Constraints on neutron stars theories from nearby neutron star observations

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D. Breitschwerdt, V. Suleimanov, K. Werner

➔ Short Intro on young nearby neutron stars

➔ Constraining the Equation-of-State (EoS)
with optical and X-ray observations of young neutron stars

➔ Identifying birth places of young nearby neutron stars

The *Magnificent Seven* Neutron stars (M7 NS):

otion

yr]

RX

RX

RX

RX

RX

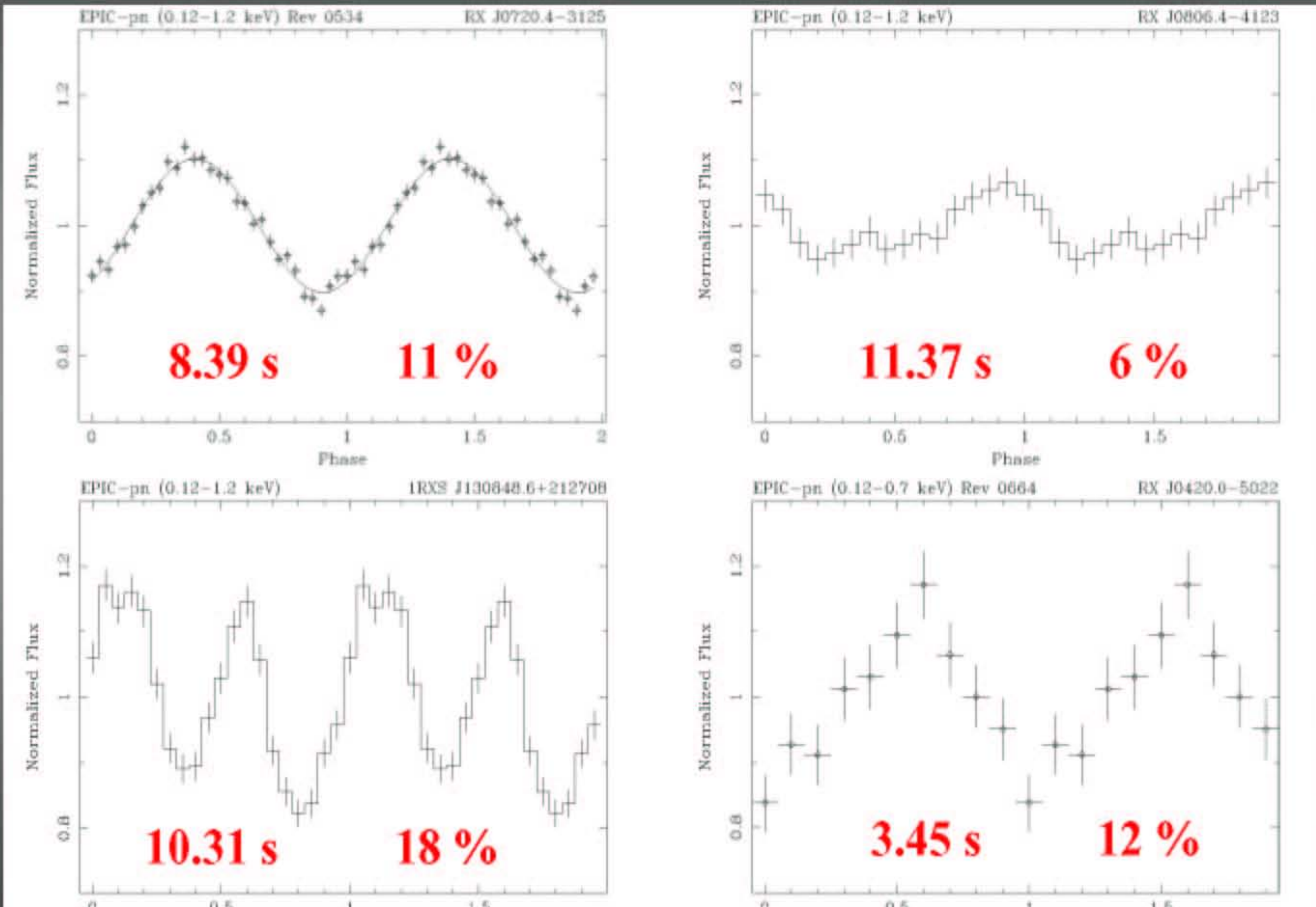
RX

RX

(Walter, Wolk, Neuhauser 1996 Nature)

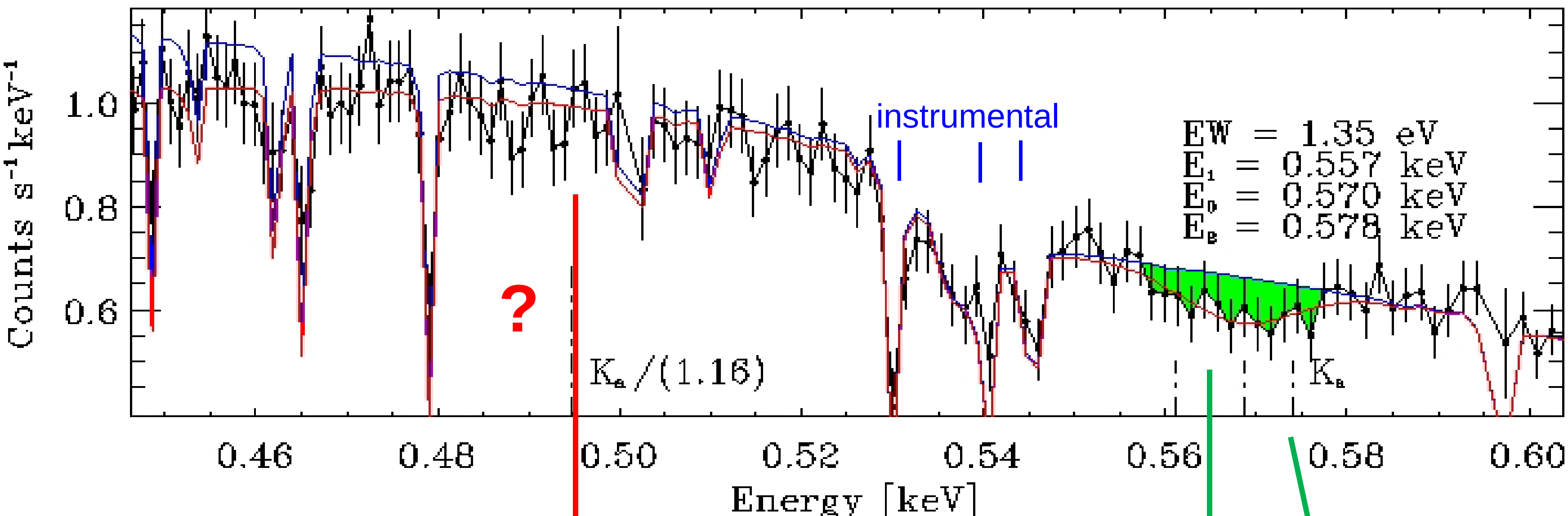
(Walter et al. 1997)

X-ray pulsations



Goal: Constraining equation-of-state

Case 1: Atomic line in RXJ0720



O VII
K-alpha line
red-shifted
for g_r = 0.16

Possibly
a few
O VII lines
at rest
(interstellar)

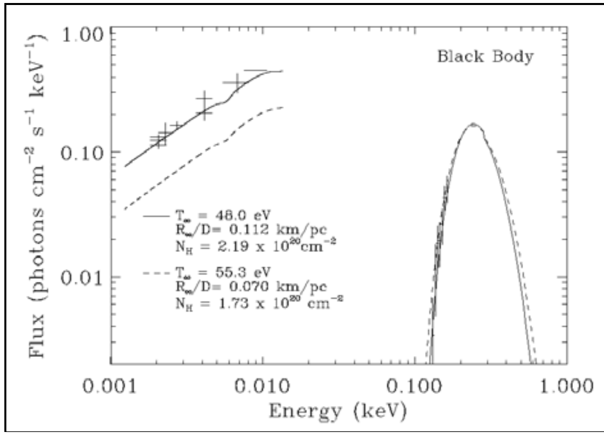
O VII
K-alpha line
at rest (lab)

g_r = (1-2GM/Rc^2)^1/2

Possible identification of atomic line in M7 neutron star (Hambaryan, Neuhäuser et al. 2009 A&A Letters) ➔ compactness, i.e. mass / radius, i.e. a constraint for EoS

Goal: Constraining equation-of-state

Case 2: Radius of RXJ1856 from surface observations



M7 are radio-quiet thermally emitting Neutron Stars, we observe their surface.

XMM & Chandra X-ray spectra give temperature T from spectral fitting

Optical imaging photometry (e.g. Hubble Space Telescope) gives brightness

Multiple optical imaging gives parallaxe or distance

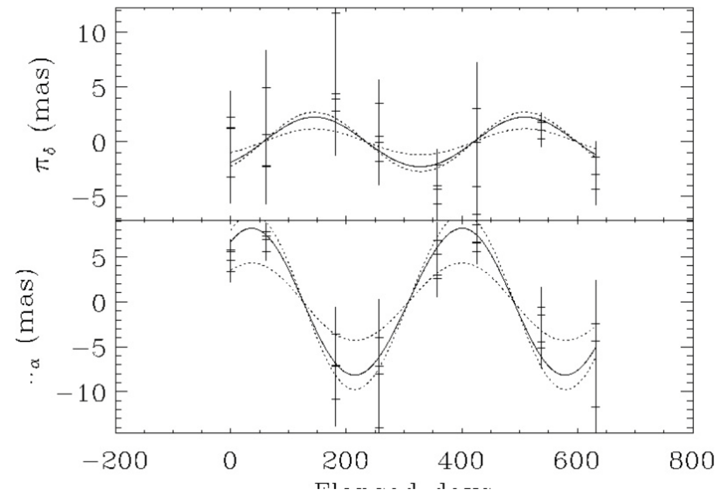
Distance and brightness give luminosity L

Luminosity L and temperature T give radius R   ($L = 4 \pi \sigma R^2 T^4$)

Previous discrepancy on distance …

117 +/- 12 pc (Walter & Lattimer 2002) with 3 obs
  (➔ R = 17 km at infinity, Trümper 2004)

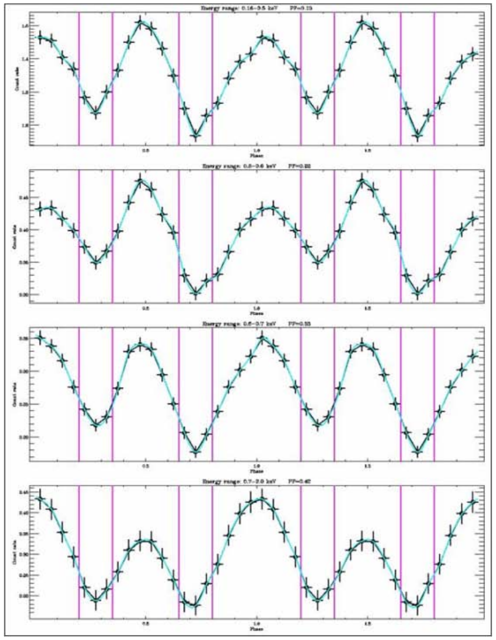
160 – 180 pc (Kaplan and van Kerkwijk 2007) 8 obs



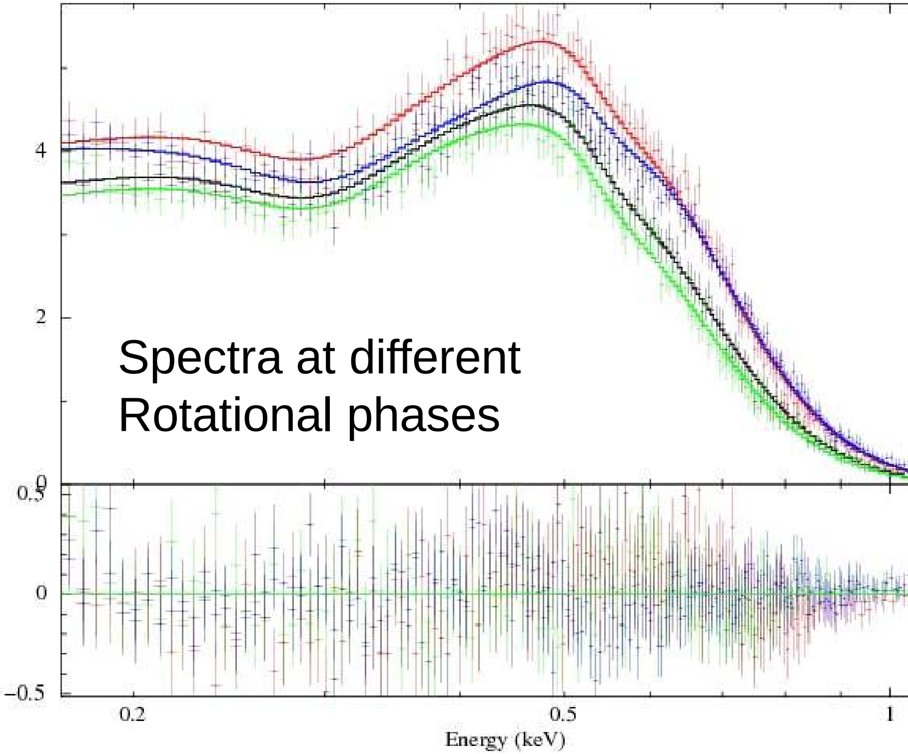
Goal: Constraining equation-of-state

Case 3: Compactness from phase-resolved spectroscopy

Light curves in different energy bands



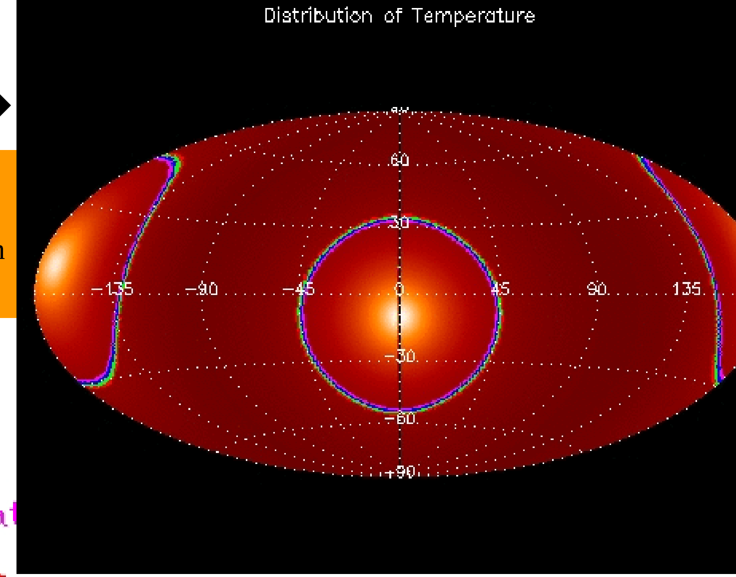
E	PF
0.16 – 0.5 keV	13%
0.5 – 0.6 keV	22%
0.6 – 0.7 keV	33%
0.7 – 2 keV	42%



Spectra at different
Rotational phases

RBS 1223 = RXJ 1308
double-hamped light curve
(but largest pulse fraction, 18 %)

Our new model:
temperature distribution (emitting area)→

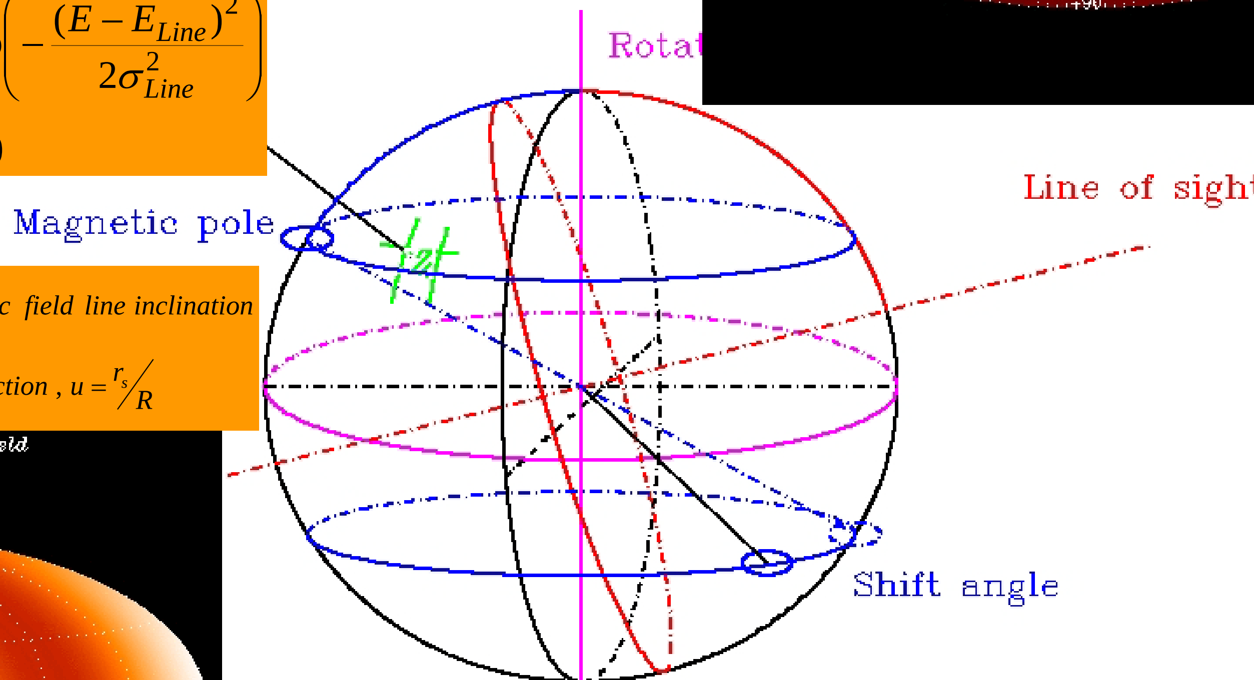


$$T^4 = T_{1,2}^4 \left(\frac{\cos^2 \vartheta}{\cos^2 \vartheta + a_{1,2} \sin^2 \vartheta} \right) + T_{\min}^4$$

and mag. field distribution (bottom)

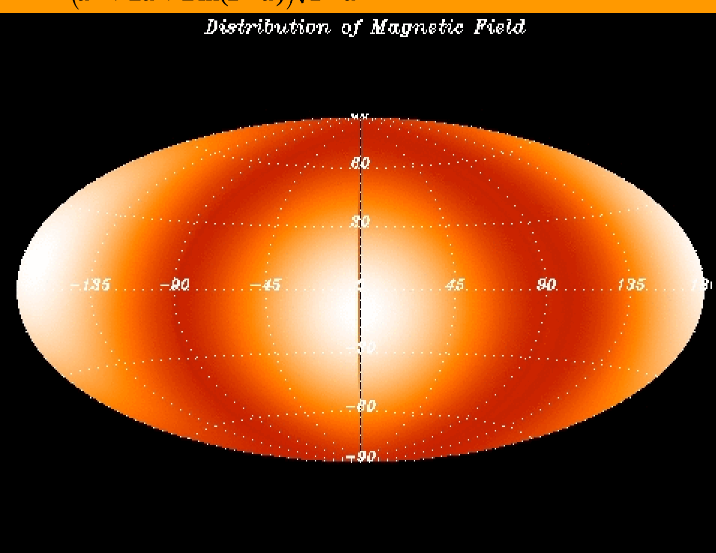
$$F_\nu = B_\nu \exp(-\tau), \quad \tau = \tau_0 \exp\left(-\frac{(E - E_{Line})^2}{2\sigma_{Line}^2} \right)$$

$$E_{Line} = 0.635\, keV\, (B/10^{14} G)$$



$$B = B_{12} \sqrt{\cos^2 \phi + \left(f/2 \right) \sin^2 \phi}\ , \ \phi - magnetic\ \ field\ \ line\ \ inclination$$

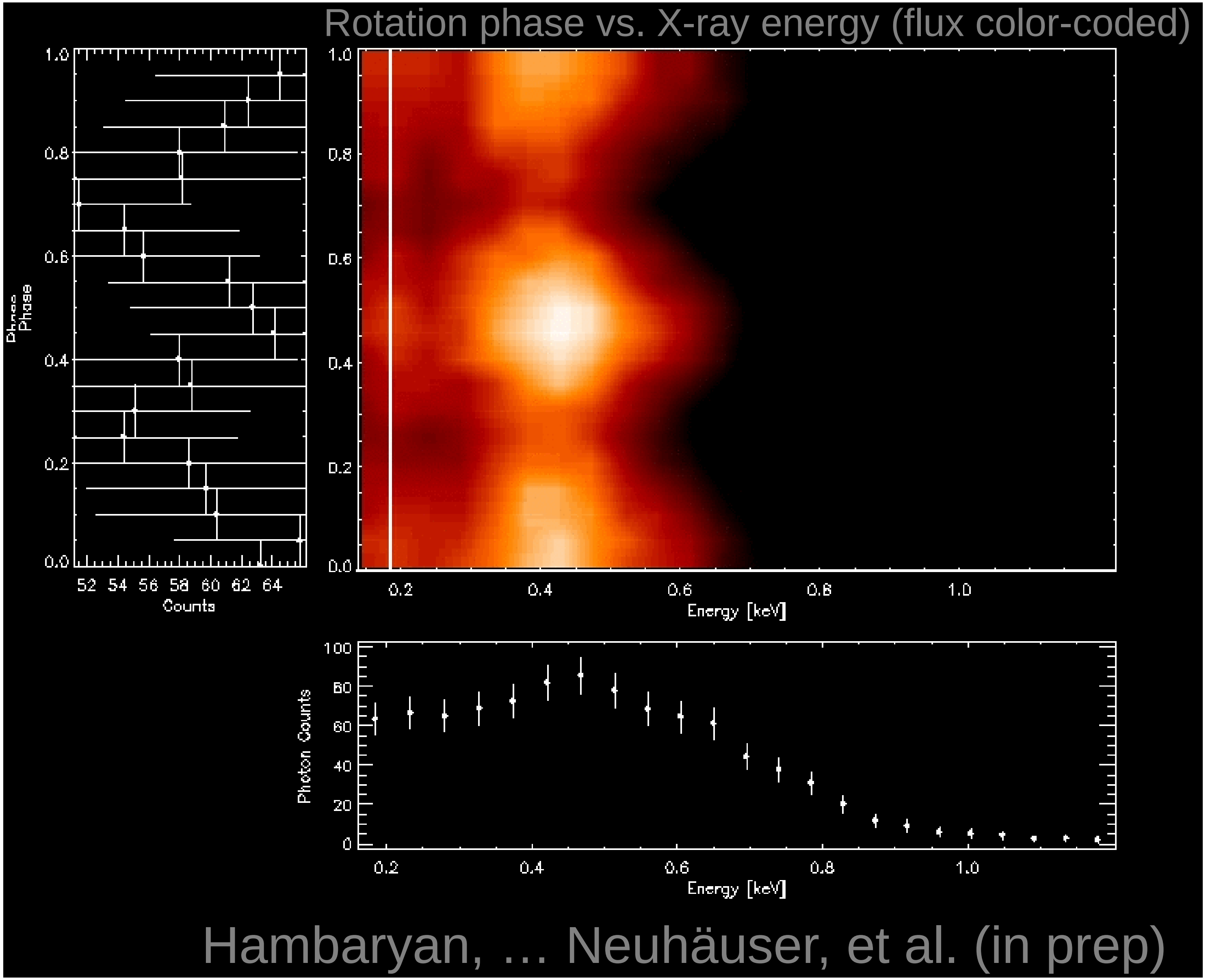
$$f = 2 \frac{u^2 - 2u - 2(1-u)\ln(1-u)}{\left(u^2 + 2u + 2\ln(1-u)\right)\sqrt{1-u}}\ , \ GR\ correction\ , \ u = {r_s}/{R}$$



Model computes rotational phase-resolved spectra for
Condensed Fe surface + thin partially ionized H atmo

Suleimanov, Hambaryan, … Neuhäuser et al. (2010) A&A

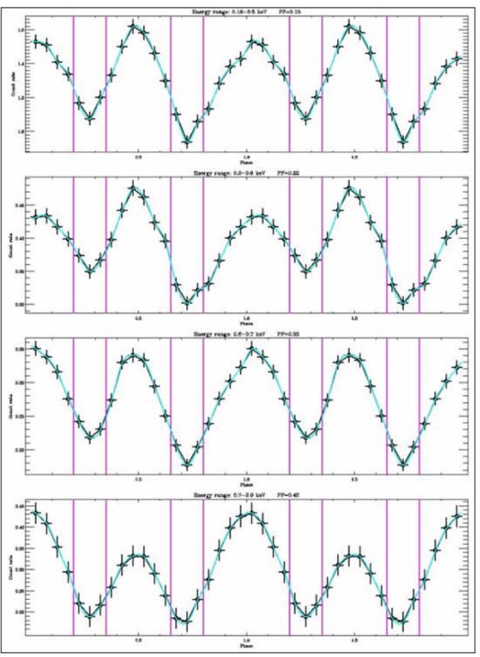
Spectrum and light curve
or phase-resolved spectroscopy



Goal: Constraining equation-of-state

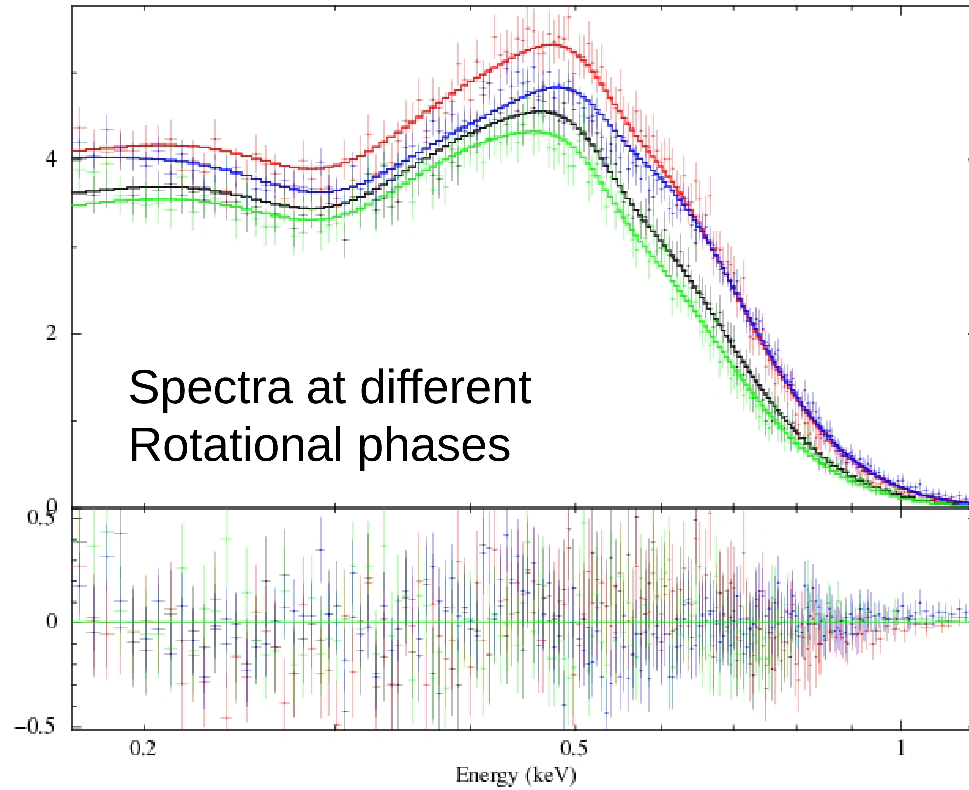
Case 3: Compactness from phase-resolved spectroscopy: RBS1223

Markov-Chain Monte-Carlo fitting of XMM data on RBS1223 with our model



E	PF
0.16 – 0.5 keV	13%
0.5 – 0.6 keV	22%
0.6 – 0.7 keV	33%
0.7 – 2 keV	42%

14 2 fharm	redshift	0.160800 frozen
15 2 fharm	phase1	0.0 frozen
16 2 fharm	phase2	1.00000 frozen
17 2 fharm	mod1	1 frozen
18 2 fharm	mod2	0 frozen
19 2 fharm	norm	16.3753 ±1764.26



➔ grav. redshift g_r ➔ Mass / Radius
i.e. another constraint on the EoS
(Hambaryan, … Neuhäuser in prep.)

Constraining the equation of state

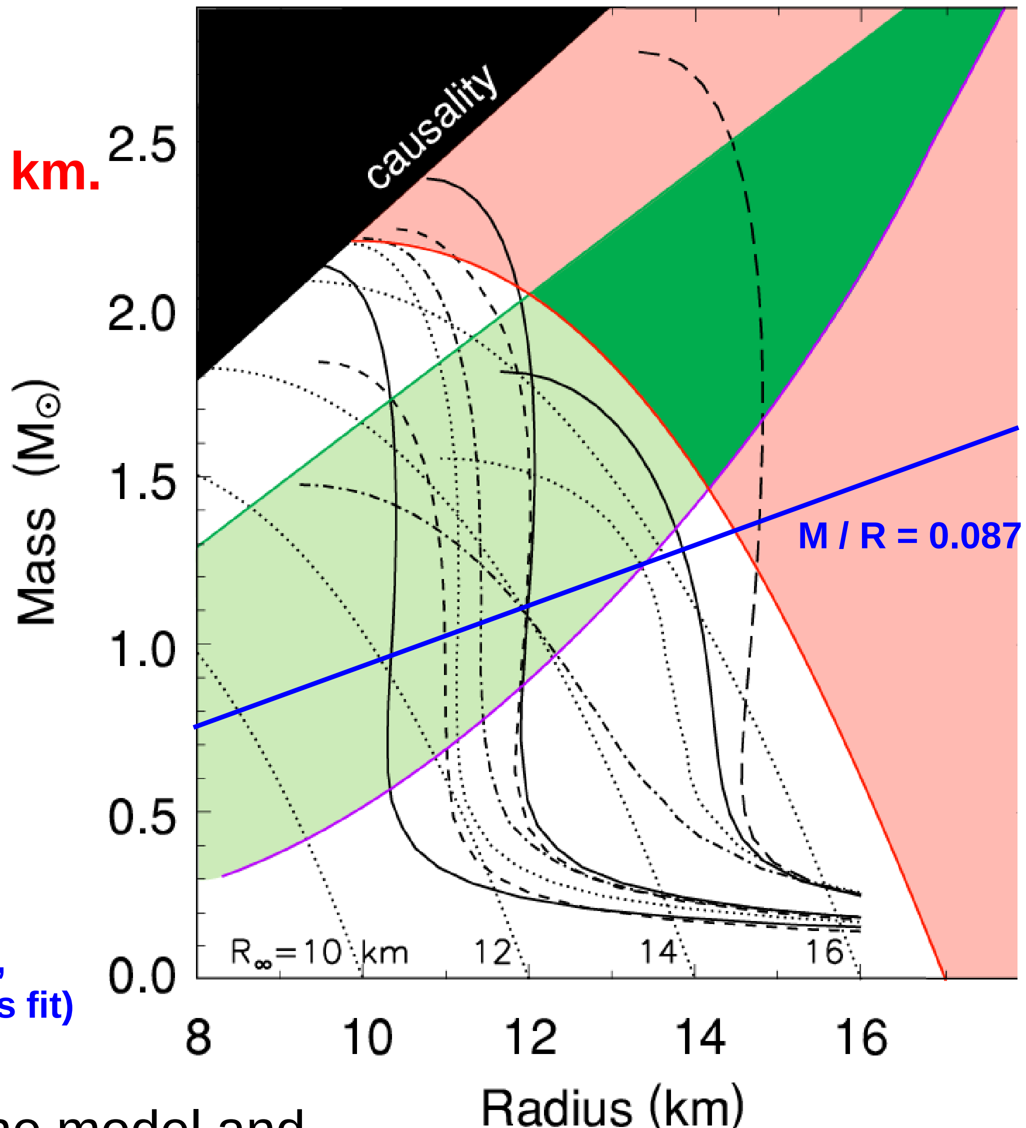
Radius of RX J1856: R = 17 km (at infinity)
first Trümper et al. 2004: R = 17 km.
again by Walter, … Lattimer, …
Neuhäuser et al. 2010, subm.
Needs distance to +/- 5%
Depends on atmo model !

M / R = 0.096 for X7 47 Tuc (Heinke et al. 2006)

M / R = 0.096 for LMXRBs (Suleimanov & Poutanen 2006)

M / R = 0.089 for Cas A (Wyn & Heinke 2009)

M / R = 0.087 for RBS 1223
(Suleimanov, …Neuhäuser et al. 2010: Model, Hambaryan, …, Neuhäuser et al. in prep.: Obs fit)
Independent of distance !!!

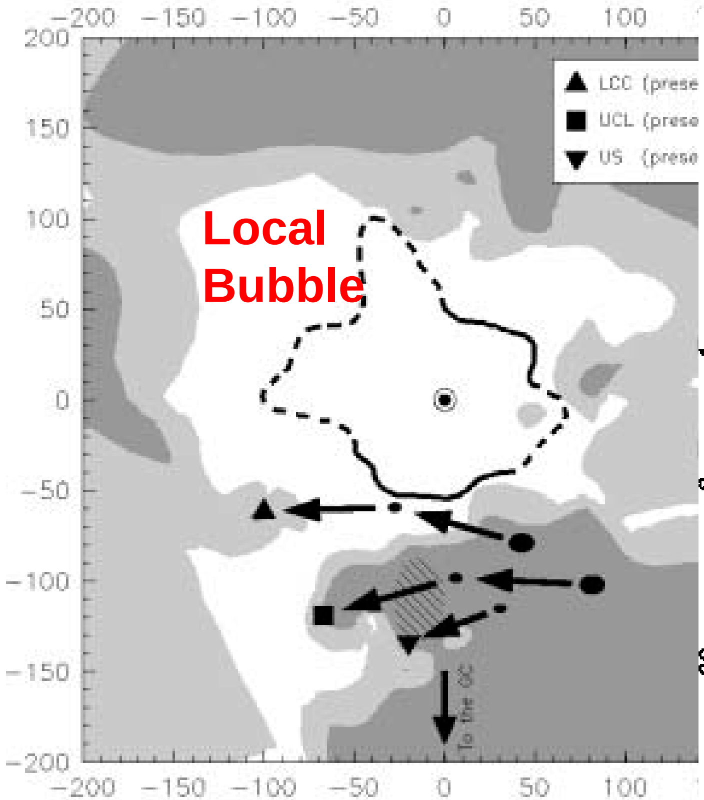


Next: further improvements on the model and phase-resolved spectroscopy to get M/R for 6 more M7 Neutron Stars.
In particular phase-resolved spectra for RXJ1856 ➔ M/R (in addition to R)

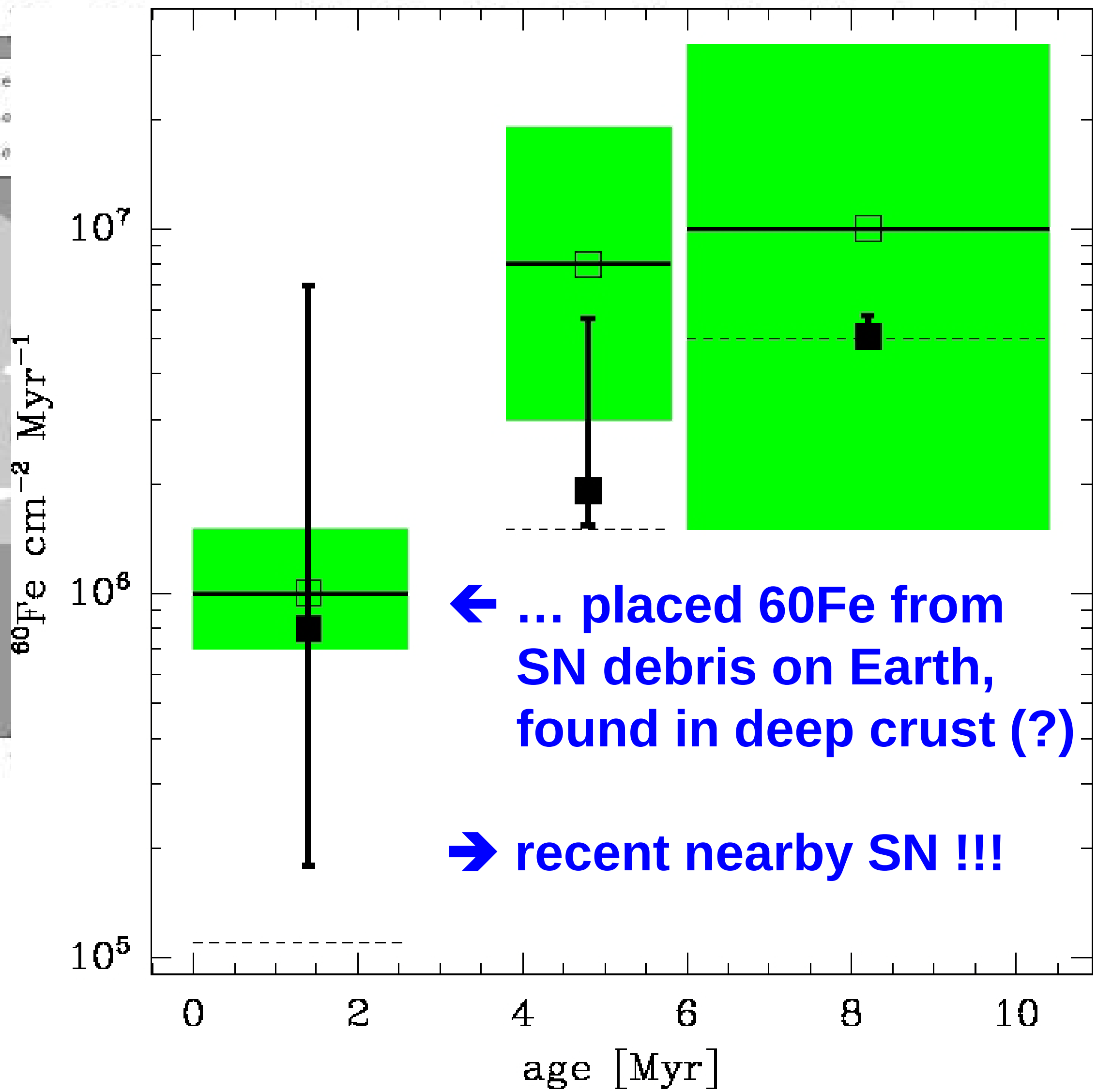
Part 2:

Identifying birth places
of young isolated neutron stars
by tracing back their motion …

SN in ScoCenLup triggered more star formation, cleared Local Bubble (?), and …



Breitschwerdt et al. 1996 etc.
Breitschwerdt & Berghöfer 2002
Maiz-Appelaniz et al. 2001
Benitez et al. 2002
Knie et al. 1999, 2004
Rugel et al. 2009:
2.62 Myrs 60Fe half-life



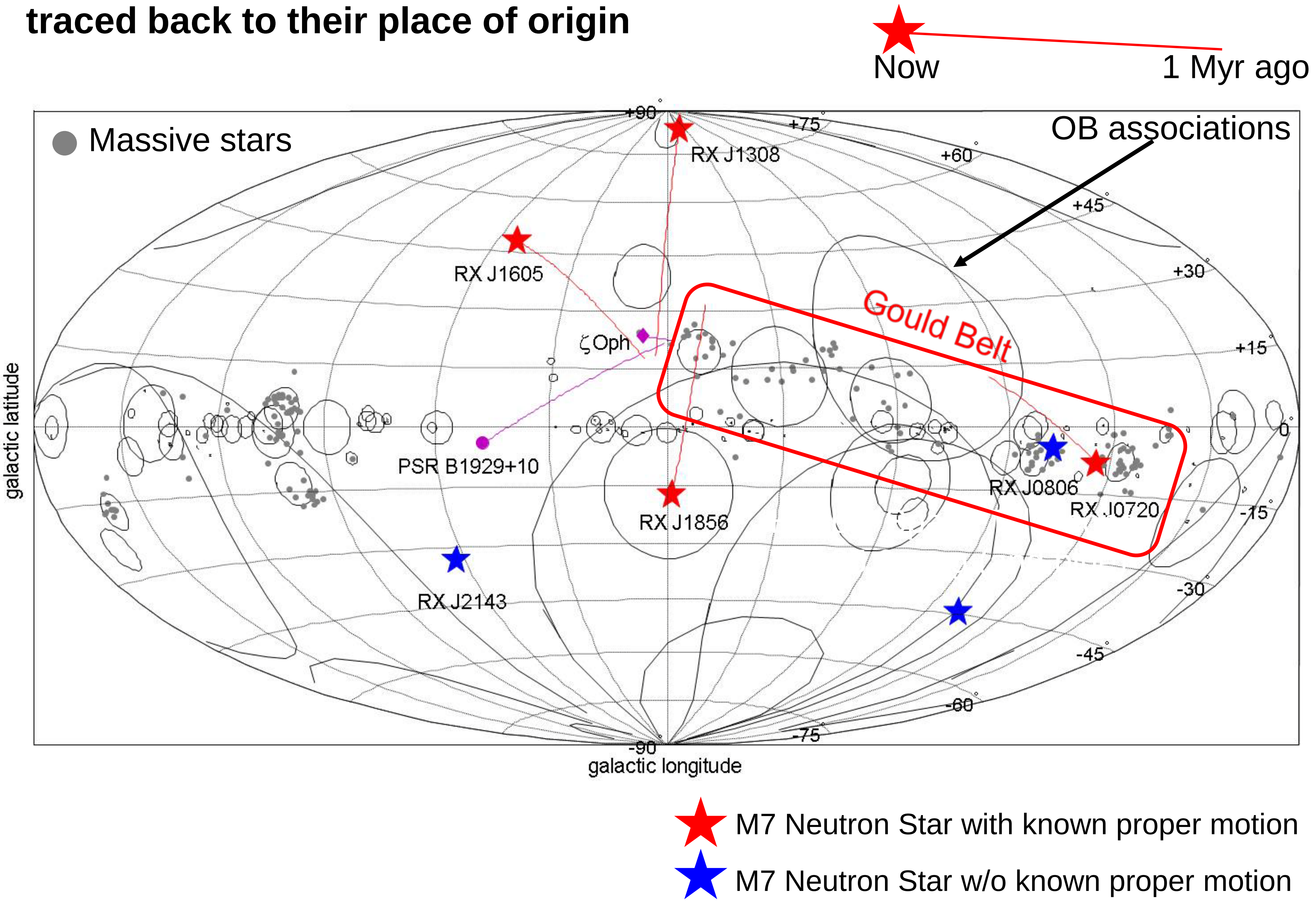
← … placed 60Fe from SN debris on Earth, found in deep crust (?)

→ recent nearby SN !!!

Find young NS which was born in that SN
→ distance and exact timing of SN
(+ progenitor star mass to test SN yield of 60Fe)
… feasible due to NS cooling curves ... few Myrs …

Isolated young neutron stars traced back to their place of origin

Nina Tetzlaff (Jena)



Identifying birth places of young isolated neutron stars

Method

OB association/ cluster
Neutron stars
Runaway stars

- tracing back stars and associations in Galactic potential
- find closest encounter with association or run-away star or Bubble in the past
- repeating procedure with varying the observables within their confidence intervals (Monte-Carlo simulation) with rad. vel. from NS space velocity distribution

→ probability distribution for seperation between neutron star and run-away star

<u>Example:</u>
PSR B 1929+10 and runaway star ς Oph
→Probably at the same place ≈1Myr ago in UpSco (Hgwf01, Tetzlaff et al. 2010)

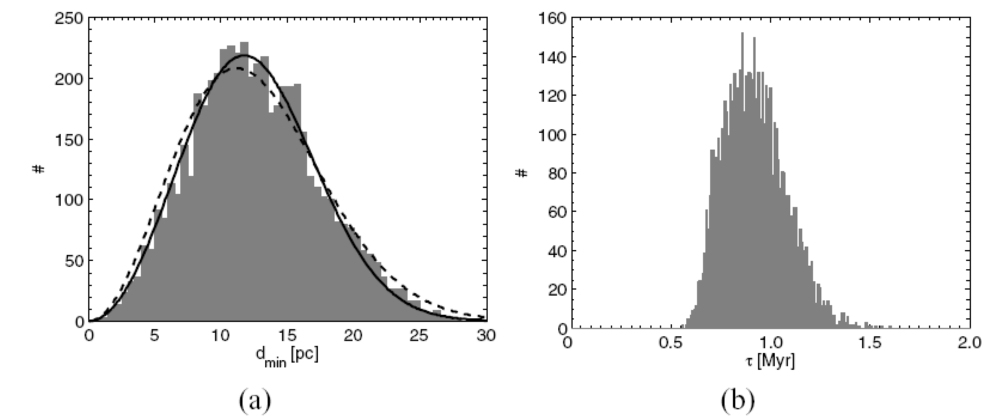
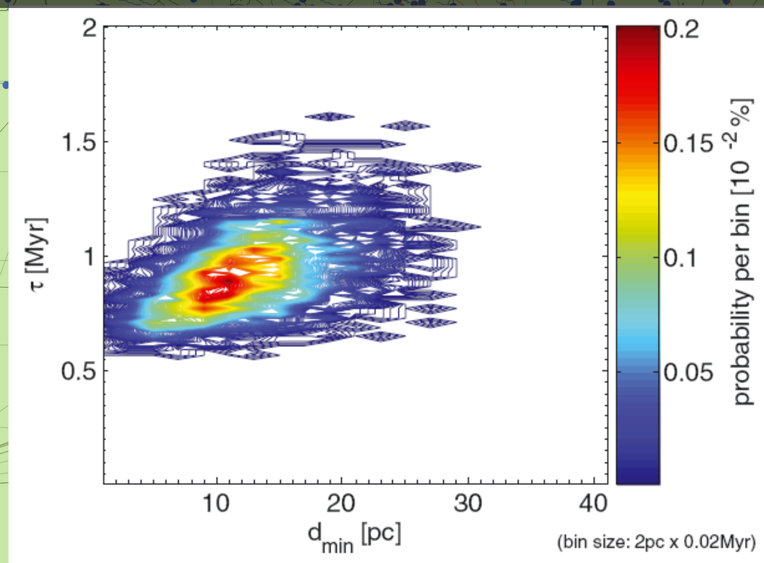


Figure 1. (a) Distribution of minimum separations $d_{\rm min}$ of the 5367 runs for which both objects were not farther than 10 pc from the US centre with updated pulsar data. Drawn as well are theoretical curves for 3D Gaussian distributions (equations 1 and 2) with $\mu = 9.0$ pc and $\sigma = 4.0$ pc (solid) and



Identifying birth places of young isolated neutron stars

RX J1856.5-3754

Table 4. Potential parent associations of RX J1856.5−3754. Columns 2 and 3 mark the boundaries of a 68 per cent area in the $\tau - d_{\min}$ contour plot for which the current neutron star parameters (Columns 4–7, radial velocity $v_{\rm r}$, proper motion μ_α^* and μ_δ and parallax π) were obtained, and Columns 8–10 indicate the distance to the Sun $d_\odot$ and equatorial coordinates (J2000.0) of the potential SN. Column 7 gives the space velocity (ejection speed) $v_{\rm space}$ derived from proper motion and radial velocity. For the deduction of the values given in Columns 4–11, please see Appendix B.

Association	$d_{\min}$ (pc)	τ (Myr)	$v_{\rm r}$ (km s^{-1})	$\mu_{\alpha*}$ (mas yr^{-1})	μ_δ (mas yr^{-1})	$v_{\rm space}$ (km s^{-1})	π (mas)	$d_\odot$ (pc)	α (°)	δ (°)
US	5…3	0.28…0.34	193^{+45}_{-32}	326.7 ± 0.8	-59.1 ± 0.7	349^{+40}_{-32}	$5.41^{+0.33}_{-0.28}$	140…163	$243.21^{+0.56}_{-0.52}$	$-23.66^{+0.31}_{-0.29}$
β Pic-Cap	35…53	0.10…0.15	1190^{+167}_{-172}	326.7 ± 0.8	-59.1 ± 0.7	1222^{+165}_{-173}	$5.71^{+0.49}$ [illegible]	40^{+5} [illegible]	221…233	−18… − 8
Ext. R CrA	26…54	0.10…0.15	406^{+121}_{-88}	326.7 ± 0.8	-59.1 ± 0.7	492^{+113}_{-81}				
AB Dor	44…60	0.12…0.16	1146^{+138}_{-152}	326.7 ± 0.8	-59.1 ± 0.7	1177^{+137}_{-151}				
Sco OB4	25…33	1.26…1.51	-604^{+31}_{-20}	326.7 ± 0.8	-59.1 ± 0.7	664^{+25}_{-35}				

- bow shock suggests relatively small (negative) radial velocity (Kerkwijk & Kulkarni 2001)
- UpSco most likely birth association for RX J1856
- using a smaller distance (≈ 120 pc: Walter & Lattimer 2002, Walter et al. 2010, subm.) strengthens UpSco hypothesis and suggests $v_r \approx -25^{+58}_{-24}$ km/s

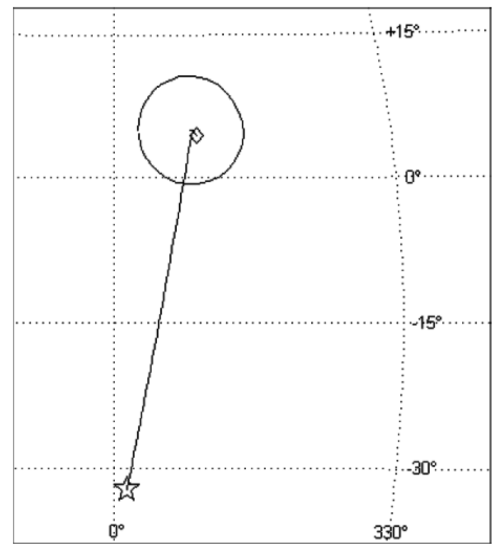


Figure 4. Past trajectories for RX J1856.5−3754 and US projected on a Galactic coordinate system (for a particular set of input parameters consistent with Table 4). Present positions are marked with a star for the neutron star and a diamond for the association. The large circle reflects an association radius of 15 pc.

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Identifying birth places of young isolated neutron stars

RX J0720.4-3125

Table 6. Potential parent associations of RX J0720.4−3125, columns as in Table 4.

Association	d_{min} (pc)	τ (Myr)	v_r (km s^{-1})	$\mu_{\alpha*}$ (mas yr^{-1})	μ_δ (mas yr^{-1})	v_{space} (km s^{-1})	π (mas)	$d_\odot$ (pc)	α (°)	δ (°)
TWA	0…12	0.34…0.46	502^{+111}_{-88}	-93.9 ± 2.2	52.8 ± 2.3	518^{+112}_{-90}	$4.06^{+0.47}_{-0.49}$	48…67	$187.10^{+3.44}_{-2.91}$	$-37.98^{+1.53}_{-1.38}$
Tuc-Hor	44…80	0.26…0.52	476^{+128}_{-73}	-93.8 ± 2.2	52.8 ± 2.3	492^{+129}_{-75}	$4.12^{+0.55}_{-0.47}$	35…70	$190.19^{+4.00}_{-4.97}$	$-37.29^{+1.30}_{-1.44}$
β Pic-Cap	35…84	0.31…0.61	468^{+106}_{-87}	-93.9 ± 2.2	52.8 ± 2.3	486^{+107}[illegible]	$3.94^{+0.53}$[illegible]	38…78	$209.87^{+3.13}$[illegible]	$-28.52^{+2.04}$[illegible]
HD 141569	12…22	0.52…0.75	469^{+108}_{-70}	-93.8 ± 2.2	53.0 ± 2.3					
Pup OB3	14…42	0.47…0.61	-375^{+144}_{-150}	-94.0 ± 2.1	52.9 ± 2.3					
Tr 10	23…40	0.44…0.65	290^{+143}_{-110}	-93.8 ± 2.2	53.1 ± 2.2					

- n_H suggests ≈ 250 pc (Posselt et al. 2007)
- Kaplan et al. (2007) suggest ≈ 360 pc from parallaxe obs
- TWA most likely birth association for RX J0720.4-3125

→ recent nearby supernova – maybe contribution to ^{60}Fe found in Earth‘s crust (rel. low mass progenitor of $\approx 10\ M_{Sun}$ not inconsistent with present mass function of TWA)

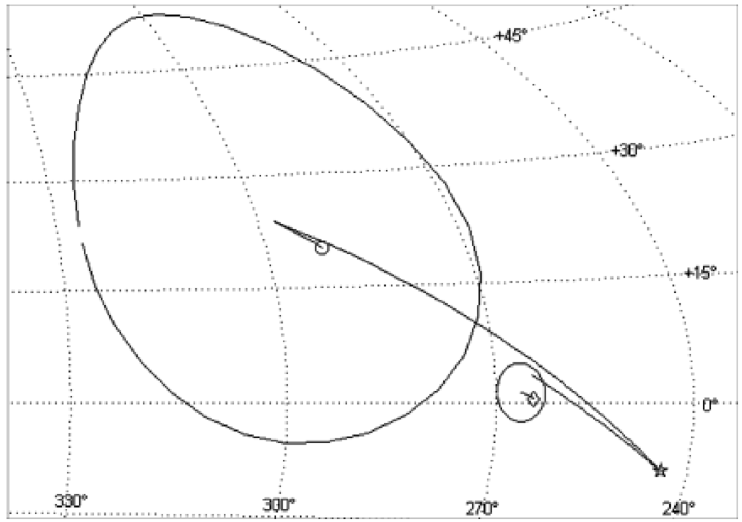

Figure 6. Past trajectories for RX J0720.4−3125 and Tr 10 and TWA, respectively, projected on a Galactic coordinate system (for particular sets of input parameters consistent with Table 6). Present positions are marked with a star for the neutron star and a diamond for Tr 10 and an open circle for TWA. Large circles reflect association extensions (radii of 23 pc for Tr 10 and 33 pc for TWA).

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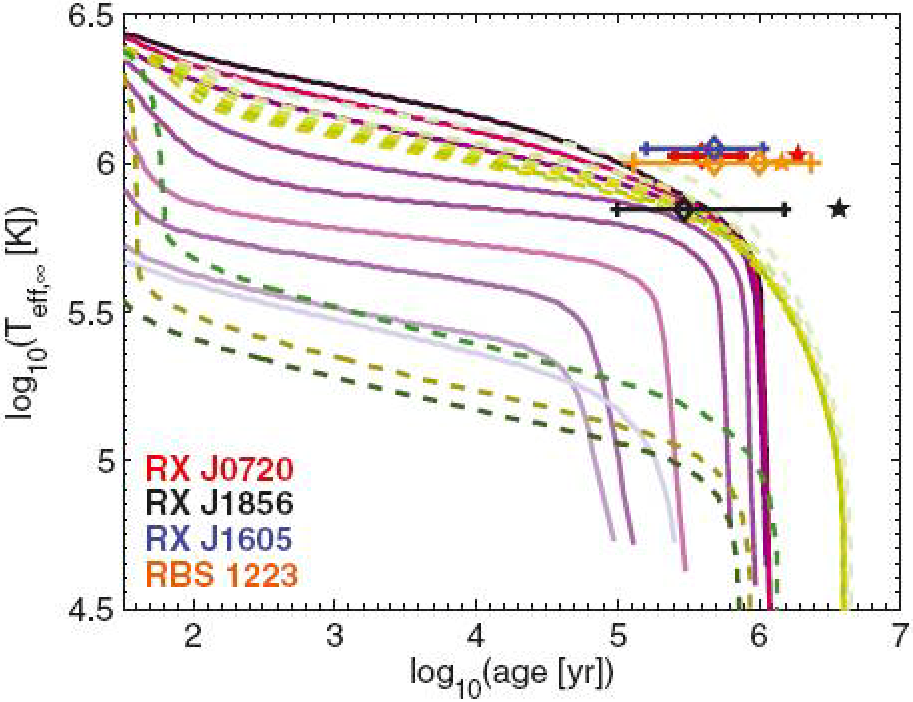
Our kinematic ages fit cooling curves better than characteristic ages



RX J	Association	τ_{kin} (Myr)	τ_{char} (Myr)	$T_{eff,\infty}$ (10^3 K)	M_{prog} ($M_\odot$)
1856.5−3754	US	≈0.3	3.8	696	≈29
0720.4−3125	TWA	≈0.4	1.9	1044	≈10
	Tr 10	≈0.5			≈10
1605.3+3249	Sco-Cen	≈0.5	–	1113	≈29
	Ext. R CrA	≈0.5			≈15
RBS 1223	Sco-Cen	≈0.5	1.5	998	≈29
	Ext. R CrA	≈0.5			≈15
	Sct OB2	≈ 1			≈38

Figure 12. The four M7 members inserted into a cooling diagram. Filled stars mark the characteristic spin-down age (see Table 3) whereas horizontal lines characterize an area of the kinematic age (lower and upper values from associations in tables of Section 5). Open diamonds show the kinematic age for the associations summarized in Table 12. Effective temperatures can be found in Table 13. The purple set of cooling curves was adopted from Popov et al. (2006) (solid lines, for masses of 1.05, 1.13, 1.22, 1.28, 1.35, 1.45, 1.55, 1.65 and 1.75 $M_\odot$ from top to bottom; model from Grigorian, Blaschke & Voskresensky 2005), the green set has been kindly provided by A. D. Kaminker (dashed lines, includes superconductive protons and

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Another test of Equations-of-State (in cooling models)

Isolated young neutron stars traced back to their place of origin:

Problems: RV ? more than one cluster possible ?
Hence, we need additional evidence …

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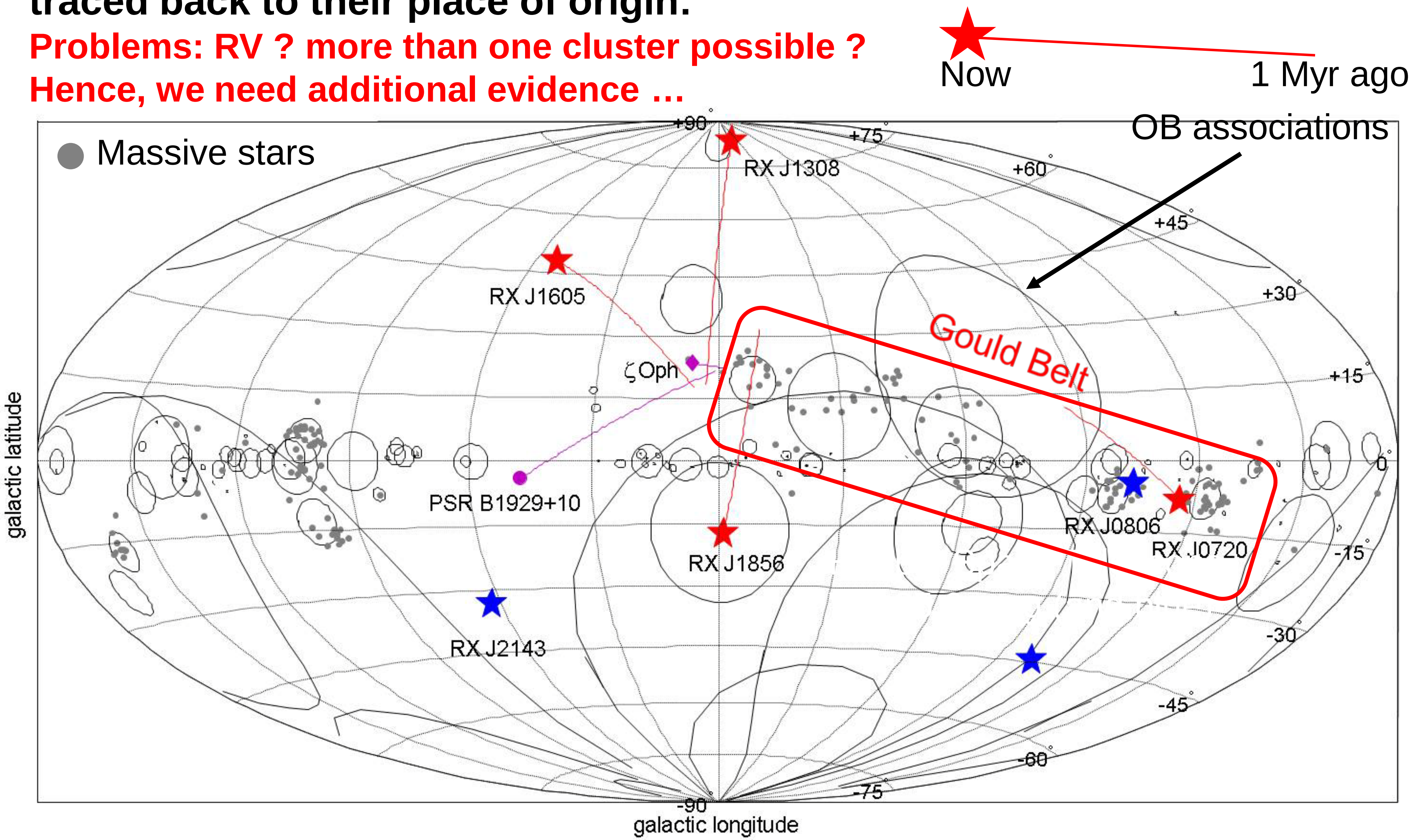


Compare(d) NS traces with **OB associations**,
Next also: gamma sources, SNRs,
Bubbles, run-away stars, …

M7 Neutron Star with known proper motion

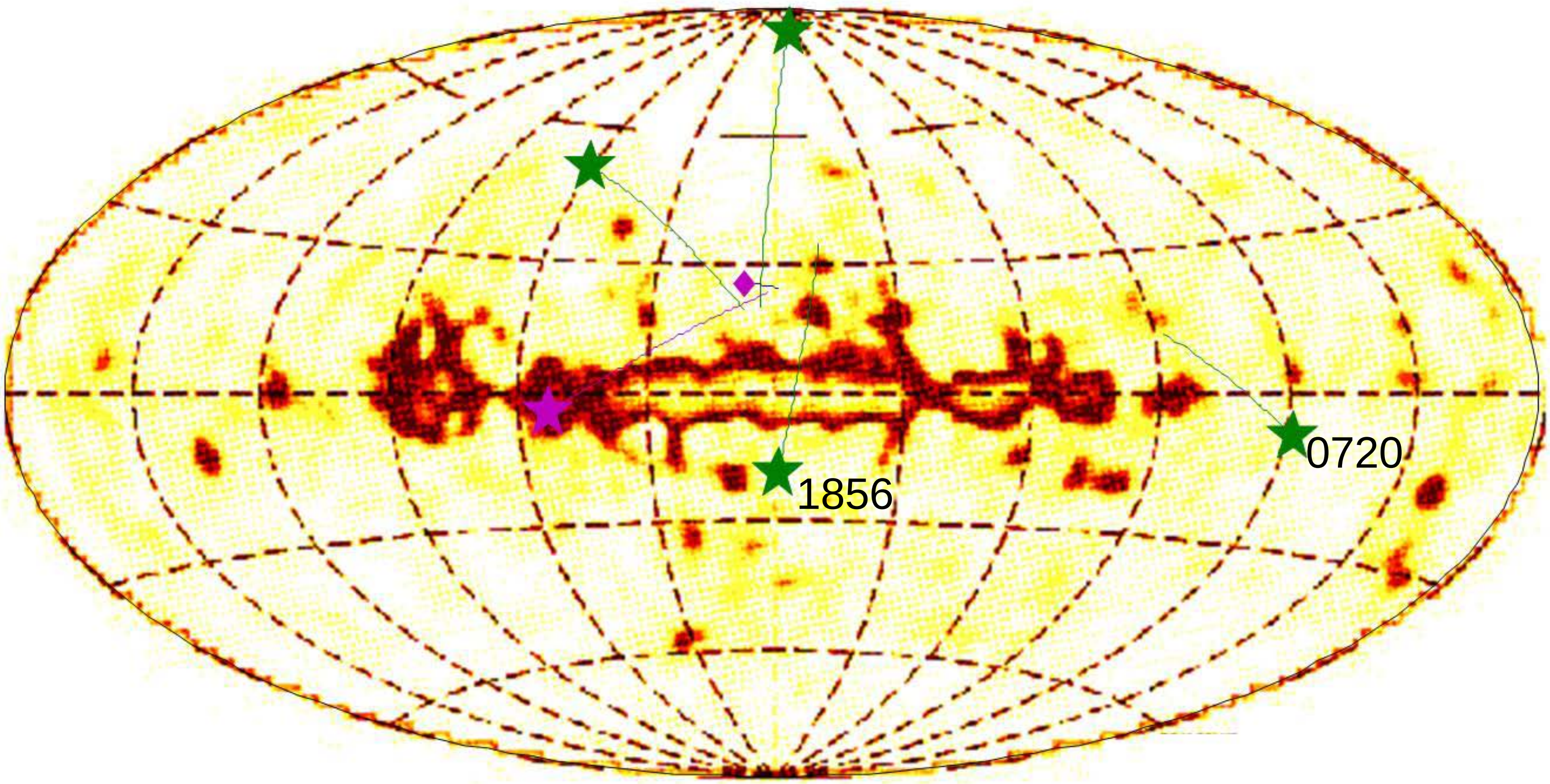
M7 Neutron Star w/o known proper motion

Isolated young neutron stars traced back to their place of origin

Nina Tetzlaff (Jena)

M7 Neutron Star with proper motion

PSR 1929 met ζ Oph



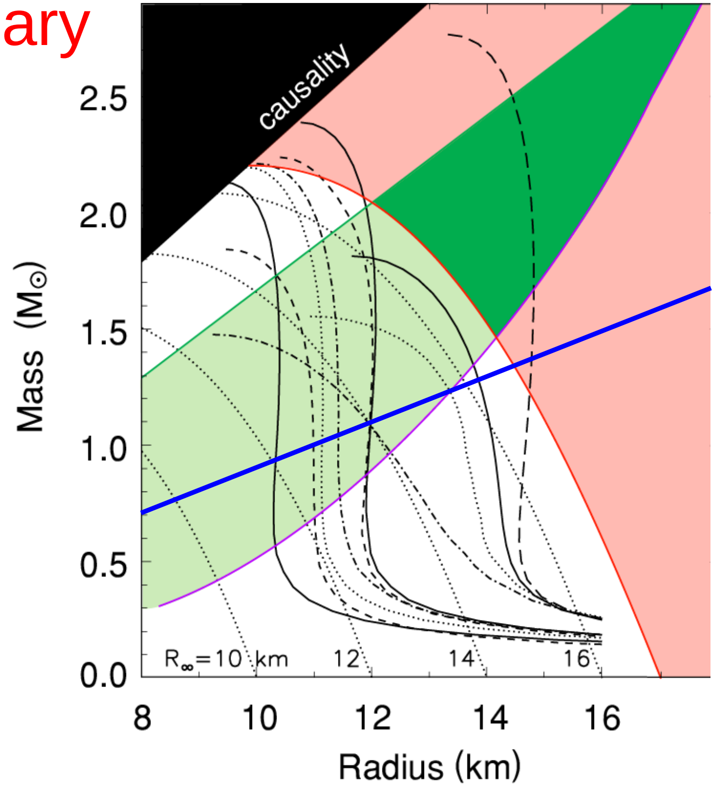
Gamma map from
Diehl et al. (2006) for 26Al

Compare NS traces with
OB associations, **gamma sources,**
SNRs, run-away stars, Bubbles …

DFG SFB / TR 7

Grav. Waves

Summary



M / R = 0.087

From phase-Resolved spectra (RBS 1223)

R = 17 km (infinity)

From distance, flux, and temperature (RXJ1856)

➔ Constraints on the EoS possible from X-ray and optical observations, more coming soon …

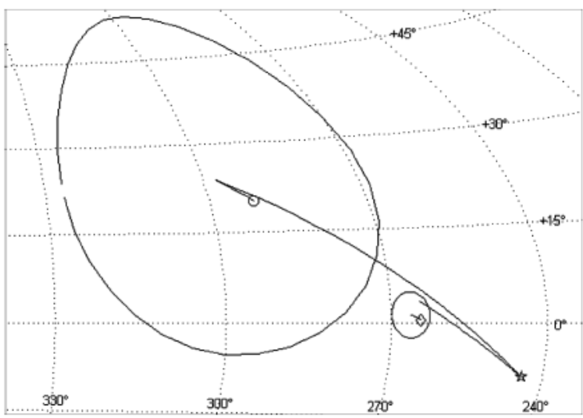


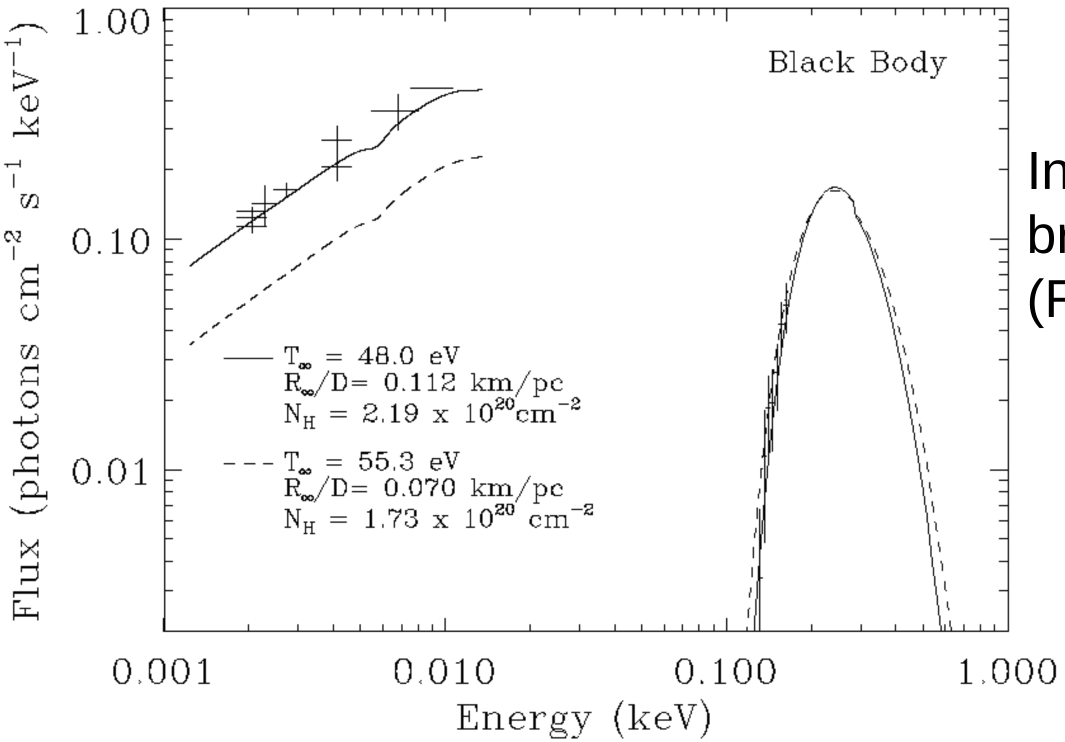
Figure 6. Past trajectories for RX J0720.4−3125 and Tr 10 and TWA, respectively, projected on a Galactic coordinate system (for particular sets of input parameters consistent with Table 6). Present positions are marked with a star for the neutron star and a diamond for Tr 10 and an open circle for TWA. Large circles reflect association extensions (radii of 23 pc for Tr 10 and 33 pc for TWA).

➔ Identification of birth places of young nearby neutron stars seems possible, but no clear case yet. More evidence being searched for, e.g. run-away stars and gamma sources

➔ If the Neutron Star can be found that was born in the SN that placed 60Fe on Earth crust, then we get time and distance of SN.

end

Optical brighter than expected:
The optical excess



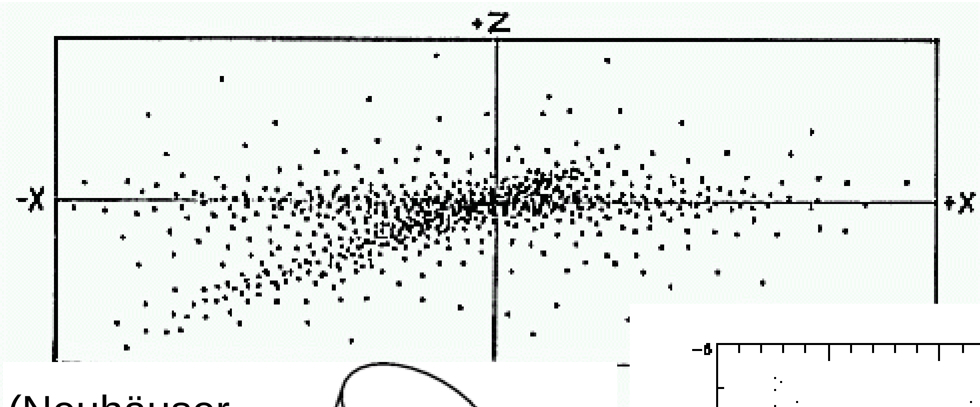
RX J1856

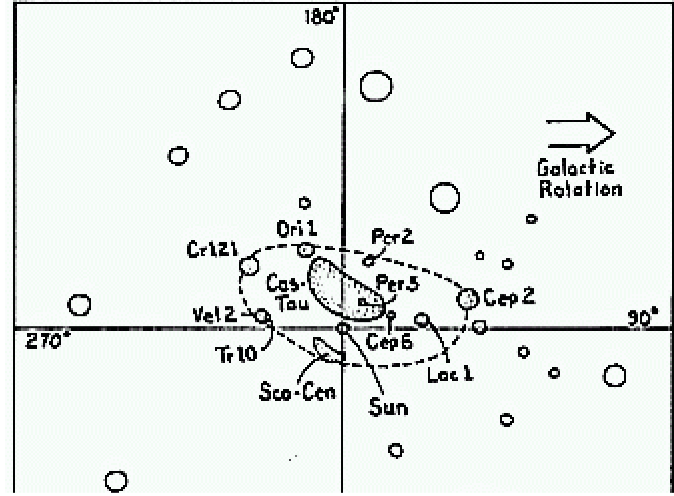
In the optical a factor 3 brighter than expected (ROSAT / HST)

(Pons, …, Neuhäuser et al. 2002)

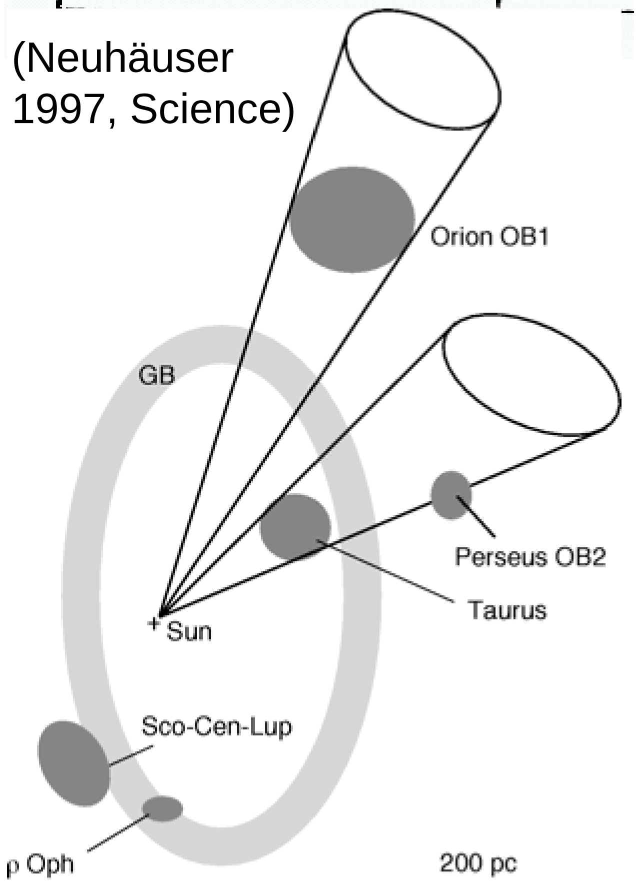
RX J0720	RX J1605	RBS1223	RX J0420
Faktor ~ 5	**Faktor ~14**	**Faktor < 5**	**Faktor < 12**
Motch & Haberl (1998)	Motch et al. (2004)	Kaplan et al. (2001)	Haberl et al. (2004)

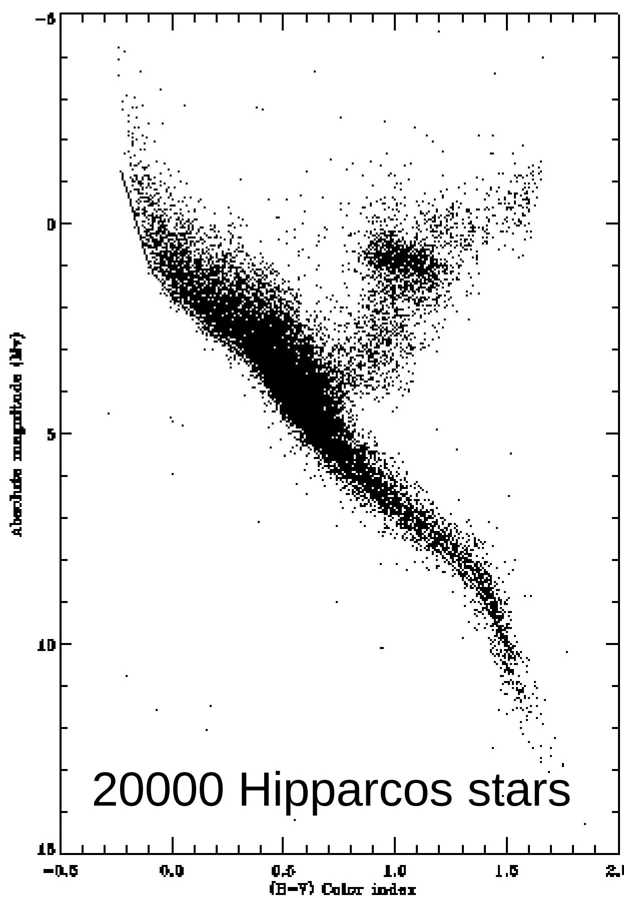
Gould Belt as laboratory to study Life cycle of stars and matter





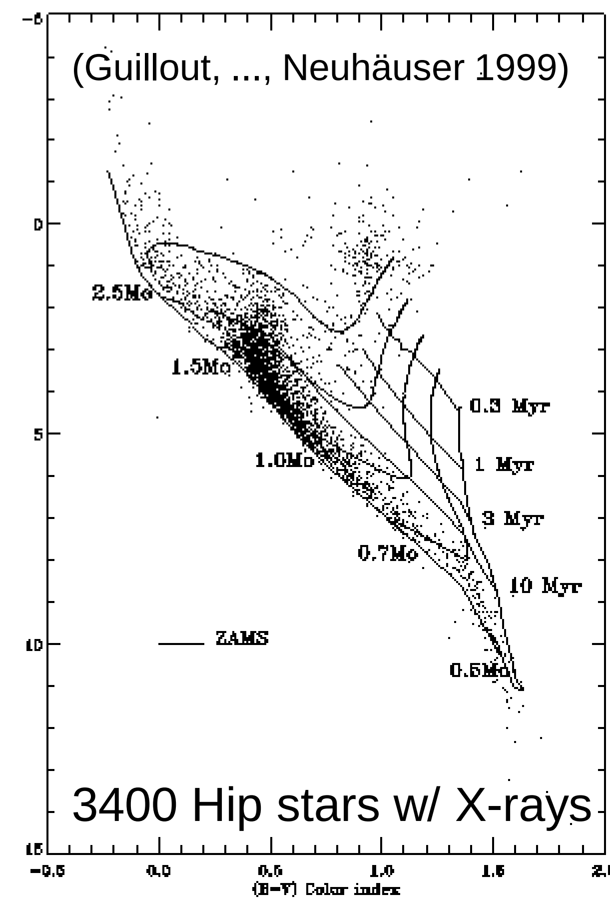
(Neuhäuser 1997, Science)



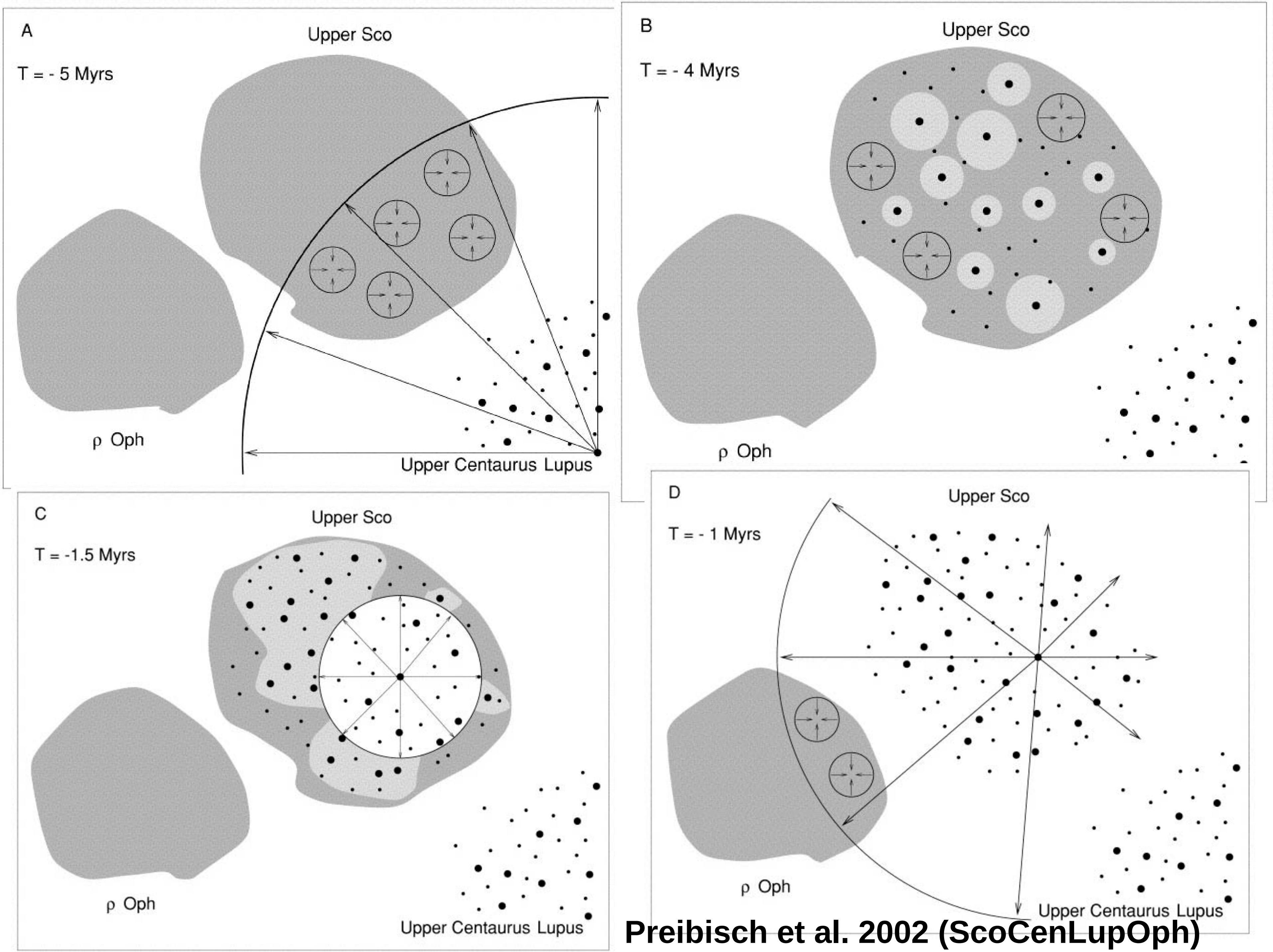


20000 Hipparcos stars

(Guillout, ..., Neuhäuser 1999)



3400 Hip stars w/ X-rays



Preibisch et al. 2002 (ScoCenLupOph)

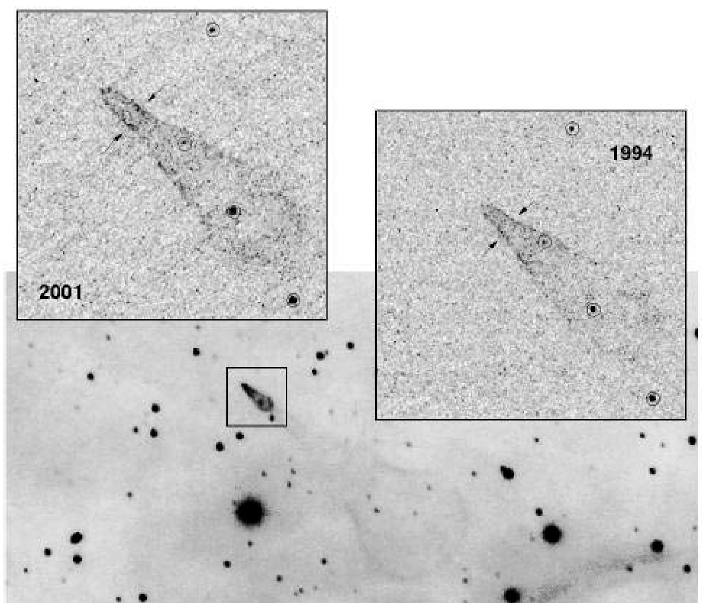
Identifying birth places of young isolated neutron stars

The Guitar Pulsar

Table 2. Potential parent associations of the Guitar pulsar (PSR B2224+65).

Association	$d_{\rm min}$ (pc)	τ (Myr)	$v_{\rm r}$ (km s^{-1})	μ_α^* (mas yr^{-1})	μ_δ (mas yr^{-1})	π (mas)	$d_\odot$ (pc)	α (°)	δ (°)
Vul OB1[a]	28–110	1.06–1.18	193^{+70}_{-73}	144 ± 3	112 ± 3	$0.52^{+0.02}_{-0.02}$	2477–2630	$295.82^{+1.00}_{-0.66}$	23.3–26.2
NGC 6823[b]	25–107	0.95–1.07	349^{+102}_{-75}	144 ± 3	112 ± 3	$0.52^{+0.02}_{-0.01}$	2230–2390	$295.97^{+0.83}_{-0.67}$	23.5–26.3
Cyg OB3[c]	20–65	0.74–0.82	-27^{+81}_{-70}	144 ± 3	112 ± 3	$0.52^{+0.01}_{-0.01}$	2285–2385	$302.08^{+0.84}_{-0.53}$	36.7–38.2
Cyg OB1[d]	45–82	0.50–0.57	867^{+167}_{-143}	144 ± 3	111 ± 3	$0.52^{+0.02}_{-0.02}$	1640–1760	$303.35^{+0.55}_{-0.52}$	$39.54^{+0.26}_{-0.30}$

high transverse velocity (>1500 km/s)
and well investigated bow shock
(Chatterjee & Cordes 2004) ....➔
suggest $v_r \approx 0$ km/s



Kinematic age (0.8 Myr) < characteristic age (1.1 Myr)

→Cyg OB3 most probable parent association

➔ For 8 Myr cluster age, progenitor mass 21-37 Sun
(Tetzlaff, Neuhäuser, Hohle 2009 MNRAS)

Identifying birth places of young isolated neutron stars

Runaway stars

• former companions of neutron star progenitors (Binary Supernova Scenario, Blaauw 1961) or
• ejected from young dense massive stellar clusters (Dynamical Ejection Scenario, Poveda et al. 1967)

➢ two stellar populations (Stone 1979):
  • normal Population I stars (typically low peculiar space velocities)
  • runaway stars (typically larger peculiar space velocities)

• approximately 2700 runaway stars (members of the high velocity group, dashed-dotted line) found in the Hipparcos catalogue
(Tetzlaff, Neuhäuser, Hohle 2010, submitted)

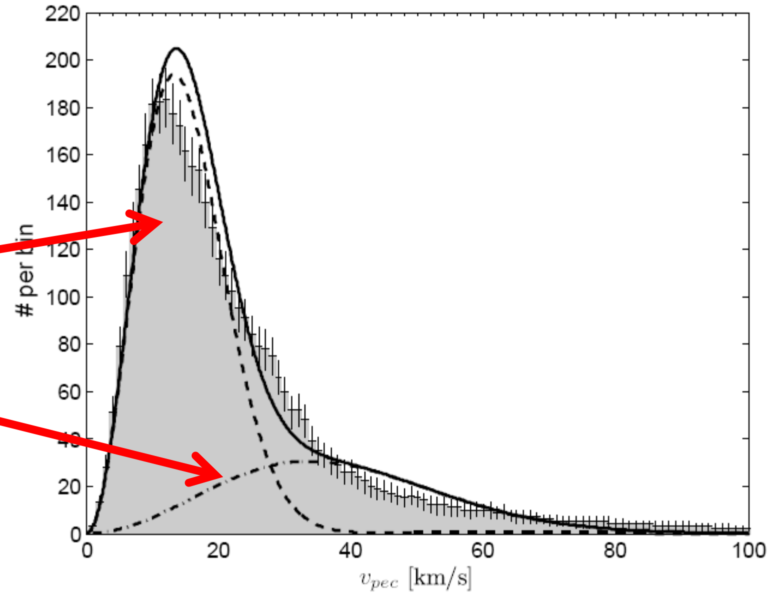


Figure 1. Distribution of the peculiar space velocity v_{pec}. The dashed curve shows the distribution for the low velocity group whereas the dashed-dotted curve is for the high velocity group. The two curves intersect at $v_{pec} = 28\,\mathrm{km/s}$. The total distribution as the sum of the two is represented by the full line.

Tetzlaff, Neuhäuser, Hohle 2010, submitted

Identifying birth places of neutron stars:

Next steps

➔ Calculate past flight path for all (~54) young (< 50 Myr) nearby (< 3 kpc) neutron stars (so far 5 NS done).

➔ Compare to catalog of super nova remnants.

➔ Compare NS flight path to Associations/Clusters
and the Local Bubble and other bubbles

➔ Compile catalog of massive young run-away stars
(which formed in super novae in binaries) (ongoing)
and compare NS flight path to flight path of all (~ 2700) run-away stars

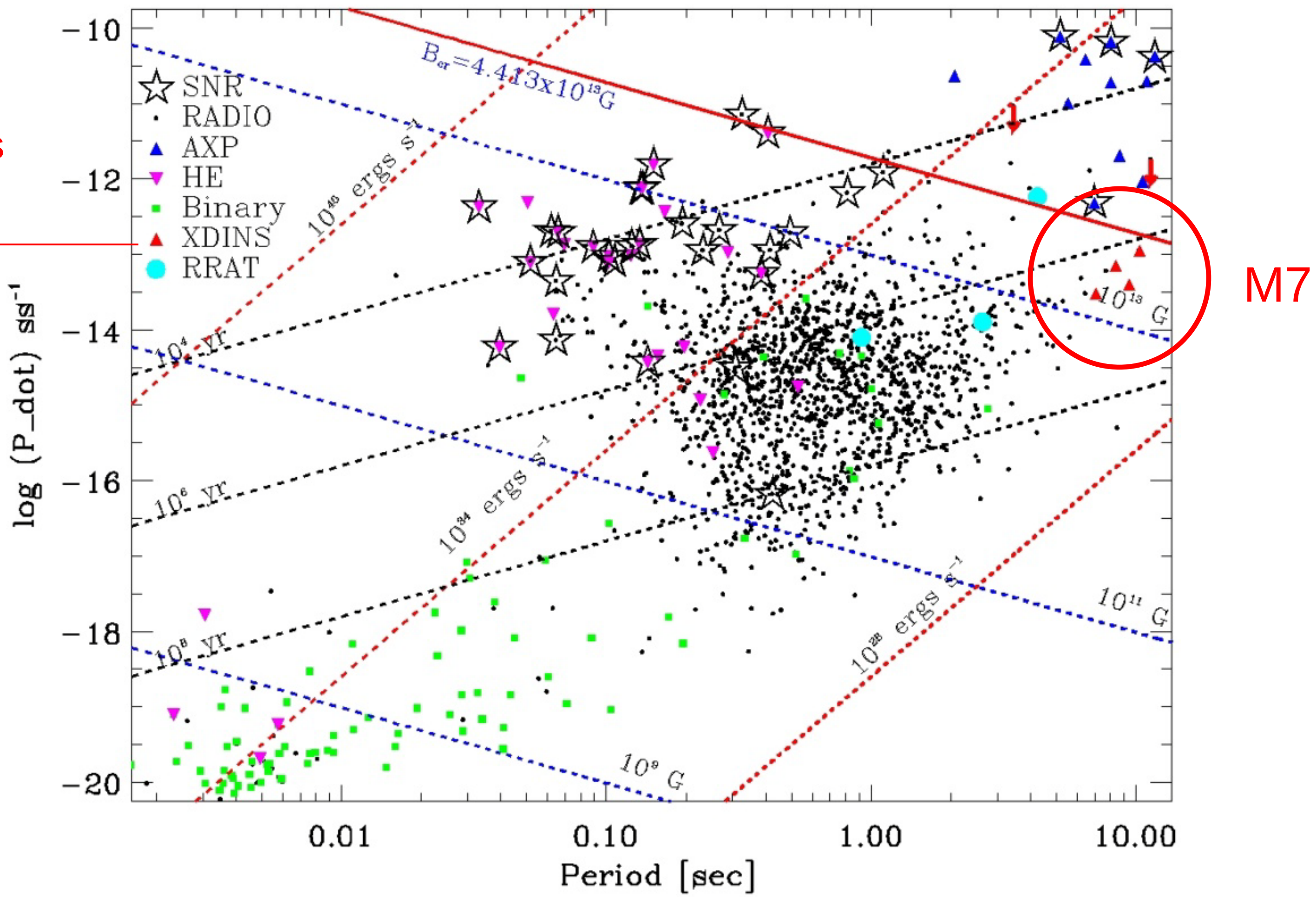
➔ Compare with catalog of 26 Al gamma-ray sources (due to SN).

Magnificent Seven Neutron Stars

P – P dot diagram

(from ATNF 15 May 2010)

X-ray dim
Isolated neutron stars
(XDINS)
=
M7 neutron stars

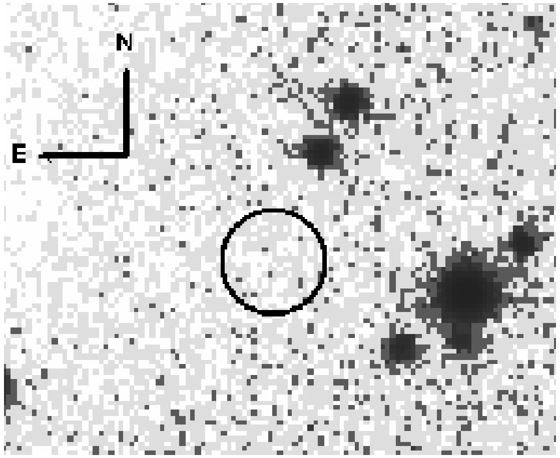


may have evolved from AXPs or SGRs

Related to RRATs ?

Relevant for studying Pulsar birth rates

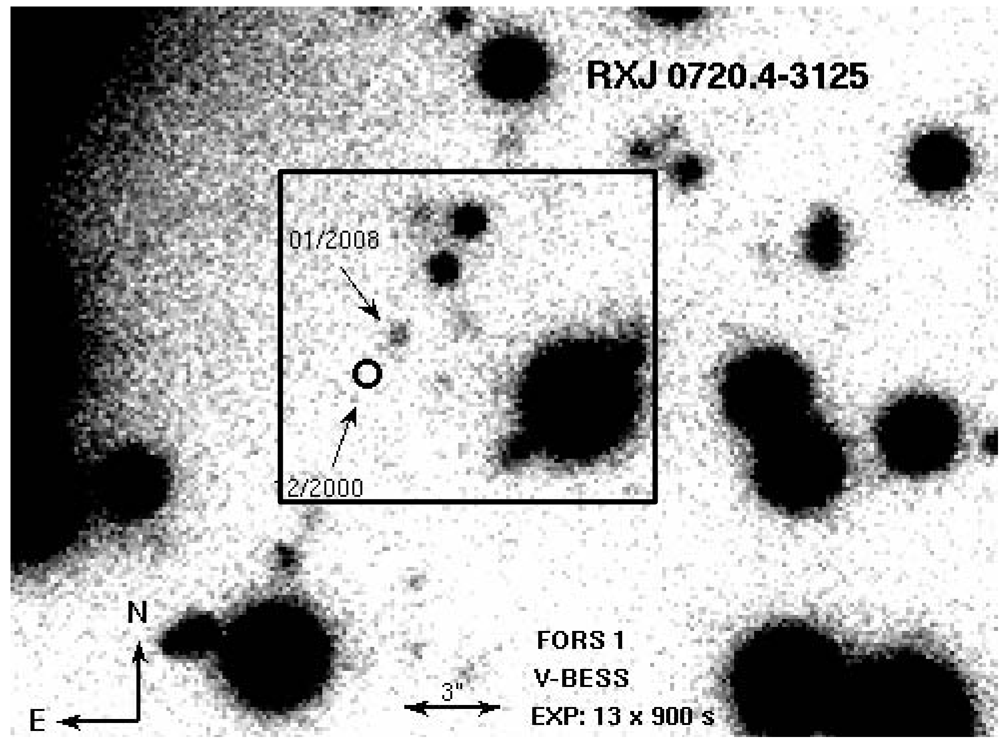
Deep optical and infrared imaging
of isolated neutron star RXJ0720



No detection of RXJ0720
in the near infrared.

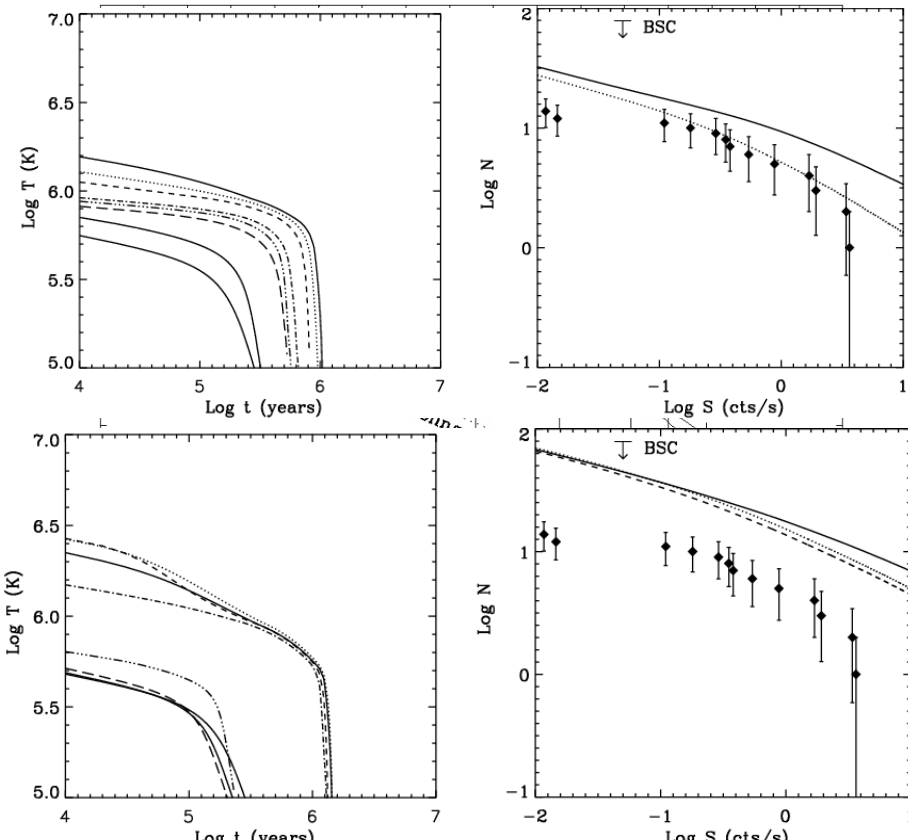
Upper limits for companions
15 Jup masses
(Posselt, Neuhäuser, Haberl 2009 A&A)

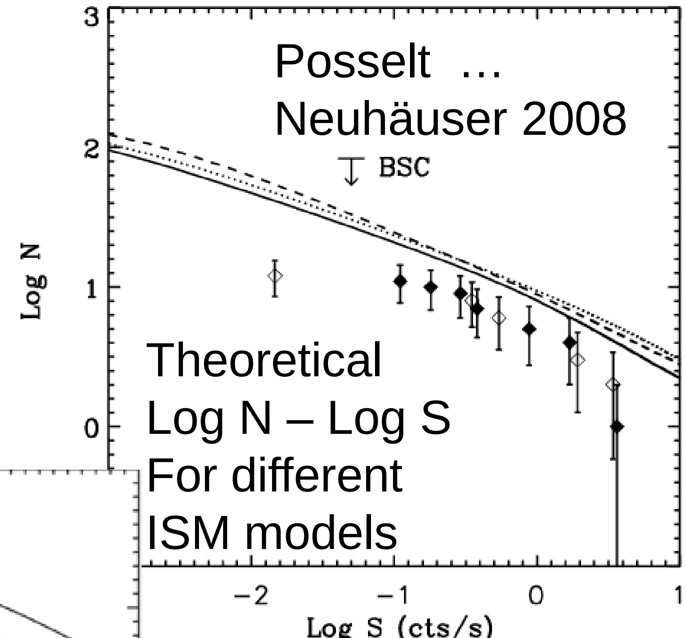
Mass determination would be
possible via companions
and/or with gravitational lensing
when NS moves before
background star …



First detection of RXJ0720 in V band.
New/better position and proper motion.
(Eisenbeiss, …, Neuhäuser et al. 2010 AN)

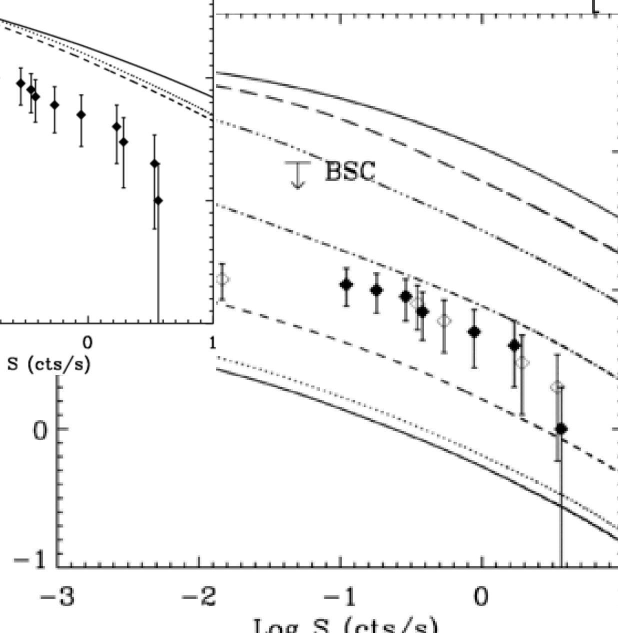
Log N – Log S





Posselt … Neuhäuser 2008

Theoretical Log N – Log S For different ISM models



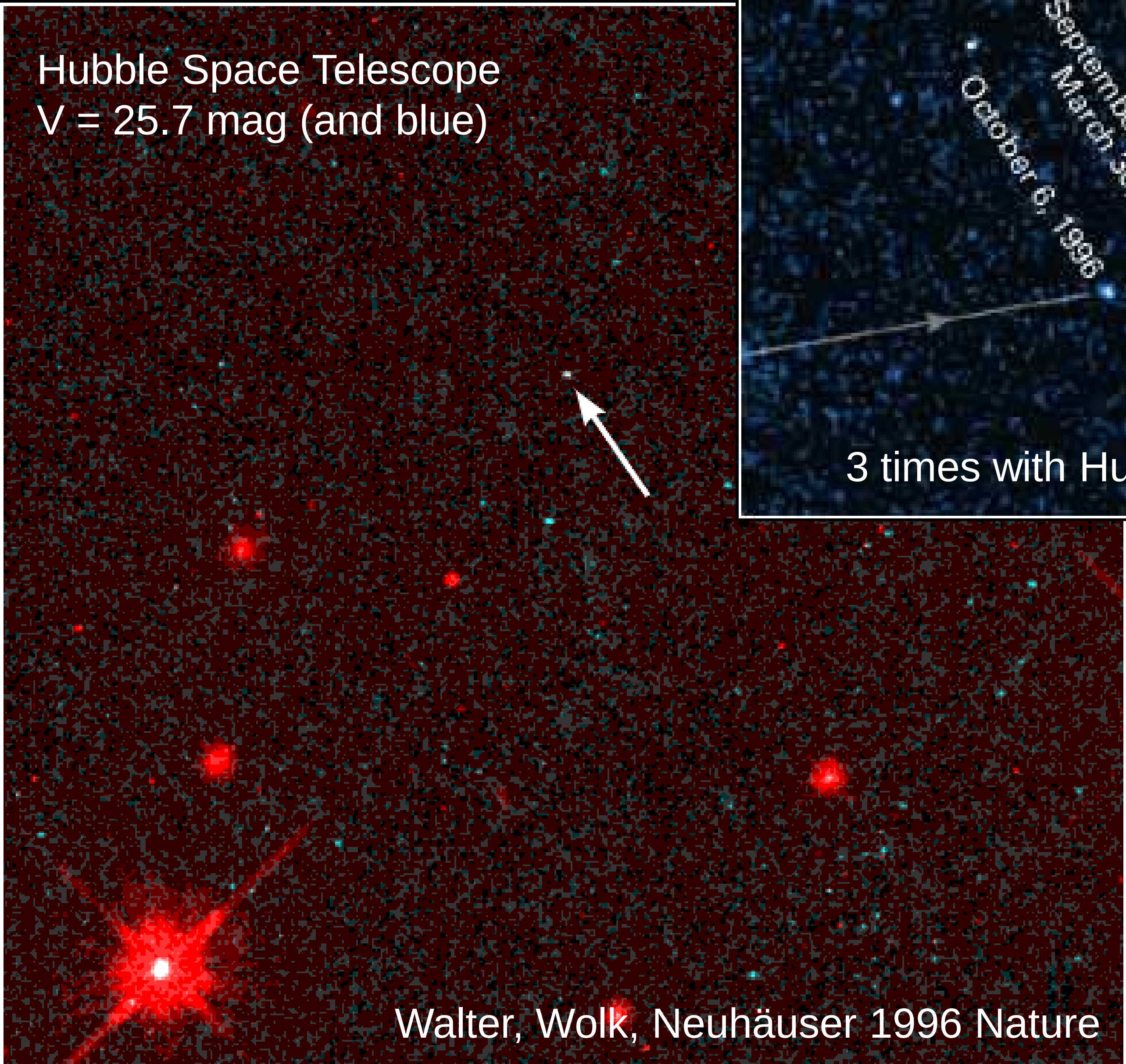
Theoretical Log N – Log S For different Neutron Star magnetic fields

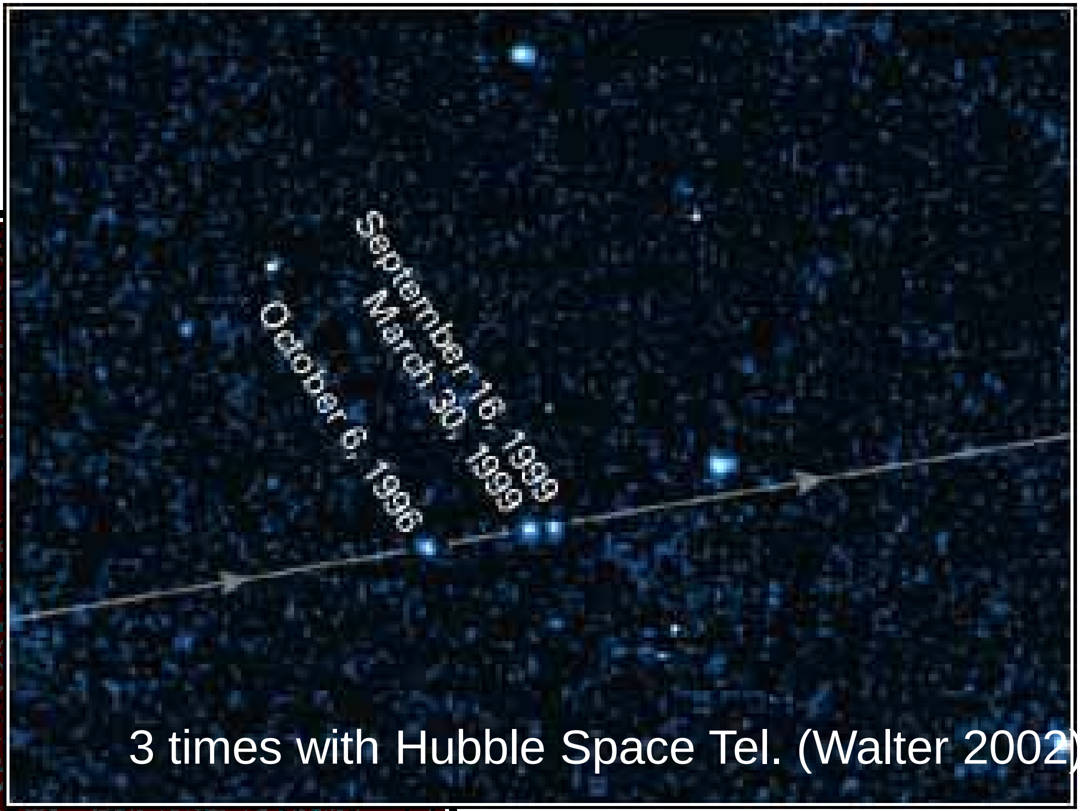
(Popov et al. 2010)

For N isolated neutron stars for , e.g., ROSAT count rate S (first by Neuhäuser & Trümper

Or different cooling models, (different EoS) Popov et al. 1996

RXJ1856


Hubble Space Telescope
V = 25.7 mag (and blue)
Walter, Wolk, Neuhäuser 1996 Nature


September 16, 1999
March 30, 1999
October 6, 1996
3 times with Hubble Space Tel. (Walter 2002)