Early and late stages of evolution

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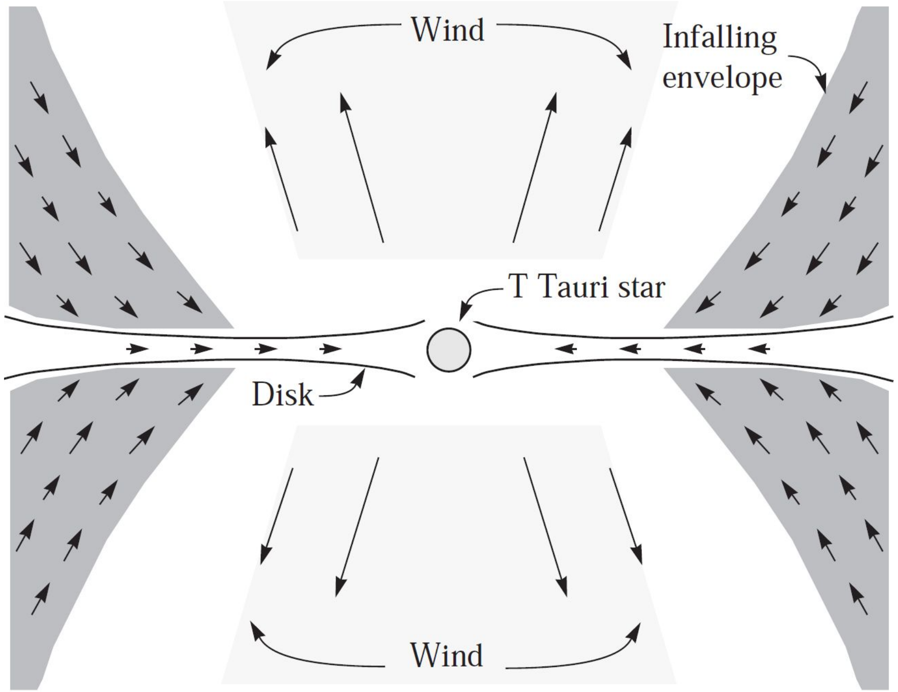
Outline

- Introduction
  - The observable stages of early and late stellar evolution
  - *Gaia* and *Gaia* Alerts
- Results for early stages of stellar evolution
- Results for late stages of stellar evolution
- Summary

Introduction: the early stages



Hartmann & Kenyon (1996)

- Gas and dust fall from the envelope onto the outer disk
- The material accretes onto the stellar surface
- A fraction of the infalling matter is removed by outflows
- Accretion → heating of the disk, increases the luminosity of the star
- In this talk: low-mass young stellar objects (<2 solar mass) – observable in the optical while still accreting

Introduction: mass accretion in young stellar objects

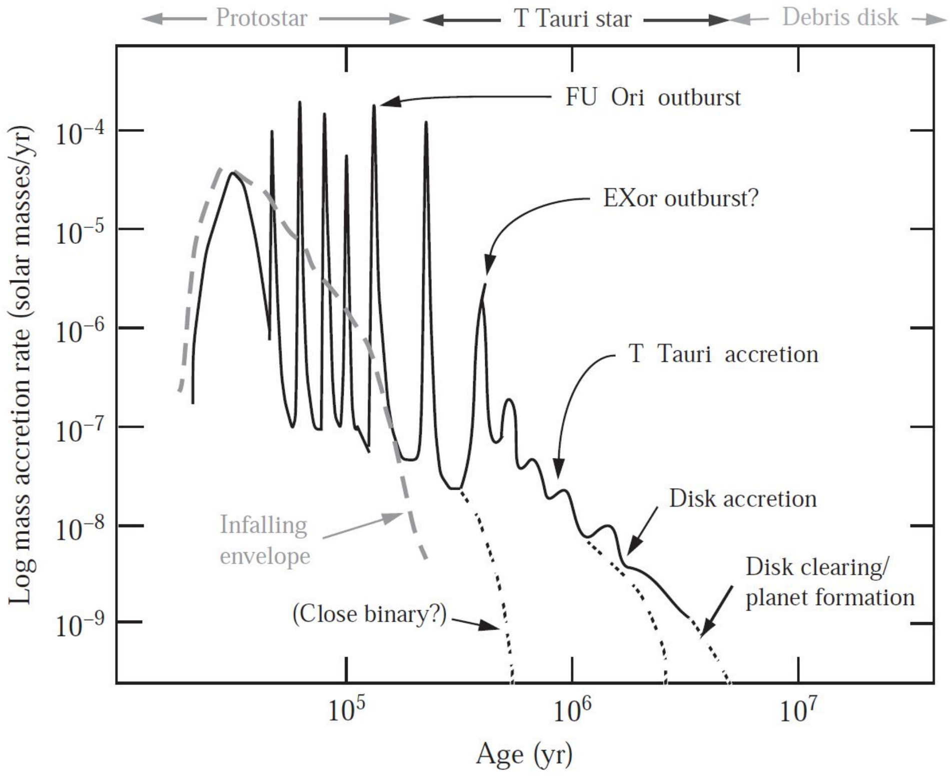
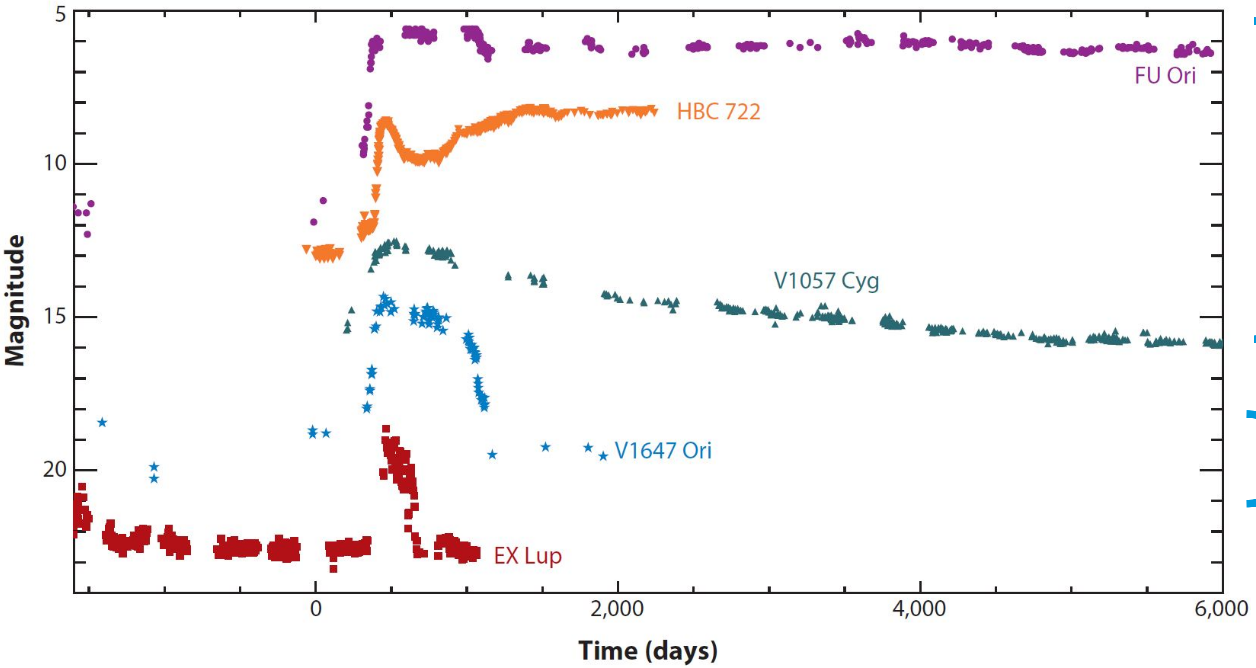


Figure adopted from Hartmann (2009)

- Accretion: not a smooth process
- Inhomogeneous in space and time
- Can vary by orders of magnitude
- The accretion rates can be increased by thermal or gravitational instabilities
- Episodic accretion is a common scenario in the early evolution of stars
- Examples can be identified in *Gaia* light curves

Introduction: examples of episodic accretion



Long-term outburst:
FU Orionis (FUors)
(e.g. Audard et al. 2014, Fischer et al. 2022)

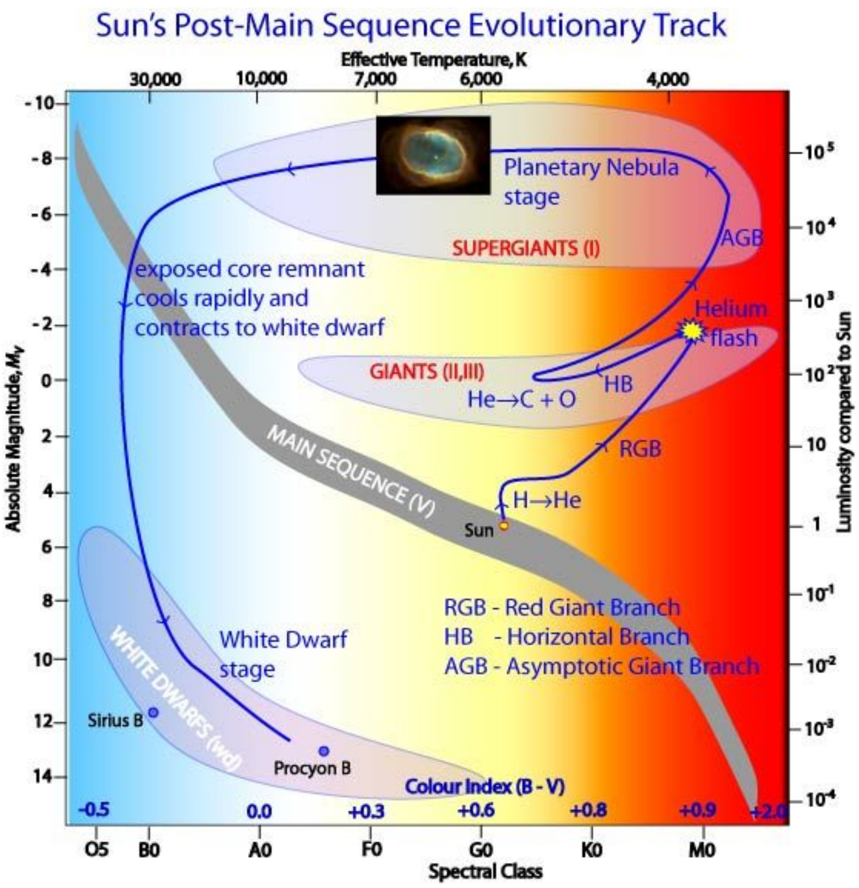
Short-term outburst:
EX Lupi (EXors)
(e.g. Herbig 2008)

Figure adopted from Kóspál et al. (2011)

In this talk: results for low-mass YSOs

- Also intermediate types
- Classification: spectroscopy

Late stages of low and intermediate mass stars



- Exhaust the core hydrogen and evolve off the main sequence into a red giant
- Helium-burning starts → horizontal branch, then expand to become an AGB star
- Ejection of the outer layers of the star → planetary nebulae
- The remnant core cools and contracts to a white dwarf
- The upper limit of the mass of white dwarfs: 1.4 solar masses – the Chandrasekhar limit

Late stages of high mass stars

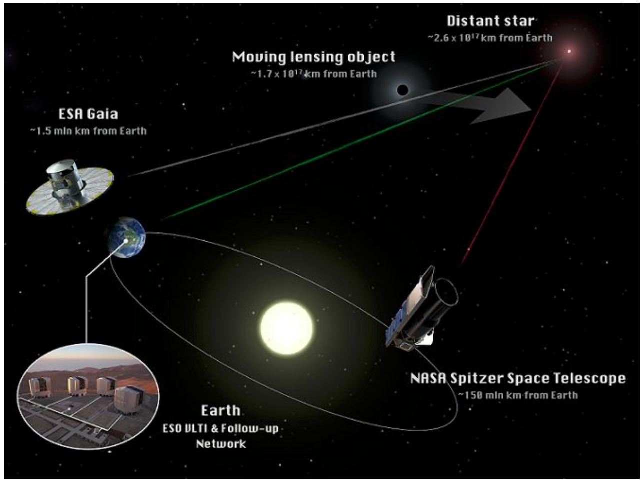
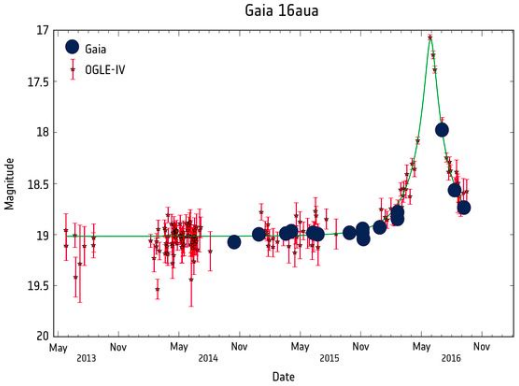


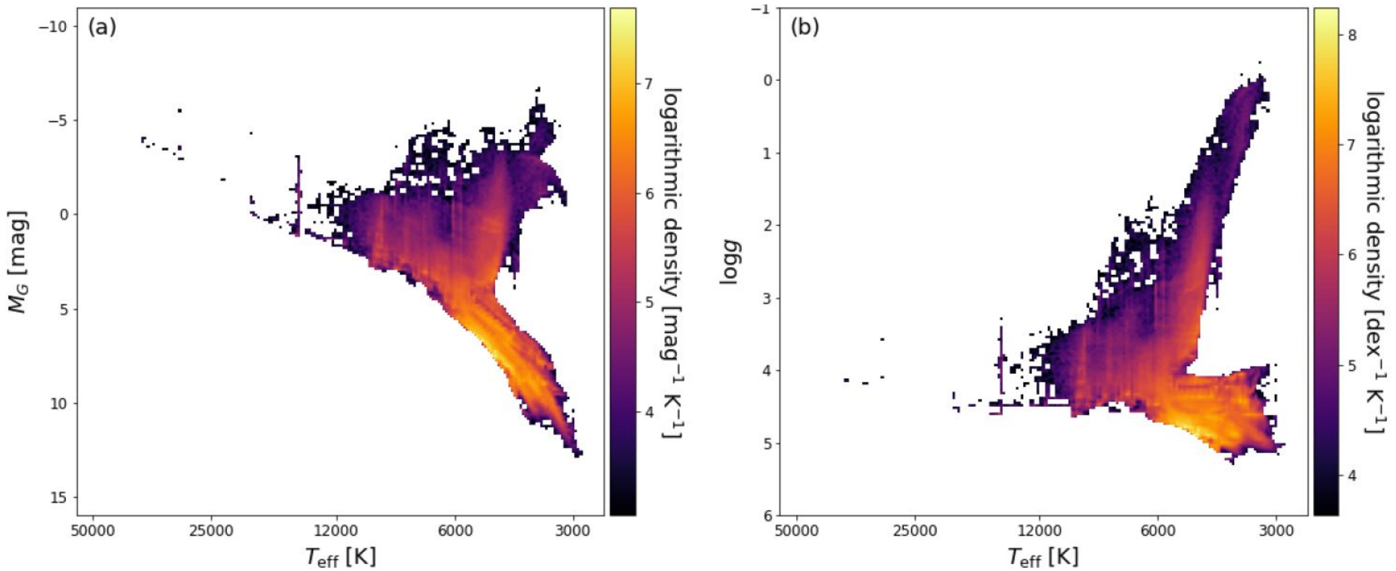
Image credit: K. Rybicki, L. Wyrzykowski, A. Cassan, E. Bachelet.

Image credit: ESA/Gaia/DPAC, L. Wyrzykowski, OGLE team (Warsaw), Z. Kostrzewa-Rutkowska (SRON/RU)



- Massive stars typically become type II (core collapse) supernovae, e.g. SN 1987A, end product: neutron star or black hole
- Type I SN: binary stars, a giant and a white dwarf, explosion when the WD reaches the Chandrasekhar limit
- SN detections: directly in *Gaia* light curves
- Detections of compact objects, e.g. neutron stars and black holes: gravitational microlensing

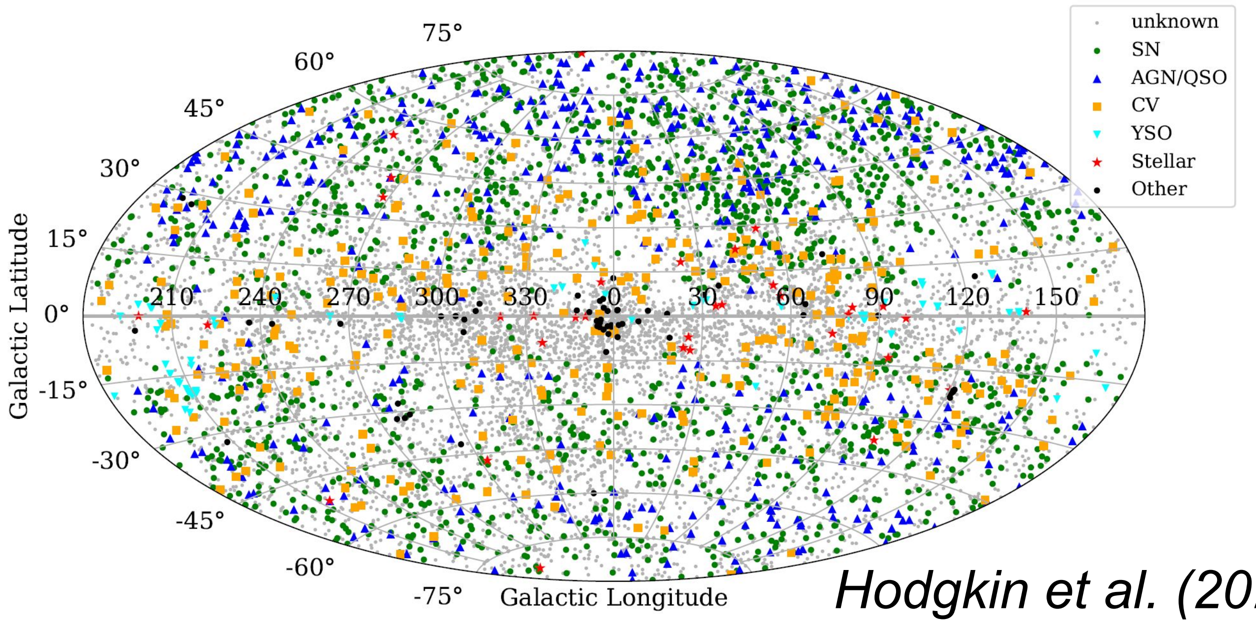
What can we learn from *Gaia*?



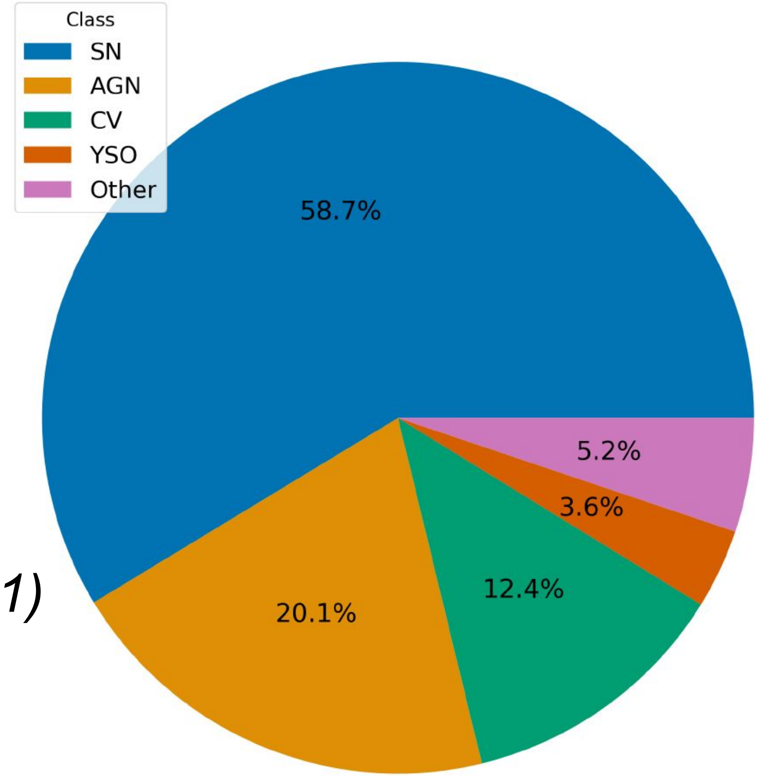
Andrae et al., Creevey et al., Fouesneau et al. 2023

- Photometry, astrometry, low resolution spectra
- Parameters that help to characterize the evolutionary state: T_{eff}, $\log g$, A_G, stellar radius, mass, age

Gaia Photometric Science Alerts

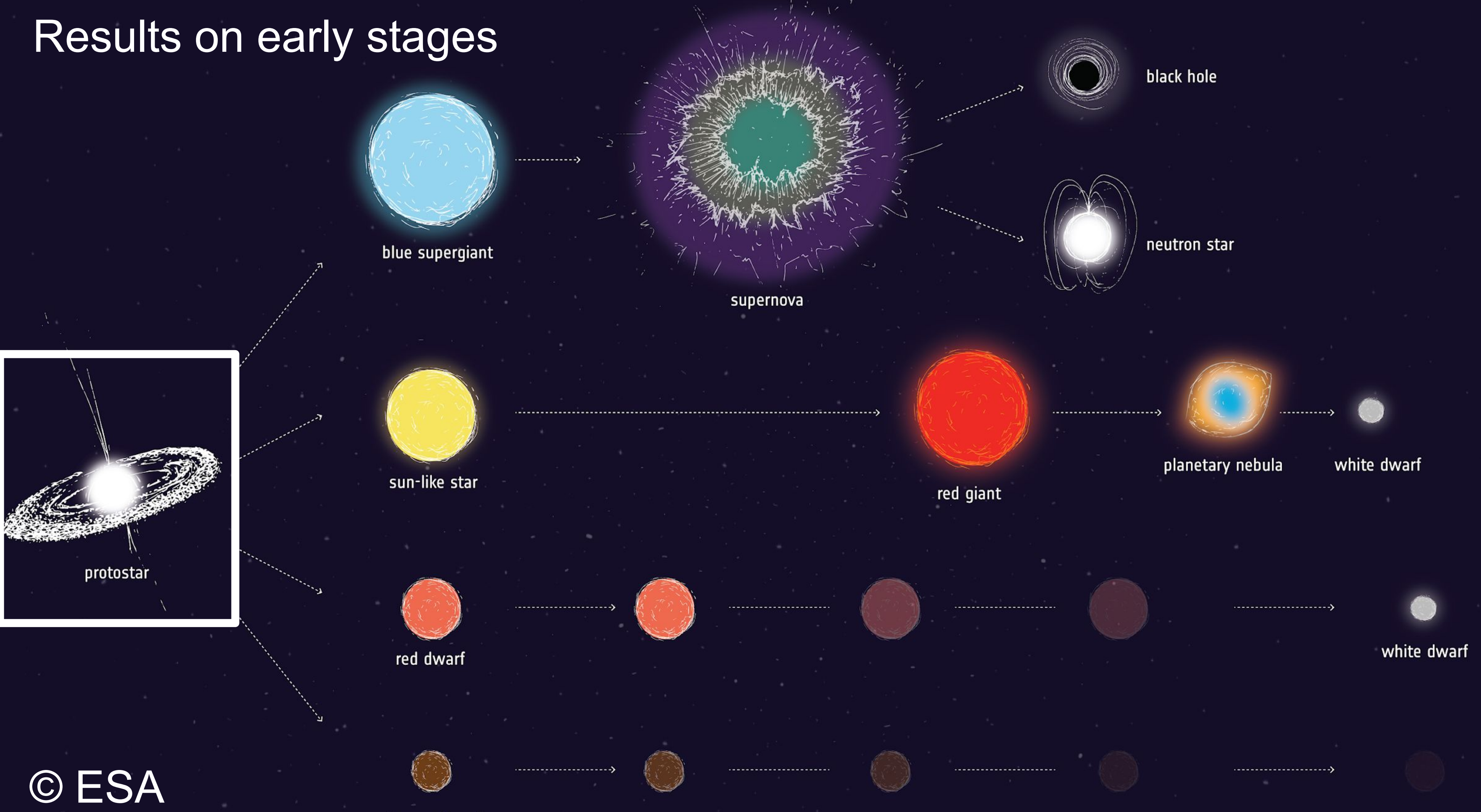


Hodgkin et al. (2021)



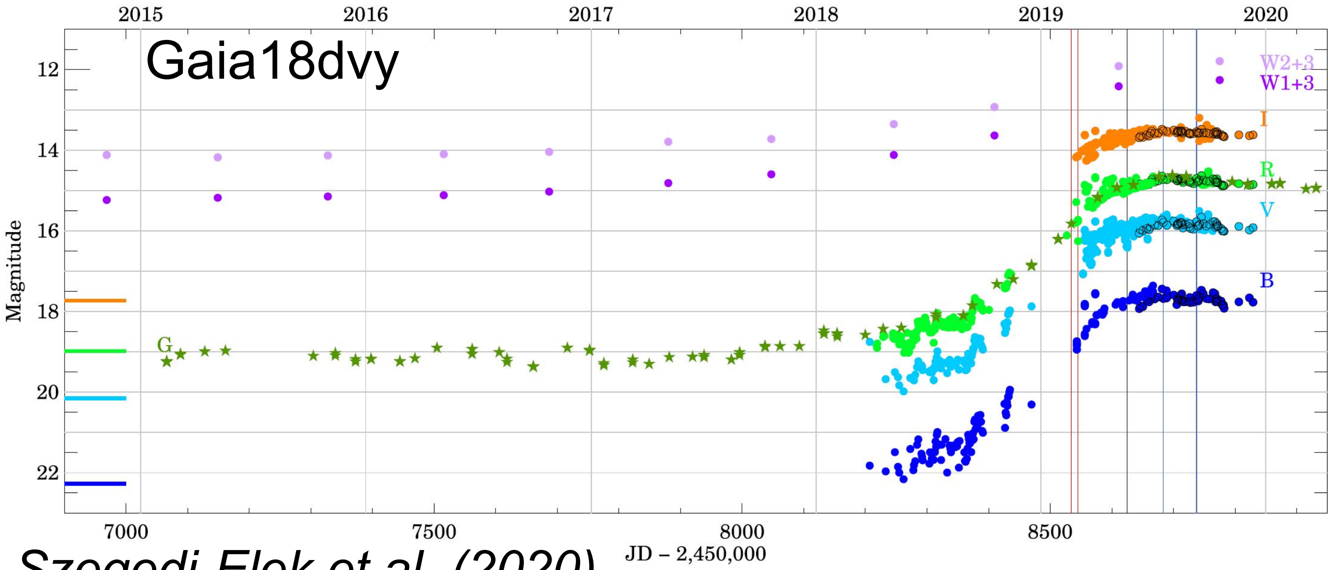
- *Gaia* G light curves for variable sources
- Combined with follow-up observations

Results on early stages

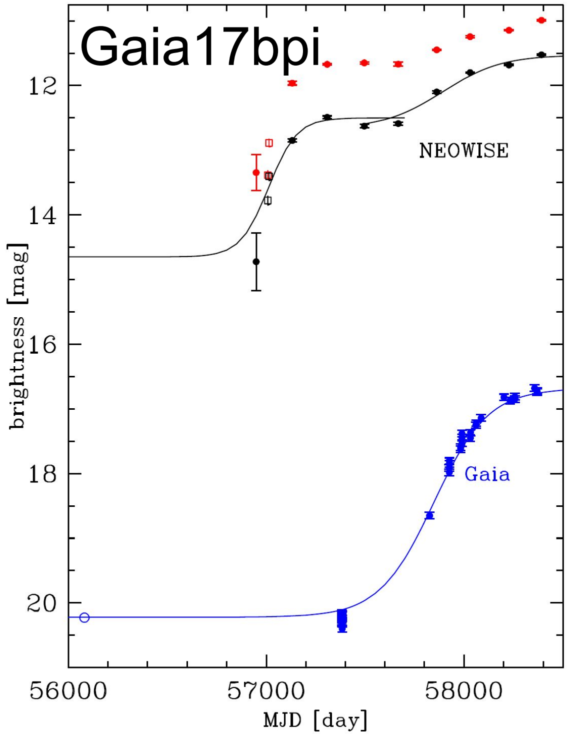


Discovery of eruptive YSOs using *Gaia* alerts: FUors

- Two FUor discoveries
- Typically discovered in the brightening phase
- Confirmation using spectroscopy



Szegedi-Elek et al. (2020)



Hillenbrand et al. (2018)

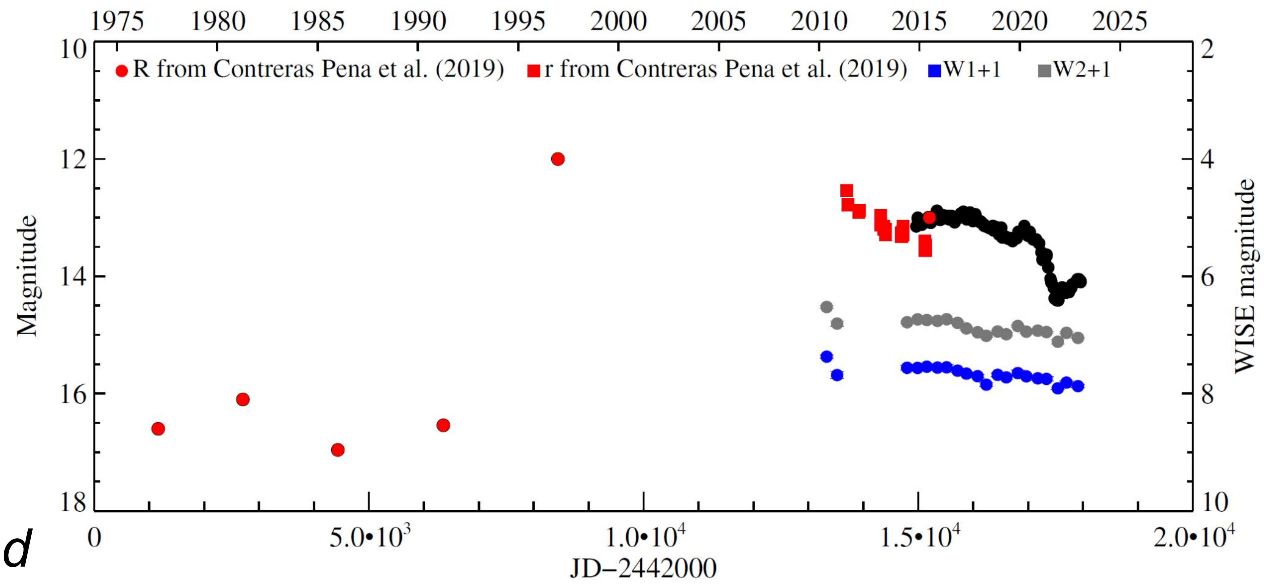
Discovery of eruptive YSOs using *Gaia* alerts: FUors

- Two FUor discoveries
- Typically discovered in the brightening phase
- Confirmation using spectroscopy

Gaia21elv:

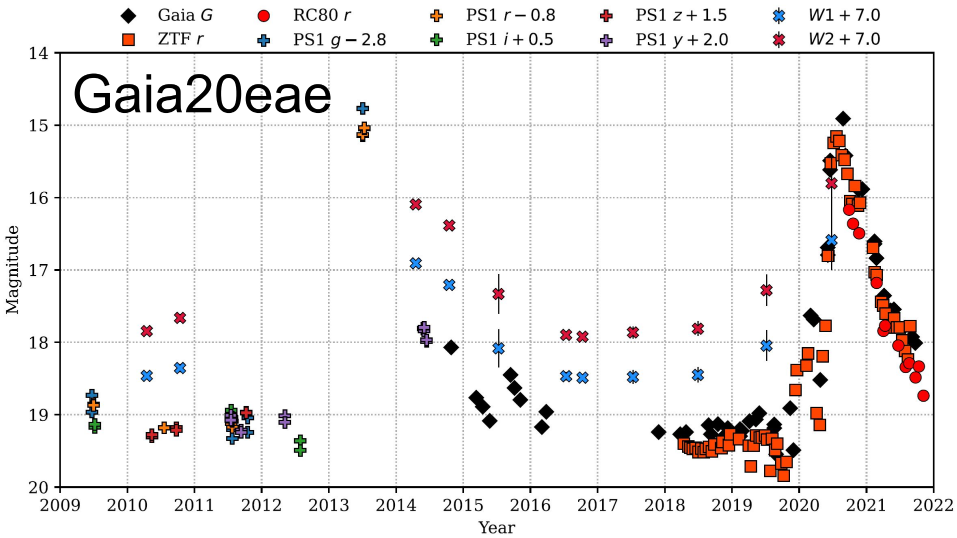
the third FUor discovered from *Gaia* alerts, confirmation using spectroscopy

Nagy et al., submitted



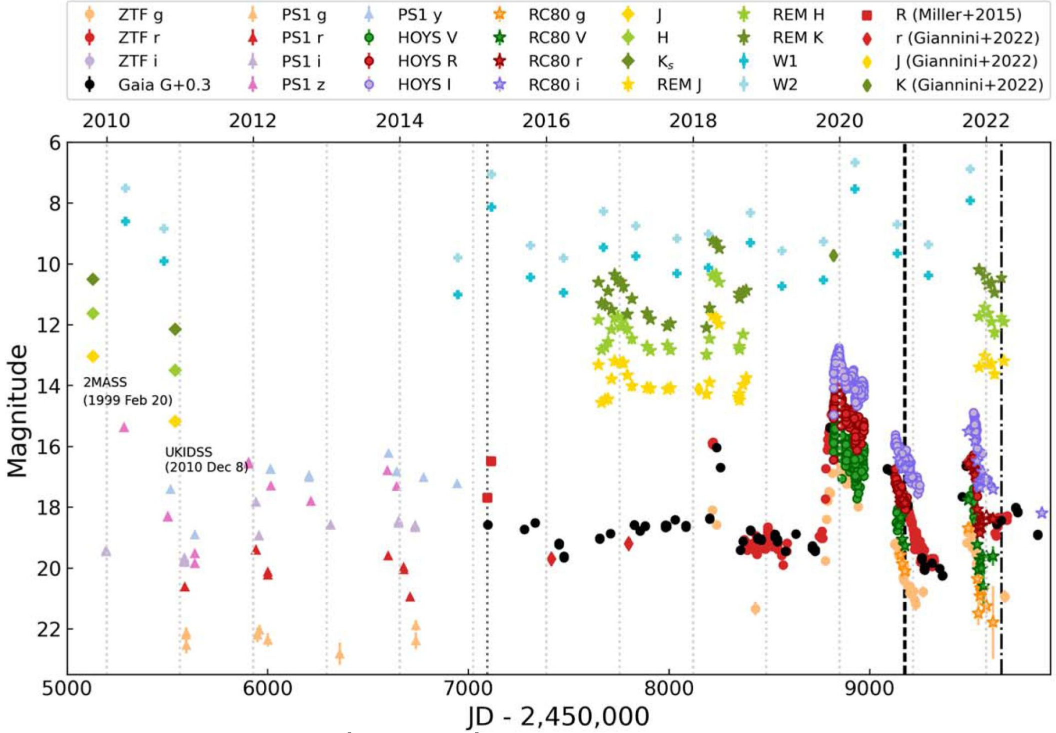
Discovery of eruptive YSOs using *Gaia* alerts: EXors

EXor discoveries



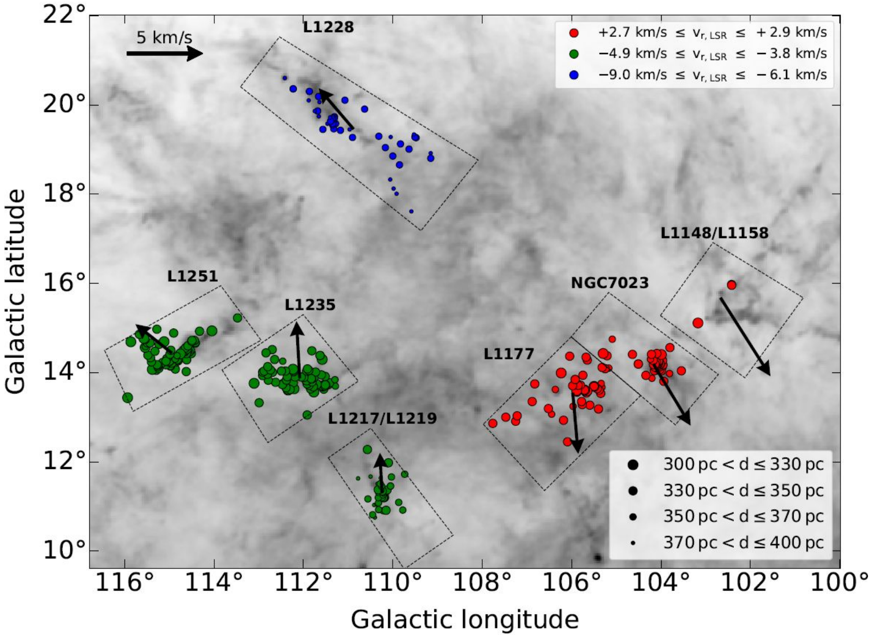
Cruz-Sáenz de Miera et al. (2022)
Ghosh et al. (2022)

Gaia19fct

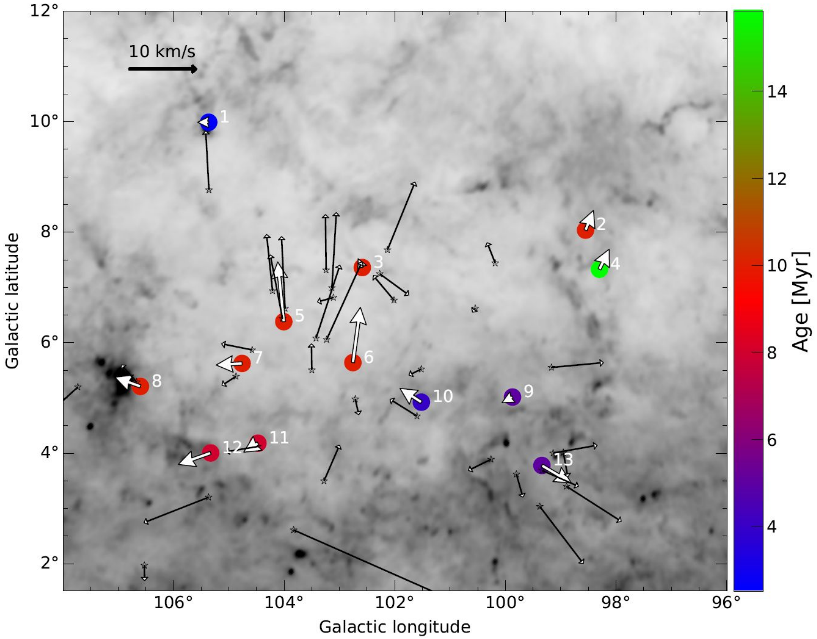


Park et al. (2022)

Young stellar clusters: Cepheus flare & OB2



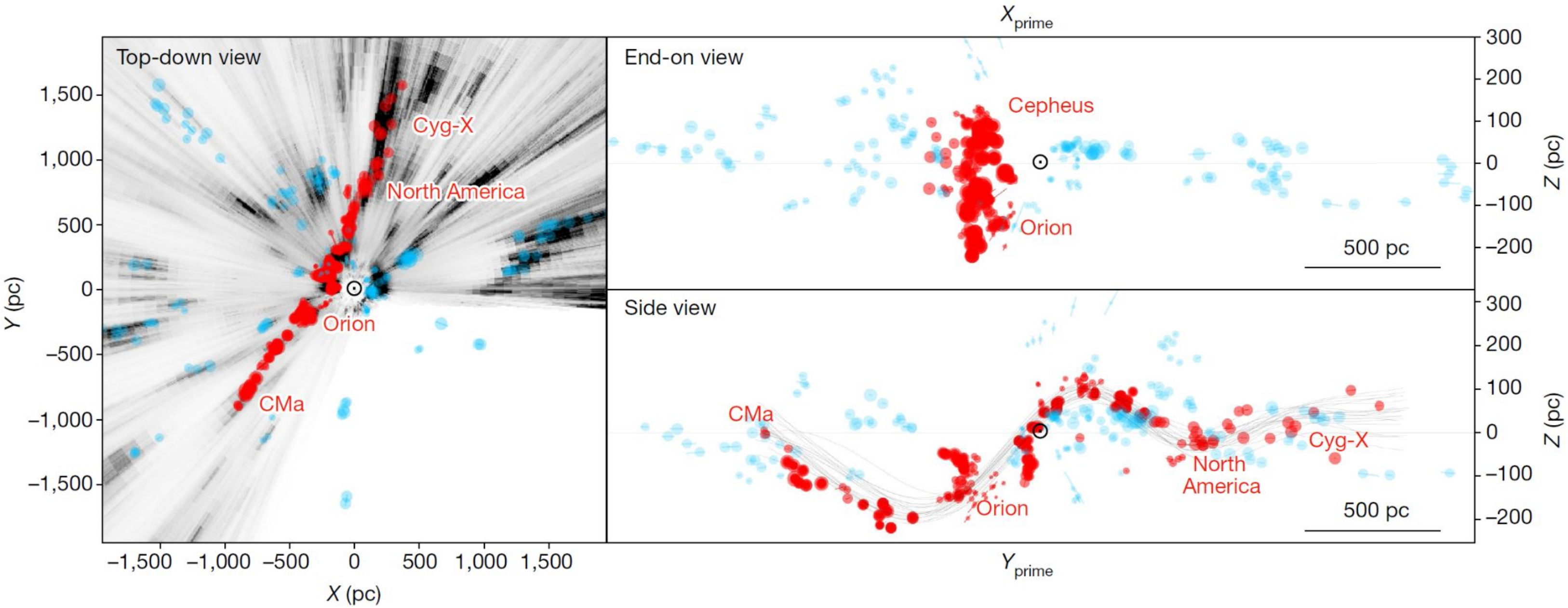
Szilágyi et al. (2021, 2023)



- Search for YSOs and candidates with similar distances
- Three major kinematic subsystems

- Star formation started ~10 million years ago
- The southern clusters have been accelerated by the expanding bubble

A Galactic-scale gas wave in the solar neighbourhood

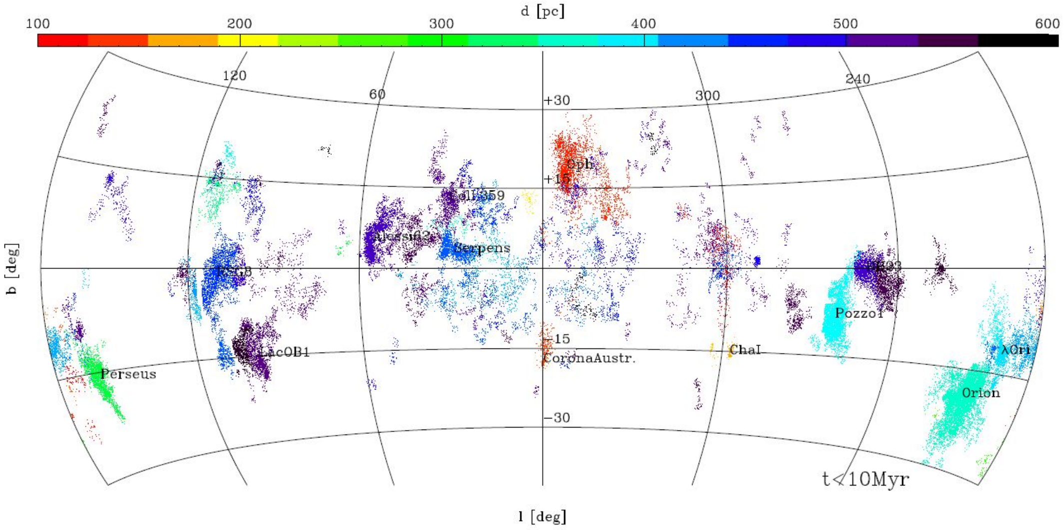


Alves et al. 2020, Zucker et al. 2019, 2020

- ‘Radcliffe wave’: a narrow and coherent 2.7 kpc arrangement of dense gas
- Contains many of the clouds which were associated with the Gould Belt
- Distances from *Gaia* DR2 parallaxes

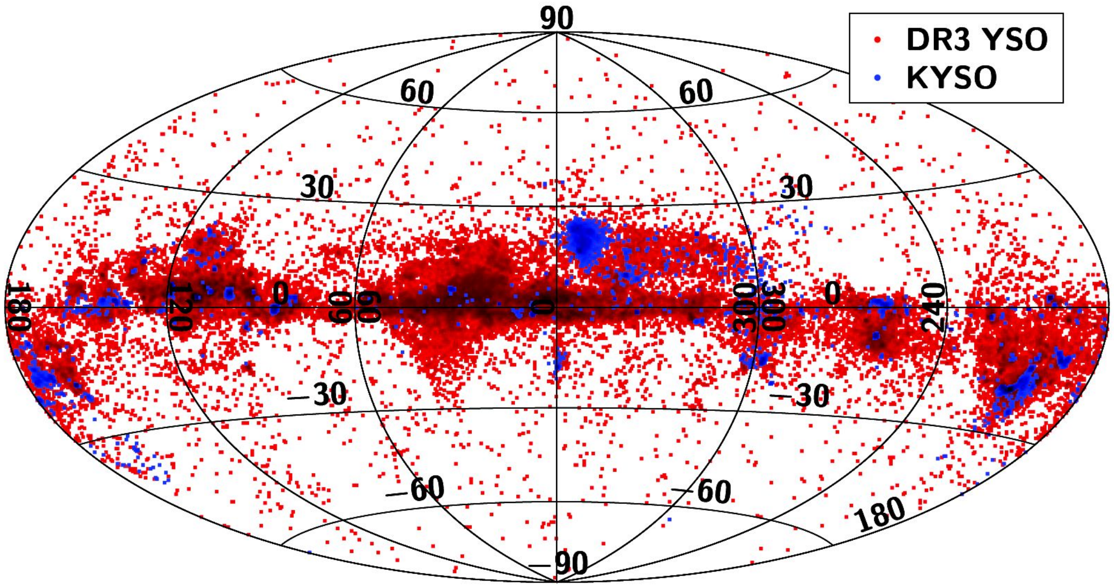
Star forming regions within 1.5 kpc

- Map of the nearby regions of star formation, including newly discovered ones.
- Machine learning unsupervised clustering algorithm + *Gaia* color-magnitude diagrams
- More than 100,000 young low mass stars in hundreds of star-forming regions <10 million years, within 1.5 kpc.
- Many newly identified young stars



Prisinzano et al. (2022)

The *Gaia* DR3 YSO catalogue

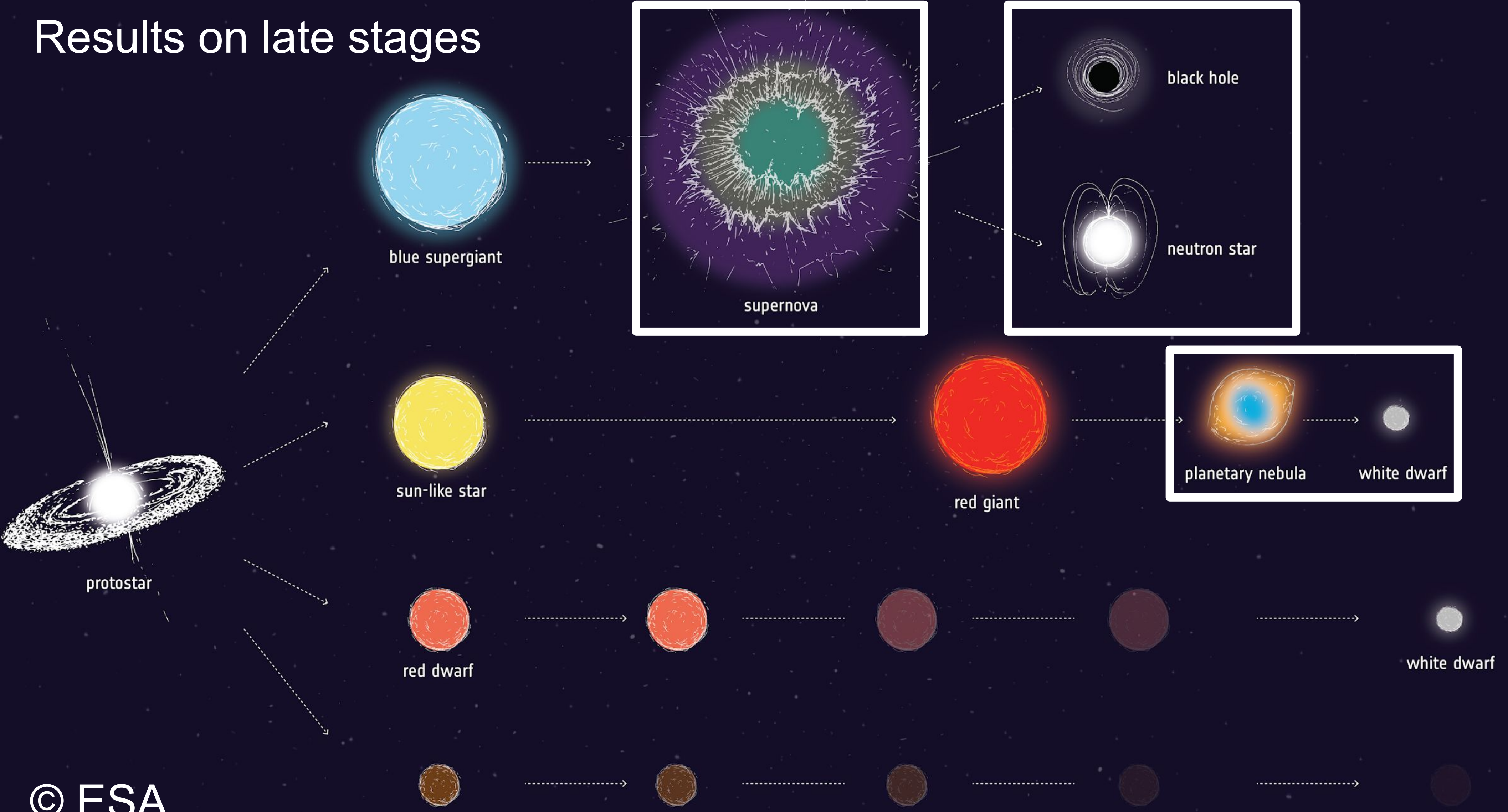


Marton et al. (2023)

- Validating the variable YSO candidates (79 375) from *Gaia* DR3 (Eyer et al. 2023)
- Based on color, brightness, distance, apparent position on the sky
- Confirmation, that *Gaia* is more sensitive to more evolved YSOs

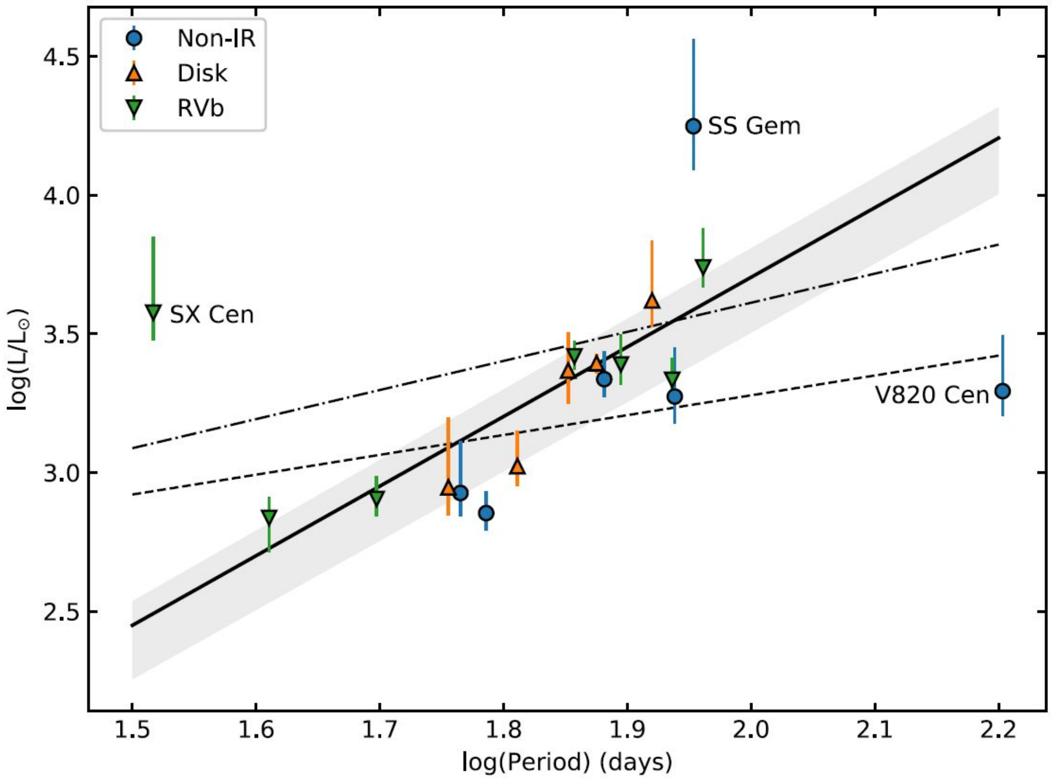
- Around 40 000 sources are newly discovered YSOs
- Upper limit for contamination level: 26.7%

Results on late stages



Physical Properties of Galactic RV Tauri Stars

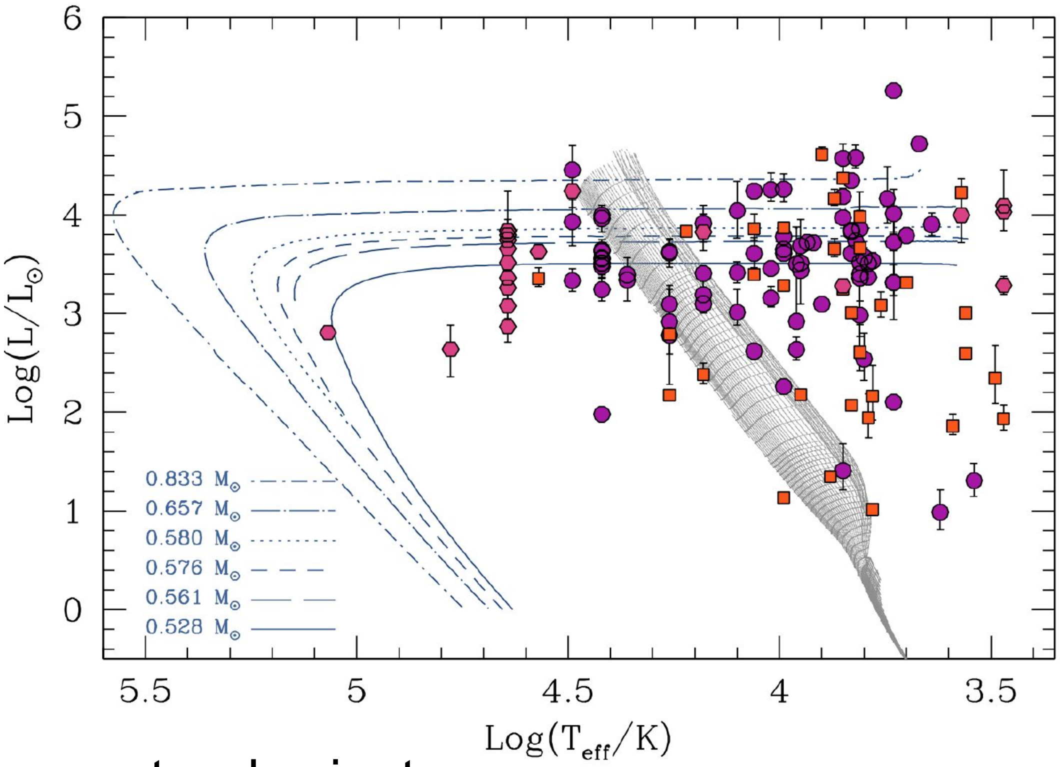
- **RV Tauri stars:** in the post-AGB phase
  - In the instability strip
  - 10^3-10^4 solar luminosity
  - Period: 20-90 days
- Gaia DR2 parallaxes, *G*-band magnitudes, and effective temperatures to calculate the distances, luminosities, and radii using a probabilistic approach.



Bódi & Kiss (2019)

A census of post-AGB stars in *Gaia* DR3

- *Gaia* DR3 parallax-based distances + extinction corrected integrated fluxes → luminosities for 185 post-AGB star candidates
- HR diagram of the largest number of post-AGB candidates to date
- A significant fraction of the objects fall outside the typical luminosity range (theoretical evolutionary post-AGB tracks)

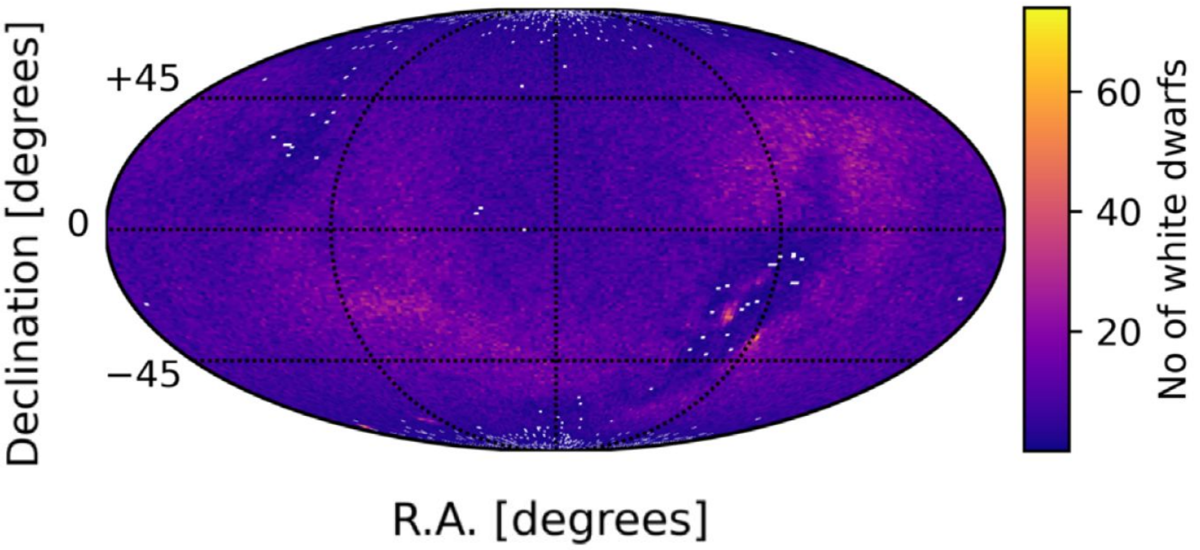


- Underluminous post-AGB candidates: post-red giant branch objects (the result of binary evolution)

Oudmaijer et al. (2022)

A catalogue of white dwarfs in *Gaia* EDR3

- Stars compatible with the white dwarf locus in the HRD
- Selection criteria in absolute magnitude, colour, and *Gaia* quality flags
- Comparison to 30000 spectroscopically confirmed white dwarfs and contaminants from the Sloan Digital Sky Survey

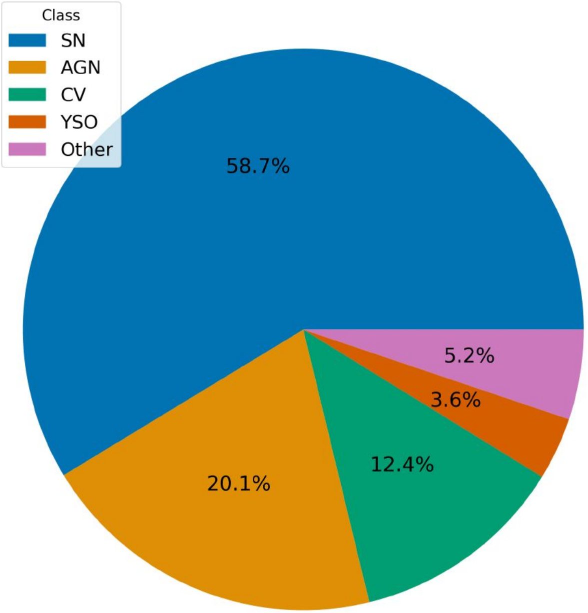


Gentile Fusillo et al. (2021)

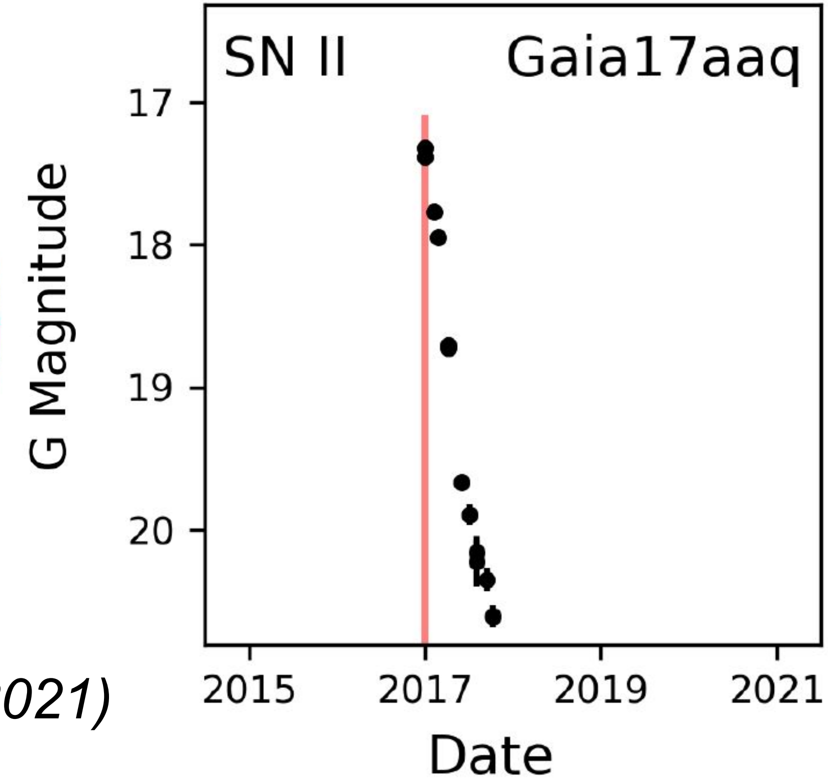
- 359 000 high-confidence white dwarf candidates
- Stellar parameters (effective temperature, surface gravity, and mass)

Supernova discoveries from the *Gaia* Alerts

- **Gaia16apd**: extremely, UV-bright super-luminous SN (Kangas et al. 2017; Nicholl et al. 2017)
- **Gaia17biu**: a hydrogen-poor super-luminous supernova (Xiang et al. 2017; Dong et al. 2017; Bose et al. 2018)

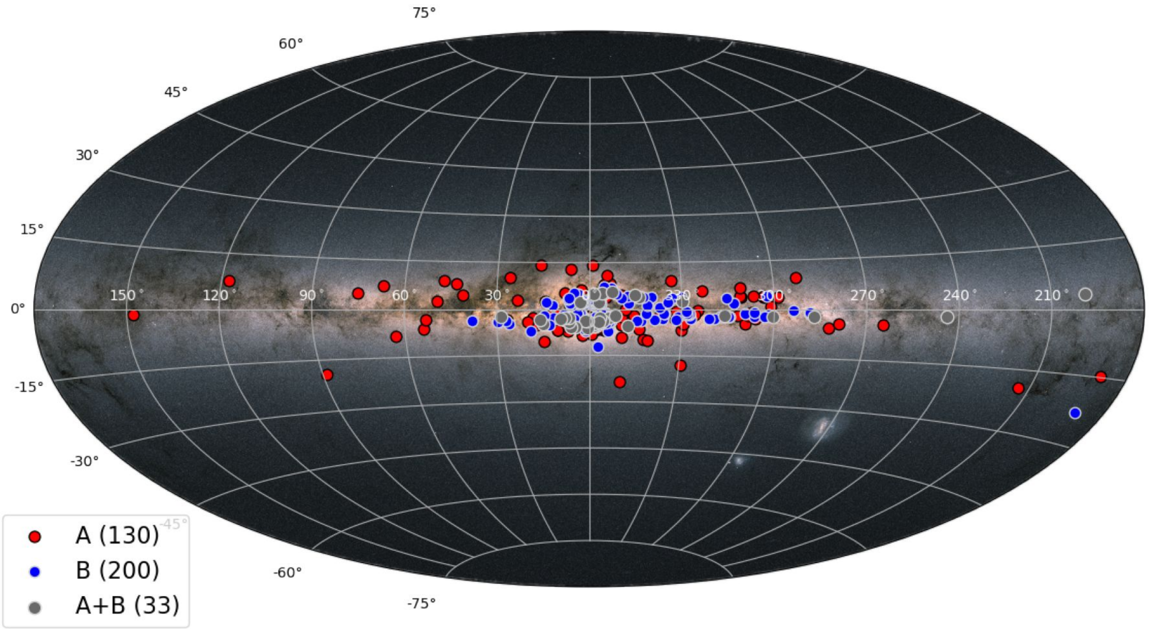


Hodgkin et al. (2021)



The first *Gaia* catalogue of microlensing events

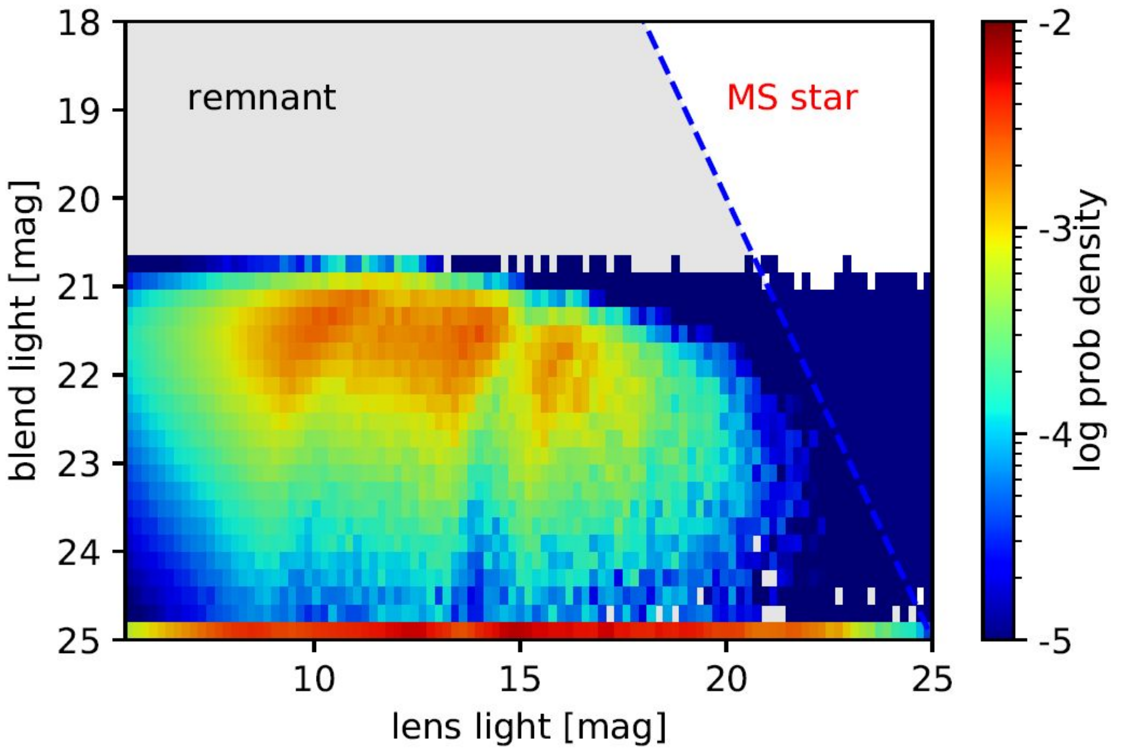
- Analysing the light curves of around 2 billion sources of *Gaia* DR3 from all over the sky covering 34 months, between 2014 and 2017
- The properties of 363 microlensing events
- 90 events are reported first
- Contamination < 1%



Wyrzykowski et al. (2023)

Microlensing from *Gaia* alerts

- More than 400 candidate microlensing events in the *Gaia* alerts
- Not all of them are related to compact objects, some are caused by main-sequence stars
- A long-lasting event: Gaia18cbf
- Most likely lens masses: 1.71–2.65 M_{Sun}
- Possibly a neutron star or a black hole



Kruszynska et el. (2022)

Summary

- The distances and stellar parameters obtained by *Gaia* revolutionize stellar physics
- *Gaia* alerts: many new discoveries of variable sources, such as eruptive young stars, supernovae, or gravitational microlensing candidates
- Understanding the 3D structure of the Milky Way, including those of star forming regions
- Indirect discovery of ‘hidden’, compact objects (black holes, neutron stars) using gravitational microlensing

→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM