A pulsar-helium star compact binary system formed by common envelope evolution



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Background: NS+He star

- In binary systems, He star can be formed via

① Roche lobe overflow (RLO)

② Common envelop (CE) evolution

Rapid orbital decay in $\lesssim 10^3$ yr

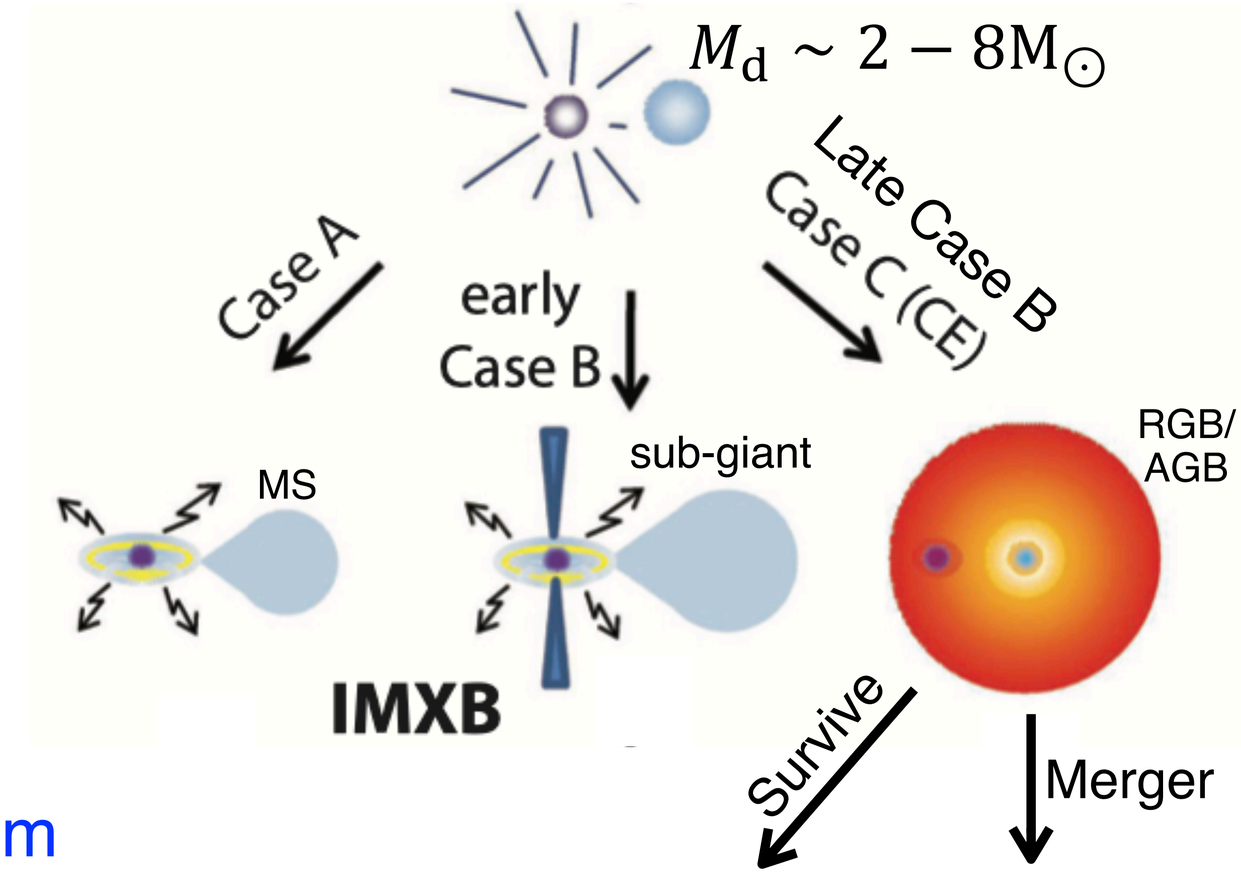
- Short-lived system

→ Rare in nature, no confirmed system

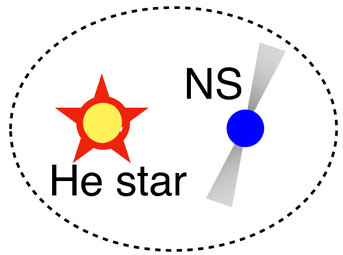
- Progenitor of IMBP, DNS…

→ Important for binary evolution

T. M. Tauris, 2011

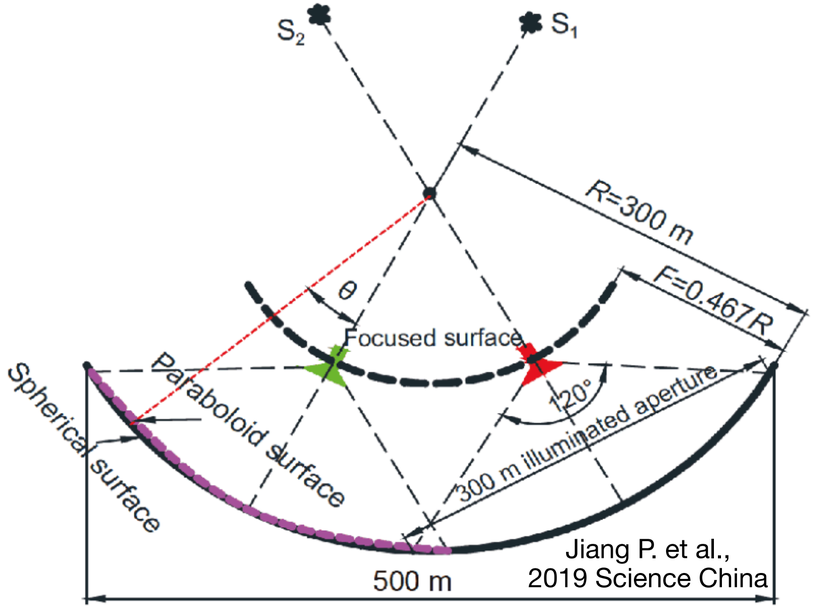


How to detect?
He star: optical
NS: X/γ-ray/radio

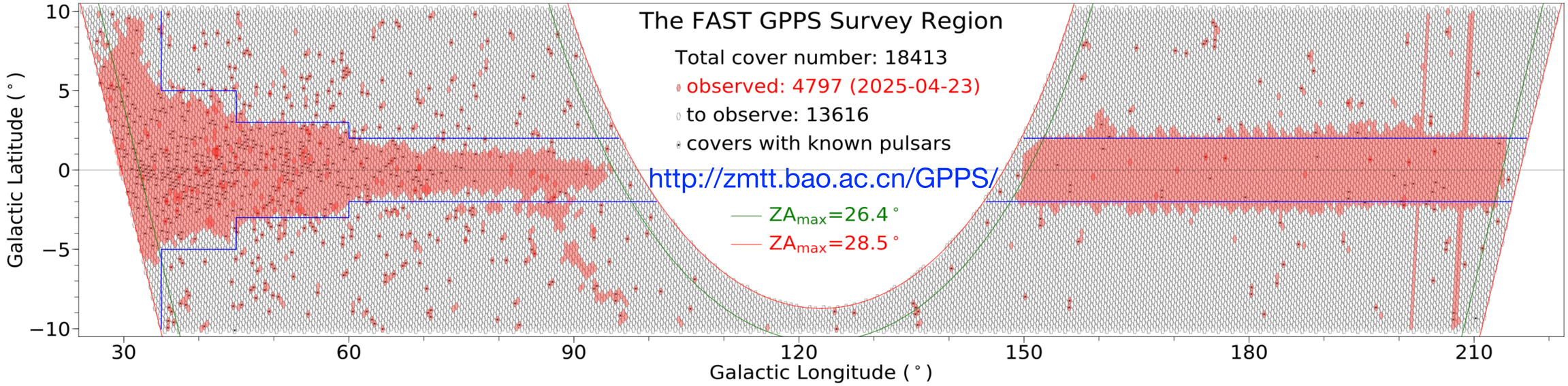




Background: FAST GPPS survey

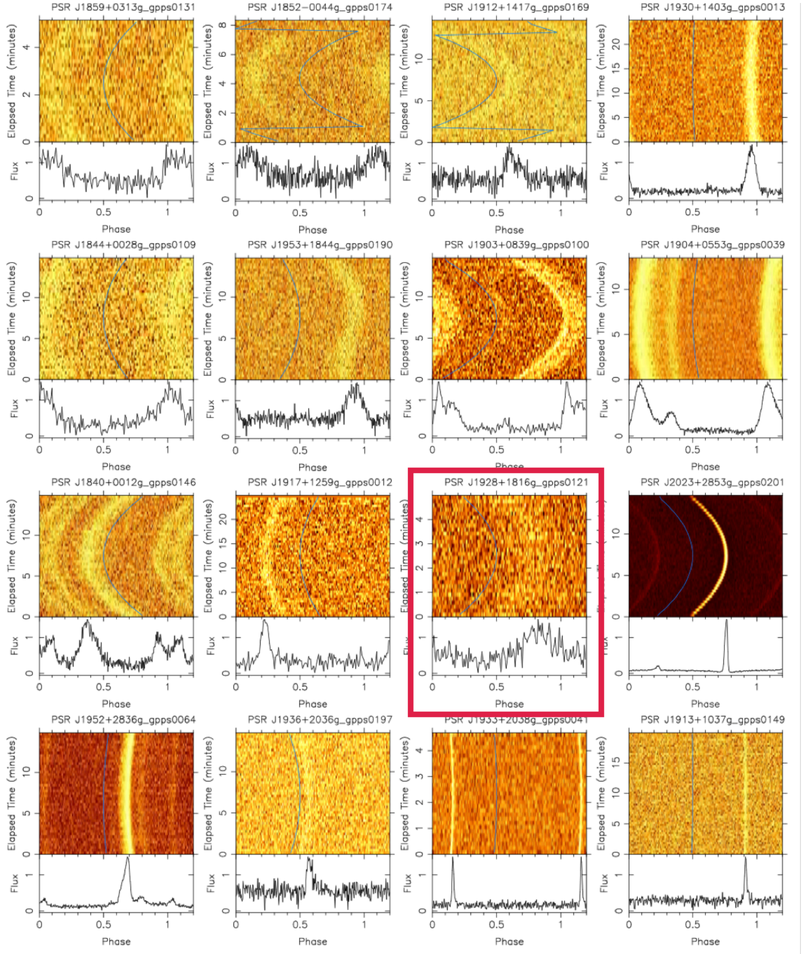


- FAST is the most sensitive radio telescope, excellent tool for pulsar research
- FAST GPPS survey FAST sky & $gb \pm 10°$
  769 new pulsars ~160 in binaries
- Many unique binary pulsars!

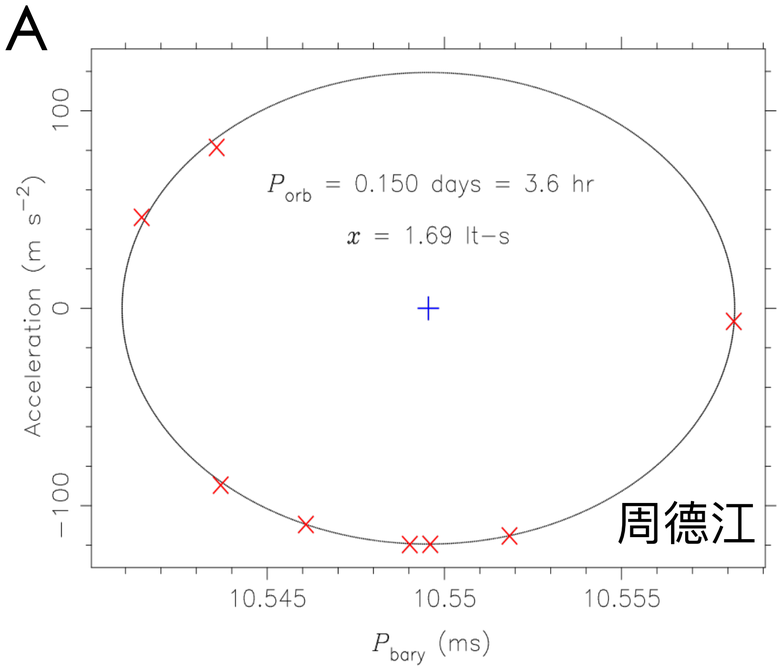


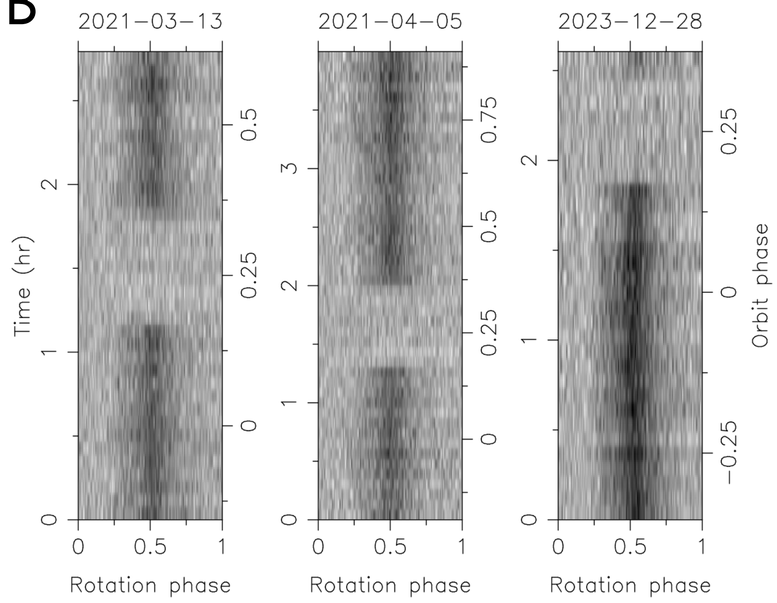
The discovery of PSR J1928+1815

binary pulsars discovered by FAST GPPS survey



Han J.L. et al., 2021 RAA





A. Fitting barycentric P and orbital acceleration Acc

$P = 10.55$ ms, $P_{\rm orb} = 3.6$ hr, $x = 1.7$ lt–s

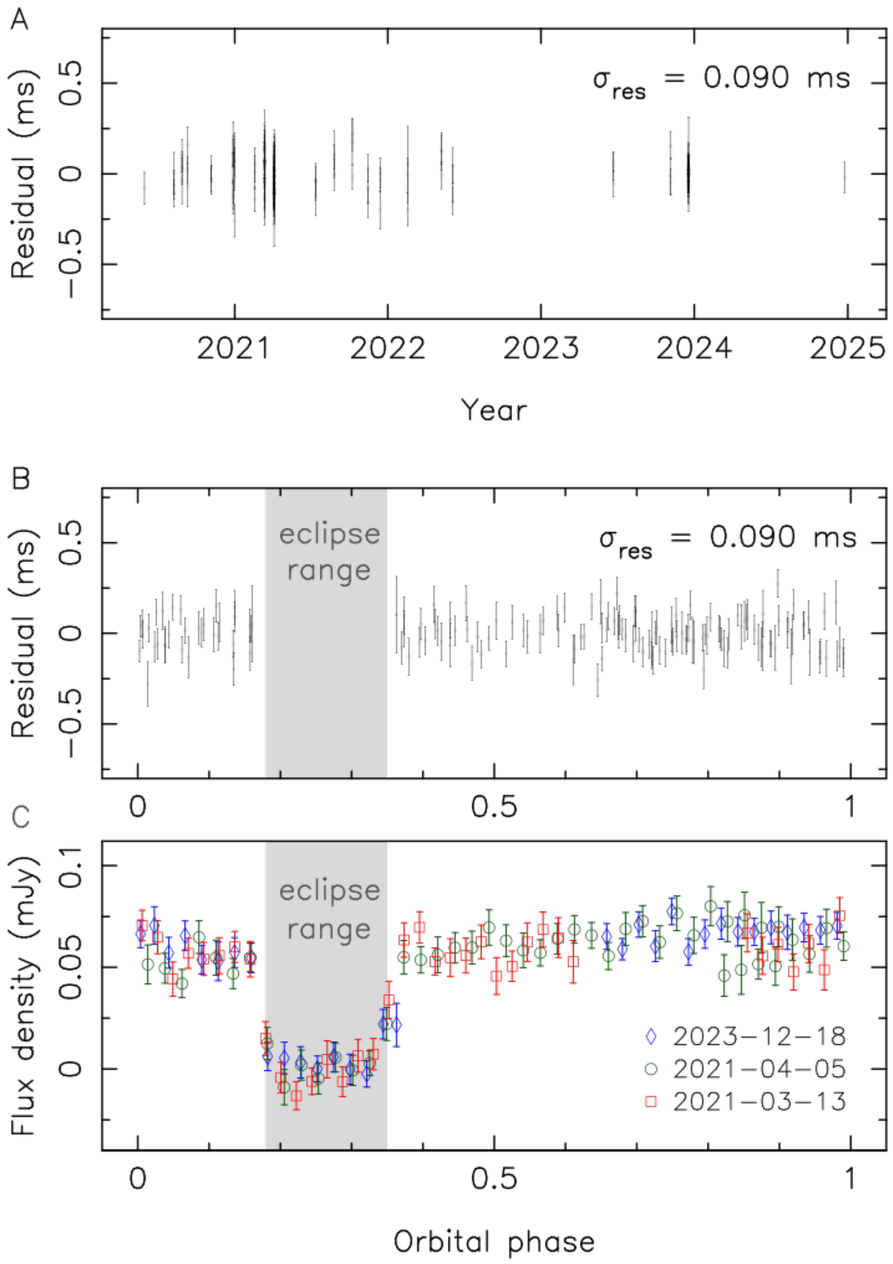
B. The pulsar is regularly eclipsed for 17% of its orbital period

→companion not compact object

Yang Z.L. et al., 2025, Science

Timing result of PSR J1928+1815

Parameter	Value
Observation date span (MJD)	58999 to 60668
Number of TOAs	152
Reduced χ^2 value	1.296
MJD of period determination	59408
Right ascension, α (J2000 equinox)	$19^h28^m08^s.34901\pm0.00041$
Declination, δ (J2000 equinox)	$+18°15'30''.270\pm0.010$
Spin period, P	$0.0105494989888508\pm0.0000000000000078$ s
Spin period derivative, $\dot{P}$	$(3.63405\pm0.00022)\times10^{-18}$ s s^{-1}
Spin frequency, ν	$94.791231418368\pm0.000000000070$ Hz
Spin frequency derivative, $\dot{\nu}$	$(-3.26534 \pm 0.00020) \times 10^{-14}$ Hz s^{-1}
Spin-down luminosity, $\dot{E}$	1.2×10^{35} erg s^{-1}
Characteristic age, τ_c	46 million years
Dispersion measure, DM	346.158 ± 0.014 pc cm^{-3}
Faraday rotation measure, RM	254.3 ± 3.0 rad m^{-2}
Orbital period, P_{orb}	$0.14990246322\pm0.00000000028$ days
Rate of change of orbital period, $\dot{P}_{orb}$	$(-4.3 \pm 4.5) \times 10^{-13}$ s s^{-1}
Projected semi-major axis, x	1.698628 ± 0.000020 light-seconds
Rate of change of x, $\dot{x}$	$(1.9 \pm 3.8) \times 10^{-13}$ light-seconds s^{-1}
Time of ascending node passage, T_{asc} (MJD)	$59211.18761057\pm0.00000024$
First Laplace parameter, $\epsilon_1 = e \sin\omega$	$(-0.4\pm1.8)\times10^{-5}$
Second Laplace parameter, $\epsilon_2 = e \cos\omega$	$(0.7\pm1.5)\times10^{-5}$
Mass function	$0.2341854\pm0.0000074\ M_\odot$
Coalescence time, τ_{GW}	0.26 billion years



Constraint on the companion's mass and radius

A. From mass function

$$\frac{(M_{\rm c}\sin i)^3}{(M_{\rm p}+M_{\rm c})^2}=\frac{4\pi^2}{G}\frac{x^3}{P_{\rm orb}^2}=0.2342\ M_\odot$$

$$\Rightarrow M_{\rm c}>1.0\ M_\odot$$

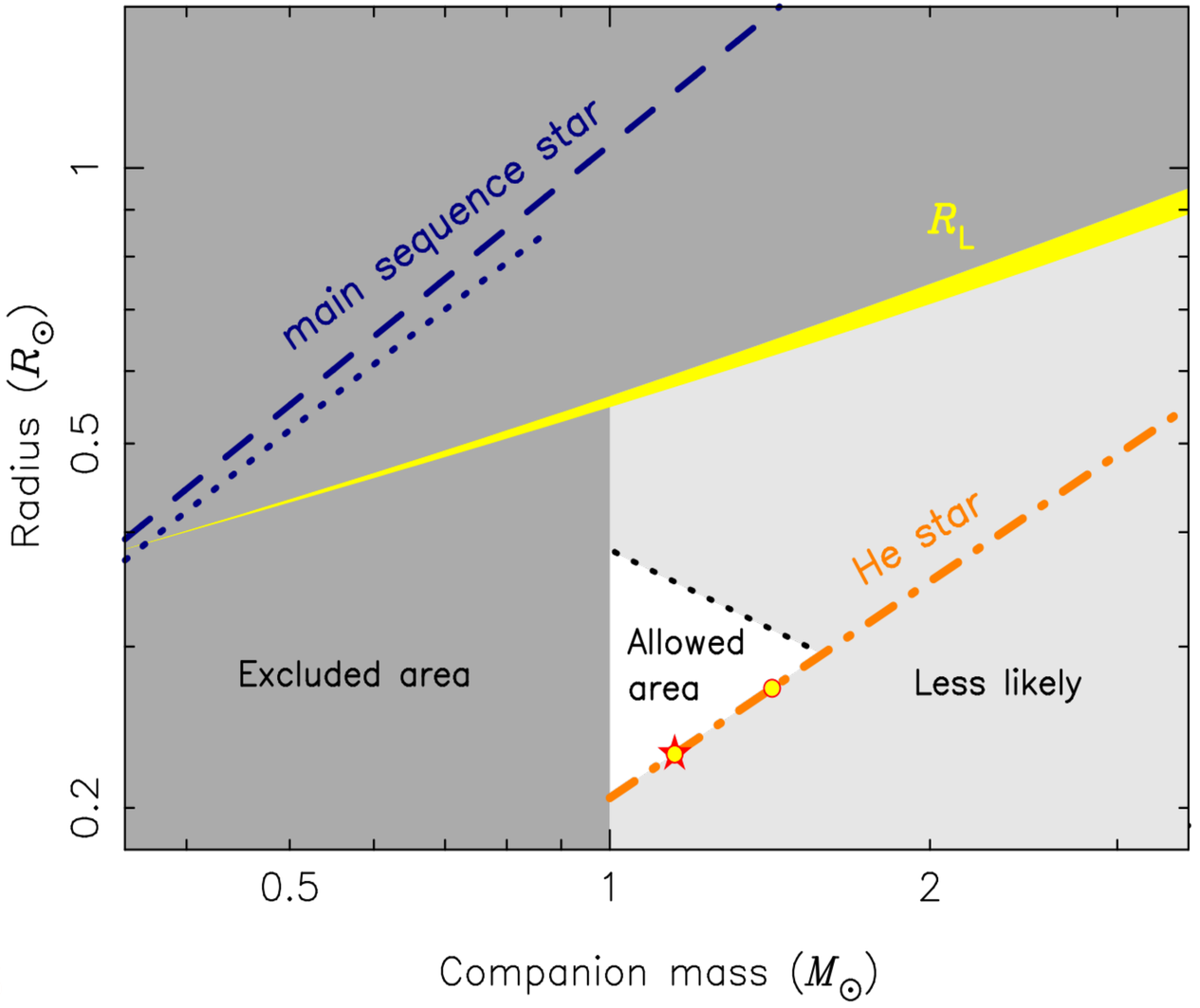
left dark grey area is excluded

B. From Roche lobe size

$$R_{\rm c}<R_{\rm L}=a\times\frac{0.49q^{2/3}}{0.6q^{2/3}+\ln(1+q^{1/3})}$$

upper dark grey area is excluded

PSR J1928+1815' companion size is smaller than a MS, larger than a WD/NS



Yang Z.L. et al., 2025, Science（景威聪）

Nature of PSR J1928+1815's companion

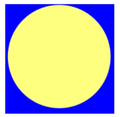
$R_c > R_L$



MS

Size too large
no radio pulsar

A stripped star with
little/no H envelope



proto-WD

$\sim 10^4$ yr shrink rapidly

short timescale



He star

10^4 yr core C burning
10^7 yr core He burning

probable case

First pulsar-He star system
Formed by common envelope evolution

$R_c \ll R_L$



WD



NS

Size too small
no long eclipse

Yang Z.L. et al., 2025, Science

Formation history and future evolution

▶Formation history:

- NS+intermediate-mass star
- At RGB stage, companion expands and starts RLO mass transfer
- CE evolution initiates

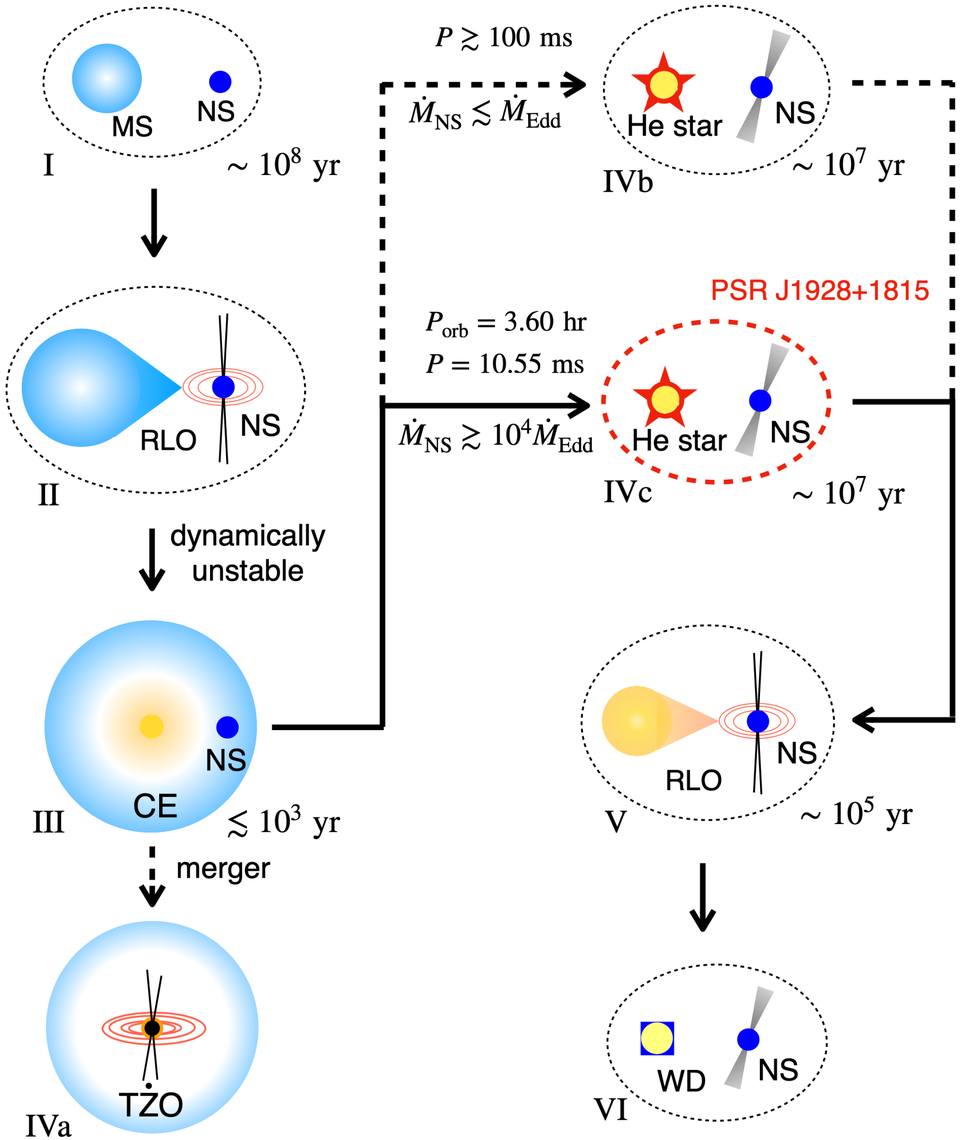
▶Future companion：

- $M_{\rm He} > 2.8\ M_\odot$ (less likely)

  Companion becomes an NS

- $M_{\rm He} < 2.8\ M_\odot$ (probably)

  Companion becomes a WD



Yang Z.L. et al., 2025, Science(葛宏伟、王博、李陆瀚)

Stellar population synthesis

Under different common envelope efficiency and kick velocities

The number of similar systems ($P_{\rm orb} = 0.1 - 0.2$ days; $M_{\rm He} = 1 - 2\ M_{\odot}$)

is only several dozen in our Galaxies

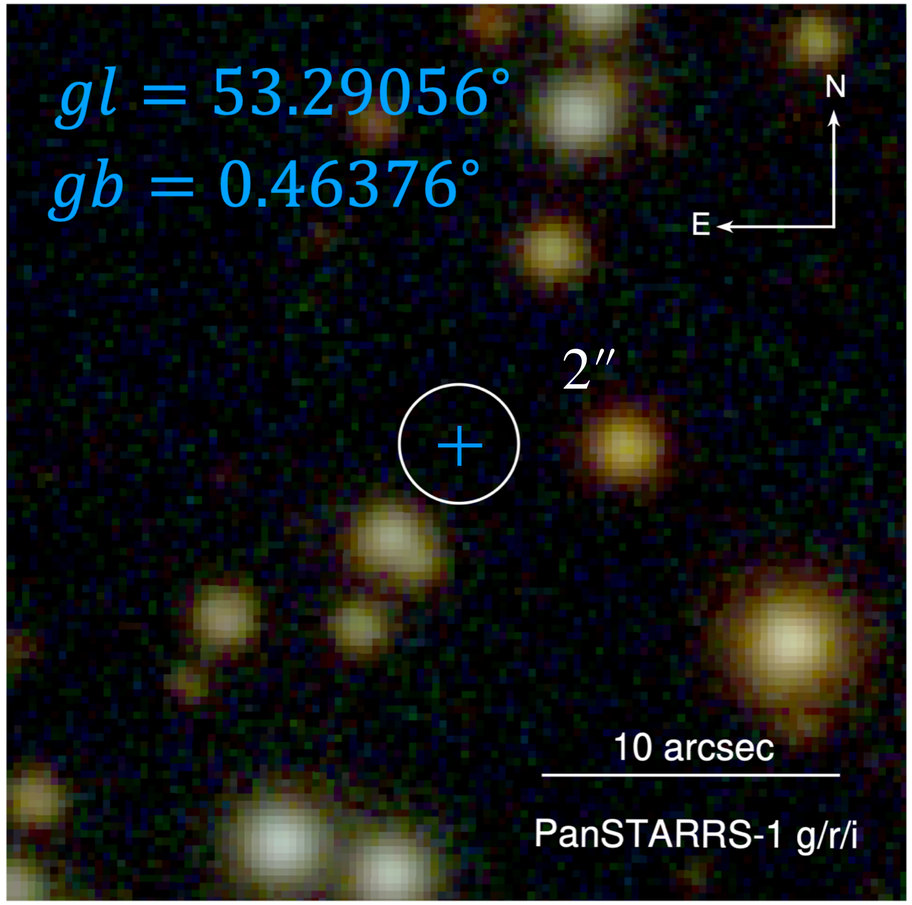
Model	$\alpha_{\rm CE}$	$V_{\rm CC}$ ($\rm km\,s^{-1}$)	$V_{\rm EC}$ ($\rm km\,s^{-1}$)	Formation rate ($10^{-6}\rm yr^{-1}$)	Binary Number helium star	Binary Number proto-white dwarf
A	0.3	265	40	3.4	41	0.017
B	0.3	265	80	1.5	19	0.007
C	0.3	320	80	1.3	16	0.007
D	1.0	265	40	7.2	84	0.035
E	1.0	265	80	3.8	45	0.019
F	1.0	320	80	3.3	39	0.016
G	3.0	265	40	5.8	62	0.030
H	3.0	265	80	3.3	38	0.017
I	3.0	320	80	3.0	33	0.015

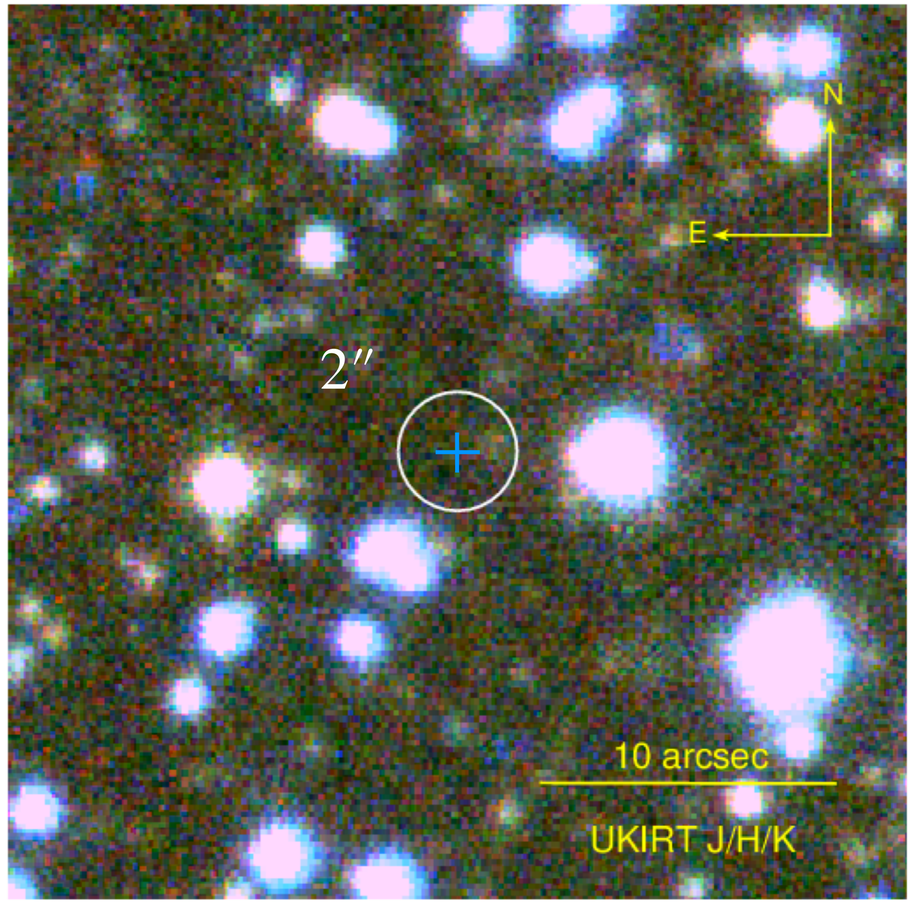
Yang Z.L. et al., 2025, Science(邵勇)

Search of the optical counterpart

Far distance $d_{\mathrm{NE2001}} = 9.7\ \mathrm{kpc}; d_{\mathrm{YMW16}} = 7.2\ \mathrm{kpc}$ + Severe extinction

undetectable in available survey image





Yang Z.L. et al., 2025, Science (王松 & 期刊编辑)

Mass constraint from no detection

Assuming $d = 8$ kpc, we obtained $M_{\rm He} < 1.6\ M_{\odot}$ (K band)

Uncertainties: distance、extinction model、
dust formation in ejection envelope…

Parameters	moldeled naked helium stars		modeled stripped helium stars		observed stripped helium stars		extinction in the band	Obs. limits
$M_{\rm He}(M_{\odot})$	1.0	1.6	1.0	1.6	1.0	1.6	···	···
$\log_{10}(L_{\rm He}/L_{\odot})$	···	···	···	···	$2.41^{+0.75}_{-0.77}$	$3.11^{+0.78}_{-0.80}$	···	···
$T_{\rm eff}$ (kK)	50	63	43	53	31^{+13}_{-14}	42^{+19}_{-19}	···	···
g (mag)	17.2	16.1	16.4	15.5	$15.81^{+0.47}_{-0.44}$	$14.94^{+0.35}_{-0.35}$	17.7	23.3
r (mag)	17.7	16.6	16.9	16.0	$16.24^{+0.36}_{-0.34}$	$15.41^{+0.27}_{-0.27}$	13.2	23.2
i (mag)	18.1	17.0	17.3	16.4	$16.60^{+0.30}_{-0.28}$	$15.79^{+0.22}_{-0.22}$	9.9	23.1
z (mag)	18.4	17.4	17.6	16.7	$16.91^{+0.25}_{-0.23}$	$16.1^{+0.19}_{-0.16}$	7.8	22.3
y (mag)	18.7	17.6	17.9	17.0	$17.15^{+0.22}_{-0.21}$	$16.36^{+0.16}_{-0.16}$	6.4	21.4
J (mag)	18.1	17.0	17.3	16.4	$16.56^{+0.19}_{-0.17}$	$15.78^{+0.14}_{-0.13}$	4.0	19.9
H (mag)	18.2	17.2	17.4	16.5	$16.66^{+0.14}_{-0.13}$	$15.90^{+0.10}_{-0.10}$	2.4	19.0
K (mag)	18.3	17.3	17.5	16.6	$16.75^{+0.10}_{-0.10}$	$16.00^{+0.08}_{-0.08}$	1.5	18.8

最佳限制 **Yang Z.L.** et al., 2025, Science（陈文聪 & 侯立刚 & 陈丙秋）

Pulsar recycling of PSR J1928+1815

- Spin period P & accreted mass $\Delta M_{\rm NS}$

$$\Delta M_{\rm NS} \gtrsim 0.22 M_\odot \times \frac{(M_{\rm p}/M_\odot)^{1/3}}{(P/{\rm ms})^{4/3}}$$

- $P = 10.55{\rm ms}$, $\Delta M_{\rm NS} \gtrsim 0.01\ M_\odot$
- Gravitational potential→photons

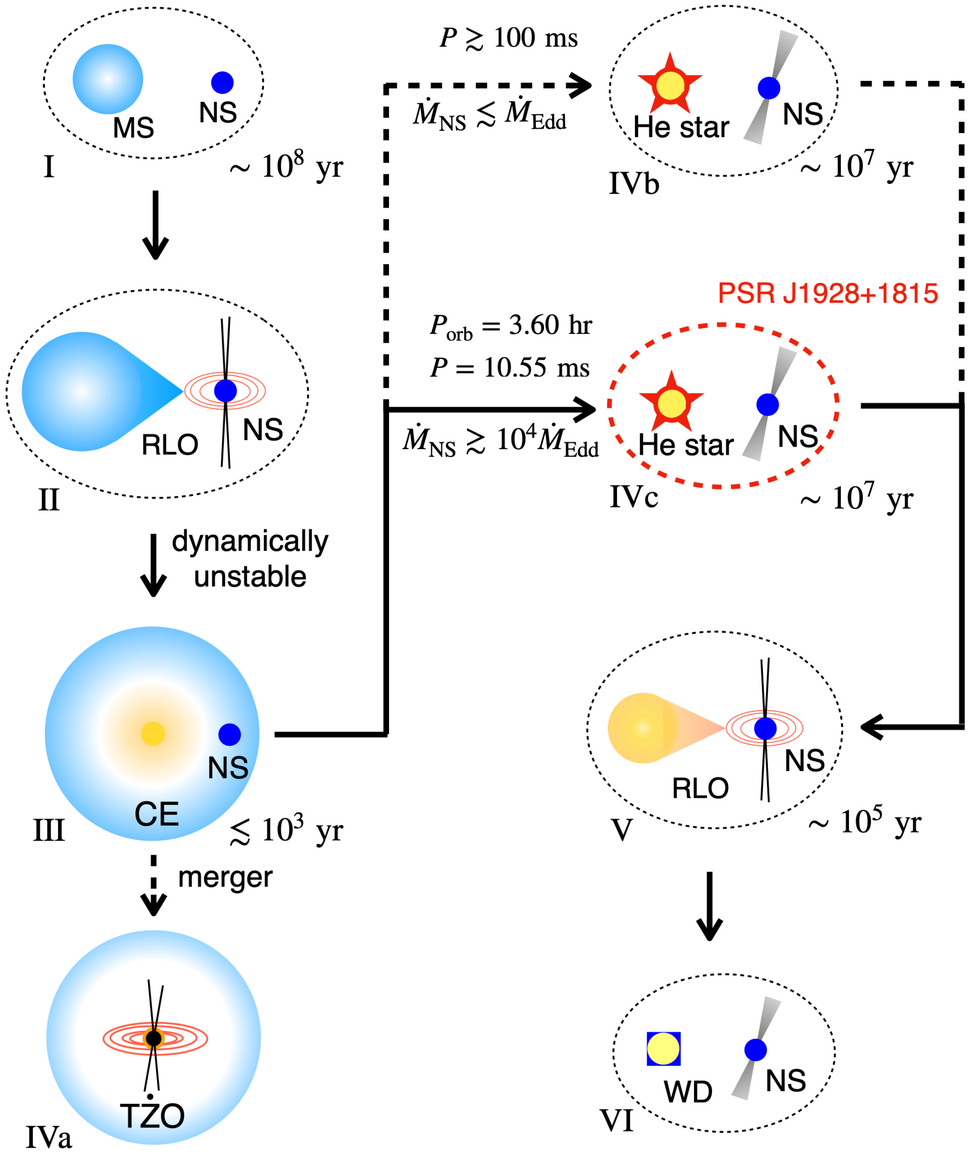
$$\dot{M}_{\rm NS} \lesssim \dot{M}_{\rm Edd} \sim 10^{-8} M_\odot {\rm yr}^{-1}$$

Require $\gtrsim 10^6$yr MT time

- Gravitational potential→neutrinos

$$\dot{M}_{\rm NS} \gtrsim 10^4 \dot{M}_{\rm Edd} \sim 10^{-4} M_\odot {\rm yr}^{-1}$$

Require dense environment



Emission geometry of PSR J1928+1815

During RLO (Biryukov, 2021)

$\zeta - i$ gose to $0°$ & $\alpha \uparrow$

But PSR J1928+1815 has:

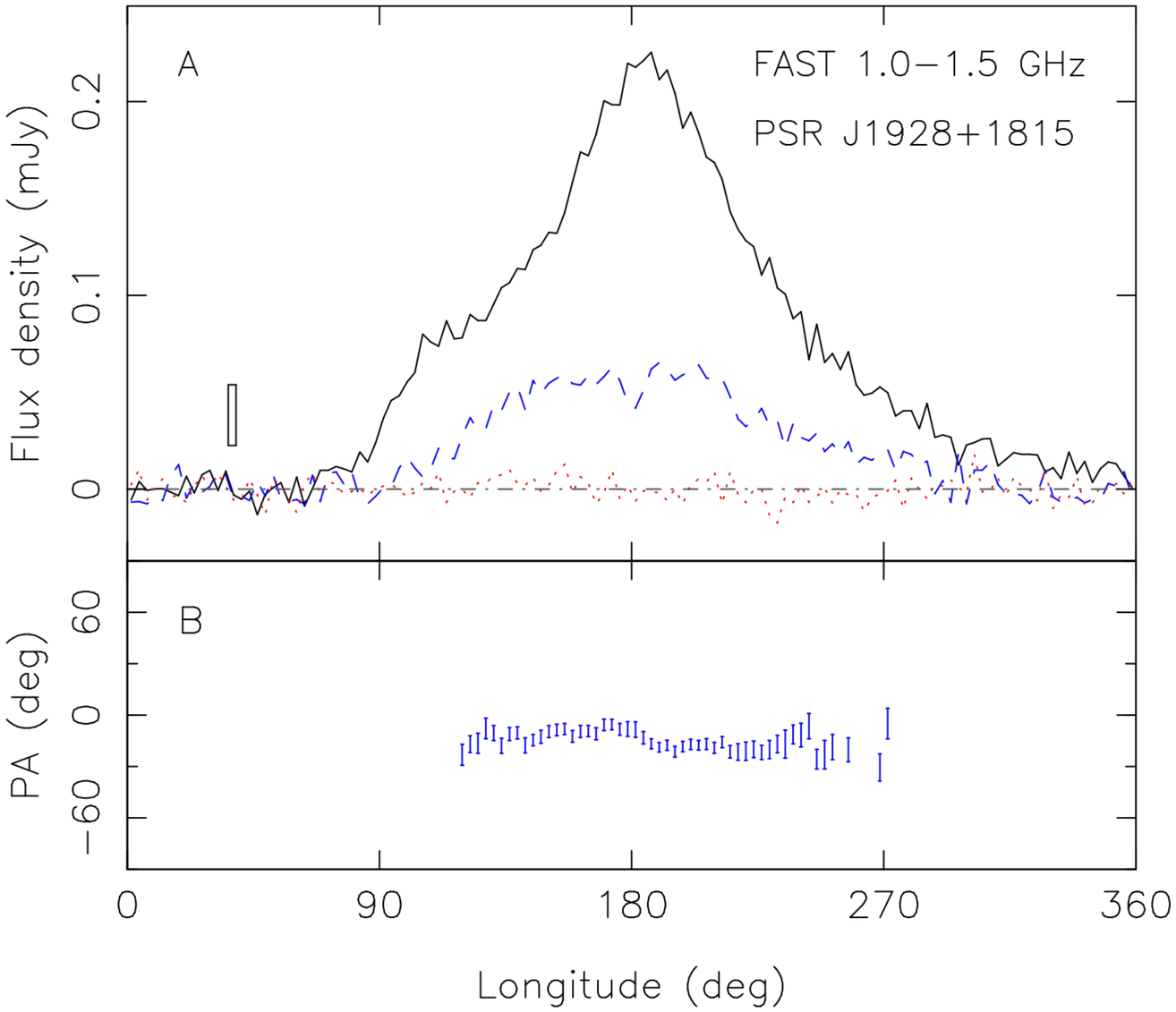
A. Wide total intensity profile

B. Flat P.A. curve, in RVM model

$$\left(\frac{d\psi}{d\phi}\right)_{\max} = \frac{\sin\alpha}{\sin\beta} \ll 1 \ (\alpha + \beta \equiv \zeta)$$

→ small α, ζ & $\alpha \ll \zeta$

Unique mass accretion?



Yang Z.L. et al., 2025, Science（刘继峰）

Summary

- PSR J1928+1815 is an eclipsing MSP discovered in FAST GPPS survey. Probably its companion is a helium star.
- Direct product of CE evolution, progenitor of NS+WD system. Only several dozen similar systems in Galaxy.
- The optical/infrared counterpart is undetectable due to a large distance and severe extinction.
- Observational evidence for CE evolution channel of binary pulsar formation.
- Constrain the mass accretion during CE phase.

Thanks!