Search for neutron stars from the supernovae that delivered ^{60}Fe to Earth to constrain supernova nucleosynthesis

Ralph Neuhäuser, Kai-Uwe Michel, Valeri Hambaryan, Frank Gießler

Astrophysical Institute and University Observatory Jena

Germany

(1) Tracing back runaway stars and pulsars

(2) Nearby High-mass X-ray binaries

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Motivation

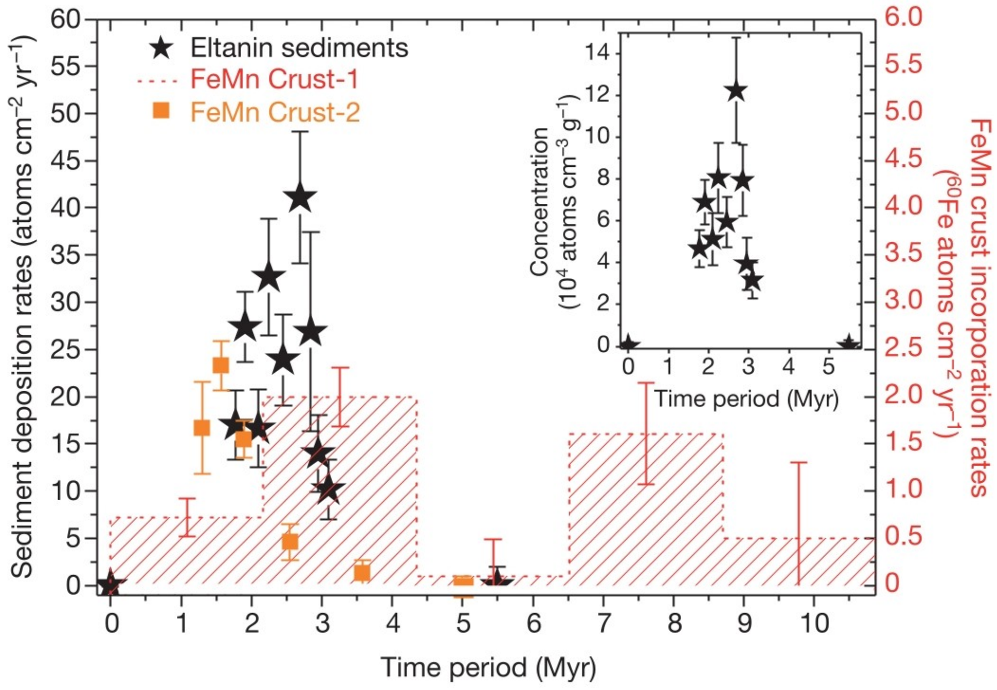
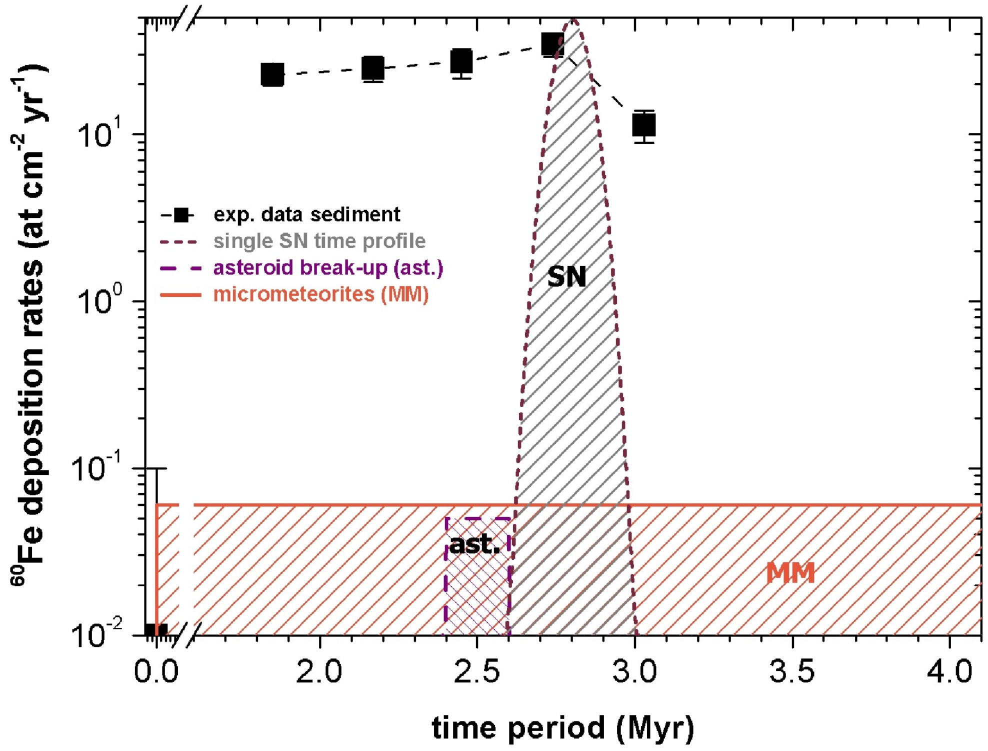


Figure 1 | Deposition rates for sediment (150-kyr averaged data) and incorporation rates for two crust samples. ^{60}Fe concentrations (^{60}Fe per gram) for the sediment are given in the inset; they were on average 6.7×10^4 atoms per gram between 1.7 Myr and 3.2 Myr, but 260×10^4 atoms per gram of crust and 95×10^4 atoms per gram of nodule, reflecting the difference in growth rate and incorporation efficiency (see Supplementary Information). The error bars (1σ Poisson statistics) include all uncertainties and scale with decay correction, so that uncertainties and upper limits become larger for older samples. The absolute ages for the sediment samples have an uncertainty of 0.1 Myr, except for the 5.5-Myr-old sediments, which have an uncertainty of about 1 Myr. The age of Crust-1 has an uncertainty of 0.3 Myr and the age of Crust-2 has an uncertainty of 0.5 Myr.

$$F = \frac{U}{4}\frac{M_{ej}}{4\pi A m_p r^2} e^{-\frac{t}{\tau}}$$

Supplementary Figure S6: Comparison of the measured ^{60}Fe deposition rates from the sediment data (black squares) with models of interplanetary influx of ^{60}Fe. Micrometeorites (MM) and an asteroid break-up (10 km size) with a 200 kyr deposition spread are plotted. Also shown is a Gaussian-approximation of a single SN time-profile with a full-width-half-maximum of 150 kyr as a guide to the eye.



Wallner *et al. 2016*, *Nature* **532**, 69–72

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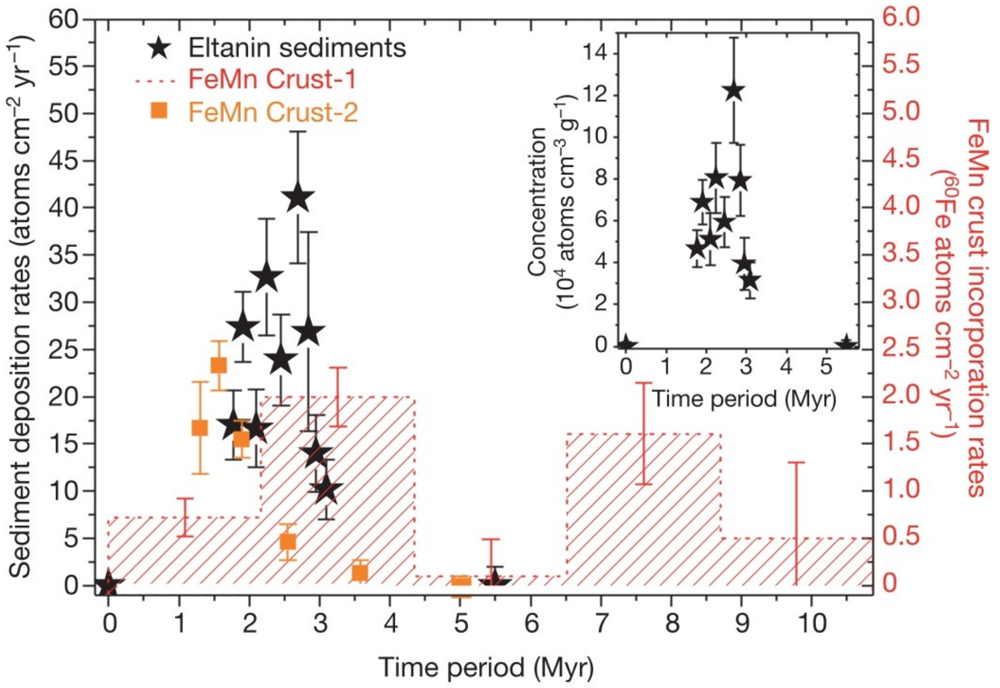

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The ^{60}Fe signal from

1.5-3.2 Myr ago originates

from **several** nearby

supernovae (~100 pc),

prob. Sco-Cen-Lup region.

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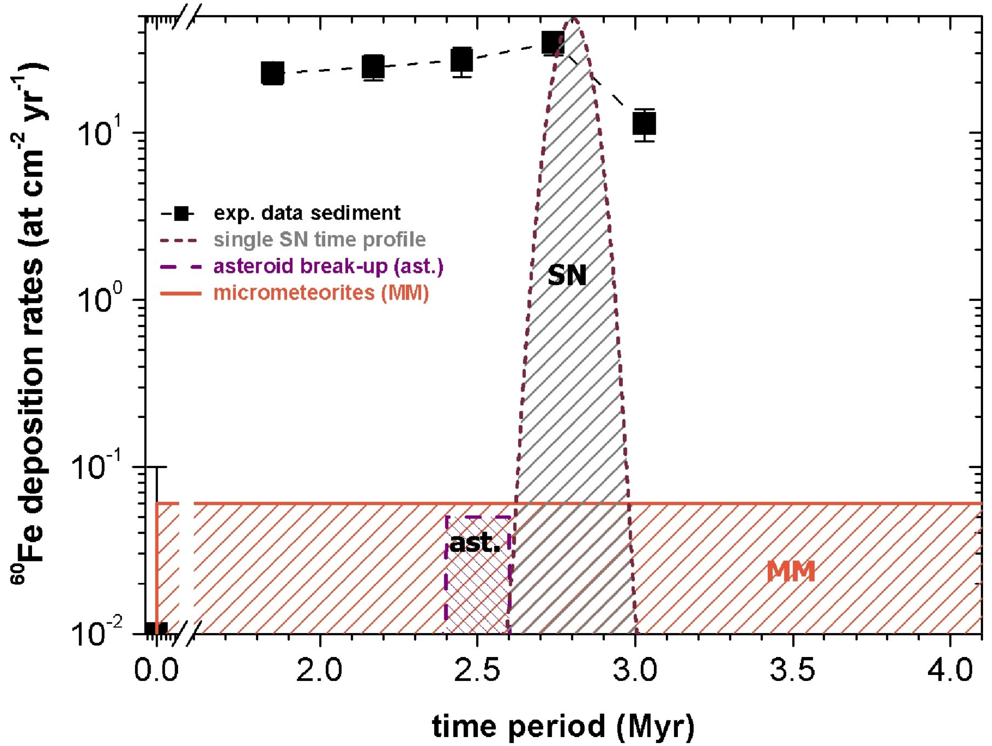

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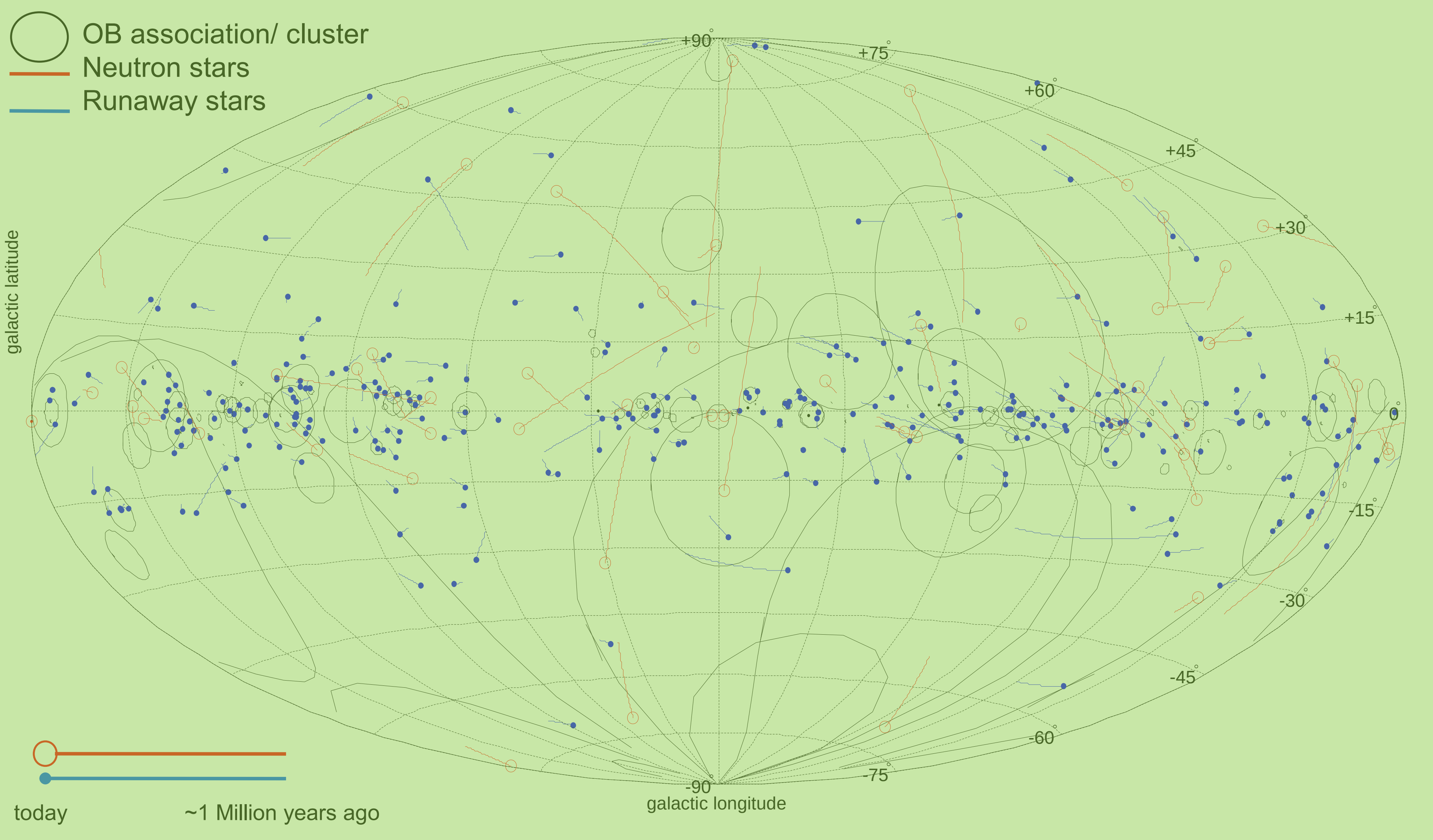
Our Project



Tetzlaff et al. 2010ies

- Search for neutron star(s) formed in those Supernovae that released 60-Fe
- by tracing back runaway stars and neutron stars to find pairs, whose components were at the same time at the same place
- to constrain time and location (distance) of the SNe
- can be outside of supernova remnants, i.e. much older (1-3 Myr)

Tracing back stars thru the Galactic potential

The equation of motion

$$\ddot{\vec{r}} = -\vec{\nabla}\Phi$$

or the system of equations

$$\dot{x} = u \qquad \dot{y} = v \qquad \dot{z} = w$$

$$\dot{u} = -\frac{\partial\Phi}{\partial x} \qquad \dot{v} = -\frac{\partial\Phi}{\partial y} \qquad \dot{w} = -\frac{\partial\Phi}{\partial z}$$

$$\Phi = \Phi_{disk} + \Phi_{sphere} + \Phi_{halo}$$

$$\Phi_{disk} = -\frac{GM_{disk}}{\sqrt{x^2 + y^2 + \left(a + \sqrt{z^2 + b^2}\right)^2}}$$

$$\Phi_{sphere} = -\frac{GM_{sphere}}{c + \sqrt{x^2 + y^2 + z^2}}$$

$$\Phi_{halo} = v_{halo}^2 \ln(x^2 + y^2 + z^2 + d^2)$$

Previous work by Tetzlaff, Neuhäuser et al. 2009-2014,
now new software and more recent potential(s)

Constants:

$G = 4.5\text{e-}15\ \mathrm{pc}^3 / (M_\odot\ \mathrm{yr}^2)$

$M_{disk} = 1.0\text{e}11\ M_\odot$

$M_{sphere} = 3.4\text{e}10\ M_\odot$

a = 6500 pc, b = 260 pc,
c = 700 pc, d = 12000 pc

v_{halo} = 128 km/s

Johnston, Hernquist, Bolte 1996 ApJ

Miyamoto-Nagai potential (1975)

Hernquist potential (1990)

Log potential; Runge-Kutta-Fehlberg (4, 5) integration
(2 new codes by Frank Gießler and Valeri Hambaryan)

Tracing back stars thru the Galactic potential

<u>Input:</u>

~ 400+ runaway stars:

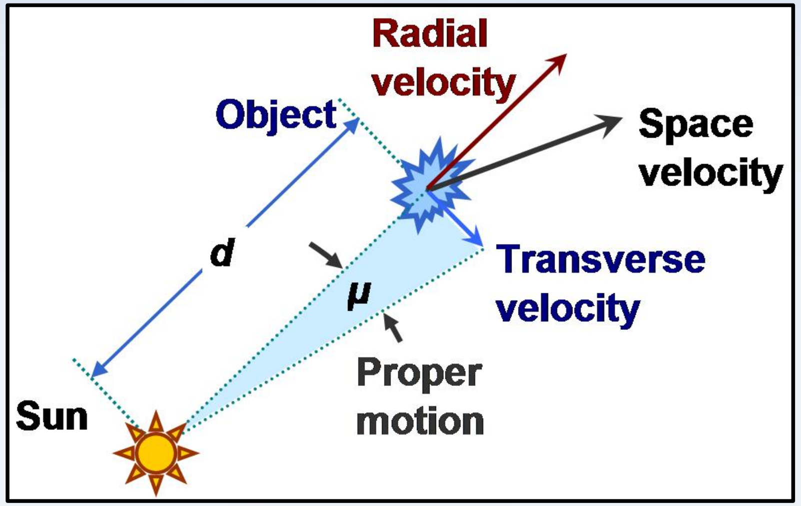
Position, parallax, proper motion, and radial velocity (6D) all well known

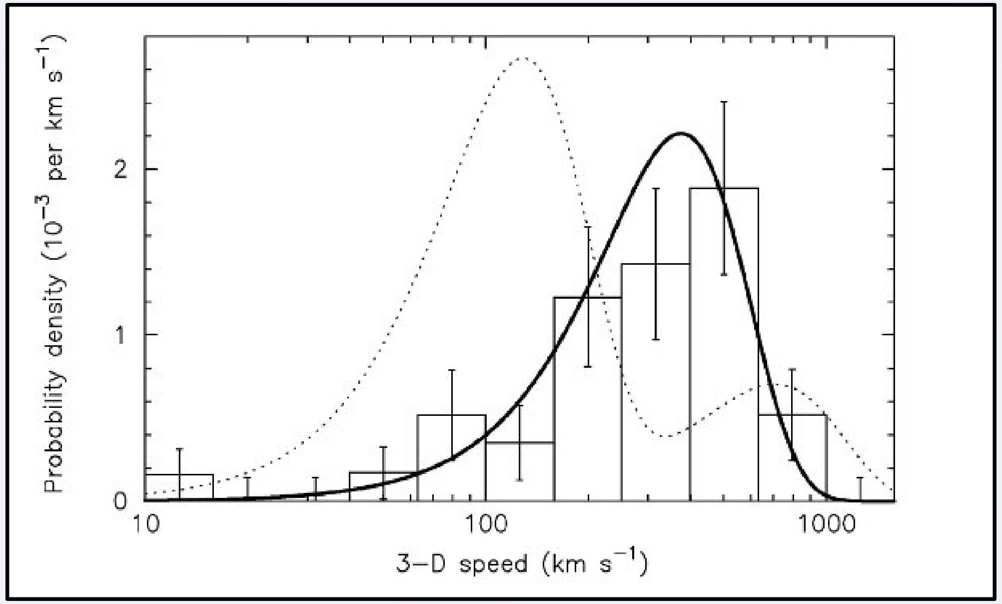
~ 400 neutron stars:
(up to a few Myr, up to a few kpc)

Position, parallax, and proper motion (5D) all well known

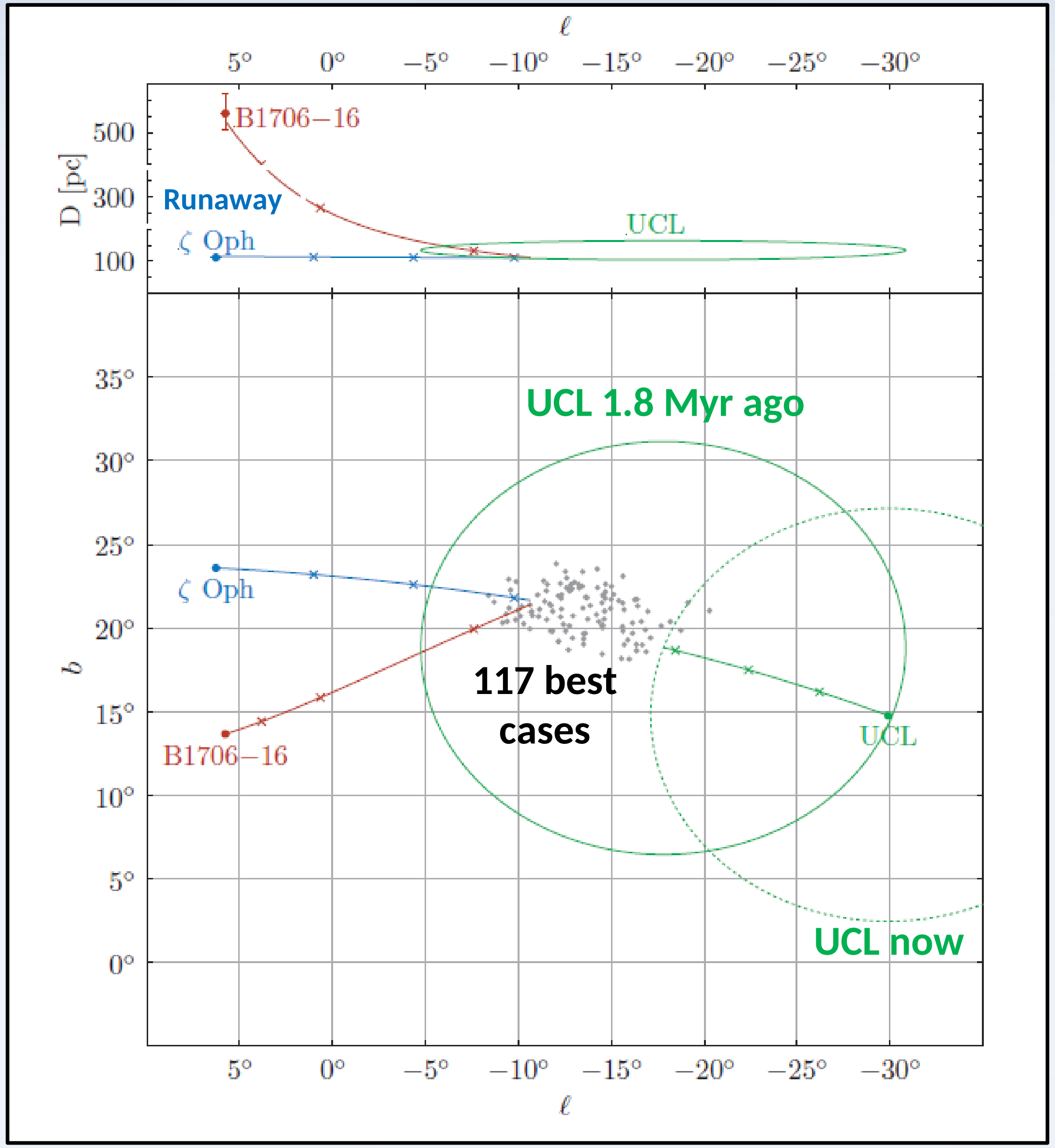
Radial velocity often usually unknown (few exceptions, e.g. bow shocks)

RV drawn from Hobbs et al. (2005) distribution (Maxwellian with rms = 265 km/s), Monte-Carlo-Simulation with 3 million runs





New candidate pair



<u>Runaway star ζ **Oph** + Neutron star **PSR B1706**</u>

~1.8 Myr ago in UpCenLup

at the same time
at the same location
within 0.5 pc in UCL

(SN in binary at ~110 pc dist.)

Table 1: Predicted Supernova position:

for best case approach within 0.5 pc inside UCL:	1.58 Myr ago	present day
Galactic longitude l	$-10.7°$	$-18.9°$
Galactic latitude b	$21.55°$	$13.4°$
Distance from Earth	111.2 pc	107.9 pc
(for pulsar radial velocity 265.5 km/s)		
for 117 best case approaches within 10 pc inside UCL:	1.78 ± 0.21 Myr ago	present day
Galactic longitude l	$-13 \pm 3°$	$-16 \pm 4°$
Galactic latitude b	$21 \pm 2°$	$15 \pm 3°$
Distance from Earth	107 ± 4 pc	109 ± 5 pc
(for pulsar radial velocity 260 ± 43 km/s)		

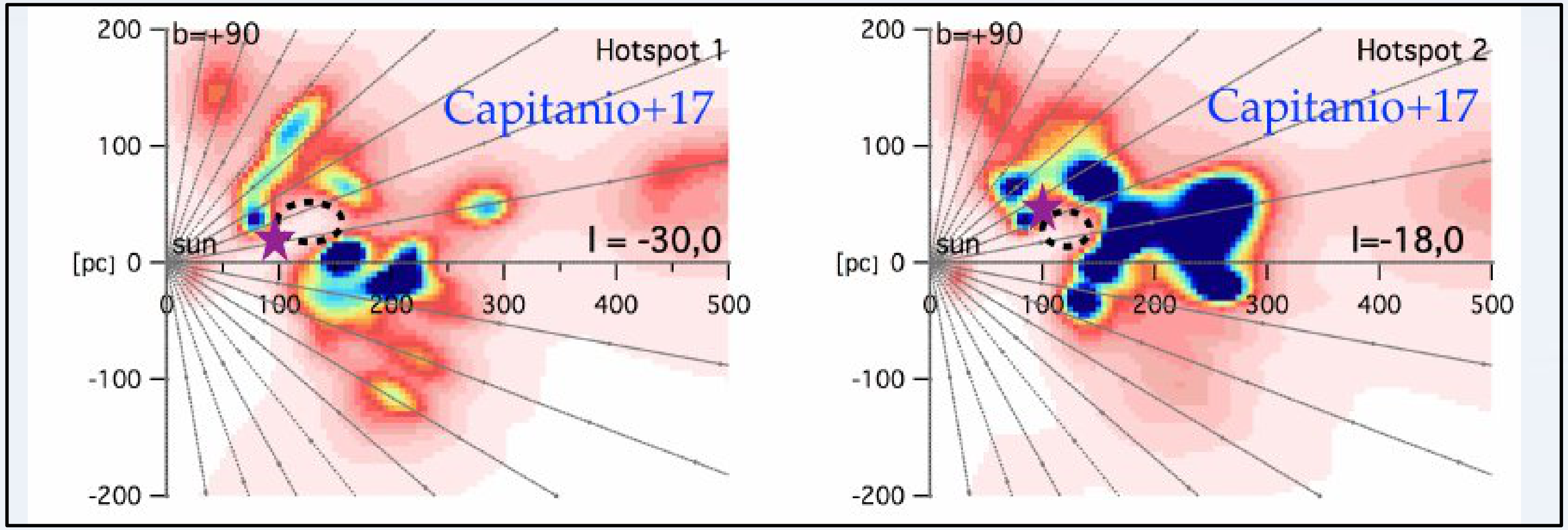
Note: More details and input parameters in Tables S3 and S4.

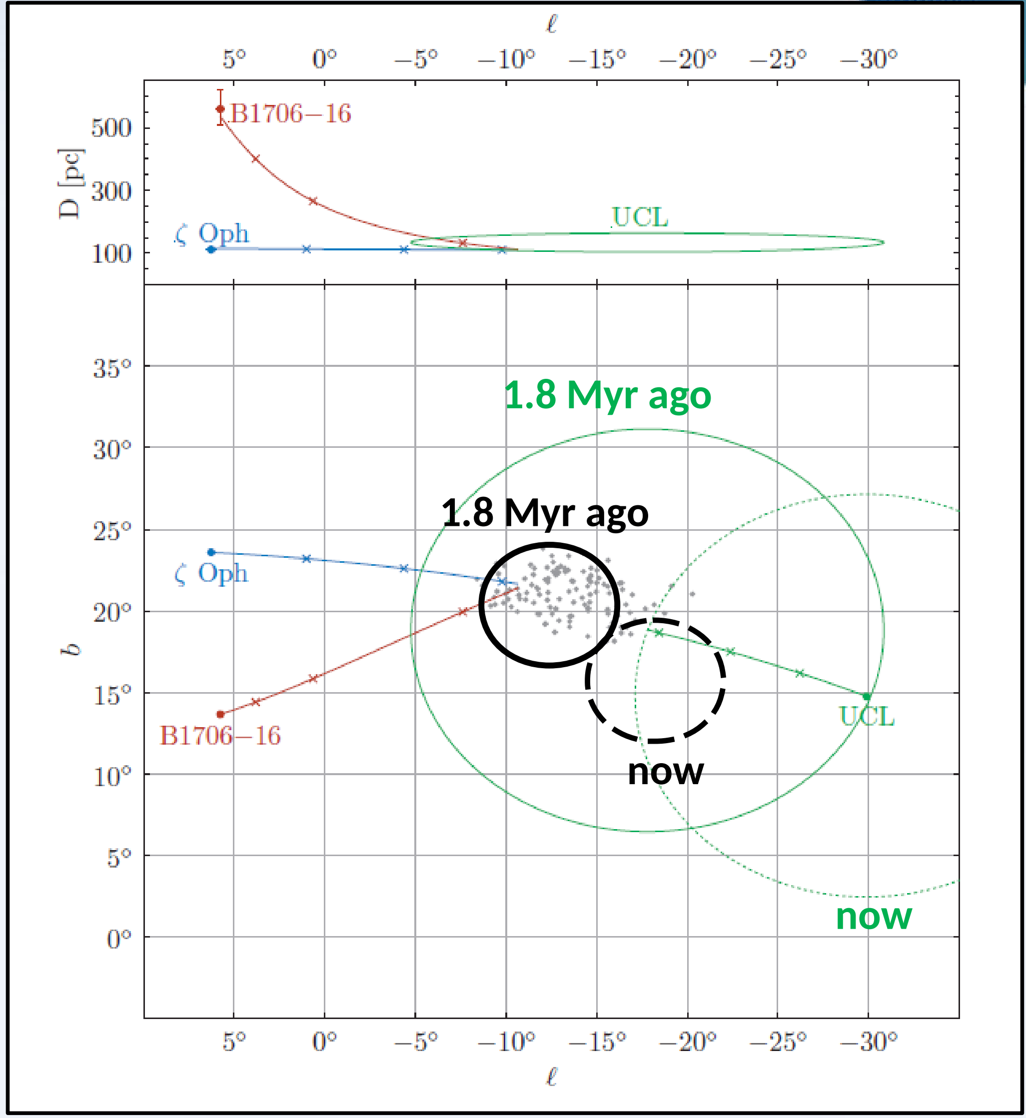
Neuhäuser, Gießler, Hambaryan, 2020, MNRAS

A supernova that delivered ^{60}Fe

A cavity in the ISM at our expected SN position

(detected by Capitanio et al. 2017)

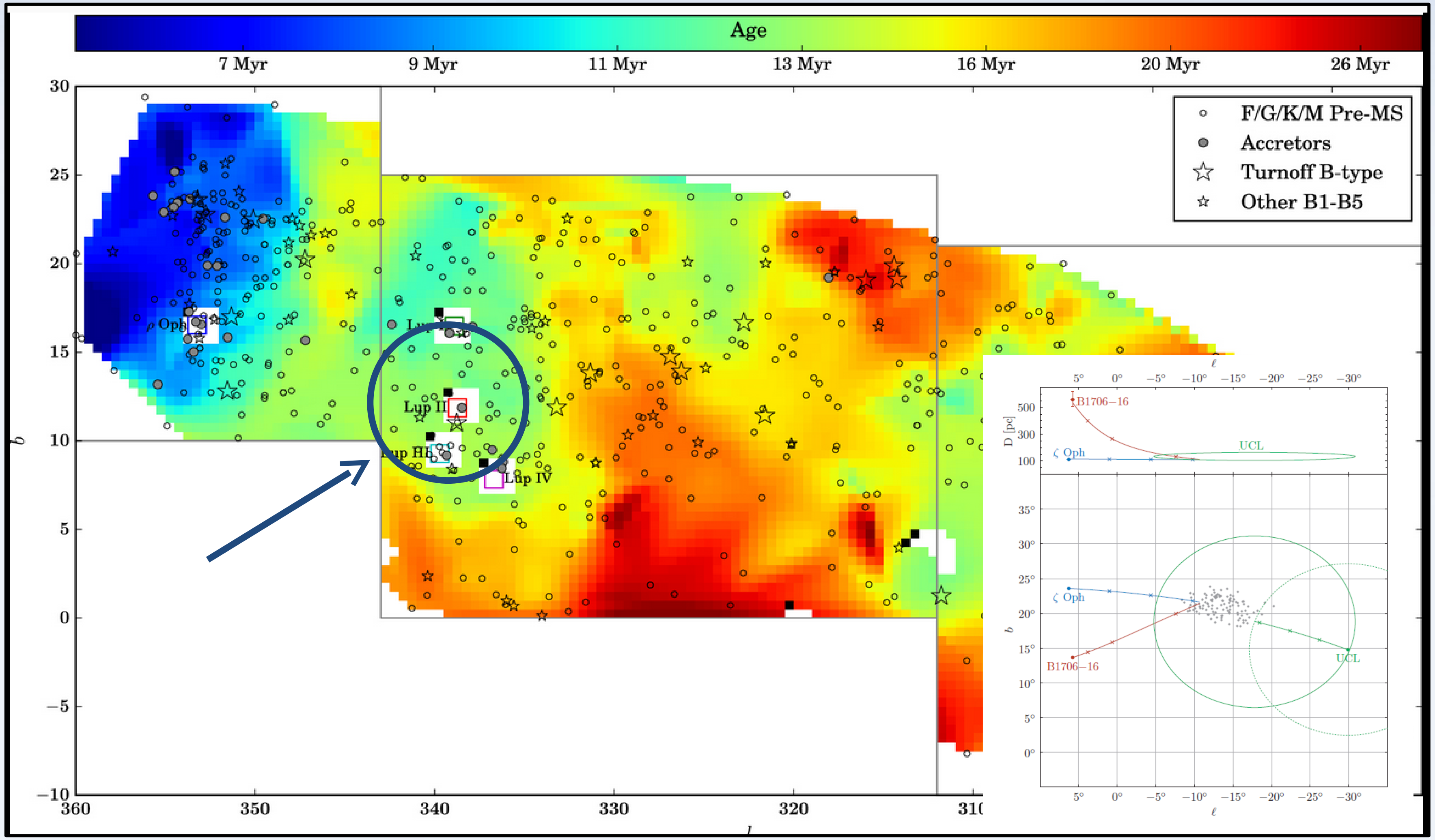




(adaption from D. Breitschwerdt)

Position also consistent with 2nd or 2nd-to-last expected supernova in Breitschwerdt et al. 2016 and Schulreich, Feige, Breitschwert 2023

Estimating the mass of the neutron star progenitor

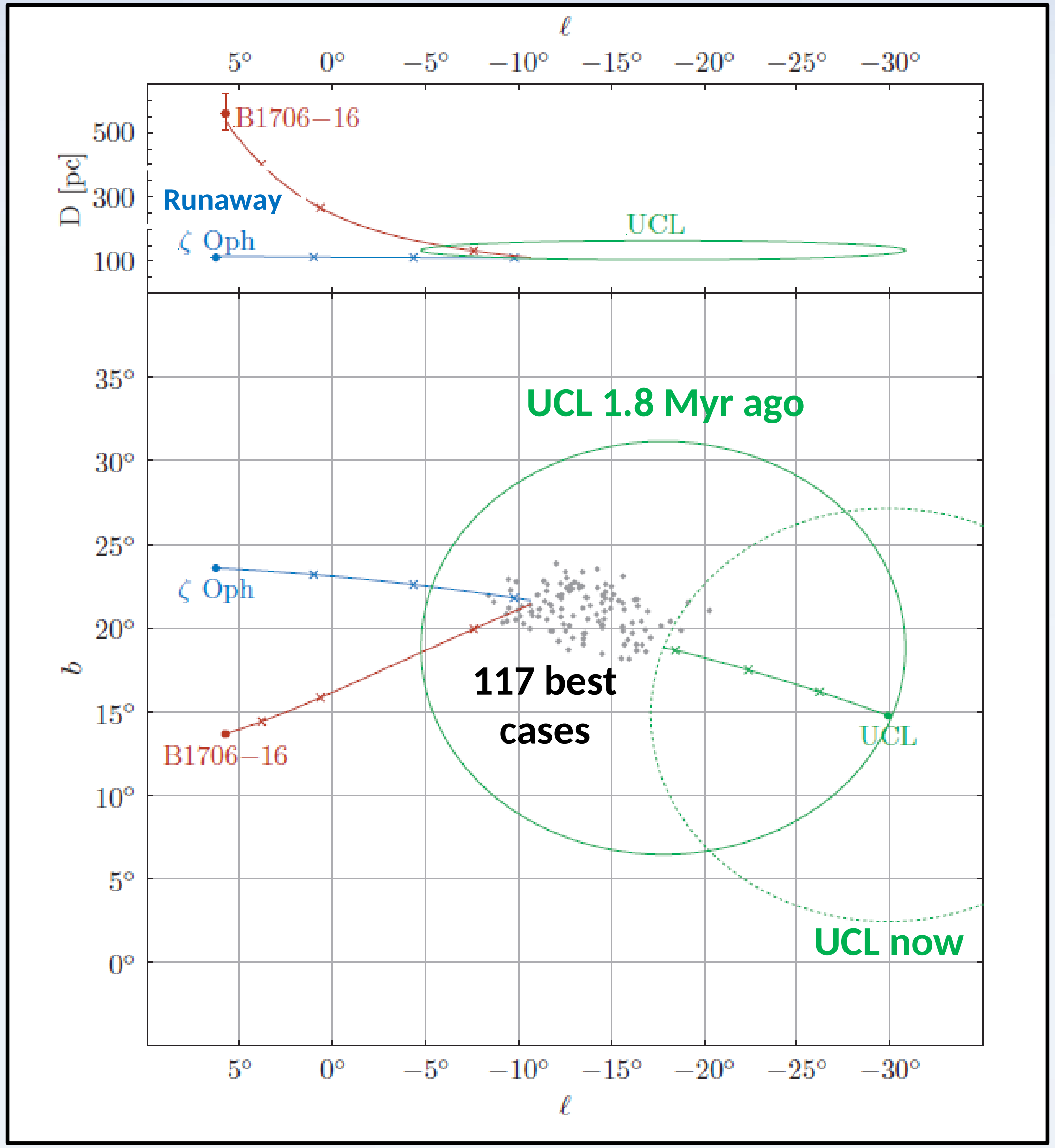


$$M_{\zeta Oph} + M_{NSprog} > 2 \cdot (M_{\zeta Oph} + M_{NS})$$

$$M_{\zeta Oph} = 13\ M_{\odot} \qquad M_{NS} = 1.4\ M_{\odot} \quad \rightarrow \quad M_{NSprog} \sim 16\ M_{\odot}$$

- Association age UCL 16±2 Myr (or within 10-20 Myr)
- Age of SN area ~12-15 Myr (Pecaut & Mamajek 2016)
- That age (12-15 Myr) minus flight time (~1.8 Myr) gives SN progenitor lifetime and then its mass (~15-19 Msun)
- System gets unbound, when more than half of the total mass gets ejected and/or sufficient pulsar kick
- hence, progenitor mass at least ~16 Msun (and at most 19 Msun)
- 3D space velocity of runaway = its former orbital velocity
- Orbital period 20-22 yr and separation 23-25 au (for circular orbit) before SN

Summary



Neuhäuser, Gießler, Hambaryan, 2020, MNRAS

This is probably one of the SNe that delivered 60-Fe to Earth:

$$F = \frac{U}{4} \frac{M_{ej}}{4\pi A m_p r^2} e^{-\frac{t}{\tau}}$$

We determined r and t:

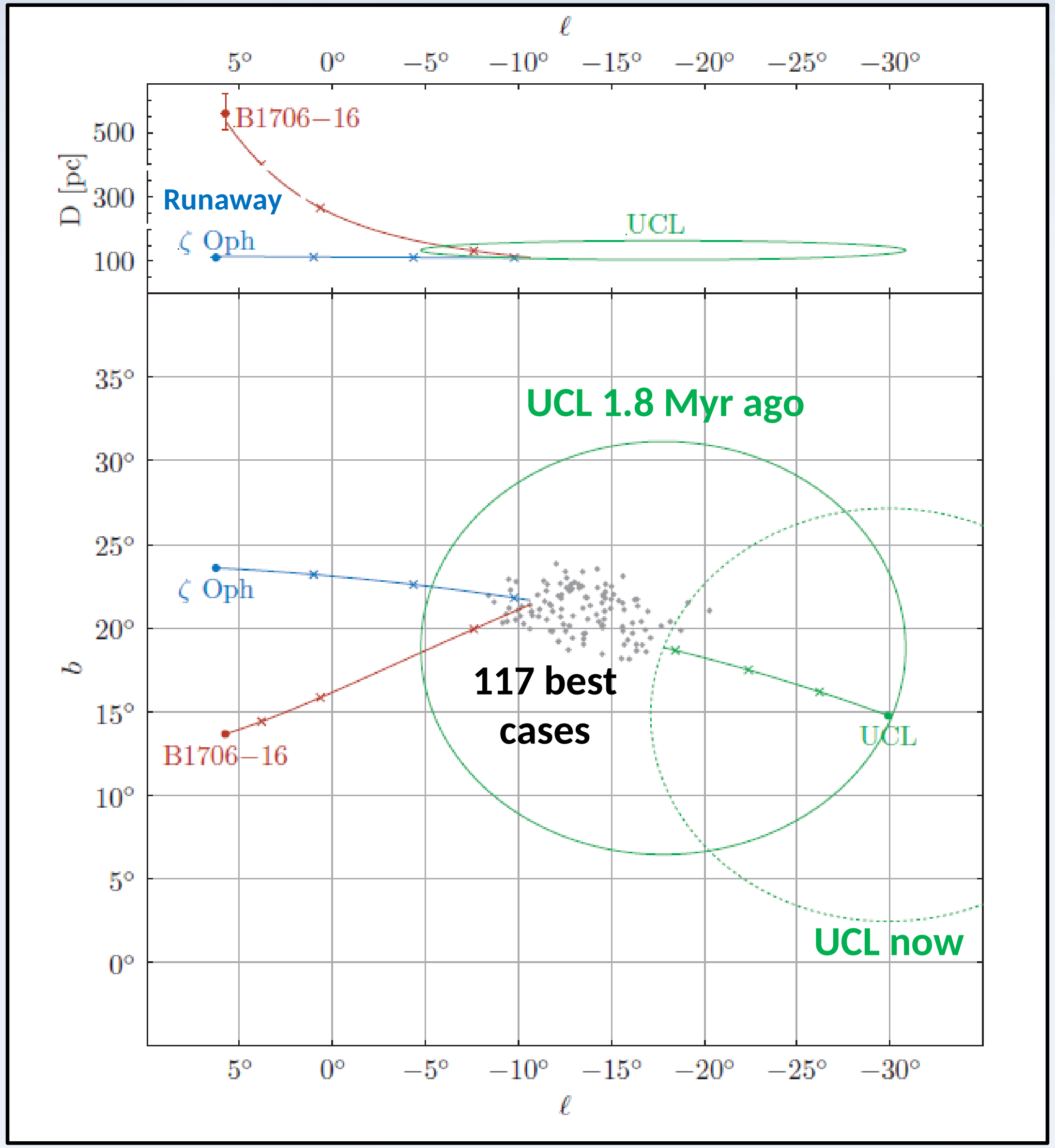
r ~ 110 pc

t ~ 1.8 Myr ago

SN-nucleosynthesis test (M_{ej}) possible, if Uptake U would be known

(Fluence F and ^{60}Fe lifetime τ known)

Summary



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Outlook:

We will search for more such cases
with new Pulsars and new Gaia-runaway stars

Plus search for High-Mass X-ray binaries (HMXB),
i.e. binaries from a high-mass star
and a compact object (neutron star)
that remained bound after the 1st SN

Search for HMXBs in the Solar Neighborhood

PhD Thesis - Kai-Uwe Michel

- Sample: OB stars within ~160 pc (N=709)

- combining optical and x-ray observations

  optical: Gaia DR3, Gaia DR2, HIP, 2MASS

  X-ray: eROSITA, ROSAT, XMM-Newton, Chandra, Einstein, Uhuru

- photometric analysis, determination of bolometric luminosity L_{bol}

- calculation of characteristic property: L_X/L_{bol}

preliminary results:

several candidates with high L_X/L_{bol} could be identified from the sample

current steps:

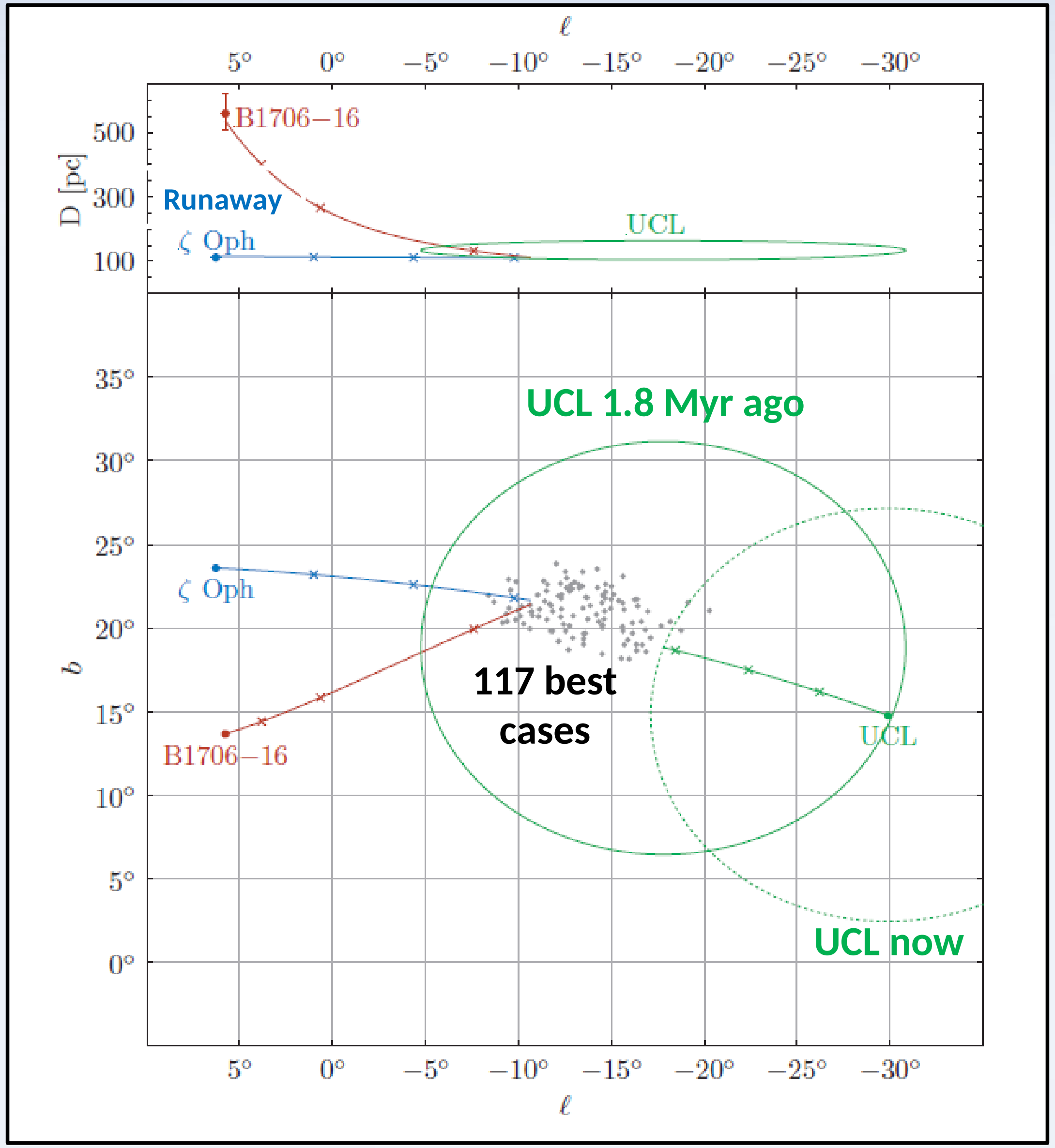
- detailed analysis of all available X-ray data

- to check for characteristics like pulsations or a non-thermal spectrum

- high angular resolution IR AO observations to identify close young low-mass companions to the targets

- spectroscopic observation and RV measurement for further potential candidates

Summary



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