N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

Seminar Series
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Merger remnants and double-faced stars: studying exotic white dwarfs with ZTF and Gaia

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Burke Fellow

ZTF

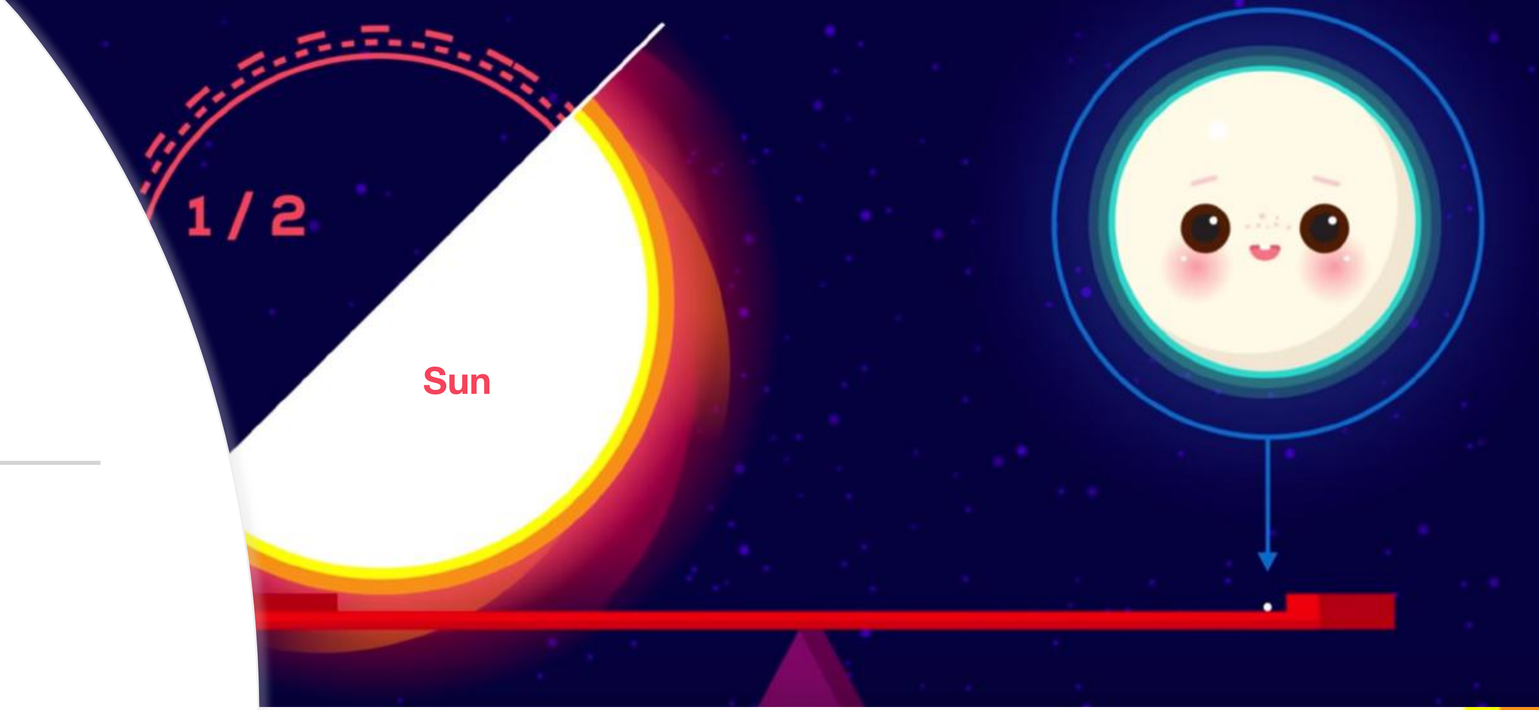
Caltech

White dwarfs are the most common star corpses

> 95 % of stars become white dwarfs

The typical white dwarf

- Mass ~ half the mass of the Sun
- Radius ~ that of the Earth



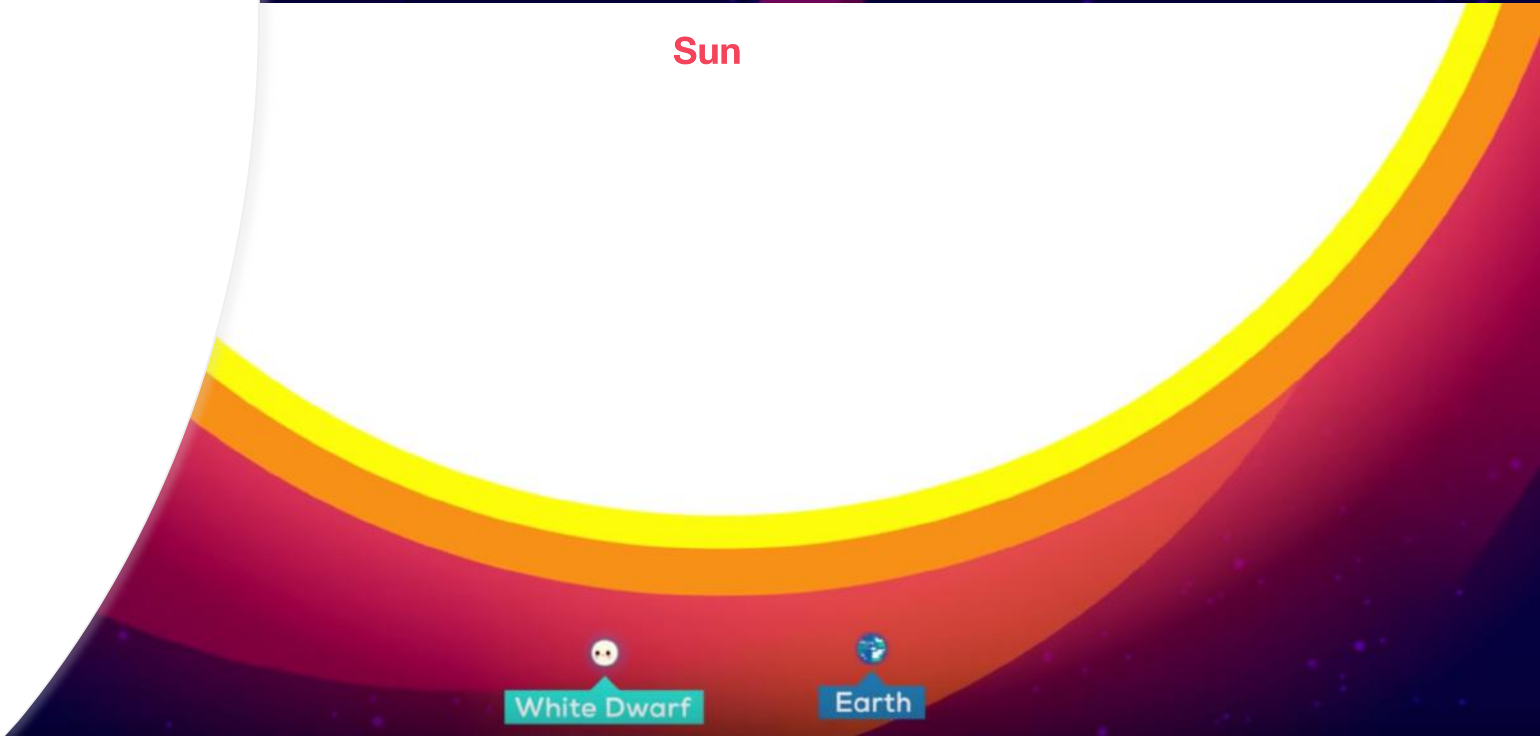
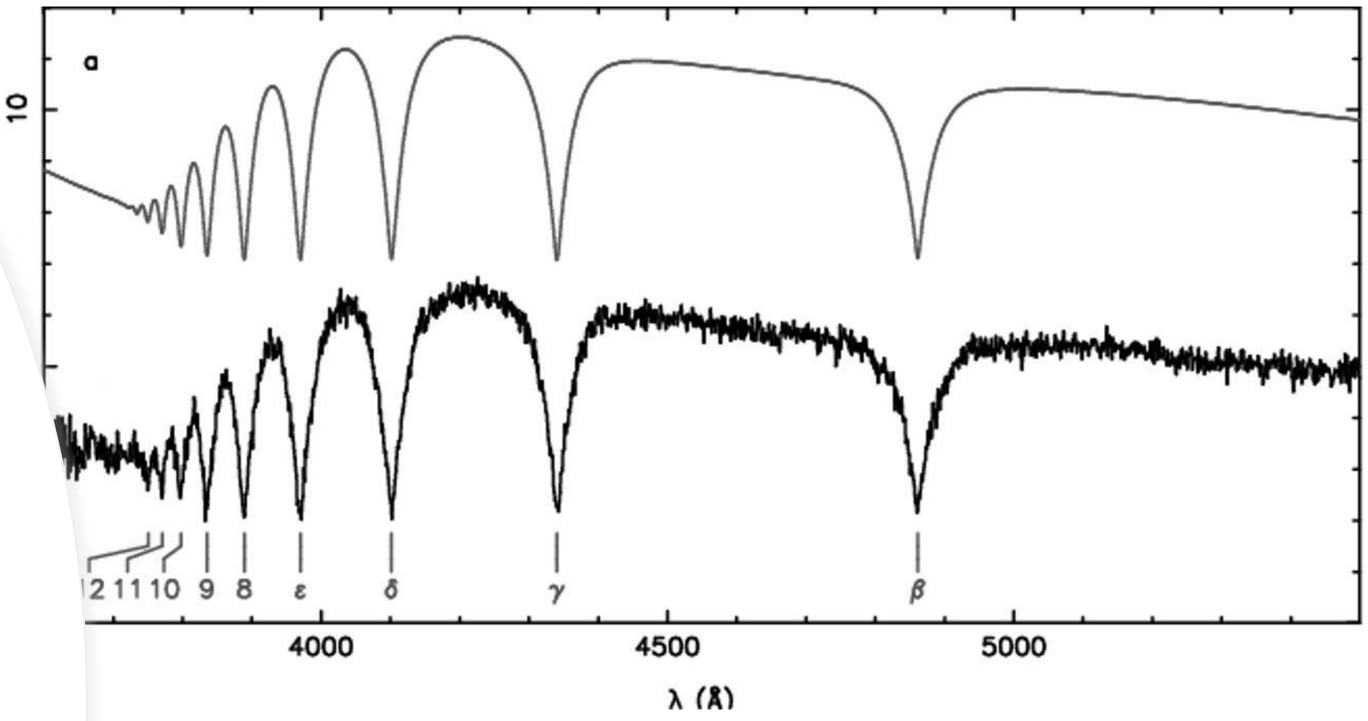
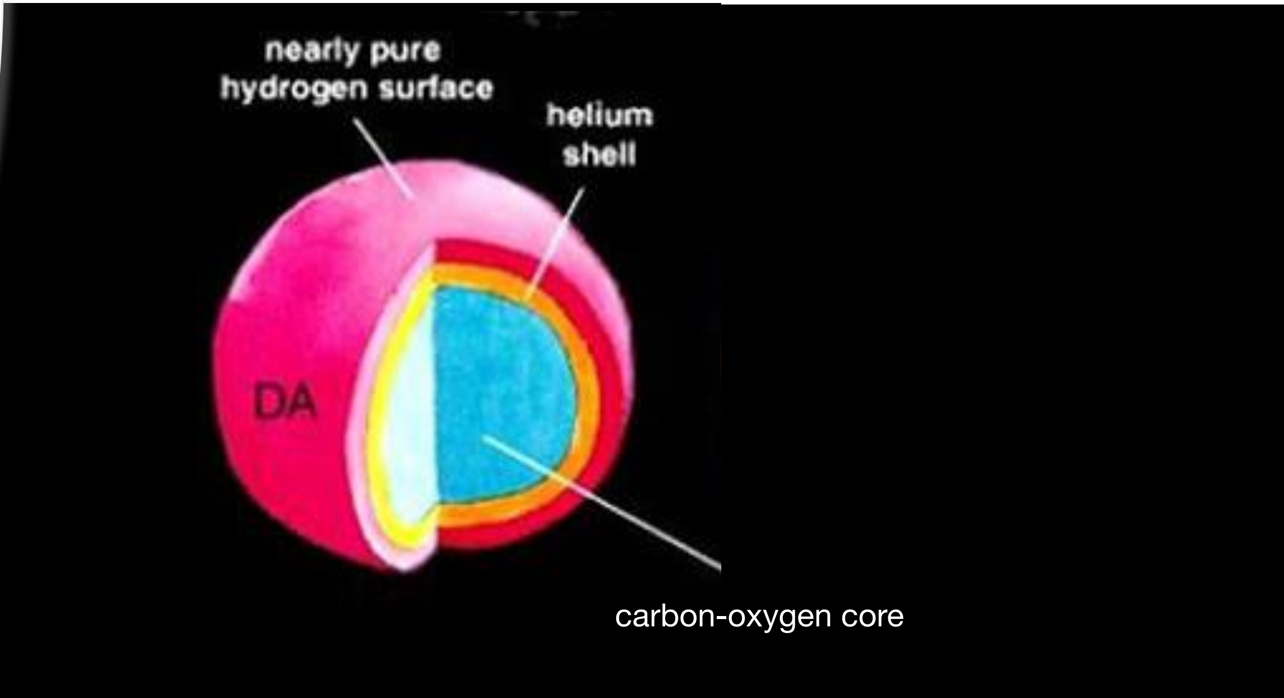


Illustration: Kurzgesagt

The typical white dwarf

- Mass ~ half the mass of the Sun
- Radius ~ that of the Earth
- Hydrogen dominated atmosphere (DA)
- Carbon-oxygen core





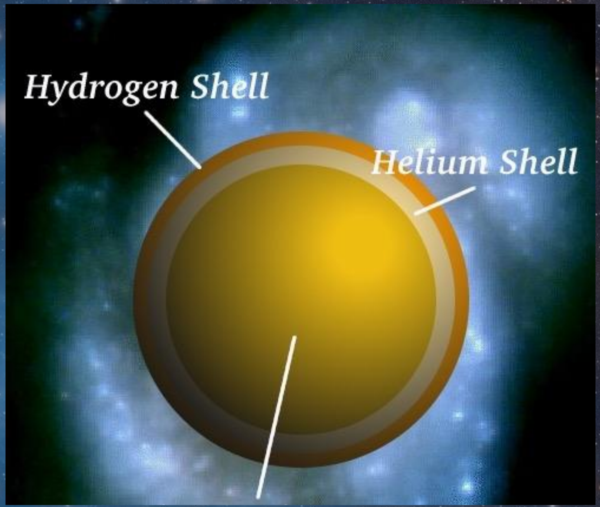
Open questions: the atypical ones

Massive white dwarfs

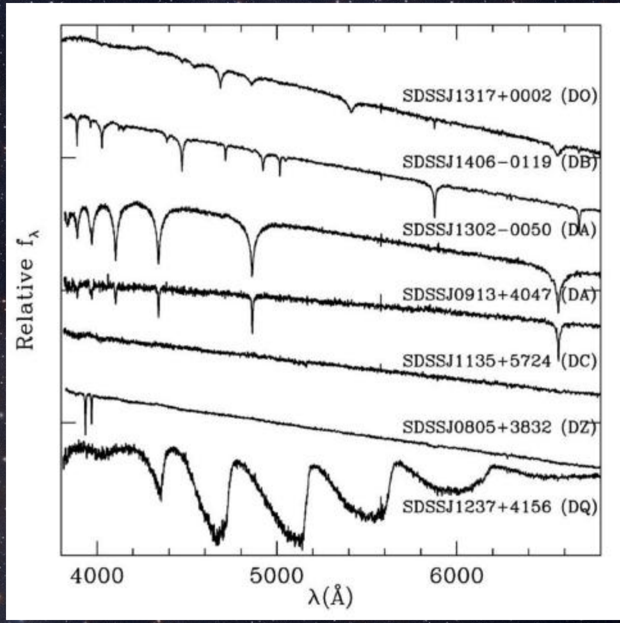
- What's the composition of high mass white dwarfs?
- What is the relation between the initial mass of the progenitor star and the final mass of the white dwarf?

Different atmospheric composition

- DO / DB – helium dominated atmospheres
- DQ – carbon dominated atmospheres
- DZ – polluted with metals
- DC – featureless …



Carbon and Oxygen or Oxygen and Neon?



Magnetic white dwarfs

- ~20% of white dwarfs are observed to be magnetic
- Magnetic fields range from a few tens of kG to almost 10^9 G
- Many theories, including DOUBLE WHITE DWARF MERGERS

Progenitors of type Ia supernovae?

- Double degenerate mergers? Accreting WDs?

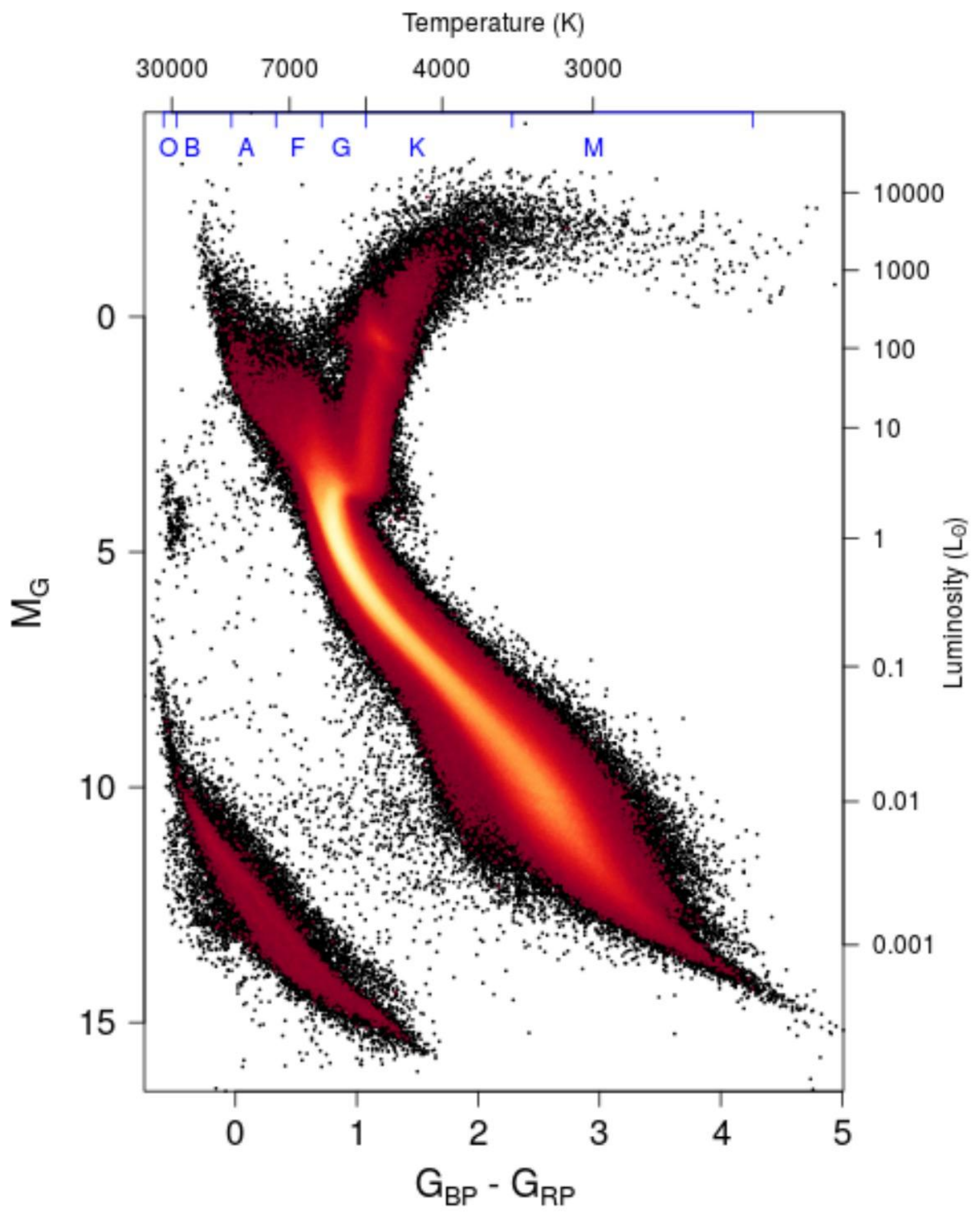
Finding white dwarfs

Before Gaia

- WDs identified through spectroscopy (SDSS)
- Or through multiple-filter photometry and reduced proper motions
- Biased and incomplete sample

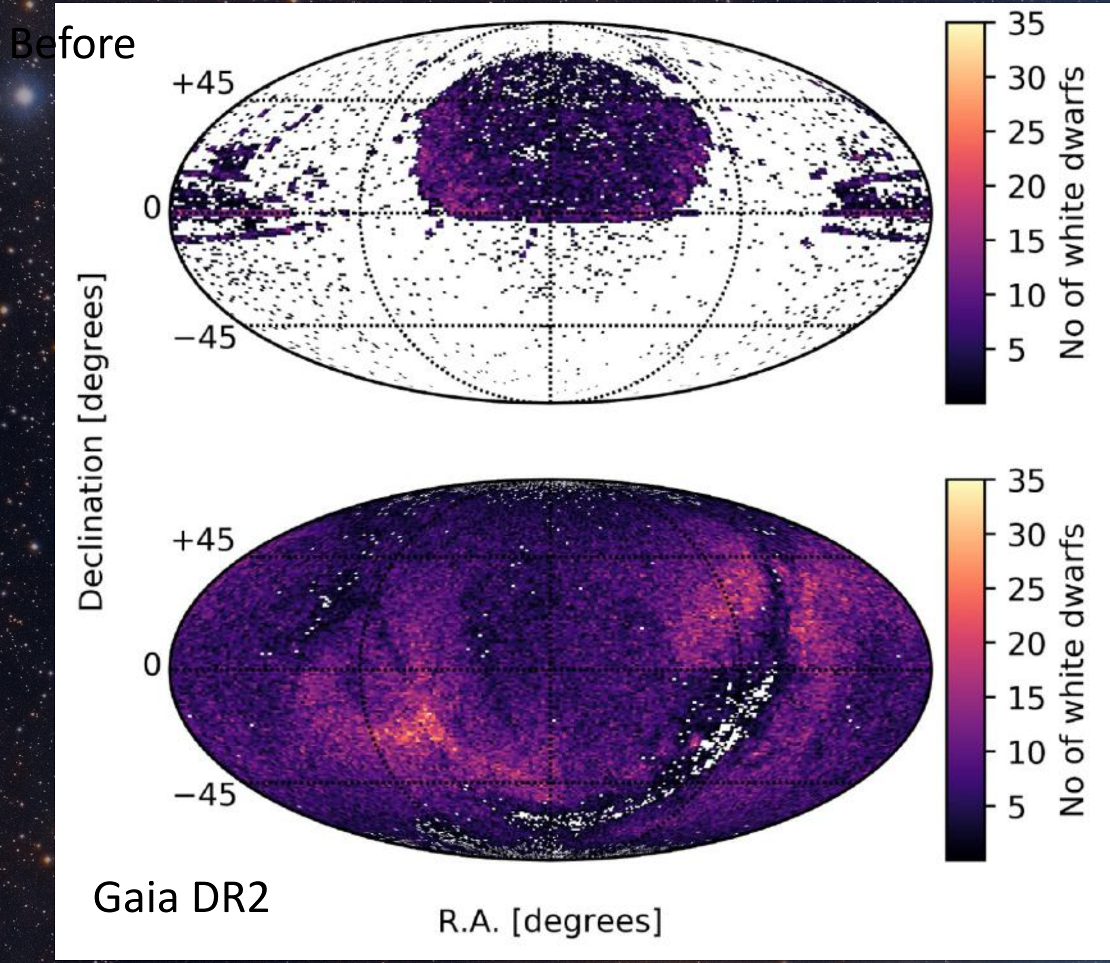
After Gaia

- Precise photometry and astrometry for billions of stars, including white dwarfs
- Now we can identify white dwarfs with color and absolute magnitude



Babusiaux+ 2018

Gaia white dwarf catalog



Gentile Fusillo+ 2019

Before Gaia

- About 35,000 WDs known, mostly in the northern sky

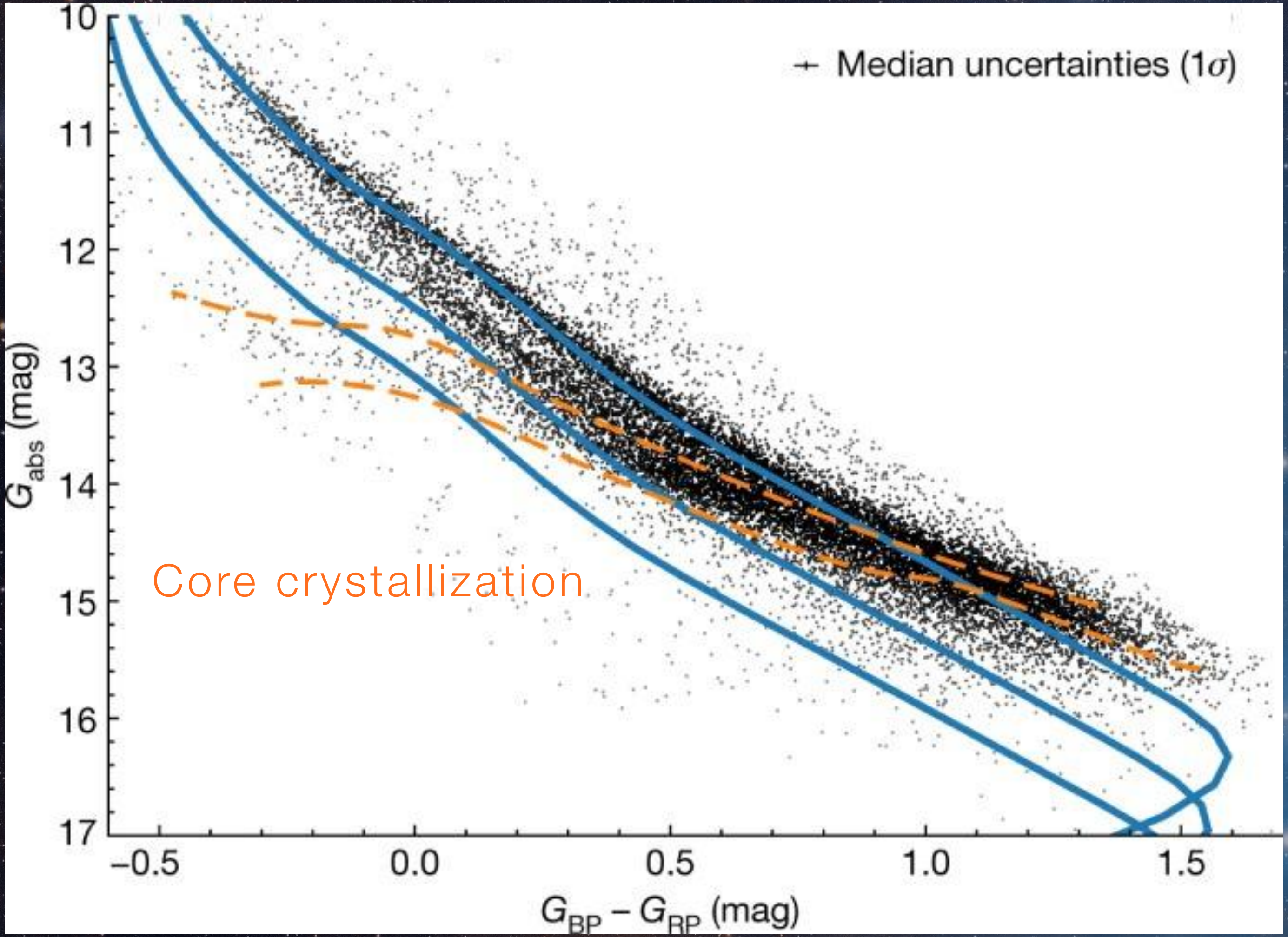
After DR2

- ~260,000 photometrically identified white dwarfs (Gentile Fusillo+ 2019)

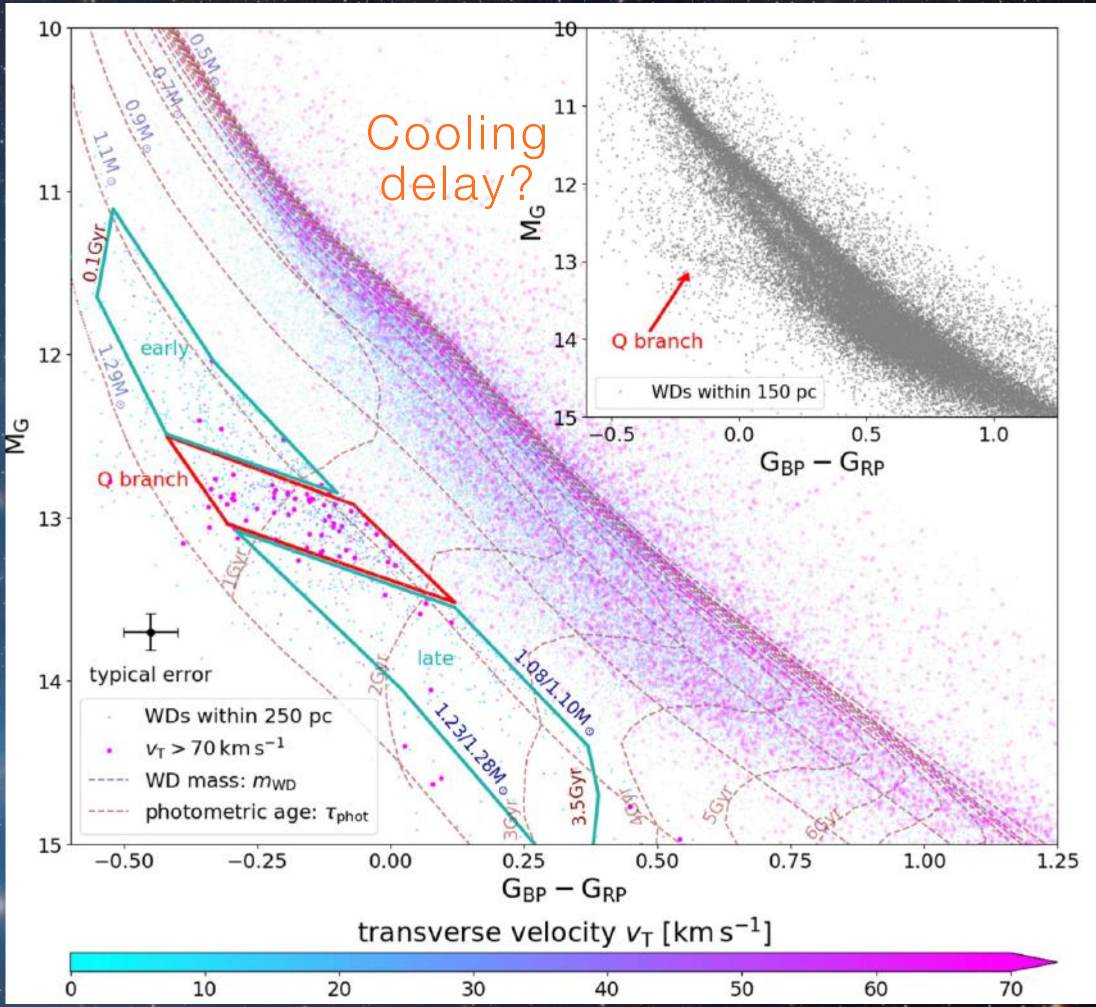
After eDR3

- Better parallax, more uniform, deeper:
- ~ 400,000 white dwarfs (Gentile Fusillo+ 2021)

The cooling of massive WDs

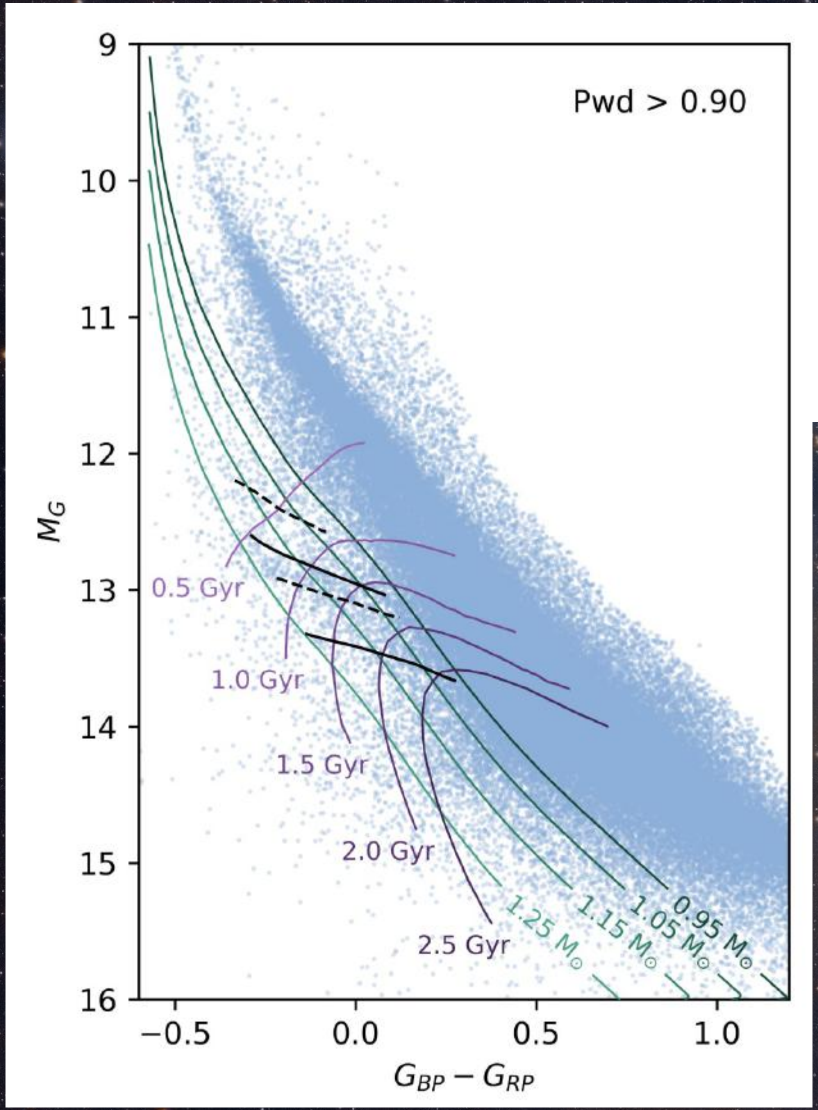


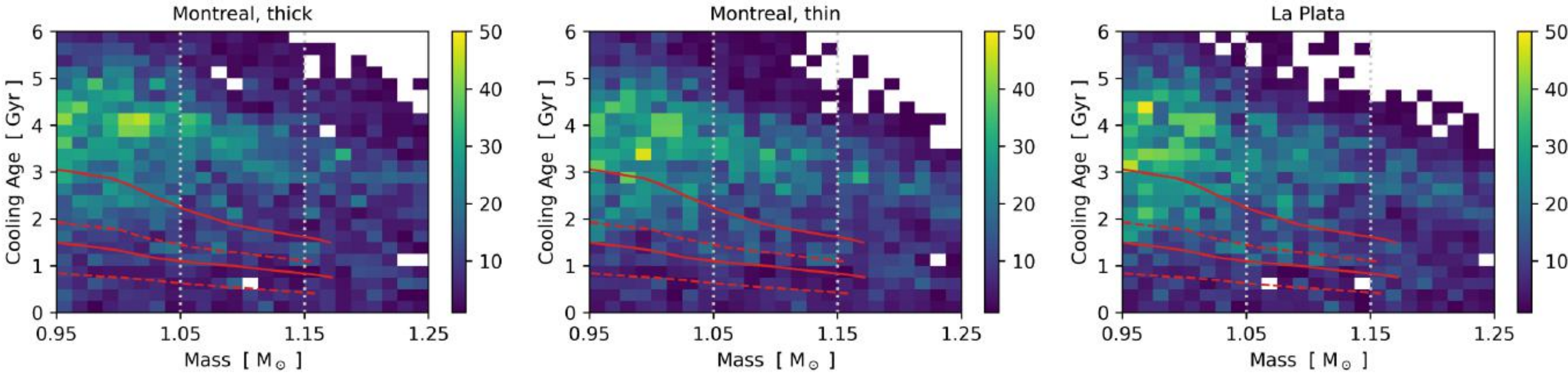
Tremblay+ 2019



Cheng+ 2019

The cooling of massive WDs

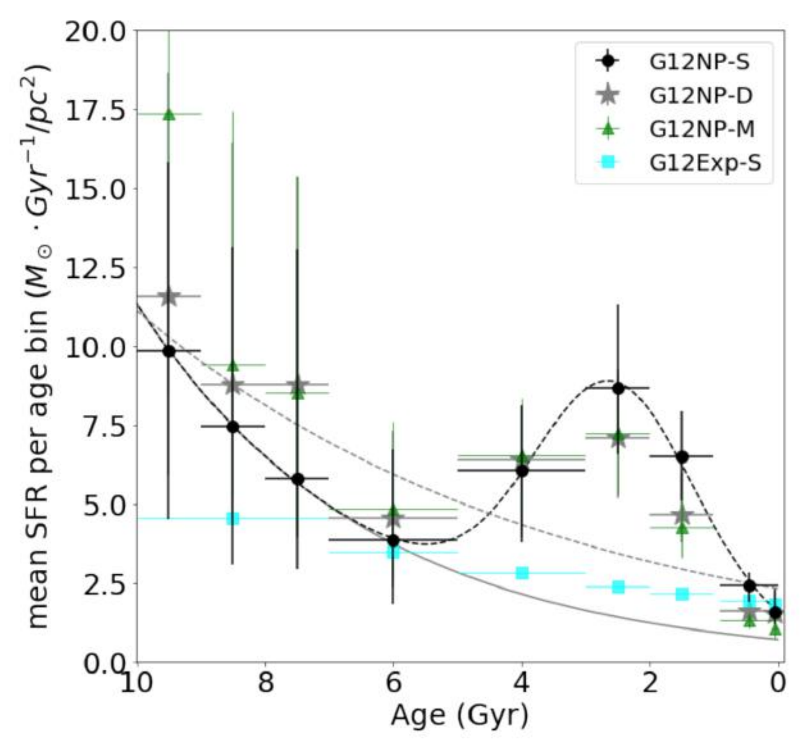


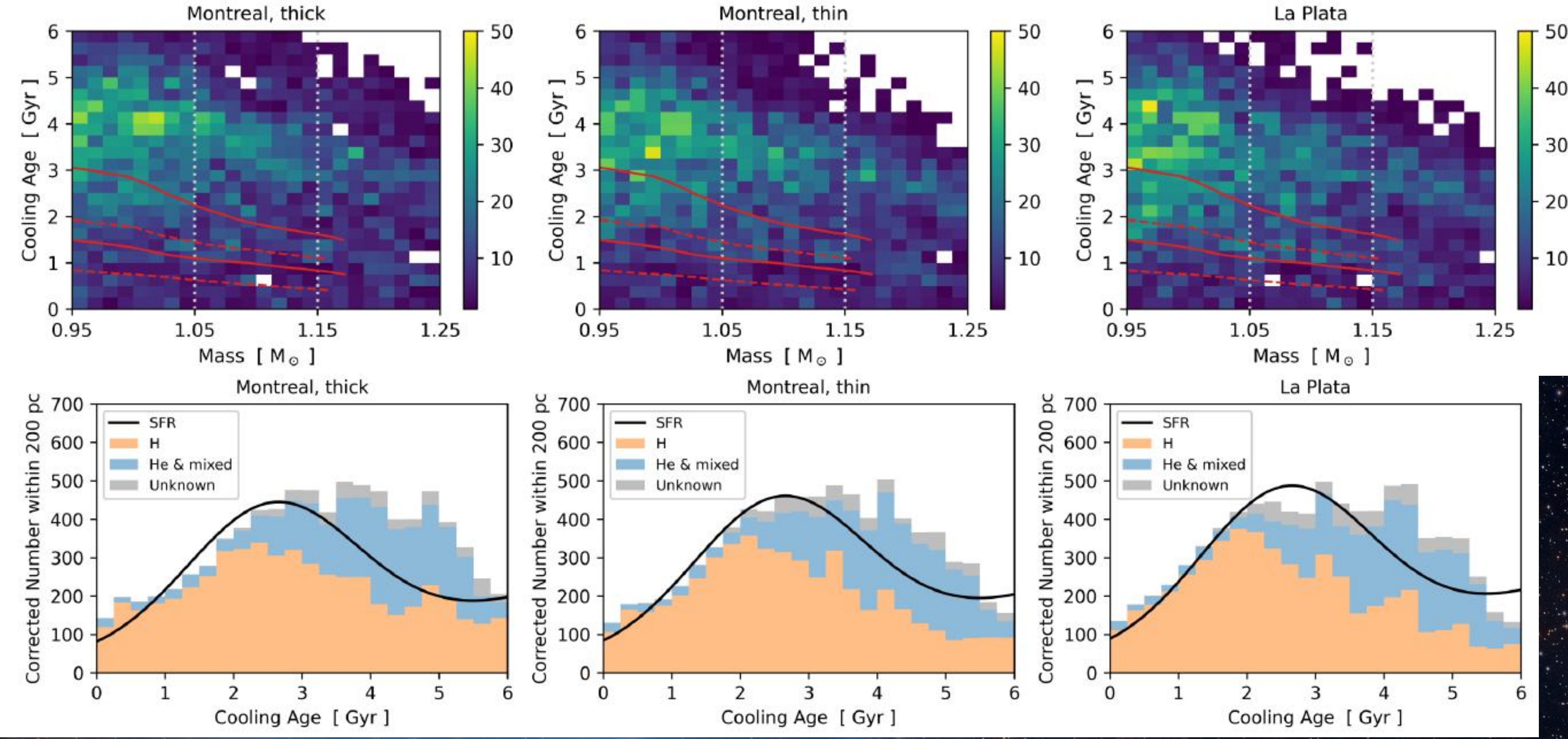


- An excess of white dwarfs?
- Do white dwarfs stay brighter for longer than our models predict?

Fleury, Caiazzo & Heyl 2021

The cooling of massive WDs





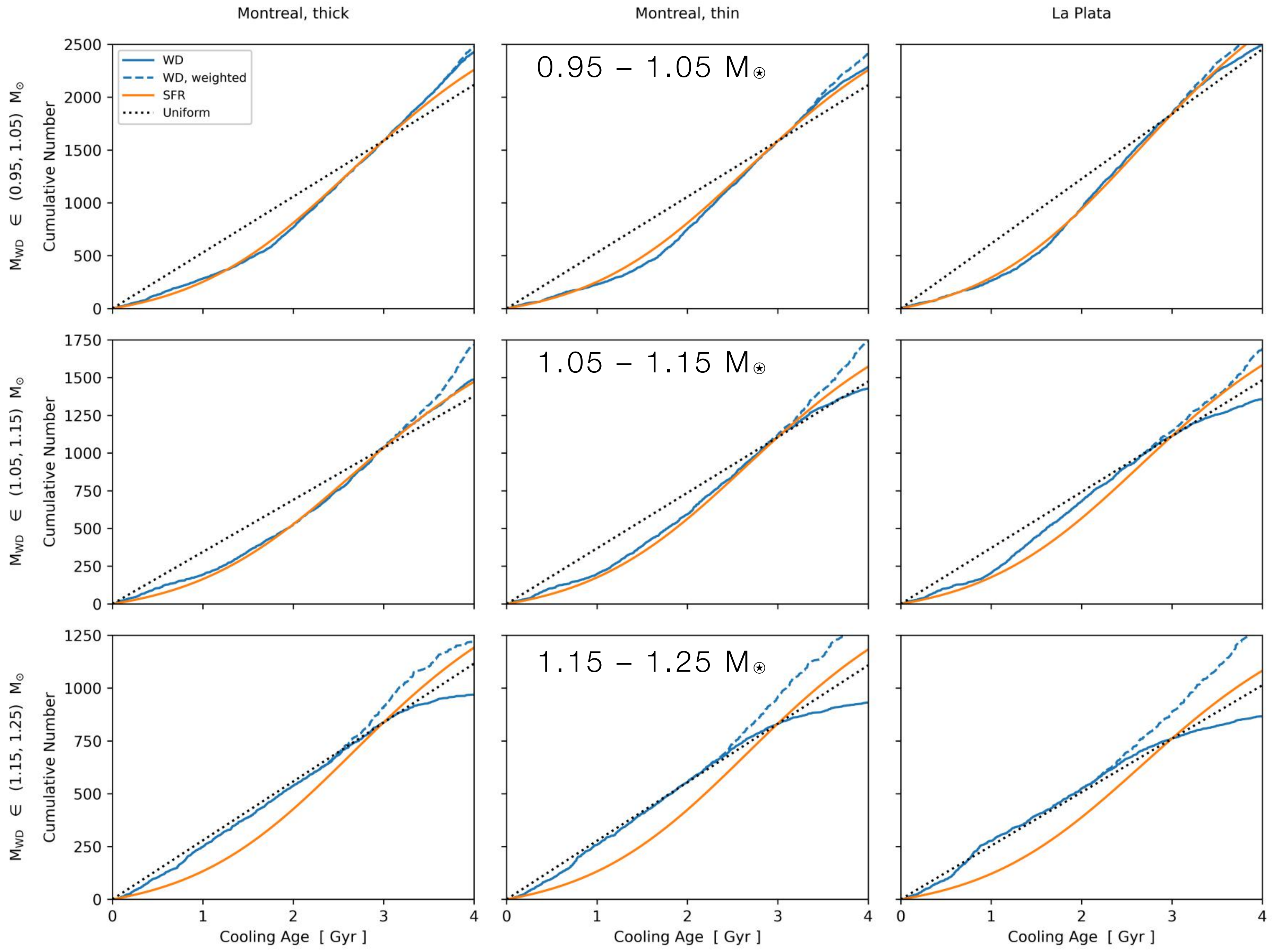
Mor+2019

Gaia DR2

- An increase in star formation rate between 4 and 2 Gyr ago, possibly due to a merger event

- The increase in SFR explain very nicely the overabundance of white dwarfs!

Fleury, Caiazzo & Heyl 2021



- SFR
- Observed
-- Uniform

- The two lower mass bins follow the star formation history
- The highest mass bin follow a uniform distribution
- The highest bin contains a large fraction of white-dwarf merger remnants

Fleury, Caiazzo & Heyl 2021

How do you find a merger remnant?

- Massive
- Highly magnetized
- Rapidly rotating

....you search with ZTF!

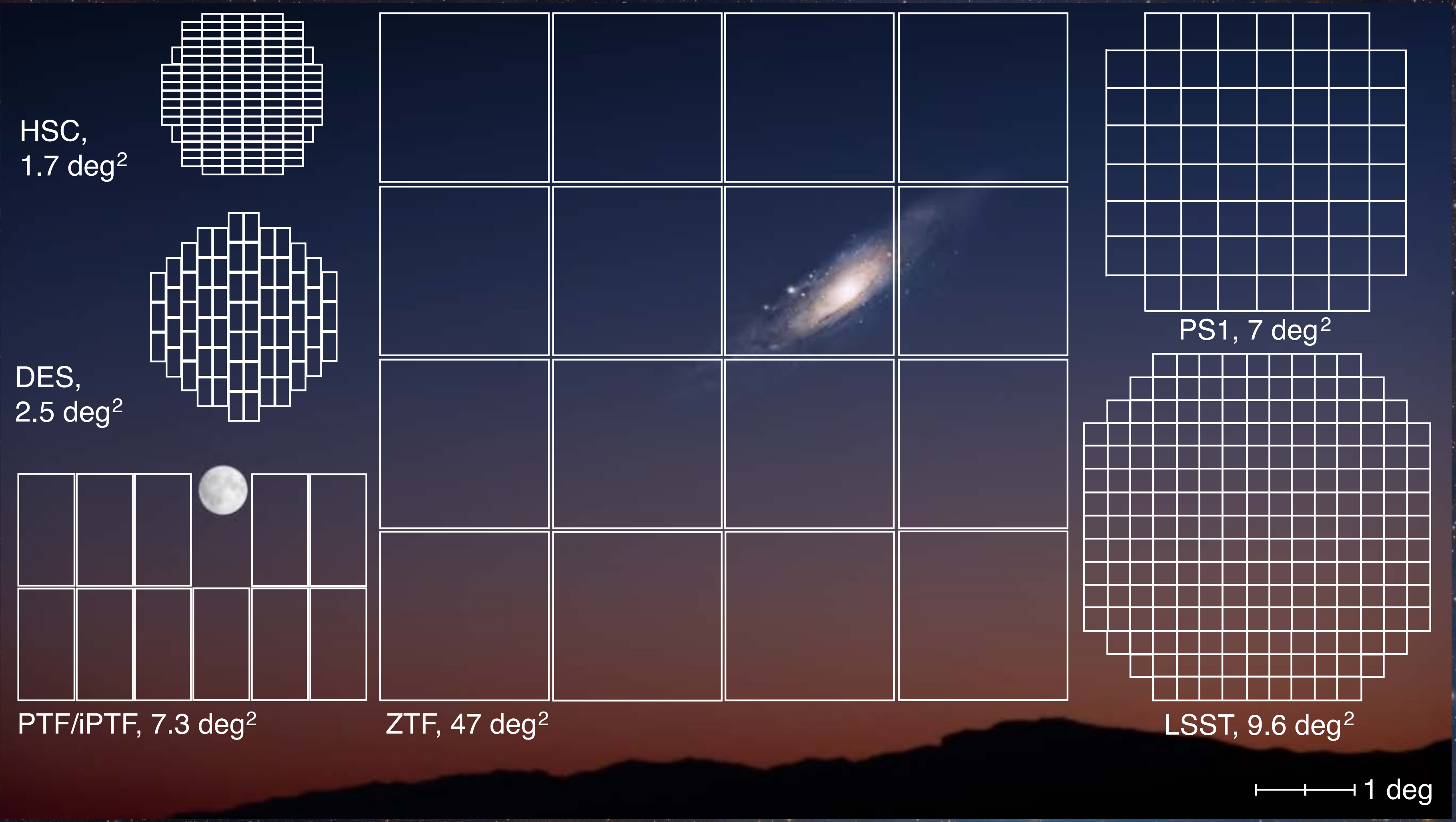
Zwicky Transient Facility

S. R. Kulkarni
Principal Investigator

M. Graham
Project Scientist

E. Bellm
Survey Scientist

Variable Stars Facility as well



- Huge field of view: 47 square degrees
- Almost daily cadence over the entire northern sky
- Hundreds of epochs for each source

- And the amazing software developed by Kevin Burdge, Przemek Mròz and all the variable stars group

How do you find a merger remnant?

- Massive
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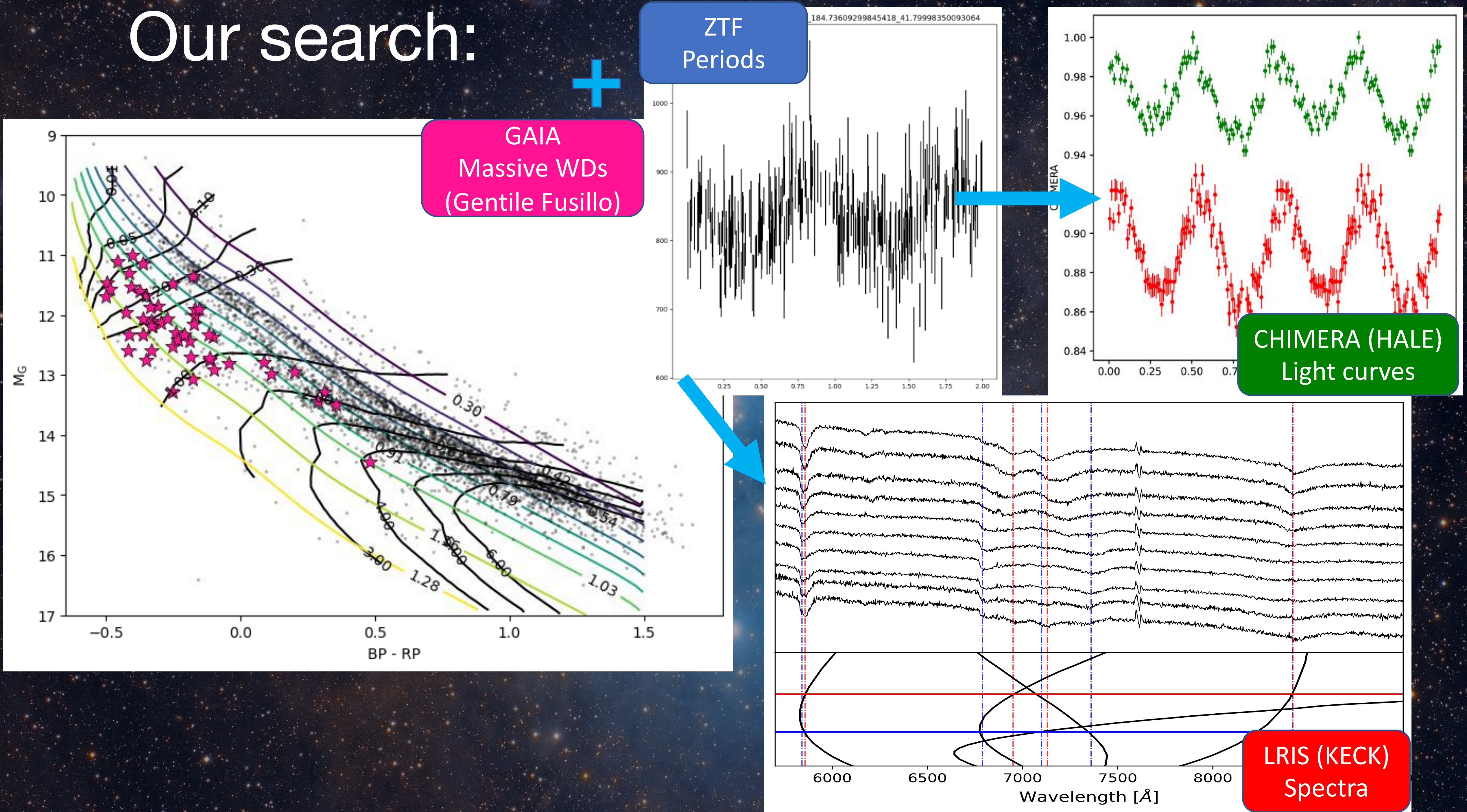
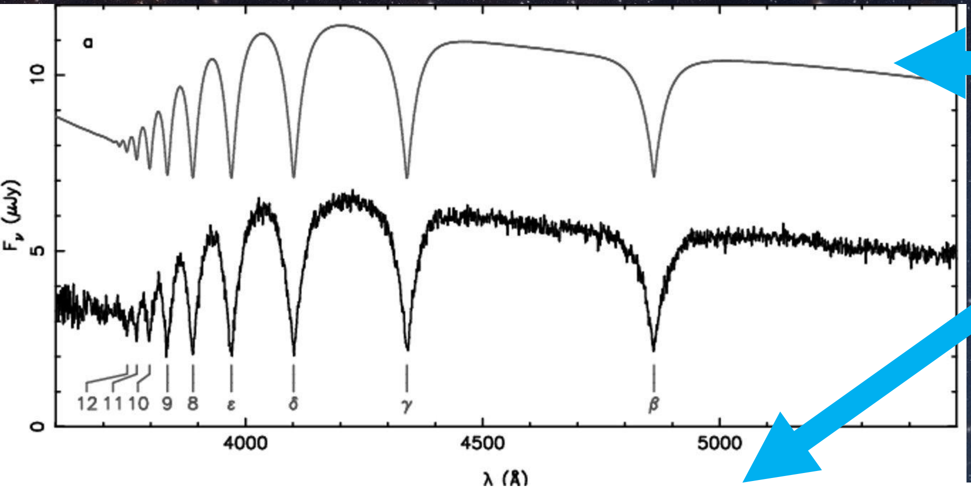
….you search with ZTF!

Our search:



+
GAIA
Massive WDs
(Gentile Fusillo)
ZTF
Periods
184.73609299845418_41.79998350093064
CHIMERA (HALE)
Light curves
LRIS (KECK)
Spectra
BP - RP
M_G
Wavelength [Å]

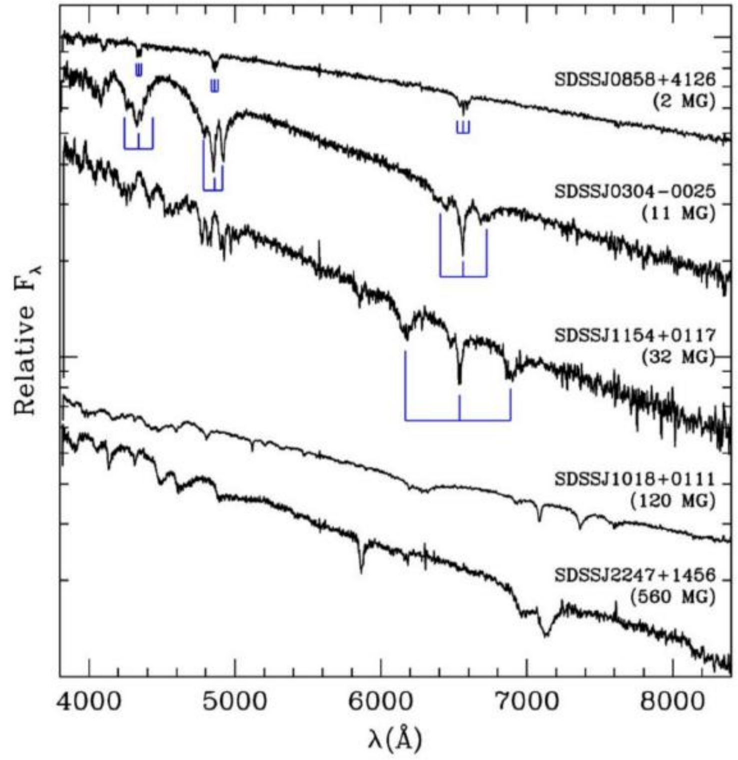
Are they magnetic?

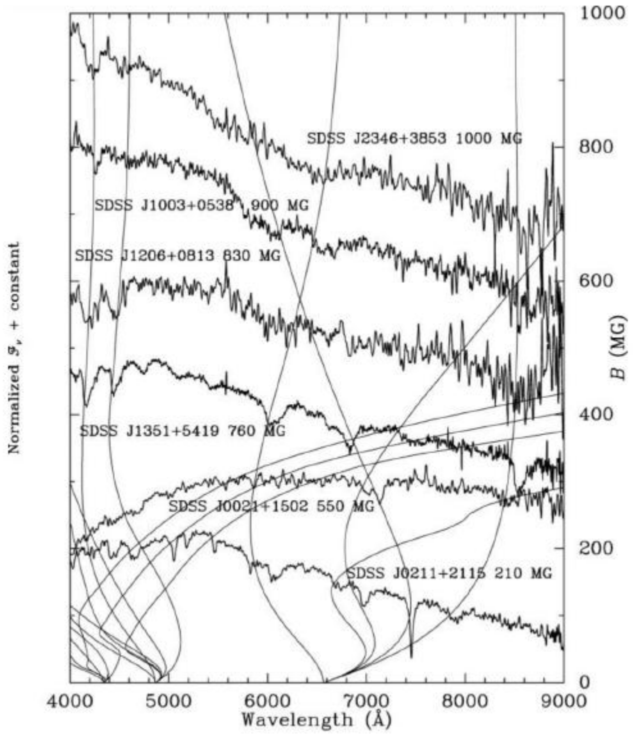


Non-magnetic spectrum

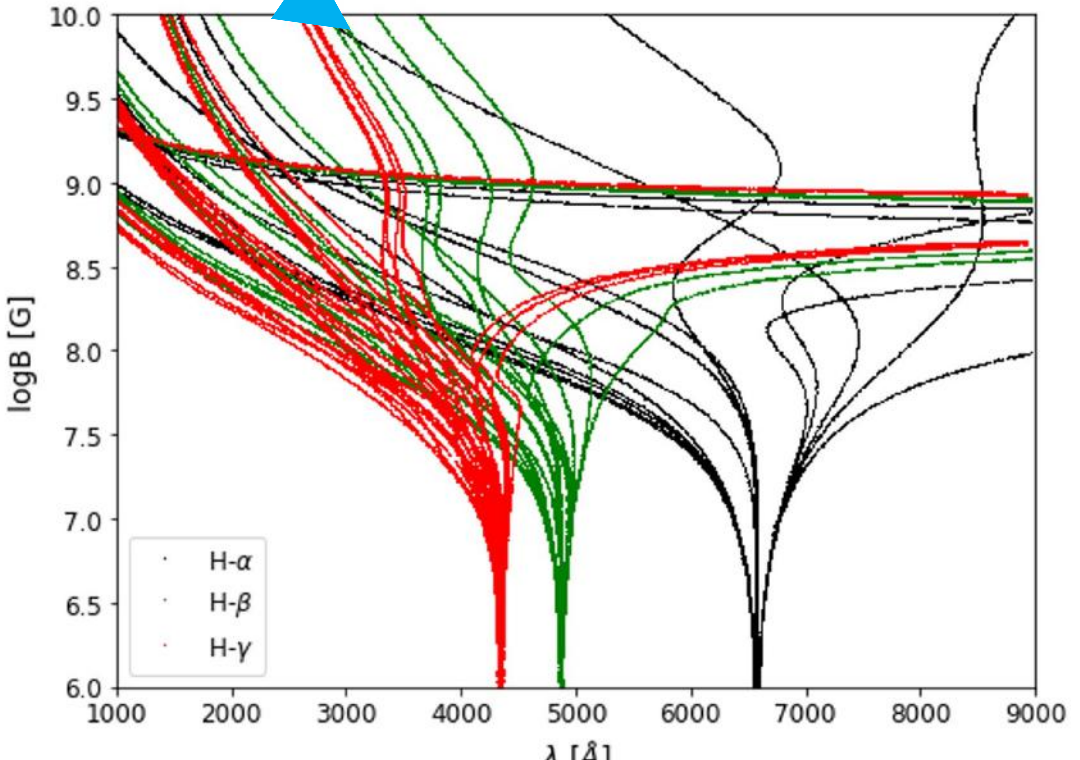
In magnetic WDs the degeneracy of the hydrogen energy levels is lifted -> Zeeman splitting

At high fields, the energy of each transition gets shifted by a large amount





(Vanlandingham et al. 2005)




Article

A highly magnetized and rapidly rotating white dwarf as small as the Moon

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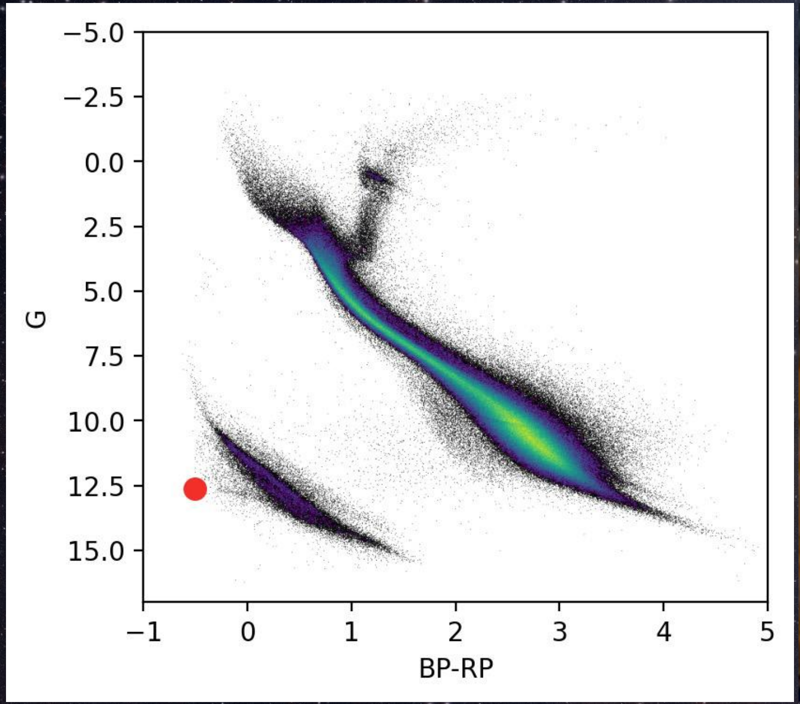
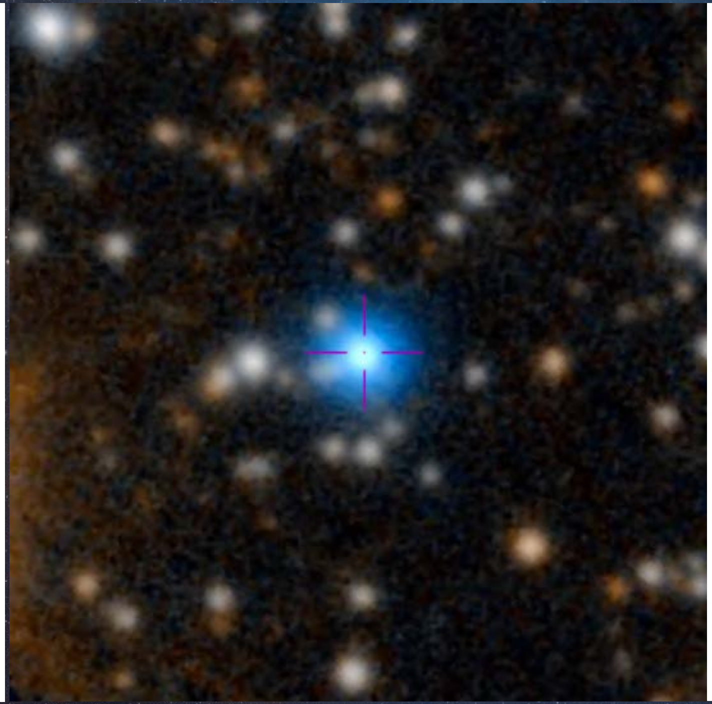
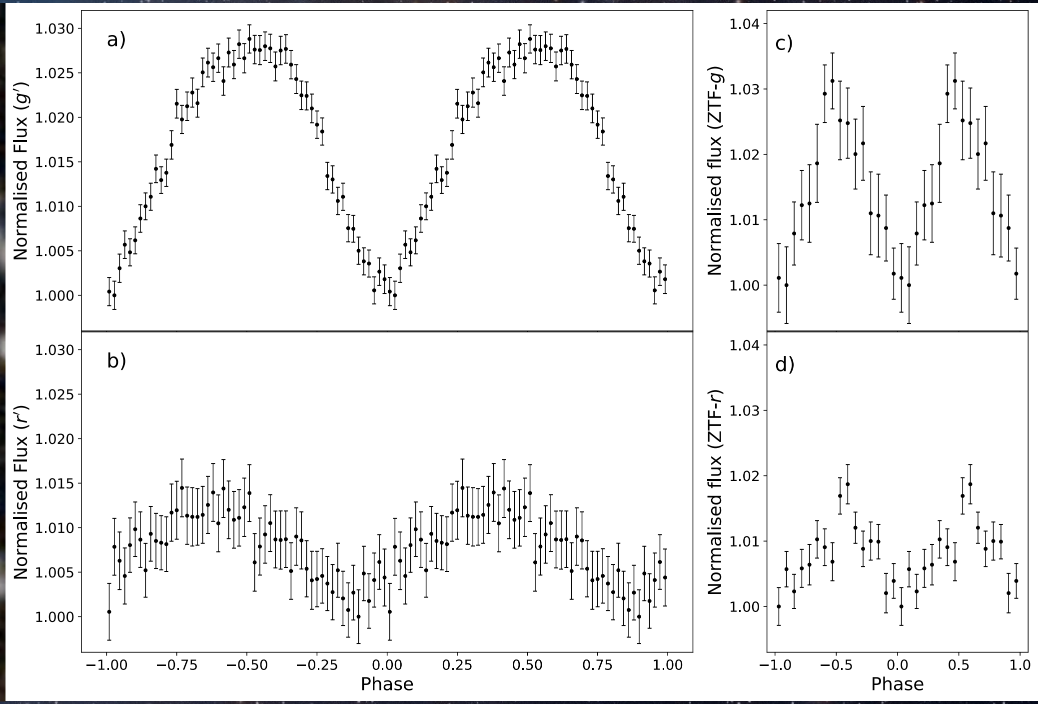
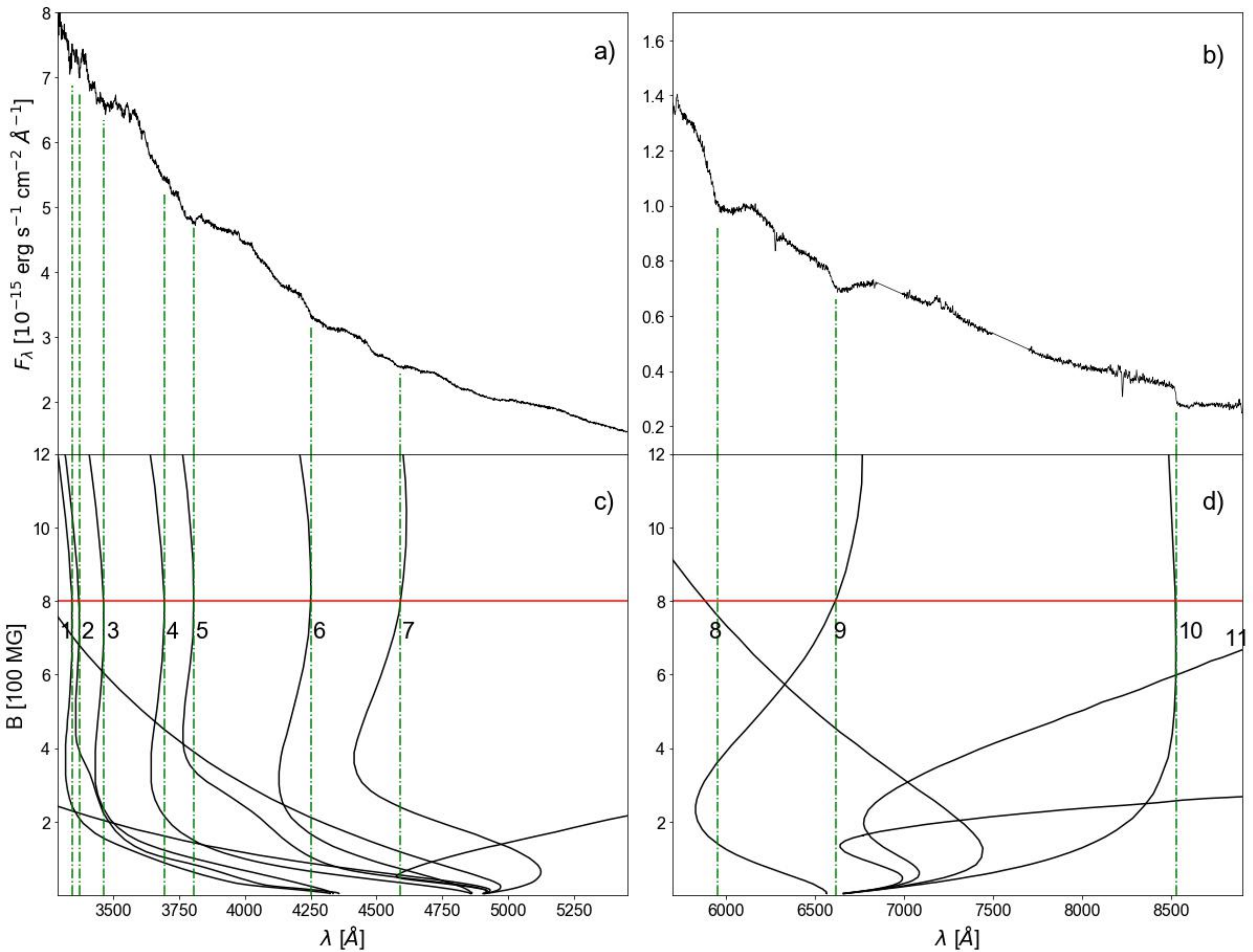
- ZTF 1901+1458
- 6.94 min period
- extremely blue



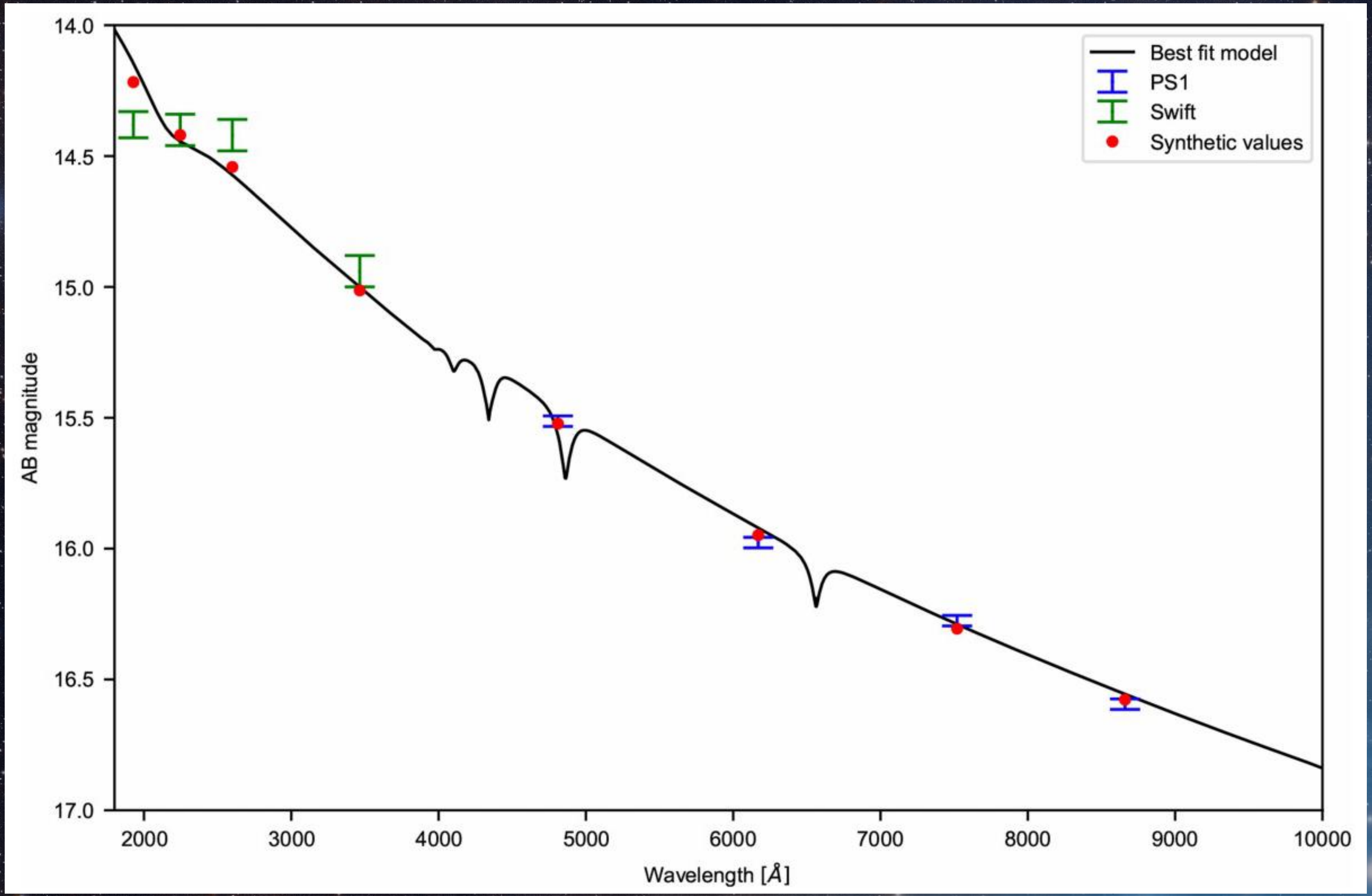


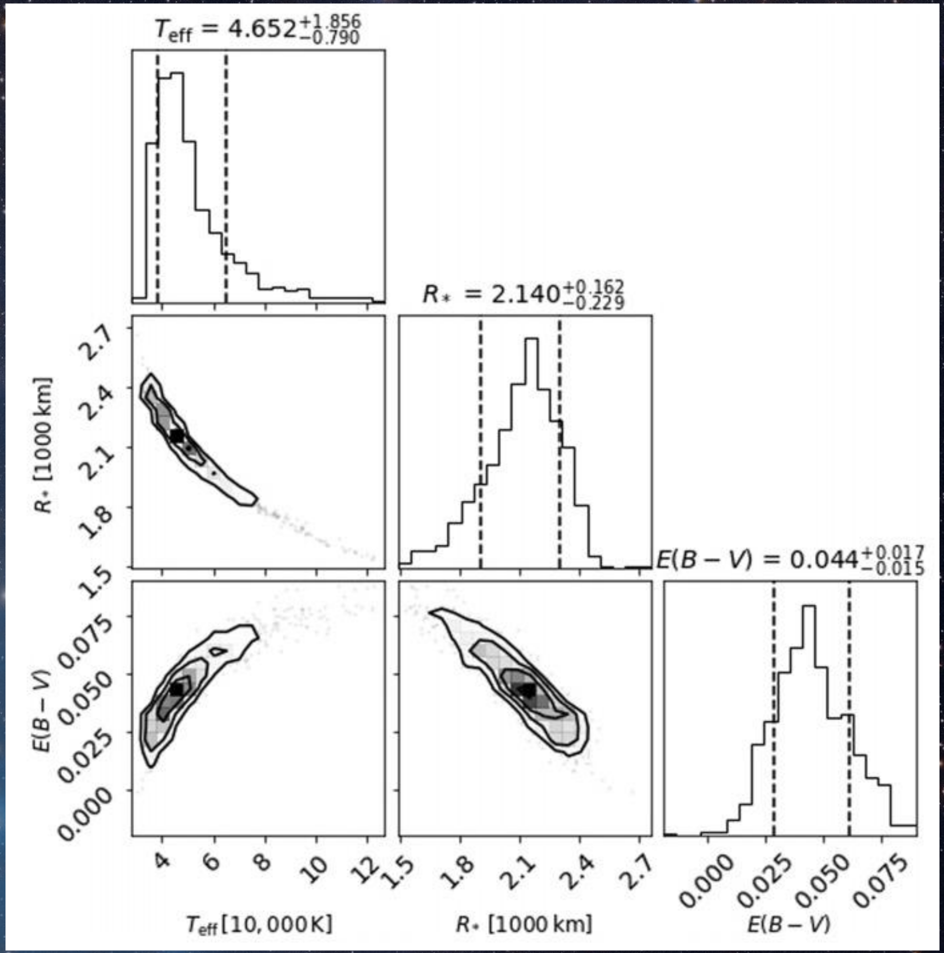




- Co-added spectrum from LRIS on Keck
- Most features identified at a field of ~800 MG
- Features changing with phase suggest changes in the field over the surface

Photometric fitting



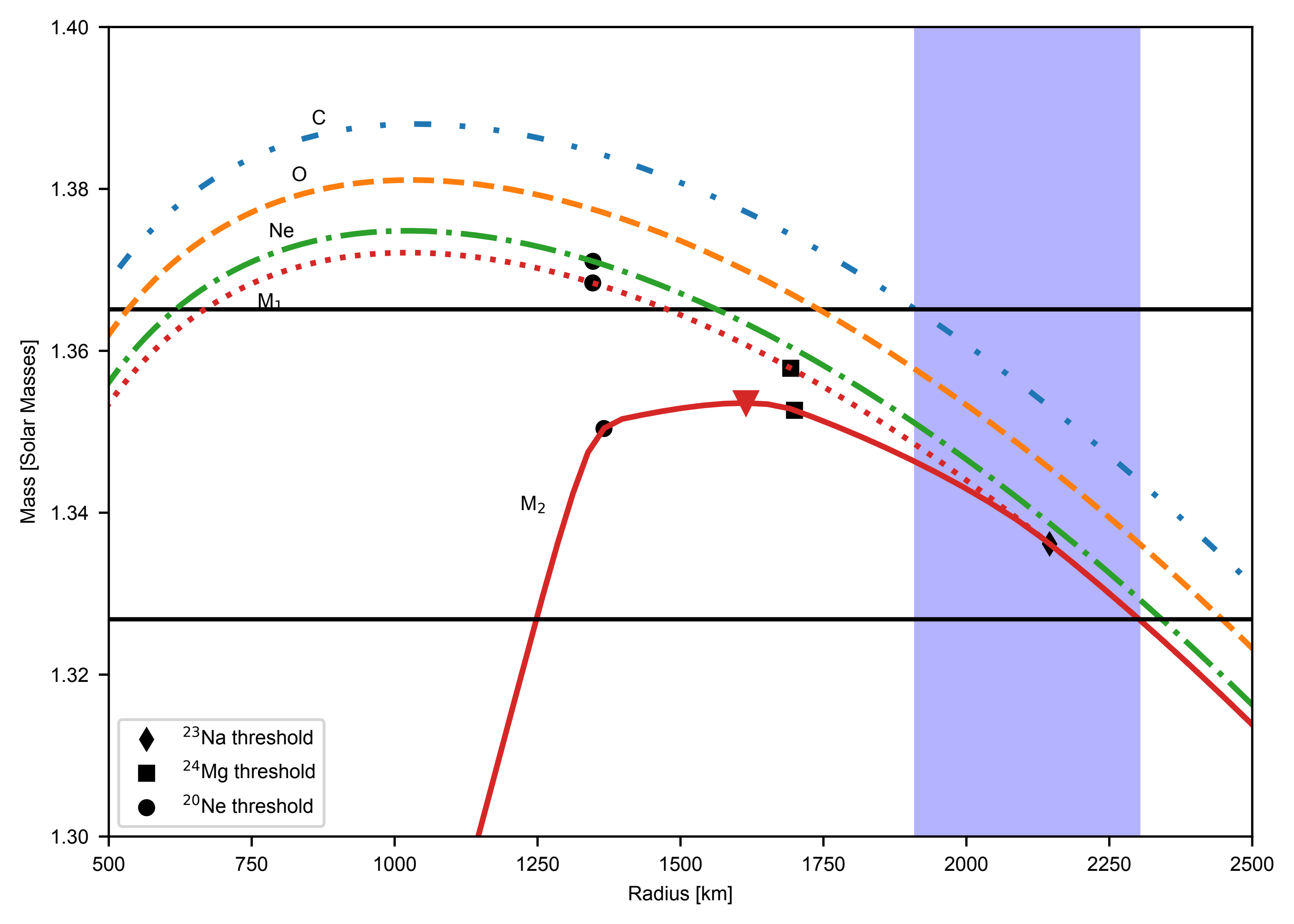


- T_{eff} = 46,000 K
- R = 2140 km
- E(B-V) = 0.044

- Small radius means large mass
- Depending on the composition, 1.33-1.37 solar masses

Image by Giuseppe Parisi

The first white dwarf to be cooling through Urca processes

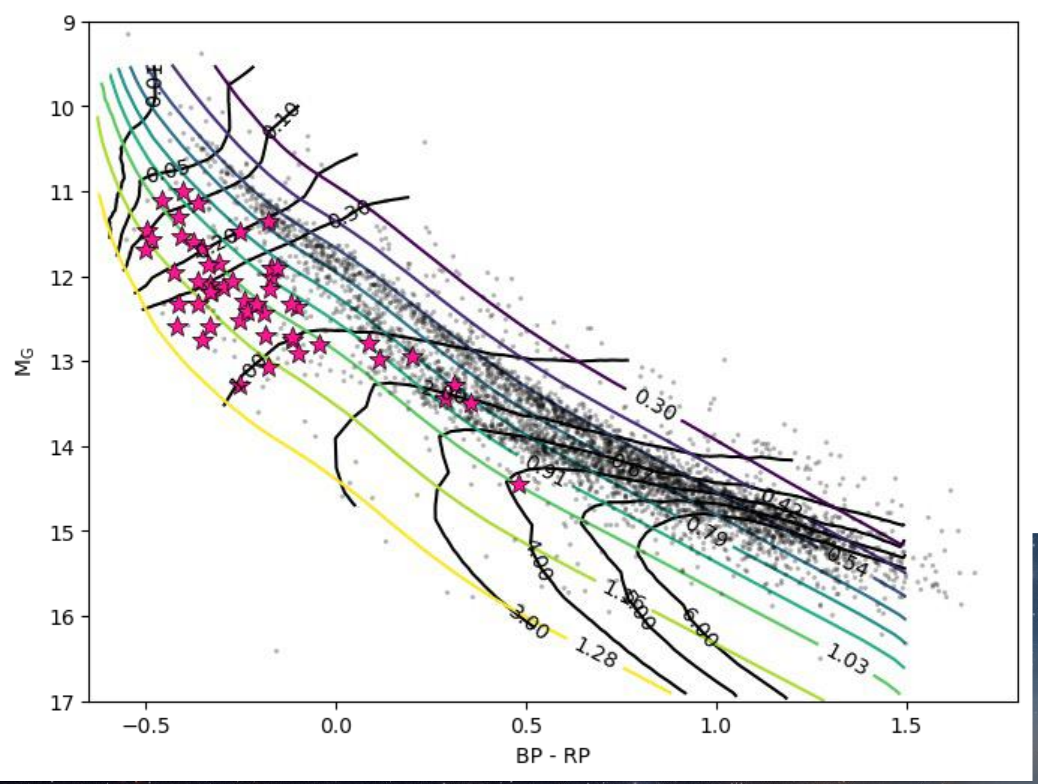


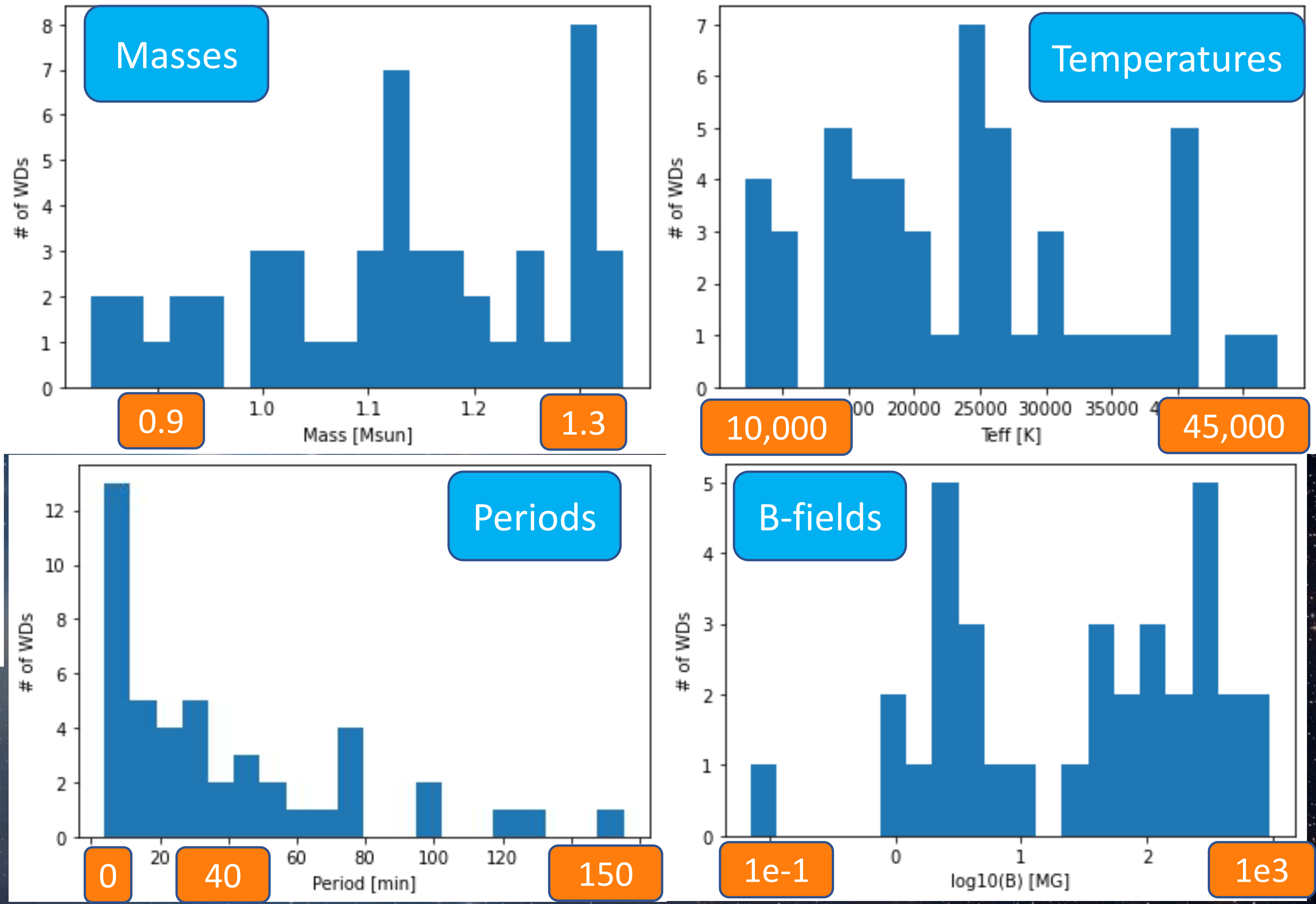
- The density in the core is so high that the sodium is undergoing electron capture
- The neutrino emissions from this process (also called Urca) is contributing strongly to the cooling of the white dwarf
- As more sodium sediments in the core, more electrons are captured and the white dwarf will keep shrinking
- The WD might be metastable and headed toward collapse

Fate of the white dwarf

- If the star collapses, depending on the dynamics of oxygen burning it may explode in a thermonuclear supernova or collapse into a neutron star.
- The resulting neutron star would look like a normal young pulsar, with a magnetic field of about 2×10^{13} G and a period of ~15 ms.
- Very speculative, but if true, also very common, only 40 pc away.

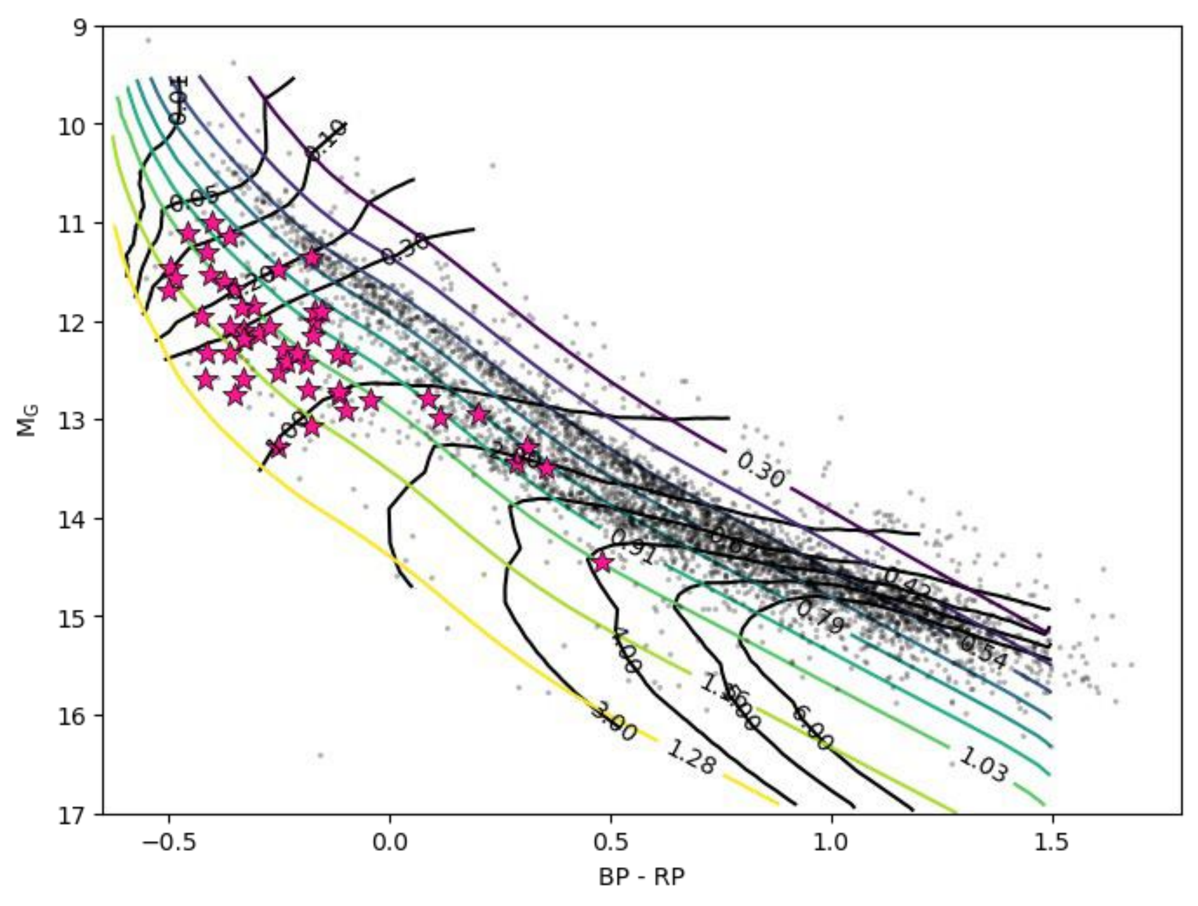
Almost full sample: 50 candidates





- Massive
- Rapidly Rotating
- Warm-Hot
- 30 magnetic
- 20 Featureless or strange

A sample of bona-fide merger remnants



Understanding merger remnants and their properties

- What is the chemical composition of white-dwarf merger remnants?
- Do they evolve differently from white dwarfs born from a single star?
- What is their distribution in masses, ages, periods and magnetic fields?
- What is the delay time between the formation of the white dwarf binary progenitor and the merger?

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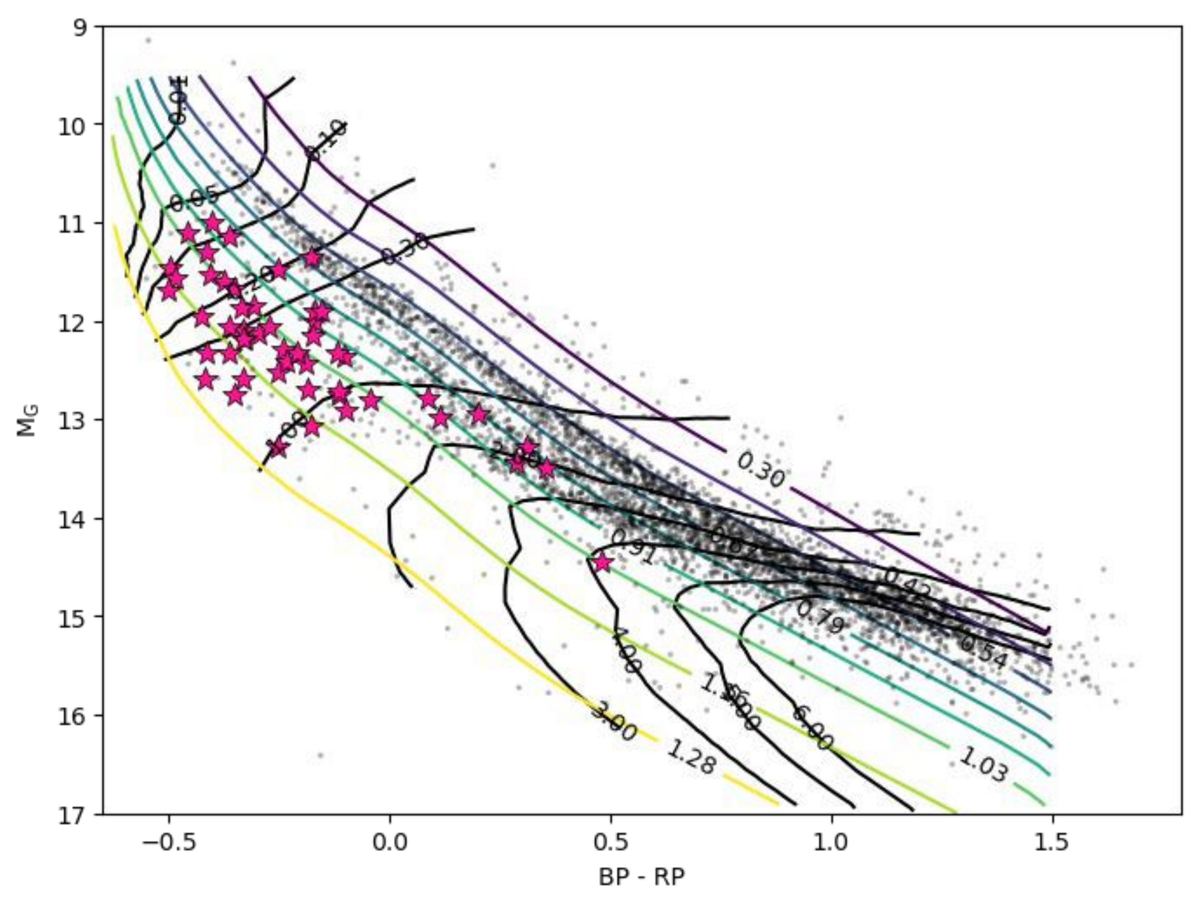

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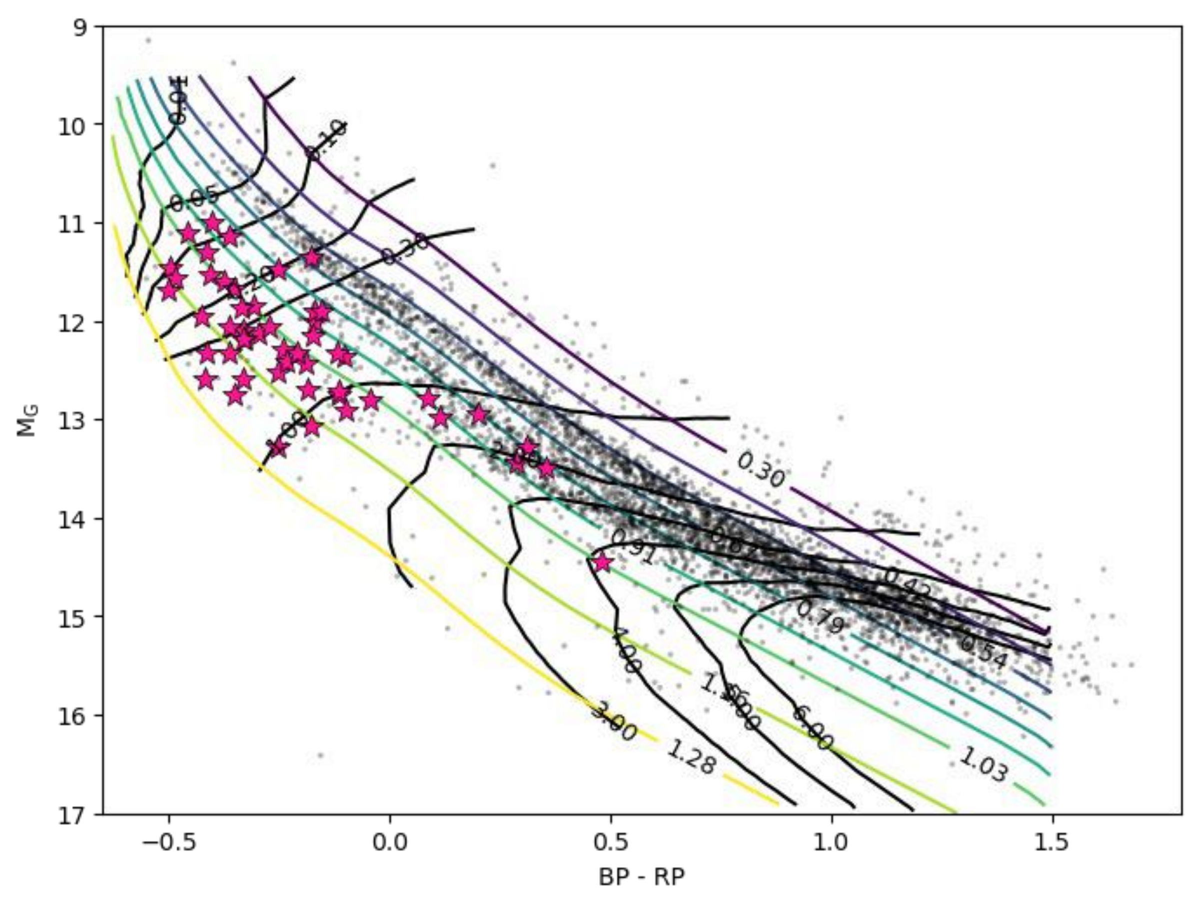
Finding the merger rate in the Galaxy

- What’s the contribution to the supernova rate?
- How many close white dwarf binaries are in the Galaxy, and how many will we find with LISA?

A sample of bona-fide merger remnants



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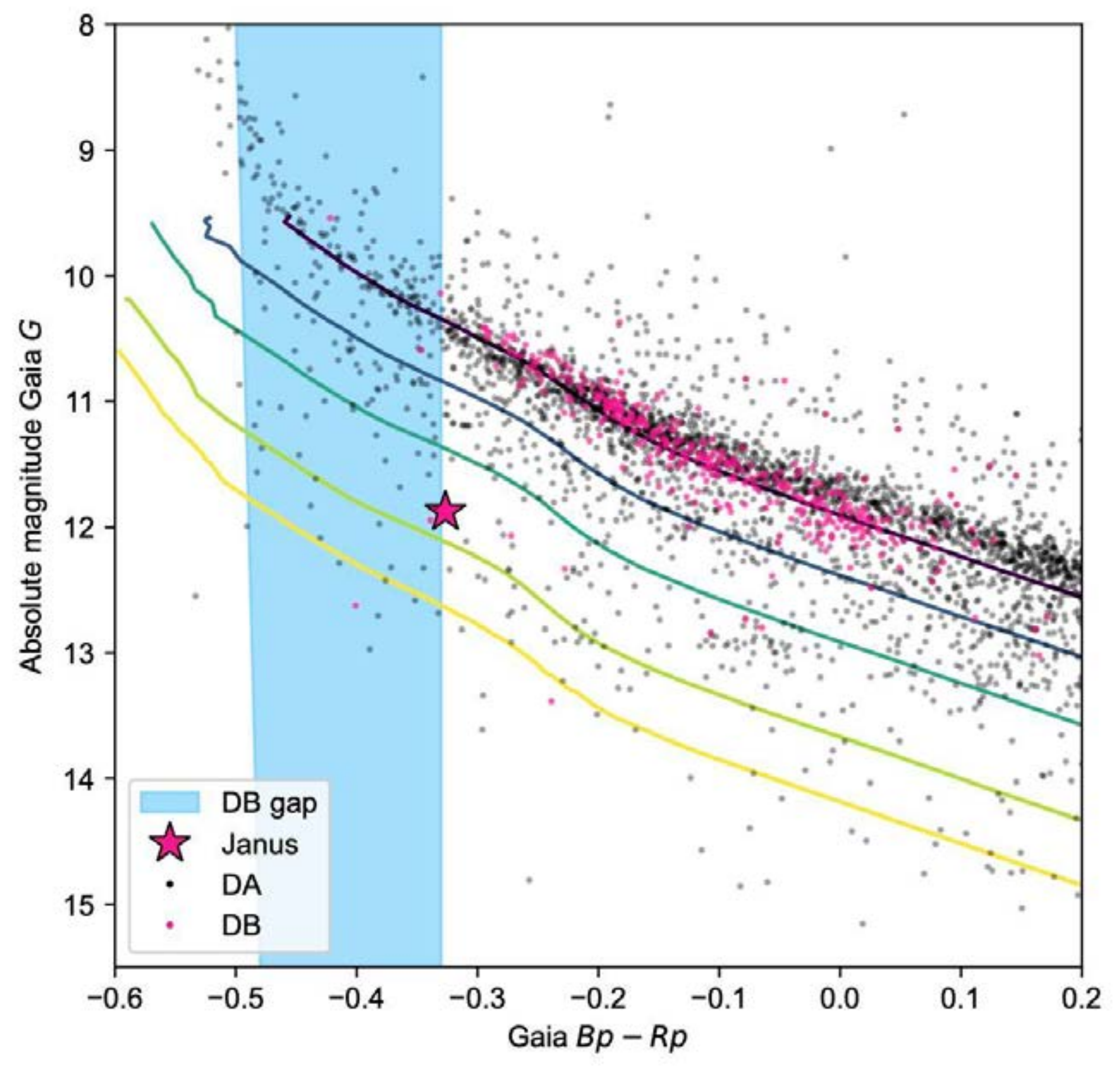
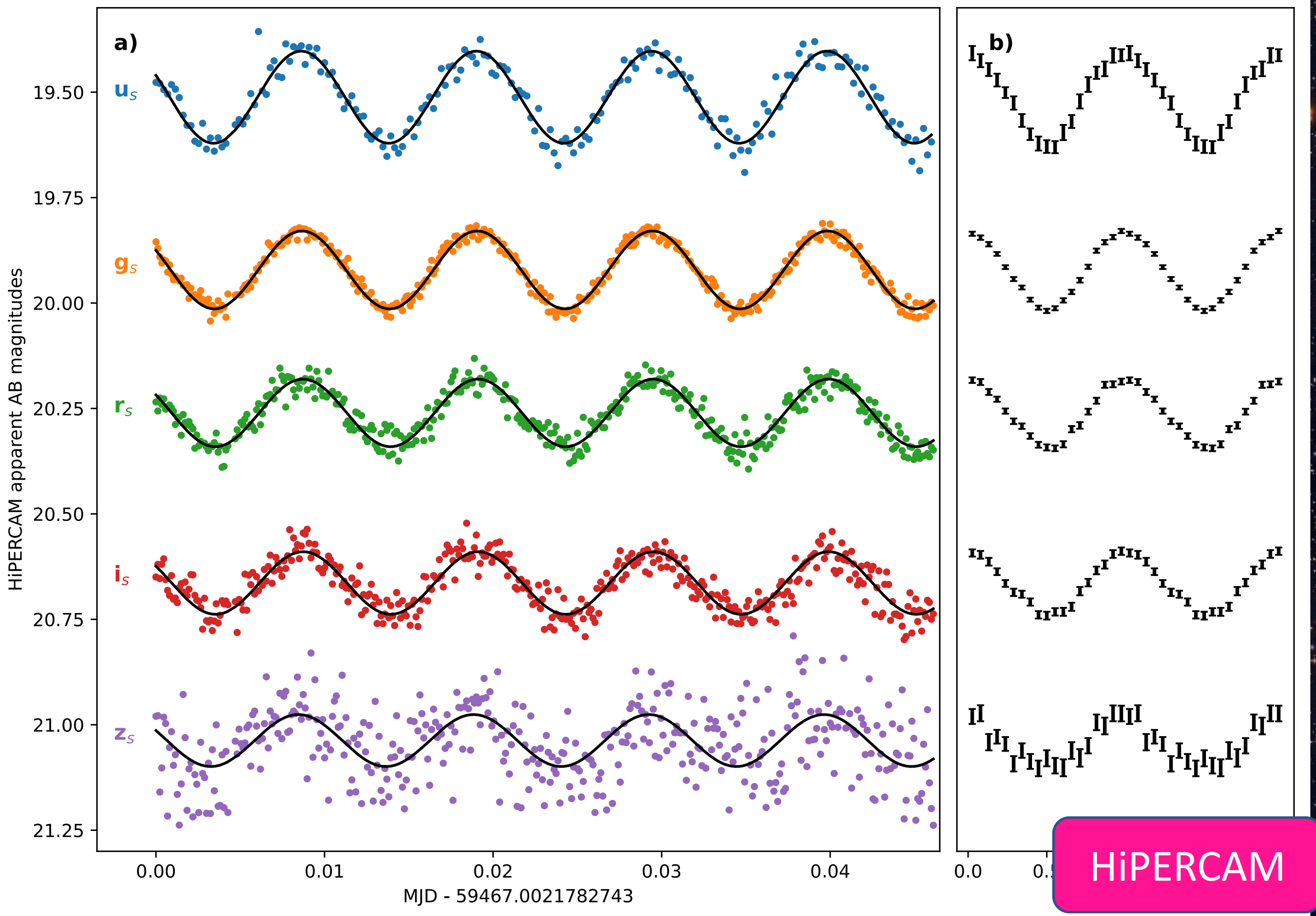
Understanding magnetic fields in white dwarfs

- Are magnetic fields the result of the merger?
- How does magnetic field affect the spectrum of highly magnetized white dwarfs?

Janus, a new class of variables WDs

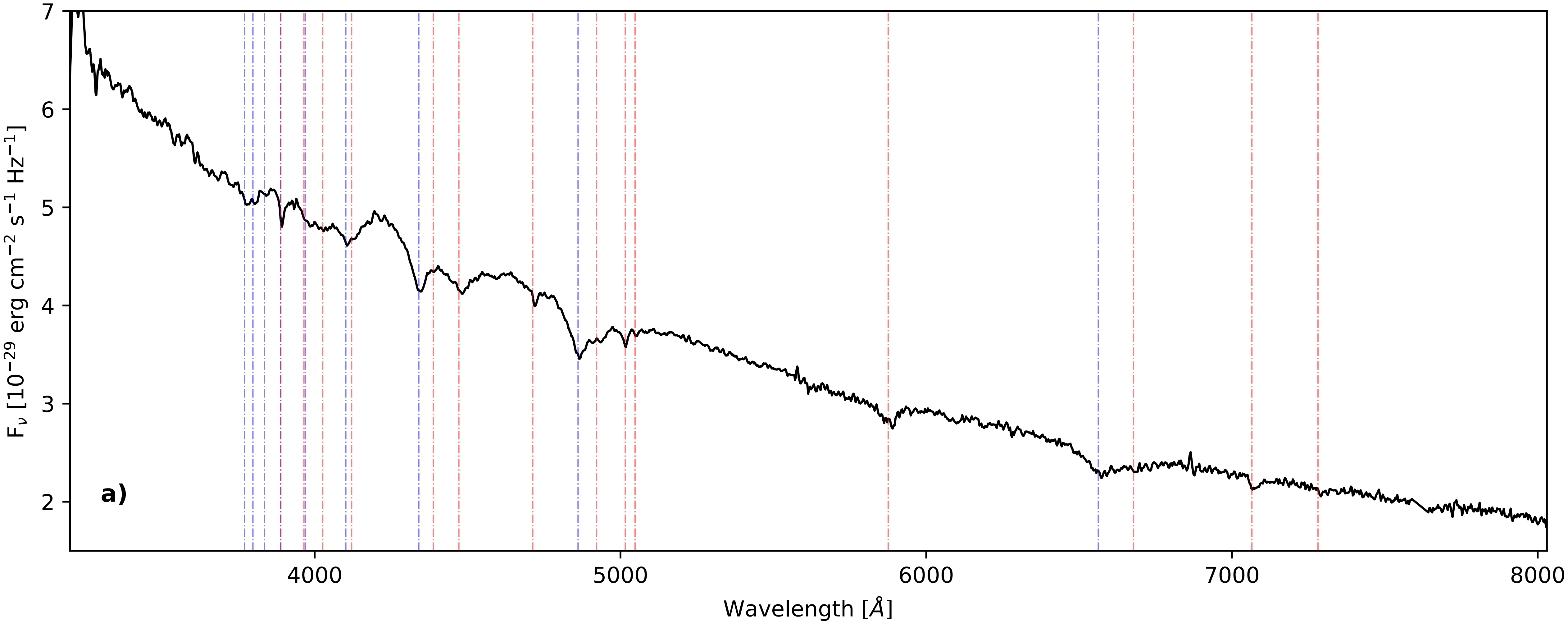




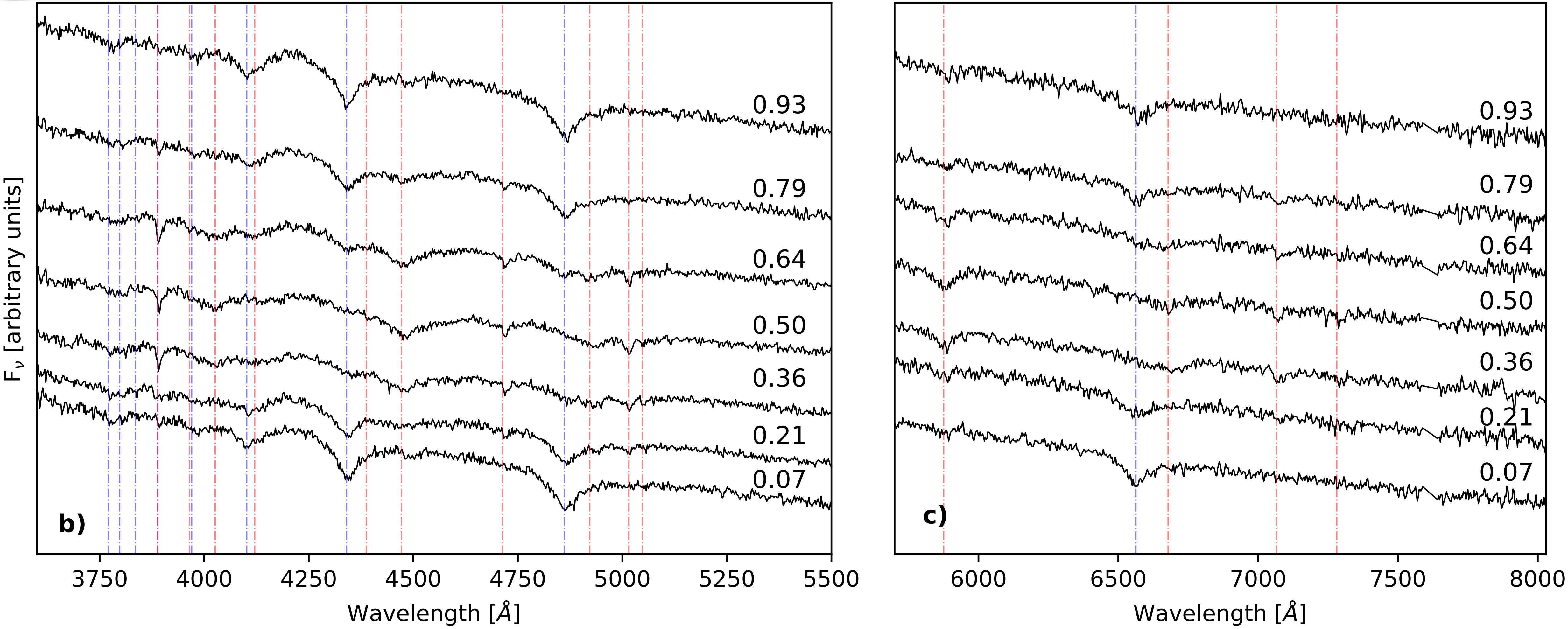
HiPERCAM

- Period: 15 minutes

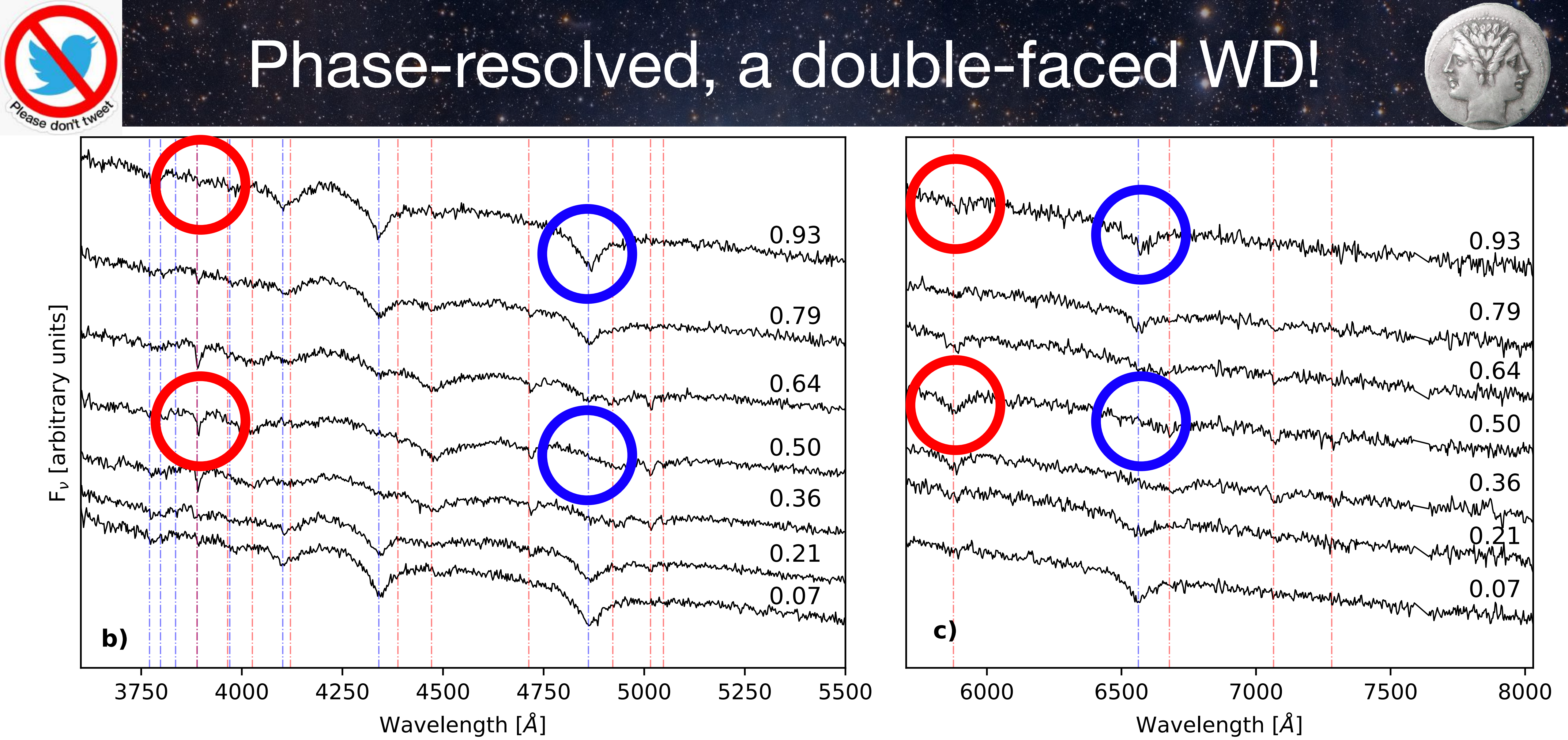
Phase-averaged spectrum



Phase-resolved, a double-faced WD!



Phase-resolved, a double-faced WD!



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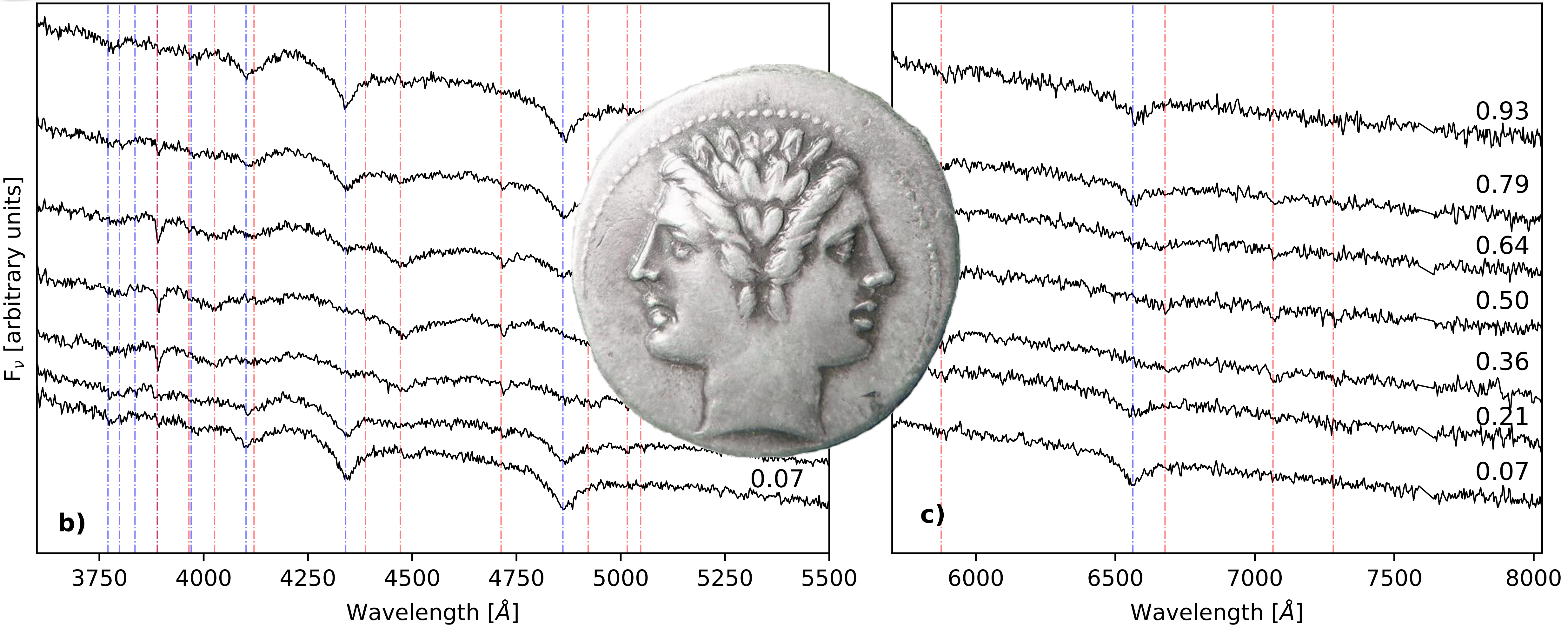
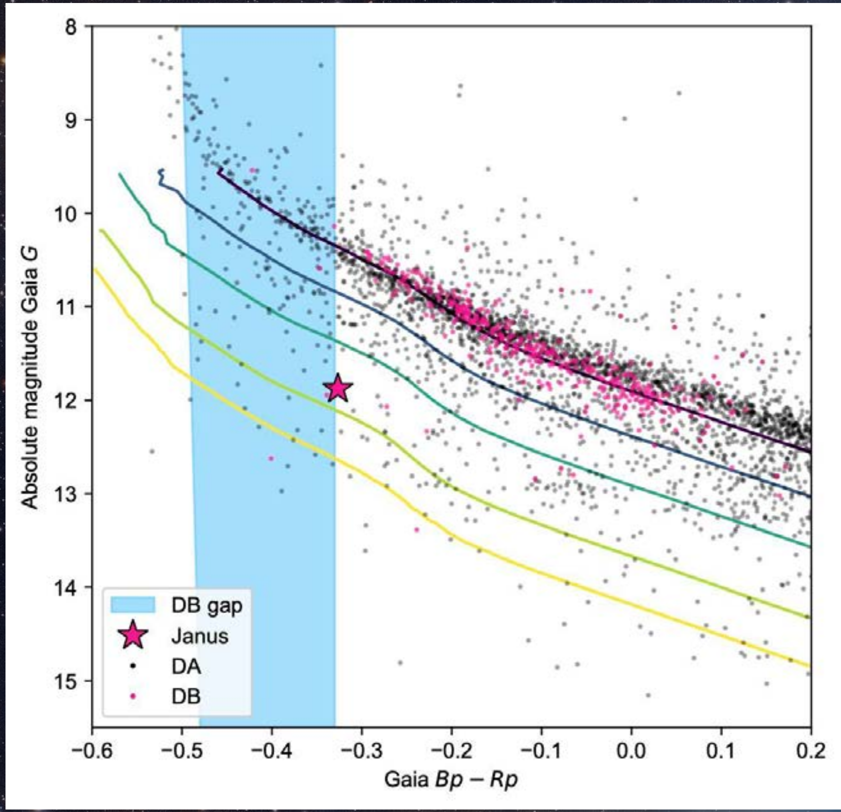
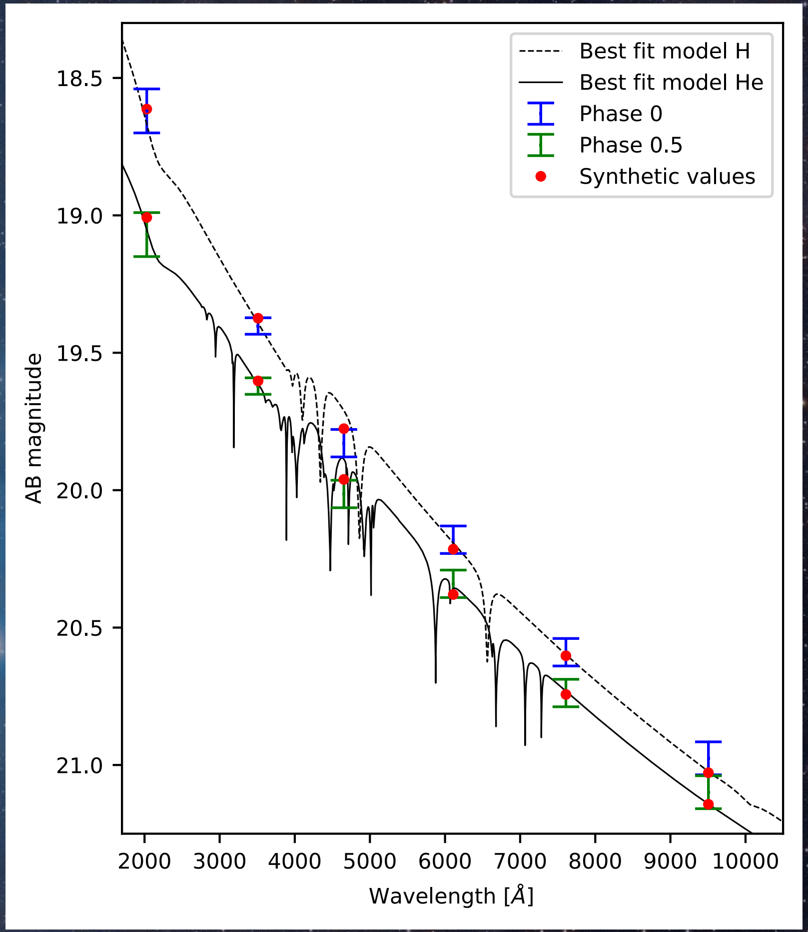


Janus, a transitioning WD?



- WDs with a very small hydrogen content appear as DA between temperatures of 50,000 K and 30,000 K, the so-called **DB GAP**



- At the the low end of the DB gap, strong mixing in the helium layer dilutes the hydrogen: DBs and DBAs appear
- If there is a magnetic field strong enough to inhibit convection on part of the surface, we can still see hydrogen

Janus, a hydrogen ocean?