Degenerate Objects – white dwarfs & neutron stars

The Variable Universe – Lecture 08
Fall Semester 2022

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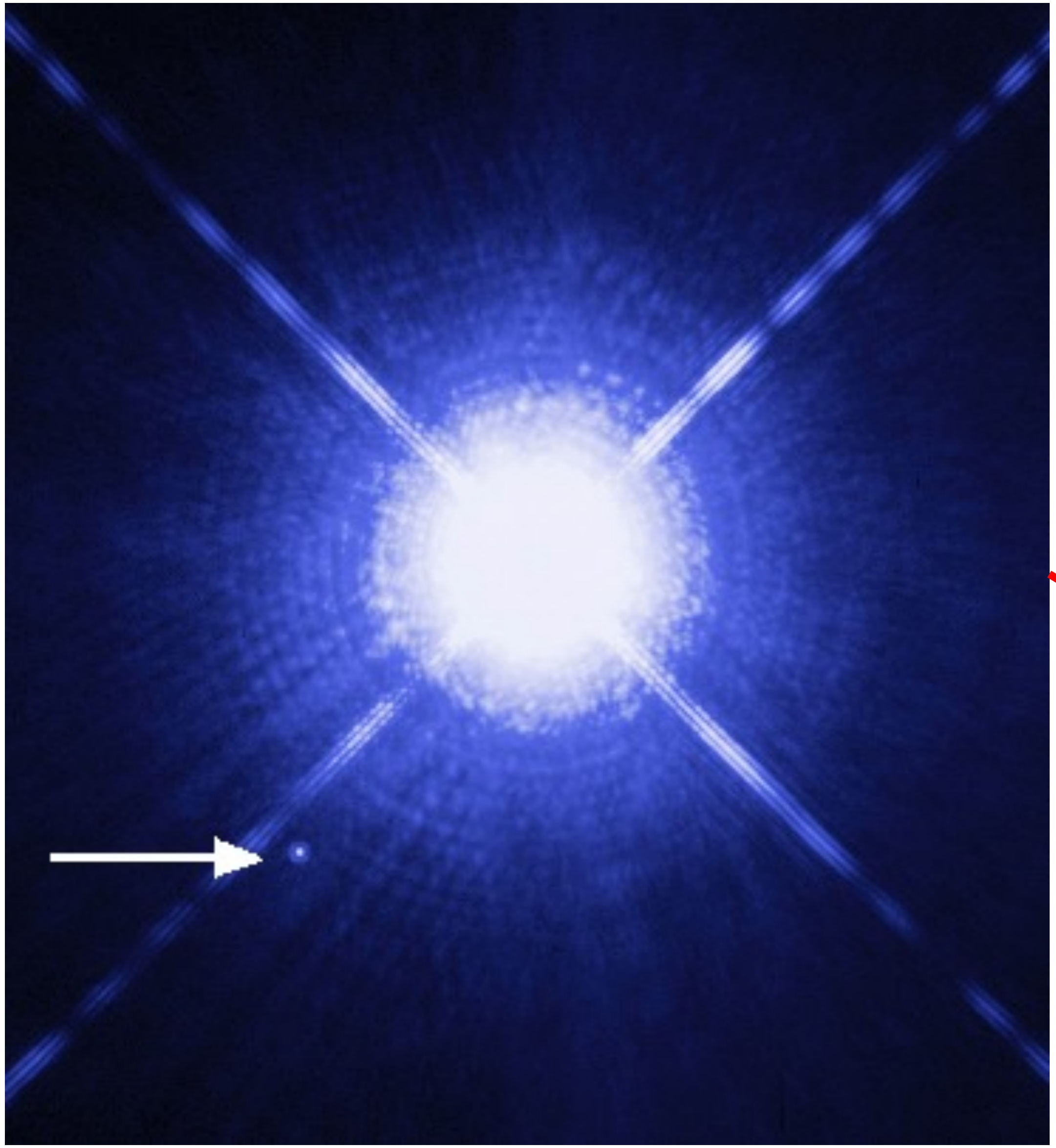
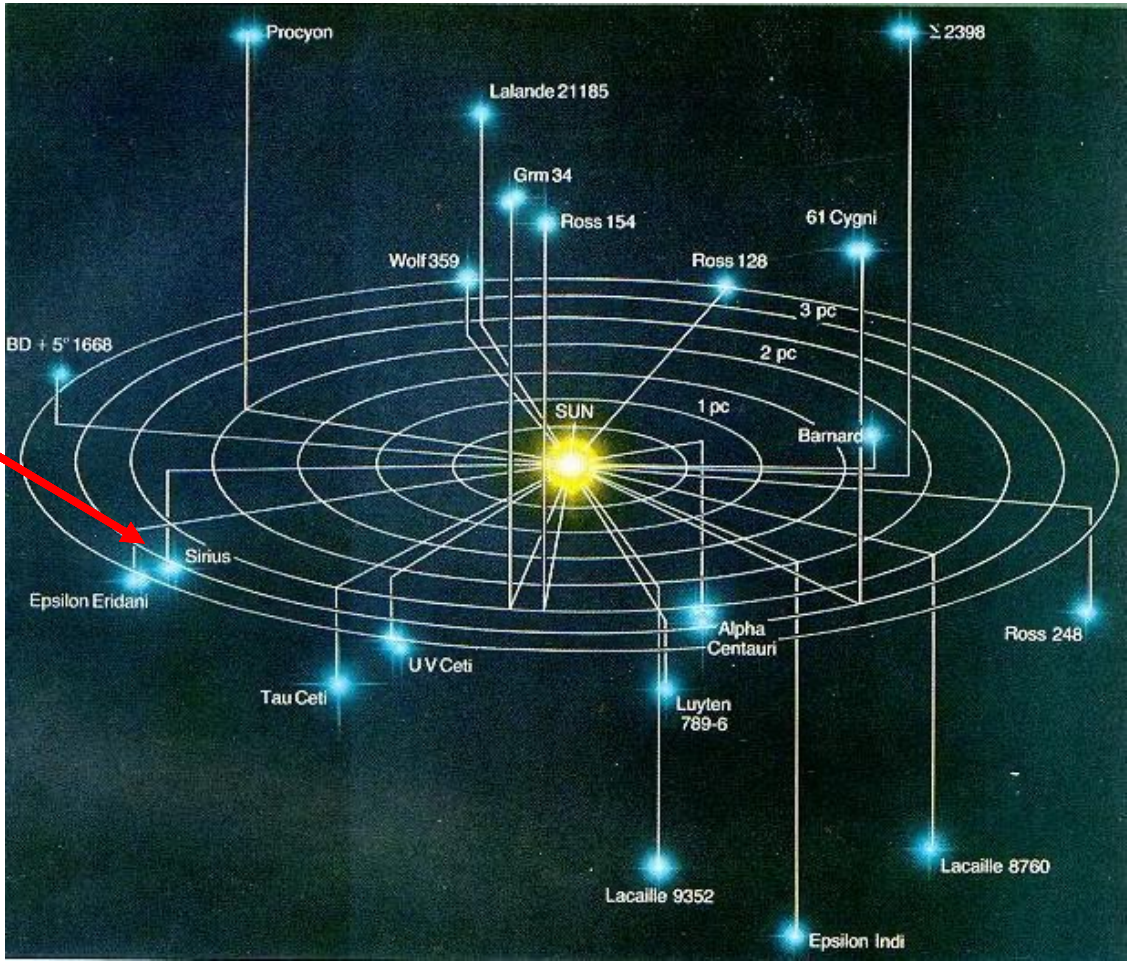
Questions from last week?

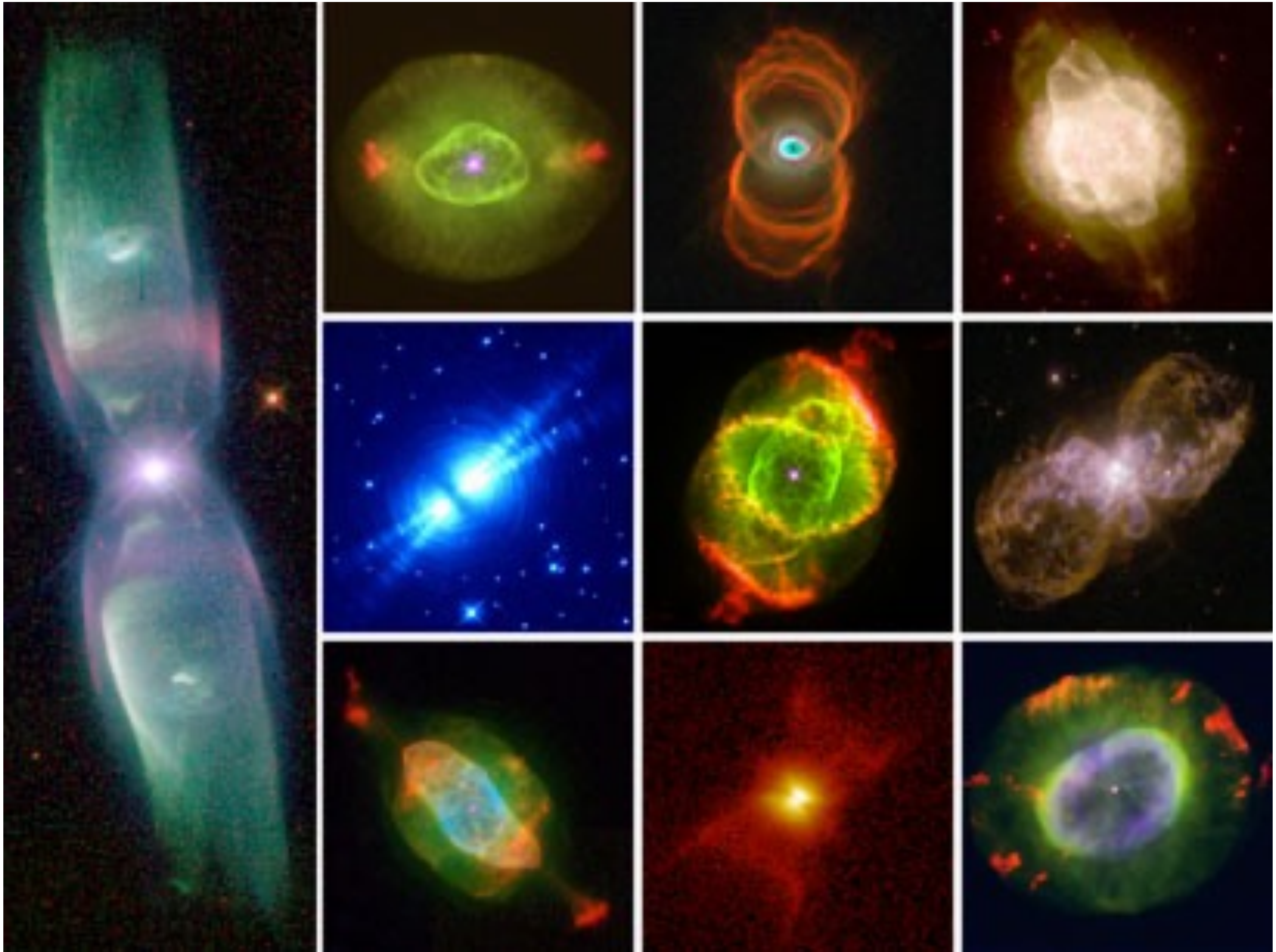
White Dwarfs





A white dwarf in the making

Southern Ring Nebula observed with JWST NIRCAM & MIRI. Credit: STScI/NASA/ESA/CSA



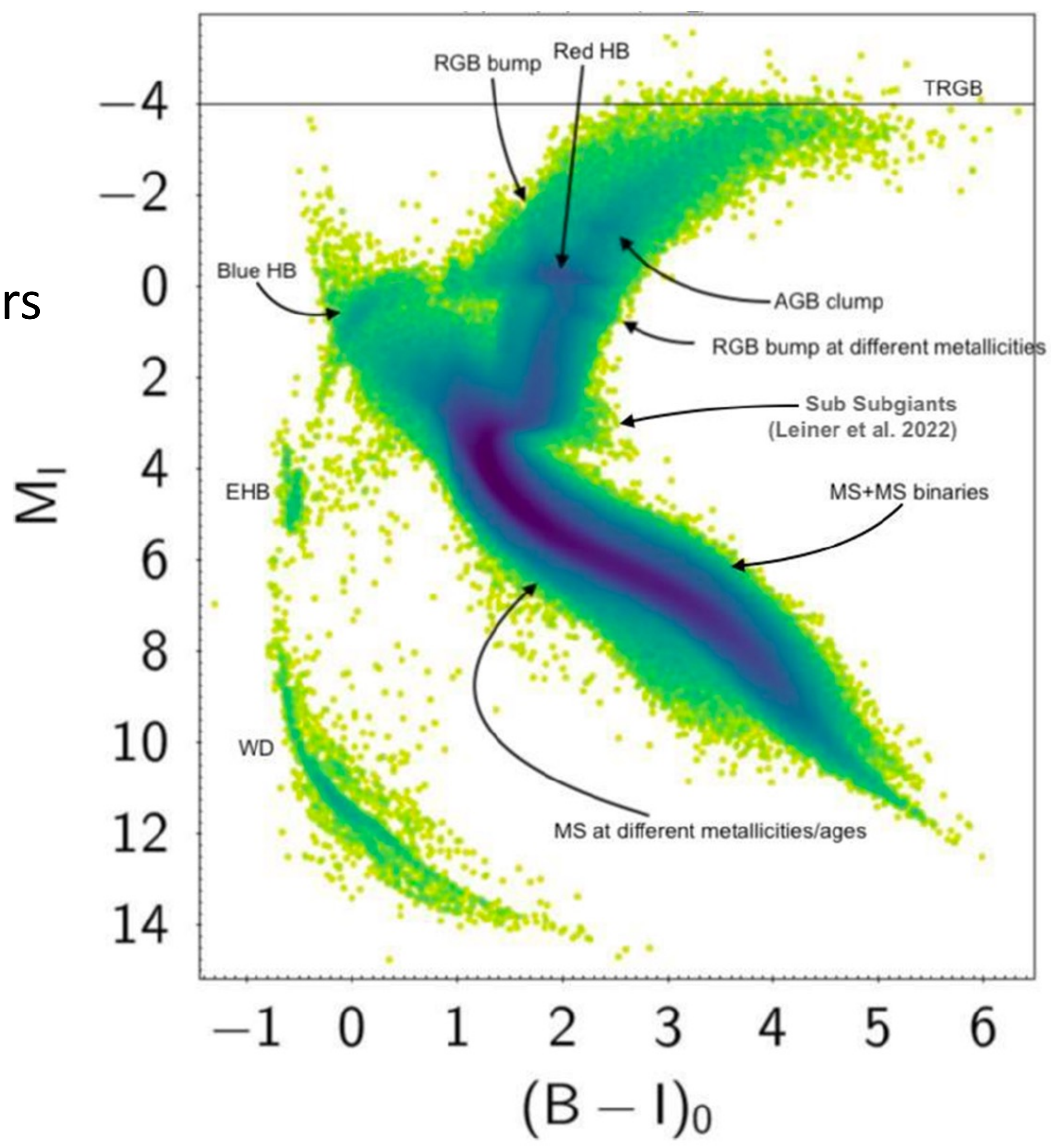
White Dwarf Origins

"Inside every red giant there is a white dwarf waiting to get out" (Brian Warner)

- Stellar masses < 8 Msol end up as WDs
- Stars > 2 Msun recycle more mass to ISM than remains in WD!
- Main Sequence: H -> He (pp-chain or CNO cycle)
- Red giant stage: He -> C+O (triple-alpha process)
- Core H, core-He, shell H and He burning around C/O core
- Most WDs are CO WDs
- Carbon fusion requires ~ 1e9 K at core
- Insufficient mass to ignite: core becomes white dwarf; otherwise CCSN -> NS
- ONeMg or ONe white dwarfs may result from stellar masses ~ 8 – 10.5 Msol where C could fuse, but not Neon or Mg
- Binary interactions responsible for very low mass Helium WDs

White Dwarfs

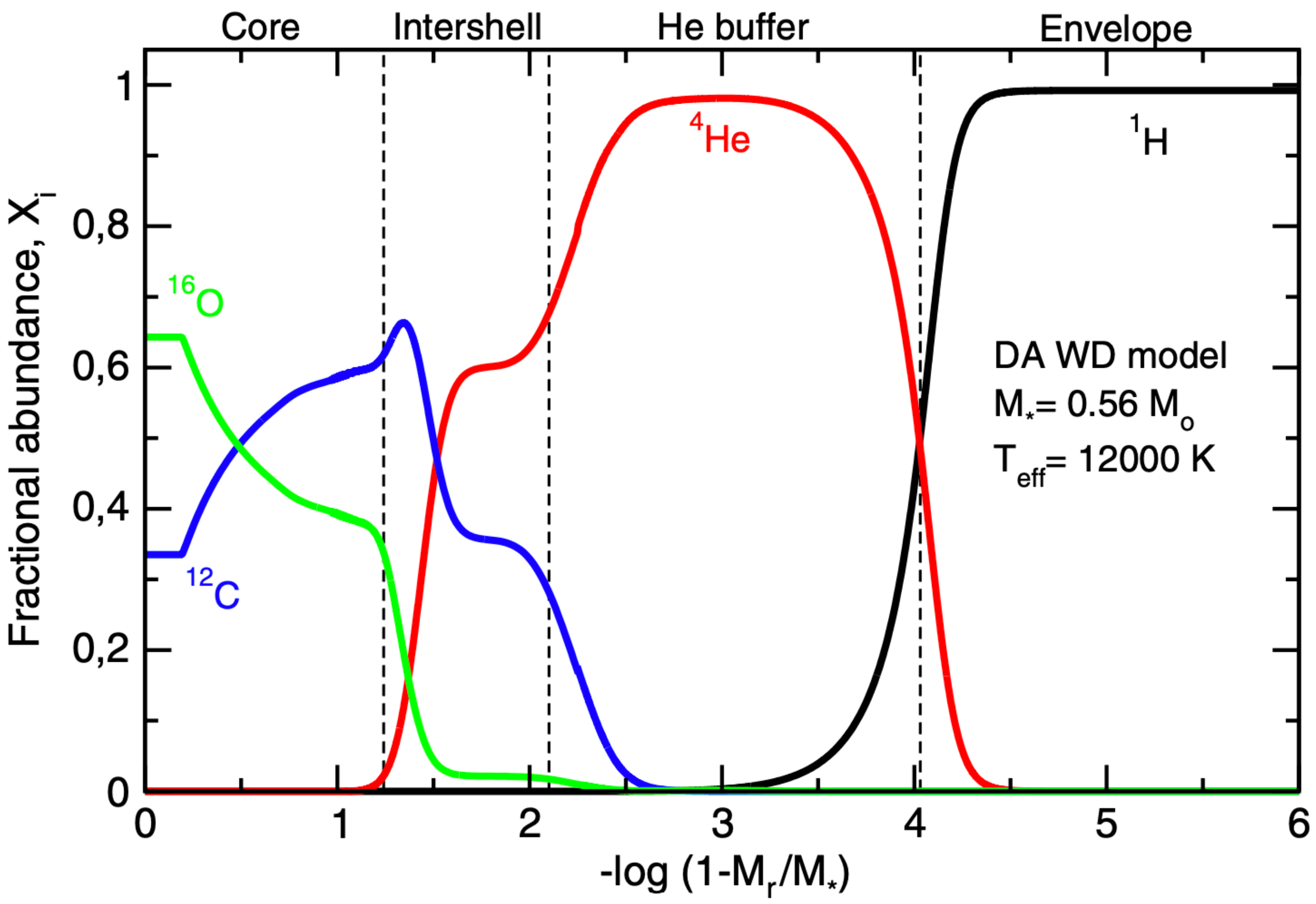
- End point of stellar evolution for 98% of stars
- Electron degeneracy pressure prevents collapse
- No fusion, what powers the radiation?
- How long does cooling take?
- Typical mass 0.6 Msol
- Very small objects: 1% Rsol ~ 1 R_Earth
- Density 1ton/cm^3 ; one teaspoon of WD matter rougly one Elephant on Earth
- 359 000 high-confidence WDs in Gaia EDR3



Gaia IoW 2022-05-23 using DR3 synthetic photometry

White dwarf structure (roughly)

Corsico (2019)

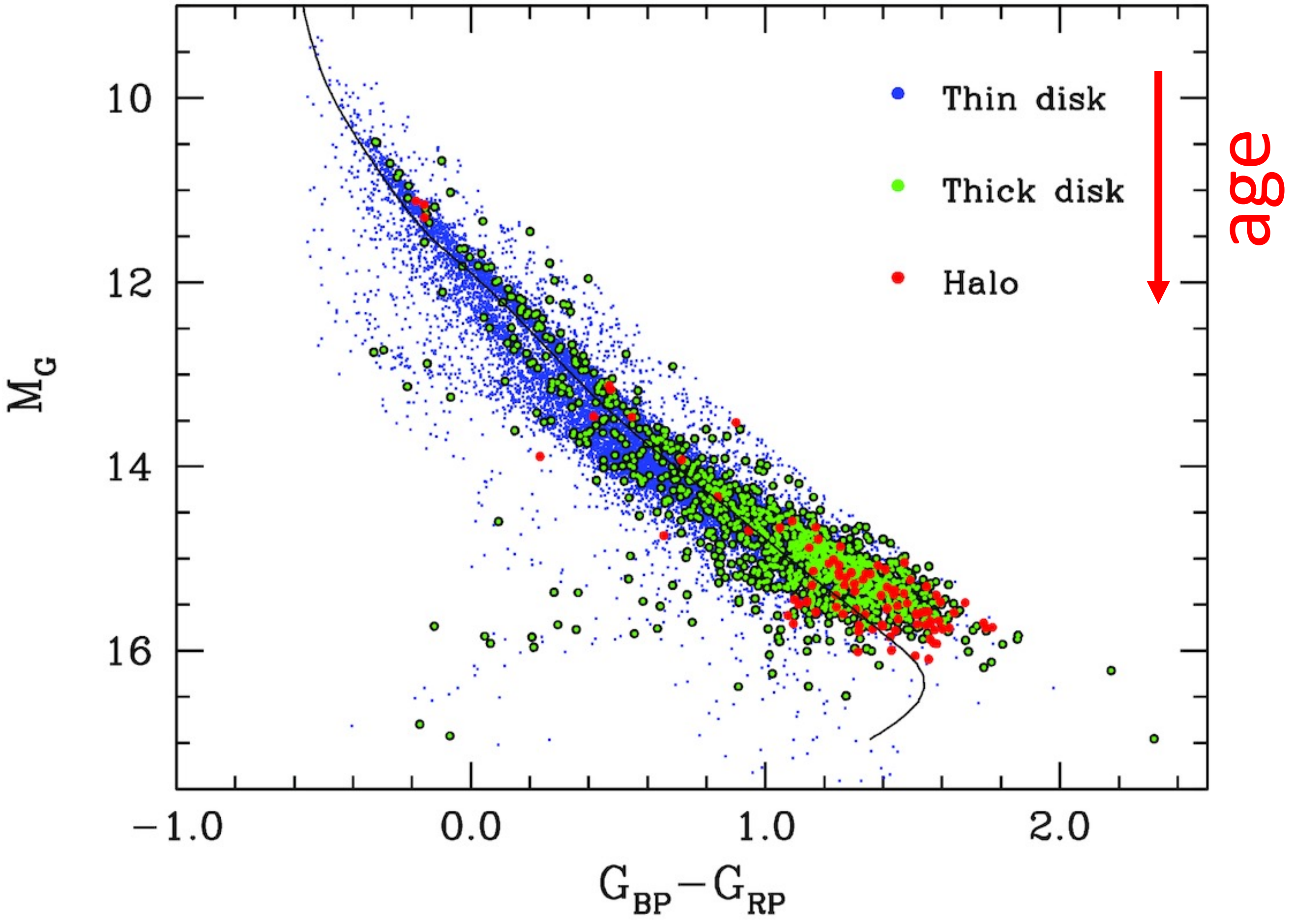


Mass fraction 90% 99% 99.9% 99.99% 99.999%

The 100pc Gaia sample of single white dwarfs

Torres et al. (2019)

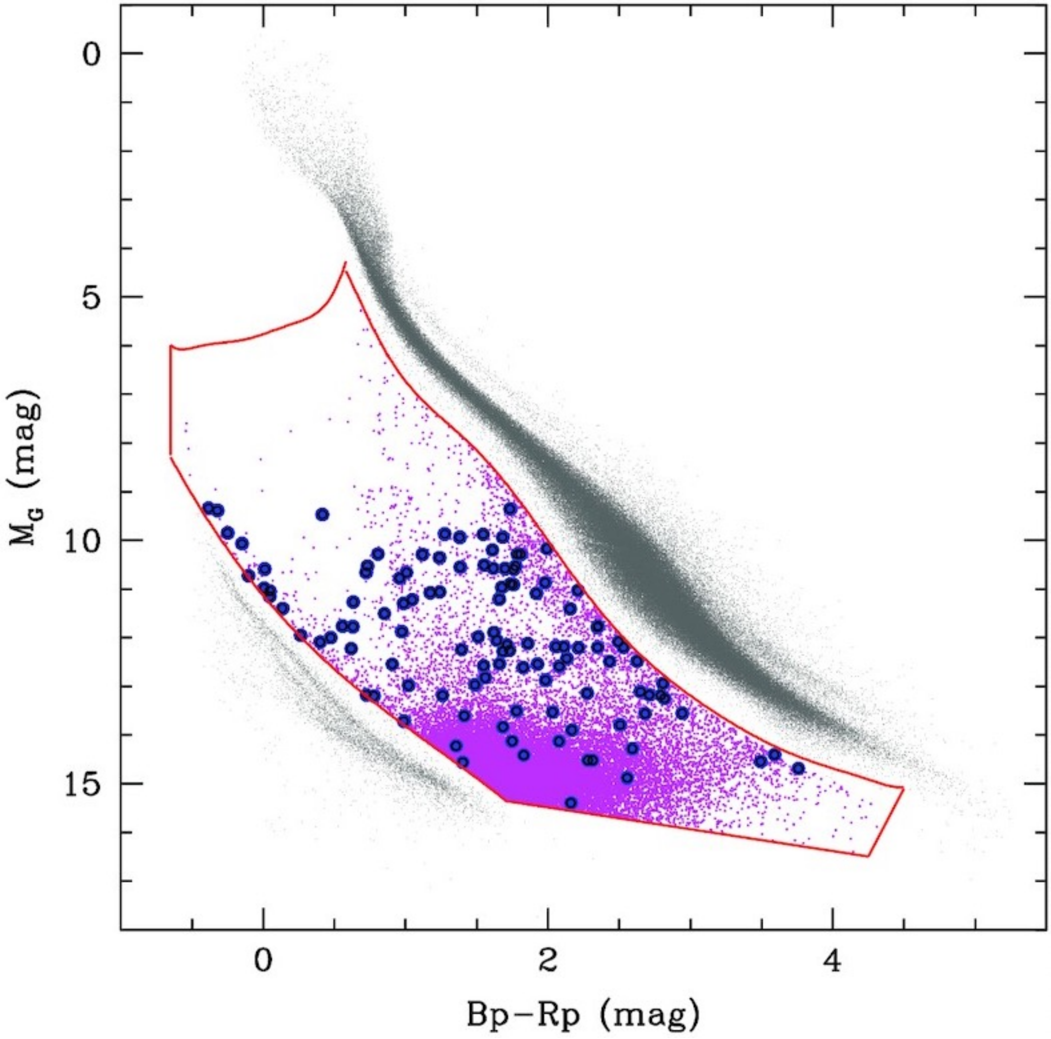
- 100pc sample >90% complete
- 13732 WDs within 100pc!
  - 12227 thin disk (74%)
  - 1410 thick disk (25%)
  - 95 halo (1%)
  - ~4% of all stars in 100pc!
- 8 of 100 closest stars WDs



WDMS binaries: white dwarfs in hiding

Rebassa-Mansergas et al. 2021

- 112 at 100pc (97 new detections)
- < 1% of all WDs in 100pc
- 80 +/- 9 % complete (types seen here)
- Only ~9% of WDMS detectable: population 10x larger
- Total density: $(3.7 \pm 1.9) \times 10^{-4} pc^{-3}$



White dwarf evolution: cooling

- Core approximately isothermal due to e-degeneracy
- Ions dominate heat capacity & behave like classical gas
- Thin (very little mass), non-degenerate layer forms insulating blanket that controls heat loss to outside
- Age-luminosity relation:

$$\log(\tau_{cool}) \approx const - \frac{5}{7}\log\left(\frac{L}{L_\odot}\right)$$

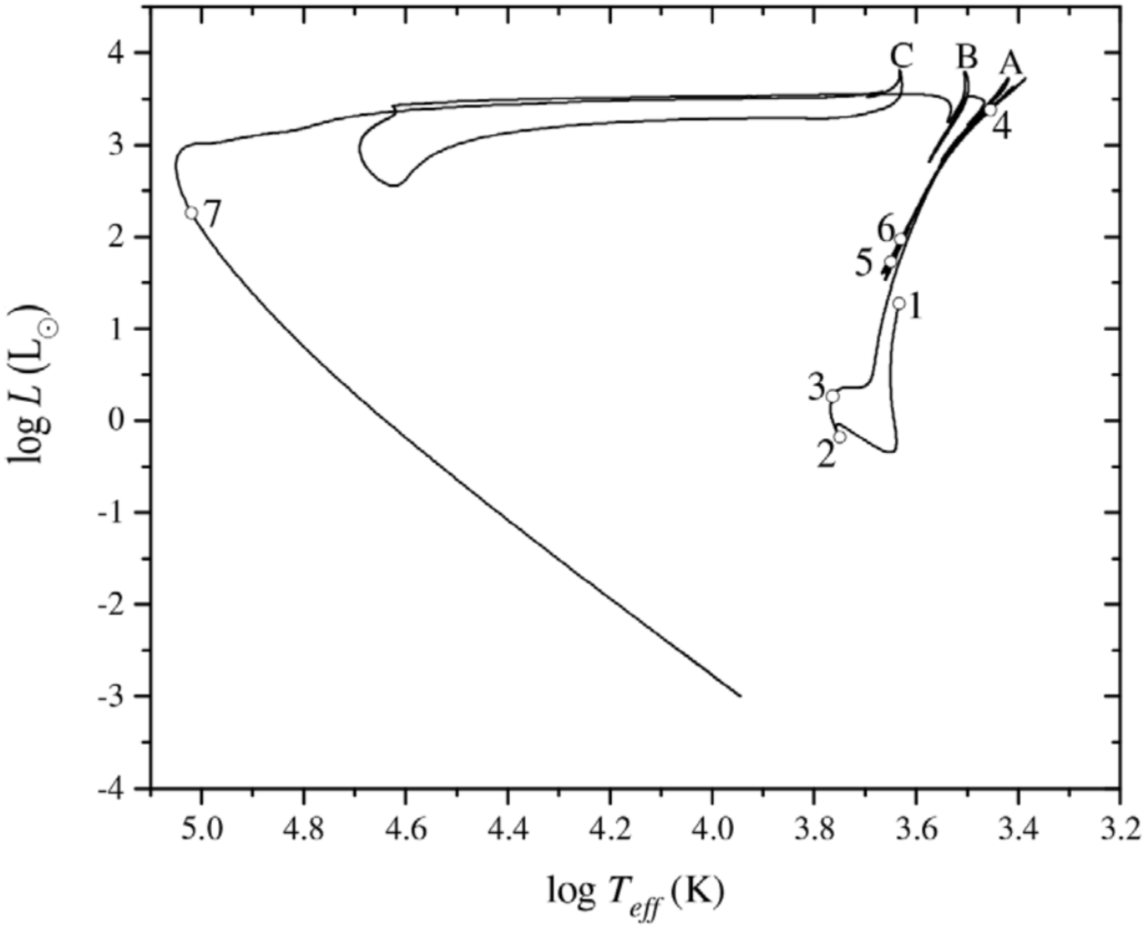
Mestel (1952)
Van Horn (1971)

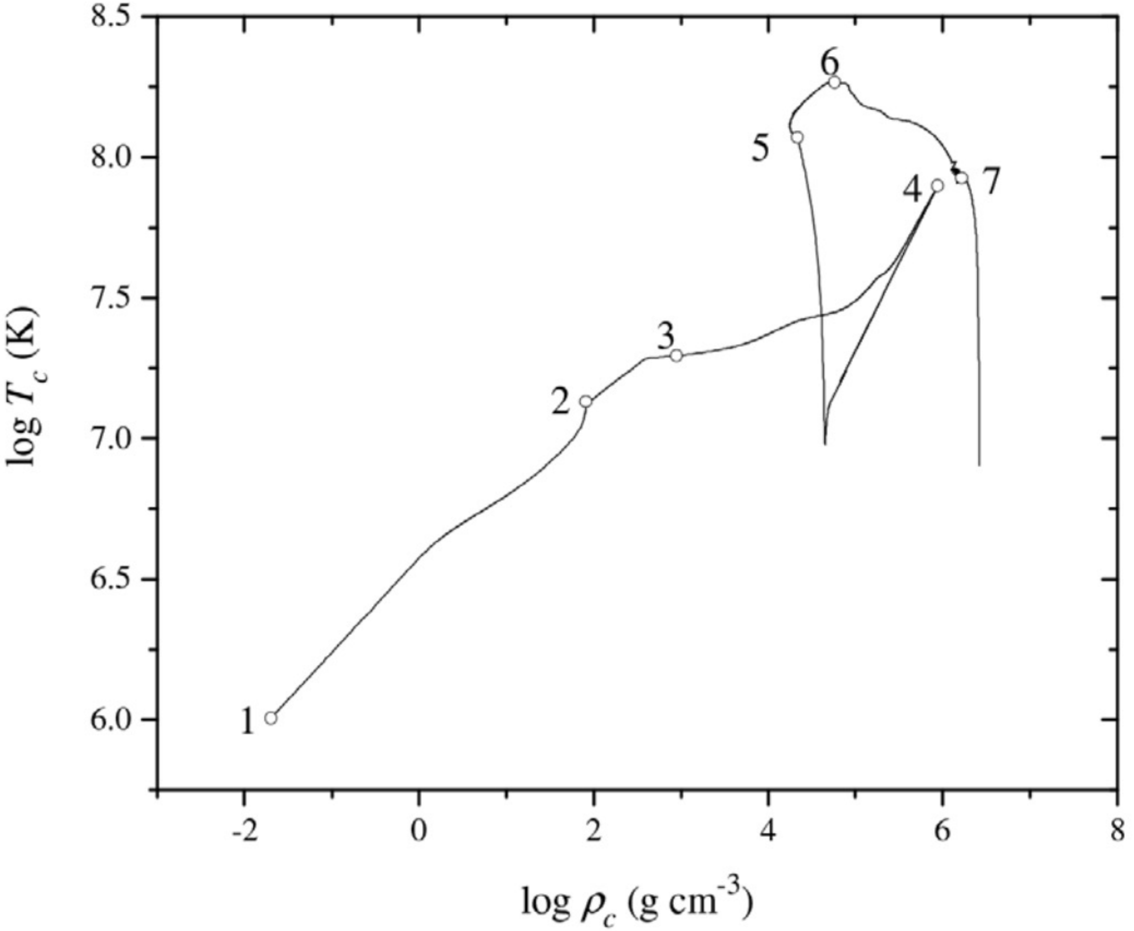
- Second-order effects:
  - Neutrino energy loss
  - Residual H-burning in H-layer
  - Gravitational contraction & settling of heavy elements
  - Surface convection
  - crystallization

White Dwarf Cooling

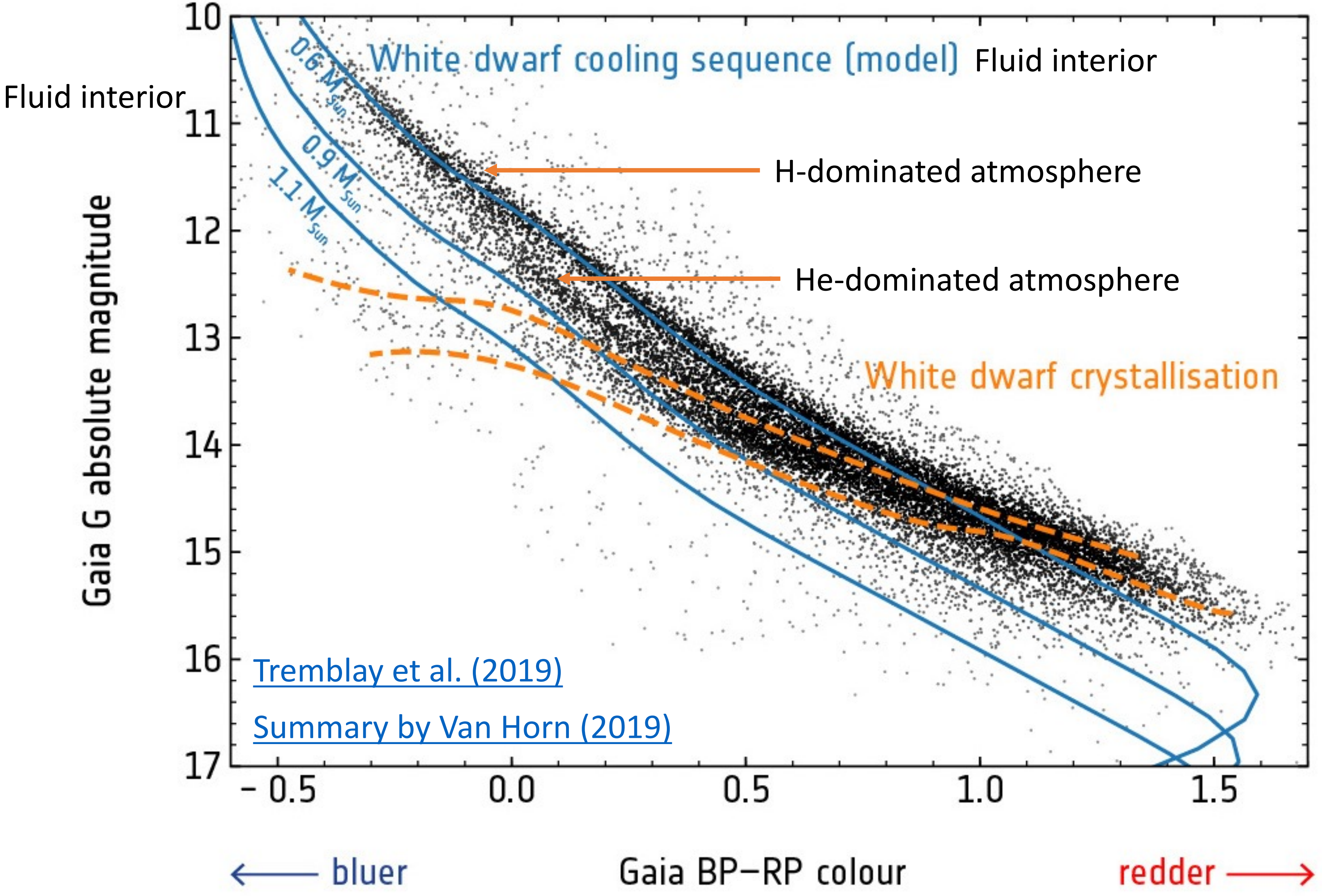
$$\log(\tau_{cool}) \approx const - \frac{5}{7}\log\left(\frac{L}{L_\odot}\right)$$

Mestel (1952)
Van Horn (1971)





Crystallization detected by Gaia & SDSS

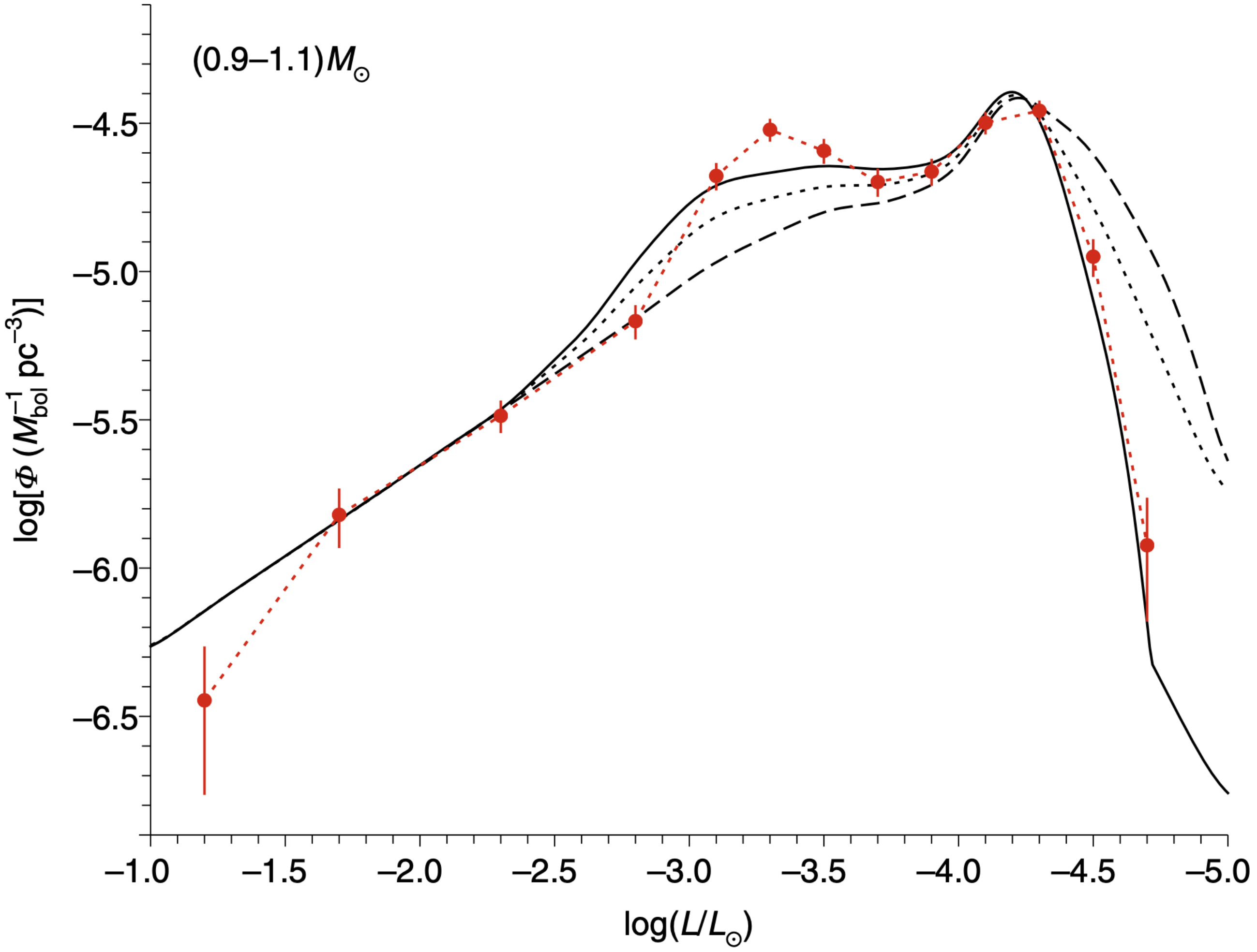


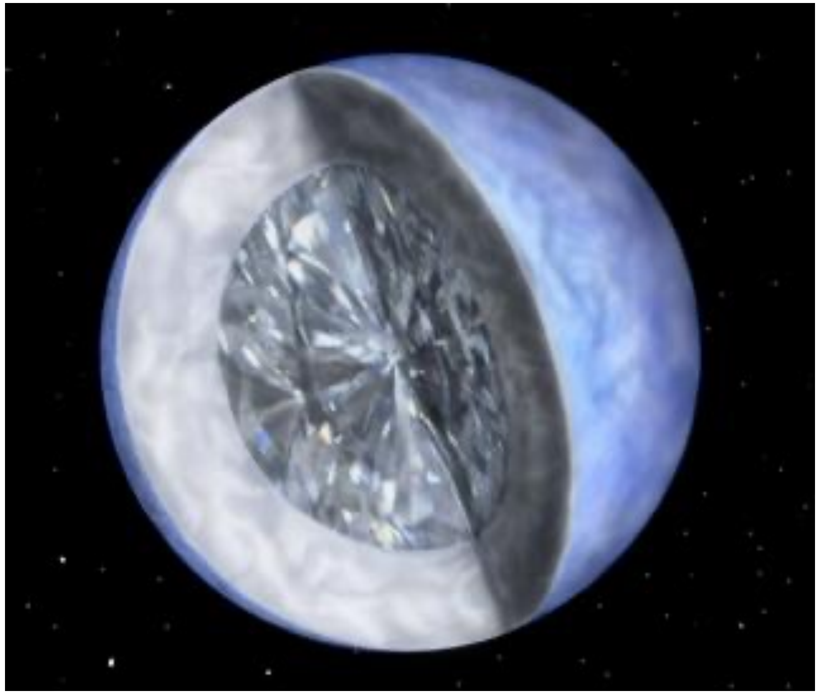
Tremblay et al. (2019)

Summary by Van Horn (2019)

Core crystallization detected by Gaia & SDSS

Tremblay et al. (2019)   Summary by Van Horn (2019)



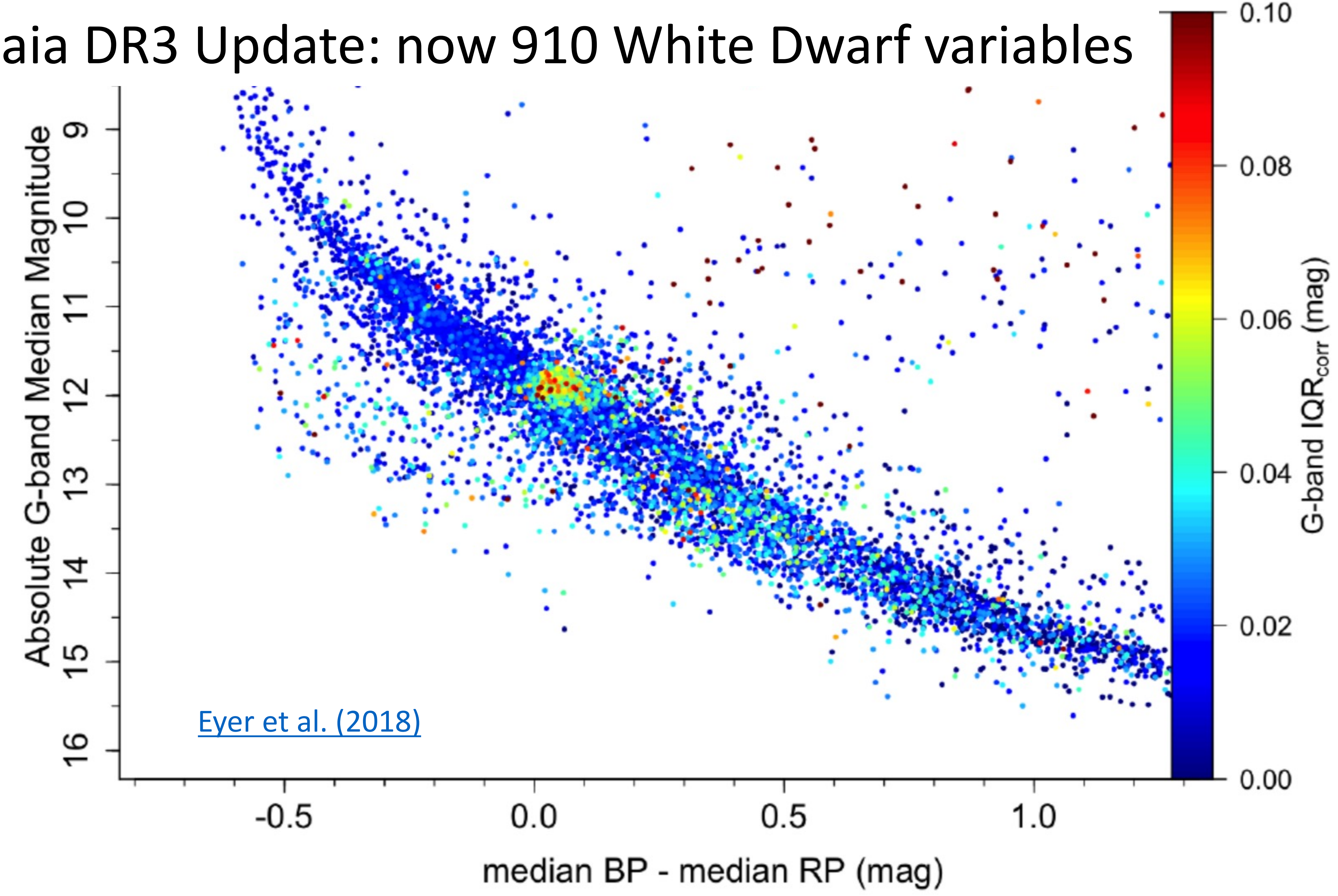


Constraints from asteroseismology in high-mass ZZ Ceti BPM 37093 by Metcalfe et al. (2004)

Brassard & Fontaine (2005)

White dwarf variability

Gaia DR3 Update: now 910 White Dwarf variables

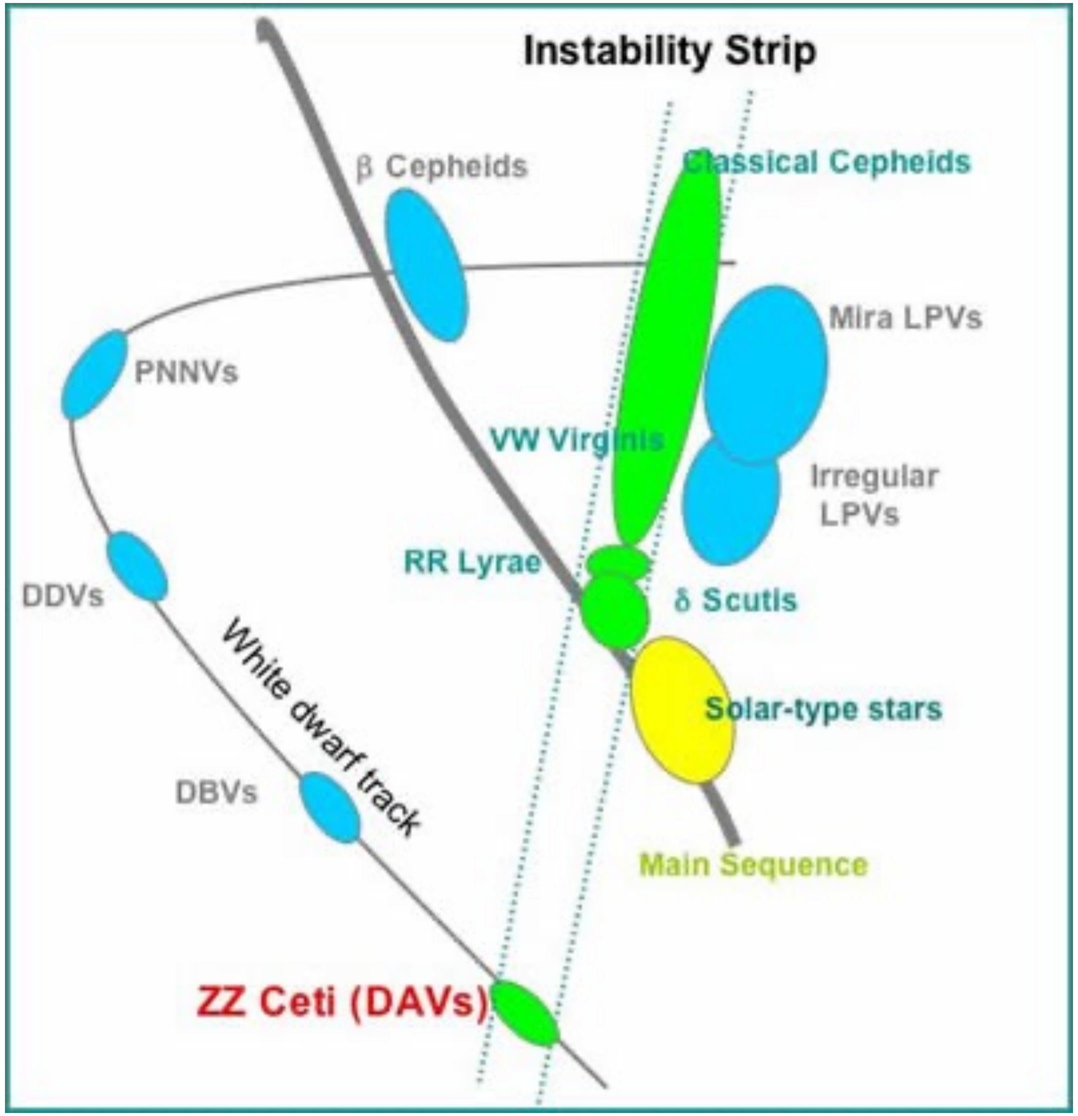


Eyer et al. (2018)

White Dwarf Pulsations

1mmag to 0.2 mag amplitudes

30 – 1200 s periods



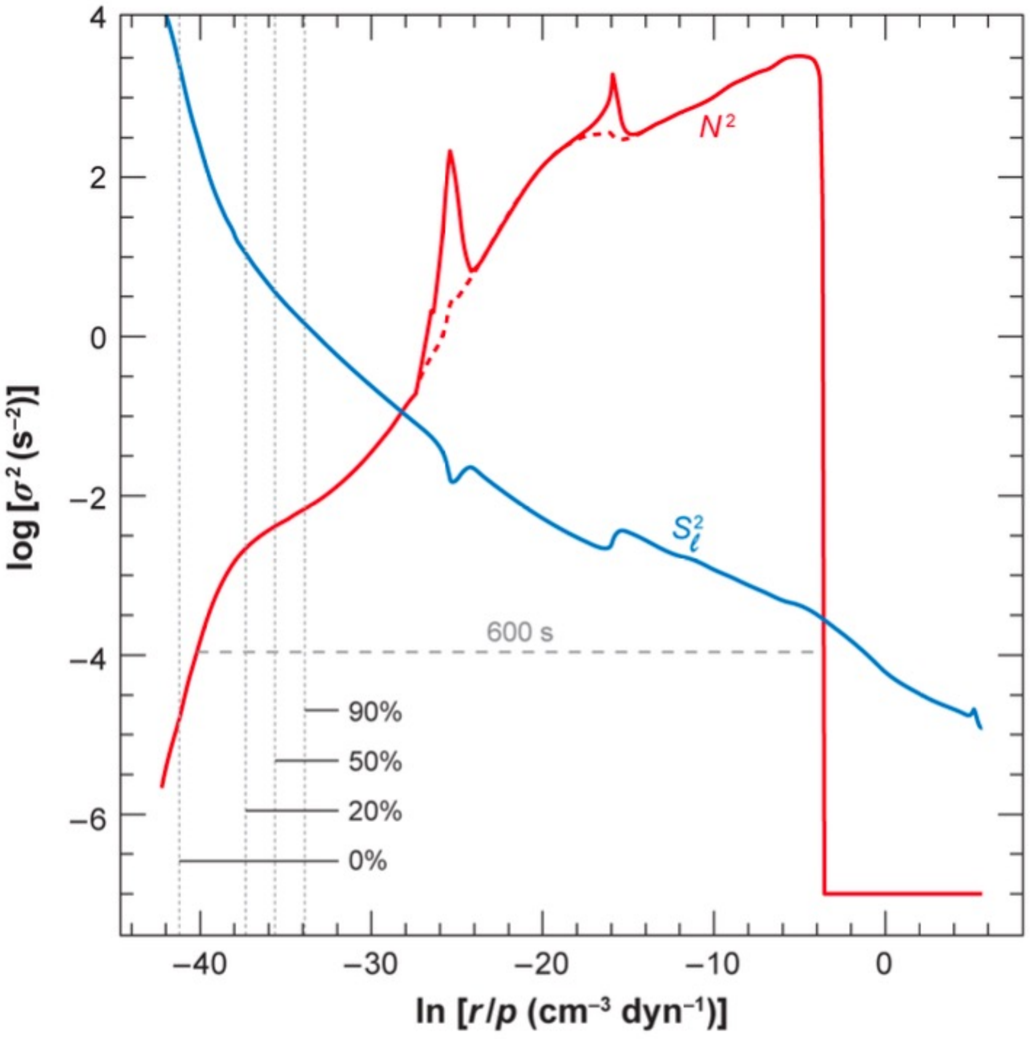
Types of pulsating White Dwarfs

WD generally:	Types of pulsating white dwarf[4][7][8][10]		Prototypes
84% DA	**DAV** (GCVS: ZZA)	DA spectral type, having only hydrogen absorption lines in its spectrum	ZZ Ceti
~16% DB	**DBV** (GCVS: ZZB)	DB spectral type, having only helium absorption lines in its spectrum	V777 Her
< 1 % the rest	**GW Vir** (GCVS: ZZO)	Atmosphere mostly C, He and O; may be divided into **DOV** and **PNNV** stars	PG 1159
	DQV	DQ spectral type; hot, carbon-dominated atmosphere	Dufour+2007
	ELMV	DA spectral type; $\lesssim 0.2 M_\odot$	

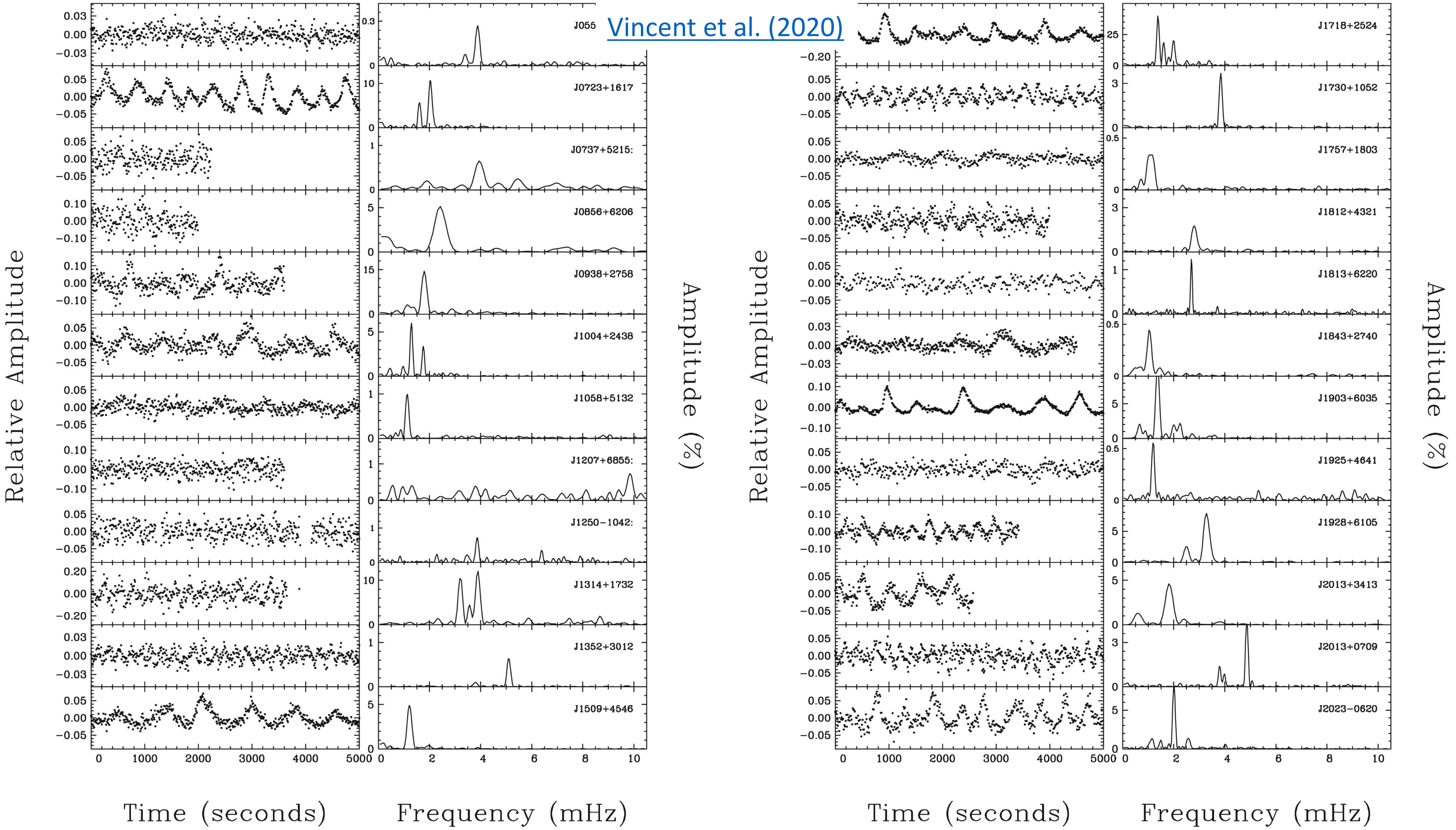
WDs feature non-radial g-mode pulsations

Winget & Kepler (2008)

- Photometric & spectroscopic variability in ZZ Ceti P=12.5min (Landolt 1968)
- p-mode pulsations on Lamb frequency: too fast & vertical displacement tough
- g-mode pulsations along equipotential surfaces! ~ 100+ seconds
- Mode identification from multiplets, chromatic amplitudes, or line profiles
- $\sigma_{k,l,m} \approx \left\langle \frac{N^2 \ell(\ell+1)}{k^2 r^2} \right\rangle^{1/2} + \left[1 - \frac{C_k}{\ell(\ell+1)}\right] m\Omega$



Vincent et al. (2020)



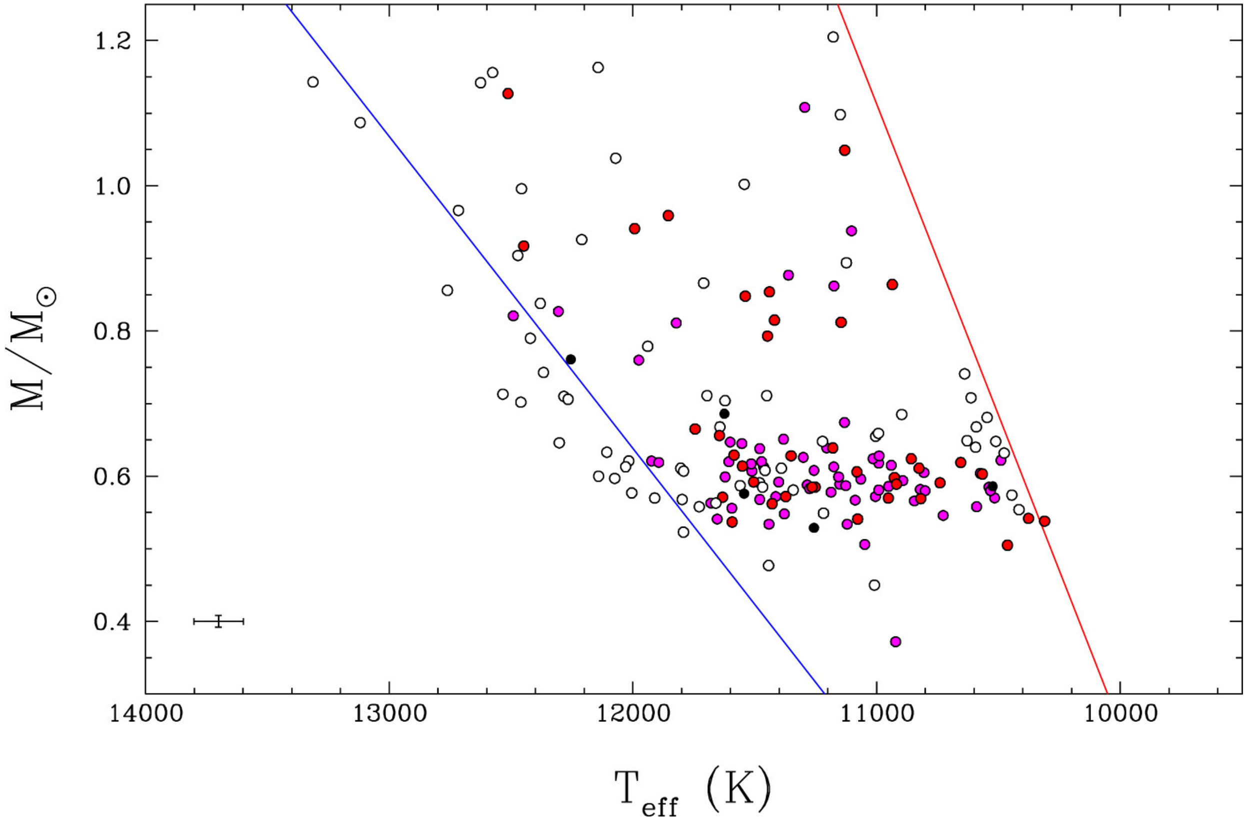
DAV pulsations driven by a Hydrogen PIZ

- Hydrogen richness in DAV (ZZ Ceti) stars
- Instrumentation developments : two-star photometers (Nather 1973)
- Late 1970s: ZZ Ceti stars homogeneous class of normal DA WDs
- 1981 & 1982: Mode driving due to partial H ionization zone explained
- Low $\ell \sim 1{,}2$ non-radial g-mode pulsasations drvien by H PIZ
- Winget (1981,1982) found driving on He PIZ in models: predicted DBV pulsations that were later found
- Likely the kappa-gamma mechanism: compression energy stored in opacity change (kappa) due to ionization

The ZZ Ceti Instability Strip (DAV)

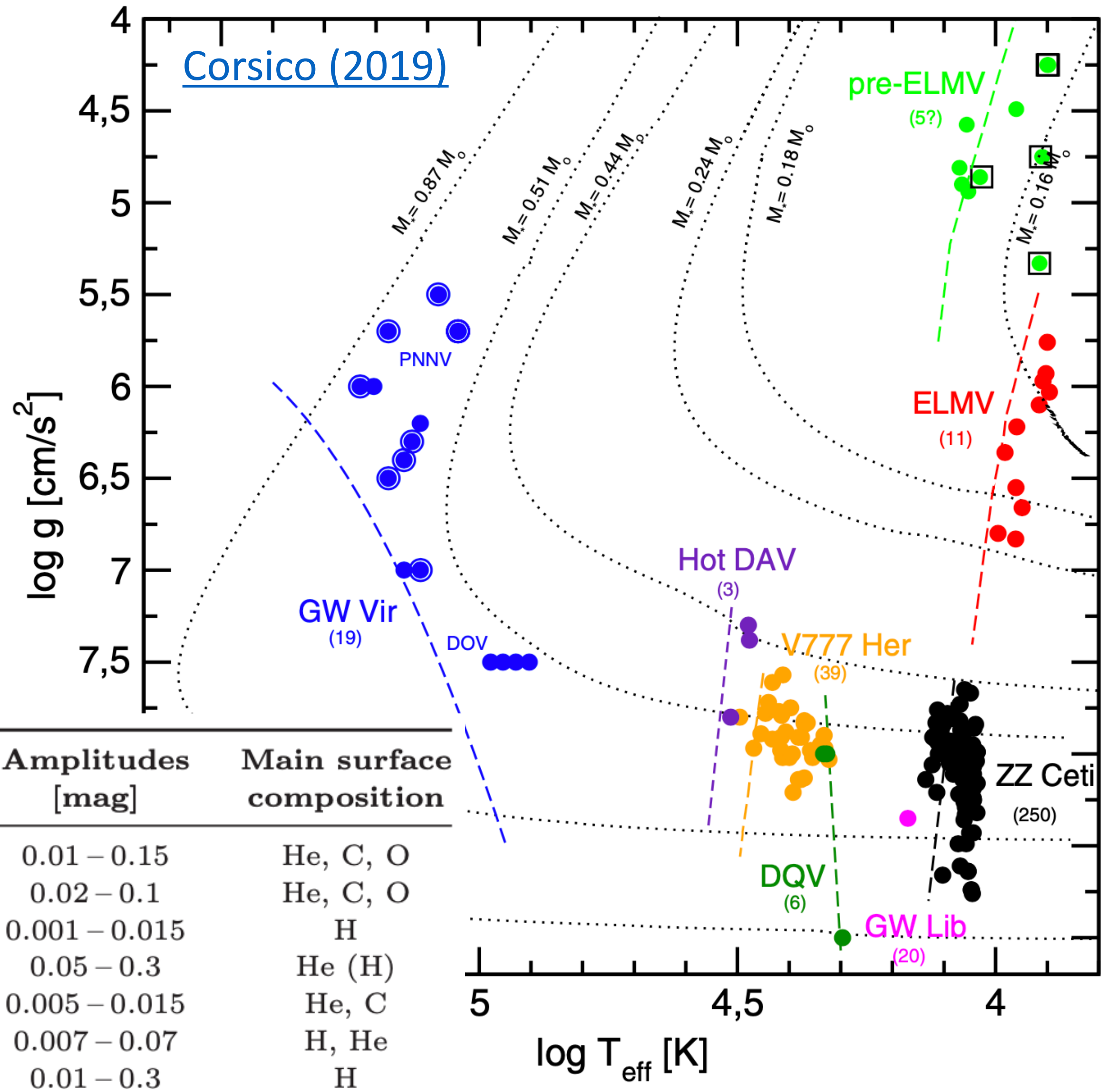
- 319 ZZ Ceti known in 2020
- 910 White Dwarf Variables in Gaia DR3
- Variability due to non-radial pulsations
- g-modes: gravity restoring force
- Periods between 30s and 25 min
- Restricted Teff range
- Purity of IS open question: low amplitude variations undetected?
- Rate of period change tracks cooling process

Vincent et al. (2020)



WD instability strips

- Multiple regions of instability clearly discernible
- Pulsations allow to unravel WD interior structure & test models



Class	Year of disc. (#)	$T_{\rm eff}$ [×1000 K]	log g [C.G.S.]	Periods [s]	Amplitudes [mag]	Main surface composition
GW Vir (PNNV)	1984 (10)	100 – 180	5.5 – 7	420 – 6000	0.01 – 0.15	He, C, O
GW Vir (DOV)	1979 (9)	80 – 100	7.3 – 7.7	300 – 2600	0.02 – 0.1	He, C, O
Hot DAV (?)	2013 (3)	30 – 32.6	7.3 – 7.8	160 – 705	0.001 – 0.015	H
V777 Her (DBV)	1982 (27)	22.4 – 32	7.5 – 8.3	120 – 1080	0.05 – 0.3	He (H)
DQV (?)	2008 (6)	19 – 22	8 – 9	240 – 1100	0.005 – 0.015	He, C
GW Lib	1998 (20)	10.5 – 16	8.35 – 8.7	100 – 1900	0.007 – 0.07	H, He
ZZ Cet (DAV)	1968 (260)	10.4 – 12.4	7.5 – 9.1	100 – 1400	0.01 – 0.3	H
pre-ELMV	2013 (5)	8 – 13	4 – 5	300 – 5000	0.001 – 0.05	He, H
ELMV	2012 (11)	7.8 – 10	6 – 6.8	100 – 6300	0.002 – 0.044	H

Corsico (2019)

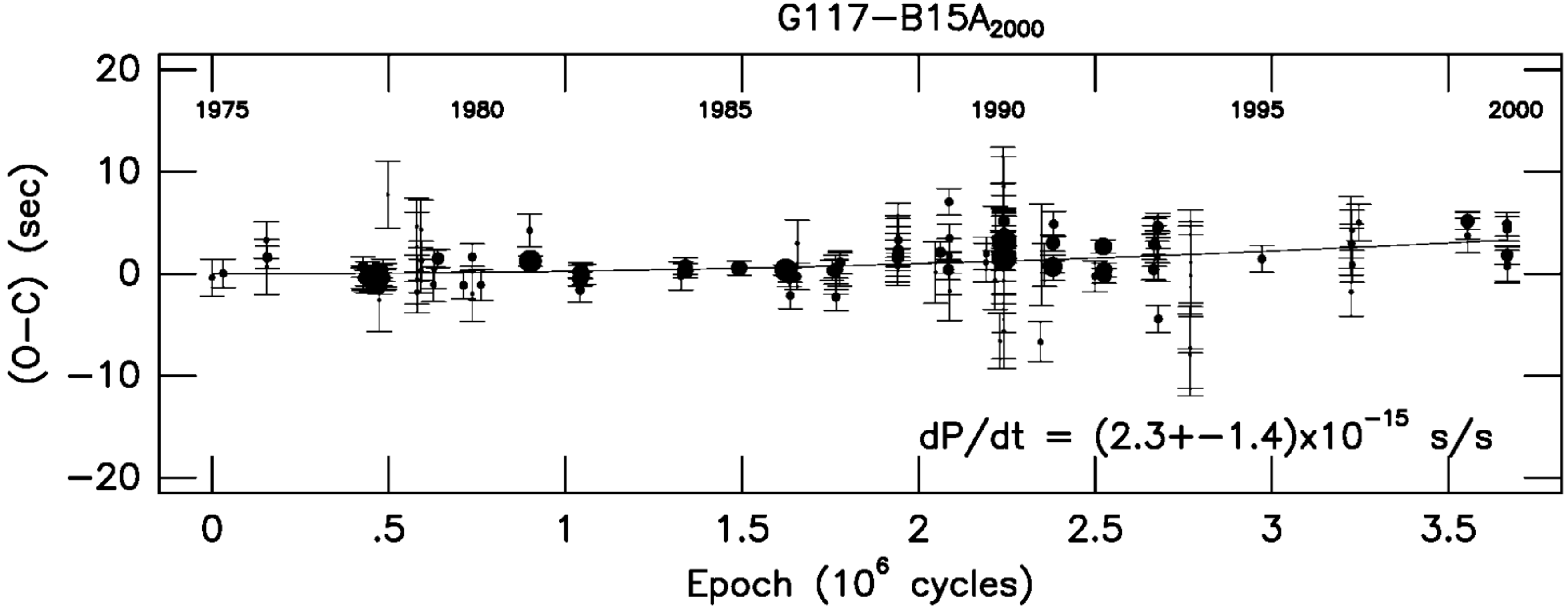
What is the most stable clock in the Universe?

Stability of a clock is determined by ratio $\dot{P}/P$

Most stable human-made:
Optical-lattice-trapped cold-Ytterbium clocks lose 1s per 15 billion years (4.7x10^17s) (Breakthrough Prize Fundamental Phys 2022)

Measuring period change via O-C diagrams

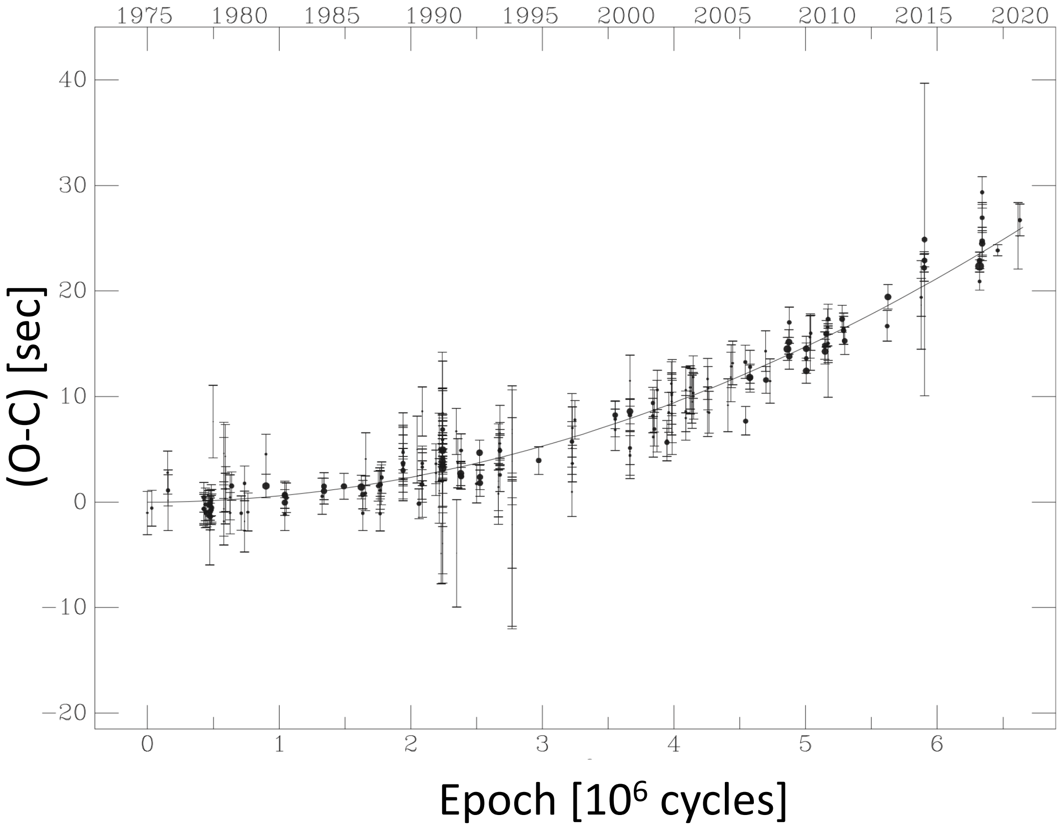
- $(O - C) = \Delta E_0 + \Delta P + \frac{1}{2} P\dot{P}E^2$
- $\Delta E_0 = (T^0_{max} - T^1_{max})$; $\Delta P = \left(P - P_{t=T^0_{max}}\right)$; E is # cycles since start



G117-B15A (RY LMi): 1s lost per 6.2 million yr

[Kepler et al. (2021)]

- Among the hottest ZZ Ceti stars
- P = 215s dominant (6 known)
- $\dot{P} = (5.12 \pm 0.82)\times 10^{-15}\ s\ s^{-1}$
- Possible O-C signal sources:
  - Orbital motion (difficult to rule out)
  - Residual contraction (decreases P)
  - Cooling (increases P, matches models)
  - Proper motion (several times smaller)



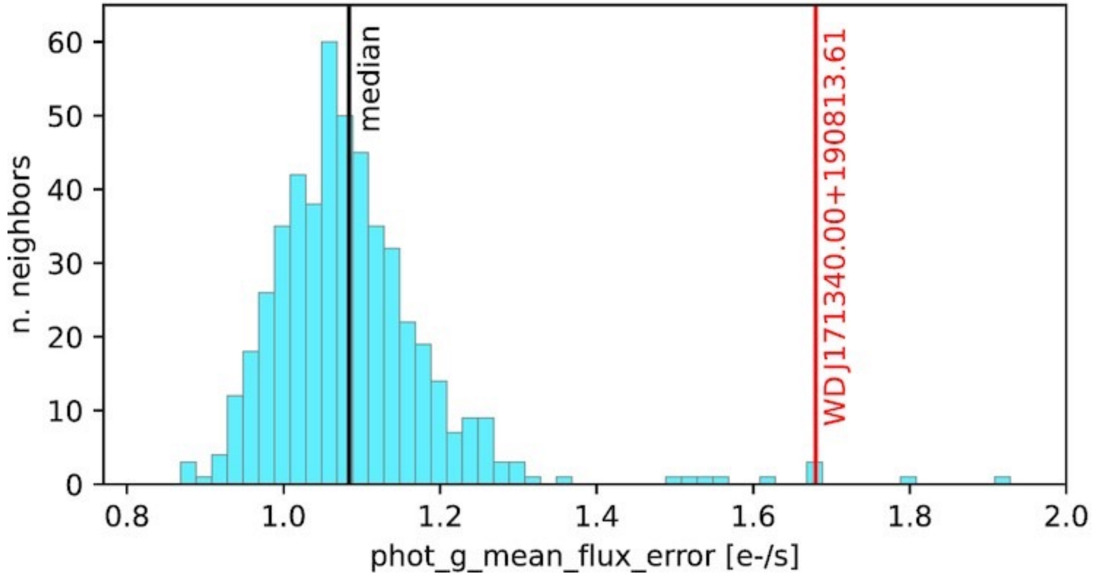
$$\dot{P}_{pm} = 2.430\times 10^{-18} P[s](\mu[\text{arcsec}\, yr^{-1}])^2\ (\pi\ [arcsec])^{-1} \approx (0.3532 \pm 0.00024)\times 10^{-15} s\ s^{-1}$$

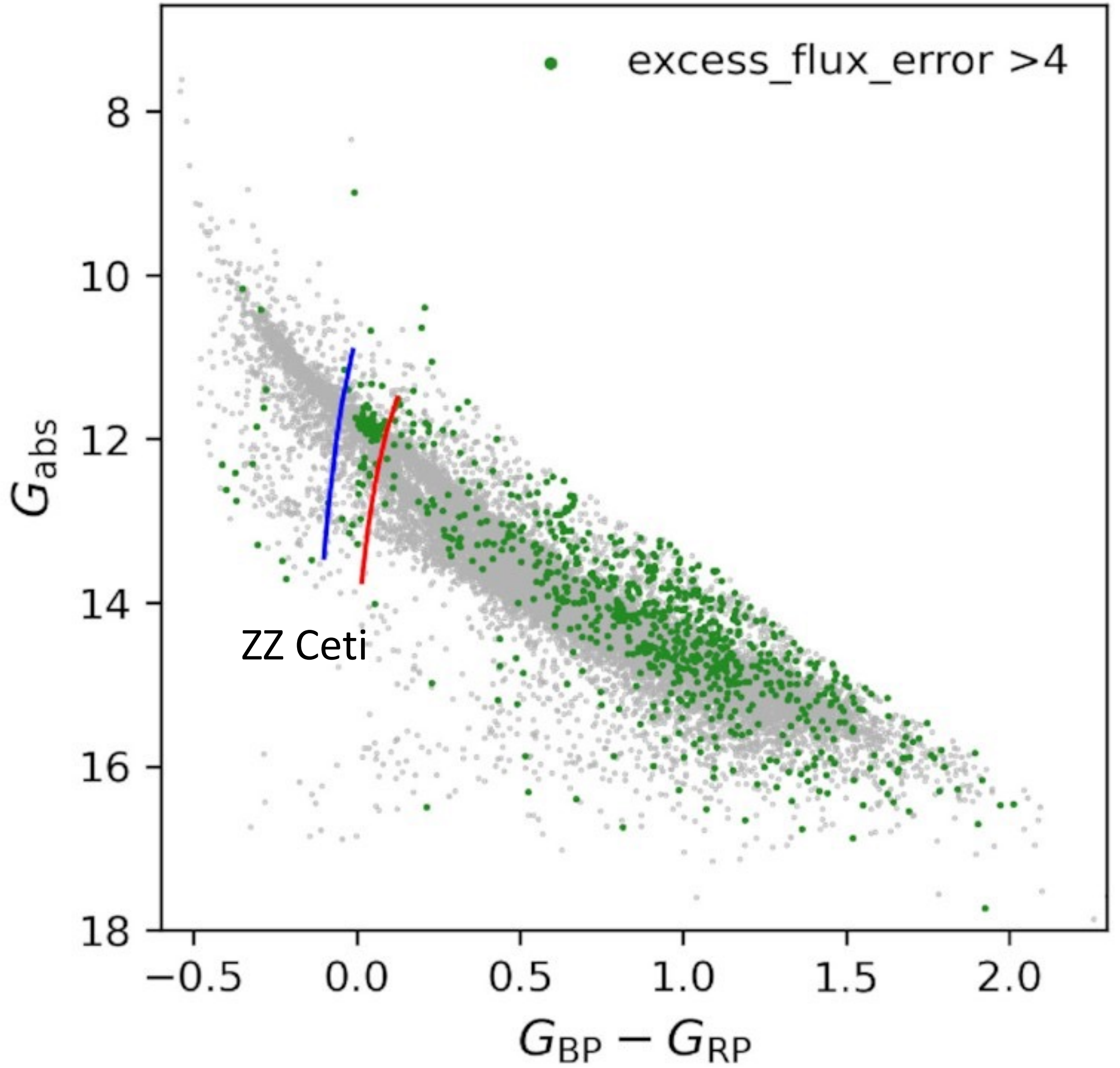
Detecting variability without published time series

Detecting variability without time-series

[Gentile Fusillo et al. (2021)](#)

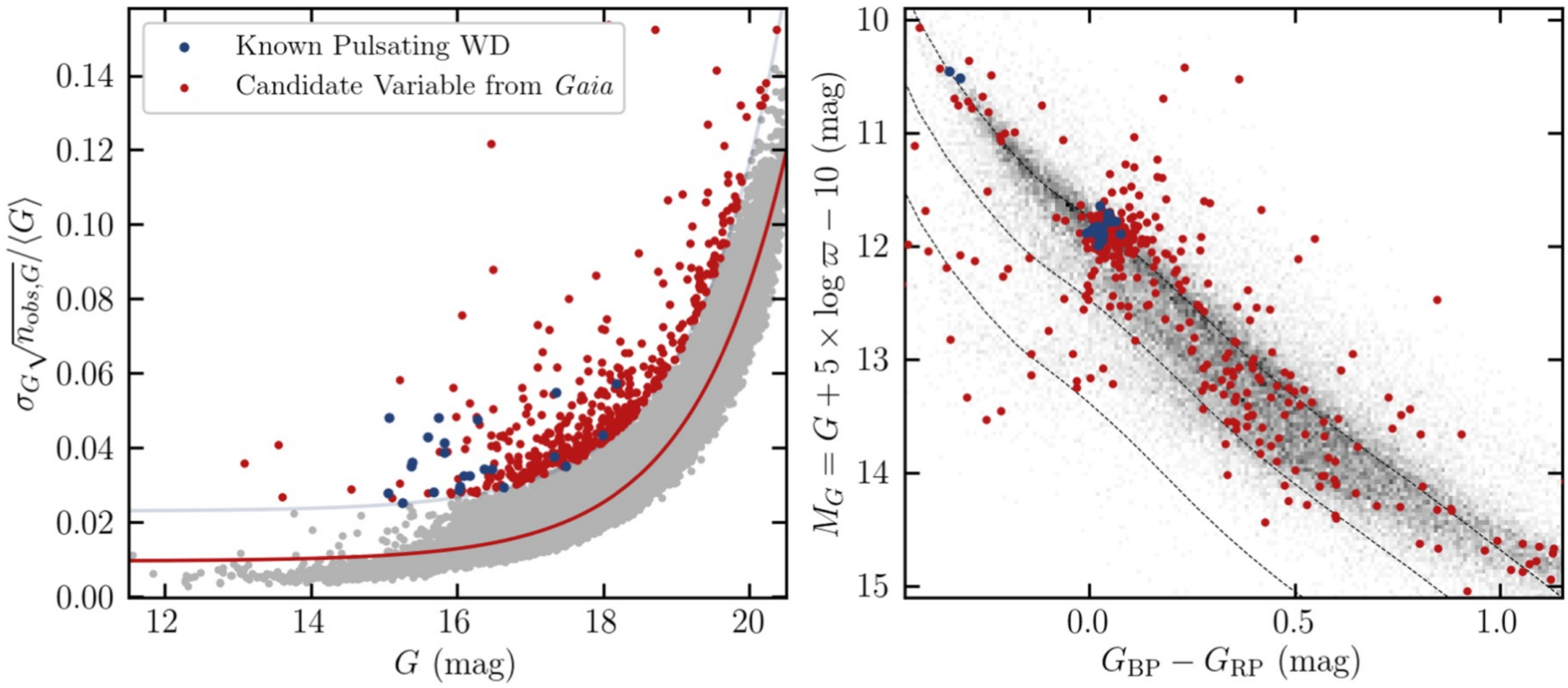
- Excess_flux_error = log10(flux_error) / MAD(log10(flux_neighbors))
- 5.7% have excess_flux_error > 4





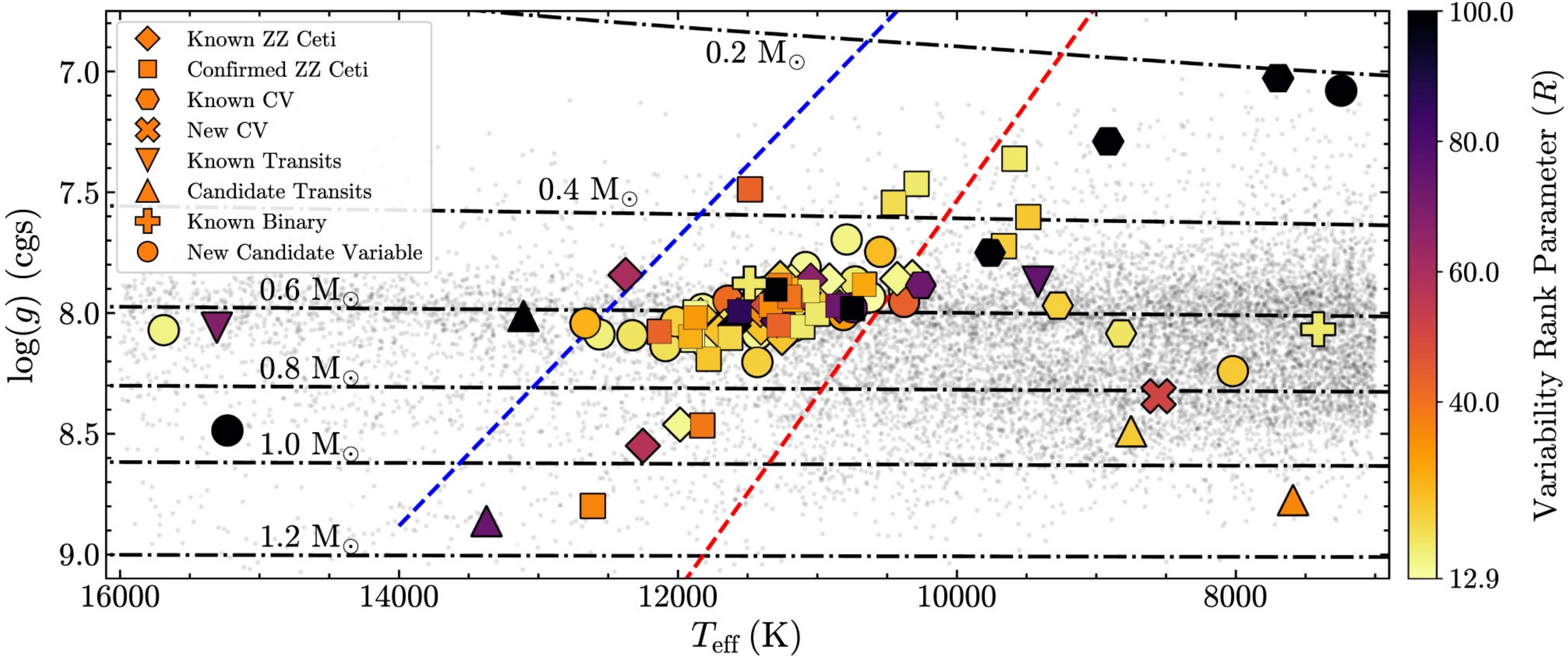
Detecting White Dwarf Variability with few observations

Guidry et al. (2021)



Sampling the ZZ Ceti Instability Strip without time series data

Guidry et al. (2021)



Other variability origins in WDs

Examples

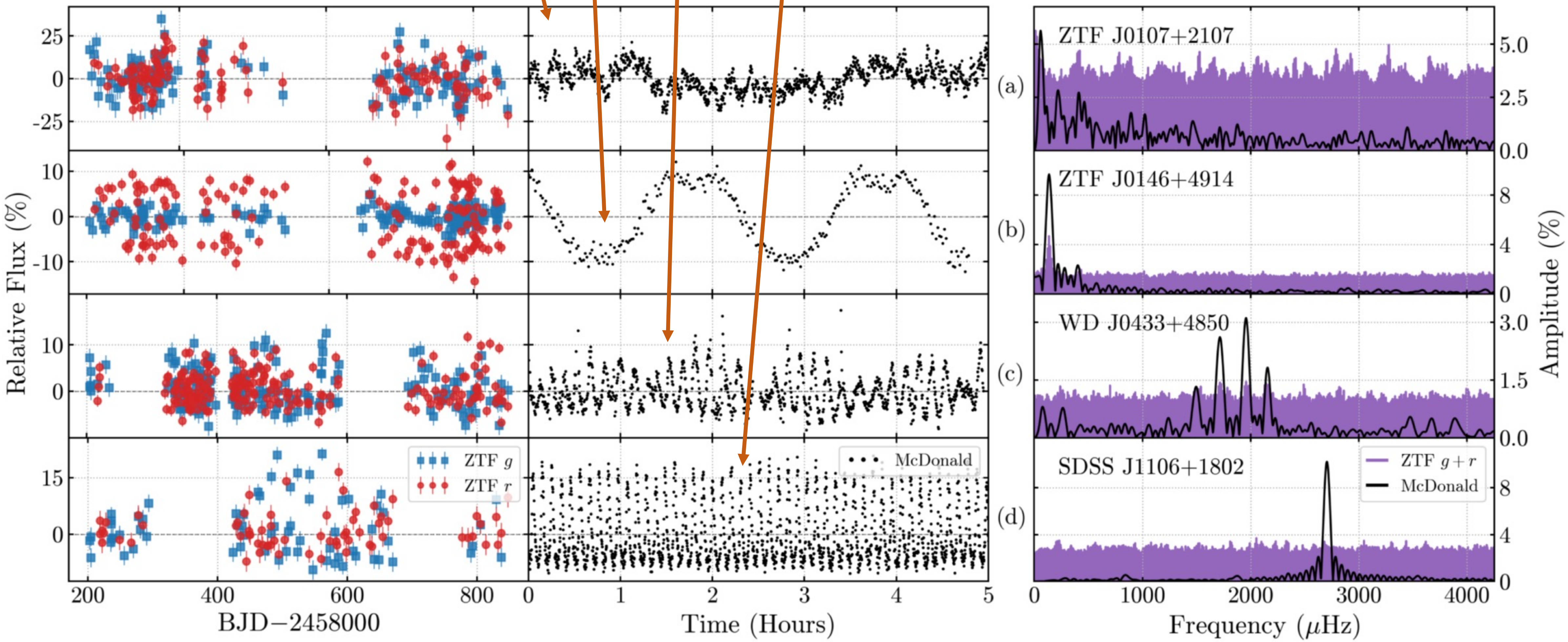
Guidry et al. (2021)

Transiting debris candidate

Polar

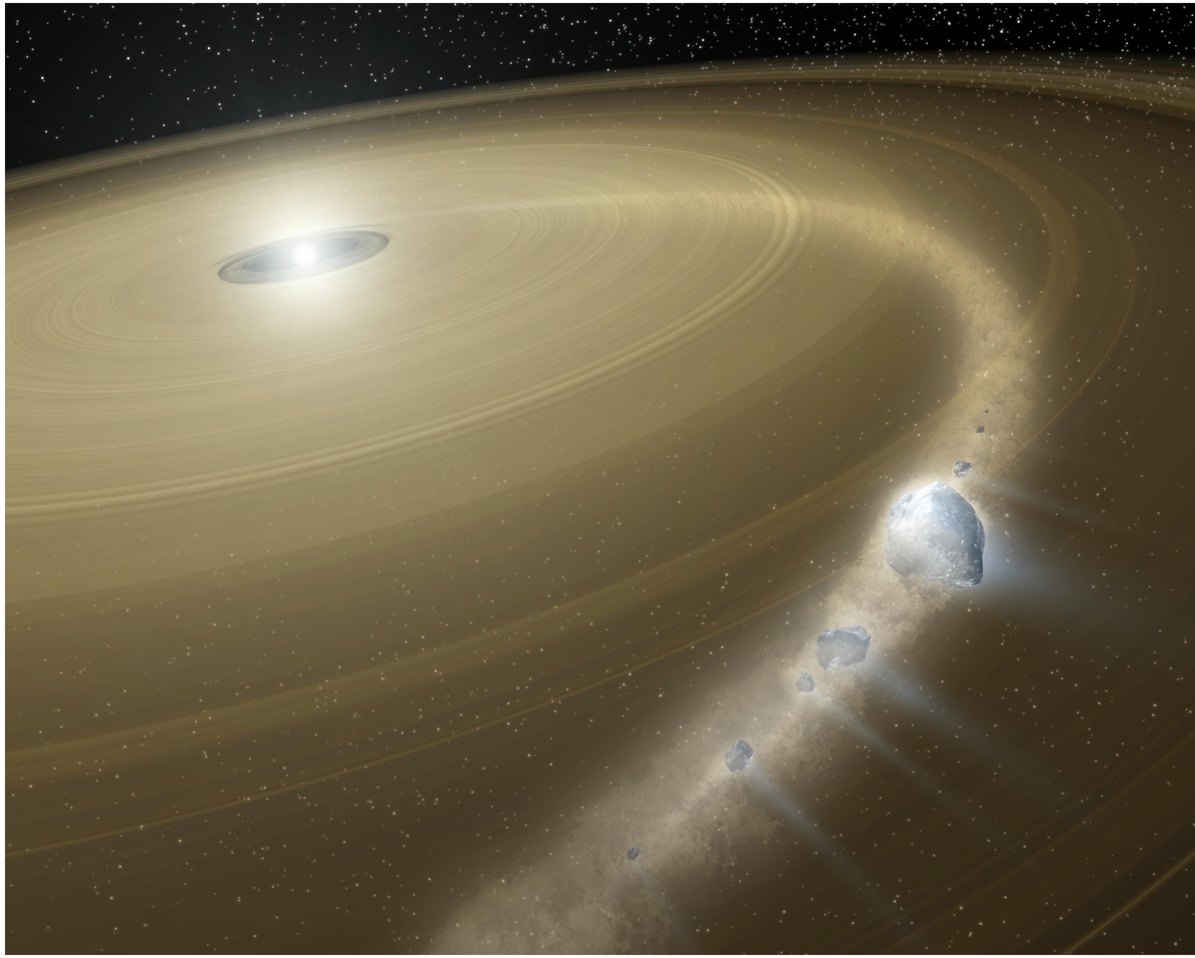
Known ZZ Ceti

New high-mass ZZ Ceti



Transiting debris disks

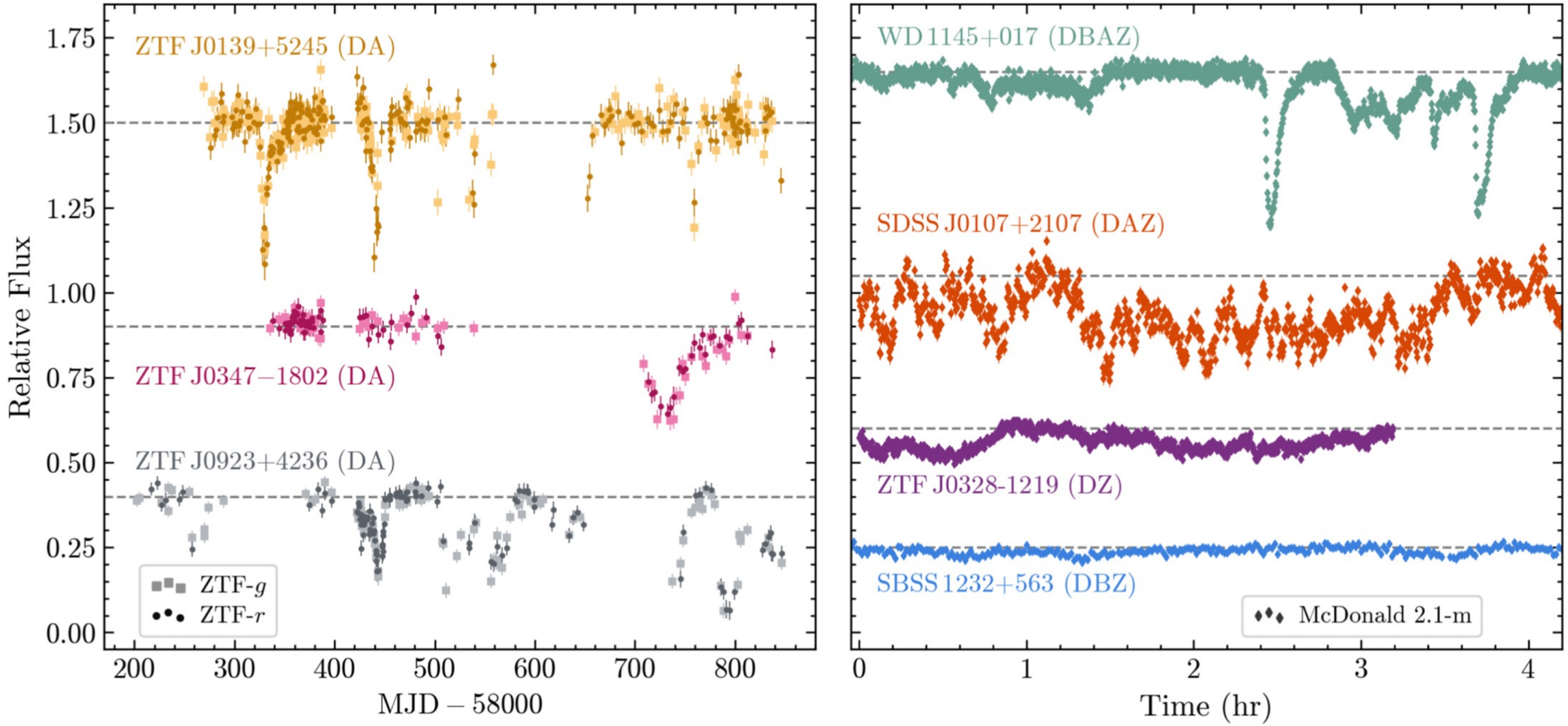
- 25% of WDs show traces of metals: Ca & Si, also Mg, Fe, Na et al.
- Photospheric pollution by ongoing accretion
- Source: tidally disrupted planets/comets/asteroids/etc.
- Maybe formed after AGB phase?
- Bonsor et al. (2022): photospheric pollution implies faster planet formation than previously thought
- Jovian planet detected by transits and emission line RVs



Credit: NASA/JPL-Caltech/T. Pyle (SSC)

Transiting debris

Guidry et al. (2021)

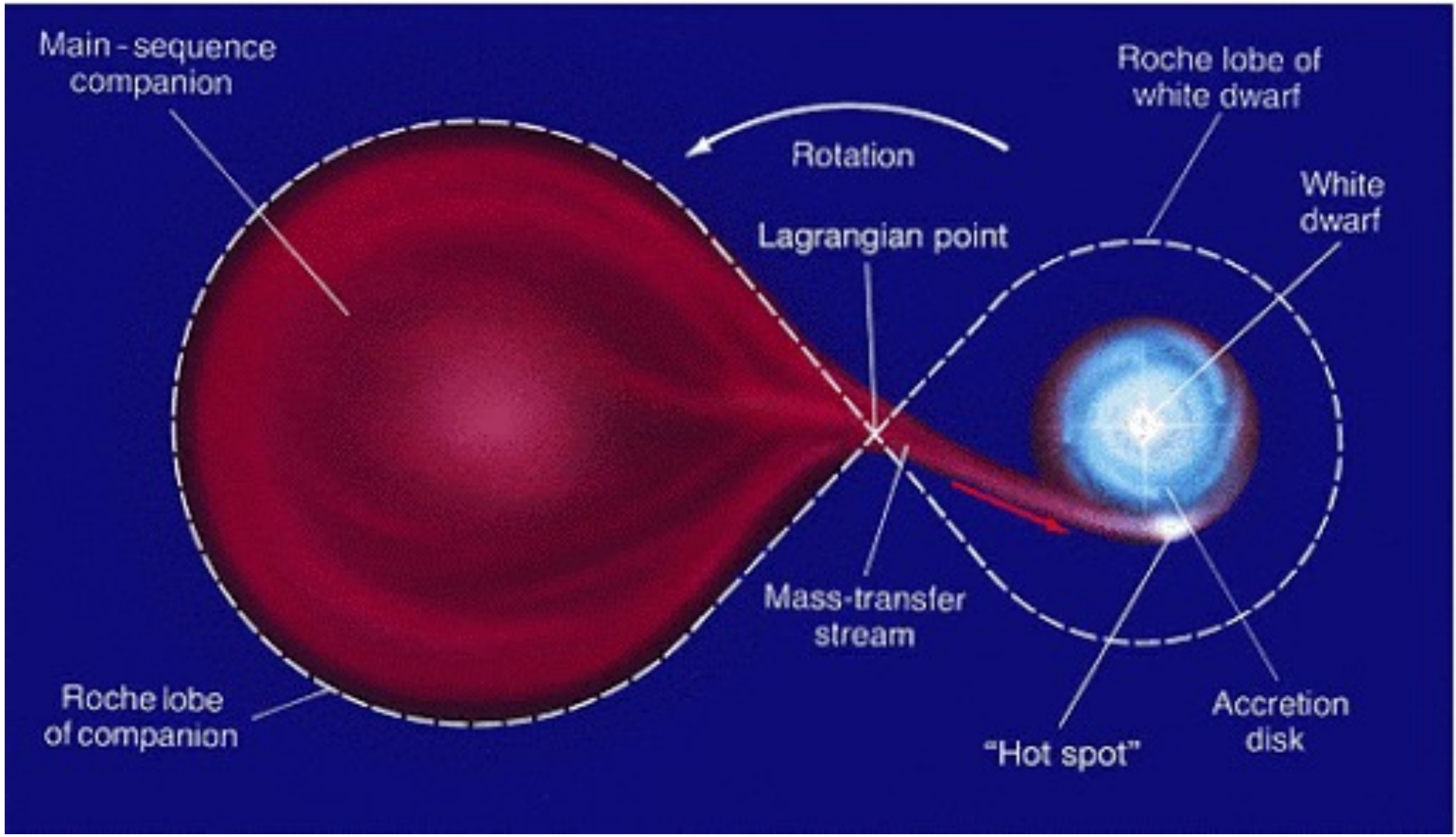


Summary I: White dwarfs with Gaia

- Hundreds of thousands of new WDs discovered
- Many new binary systems
- WD instability strips are getting mapped in detail
- Cooling sequence slowed by crystallization
- Minor bodies & debris disks
- Star catalogs can bely variability even if no time-series data is provided!

Cataclysmic Variables

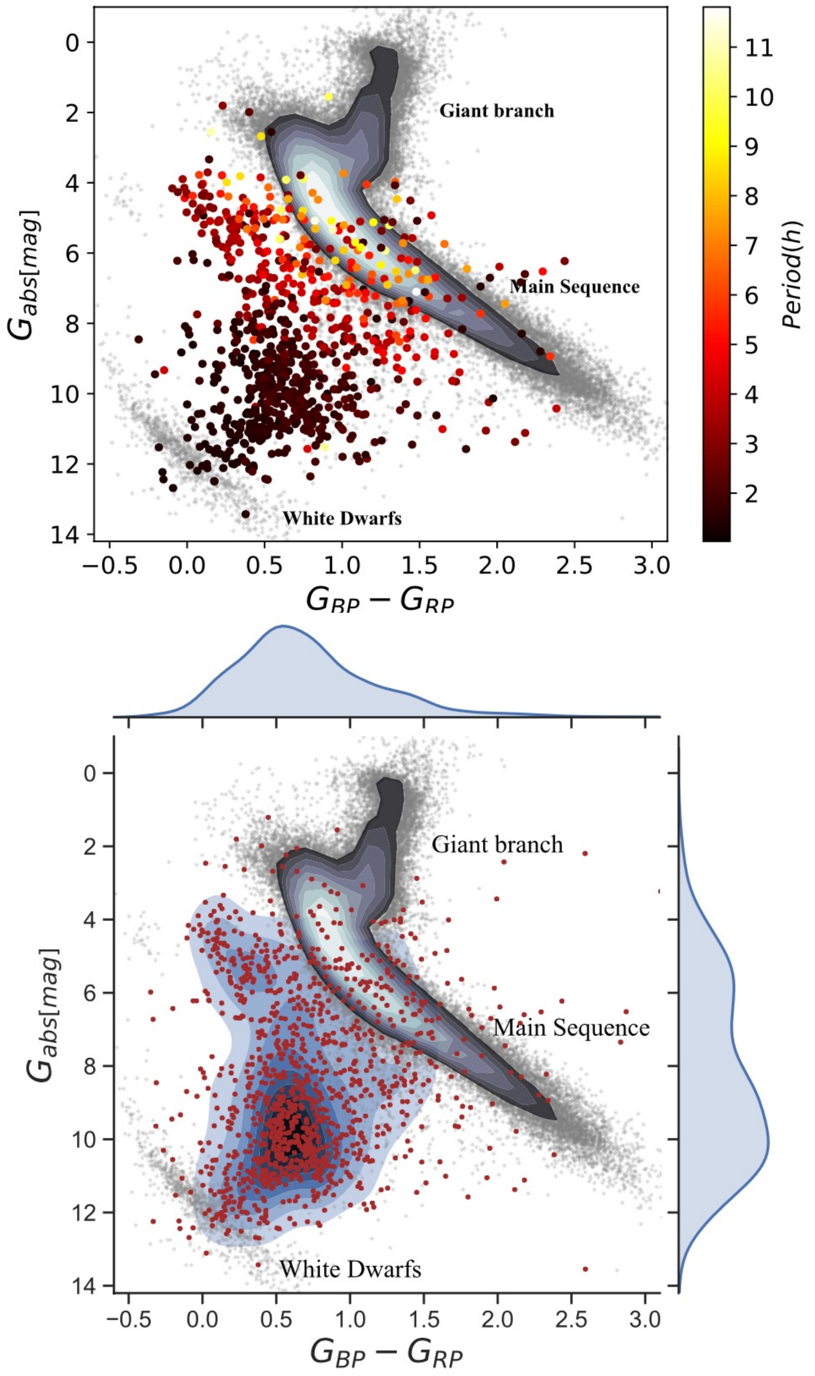
Semi-detached binaries of White Dwarf + MS in short-period binary w/ RLOF and accretion disk

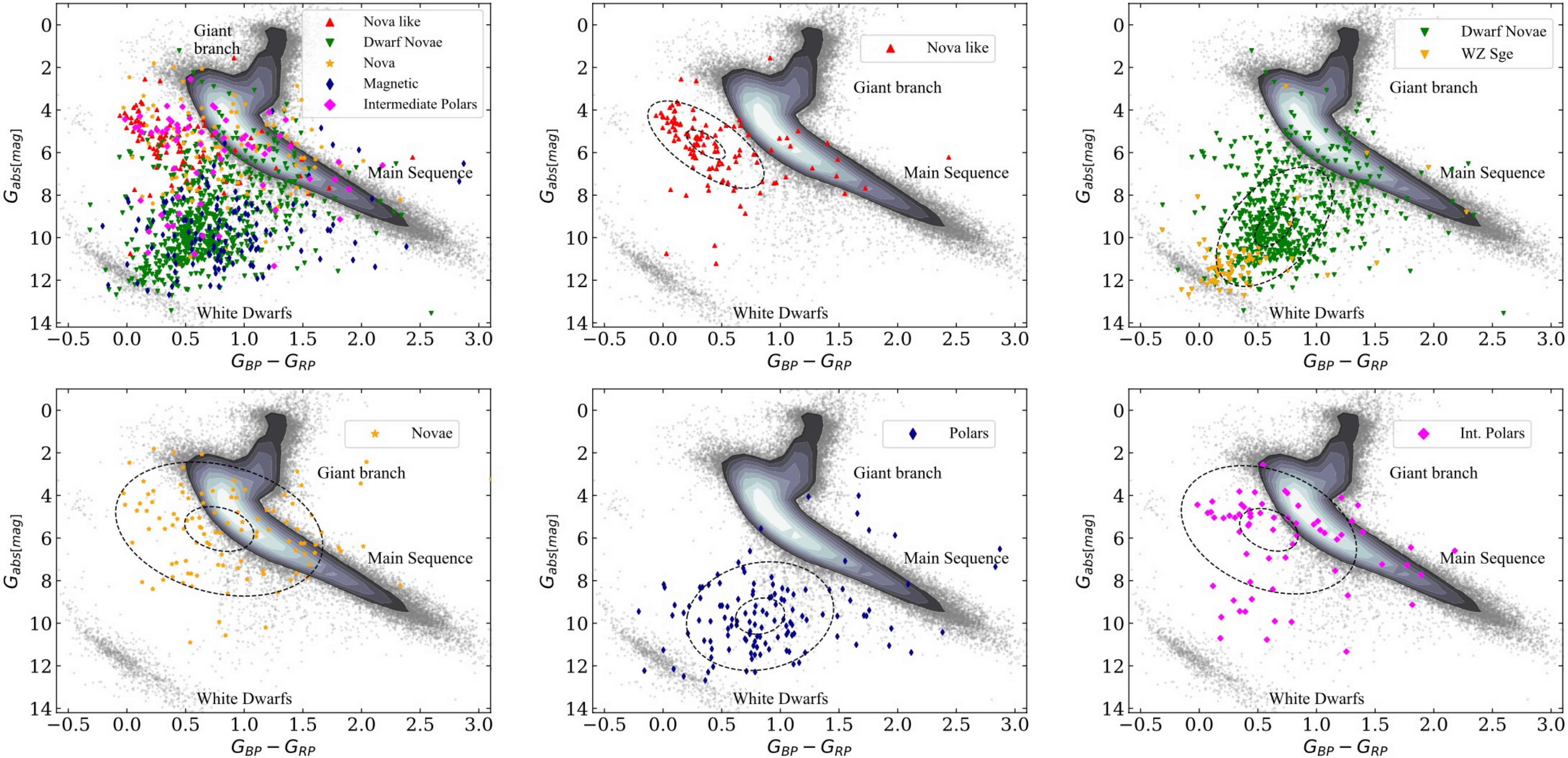


Cataclysmic Variables

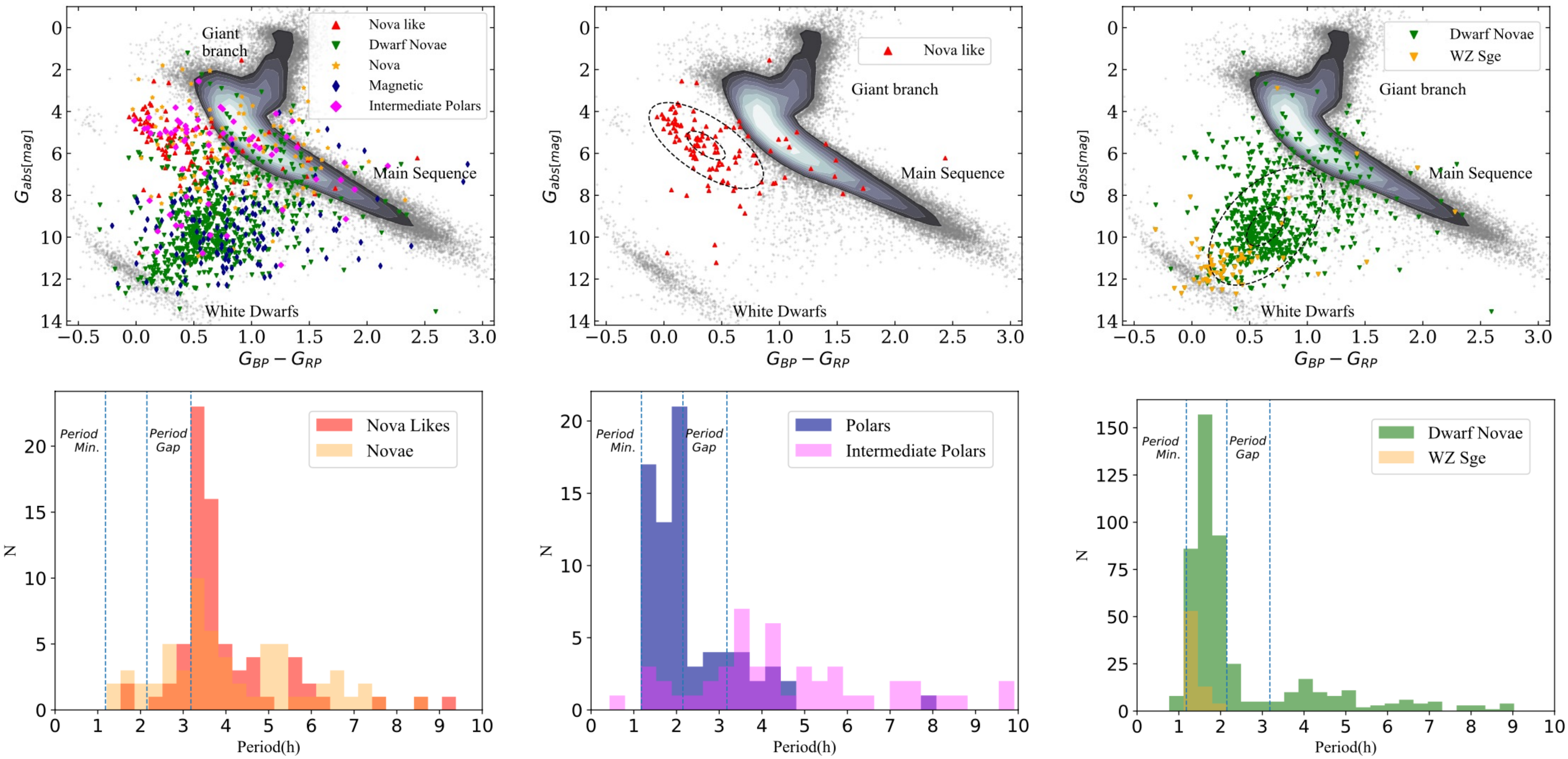
- Long-term evolution from wide orbit w/ high mass-transfer to tight orbit with slow mass-transfer
- Period minimum (76-80min): donor turns into brown dwarf
- Peculiar mags & colors due to interactions
- First absolute mag CMD thanks to Gaia

Abril+20




Nova like
Dwarf Novae
Nova
Magnetic
Intermediate Polars
Giant branch
Main Sequence
White Dwarfs
WZ Sge
Novae
Polars
Int. Polars
$G_{abs[mag]}$
$G_{BP} - G_{RP}$

Abril+2019

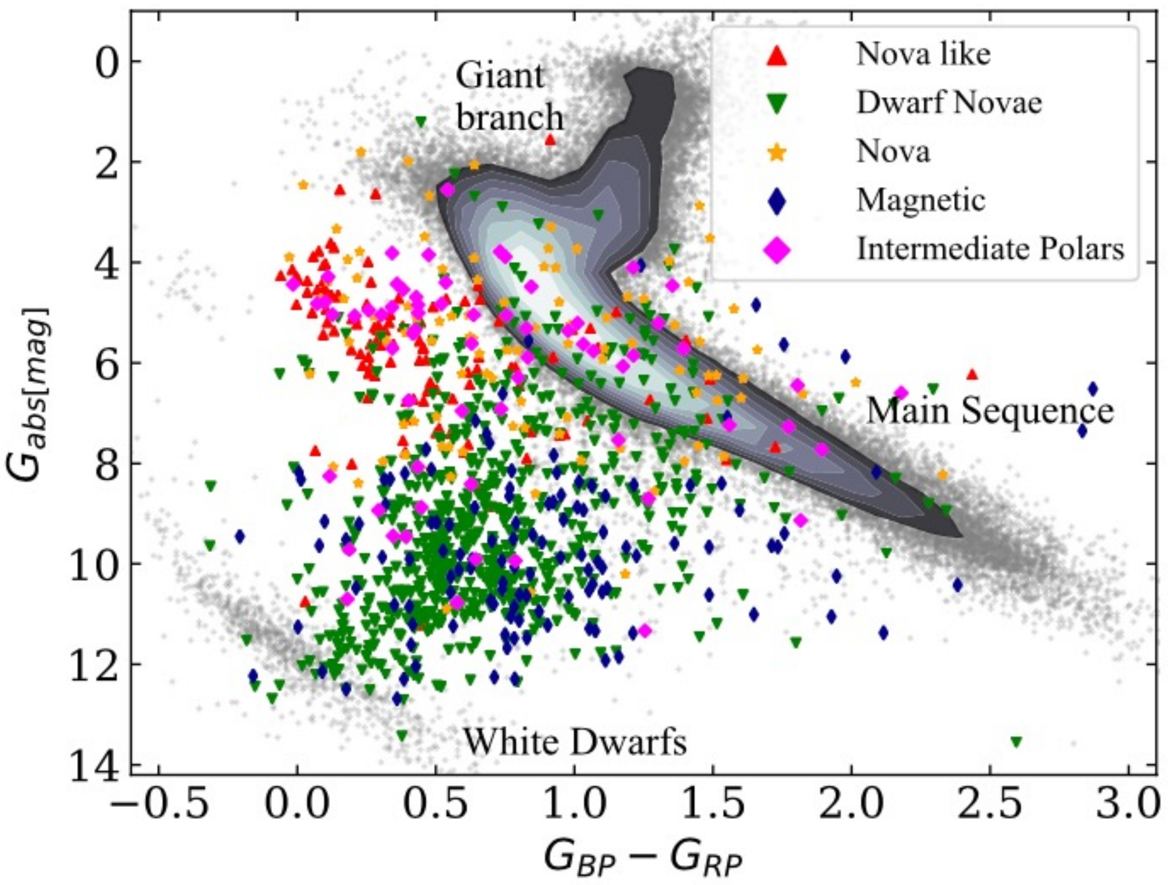


Decreasing period => bluer & fainter

Abril+2019

Cataclysmic Variables

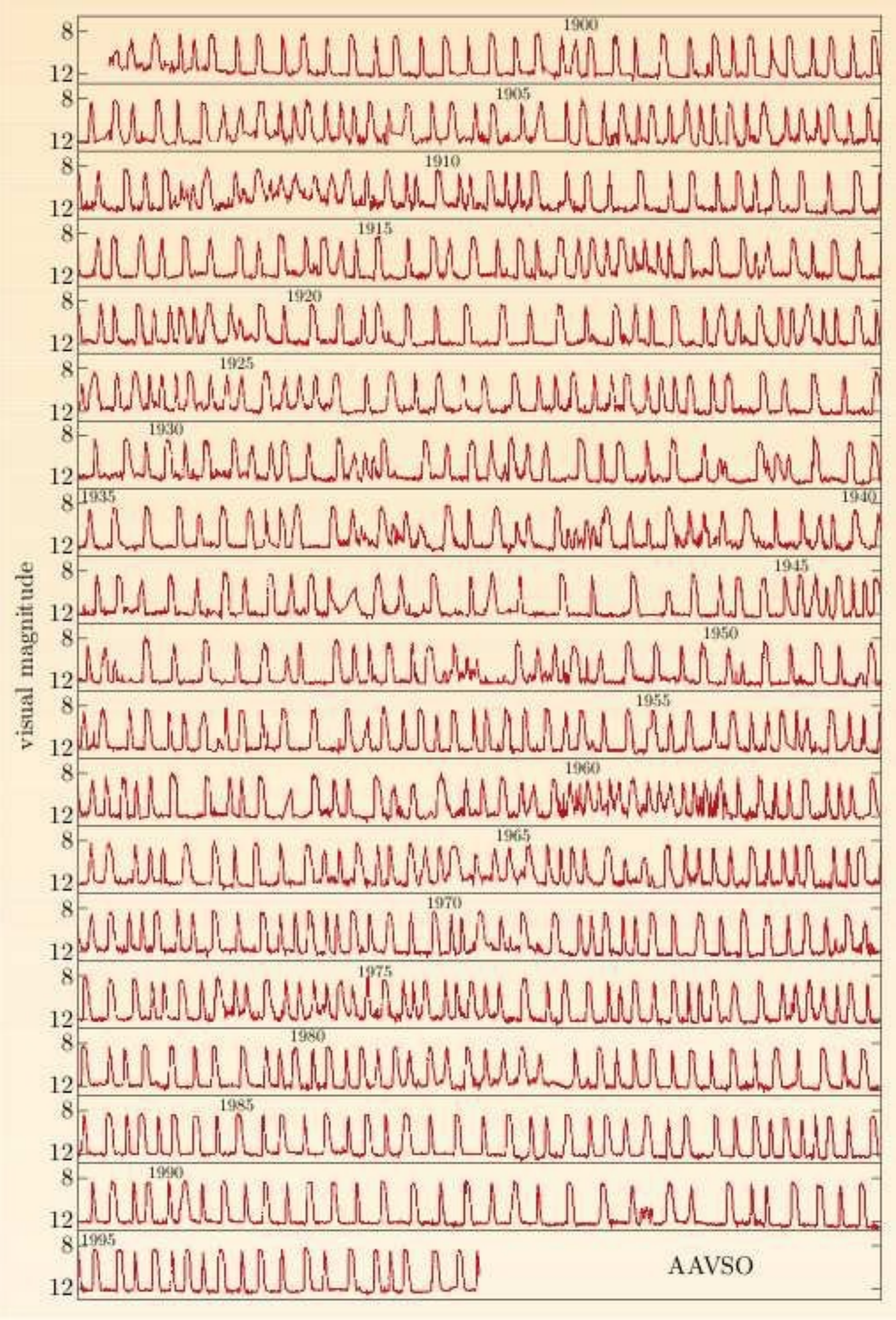
- CV Periods: longer = closer to MS, shorter = closer to WD
- Consequence of size of Roche Lobe of secondary : larger more luminous = longer separation
- Nova-likes dominated by a high mass-transfer accretion disc, overshines WD and secondary star at optical and even infrared wavelengths. Colour and absolute magnitude mainly depends on inclination
- Old Novae and intermediate polars in similar spot
- Polars do not accrete mass through a disc, are much fainter. Spread in color and mag depending on secondary. They are the reddest and faintest of all the CV subgroups.
- Dwarf Novae: secondary star between early K-type and brown dwarf => broad range in colours and magnitude. Regular outbursts increasing their brightness & blueness.
- WZ Sge: Dwarf Novae characterised by great outburst amplitudes, slow declines and long intervals between outbursts compared with ordinary DNe. Concentrate near WD area. CVs with the lowest mass transfer and faintest secondary stars. The disc is only visible in some emission lines, the secondary does not contribute to the optical range at all.



Abril+2019

Novae

- Episodic accretion w/ violent eruptions
- Accreted material ignites H-burning once sufficient pressure & Temperature at bottom of new surface layer
- Runaway thermonuclear reaction converts H to heavier elements (burning increases temperature, causing burning to accelerate)
- Majority of accreted surface layer is ejected at speeds ~ 1500 km/s
- Repeating events: recurrent Novae

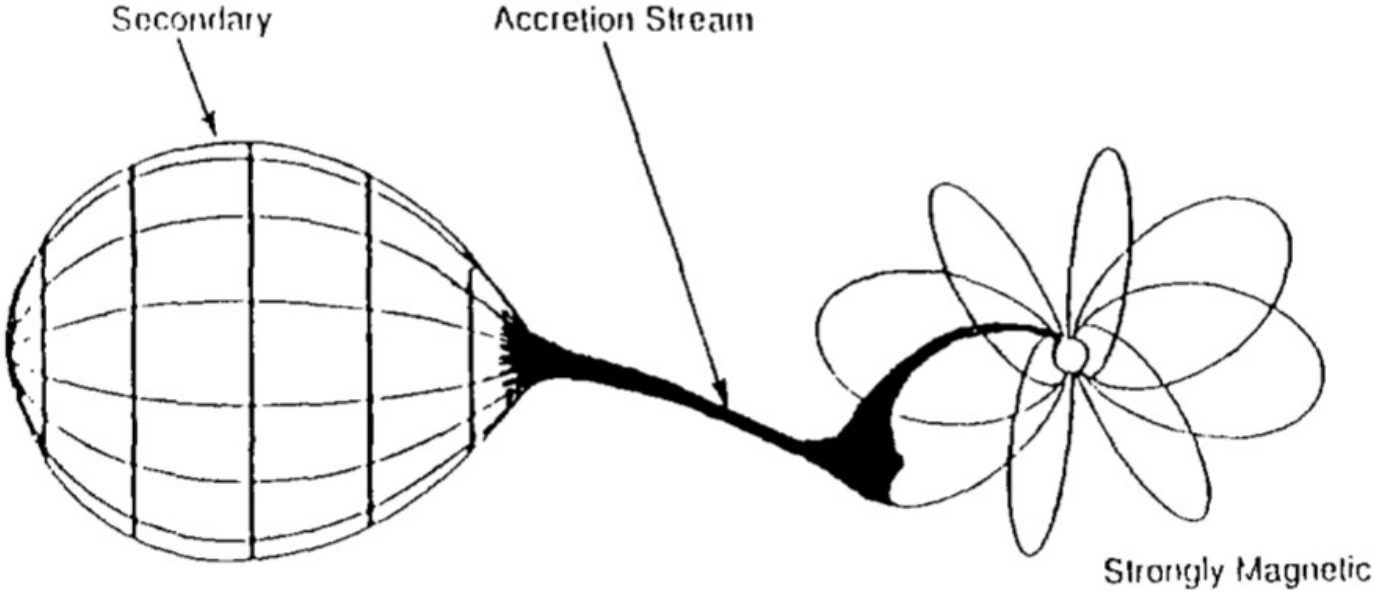


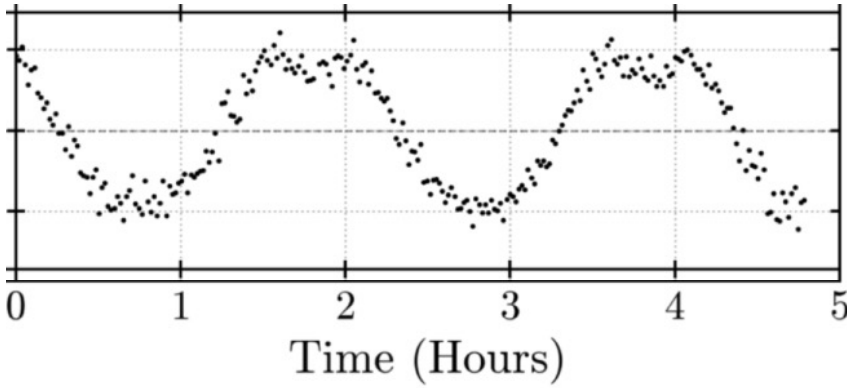
SS Cygni, Kolb (2010)

“Polars”: WD + red dwarf interacting binaries

Cropper (1990)

- B-fields up to 10^{10} - 10^{11} G
- Accretion over very small area at high velocity: shock
- Light curve depends on orientation
- Synchronized rotation
- X-ray emission post-shock (high soft-to-hard ratio)
- Cyclotron radiation due to electrons moving in B-field leads to optical and NIR emission
- Strong & variable polarization





Neutron stars & Pulsars

Material	*Density in kg/m³*	*Notes*
Supermassive black hole	c. 1,000[34]	Critical density of a black hole of around 10^8 solar masses.
Water (fresh)	1,000	At STP
Osmium	22,610	Near room temperature
The core of the Sun	c. 150,000	
White dwarf	1×10^9[1]	
Atomic nuclei	2.3×10^{17}[35]	Does not depend strongly on size of nucleus
Neutron star core	8.4×10^{16} – 1×10^{18}	
Small black hole	2×10^{30}[36]	Critical density of an Earth-mass black hole.

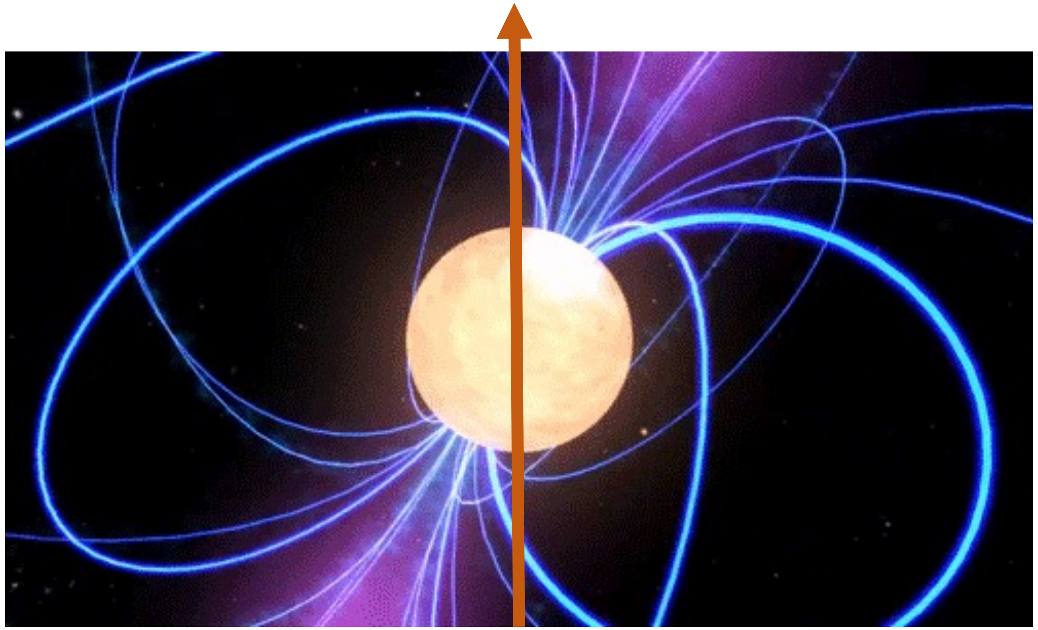
What are neutron stars?

- Leftovers from core-collapse supernovae of stars with 10-25 Msol
- Protons and electrons combine to neutrons during collapse
- Typical size 10km, typical mass 1.35 Msol
- Superfluid neutrons in the core: neutron drip (cannot continue adding n)
- No active heat generation; cooling over time
- Gravitational collapse prevented by
  - neutron degeneracy pressure
  - Strong repulsive nuclear force much stronger than n degeneracy
- Maximum mass due to GR instability: 1.8-2.5 Msol
- Higher masses collapse to black holes

Pulsars : pulsed radiation from NS

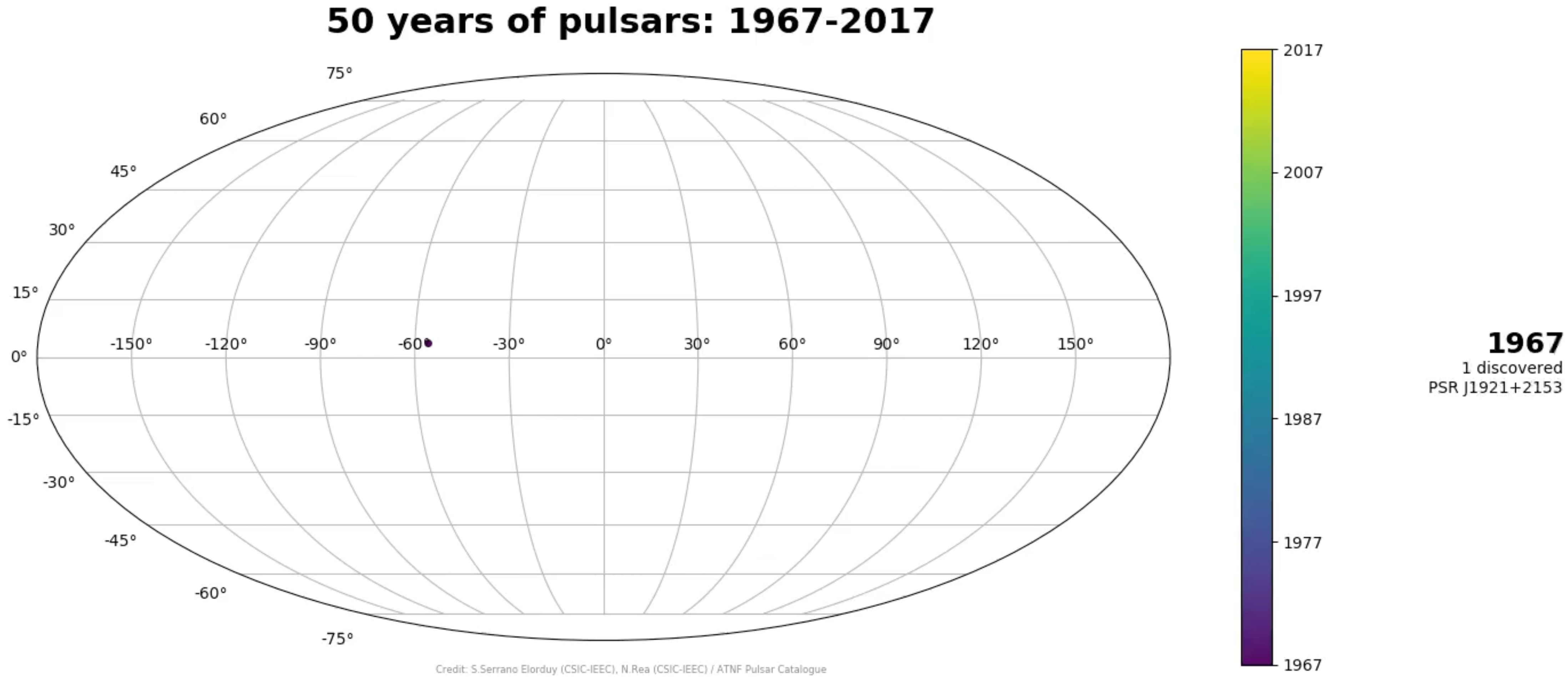
- > 3000 pulsars known (Catalog link)
- 10 subclasses w/ different emission mechanisms:
    - Rotational energy by magnetic dipolar losses
    - Thermal emission from surface overheated by strong magnetic fields (10^{13}G)
    - Accretion of material from companion stars
- Slowest (0.042 Hz) and fastest (707Hz) span 5 orders in P

(left): Antony Hewish (11 May 1924 – 13 Sep 2021)
Nobel Prize Physics 1974 for discovery of Pulsars
(right): Jocelyn Bell Burnell (15 July 1943), co-discoverer



Pulsar discoveries

Rea (2017)



Magnetars

Kaspi & Beloborodov (2017)

- Fairly new field, highly active - 30 known in 2017 (Catalog link)
- Strongest B-fields in the Universe: 10^{13} - 10^{15} G , highly tangled
- Wide array of X-ray activity: short bursts, large outbursts, giant flares, quasi-periodic oscillations, spin-down, glitches, anti-glitches
- Explanation likely a catastrophic reconfiguration of magnetic fields that breaks neutron-star crust
- Flares and outbursts may explain fast radio bursts
- Soft gamma-ray repeaters (SGRs): emit giant flares repeatedly leading to short X-ray bursts

Differences Pulsars vs Magnetars

White et al. (2021)

- At least 10% of young pulsars (spin-down ages $\tau = P/2\dot{P}$ < 10^4 yr) are magnetars
- 8 of 30 Magnetars associated with Supernova remnants (SNR)
- 52 of 682 of young pulsars associated with SNRs; Cui et al. (2021)
- Magnetars are closer to the Galactic plane (younger population)
- Magnetar B-fields $10^{13} - 10^{15}$ G; Pulsars $10^{11} - 10^{13}$ G
- Magnetars (2-12s) rotate slower than pulsars (0.1s to a few s) and young pulsars (< 0.5s; initial periods around 0.30 +/- 0.15s)
- Origin of dichotomy likely related to magnetic braking, see White et al. (2021) for details

The famous Crab

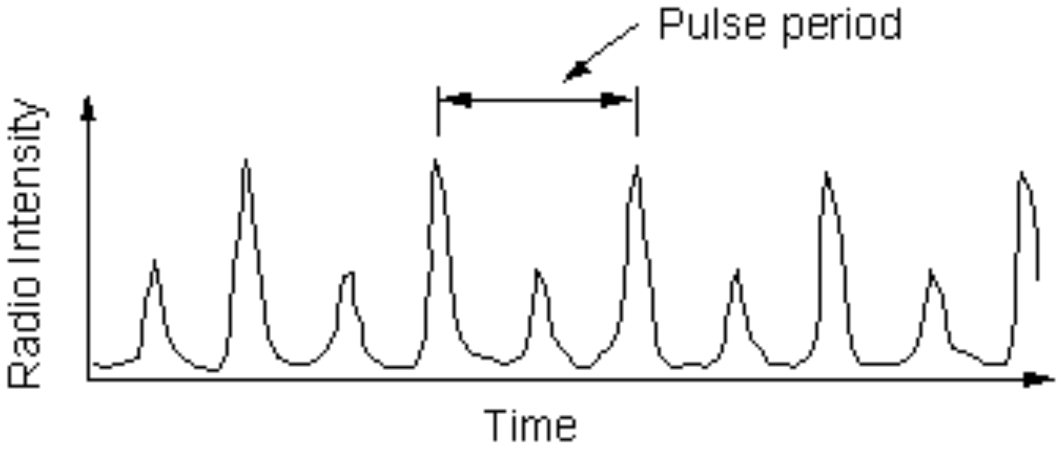
Nearby neutron star born during naked eye supernovae event SN1054

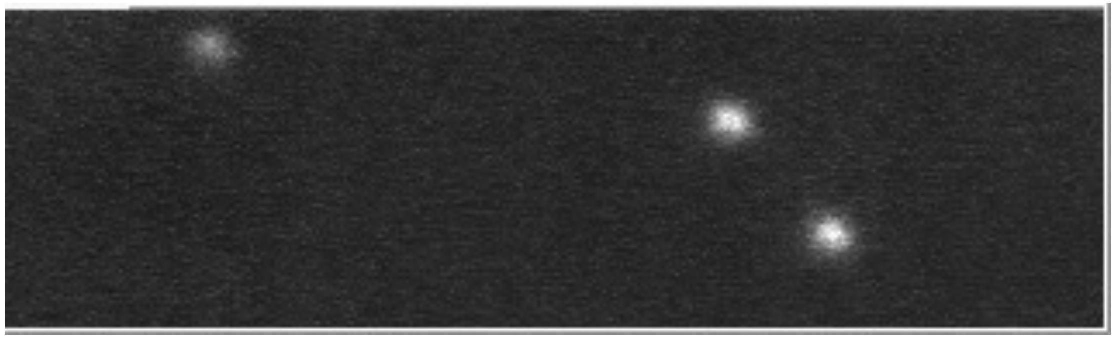
Surrounding nebula cataloged by Charles Messier in search of comets: designation M1

1973: Kitt Peak 4m
2001: Kitt Peak 0.4m CCD
https://apod.nasa.gov/apod/ap011227.html

The Crab Pulsar

- Rare case: pulses seen in optical
- Pulse period: P = 33 ms
- Relativistic wind causes synchrotron emission: gamma through radio waves
- Most dynamic feature: termination shock where wind collides w/ CSM
- $\dot{P} \approx 38ns/d$ due to wind



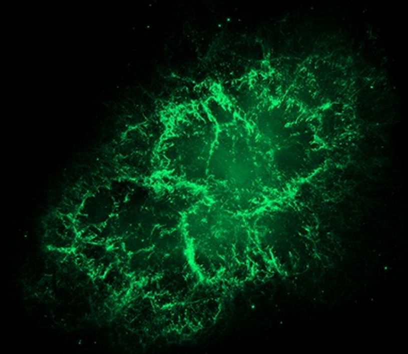


X-ray, Optical & IR composite, 5arcmin (10ly) across
X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA-JPL-Caltech

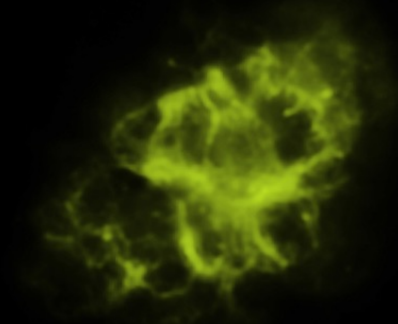
The Crab Nebula

UV

Optical



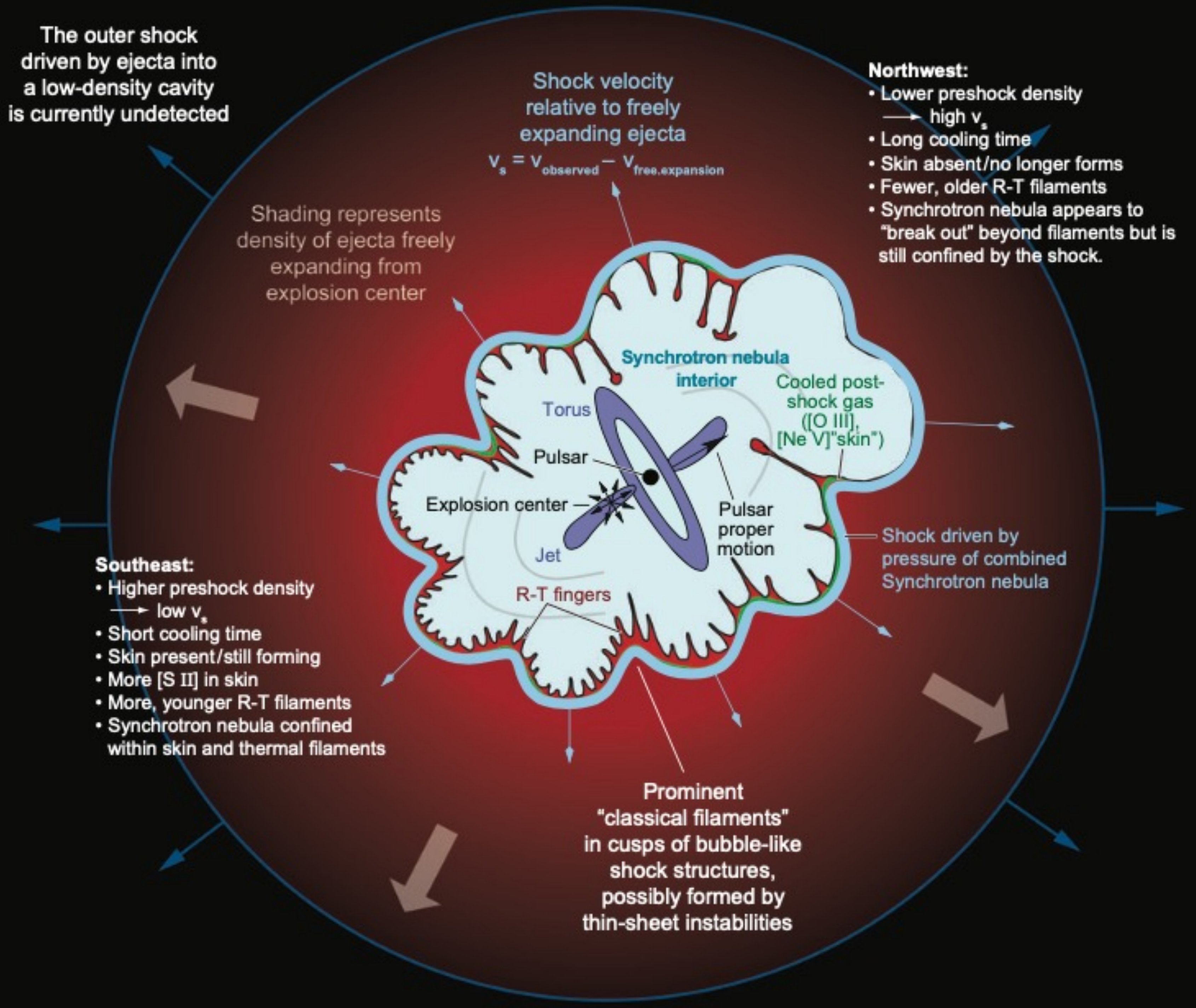
Infrared



Radio

Composite incl. X-rays

X-ray: NASA/CXC/SAO; Optical: NASA/STScI; Infrared: NASA/JPL/Caltech;
Radio: NSF/NRAO/VLA; Ultraviolet: ESA/XMM-Newton


The outer shock driven by ejecta into a low-density cavity is currently undetected
Shock velocity relative to freely expanding ejecta
$v_s = v_{observed} - v_{free.expansion}$
Northwest:
• Lower preshock density → high v_s
• Long cooling time
• Skin absent/no longer forms
• Fewer, older R-T filaments
• Synchrotron nebula appears to "break out" beyond filaments but is still confined by the shock.
Shading represents density of ejecta freely expanding from explosion center
Synchrotron nebula interior
Cooled post-shock gas ([O III], [Ne V]"skin")
Torus
Pulsar
Explosion center
Jet
Pulsar proper motion
R-T fingers
Shock driven by pressure of combined Synchrotron nebula
Southeast:
• Higher preshock density → low v_s
• Short cooling time
• Skin present/still forming
• More [S II] in skin
• More, younger R-T filaments
• Synchrotron nebula confined within skin and thermal filaments
Prominent "classical filaments" in cusps of bubble-like shock structures, possibly formed by thin-sheet instabilities

Hester (2008)


https://chandra.harvard.edu/resources/illustrations/gifs/index.html

Questions?