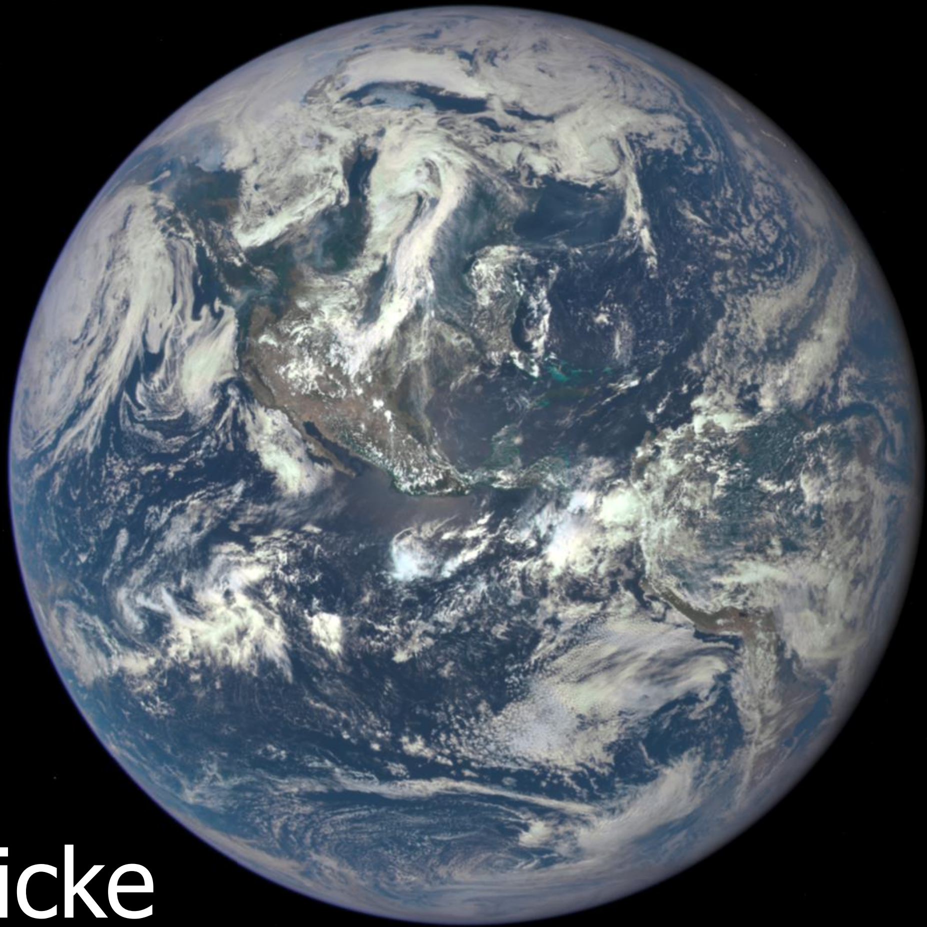
Evolved planetary systems around white dwarfs



Boris Gänsicke

THE UNIVERSITY OF WARWICK

1. **The late evolution of planetary systems**
2. **Signposts of evolved planetary systems**
3. **Bulk abundances**
4. **Architectures**

The late evolution of planetary systems

A large fraction of solar-like stars has planets

(e.g. Cassan et al. 2012, Nature 481, 167; Fressin et al. 2013, ApJ 766, 81)

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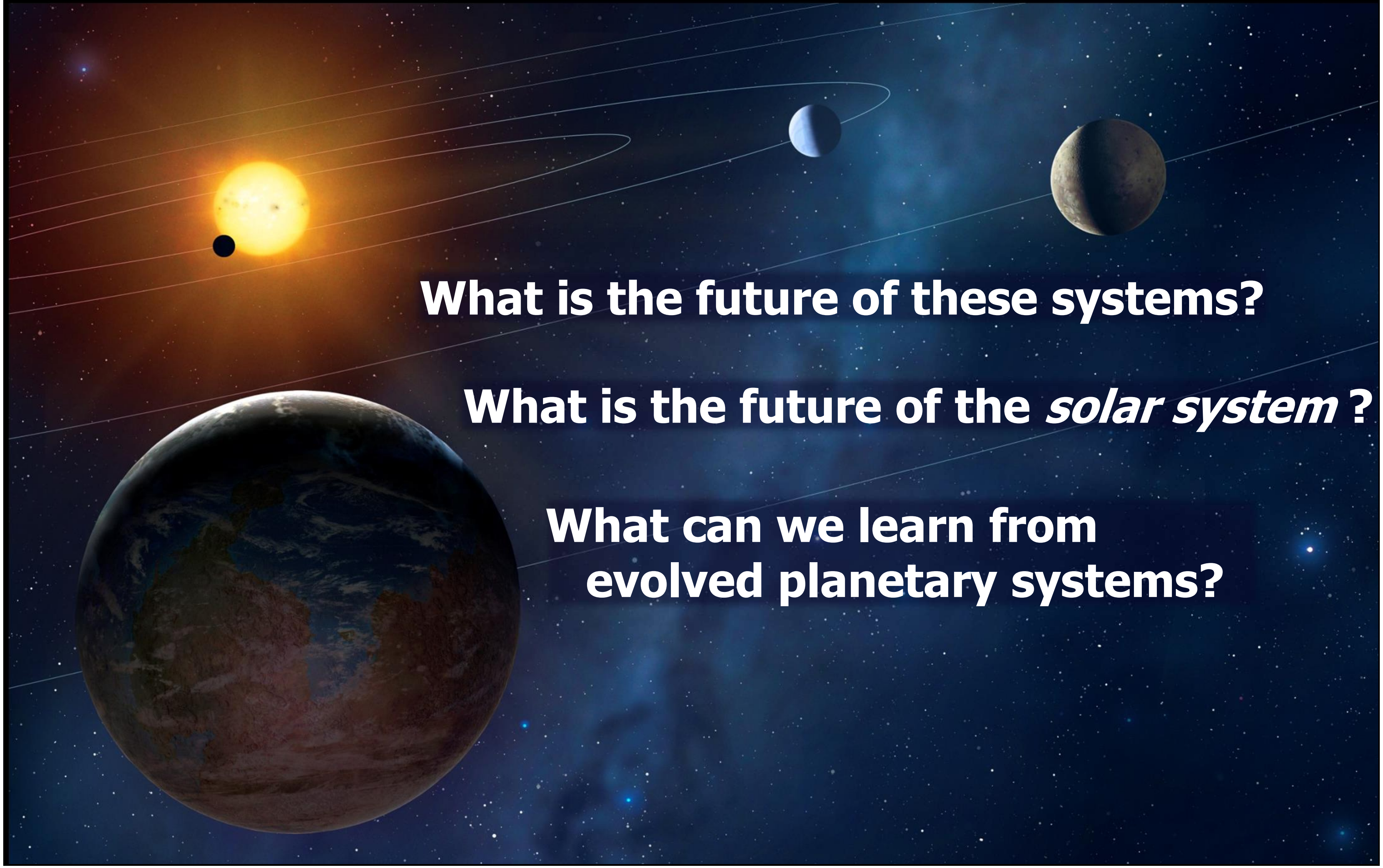
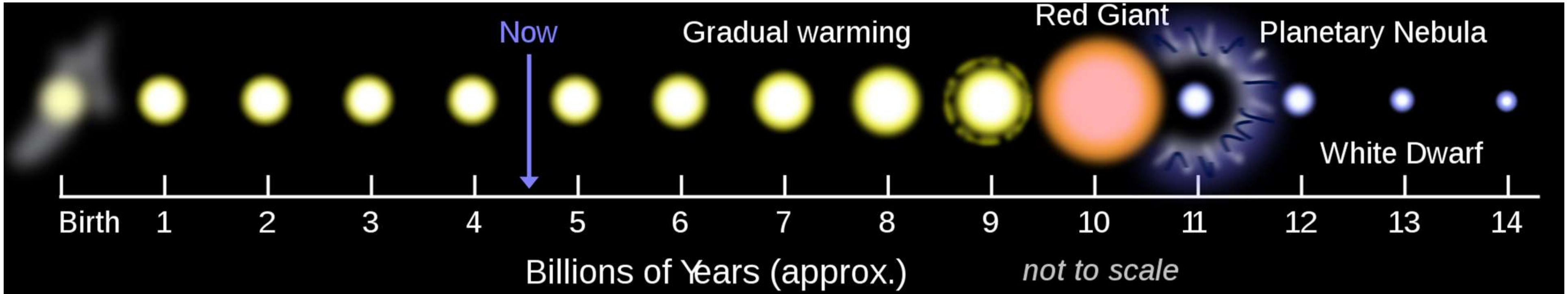


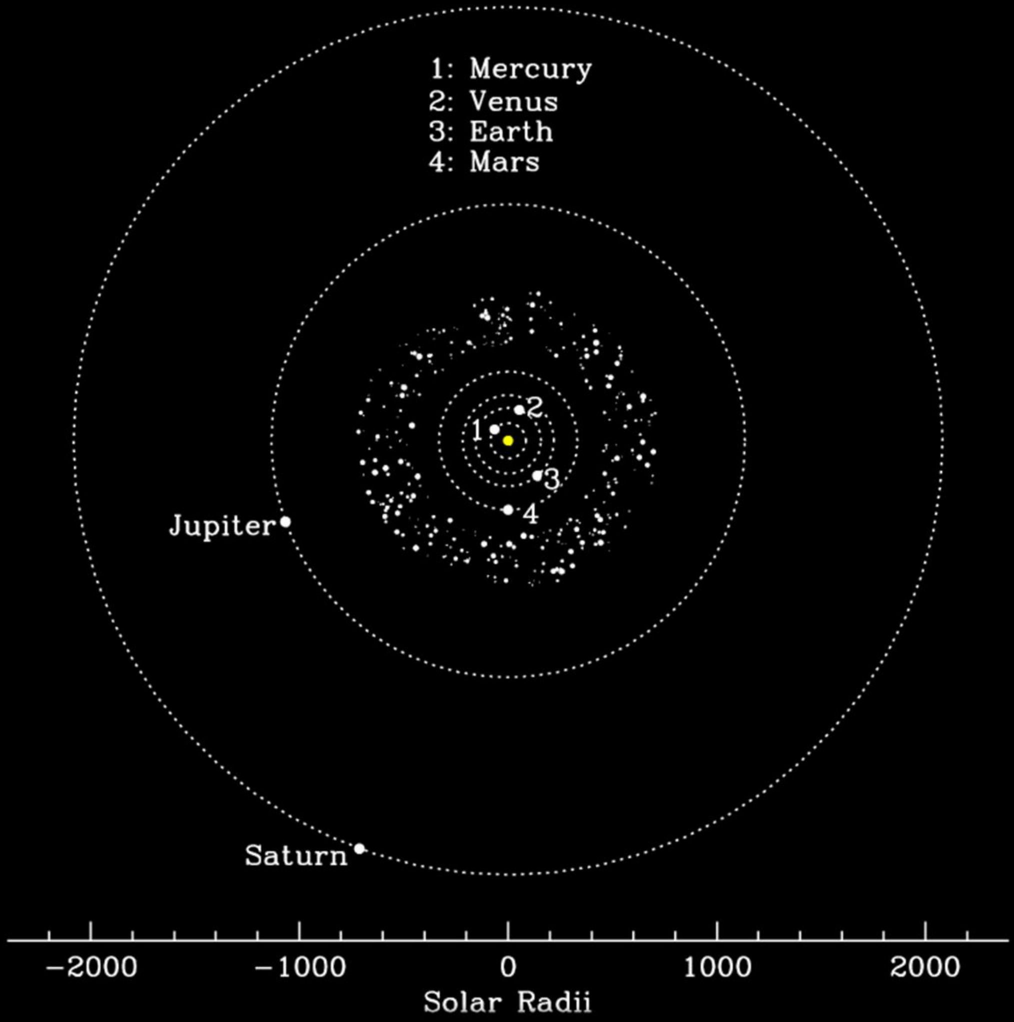
What is the future of these systems?

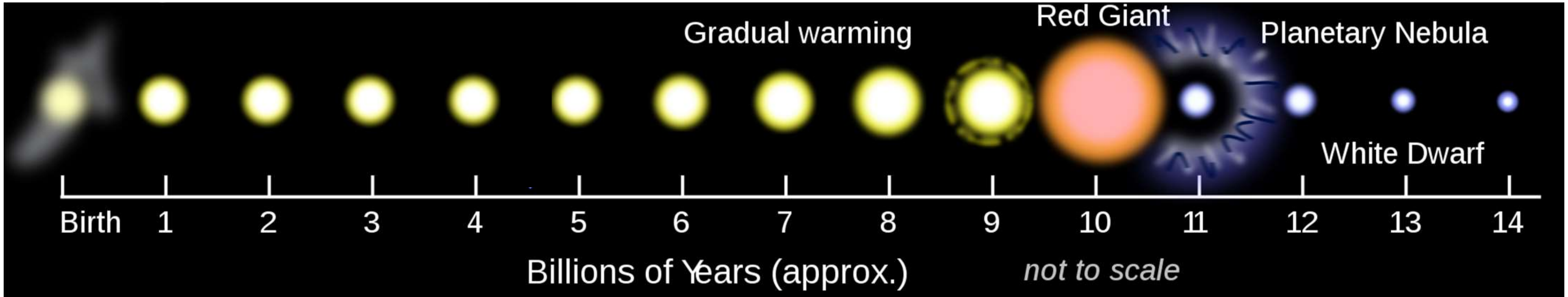
What is the future of the *solar system* ?

What can we learn from evolved planetary systems?

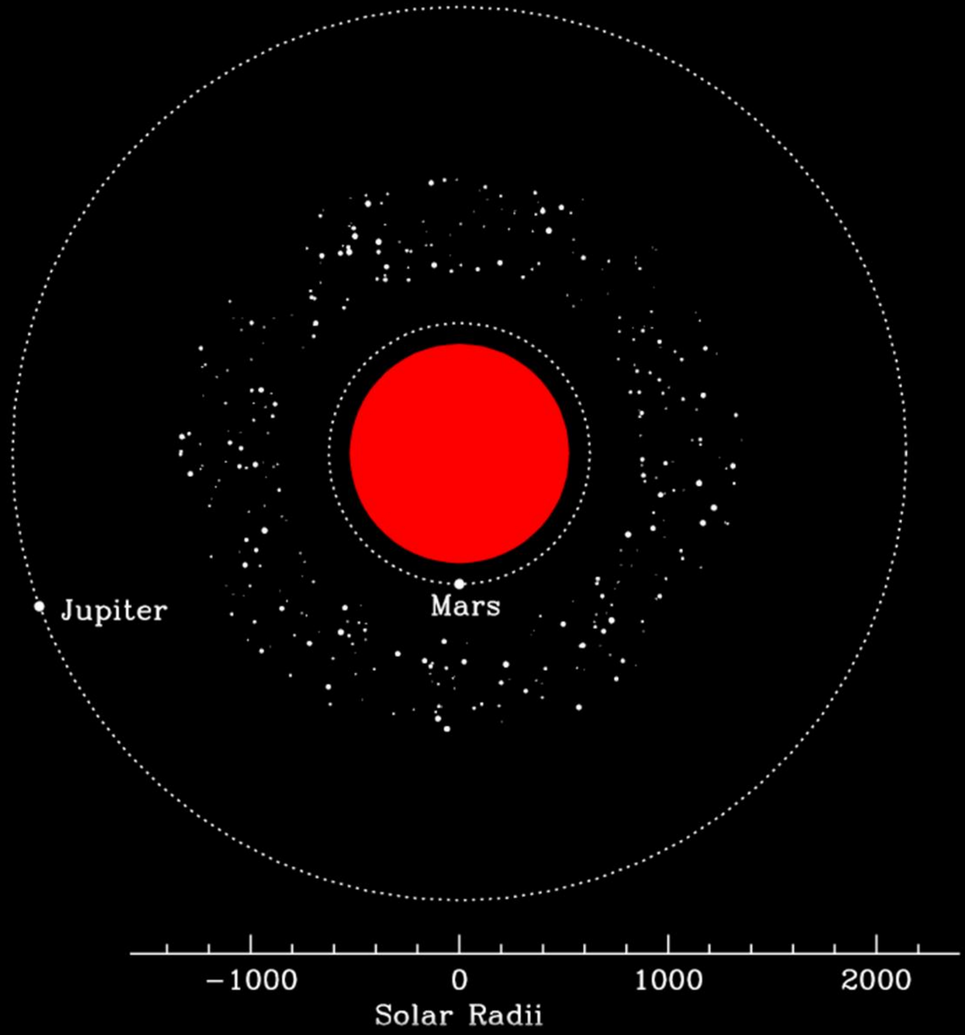

Now
Gradual warming
Red Giant
Planetary Nebula
White Dwarf
Birth 1 2 3 4 5 6 7 8 9 10 11 12 13 14
Billions of Years (approx.)
not to scale

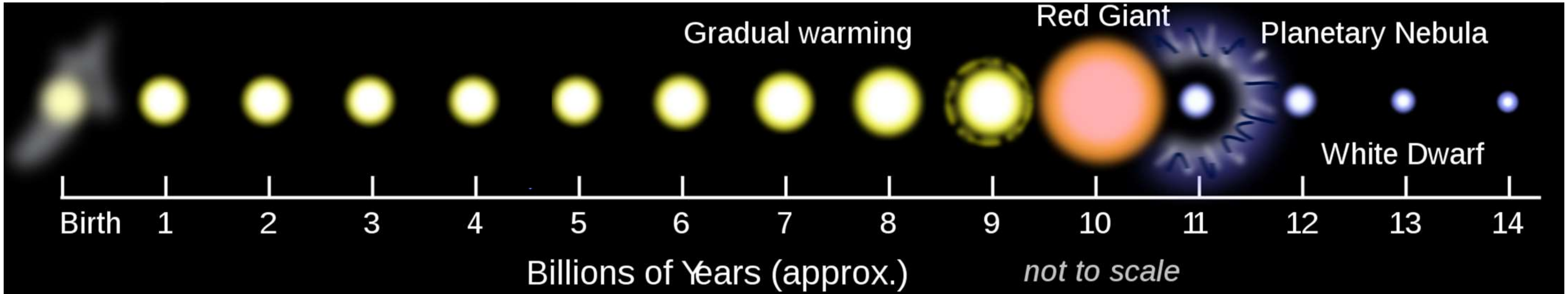
Today


1: Mercury
2: Venus
3: Earth
4: Mars
Jupiter
Saturn
1
2
3
4
−2000 −1000 0 1000 2000
Solar Radii

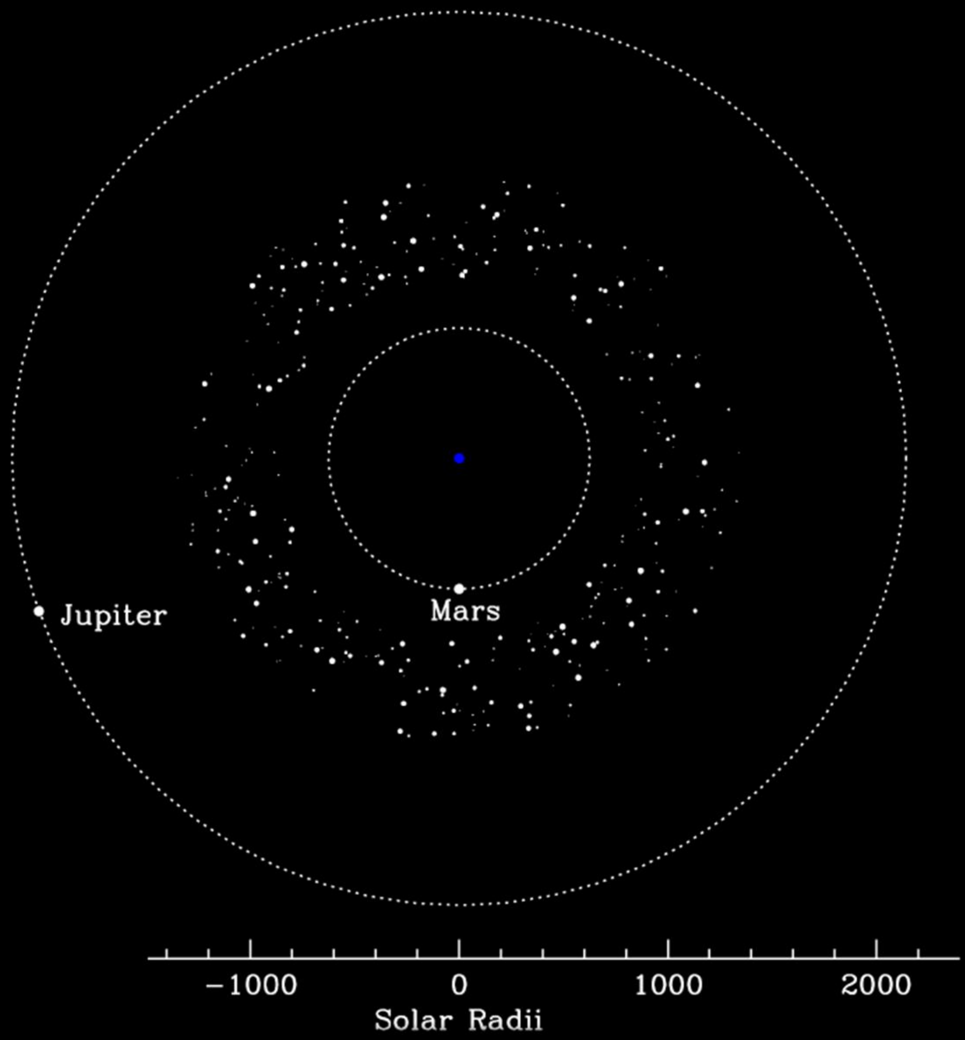


5 billion years from now



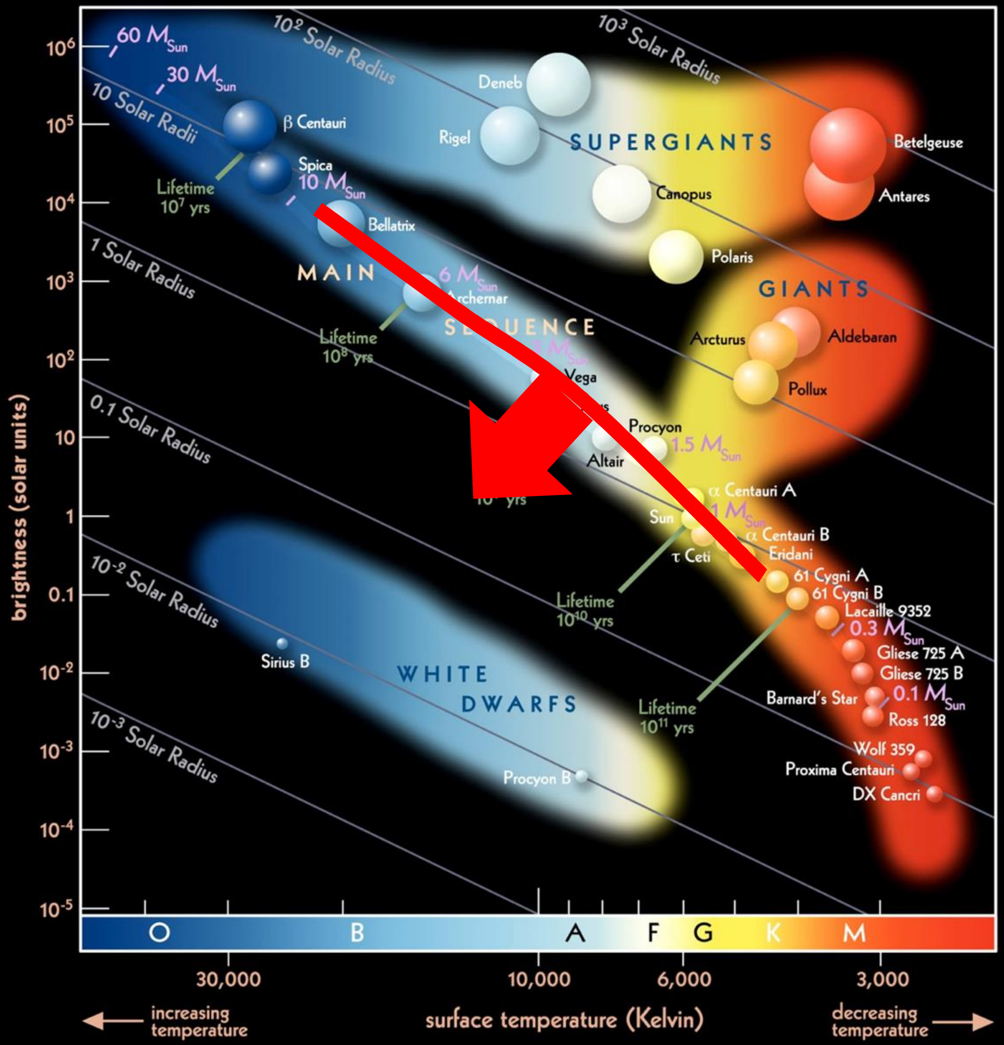


8 billion years from now

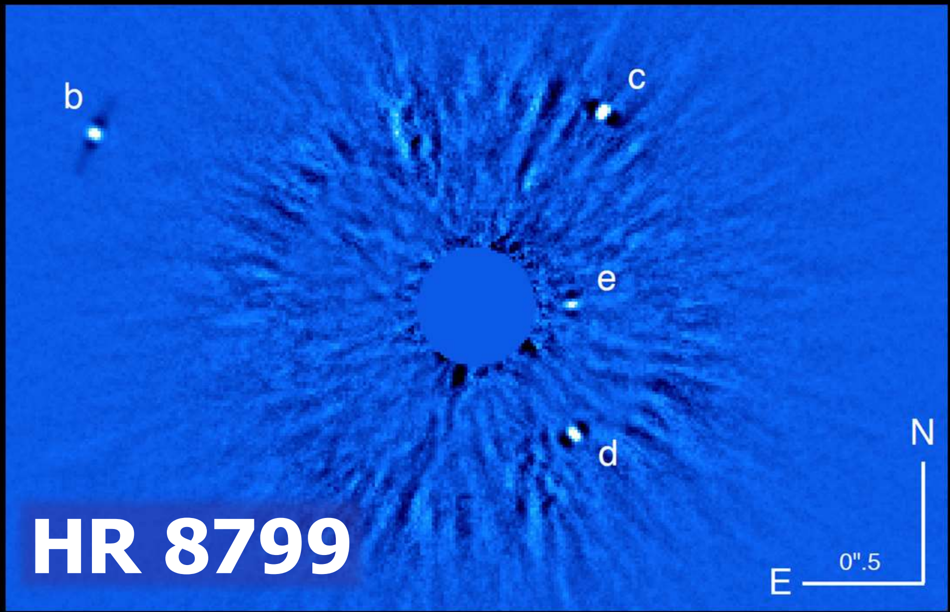


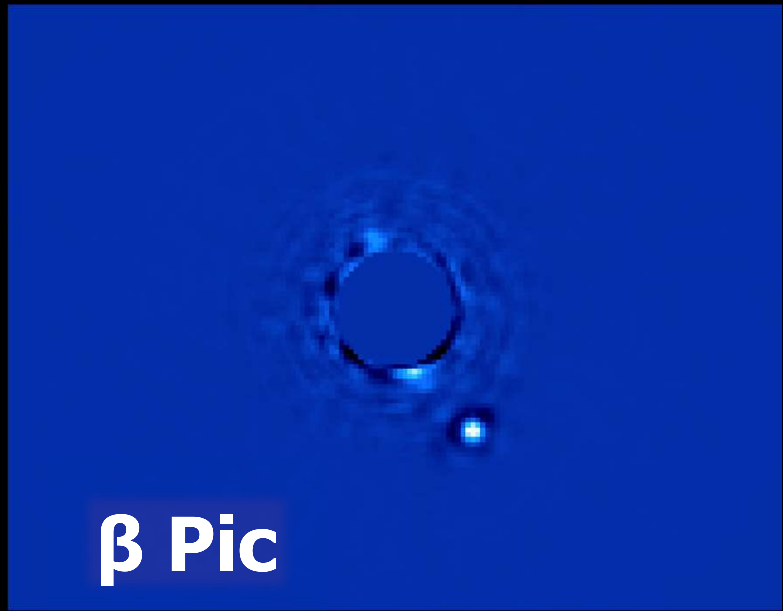
e.g. Duncan & Lissauer, Icarus 1998, 134, 303
Burleigh et al. 2002, MNRAS 331, L41

(almost) all planet host stars will become white dwarfs:
Earth-sized, ~solar-mass e⁻ degenerate objects



Future white dwarf planetary systems





M=1.47M⊙
MS life time: 3Gyr

M=1.75M⊙
MS life time: 1.6Gyr

⇒ Both will soon join the white dwarf populations

Signposts of evolved planetary systems:

Quiz time:

When was the first observational evidence for other planetary systems obtained?

Signposts of evolved planetary systems:

- metals

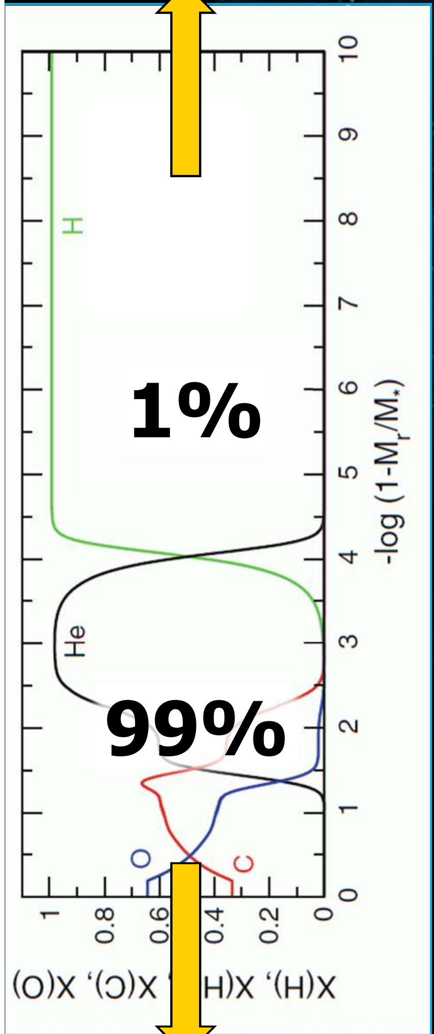
<u>Quiz time:</u>

When was the first observational evidence for other planetary systems obtained?

⇒1917

White dwarfs are chemically stratified

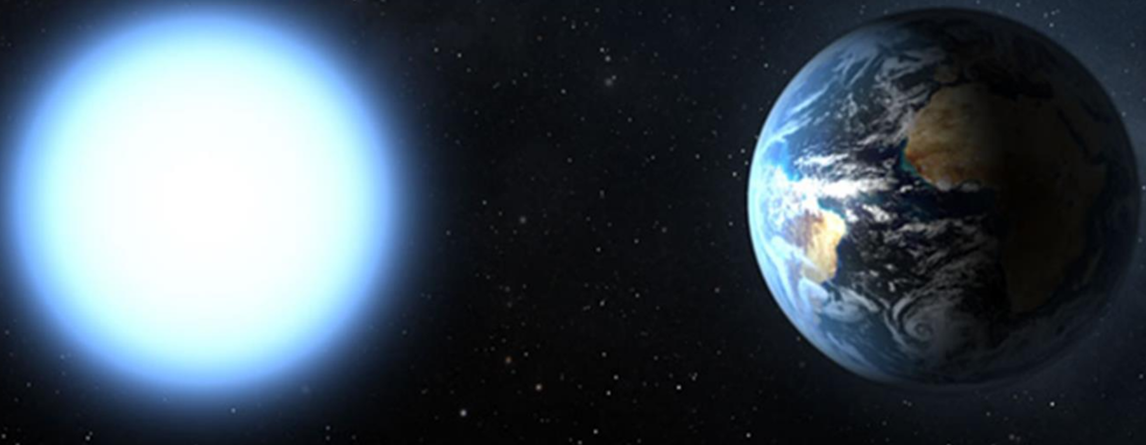
Pure H or He atmosphere



C/O core

$$R_{wd} \approx 0.01 R_\odot \approx R_\oplus$$

$$M_{wd} \approx 0.65\ M_\odot$$

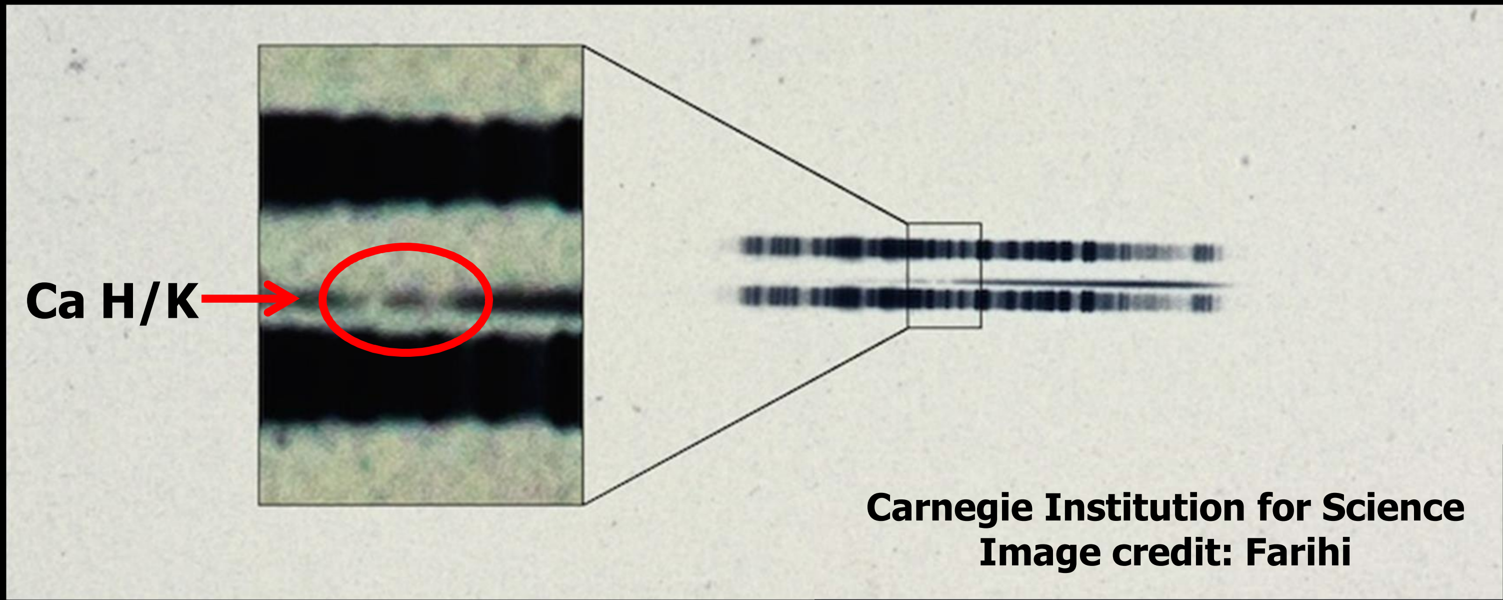


$g \sim 10^6\ ms^{-2}$

$g = 9.8 ms^{-2}$

Althaus et al. 2010, A&A Rev 18, 471

1917: Van Maanen’s star

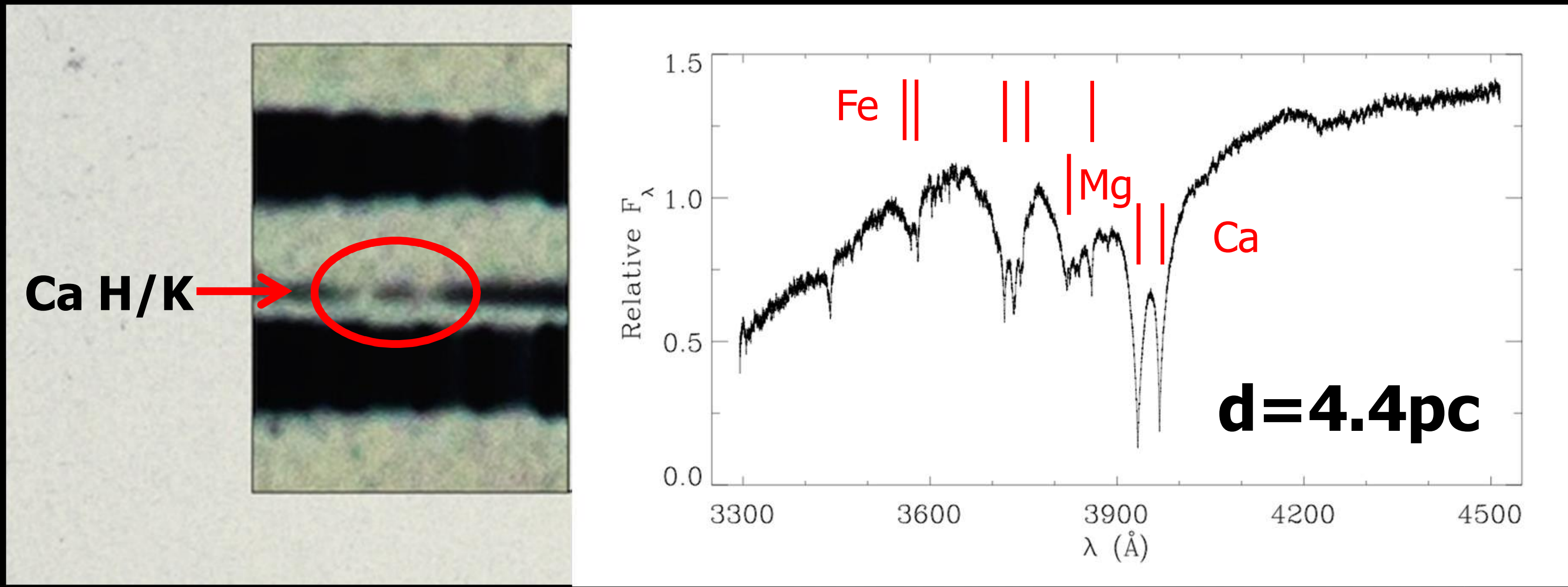


Van Maanen
1917, PASP 29, 258
1920, Cont. Mt. Wilson Obs. 182

TWO FAINT STARS WITH LARGE PROPER MOTION.

1. In a search for companions of stars with large proper motion two plates of the region of Lalande 1299 were taken on September 15, 1914, and two on September 12, 1917. The plates do not show any companion of Lalande 1299 ($\mu = 1''.37$ in p = 146°.9), but reveal a star which has an even larger motion. This star is located

The 3rd closest white dwarf

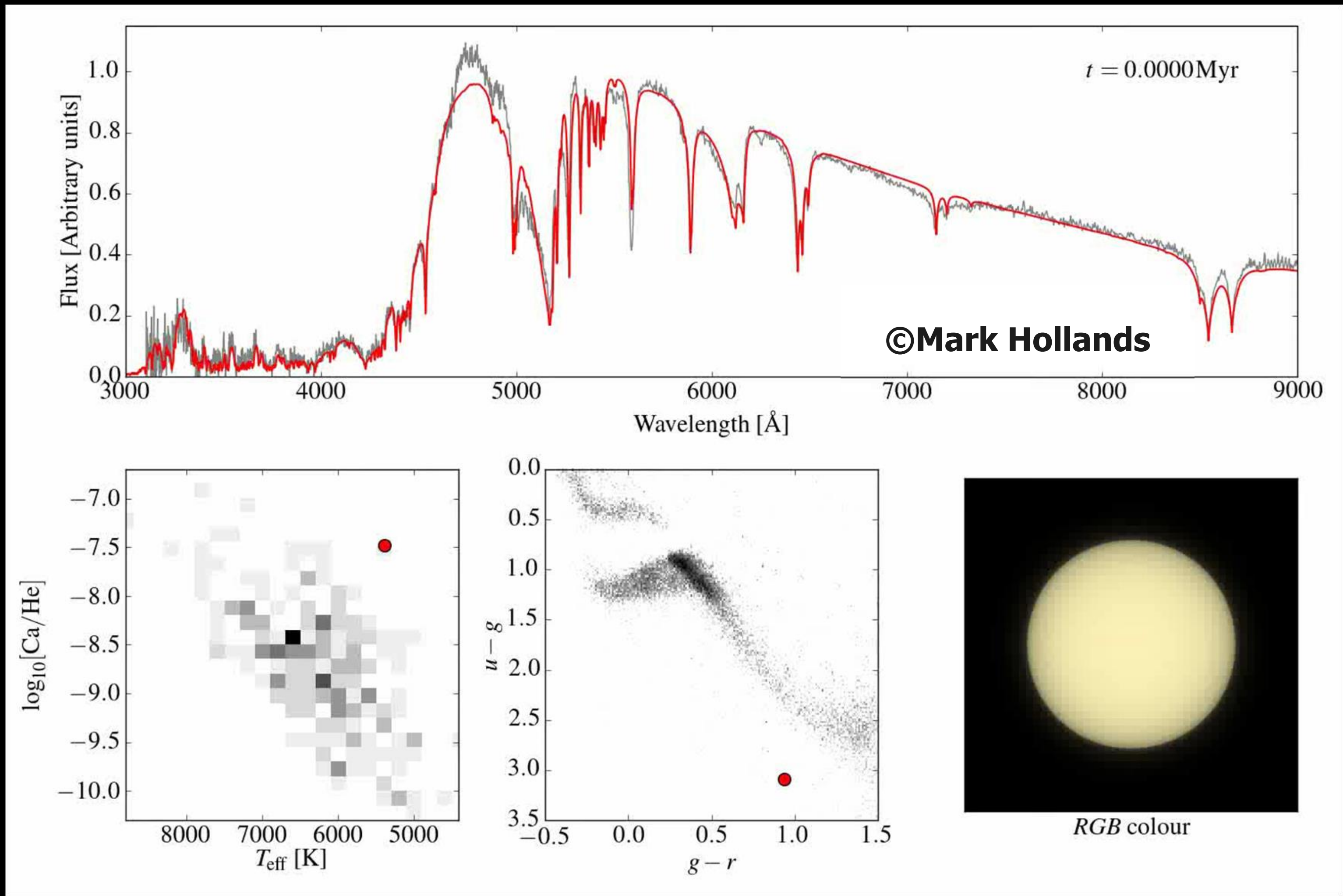


a) **Anonymous 1,** $\alpha = 0^h43^m52^s$, $\delta = +4°55'$. In *Publications of the Astronomical Society of the Pacific*, December 1917, I announced that this star has a proper motion of 3″.01 annually; Seares found the photo-visual and photographic magnitudes to be 12.34 and 12.91, respectively. The spectrum is F0. The absolute parallax of +0″.246 gives for the absolute magnitudes, +14.3 photo-visual and +14.8 photographic. It is, therefore, by far the faintest F-type star known at the present time.

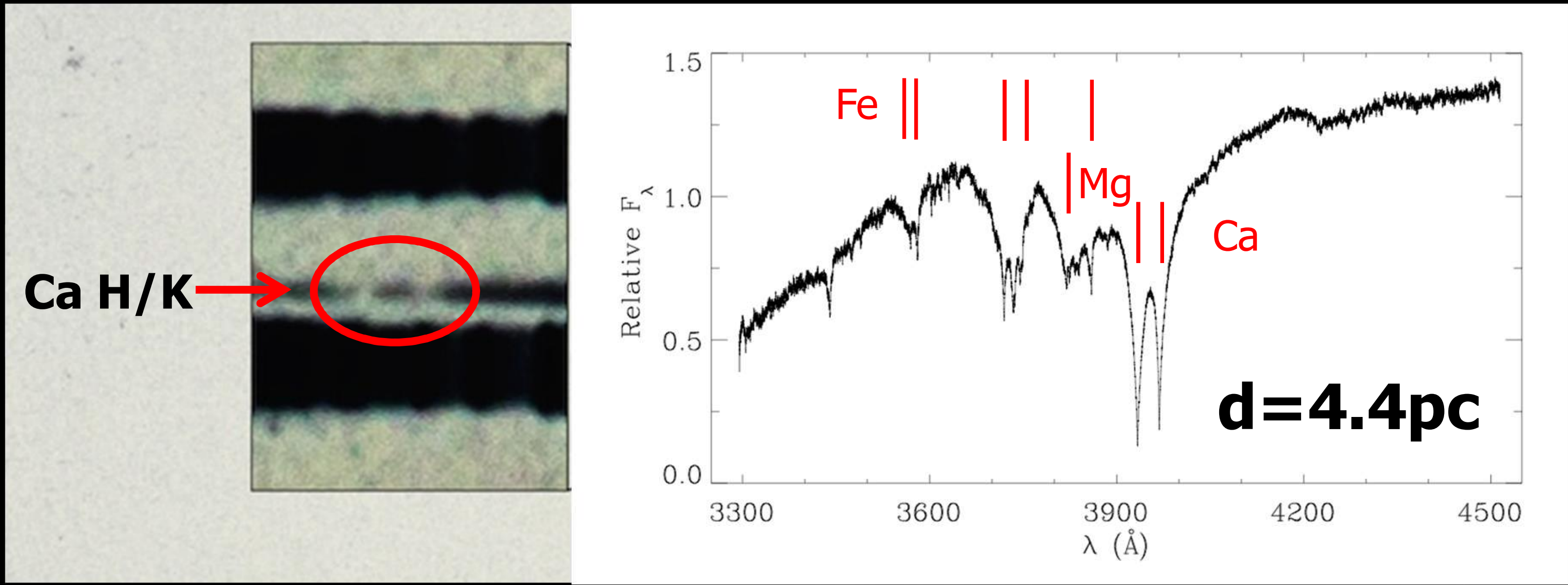
Van Maanen
1917, PASP 29, 258
1920, Cont. Mt. Wilson Obs. 182

Self-cleaning atmospheres

Diffusion time scale « cooling age



The 3rd closest white dwarf

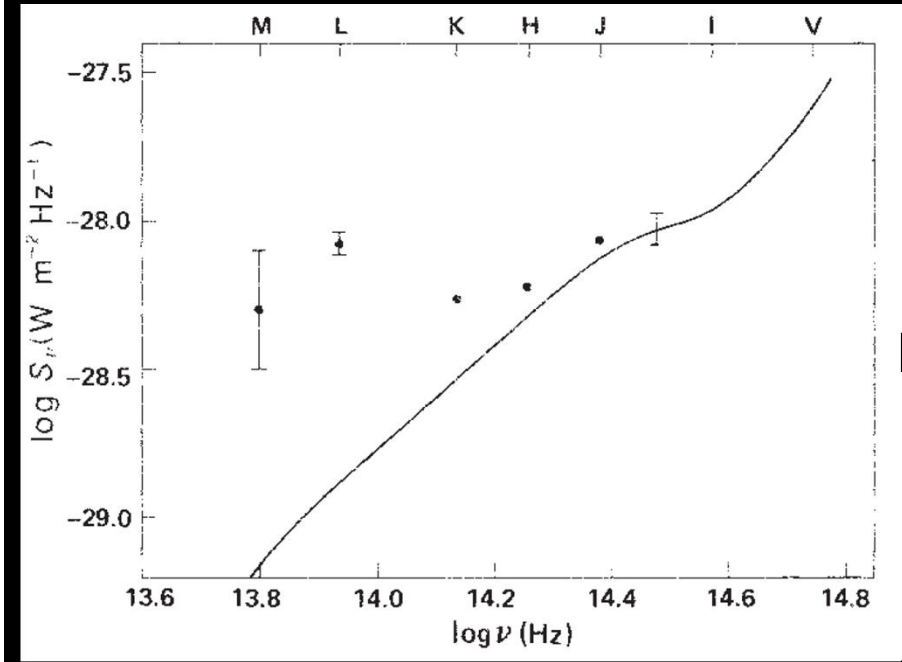


External pollution,
but where do the metals come from?

Signposts of evolved planetary systems:

- metals
- dust discs

1987: G29-38, brown dwarf or dust?



What might be a plausible source of dust grains this close to the remnant of a star that underwent a red giant expansion not quite 10^9 yr ago? Occasional cometary impacts onto white dwarf stars may explain certain photospheric spectroscopic peculiarities[12] and it has been suggested recently that near-misses of comets and white dwarfs could effectively produce circumstellar gas in orbit around the white dwarf (M. Jura, F. Coroniti and C. Alcock, in preparation). Possible evidence for the

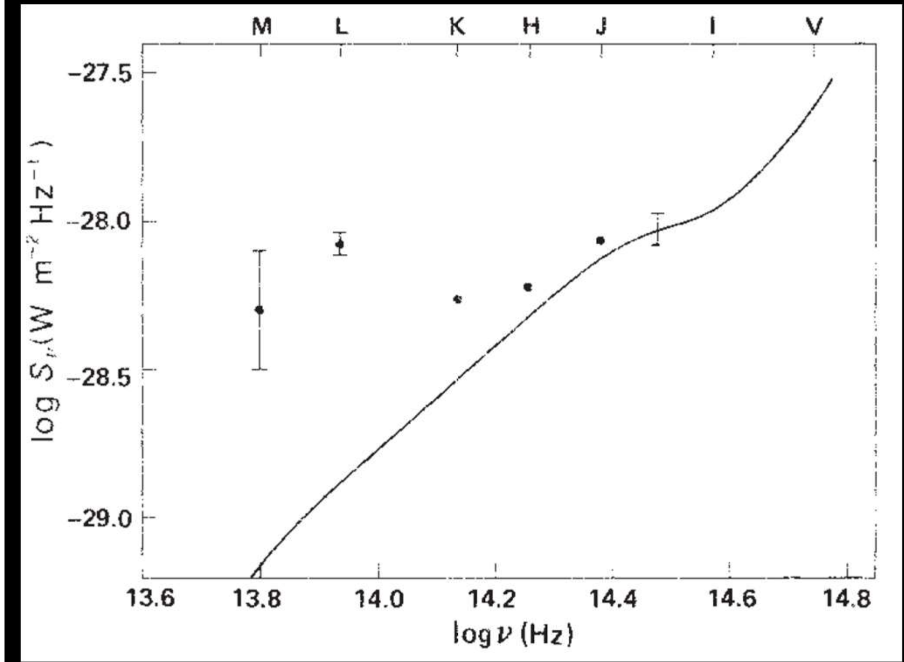
• • •

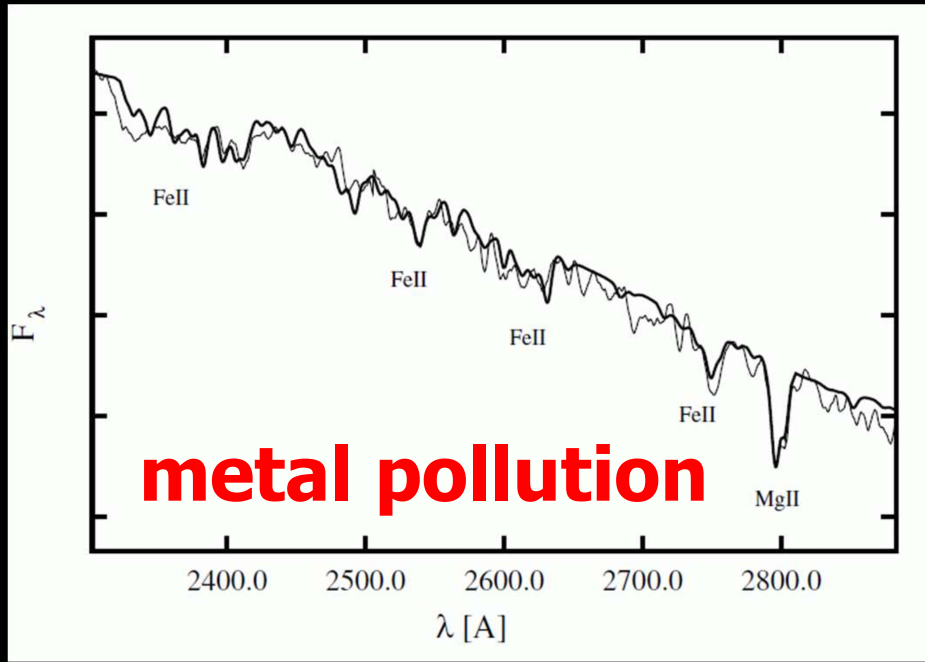
unlikely given the rapid depletion due to the Poynting–Robertson effect and the absence of any spectral peculiarities in its photospheric spectrum (J. Greenstein, personal communication) which might be expected[12] as a consequence of the rapid accretion of the orbiting material.

A more attractive possibility is that a warm brown dwarf is in orbit around G29 − 38. The upper mass limit for brown dwarfs

Zuckerman & Becklin 1987, *Nature* 330, 138

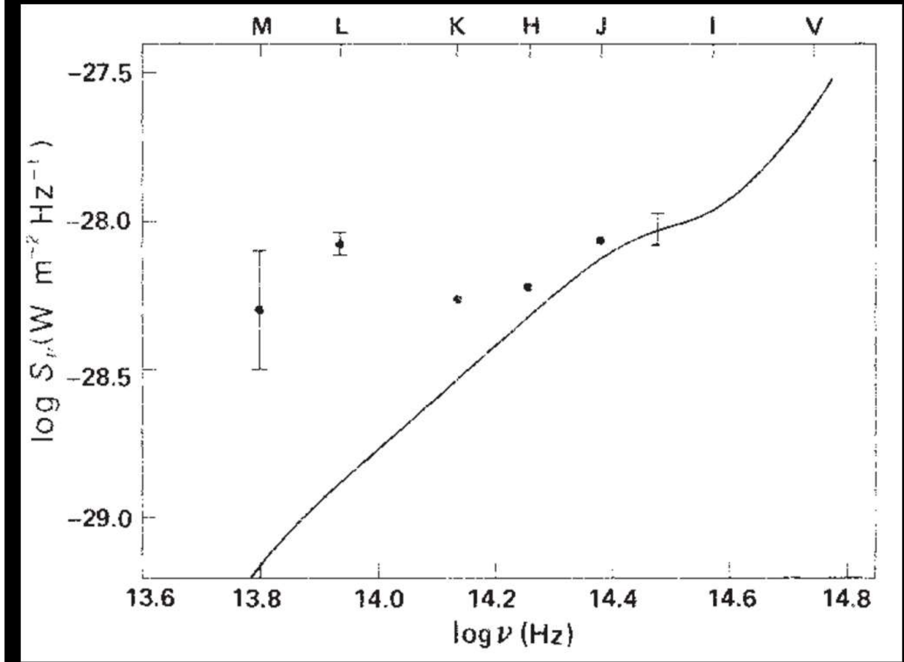
1987: G29-38, brown dwarf or dust?

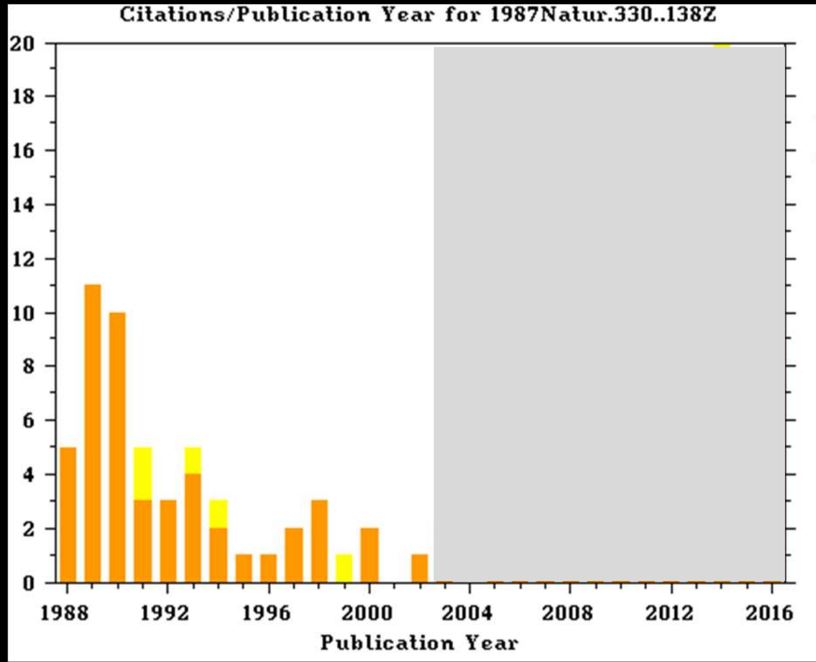




Koester et al. 1997, A&A 320, L57

1987: G29-38, brown dwarf or dust?





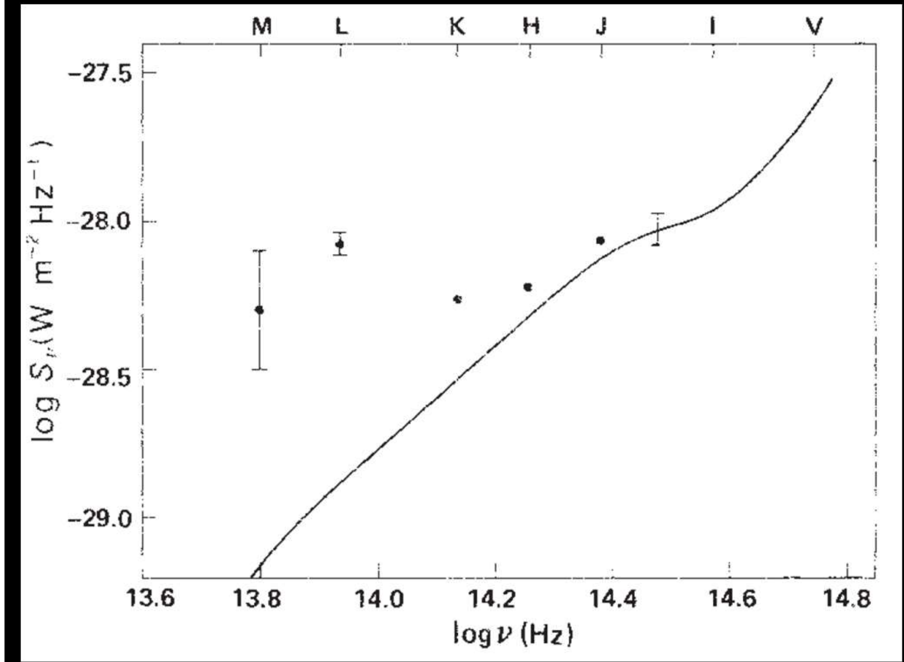
Zuckerman & Becklin 1987, *Nature* 330, 138

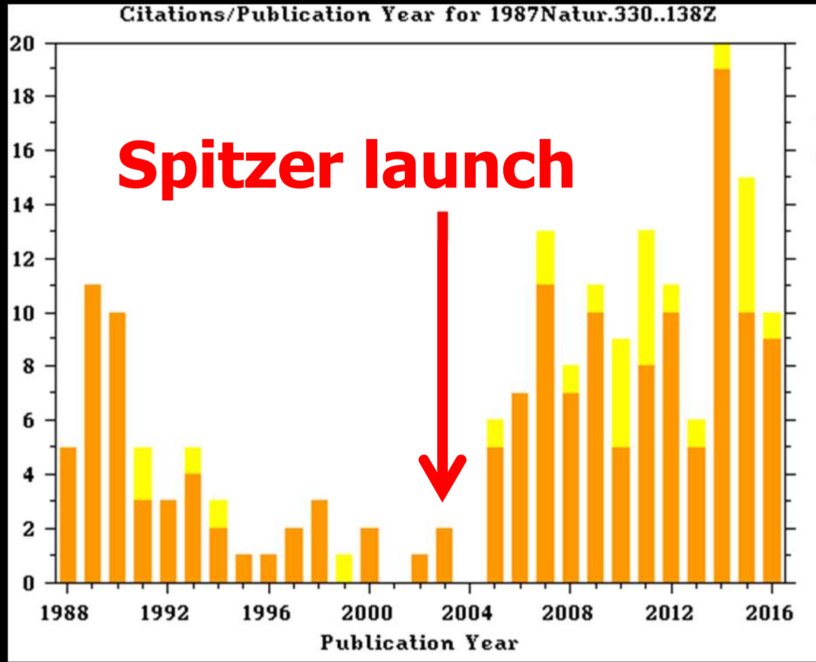
Tidally disrupted asteroids

Jura 2003, ApJ 584, L91

Debes et al. 2012, ApJ 747, 148
Veras et al. 2014, MNRAS 445, 2244
Veras et al. 2015, MNRAS 451, 3453

1987: G29-38, brown dwarf or dust?

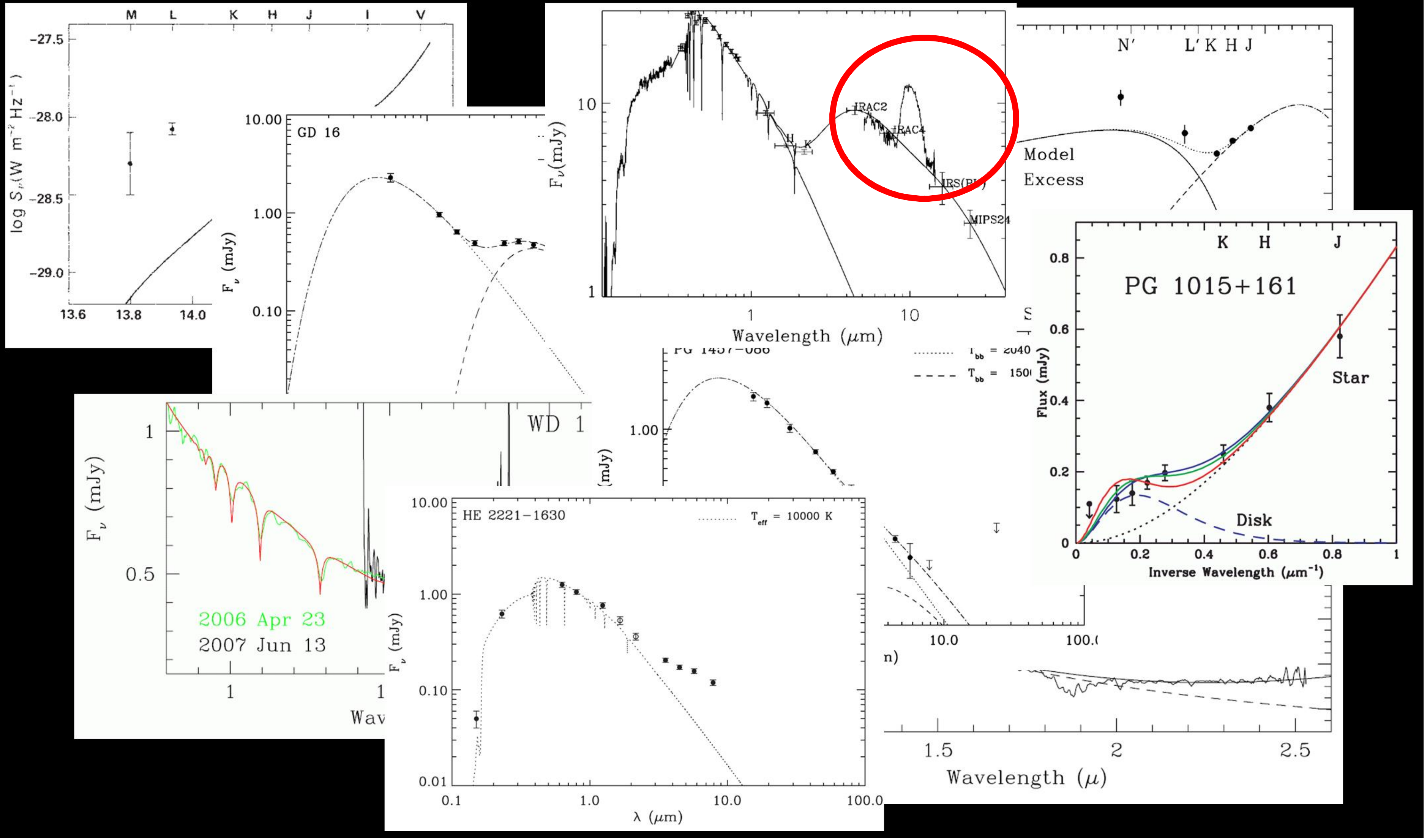




Zuckerman & Becklin 1987, *Nature* 330, 138

Dust around ~40 white dwarfs

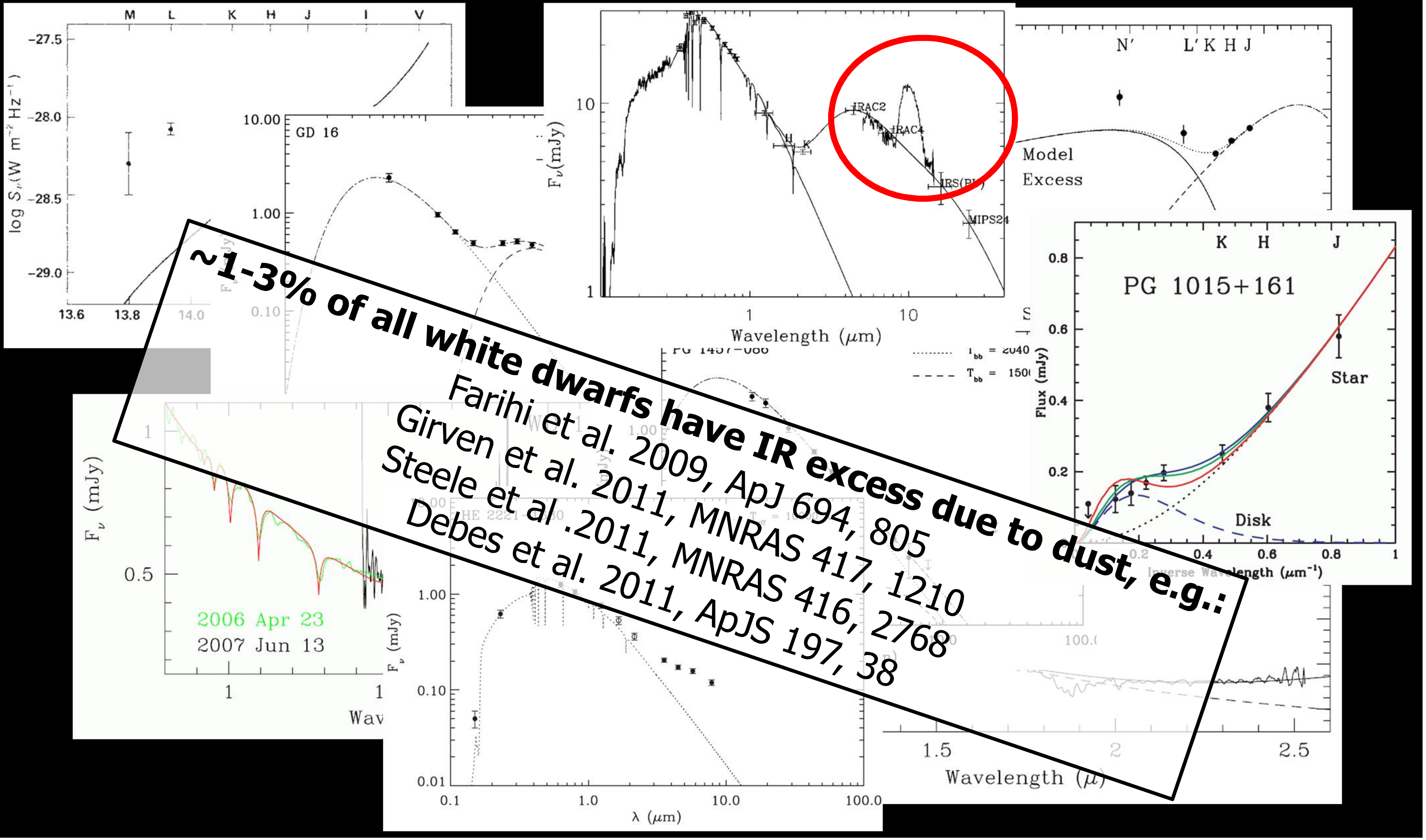
Zuckerman et al. 1987, *Nature* 330, 138; Graham et al. 1990, ApJ 357, 216; Kilic et al. 2005, ApJ 632, L115; Becklin et al. 2005, ApJ 632, L119; Reach et al. 2005, ApJ 635, L161; Jura et al. 2007, AJ 133, 1927; Kilic et al. 2007, ApJ 660, 641; von Hippel et al. 2007, ApJ 662, 544; Jura et al. 2007, ApJ 663, 1285; Farihi et al. 2008, ApJ 674,431; Jura et al. 2009, AJ 137, 3191; Reach et al. 2009, ApJ 693, 697; Farihi et al. 2009, ApJ 694, 805; Brinkworth et al. 2009, ApJ 696, 1402; Farihi et al. 2010, ApJ 714, 1386; Dufour et al. 2010, ApJ 719, 803; Vennes et al. 2010, MNRAS 404, L40; Farihi et al. 2011, ApJ 728, L8; Debes et al. 2011, ApJ 729, 4; Farihi et al. 2012, MNRAS 421, 1635; Barber et al. 2012, ApJ 760, 26



Papakolea Beach, Hawaii: Olivine

Dust around ~40 white dwarfs

Zuckerman et al. 1987, *Nature* 330, 138; Graham et al. 1990, [illegible] 357, 216; Kilic et al. 2005, ApJ 632, L115; Becklin et al. 2005, ApJ 632, L119; Reach et al. 2005, ApJ 635, L161; Jura et al. 2007, AJ 133, 1927; Kilic et al. 2007, ApJ 660, 641; von Hippel et al. 2007, ApJ 662, 544; Jura et al. 2007, ApJ 663, 1285; Farihi et al. 2008, ApJ 674,431; Jura et al. 2009, AJ 137, 3191; Reach et al. 2009, ApJ 693, 697; Farihi et al. 2009, ApJ 694, 805; Brinkworth et al. 2009, ApJ 696, 1402; Farihi et al. 2010, ApJ 714, 1386; Dufour et al. 2010, ApJ 719, 803; Vennes et al. 2010, MNRAS 404, L40; Farihi et al. 2011, ApJ 728, L8; Debes et al. 2011, ApJ 729, 4; Farihi et al. 2012, MNRAS 421, 1635; Barber et al. 2012, ApJ 760, 26



~1-3% of all white dwarfs have IR excess due to dust, e.g.:

Farihi et al. 2009, ApJ 694, 805

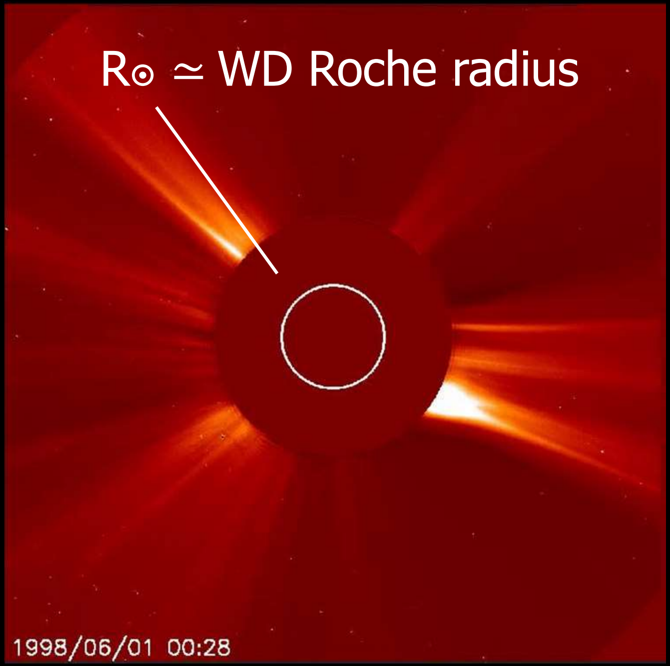
Girven et al. 2011, MNRAS 417, 1210

Steele et al .2011, MNRAS 416, 2768

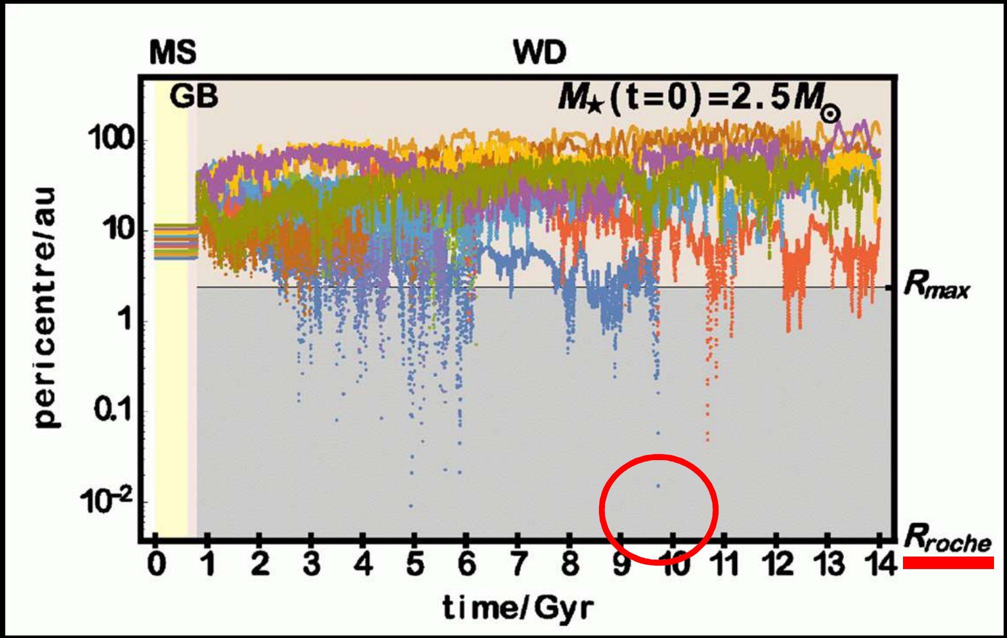
Debes et al. 2011, ApJS 197, 38

Scattering planetesimals towards the WD...

and maybe moons & planets



SOHO Lasco C2 data

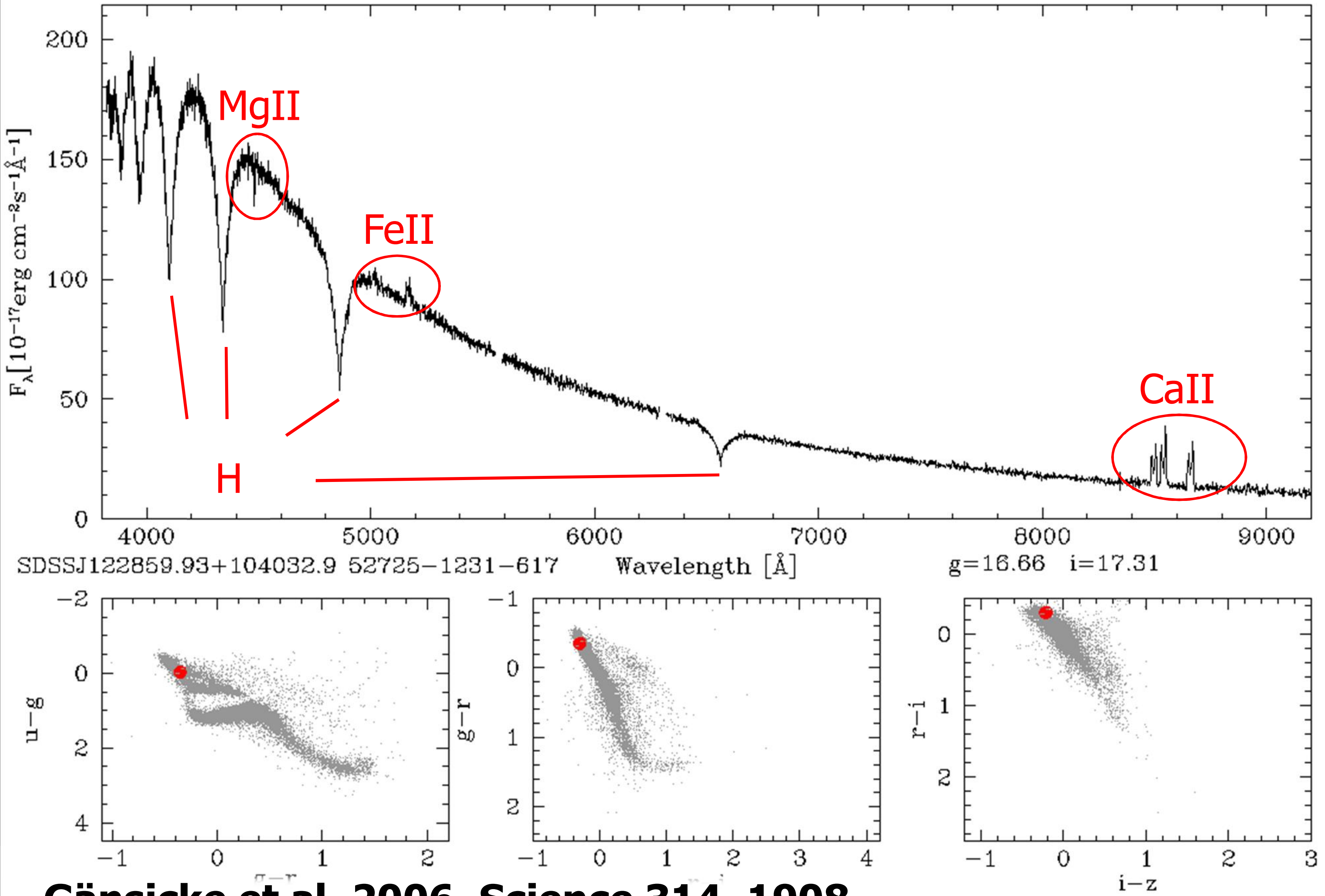


Veras & Gänsicke 2015, MNRAS 447 149
Payne et al. 2017, MNRAS 464, 2557

Signposts of evolved planetary systems:

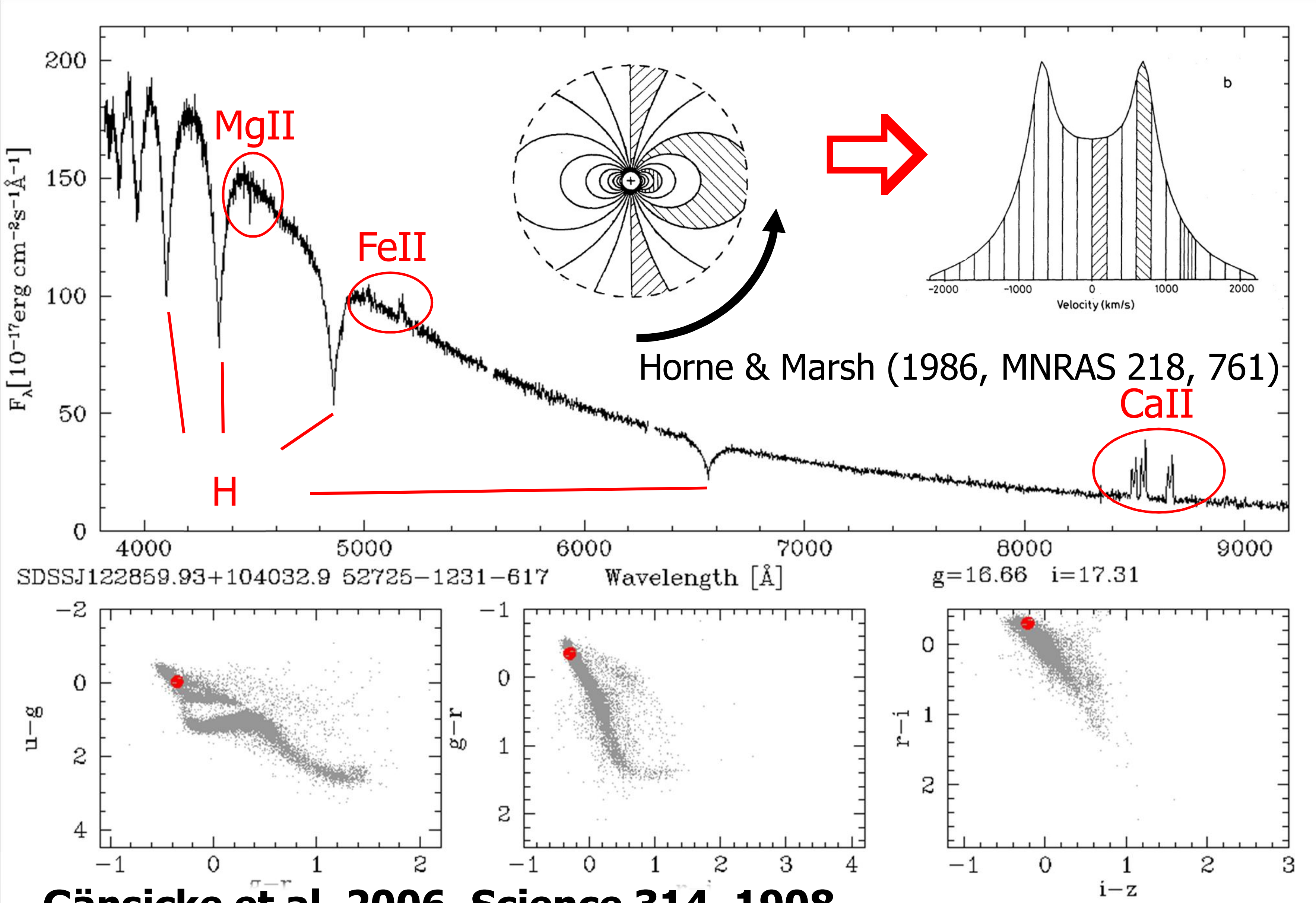
- metals
- dust discs
- gas discs

Gaseous debris discs



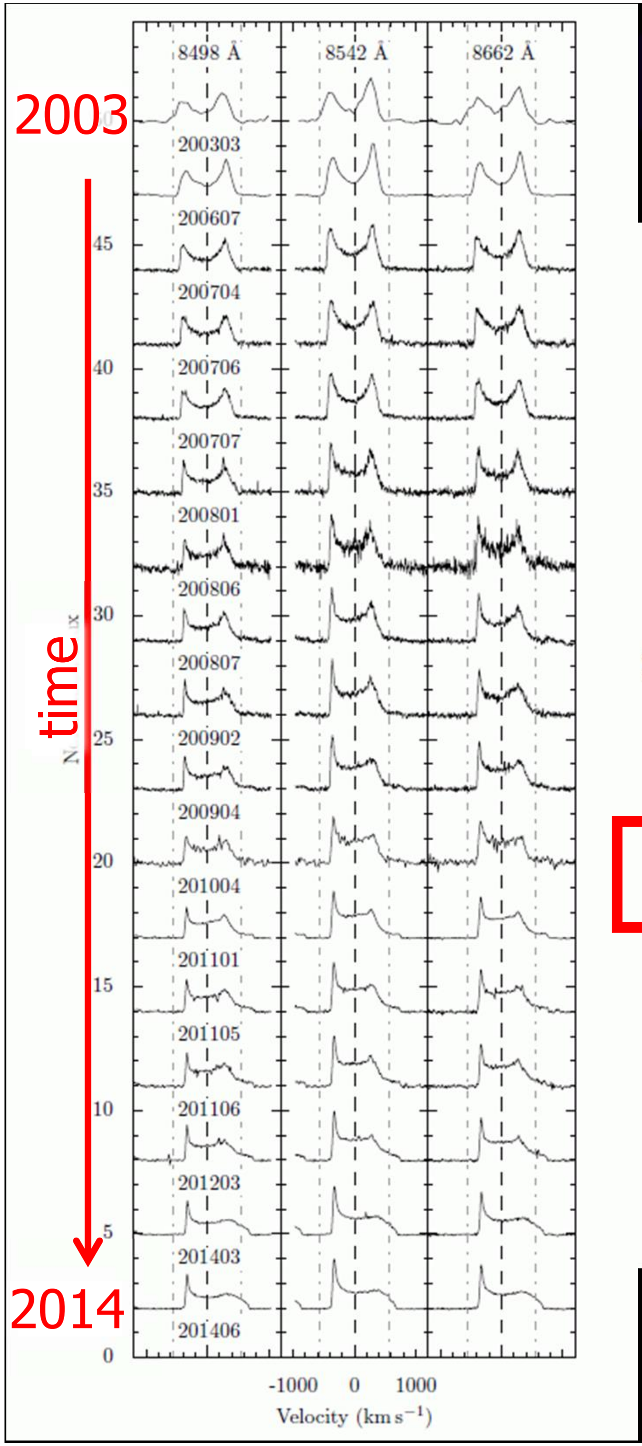
Gänsicke et al. 2006, Science 314, 1908

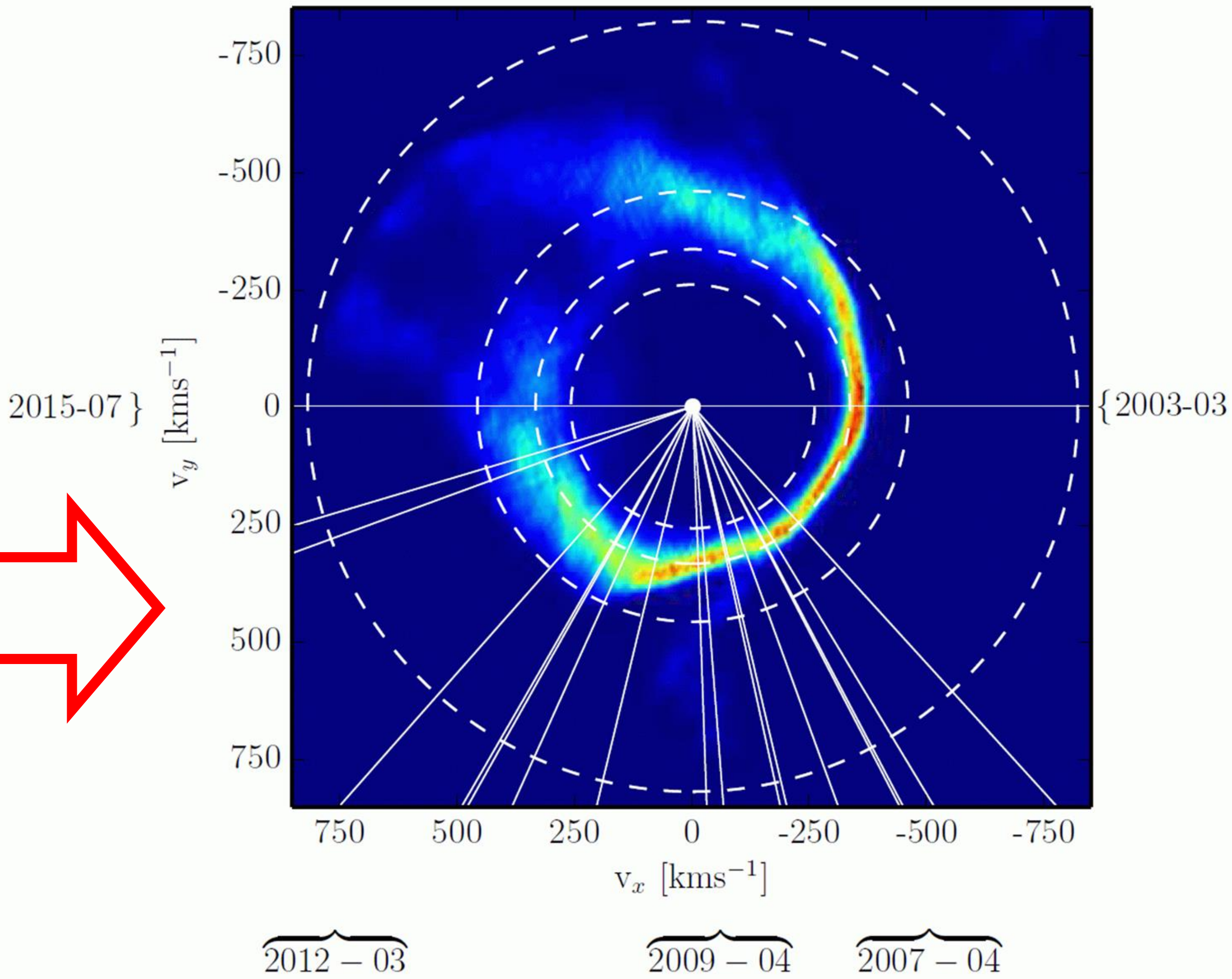
Gaseous debris discs



Gänsicke et al. 2006, Science 314, 1908

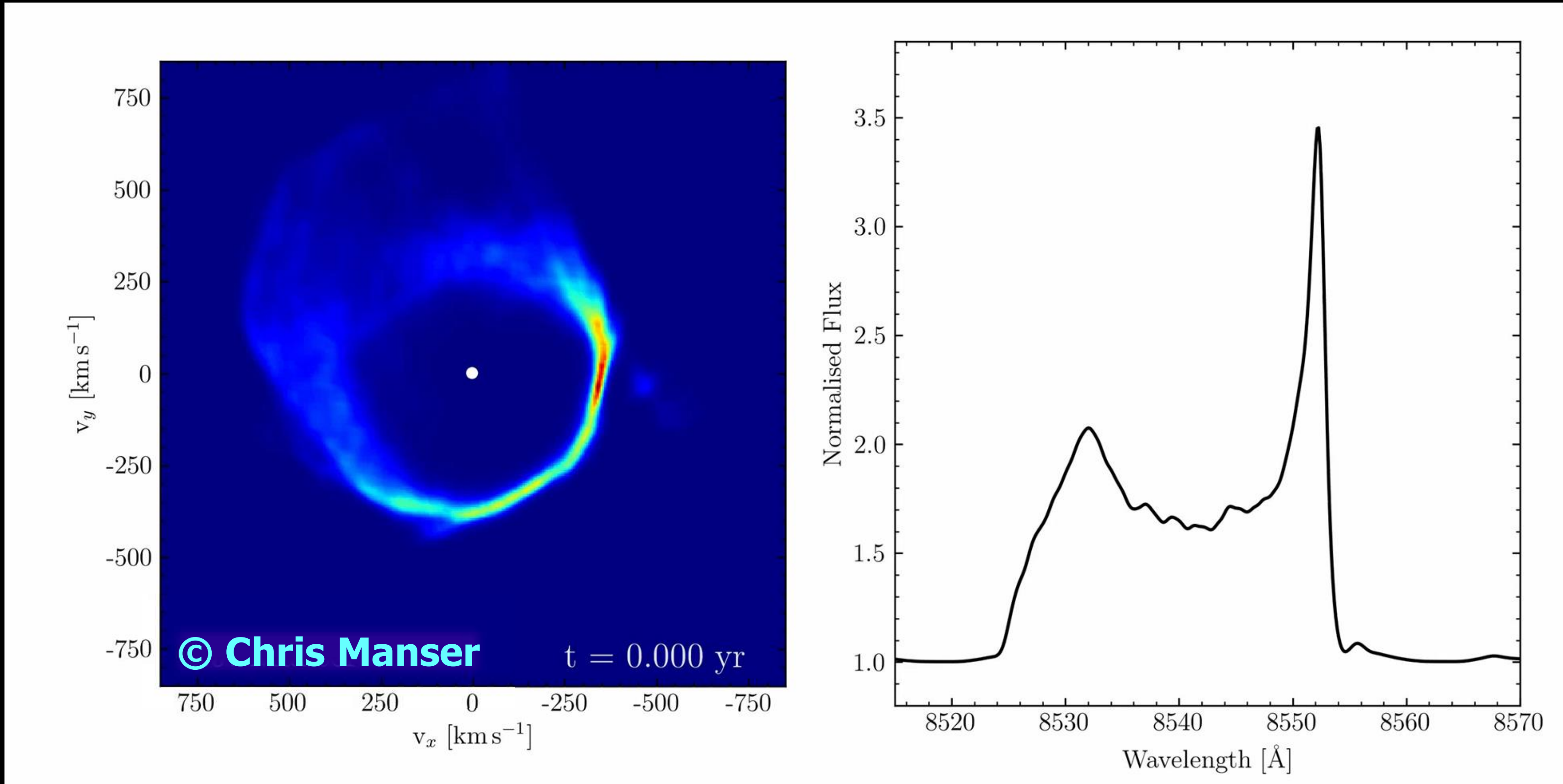
Indirect imaging of debris discs around white dwarfs





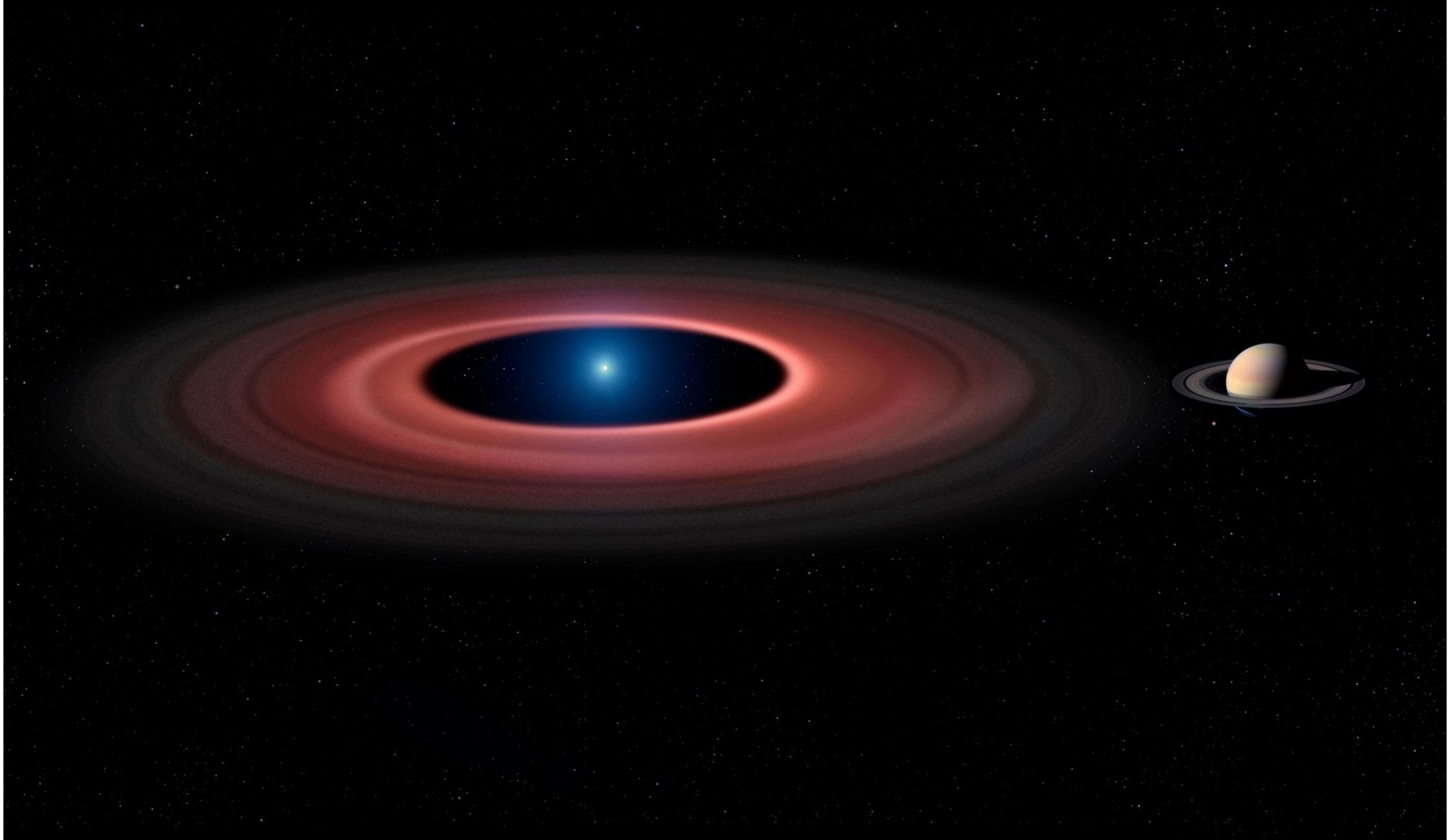
Manser et al. 2016, MNRAS 455, 4467

Precession on ≃ 25 year period (GR?)
!! orbital period ≃ hours !!
⇒ mechanism to maintain intensity pattern needed



Familiar debris rings

Debris rings on steroids

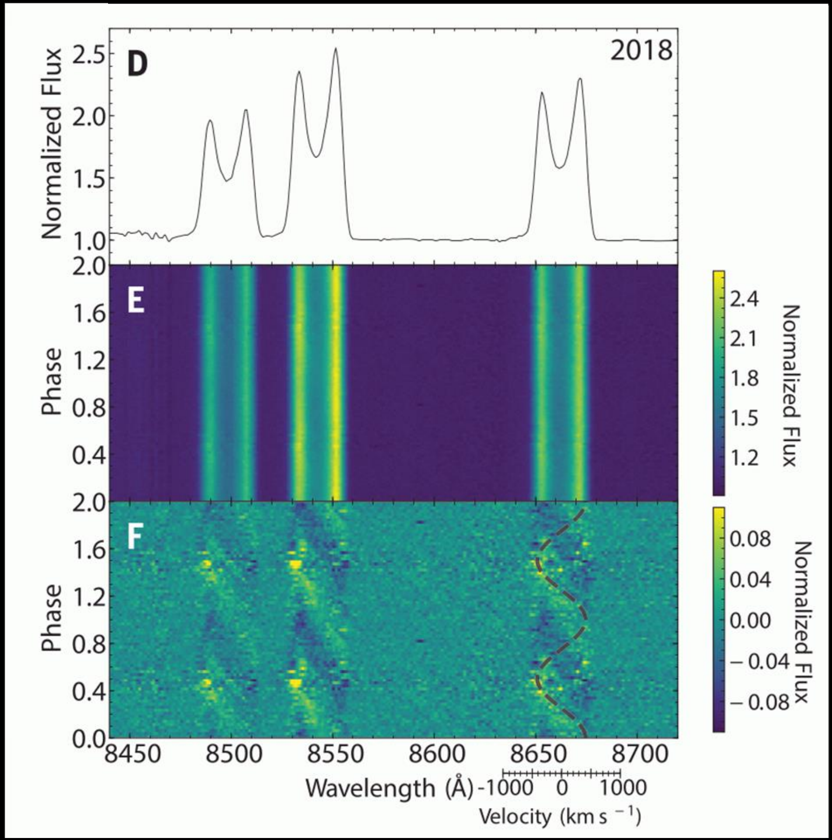


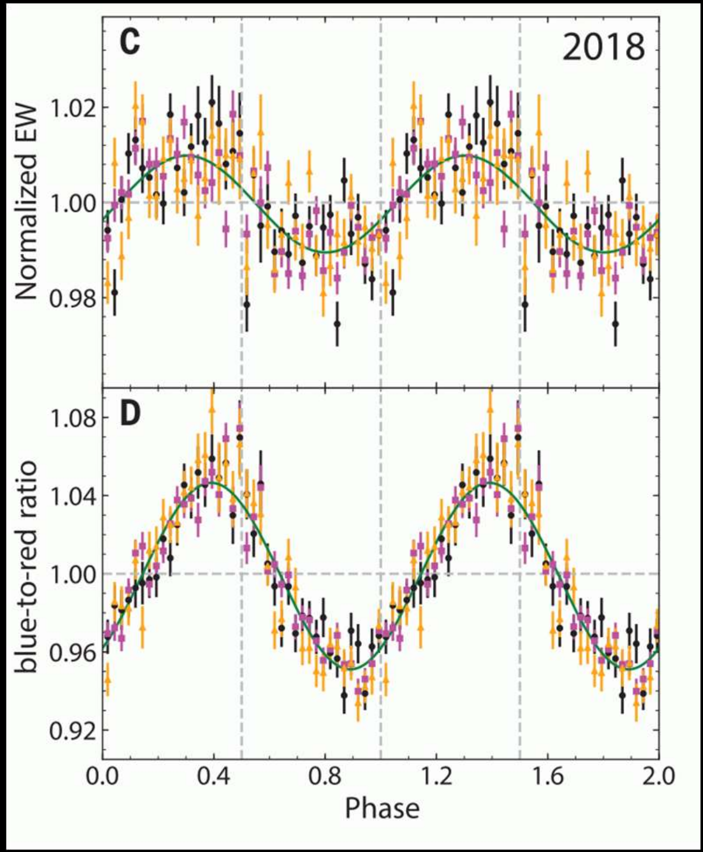
Signposts of evolved planetary systems:

- metals
- dust discs
- gas discs
- solid planetesimals

Spectroscopic detection of a coherent 123.4min period ⇒ A solid planetesimal

5 nights @ GTC in 2017 & 2018, 519 spectra, ≃140sec cadence





Manser et al. 2019, Science 364, 66

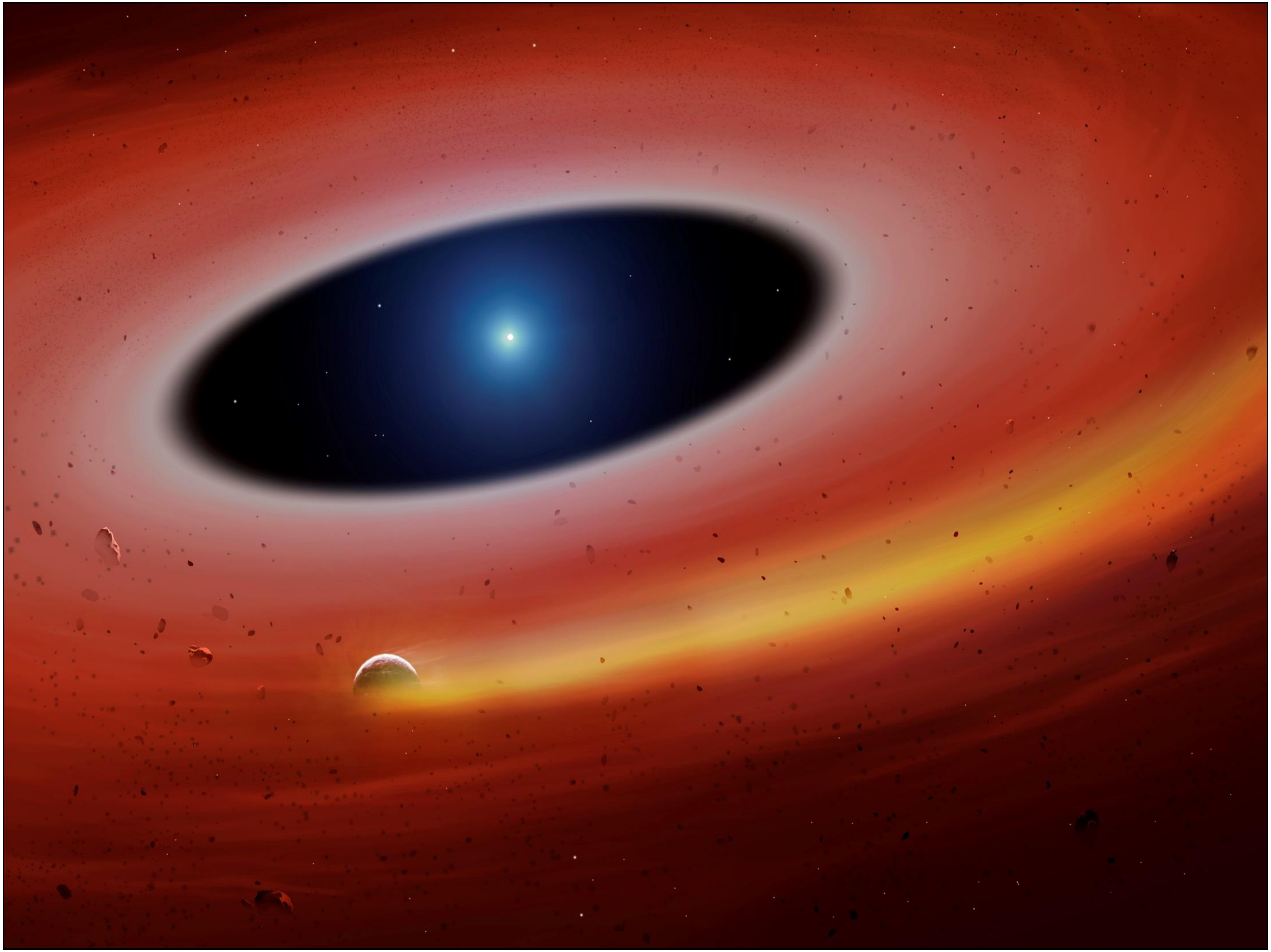
Why a solid planetesimal?

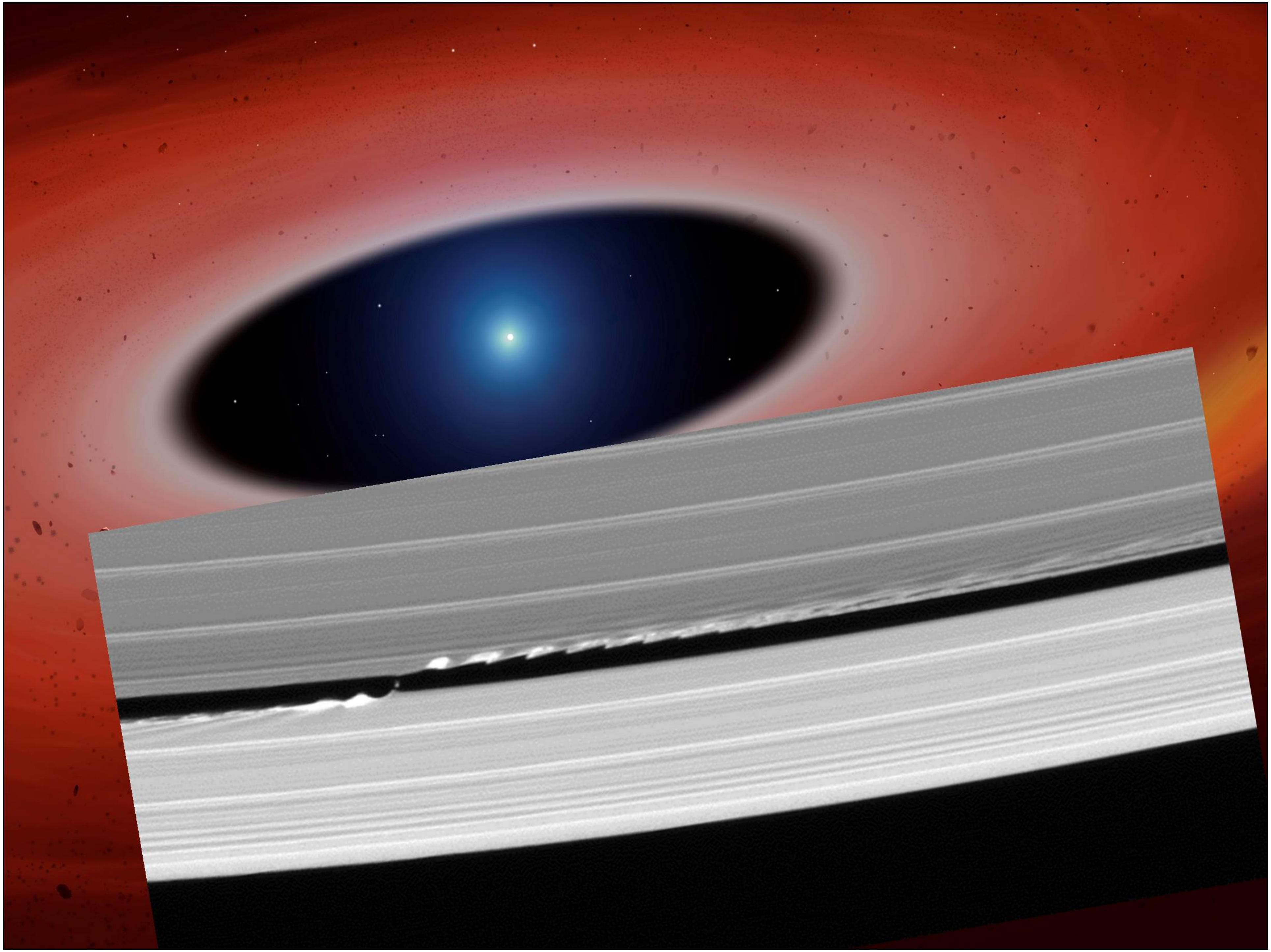
- Period stable for > 4400 orbital cycles
  ⇒ no plausible mechanism for disc origin

- No RV variation
  ⇒ $M_p < 7M_J$

- Stable against tidal disruption @ P=123.4min
  ⇒ $\rho \simeq 8$ gcm^{-3} for spherical shape / internal strength
  ⇒ $4 \lesssim$ size $\lesssim 600$km

- Planetesimal may be the source of the CaII gas
  ⇒ cause of the ≃25yr precession?

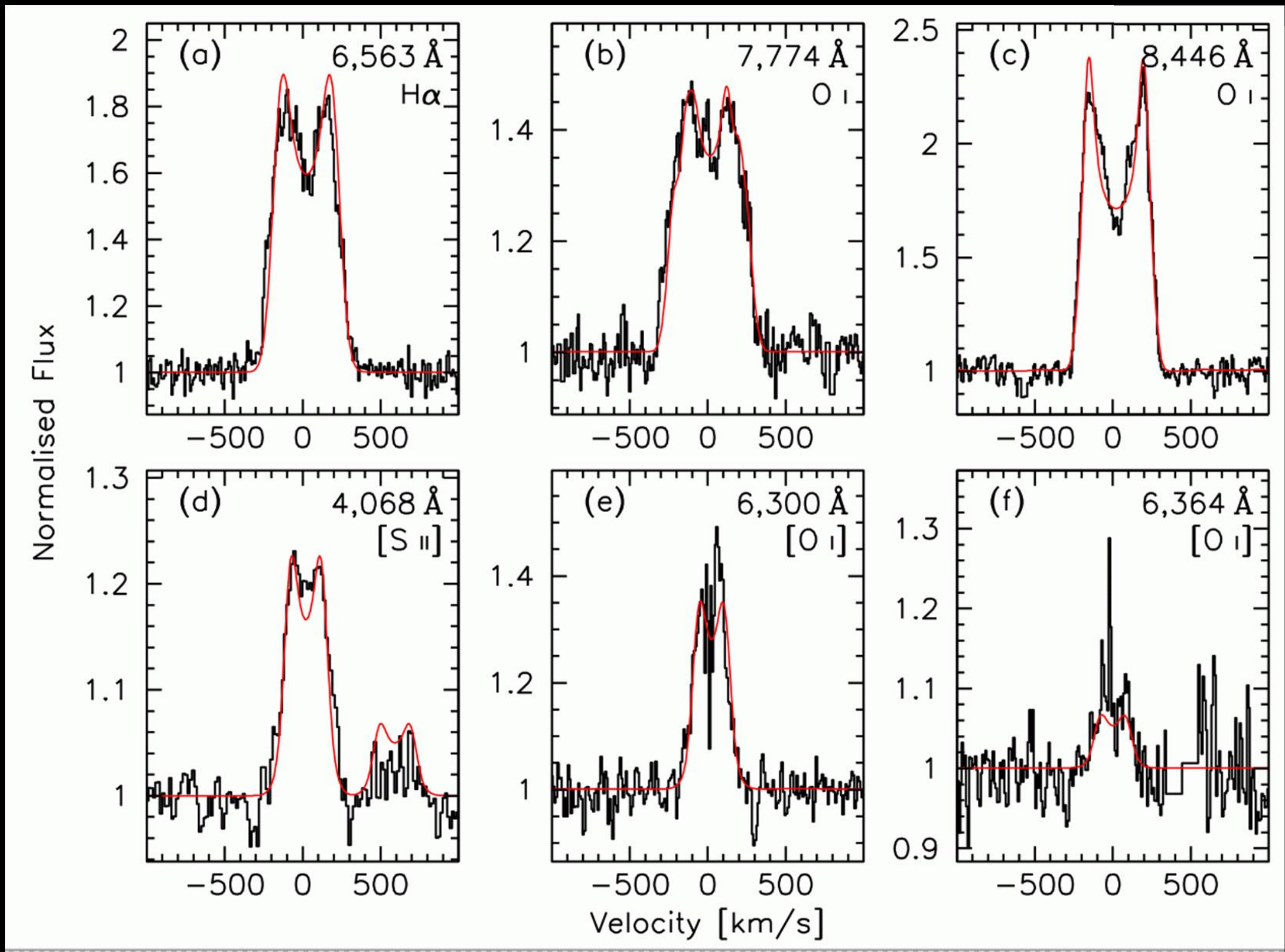




Another gaseous debris disc. Wait: H, O & S?

= volatiles

Gänsicke et al. Nature in press



Quick look into solar-system textbooks
⇒ this white dwarf is evaporating and accreting
a *close-in giant planet!*

Lodders & Fegley, Chemistry of the Solar System

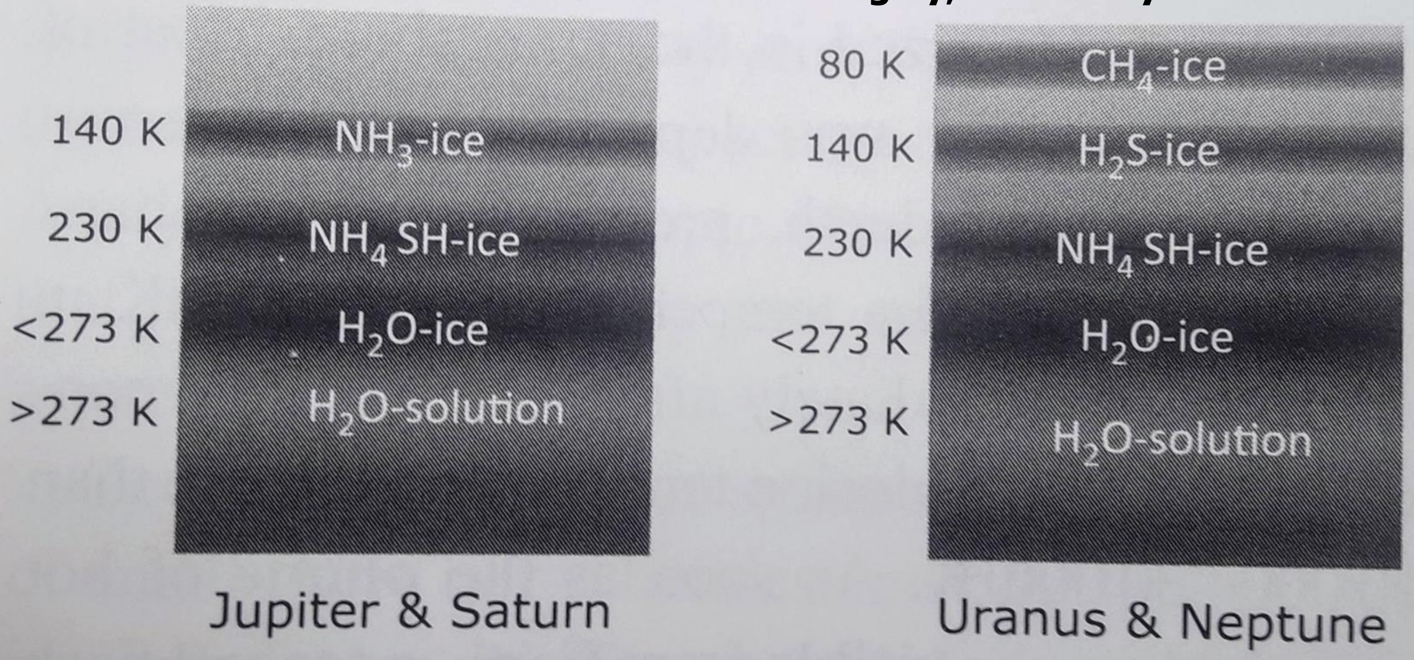
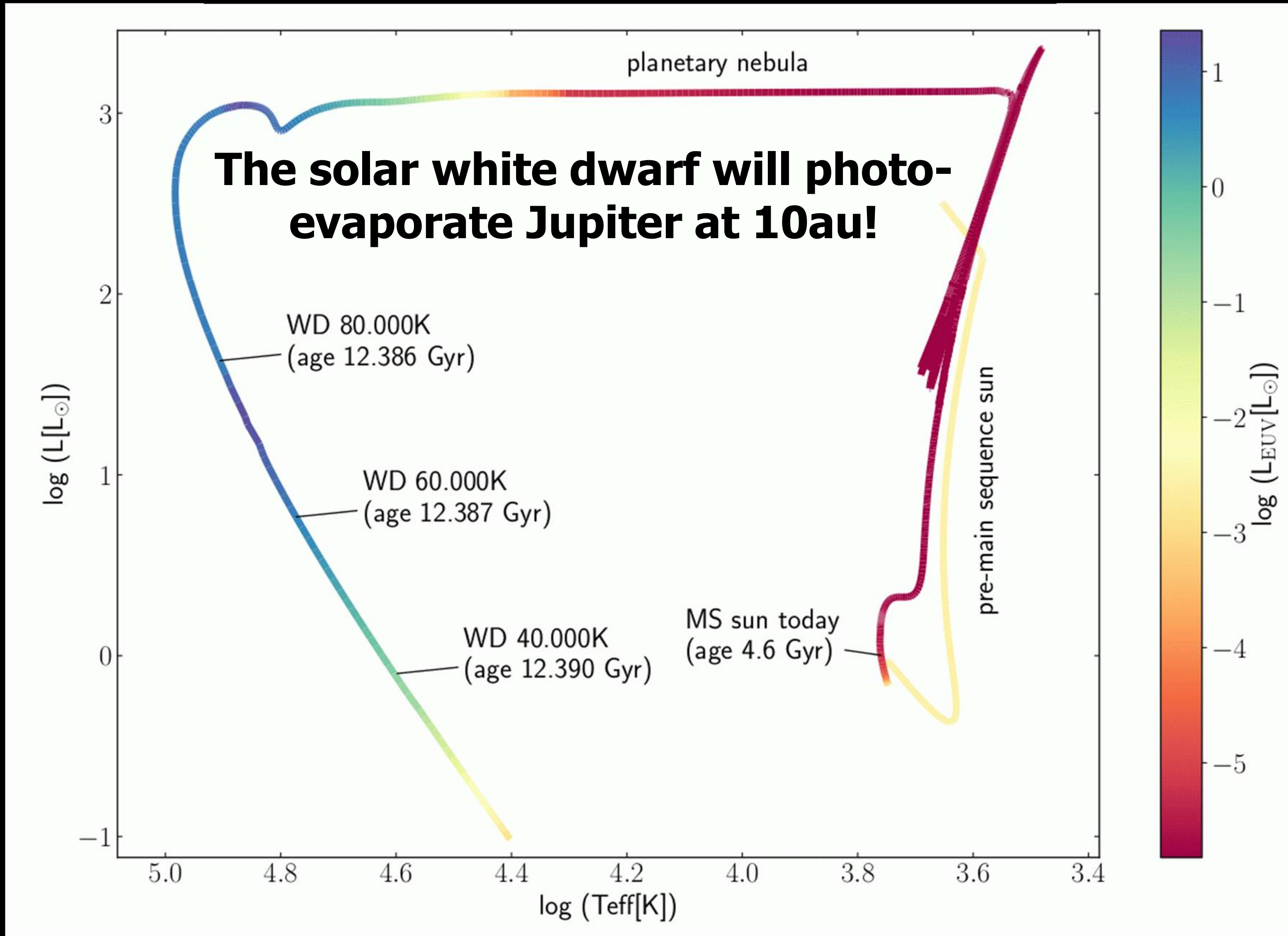


Figure 8.8 Illustration of the theoretically derived cloud layers on the giant planets.

White dwarfs are GREAT at photo-evaporating giant planets

Schreiber et al. ApJ Letters in press



Signposts of evolved planetary systems:

- metals
- dust discs
- gas discs
- solid planetesimals
- transits

WD1145+017: the smoking gun

metals, dust, gas & transits

Vanderburg et al. 2015, Nature 526, 546

Gänsicke et al. 2016, ApJL 818, 7

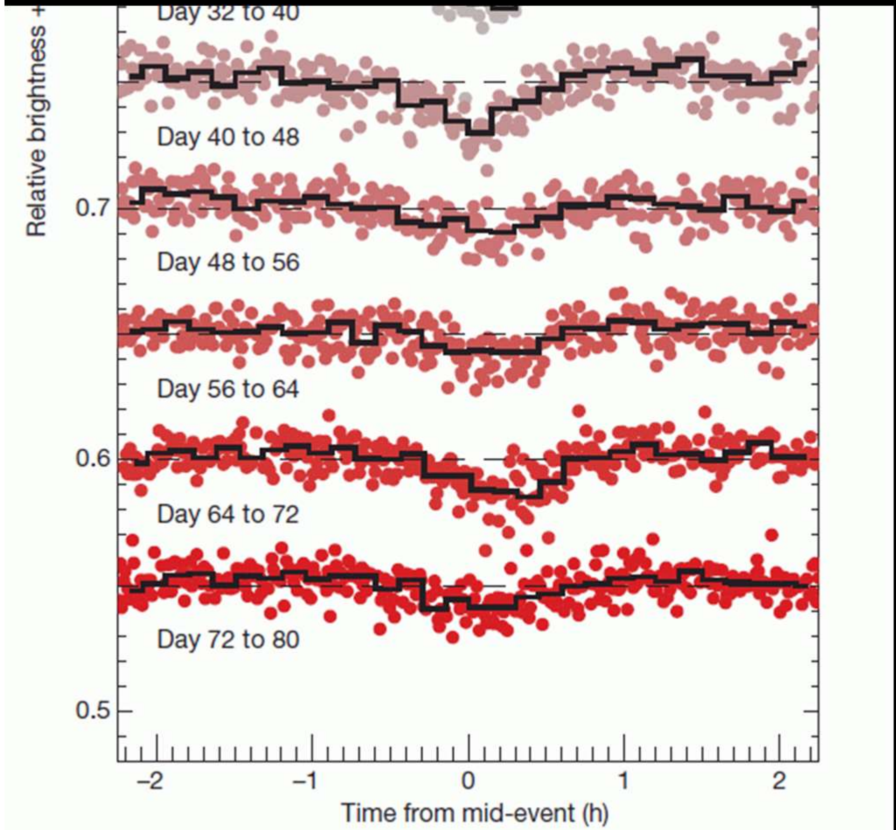
Rappaport et al. 2016, MNRAS 458, 3904

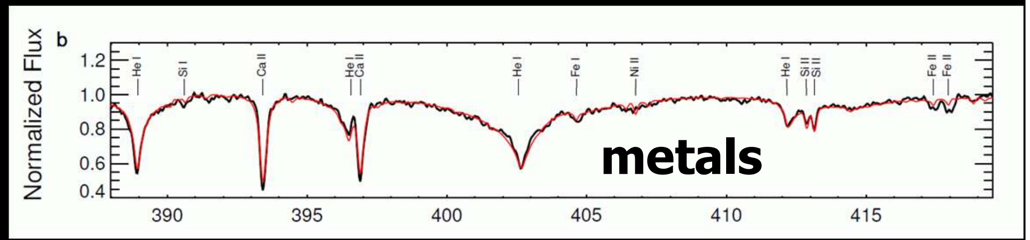
Xu et al. 2016, ApJL 816, 22

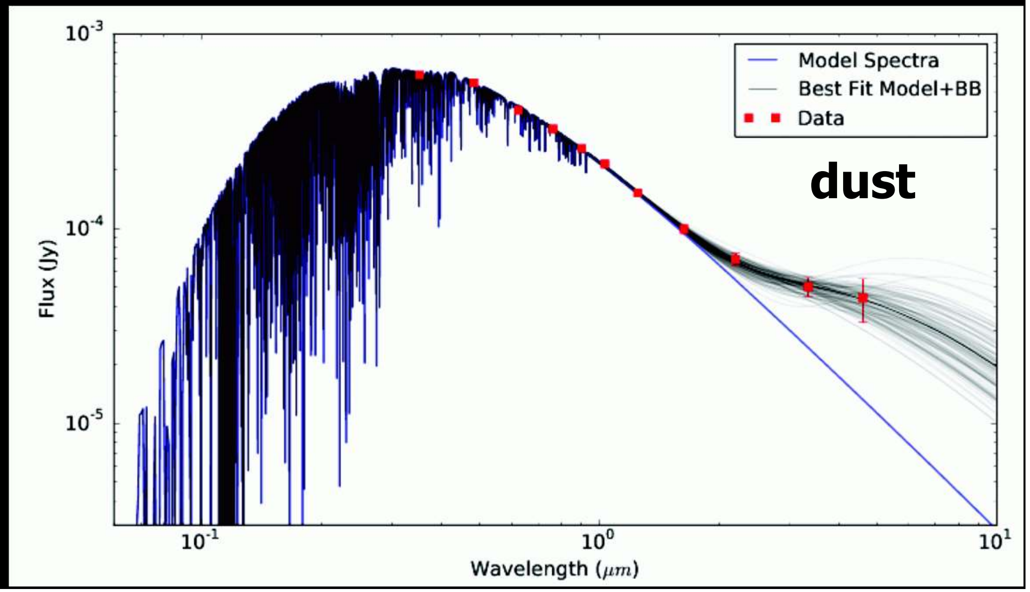
Redfield et al. 2017, ApJ 839, 42

Gary et al. 2017, MNRAS 465, 3267

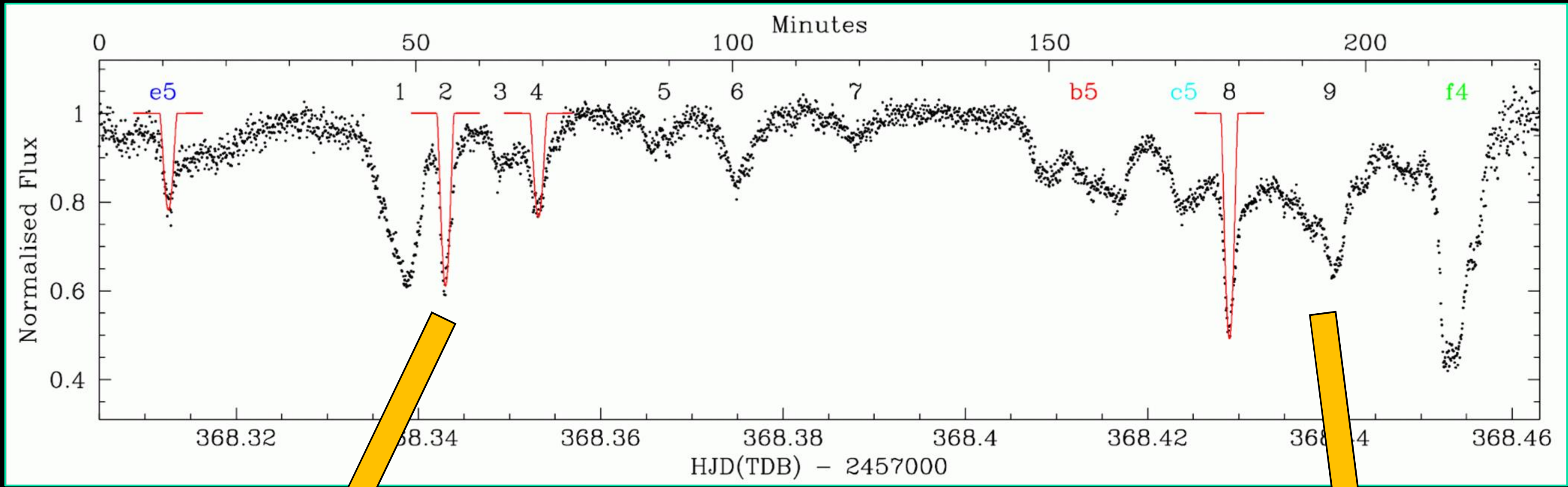
Hallakoun et al. 2017, MNRAS 469, 3213







Large occulters

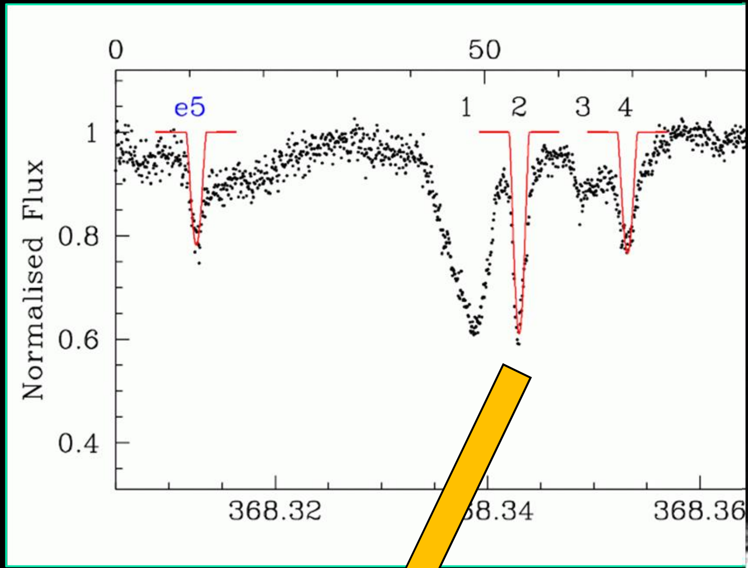


~3min duration
⇨ $R_{cloud} \gtrsim 2\text{-}4 R_{wd}$

Average extinction≃10%
⇒ $dM/dt \sim 10^{11}$ g/s

Gänsicke et al. 2016, ApJ 818, L7

Large occulters



~3min duration

⇨ $R_{cloud} \gtrsim 2\text{-}4 R_{wd}$

Outburst on 67P/Churyumov–Gerasimenko observed by ROSETTA

Gänsicke et al. 2016, ApJ 818, L7

Ever-changing shapes…

WD 1145+017 photometric observations during eight months of high activity

B. L. Gary,[1★] S. Rappaport,[2★] T. G. Kaye,[3] R. Alonso[4] and F.-J. Hambsch

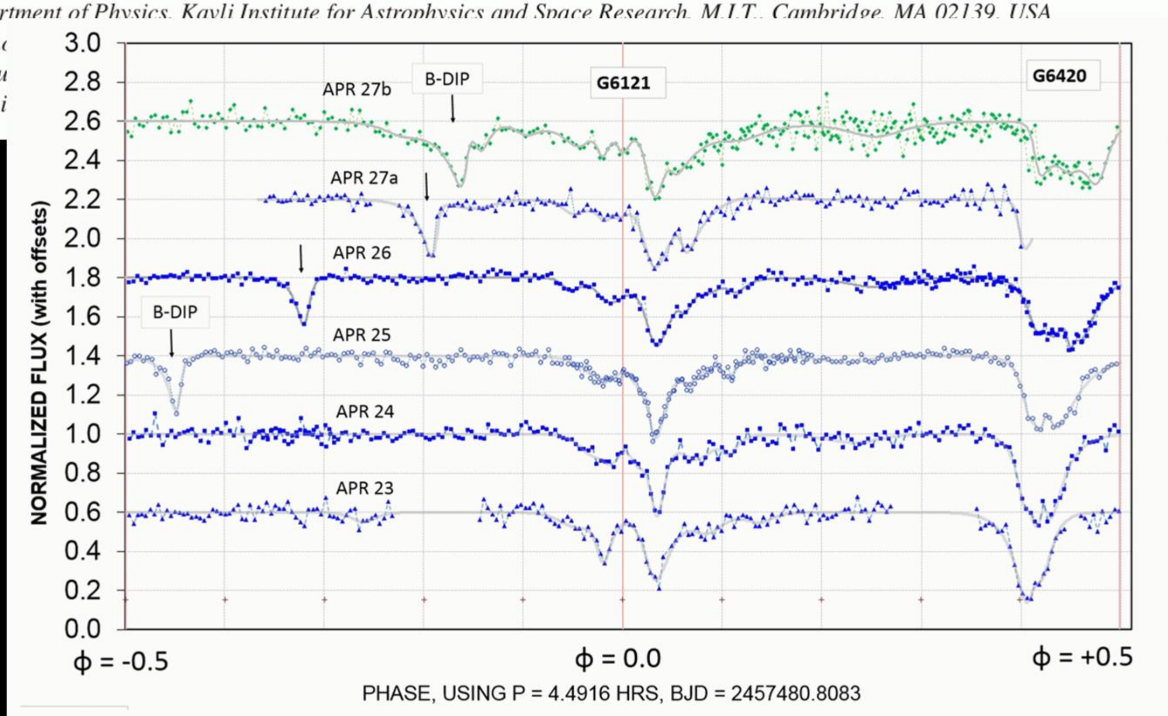
[1]*Hereford Arizona Observatory, Hereford, AZ 85615, USA*

[2]*Department of Physics, Kavli Institute for Astrophysics and Space Research, M.I.T., Cambridge, MA 02139, USA*

[3]*Raem*

[4]*Institu*

[5]*Vereni*



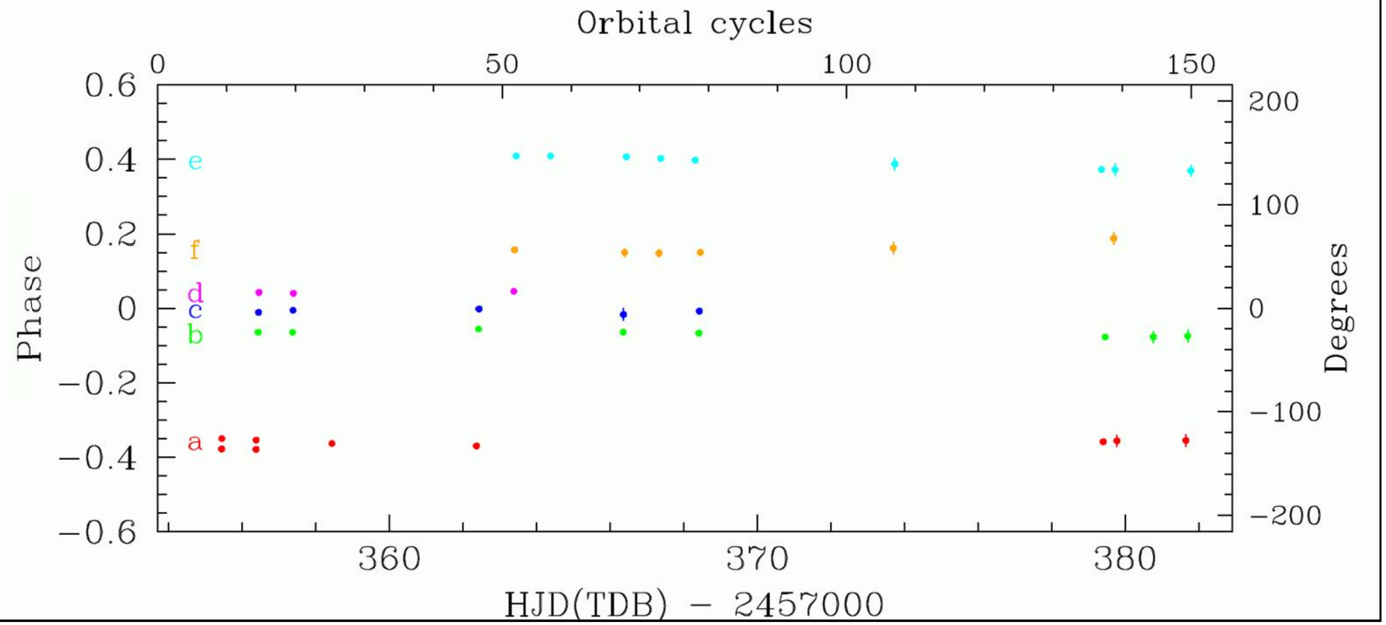
... but (mostly) stable periods!

Transits	Period (hr)	Uncertainty (hr)
a	4.49337	0.00021
b	4.49252	0.00011
c	4.49257	0.00052
d	4.49355	0.00040
e	4.49110	0.00006
f	4.49513	0.00046
mean	4.4930	0.0013

co-orbital

← **5sec!**

Gänsicke et al. 2016, ApJ 818, L7



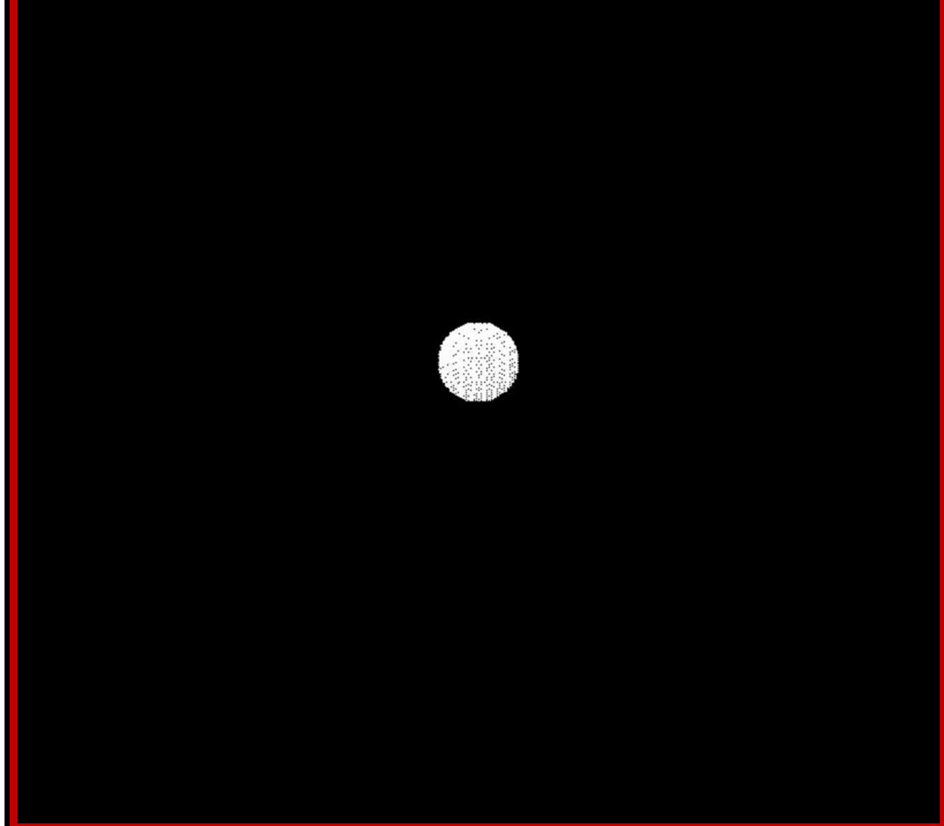
In:

Gänsicke et al. 2016, ApJ 818, L7
Rappaport et al. 2016, MNRAS 458, 3904
Gary et al. 2016, MNRAS 465, 3267

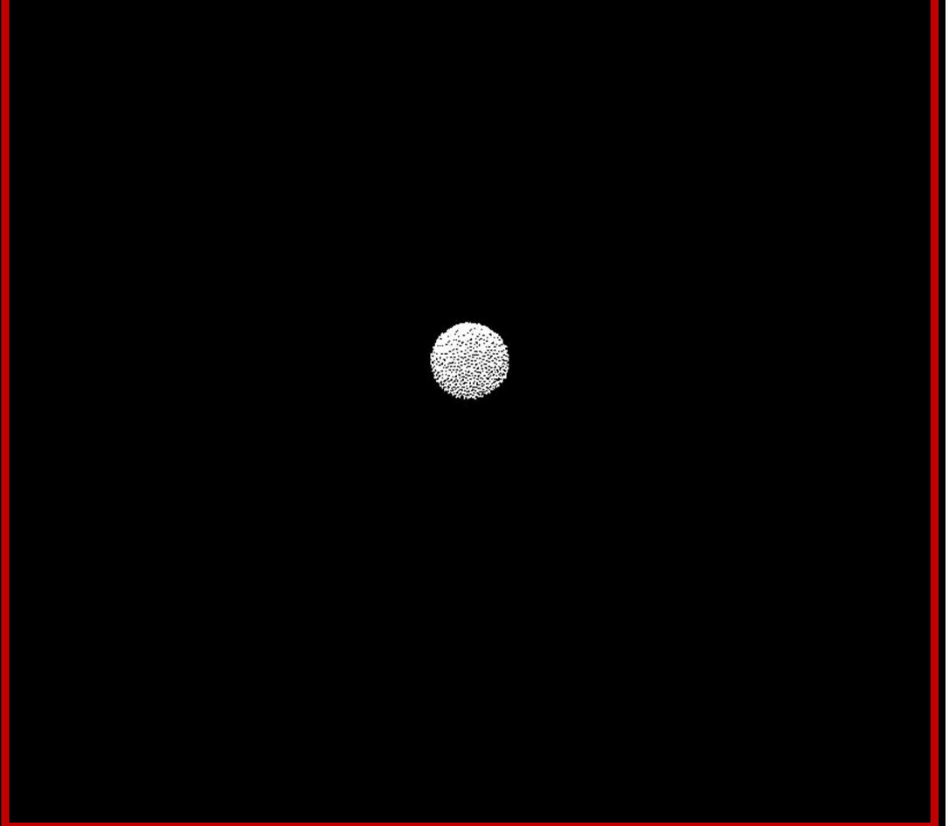
- Multiple bodies co-orbiting WD1145+017
- Transits caused by dust/gas "plumes"
- Transit activity > 2 years
- Individual transit periods stable over 100 of orbital cycles, but differ by ~5-10 sec

PKDGRAV simulations

Homogenous, ρ = 2.6 g/cm^3



Differentiated, ρ = 3.5 g/cm^3



Total disruption within a few days

Stable for >90 days, Intermittent mantle disruption

Veras et al. 2017, MNRAS 465, 1008

In:

Gänsicke et al. 2016, ApJ 818, L7
Rappaport et al. 2016, MNRAS 458, 3904
Gary et al. 2016, MNRAS 465, 3267

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Out:

Gurri et al. 2017, MNRAS 464, 321
Veras et al. 2017, MNRAS 465, 1008

- Differentiated parent body @ P=4.498h
- $M \lesssim 10^{20}$kg
- $\rho \simeq 3.5$ g/cm^3
- Nearly-circular orbit
- Releases sporadically fragments

In:

Gänsicke et al. 2016, ApJ 818, L7
Rappaport et al. 2016, MNRAS 458, 3904
Gary et al. 2016, MNRAS 465, 3267

- Multiple bo[illegible] WD1145+017
- Transits caused by dust/gas "plumes"
- Transit activity > 2 years
- Individual transit [illegible]s stable over 100 of orbital cycles, but [illegible] by ~5-10 sec

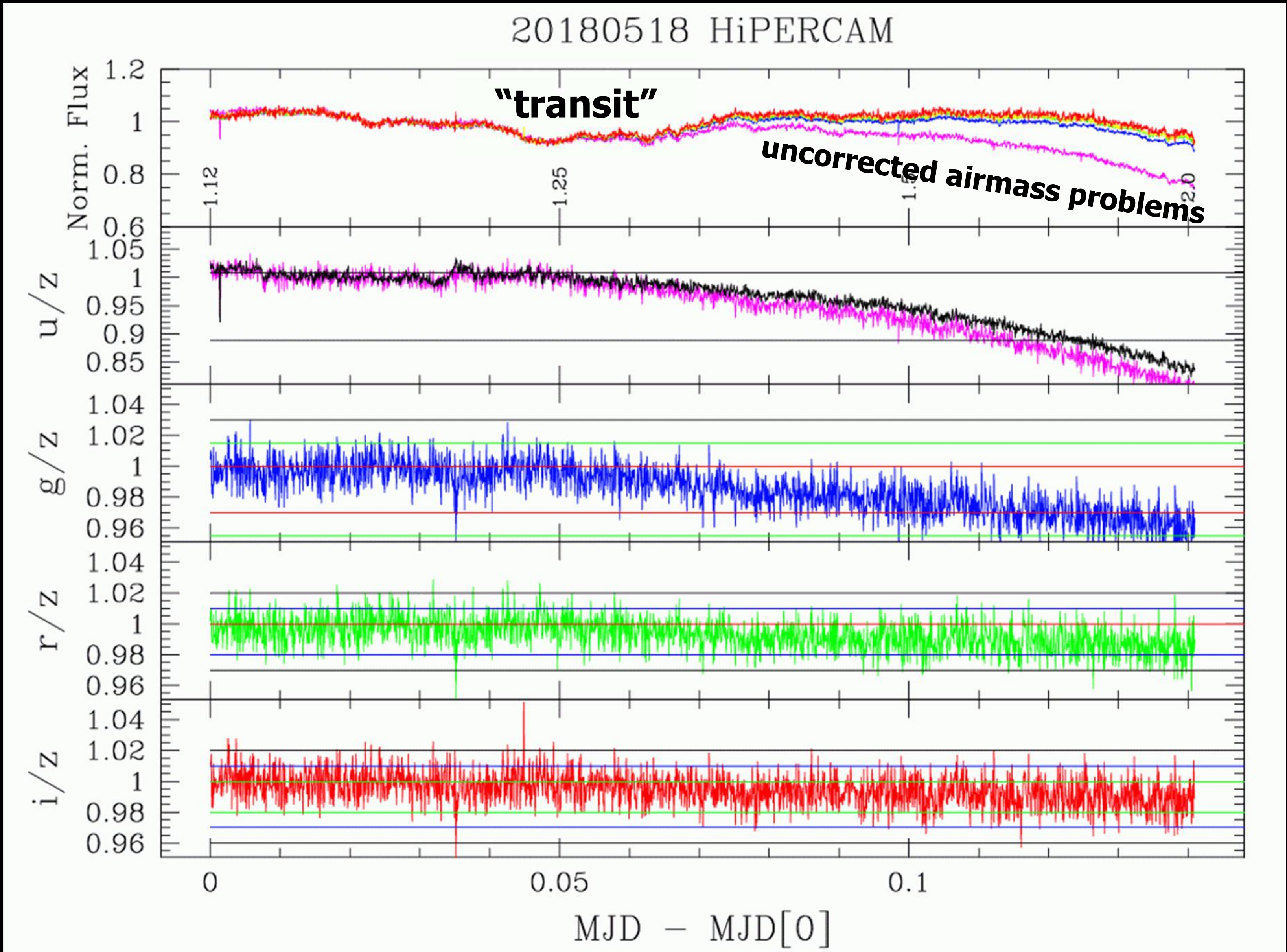
Out:

Gurri et al. 2017, MNRAS 46[illegible], 321
Veras et al. 2017, MNRAS 465, 1008

- Differentiated parent body @ P=4.498h
- $M \lesssim 10^{20}$kg
- $\rho \simeq 3.5$ g/cm^3
- Nearly-circular orbit
- Releases sporadically fragments

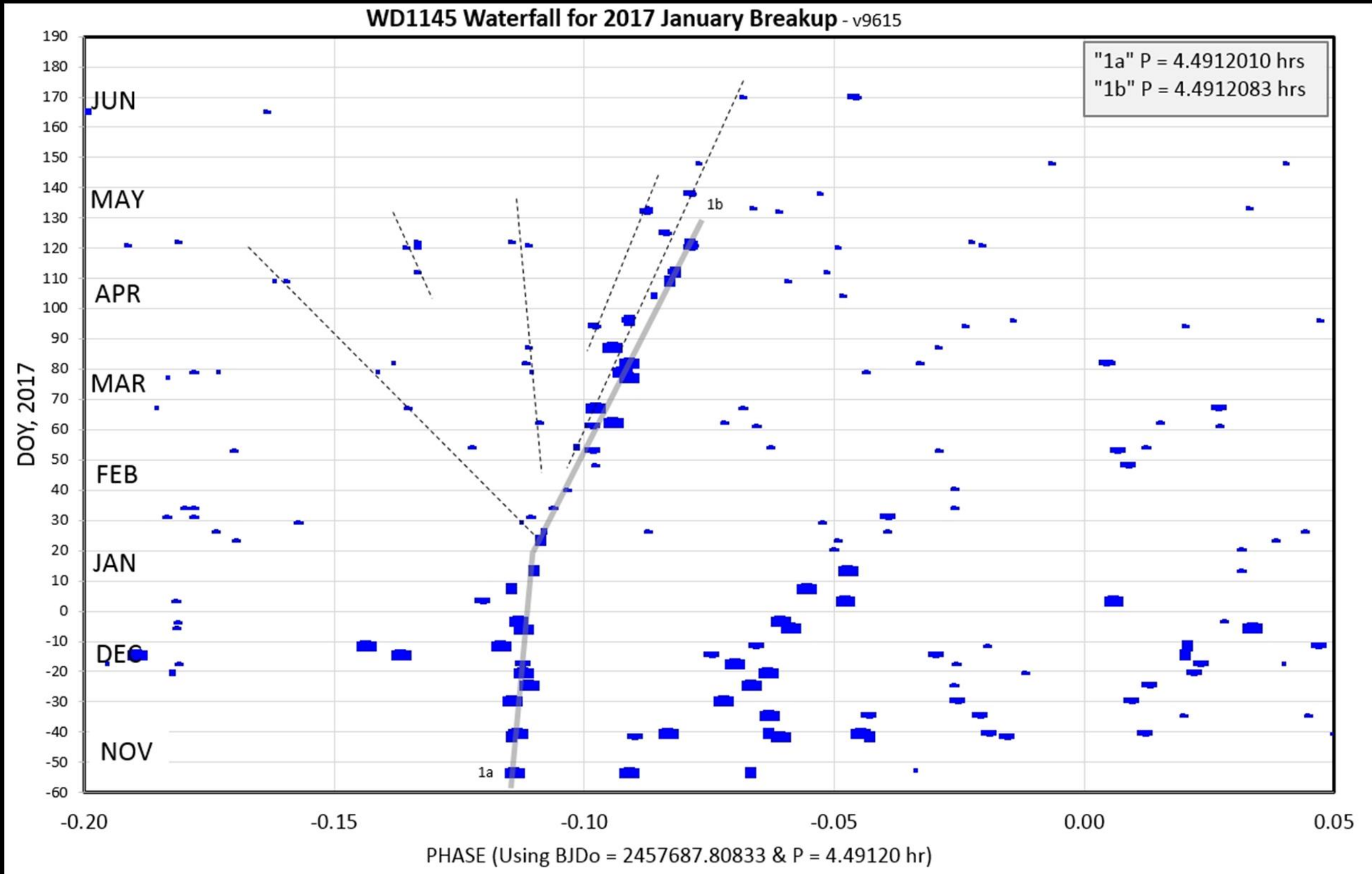
But there is *so* *much* *more* going on!

HiPERCAM: 5sec @ 10.4m GTC ☹



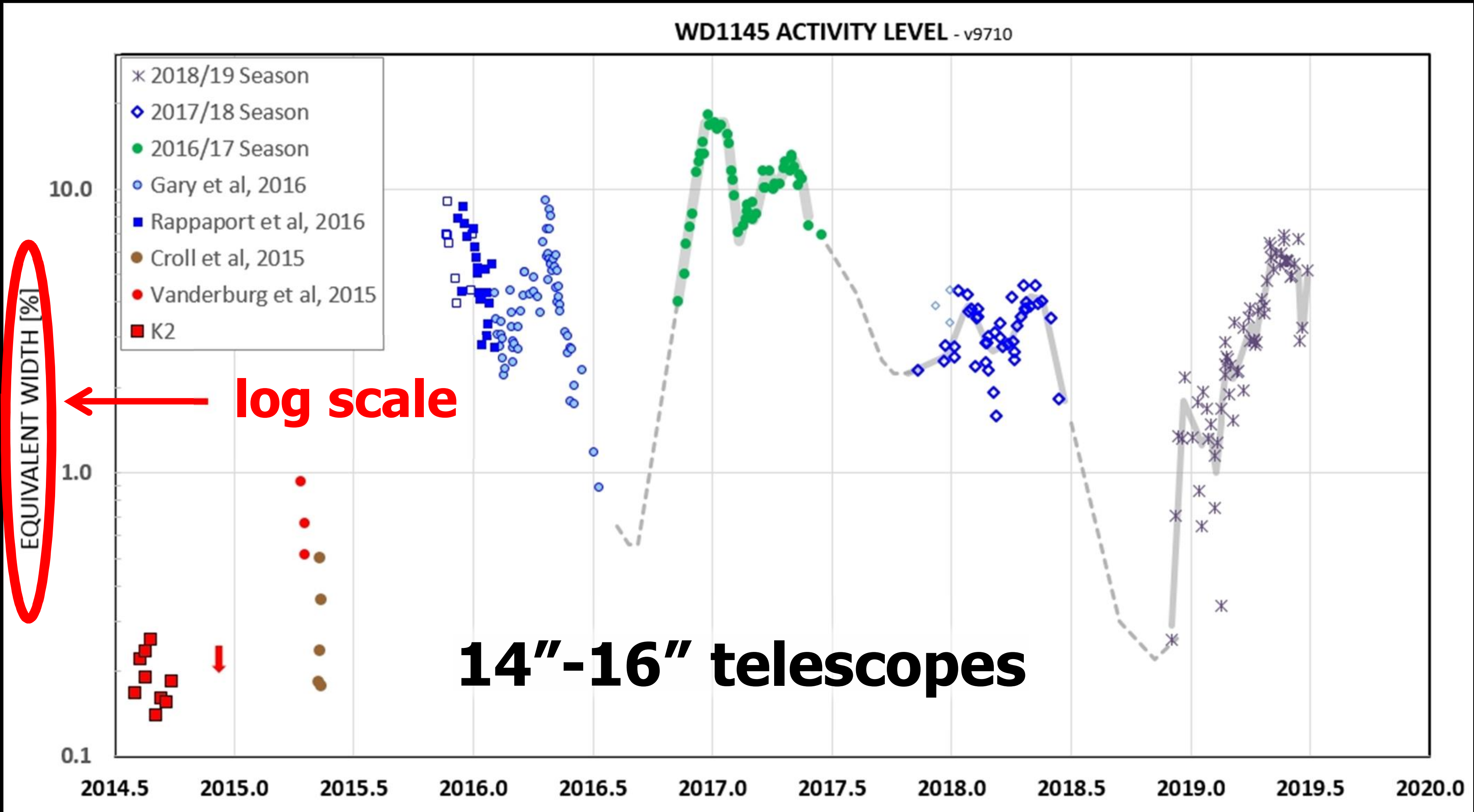
Evidence for short-lived, drifting fragments

http://www.brucegary.net/1145/



The transit activity varies dramatically

http://www.brucegary.net/1145/



One = freak

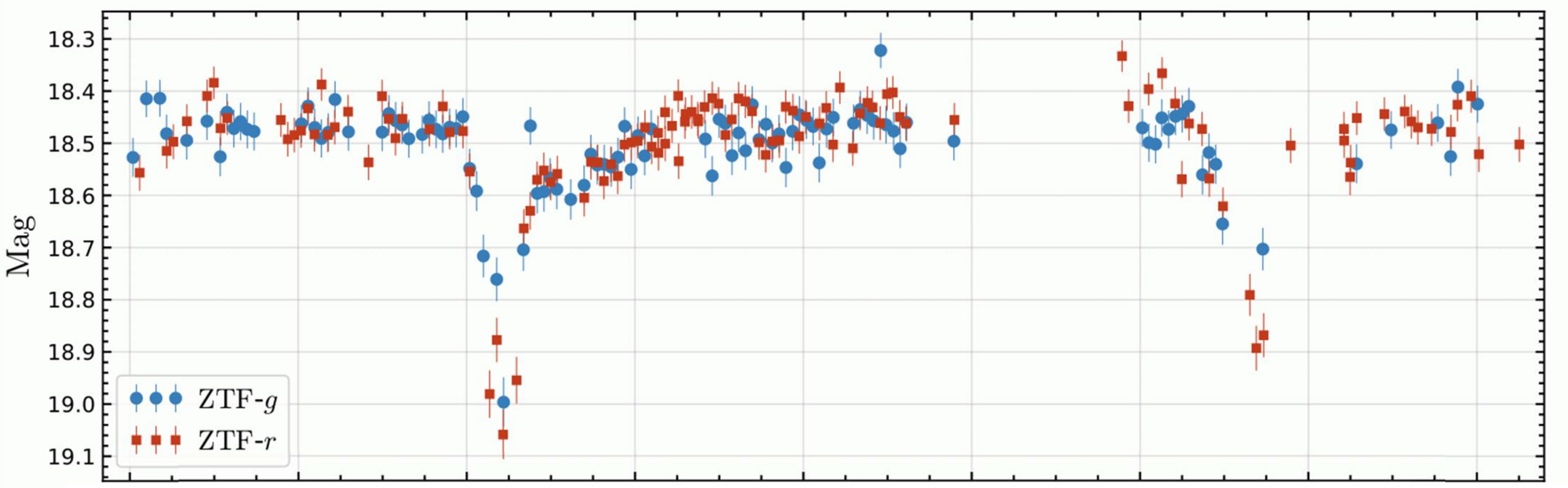
Two = coincidence

Three = a class

⇒ need to identify more systems

Transits #2: ZTF J013906.17+524536.89

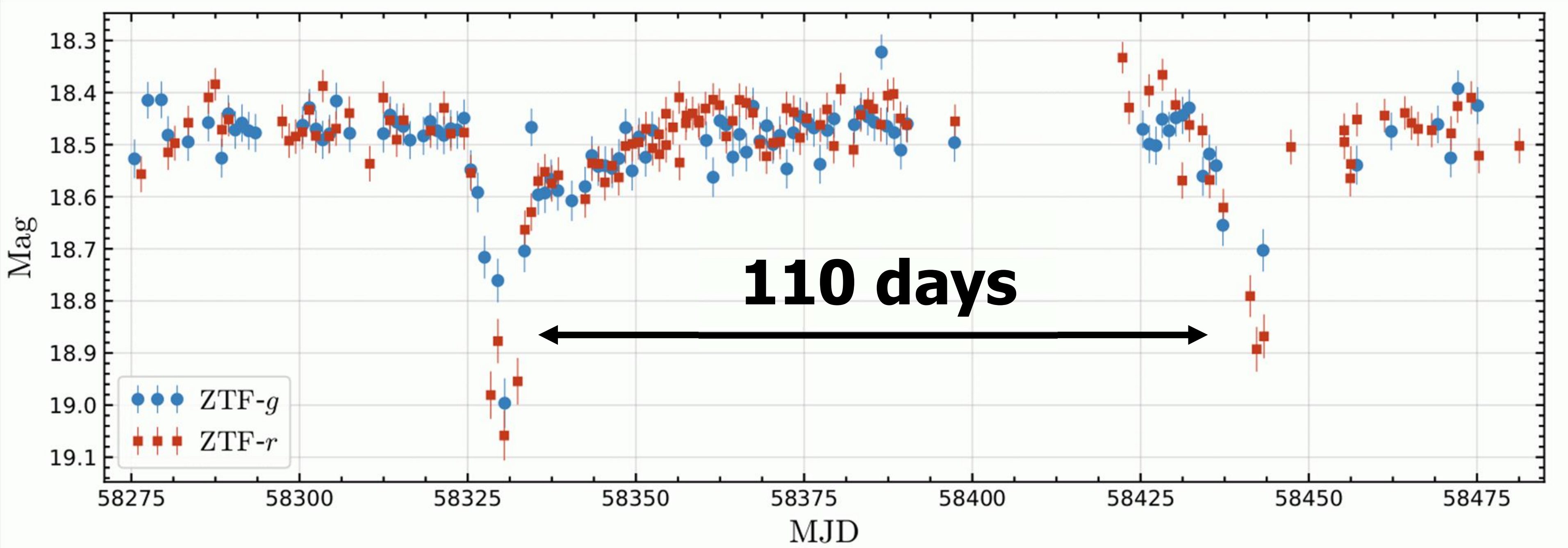
Vanderbosch et al. arXiv:1908.09839



... looks very similar to WD1145+017, right?

Transits #2: P≃110 days(!)
We need your help with this one!

Vanderbosch et al. arXiv:1908.09839



Cool, old WD, T≃10500K
Possibly accreting (Ca K detected)
Highly eccentric orbit crossing the Roche radius?

#3 has been found

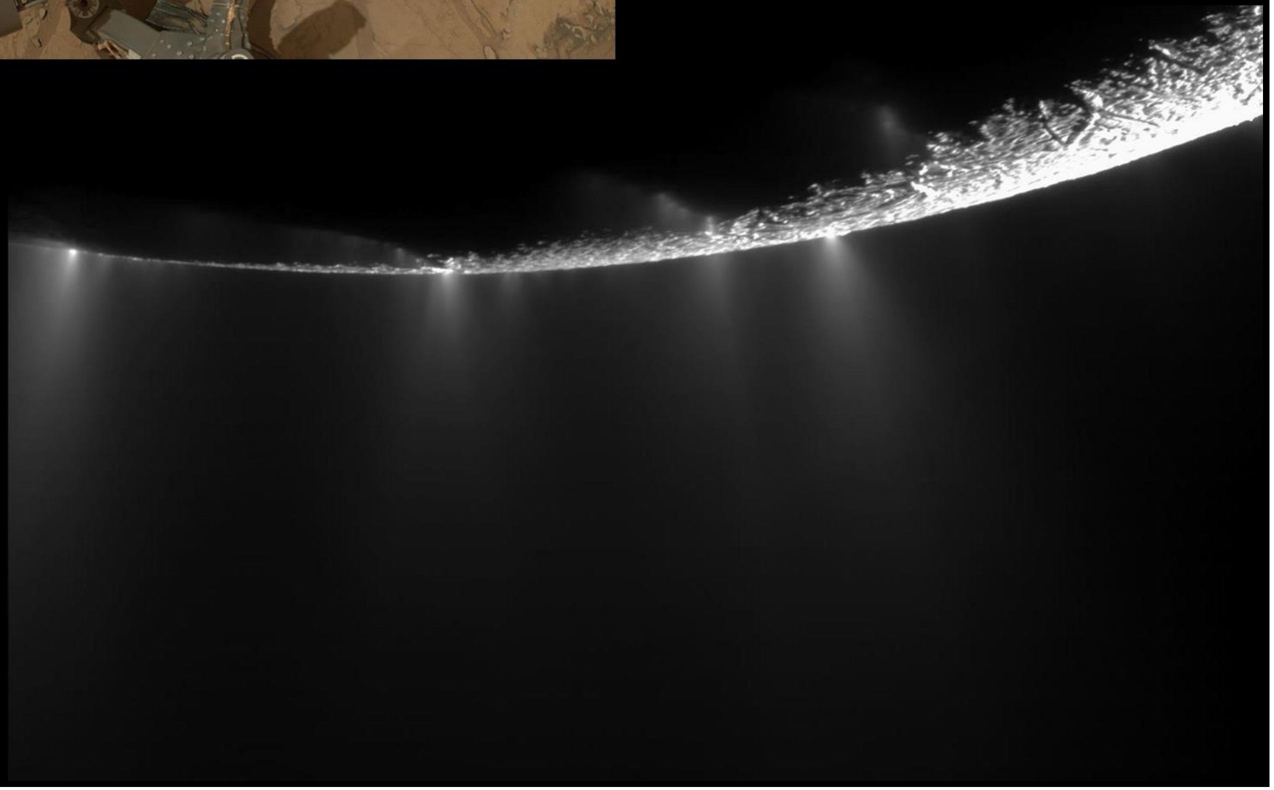
(embargoed by lead author)

Bulk abundances

or

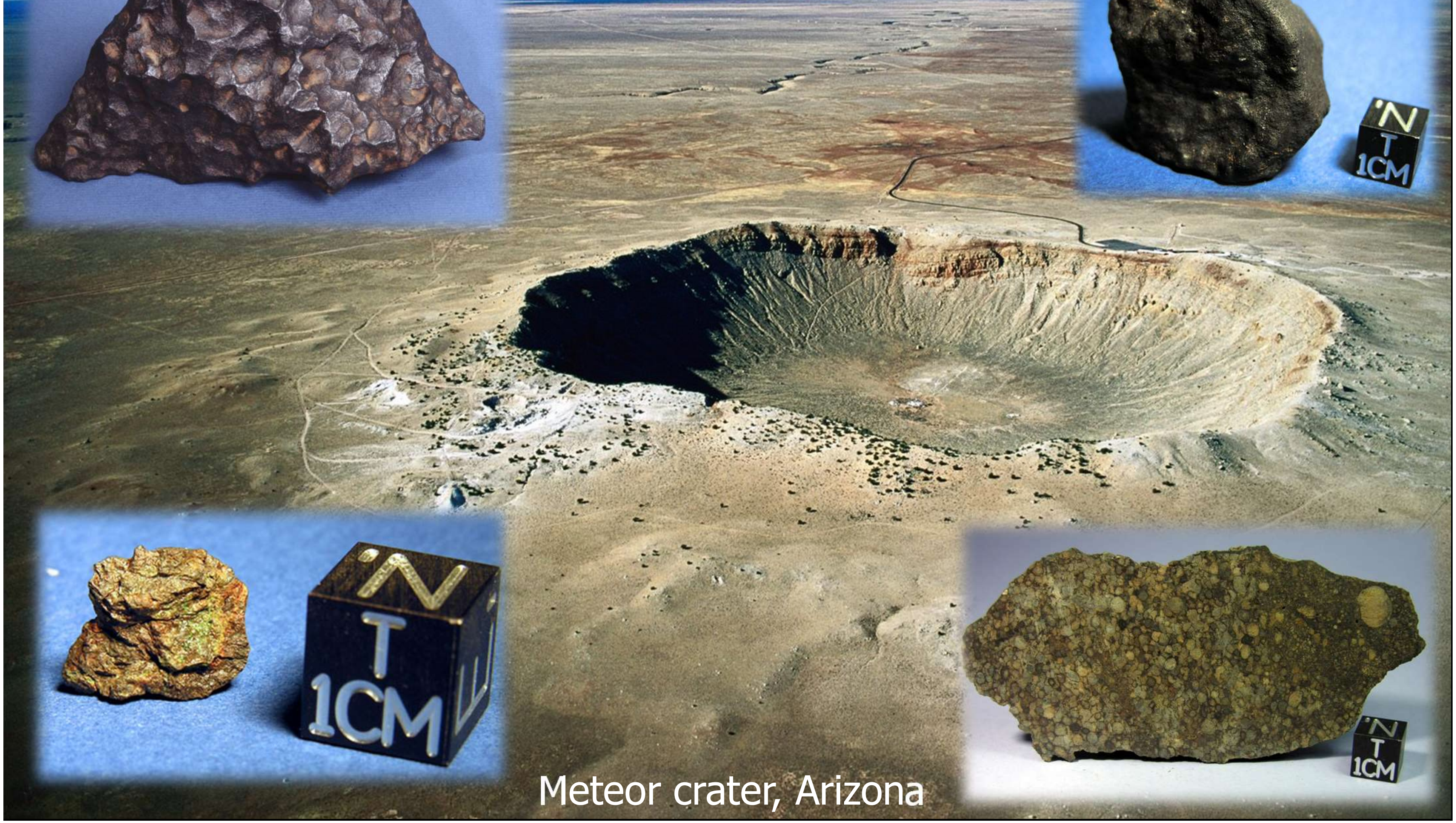
What are our and other worlds made out of?

Planetary abundances in the solar system



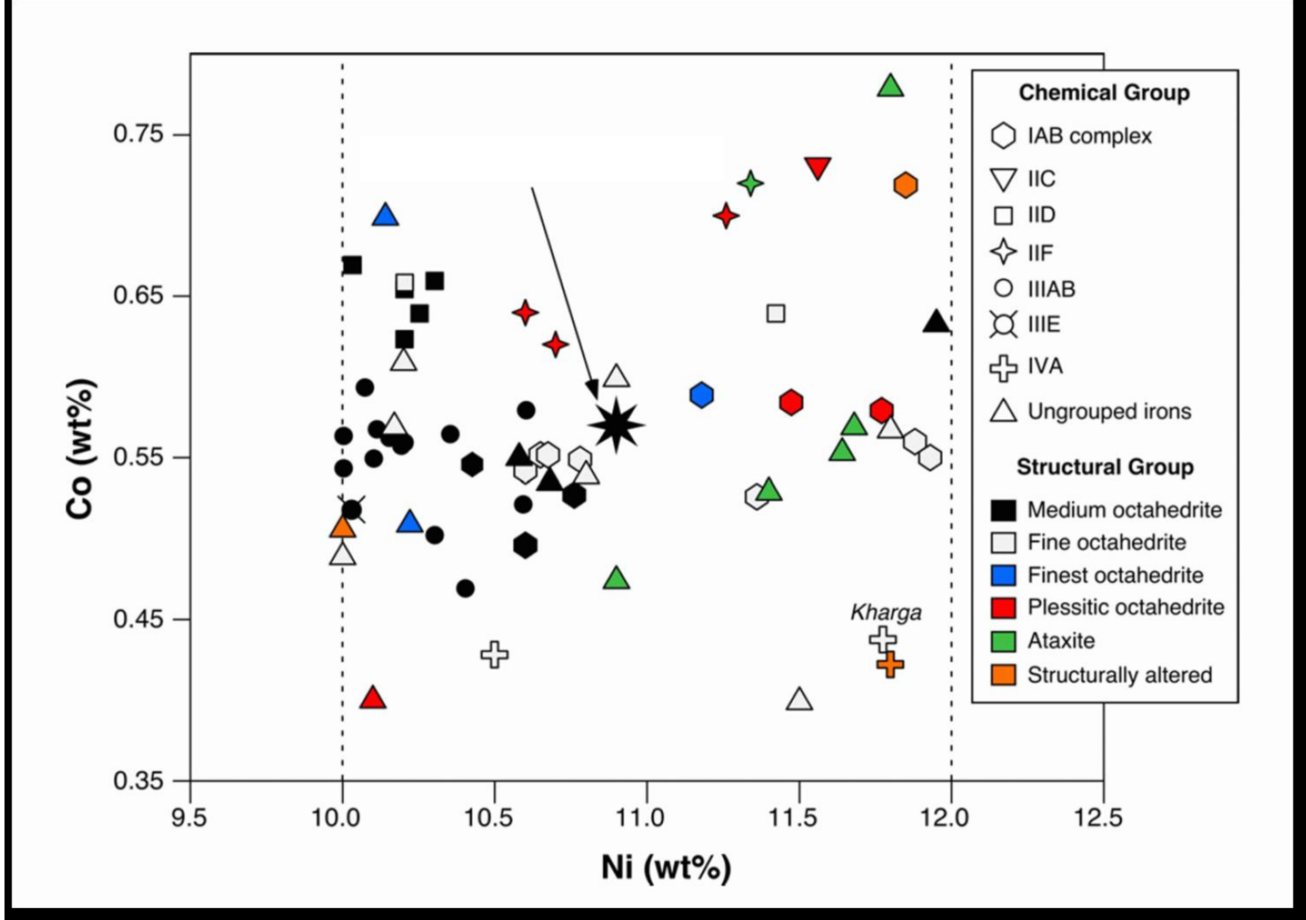
Bulk compositions in the solar system

1. Meteorite abundances
2. Cosmo-chemistry
3. Planet formation models



Meteor crater, Arizona

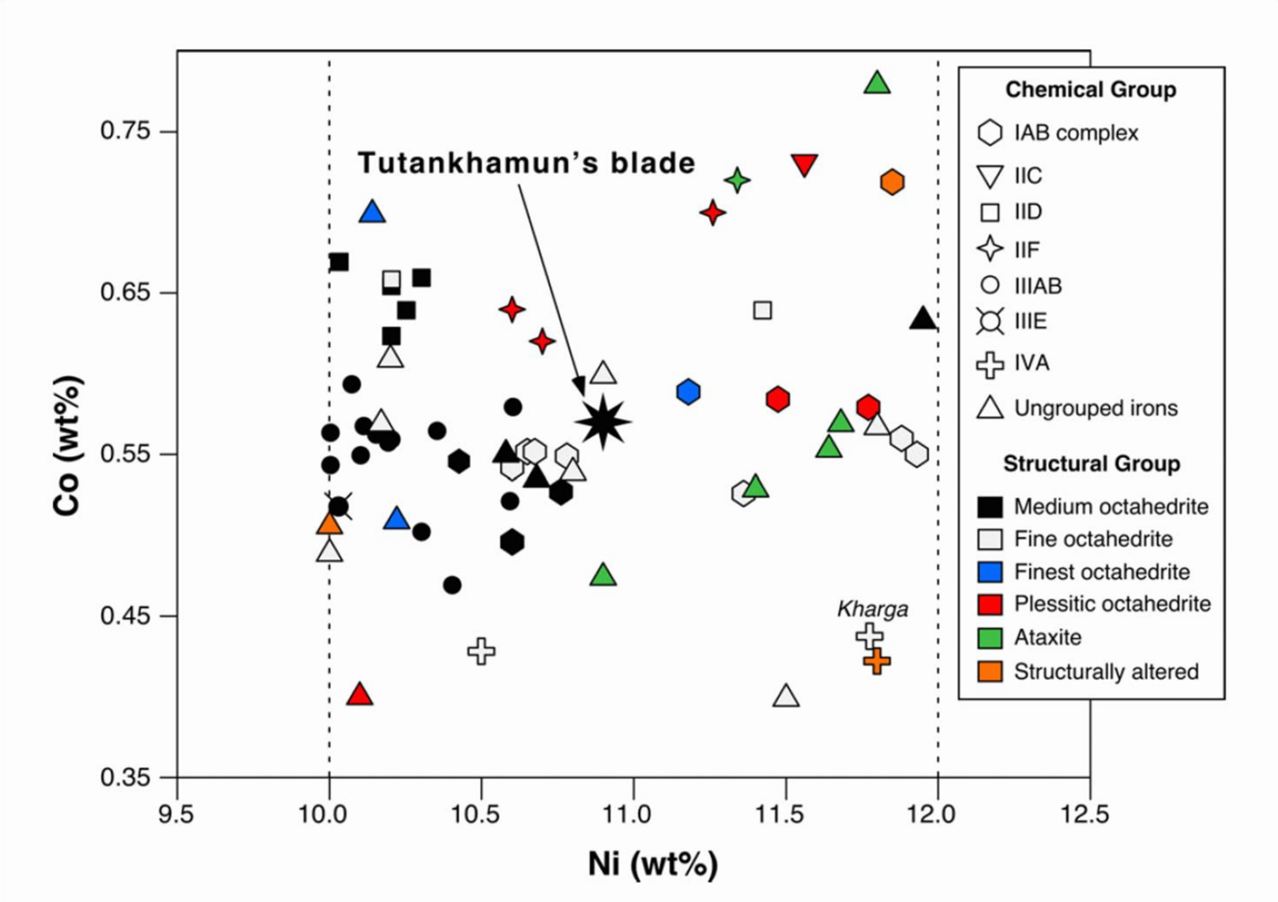
A planetary scientists view of meteorites



The Meteoritical Society

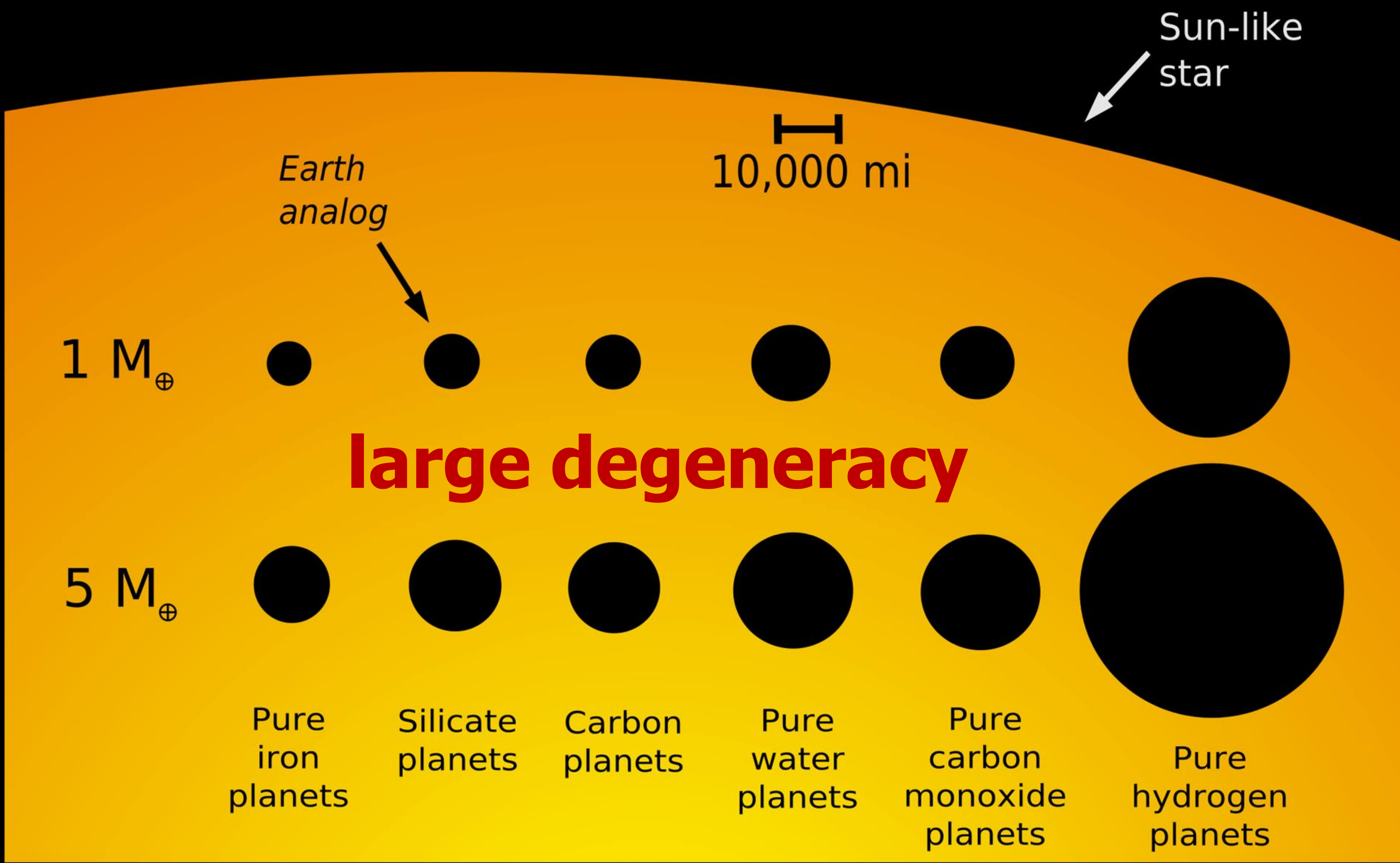
Meteoritics & Planetary Science 51, Nr 7, 1301–1309 (2016)
doi: 10.1111/maps.12664

The meteoritic origin of Tutankhamun's iron dagger blade

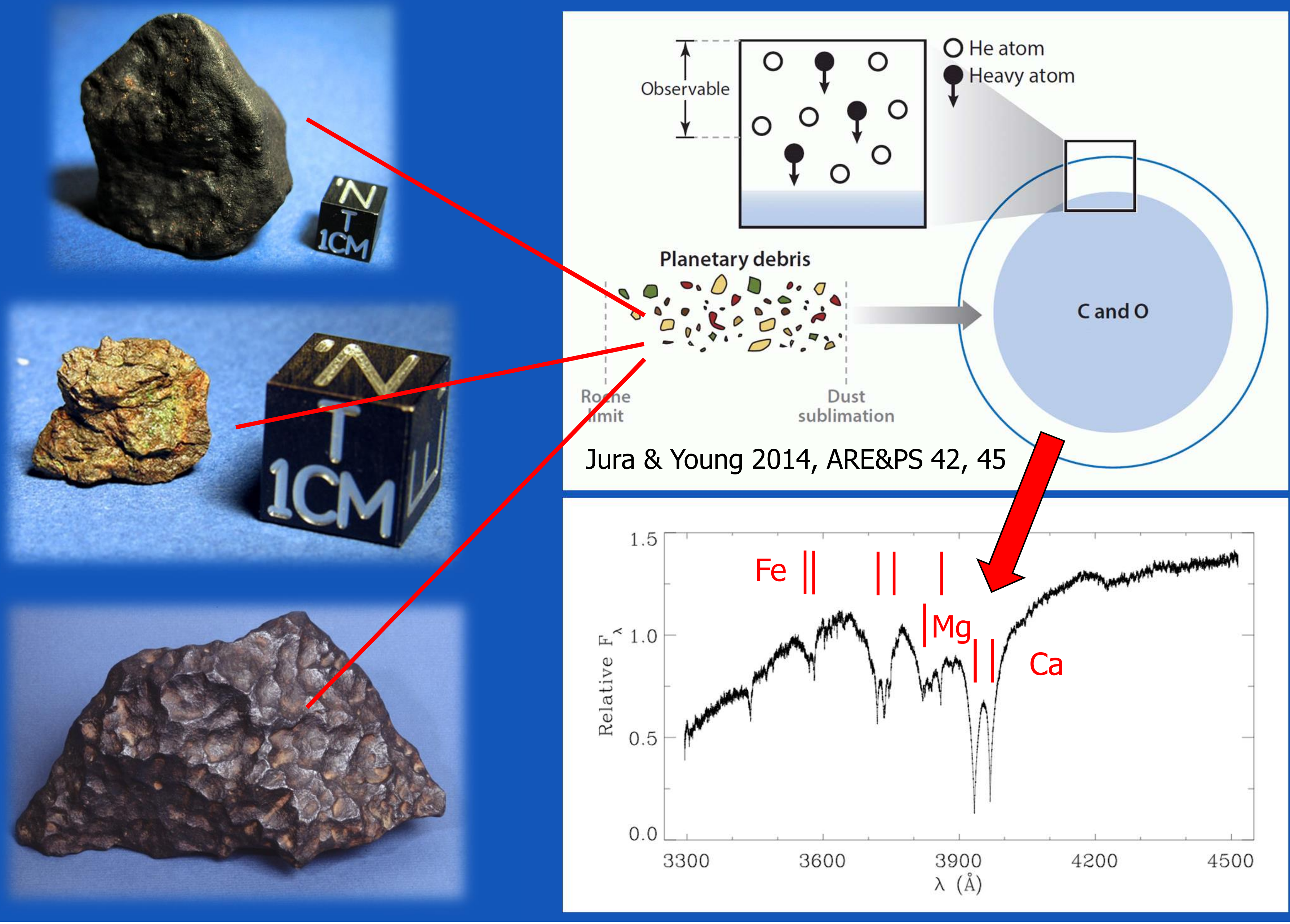


Transiting planets ⇒ M & R ⇒ bulk densities

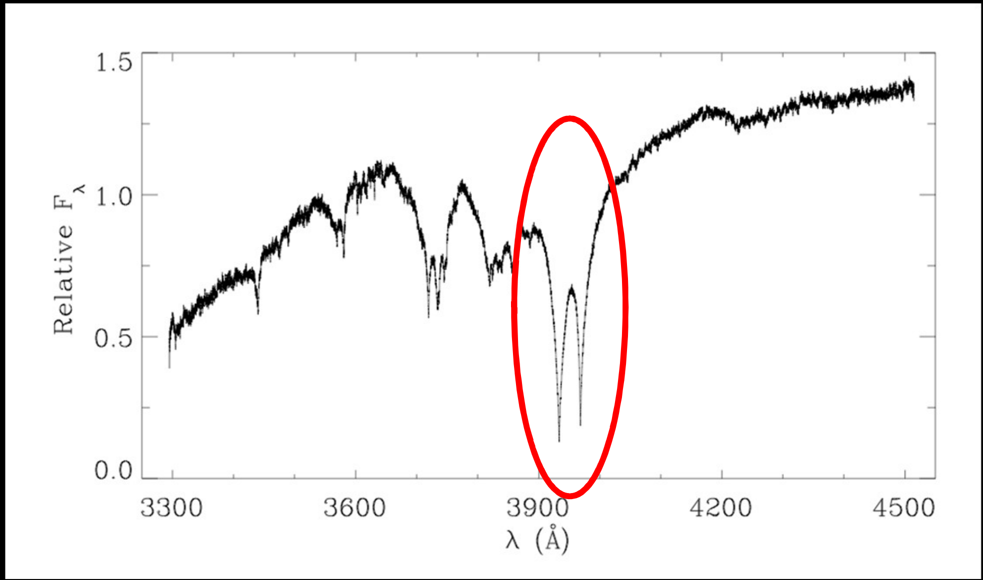
Predicted sizes of different kinds of planets



Photospheric metal pollution by planetary debris

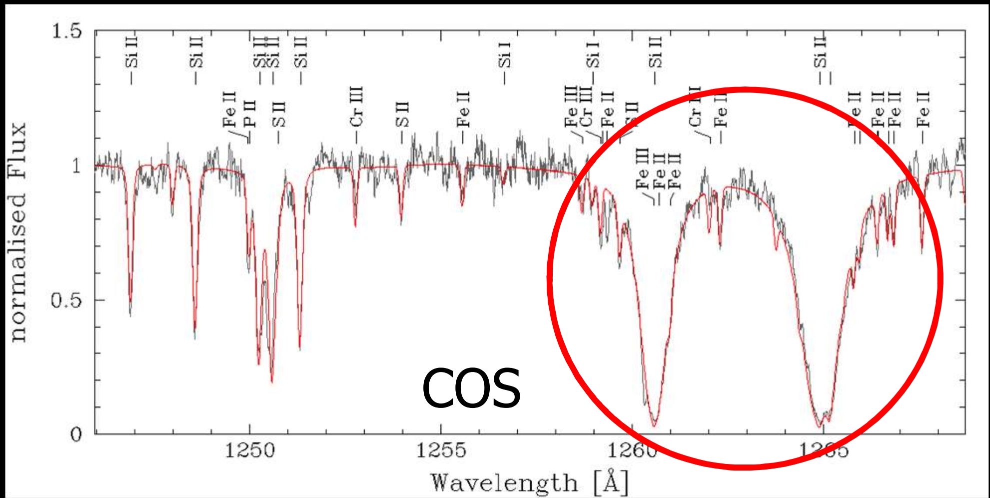


Metals as tracer of evolved planetary systems



T<13000K: Ca H/K

Temperature ⇑
Ca H/K ⇓

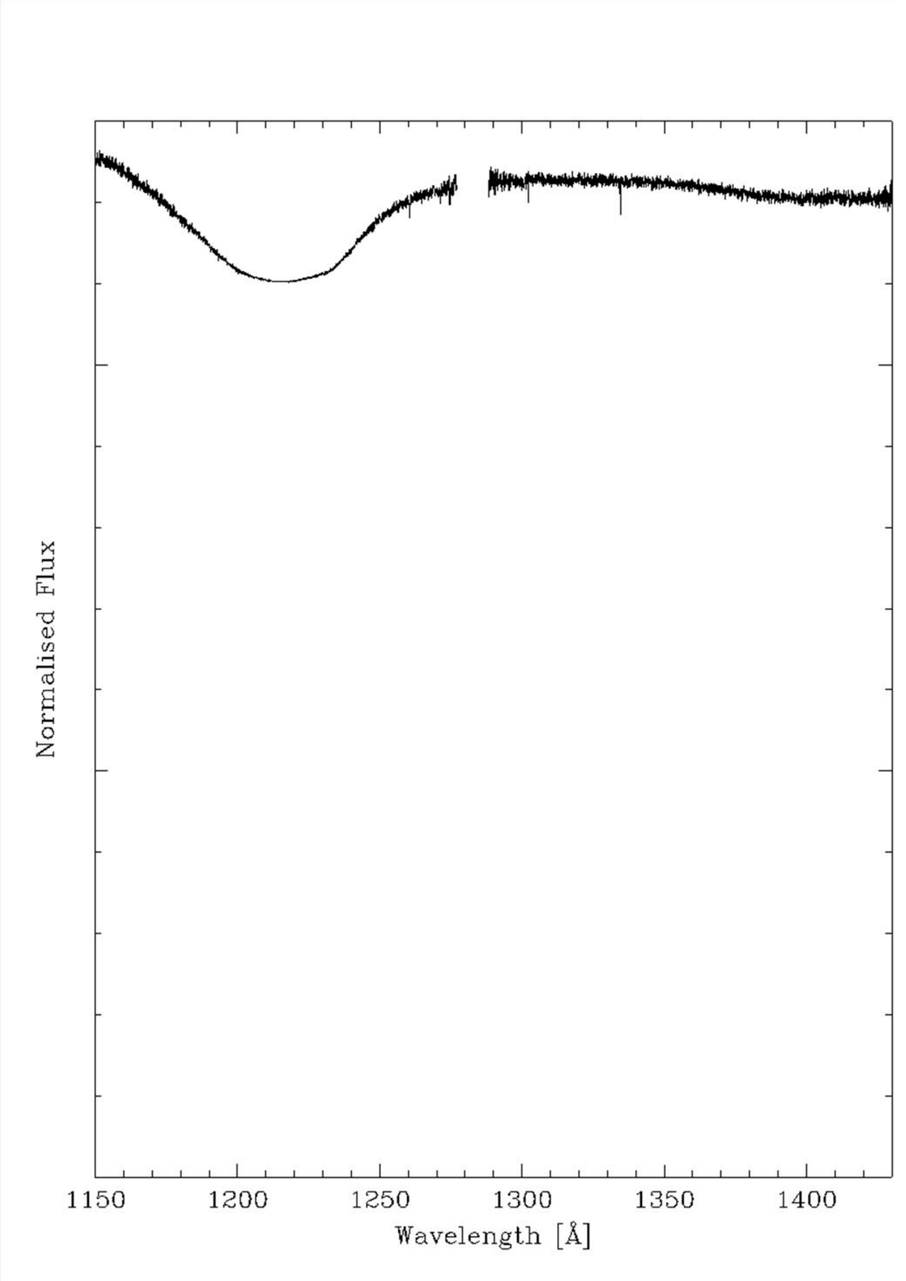


T≥15000K: Si II 1260Å

⇨ UV spectroscopy

Koester, Gänsicke, Farihi
2014 A&A 566, A34

Cycle 18-25 snapshot program



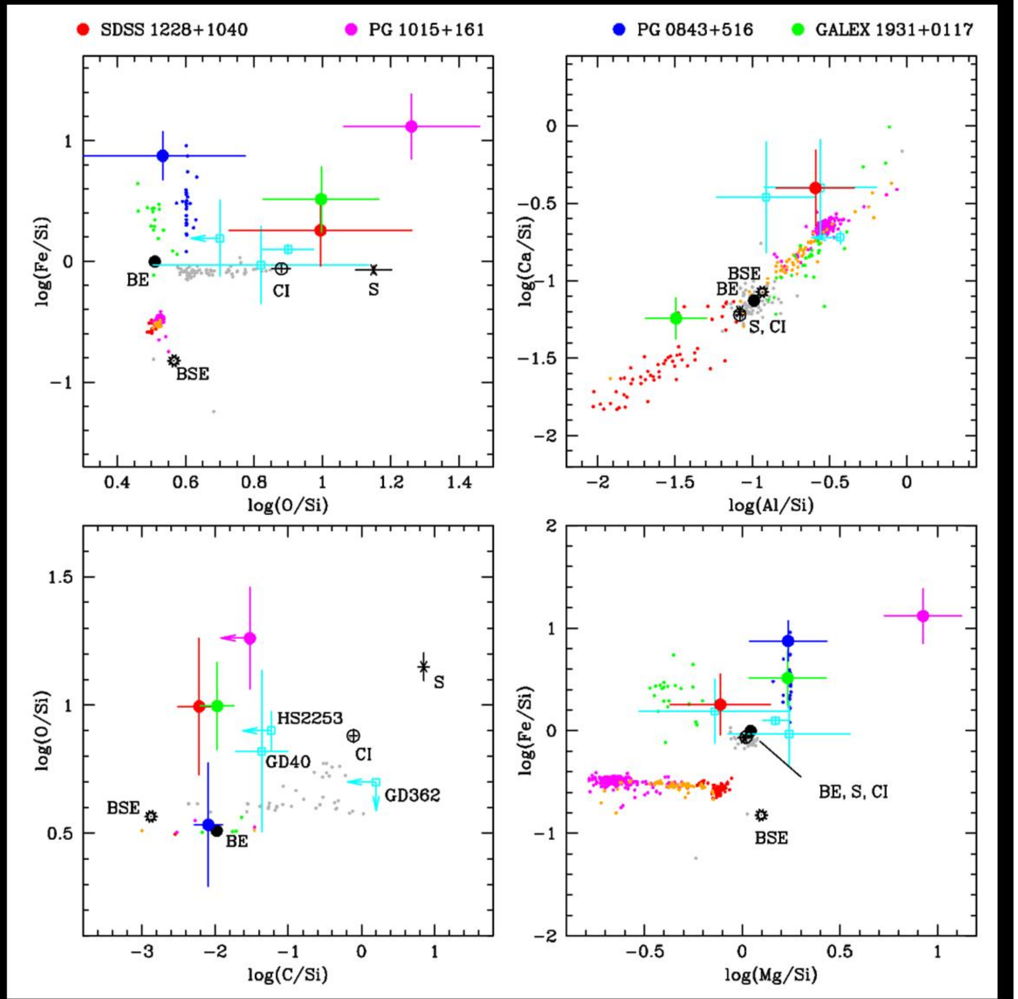
An unbiased HST/COS survey of ~160 hydrogen-atmosphere white dwarfs

- ⇒ **UV range sensitive to volatiles**
- ⇒ **short diffusion time scale (days)**
- ⇒ **if polluted, these stars accrete *now***
- ⇒ **accurate abundances**

Koester, Gänsicke, Farihi
2014 A&A 566, A34

Detailed abundance studies

O, Mg, Si, and Fe are the major constituents of the debris (*and also make up ~93% of the Earth*), variations similar to solar system



Zuckerman et al. 2011, ApJ 739, 101
Melis et al. 2011, ApJ 732, 90
Klein et al. 2011, ApJ 741, 64
Gänsicke et al. 2012, MNRAS 424, 333
Jura et al. 2015, ApJ 799, 109
Xu et al. 2014, ApJ 783, 79
Jura & Young, 2014, ARE&PS 42, 1
Wilson et al. 2016, MNRAS 459, 3282

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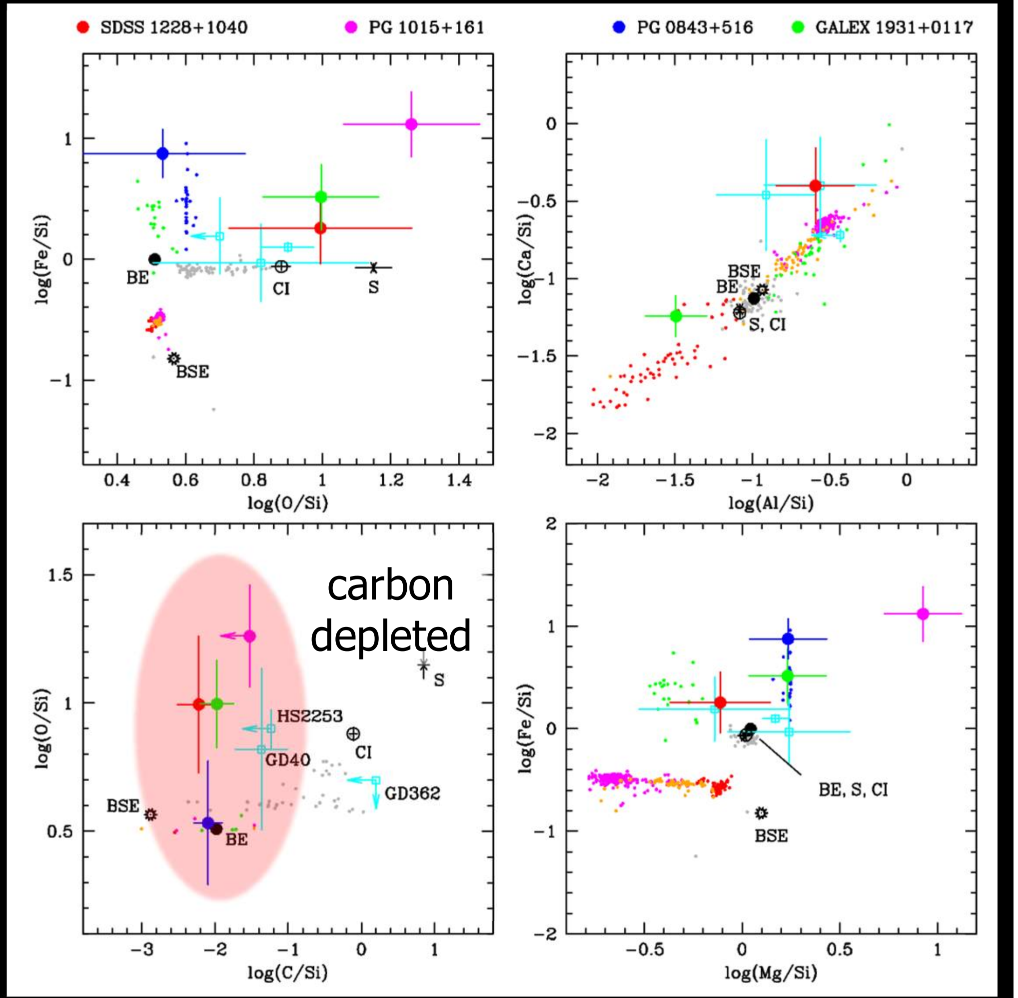
- **Volatile-depleted, similar to bulk Earth ⇨ "*rocky*"**



Zuckerman et al. 2011, ApJ 739, 101
Melis et al. 2011, ApJ 732, 90
Klein et al. 2011, ApJ 741, 64
Gänsicke et al. 2012, MNRAS 424, 333
Jura et al. 2015, ApJ 799, 109
Xu et al. 2014, ApJ 783, 79
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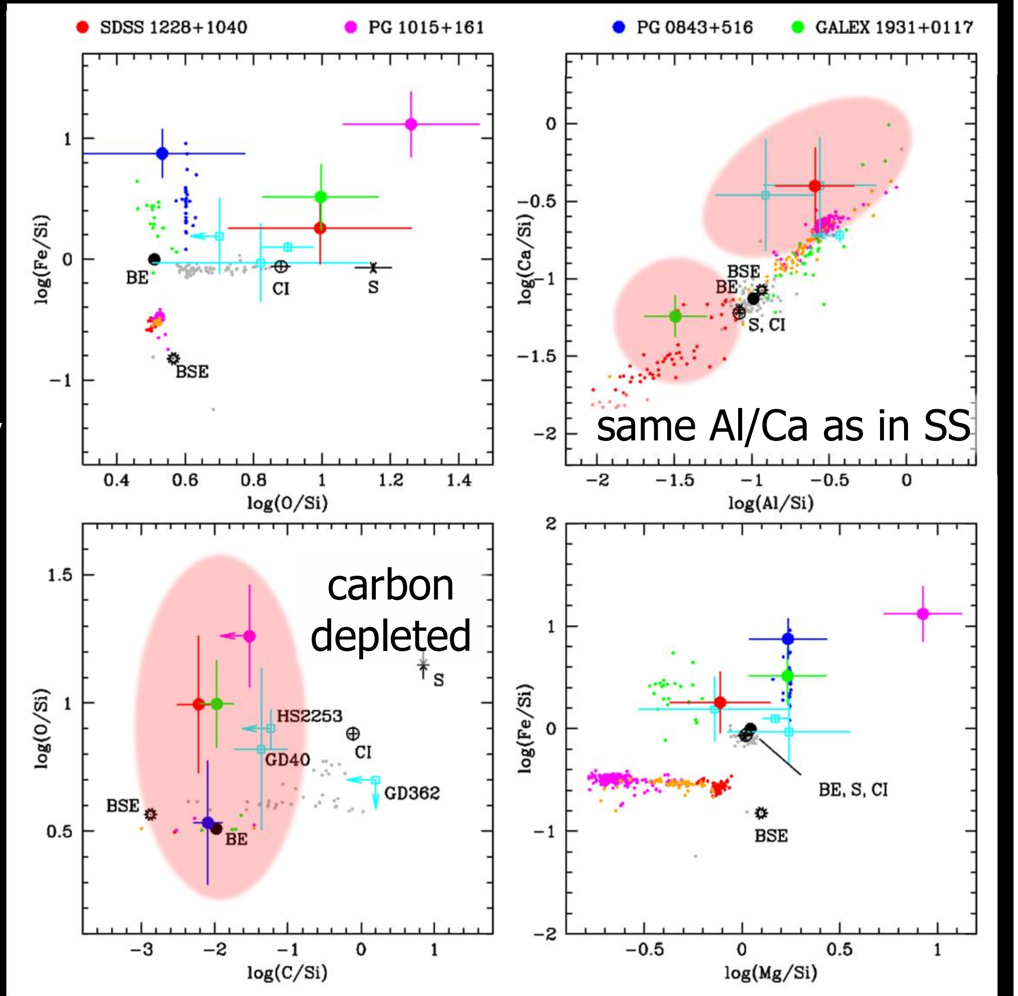

Zuckerman et al. 2011, ApJ 739, 101
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Klein et al. 2011, ApJ 741, 64
Gänsicke et al. 2012, MNRAS 424, 333
Jura et al. 2015, ApJ 799, 109
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Wilson et al. 2016, MNRAS 459, 3282

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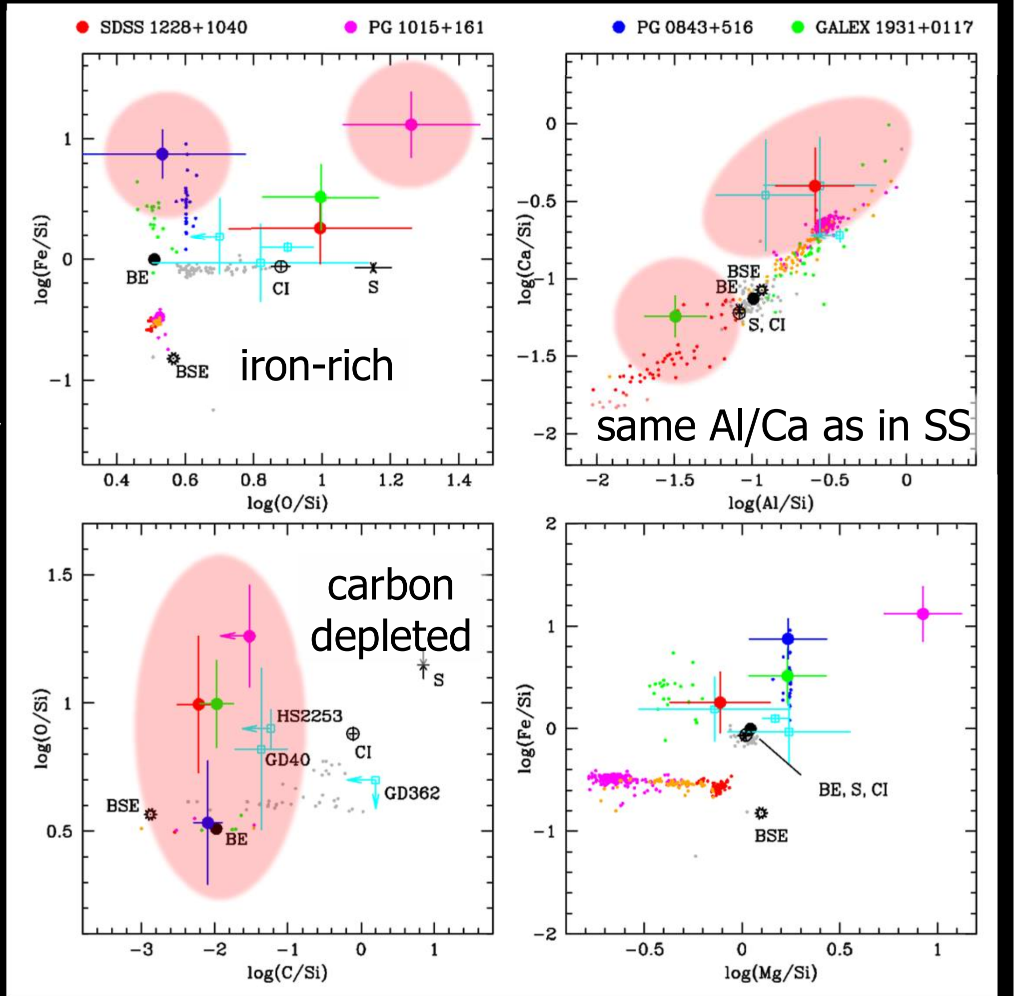
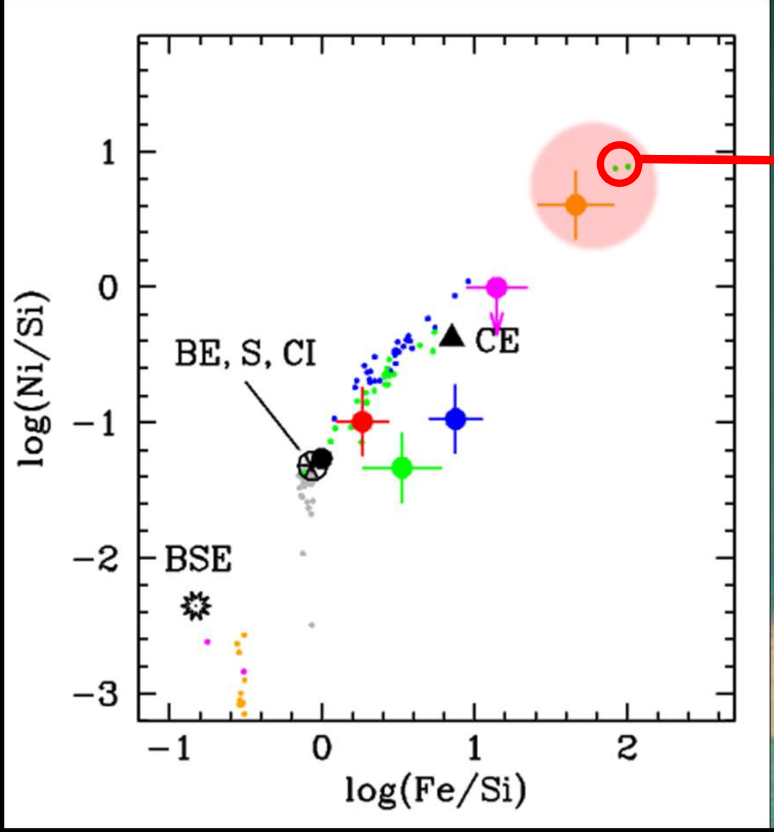
- **Refractory litophiles Ca/Al very similar to solar system bodies**
- **Evidence for differentiation (Fe, S, Cr overabundance)**

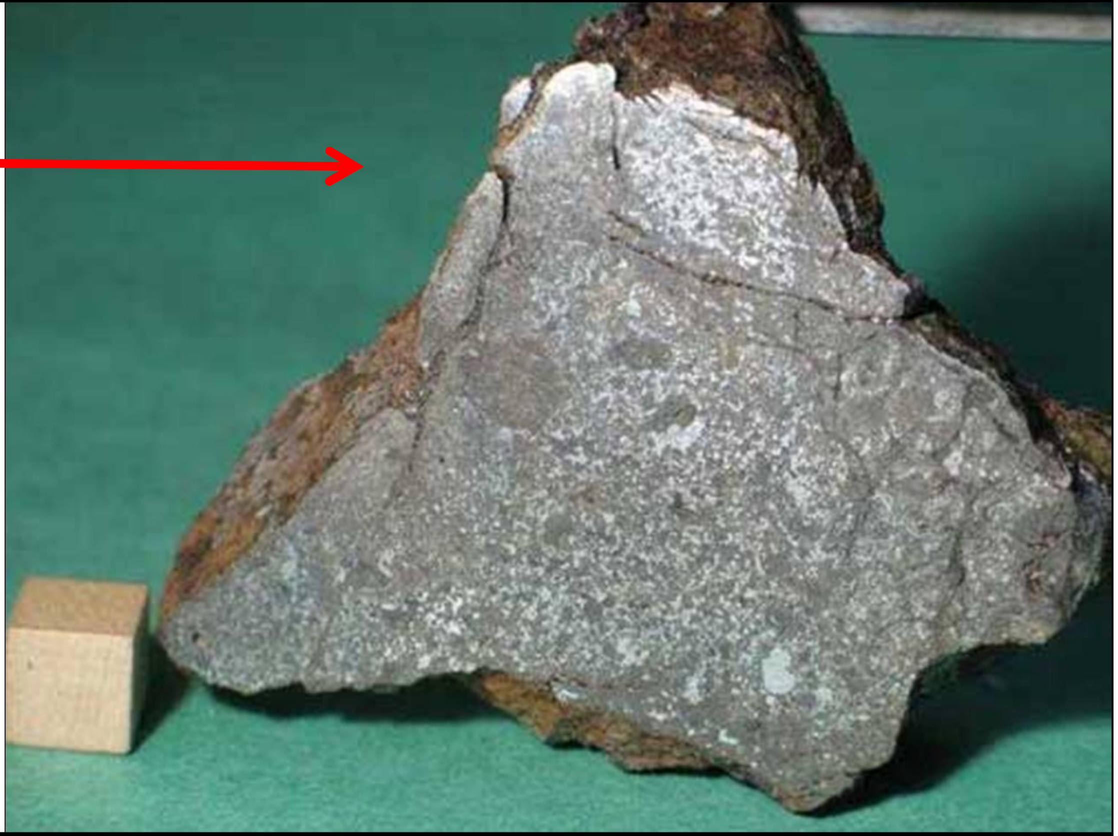


Zuckerman et al. 2011, ApJ 739, 101
Melis et al. 2011, ApJ 732, 90
Klein et al. 2011, ApJ 741, 64
Gänsicke et al. 2012, MNRAS 424, 333
Jura et al. 2015, ApJ 799, 109
Xu et al. 2014, ApJ 783, 79
Jura & Young, 2014, ARE&PS 42, 1
Wilson et al. 2016, MNRAS 459, 3282

Mesosiderite-like exo-asteroids

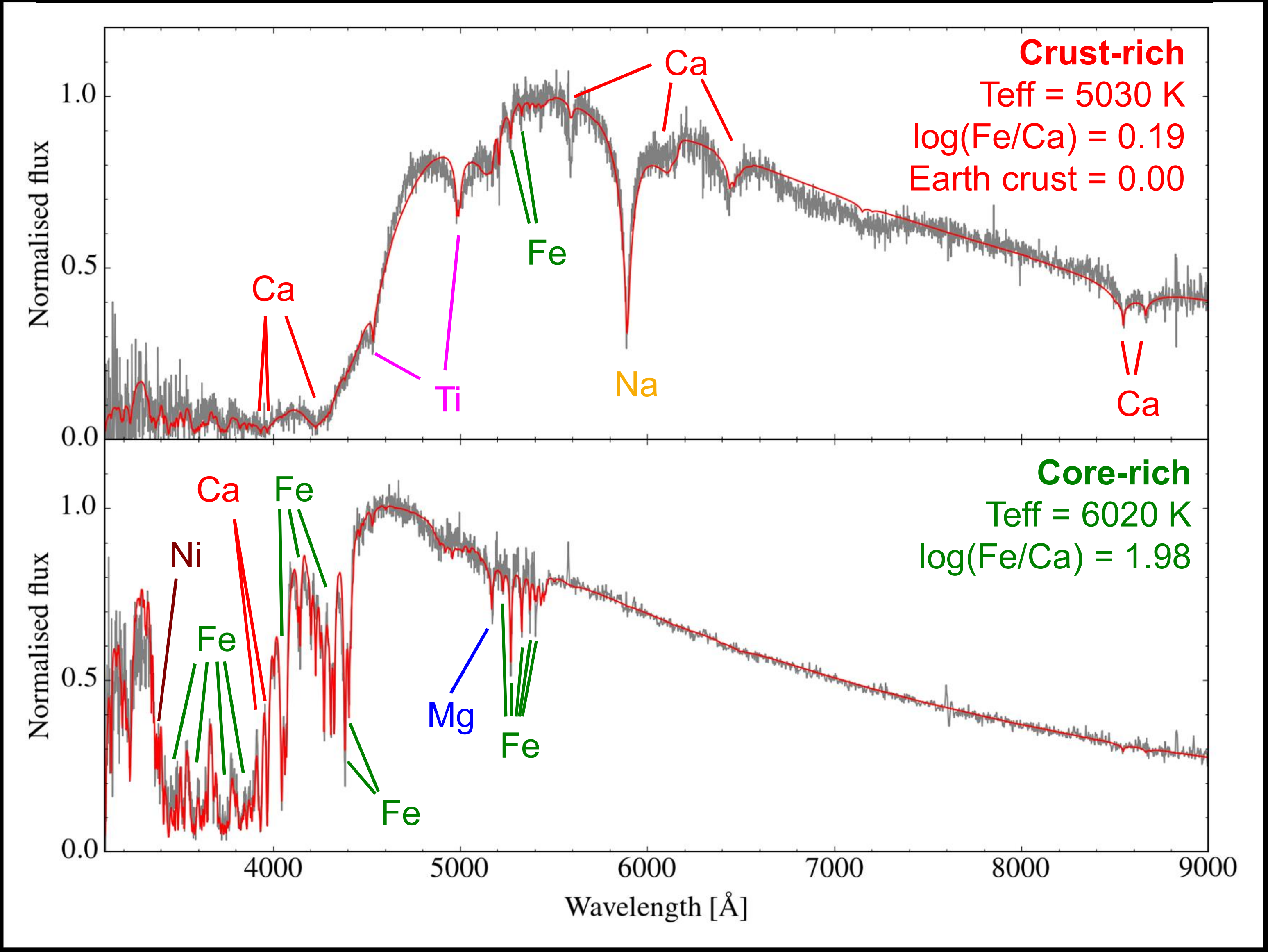
**Mesosiderite "Vaca Muerta"
origin from a ~ 200-400 km
differentiated asteroid
(Scott et al. 2001, M&PS 36, 869)**





~230 old (1-7Gyr) planetary systems

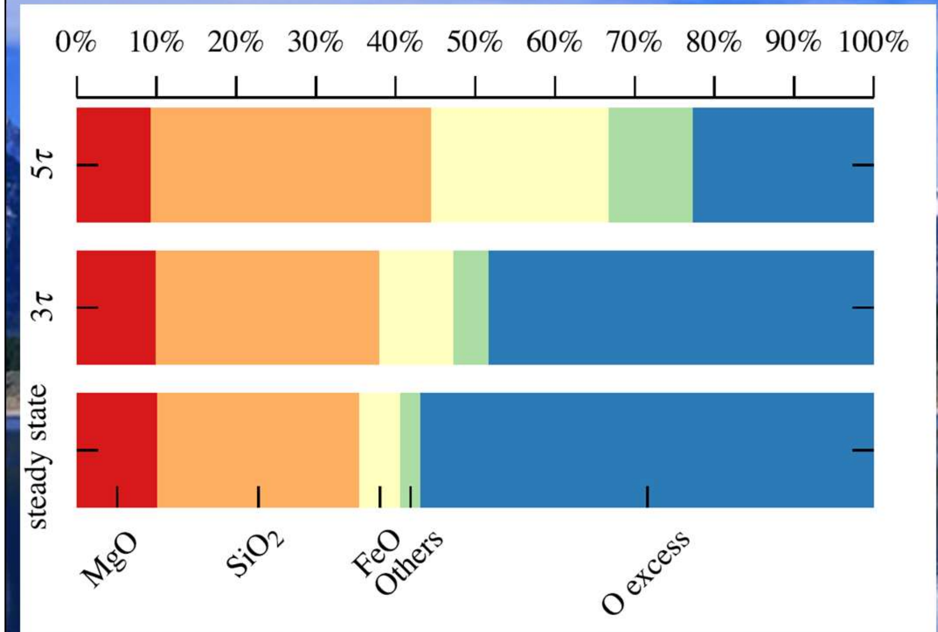
Hollands et al. 2017, MNRAS 467, 4970

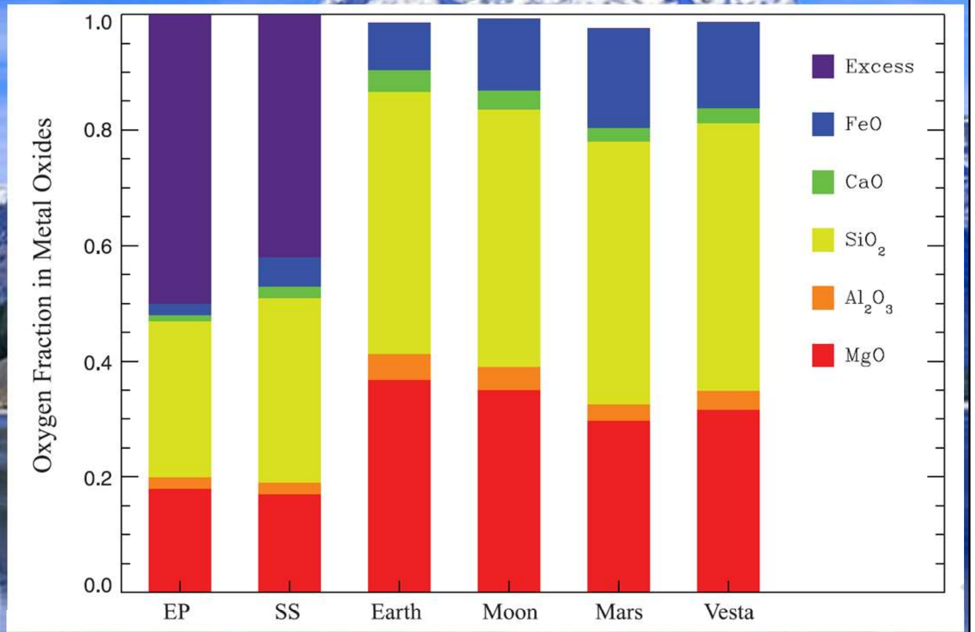


Rocks = MgO, SiO_2, FeO, Fe_2O_3, Al_2O_3, CaO, TiO_2, Cr_2O_3, MnO, ...

Water = H_2O

O-excess ⇒ water-rich planetesimals



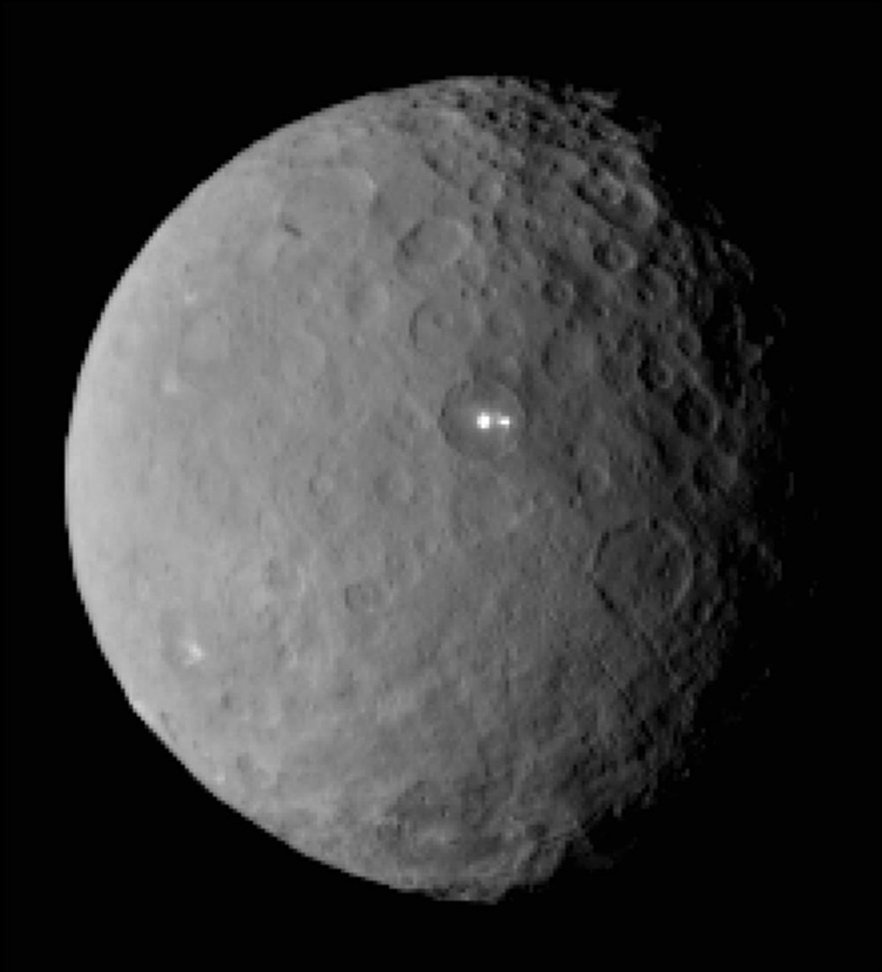


Raddi et al. 2015, MNRAS 450, 2083

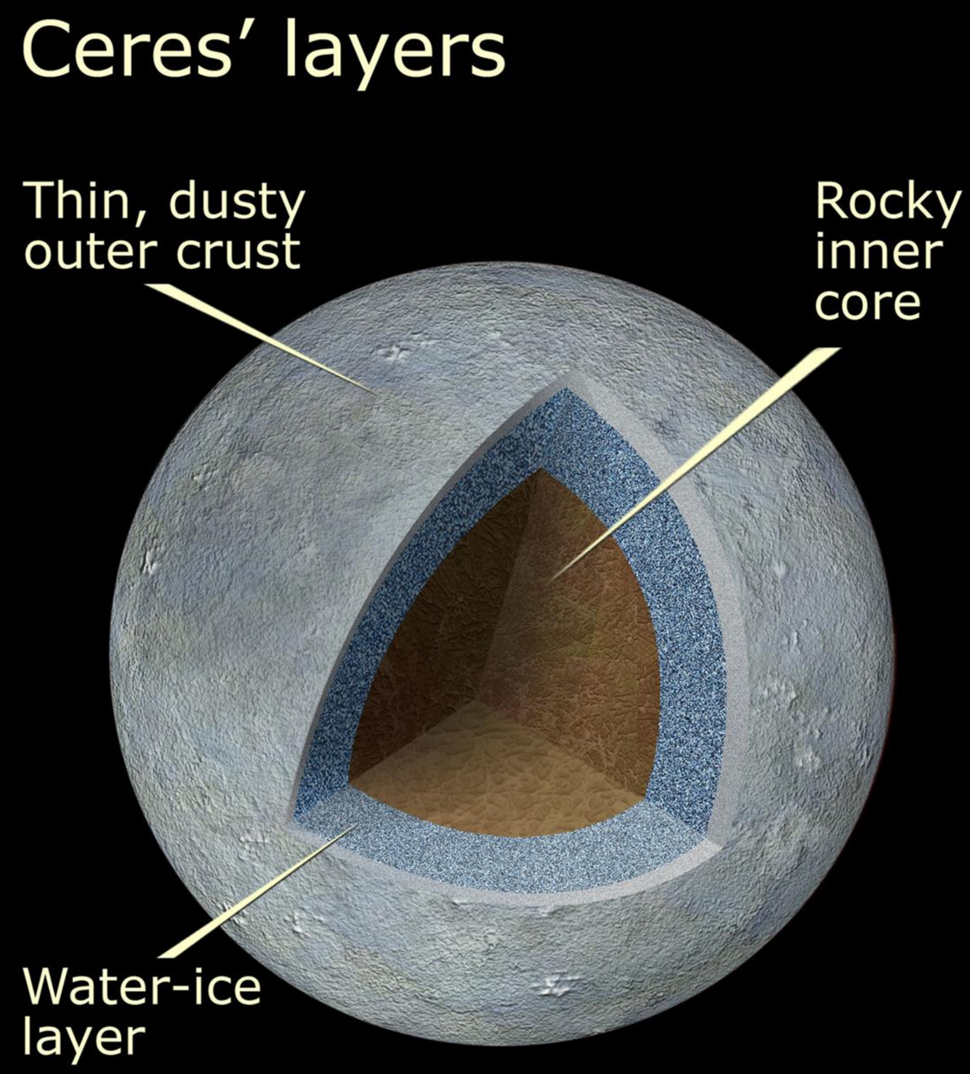
Farihi et al. 2013, Science 342, 218

- mass of parent body: ~$1x10^{21}$g - $1x10^{23}$g
- H_2O mass fraction: 25-40% ⇒ Ceres-like

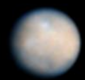
... similar to Ceres ...



DAWN



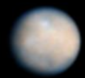
Water delivery to dry planets

7 x  **=** 

Mass: 9.0×10^{23} g
Mass fraction of $H_2$0: 25%
Mass of $H_2$0: 2.2×10^{23} g

Mass: 6.0×10^{27} g
Mass fraction of $H_2$0: 0.023%
Mass of $H_2$0: 1.4×10^{24} g

Water delivery to dry planets

7 x  **=** 

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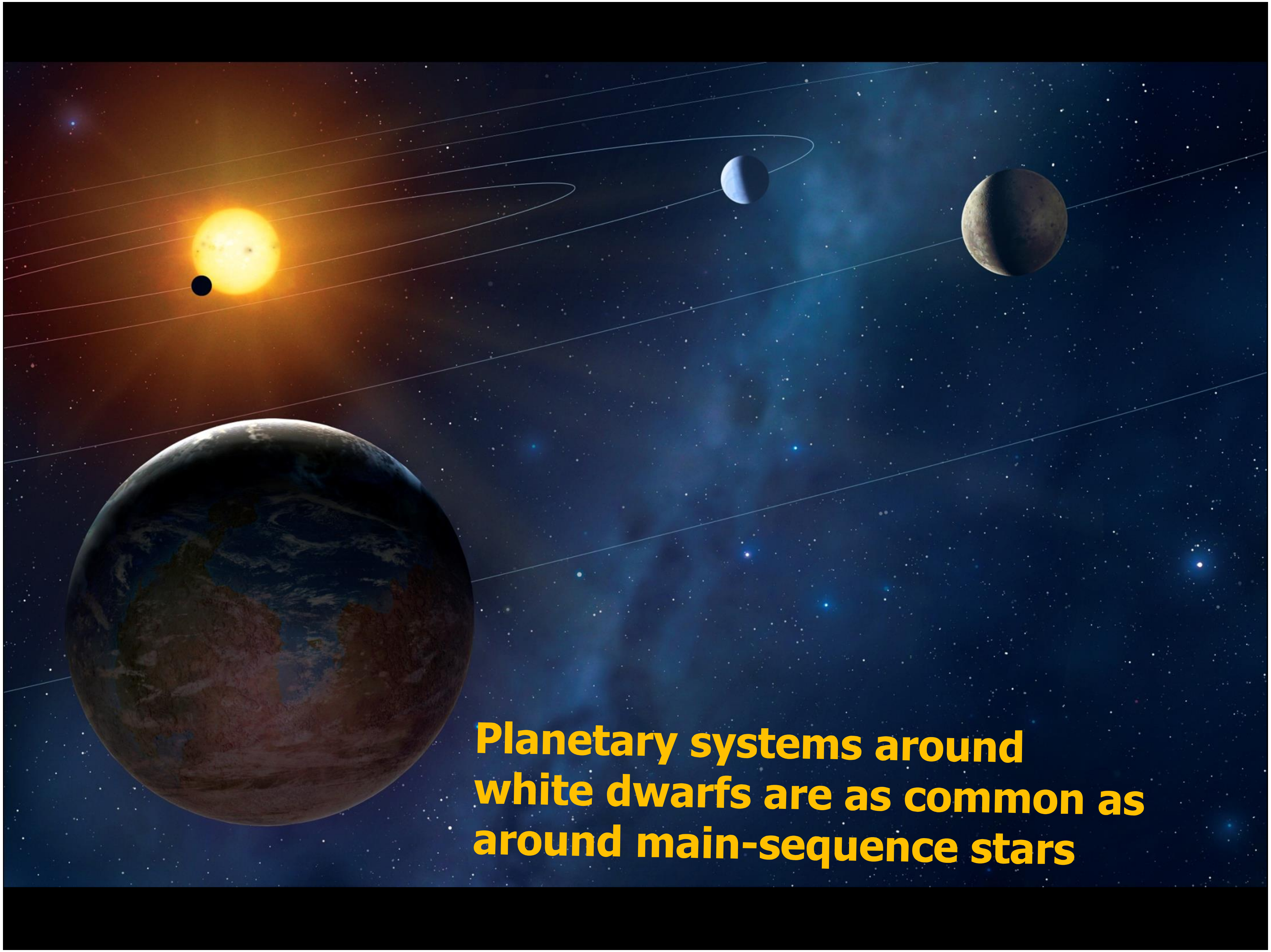
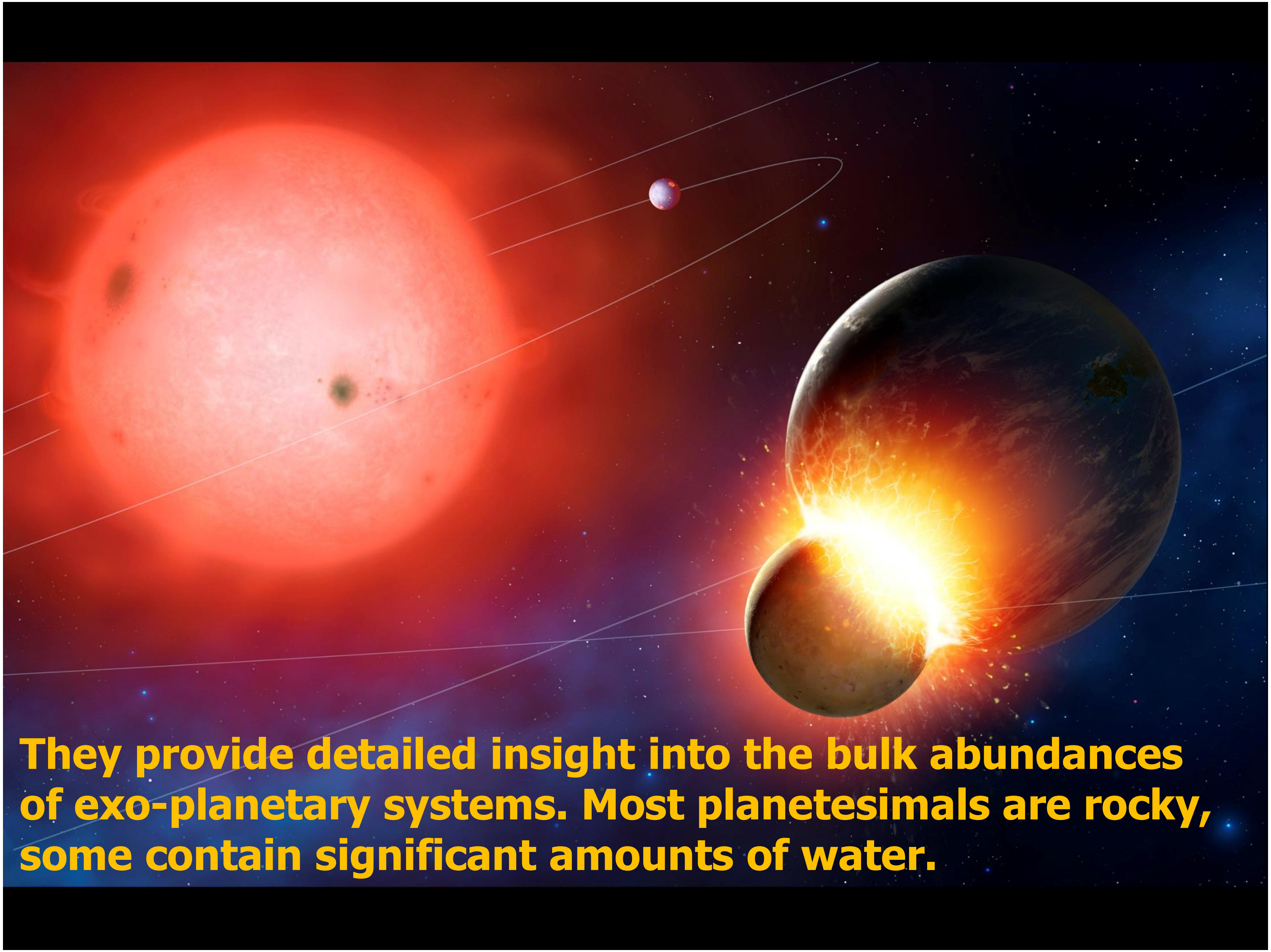
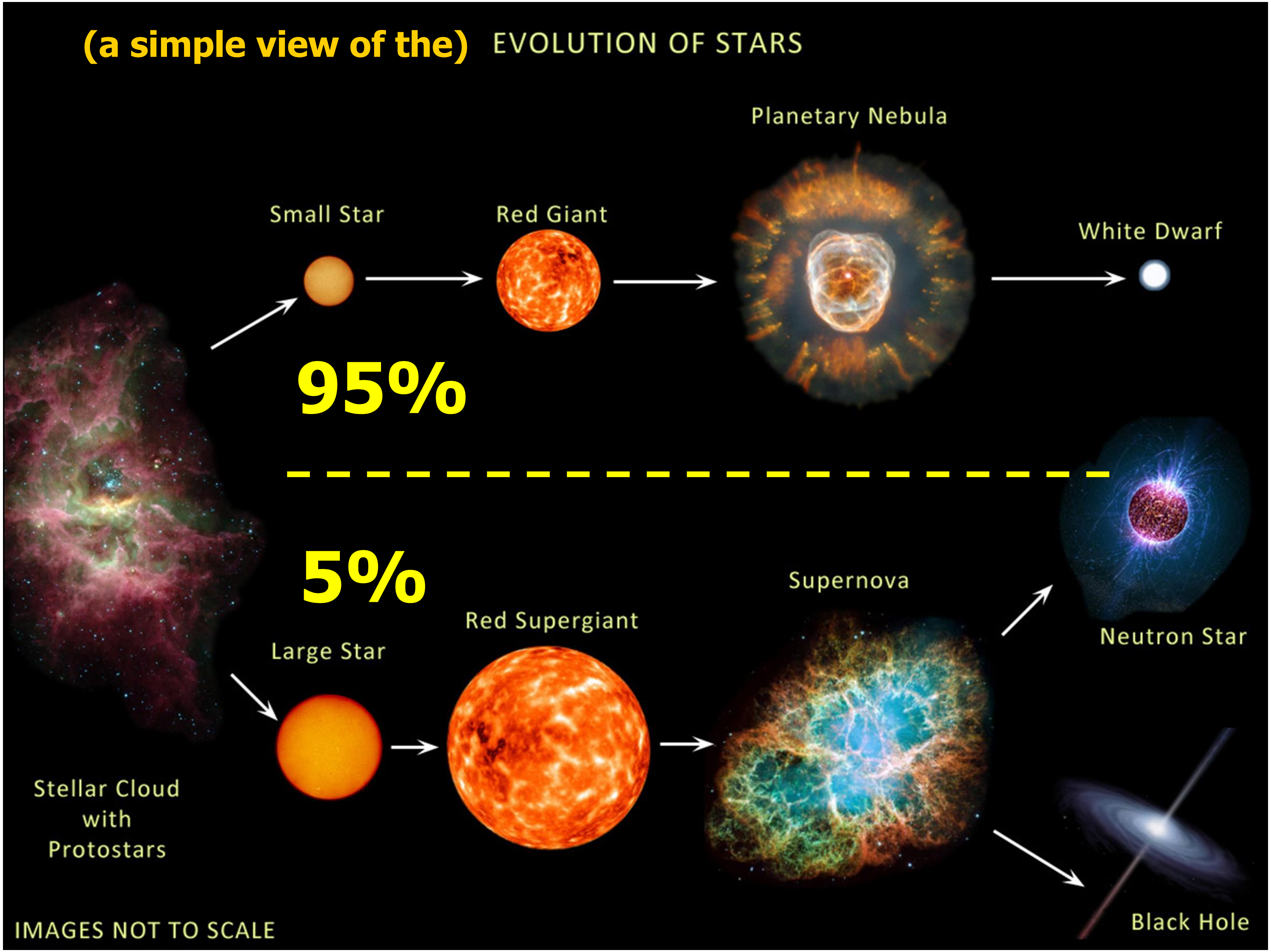

Planetary systems around
white dwarfs are as common as
around main-sequence stars


They provide detailed insight into the bulk abundances of exo-planetary systems. Most planetesimals are rocky, some contain significant amounts of water.


Disc life time? ~10^5yr
Jura 2008, AJ135, 1785
Girven et al. 2012, ApJ 749, 152
Transits: 3
⇓
Gas discs: ~0.1%
⇓
Dust discs: ~1%
⇓
Metal-pollution:25-50%
Bergfors et al. 2014, MNRAS 444, 2174
Rochetto et al. 2014, MNRAS 449, 564
Parent body masses? 10^{20}-10^{25}g
Girven et al. 2012, ApJ 749, 152
Many small vs few large events?
Wyatt et al. 2014, MNRAS 439, 3371
Underlying planetary system?
Veras et al. 2016, MNRAS 458, 3942
Tides...
Disruption...
Radiation effects (PR, YORP, Yarkovsky)...


(a simple view of the) EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
95%
5%
Supernova
Red Supergiant
Neutron Star
Large Star
Stellar Cloud with Protostars
Black Hole
IMAGES NOT TO SCALE