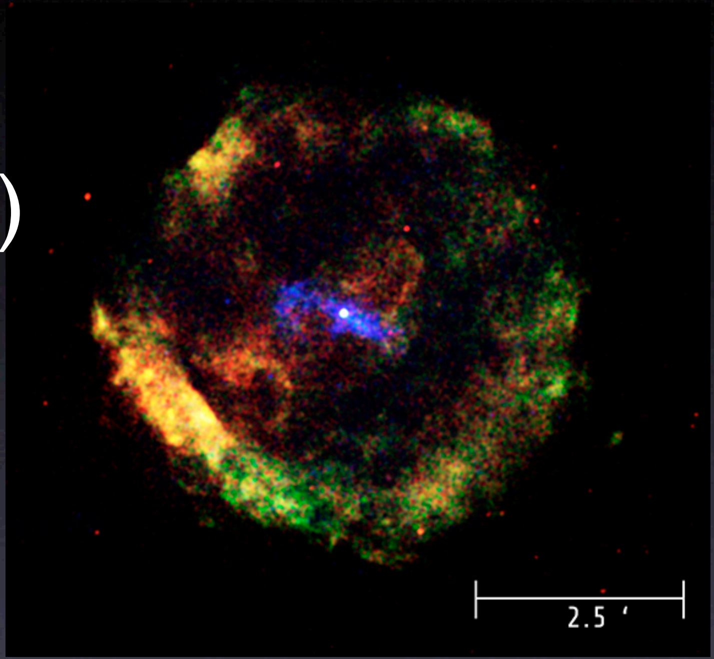




Is Cas A a Pulsar?

L: Cas A
(Chakrabarty+01)

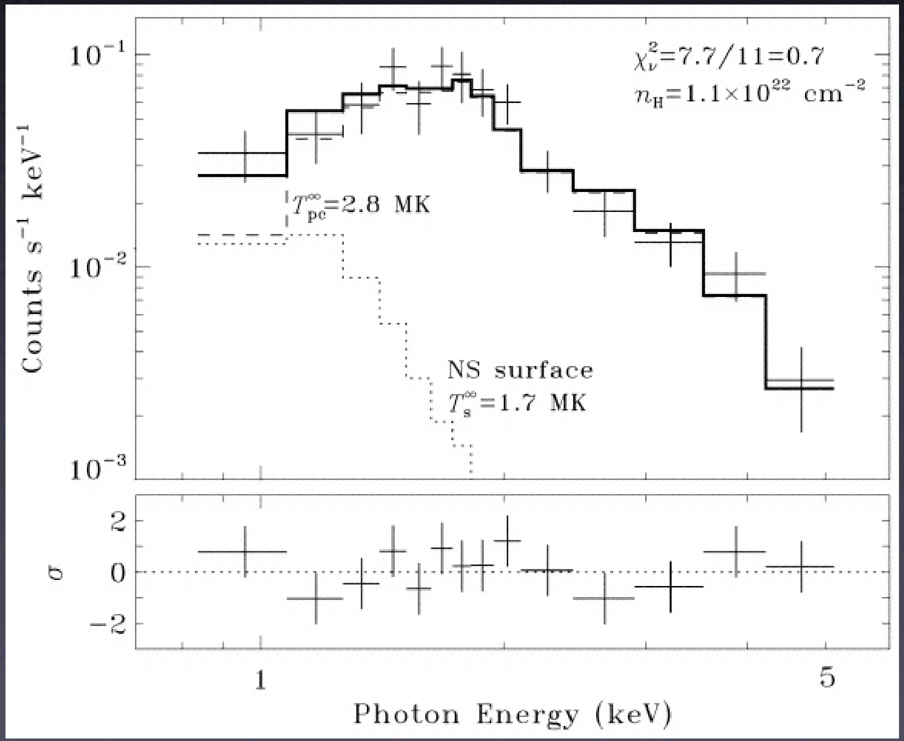
R: G11.2-0.3,
M. Roberts

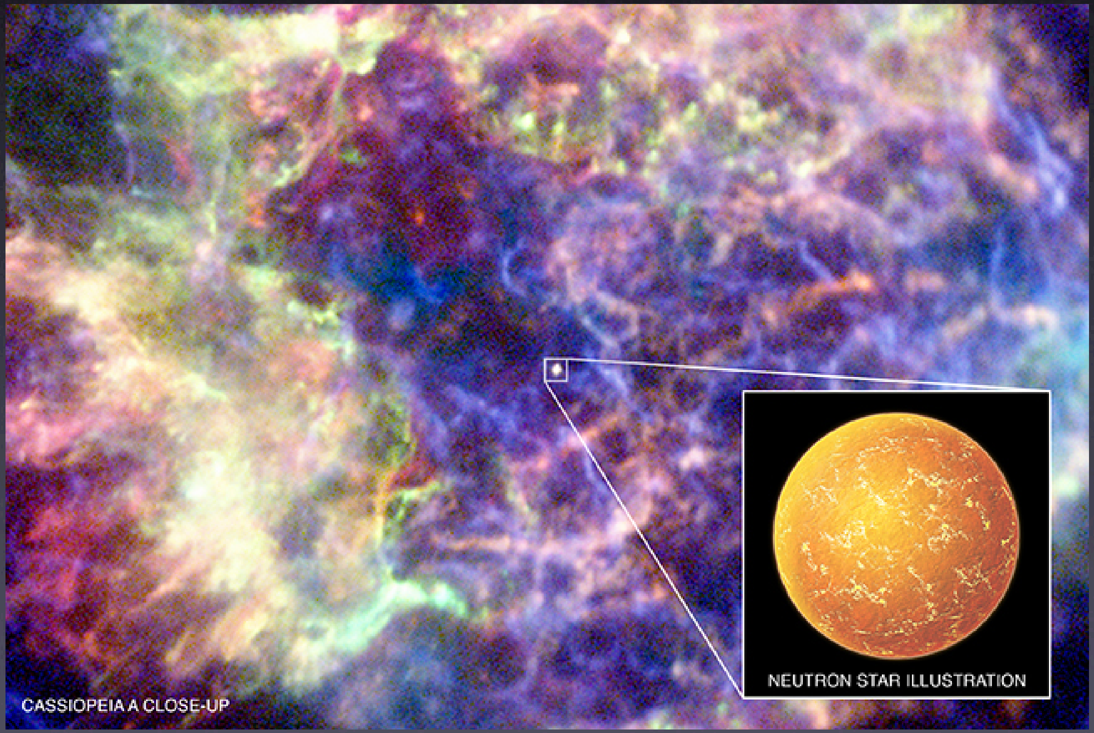


- No extended X-ray emission (Chakrabarty+01,Pavlov+09)
- No radio pulsations

Spectrum of Cas A CCO

- Consistent with blackbody
- Inferred radius ~0.3 km

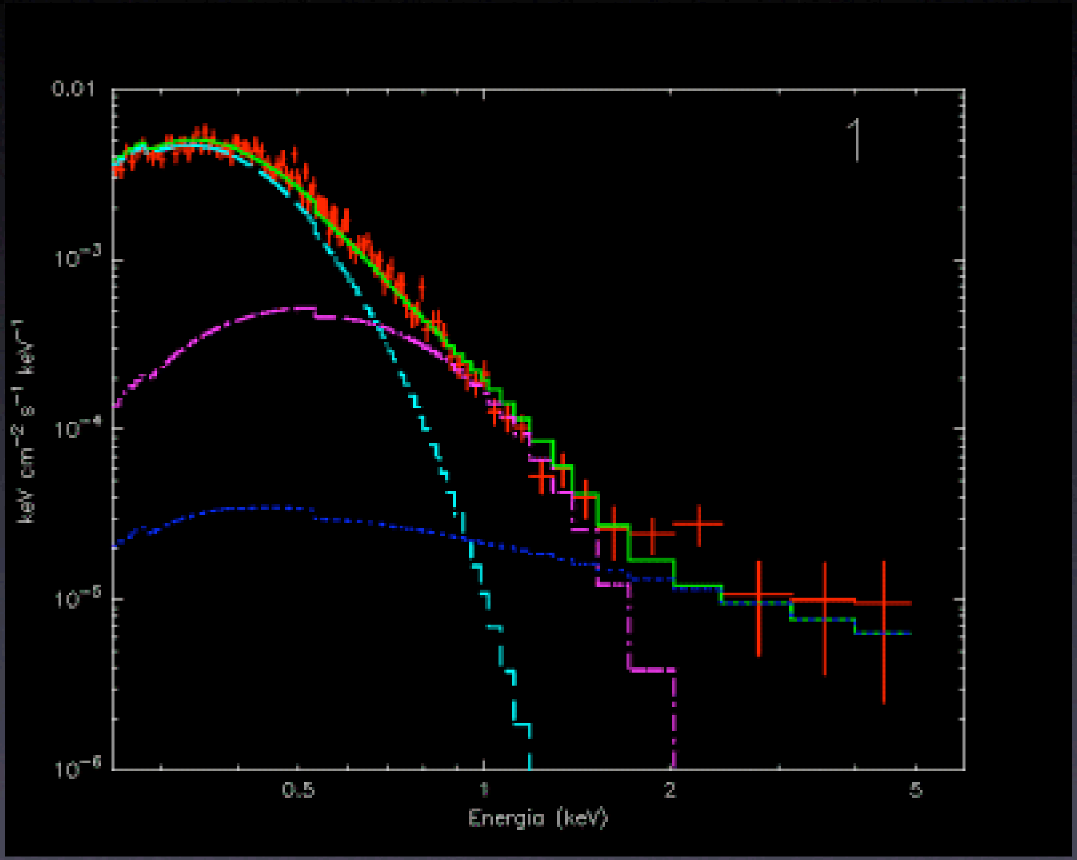




Pavlov+00

Pulsations

- Active radio pulsars show hot spots at poles
- Hot spots should produce pulsations, unless special geometry

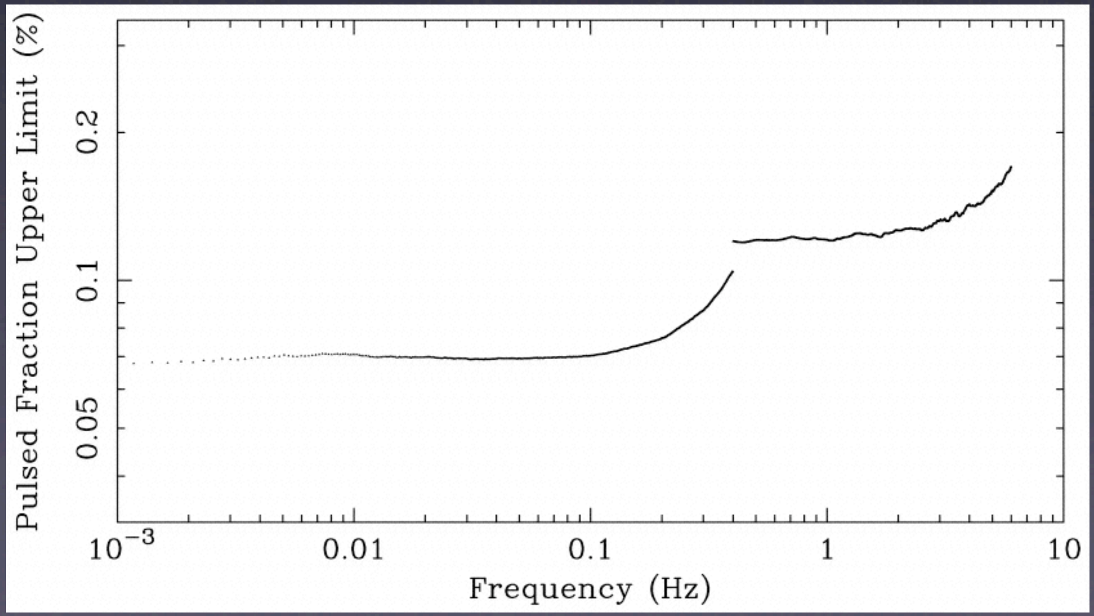


XMM phase-resolved spectra of PSR 1055-52

Timing Tests on Cas A

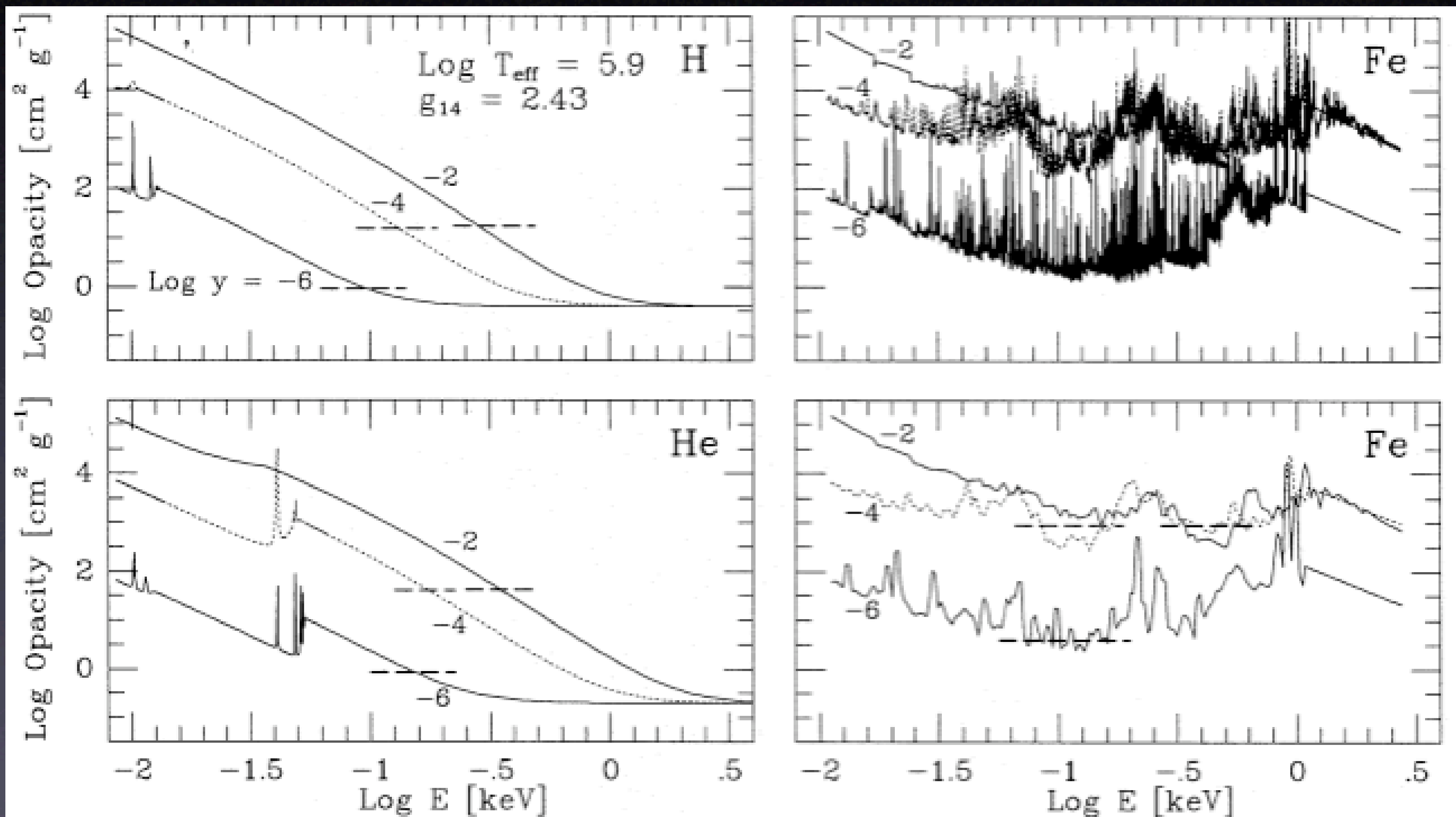
- Variability not seen 2000-2003 (Teter+04)
- No pulsations seen, pulsed fraction ~<12% (Mereghetti+02, Halpern+10)

XMM limits on pulsed fraction of Cas A CCO, Mereghetti+02



NS Atmospheric Opacities

Ionized H, He Opacity ~ ν^{-3}, free-free absorption

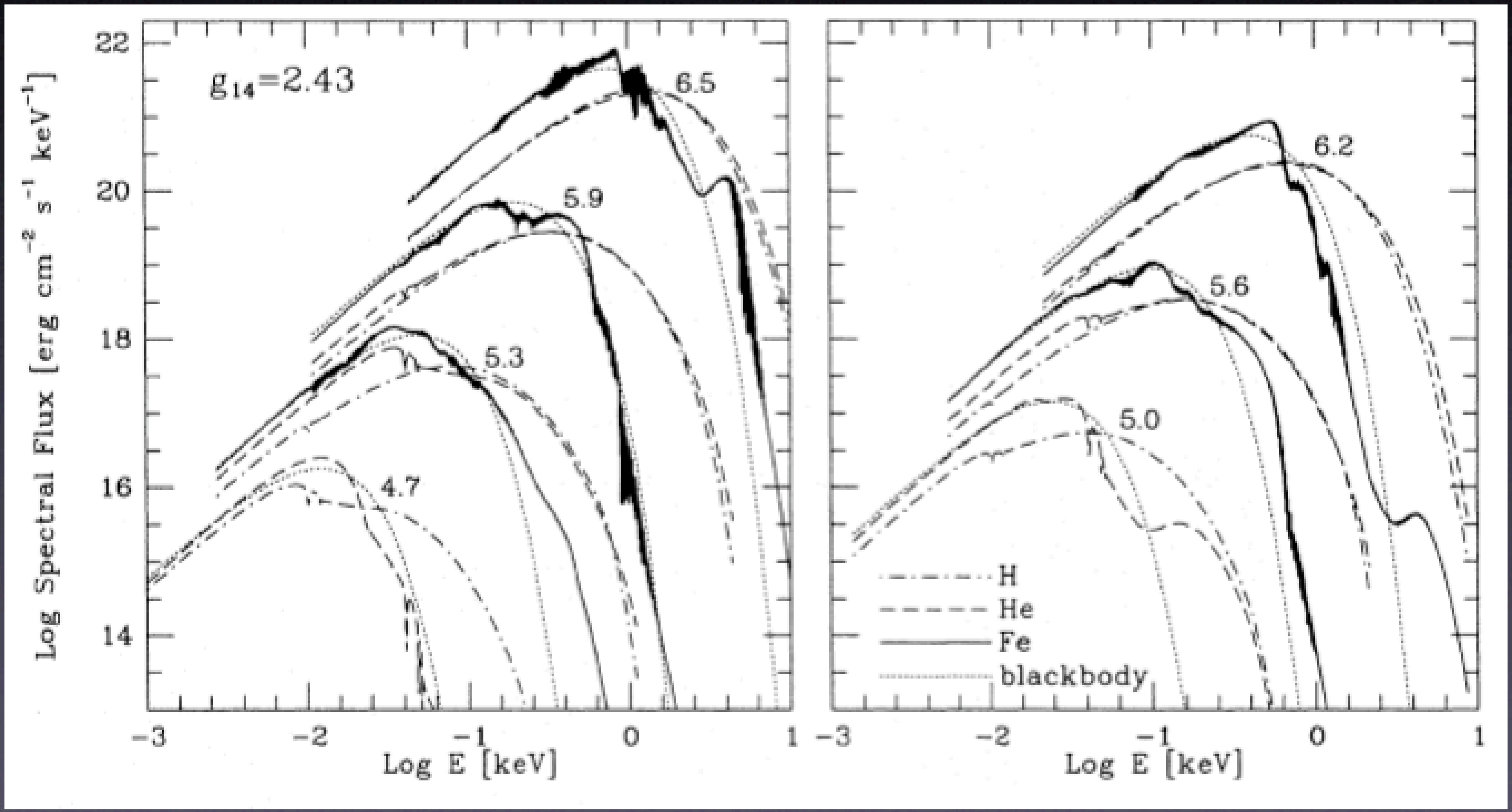


Magnetic fields important above B~10^{10} G

Zavlin+96

Low-B NS Atmospheres

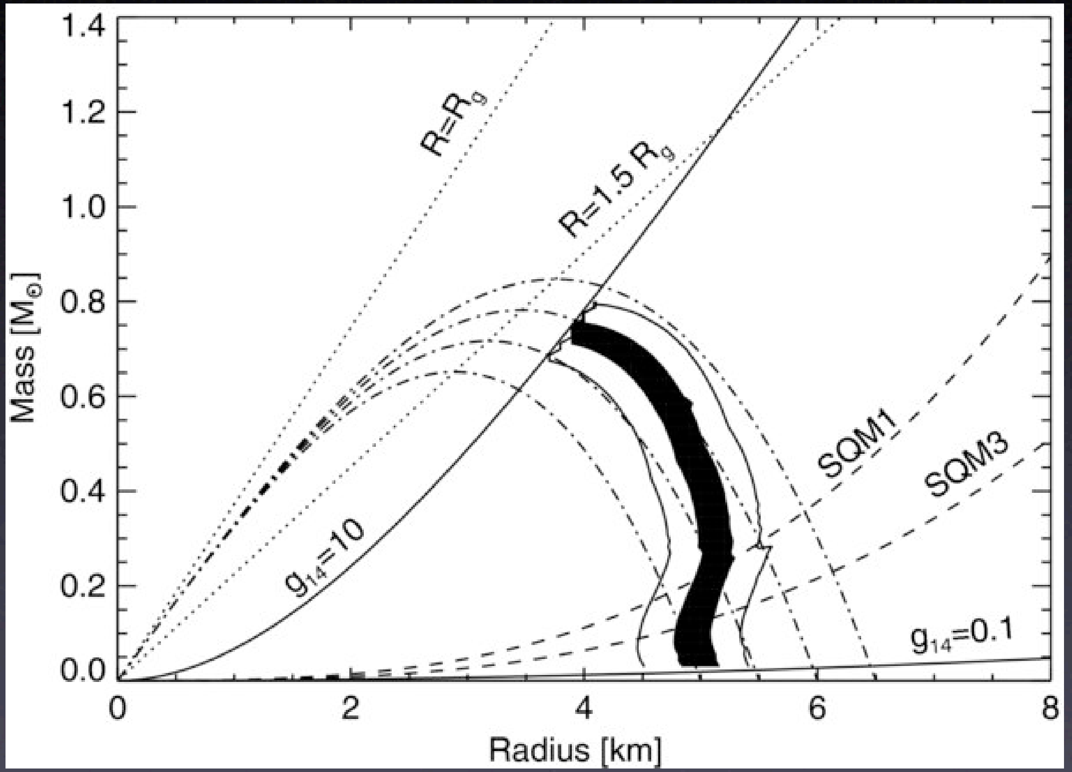
H, He shift flux to higher E vs. blackbodies
Infer larger radius for given spectrum



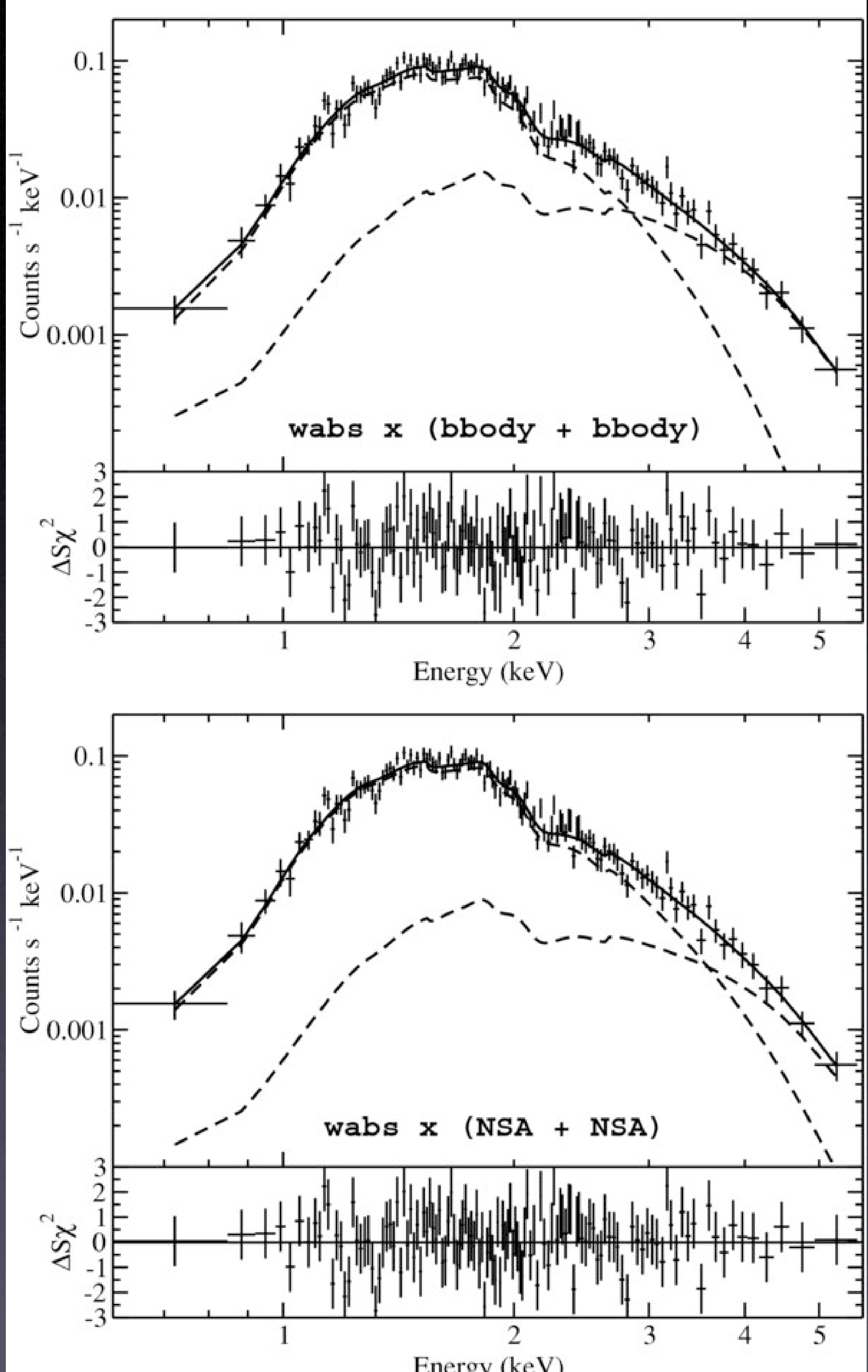
Zavlin+96

Low-B H for Cas A CCO?

- Low-B H atmosphere gives good fit to Cas A
- Inferred radius ~5 km, requires tiny quark stars



Constraints for H atmosphere, Pavlov+09



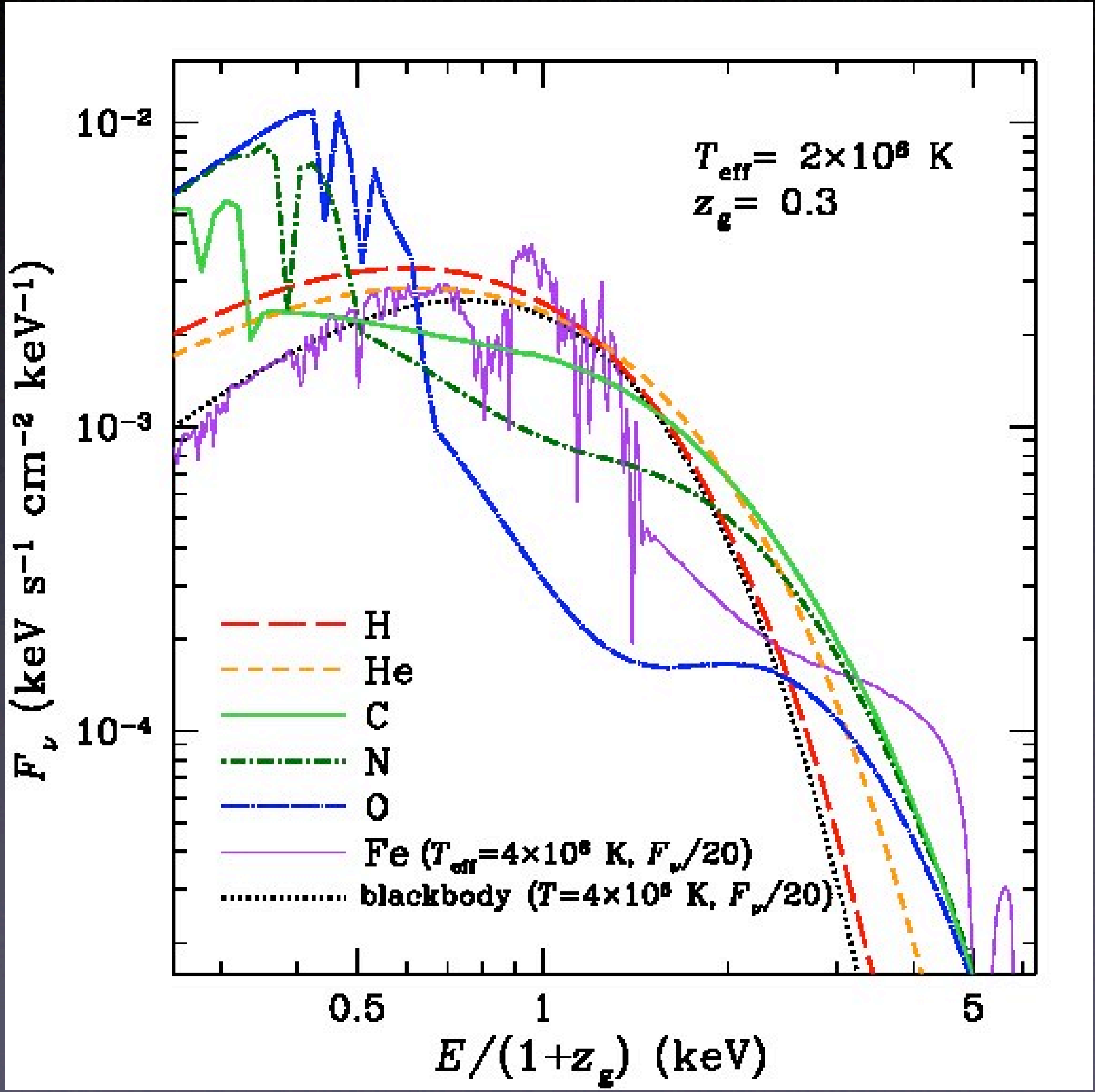
H hot spots?

- Two components (full surface + hot spot) explain spectra for R~12 km
- But should produce pulsations

Pavlov+09

Alternative atmospheres

- Variety of low-B NS atmospheres, using Opacity Project data
- N, O, Fe give features
- C harder than H, He

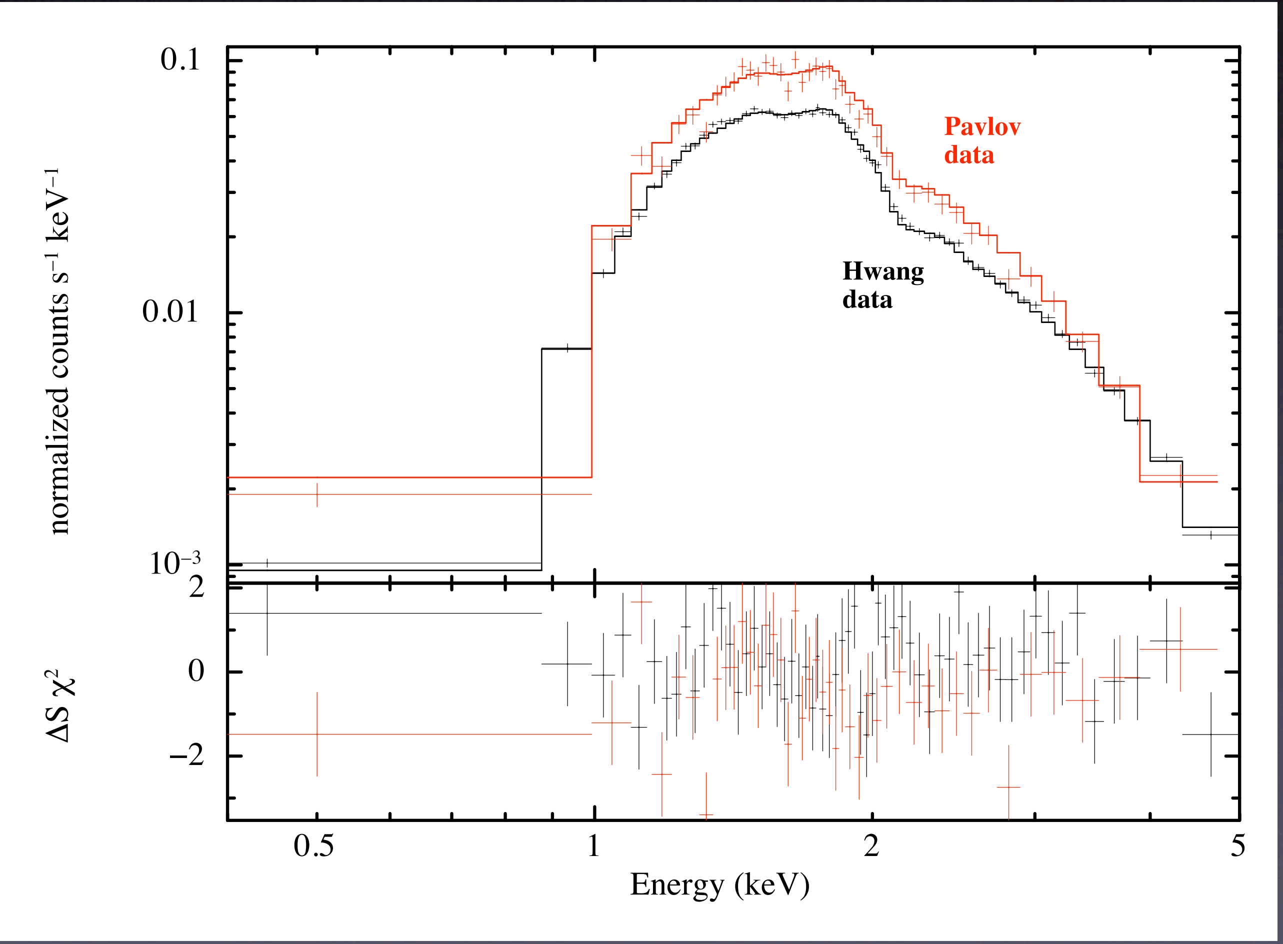


Ho & Heinke 09

Carbon Atmosphere

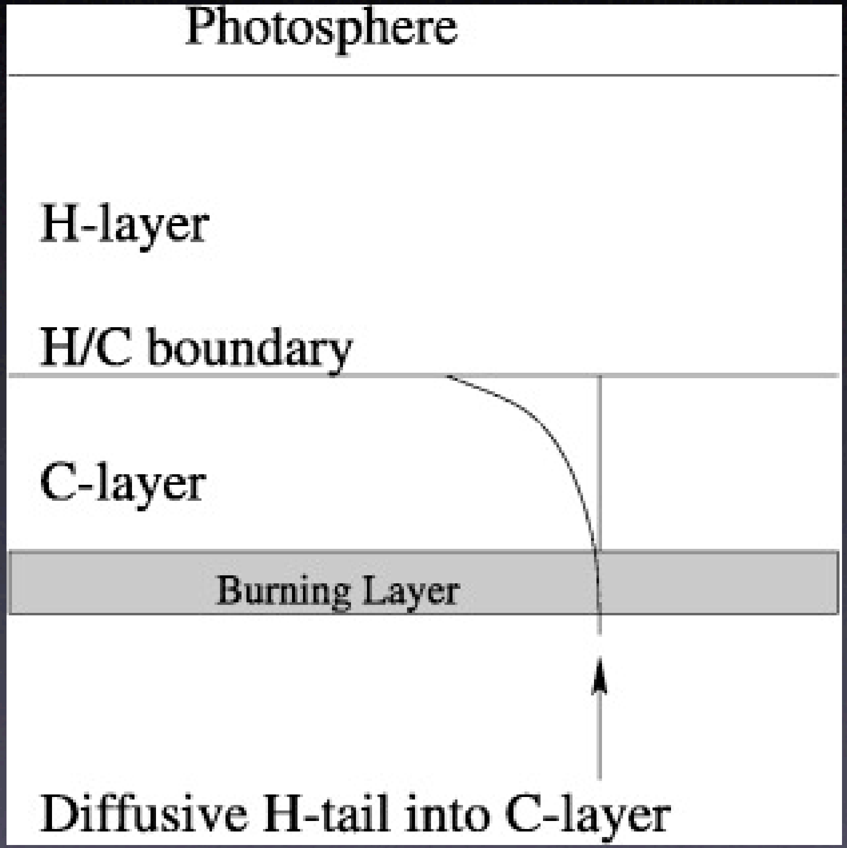
- Fit 1 Ms of Chandra data
- Only carbon atm. fit consistent with NS radius, ~10-12 km; also best fit

Ho & Heinke 09



Why a C atmosphere?

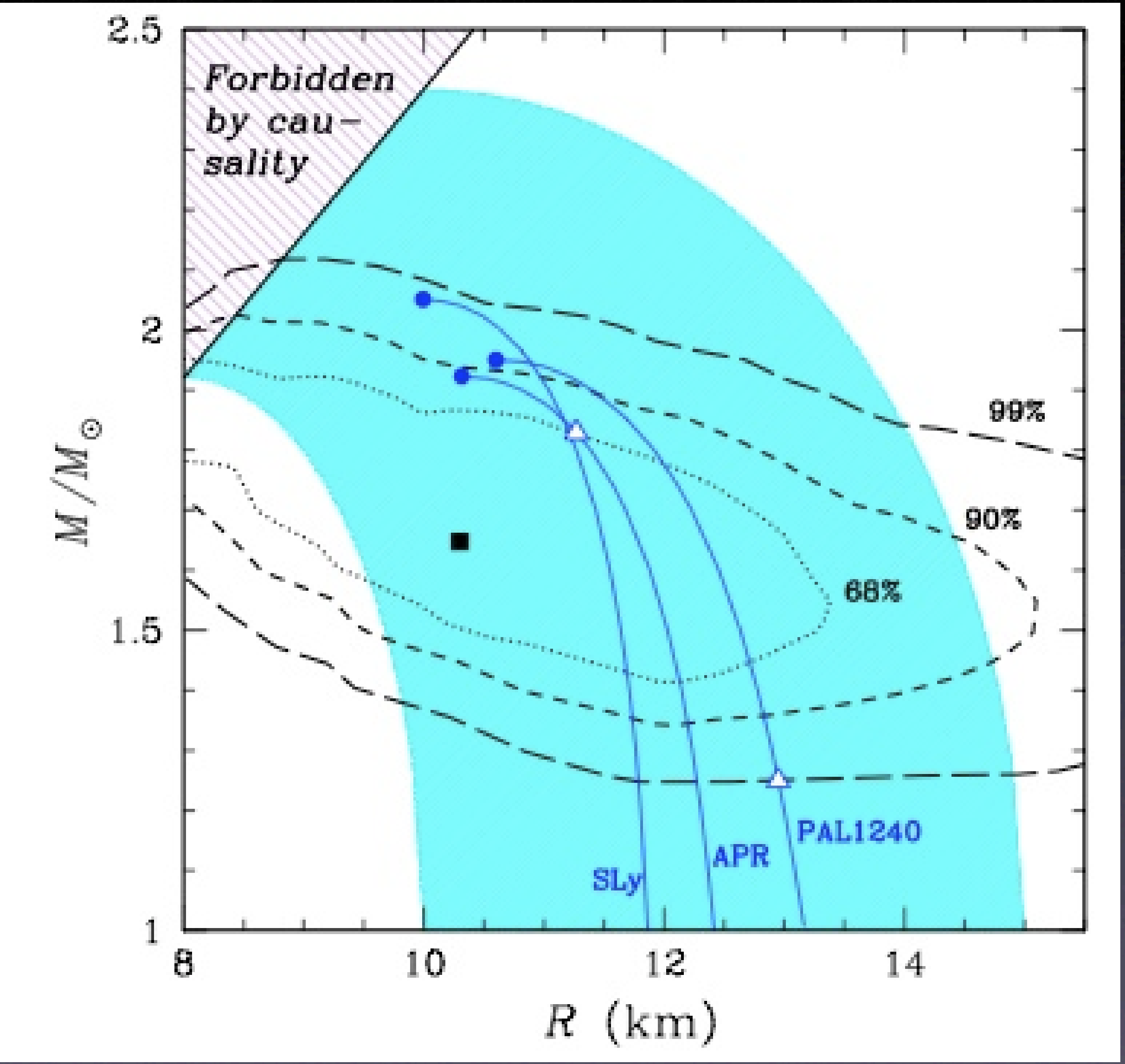
- Cas A is youngest NS
- NSs likely accrete many elements
- H, He diffuse down to hotter layers, are burned (Chang +03,Chang+10.)
- Low-B NSs burn away H, He for first 1000 years, then new H atm accretes?



Chang+03

Cas A NS constraints

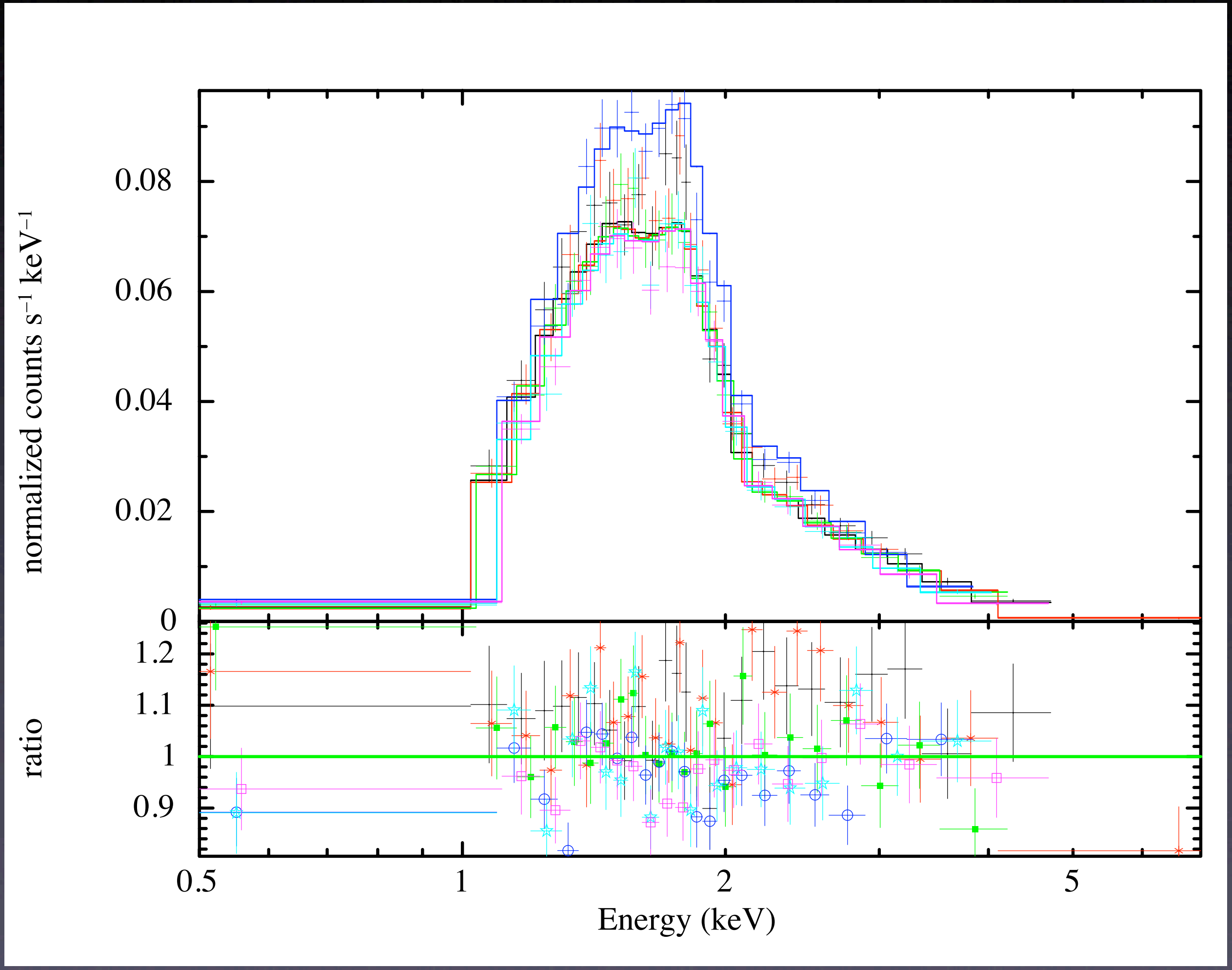
- Range of M, R are consistent with standard NS EOSs (blue region)
- Uncertainty in atmosphere composition, B, temp. homogeneity affect constraints



Yakovlev+11

Evidence of Variability

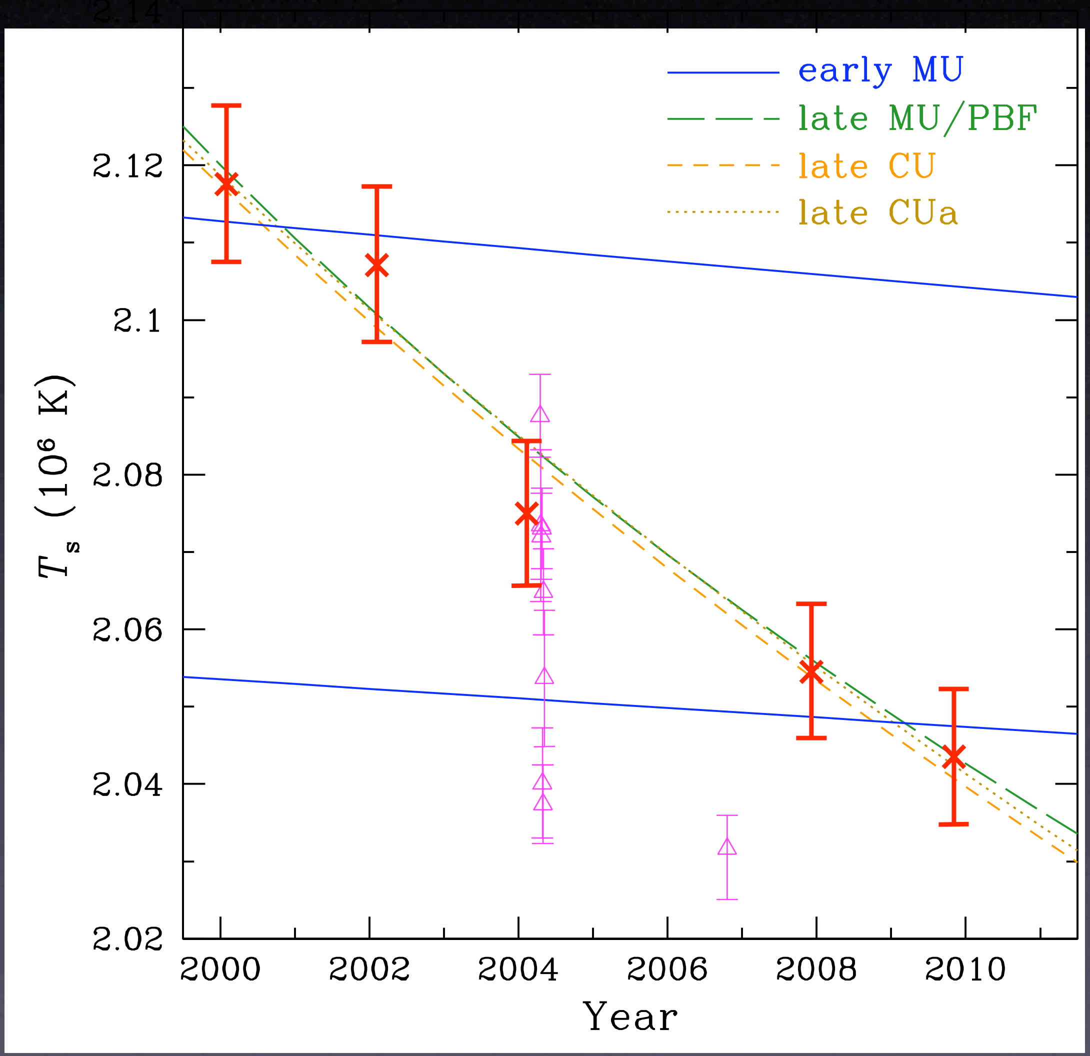
- Best-calibrated observations over 10 years show flux decrease
- Spectral uniformity rules out known calibration effects



Heinke & Ho 2010

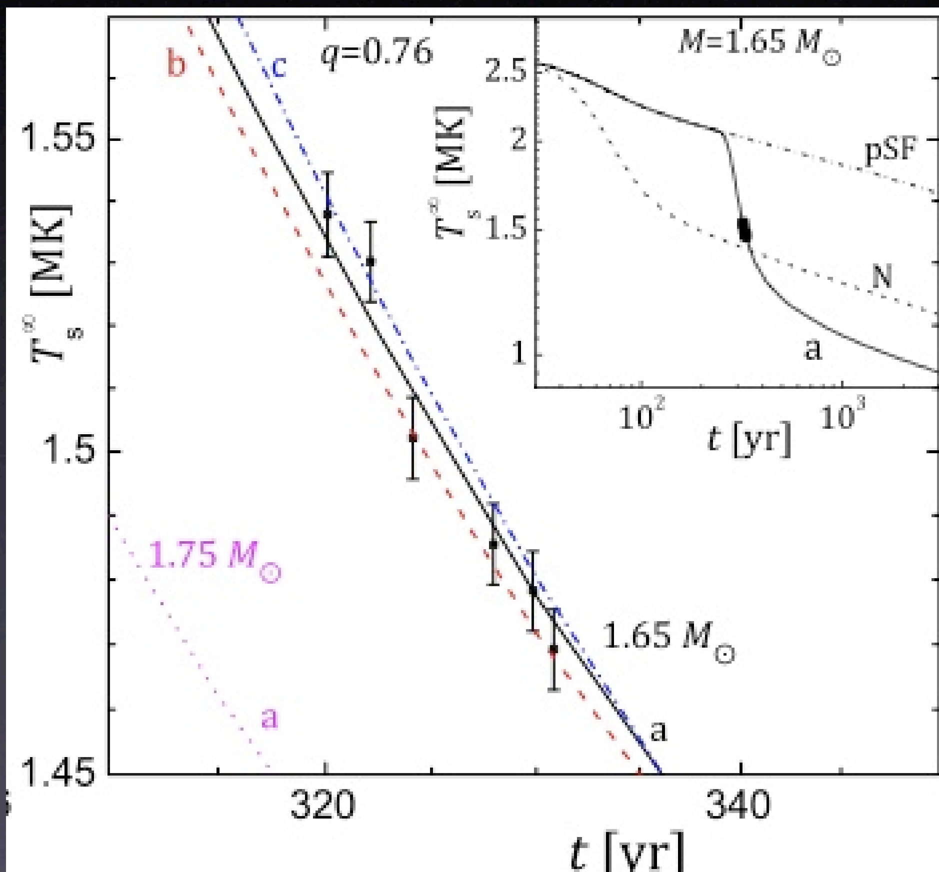
Observing Cas A Cooling

- T drops by 4% over 10 years
- First measured cooling of young NS
- Strong constraint on cooling models

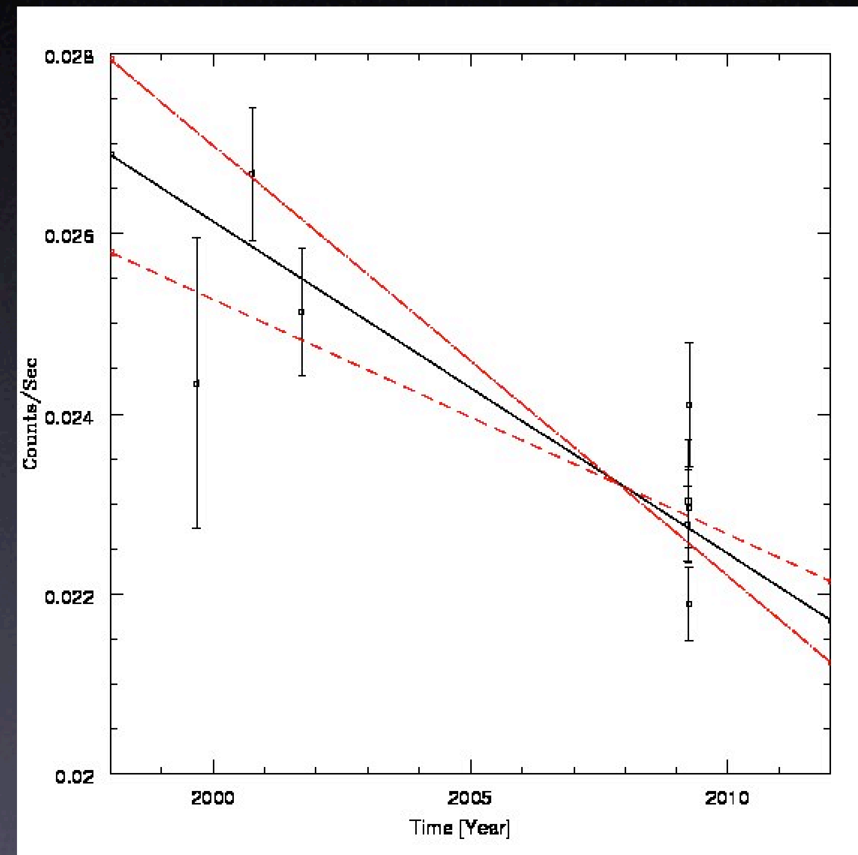


Heinke & Ho 2010

More evidence of cooling



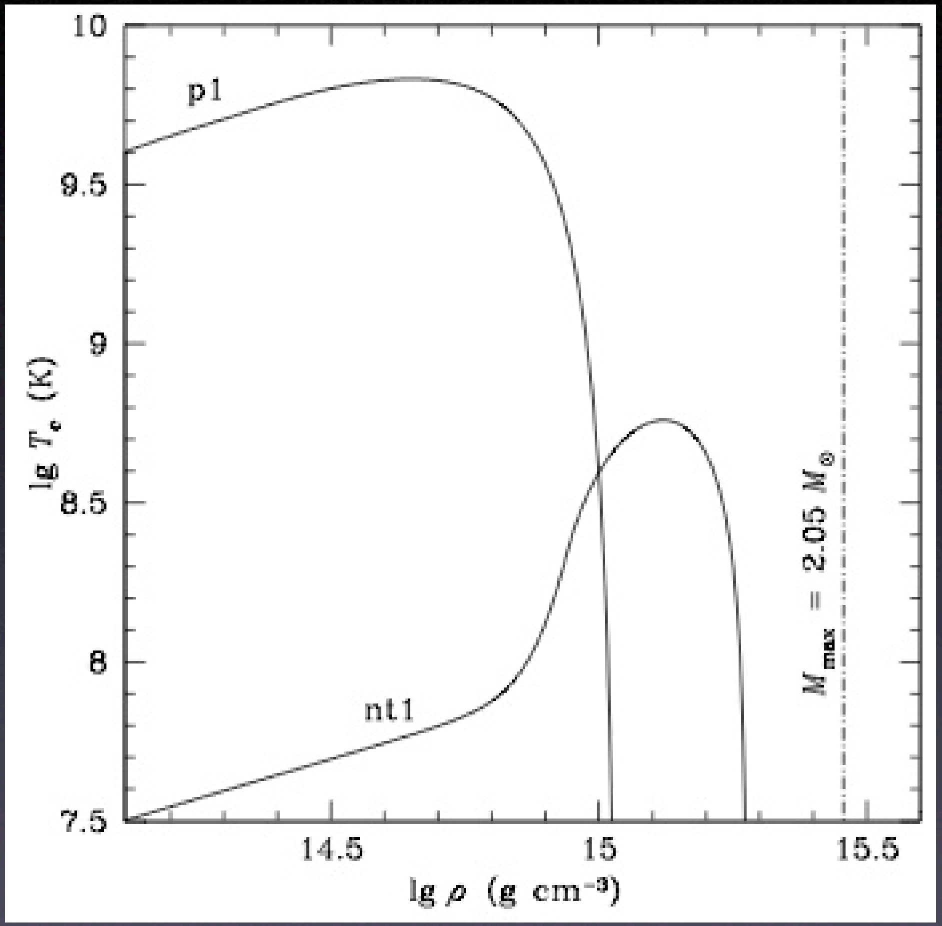
Shternin+11; new datapoint



El-Shamouty in prep; HRC-S countrate decline

Cooling by pair formation

- In superfluid, Cooper pairs break and re-form
- Formation of a pair releases energy, as neutrino-antineutrino pair
- When T of NS core drops below n SF T_crit, NS cools faster

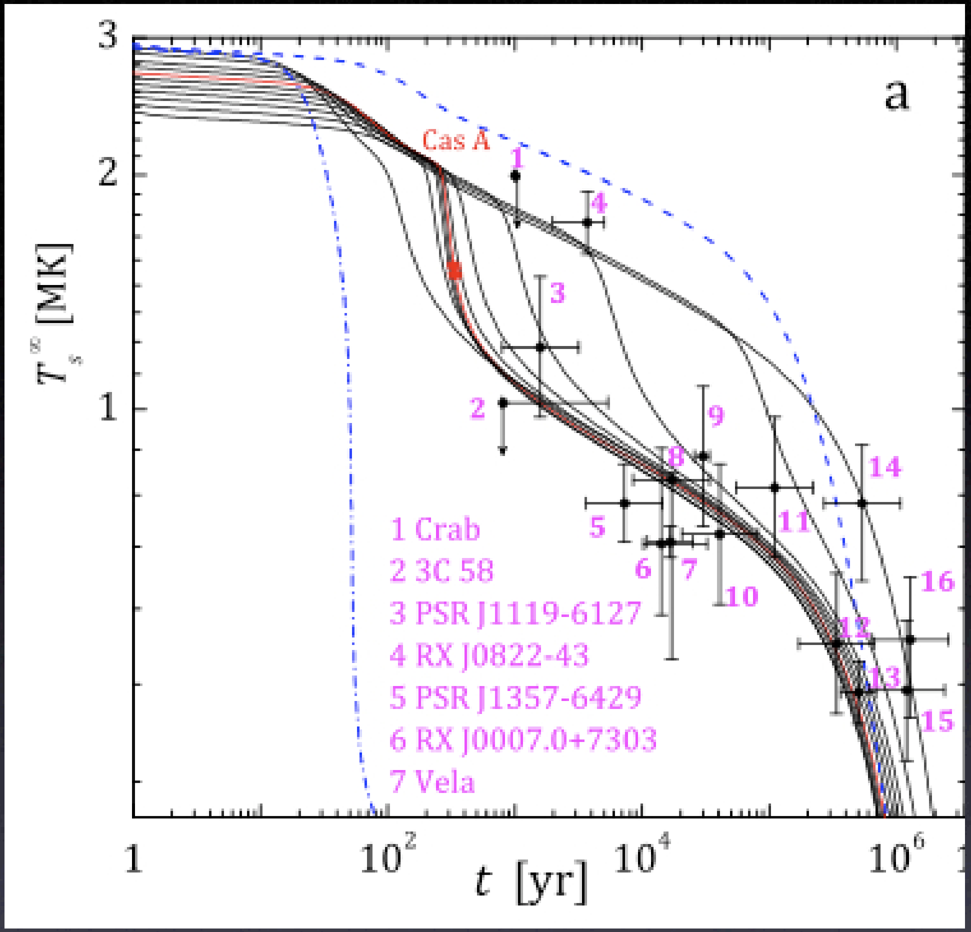


Gusakov+04; T_crit for n, p in NS

Decline in T is quite large for t~300 yrs, requires p SF to suppress URCA, n SF to give sudden cooling

Agreement between Shternin group & Dany Page group

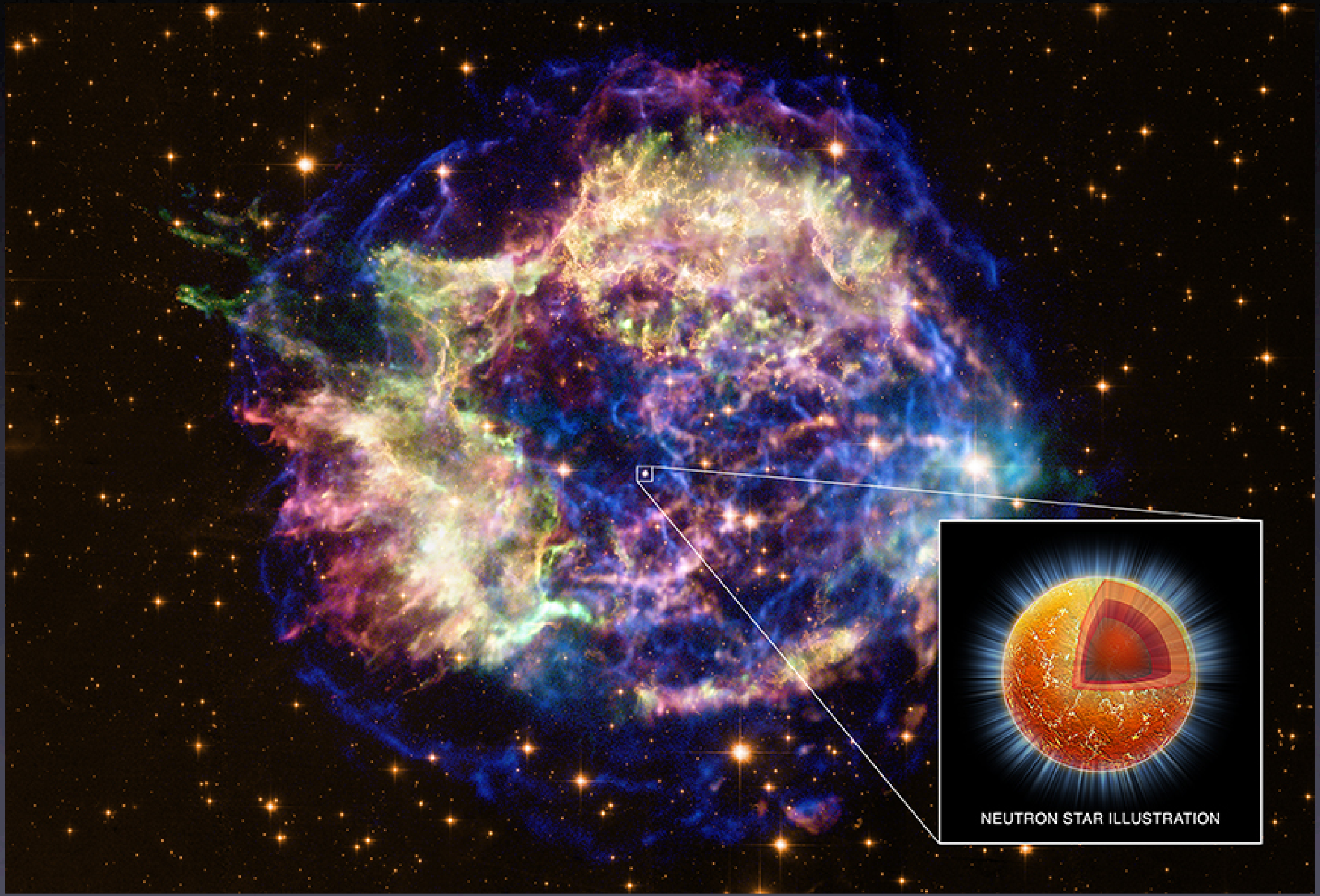
Possibly strongest evidence for superfluidity in NS cores (Shternin talk)



Shternin et al. 2011

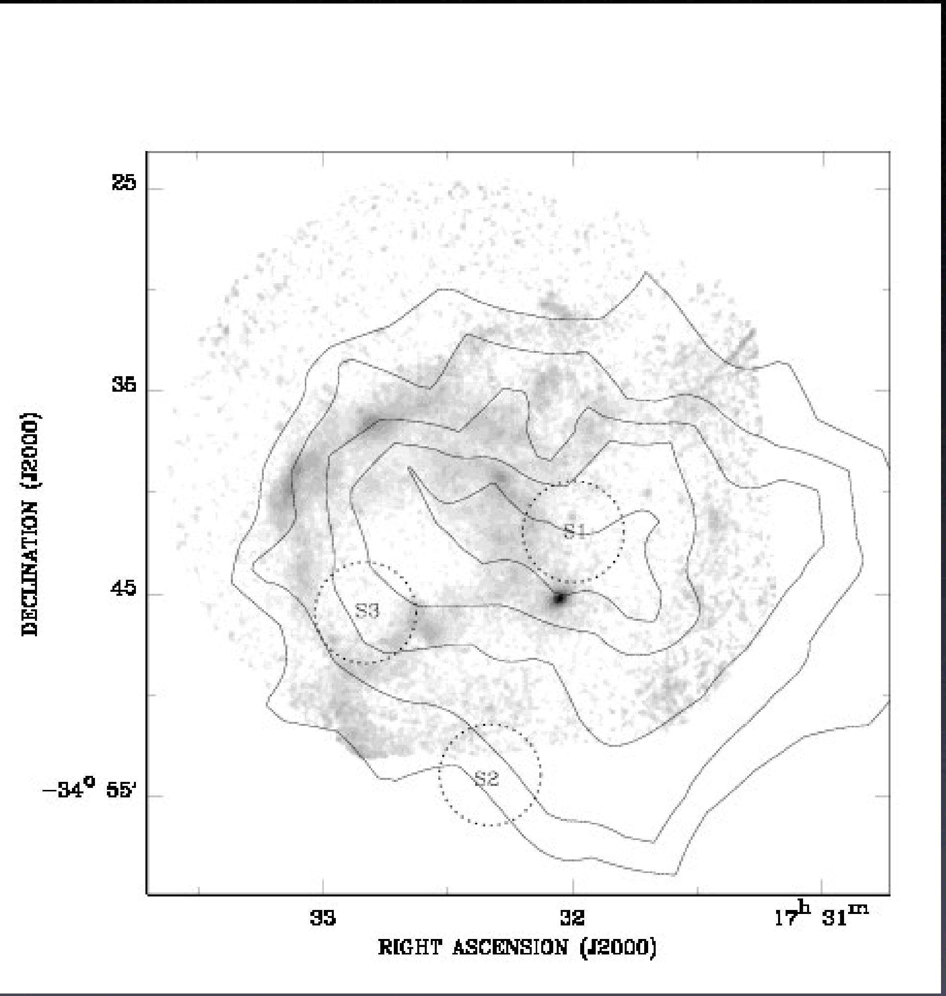
Cas A results

- First non-H NS atmosphere found
- Evolution of atmosphere?
- Cooling directly measured
- Evidence for n superfluid in core, superconducting p



Cas A (NASA Chandra/Hubble)

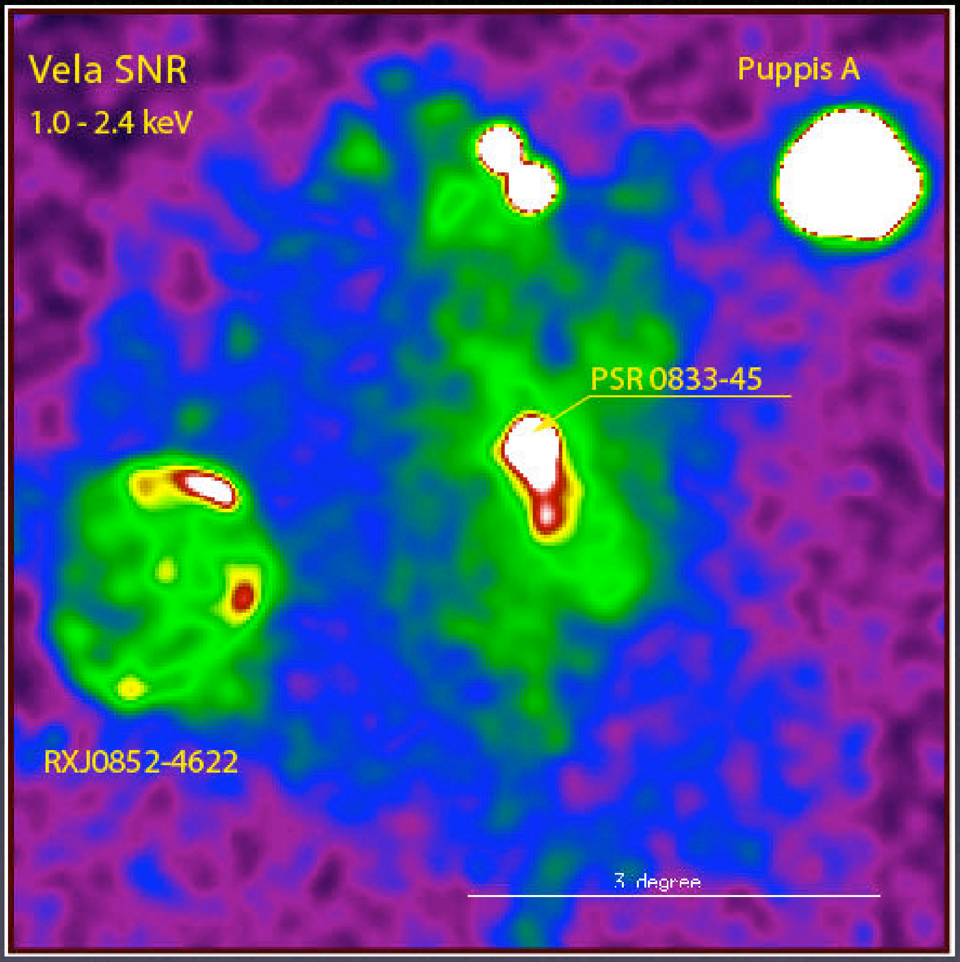
Other CCOs



G353.6-0.7, Tian+

- Six more CCOs, pulsations not yet detected, pulsed fraction <7% for two
- Are spectra consistent with uniformly emitting NSs, either H/He or C atm?
  Or are hot spots required?
- Distances & ages not well-constrained.
  Estimate distances from SNRs, NH (compare to extinction to horizontal-branch stars along line of sight)

Vela Jr. (RX J0852-4622)



Vela, Vela Jr. & Pup A SNRs,
Becker+06

Distance constrained by
Vela Molecular Ridge, <2 kpc
(Murphy & May 1991)

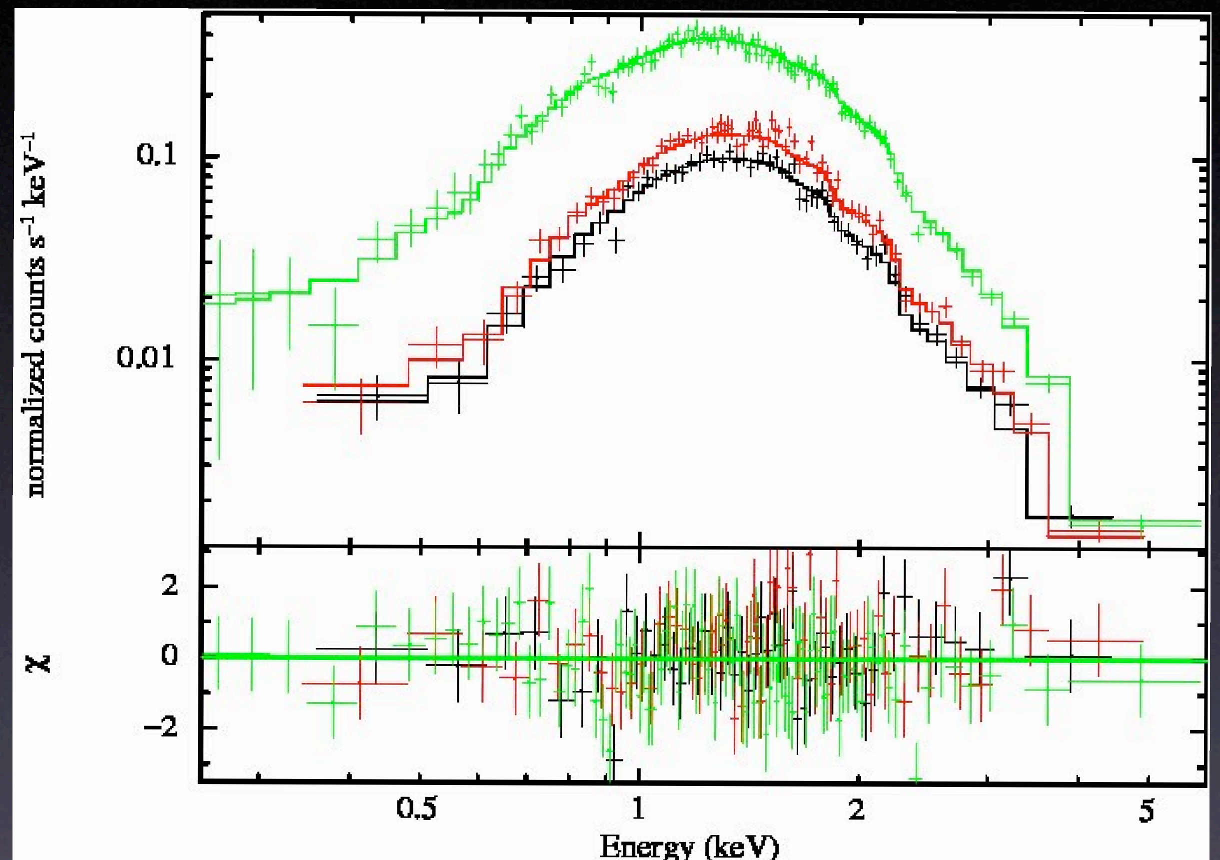
SNR expansion measured,
0.014±0.004%/yr (Allen+10),
so ~3000 years old

Hard X-ray synchrotron
in SNR requires v>3000 km/s,
estimate D=720--2140 pc

Red giant extinction, CCO L_X
suggest D~2 kpc

Vela Jr. spectra

- Fit by blackbody, H, He, C atm, assume 1.4 Msun, 10 km radius
- Required distances: 35 kpc for BB, 9.2±0.5 kpc H, 8.7±0.5 kpc He, 2.8±0.3 kpc C (~2 MK)
- Suggests hot spot, but PF <7%



Fit with single-T C atm

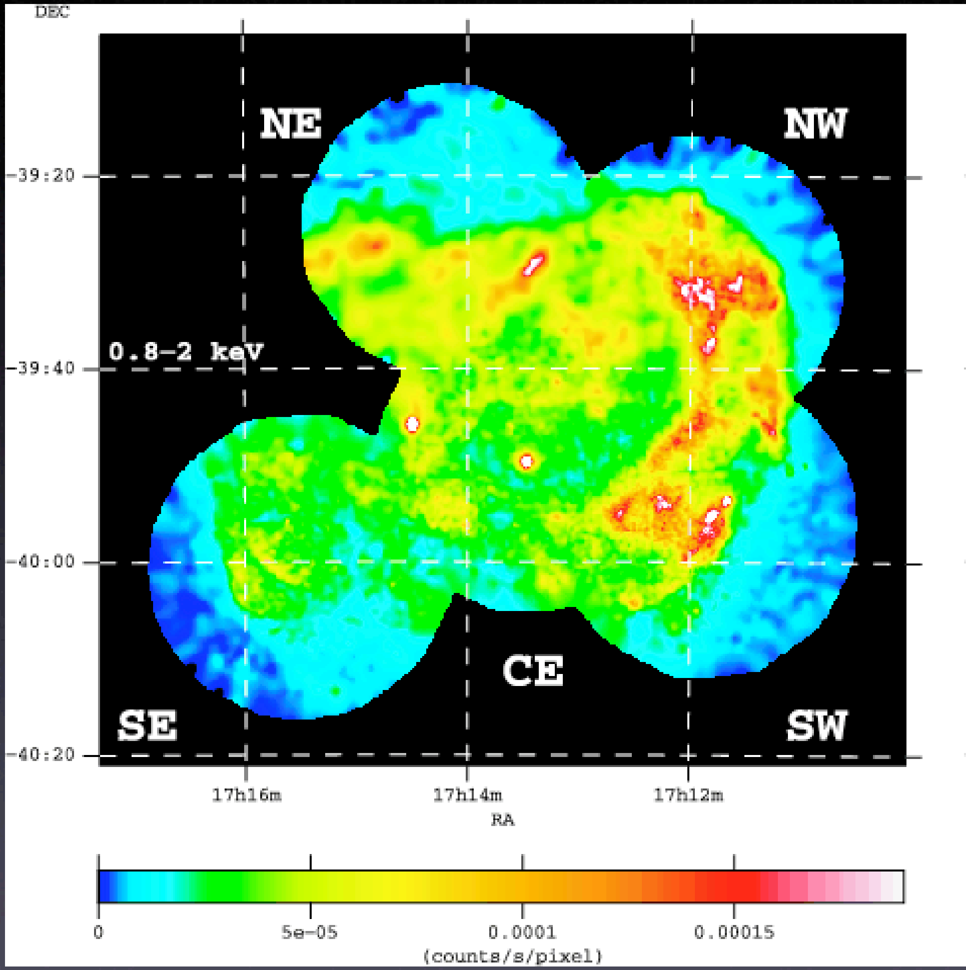
G347.3-0.7 (RX J1713.7-3946)

SNR interacting ISM clouds,
at D=1.3±0.4 kpc
(Cassam-Chenai+04, Fukui+10)

Age ~1600 years,
if SNR of 393 AD (Wang 97)

Single-T C atm fits (T_S=2 MK),
but requires D=2-2.5 kpc

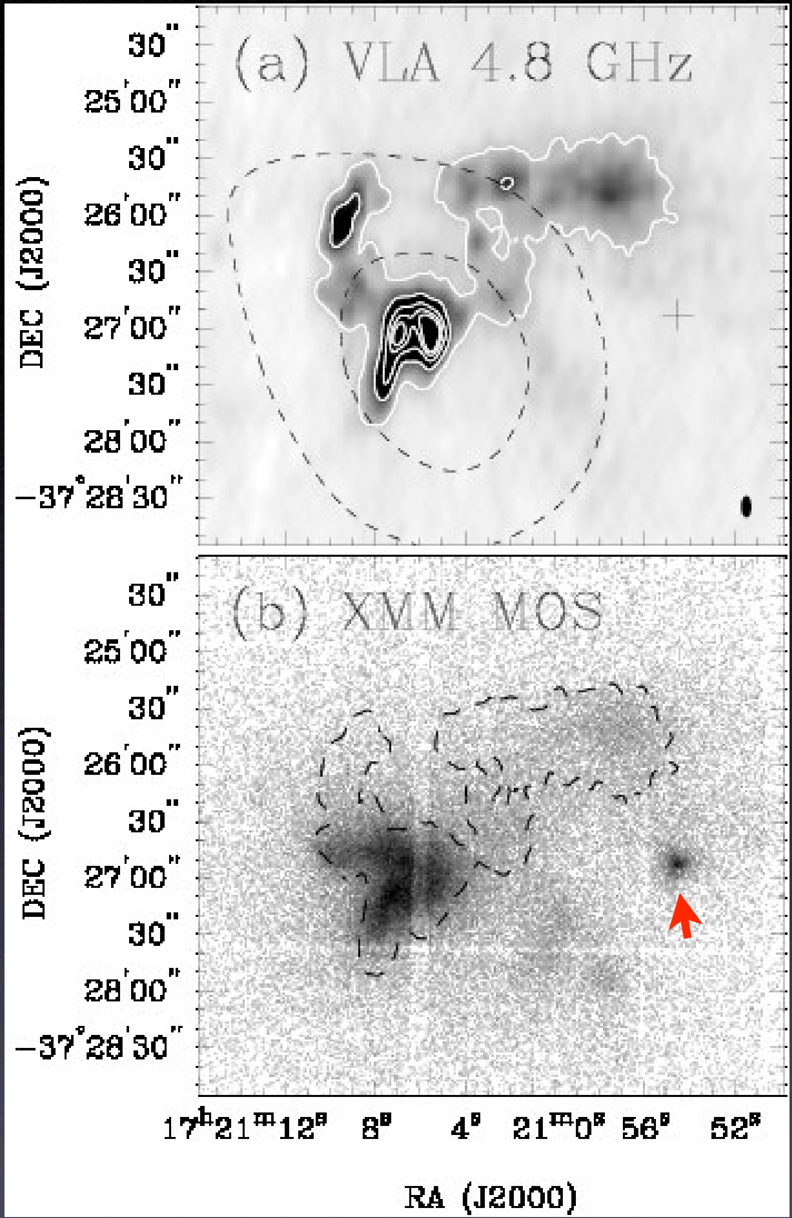
Seems to require hot spots,
but again PF<7%



G347.3-0.7 (XMM),
Cassam-Chenai+04

G350.1-0.3

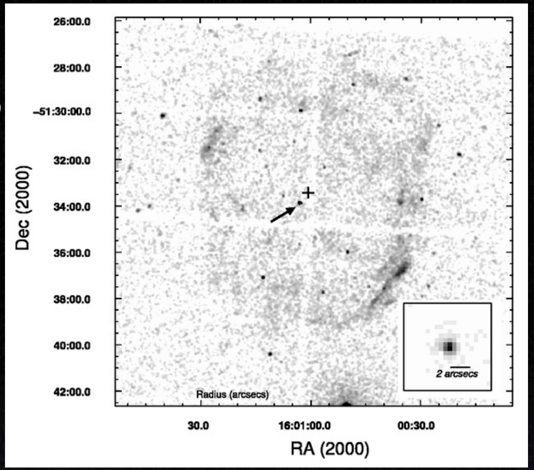
- SNR colliding H_2 cloud, age 600-1200 years, D ~ 4.5 kpc
- Consistent with single-temp C atm, T_S=2.6 MK,
  If so, T >Cas A (T_S=2 MK)
- W. Ho & I proposing to look for cooling, pulsations



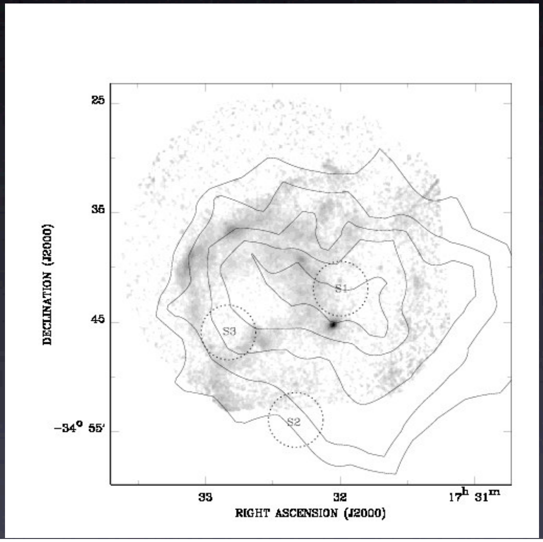
G350.1-0.3, Gaensler+08

3 more likely CCOs

G330.2+1.0,
S. Park+06

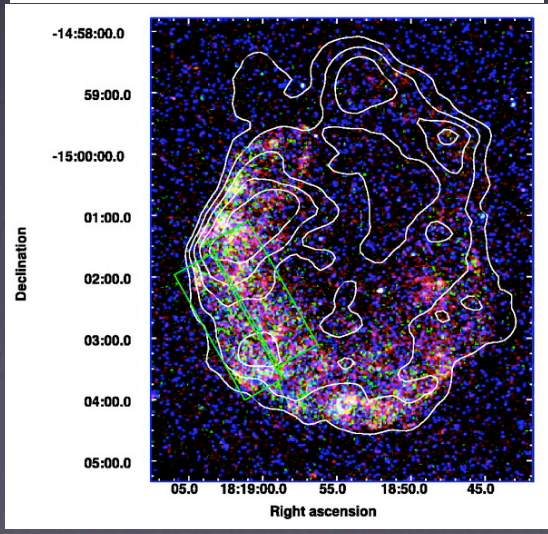


G353.6-0.7,
Tian+10



- Poor limits on pulsed fraction
- Inferred D with H/He atm too high, C atm D ok
- Distances uncertain, spectral fits unclear; more data needed

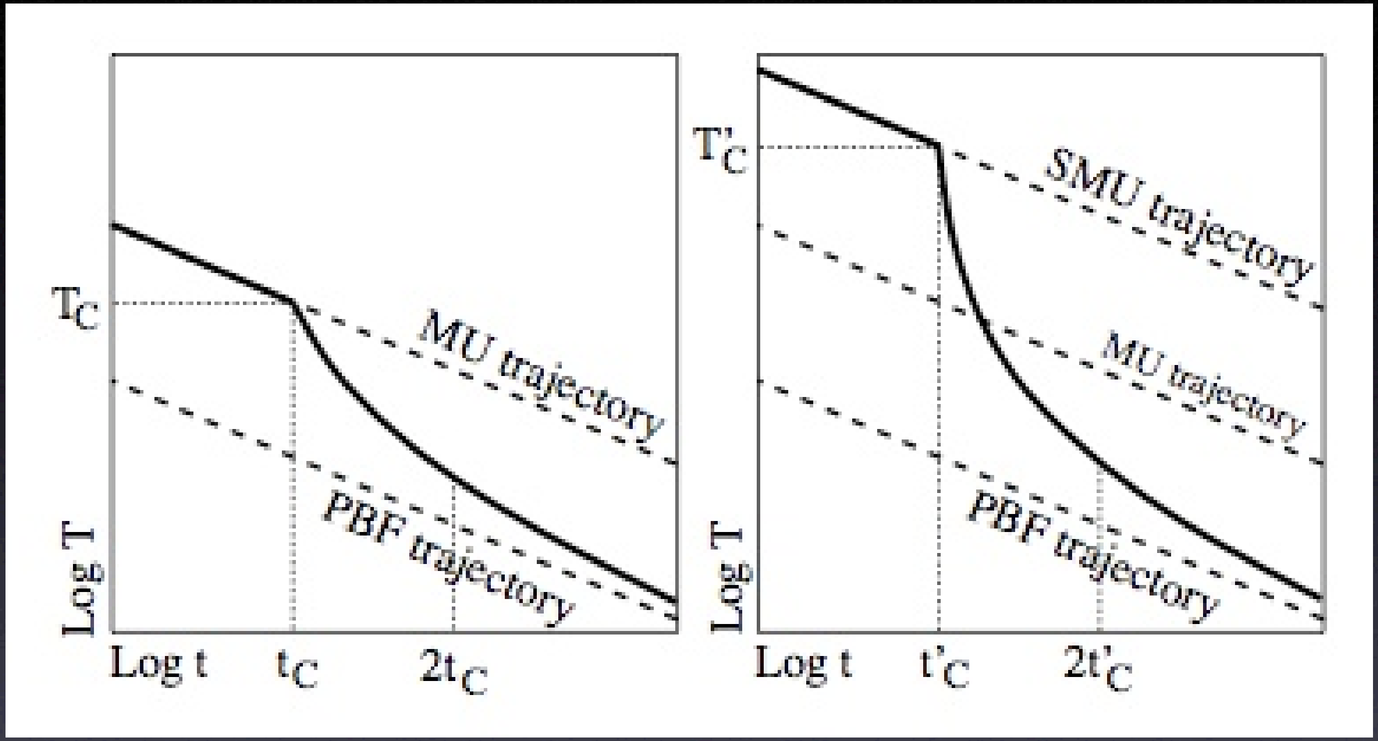
G15.9+0.2,
Reynolds+06



Future for CCOs

- Pulsations give P, B;
  searches, timing critical
- Atmosphere modeling (understand hot spots, composition, lines), observe more CCOs for features
- Follow temp. decline in Cas A,
  search for temp changes in other CCOs
- D, kT, age for more CCOs to study NS cooling

Hot NS requires p SF



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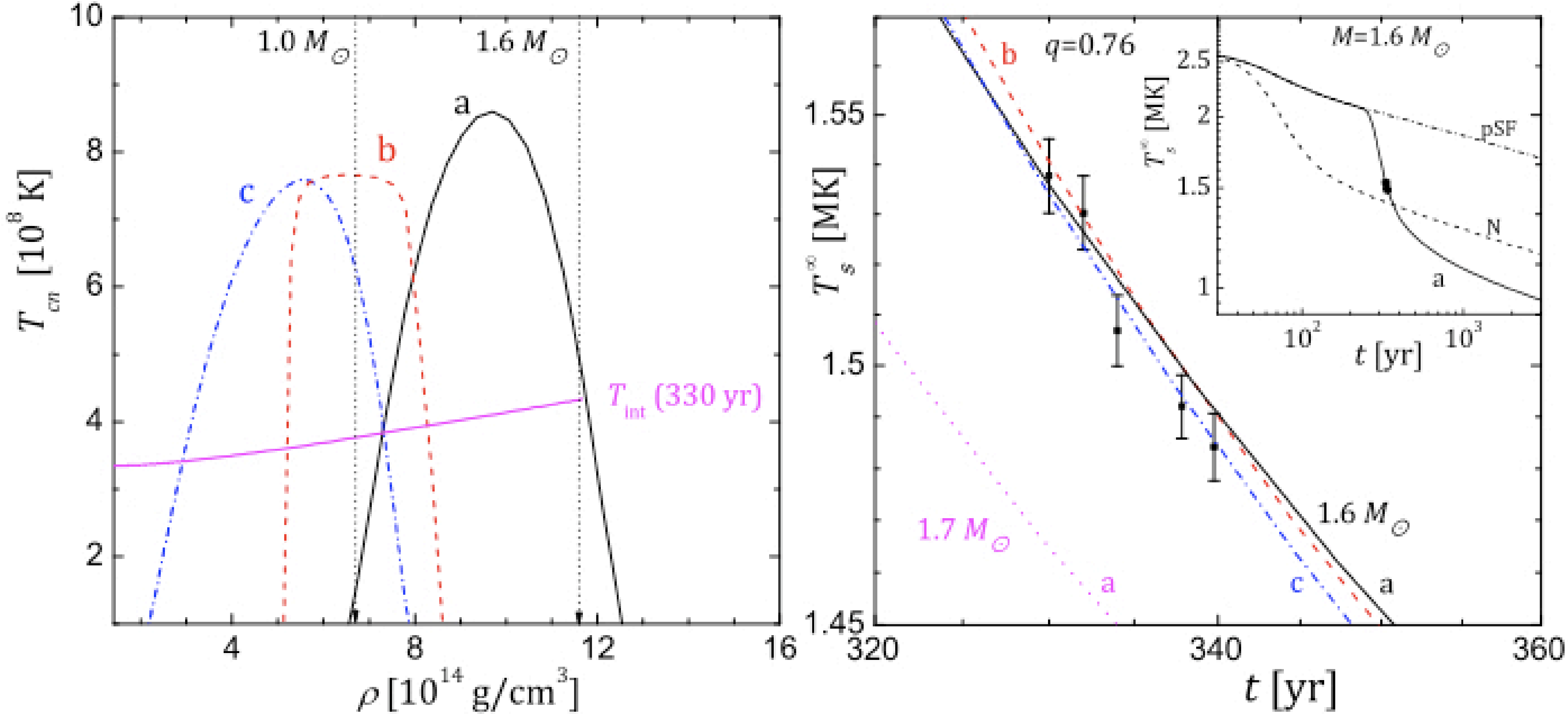
Normal (modified URCA) cooling suppressed by p SF (p pairing)

Current high T of Cas A NS requires p SF in past

Movie of NS interior T

Wynn Ho,
from Shternin
results



Neutron triplet superfluidity in NSs, Shternin+2011

Cooling by Cooper pair formation
in neutron superfluid, T_{crit}~[6-9]*10^8 K

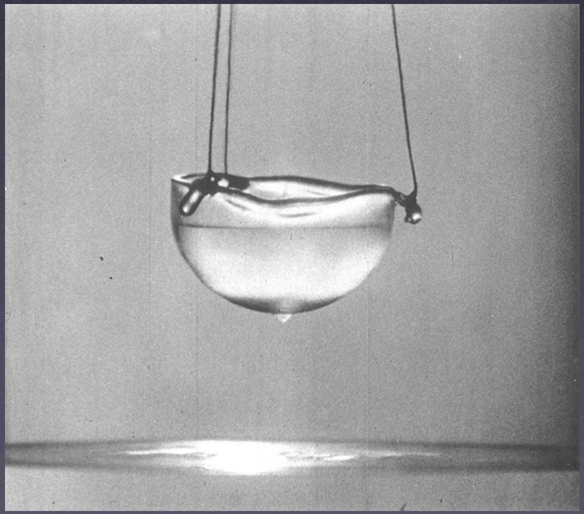
Summarizing cooling

- Large variation in cooling rates requires fast neutrino cooling in some NSs
- Fast neutrino cooling must be suppressed in other NS cores, by (proton) superfluidity
- Sudden Cas A cooling requires new source of cooling, such as pair breaking from neutron superfluidity

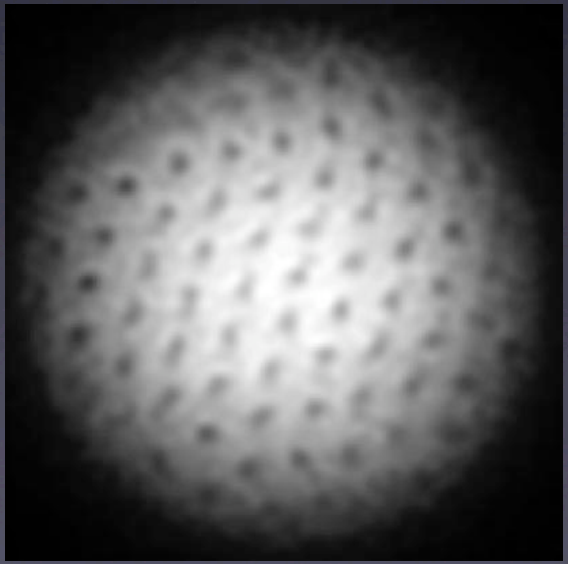
Superfluidity

Quantum pairing of the spins of particles produces superfluid state, with frictionless flow

Requires low temperatures, e.g. liquid helium <3 K.

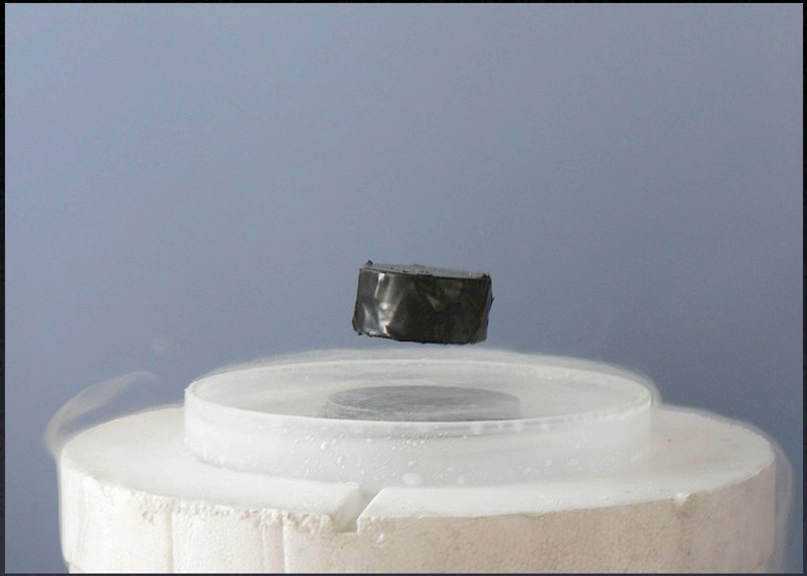


Superfluid helium has no viscosity, ang. mom. quantized in vortices



Superconductivity

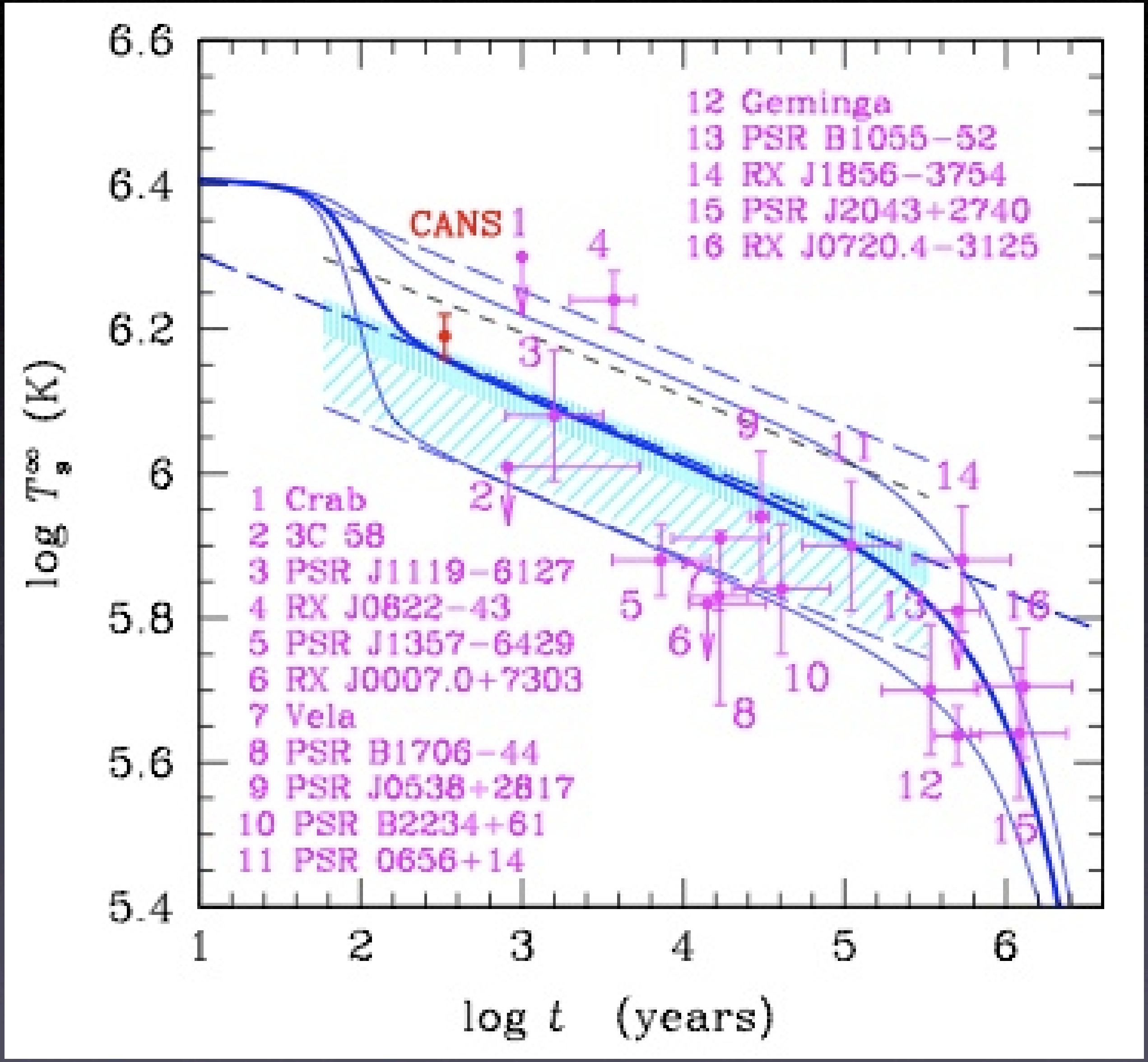
Similar physics to superfluids, but involving charged particles



Perfect electrical conductors; produce strong magnetic fields

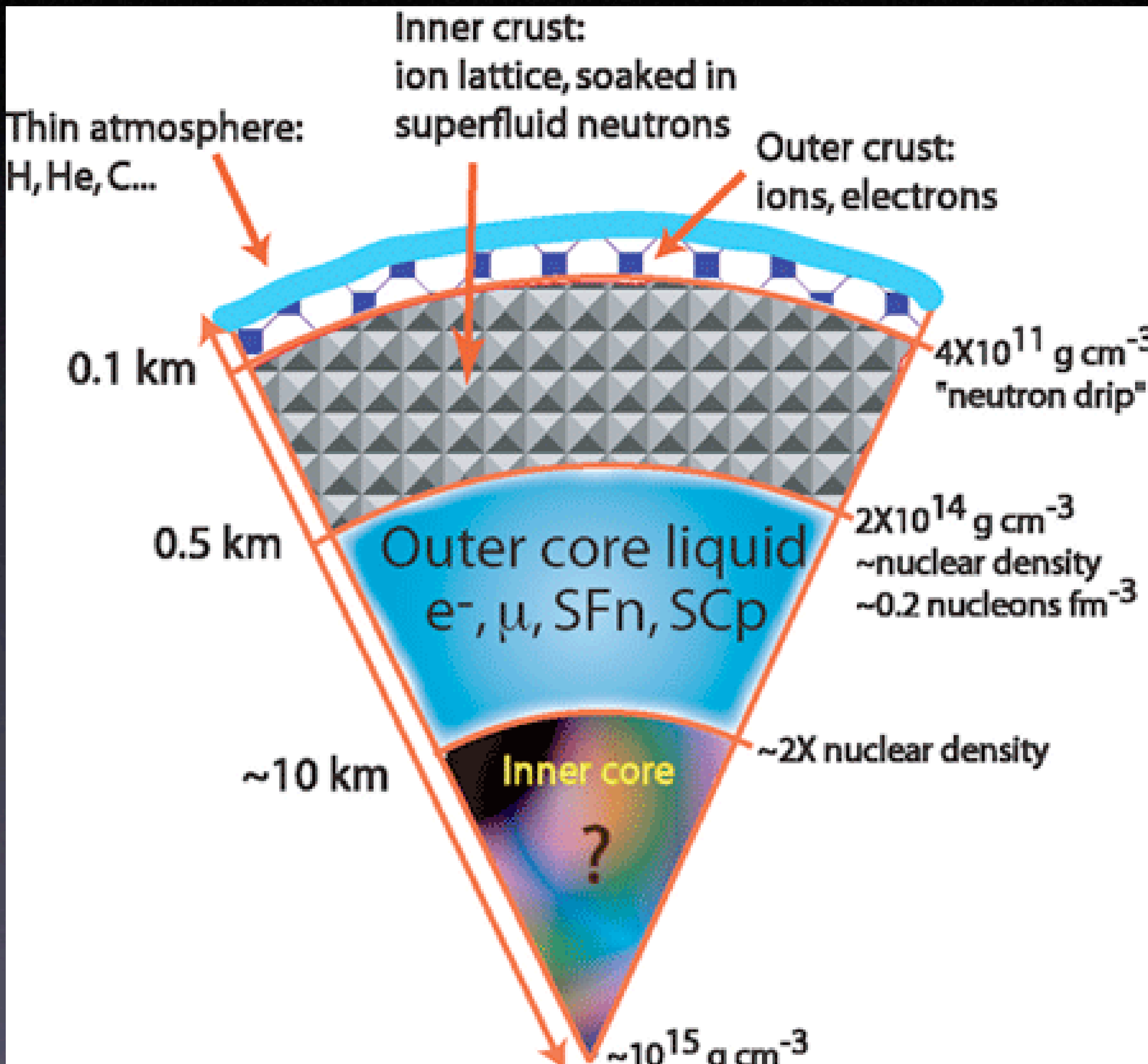
Applications: medical (MRI), particle physics (LHC), maglev trains, power transport

- Gives strong constraint on young NS cooling curves
- Options for T range; envelope elements, mass (superfluidity, URCA flavors)



Yakovlev+10

Superfluidity in NSs



Schematic, Bennett Link

NS n, p interactions may allow Cooper pairing, at "low" T

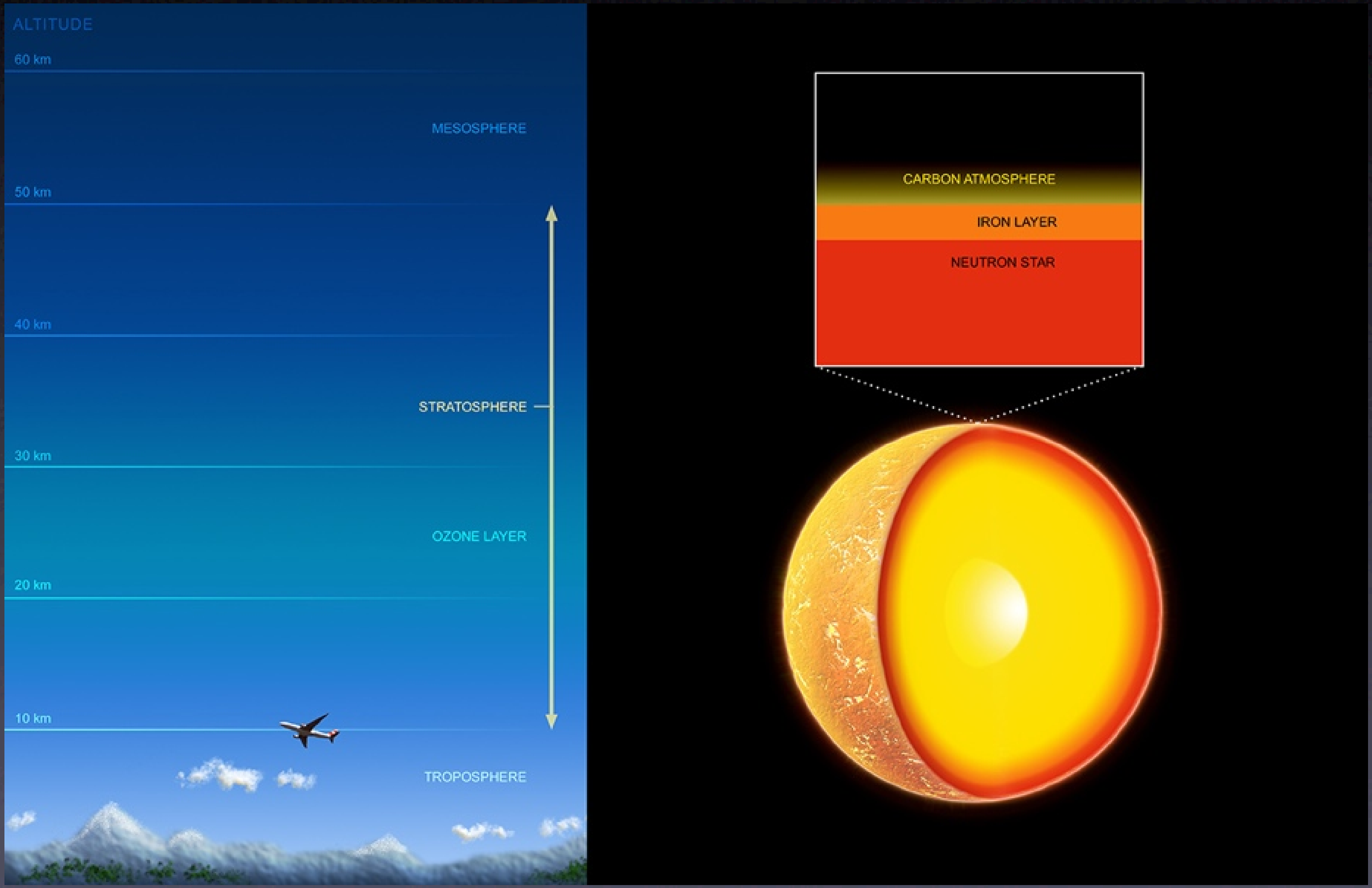
Expect singlet state SF n in outer crust, SF p throughout star

n repulsion stops singlet n SF in core, but triplet SF expected

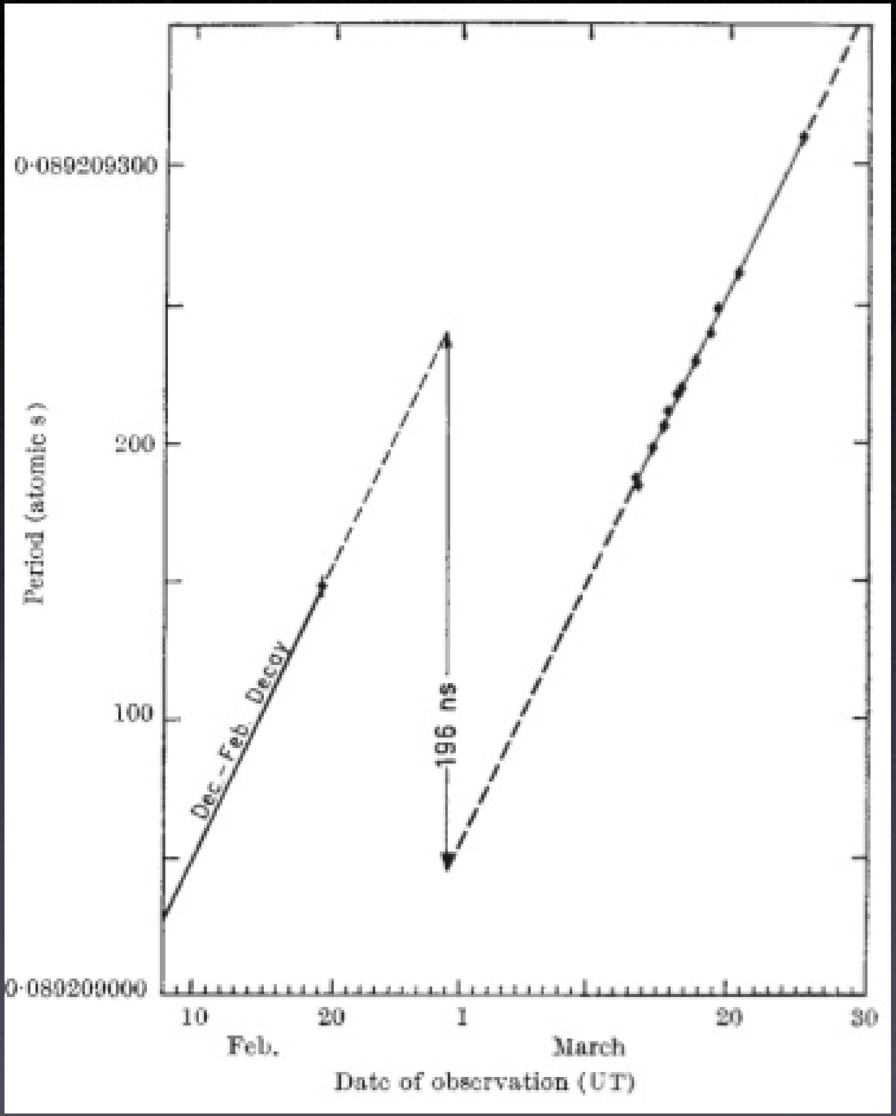
Carbon atmosphere

Scale height of Earth's atmosphere ~neutron star diameter

Scale height of neutron star atmosphere ~10 cm



Glitches



Vela Glitch
Radh. & Manchester 1969

Radio pulsars show glitches; speed-ups in spin

Understood by differing rotation of nuclear lattice, n SF in crust

Glitches represent transfer of ang. mom. to lattice

Only previous direct evidence for SF in NSs

NS cooling

Dominated by νs

Nucleon direct URCA,

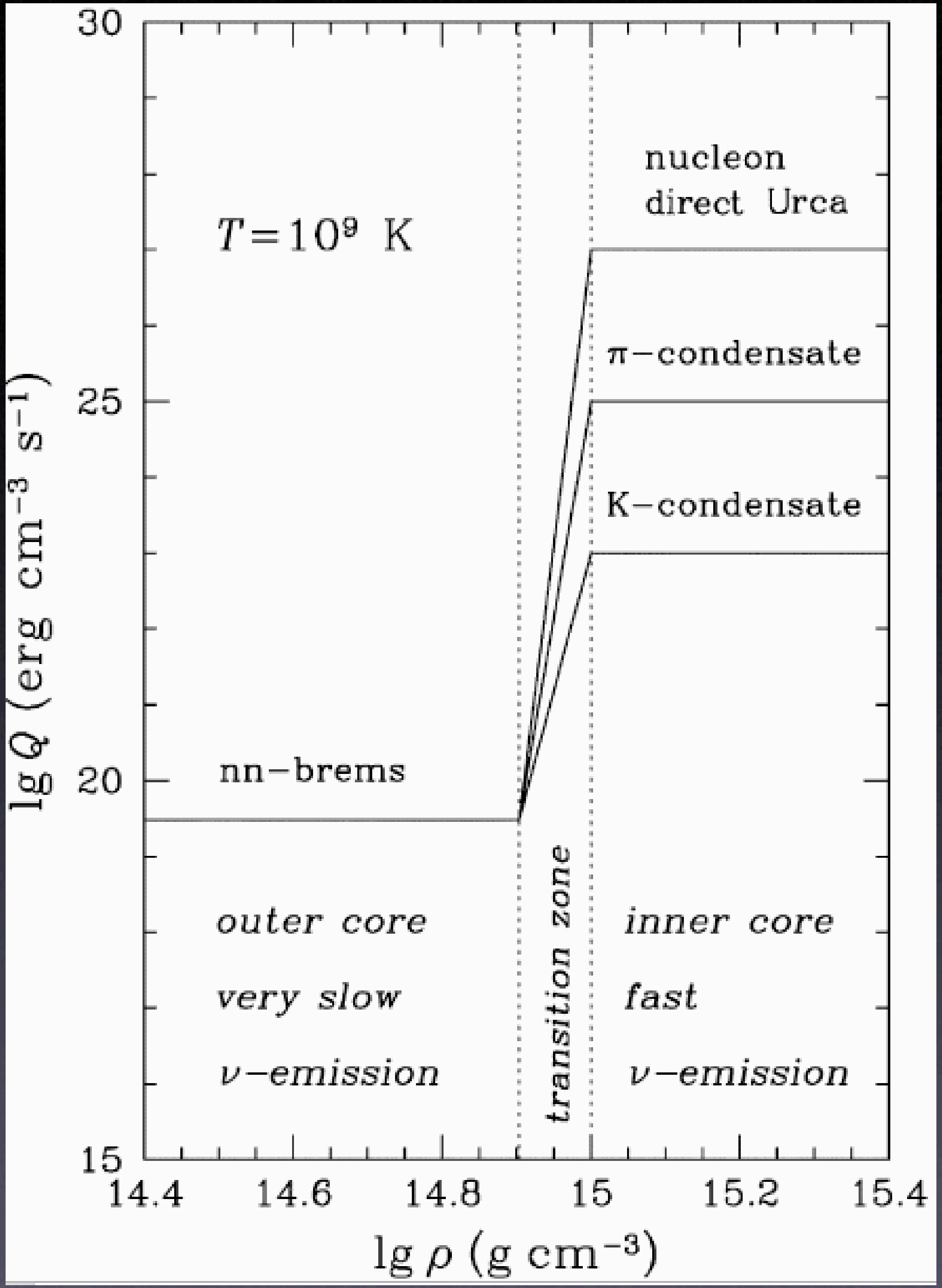
$n \to p + e + \nu$

$p + e \to n + \bar{\nu}$

Modified URCA (requires 3-nucleon interaction)

or URCA-like reactions via condensates (K, π)

URCA suppressed if particles are superfluid; n-n bremss allowed



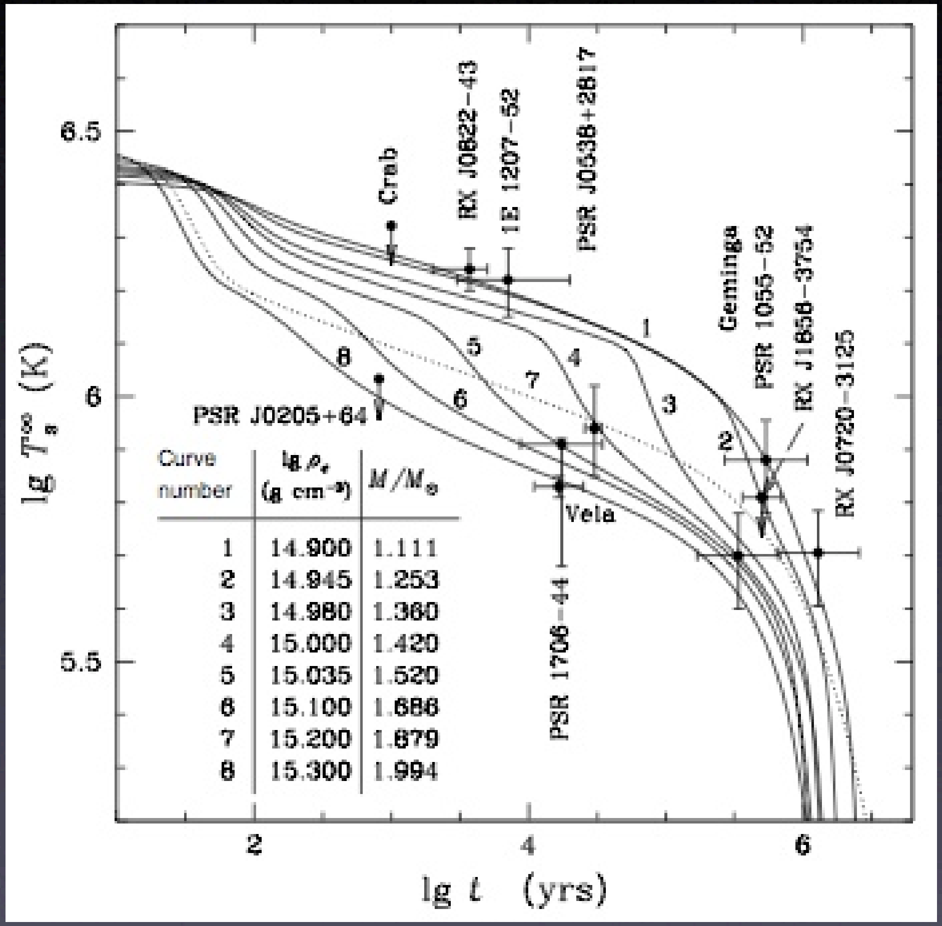
Yakovlev & Pethick 2004

Particle superfluidity suppresses all URCA mechanisms

Superfluidity allows ν emission by Cooper pair formation, below Tc

Dropping below Tc ignites quick T drop

Proton, neutron superfluidity Tc curves



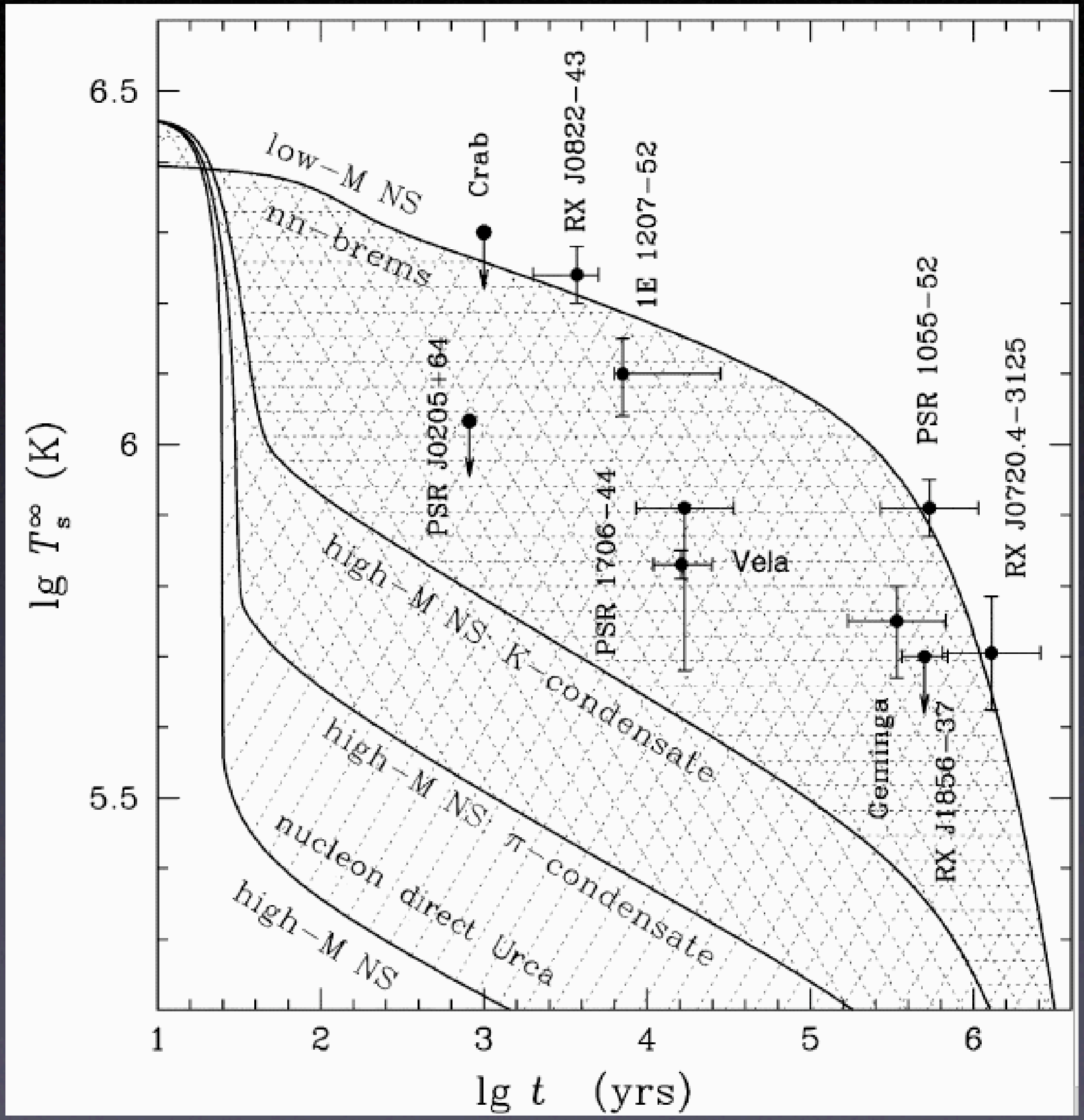
Gusakov+04; superfluidity below (toy) curves

Cooling of young NSs

More massive NSs
can access rapid cooling
at center

Range of cooling rates set
by NS ν emission process

Young NSs give small
range of cooling rates



Yakovlev & Pethick 2004