Ejected thermonuclear-supernova survivors in *Gaia*

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In collaboration with:

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Expanding the Gaia legacy: the role of Spanish ground-based facilities
Barcelona, 18/02/2020

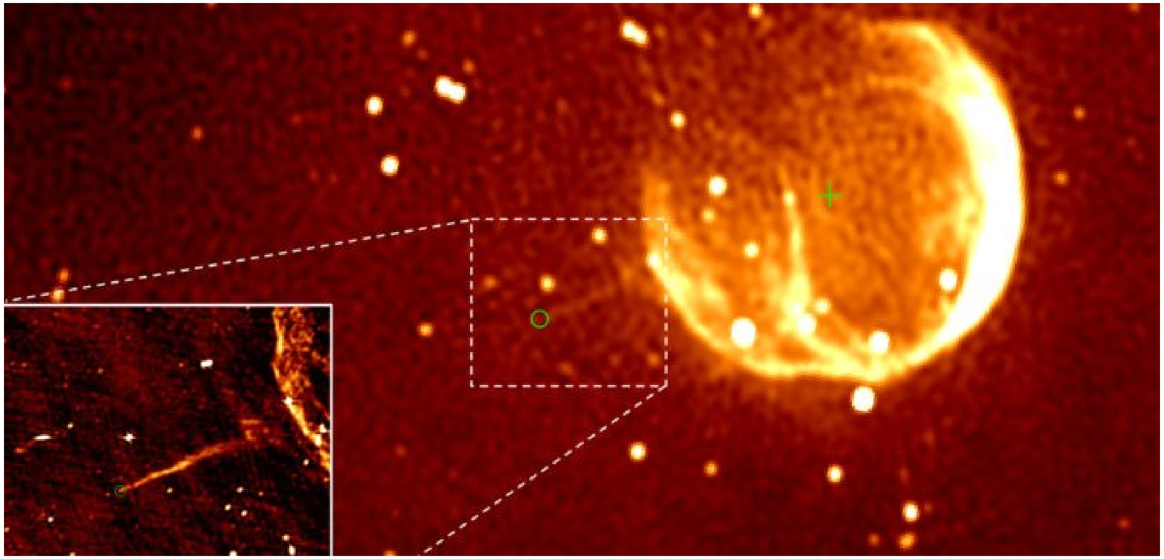
Key motivations

- Kinematically peculiar white dwarf-related stars are likely messengers of some of the most violent phenomena in nature (i.e. thermonuclear supernovae)
- Spectroscopic and kinematic analysis can help to constrain their formation mechanisms and past history

Fast(est) runaway or hyper-runaway stars via binary ejection mechanism

Core-collapse supernovae: neutron star + companion both runaways

(Blaauw 1961; Tauris 2015, MNRAS, 448, 6)



(Schinzel et al. 2019, ApJL, 876, L17)

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(Blaauw 1961; Tauris 2015, MNRAS, 448, 6)

If mass loss ≥ ½ total mass of binary (Hills 1983)

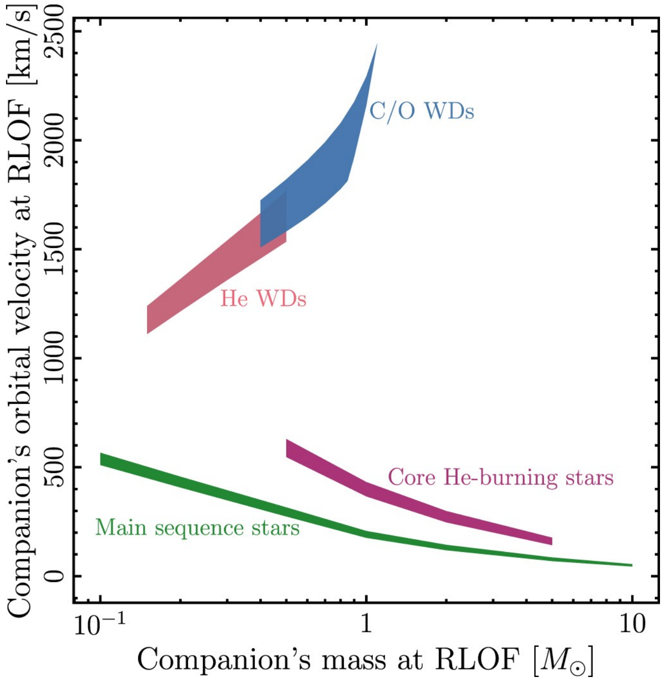
$$\langle(\Delta M/M_0)_{min}\rangle 0.5 \times [1 - (V_{kick}/V_{circular})^2]$$

Ejection velocity = orbital velocity ± other effects
(kick, interaction with ejecta…)

Fast(est) runaway or hyper-runaway stars via binary ejection mechanism

Thermonuclear supernovae (Type Ia): ejected donor star

(Justham et al. 2006, A&A, 493, 1081; Wang & Han 2009, A&A, 508, 27)

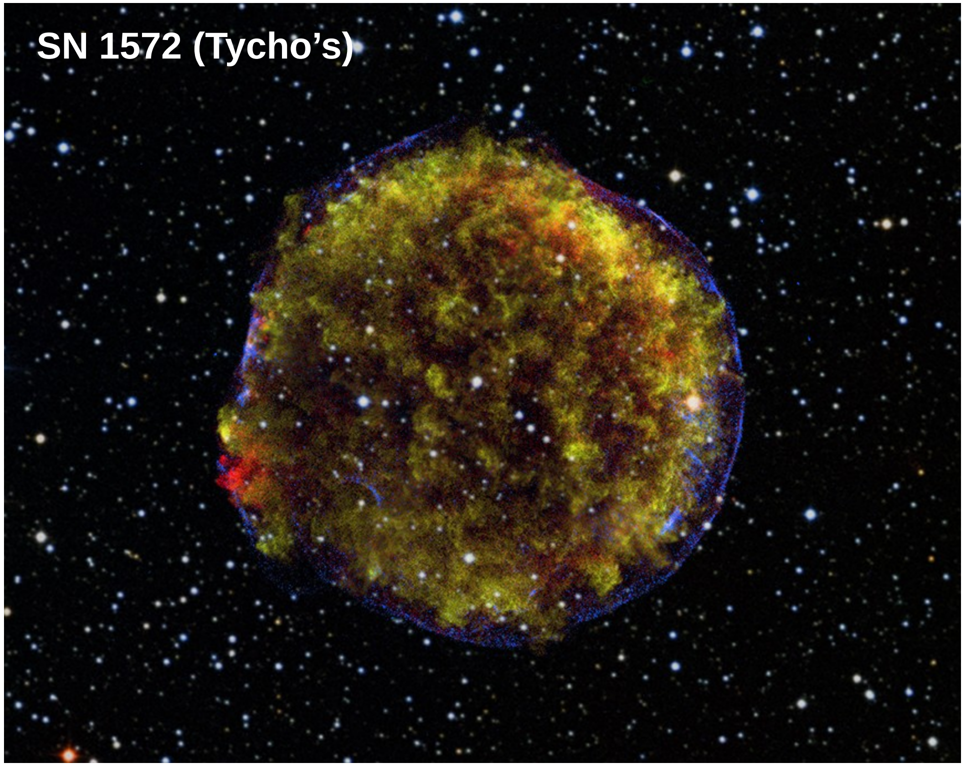


(Shen et al. 2018, ApJ, 865, 15)

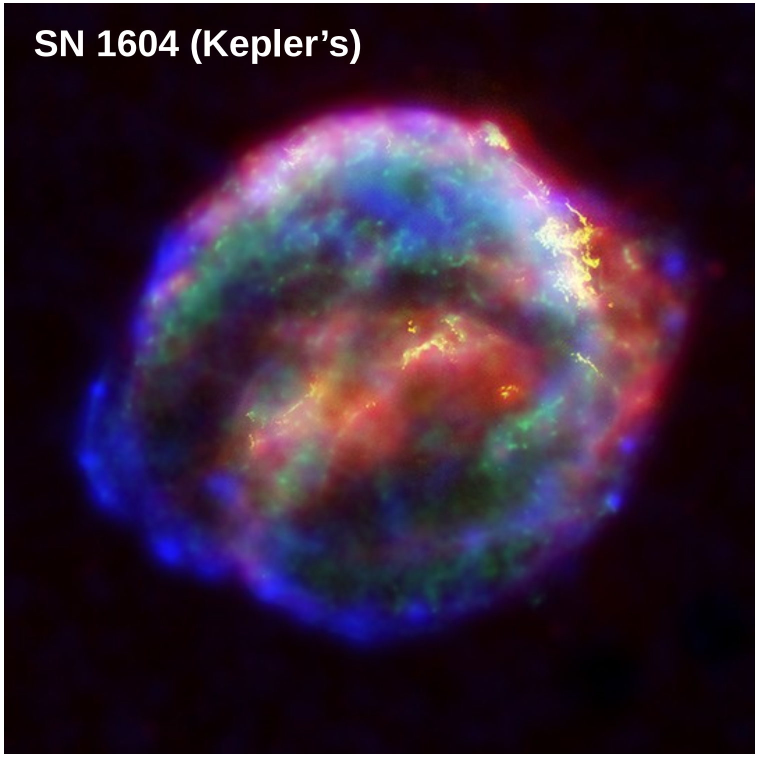
Fast(est) runaway stars formed via the binary ejection mechanism

Galactic supernova remnants

No clear evidence of surviving non-degenerate donor stars



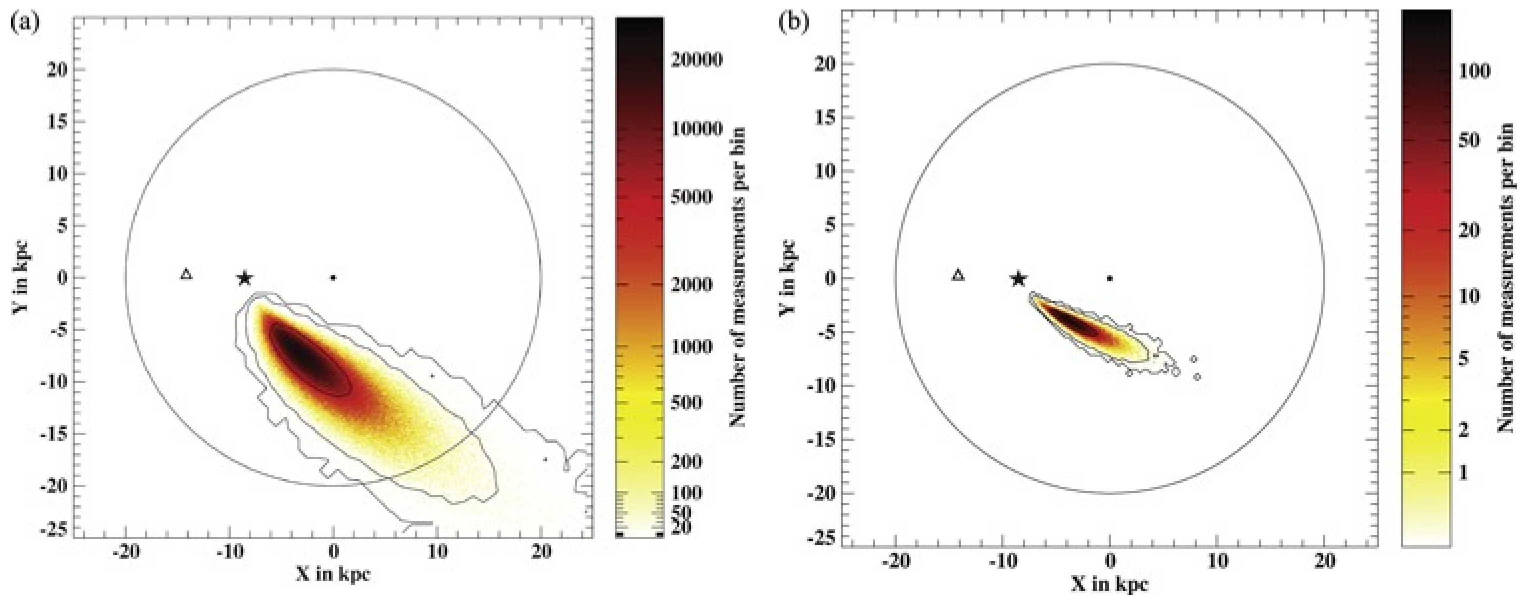
Williams et al. (2016), ApJL, 823, L32



(Credit: NASA/ESA/JHU/R.Sankrit & W.Blair)

Fast(est) runaway or hyper-runaway stars via binary ejection mechanism

Type Ia supernova hot subdwarf donor
US 708 (Geier et al. 2015, Sci, 347, 1126)

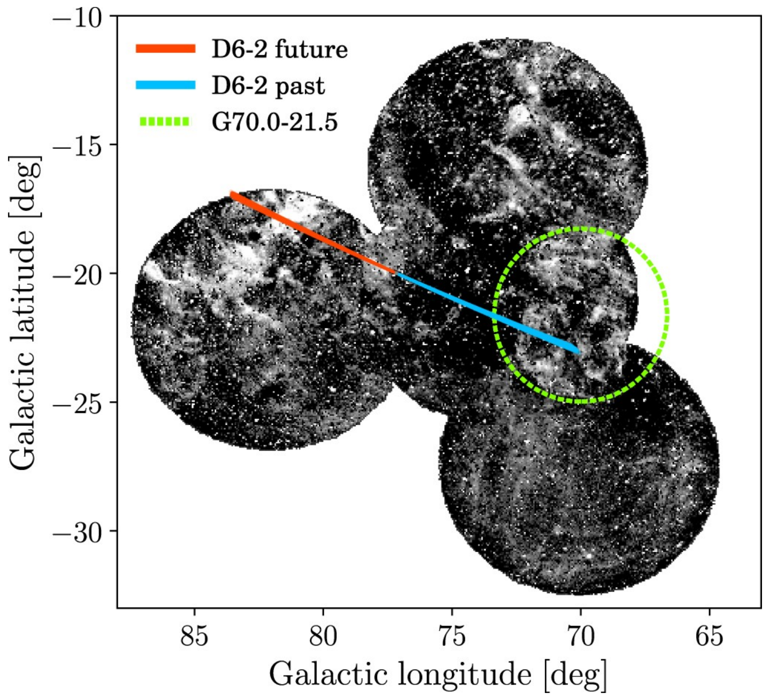


Fast(est) runaway stars formed via the binary ejection mechanism

Type Ia supernova white dwarf donors

D^6 stars (Shen et al. 2018, ApJ, 865, 15)

discovered with *Gaia* DR2



Fast(est) runaway stars formed via the binary ejection mechanism

Peculiar thermonuclear supernovae:

Partly burnt white dwarf survivor ***("Zombie Stars")*** + donor star both runaway

Fast(est) runaway stars formed via the binary ejection mechanism

Peculiar thermonuclear supernovae:

Partly burnt white dwarf survivor ***("Zombie Stars")*** + donor star both runaway

First example is the star LP 40-365

(Vennes, Nemeth, Kawka et al. 2017, Sci, 357, 680)

(Raddi, Hollands, Koester et al. 2018a, ApJ, 858, 3;
Raddi, Hollands, Gänsicke et al. 2018b, MNRAS, 479, L96)

Now a class of its own including 4 stars

(Raddi, Hollands, Koester et al. 2019, MNRAS, 489, 1489)

Peculiar thermonuclear supernovae

Supernova Type Iax
(2002-cx; Li et al. 2003; Jha et al. 2006; Foley et al. 2013)

- **Observations:**
  - lower-luminosity
  - slow ejecta velocity
  - association to young disc population
  - 10% of thermonuclear supernovae
  - surviving remnant?

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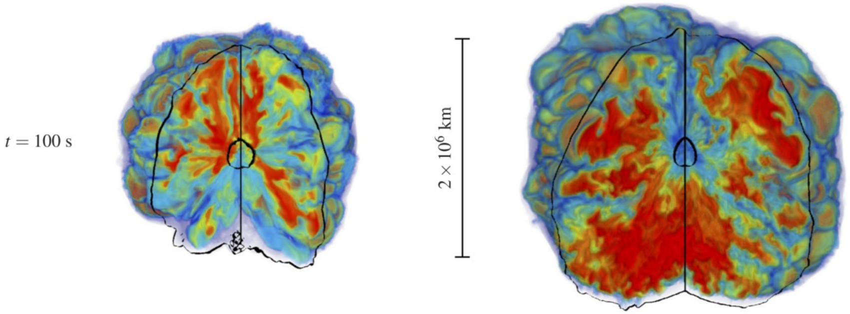


- **Theory:**
  - Pure deflagration of near Chandrasekhar mass CO (or hybrid CONe) white dwarfs
  - single-degenerate binary with He-burning donor
  - **surviving remnant** (partial C-, O-, Si-buring)
  - large kicks (?)
  - binary may or may not be disrupted

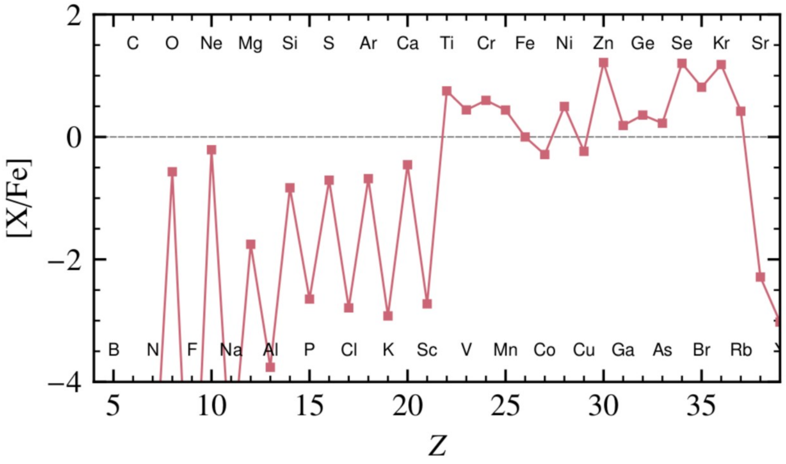
(Wang et al. 2013; Jordan et al. 2012; Kromer et al. 2013; Fink et al. 2014; Kromer et al. 2015, Shen & Schwab 2017; Zhang et al. 2019, Bauer et al. 2019)

Peculiar thermonuclear supernovae

Thermonuclear Electron-Capture Supernovae (tECSN)

- **Theory:**
  - Pure deflagration of near Chandrasekhar mass ONe white
  - Avoids accretion-induced collapse
  - single-degenerate binary
  - **surviving remnant** (Fe- and Ni-rich)
  - large kicks (?)

(Nomoto & Kondo 1991; Isern et al. 1991; Jones et al. 2016, 2019)



Nuclear reaction yields

Peculiar thermonuclear supernovae

Thermonuclear Electron-Capture Supernovae (tECSN)

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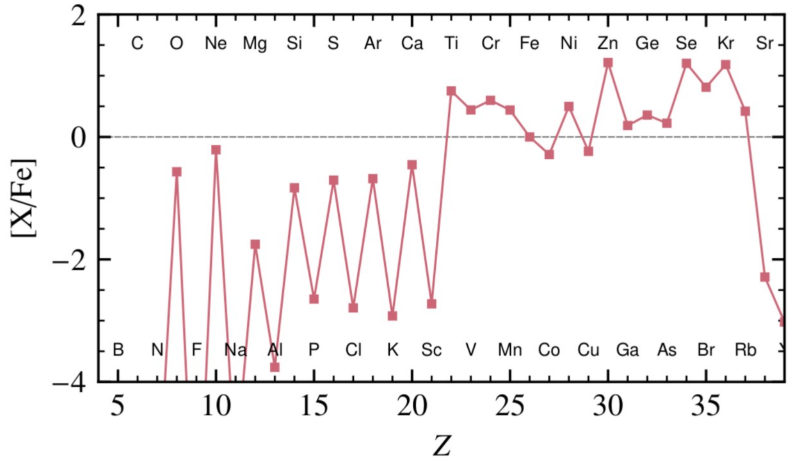
(Nomoto & Kondo 1991; Isern et al. 1991; Jones et al. 2016, 2019)

- **Observations:**
  - Ambiguous identification
  - ONe novae
  - Supernovae Type 1.5?



Nuclear reaction yields

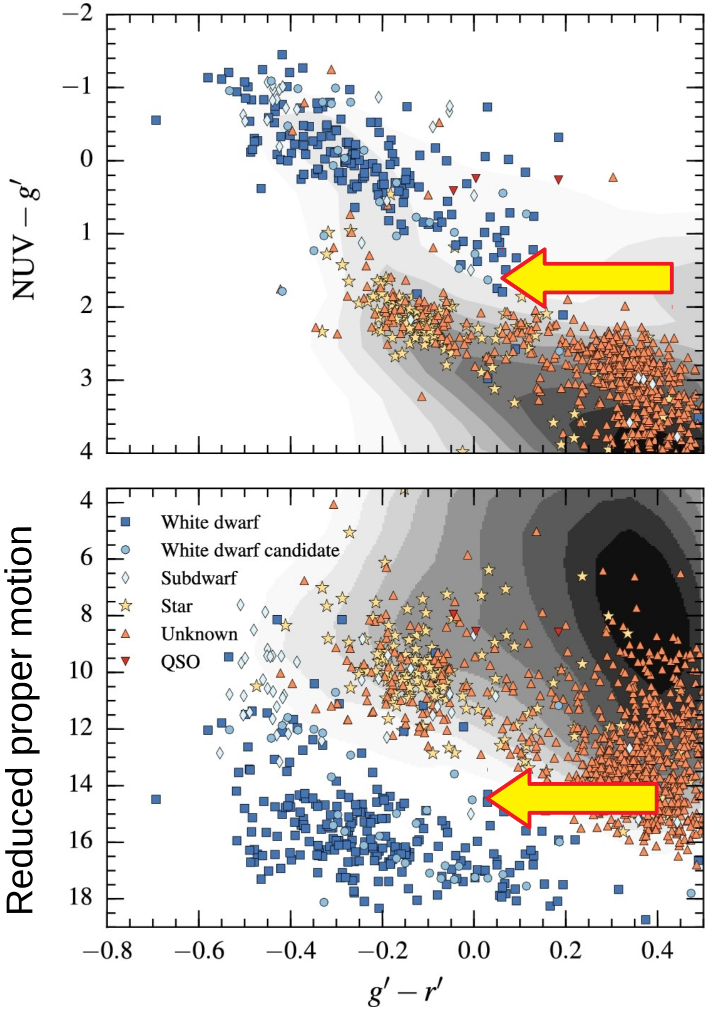
A typical white dwarf candidate

Luyten-Palomar Survey
LP 40-365, Luyten W. J. (1970)

Lowell Observatory
GD 492, Giclas et al. (1970)
White dwarf suspect until 2017

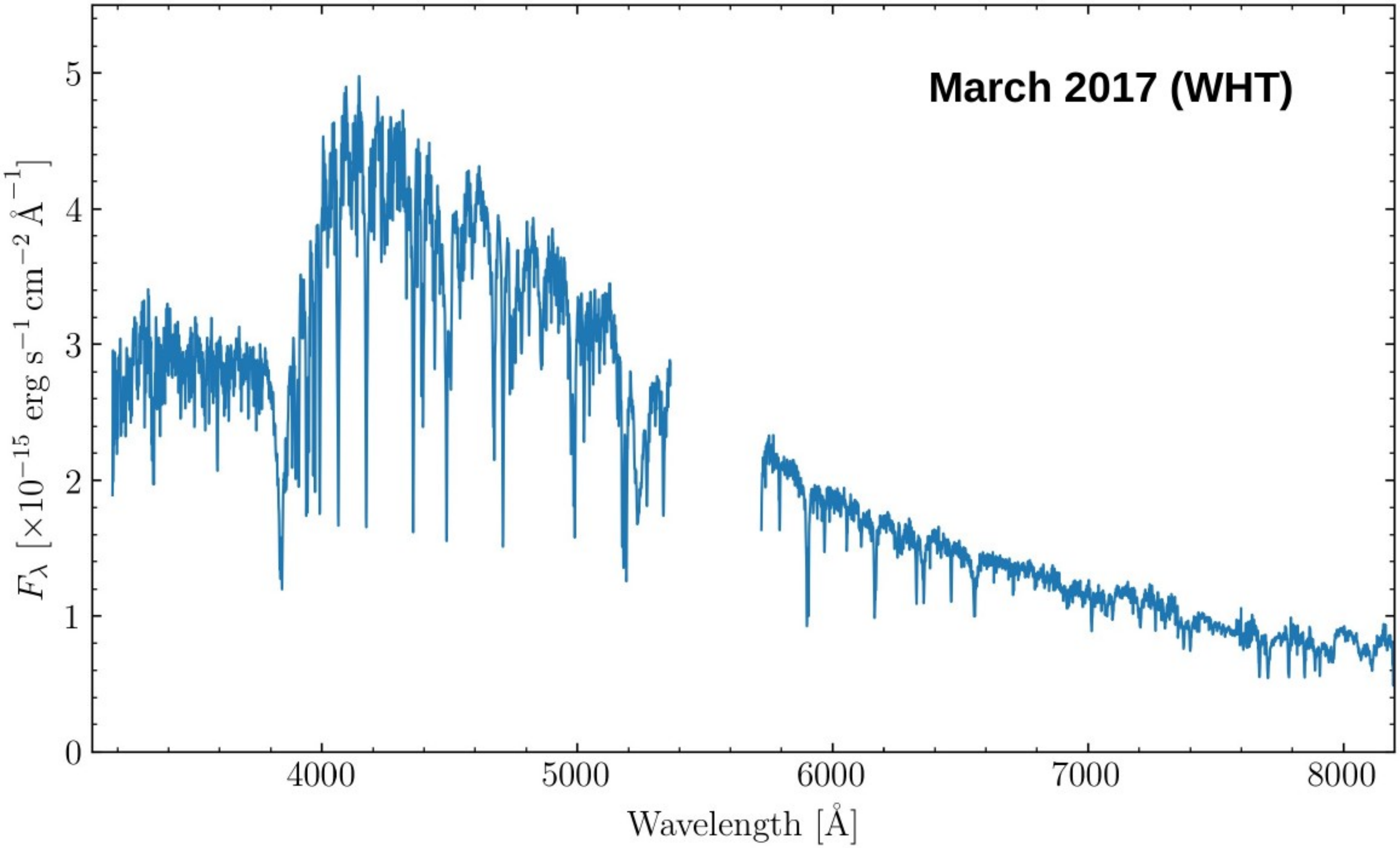
Based on photometric +
proper motion classification only

***Gaia* Data Release 2**
μ = 157 mas/yr



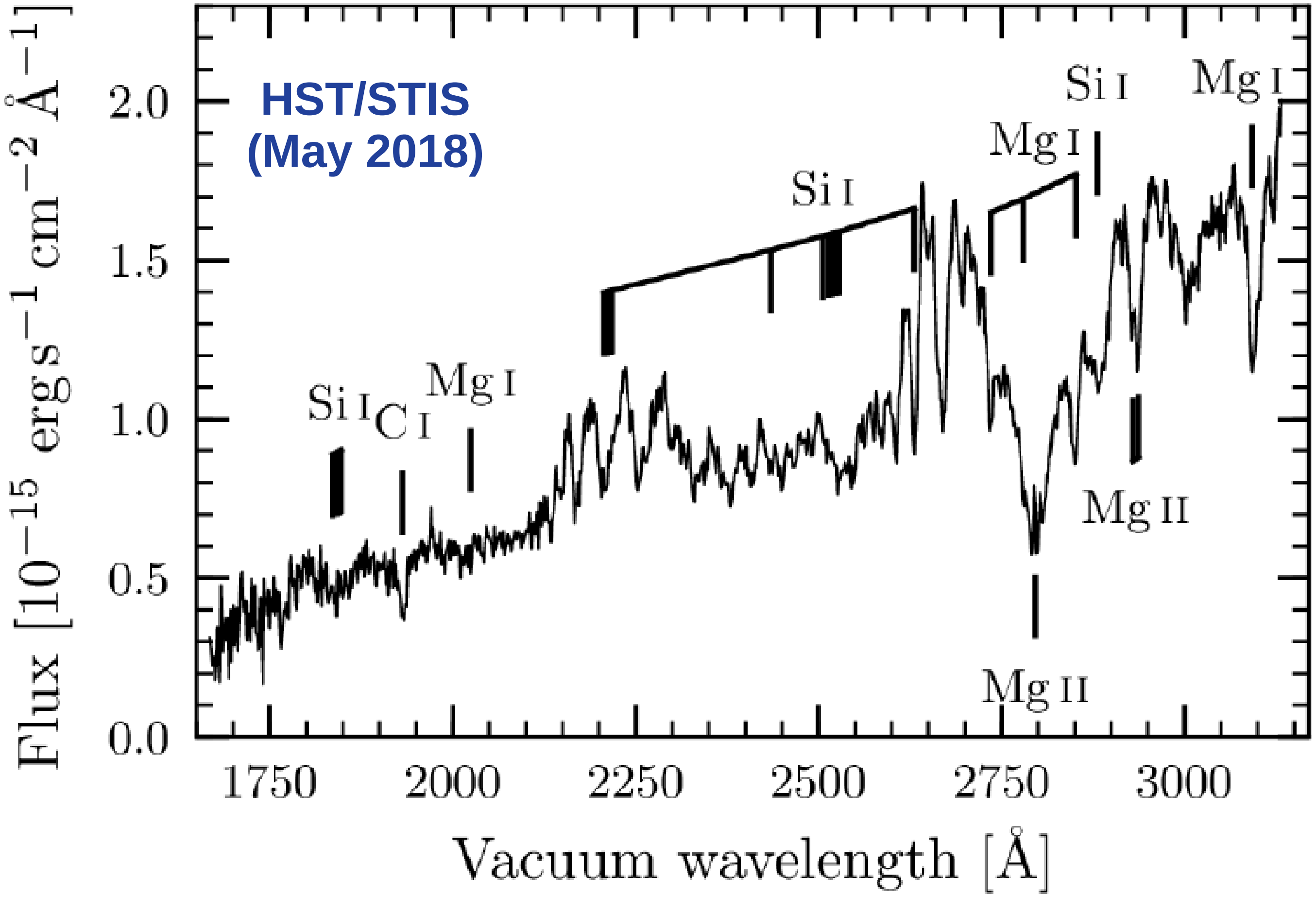
Raddi et al. (2017), MNRAS 472, 4173

A unique spectral appearance



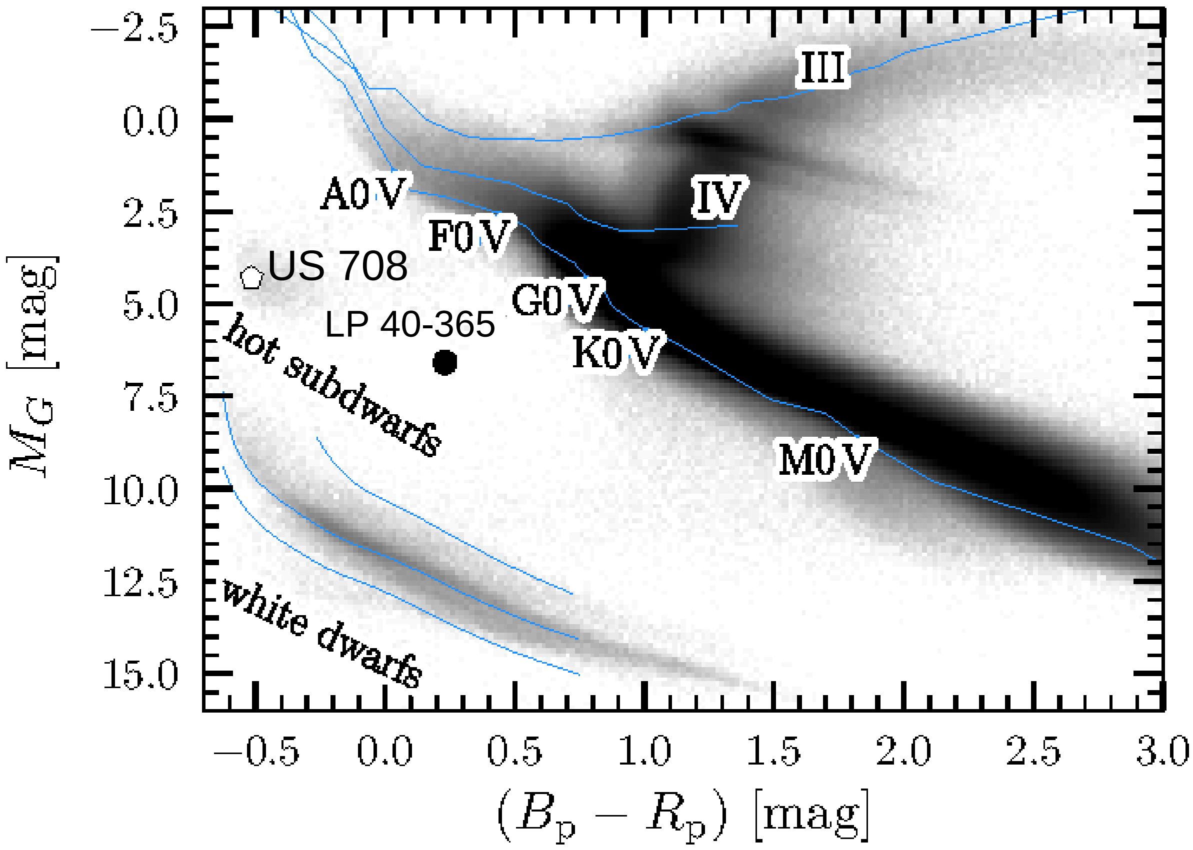
No H and He lines – **Atmosphere dominated by Ne, O, Mg**
Neutral and singly ionised: O, Ne, Na, Mg, Al, Si, Ca, Ti, Cr, Mn, Fe, Ni

A unique spectral appearance



The *Gaia* breakthrough

Observational Hertzsprung-Russell diagram

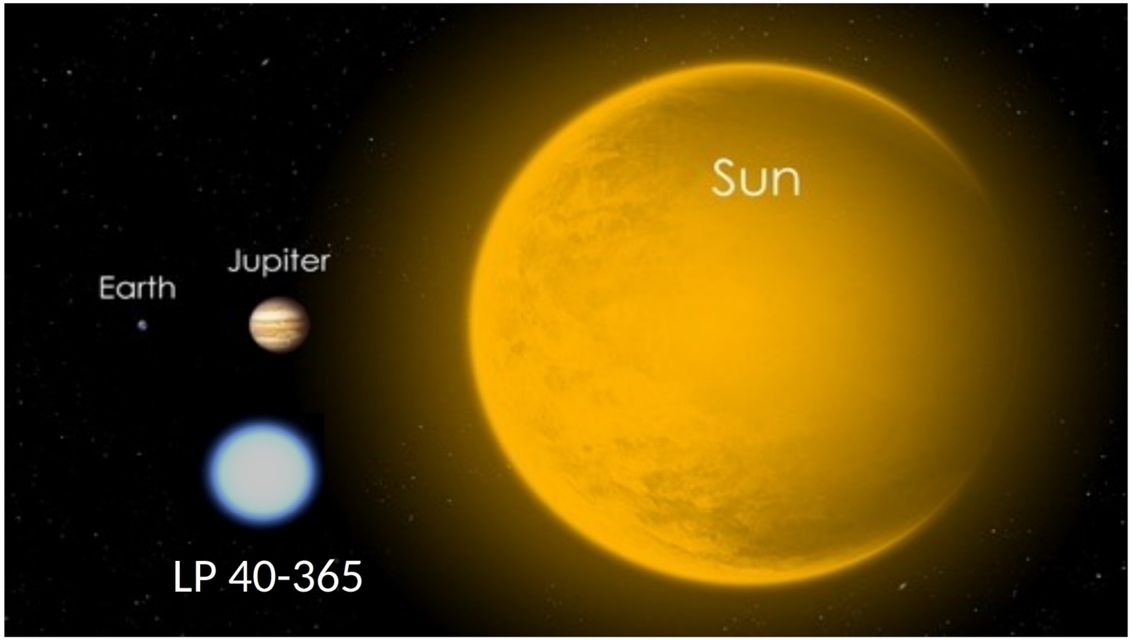


The *Gaia* breakthrough

Distance: 624 ± 14 pc

Radius: 0.16 ± 0.01 R_{sun}

Mass: $0.28^{+0.28}_{-0.14}$ M_{sun}

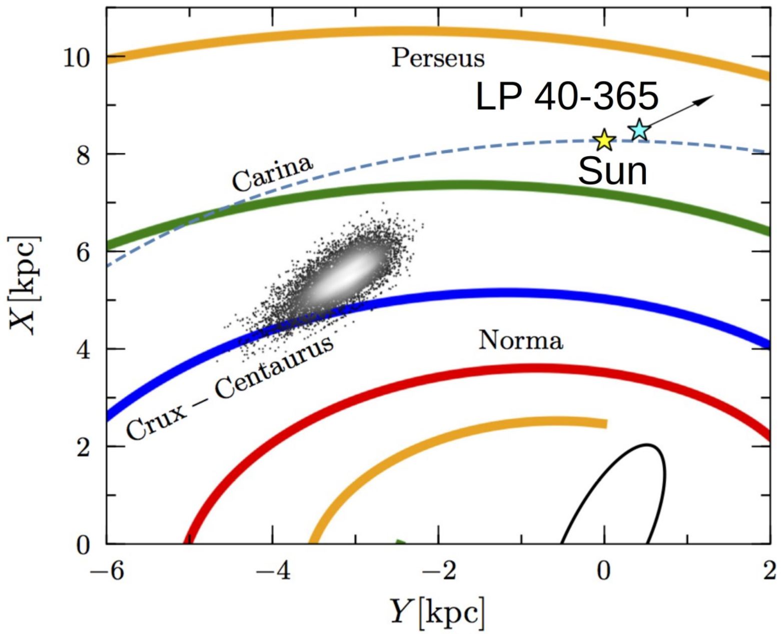


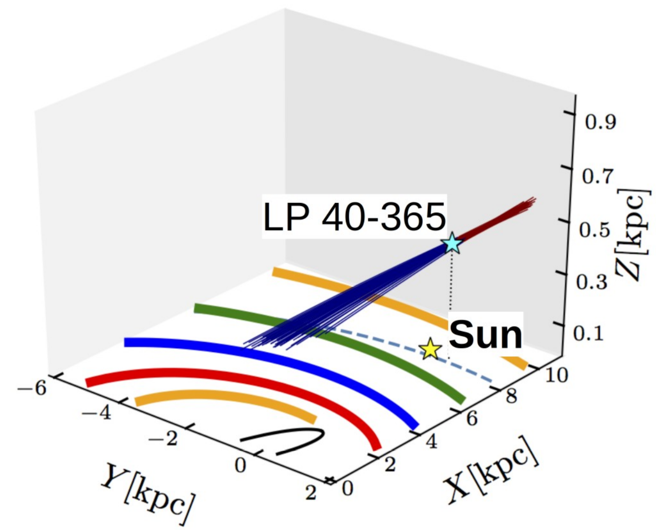
Typical white dwarf ≈ Earth's radius, mass = 0.6 M_{SUN}

LP 40-365 ≈ 2x Jupiter radius

Likely not fully degenerate

A hyper-runaway star



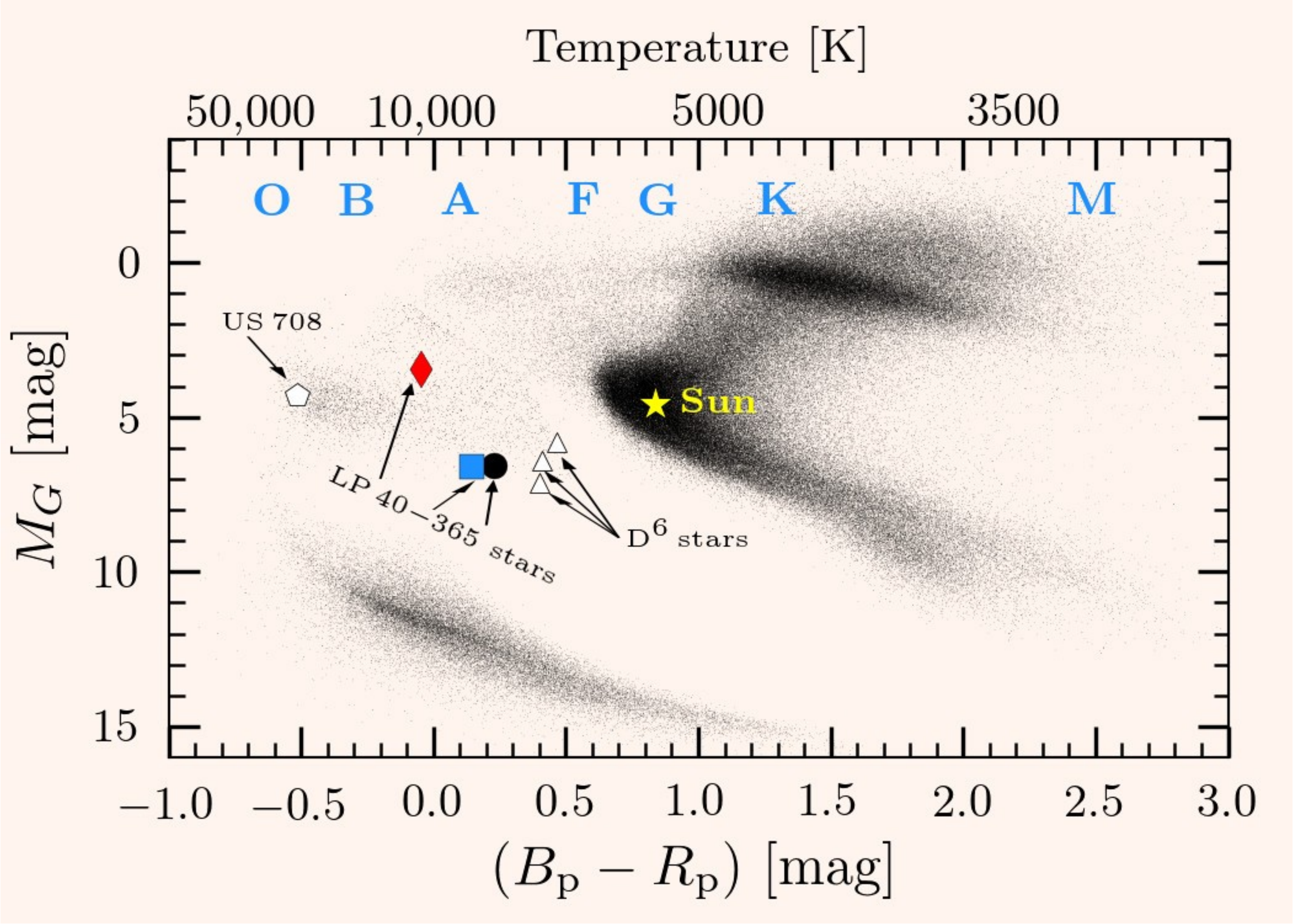


Distance: 624 ± 14 pc → **rest frame velocity** = 850 km/s;
Ejection velocity from the disc ~ 600 km/s

Progenitor: ~1hr binary with He-burning star of 0.8-1.3 M_{sun}

Could the donor star be far away at the other side of the Galaxy?

Introducing the other family members



Three new stars (but one has no *Gaia* parallax)

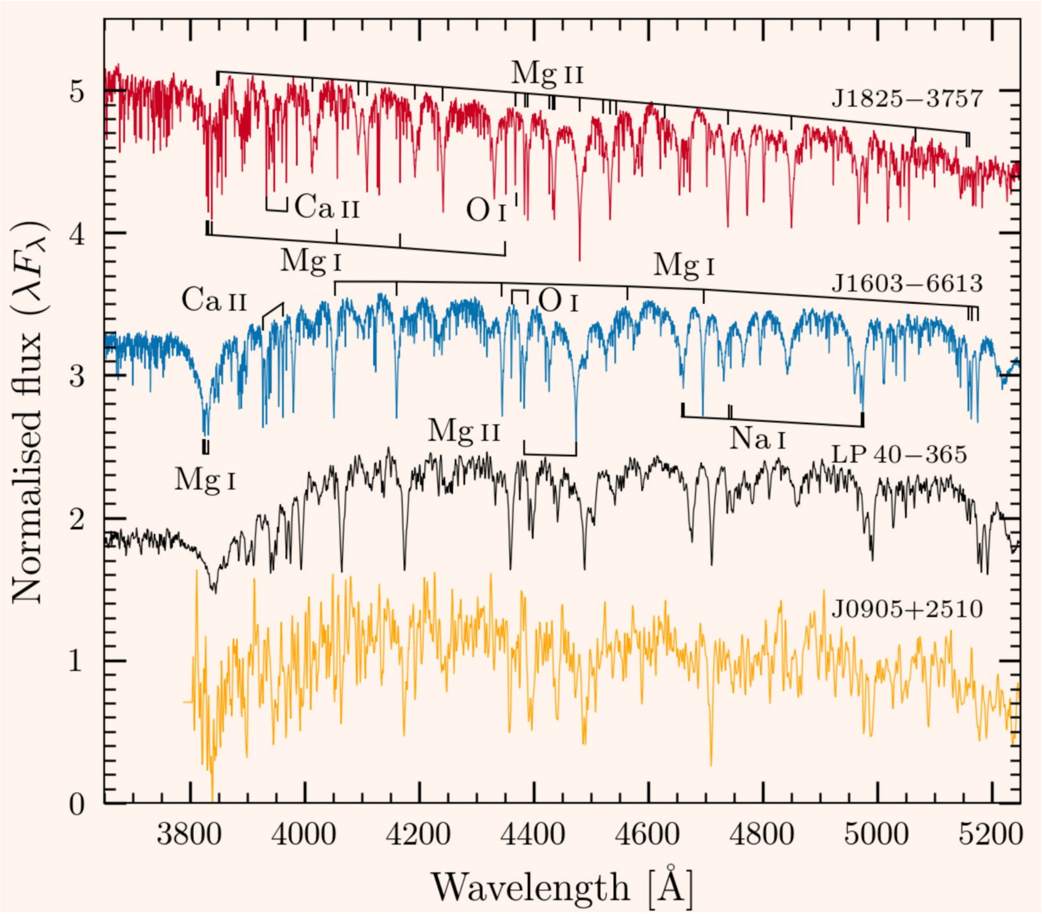
Introducing the other family members

RV = -50 km/s

RV = -480 km/s

RV = +500 km/s

RV = +300 km/s



X-Shooter

X-Shooter

ISIS

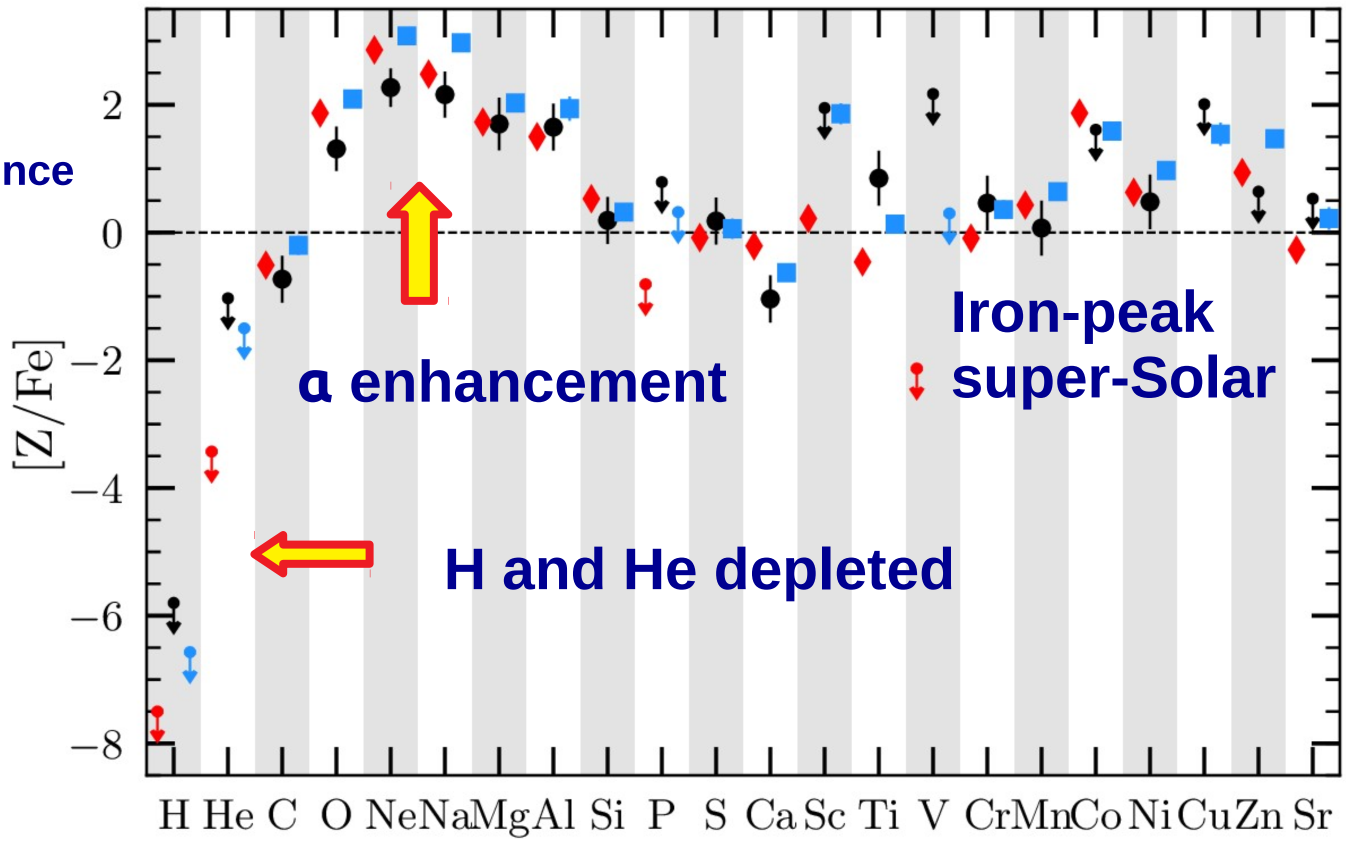
SDSS

Three new stars (but one has no *Gaia* parallax)

Remarkably similar composition

[Z/Fe] = log10(Z/Fe) - log10(Z/Fe)$_{Sun}$

Solar reference (Asplund)



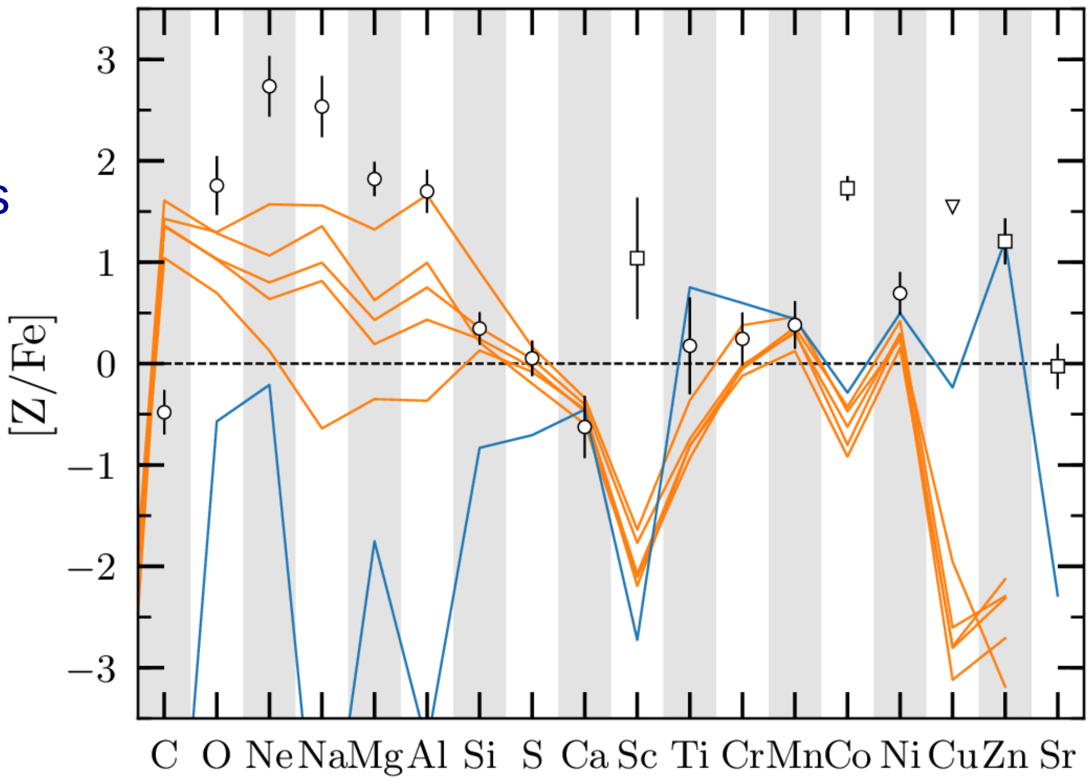
Black: LP40-365 – **Red:** J1825 – **Blue:** J1603

Comparison with theoretical bound remnants

Curves: bulk composition of bound remnants surviving pure-deflagrations

Orange: CO WD progenitor
Blue: ONe WD progenitor

Symbols:
average composition of LP 40-365 stars



Galactic trajectories

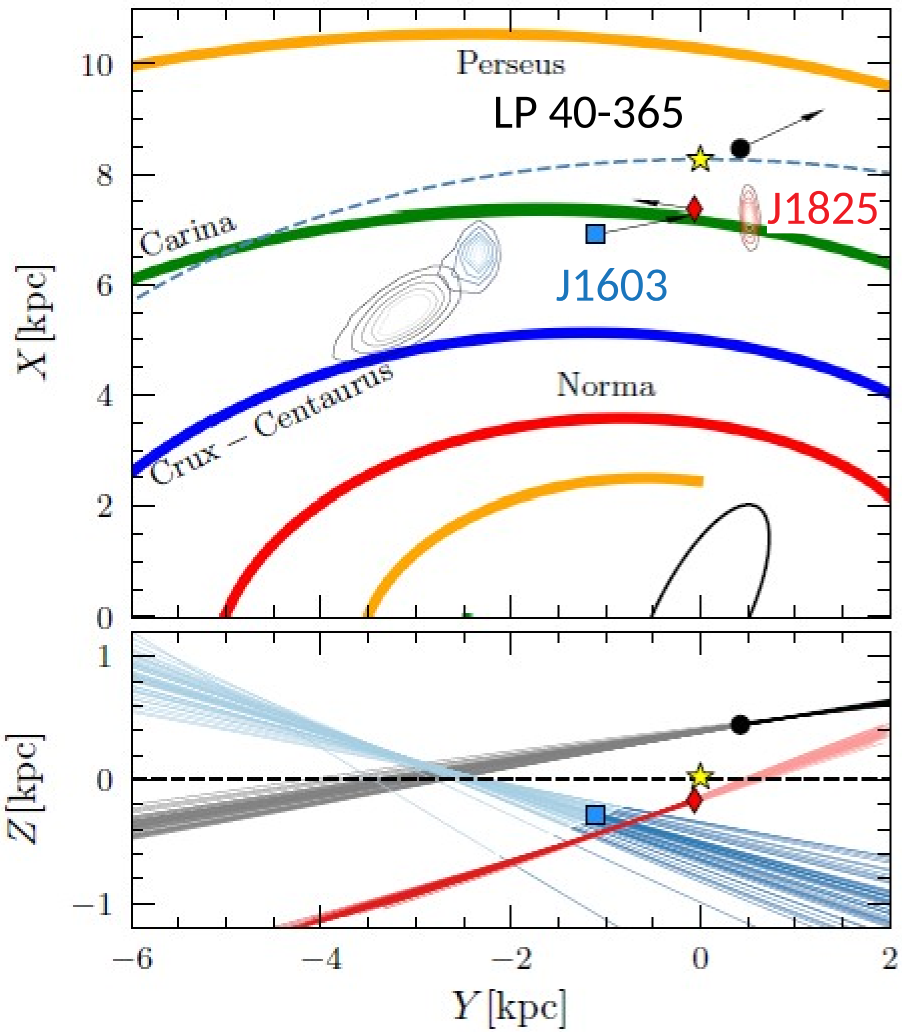
LP 40-365 and J1603
Unbound to the Milky Way
Ejected from thick disc
Rest frame velocities > 800 km/s[2]

J1825 is bound onto
a retrograde orbit
(< 10% escape probability)
Ejected from nearby the Sun

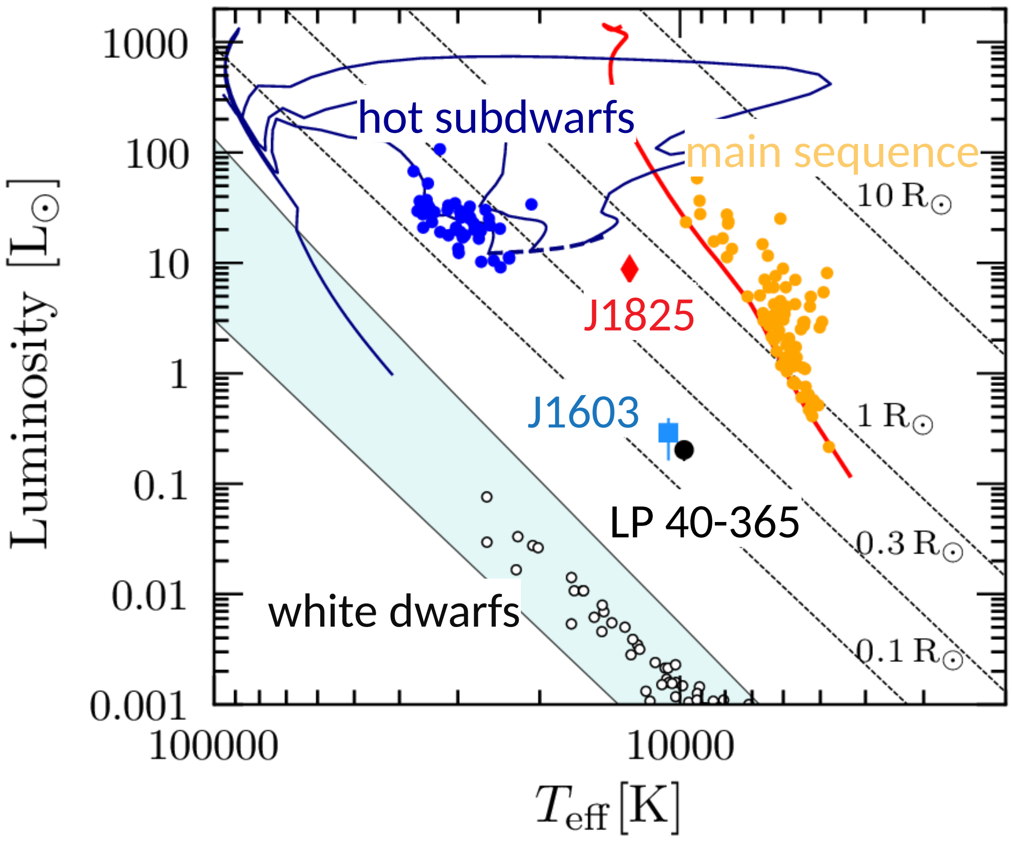
Trajectories have small inclinations

Ejection velocities ~ 550 – 600 km/s

Same progenitor scenario



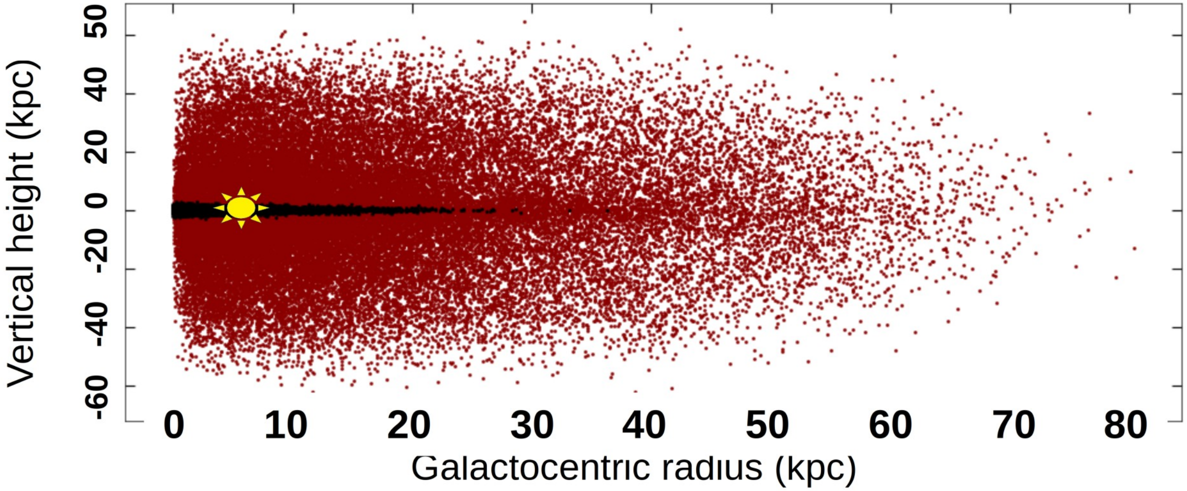
An possible evolutionary sequence



Theoretical work on these stars and related objects
(Zhang et al. 2019, Bauer et al. 2019)
Future: LP 40-365 stars will join the cooling sequence
Will they look like O-rich WDs (Kepler et al. 2016; Gänsicke et al. 2020 in prep)?

Population synthesis

- Gaussian ejection velocity distribution = 600 ± 50 km/s
- Birth rate:
  - SN Iax: 10% SN Ia (= 50,000 in 100 Myr; scaled from Li et al. 2011)
  - tECSN: similar rate of occurrence
- Space density scaled to thick disc density



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  - Expected SN Iax/tECSN bound remnants ~ 22 (still a few to find)

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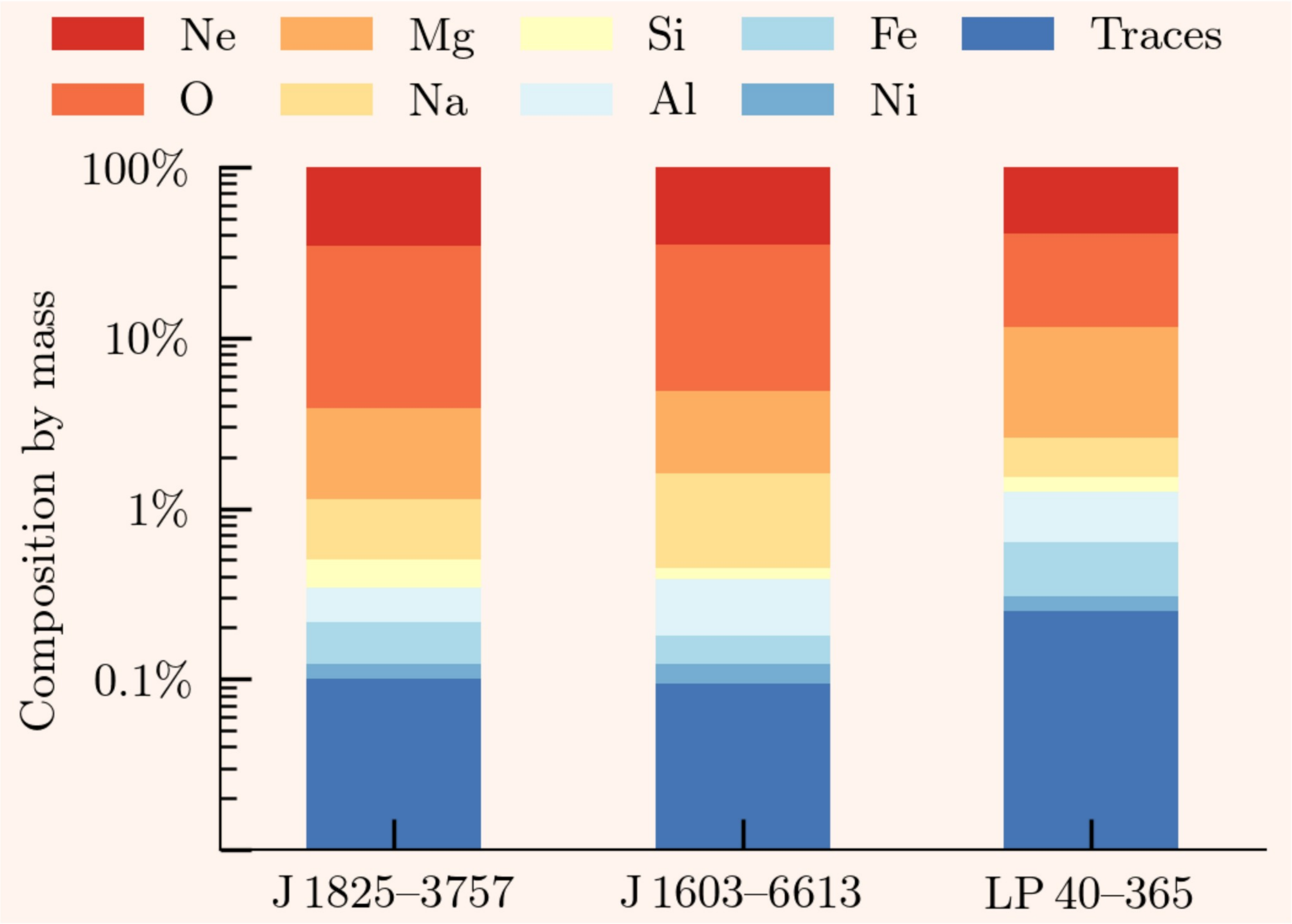
- Predictions for end of *Gaia* mission within 2 kpc from the Sun
  - Expected SN Iax/tECSN bound remnants ~ 22 (still a few to find)
- Most survivors **could be bound** to Milky Way with unspectacular proper motions ~ 40 mas/yr
- A few 100s of stars with suitable *Gaia* data await for spectroscopy

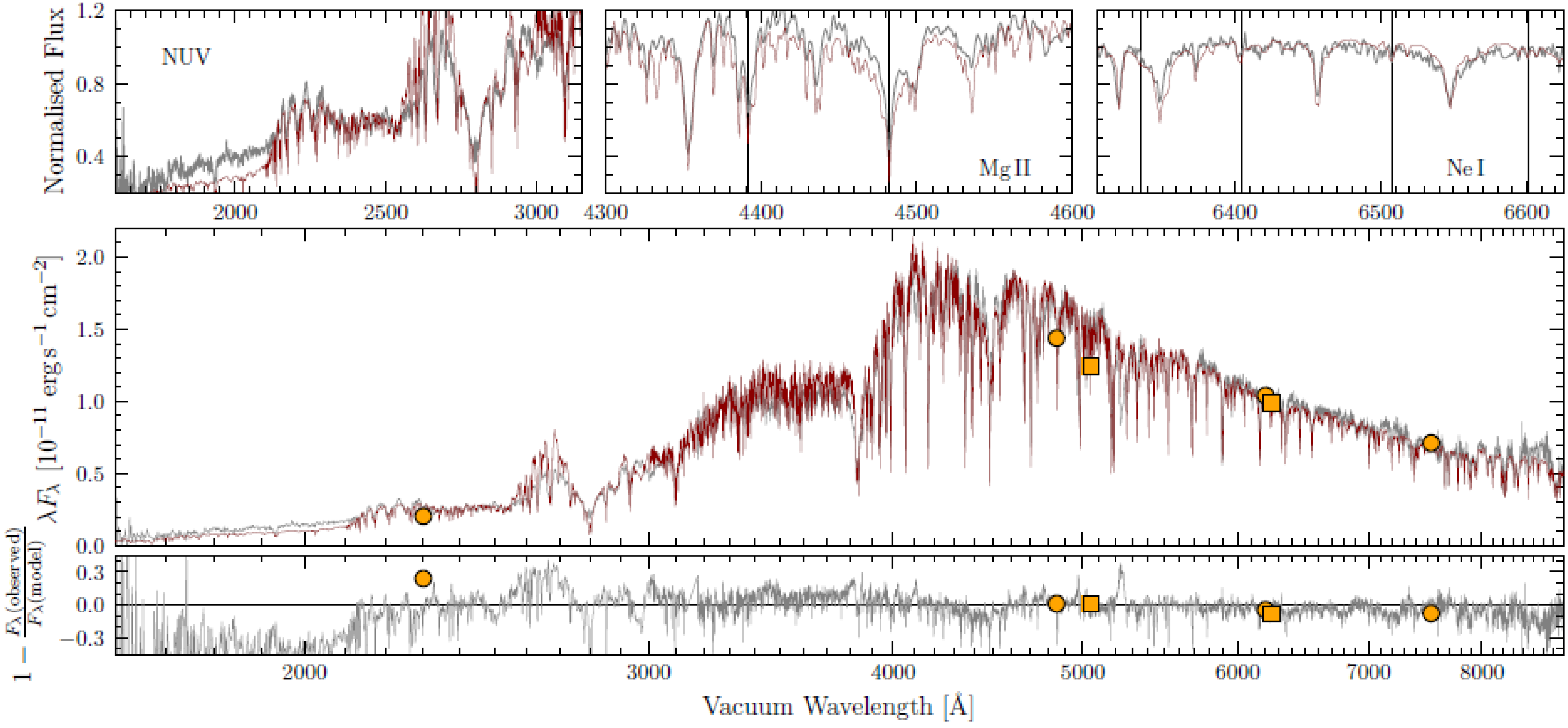
Conclusions

- **LP 40-365 is the prototype of a class of peculiar stars**
  - Mutually similar composition
  - Ejection velocity of 550–600 km/s
- **Possible survivors peculiar thermonuclear supernovae**
  - Near-Chandrasekhar mass explosions, single-degenerate scenario
  - CO, CONe, or ONe progenitors?
  - Ejected from compact binaries (0.8-1.3 M_{Sun} He-burning donor star)
  - Detection rates compatible with SNe Iax and tECSN
- **Open questions**
  - Evolution (spectral evolution, cooling ages)
  - Possible connection with O-rich white dwarfs
- **Future work**
  - Follow-up of low-proper motion candidates from *Gaia* DR2



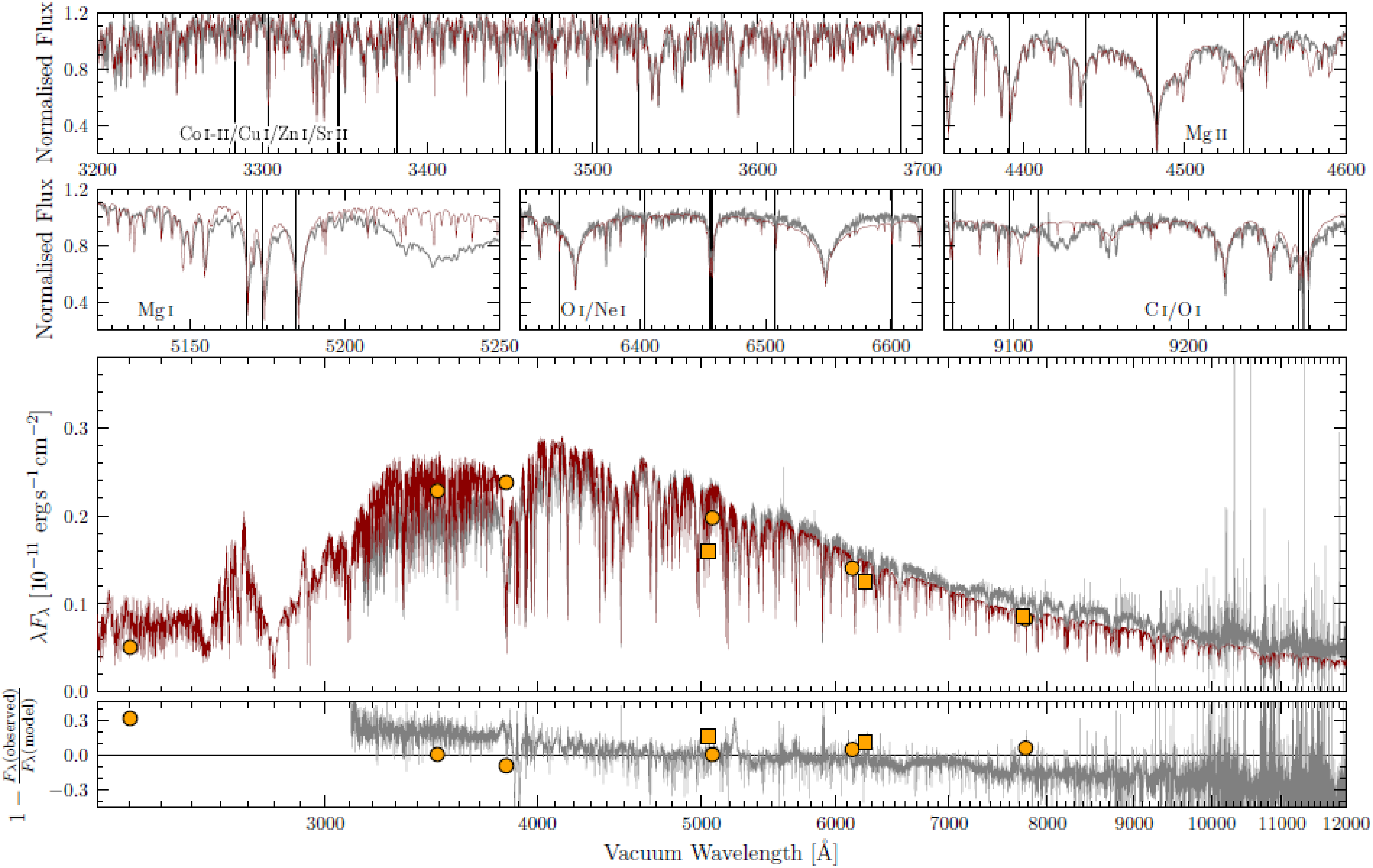
Ne
Mg
Si
Fe
Traces
O
Na
Al
Ni
Composition by mass
100%
10%
1%
0.1%
J 1825–3757
J 1603–6613
LP 40–365

LP 40-365

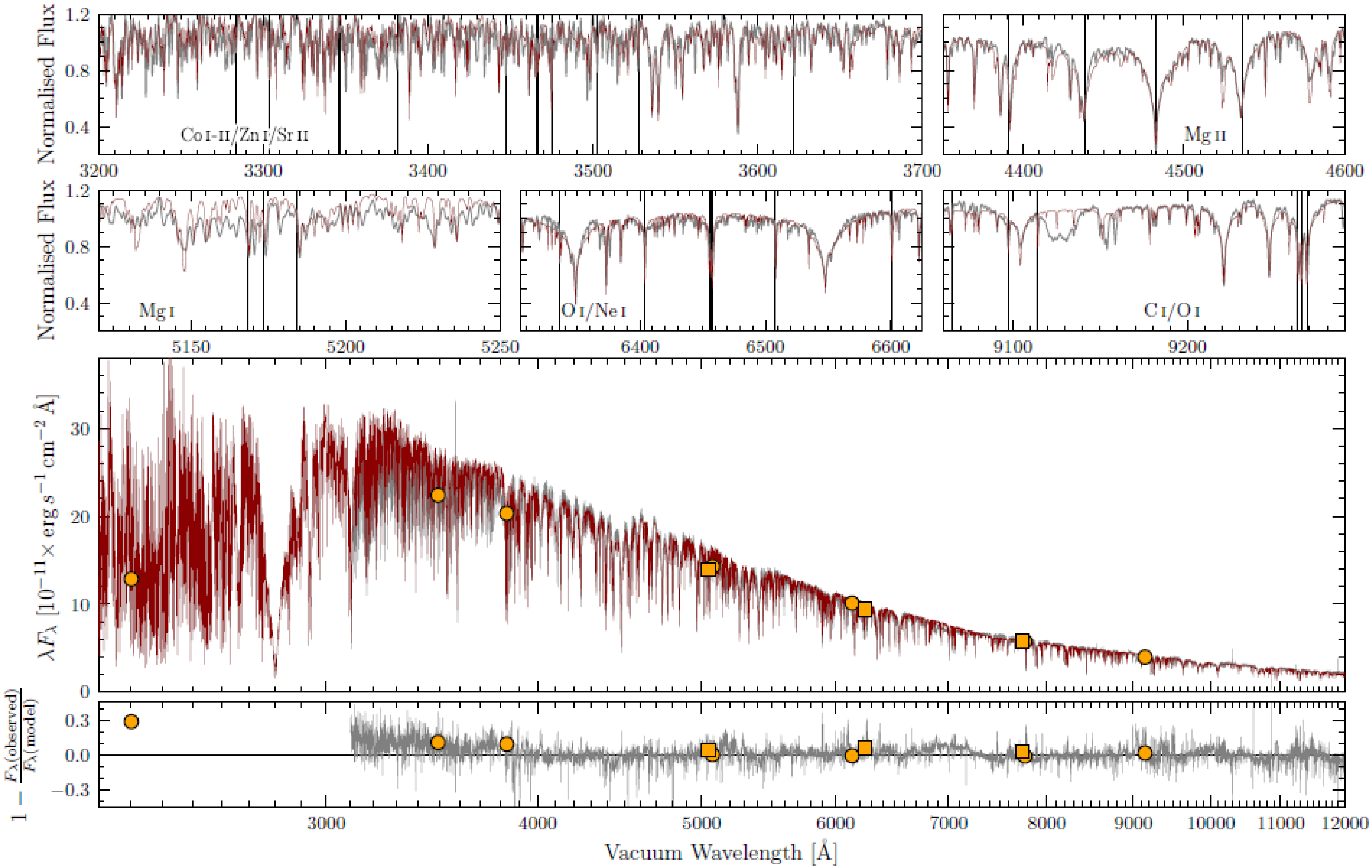


Normalised Flux
NUV
Mg II
Ne I
λF_λ [10^{-11} erg s^{-1} cm^{-2}]
$1 - \frac{F_\lambda(\text{observed})}{F_\lambda(\text{model})}$
Vacuum Wavelength [Å]

J1603-6613


Normalised Flux
Co I-II/Cu I/Zn I/Sr II
Mg II
Mg I
O I/Ne I
C I/O I
λF_λ [10^-11 erg s^-1 cm^-2]
1 − F_λ(observed)/F_λ(model)
Vacuum Wavelength [Å]

J1825-3757


Normalised Flux
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Mg II
Mg I
O I/Ne I
C I/O I
λF_λ [$10^{-11} \times$ erg s^{-1} cm^{-2} Å]
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