White Dwarfs

Endpoint of stellar evolution of most main sequence stars

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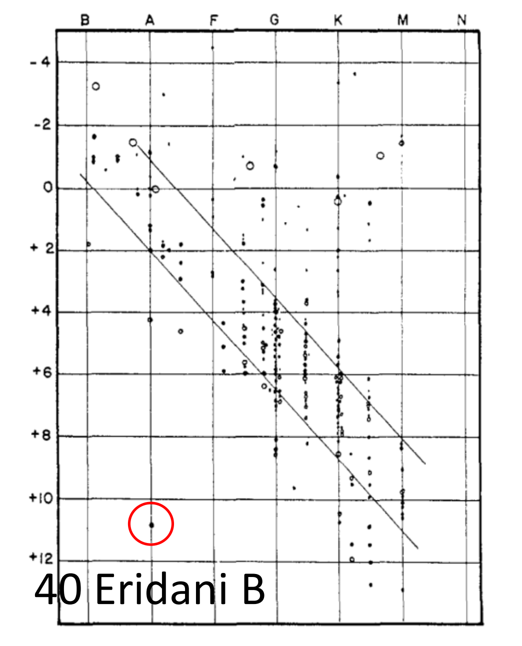
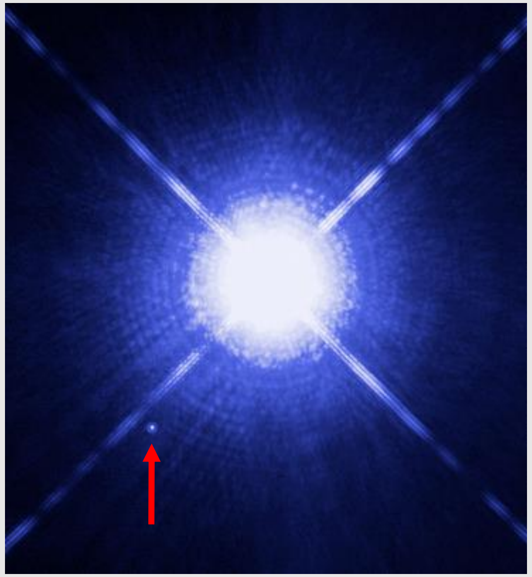
MPE

History

- Double star 40 Eridani B/C was detected on 31. January 1783 by William Herschel. In 1910 it was detected that it was of spectral type A.
- Sirius B was detected by Friedrich Bessel in 1844 through positional changes of Sirius A. In 1915 it was detected that it was of spectral type A.
- Van Maanen's star, a single white dwarf detected in 1917.
- For about 100 years it is known, that the central stars of Planetary nebulae are white dwarfs.
- By 2000 about 2000 white dwarfs stars were known, SDSS found about 9000, and Gaia (DR3) about 350000.



After Russell (1914), reproduced in Koester & Chanmugam (1990)



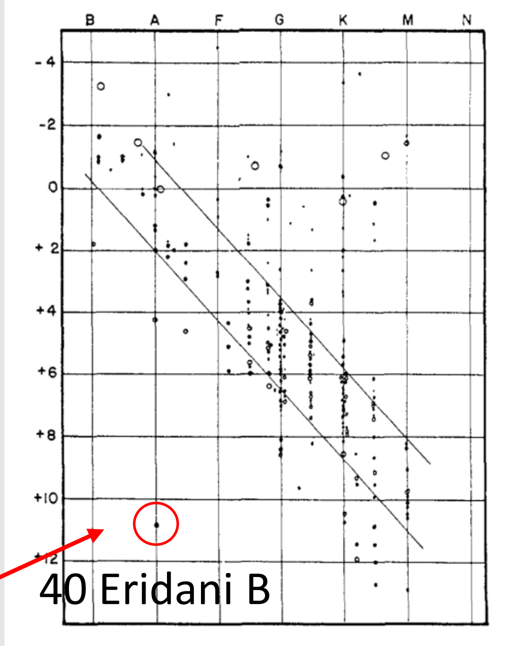
NASA, ESA, H. Bond (STScI), M. Barstow (Uni Leicester

History

$$L = 4\pi R^2 \cdot \sigma T^4$$

with $L \approx 1/10000$ to 100000
same temperature

$$R \approx 1/100$$



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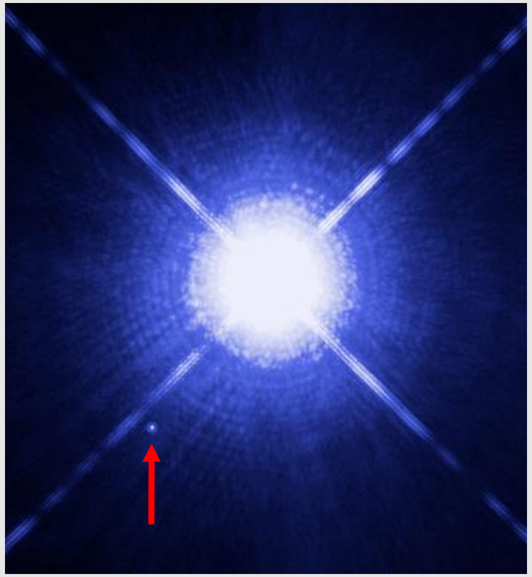

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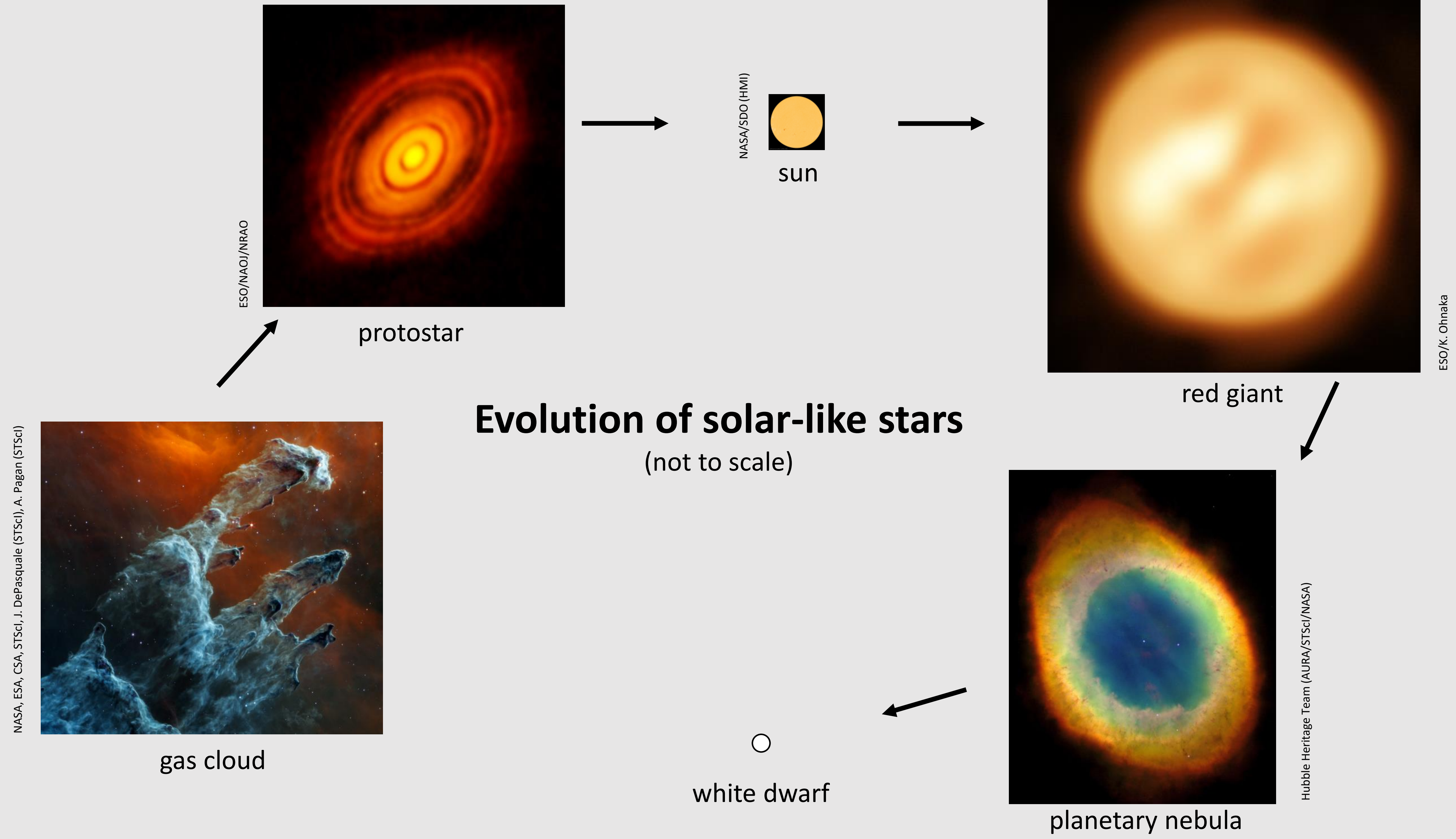
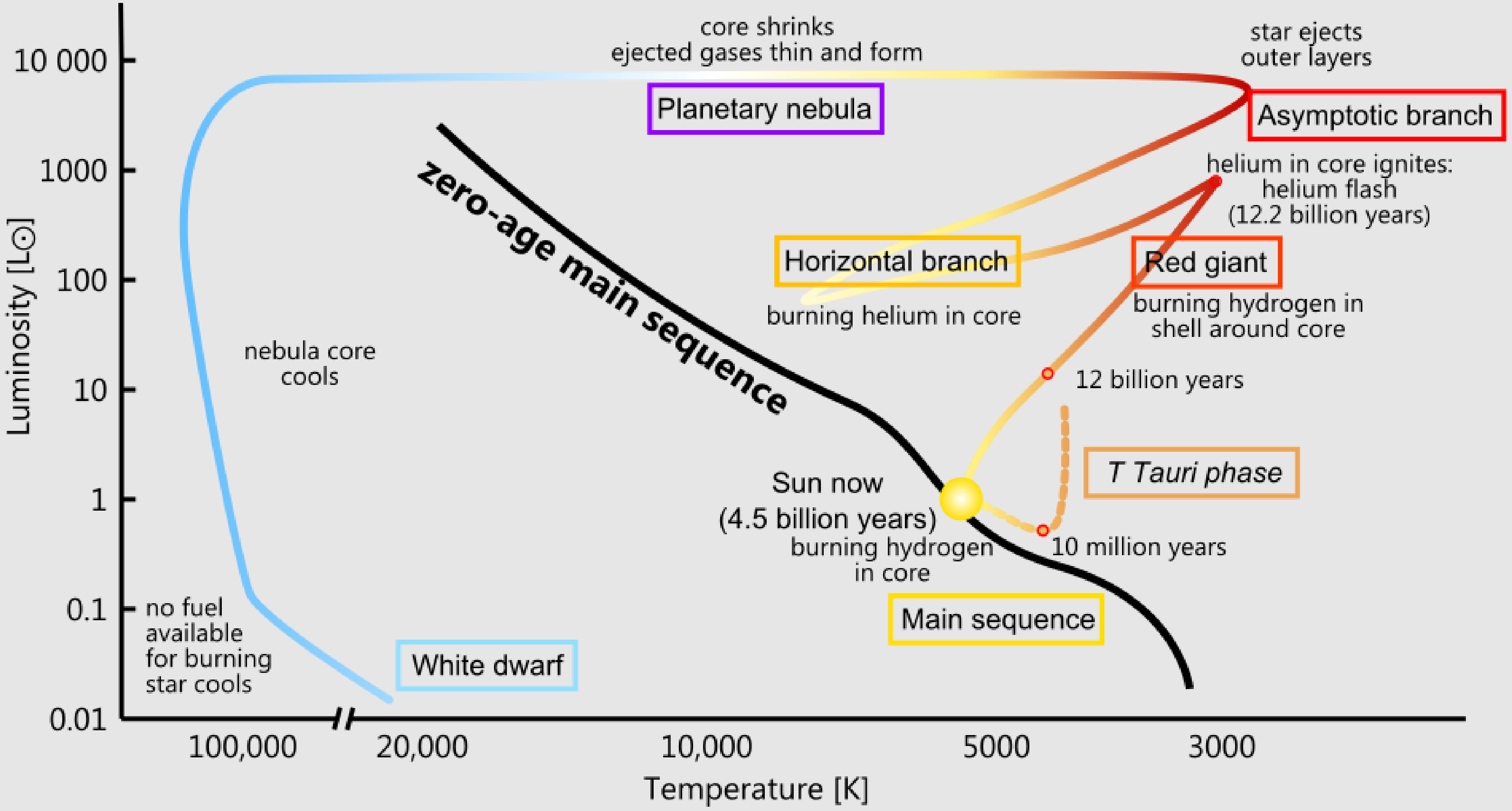
Characteristics

- compact stellar object of electron-degenerate matter
- mass: 0.2 to 1.38 $M_{\odot}$ (< Chandrasekhar mass)
- earth like diameter
- thin atmospheres of hydrogen and/or helium, sometimes with traces of metals
- temperatures between 100000 K and 4000 K
- no energy source, only residual thermal energy
- end point of stellar evolution of solar-like stars
- progenitors of Type Ia supernovae


Evolution of solar-like stars
(not to scale)
gas cloud
NASA, ESA, CSA, STScI, J. DePasquale (STScI), A. Pagan (STScI)
protostar
ESO/NAOJ/NRAO
sun
NASA/SDO (HMI)
red giant
ESO/K. Ohnaka
planetary nebula
Hubble Heritage Team (AURA/STScI/NASA)
white dwarf

Evolution of solar-like stars in the Hertzsprung-Russel-Diagram

	~9 Ga		~1 Ga		~100 Ma		~10 000 a		
Stage:	Main sequence	>	Red giant	>	Horizontal branch	>	Planetary nebula	>	White dwarf
Sun's age:	4.5 Ga (now)		12.2 Ga		12.3 Ga		12.3305 Ga		12.3306 Ga



Wikimedia commons

Formation and structure

White dwarfs are the end point of stellar evolution for main-sequence stars with masses from about 0.07 $M_\odot$ to 10 $M_\odot$.

- < 0.5 $M_\odot$:
  no helium fusion → helium core
- 0.5 $M_\odot$ to 8 $M_\odot$:
  helium fusion → carbon-oxygen core
- 8 $M_\odot$ to 10 $M_\odot$:
  carbon fusion → neon-magnesium-oxygen core
  (neon fusion → iron core and core collapse supernova)

The core is surrounded by a helium-rich layer of typivally 10^{-2} $M_\odot$, which is surrounded by a hydrogen-rich layer of typically 10^{-4} $M_\odot$ (can be orders of magnitude smaller for hydrogen-deficient stars).

Degenerate electron gas

Given the mass and radius of Sirius B, its average density is 2.1×10^{9} kg/m^3
Assuming an interior composition of pure carbon with $m=2 \times 10^{-26}$ kg
We get a number density of 1×10^{35} /m^3
and a typical distance between the carbon nuclei of $r_C = \sqrt[3]{\frac{¾\,\pi}{1\times10^{35}}} = 2.9 \times 10^{-12}$ m
For comparison the Bohr radius of carbon with one remaining electron is 8.8×10^{-12} m
No room for bound orbits -> matter in white dwarfs is completely „pressure ionised".

A similar calculation for electrons yields $r_e = 6.4 \times 10^{-10}$ m which is of the magnitude of the de Broglie wavelength ($\approx 10^{-10}$-10^{-12} m) → Fermi-Dirac statistics (Fermi 1926, Dirac1926), pressure for balancing gravity comes from the (almost) completely degenerated electrons.

Mass-Radius-Relation

For white dwarfs supported by the pressure of fully degenerate but non-relativistic electrons:

$$P \sim \left(\frac{\rho}{\mu}\right)^{\frac{5}{3}} \quad \text{and } R \sim M^{-1/3}$$

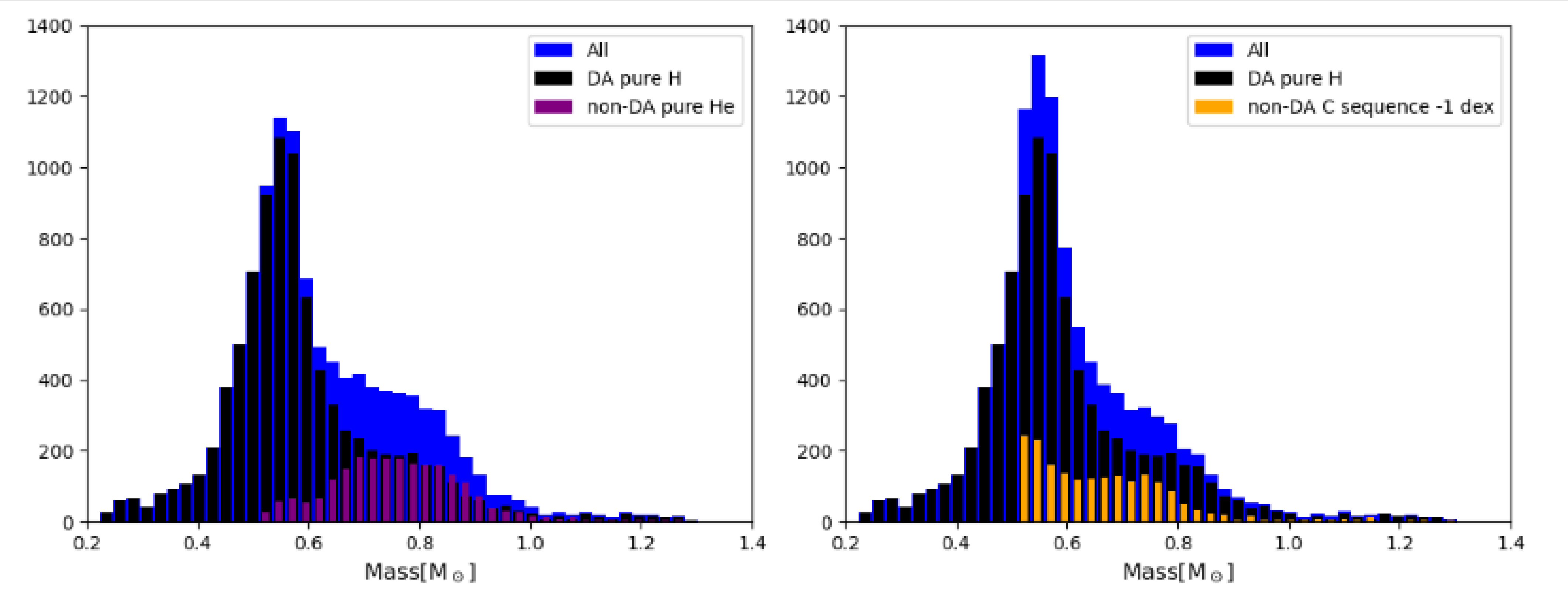
At very high densities, the electron gas becomes relativistic and the equation of state "softens"

$$P \sim \left(\frac{\rho}{\mu}\right)^{\frac{4}{3}}$$

This reduces the capacity of electron degeneracy pressure to support the white dwarf, leading to an upper limit on the mass of a stable white dwarf:

Chandrasekhar mass ≈ 1.4 $M_{\odot}$

Mass distribution



Camisassa, M. et al., A&A 674,A213 (2023)

Mass distributions of the 100 pc white dwarf population spectrally classified into DA and nonDA by Jiménez-Esteban et al. (2023).
Left panel: pure H atmosphere model for all DA white dwarfs and a pure He atmosphere model for all nonDA white dwarfs.
Right panel: C enrichment for all nonDA white dwarfs with Teff <12000K (stealth DQ white dwarfs).

Thin atmospheres

Scale height: $H = \frac{k_B\, T}{m\, g}$

Sirius B (ApJ 743, 138 (2011)):

T = 26000 K

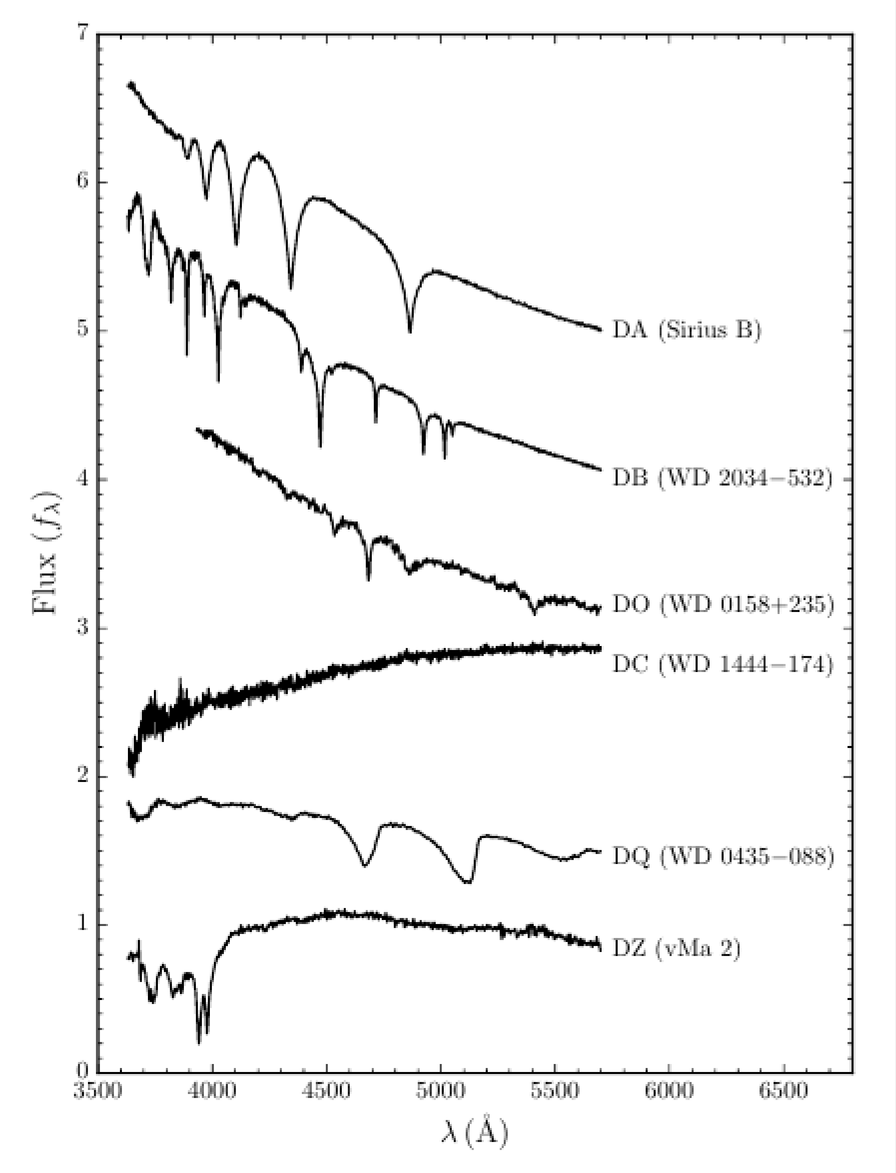
m = 1.672 10^{-27} kg (mass of H atom)

g = $3.715 \cdot 10^{8}$ cm/s^2 (log g = 8.57)

k_B = 1.38 10^{-23} J/K

→ ≈ 58 m (scale height of the earth‘s atmosphere is about 8 km)

Typical spectra and spectral types



Bergeron et al. (1997, 2011), Giammichele et al. (2012), Subasavage et al. (2017)

DA: only hydrogen lines

70% of all WDs are hydrogen-rich

DB: only lines of neutral helium

DO: singly ionized He (HeII) lines

DC: no detectable spectral lines

DQ: carbon C or C+ lines, C2 molecular bands

DZ: metal lines heavier than C

nonDA

There are also hybrid types: e.g. DAO, DBA, DAZ, DBAZ, …

Spectral evolution

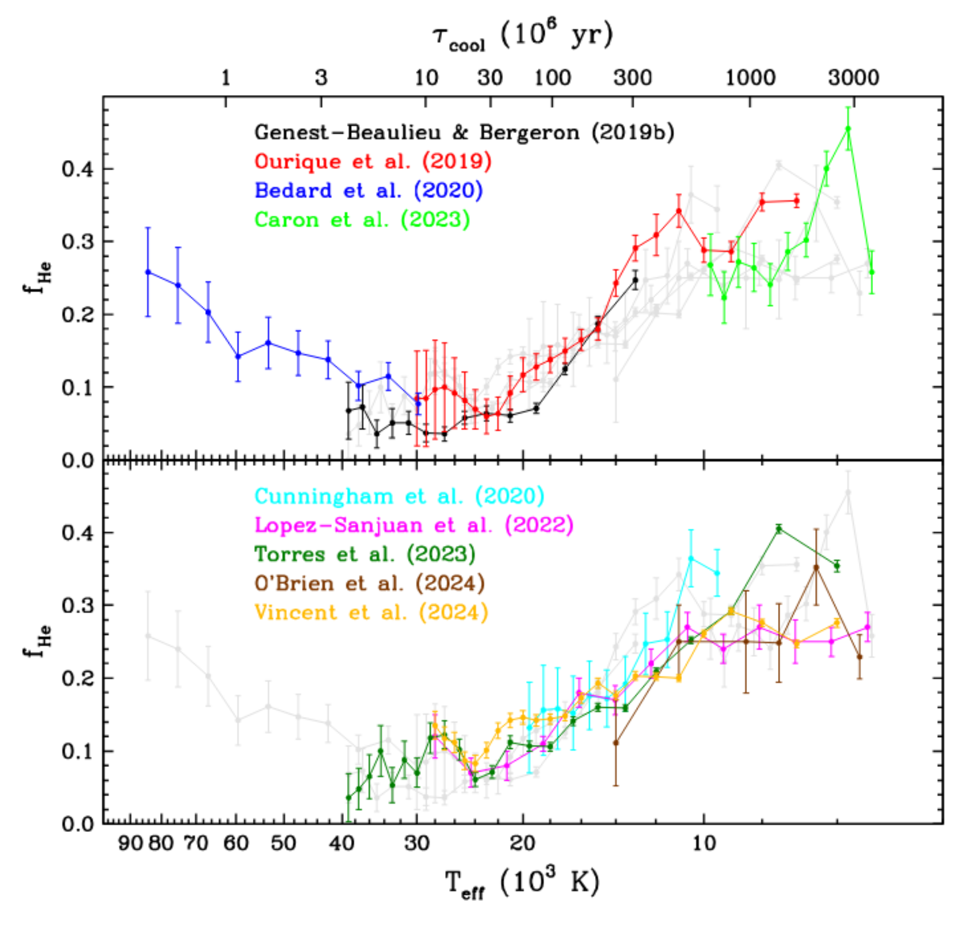
GAIA DR3 found 350000 white dwarfs with low-resolution spectra for 100000 of them.

- 20 – 30 % helium-rich atmospheres at high temperatures
- Minimum at 5 – 15 % between 40000 K and 20000 K (DB gap)
- 20 – 35 % at 10000 K

Below and above these temperatures results are uncertain

→ three evolutionary channels:

- stars that have and retain a hydrogen atmosphere (DA type)
- stars that have and retain a helium atmosphere (DO then DB type)
- stars that initially have a helium atmosphere (DO type) but then experience a helium-to-hydrogen (DO-to-DA) transition at high temperature and a hydrogen-to-helium (DA-to-DB) transition at low temperature



Fraction of helium-atmosphere white dwarfs as a function of effective temperature in various post-Gaia studies (from Bédard 2024).

White dwarfs with metal lines

Due to the strong surface gravity ($\log g \approx 8$) heavier elements should quickly sink toward the core and lighter ones float to the surface

Metals are only expected:

- for the hottest temperatures due to radiative levitation
- at the cool end of the cooling sequence due to convective mixing

If metals are observed at intermediate temperatures

$\rightarrow$ accretion of planetary debris

Around 30 white dwarfs dusty and gaseous disk were found

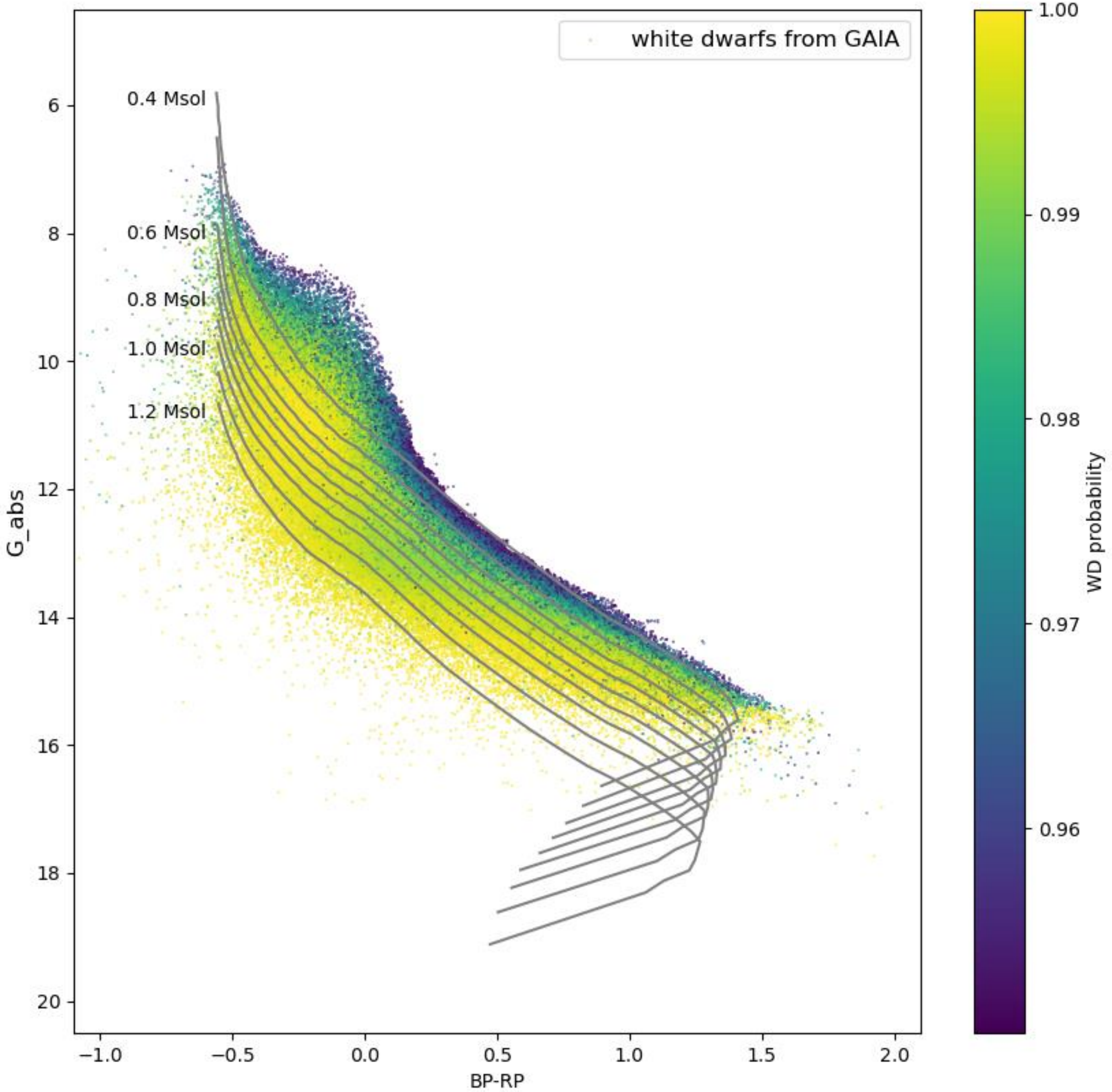
Cooling tracks

- After nuclear energy generation came to a halt, the white dwarf is left with only gravitational and thermal energy sources
- Since the electrons are already degenerate in the interior the remaining contraction is small
- The white dwarf thus evolves roughly at a constant radius along the diagonal straight line in the white dwarf region given by

$$L = 4\pi R^2 \cdot \sigma T^4$$

- This is the fate for stars in the range 1 – 8 $M_\odot$ despite differences in physical details. Stars with higher masses ignite carbon in their cores and finally become neutron stars

Cooling tracks: Althaus 2013; Camisassa 2019, 2016; Koester 2010

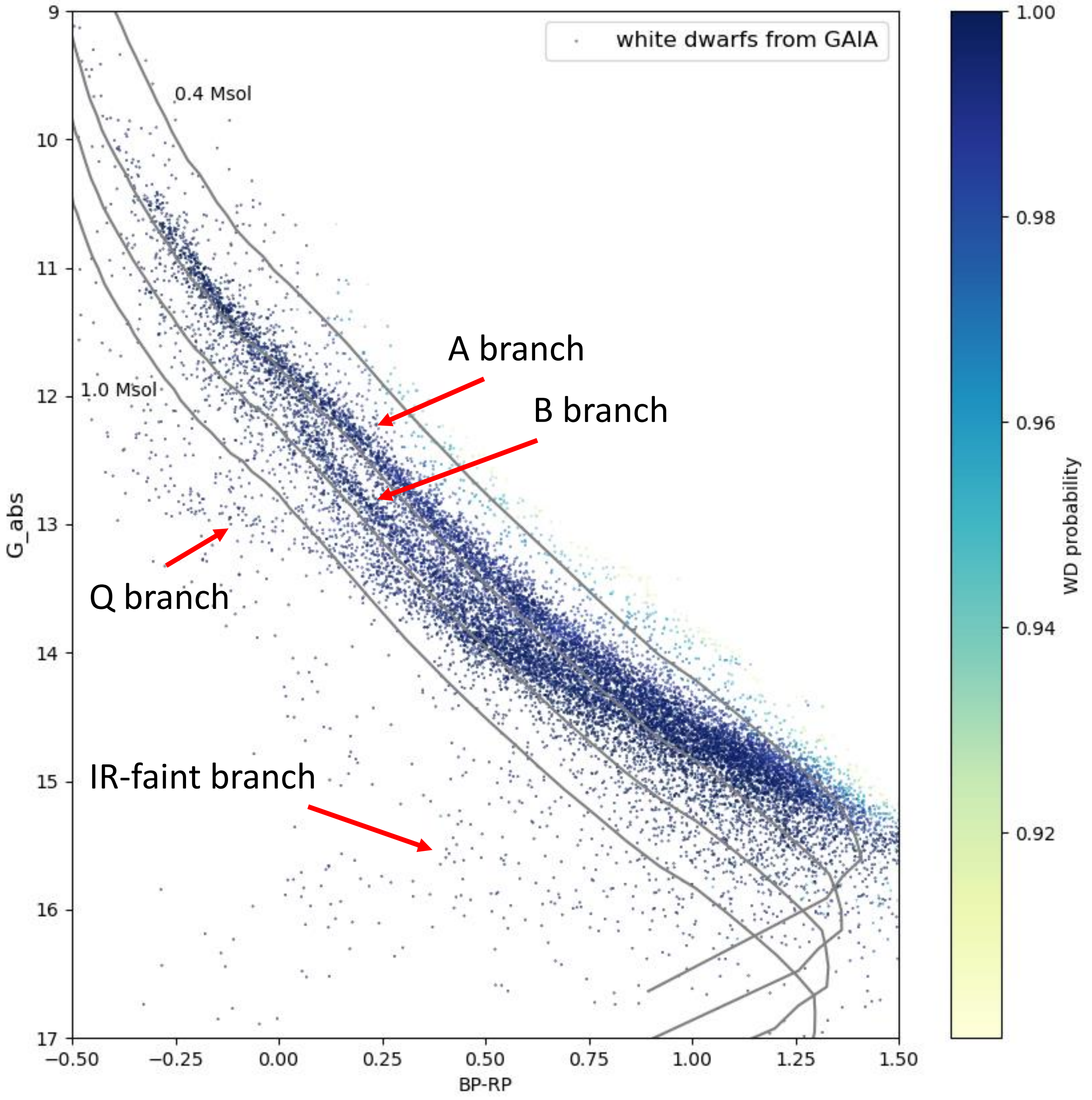


Friedrich et al., in press

Cooling sequences

GAIA white dwarf 100 pc sample revealed 4 main branches of the cooling sequence:

- A branch: hydrogen-rich white dwarfs
- B branch: helium-rich white dwarfs with T<12000 K
- Q branch: crystallization, distillation of ^{22}Ne
- IR-faint branch: IR deficit causes by collision-induced absorption by molecular hydrogen due to collisions with helium in cold H-He-atmospheres.



Cooling tracks: Althaus 2013; Camisassa 2019, 2016; Koester 2010

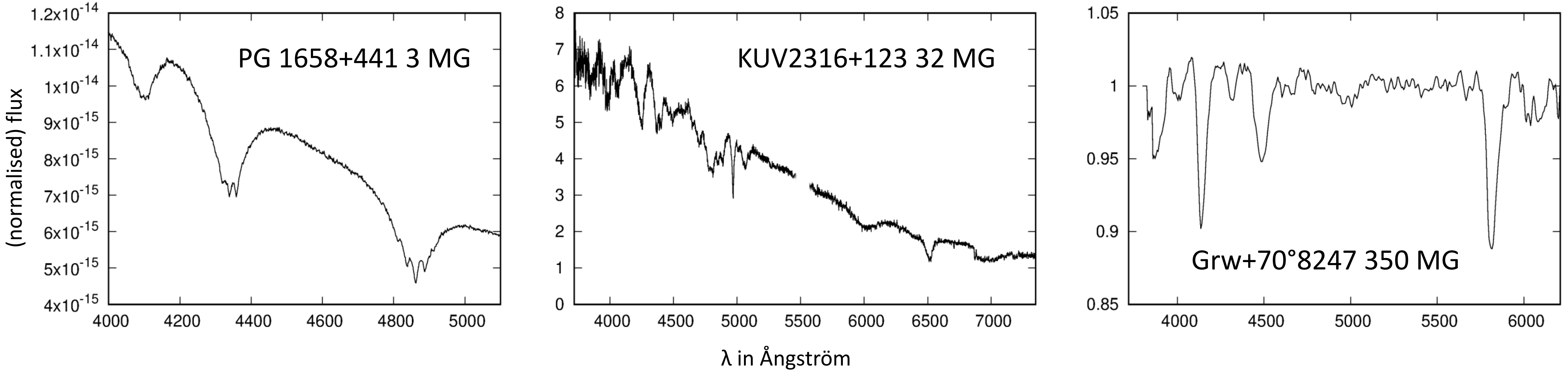
Variable white dwarfs

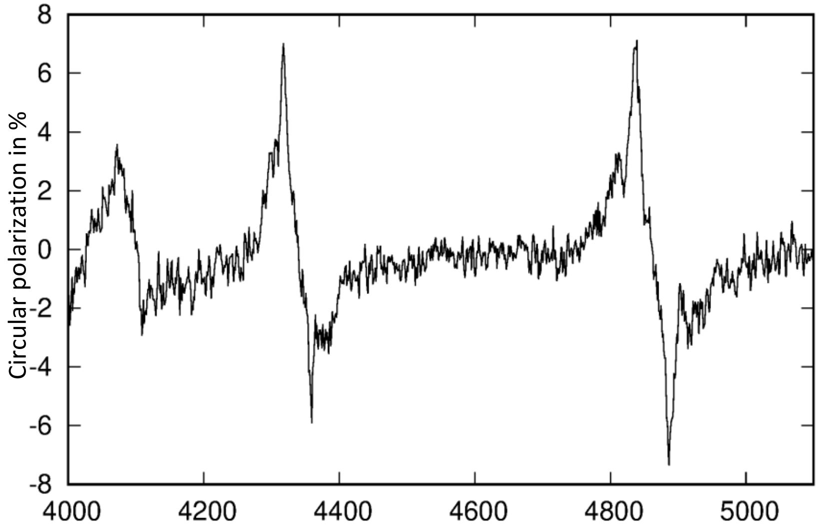
- Only about ≈ 2 − 3% of white dwarfs pulsate
- pulsations are gravity modes
- periods of ≈ 100–2500 s
- frequencies are determined by chemical stratification, rotation profile, mass, radius, temperature, and magnetic field

The cause of the onset of pulsations in white dwarfs is the partial ionization of the main constituents – H or He – of their envelopes:

- DOV (GW Vir, PG 1159): cyclic ionization of carbon and oxygen
- DBV: Teff = 32000 K – 22000 K due to the partial ionization of He
- DAV (ZZ Ceti): Teff = 12500 K − 10500 K due to the partial ionization of H

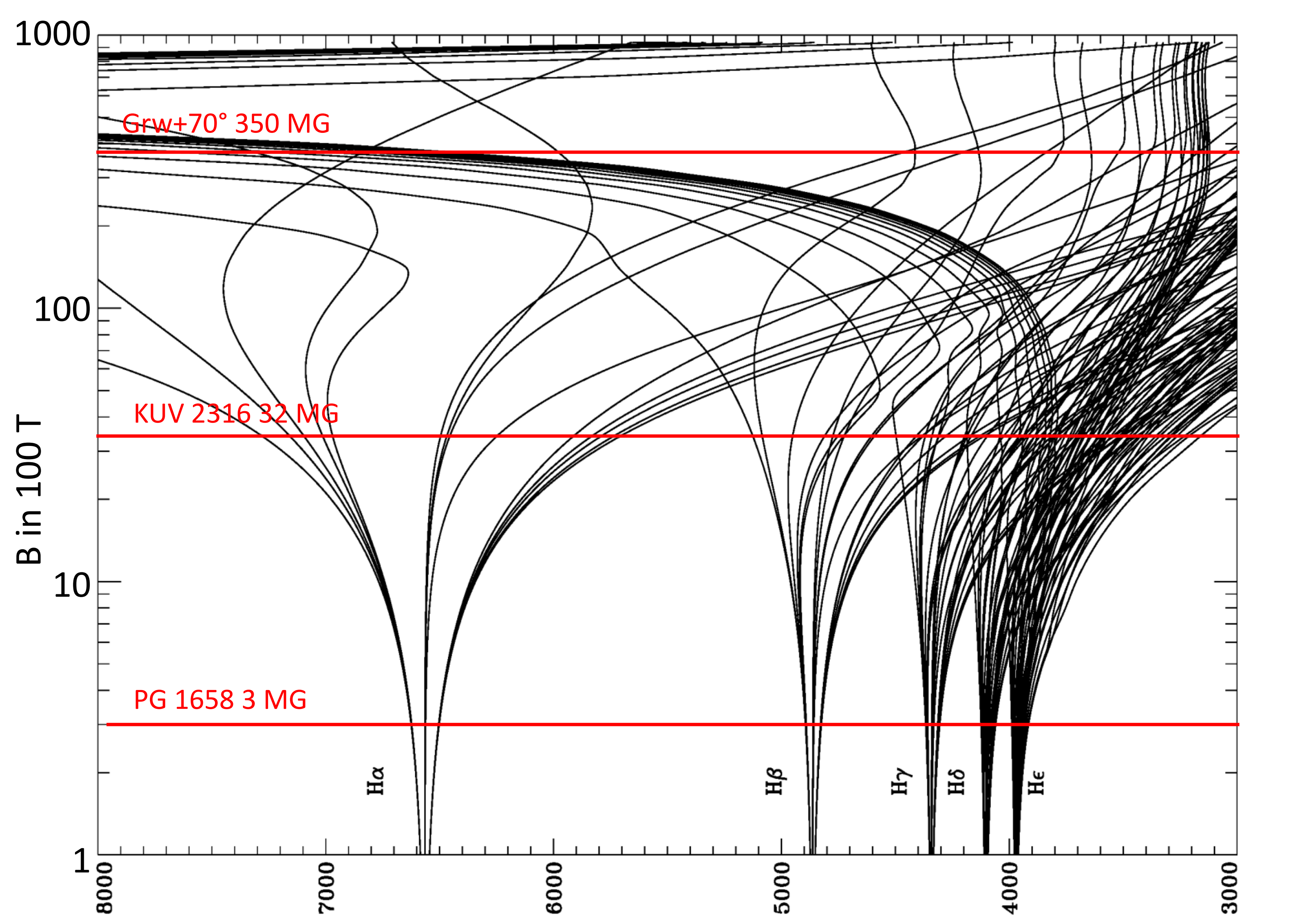
Magnetic white dwarfs





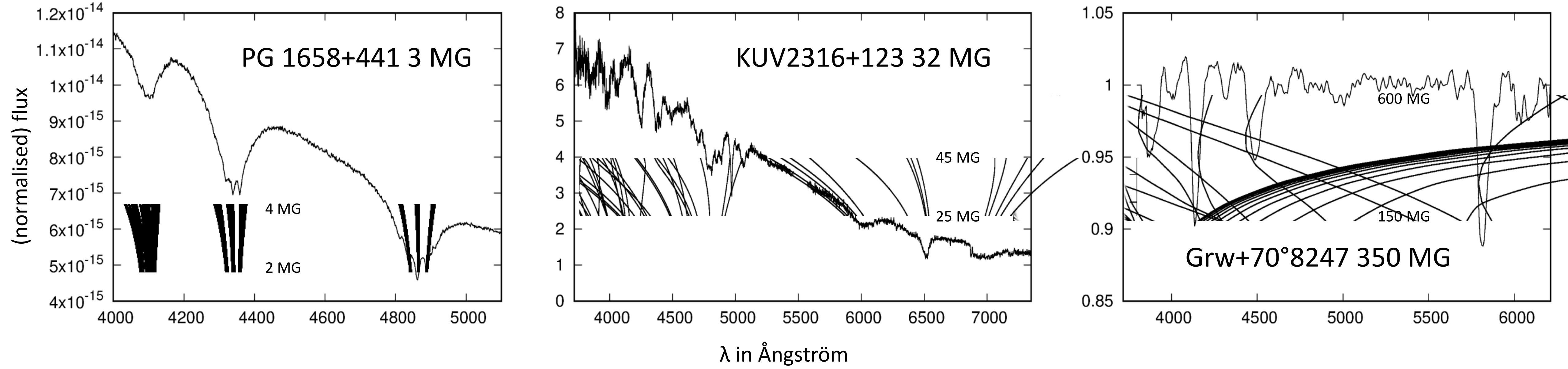
Friedrich et al., 1996; Östreicher et al., 1992

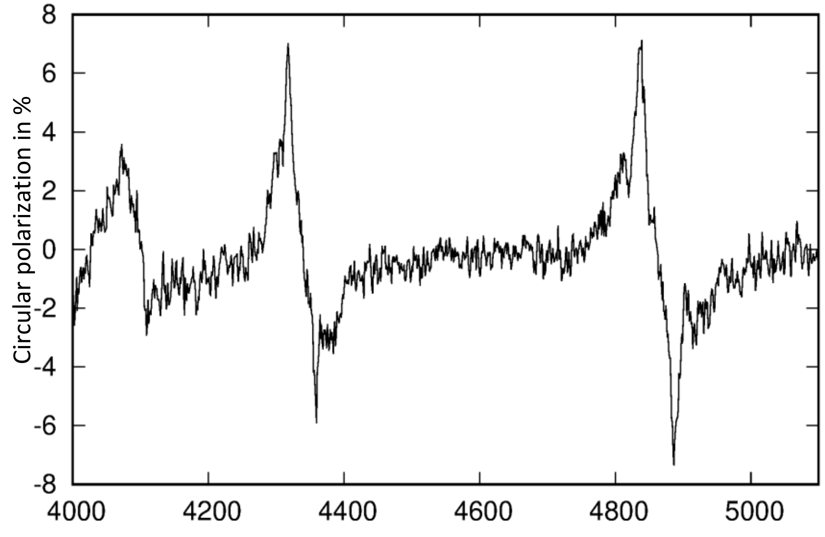
Magnetic white dwarfs

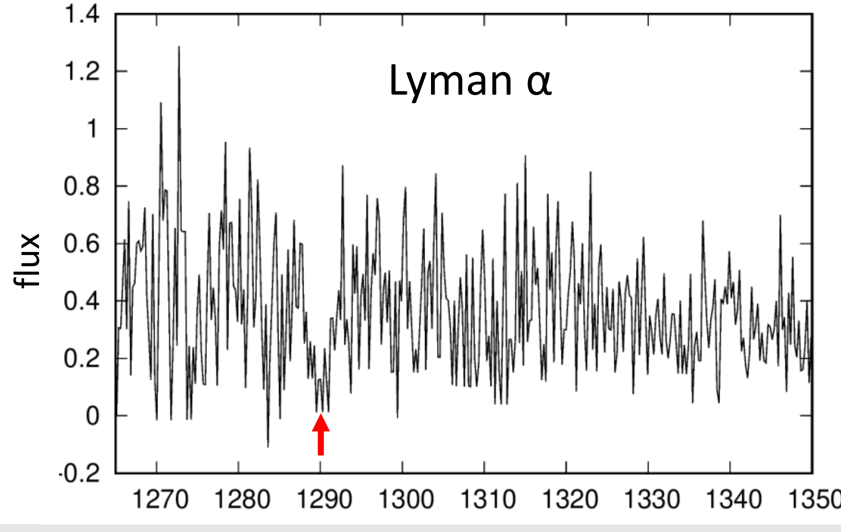


Friedrich et al., 1996

Magnetic white dwarfs

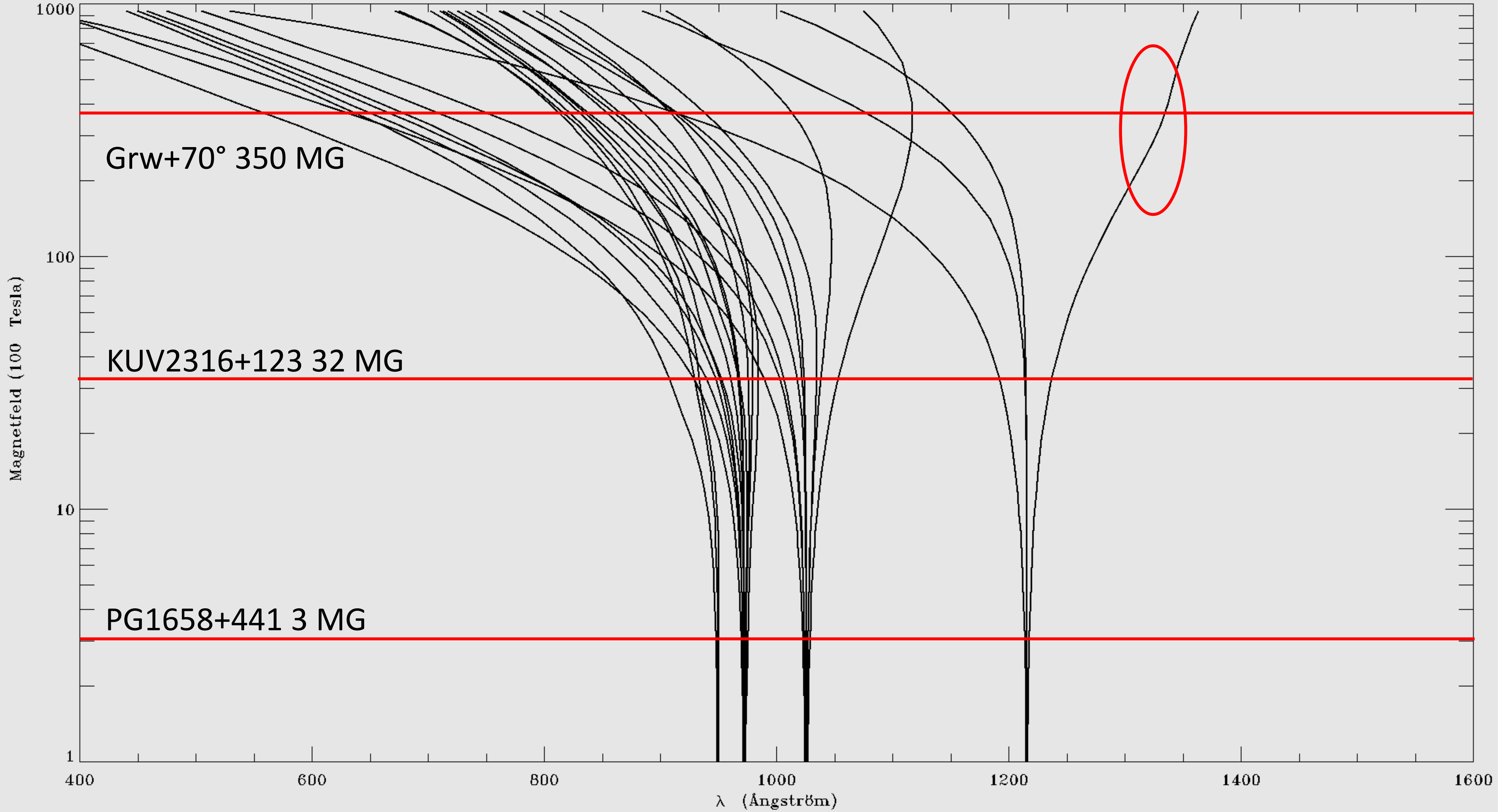






Friedrich et al., 1996; Östreicher et al., 1992

Magnetic white dwarfs

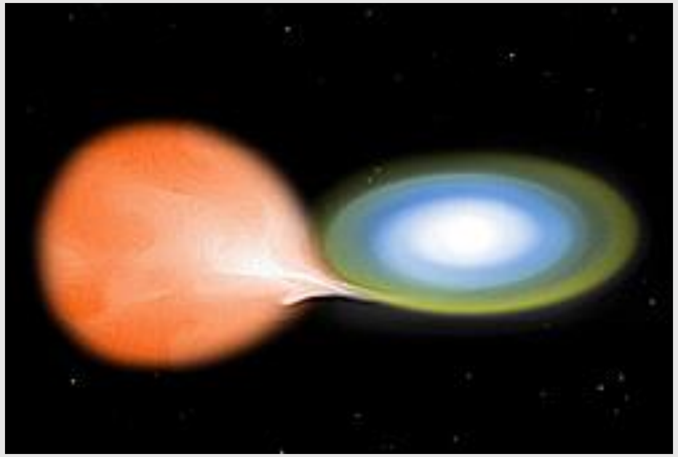


Cataclysmic Variables

In general cataclysmic variable stars (CVs) are stars which irregularly increase in brightness by a large factor, then drop back down to a quiescent state.

Supernovae Typ Ia: A white dwarf accretes matter from a companion until it reaches the Chandrasekhar mass, the white dwarfs starts to collapse, nuclear fusion ignites and releases enough energy for a supernova. Increase in luminosity, reaching an absolute magnitude of −19.3 with little variation → standard distance candle.

Classical novae: white dwarf accretes matter either from a main sequence, subgiant, or red giant star. This material is heated by the white dwarf and eventually reaches a critical temperature, causing ignition of rapid runaway fusion.



NASA/CXC/M.Weiss

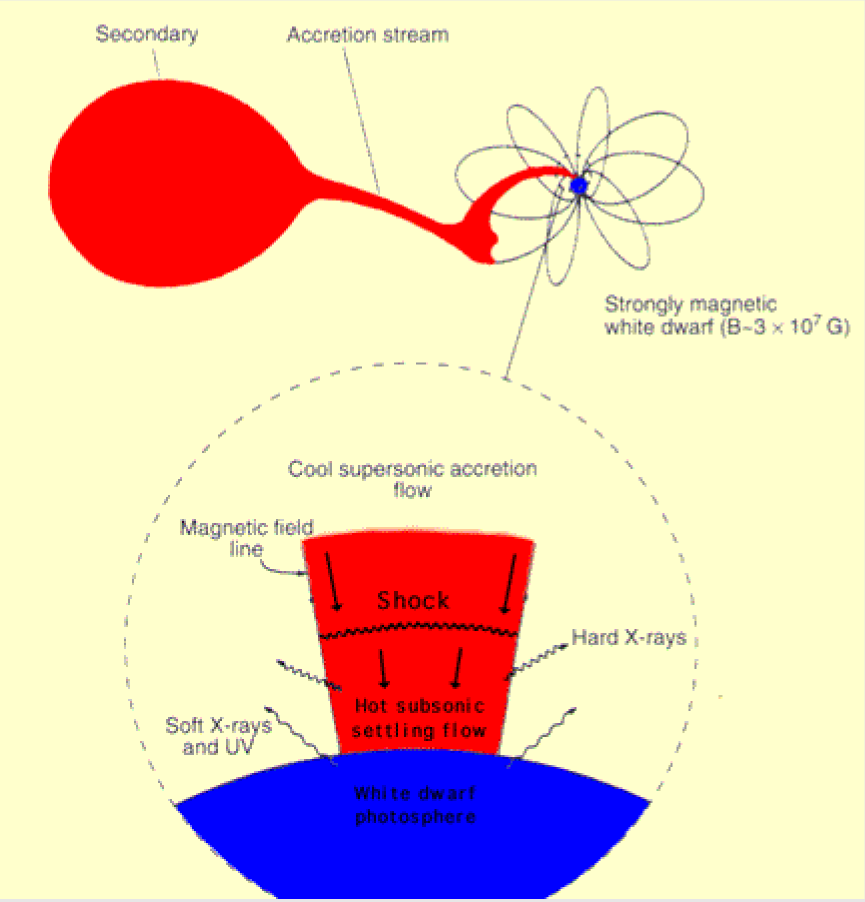
Recurrent novae: Same as classical novae, but repeats in cycles of a few decades or less depending on the mass transferred

Dwarf novae: dimmer and repeat more frequently than "classical" novae

Cataclysmic Variables

Polars: a highly magnetised (10–80 MG) white dwarf accretes matter from a low mass donor star; no accretion disk; spin and orbit period are synchronised
Intermediate polars: less strong magnetic fields as polars and the rotation of the white dwarf is not synchronised with the orbital period → (truncated) accretion disk

Polars are X-ray emitters



NASA

Cataclysmic Variables

AM Canum Venaticorum: both components are compact objects (white dwarf, neutron star, black hole); interacting white dwarf systems (double degenerates, DD) can be progenitors of SNe Ia. If they merge they can be sources of gravitational waves.

- Orbital periods between 5 and 30 minutes
- They are classified as Super Soft Sources (SSS), first identified by ROSAT, with soft X-ray spectra (kT ~ 15–80 eV).
- X-ray emission is explained by several models, the two main models are: Mass transfer from a Roche-lobe-filling white dwarf either to a magnetic or non-magnetic white dwarf.
- Rare class, only three confirmed objects. A fourth one was detected by eROSITA (Maitra et al., A&A 683, 21 (2024)).

White dwarfs with eROSITA

A bit of history:

ROSAT (launched 1990) performed the first all-sky soft X-ray survey (only 1)

- it detected 175 white dwarfs
  - mostly DAs with T_{eff} > 30000K, at which H is sufficiently ionised
  - A few non-DA of type DO and PG1159 with T_{eff} > 100000 K, at which He is sufficiently ionised to HeII

However, this was far below the expectations of several thousands. A plausible explanation was the presence of heavier elements in the atmospheres

White dwarfs with eROSITA

eROSITA performed the first all-sky X-ray survey almost 30 years after ROSAT; it completed 4 surveys

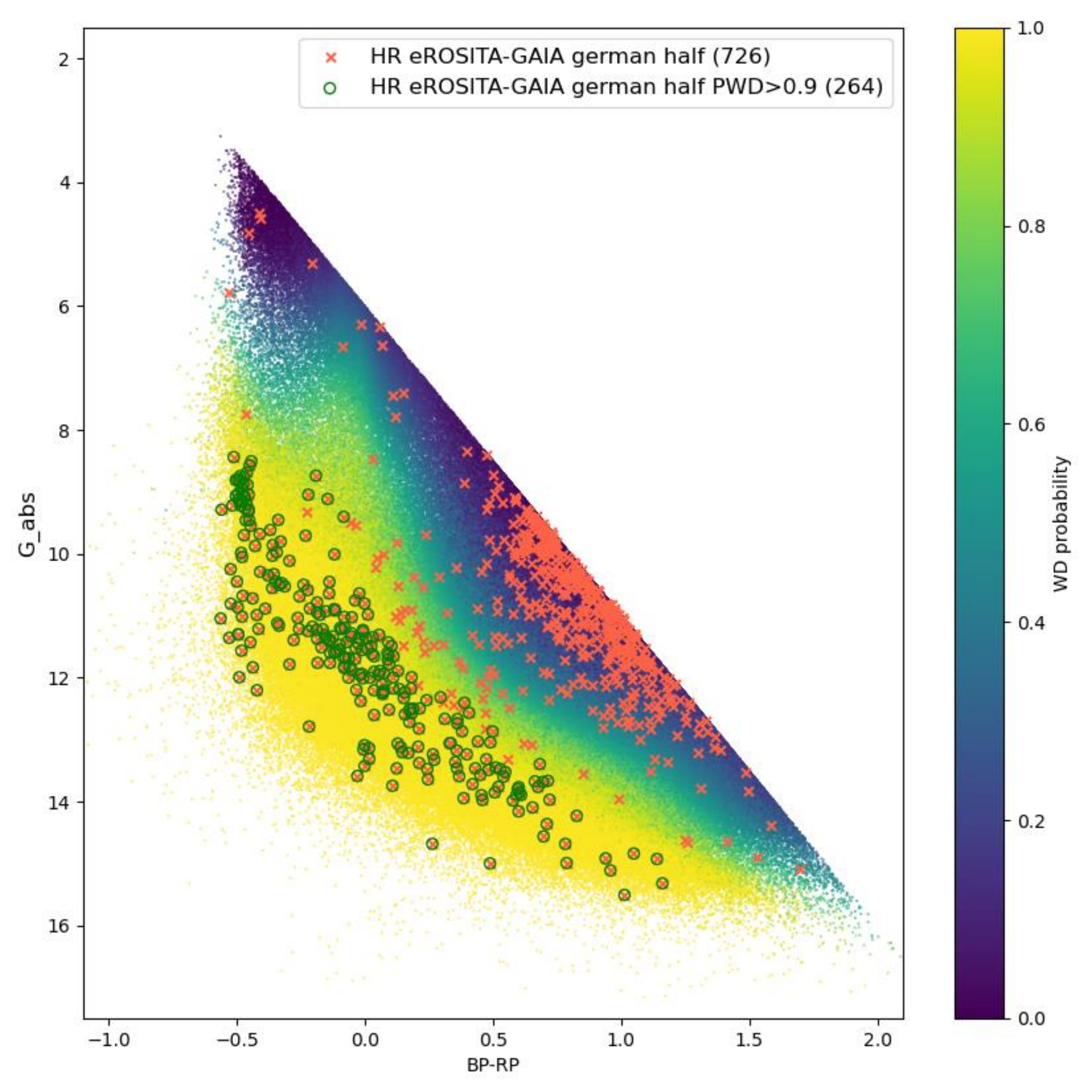
it detected 38080 soft point sources with hardness ratios

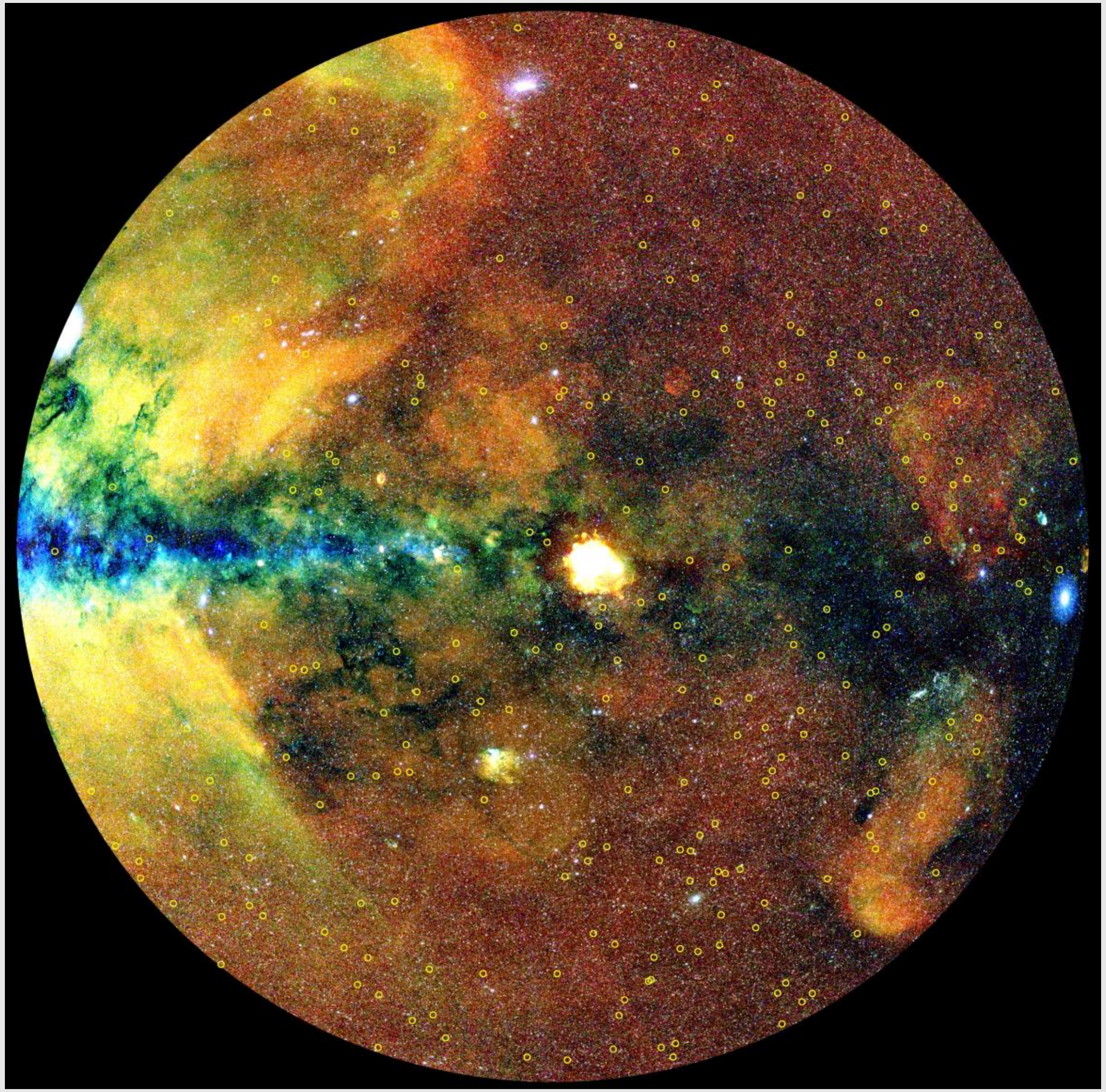
$$\frac{cts(0.5 - 1keV) - cts(0.2 - 0.5keV)}{cts(0.5 - 1keV) + cts(0.2 - 0.5keV =} \leq -0.94$$

726 sources have matches with the GAIA white dwarf ctalogue (Gentile Fusillo et al. 2021)

264 of these sources have a probability higher than 90% being a white dwarf in this catalogue.

White dwarfs with eROSITA



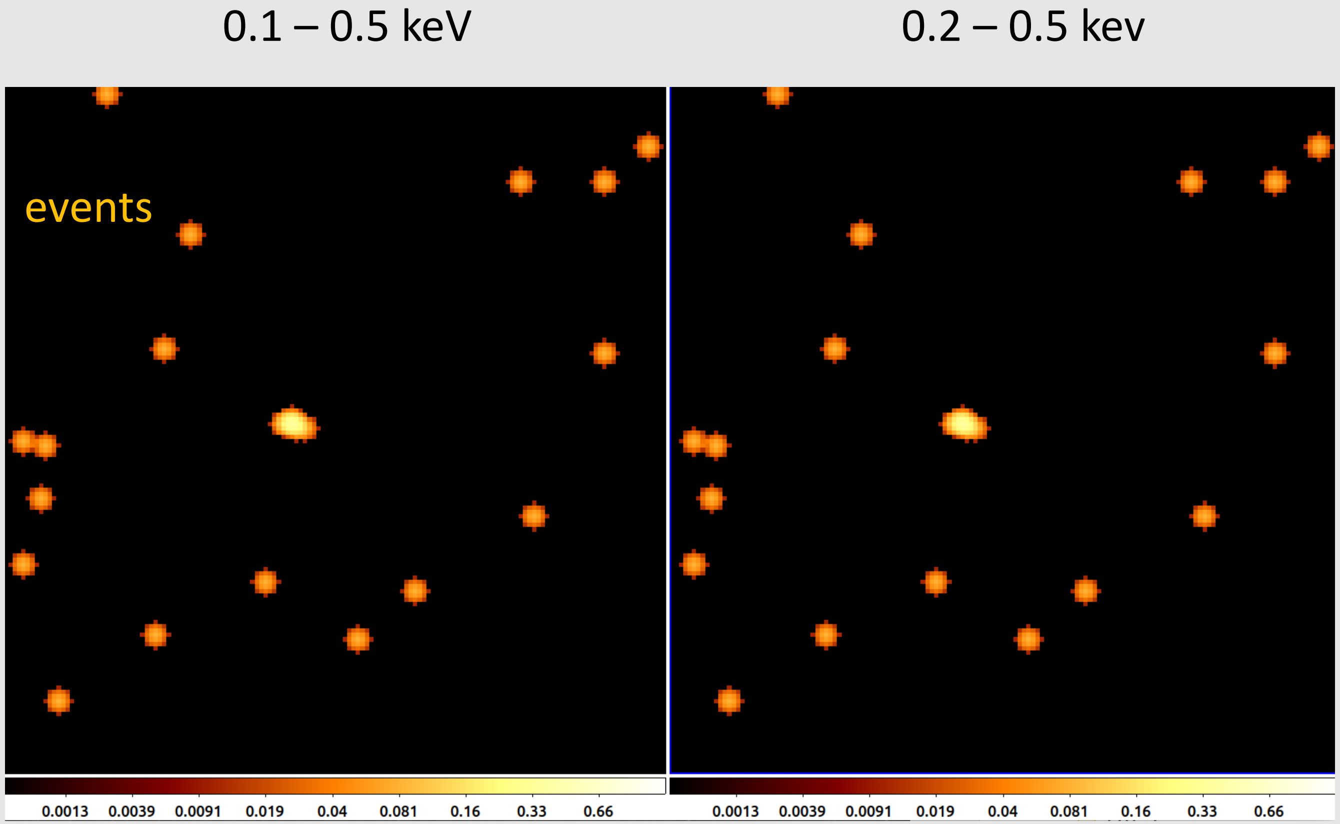


Friedrich et al., in press

White dwarfs with eROSITA

White dwarfs are Super Soft Sources

DR1 – only one survey



GD 153 (40000 K)

WD0631+107 (28000 K)

Not detected in DR1

BUT

It can be detected in eRASS:4 (0.1-0.5 keV band)!

Useful reading

- Fleming T. A., et al.: Catalogue and luminosity function of white dwarfs detected in the ROSAT all-sky survey, A&A 316, 147 (1996)
- Gentile Fusillo, N. P., et al.: A catalogue of white dwarfs in GAIA EDR3, MNRAS 508, 3877 (2021)
- Koester, D., Chanmugam, G.: Physics of white dwarfs, Rep. Prog. Phys. 53 837 (1990)
- Koester, D.: White Dwarf Stars, Planets, Stars and Stellar Systems Vol. 4, by Oswalt, Terry D., Barstow, Martin A., ISBN 978-94-007-5614-4. Springer Science+Business Media Dordrecht, 559 (2013)
- Marsh, M. C. et al.: An EUV-selected sample of DA white dwarfs from the ROSAT All-Sky Survey - II. EUV and soft X-ray properties, MNRAS 287, 705 (1997)
- McCook, G. P.; Sion, E. M. : A Catalog of Spectroscopically Identified White Dwarfs, ApJS 121, 1 (1999) https://ui.adsabs.harvard.edu/#abs/2016yCat....102035M/abstract
- Saumon, D., et al: Current Challenges in the Physics of White Dwarf Stars, Physics Reports, 988, 1 (2022)
- German Astrophysical Virtual Observatory: https://www.g-vo.org

Hands-on: download

Download from the White Dwarfs/Diffuse Emission page if you haven‘t already:

em01_193069_020_EventList_c010.fits.gz

Skytile search: https://erosita.mpe.mpg.de/dr1/erodat/skyview/skytile_search/

GD 153: 12h57m02.3s,+22d01m52.63s

Hands-on: eSASS commands

Assuming eSASS4DR1 is running

```
evtool eventfiles='em01_193069_020_EventList_c010.fits.gz' \
outfile= 'GD153_200.fits' telid='1 2 3 4 6'  clobber=yes flag=0xE000F000\
pattern=15 emin='0.2' emax='2.3' image=yes rebin=80 size=3240
```

In DS9: find the star and determine extraction radii for source and background

```
srctool eventfiles= 'GD153_200.fits'\
srccoord="icrs;12h57m02.3s,+22d01m52.63s" todo="SPEC ARF RMF" \
insts="1 2 3 4 6" srcreg='icrs;circle * * 40.0"' \
backreg='icrs;annulus * * 120.0" 200. 0"' exttype="POINT" xgrid="0.5"\
psftype="2D_PSF" flagsel=0 clobber= "no"
```

Hands-on: Xspec commands

```
>xspec
XSPEC> cpd /XS    if xwindow is not working try cpd output.ps/cps
XSPEC>setplot energy
XSPEC>data srctoolout_820_SourceSpec_00001.fits
XSPEC>plot data
XSPEC>ignore 0.1-0.2
XSPEC>ignore 0.4-**
XSPEC>statistic cstat
XSPEC>model bbody
1:bbodyrad:kT>=0.01
2:bbodyrad:norm>=0.8
XSPEC>fit
XSPEC>plot ldata chi
```