Probing the NS equation of state through X-ray spectroscopy

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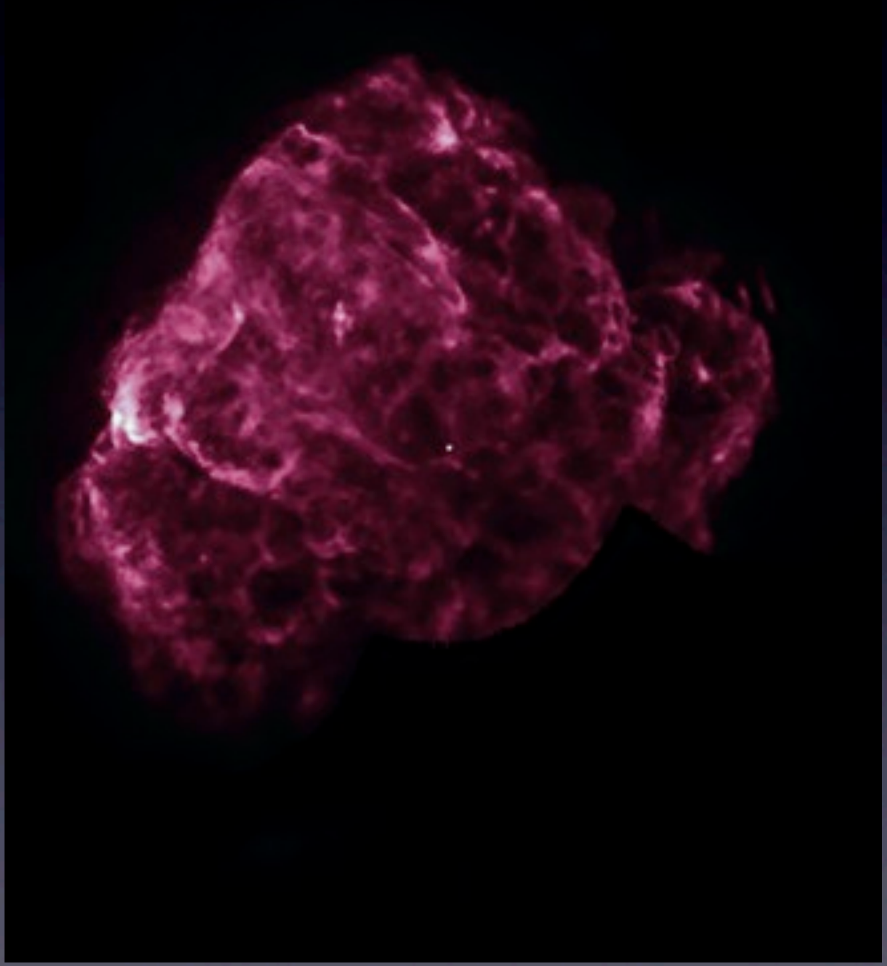
Outline

- Young NSs, low-mass X-ray binaries (LMXBs)
- Need well-understood NS atmosphere
- Spectral lines to measure grav. redshift?
- Variability: nature of emission, crust & core temperatures and variations
- Radius* constraints; from flux, temperature, distance, get emitting radius

Young NSs

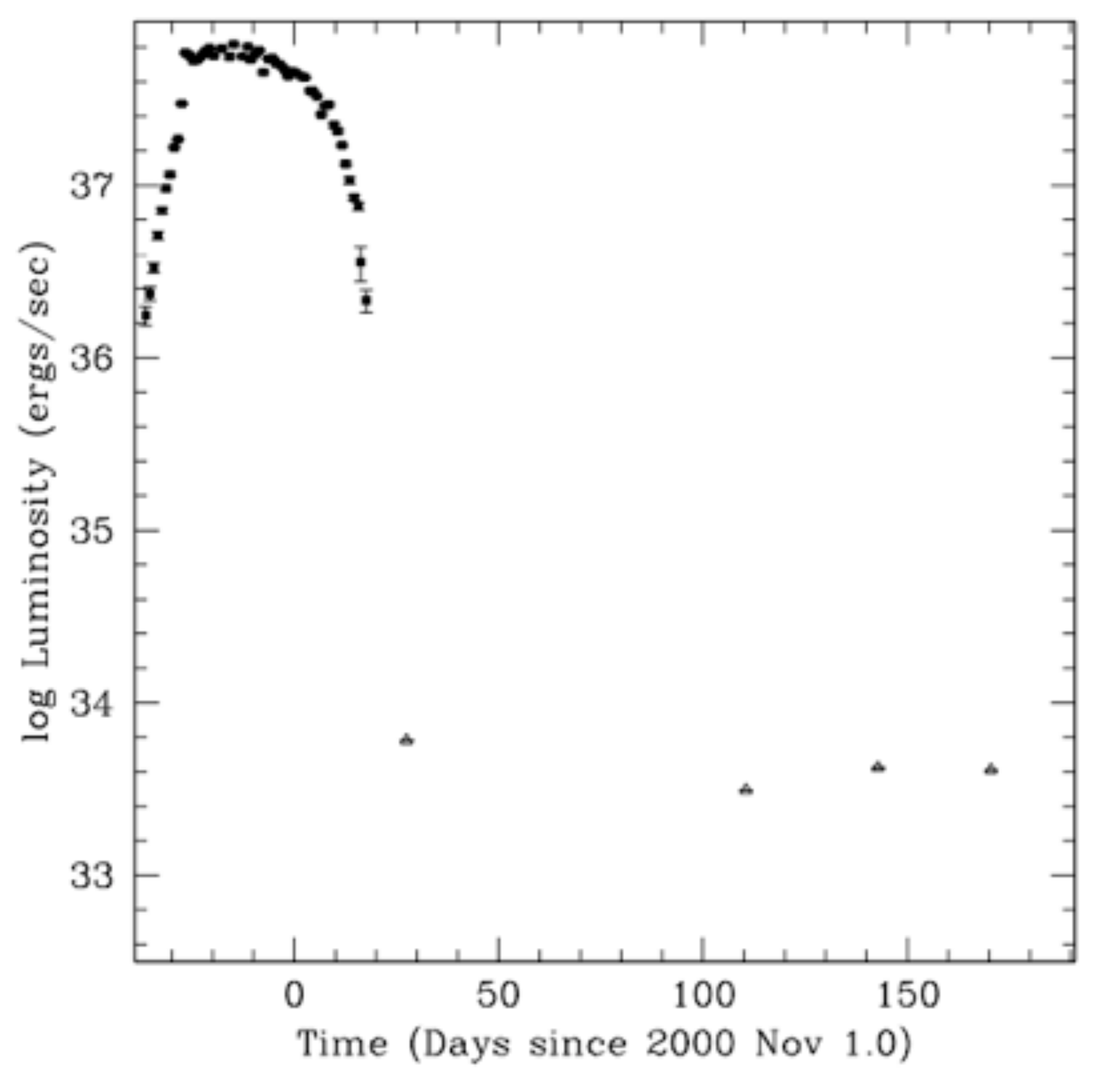
- Some still in supernova remnants (CCOs), or isolated (young pulsars, INSs)
- Cooling from supernova; thermal $L_X \sim 10^{32-34}$ erg/s
- Often show pulsations, temp inhomogeneities
- CCOs have low (logB~10-11) fields; others higher (logB~12-13)



Puppis A SNR & CCO, ROSAT

LMXBs

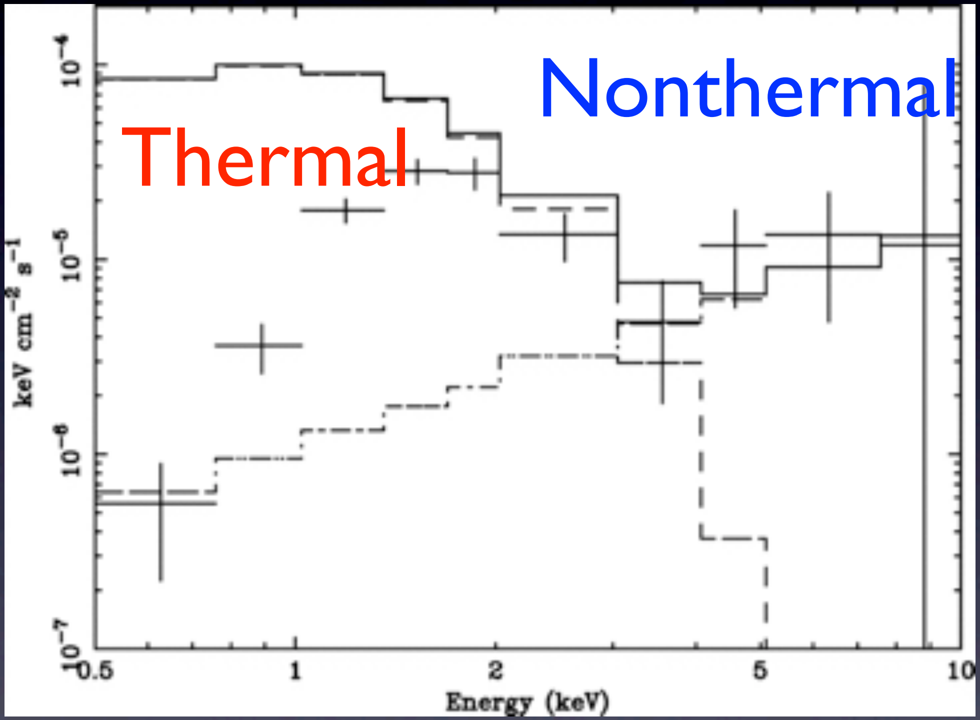
- Transients >10^3 times fainter in quiescence; accretion stops
- X-ray bursts (during accretion) last few seconds, logL~38.3
- Quiescence & bursts exhibit blackbody-like spectra



Lightcurve of Aql X-1, Rutledge+02a

Quiescent LMXBs

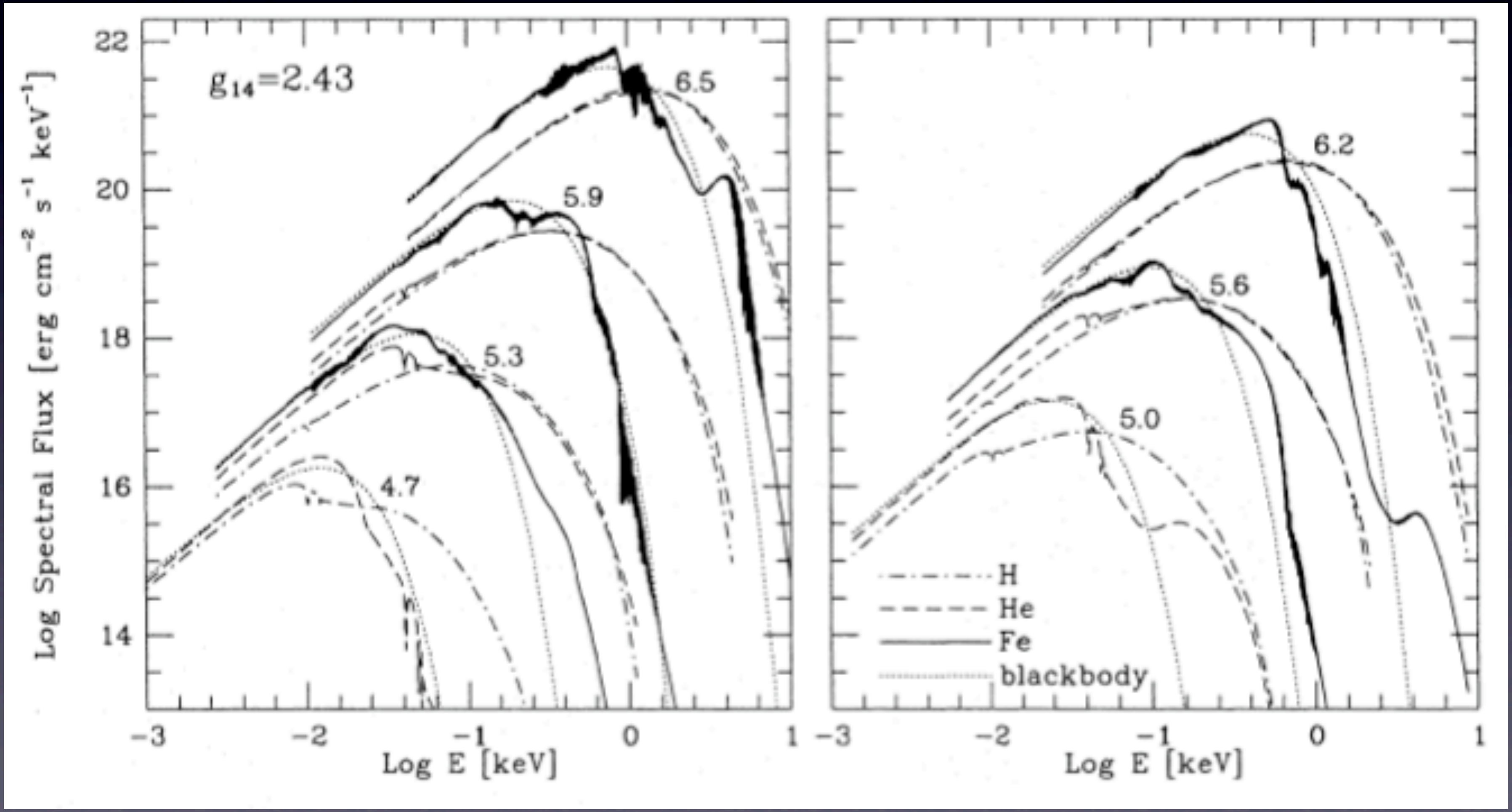
- Thermal component; NS surface, H atmosphere
- Deep crust heated by accretion, reradiates heat in quiescence
- Nonthermal (“power-law”) component; low-level accretion? pulsar wind?



X-ray spectrum of qLMXB, (unfolded) Rutledge+02b

Low-B Quiescent NS Atm

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

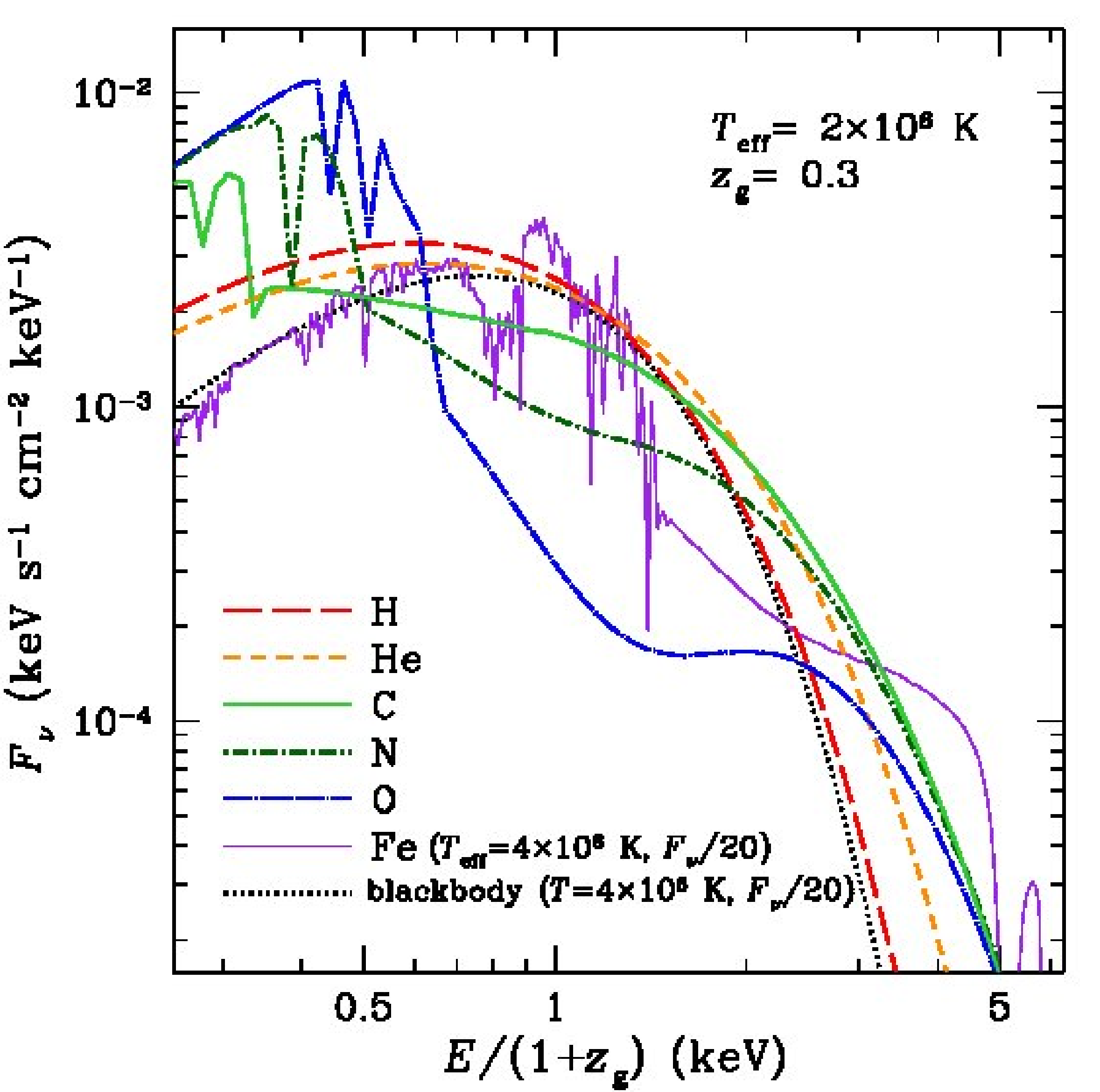


Zavlin+96, H, He, Fe atmospheres

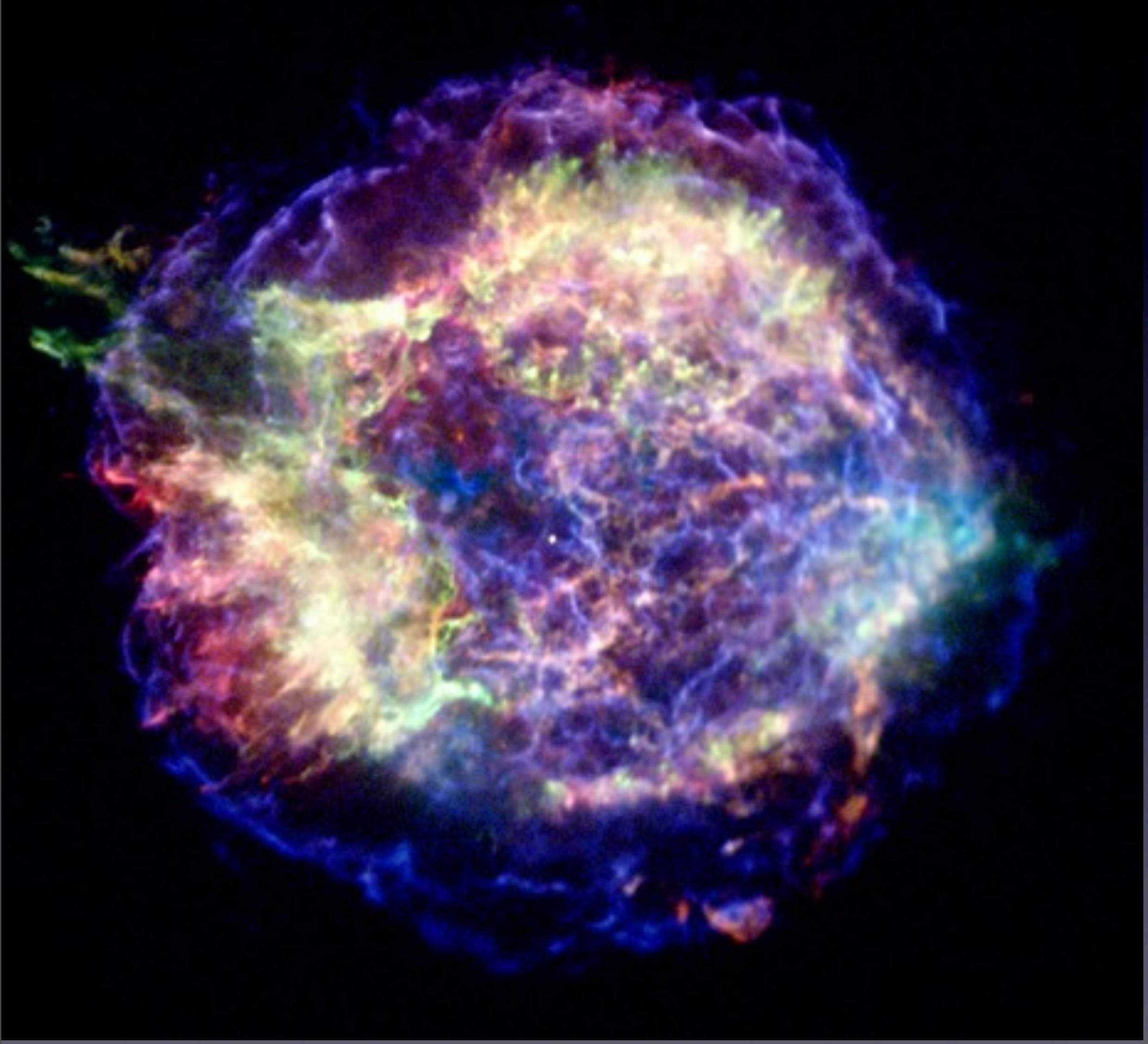
Alternative atmospheres

- Variety of low-B NS atmospheres, using Opacity Project data
- N, O, Fe give features
- C harder than H, He
- Atm stratifies quickly, H usually dominant...

Ho & Heinke 09

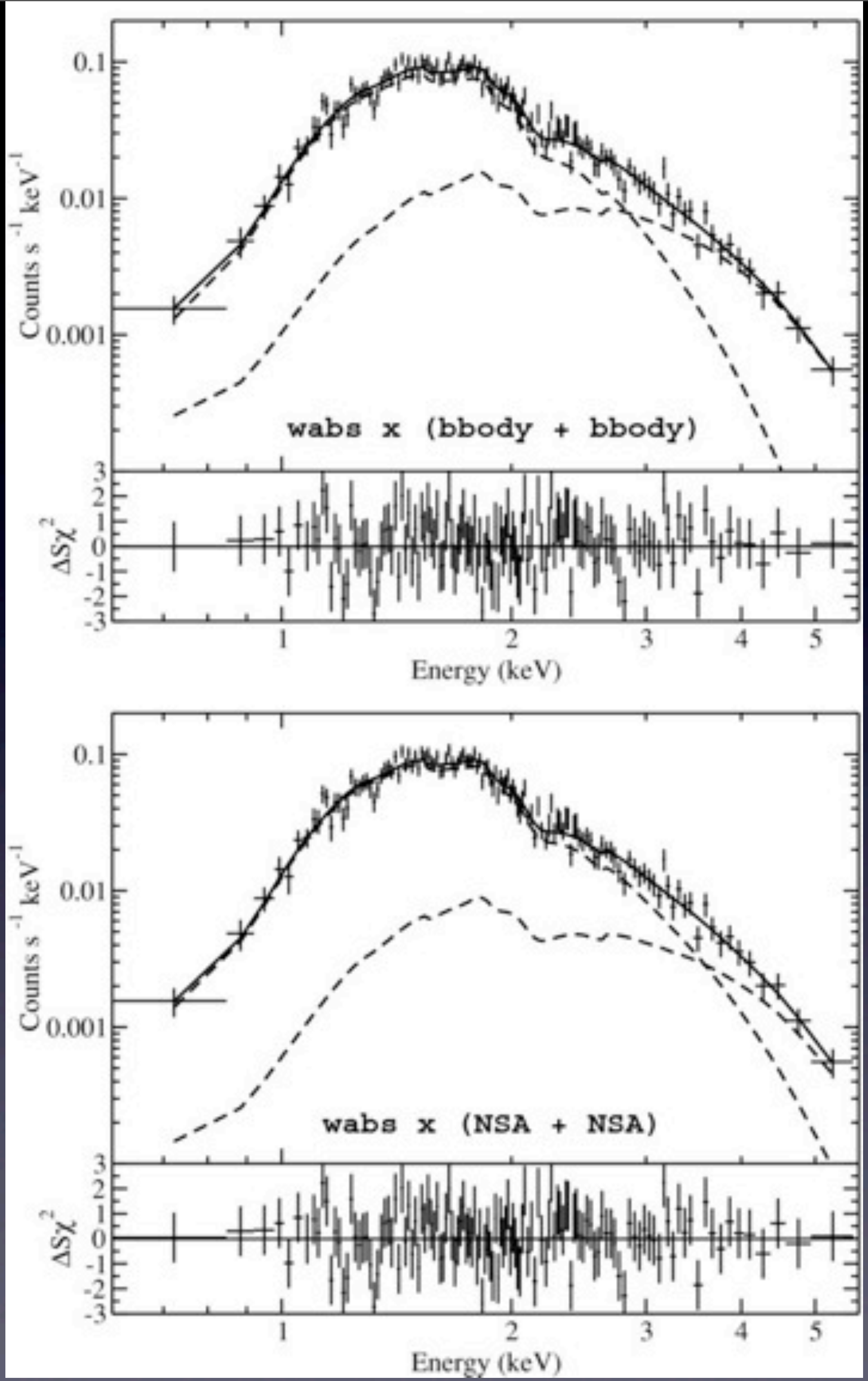


Cassiopeia A CCO



"Central Compact Object" (Tananbaum 1999)

Youngest known neutron star (only 330 years). X-rays indicated ~1 km emission area, but no pulsations?...



H atm, with hot spots?

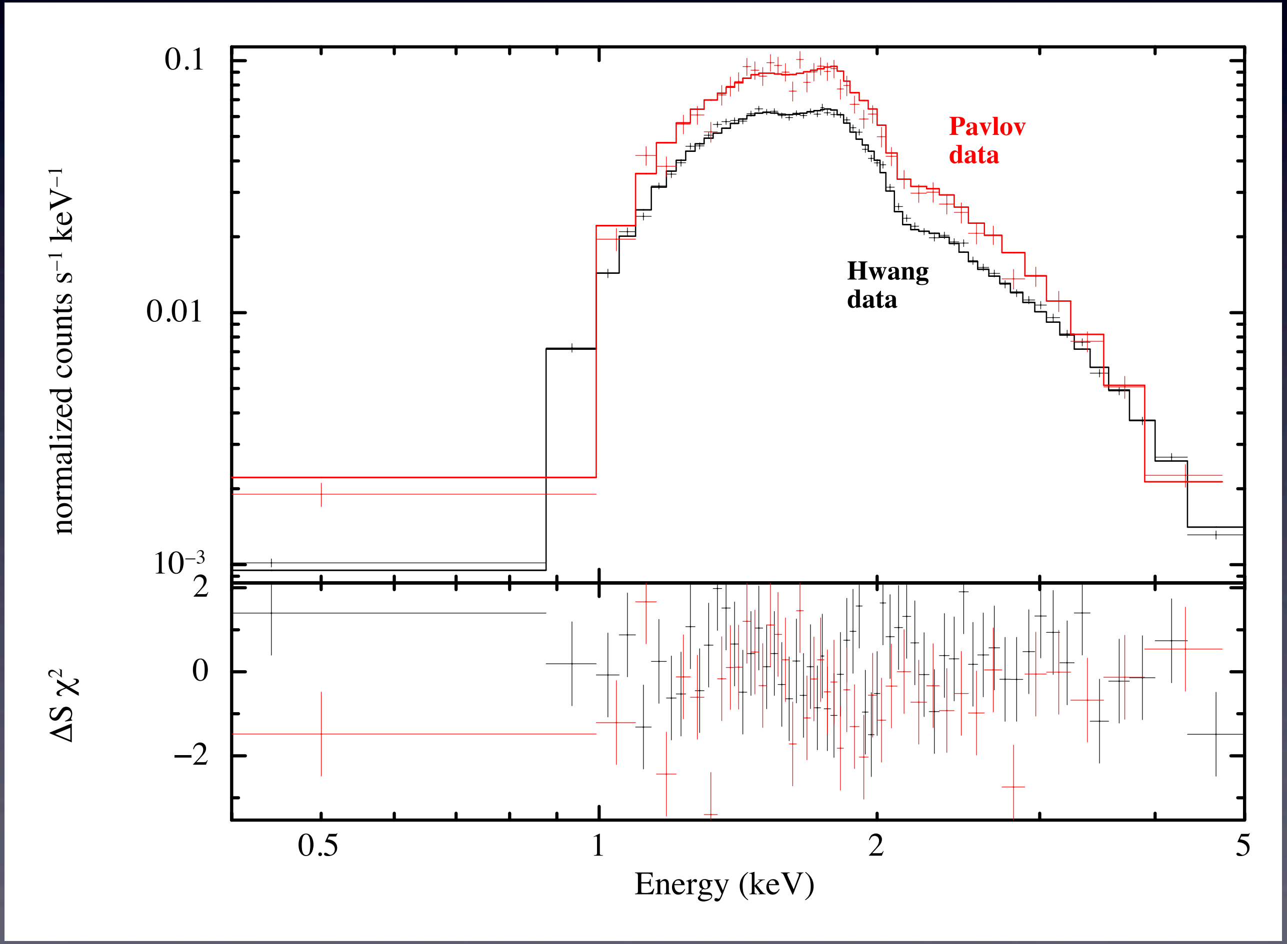
- Two components (full surface + hot spot) explain spectra for radius~12 km
- But should probably produce pulsations (see Elshamouty talk, Friday)

Pavlov+09

Carbon Atmosphere for Cas A NS

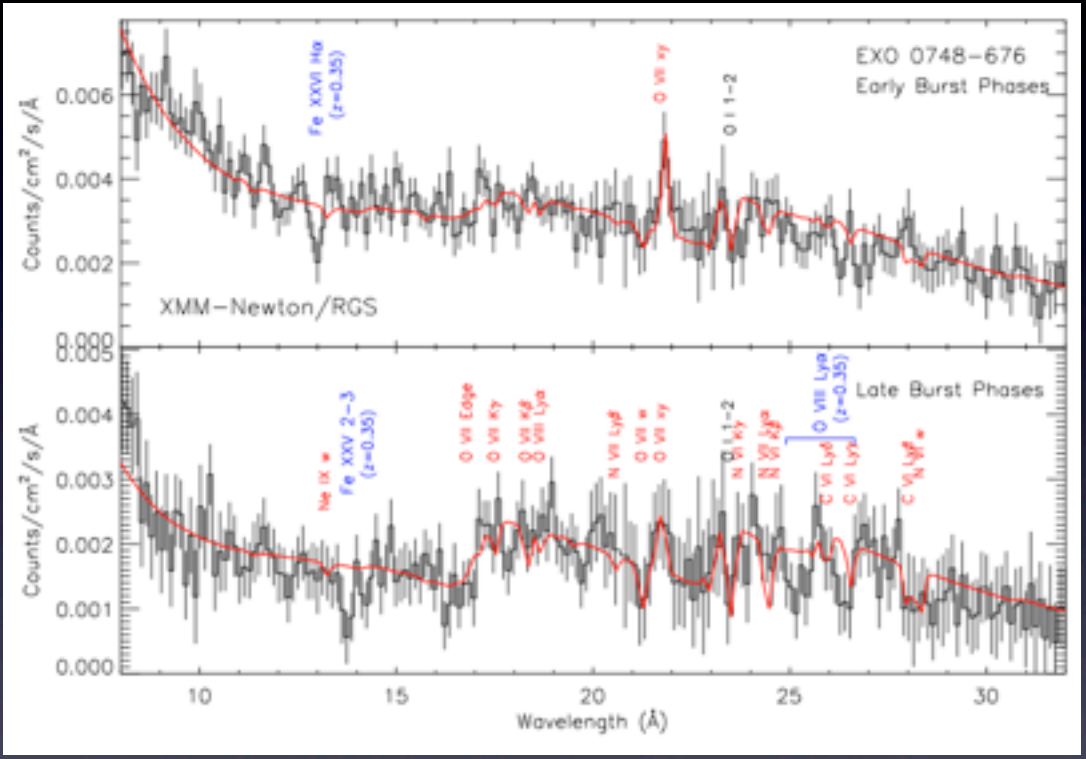
- Carbon atm. fit consistent with NS radius, ~10-12 km
- Hot young NS could burn H, He in atmosphere; so C plausible (Chang +10)

Ho & Heinke 09



Spectral lines

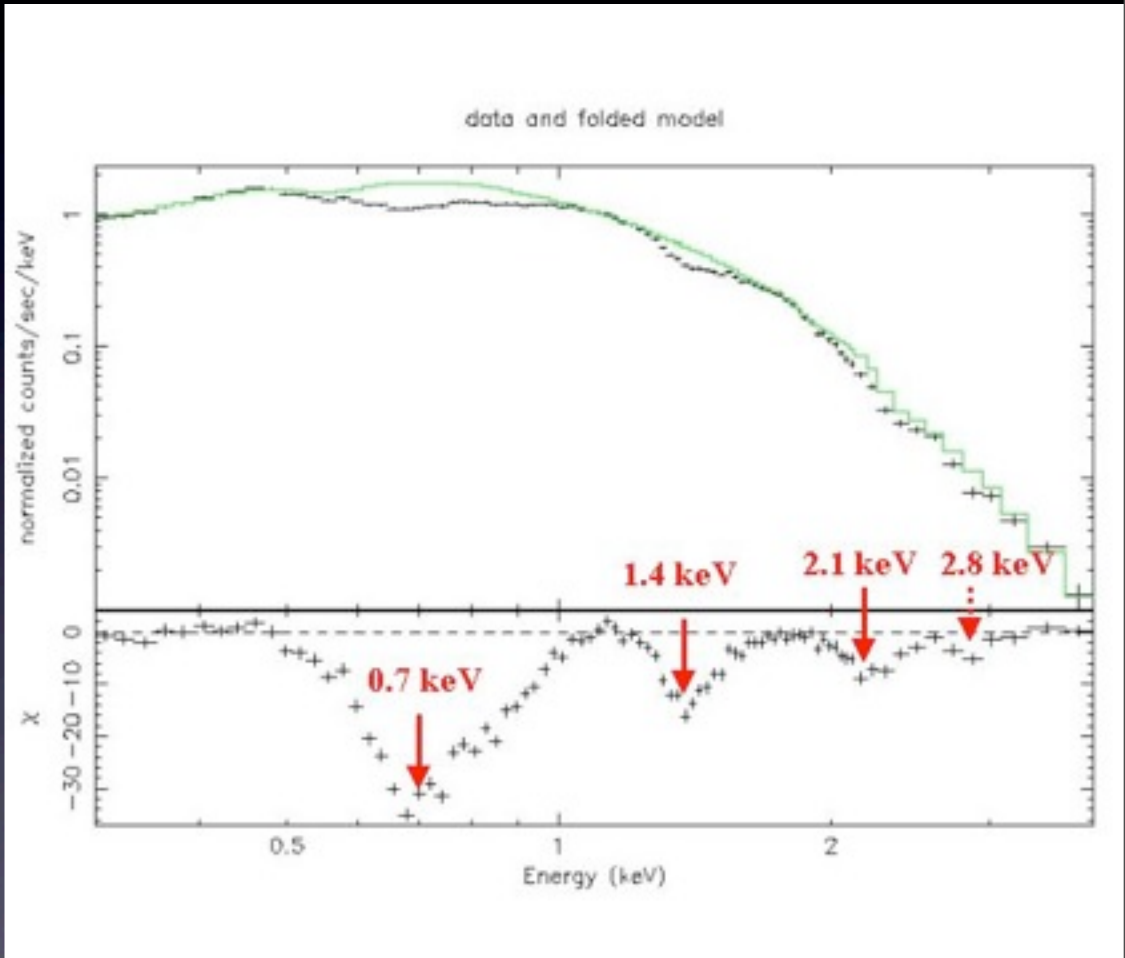
- Identification of an atomic spectral line from surface could give redshift, M/R
- Spectral lines from bursts claimed to give z=1.35 (Cottam+02).
- However, fast NS spin would smear surface lines; absorption lines not replicated



EXO 0748-676 high-res spectra, Cottam+02

Spectral lines

- 2-4 absorption lines identified from young NS 1E1207 (Sanwal+01, Bignami+03)
- Difficult to ascertain nature
- Now identified as cyclotron lines (Suleimanov+10), so constrain B field, not redshift



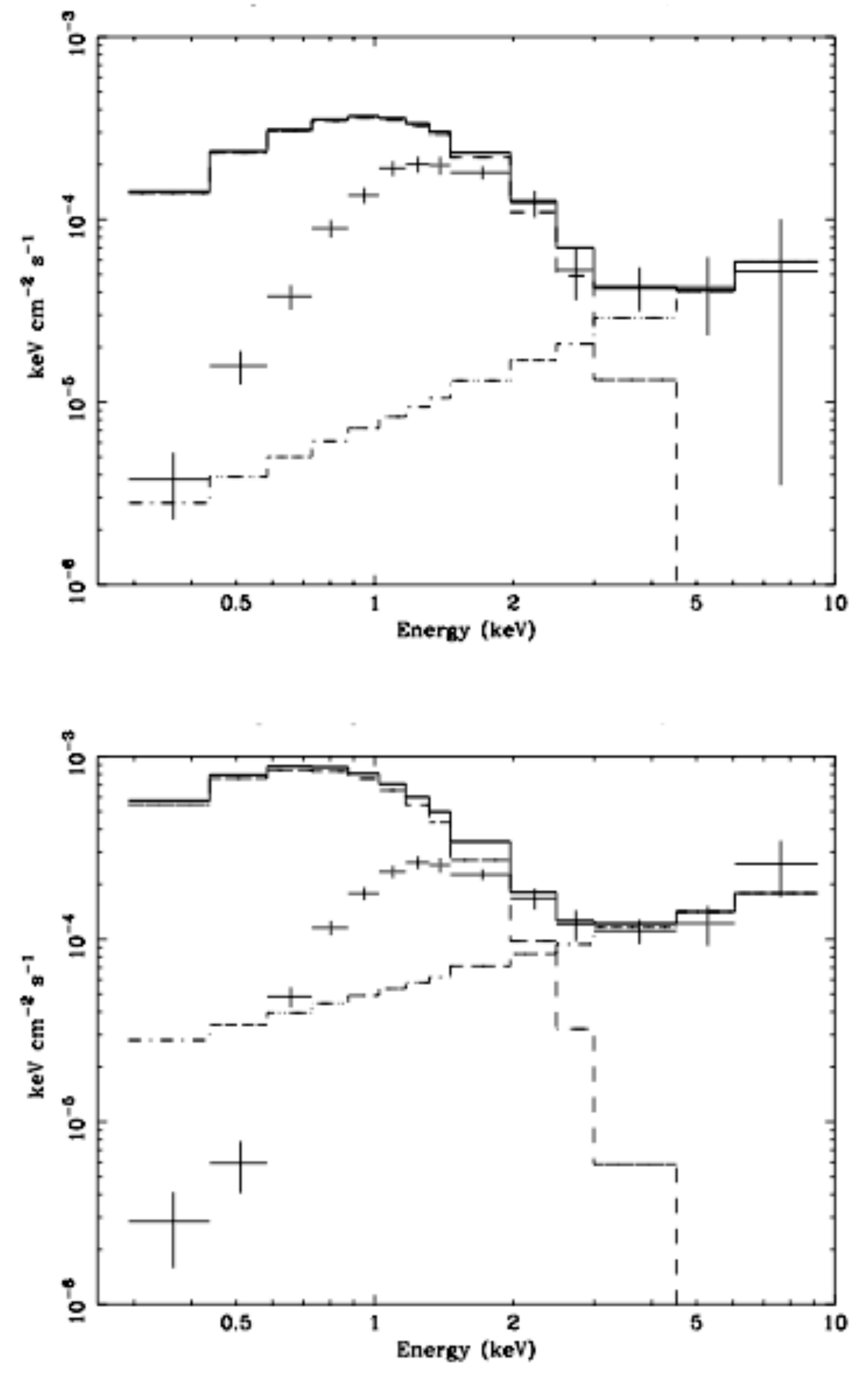
1E1207, Bignami+03

Variability of quiescent NSs

- Nature of thermal X-ray emission:
continuing accretion?
heat release from crust, post-accretion?
slow heat release from core?
- Predict different thermal variations
- Thermal variability can constrain NS interior physics

Continuing accretion

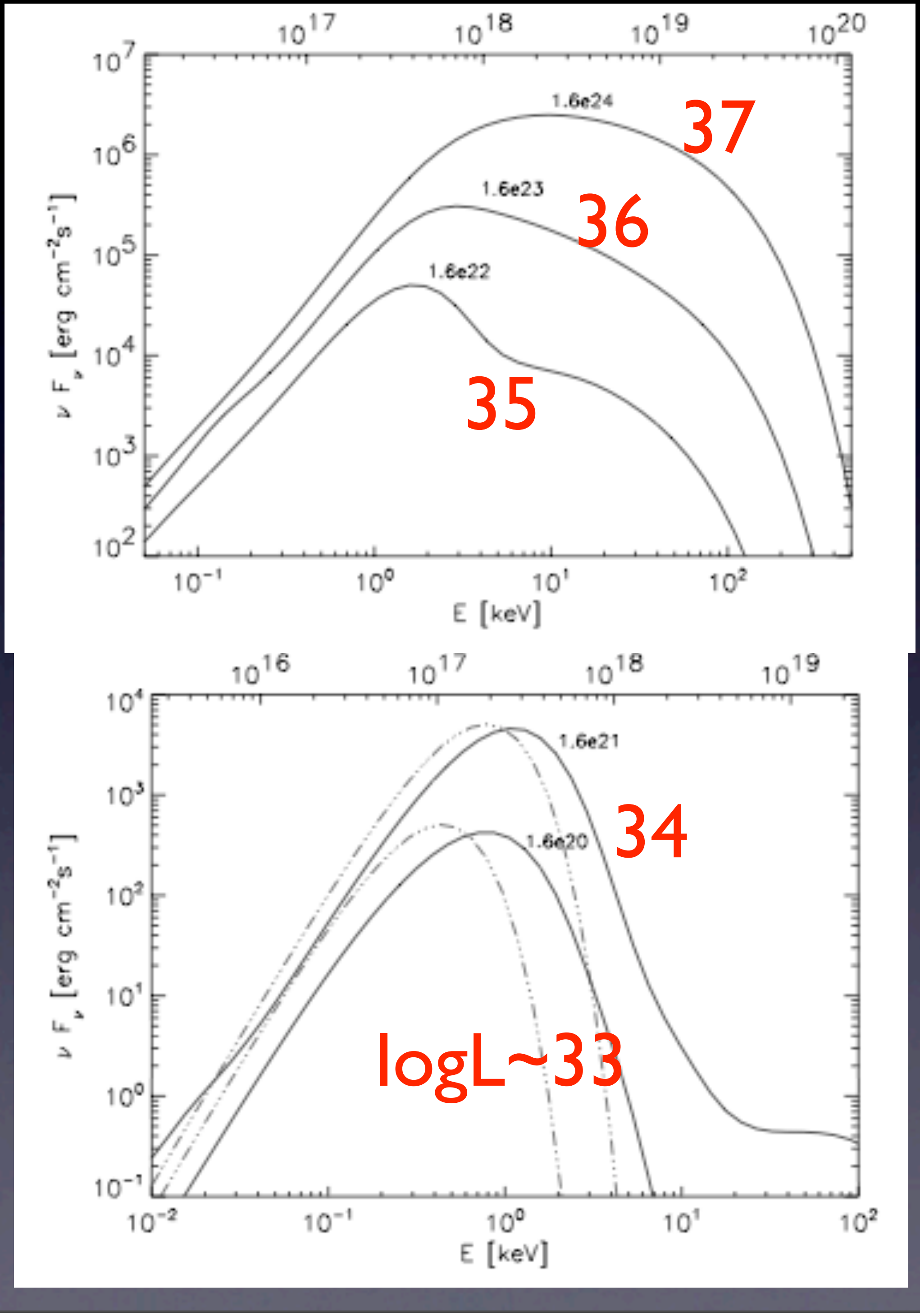
- Thermal variation from accretion in quiescence in several LMXBs (e.g. Rutledge+02a, Cackett +10; Bernardini talk)
- Other quiescent LMXBs show no variation; <1% temp variation over 2 years (Heinke+06)



Rutledge+02a, Aql X-1

Origin of power-law

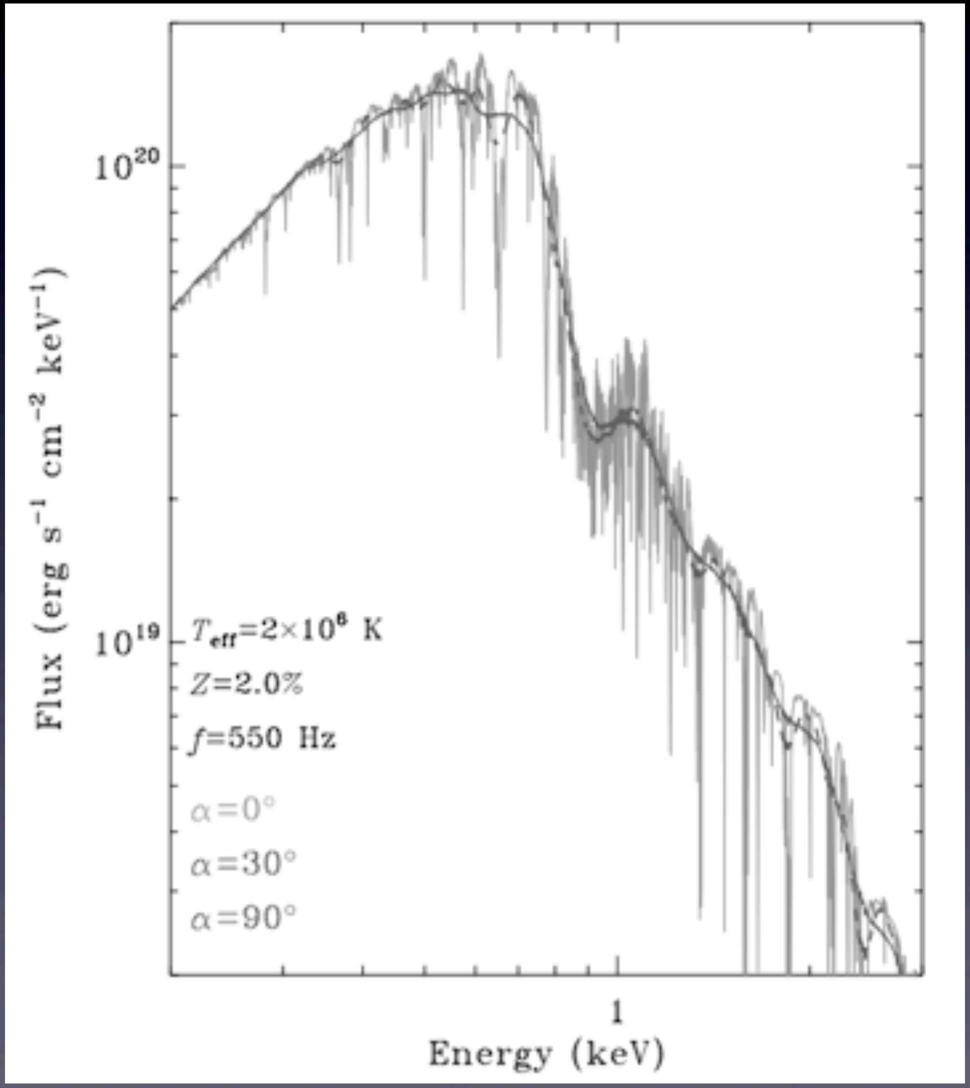
- Deufel+01 calculate model spectra of NSs accreting via ADAF (hot flow)
- Atmosphere's optical depth increases with L
- Suggests PL+ thermal signals low-level accretion?



Deufel+01

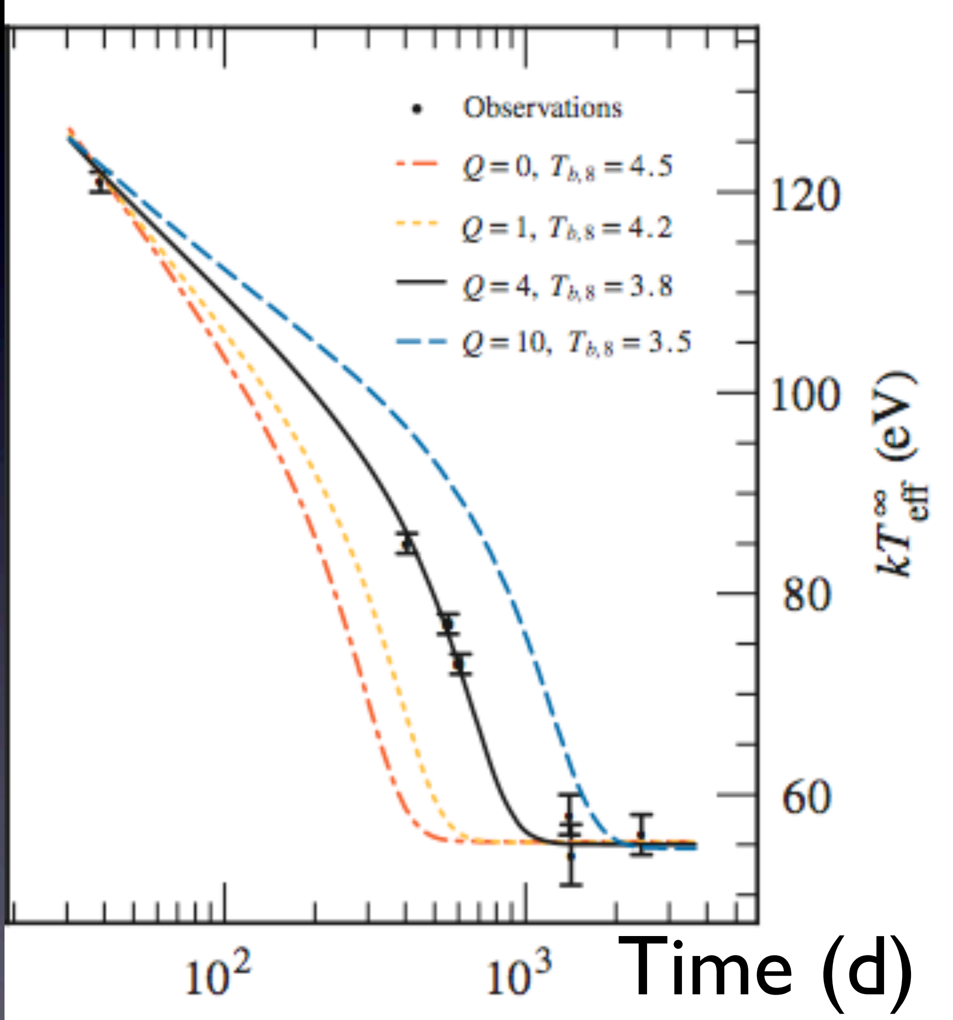
Effects on atmosphere

- NS atmospheres stratify in ~30 s
- Low-level accretion may allow heavy elements
- Would imprint lines into spectrum--testable with Astro-H (2015)?



Solar metallicity, Rutledge+02a

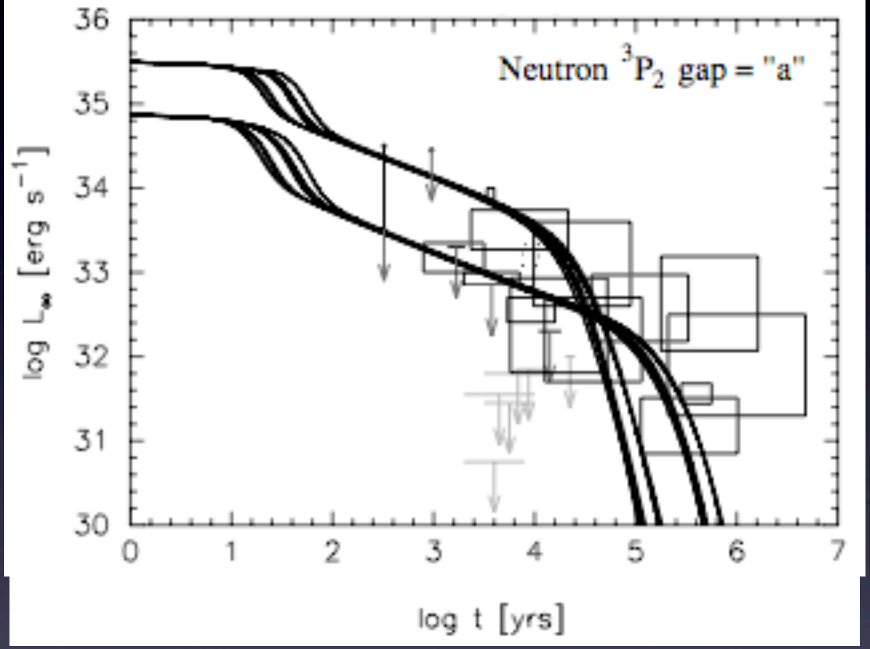
Crust cooling, post-accretion



MXB 1659+29, Brown+09

- Outer crust heated, cools quickly
- Crust cooling rate measures crust thermal conductivity, heating rate (Rutledge+02)
- Cooling of two NSs shows neutrons superfluid in crust, conductivity high & impurity low (Shternin+07, Brown +09)
- See Degenaar, Aguilera talks

Cooling young NSs

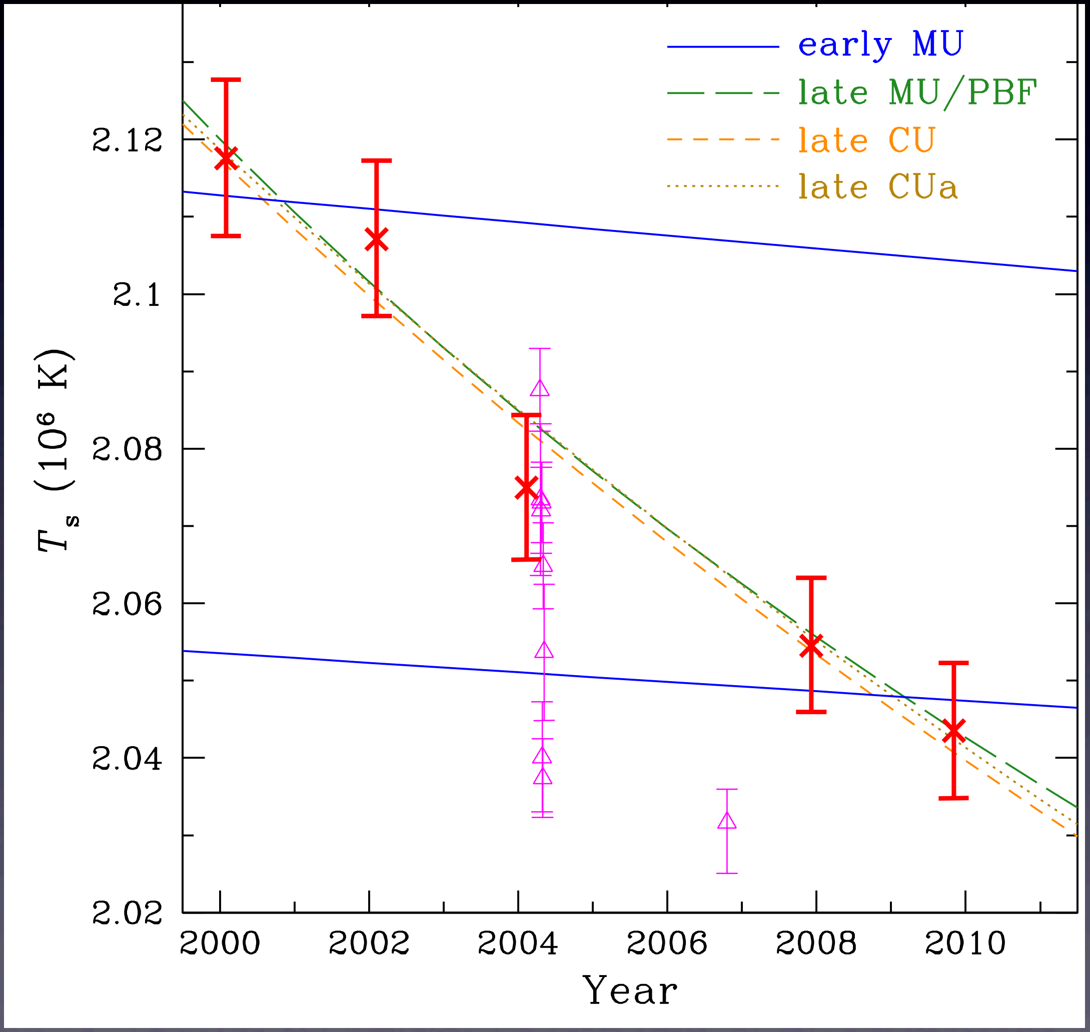


Page+09; boxes are observations, lines are NS cooling tracks

- Young NSs cool by ν emission; Urca processes, n-n bremss, superfluid pair formation
- Depend on core composition, superfluid critical temp.
- Envelope conductivity affects surface temp, atmosphere affects X-ray spectrum
- See Yakovlev, Ho, Vigano, Gill talks

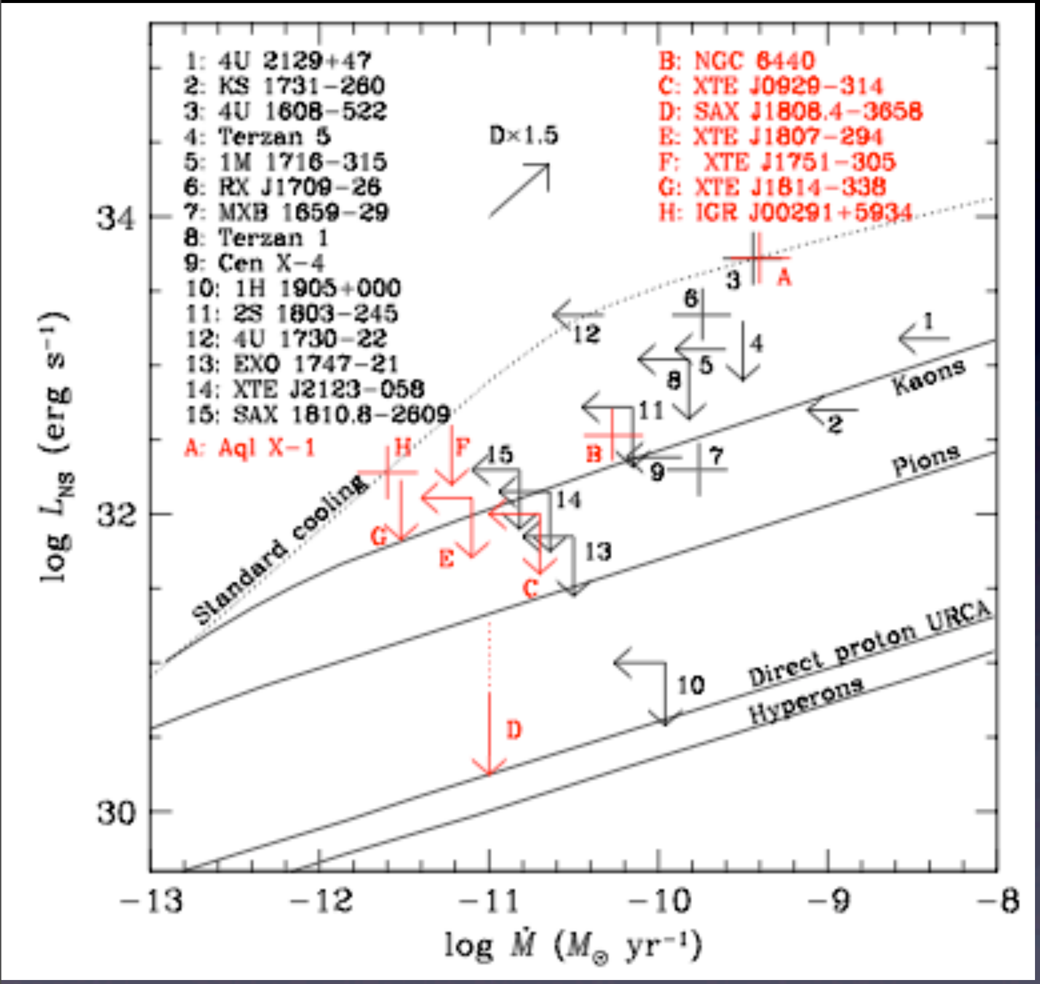
Observing Cas A Cooling

- T drop measured at 3.6±0.6% over 10 years
- Strong constraint on NS cooling; requires superfluid transition in core (Yakovlev talk)
- Calibration concerns. Other measurements: T declines of 1.0±0.6% (Posselt+13), 1.3±0.6% (Elshamouty+13)



Heinke & Ho 2010

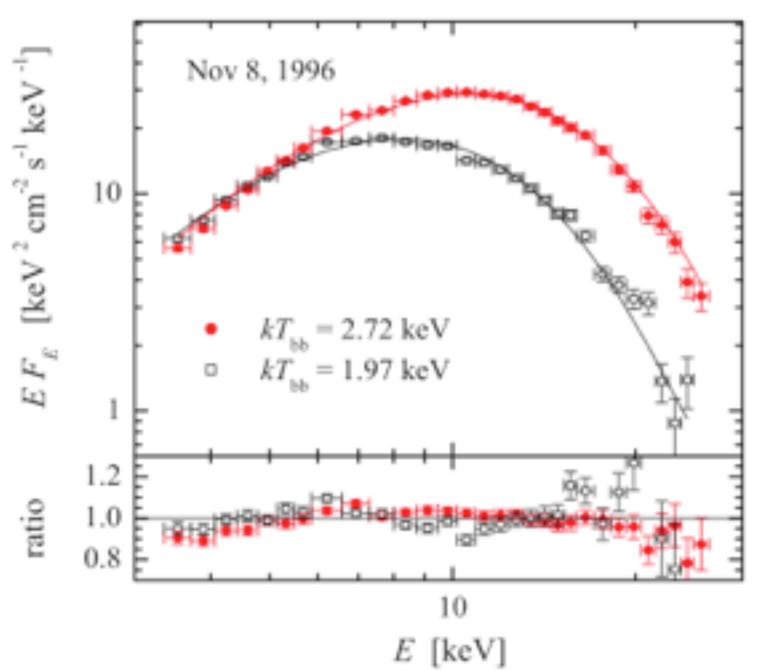
Quiescent X-ray binary T



Heinke+09; quiescent L_X vs. mass transfer rates

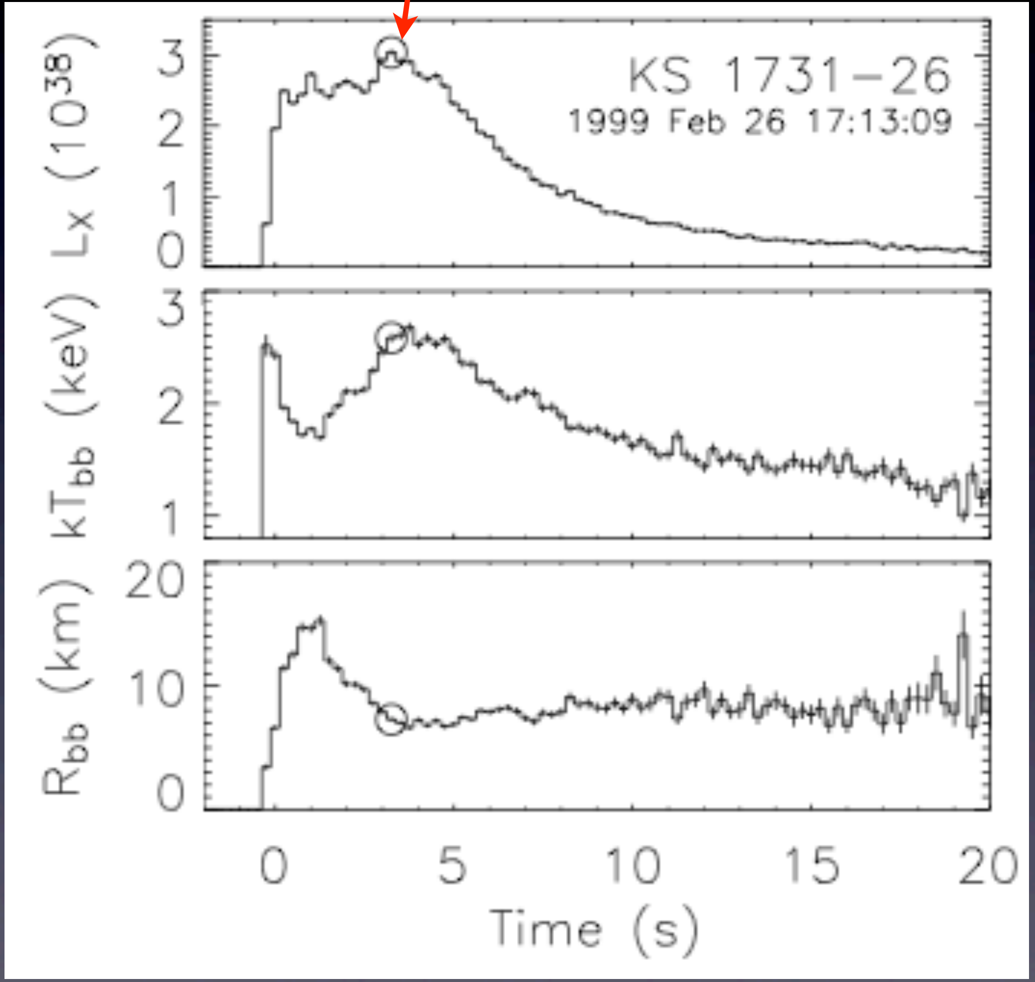
- NS core is heated by fusion of heavy elements in inner crust during accretion (Brown+98)
- Comparing time-averaged accretion rate to quiescent NS L_X constrains ν flux from core (Colpi+01, Yakovlev+04, Wijnands+13)
- Two NSs require very strong Urca cooling (Jonker +06, Heinke+07)

X-ray bursts



Suleimanov+11

Touchdown

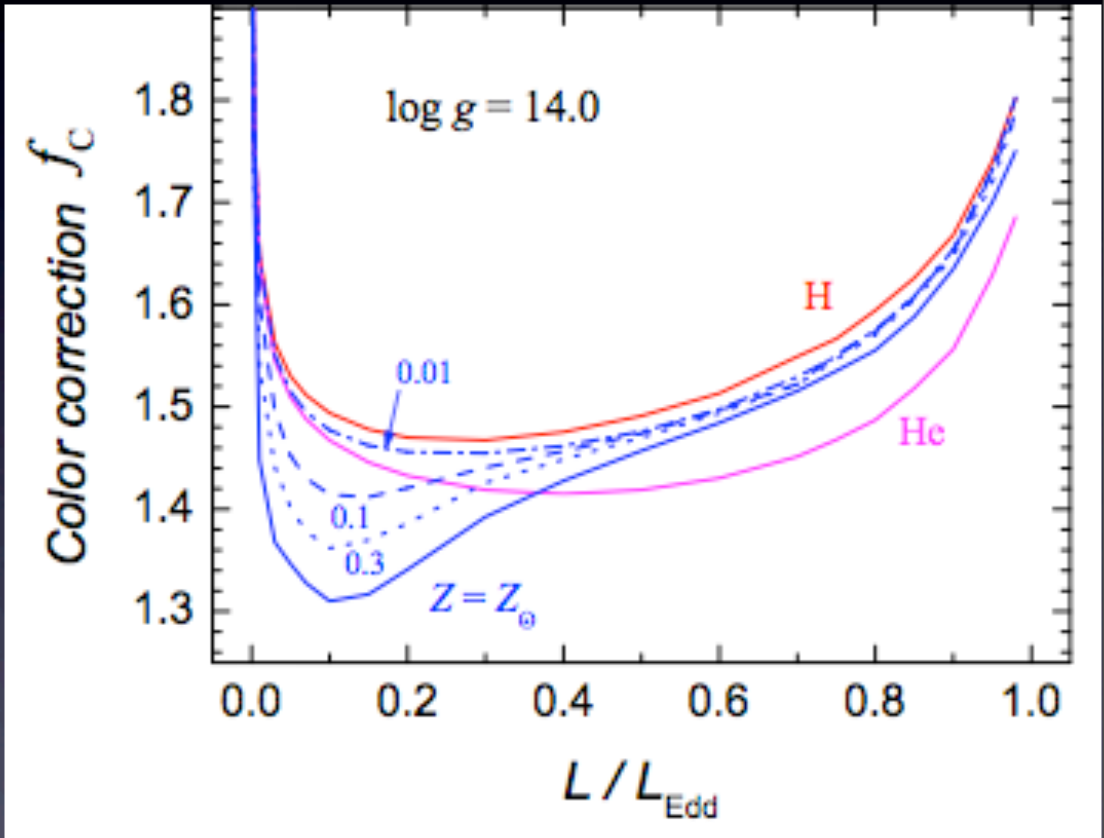


Galloway+08

- Burning of He and/or H to heavy elements
- Photosphere can expand; inferred blackbody radius ~constant after

Color corrections

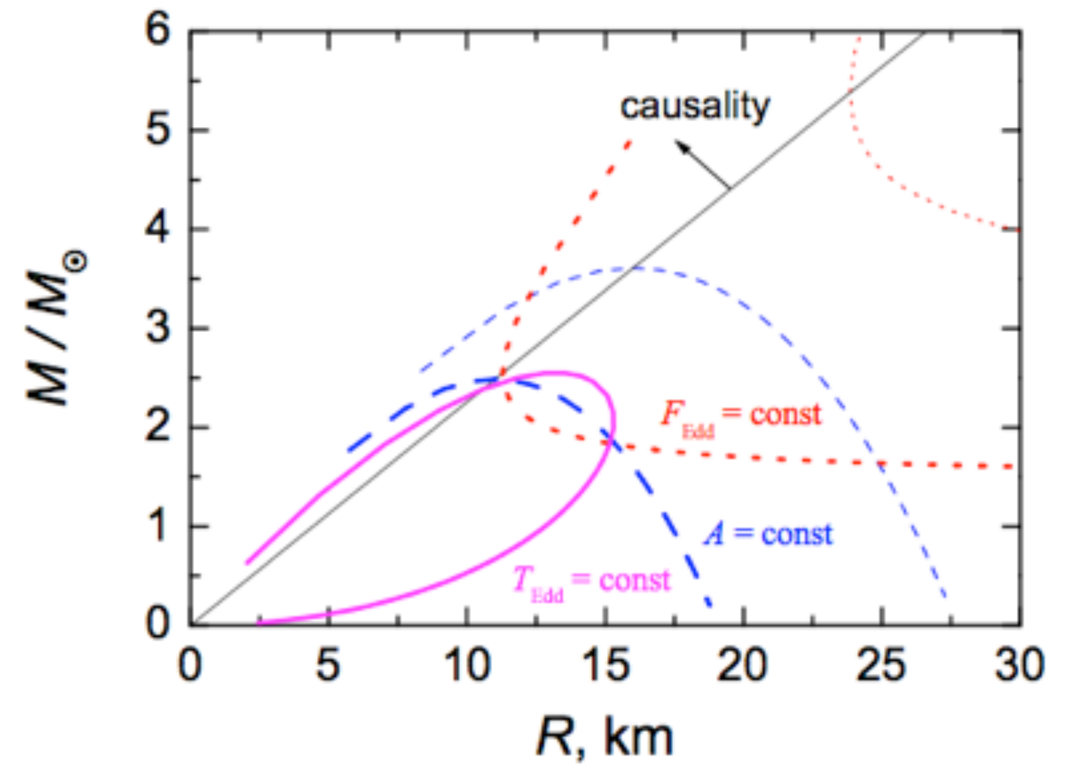
- At high T, Compton scattering alters spectrum
- Depends on composition
- Compare kT to BB prediction, get color correction f_C
- Should vary with L



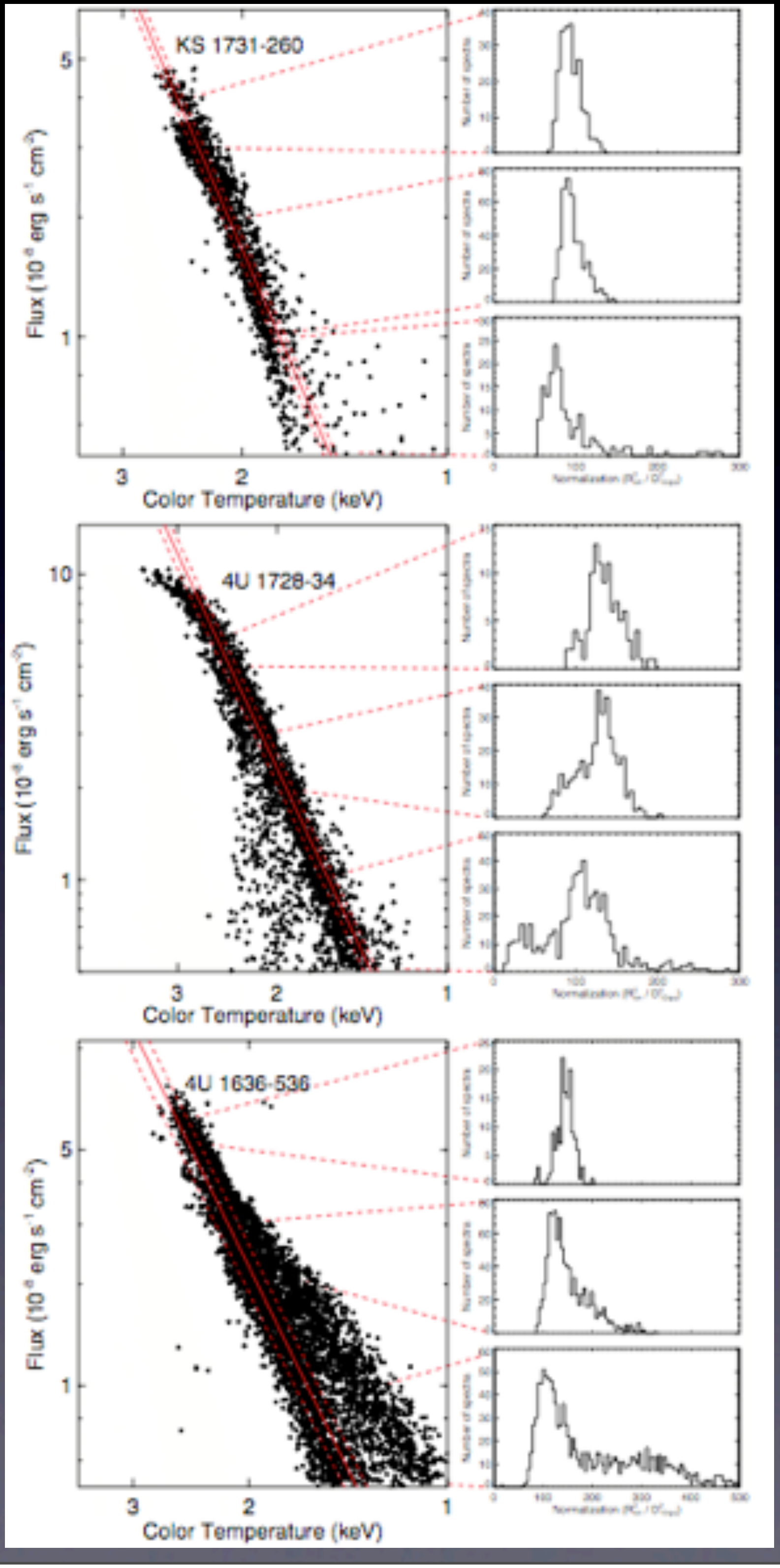
Suleimanov+11

Mass/radius constraints

- Area: $F=\sigma T^4 * R_\infty^2/4D^2$
- Radiation at Eddington limit lifts mass;
- $F_{Edd}=GMc/(\sigma D^2[1+z])$
- T_{Edd}; corresponding kT.



Constraints from 3 methods; Suleimanov+11



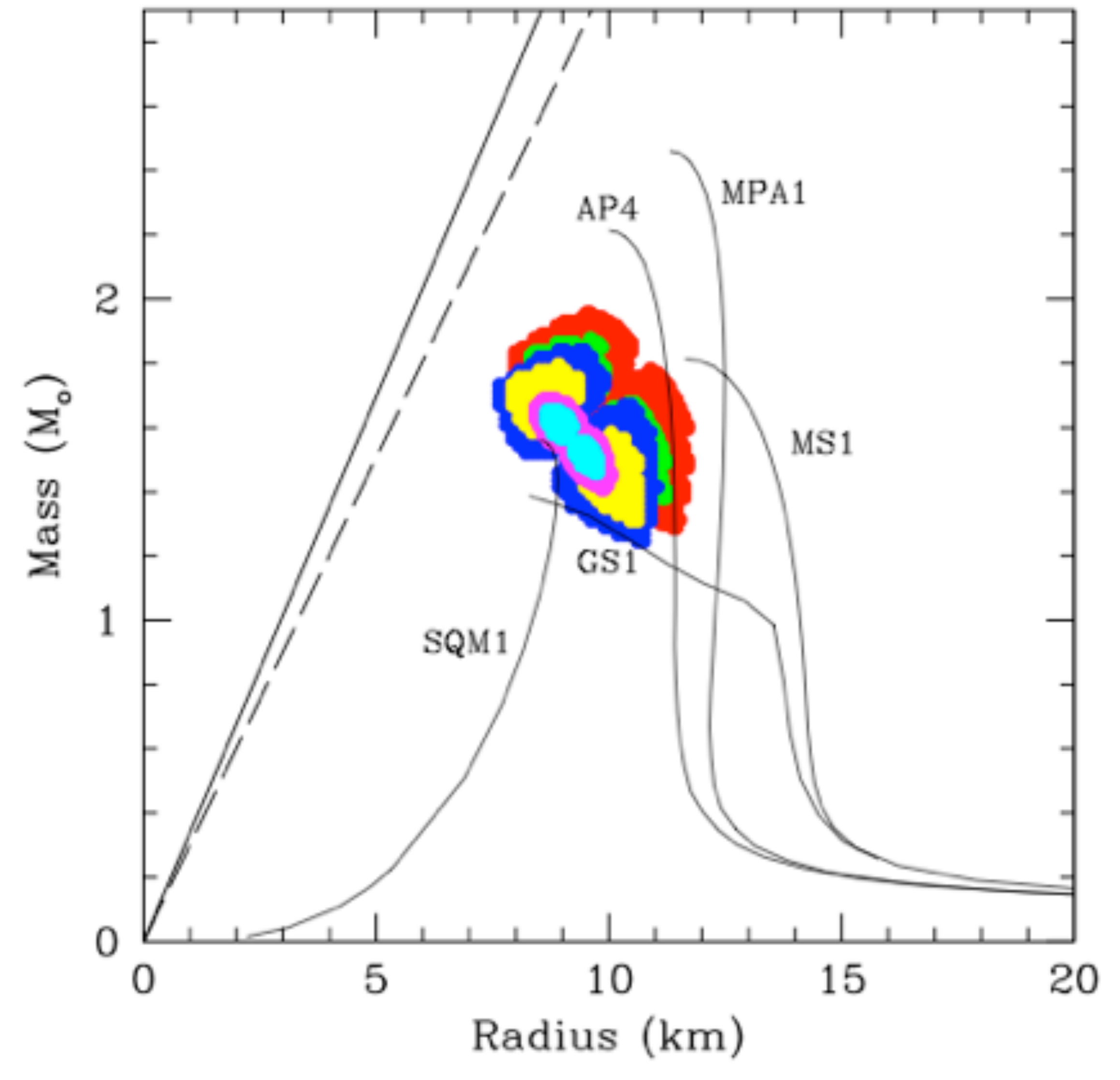
X-ray bursts

- X-ray flux $\propto T^4$ in tail
- Reproducible areas & F_{Edd}, permit well-constrained M/R
- Uncertainties in atmosphere modeling, fraction of surface, radius of emission, etc. (Steiner+10, Suleimanov+11, Zamfir+12)

Guver+2012

Ozel/Guver burst fits

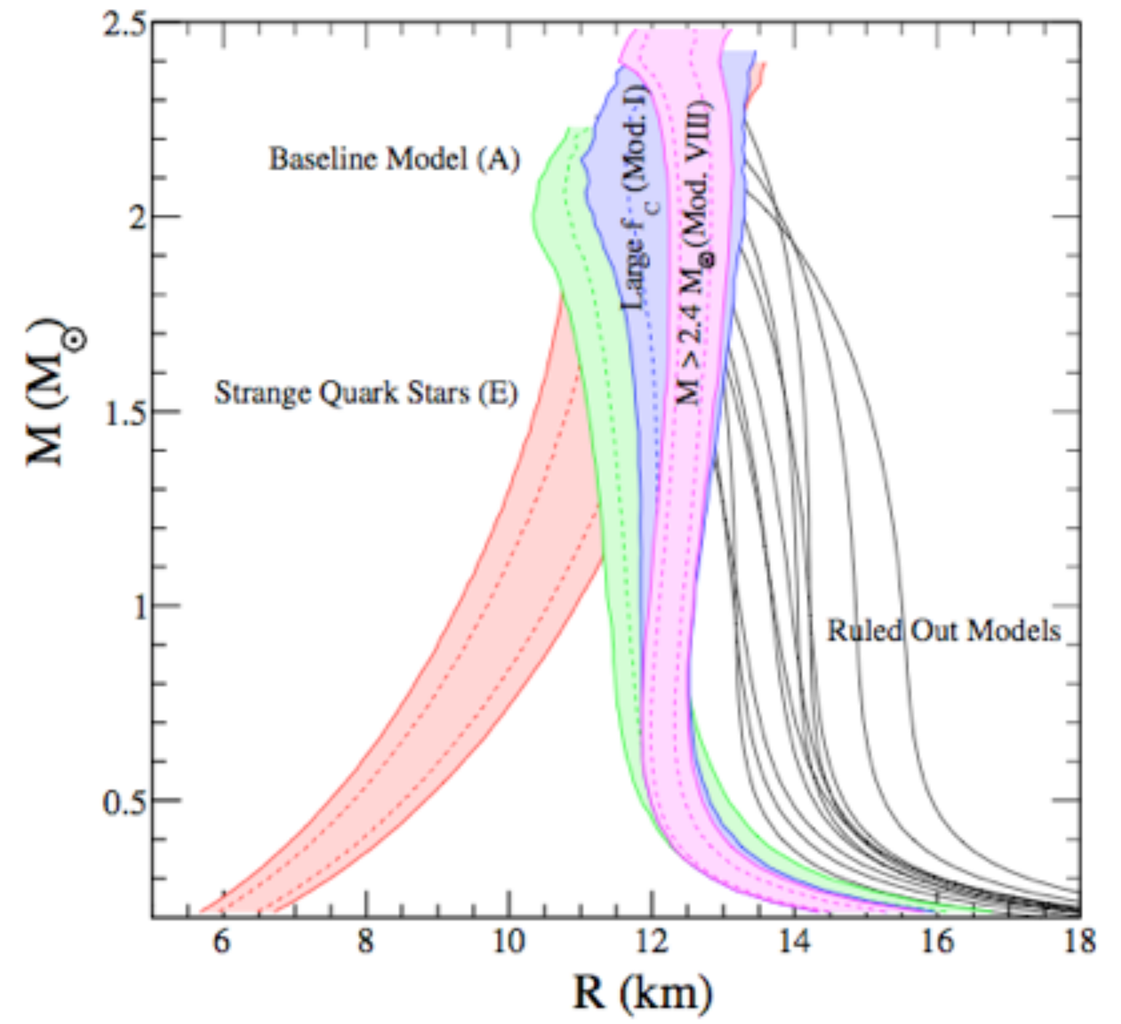
- Ozel & Guver used RXTE bursts (overlap of area and F_{Edd} constraints), measured M, R for 3 NSs with known distances
- Calculated low radii, below 10 km



Ozel+10 (1σ, 2σ constraints)

Other interpretations

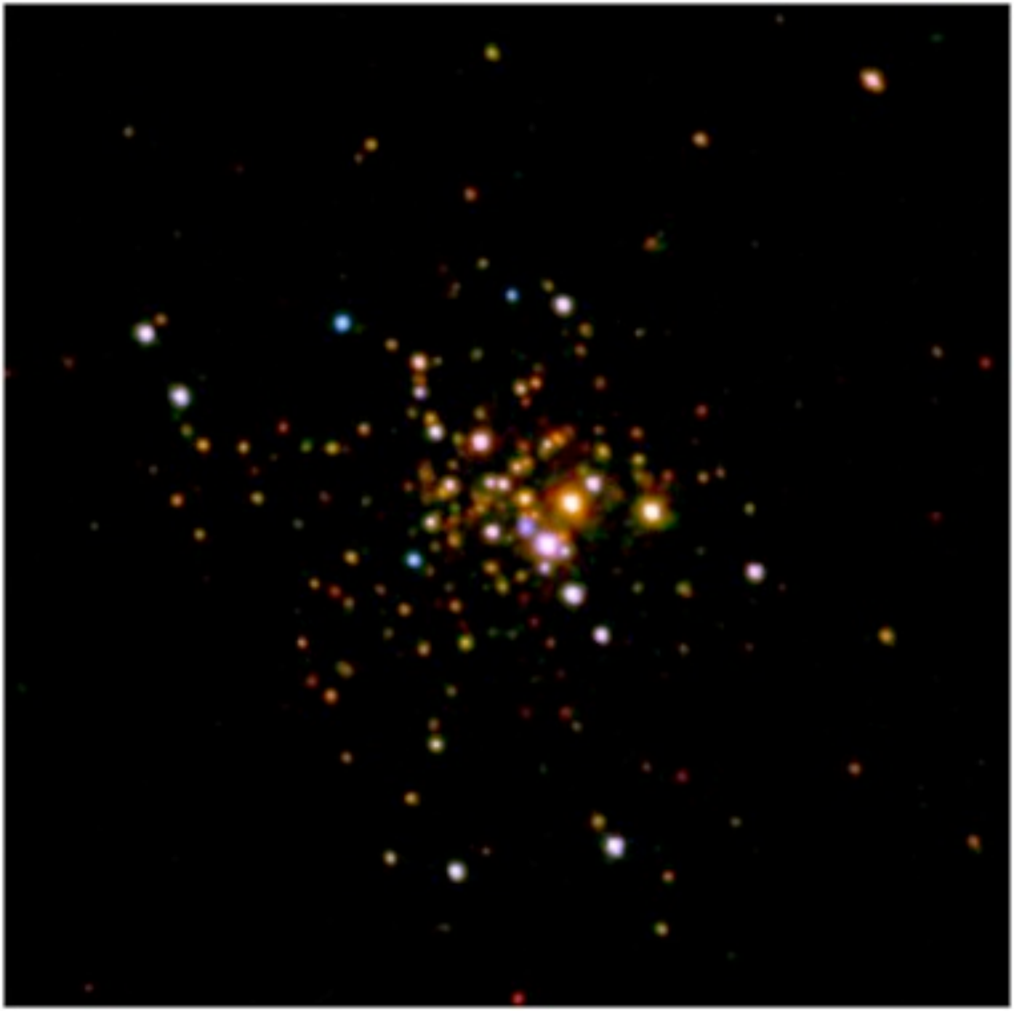
- Steiner+10,+13 dispute Ozel analyses, find larger radii
- Combine nuclear experiments, bursts, quiescent LMXBs



Constraints from bursts, qLMXBs; Steiner+13

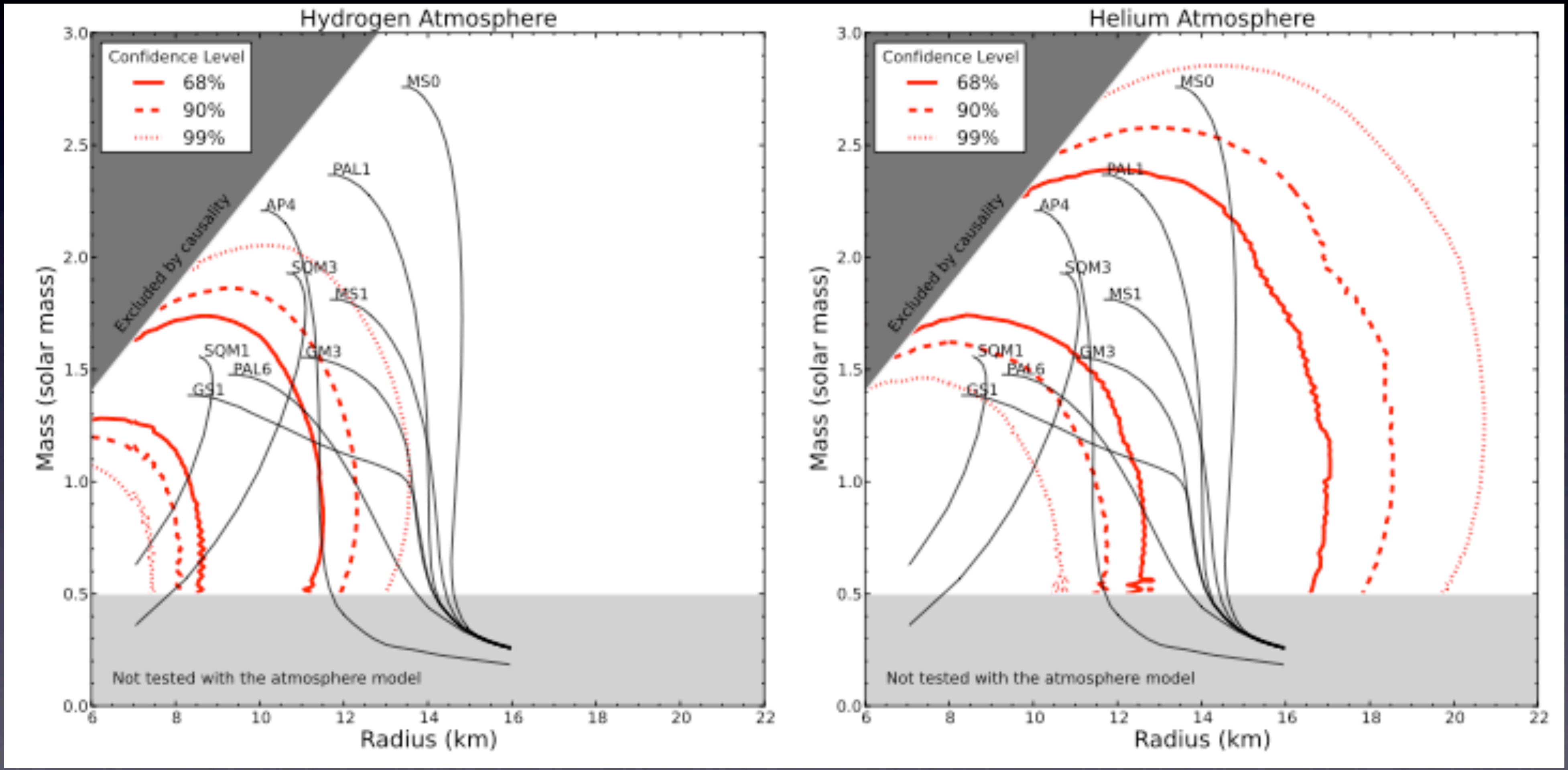
Quiescent LMXBs

- Use globular clusters (known distances)
- Identified by thermal spectra; best targets lack nonthermal component, have little gas/dust



Chandra image of 47 Tuc, Heinke+05

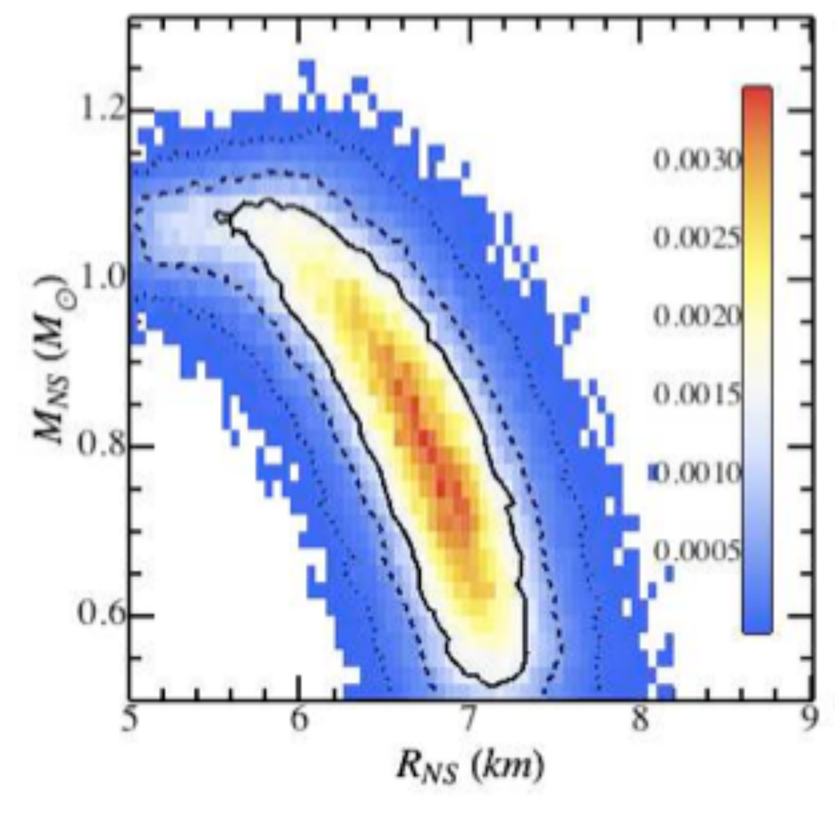
H vs. He atmospheres



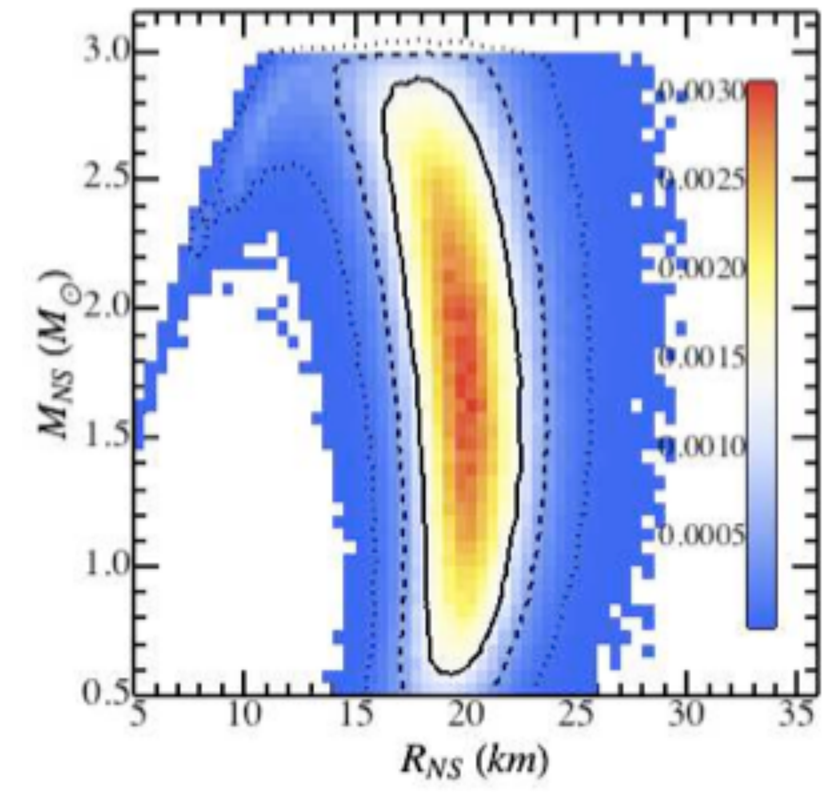
H vs. He atm. fits to M28 qLMXB, Servillat+12

Guillot+13 analyses

Analysed 5 objects; two give extreme values



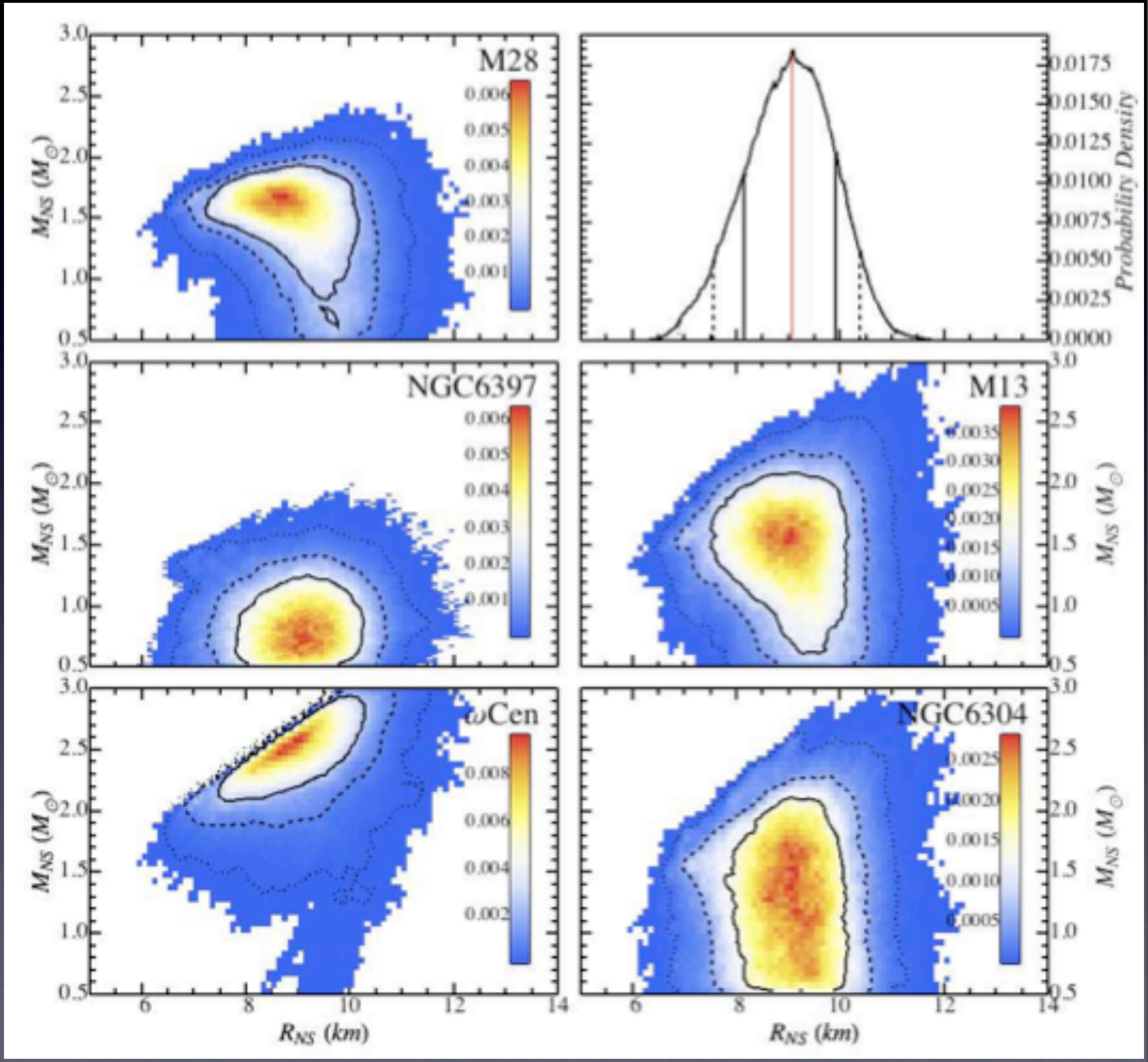
NGC 6397

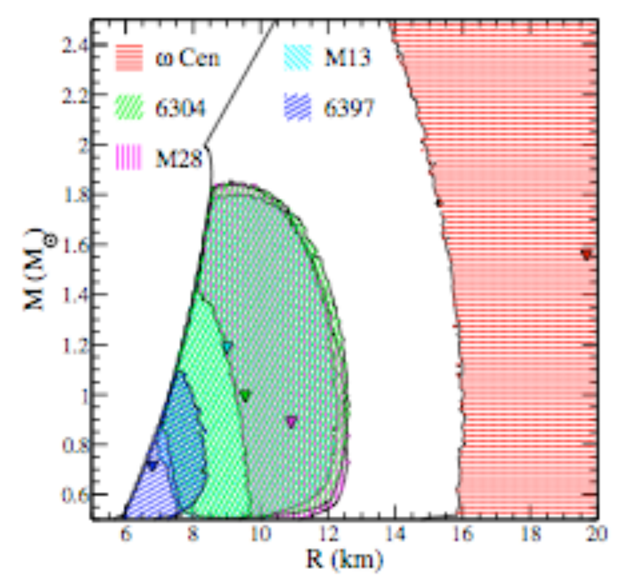


ω Cen

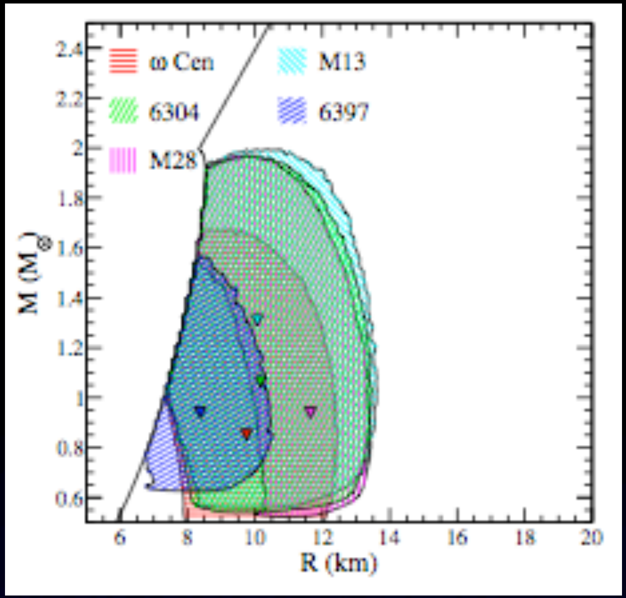
Guillot meta-analysis

- Assume same radius for all
- Calculate low radius, wide range of masses

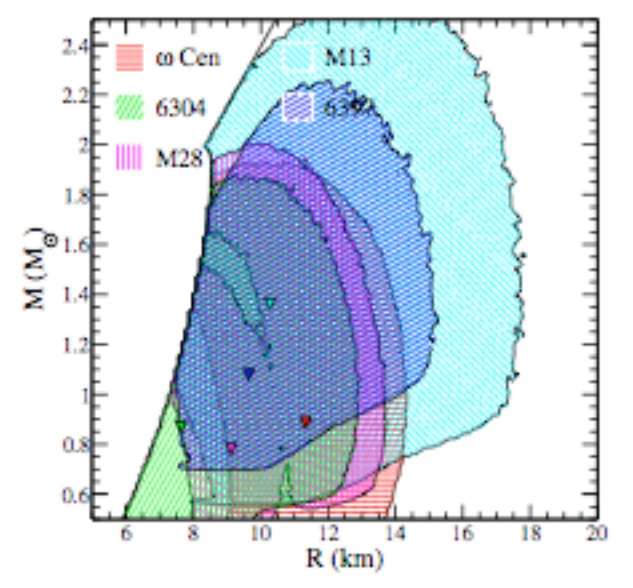




Guillot+13, 90% conf

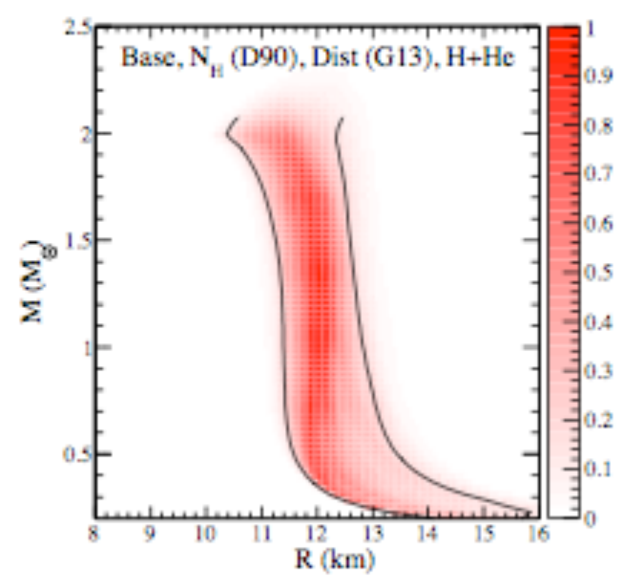


Lattimer+14; assume N_H from cluster



Lattimer+14; estimate effect allowing He

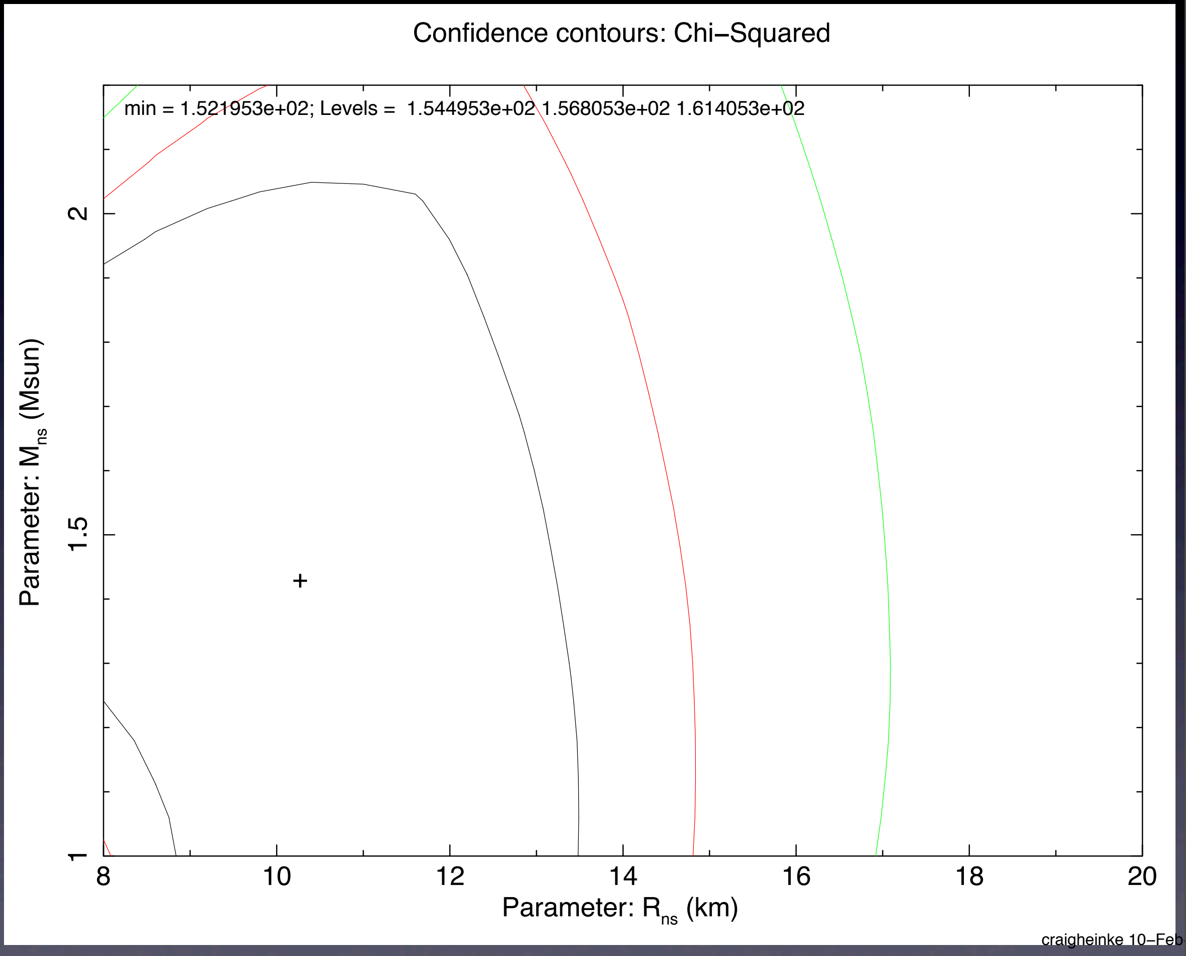
Purely theoretical



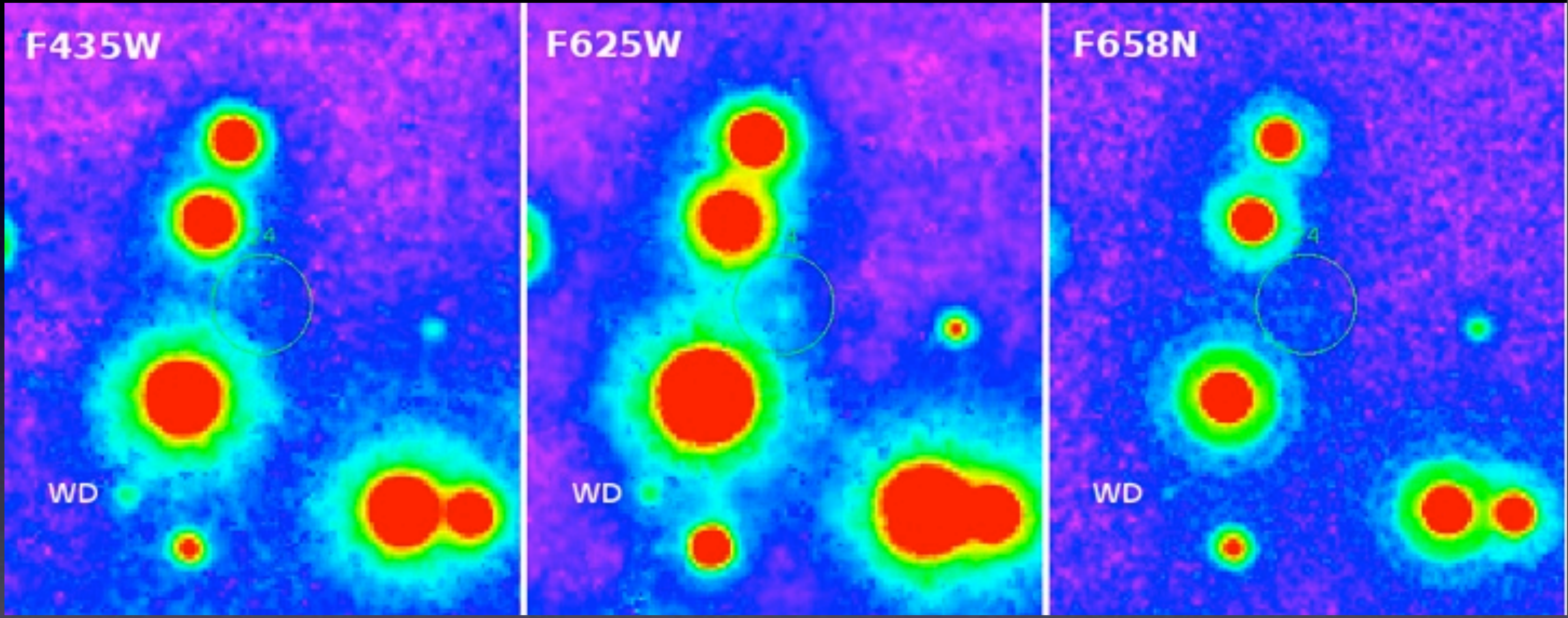
Lattimer+14; include priors from nuclear experiments

ω Cen

- Correct abundances change R by ~25% (G+13: 21±3 km; new N_H: 16^{+7}_{-5} km)
- Add new Chandra data, find R=10^{+3}_{-5} km (for M=1.4 Msun)



NGC 6397: He atmosphere?



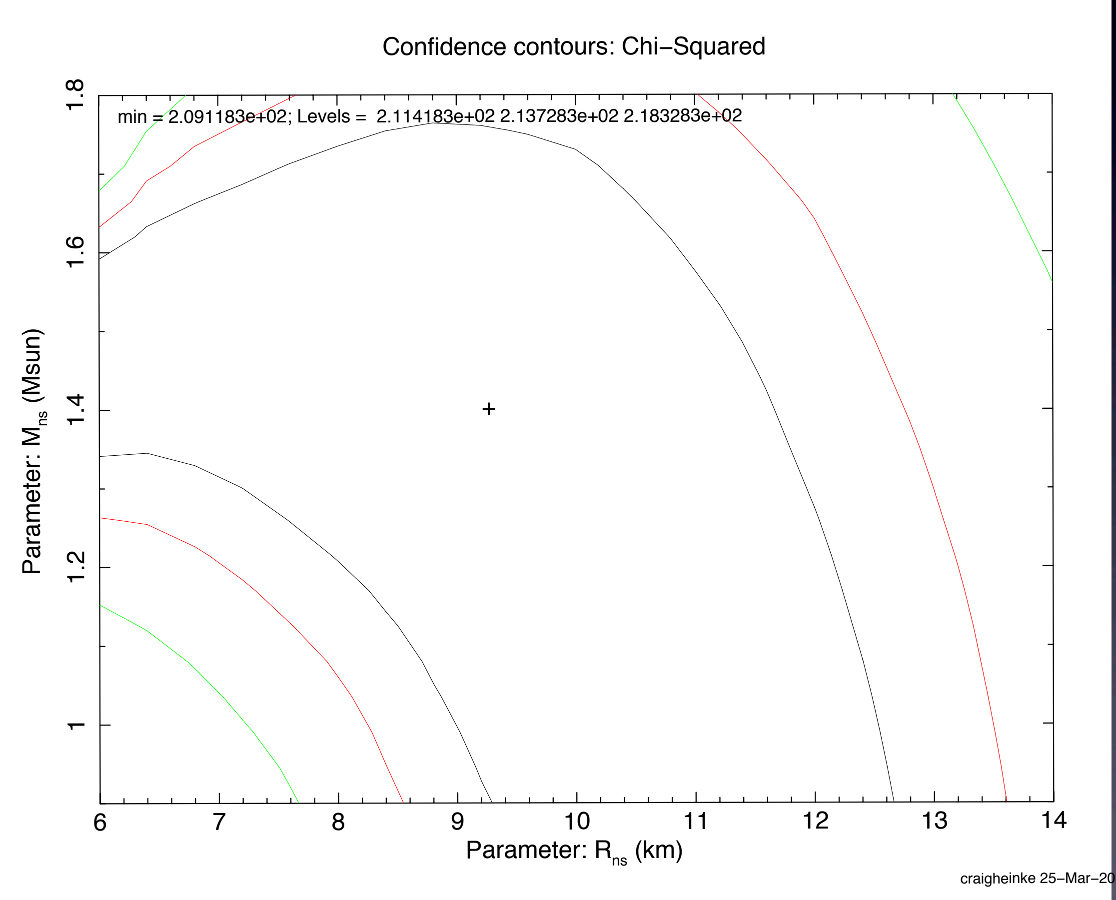
Deep HST imaging: likely counterpart in R, but no Hα.

Other qLMXBs show Hα;

suggests He WD companion.

NGC 6397 radius

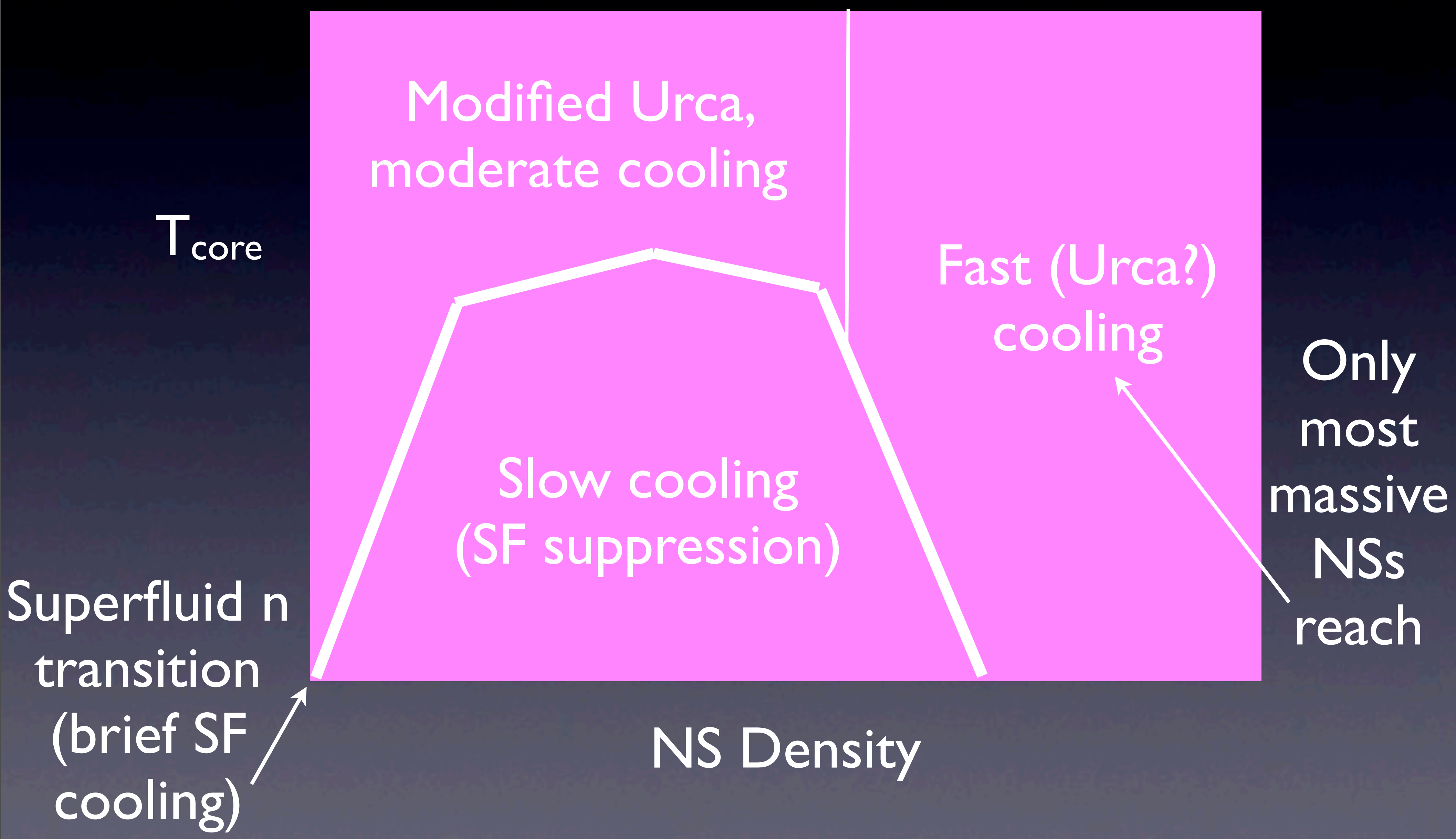
- H atmosphere requires R<8 km for M>1.2 Msun
- He atmosphere allows R<13 km; strongly preferred!



Conclusions

- X-ray spectroscopy permits interesting constraints
- Spectral lines promising, no constraints yet
- Cooling constrains crust microphysics, interior neutrino emissivity
- Radius constraints: camps arguing over 8-13 km range (I favor 11-13 km)

Simple cooling picture



Modified Urca, moderate cooling

Fast (Urca?) cooling

Slow cooling (SF suppression)

T_{core}

NS Density

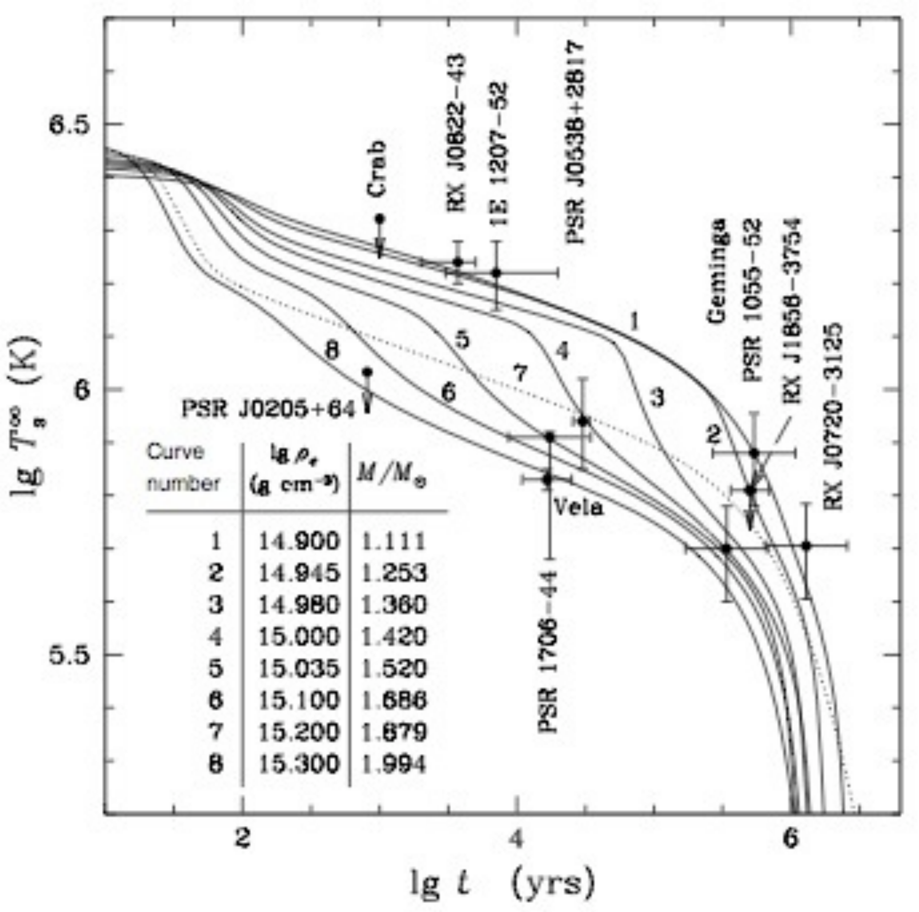
Superfluid n transition (brief SF cooling)

Only most massive NSs reach

Measuring NS temps constrains NS cooling behavior

Expect different cooling paths, as NSs have different masses, atmospheres

Cooling curves can have quick SFT drop; but not fast enough to match data



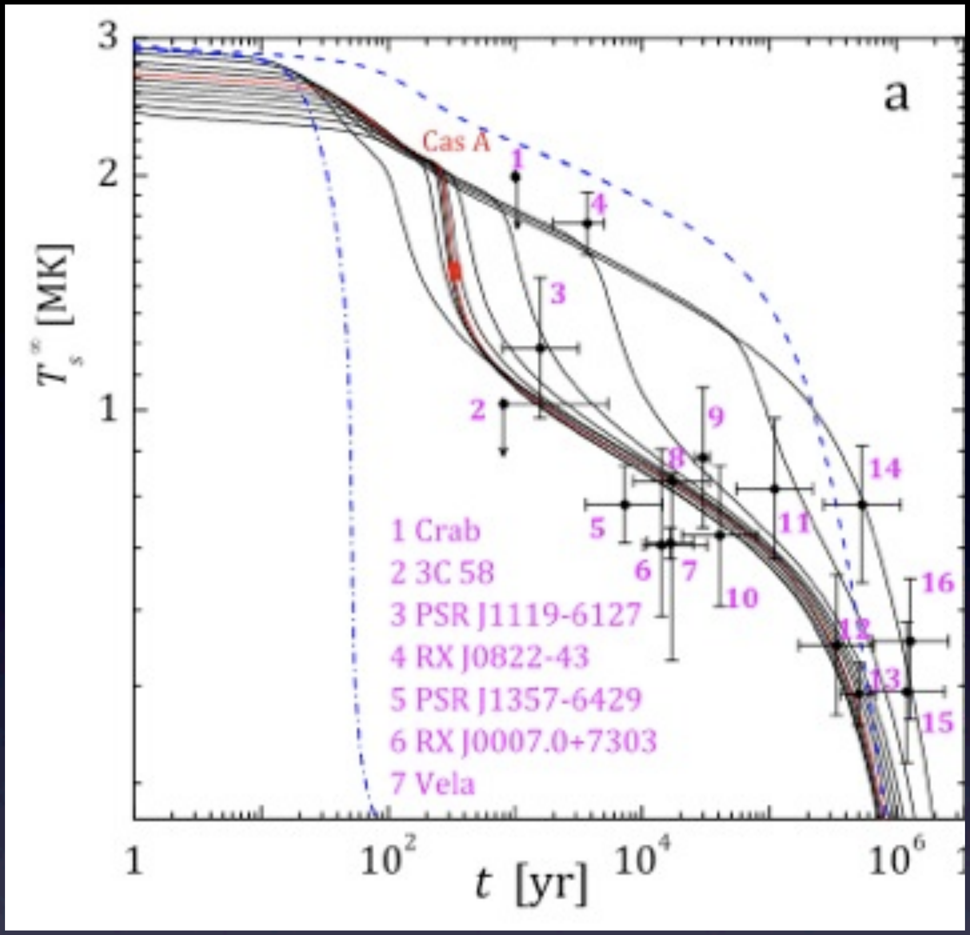
Curve number	lg ρ_c (g cm^{-3})	$M/M_\odot$
1	14.900	1.111
2	14.945	1.253
3	14.980	1.360
4	15.000	1.420
5	15.035	1.520
6	15.100	1.686
7	15.200	1.879
8	15.300	1.994

Gusakov+04; cooling curves with SFT drops

Cas A started cooling quickly very recently

Seems to require p SF to suppress Urca, n SF to give sudden cooling

To fit cooling, neutron SF T_C should have broad peak~7-9*10^8 K, proton SF T_C > 2*10^9 K

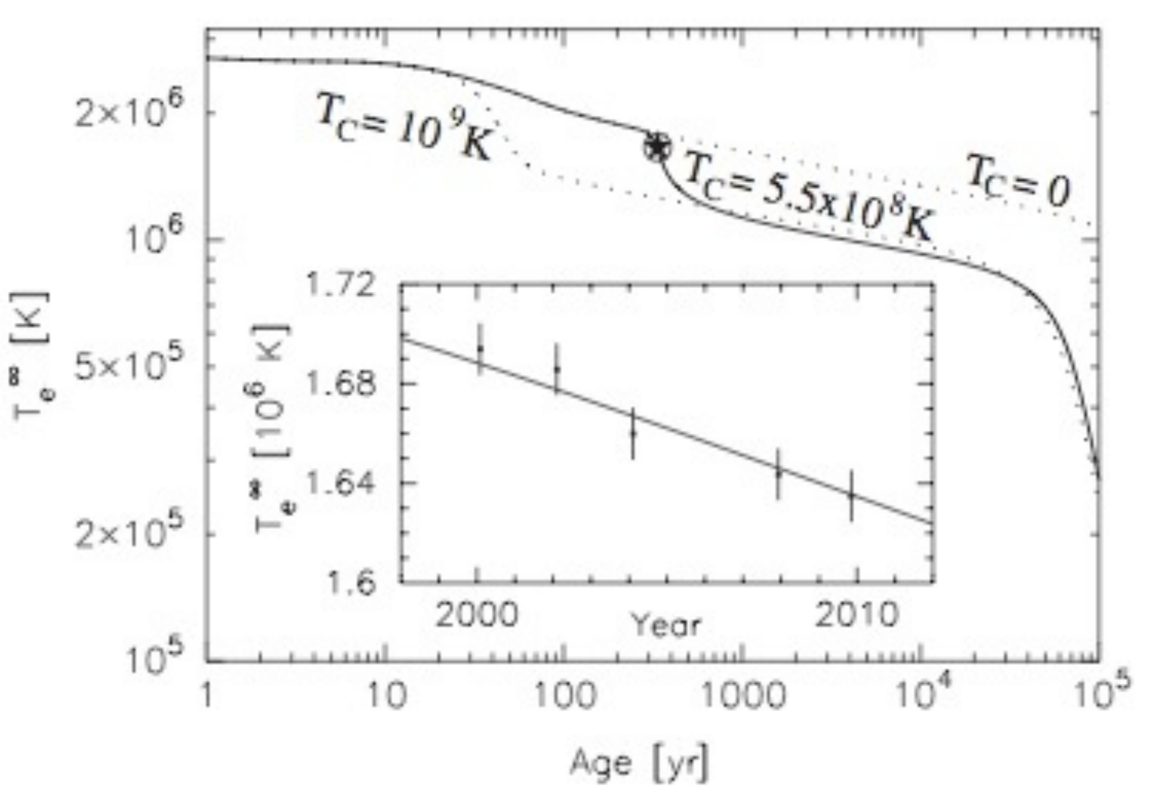


Shternin et al. 2011

Another group of theorists interpreted Cas A observations in same way

Page+11 find neutron SF T_C~5*10^8 K, proton SF T_C>10^9 K

Agreement between two top theory groups



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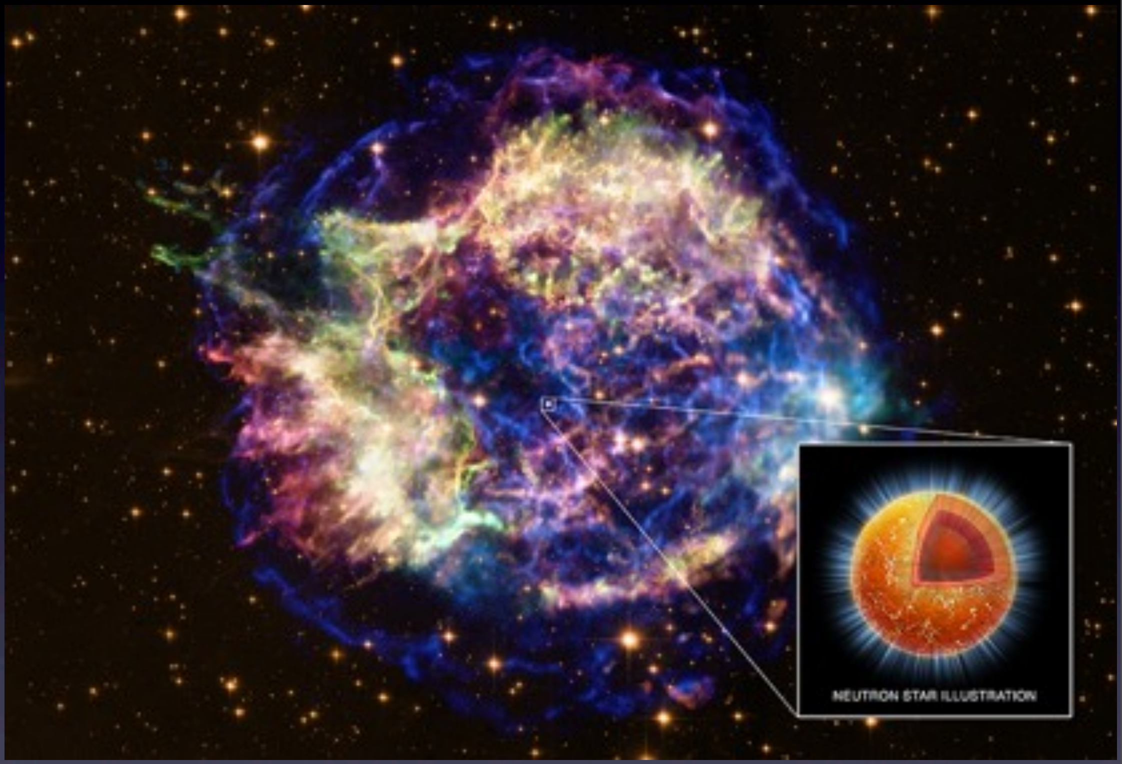
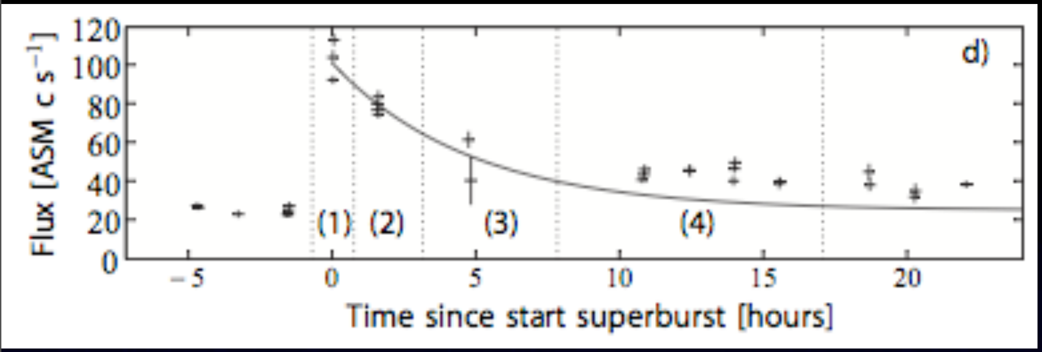
Conclusions

- X-ray observations can constrain NS interior structure
- Crust conductivity, core neutrino emission, compactness of NS
- Cooling directly measured in Cas A NS
- Evidence for neutron SF in core

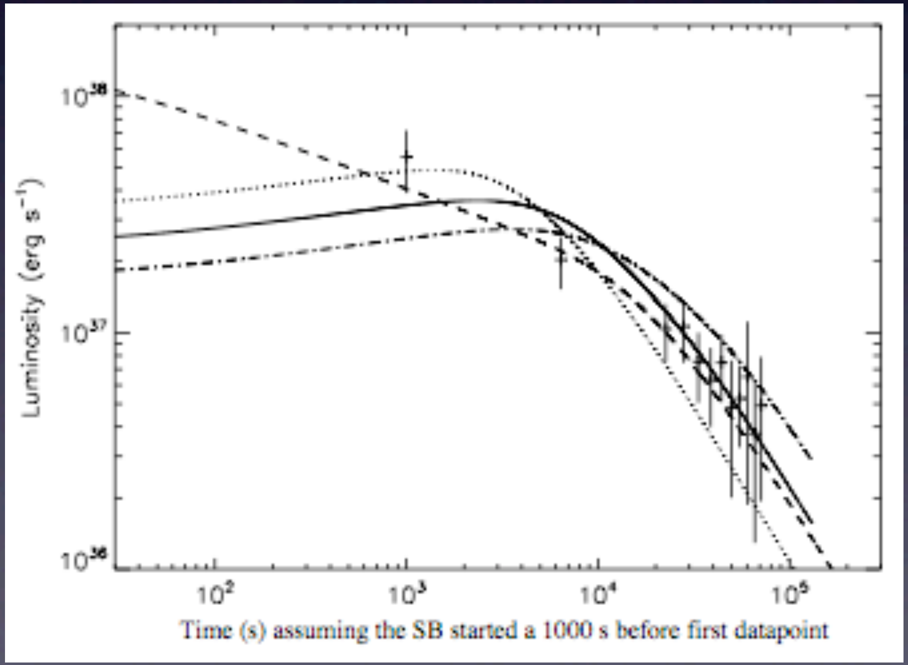


Cas A (NASA Chandra/Hubble)

Superburst ignition



Keek+08, superburst lightcurve



Altamirano+12, Terzan 5 superburst

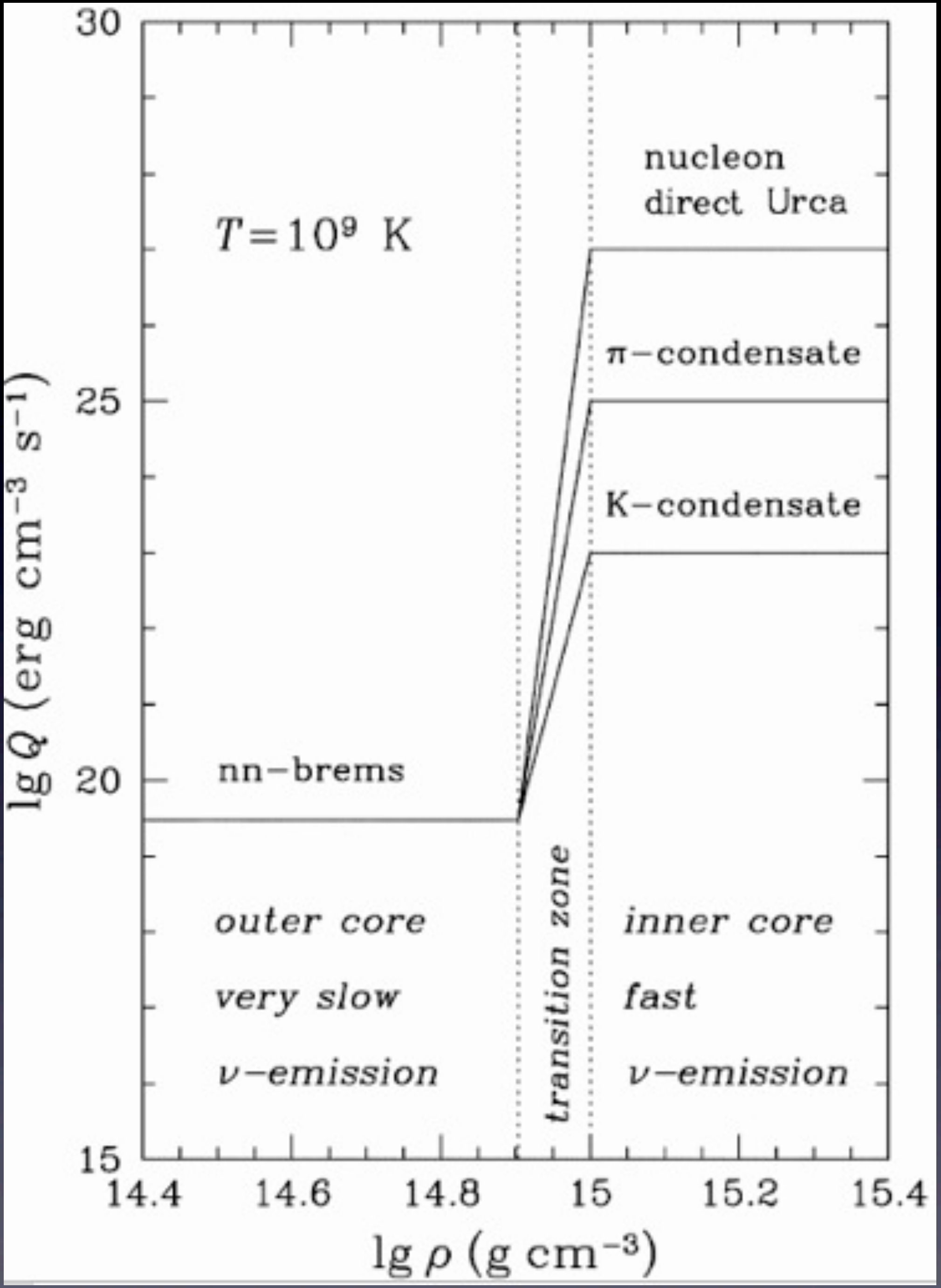
- Superbursts burn carbon, making longer bursts
- Making superbursts requires C production, high T
- Current crustal heating models don’t ignite C in two observed NSs; more heating required

Density dependence

URCA processes only at high density

URCA suppressed by superfluidity, depends on density, temp

Highest-mass NSs will have denser cores, so will cool faster



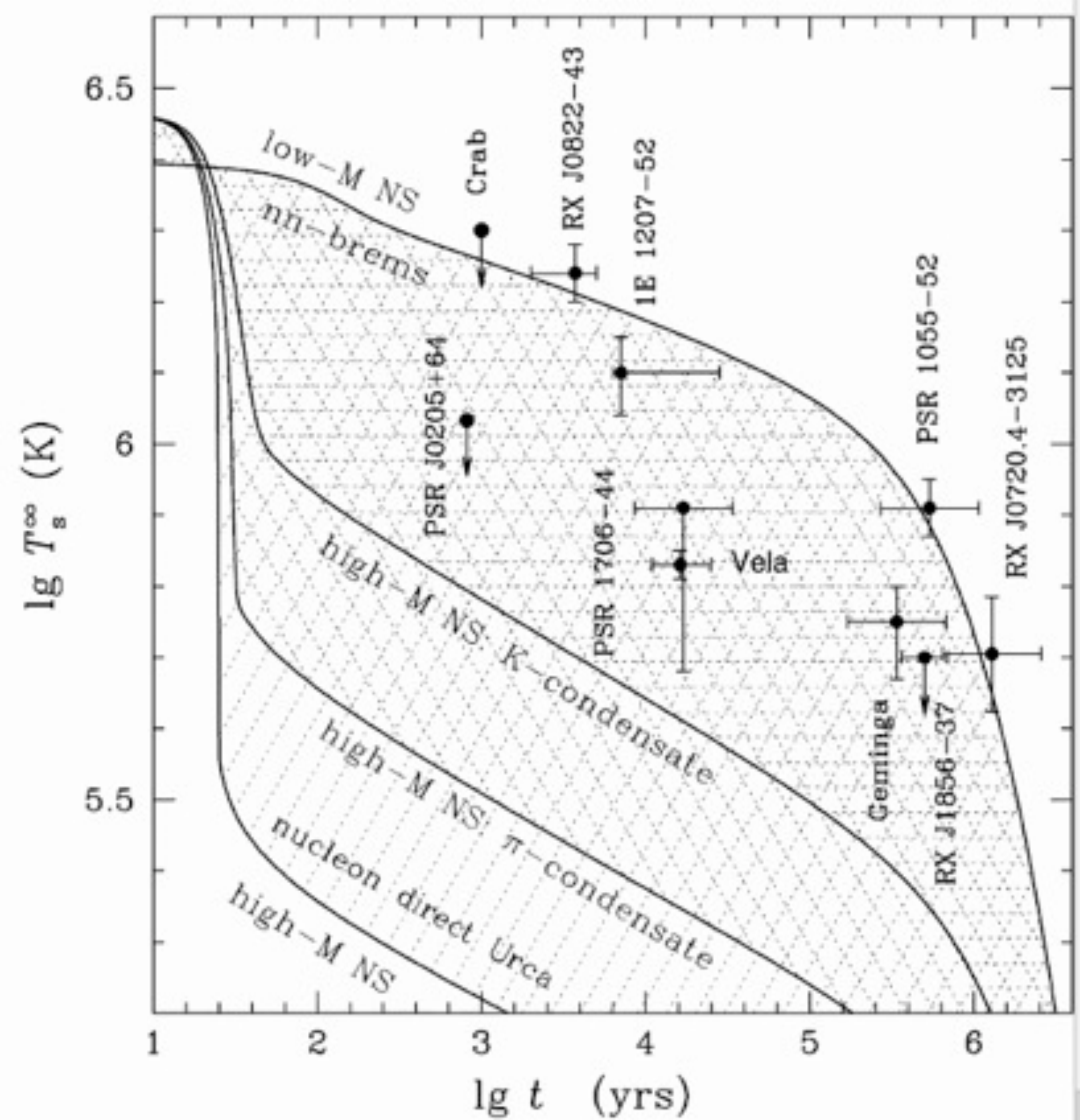
Yakovlev & Pethick 2004

Cooling of young NSs

More massive NSs
can access rapid cooling
at center

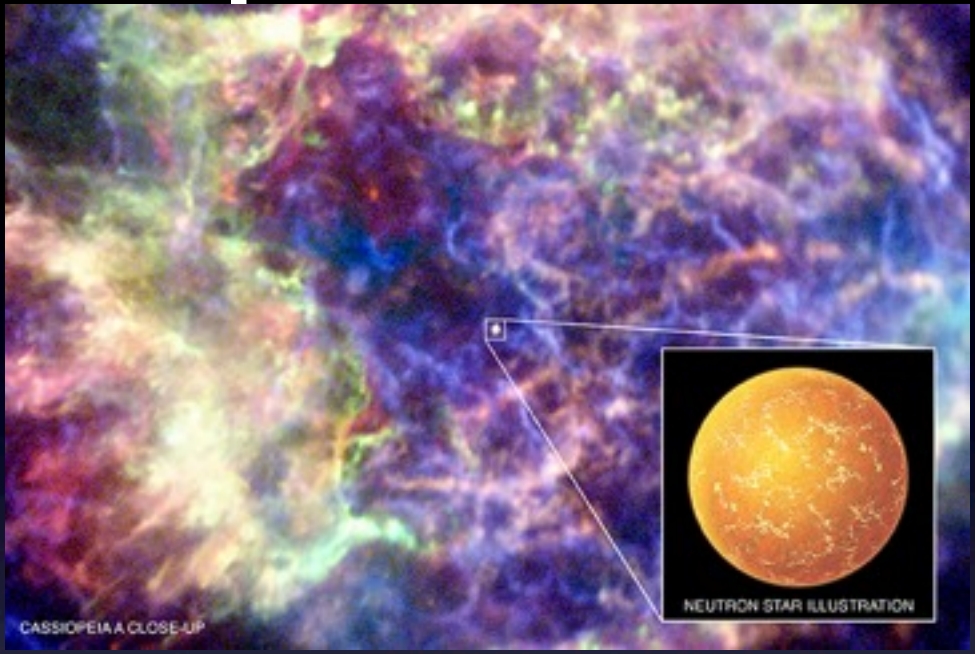
Range of cooling rates set
by NS ν emission process

Young NSs give small
range of cooling rates

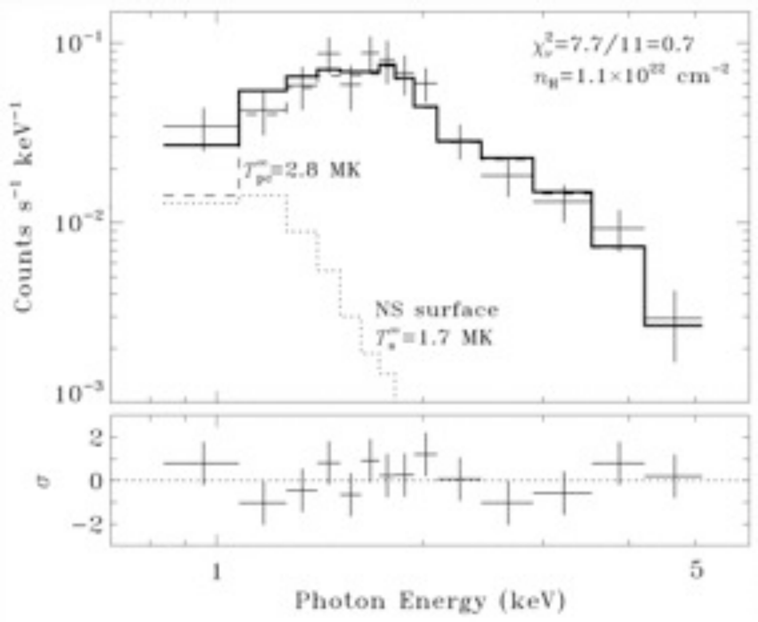


Yakovlev & Pethick 2004

Spectrum of Cas A CCO



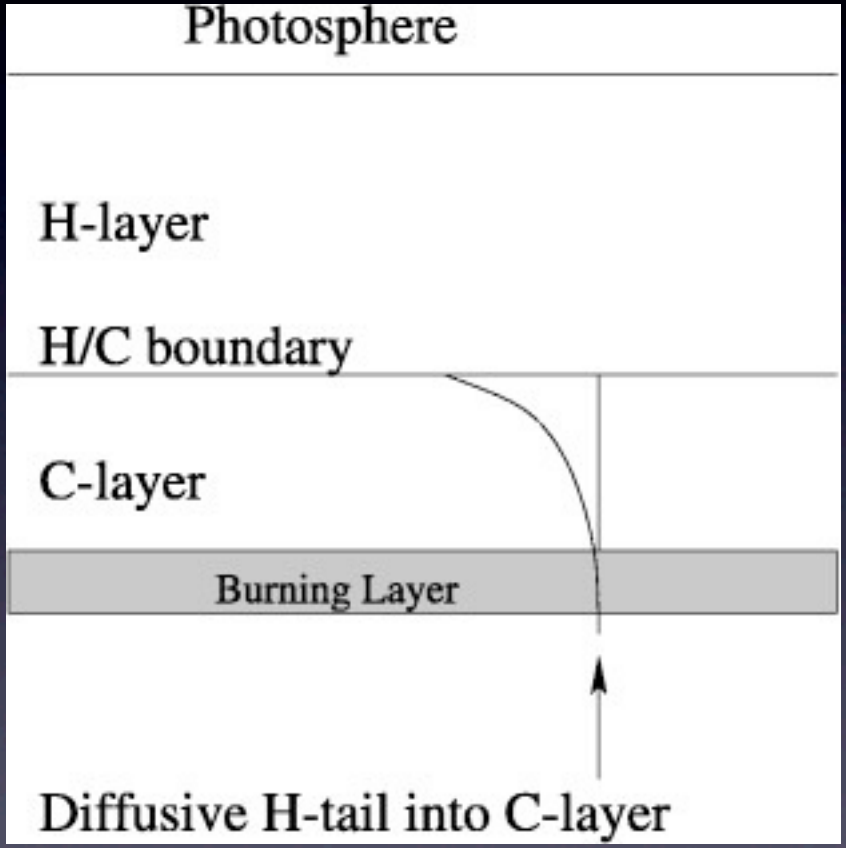
- Consistent with blackbody
- If blackbody, $F_{surf}=\sigma T^4$, so with F_{obs}, T, get angle on sky; with distance, get radius
- Inferred radius ~0.3 km



Pavlov+00

Why a C atmosphere?

- Elements settle in ~30 s, H floats; should be on top (and other NSs show H).
- Right after supernova, NS very hot
- Some of H, He at hotter layers, fuse to C (Chang+03, Chang+10)
- NSs burn away H, He for a few years. Then NS cools, H slowly accumulates again, taking ~1000 (?) yrs to make H atm.

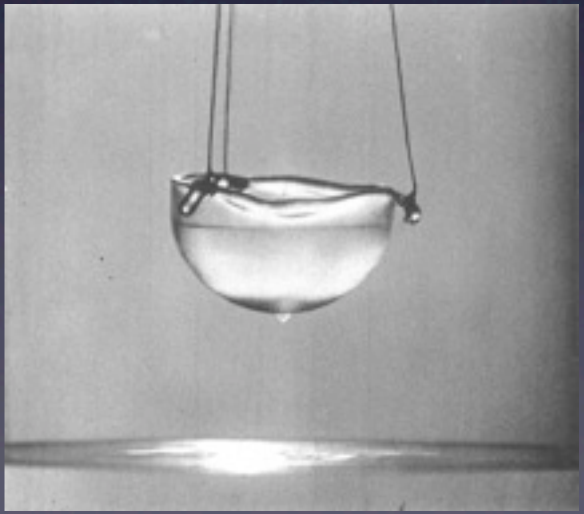


Chang+03

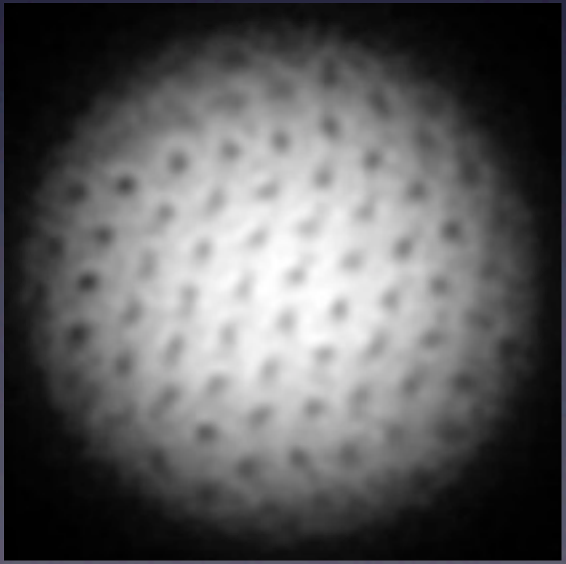
Superfluidity

Quantum pairing of fermion spins at low T
→superfluid state, frictionless flow,
quantized angular momentum (vortices)

Neutrons and protons in NSs theorized to be superfluid up to millions of K

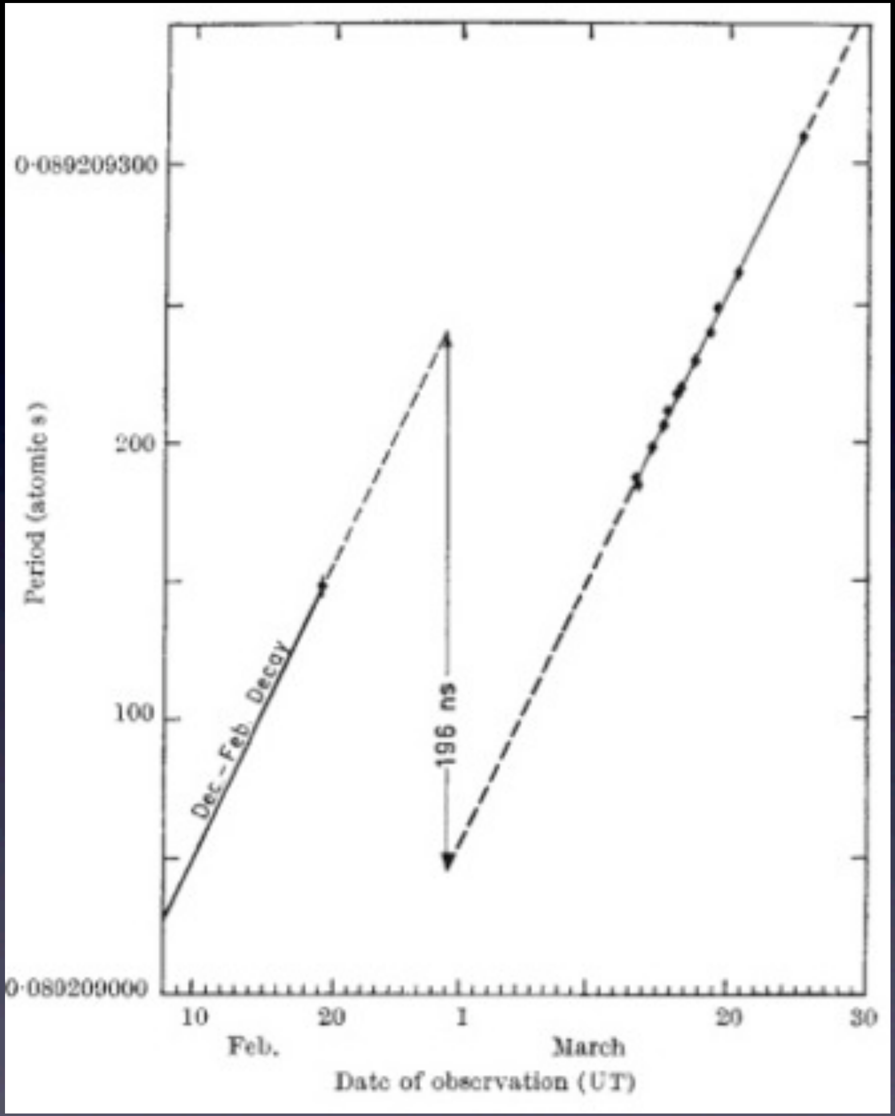


One n SF state in crust,
2nd n SF state in core,
& p SF in core



Superfluid He behavior
A. Leitner, A. Schirotzek & W. Ketterle

Glitches



Vela Glitch
Radh. & Manchester 1969

Radio pulsars show glitches; speed-ups in spin

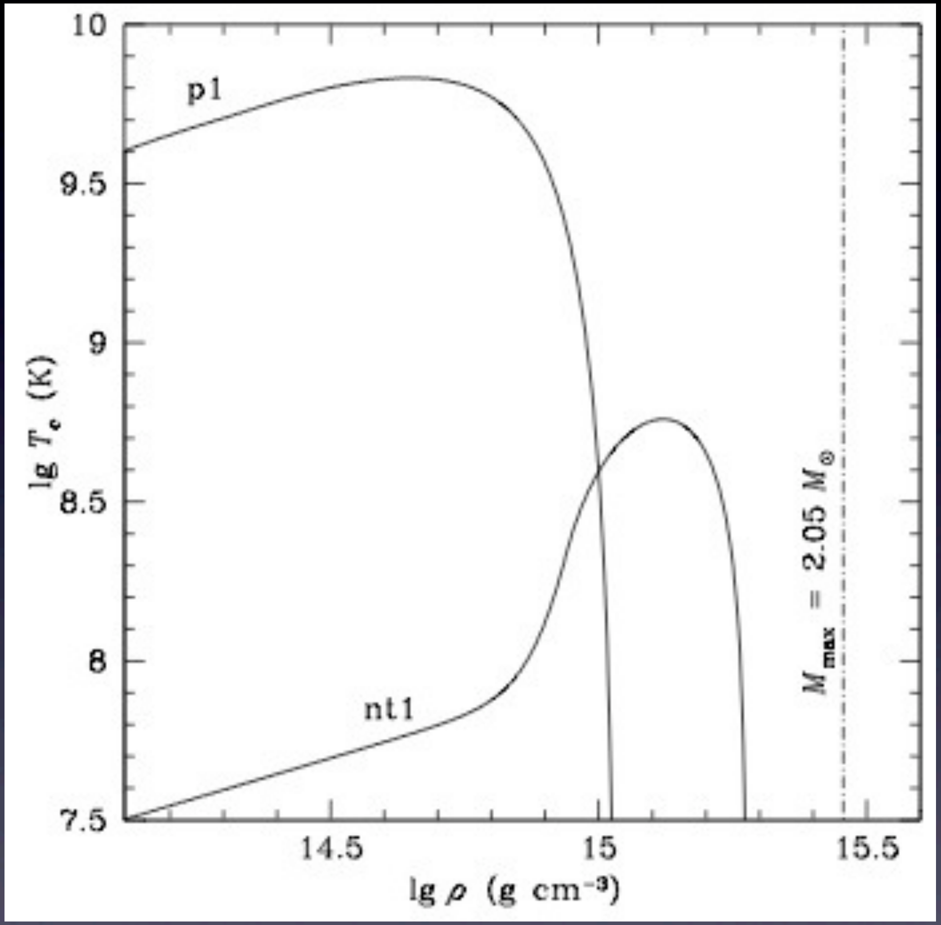
Understood by differing rotation of nuclear lattice, n SF in crust

Glitches represent transfer of ang. mom. to lattice

Only previous direct evidence for SF in NSs, & only in crust

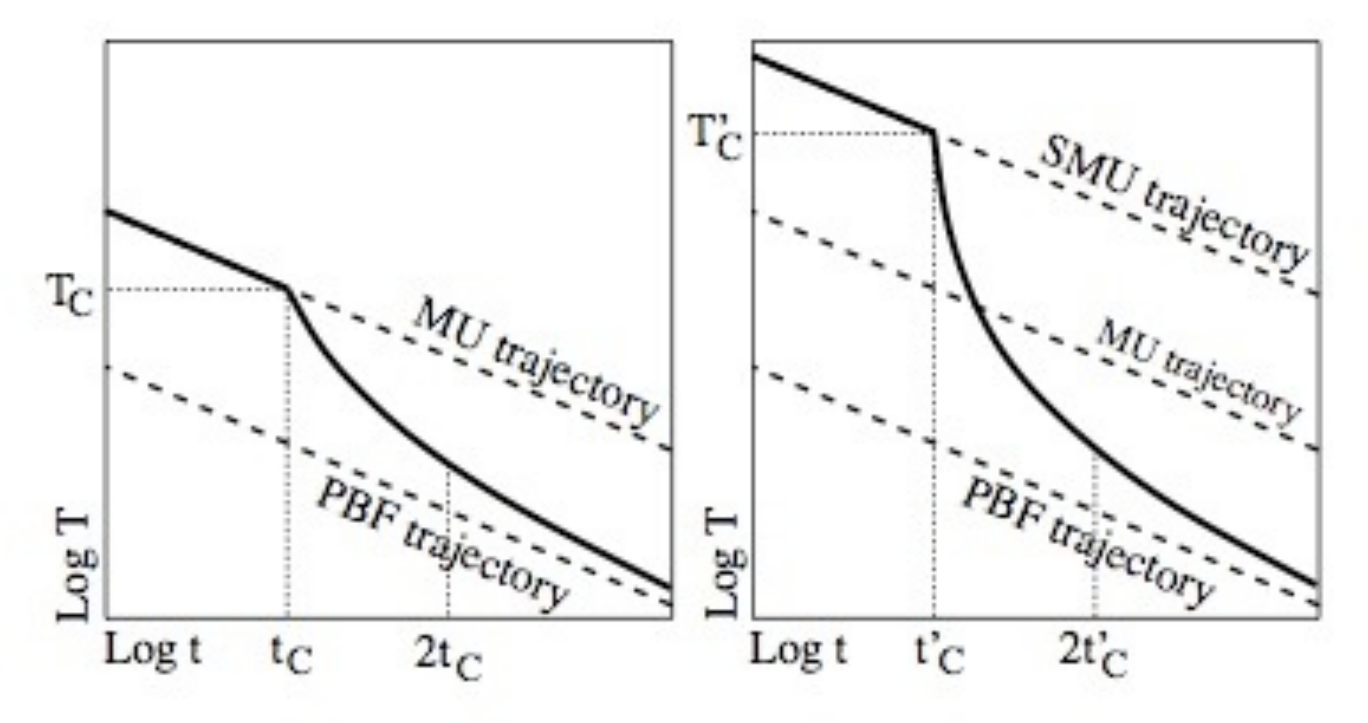
Superfluid transitions

- 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

Hot NS requires p SF



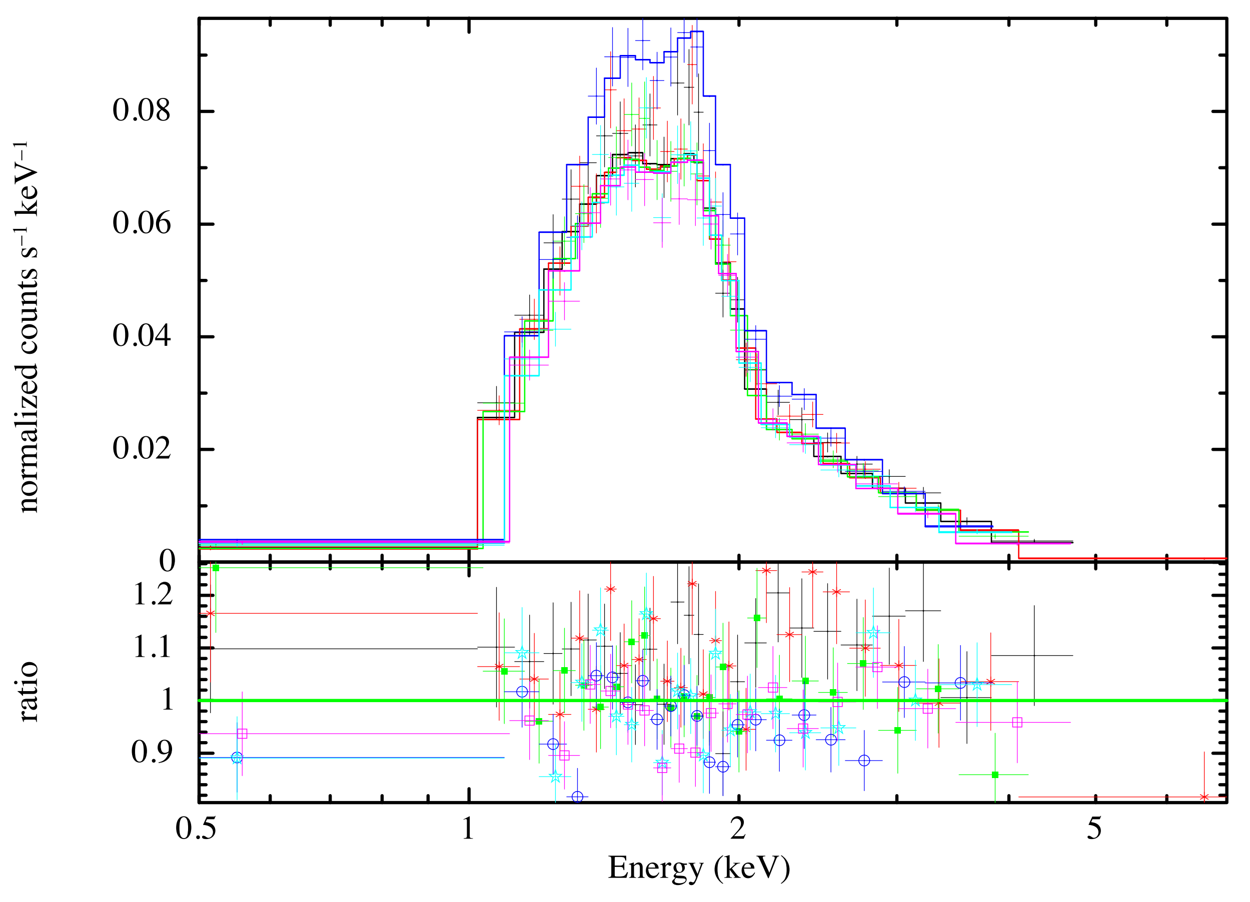
Page+11

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

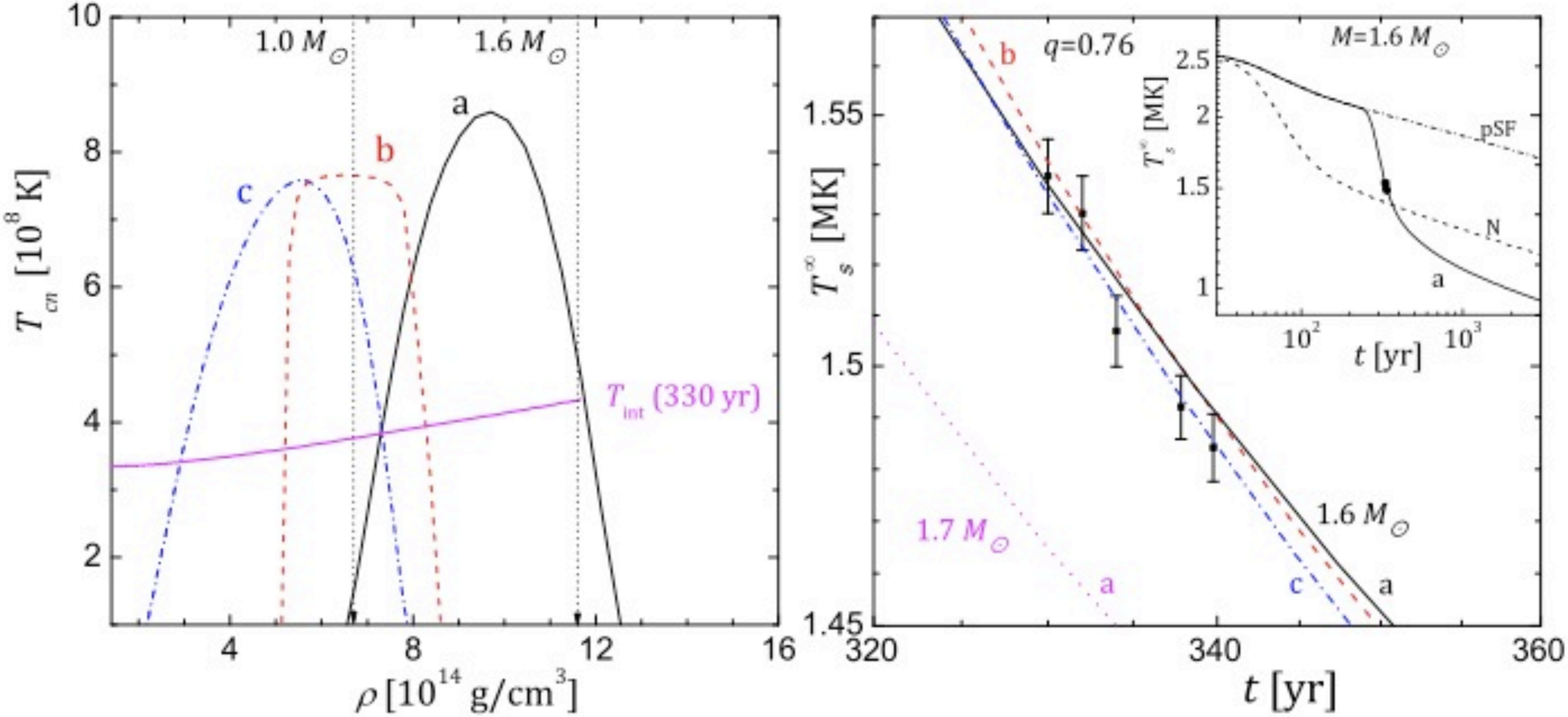
Very rapid T drop of Cas A NS requires p SF to suppress Urca

Evidence of Variability

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



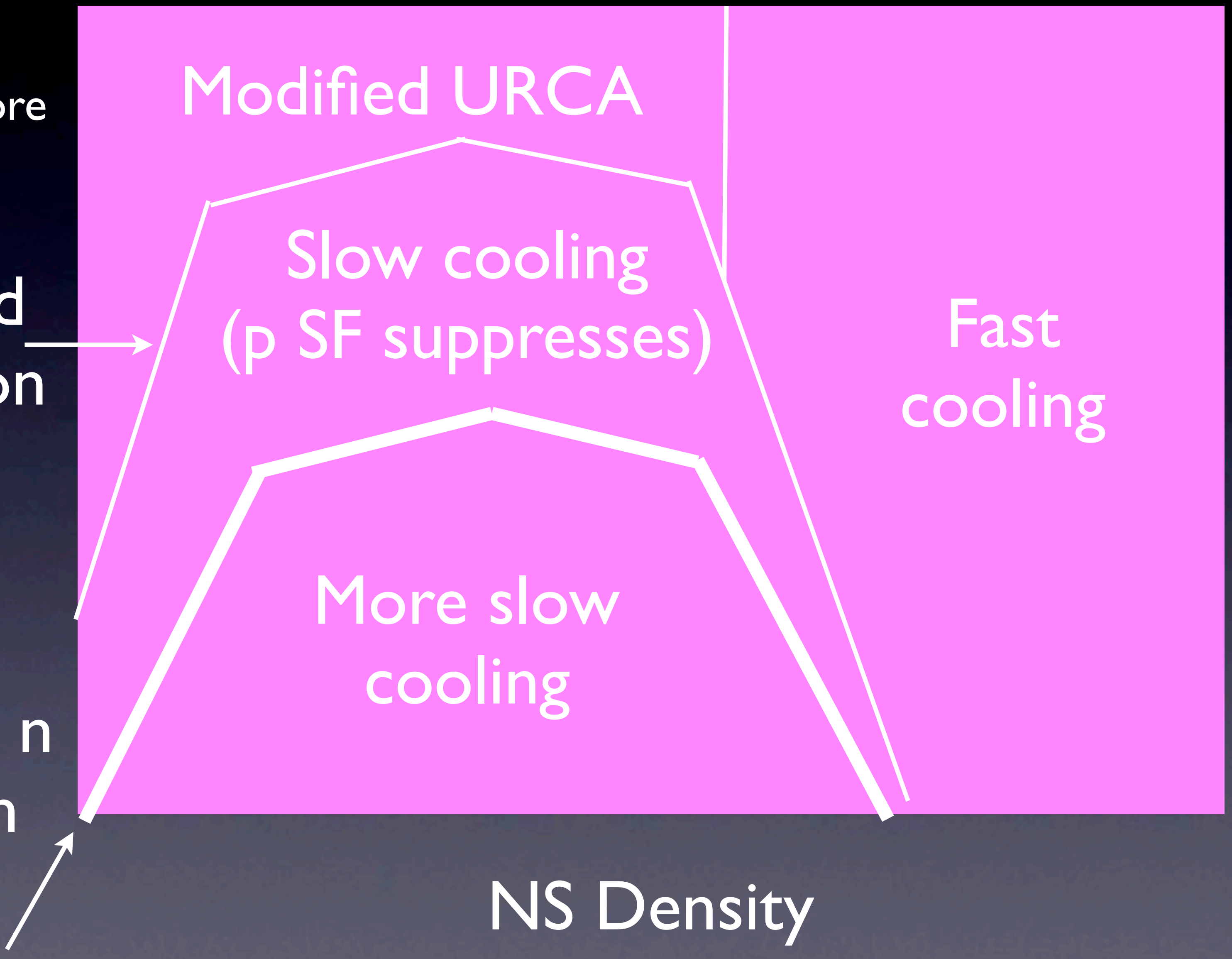
Heinke & Ho 2010



Neutron triplet superfluidity in NSs, Shternin+2011

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

Cooling, with protons



T_{core}

Modified URCA

Slow cooling
(p SF suppresses)

More slow
cooling

Fast
cooling

Superfluid
p transition

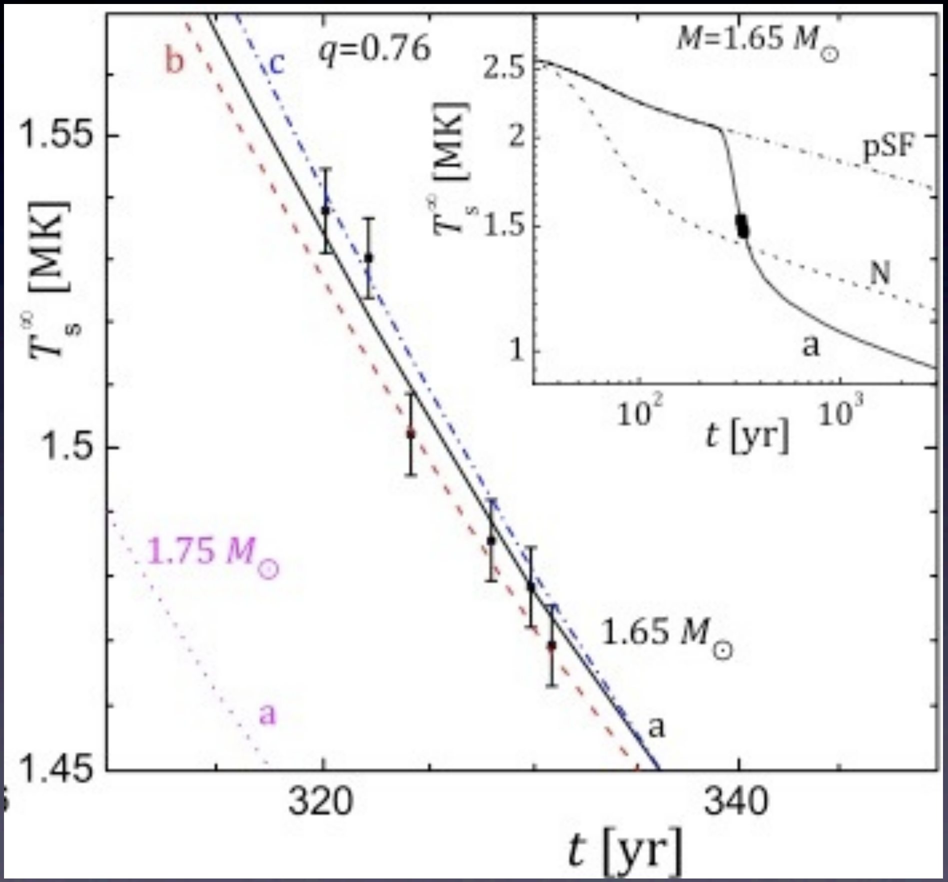
Superfluid n
transition
(brief SF
cooling)

NS Density

T drop challenged

- Most ACIS-S obs in special mode due to telemetry limits (Cas A bright)
- R. Rutledge found calibration concern in this mode; CXC confirms it, but effect is small (~3% flux drop, vs. 20% drop for Cas A NS)
- G. Pavlov taking special obs to check T drop
- K. Elshamouty studying all other Chandra obs (defending master’s this July)

Continued cooling



Shternin+11

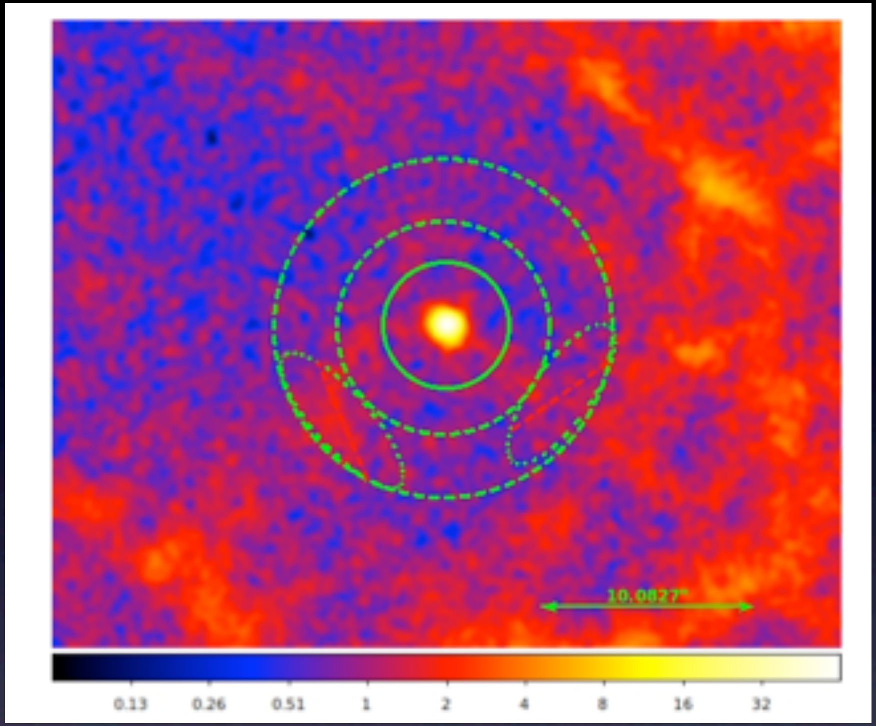
Sixth datapoint measured with same instrument (Shternin+11)

Penn State, McGill groups skeptical, testing calibration of instrument

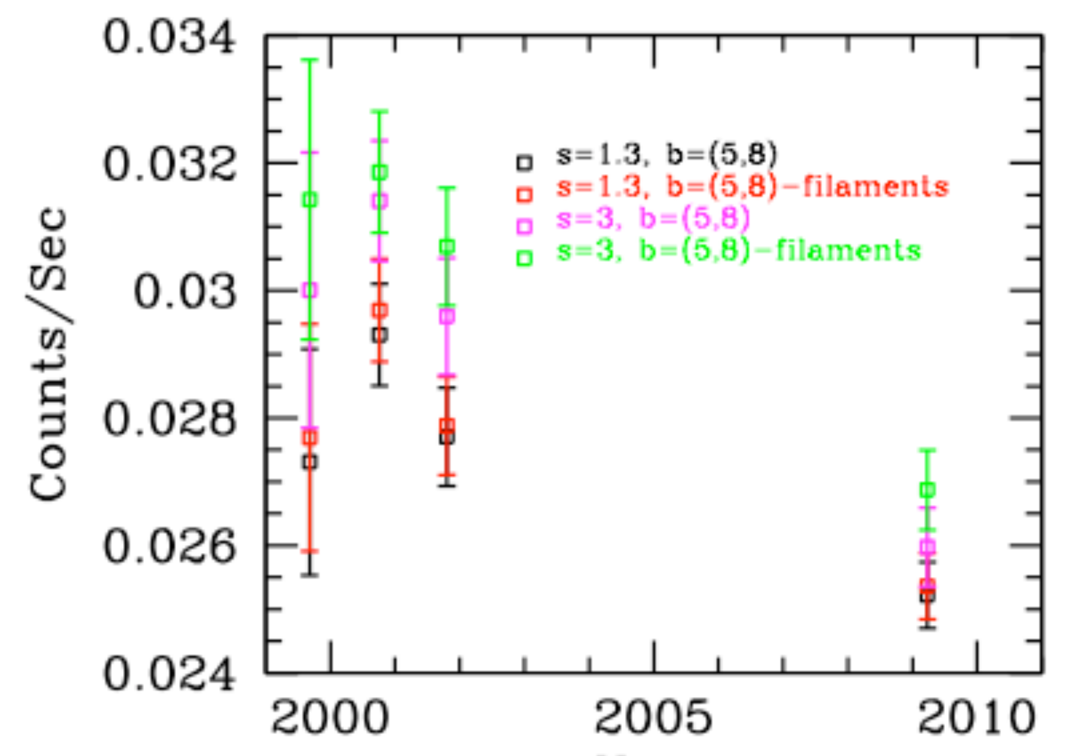
Alternative theories:

- R-mode heating (Yang+11), or Urca delayed by initially rapid rotation (Negrieros+11,12). Require fast (>100 Hz) spin, unlike other CCOs (~10 Hz), unlikely.
- Or, surface only now reaching equilibrium with cold core (Heinke+10, Blaschke+11). Requires low thermal conductivity, seems ruled out by cooling of long-outburst accreting NSs (Shternin+07; Yakovlev+11)

Testing with HRC-S



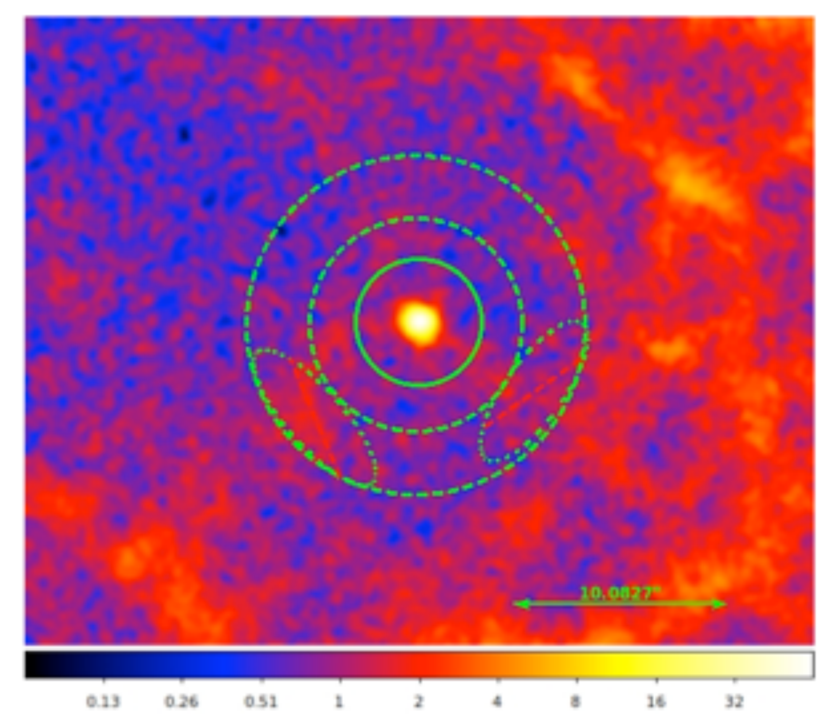
ACIS combined image



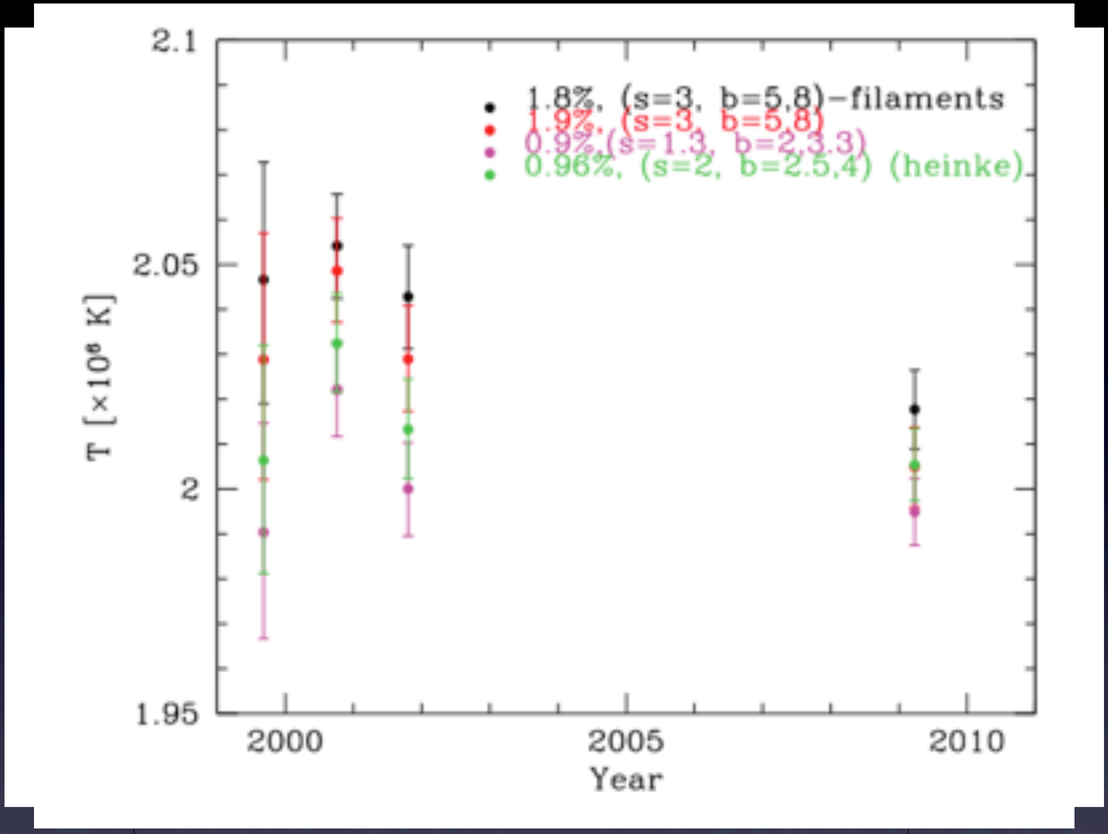
HRC-S results for diff. source, bg extraction regions

Long Chandra HRC-S obs show count decline; but time-variable SNR filaments cross NS, making bg unclear (Elshamouty+ in prep)

Testing with HRC-S



ACIS combined image



HRC-S results for diff. source, bg extraction regions

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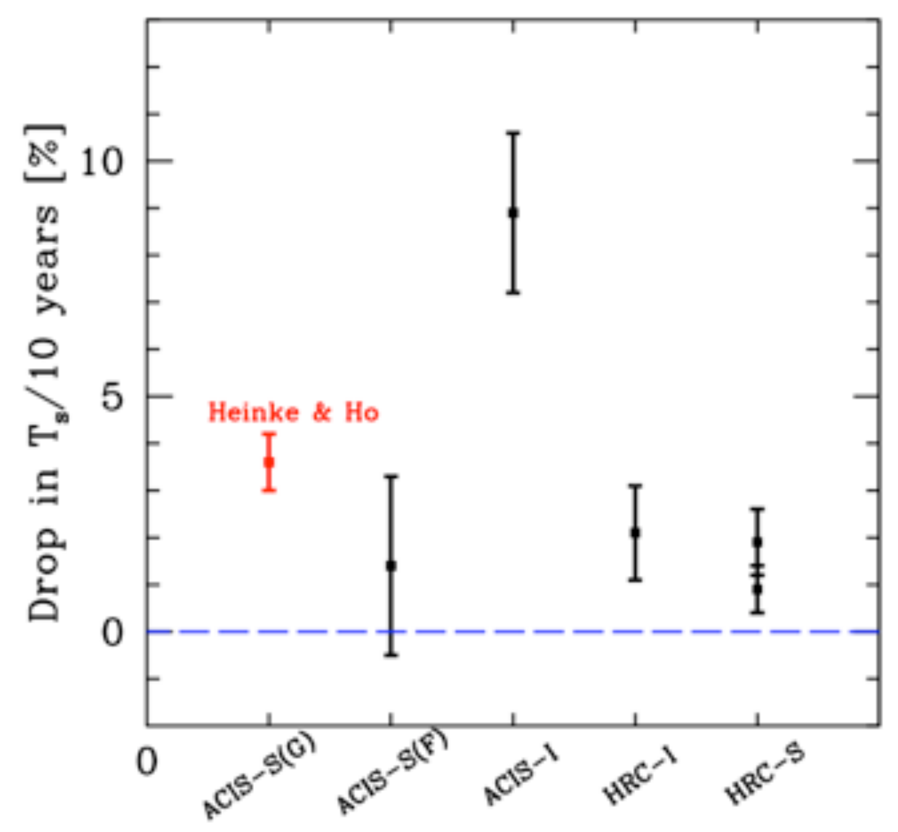
Comparing instruments



Comparison of all Chandra data, Elshamouty+ in prep

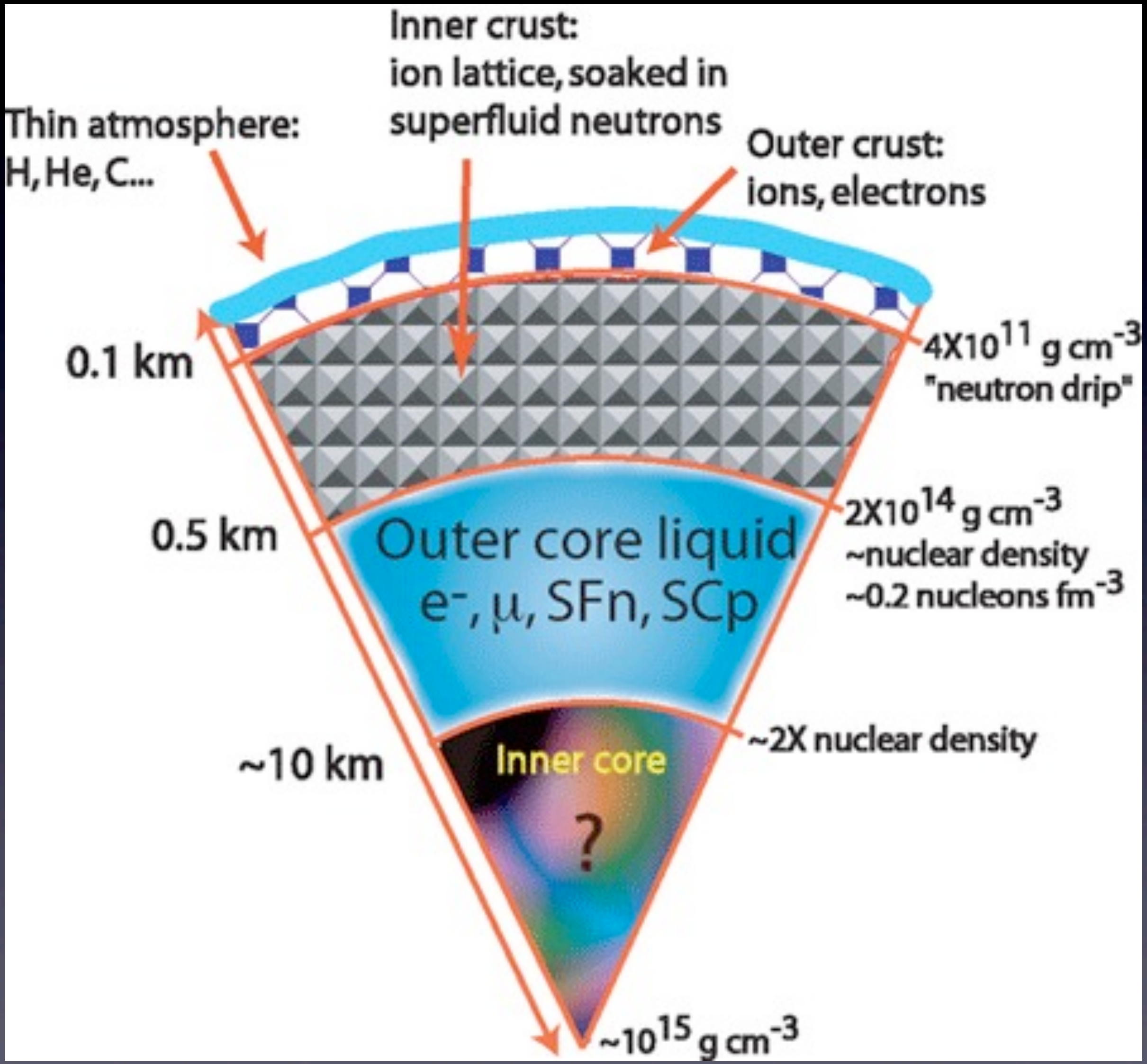
Systematic uncertainties; e.g. ACIS-I, HRC-I data at different detector positions.
HRC-S subtle effects under study.

All data indicate T decline; converging on ~3% (vs. 4%).
Reducing T drop to ~2% would still require neutron SF, but not proton SF.

Movie of NS interior T

Wynn Ho,
from Shternin
results

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