Cooling of the Cas A Neutron Star

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Seattle INT meeting, July 28, 2011

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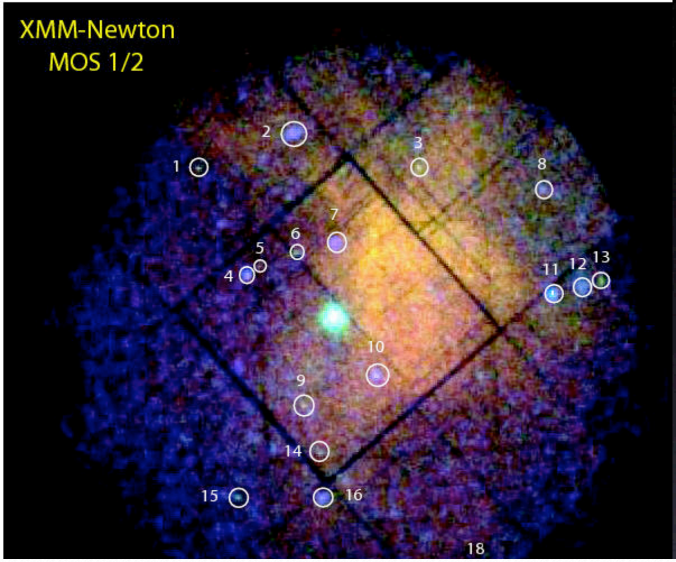
Central Compact Objects (CCOs)

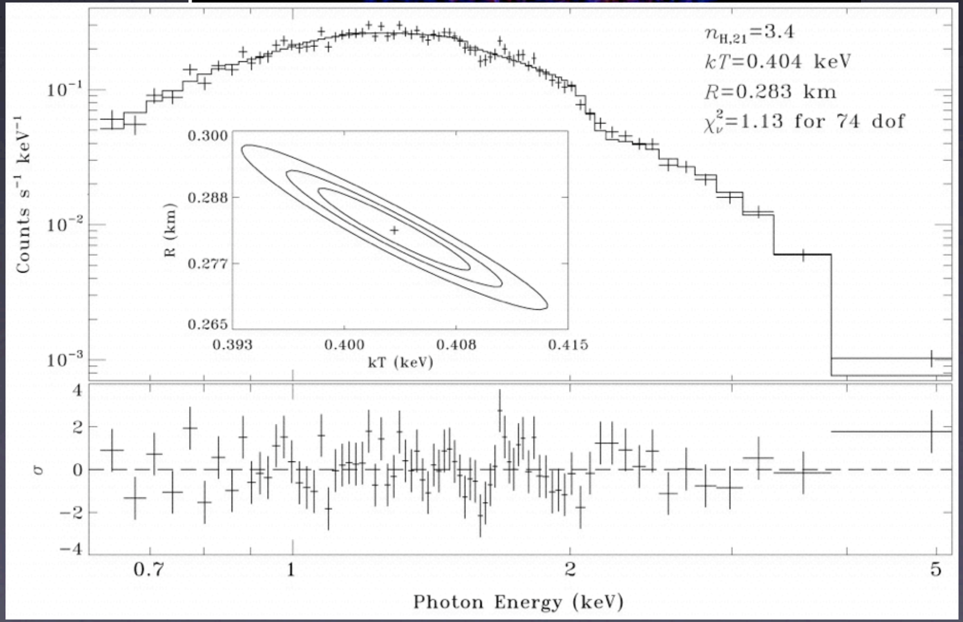
- 10 CCOs: X-ray point sources inside supernova remnants (omit RCW 103)
- Thermal BB-like spectra, long-term variability <5% (Pavlov+03)
- Young NSs, not radio pulsars

Puppis A, ROSAT

Thermal X-ray Emission

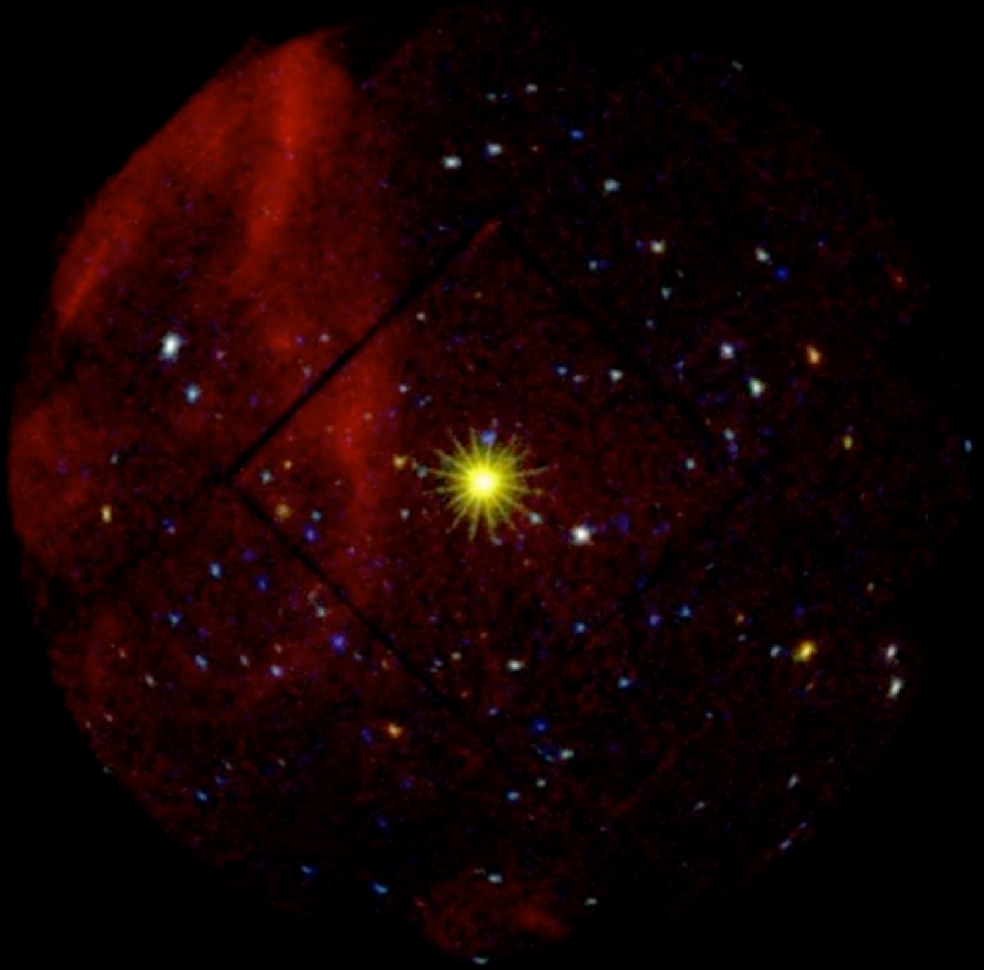
- CCOs show thermal, BB-like X-ray emission, kT~0.1-0.4 keV, L_X~10^{33}-10^{34} ergs/s
- No optical, radio, IR counterparts
- Seem to be quiet NSs

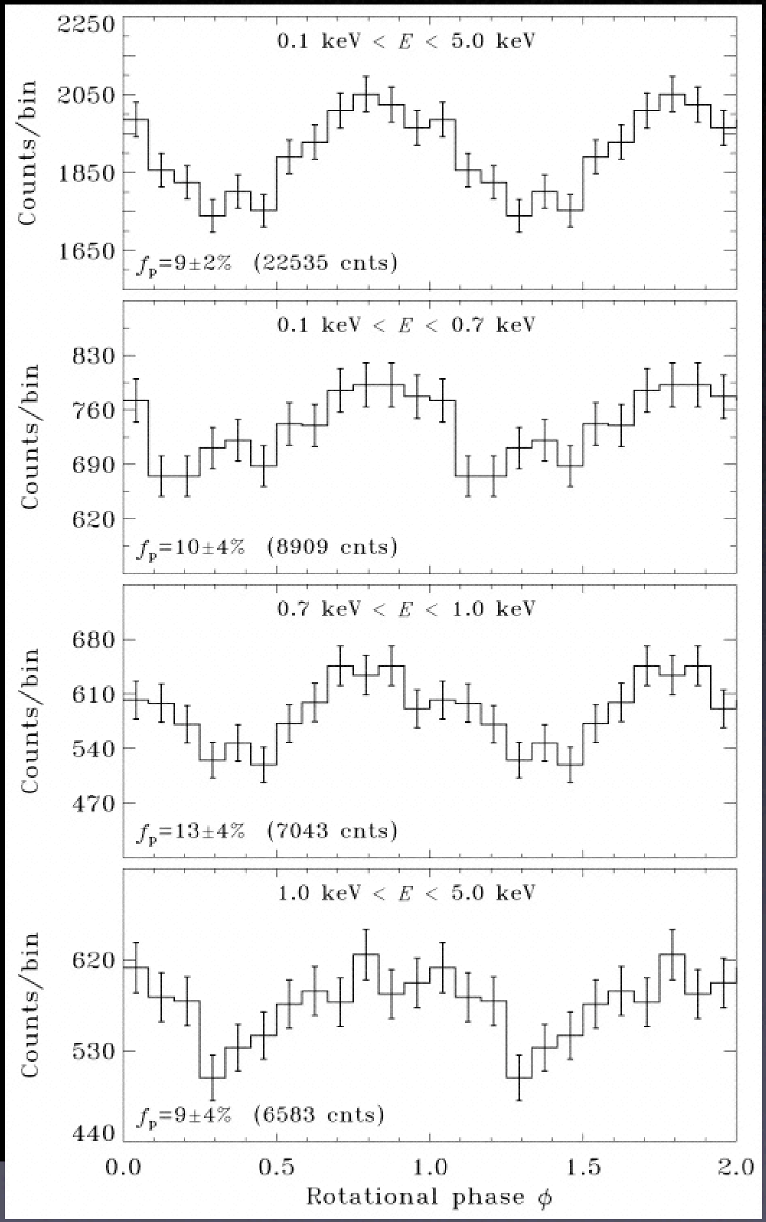




Vela Jr. CCO spectrum, Kargaltsev+02

1E1207.4-5209



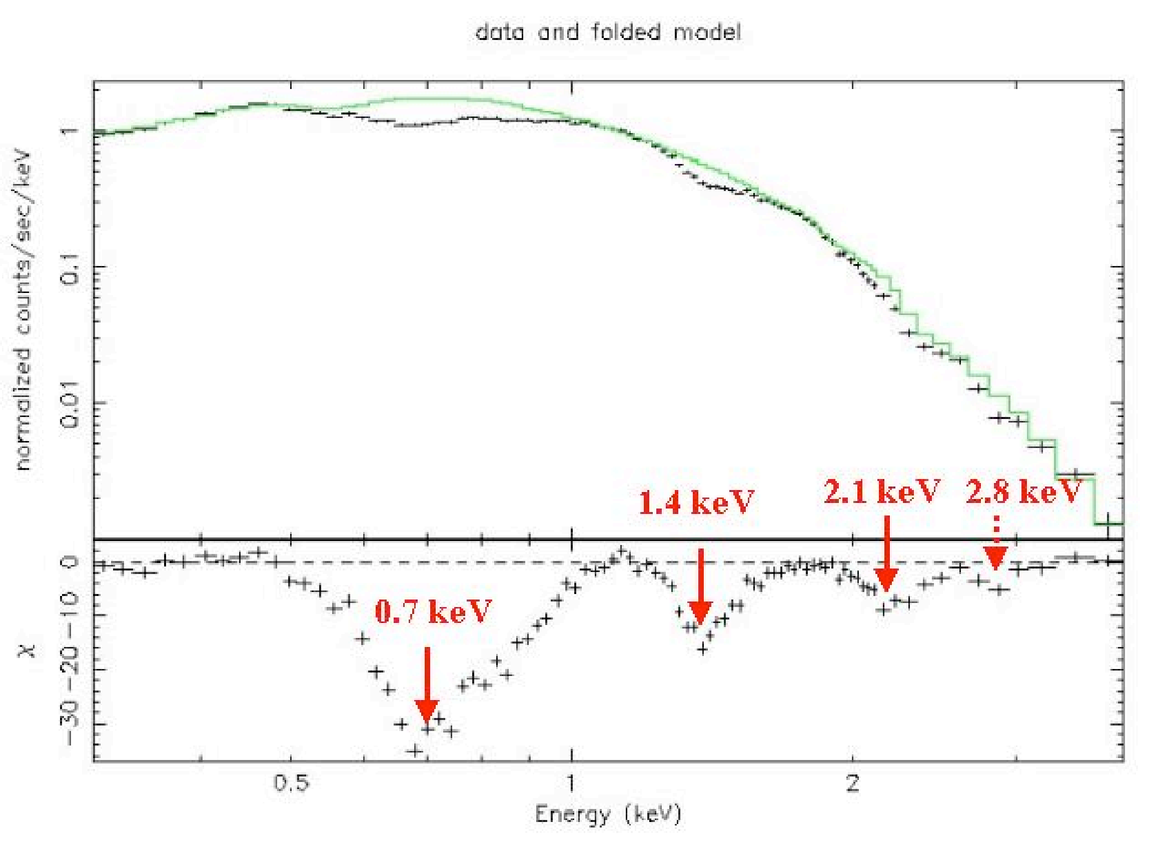


Zavlin+00

0.424 s X-ray pulsations,
7% pulsed fraction

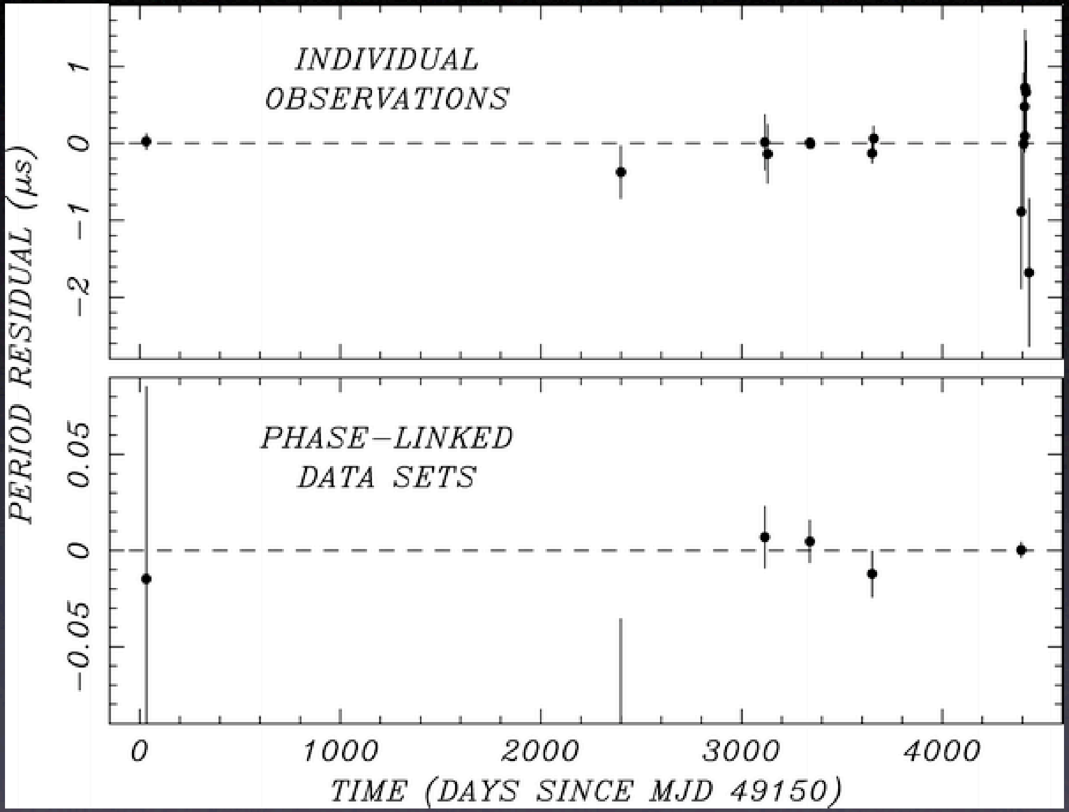
1E1207 spectrum

- 3-4 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

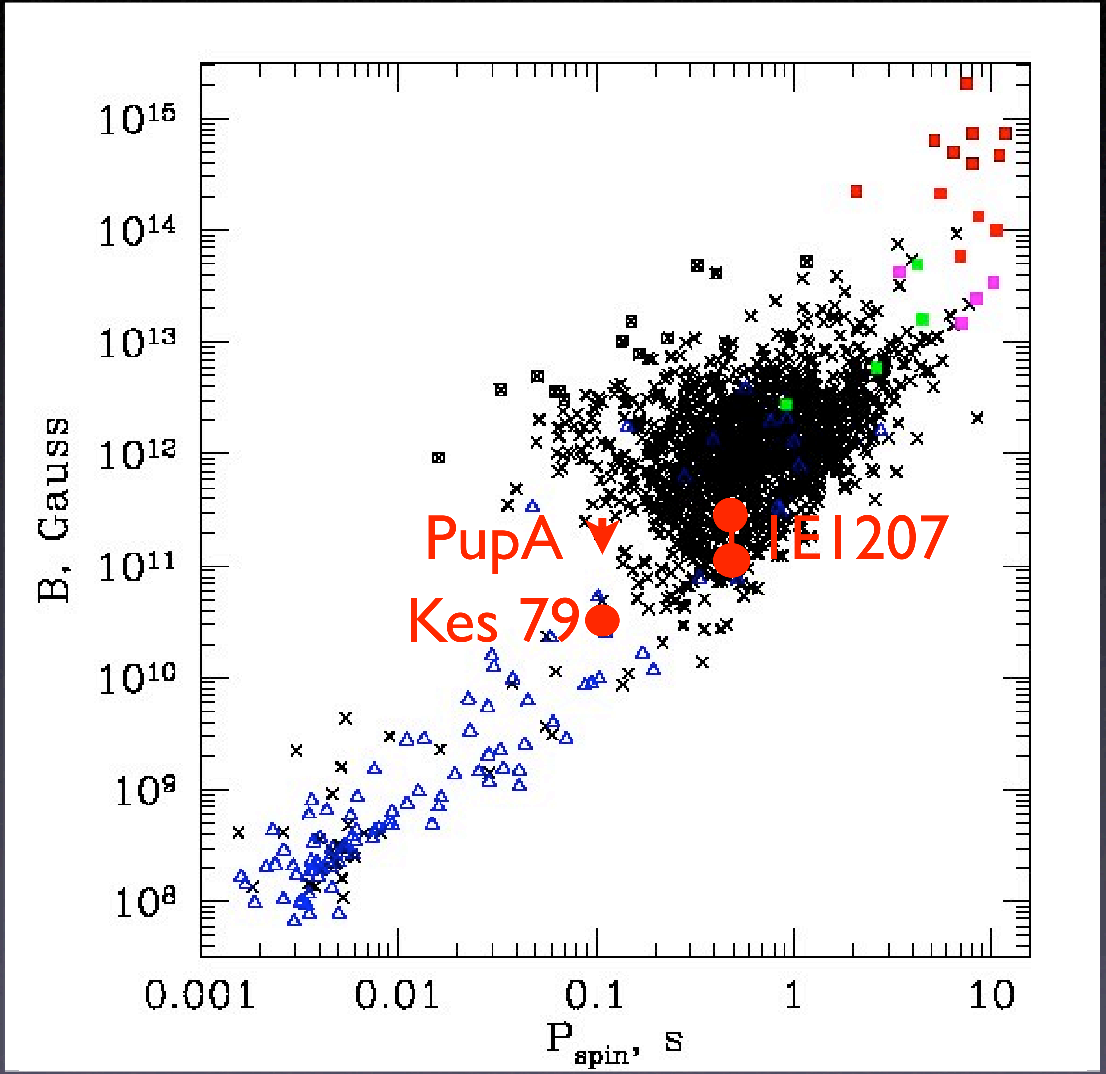


Gotthelf & Halpern 07:
No P changes (1993-2005),
$dP/dt < 10^{-16}$

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

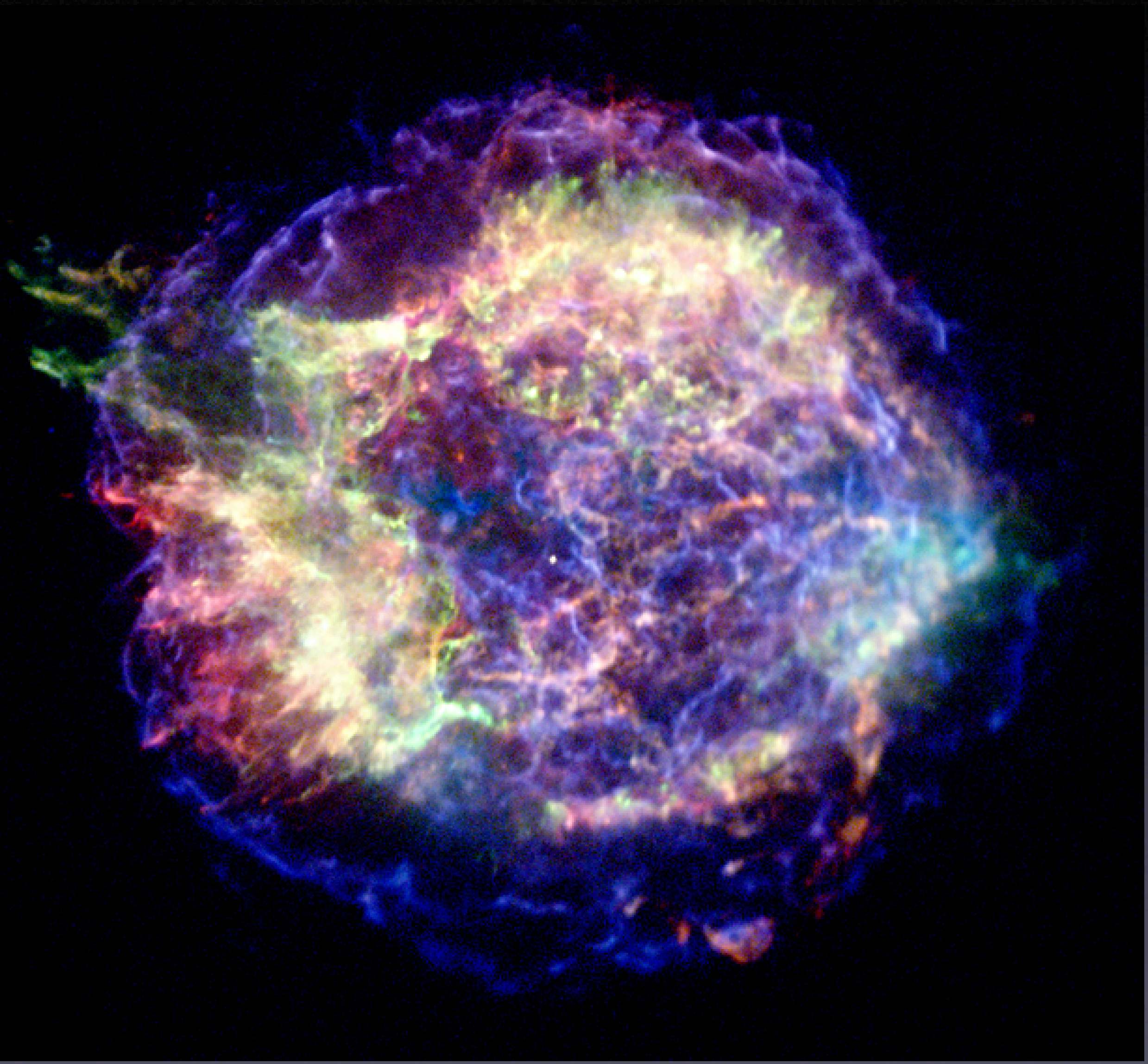
Low-B neutron stars

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



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

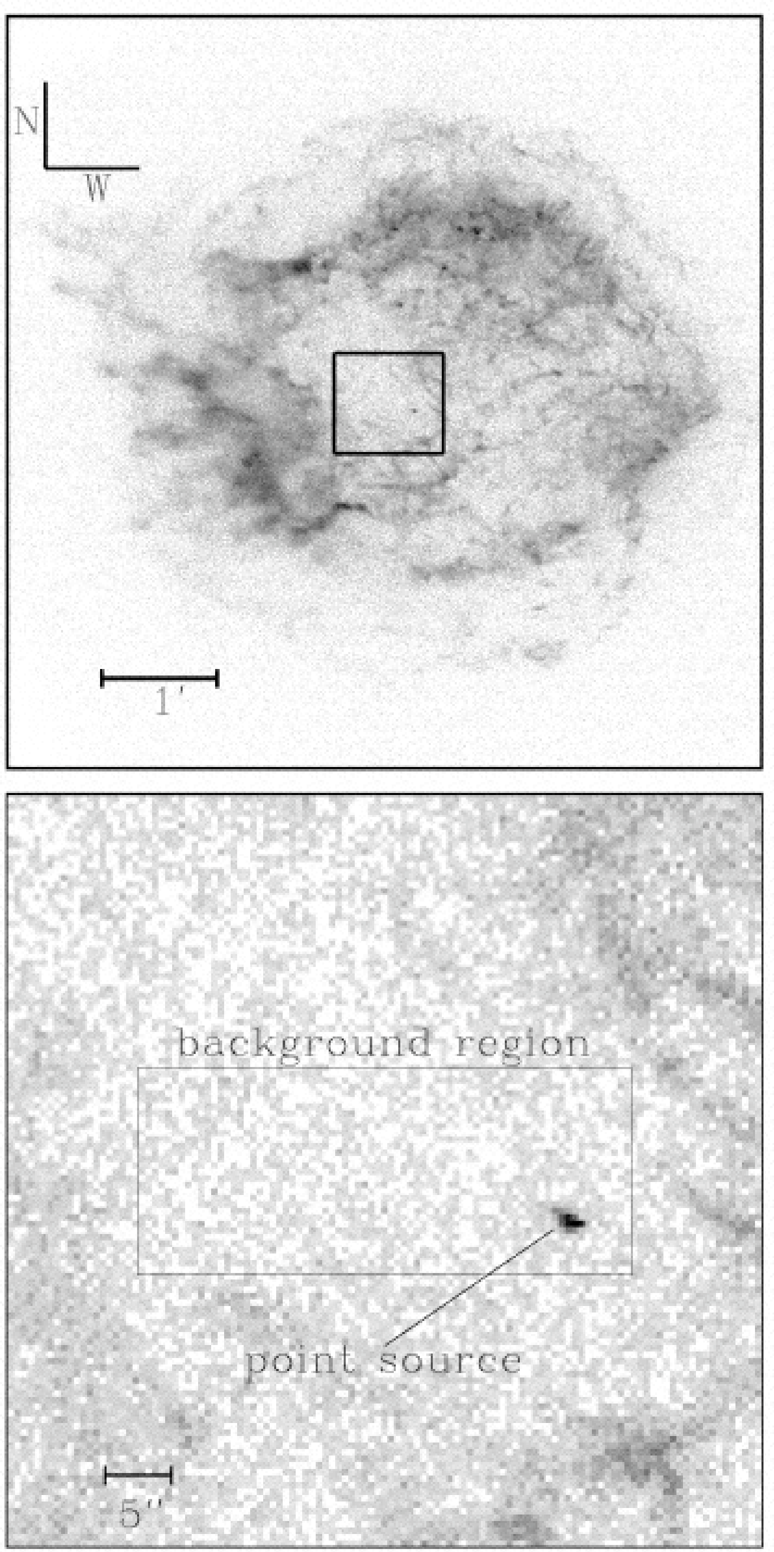
Cassiopeia A CCO



Chandra discovery 1999

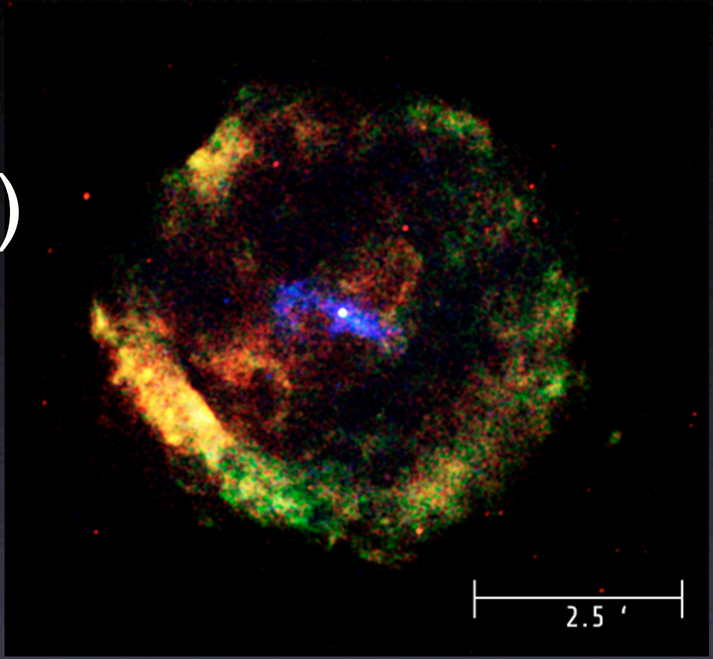
Youngest known
supernova remnant
with central NS

Is Cas A a Pulsar?



L: Cas A
(Chakrabarty+01)

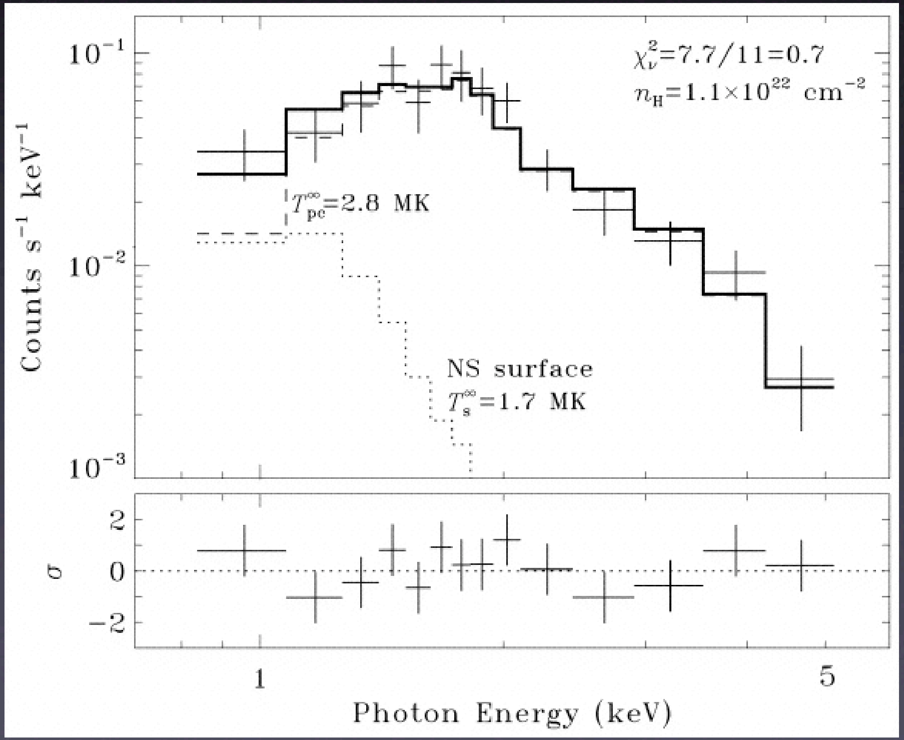
R: G11.2-0.3,
M. Roberts

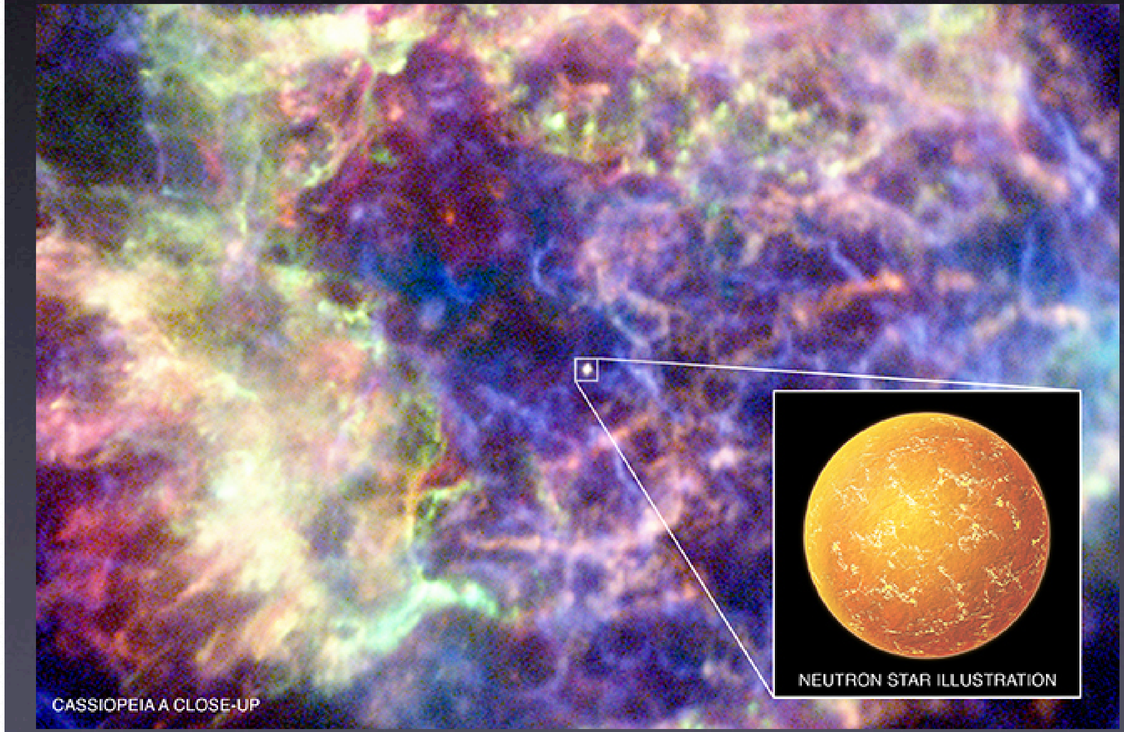


- No extended X-ray emission (Chakrabarty+01,Pavlov+09)
- No radio pulsations

Spectrum of Cas A CCO

- Consistent with blackbody
- Inferred radius ~0.3 km

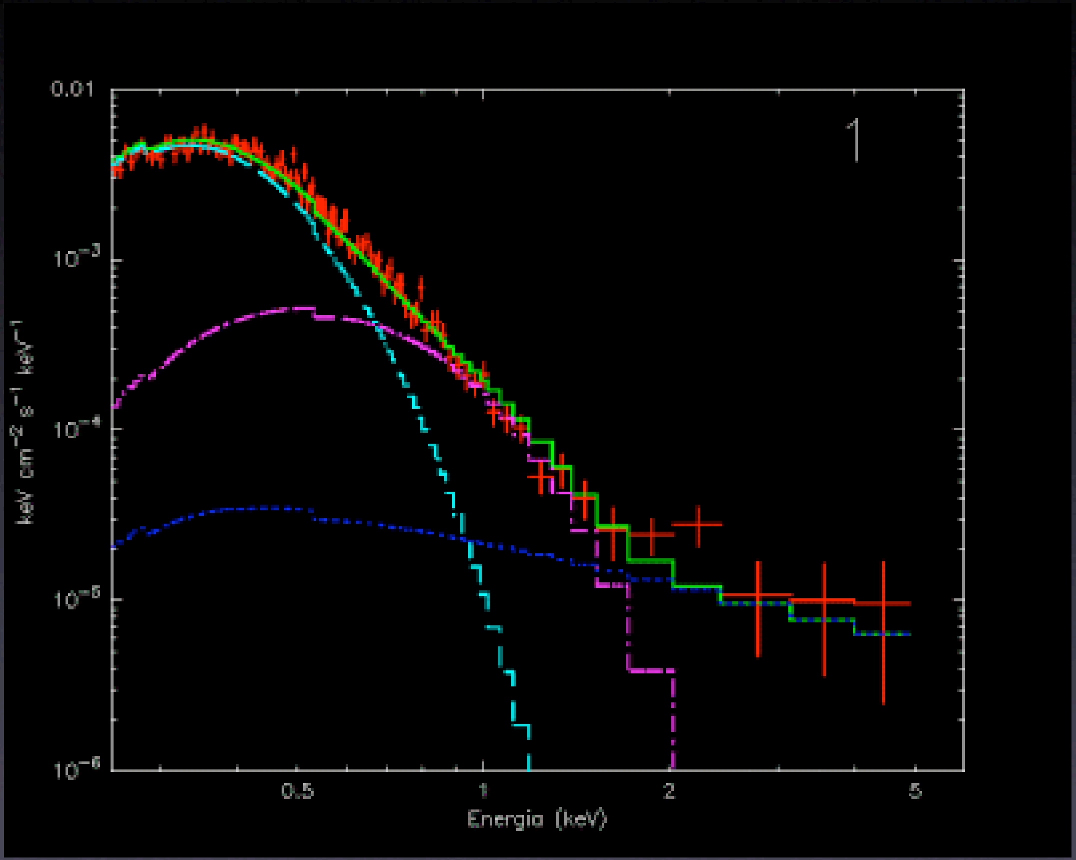




Pavlov+00

Pulsations

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

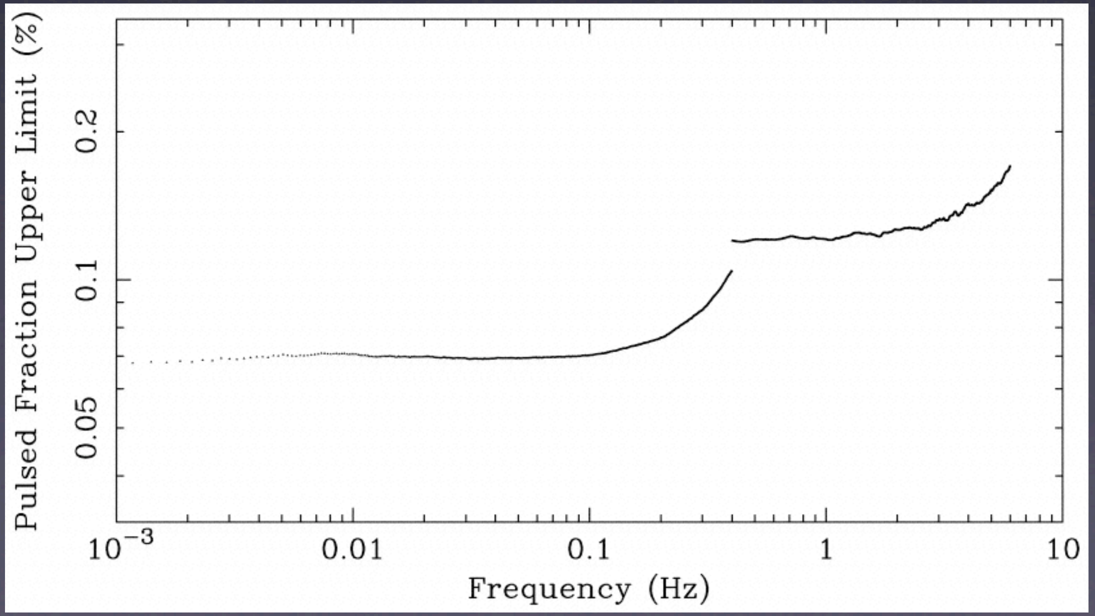


XMM phase-resolved spectra of PSR 1055-52

Timing Tests on Cas A

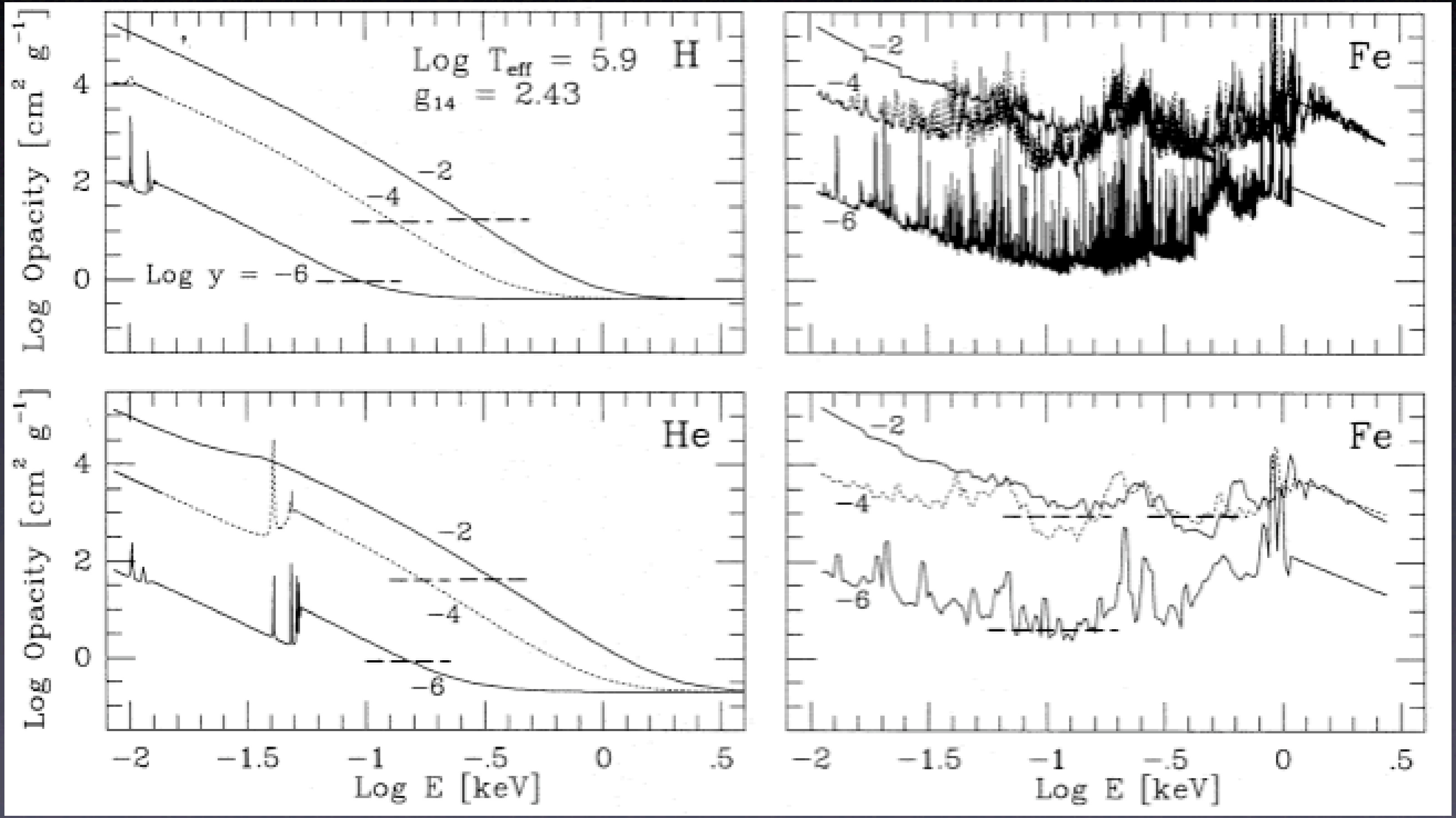
- Variability not seen 2000-2003 (Teter+04)
- No pulsations seen, pulsed fraction ~<12% (Mereghetti+02, Halpern+10)

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



NS Atmospheric Opacities

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

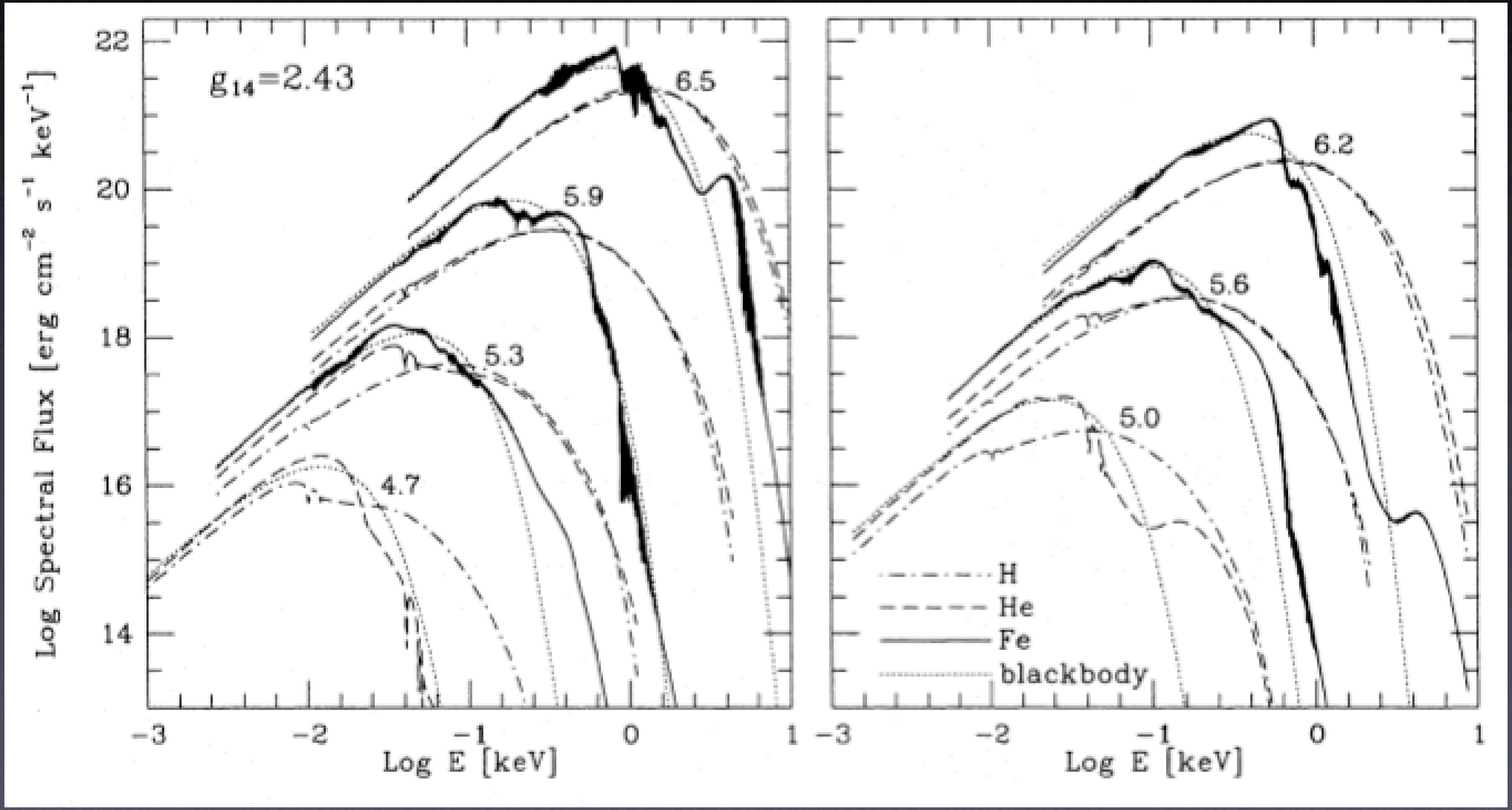


Magnetic fields important above B~10^{10} G

Zavlin+96

Low-B NS Atmospheres

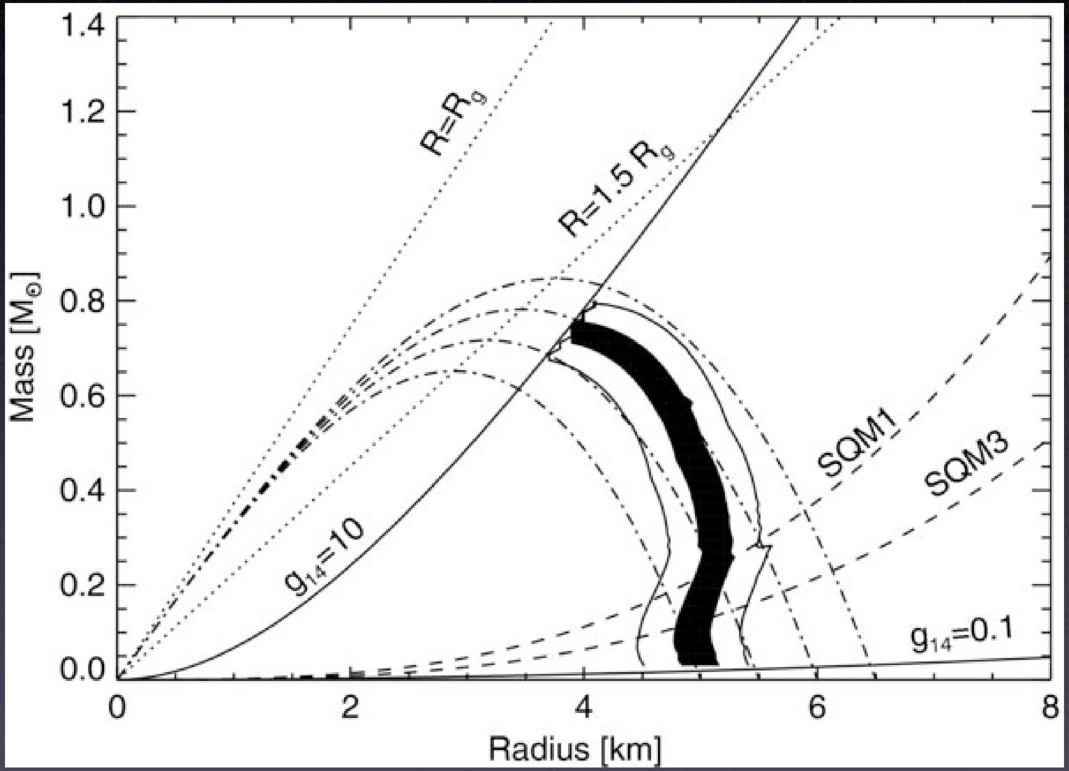
H, He shift flux to higher E vs. blackbodies
Infer larger radius for given spectrum



Zavlin+96

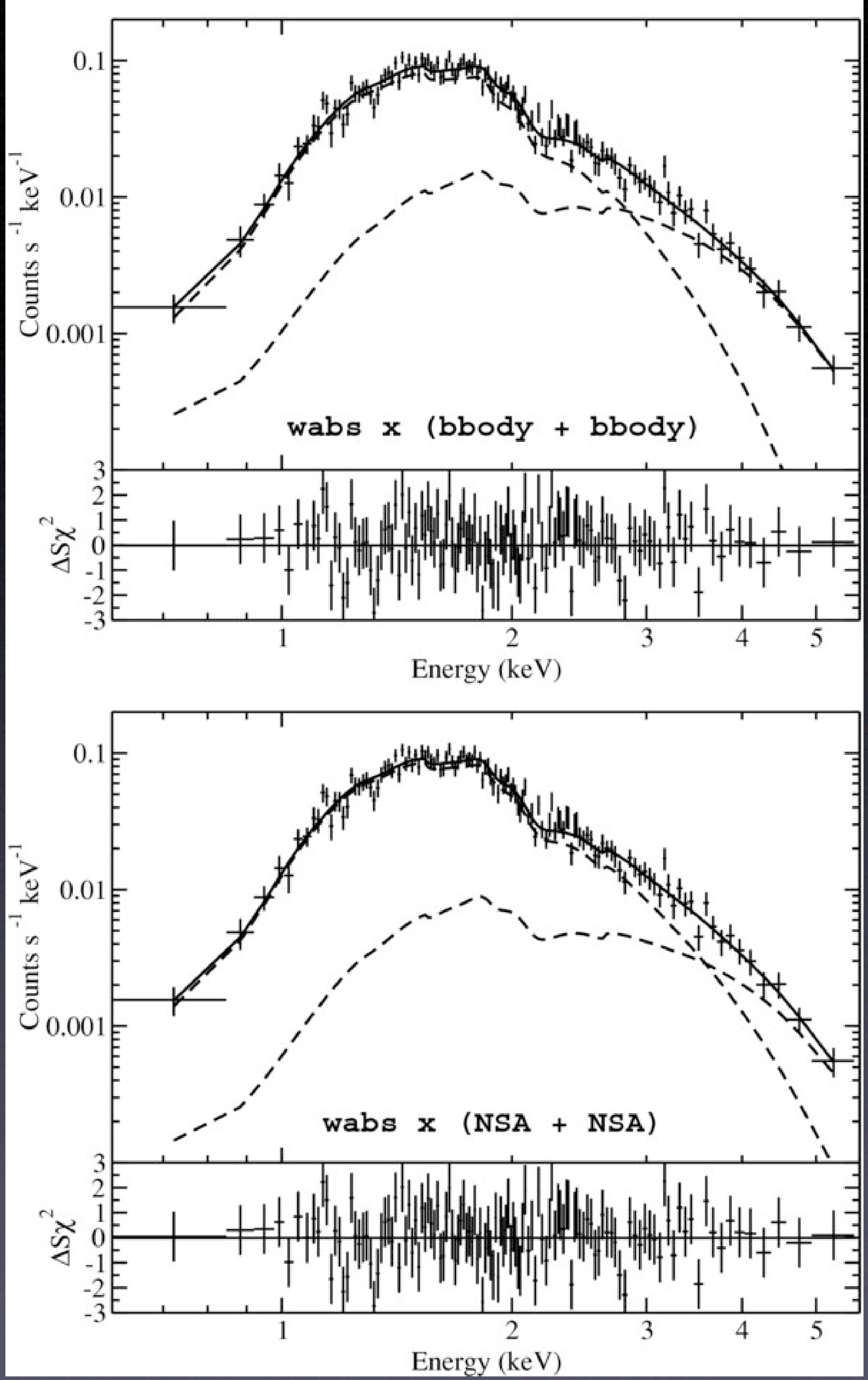
Low-B H for Cas A CCO?

- 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?



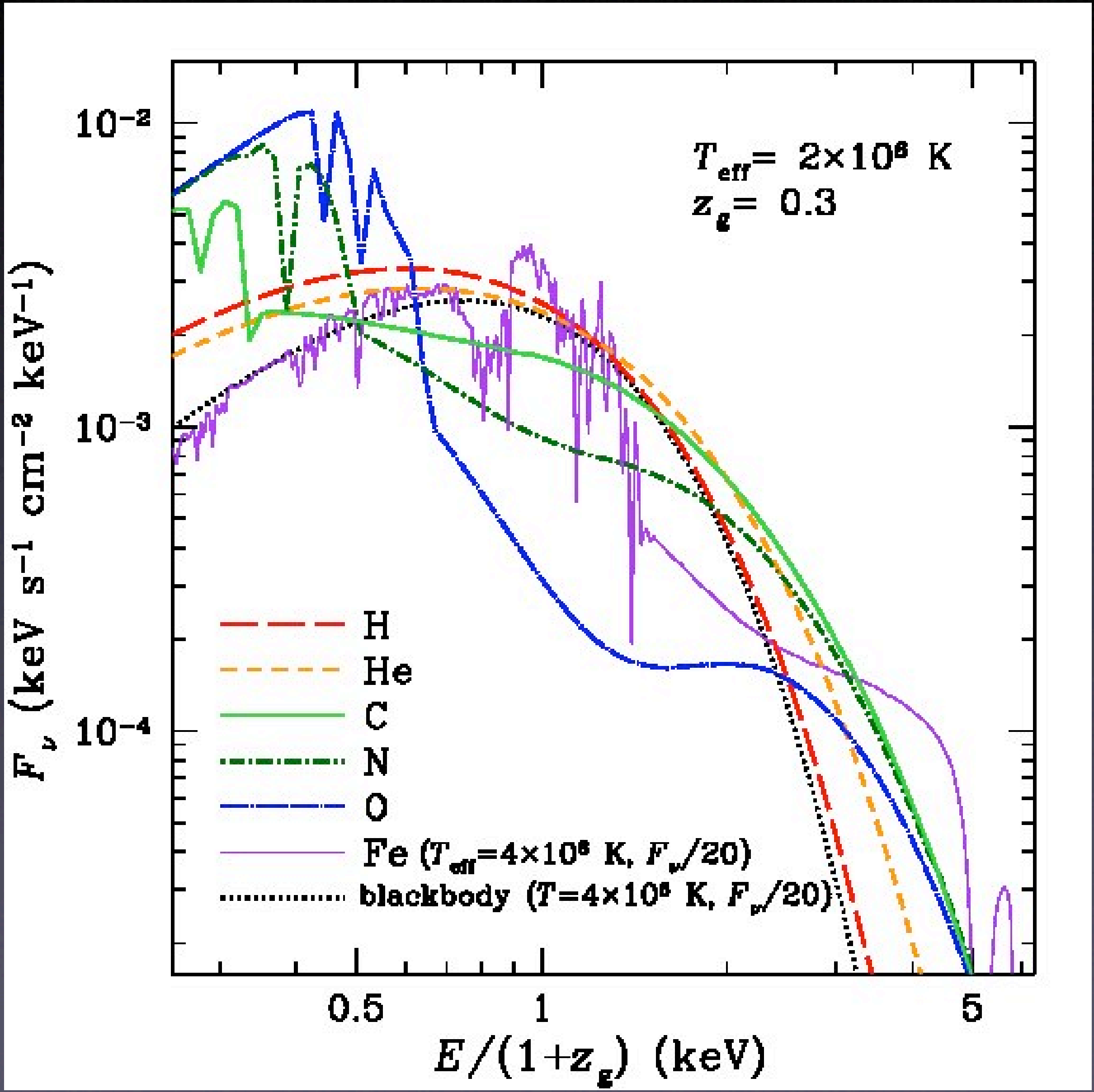
- Two components (full surface + hot spot) explain spectra for R~12 km
- But should probably produce pulsations

Pavlov+09

Alternative atmospheres

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

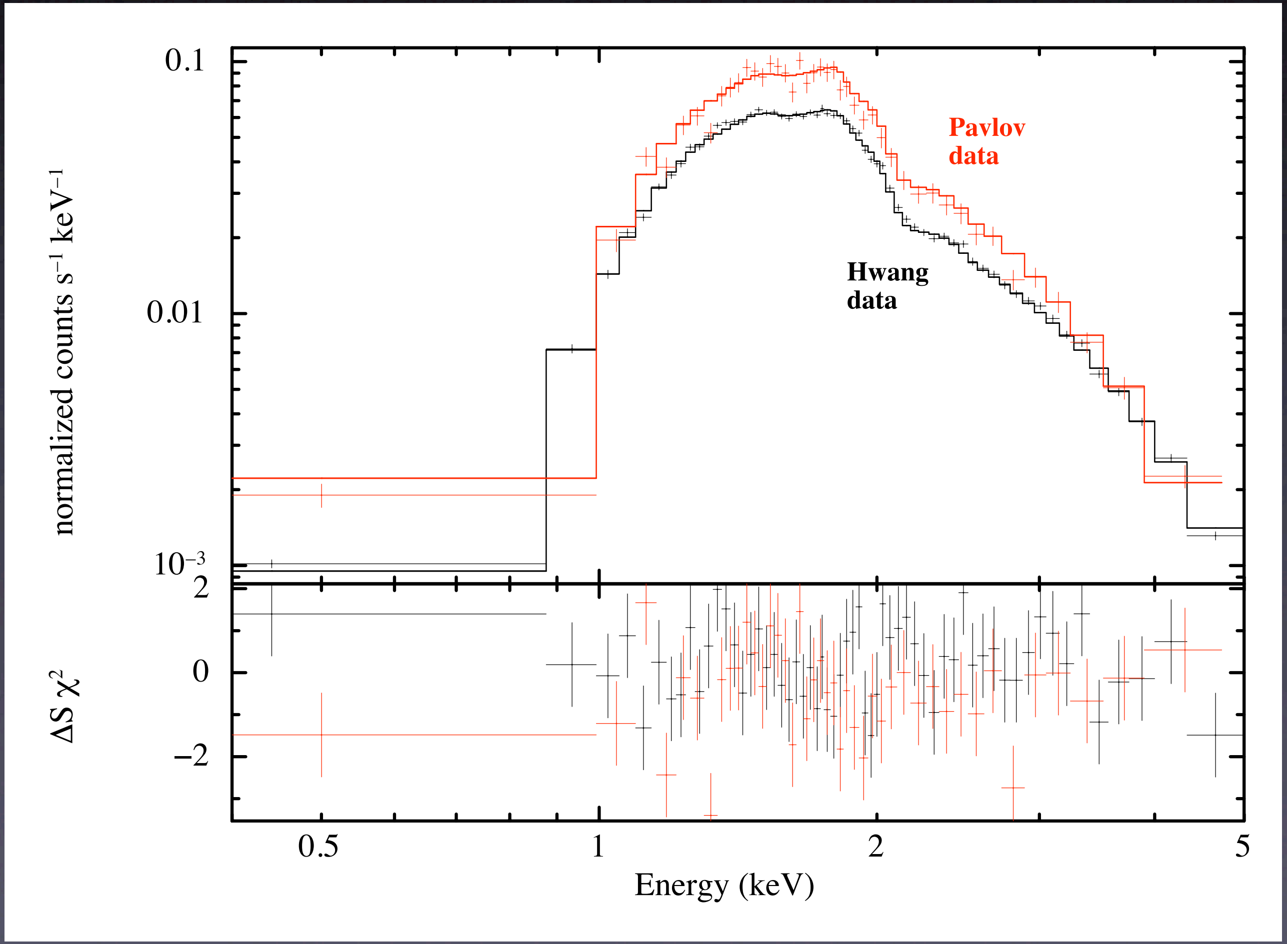
Ho & Heinke 09



Carbon Atmosphere

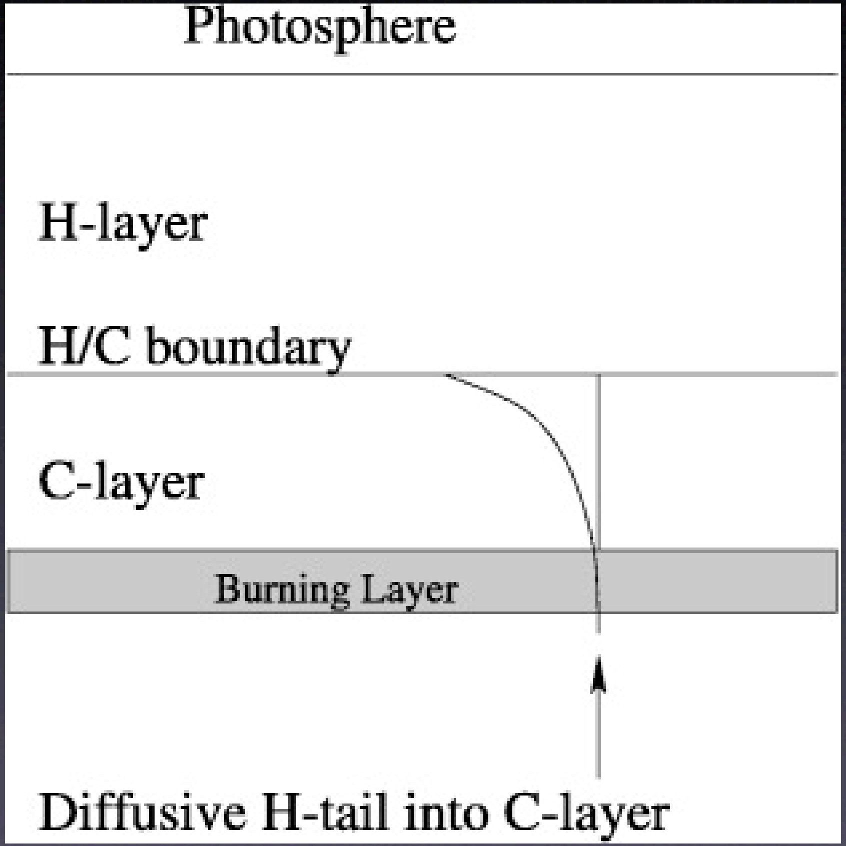
- Fit 1 Ms of Chandra data
- Only carbon atm. fit consistent with NS radius, ~10-12 km; also best fit

Ho & Heinke 09



Why a C atmosphere?

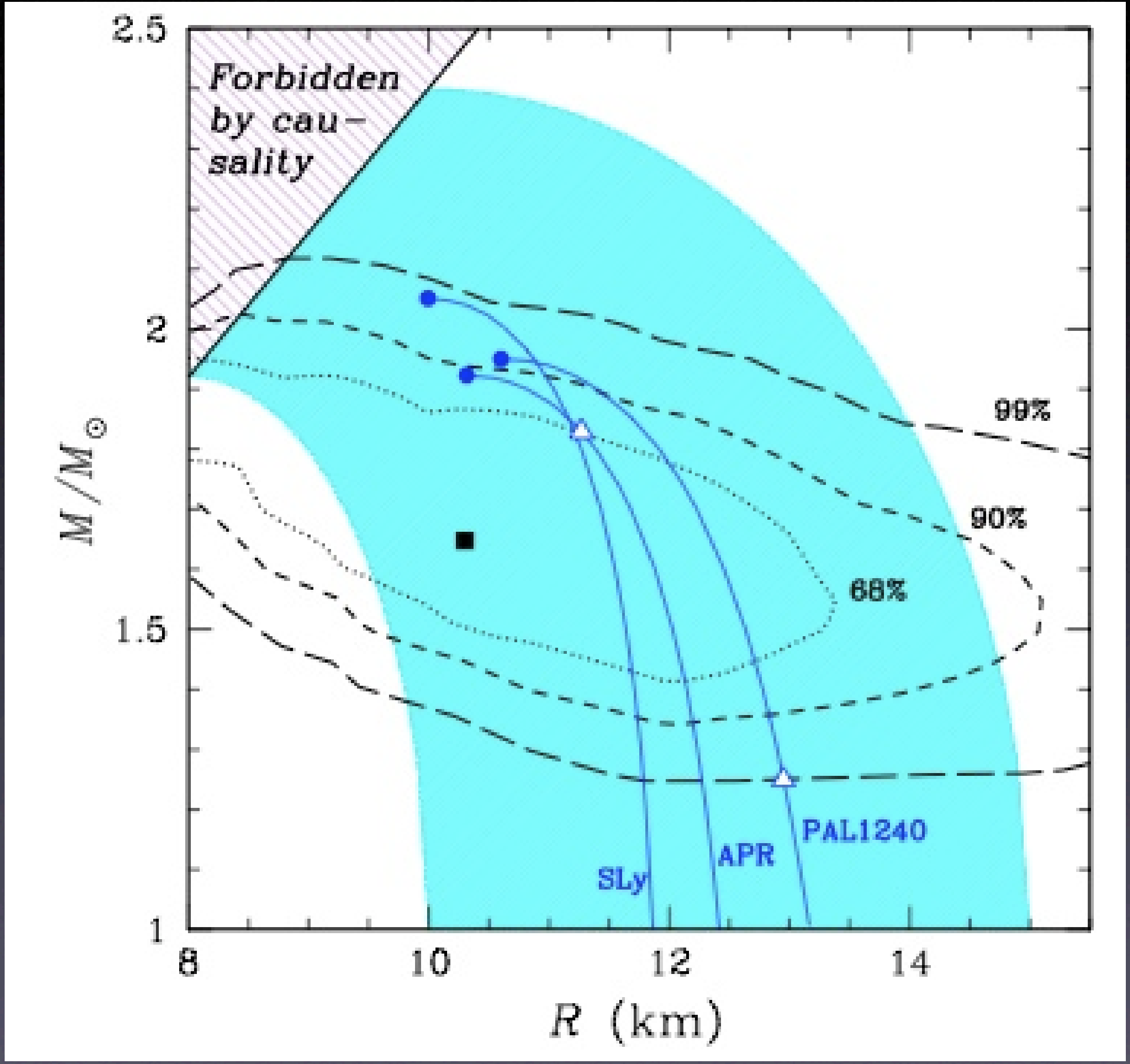
- Cas A is youngest NS
- NSs likely accrete many elements
- H, He diffuse down to hotter layers, are burned (Chang +03,Chang+10.)
- Low-B NSs burn away H, He for first 1000 years, then new H atm accretes?



Chang+03

Cas A NS constraints

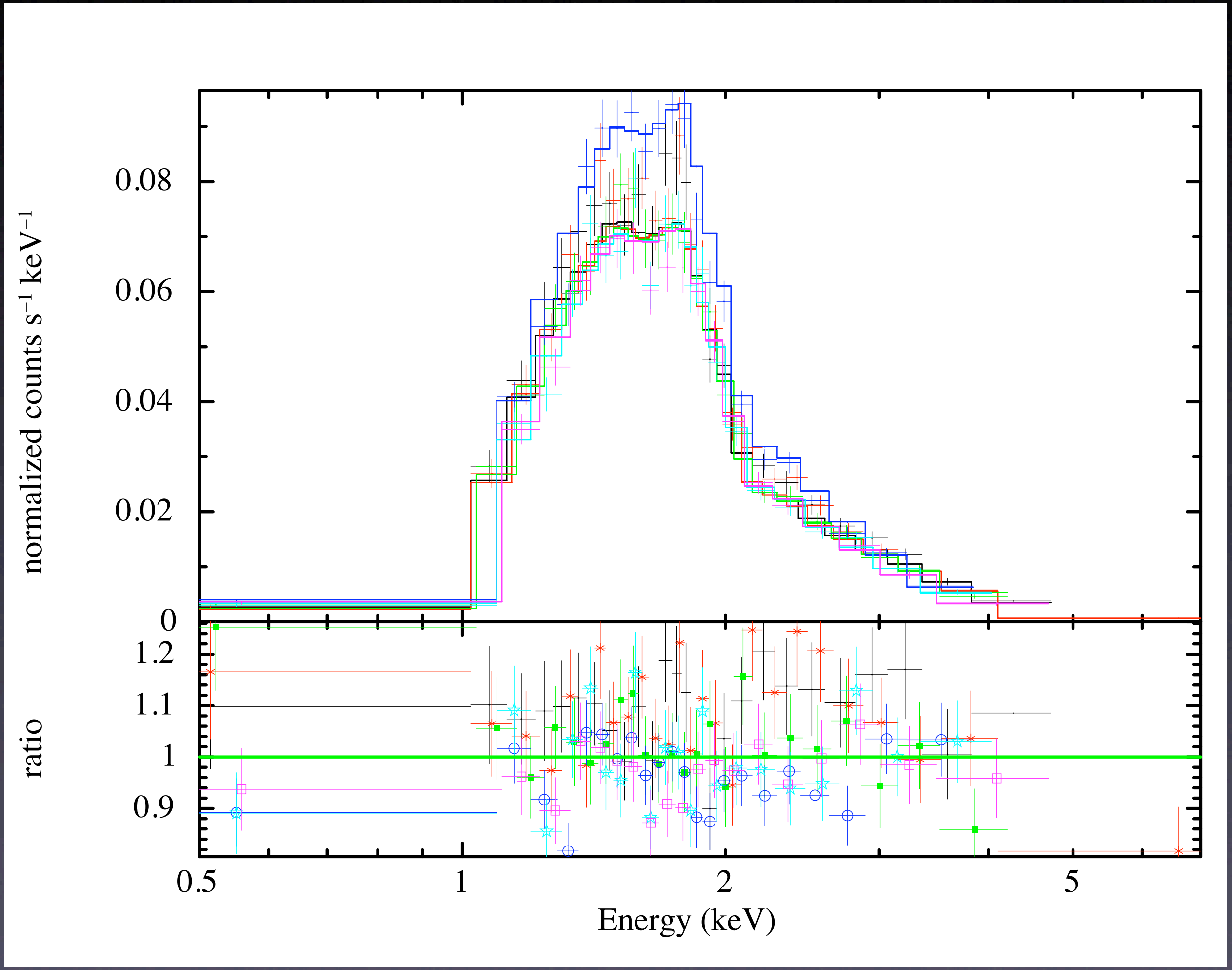
- Range of M, R are consistent with standard NS EOSs (blue region)
- Uncertainty in atmosphere composition, B, temp. homogeneity affect constraints



Yakovlev+11

Evidence of Variability

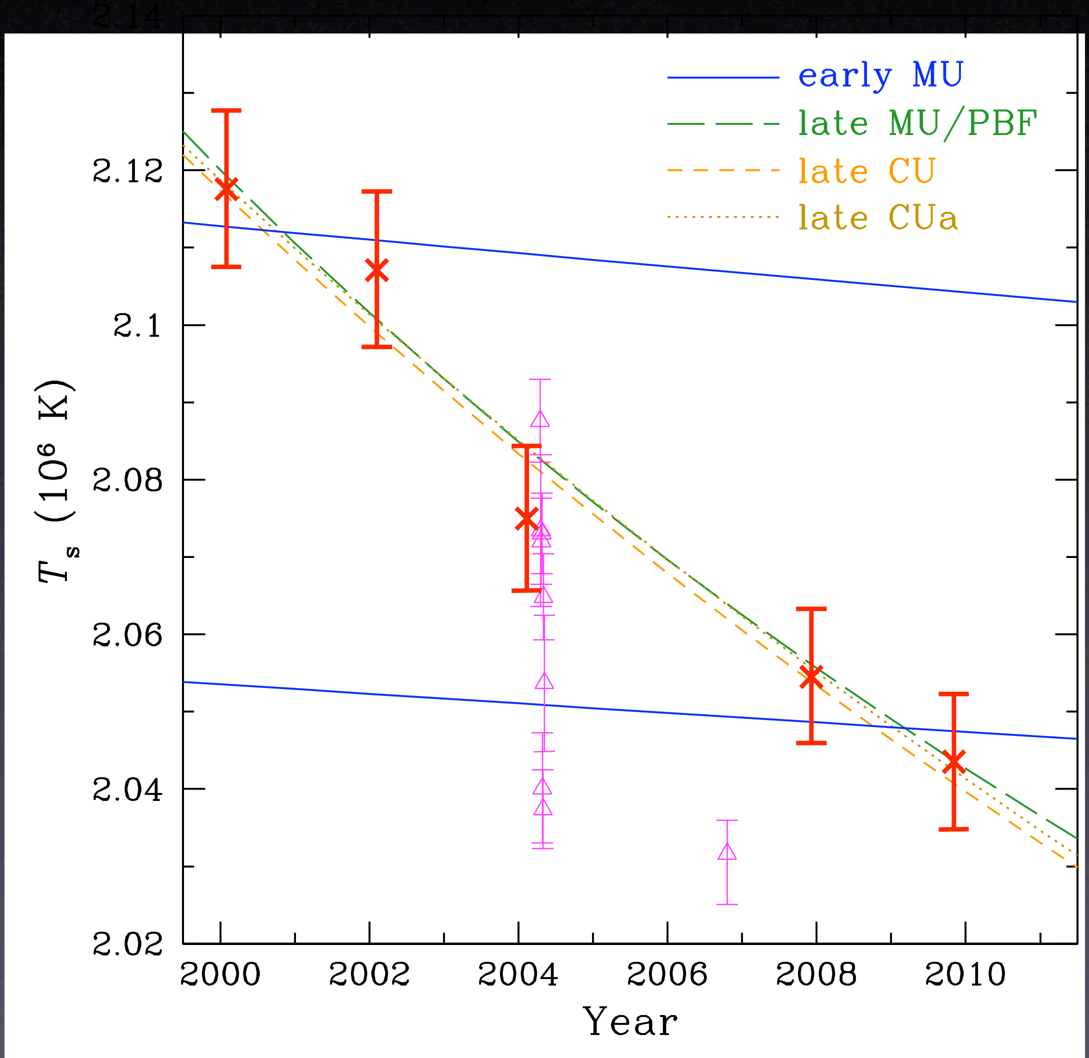
- Best-calibrated observations over 10 years show flux decrease
- Spectral uniformity rules out known calibration effects



Heinke & Ho 2010

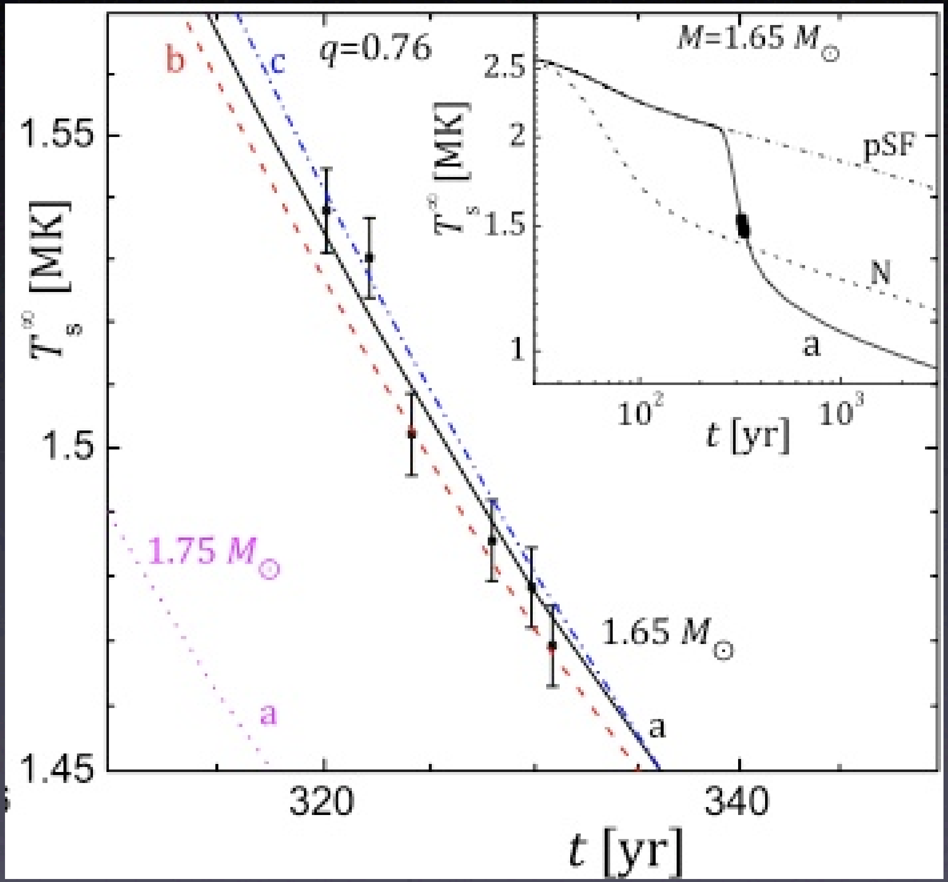
Observing Cas A Cooling

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

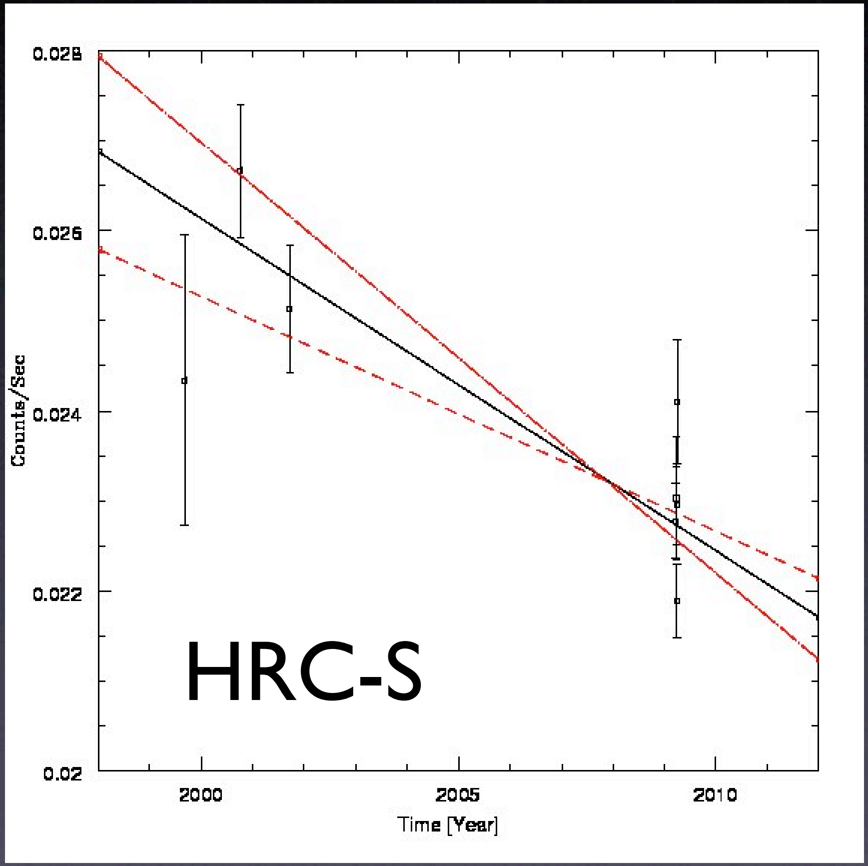


Heinke & Ho 2010

More evidence of cooling



Shternin+11; new datapoint, & explanation (w/Page+11)



El-Shamouty in prep; HRC-S, ACIS-I countrate declines

NS cooling

Dominated by νs

Nucleon direct URCA,

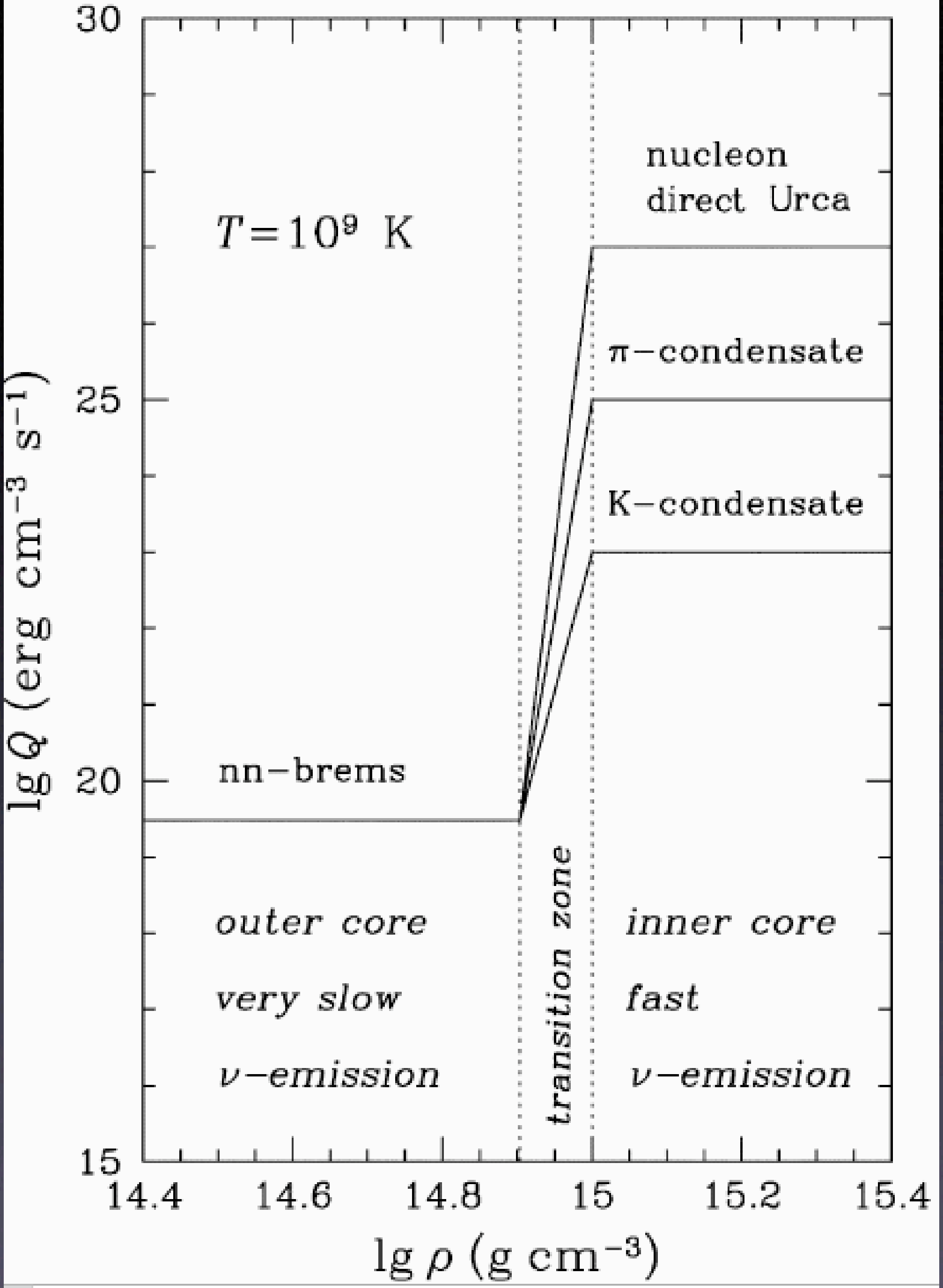
$n \rightarrow p + e + \nu$

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

Modified URCA (requires 3-nucleon interaction)

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

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

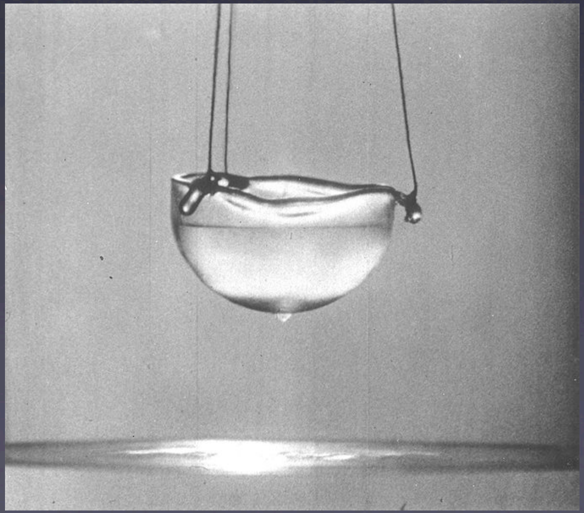


Yakovlev & Pethick 2004

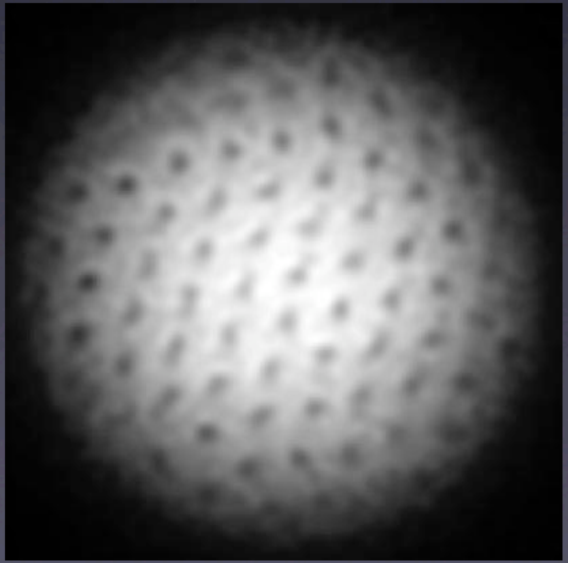
Superfluidity

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

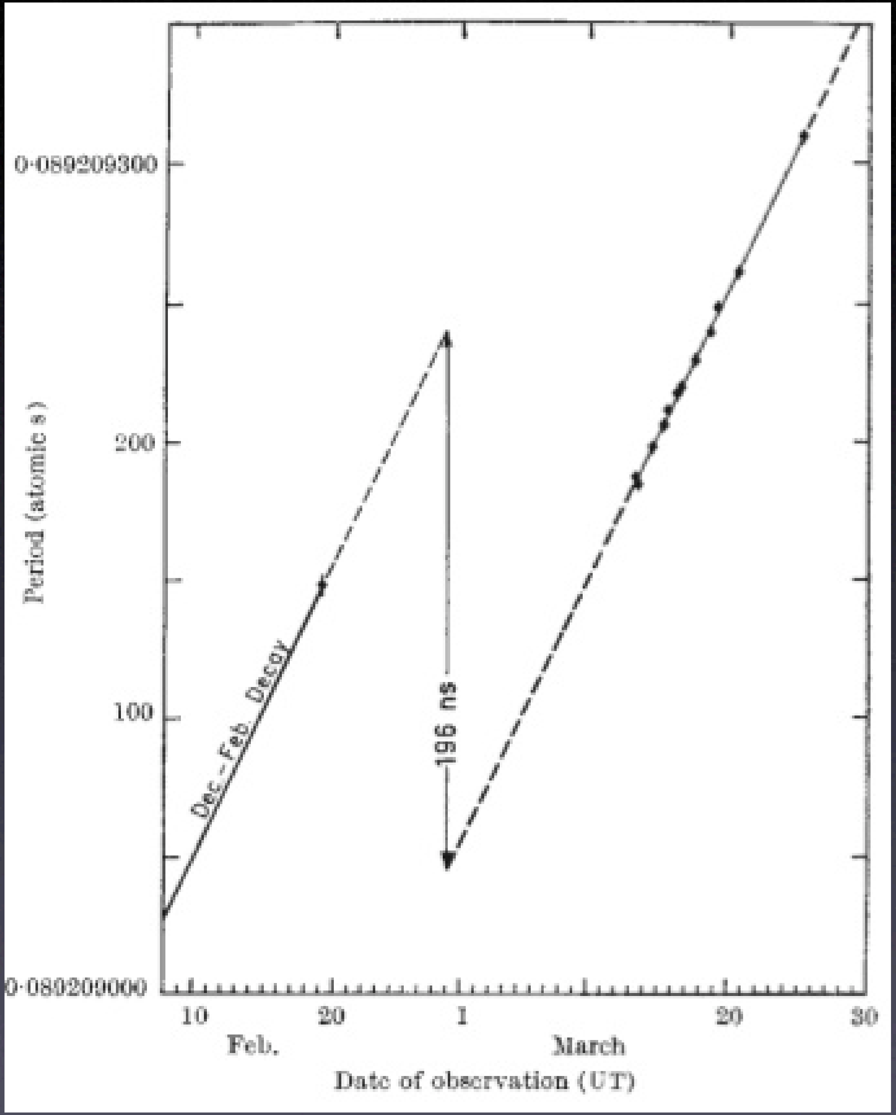
Requires "low" temperatures,
e.g. liquid helium <3 K.



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



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

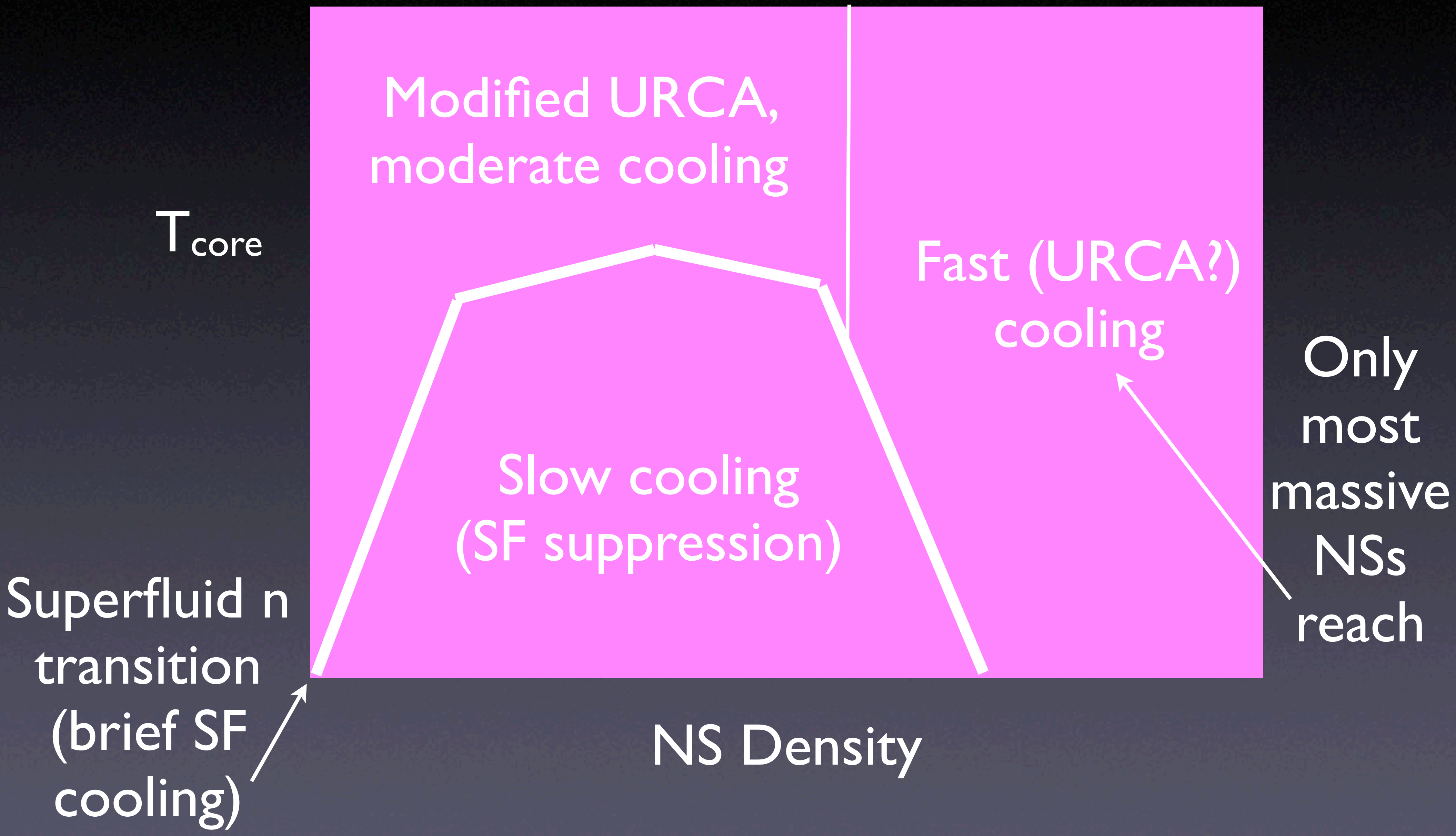
Glitches represent transfer of ang. mom. to lattice

Only previous direct evidence for SF in NSs, & only in crust (singlet n SF in crust, triplet n SF in core expected)

Effects of core superfluidity

- Superfluid p or n prevent URCA processes
- NS cores well below SF T_C cool by slow n-n bremss
- Around n SF T_C, brief fast cooling phase; n pairing releases ν-$\bar{\nu}$ pair. At T_C, pairs break, re-form, producing rapid (brief) cooling
-

Simple cooling picture



Modified URCA, moderate cooling

Fast (URCA?) cooling

T_{core}

Slow cooling (SF suppression)

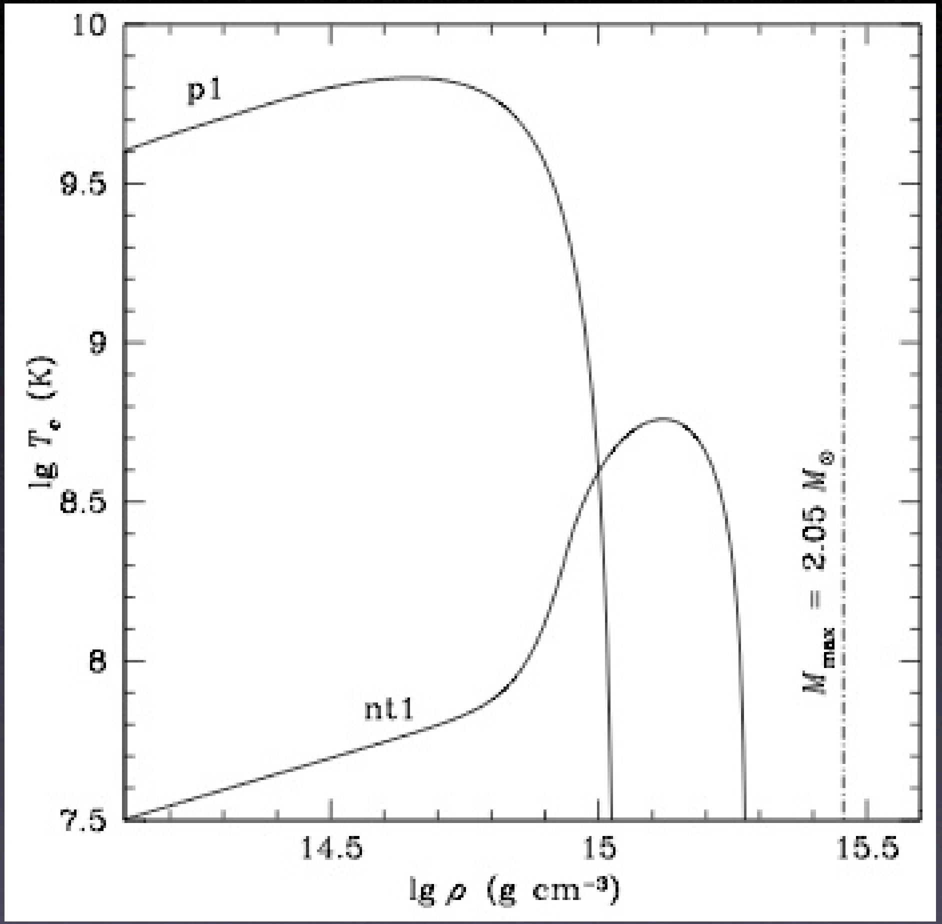
Only most massive NSs reach

Superfluid n transition (brief SF cooling)

NS Density

Superfluid transitions

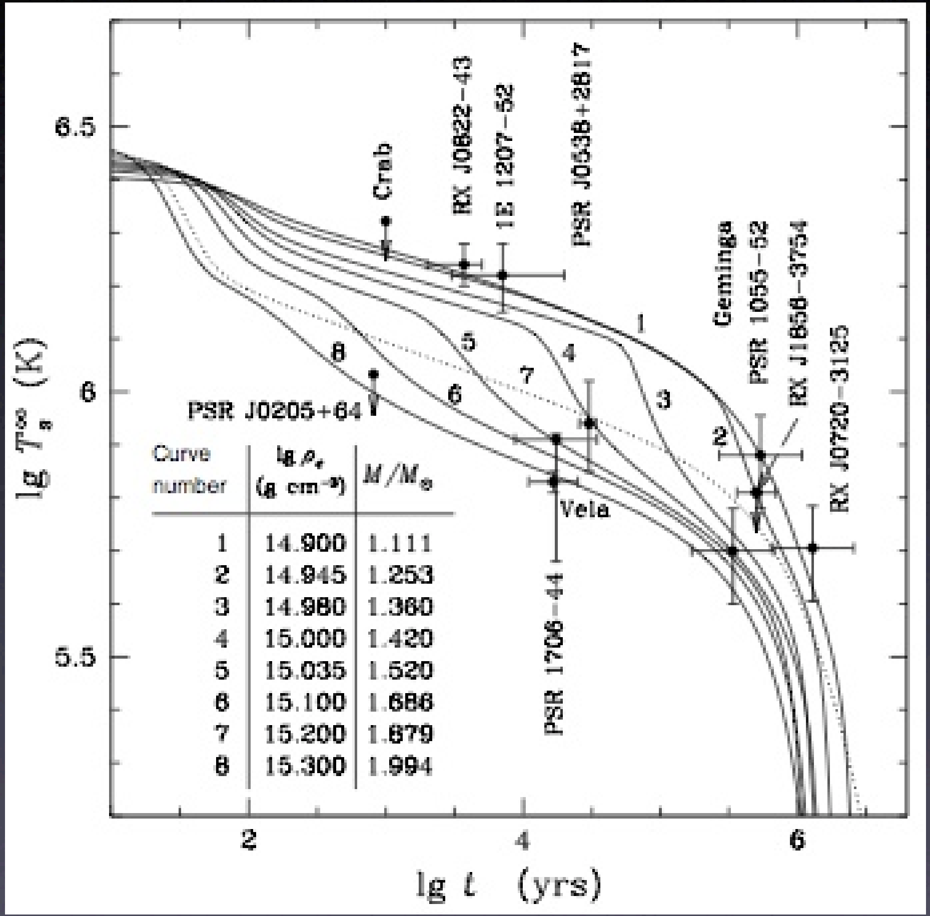
- SF critical temperatures depend on density
- SF p, n T_Cs not known
- p T_C estimated higher than core (triplet) n T_C.



Gusakov+04; one T_C theory for n, p SFs in NS

Cooling curves can have quick SF drop

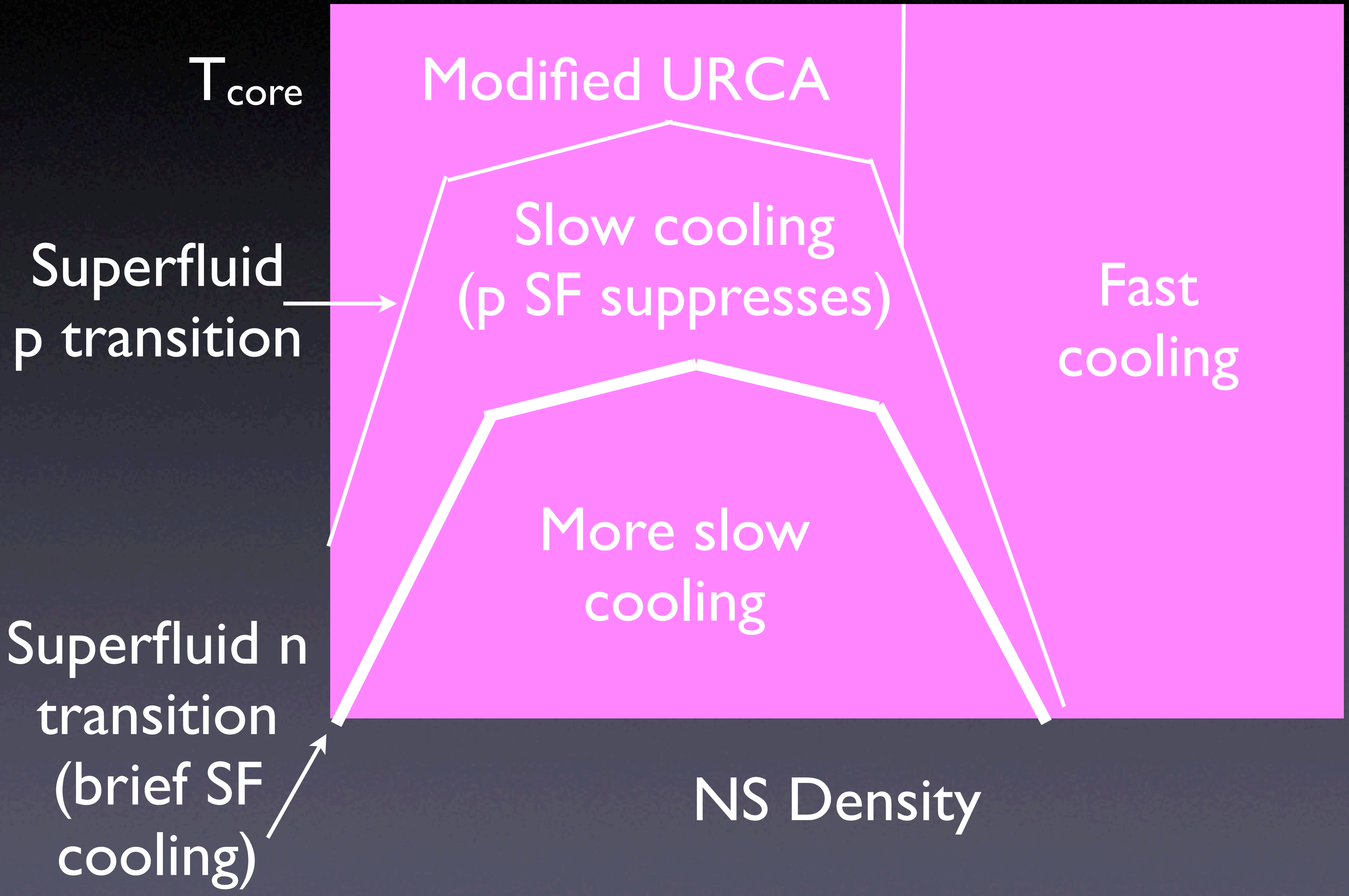
Time at which NS hits SF TC depends on prior cooling, on NS mass, envelope structure



Curve number	$\lg \rho_c$ (g cm^{-3})	$M/M_\odot$
1	14.900	1.111
2	14.945	1.253
3	14.980	1.360
4	15.000	1.420
5	15.035	1.520
6	15.100	1.686
7	15.200	1.879
8	15.300	1.994

Gusakov+04; cooling curves with SF T drops

Cooling, with protons



T_{core}

Modified URCA

Slow cooling
(p SF suppresses)

Superfluid
p transition

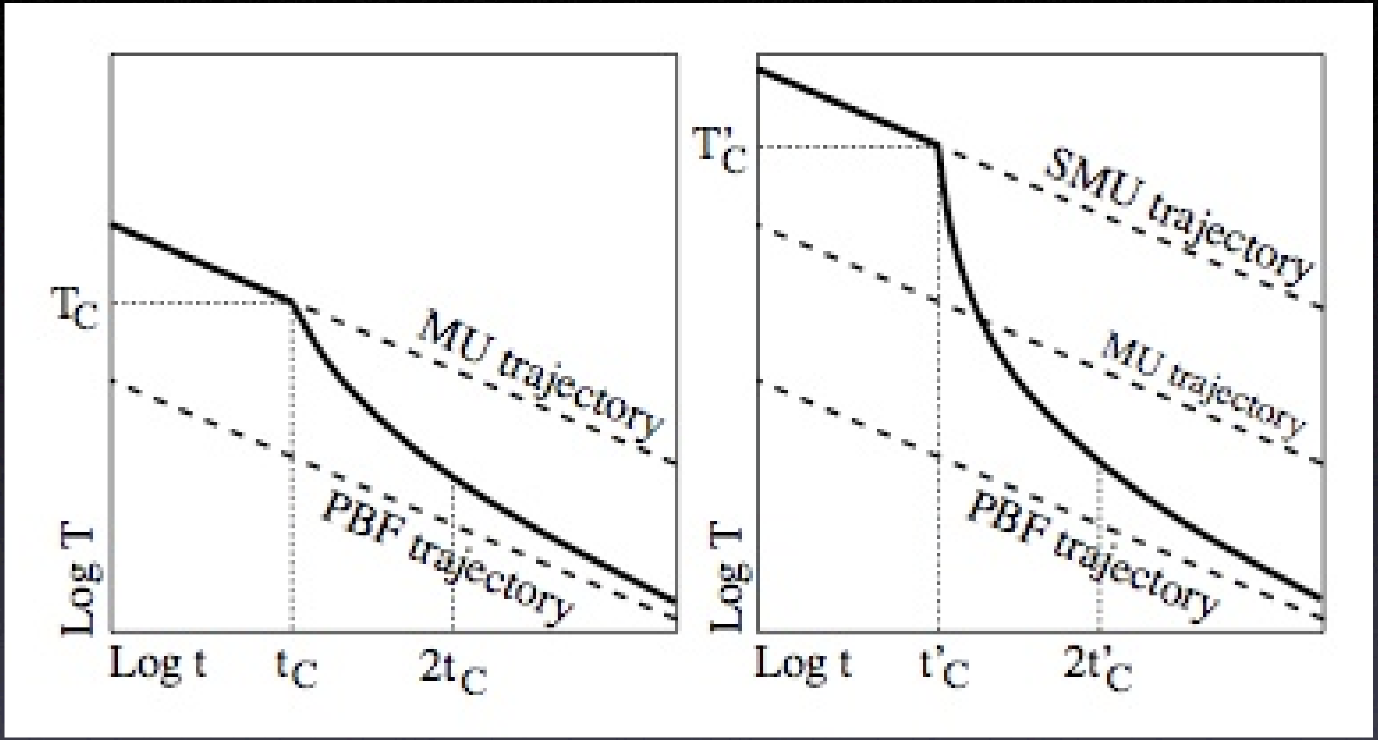
Fast
cooling

More slow
cooling

Superfluid n
transition
(brief SF
cooling)

NS Density

Hot NS requires p SF



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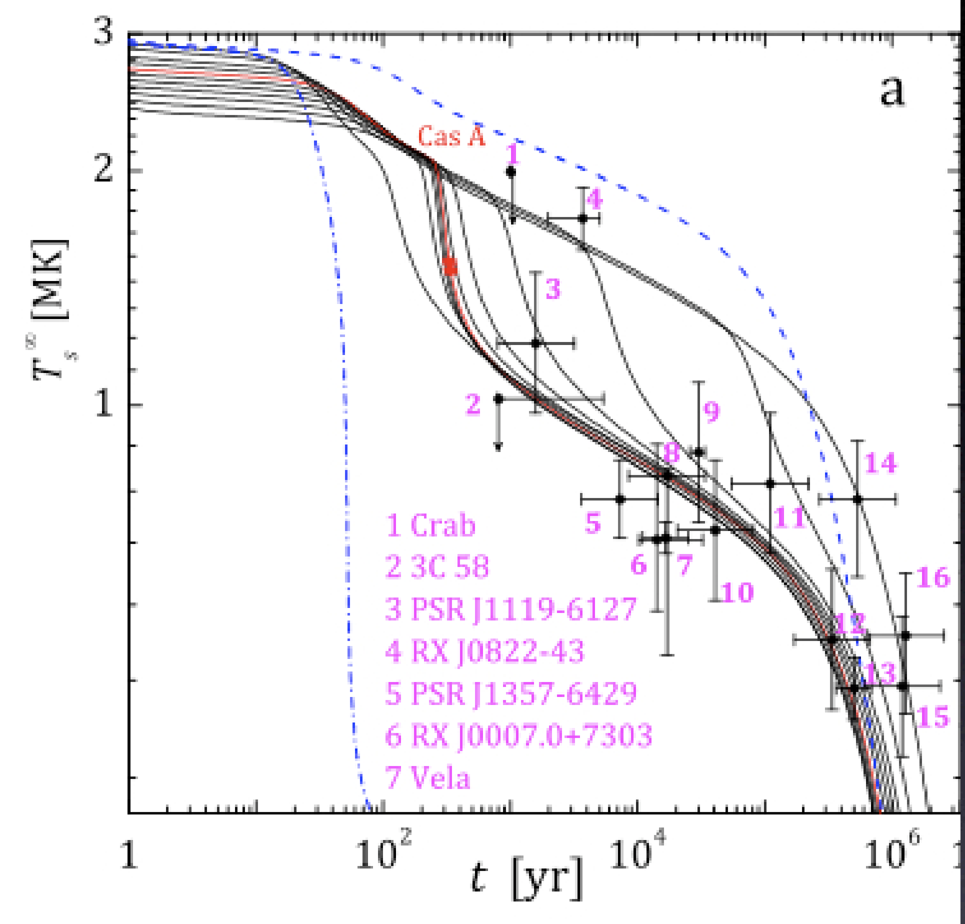
Normal (modified URCA) cooling
suppressed by p SF (p pairing)

Very rapid T drop of Cas A NS
requires p SF to suppress Urca

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

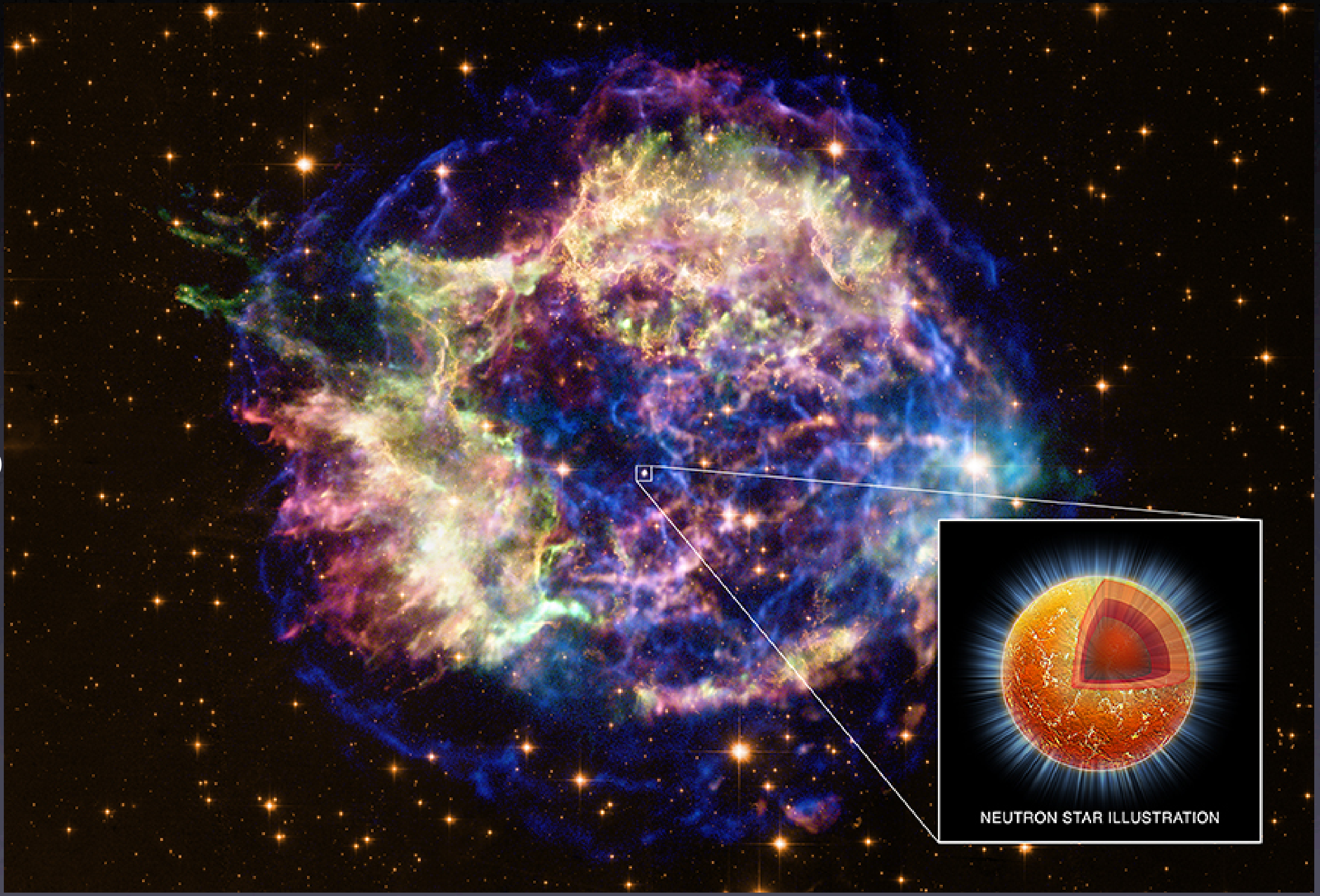
Probably strongest evidence for superfluidity in NS cores



Shternin et al. 2011

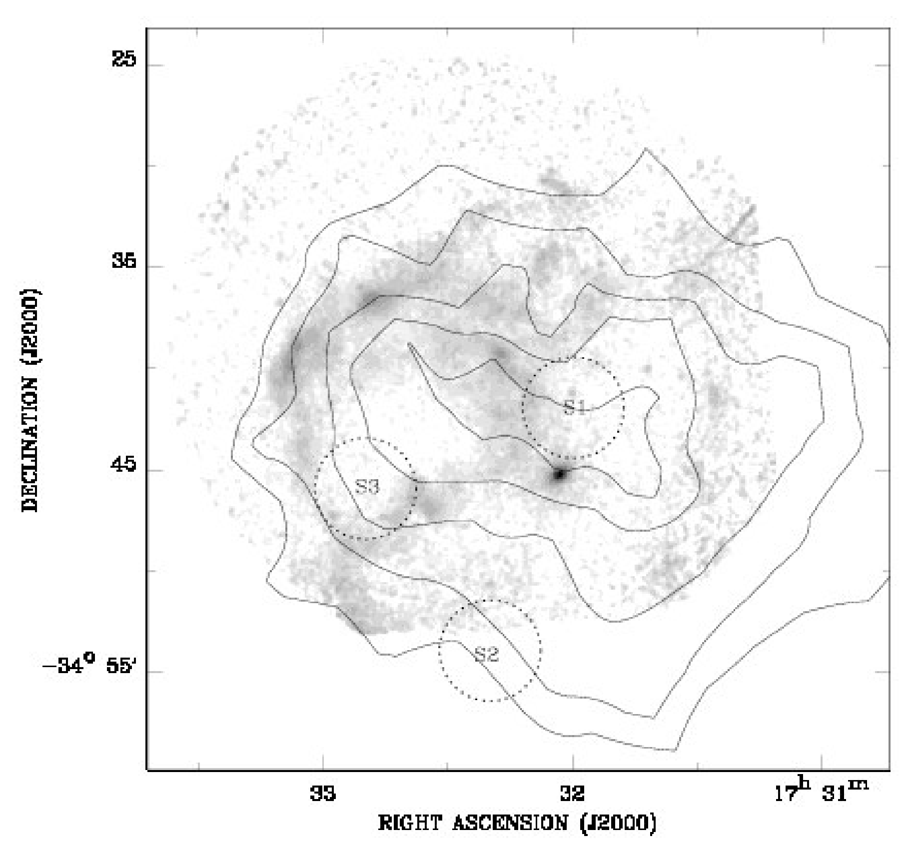
Cas A results

- First non-H NS atmosphere found
- Cooling directly measured
- Direct evidence fo n SF in core, indirect for p SF
- Future obs to test cooling, constrain superfluidity models



Cas A (NASA Chandra/Hubble)

Other CCOs



G353.6-0.7, Tian+

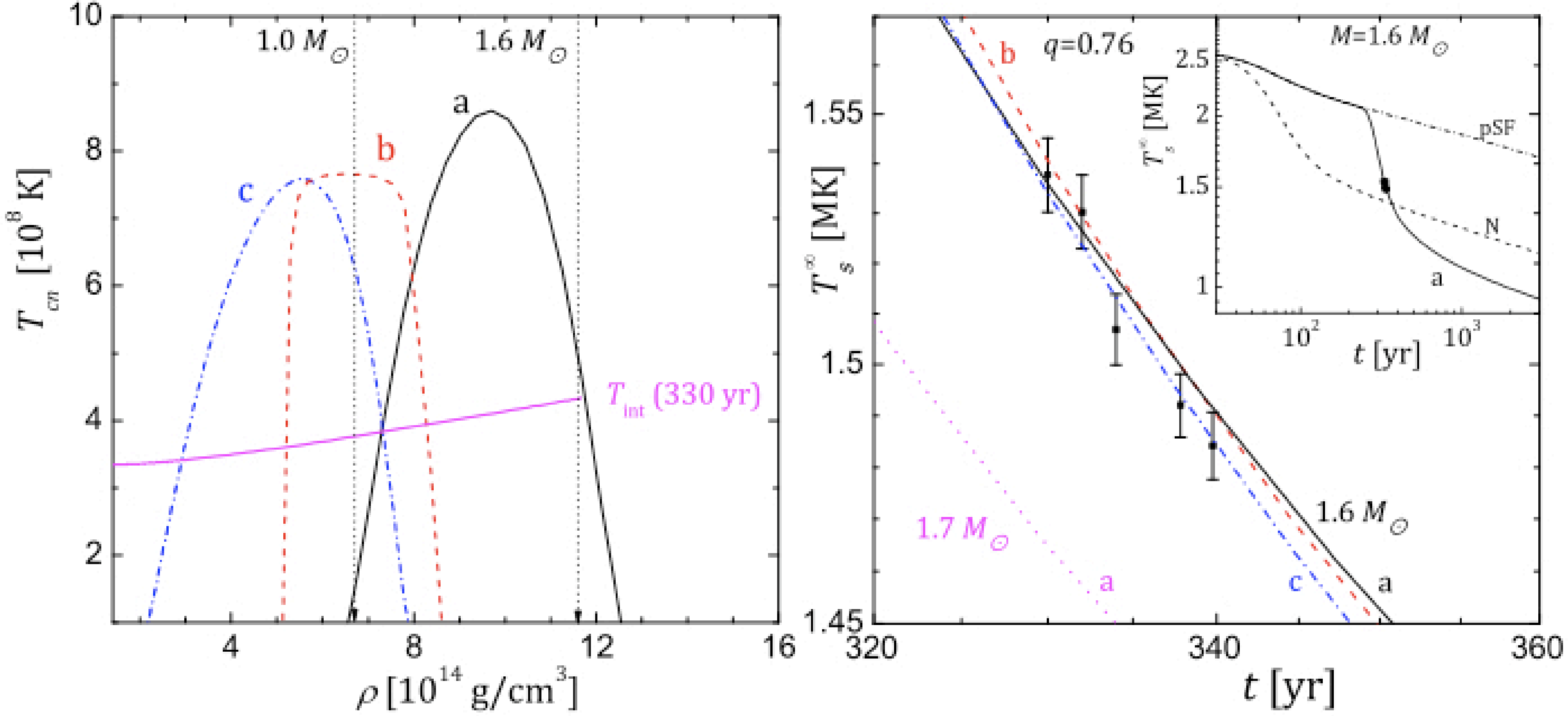
- Six more CCOs where pulsations not yet detected, pulsed fraction <7% for two
- Are spectra consistent with uniformly emitting NSs, either H/He or C atm?
  Or are hot spots required?
- Distances & ages not well-constrained.
  Estimate distances from SNRs, NH (compare to extinction to horizontal-branch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

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

Movie of NS interior T

Wynn Ho,
from Shternin
results



Neutron triplet superfluidity in NSs, Shternin+2011

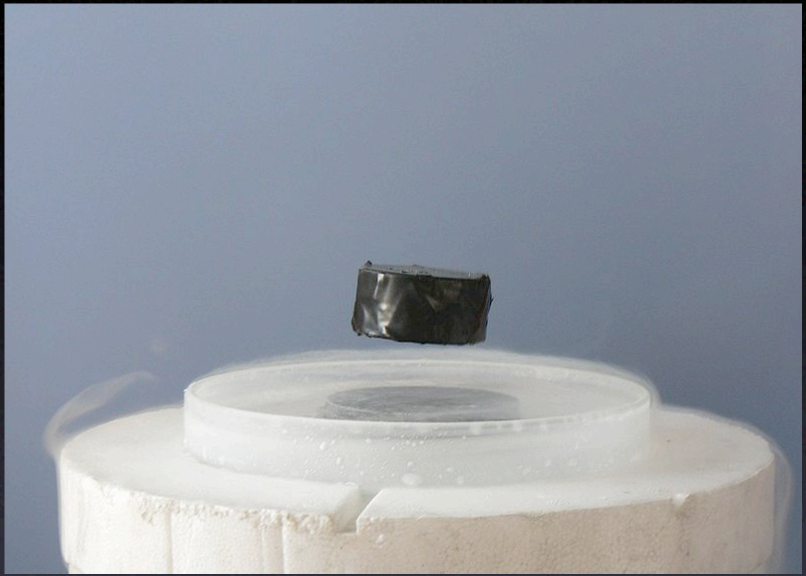
Cooling by Cooper pair formation
in neutron superfluid, T_{crit}~[6-9]*10^8 K

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

Superconductivity

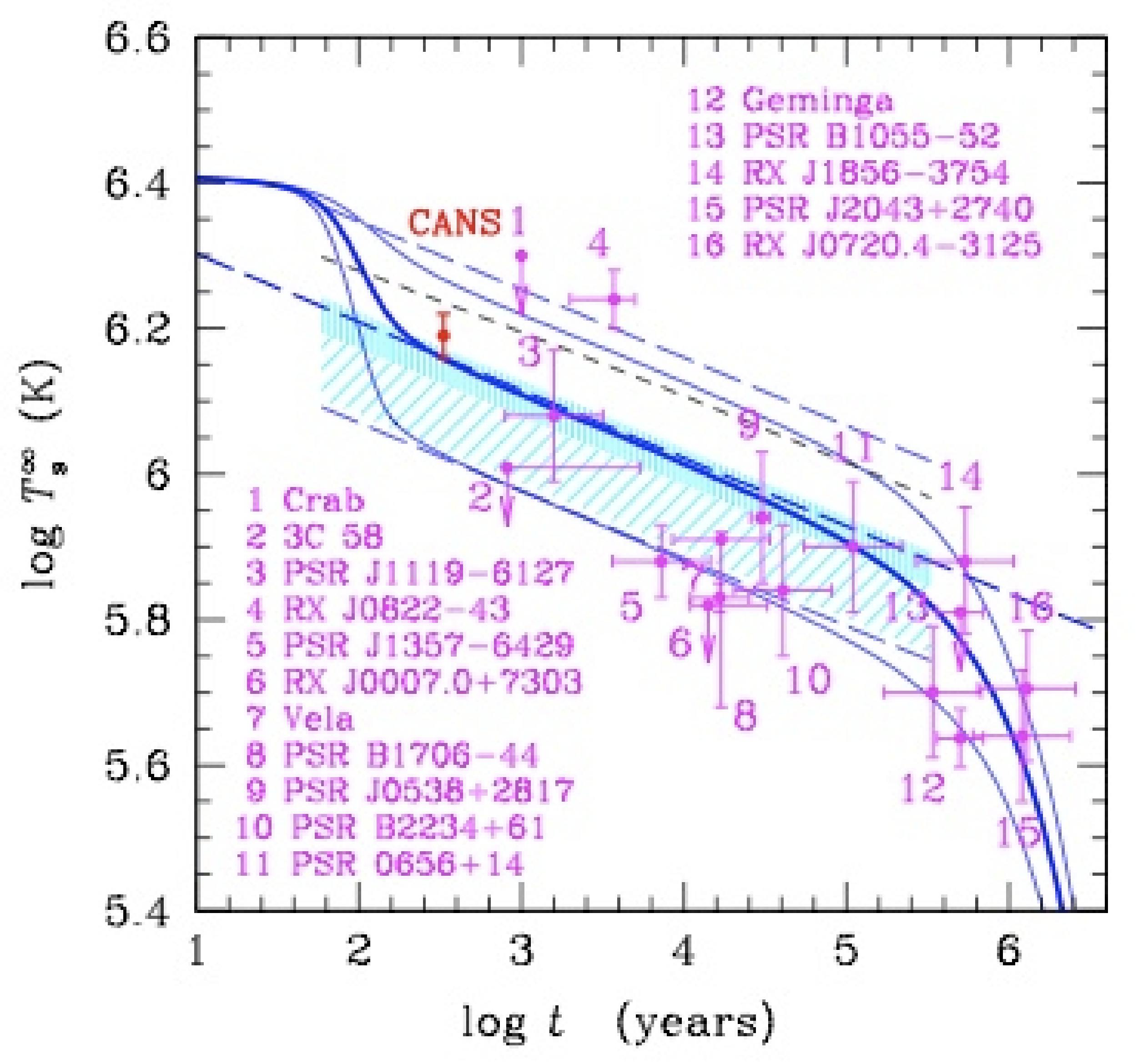
Similar physics to superfluids, but involving charged particles



Perfect electrical conductors; produce strong magnetic fields

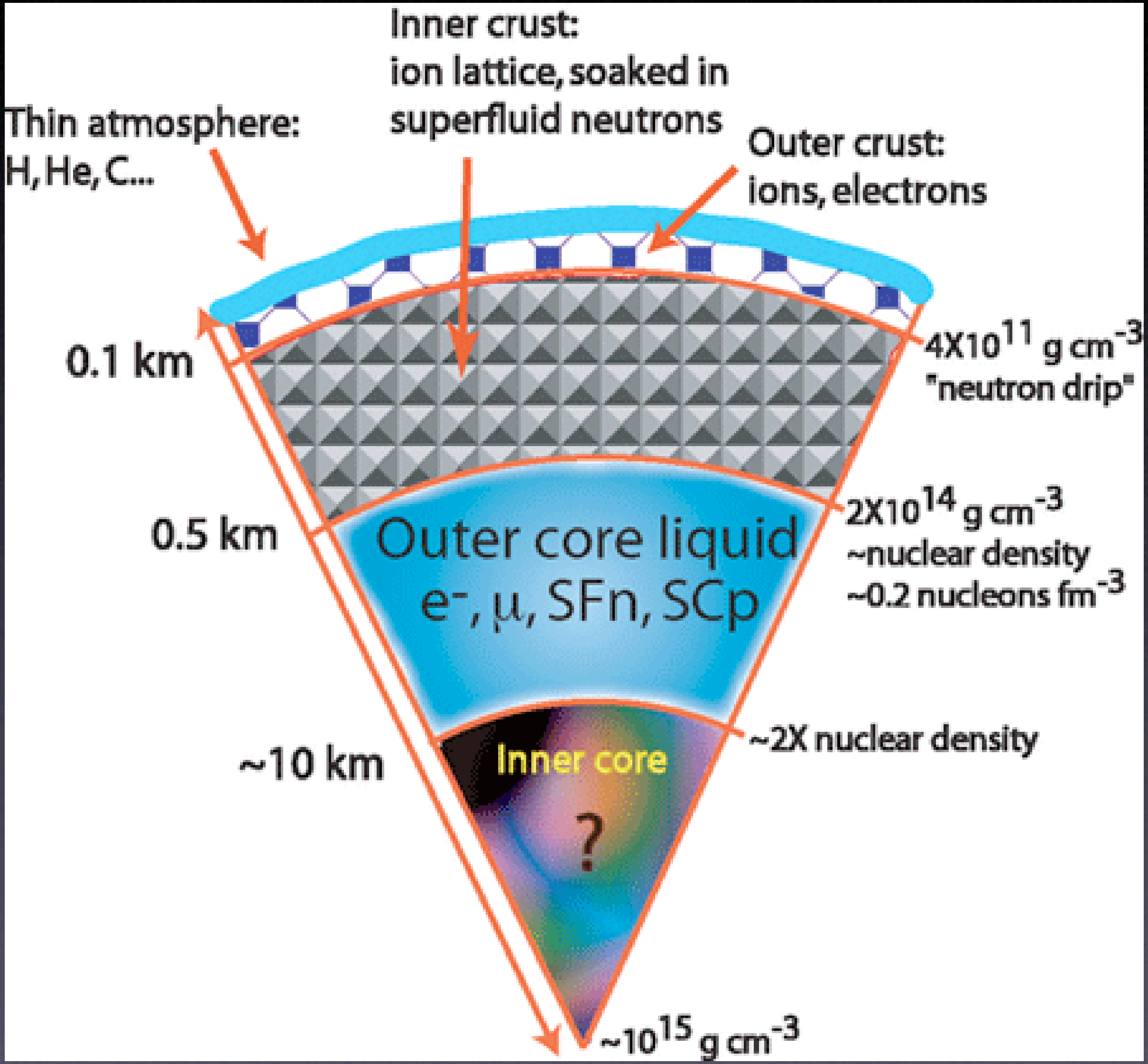
Applications: medical (MRI), particle physics (LHC), maglev trains, power transport

- 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

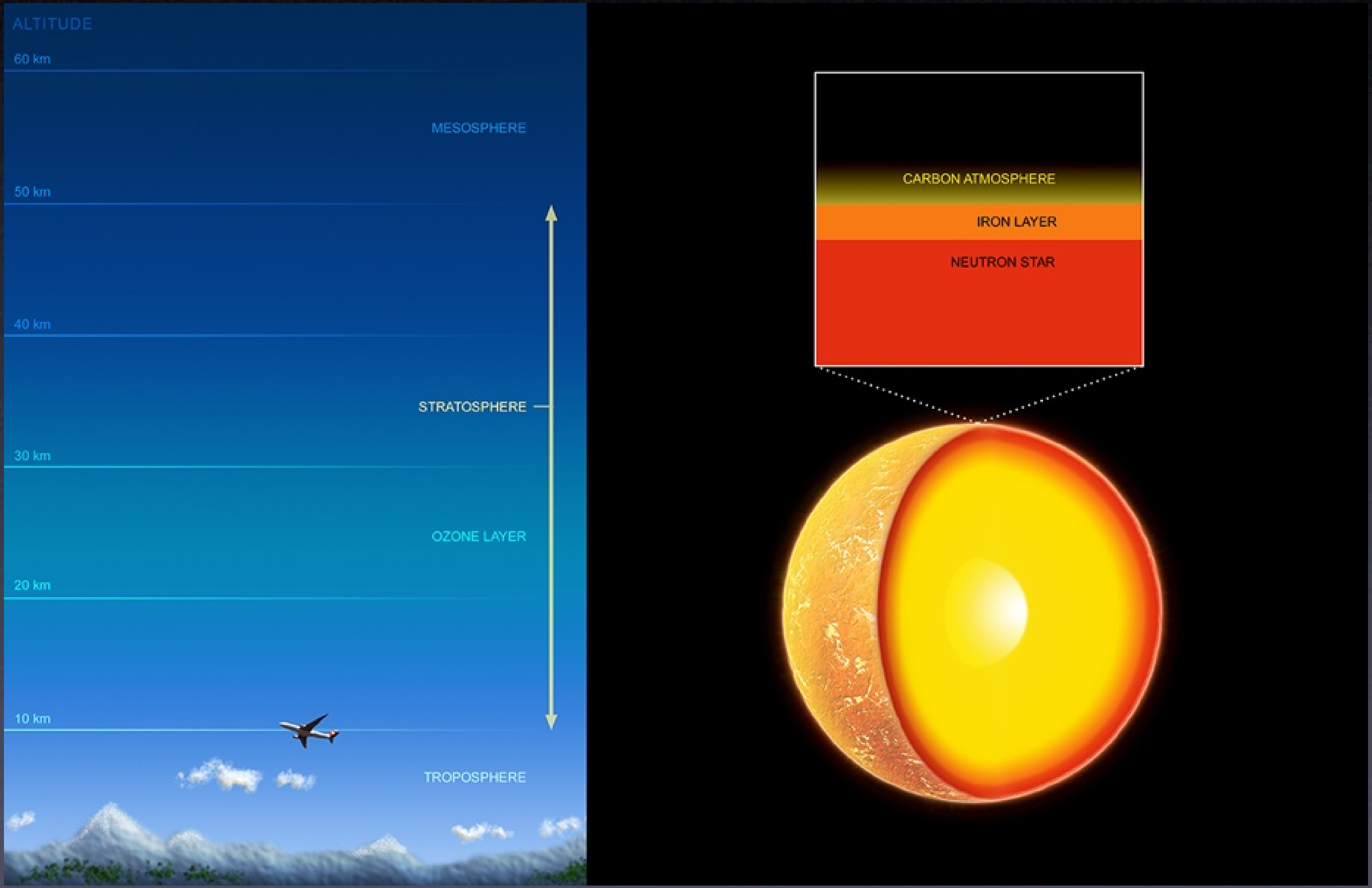
Expect singlet state SF n in outer crust, SF p throughout star

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

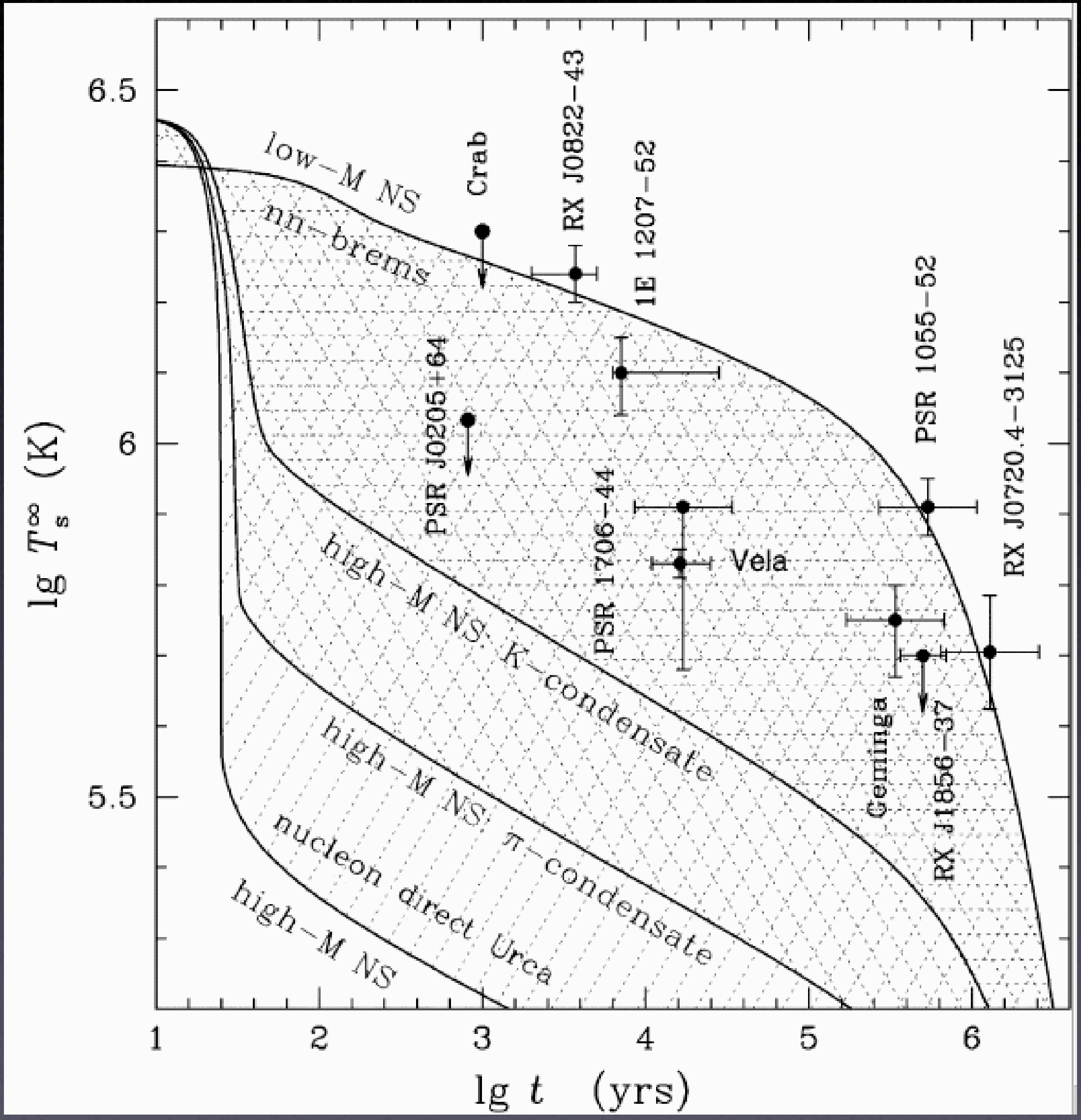


Cooling of young NSs

More massive NSs
can access rapid cooling
at center

Range of cooling rates set
by NS ν emission process

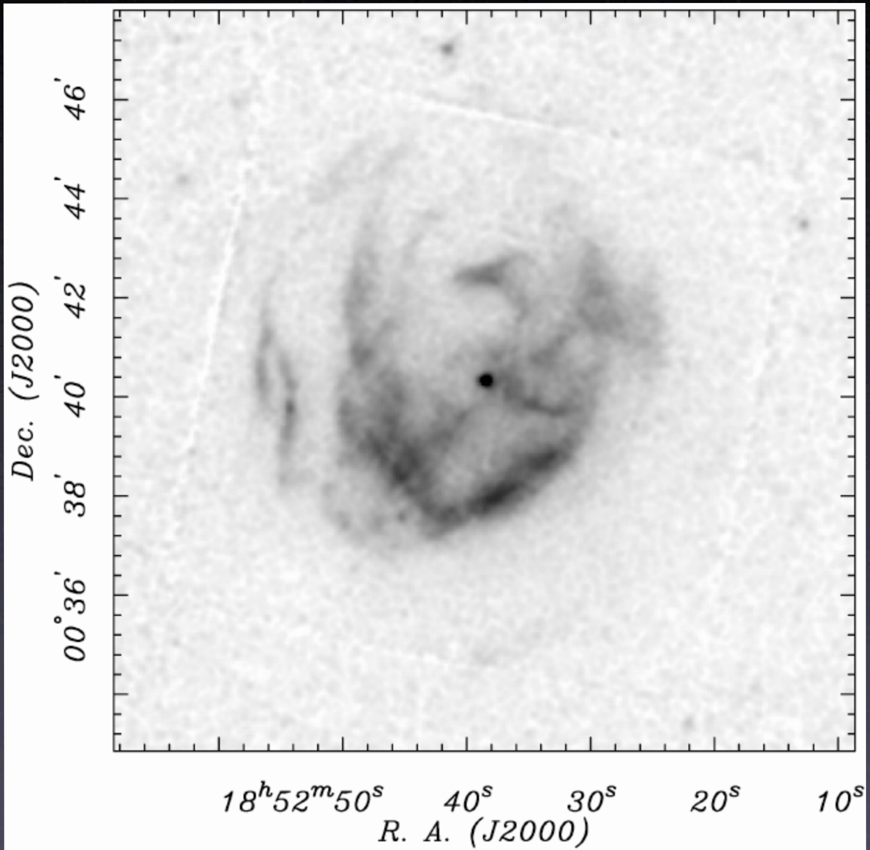
Young NSs give small
range of cooling rates

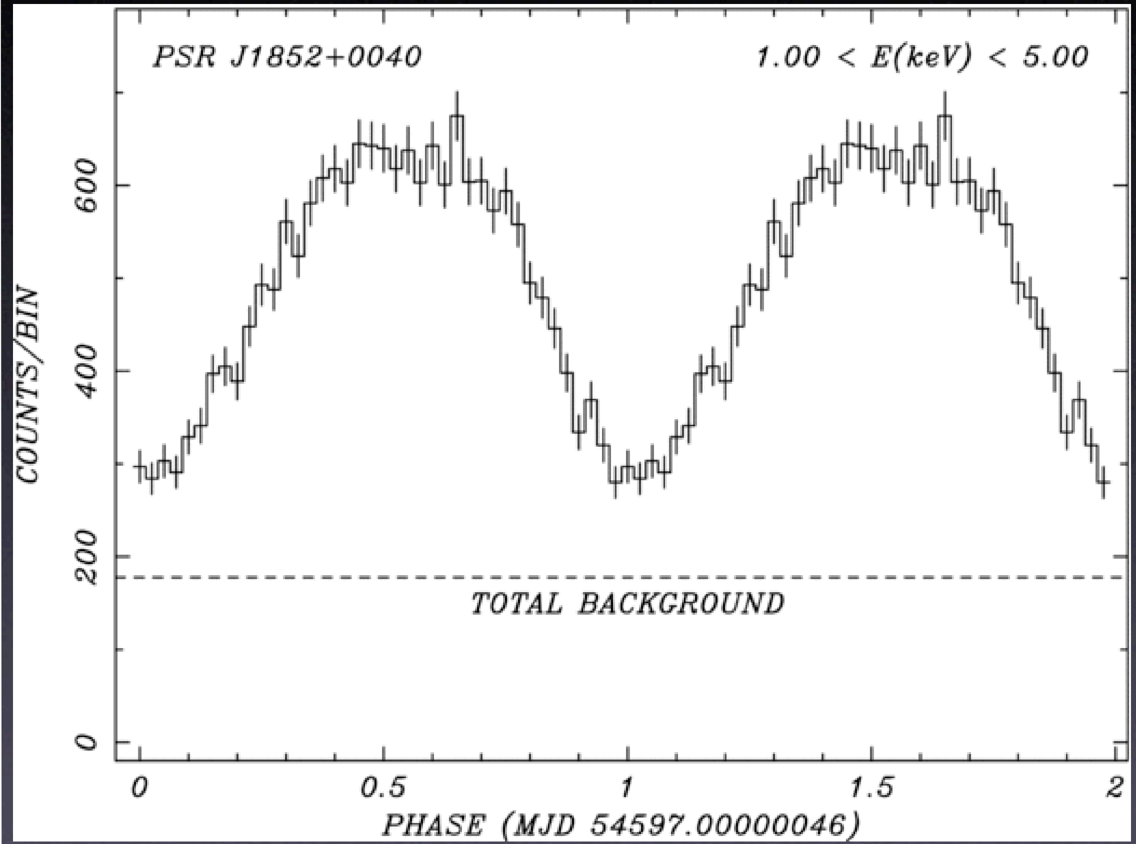


Yakovlev & Pethick 2004

Kes 79: 64% Pulsed Fraction

Only CCO with >12% pulsed fraction

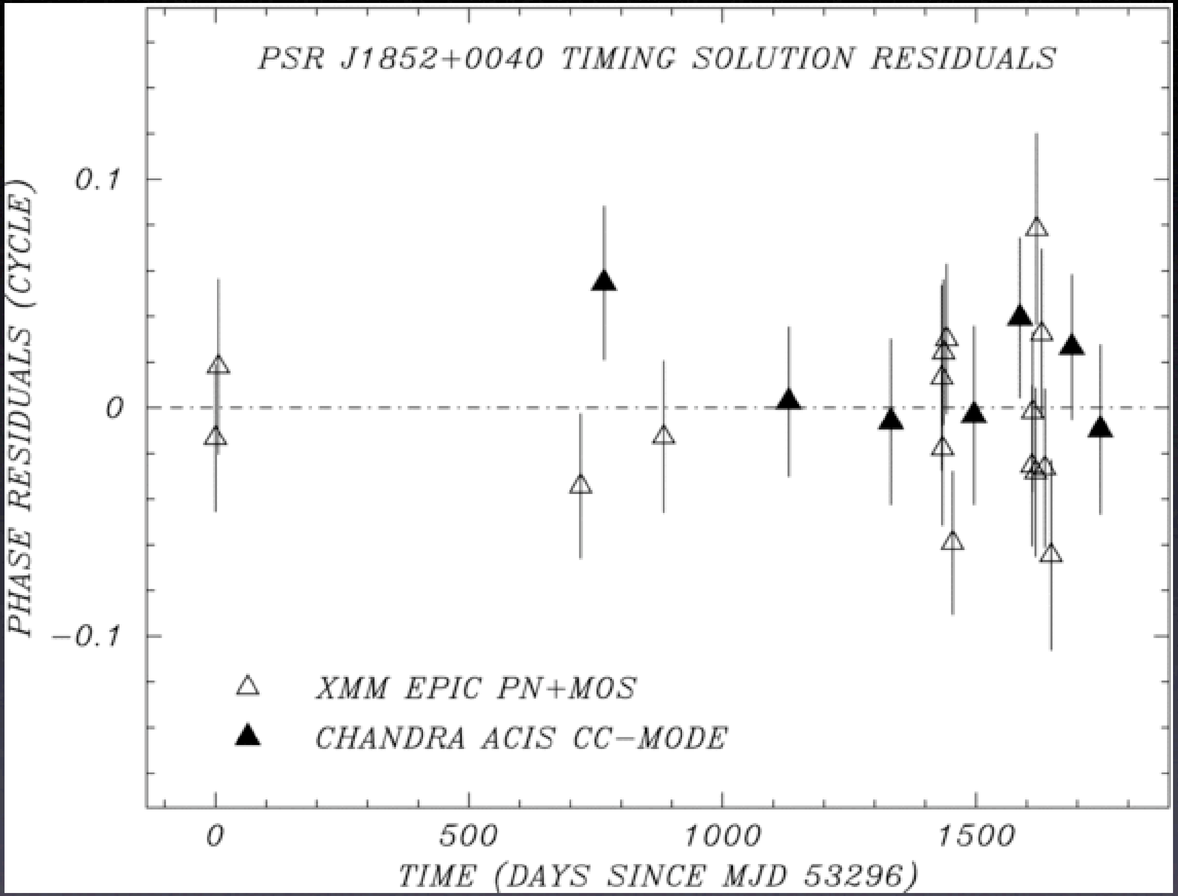




Kes 79, Gotthelf+05

Pulse profile, Halpern+10
0.105s

Kes 79: First Pdot



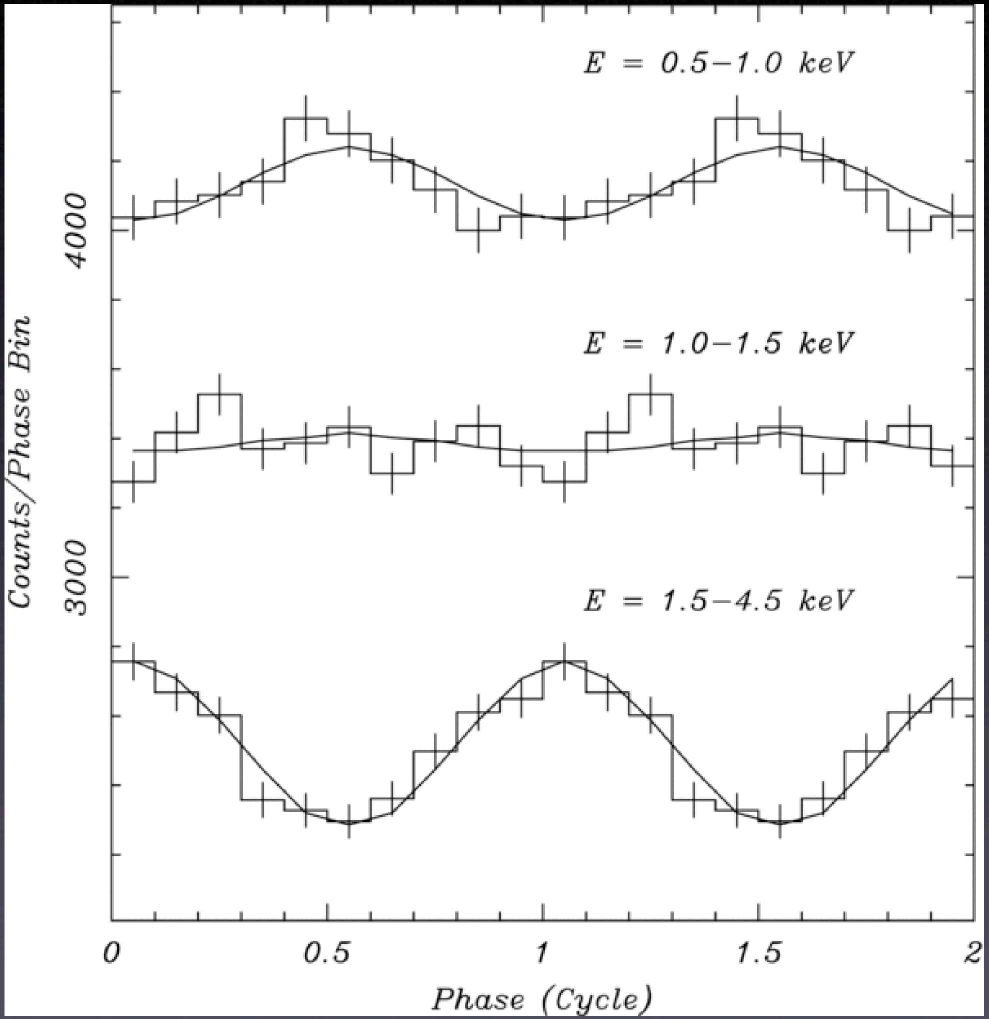
Kes 79 ephemeris, Halpern+10

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

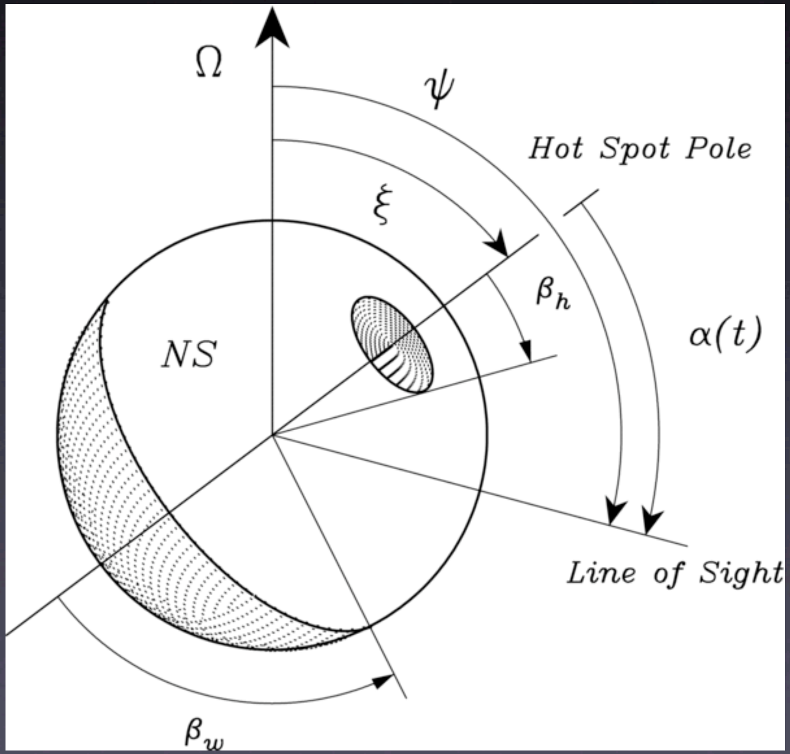
Difficult problem: highly pulsed emission & low B field???

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

Puppis A: Two spots



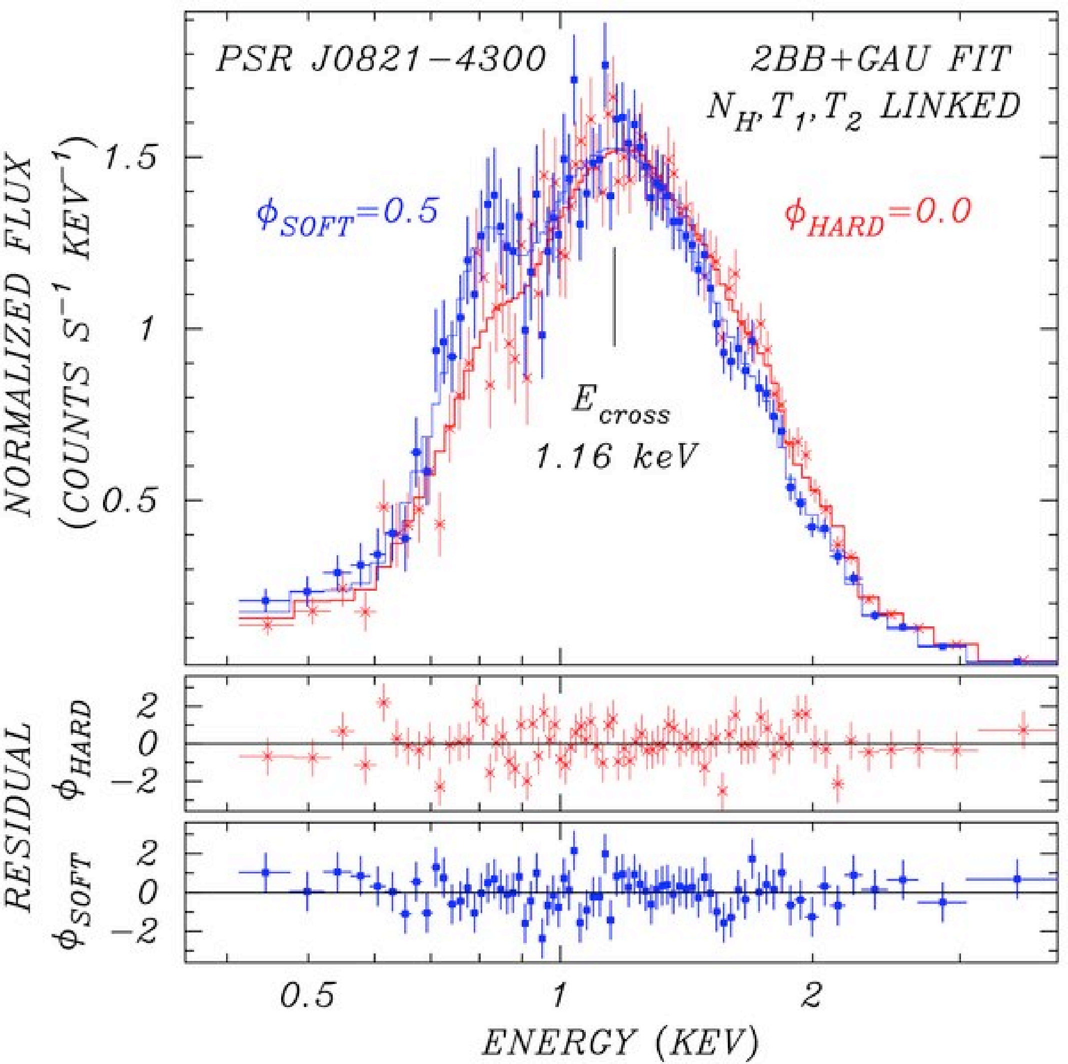
No overall modulation; pulsations at low, high energies; two spots?



Lightcurves, Gotthelf+10

Spot model, Gotthelf+10

Puppis A spectrum



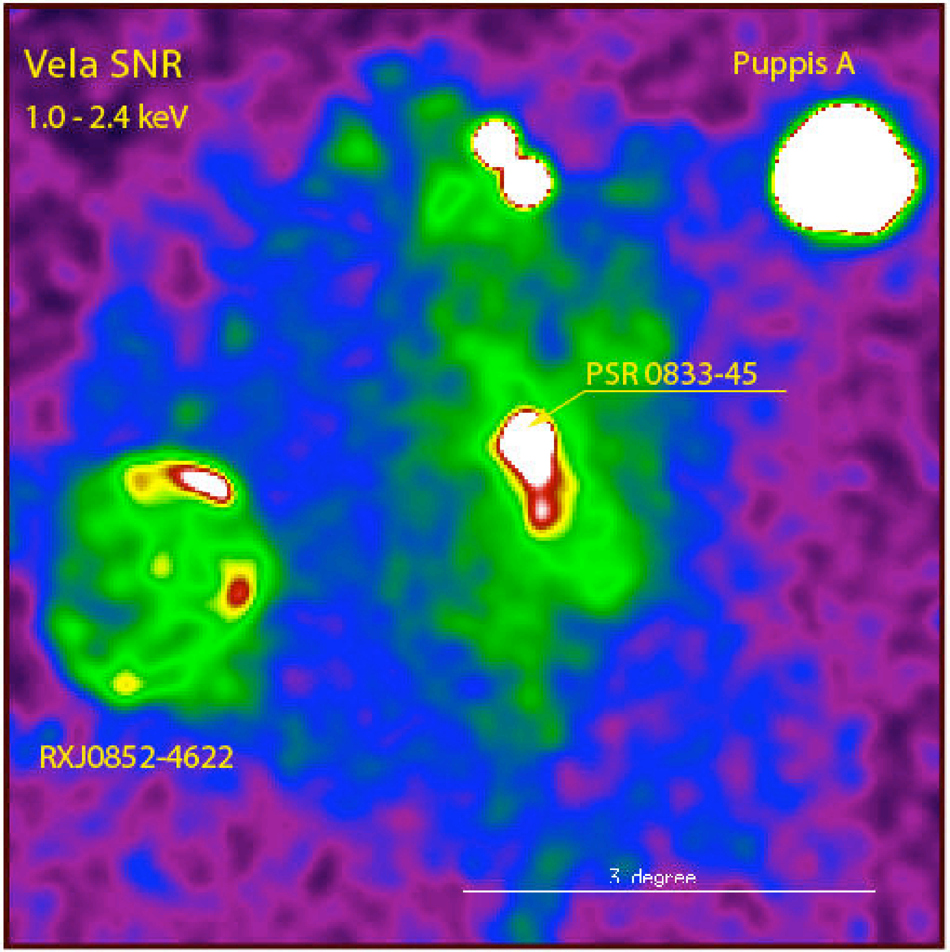
Spectrum, Gotthelf+09

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)

Vela Jr. (RX J0852-4622)



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

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

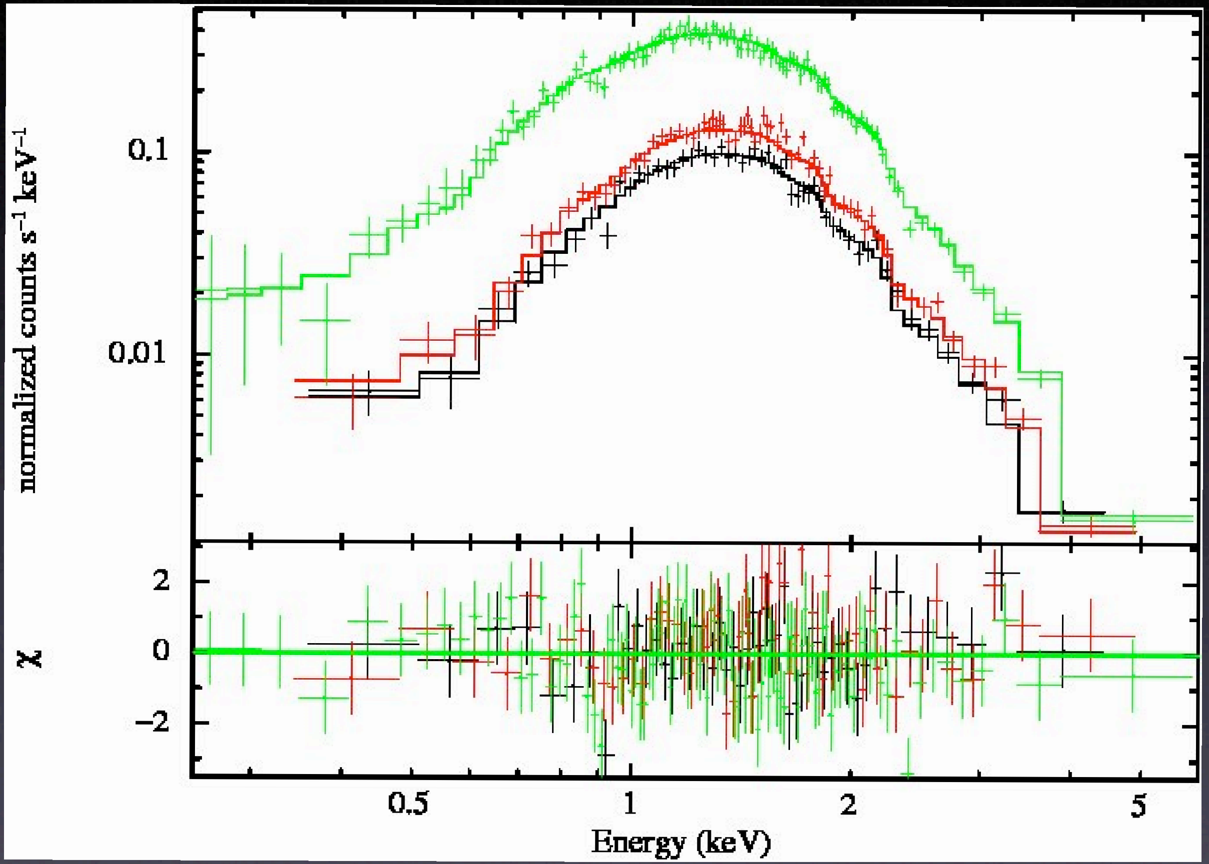
SNR expansion measured,
0.014±0.004%/yr (Allen+10),
so ~3000 years old

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

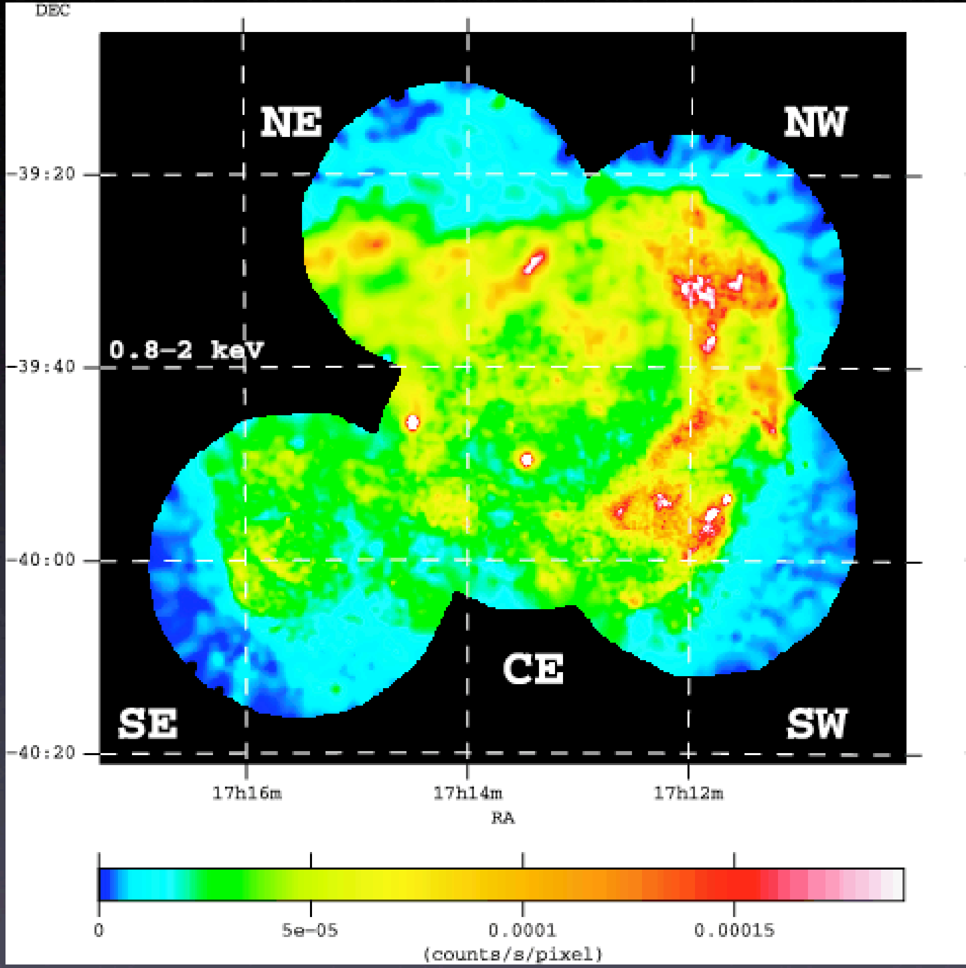
G347.3-0.7 (RX J1713.7-3946)

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

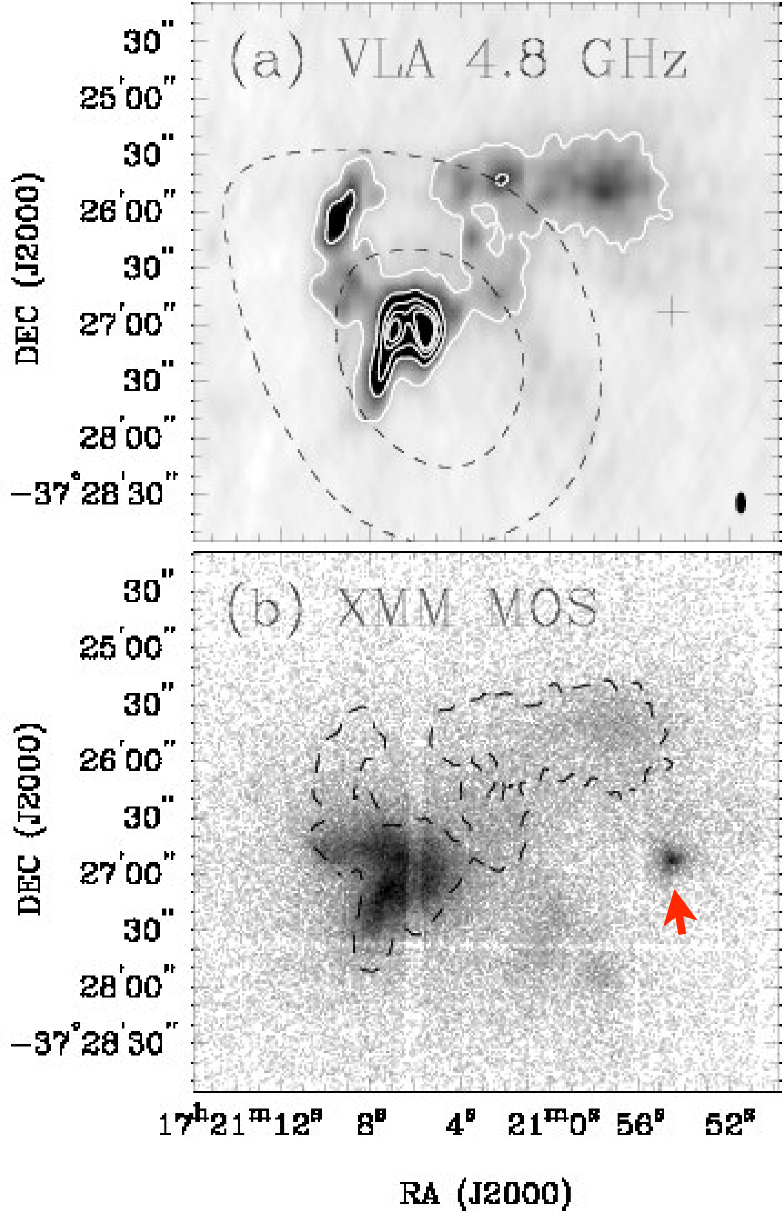
Seems to require hot spots,
but again PF<7%



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

G350.1-0.3

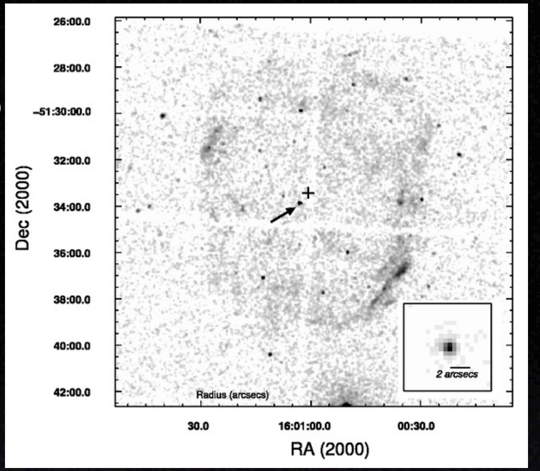
- SNR colliding H_2 cloud, age 600-1200 years, D ~ 4.5 kpc
- Consistent with single-temp C atm, T_S=2.6 MK,
  If so, T >Cas A (T_S=2 MK)
- W. Ho & I proposing to look for cooling, pulsations



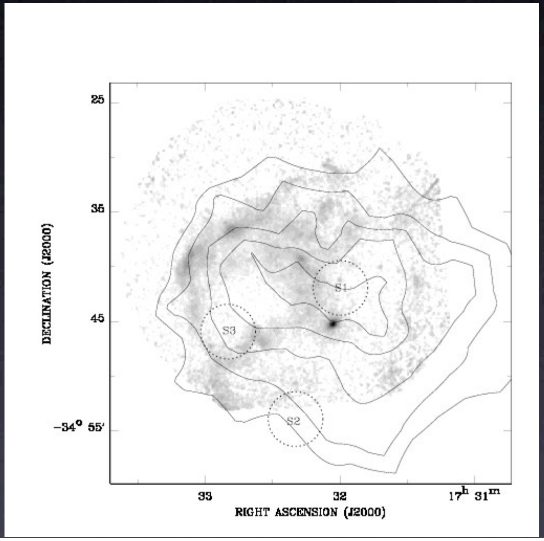
G350.1-0.3, Gaensler+08

3 more likely CCOs

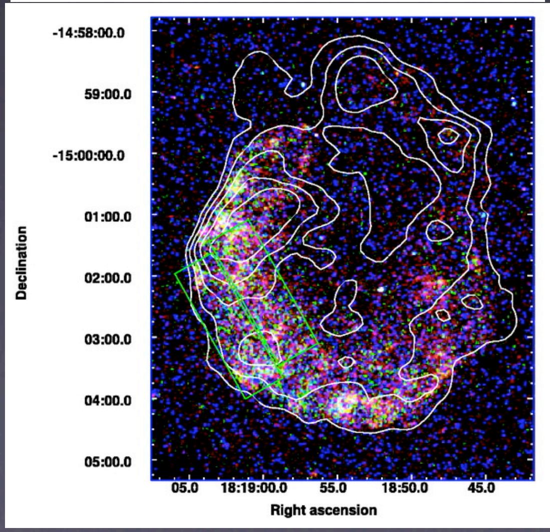
- Poor limits on pulsed fraction
- Inferred D with H/He atm too high, C atm D ok
- Distances uncertain, spectral fits unclear; more data needed



G330.2+1.0, S. Park+06



G353.6-0.7, Tian+10



G15.9+0.2, Reynolds+06