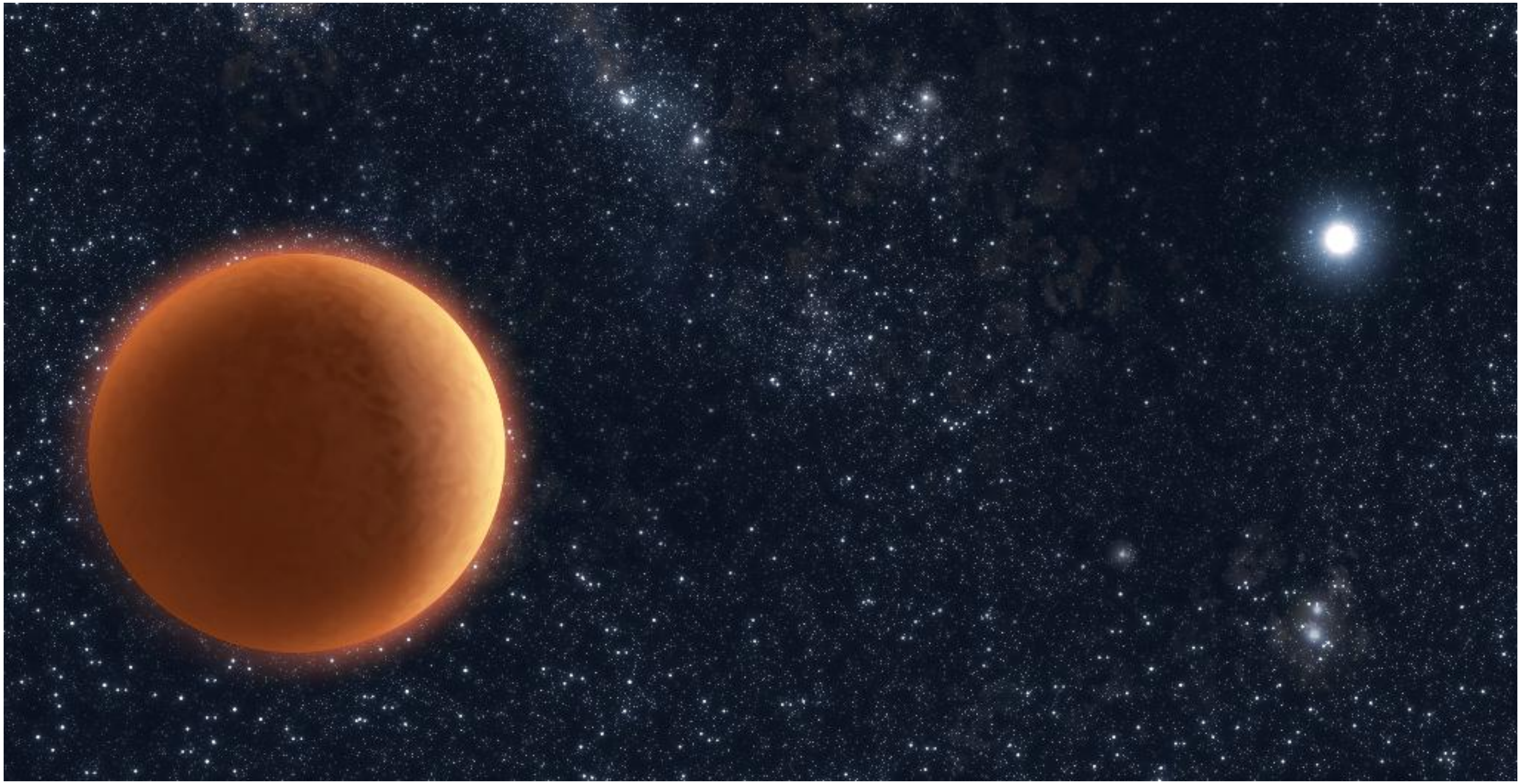

The death of solar systems:
searching for old planets around white dwarfs

Matt Burleigh

University *of* Leicester

with thanks to:

- Sarah Casewell, Martin Barstow, Richard Jameson, Katherine Lawrie, Nathan Dickinson, Melissa McHugh (Leicester)
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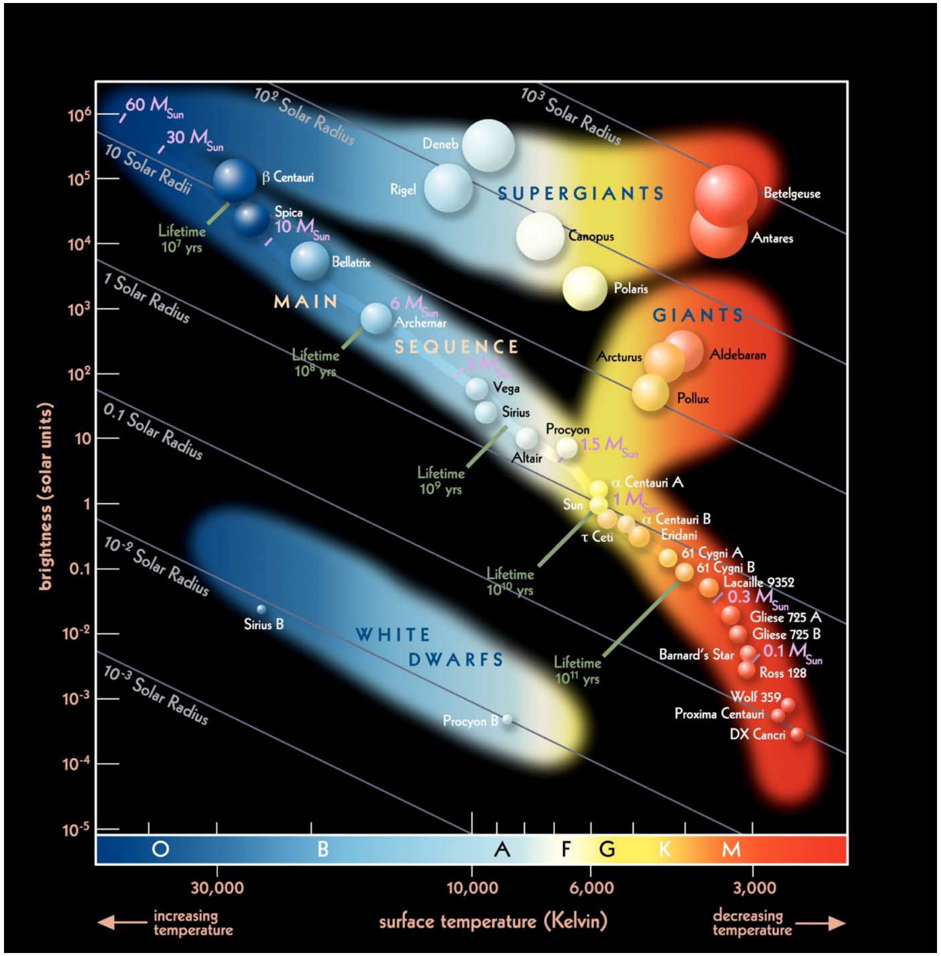
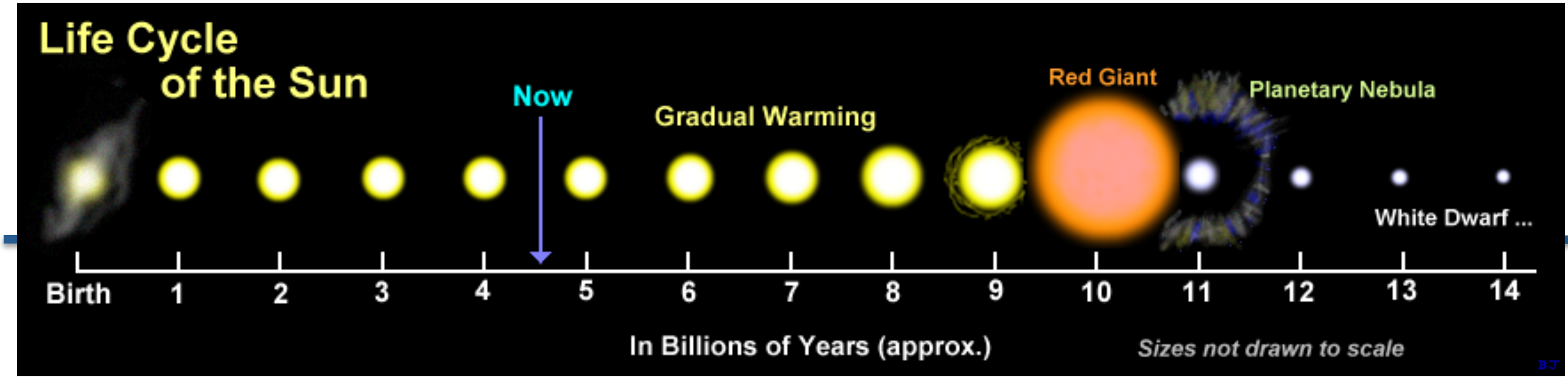
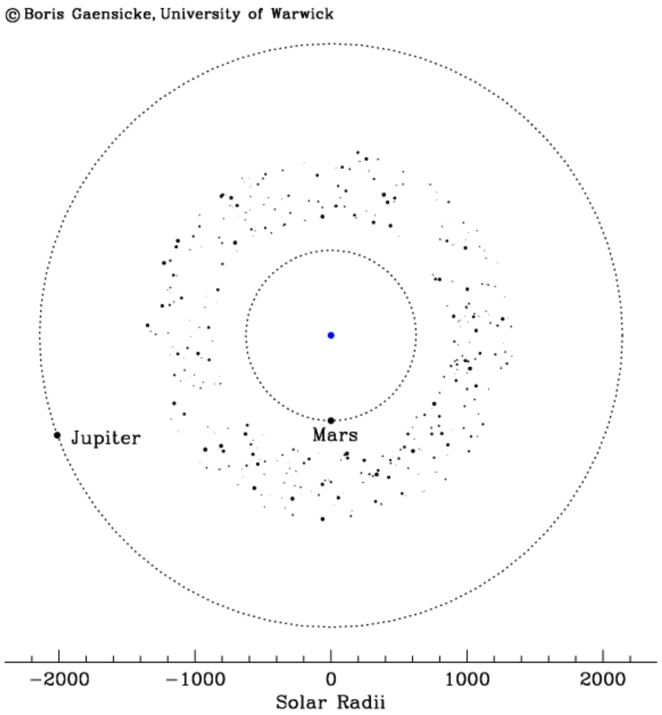
- Ted von Hippel, Fergal Mullally (Kepler)
- Avril Day-Jones, Ben Burningham, David Pinfield (Herts)

All planet-host stars become white dwarfs



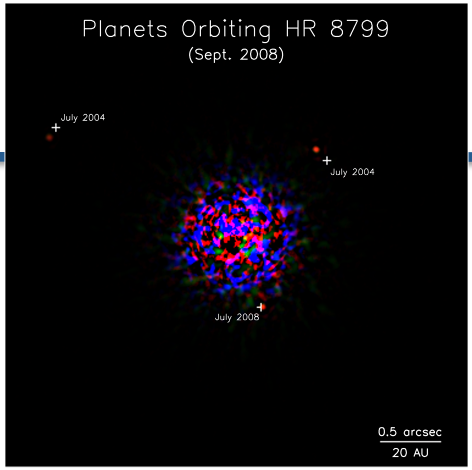


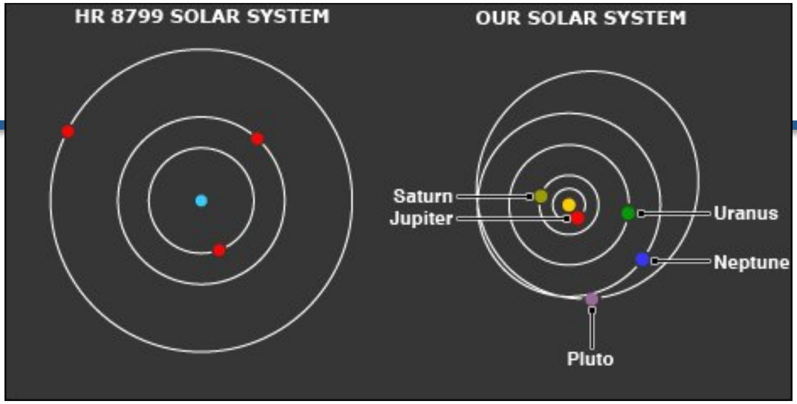
- Red giant destroys inner planets
  - *but brown dwarfs survive via common envelope evolution*
- Orbits of outer planets expand by factor M_{MS}/M_{WD} (Jeans 1924)
  - *Become unstable, scattering, high eccentricities…..*



- Burleigh, Clarke & Hodgkin 2002, MNRAS, 331, L41
- Debes & Sigurdsson 2002
- Villaver & Livio 2007, 2009
- Nordhaus et al. 2010
- Veras et al. 2011, 2012
- Debes et al. 2012
- Kratter & Perets 2012

HR8799 as a white dwarf…





- HR8799: A5V 1.2-1.8M_{jup} 39pc 30-160Myr old
- Planets: 5M_{jup} @ 68AU, 10M_{jup} @ 38AU, 10M_{jup} @ 24AU, 7M_{Jup} @14AU

- Will evolve after 1.75Gyr to a 0.58M_{sun} white dwarf
- Planet orbits expand by factor ~3 to ~200AU,~120AU, 75AU & 45AU

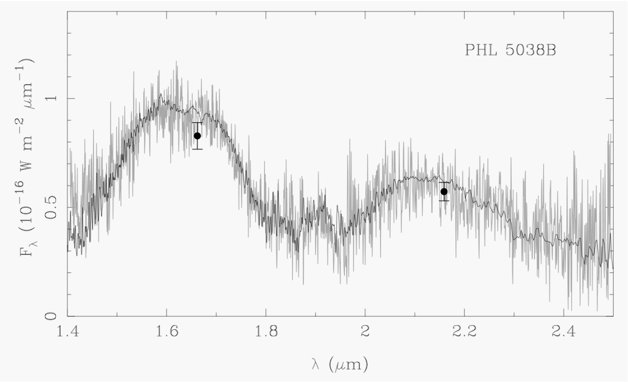
- Let WD cool to 10,000K over ~0.5Gyr….system age now 2.25Gyr…
- 10M_{jup} planet will be J=23.8 @39pc
  – *How common are HR8799-like systems?*

Evidence for old planetary systems

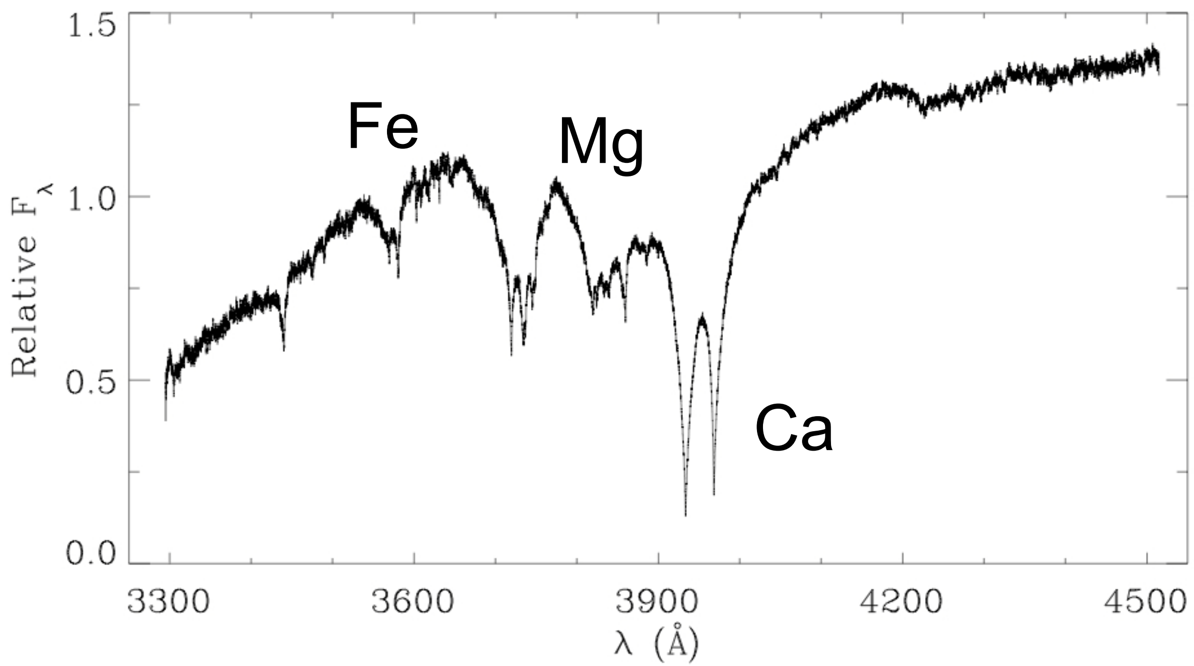
1. Planets have been found by radial velocity technique around evolved giant stars
   - >3% of stars $M>1.8M_{sun}$ have planets $>5M_{Jup}$ (Lovis and Mayor 2007)
2. White dwarfs have been identified as wide companions of planet-hosting stars
   - eg eps Ret (Raghavan et al. 2006, Chauvin et al. 2006, Farihi et al. 2011), GJ 86 (Farihi et al. 2013)
3. Growing number of brown dwarf companions in close and wide orbits
   - WD+BD fraction >0.5+/-0.3% Steele et al. 2011, Girven et al. 2011, Debes et al. 2011
4. Metal-rich circumstellar dust and gas disks discovered around white dwarfs

IR searches for substellar companions

- Historical searches for brown dwarf companions to WDs going back to 1980s
  - eg Probst (1983), Zuckerman & Becklin (1987), Wachter et al. (2003), Farihi et al. (2005), Dobbie et al. (2005), Tremblay & Bergeron (2007)
  - GD165B (L4), GD1400B (L6/7), WD0137-349B (L8)
- UKIDSS survey
  - ~dozen new BD candidates
  - (eg PHL5038, *Steele et al. 2009, A&A, 500, 1207*)
  - WD+L fraction >0.4+/-0.3%
  - WD+T fraction >0.2%
  - WD+BD fraction >0.5+/-0.3%
  - *Steele et al. 2011, MNRAS, 416, 2768*
  - *Girven et al. 2011, MNRAS, 417, 1210*

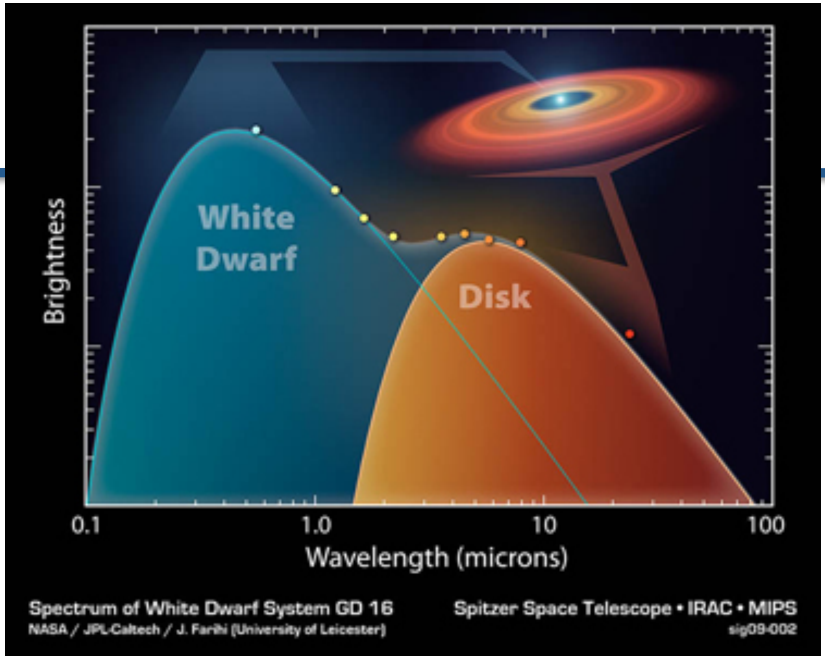


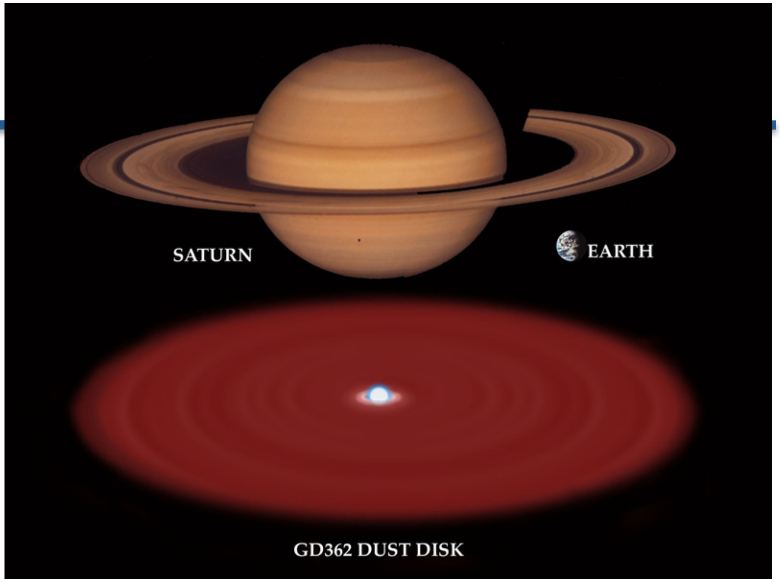
Metals in van Maanen's star



- 3rd white dwarf discovered (van Maanen 1917)
- Cool (7000K), old (>4Gyr)
- Where do the metals come from?

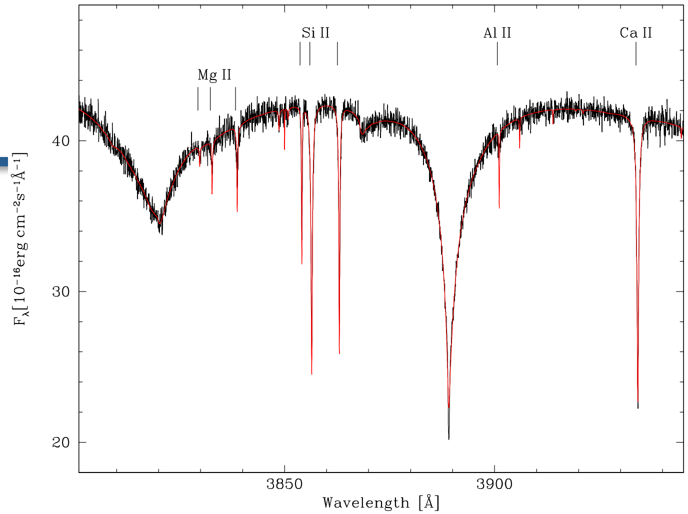
Dust disks around white dwarfs



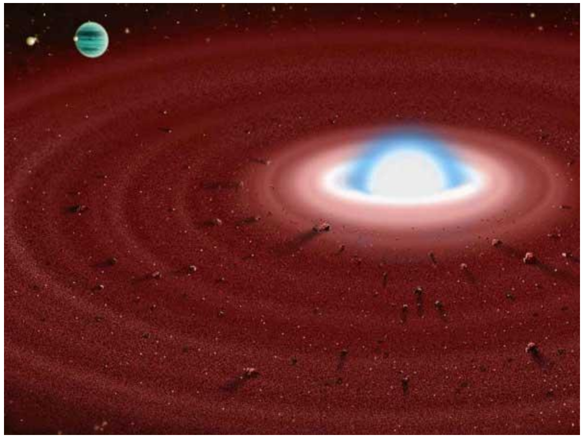


- ~30 WDs are known to be surrounded by dust disks
- Disks identified as near-IR and mid-IR excesses, $500^{o}K < T < 1200^{o}K$
- Disks within a few solar radii of the WDs
- Material within the disks is being accreted onto the WD atmosphere
  - Finally explains WDs with metal-polluted atmospheres

White dwarfs accrete planetesimals!



- Disks dominated by silicates, atmospheric C/Si & C/O ratios similar to bulk Earth
- "Standard model" disk forms from tidal disruption of asteroid or minor planet
  - HE 0446−2531 ~ $8.0\text{x}10^{24}$ g (Girven et al. 2012, ApJ 749, 154)
  - Pluto ~$1.3\text{x}10^{25}$g Charon ~$1.5\text{x}10^{24}$ g Ceres ~$9.4\text{x}10^{23}$g
- Suggests at least ~20% of WDs may have rocky companions
  - If all polluted WDs have accreted terrestrial material at some point
- But asteroids have to be moved by something:
  - *Where are the perturbing giant planets?*



Mon. Not. R. Astron. Soc. 331, L41–L45 (2002)

Imaging planets around nearby white dwarfs

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ABSTRACT

We suggest that Jovian planets will survive the late stages of stellar evolution, and that white dwarfs will retain planetary systems in wide orbits ($\gtrsim 5$ au). Utilizing evolutionary models for Jovian planets, we show that infrared imaging with 8-m class telescopes of suitable nearby white dwarfs should allow us to resolve and detect companions $\gtrsim 3M_{JUP}$. Detection of massive planetary companions to nearby white dwarfs would prove that such objects can survive the final stages of stellar evolution, place constraints on the frequency of main-sequence stars with planetary systems dynamically similar to our own and allow direct spectroscopic investigation of their composition and structure.

Key words: planetary systems – white dwarfs.

1 INTRODUCTION

Over 70 extra-solar planets have now been detected since the discovery of a companion to the solar-type star 51 Peg in 1995 (Mayor & Queloz 1995). All of these planets have been discovered via the radial velocity technique, in which the presence of a planet is inferred by the motion of the central star around the barycentre of the system. Instrumental and intrinsic noise limit the sensitivity of these studies to Saturn-mass companions in short-period orbits, with more massive companions detectable in more distant orbits. The duration of current programmes limits this to ~3.5 au (Fischer et al. 2002), although some systems do display interesting trends indicative of more distant companions. Therefore, we have little information on systems with massive companions at large radii, such as our own Solar system. The only constraint on Jovian-like systems comes from micro-lensing statistics, which suggest less than 1/3 of M stars have Jupiter-mass planets orbiting at 1.5–4 au (Gaudi et al. 2002).

The planets discovered by the radial velocity technique are not open to further *direct* study, owing to their close proximity to the much brighter parent star. The only exception to this is the transiting companion to HD 209458 ($P_{orb} \approx 3.5$ d). Transit photometry shows this planet is a gas giant, and Charbonneau et al. (2002) have recently detected sodium in its atmosphere. Still, the planet itself cannot be directly imaged.

Several groups have conducted imaging surveys of nearby main-sequence stars to search for low-mass companions, including the use of adaptive optics, coronographs and space-based observations with the *Hubble Space Telescope* (e.g. Turner et al. 2001; Neuhäuser et al. 2001; Oppenheimer et al. 2001; Kuchner & Brown 2000; Schroeder et al. 2000). However, the extreme contrast ($\gtrsim 20$ mag) and small separations (5 au = 1 arcsec at 5 pc) between main-sequence stars and Jovian planets makes sensitive surveys very difficult. To date, no planetary mass companions to nearby stars have been imaged, although several brown dwarf companions have been detected via direct imaging (e.g. Nakajima et al. 1995).

The end state of main-sequence stars with $M \lesssim 8\,M_{\odot}$, white dwarfs, are typically 10^{3}–10^{4} times less luminous than their progenitors. Thus, there is potentially a strong gain in the brightness contrast between a planet and a white dwarf when compared to a main-sequence star, assuming that planets can survive the late stages of stellar evolution. The gain in contrast is strongest in the mid-infrared, where the thermal emission of the planet peaks well into the Rayleigh–Jeans tail of the white dwarf.

Indeed, Ignace (2001) has suggested that excess infrared emission could be detectable from a hot Jupiter orbiting a 10 000 K white dwarf at a distance of ~10^{3} white dwarf radii and with an orbital period of ~10 d. Chu et al. (2001) have also suggested that, near a hot UV-bright white dwarf, the atmosphere of a Jovian planet would be photoionized and emit variable hydrogen recombination lines, which may be detected by high-dispersion spectroscopic observations. However, both these methods rely on the planet being in a close (0.01–2 au) proximity to the white dwarf, where it would be difficult to resolve.

In this letter, we discuss the potential for imaging planetary companions in wide (>5 au) orbits around nearby white dwarfs. In Section 2 we investigate the probability of a planetary system surviving the late stages of stellar evolution. We discuss the

Direct Imaging Searches Around White Dwarfs: The DODO project

Degenerate Objects around Degenerate Objects

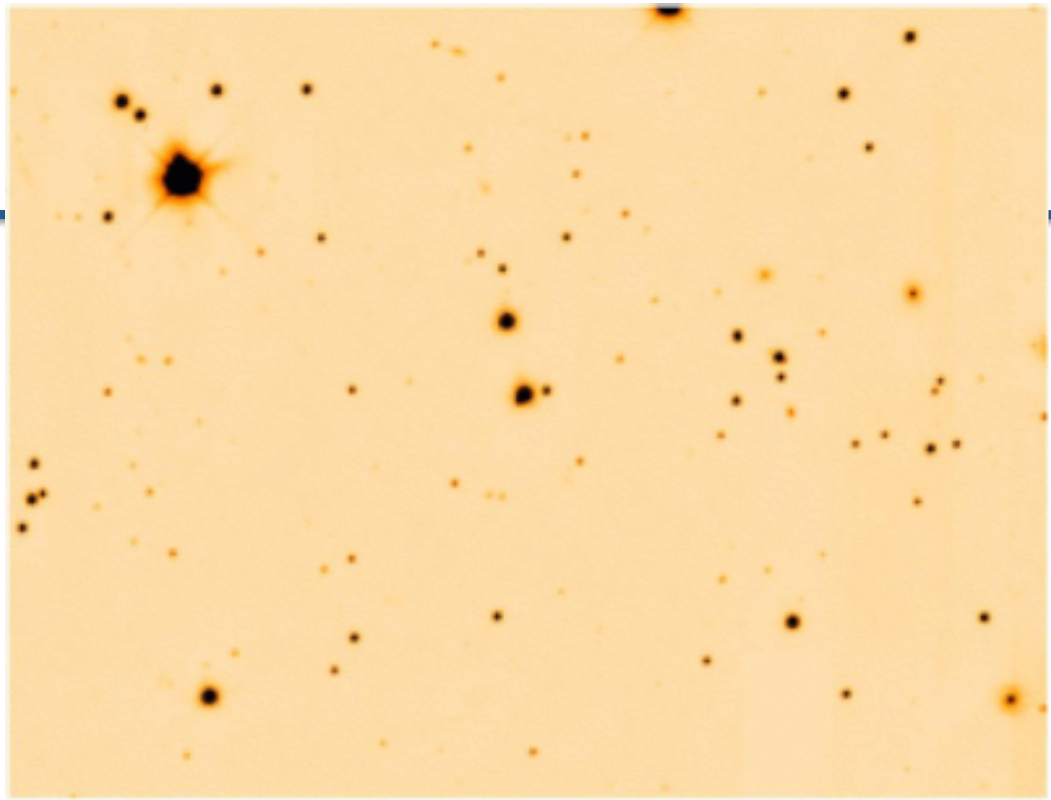
With Emma Hogan (now Gemini South) and Fraser Clarke (Oxford)

The idea: Burleigh et al. 2002, MNRAS, 331, L41
Results: Burleigh et al. 2008, MNRAS, 386, L5 and Hogan et al. 2009, MNRAS, 396, 2074

DODO Direct Imaging Survey

Hogan et al. 2009, MNRAS,396, 2074

- Selected young (<3Gyr), nearby (<20pc) WDs
  - (0.2"yr < PM < few "/yr)
  - Sample 40 stars
- Obtained deep wide near-IR (J) images with Gemini and VLT
  - Total exp time ~1hr
  - Depth J~22-24
  - Image quality typically 0.4"-0.7" (no AO!)
  - Search for candidates outside 3" radius from WD
- Wait one — few years…
  - Obtain 2nd epoch images of all systems to check for common proper motion companions
- Probe range of separations from <10AU to >1000AU
- Sensitive to masses >few M_{Jup}



^

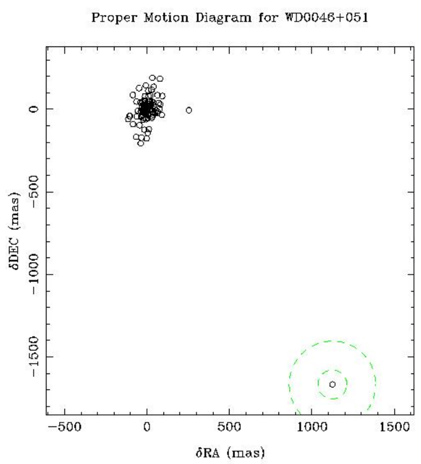
~90”

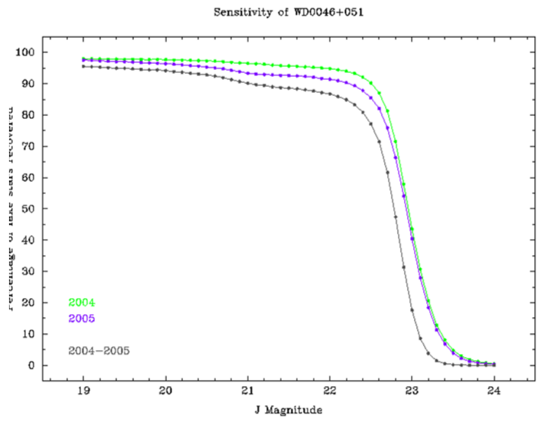
V

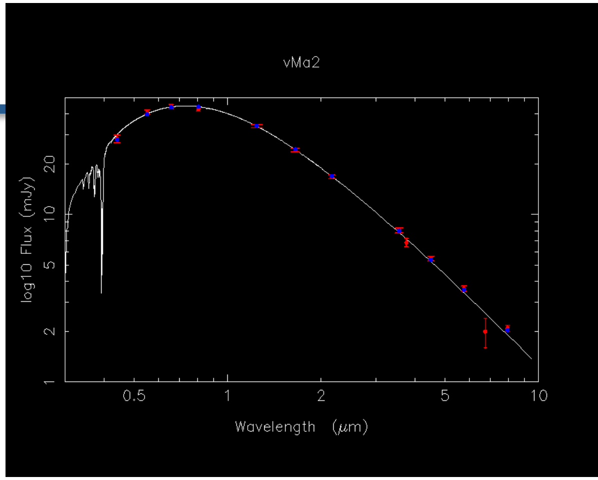
< ~120” >

- Two epochs
  - WD motion ~1” between images
  - Image depth J~23.5

Van Maanen's Star (d=4.4pc)







- DODO ground-based J-band imaging:
  - No companion found >7+/-1M_{Jup} (300+/-20K) at separations from 3"-45" / 15AU – 200AU
  - Separations around progenitor: 3 - 40AU
- Spitzer mid-IR photometry:
  - No unresolved companions > 10+/-2 M_{jup}
  - Burleigh et al. 2008, MNRAS, 386, L5

Limits on exoplanet companions to WDs from ground & space

	UKIDSS (all separations)	DODO (*resolved, >few 10s AUs*)	Spitzer (*unresolved, <few 10s AUs*)
$<75M_{Jup}$	0.5+/-0.3%		
$>13M_{Jup}$		<5%	<3%
$>10M_{Jup}$		<7%	<4%
$>6M_{Jup}$		<1/3	<12%

DODO: Hogan et al. 2009, MNRAS, 396, 2074: 28 targets

Spitzer: Farihi et al. 2008, ApJ, 681, 1470 : 34 targets

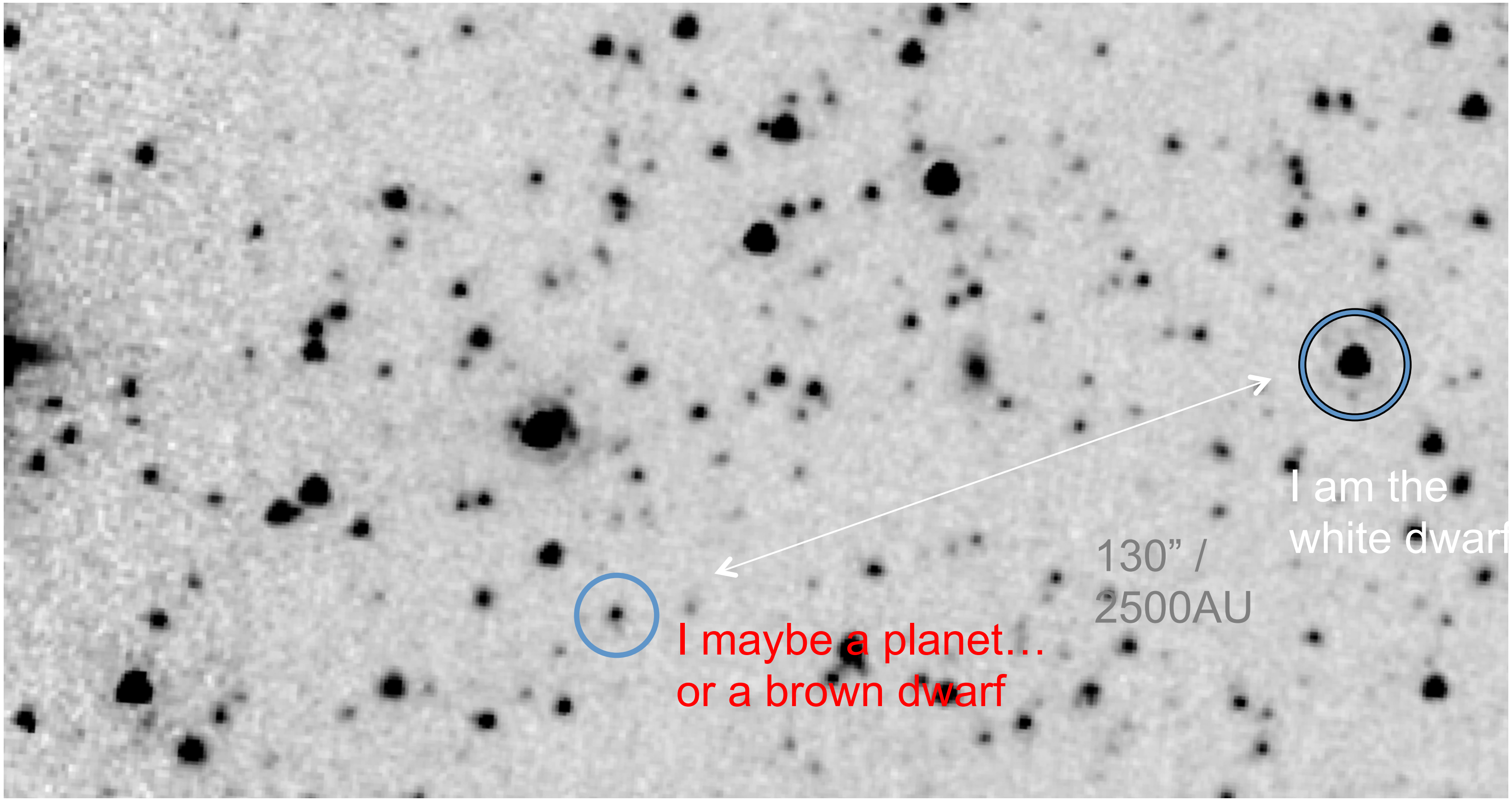
UKIDSS: Steele et al. 2011, Girven et al. 2011: ~1000 WDs

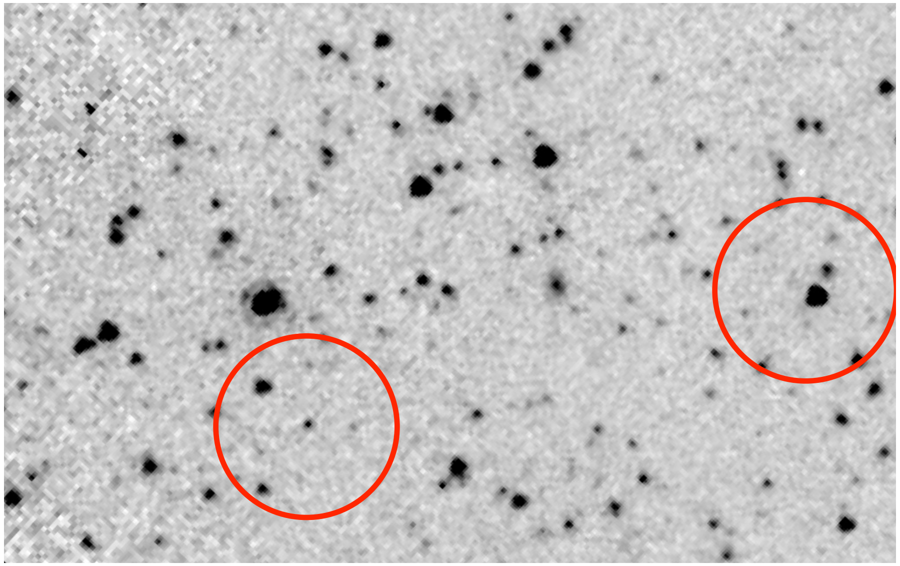
Spitzer warm mission programme

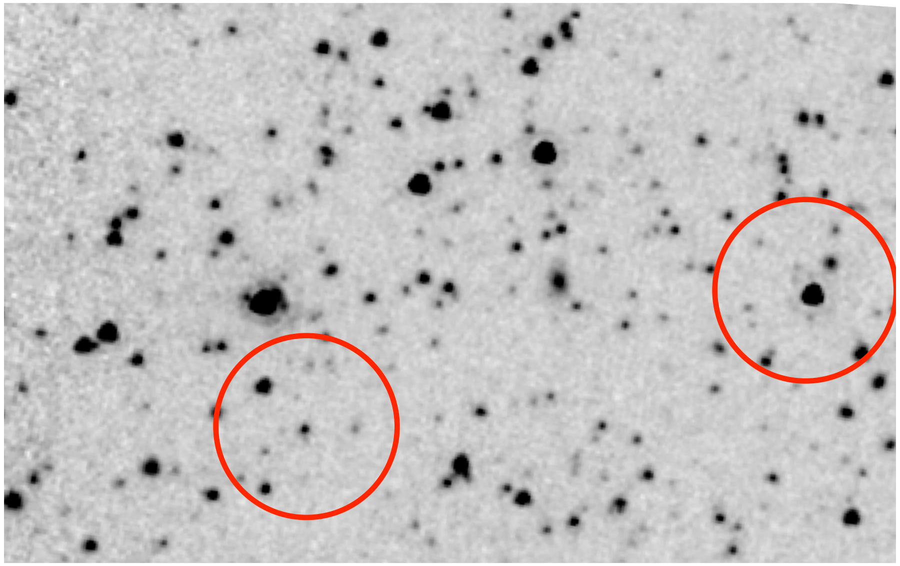
- Repeat observations of ~90 white dwarfs originally observed 2004/5
  - Prog ID: 60161
  - Title: *“Cool, spatially resolved substellar & exoplantary analogues at white dwarfs”*
    - PI: Burleigh, co-Is Farihi, Steele, Mullally, von Hippel
- Look for common proper motion companions
  - 4.5micron band only

Spitzer 4.5micron image

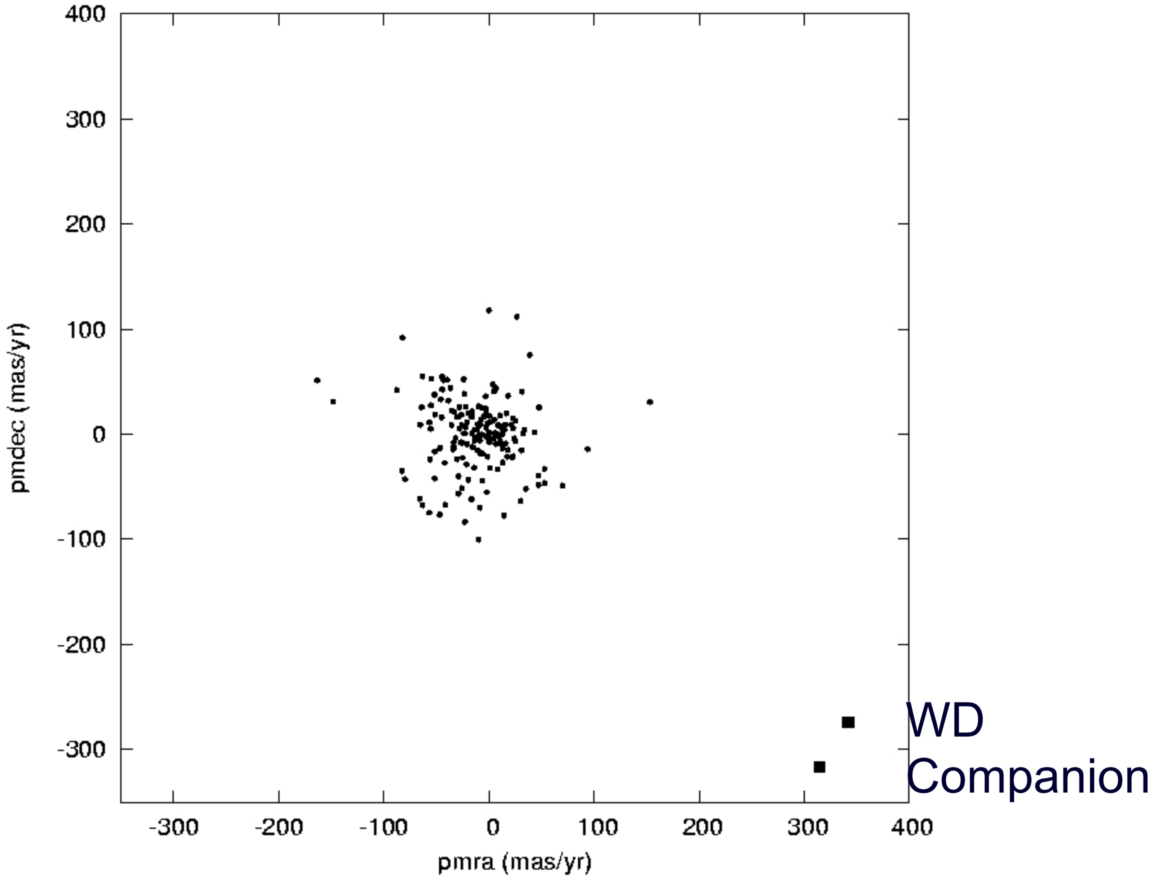
GJ3483 (LTT3059 / WD0806-661)







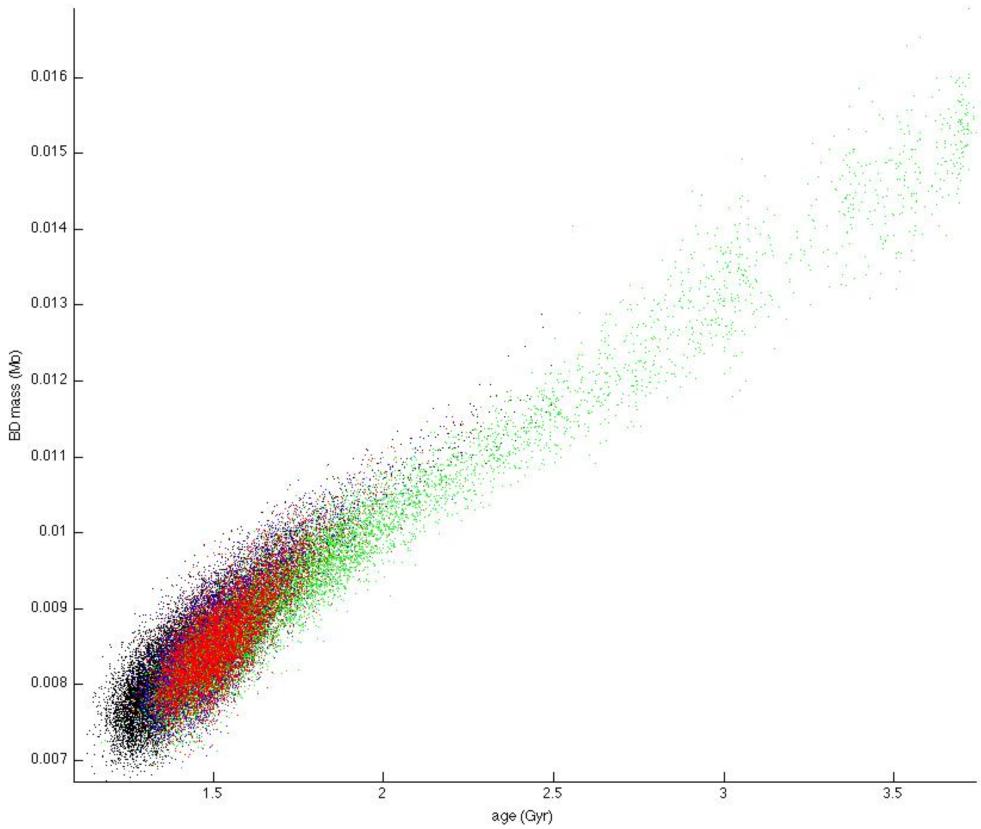
Proper motion



- PM error +/-25mas/yr

Candidate parameters

- WD
  - 0.58M_{sun},
  - Progenitor mass 1.8-2.4M_{sun}
  - Total age 1.2-2.5Gyr
  - Distance 19.2pc
- Candidate
  - 4.5micron mag = 16.75+/-0.08
  - 6-10M_{Jup}
  - 310-380K
- Binary
  - Projected separation 130" / 2500AU
  - Original separation 700AU


0.016
0.015
0.014
0.013
0.012
0.011
0.01
0.009
0.008
0.007
BD mass (Mo)
1.5
2
2.5
3
3.5
age (Gyr)

Candidate parameters

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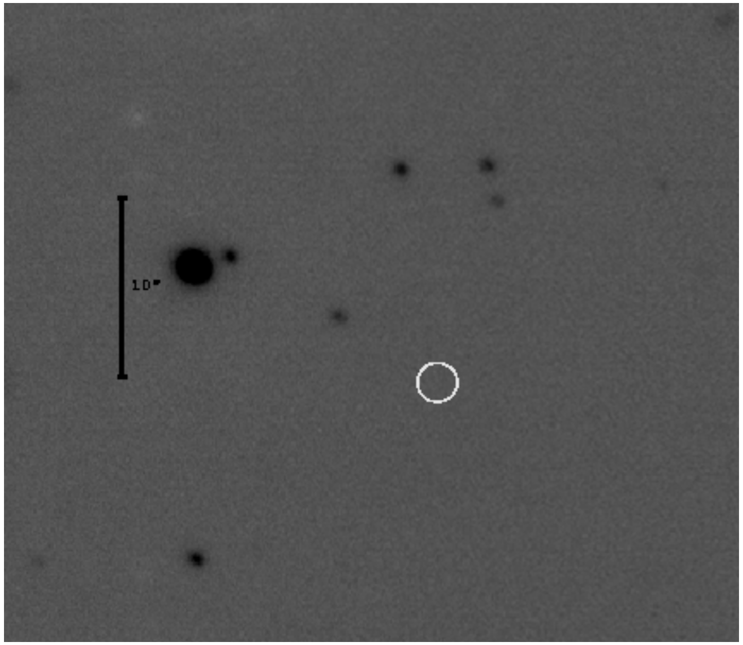
  - 310-380K
- Binary
  - Projected separation 130" / 2500AU
  - Original separation 700AU

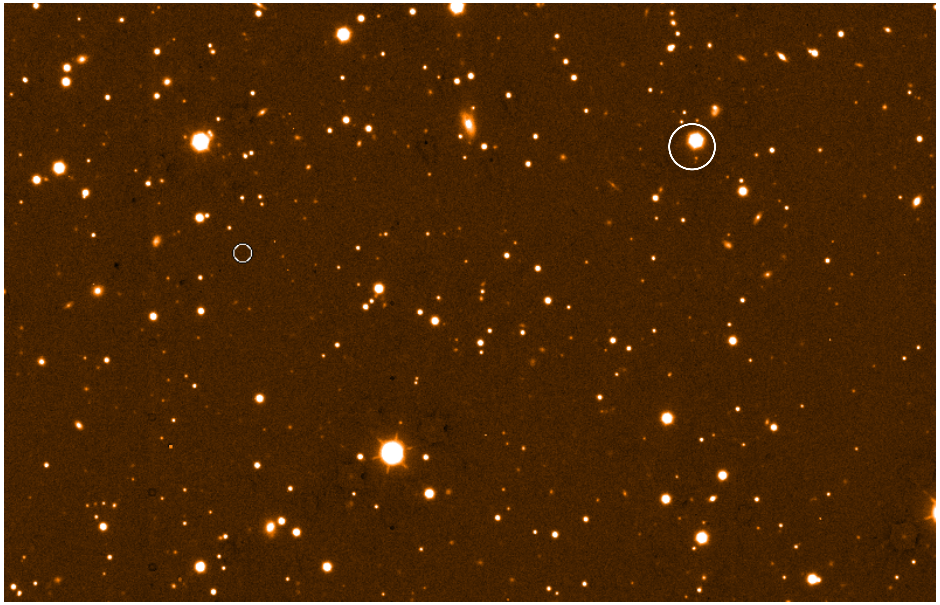
Y band observation

- VLT Hawk-I May 2012
- No detection
- Sensitivity limit Y~22.2



J-band observations

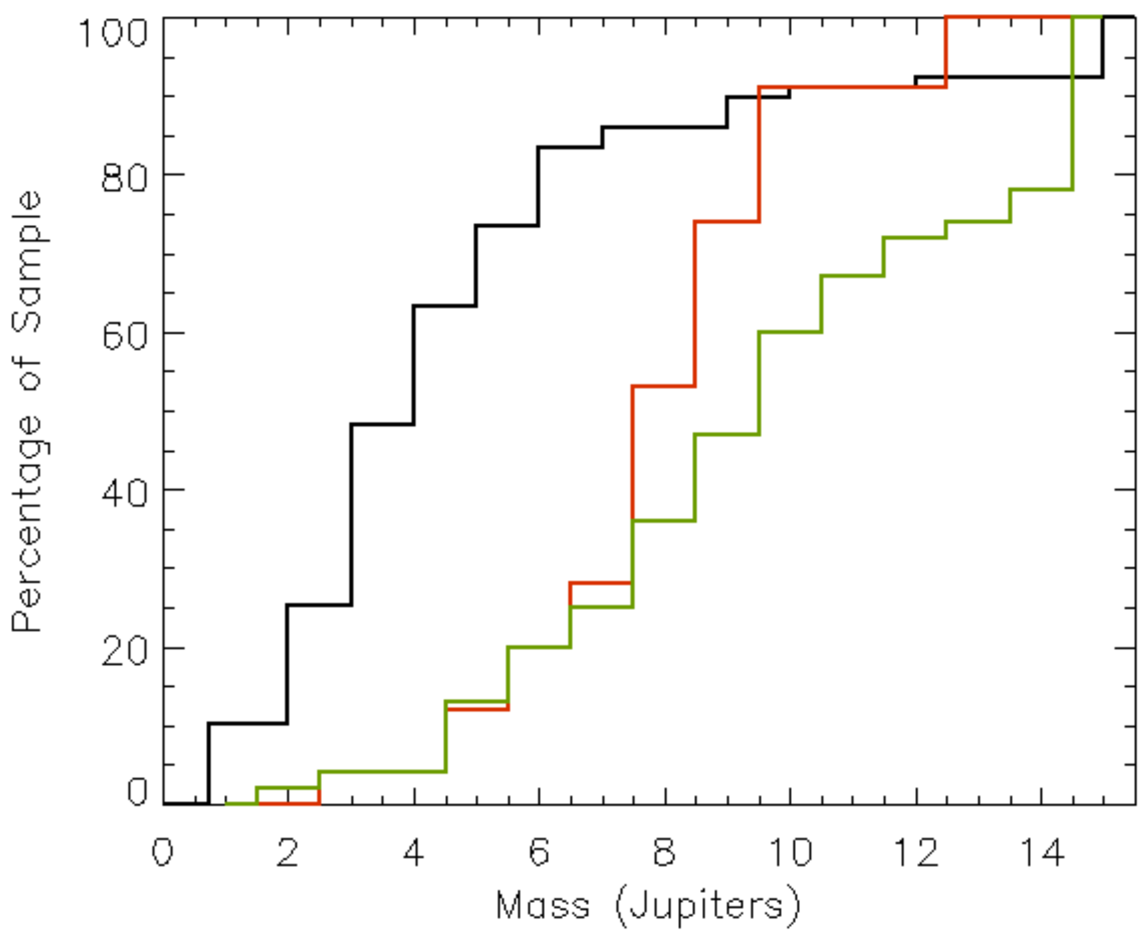
- Three hours with Magellan FourStar in March 2012
- No detection to J~23.5
  - J-[4.5] >~7
  - Redder than any known T dwarf – a Y dwarf? (Luhman et al. 2012)
  - Suggest mass 6-9M_{Jup} and 310K < T_{eff} < 350K
- Limiting sensitivity of field:
  - 2.5M_{Jup} / 200K (COND models)
  - For unresolved companions ~10M_{Jup} / 400K



Planet or brown dwarf?

- Is GJ3483B a brown dwarf or a planet?
- Forget deuterium burning limit as the discriminator
  - can we classify by formation mechanism?
- Original *projected* separation ~700AU
  - Too large for core accretion in a disk
  - Suggests disk fragmentation -> BD
    - Rodriguez et al. 2011
- But unstable, eccentric orbits expected in end states of stellar evolution
  - Debes & Sigurdsson 2002, Villaver & Livio 2007, Veras et al. 2011
  - Disk of $2M_{sun}$ star may be massive enough to make $6M_{Jup}$ companion
  - Progenitor could be an HR8799-like system
    - A5V+$7M_{Jup}$ @68AU + $10M_{Jup}$@38AU + $10M_{Jup}$@24AU

Spitzer survey completeness



Black: Spitzer resolved
Red: DODO resolved (Hogan et al. 2009)
Green: Spitzer unresolved (Farihi et al. 2008)

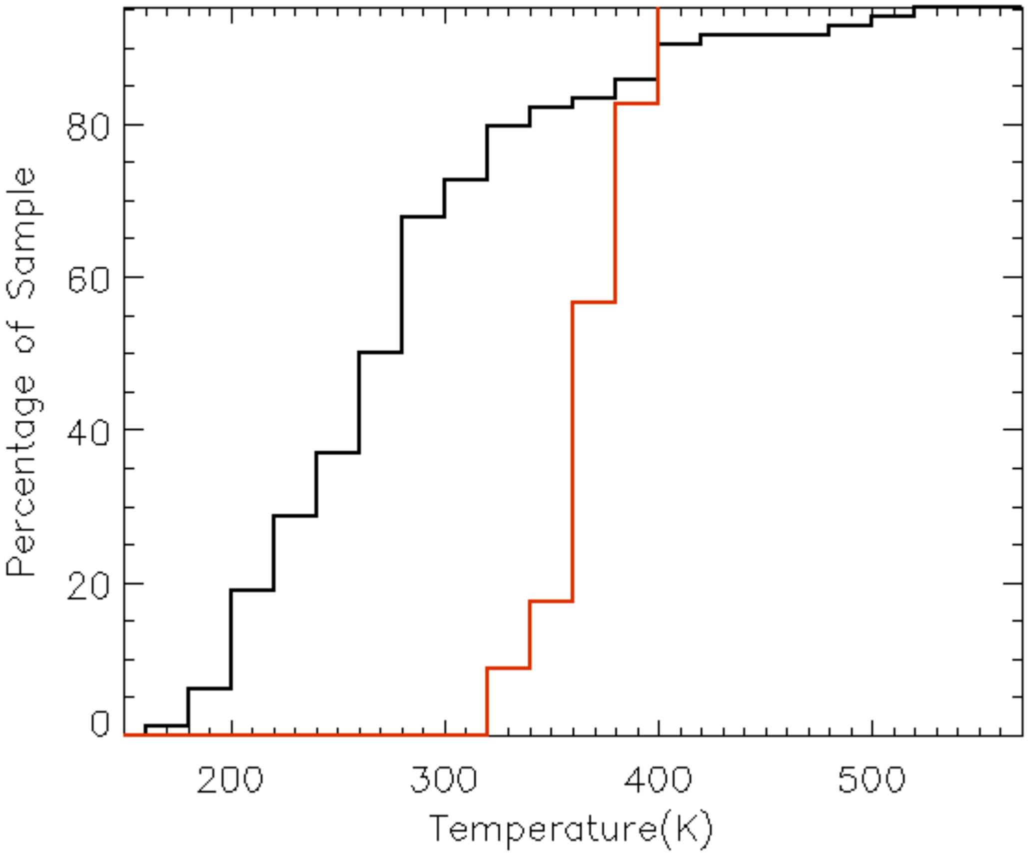
Limits on *resolved* exoplanet companions to WDs from ground & space

	DODO	Spitzer
$>13M_{Jup}$	<5%	~1%
$>10M_{Jup}$	<7%	1-2%
$>6M_{Jup}$	<1/3	1-2%

DODO: Hogan et al. 2009, MNRAS, 396, 2074: 28 targets

UKIDSS: Steele et al. 2011, Girven et al. 2011, incidence of BDs 0.5% +/-0.3%

Spitzer survey completeness



Black: Spitzer resolved
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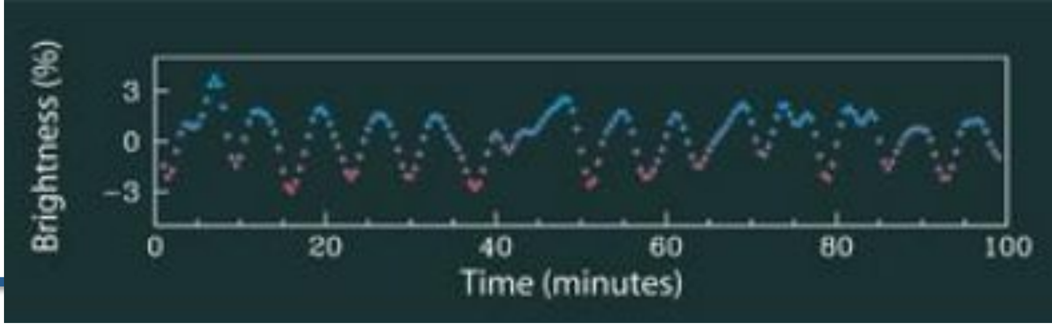
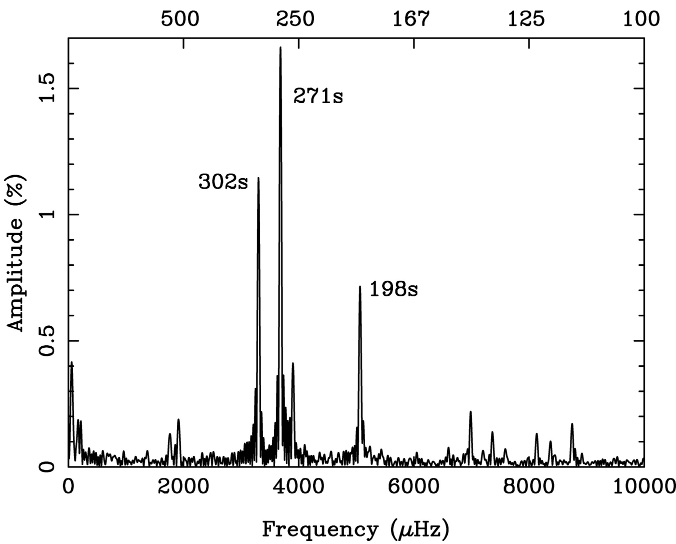
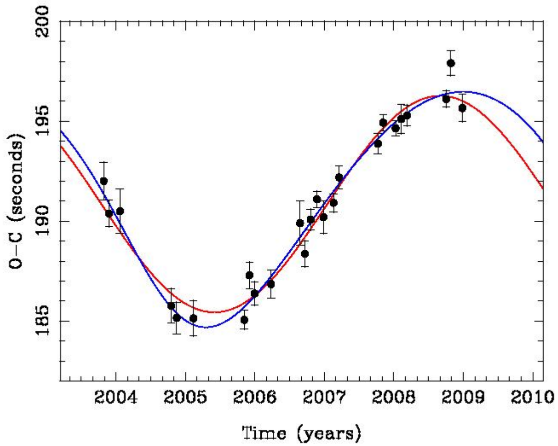
A planet around a pulsating white dwarf

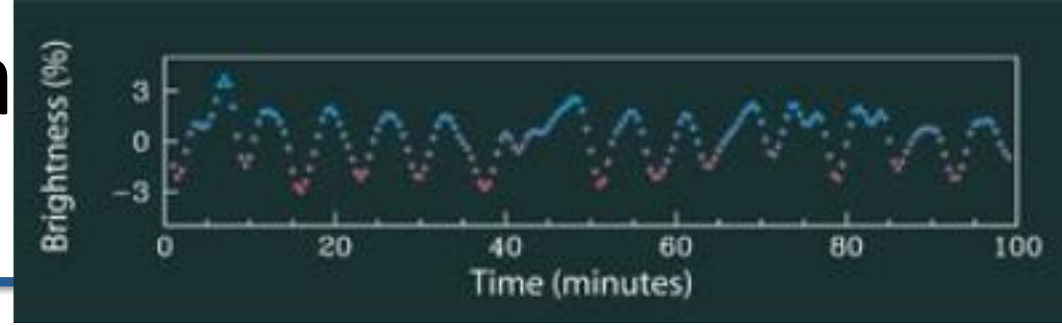


- GD66 is a non-radial pulsating WD
- Pulsation modes and frequencies extremely stable
- Periodic variations in pulse arrival times
- Best fit by 2.3M_{jup} planet in 6.8yr orbit
  - *Mullally et al. 2008, ApJ, 676, 573*
- cf 3M_{jup} planet found at pulsating hot subdwarf V391 Peg
  - *Silvotti et al. 2007, Nature, 449, 189*





A planet around a pulsating white dwarf



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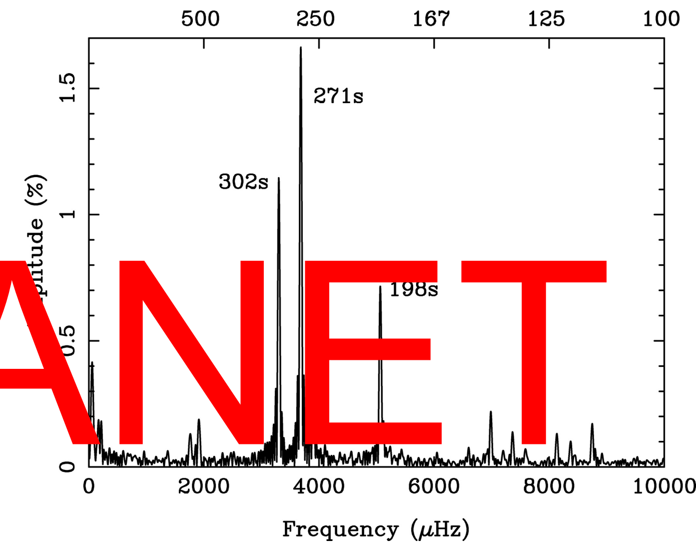
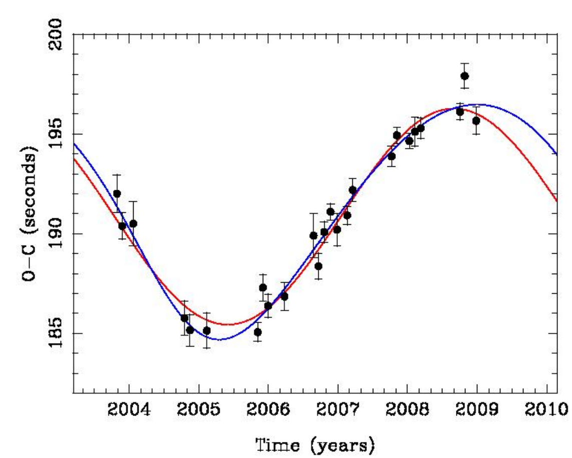
- Best fit by 2.[illegible] M_{jup} planet in [illegible]yr orbit
  - *Mullally et al. 2008, ApJ, 676, 573*
- cf 3M_{jup} planet found at pulsating hot subdwarf V391 Peg
  - *Silvotti et al. 2007, Nature, 449, 189*
- Pulsation modes 180 degrees out of phase with each other – variability can't be due to a third body

NOT A PLANET



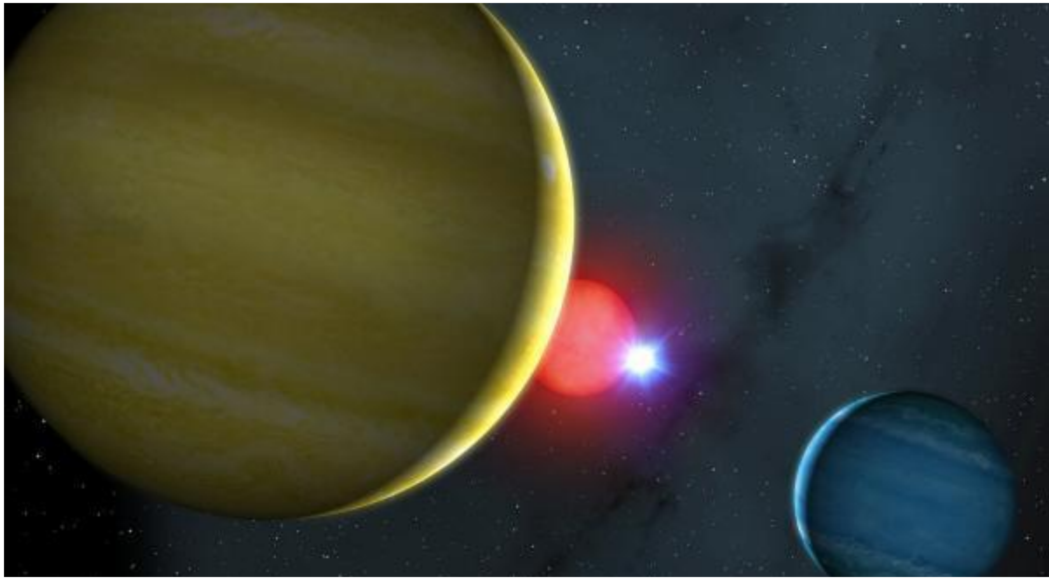


The lowest mass companions to WDs

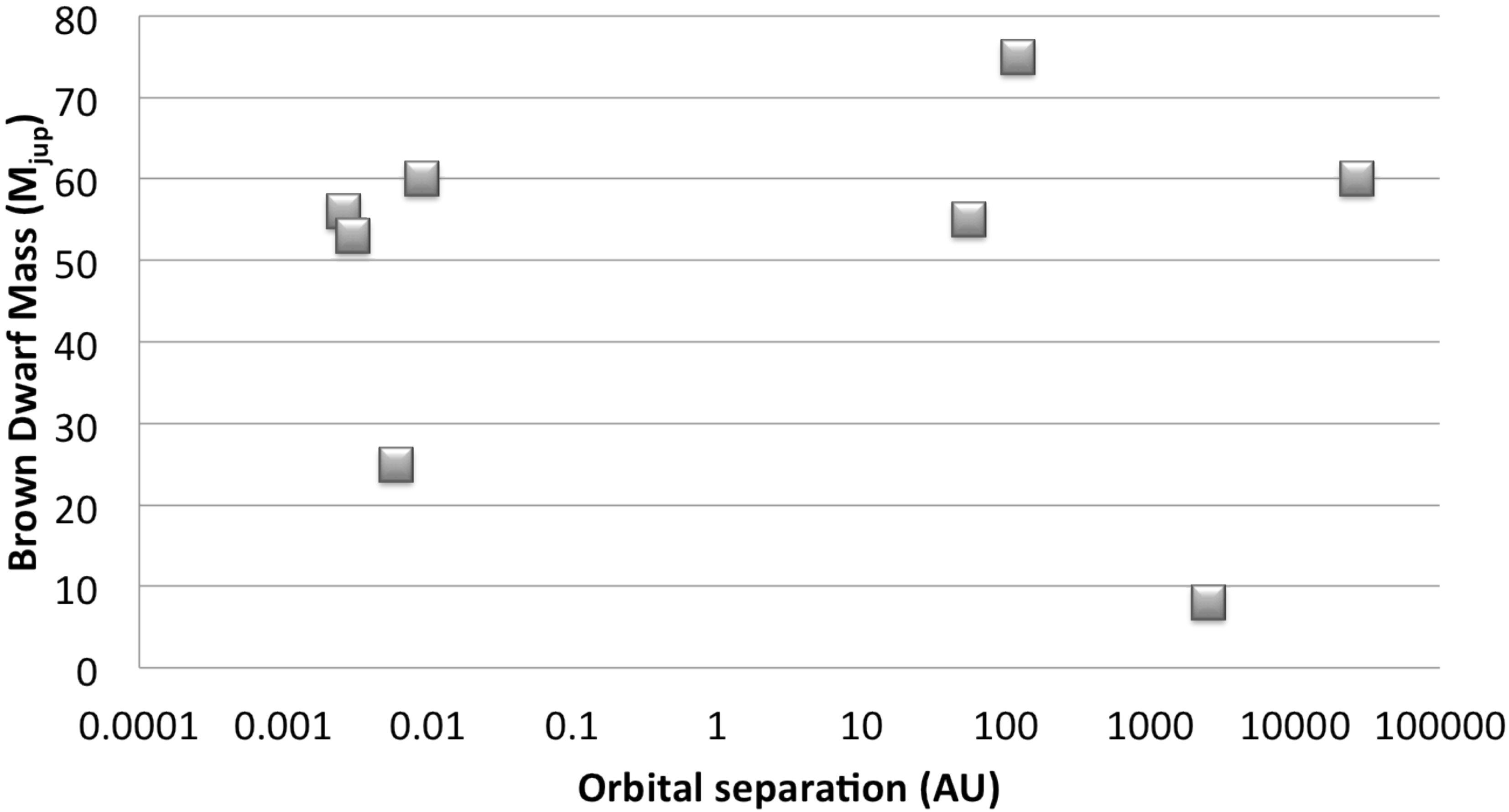
Name	Mass (M_{jup})	Period	a (AU)	Evolutionary status	Detection method	Comment	Reference
GD66 b	>2.4	~7y	>3AU	WD	Pulsation timing	Retracted	Mullally et al. 2008
GJ3483 b (WD0806-661 b)	6-9		2500	WD	Direct imaging	Y dwarf? 310K<T<350K	Luhman et al. 2011, Burleigh et al. 2013
WD0837+185	25-30	4.2hr	0.006	WD, Post-CE	Radial velocity	In Praesepe open cluster	Casewell et al. 2012
WD0137-349 B	53	1.93hr	0.003	WD, Post-CE	Radial velocity	L8 dwarf, T~1300K	Maxted et al. 2006
PHL5038 B	55		55	WD	Direct imaging	L8 dwarf, T~1400K	Steele et al. 2009
GD1400 B	60	9.98hr	0.009	WD, Post-CE	Radial velocity	L6/7 dwarf, T~1500K	Burleigh et al. 2012
LSPM 1459+0857 B	60-75		26500	WD	Direct imaging	T4.5 dwarf, T~1000K	Day-Jones et al. 2011
NN Ser b NN Ser c	6.9 2.3	15.5y 7.7y	5.4 3.4	Pre-CV (WD+M)	Eclipse timing		Beuermann et al. 2010

Planets around CVs and pre-CVs from eclipse timing

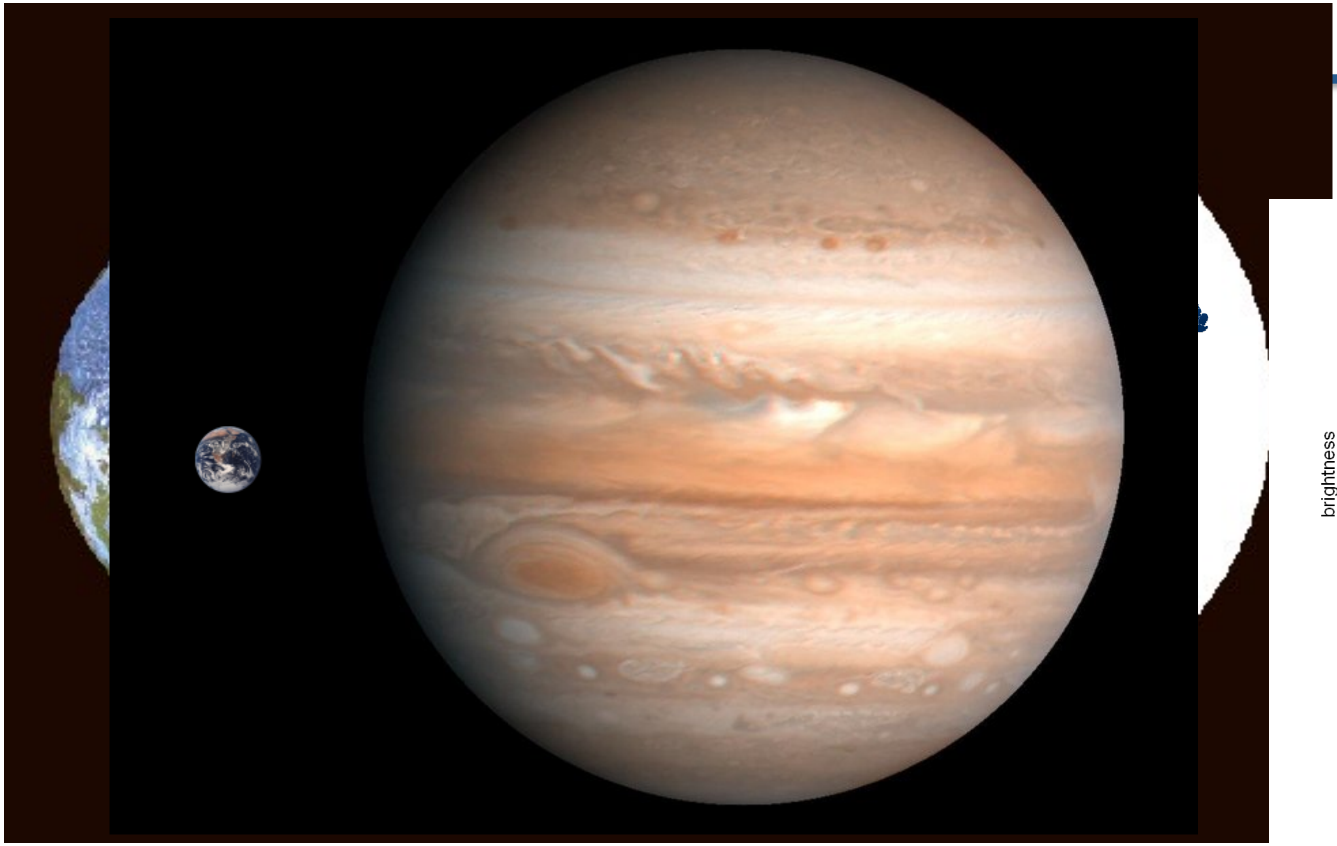
- Many claims in recent literature for planets around CVs and pre-CVs
- Caution: some refuse to follow predicted orbits
- A few do appear to be reliable
- NN Ser: non-interacting WD + M4 plus M sin I = $6.9M_{Jup}$ and $2.3M_{Jup}$ in 15.5 year and 7.7 year orbits
- Discovered before Kepler circumbinary planets!

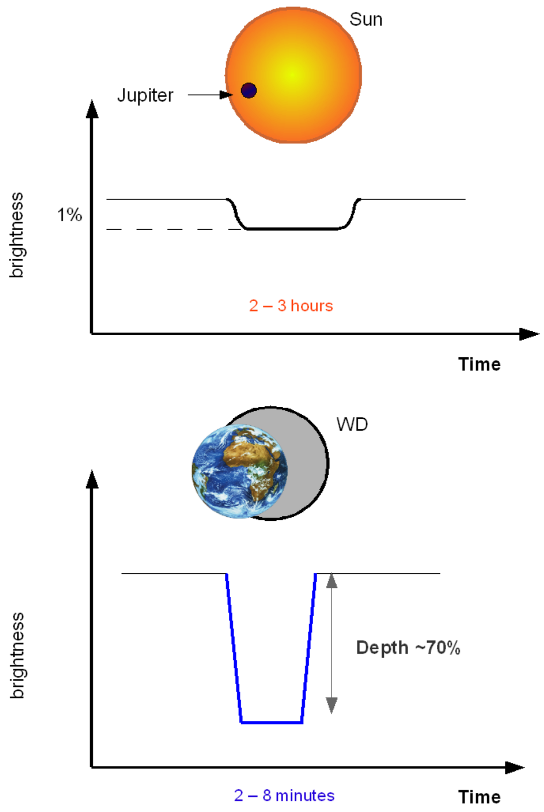


WD/BD binary separations



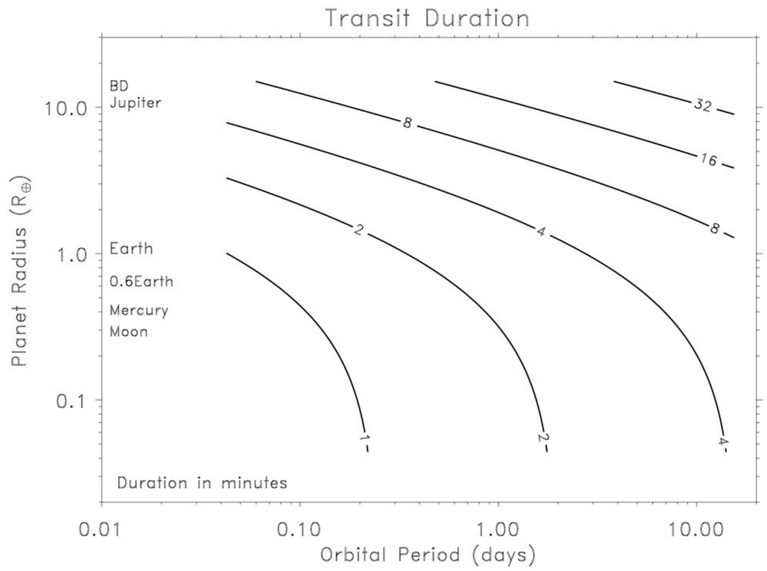
Transits of white dwarfs

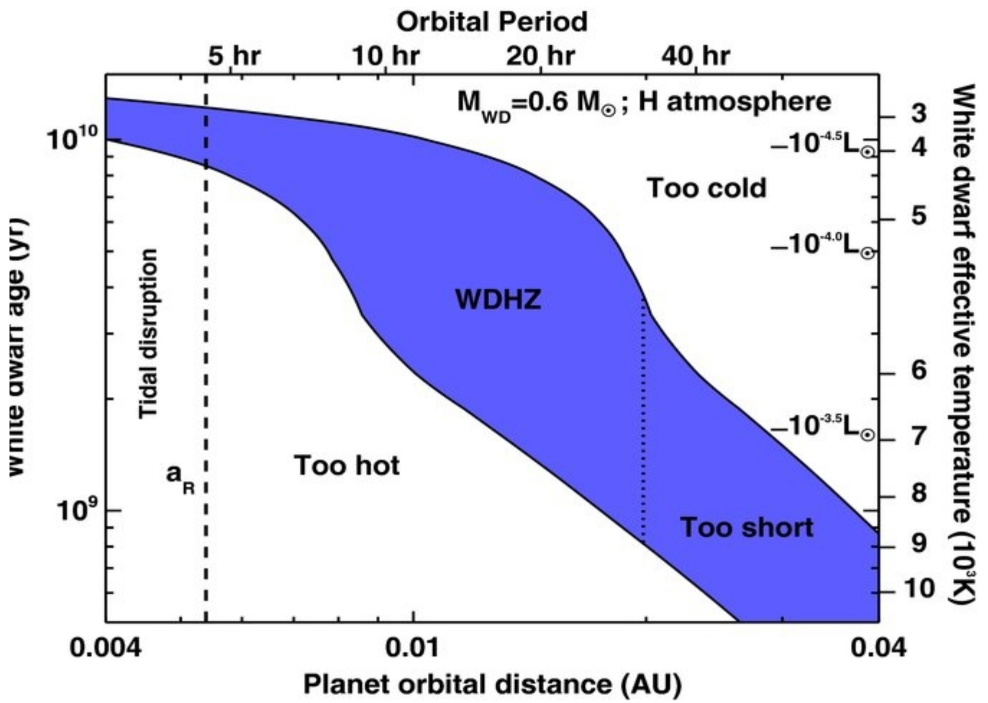




- Transit of a Jupiter: 100% or total eclipse
- Transit of an Earth: up to 100%
- Transit of Moon: ~5%
- Transit of UK: $5x10^{-4}$ (0.05%)

Transits of white dwarfs



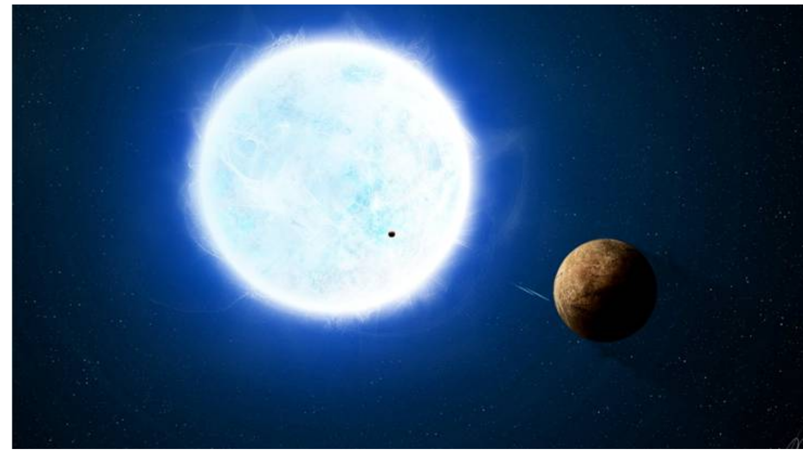


- Faedi et al 2011
- Agol et al 2011
- Fossati et al 2012
- Barnes & Heller 2012

- Loeb & Maoz 2013
- Burleigh et al. 2013…..

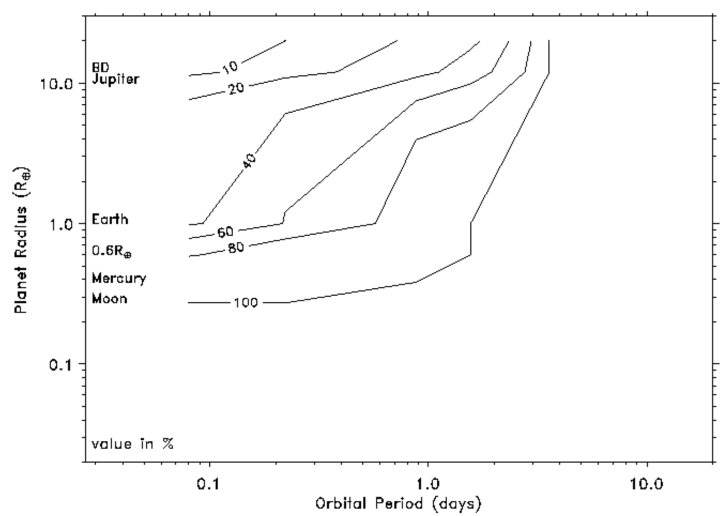
A search for eclipsing and transiting planets with SuperWASP

- SuperWASP has observed ~300 confirmed white dwarfs since 2004
  - 1% photometry to V=13, detection limit V~15
- No eclipsing or transiting companions detected
- Limiting factors:
  - cadence: 8min for WASP v transit times of 1-few mins
  - noisy data mimics transit events
  - unknown frequency of close planetary companions
    - *Survivors of common envelope evolution?*
    - *2nd generation planets?*
    - *Can rocky bodies even exist close to a WD?*
    - *Shepherd moons for dust disks?*

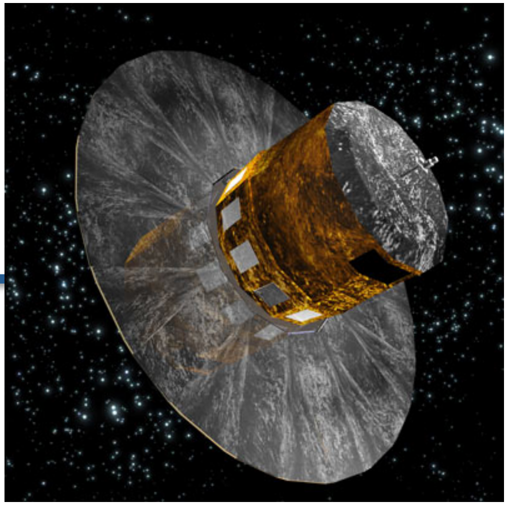


- Future:
  - *Wide field: (NGTS, Pan-Starrs, LSST, Plato)?*
  - *Target individual objects with 0.5-1.0m telescopes?*
  - *Kepler can detect asteroids in long period orbit*

Faedi, West, Burleigh, Goad, & Hebb, (2011), MNRAS, 410, 899



GAIA Astrometry



- Gaia will find 400,000 WDs extending complete sample to 50-100pc
  - At 25pc the sample is currently only 40% complete
- Can detect giant planets (>2M_{Jup}) with periods from 2.5-5years around ~1000 WDs
- 15Mjup with 10% error around ~5000 WDs
- Launch late 2013, first full astrometry data release after 40 months (2017?)
  - *Numbers courtesy Roberto Silvotti (Silvotti et al. 2011)*

Open questions, future directions

- How common are GJ3483-like objects?
  - More direct imaging searches for wide companions
  - What are their formation mechanisms?
    - Disk fragmentation?
    - Core accretion and subsequent ejection?
- Where are the perturbers that help create dust disks around white dwarfs?
  - Mid-IR photometric searches; HST, JWST, E-ELT
  - Astrometry with GAIA
- What is the lowest mass that can survive CE evolution intact to the white dwarf stage?
  - IR surveys, Transit/eclipse searches
- What is the orbital period distribution for substellar companions?
  - Are there “deserts”?
- Can rocky planets exist in close orbits to WDs?
  - Transit searches
- Can 2nd generation planets form?
  - Hot, young gas giants, metal-rich terrestrial planets?