Properties of the giant planet around β Pictoris

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Thirty years of β Pictoris - Paris - September 9, 2014

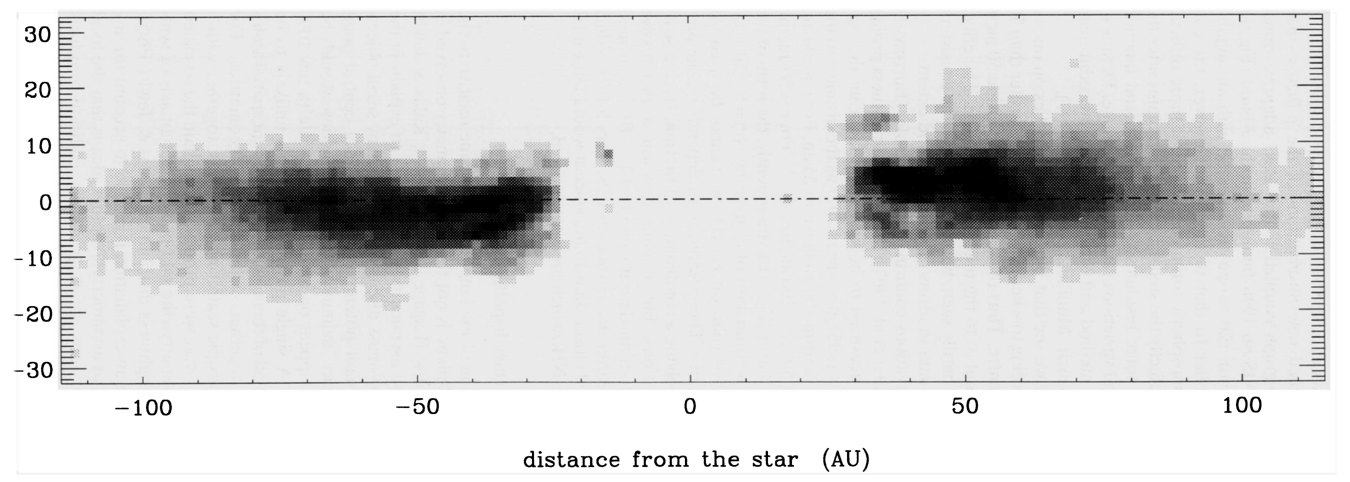
Outline

- A long-awaited discovery
- Orbital properties
- Physical properties & origins
- What can we do next?
- Conclusions

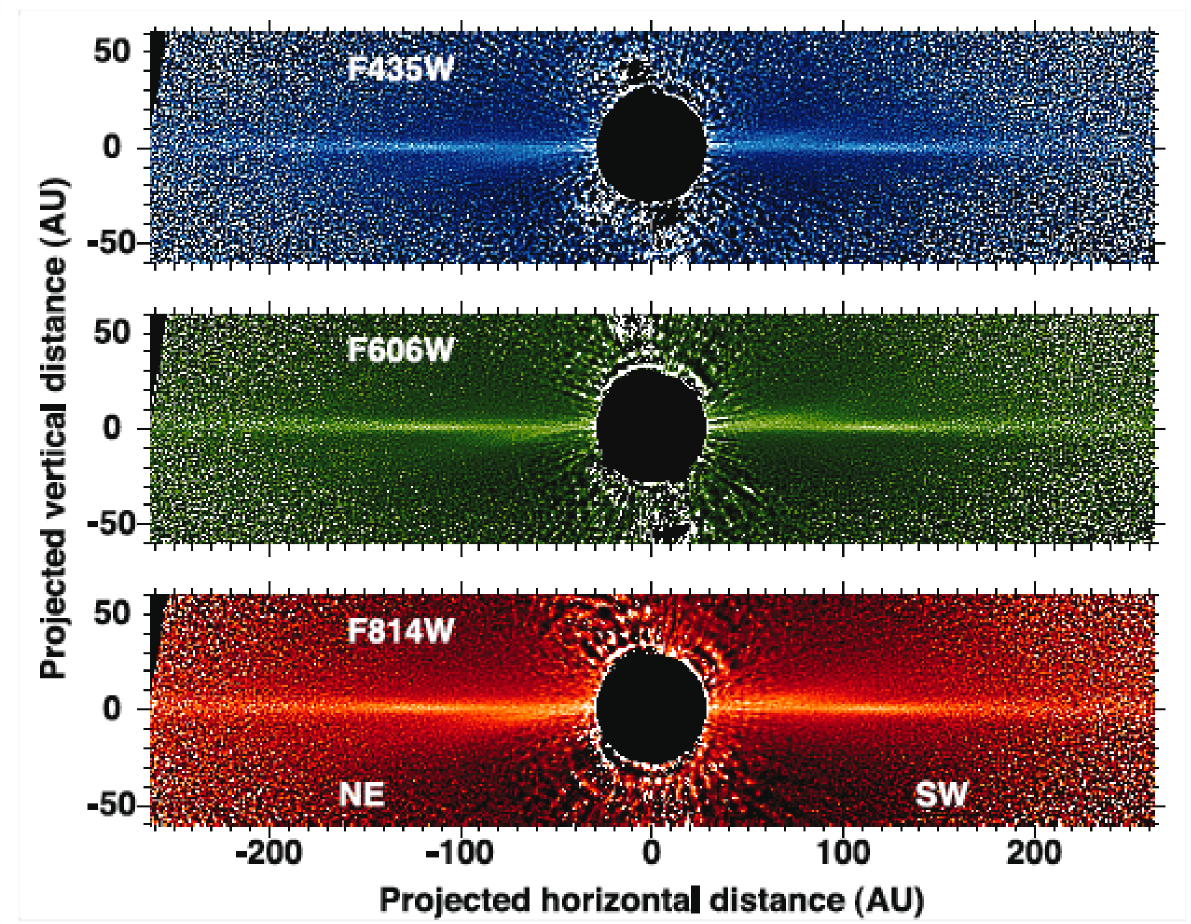
A long-awaited discovery

1/ Disk asymmetries

- Main disk (PA = 31.4°)
- Inner warp (PA = 35.6°)
- Global "Butterfly" asymmetries



Mouillet et al. 1997



Golimowski et al. 2006

If 1 planet between 3 and 20 AU on a tilted (3-5 °) orbit:

$0.5 \leq M/M_{Jup} \leq 17.5$

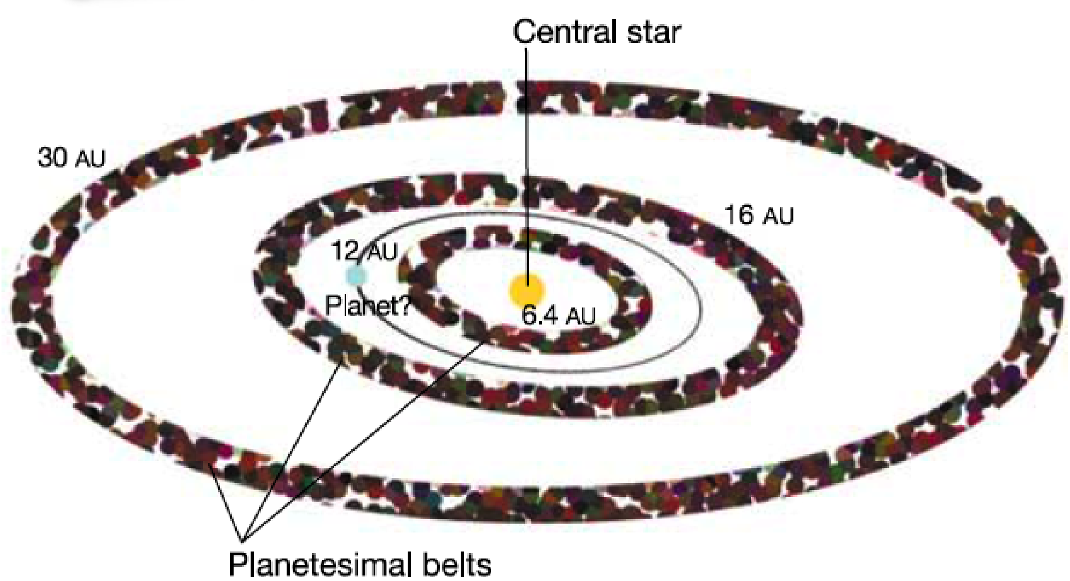
see also some more recent work by Lagrange et al. 2012 & Milli et al. 2014

A long-awaited discovery

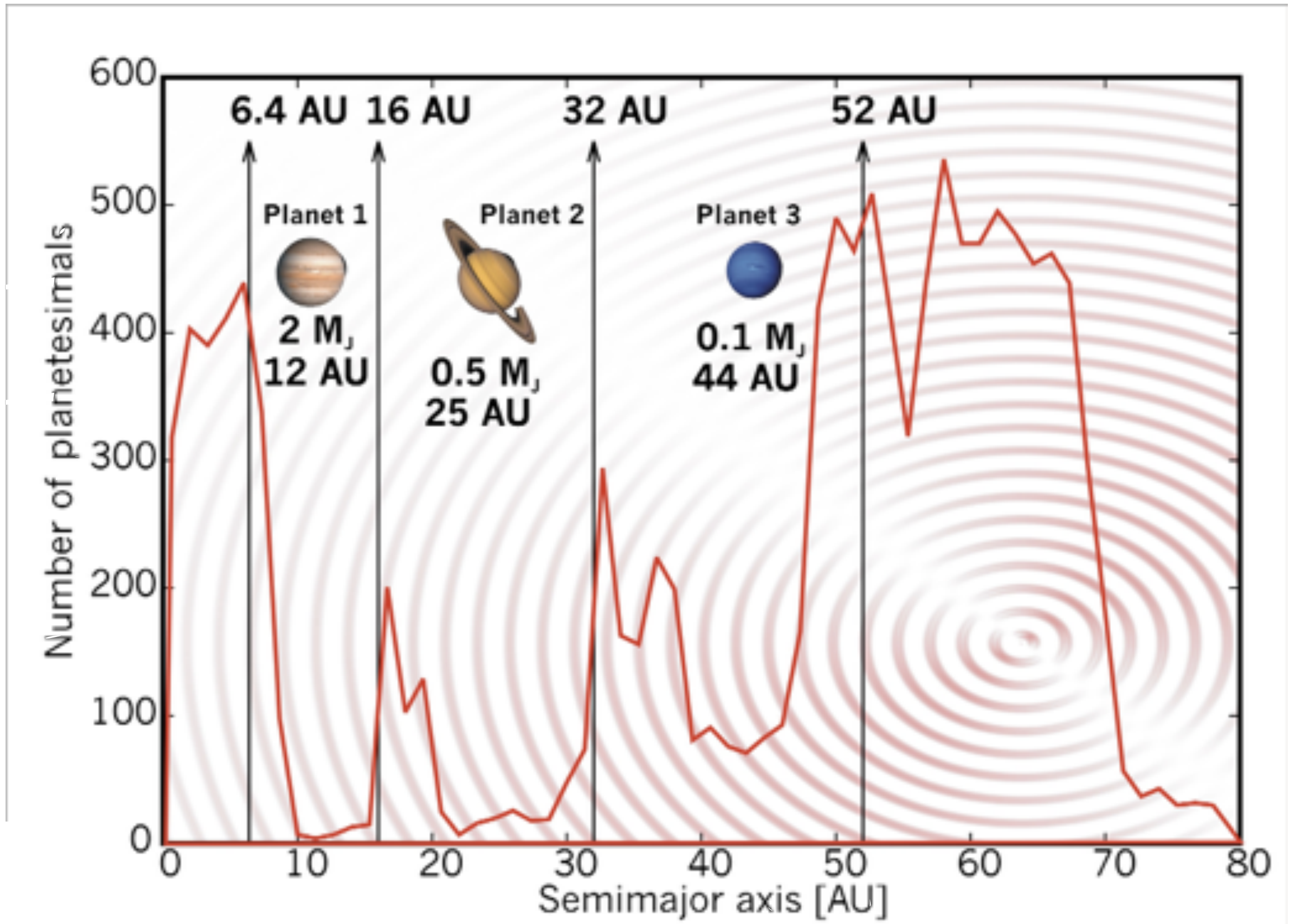
1/ Disk asymmetries

- Main disk (PA = 31.4°)
- Inner warp (PA = 35.6°)
- Global "Butterfly" asymmetries
- 4 Belts (6, 16, 32 and 52 AU)

➥ M. Keppler's poster



Okamoto et al. 2004



Freistetter et al. (2007)

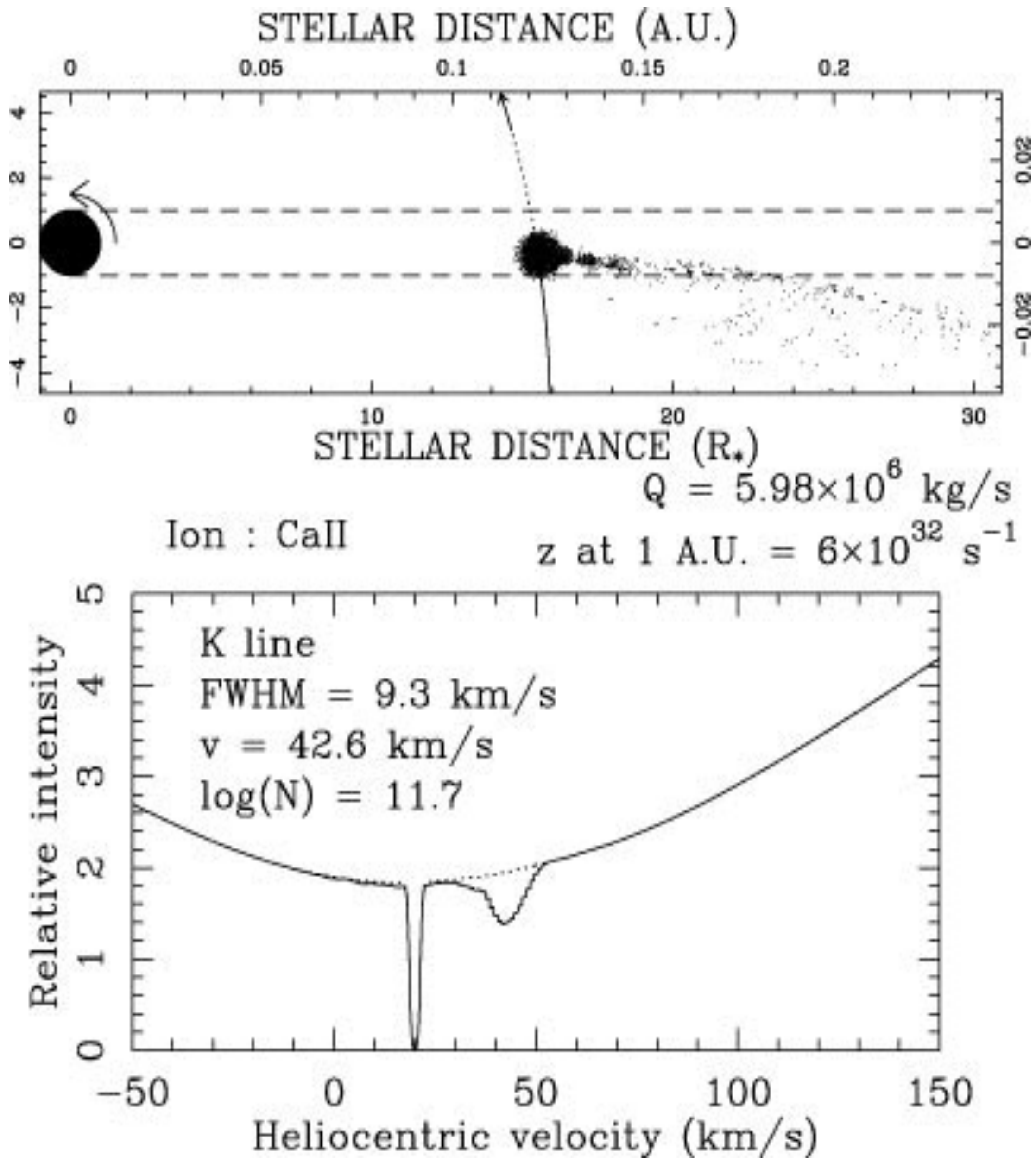
One 2–5 M_{Jup} planet at ~ 12 AU with e ≲ 0.1

A long-awaited discovery

2/ Falling evaporating bodies

Beust & Morbidelli 1990-2004 ; Beust & Valiron 2007

➥ H. Beust's talk



At least one giant planet at ~10 AU

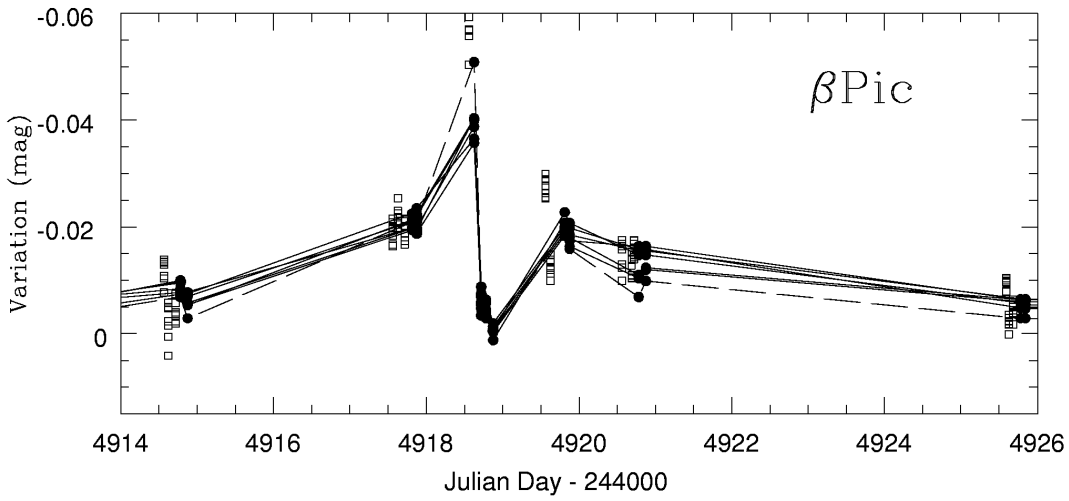
A long-awaited discovery

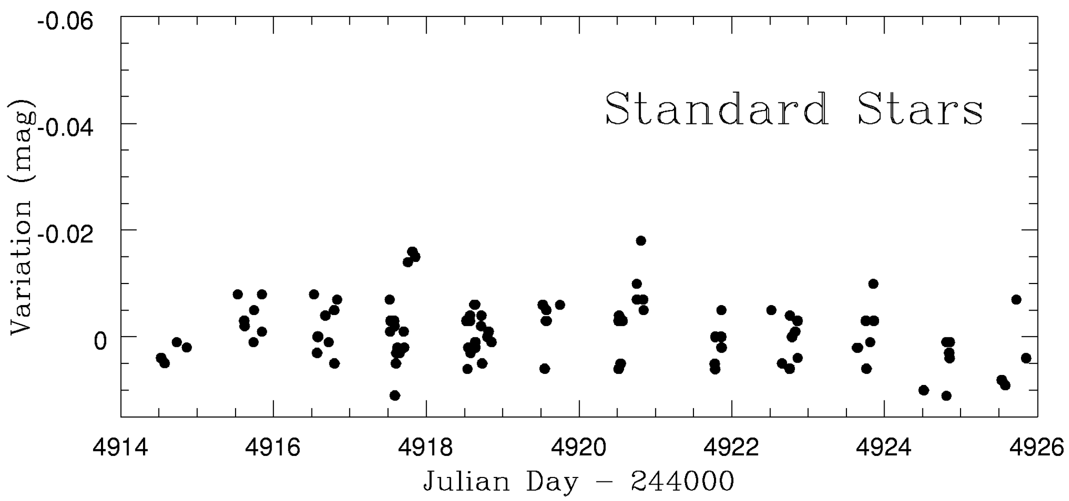
3/ Photometric event on Nov. 10, 1981 ?

Achromatic brightening by 0.06 mag in 10 days

Sharp decrease on Nov. 10

➥ A. Lecavelier's talk



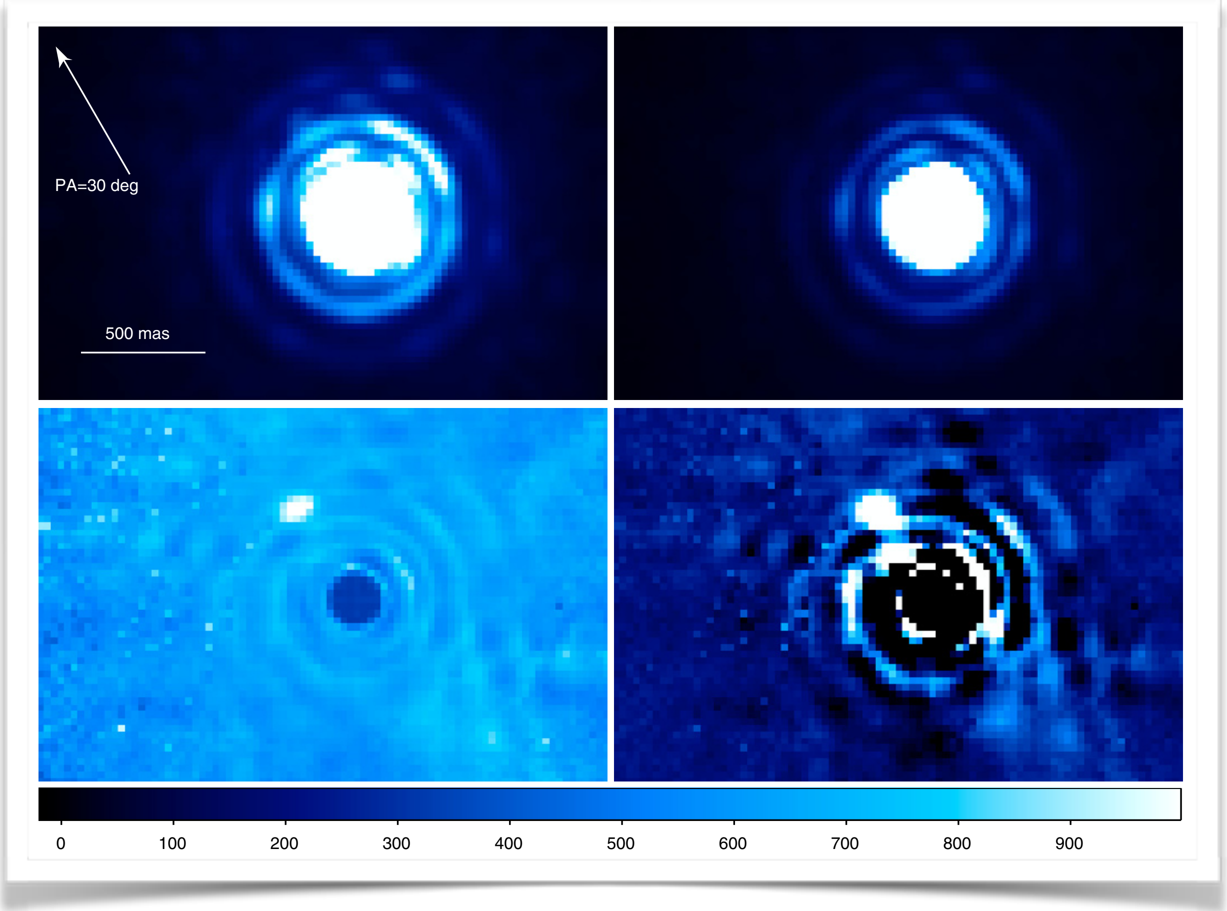


Lecavelier et al. 1995, 1997

Consistent with a *Jupiter-size planet > 6 AU*

A long-awaited discovery

The discovery



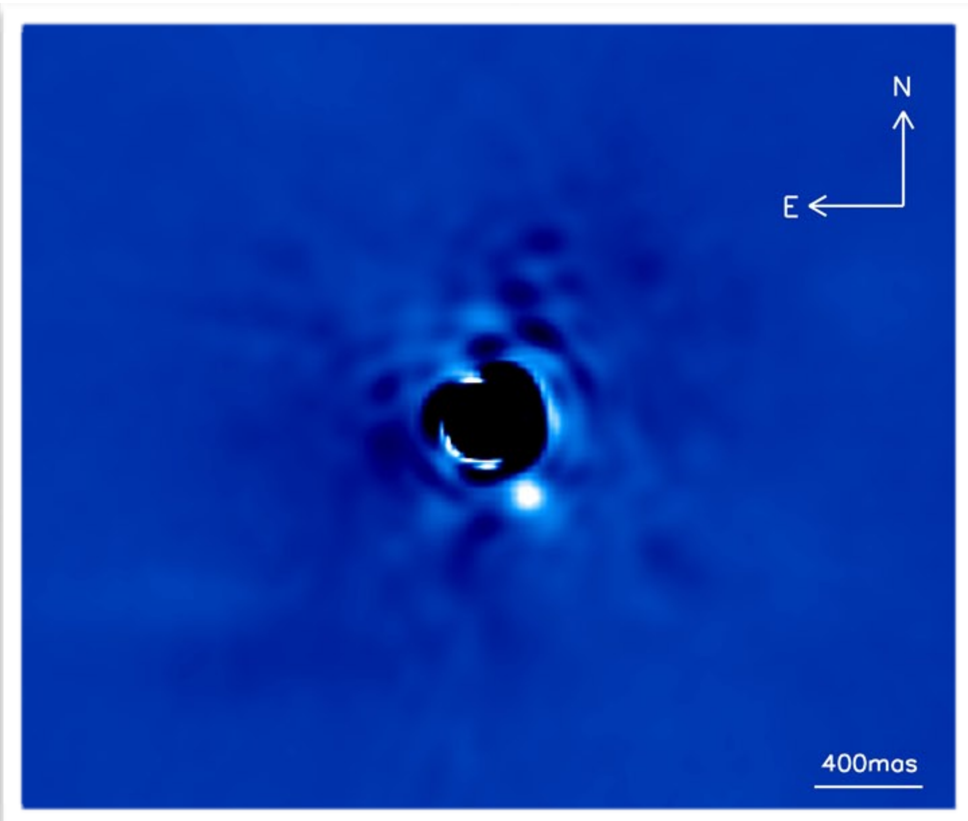
Lagrange et al. 2009

- VLT/NaCo, L′ band (3.8 µm)
- 3 datasets from Nov. 10 & 13, 2003
- field stabilized (no ADI!)

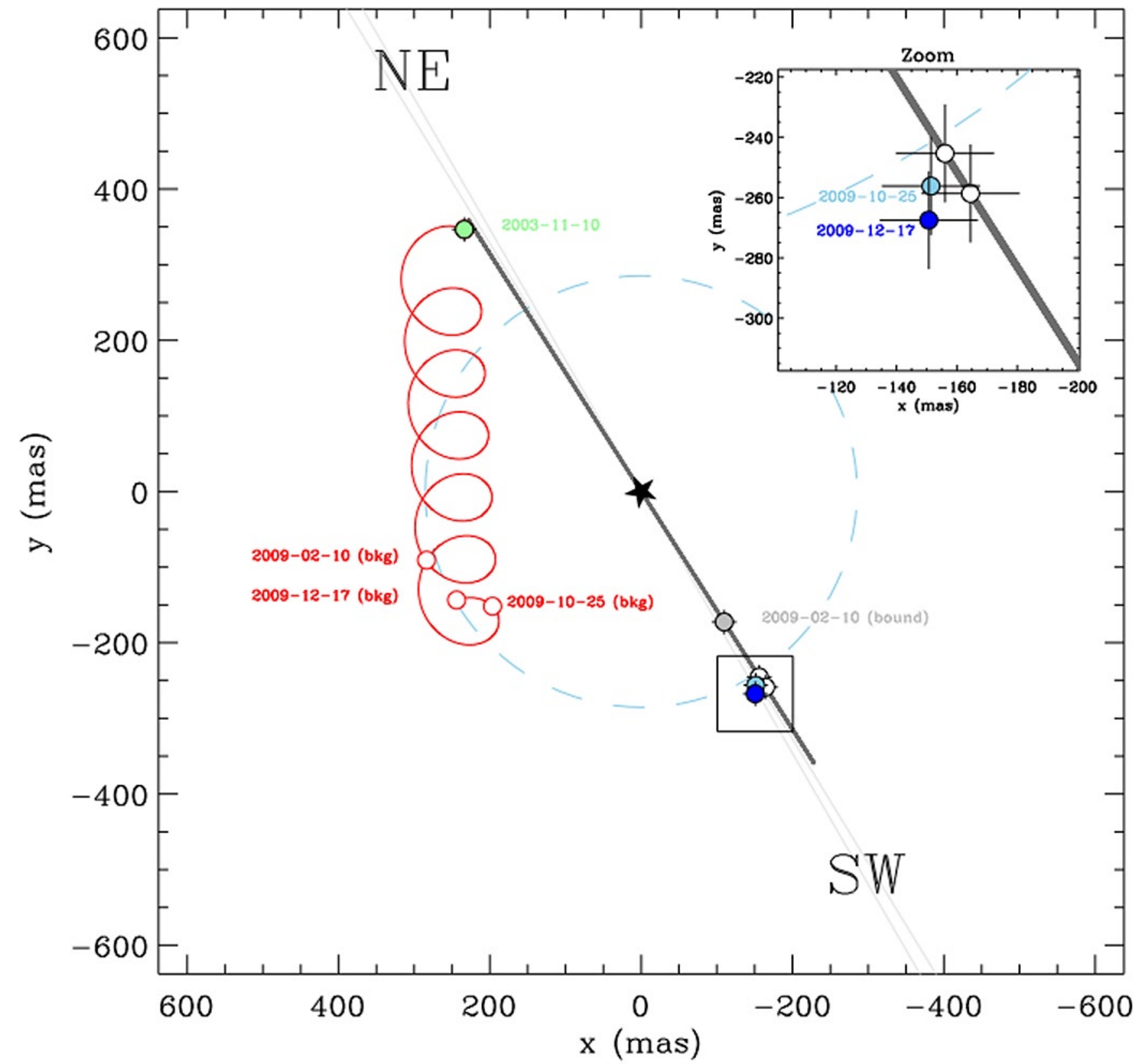
Compatible with a 8 M_{Jup} planet
Along NE side of the disk
Projected separation of 8 AU
T_{eff} around 1500 K
Comoving ?

A long-awaited discovery

The recovery

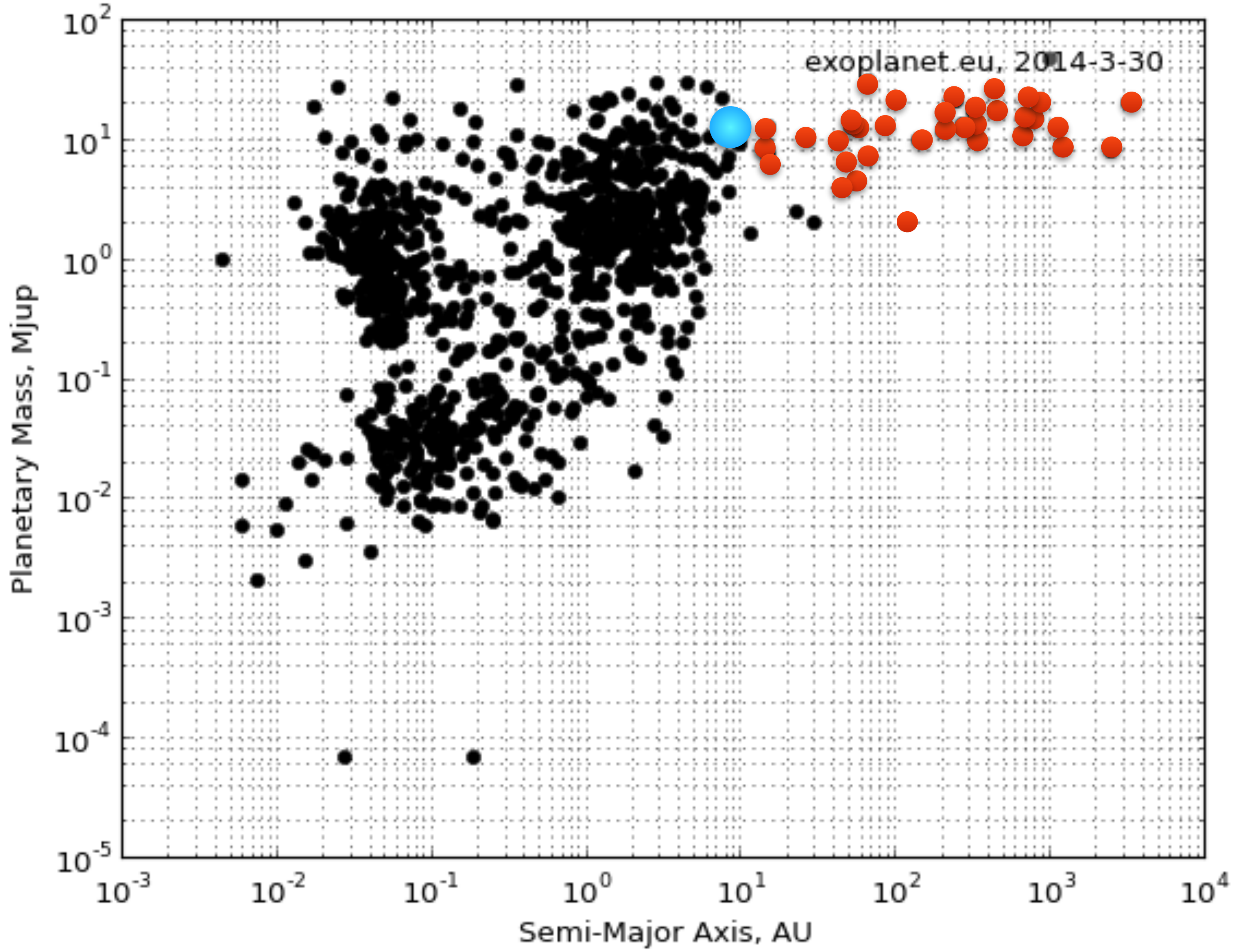


Lagrange et al. 2010



- VLT/NaCo, L′ band (3.8 μm)
- 6 datasets from Oct. to Dec. 2009
- field stabilized & ADI

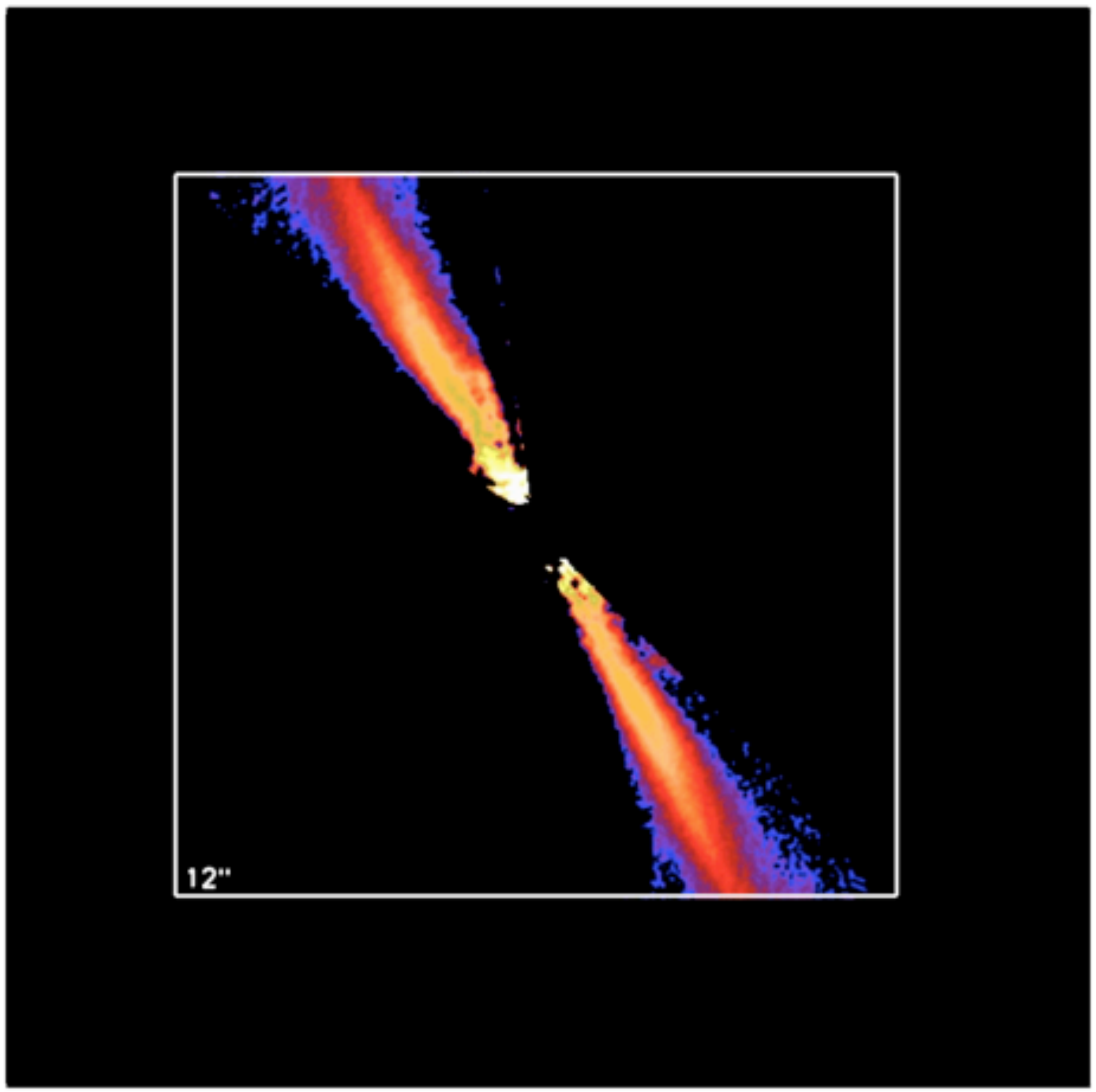
A long-awaited discovery



Orbital properties

Monitoring

➥ E. Nielsen's talk



NaCo: from Nov. 2003 until Jan. 2013

NICI: Dec. 2009 until March 2012

MagAO: December 2012

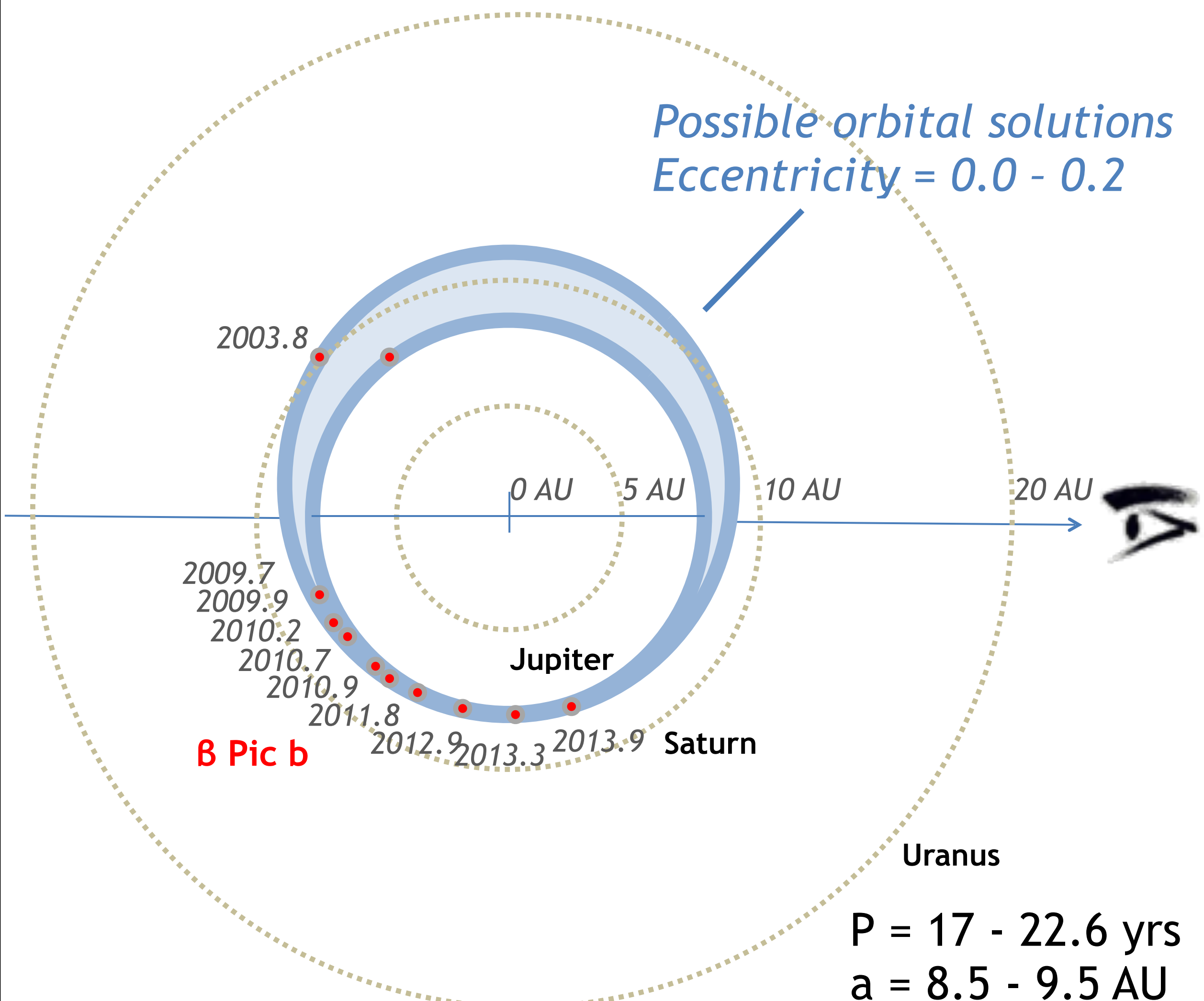
GPI: November-December 2013

Currie et al. 2011
Chauvin et al. 2012
Nielsen et al. 2014
Boccaleti et al. 2013
Macintosh et al. 2014
Bonnefoy et al. 2014
Males et al. 2014
Absil et al. 2013

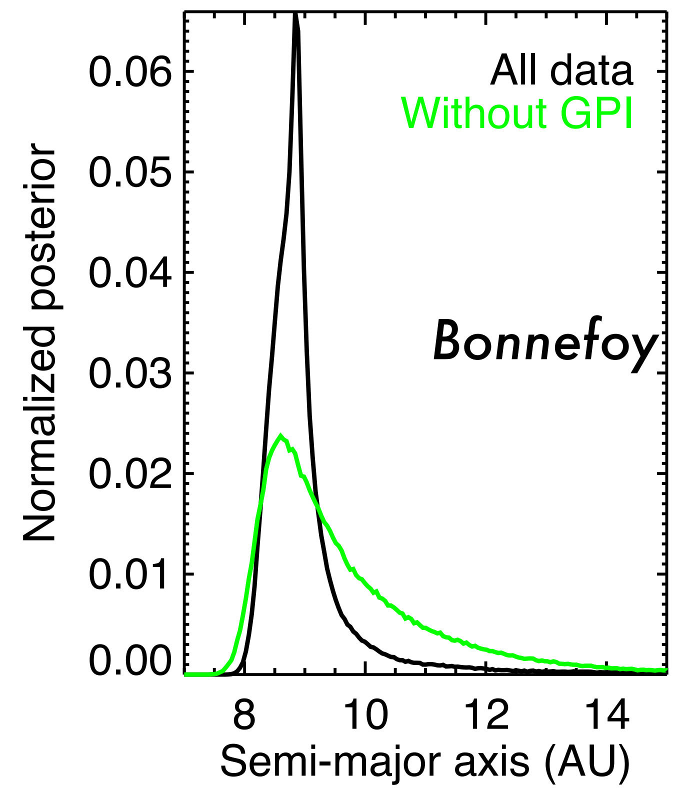
Orbital properties

Monitoring

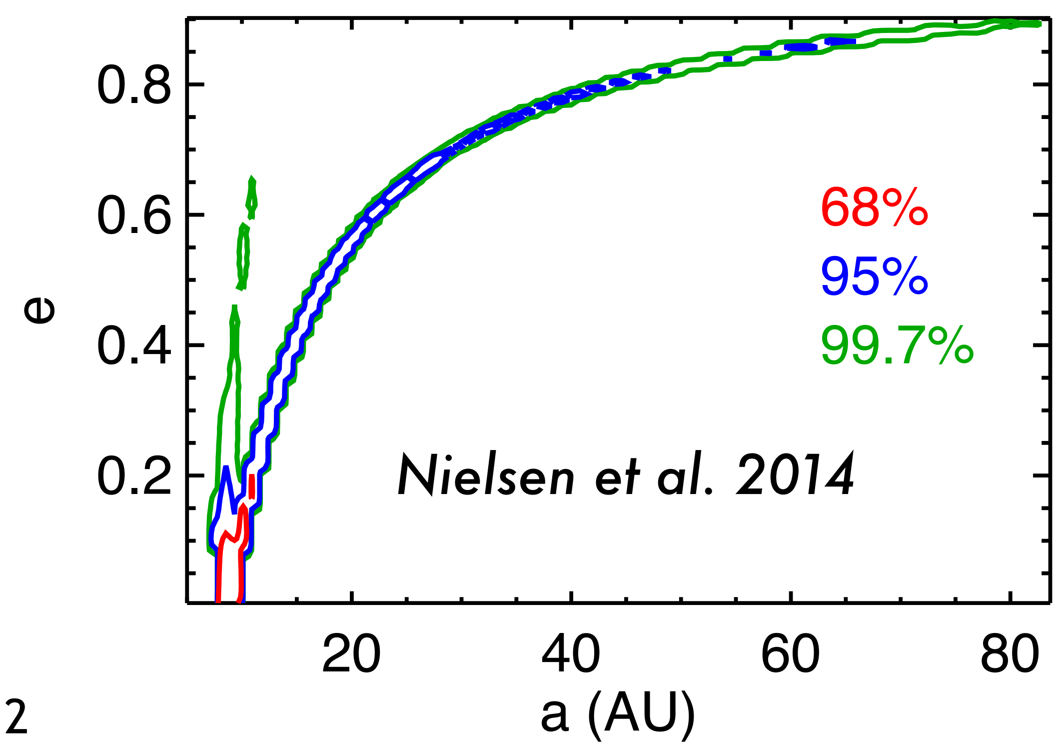
➥ E. Nielsen's talk



P = 17 - 22.6 yrs
a = 8.5 - 9.5 AU
e < 0.2
i = 90.7 +- 0.7 deg
Ω = 211.6 +- 0.5 deg
Quadrature : summer 2012



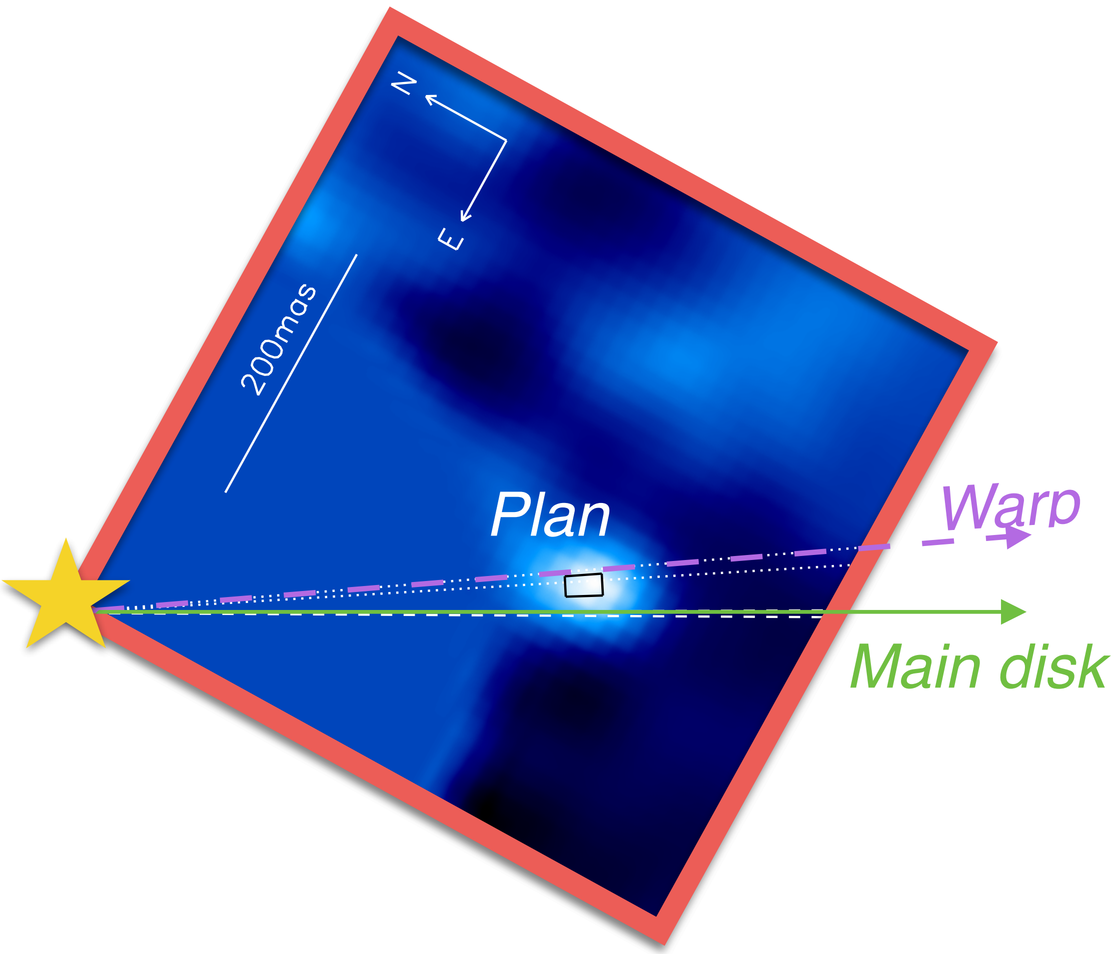
Bonnefoy et al. 2014

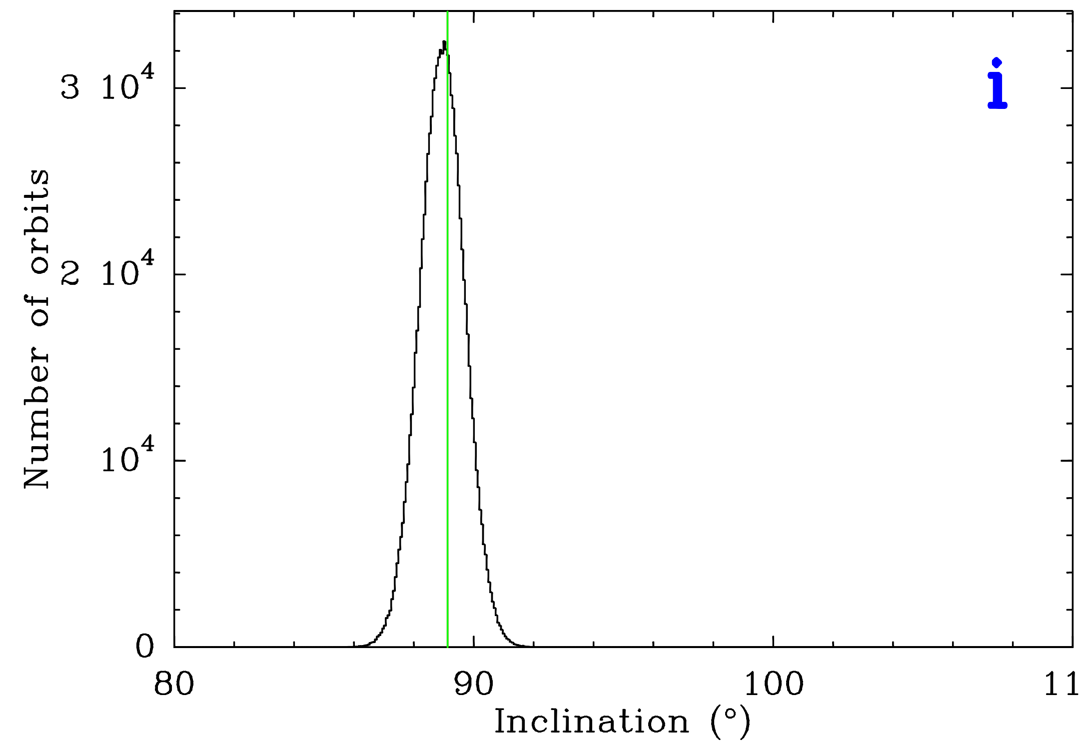


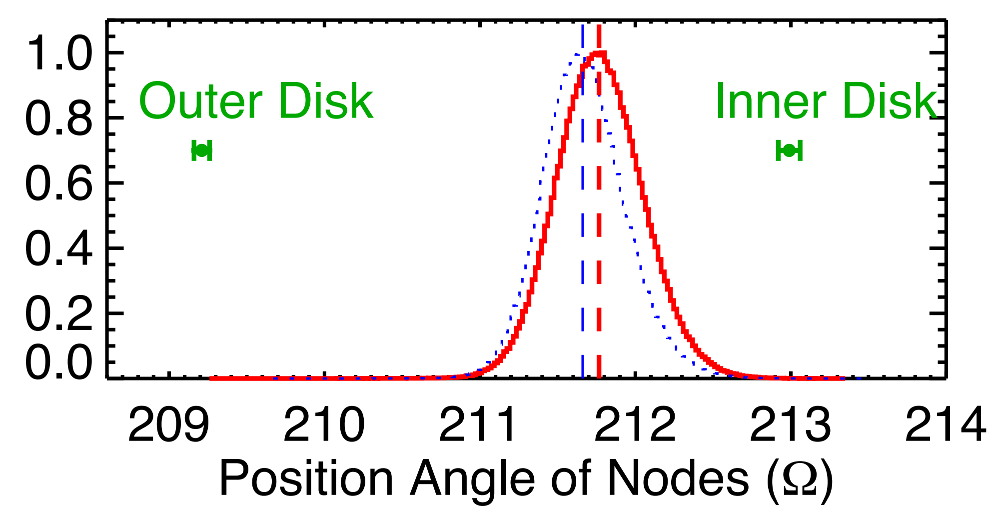
Nielsen et al. 2014

Orbital properties

Planet vs disk







Lagrange et al. 2012
Chauvin et al. 2012
Nielsen et al. 2014

➥ E. Nielsen's talk + J. Milli's poster

Orbital properties

Radial velocity & dynamical mass

Upper limits before quadrature for a circular orbit (Lagrange et al. 2012) : 15.5 M_{Jup} for a=10 AU

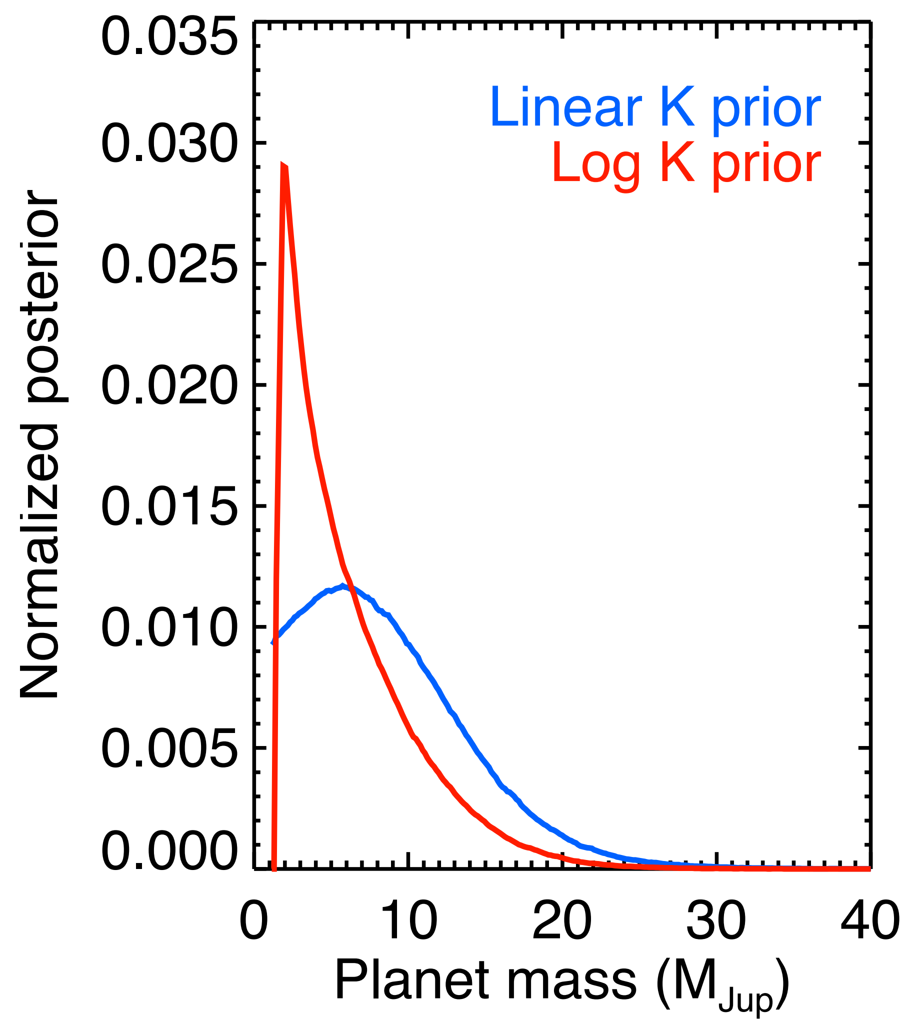
Now for two priors, RV+imaging gives:

$M \leq 20\ M_{Jup}$ (96% probability)

Lagrange et al. 2012
Bonnefoy et al. 2014
Borgniet et al. in prep

➥ S. Borgniet's talk

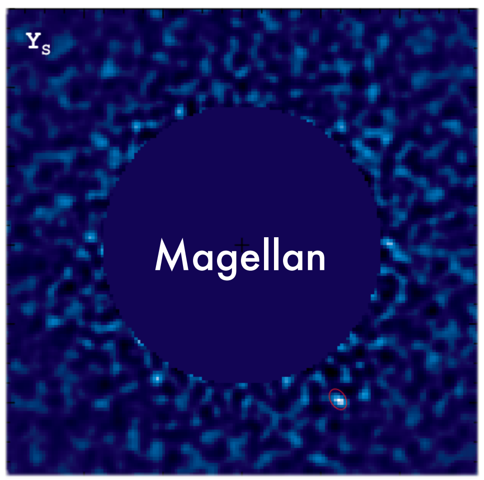
Bonnefoy et al. 2014



Physical properties & origins

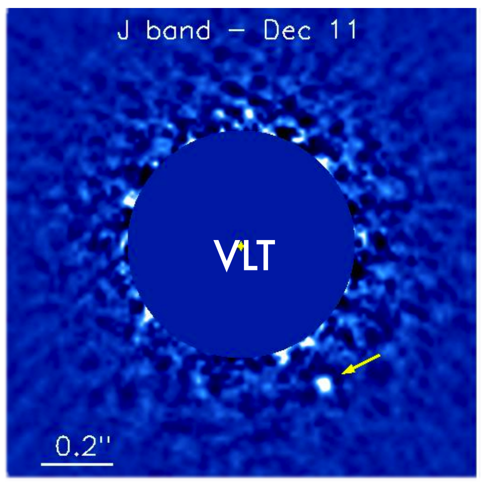
Multi-λ imaging

0.985 μm (Ys)



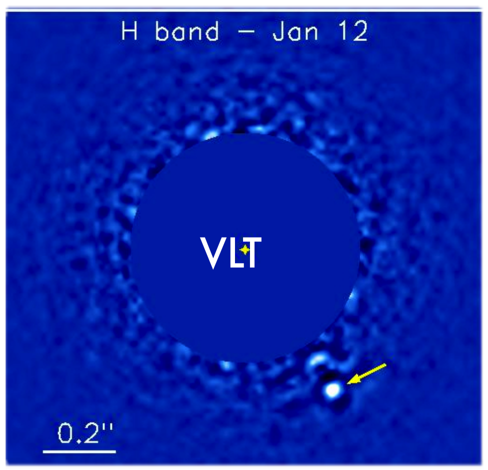
(Males et al. 2014)

1.25 μm (J)



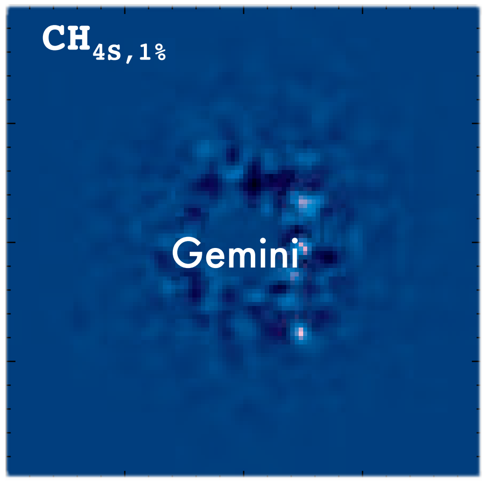
(Bonnefoy et al. 2013)

1.65 μm (H)



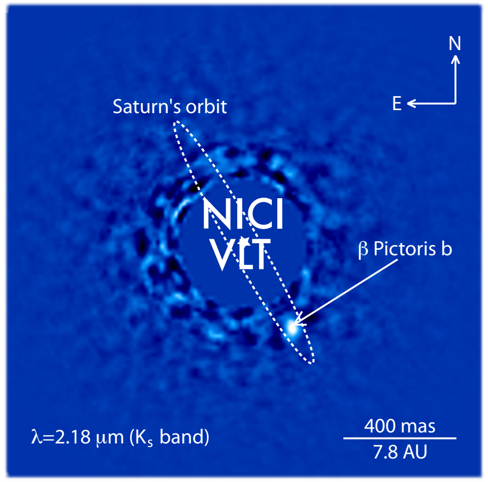
(Bonnefoy et al. 2013)

1.58 μm (CH4S)



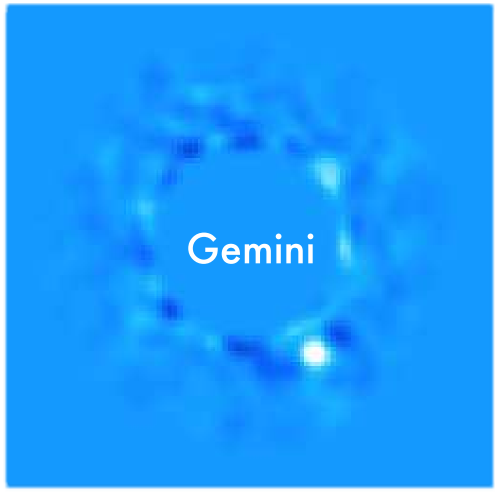
(Males et al. 2014)

2.18, 2.27 μm (Ks, K_{cont})



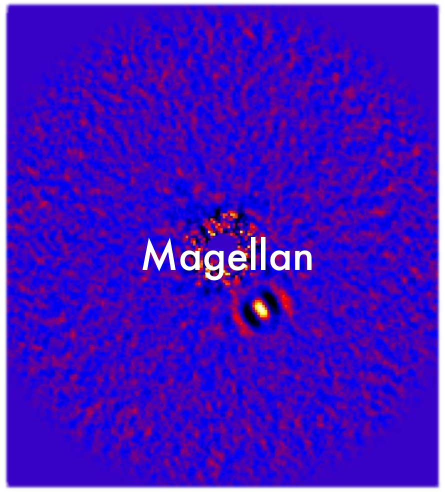
(Bonnefoy et al. 2011)
(Males et al. 2014)

3.1 μm (H_2O)



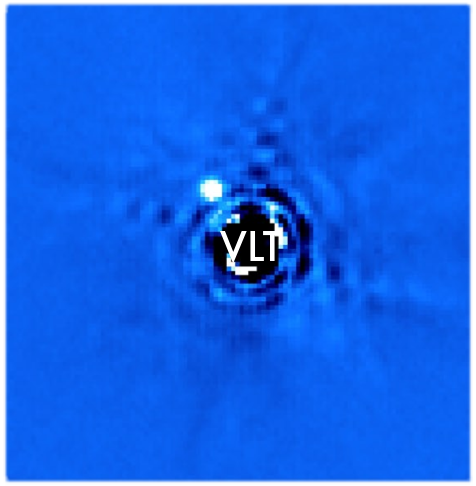
(Currie et al. 2013)

3.3 μm ([3.3])



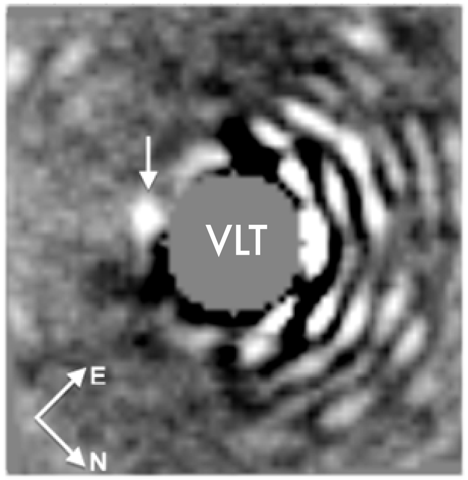
(Morzinkski et al. 2014)

3.8 μm (L ')



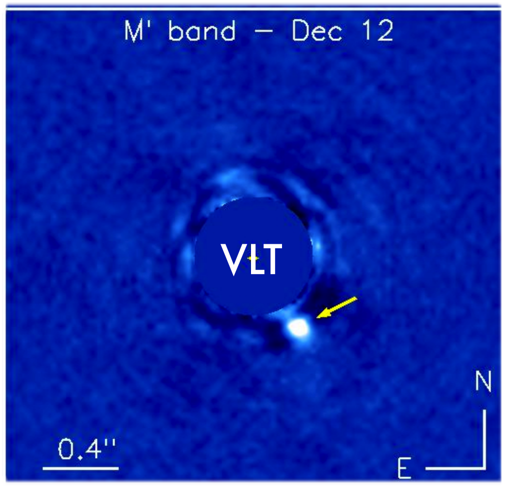
(Lagrange et al. 2009)

4.05 μm ([4.05])



(Quanz et al. 2010)

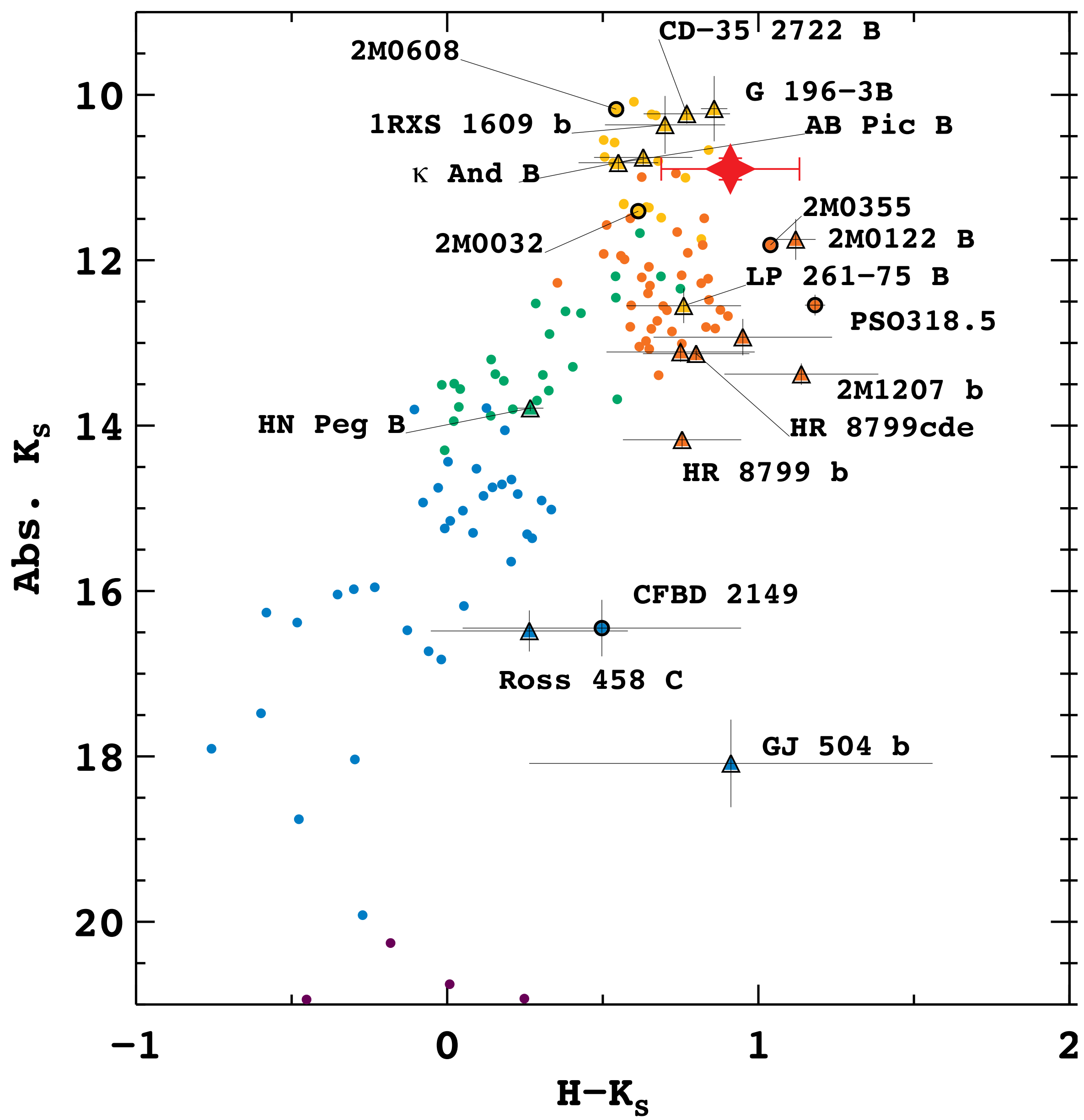
4.8 μm (M')



(Bonnefoy et al. 2013)

Physical properties & origins

Multi-λ imaging



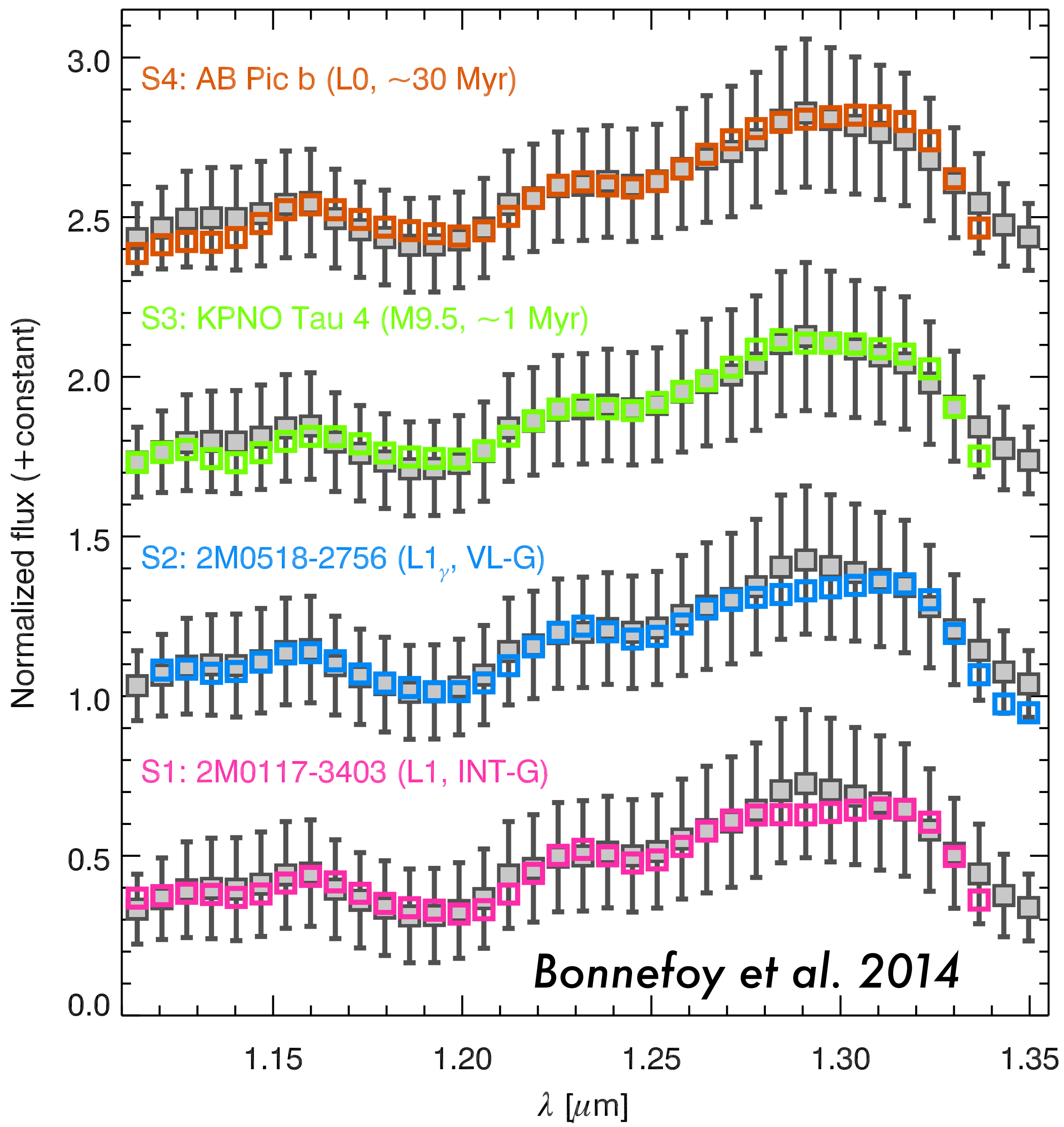
Males et al. 2014

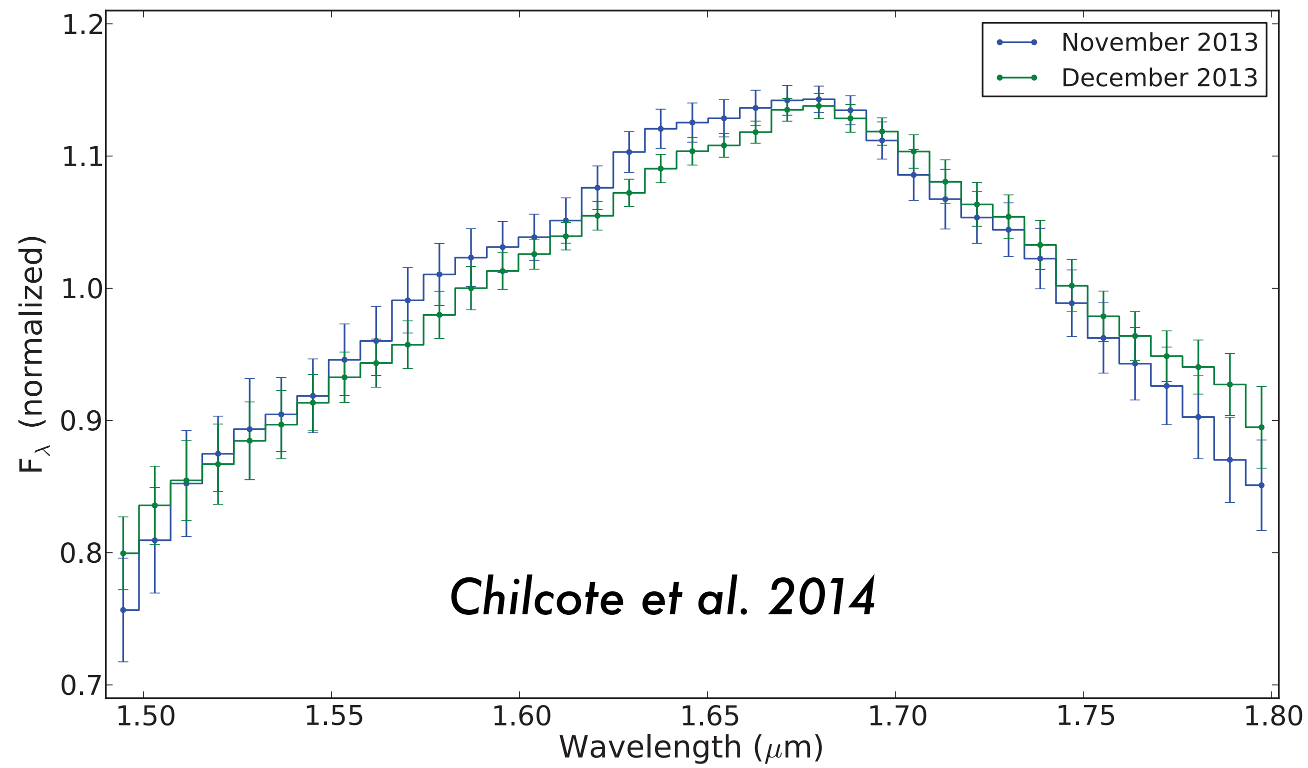
Comparable to young early-L dwarfs

⇒ Bolometric luminosity

Physical properties & origins

Spectroscopy with the planet imagers



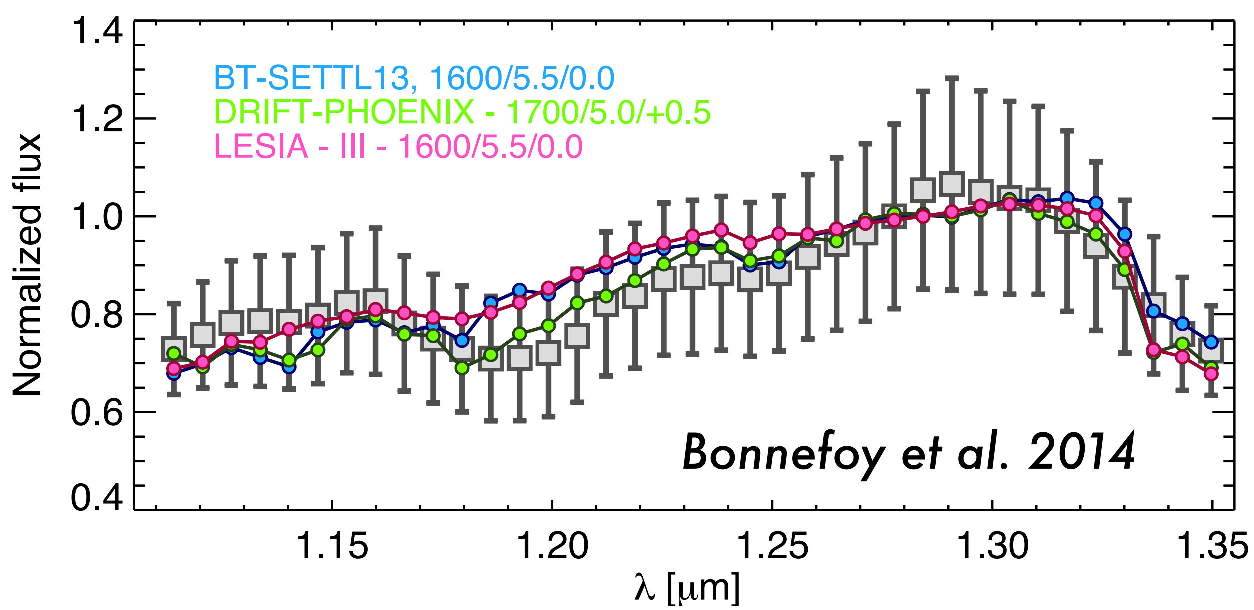


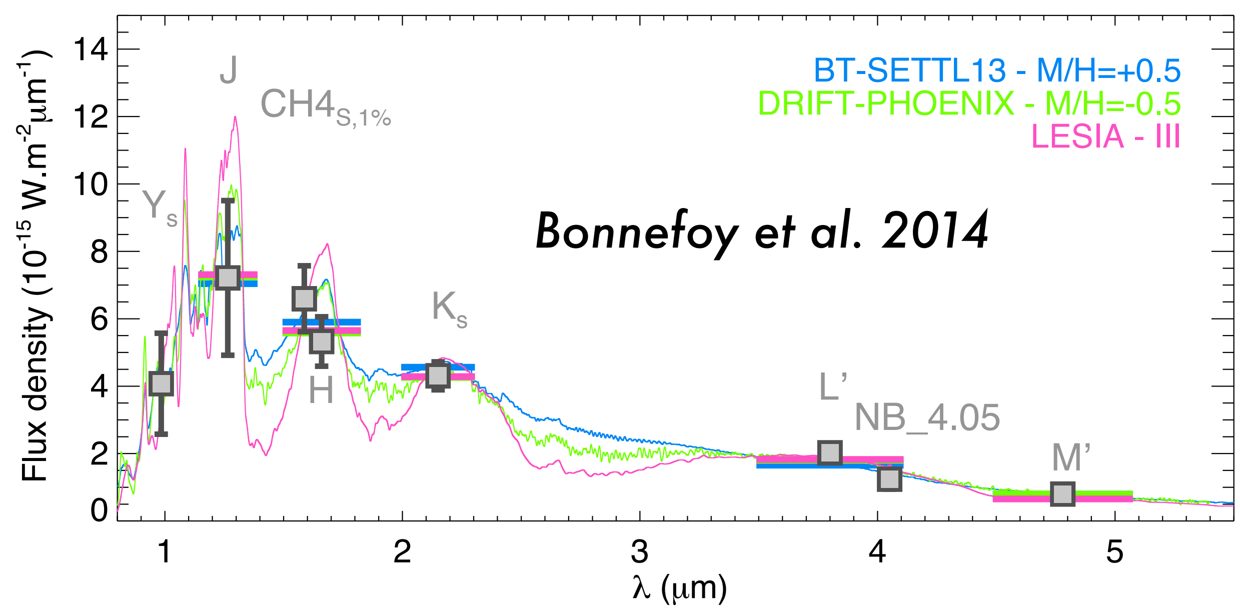
Confirm sp. type & low gravity

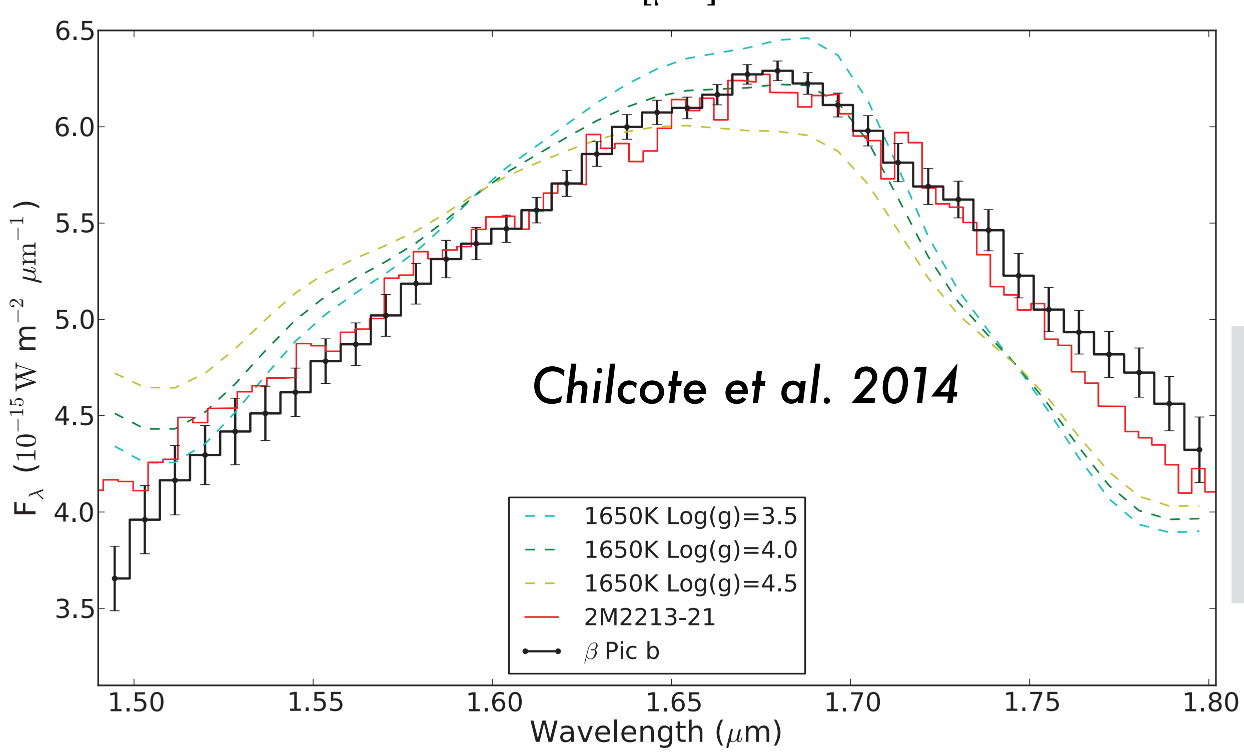
➥ J. Chilcote's talk

Physical properties & origins

Atmospheric parameters







Good test for models: BT-SETTL, DRIFT-PHOENIX, LESIA, Burrow's, Barman's

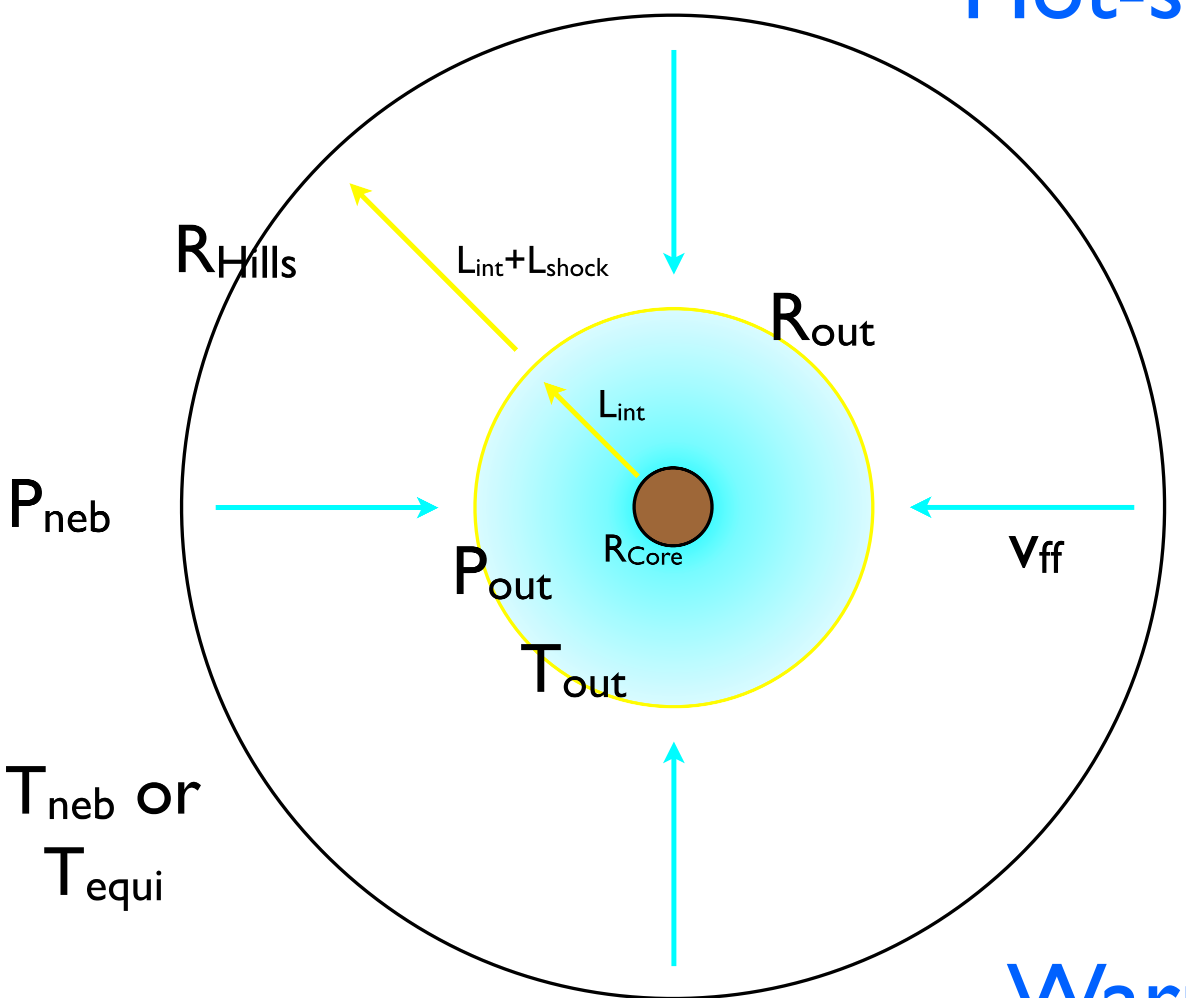
T_{eff}=1650 K, log g=4.0

⇒ R=1.4 R_{Jup}

➥ J. Chilcote's talk

Physical properties & origins

Mass & initial entropy



Courtesy C. Mordasini

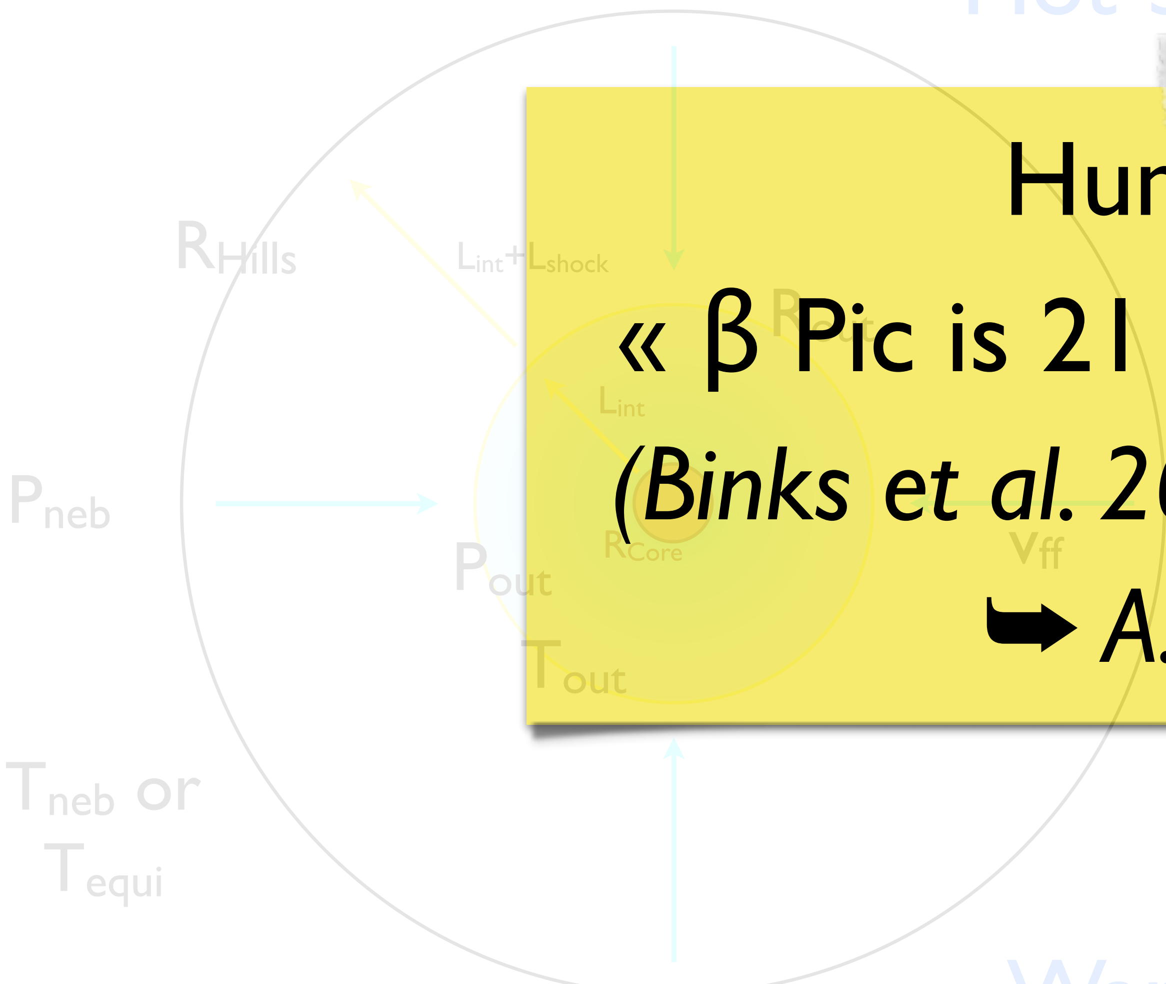
Hot-start: gravitational energy fully enters the object
(e.g Chabrier et al. 2000, Burrows et al. 1997)

Cold-start: gravitational energy of infalling gaz is radiated away into space.
(Marley et al. 2007, Fortney & Marley 2008)

Warm-start: cooling curves depend on the the initial entropy (S_{init}) and object mass (M)
(Spiegel & Burrows 2012, Marleau & Cumming 2013)

Physical properties & origins

Mass & initial entropy



Courtesy C. Mordasini

Hot-start:

(e.g Chabrier et al. 2000, Burrows et al. 1997)

Hummm wait!

« β Pic is 21 Myr old, not 12!… »

(Binks et al. 2014, Malo et al. 2014)

➥ *A. Binks's talk*

Cold-start:

infalling gas is radiated away into space.

(Marley et al. 2007, Fortney & Marley 2008)

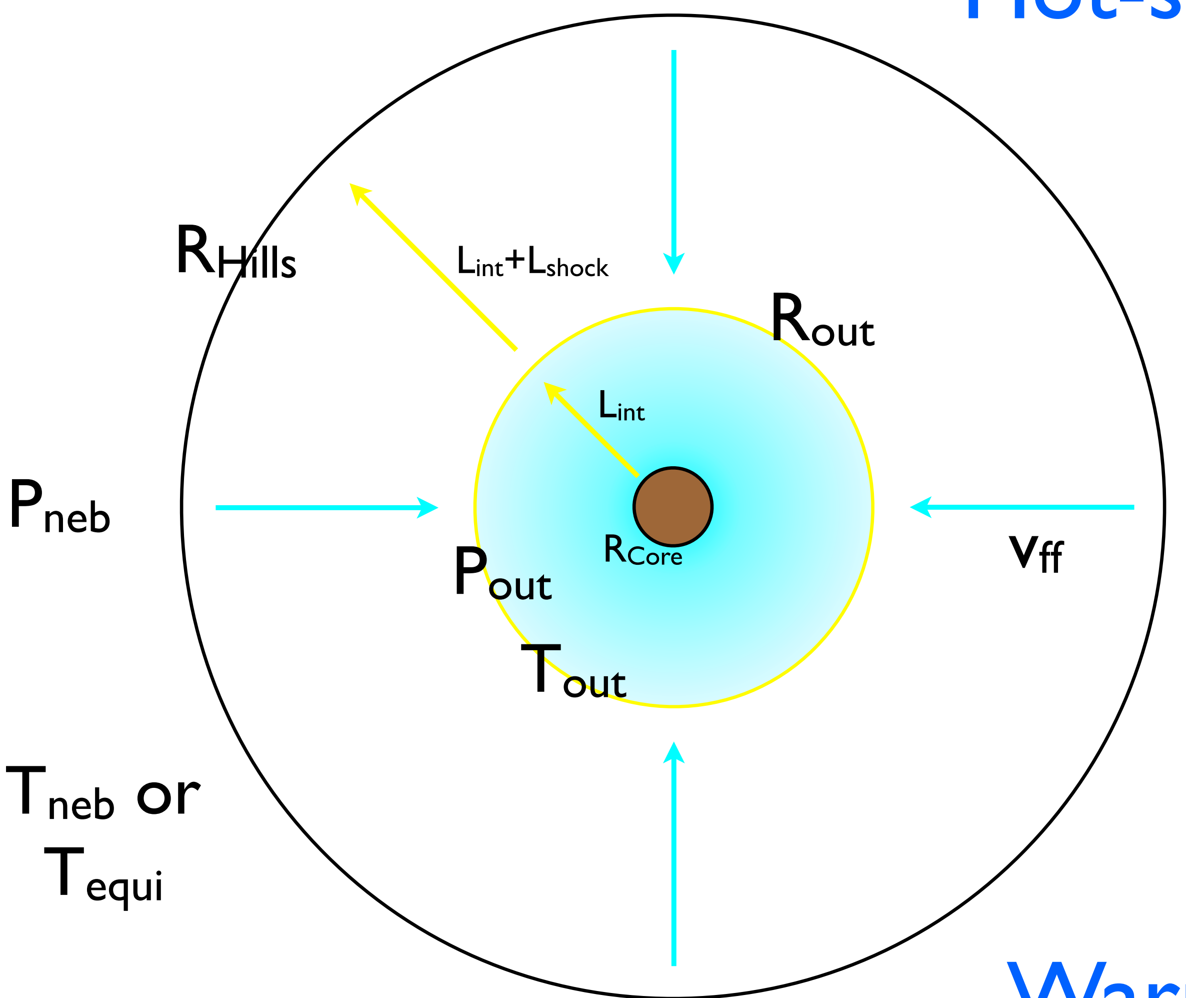
Warm-start:

the initial entropy (S

(Spiegel & Burrows 2012, Marleau & Cumming 2013)

Physical properties & origins

Mass & initial entropy



Courtesy C. Mordasini

Hot-start: gravitational energy fully enters the object

(e.g Chabrier et al. 2000, Burrows et al. 1997)

> $\Rightarrow$ *M= 10 to12 M_{Jup}*

~~**Cold-start:** gravitational energy of infalling gaz is radiated away into space.~~

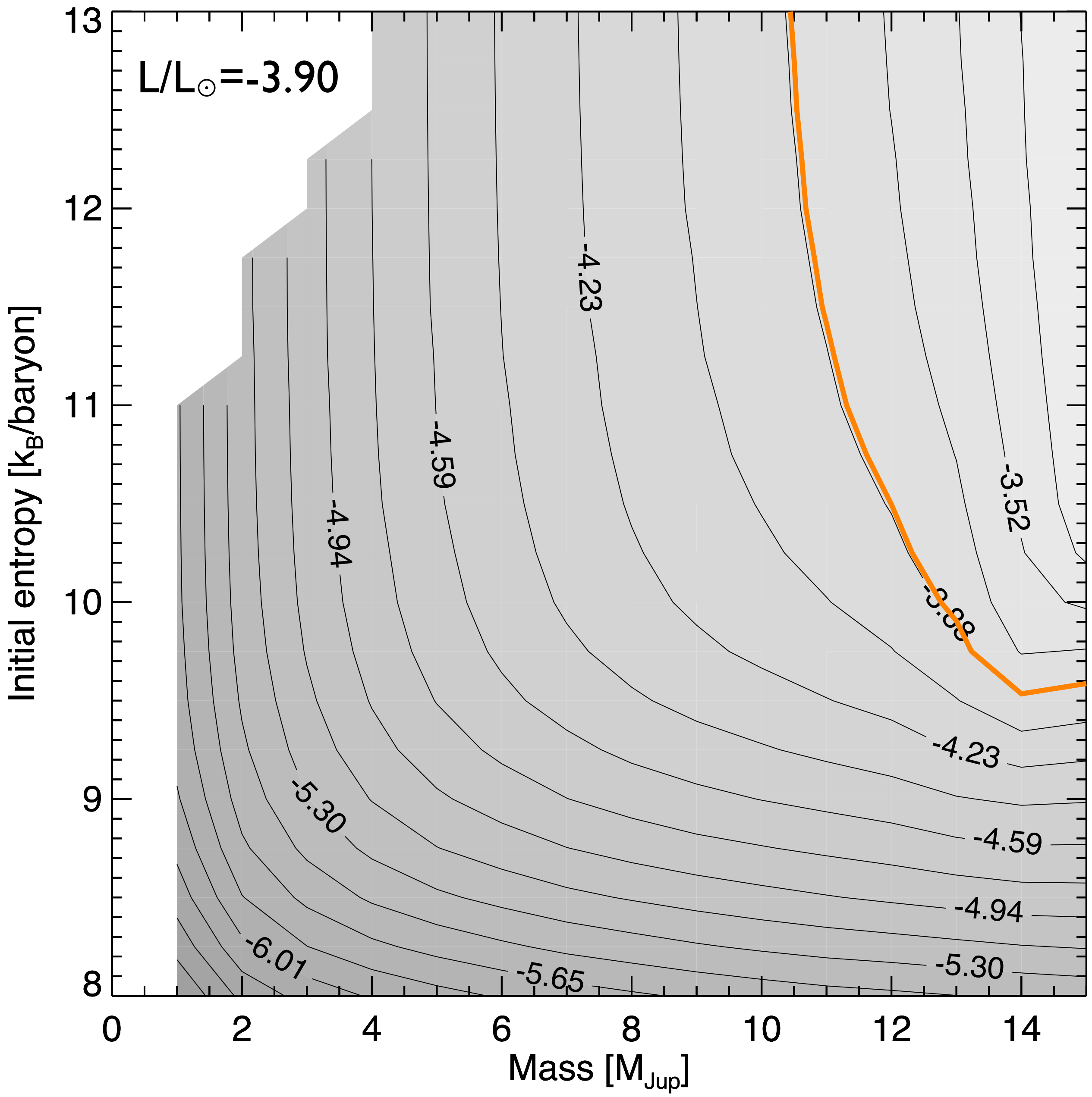
~~(Marley et al. 2007, Fortney & Marley 2008)~~

Warm-start: cooling curves depend on the the initial entropy (S_{init}) and object mass (M)

(Spiegel & Burrows 2012, Marleau & Cumming 2013)

Physical properties & origins

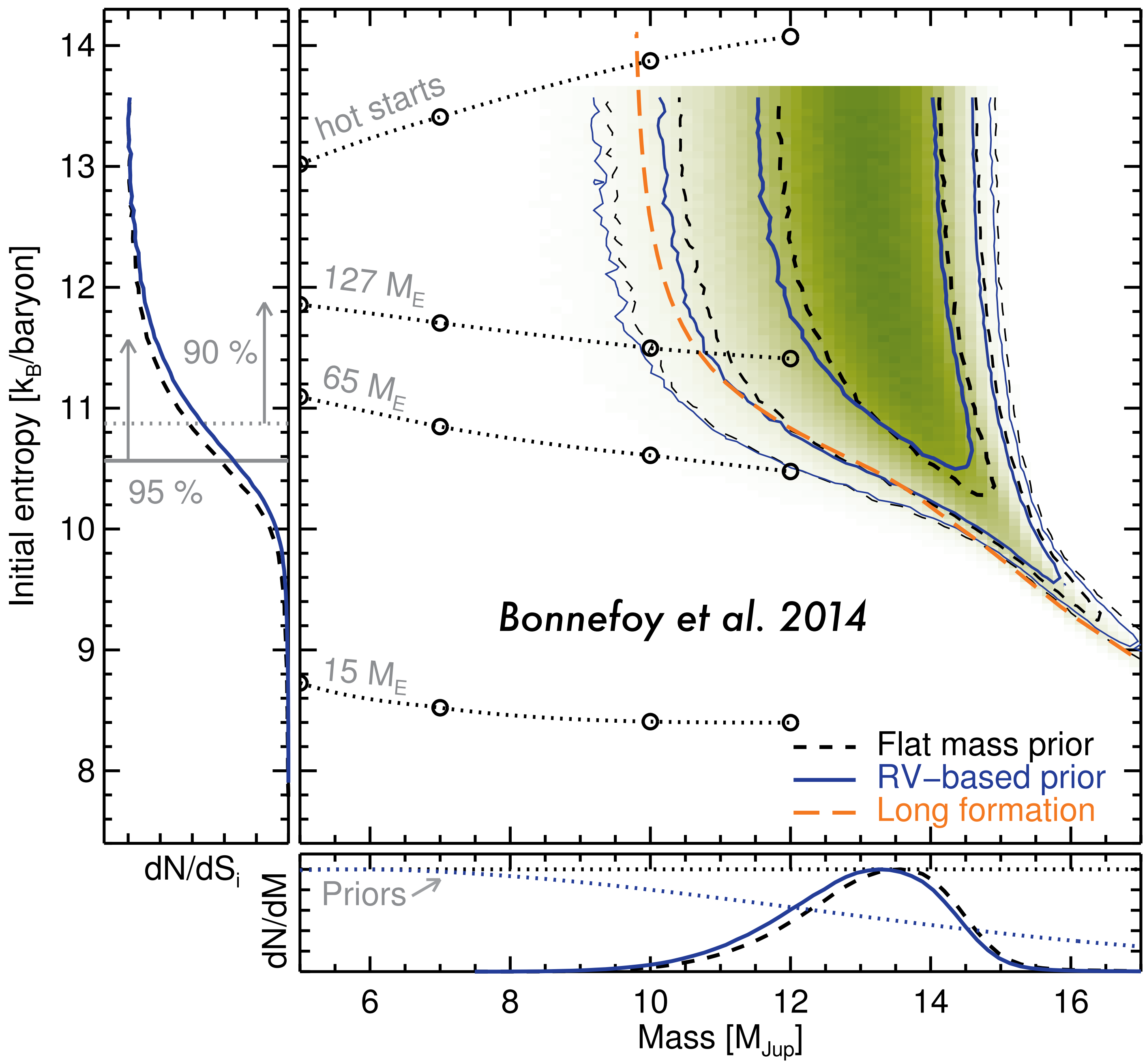
Mass & initial entropy



For a given age, predicted luminosities increase with mass and S_{init}

Physical properties & origins

Mass & initial entropy



S_{init} > 10.5 K_b/baryon

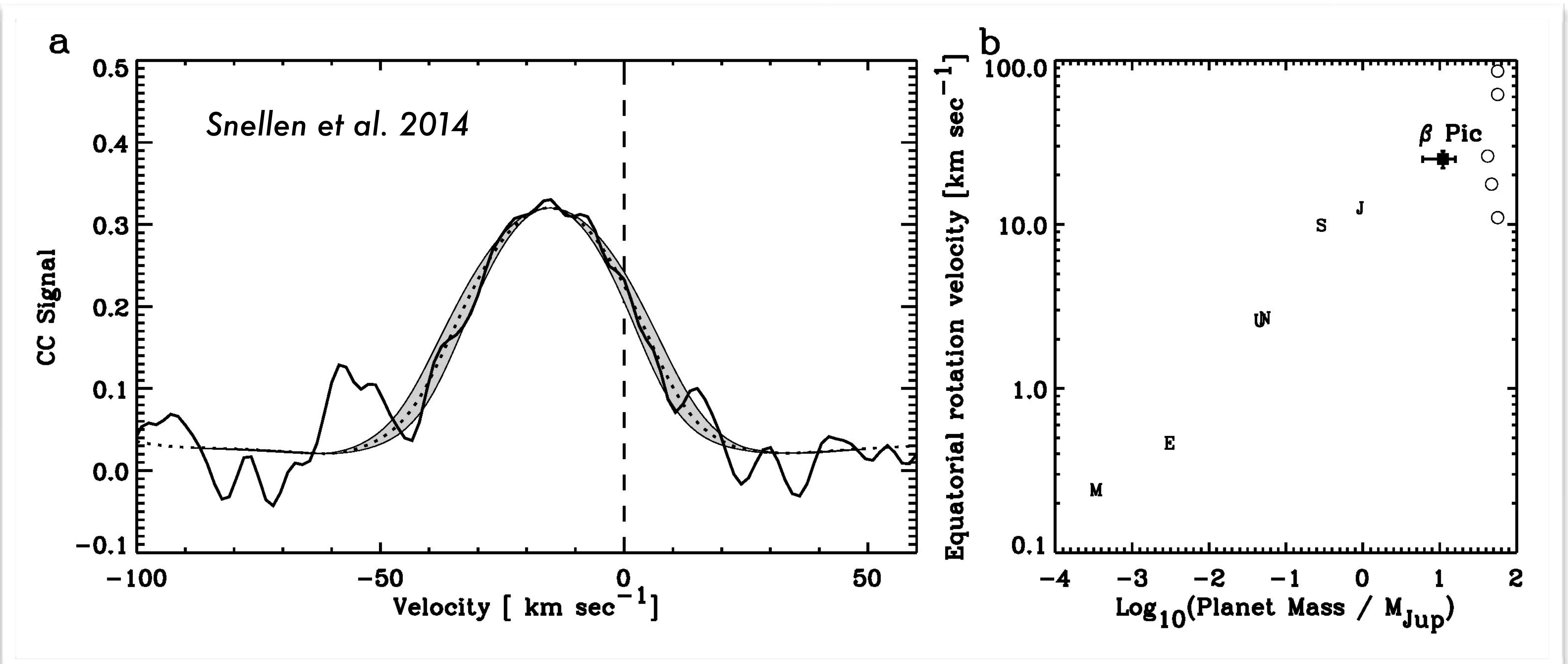
Hot-start conditions, poss. induced by the accretion of solids

$10\ M_{Jup} \leq M \leq 15.5\ M_{Jup}$

➥ J. Chilcote's talk

Physical properties & origins

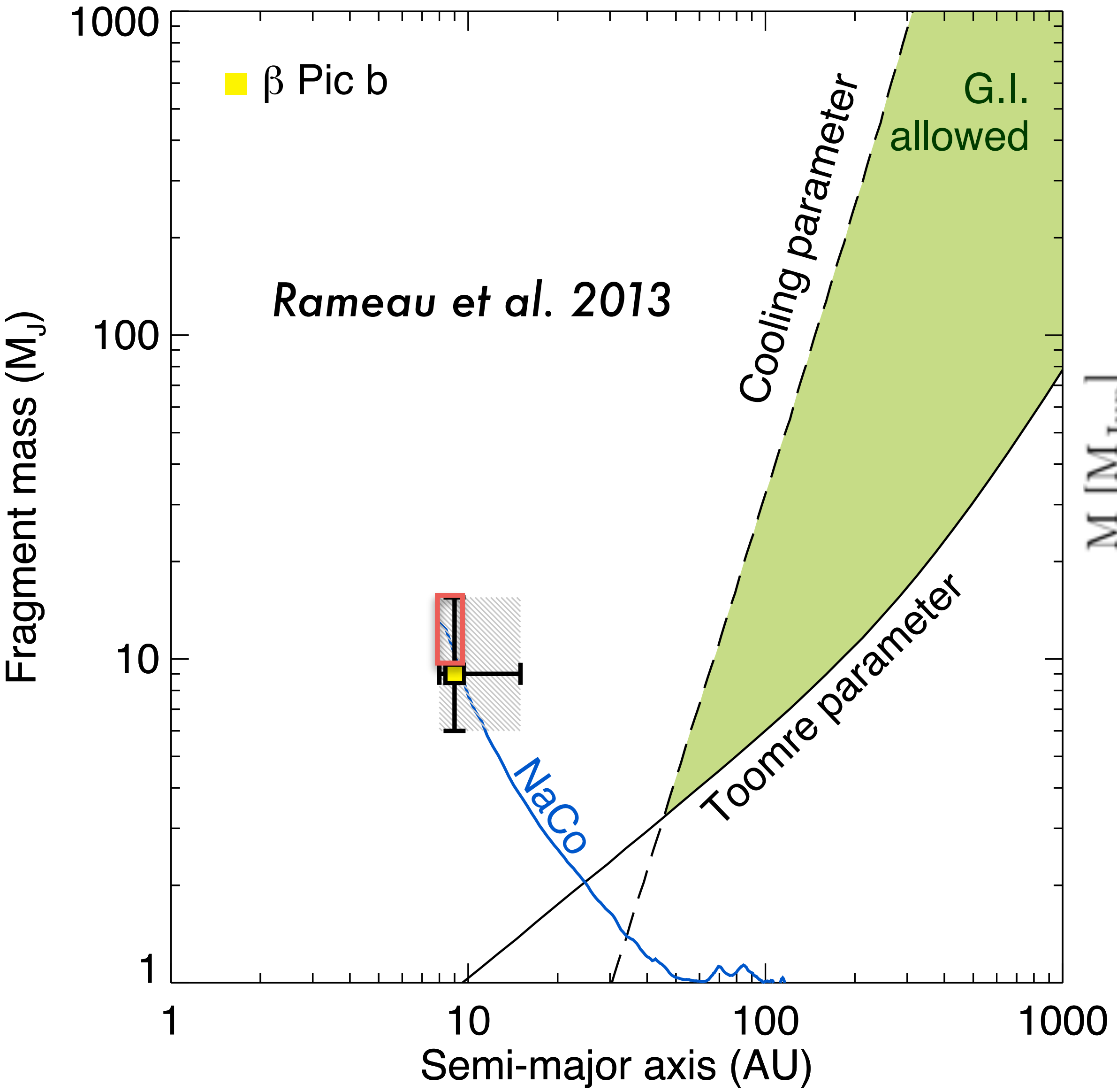
Fast spin!

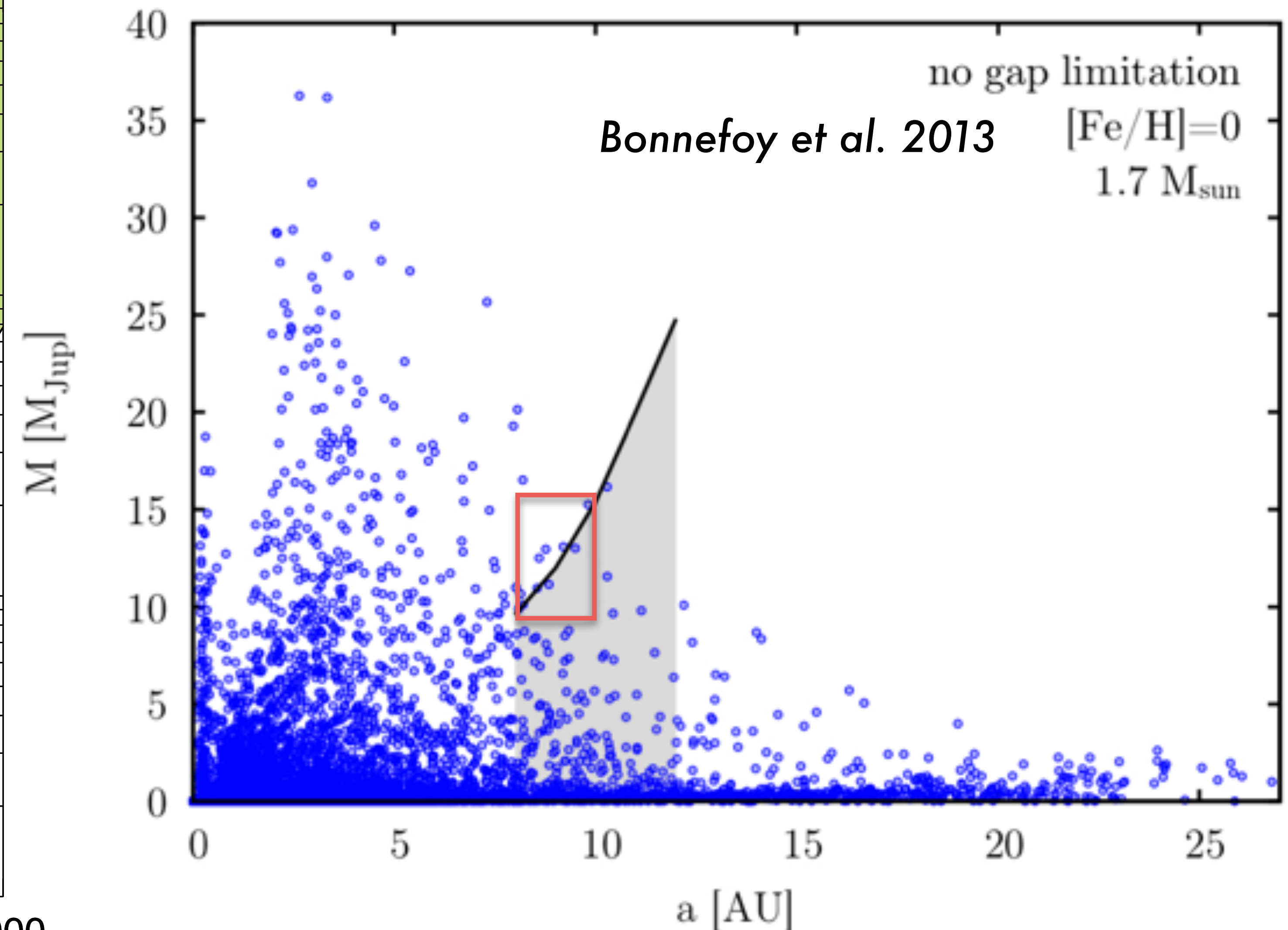


➥ J. Birkby's talk

Physical properties & origins

Formation history





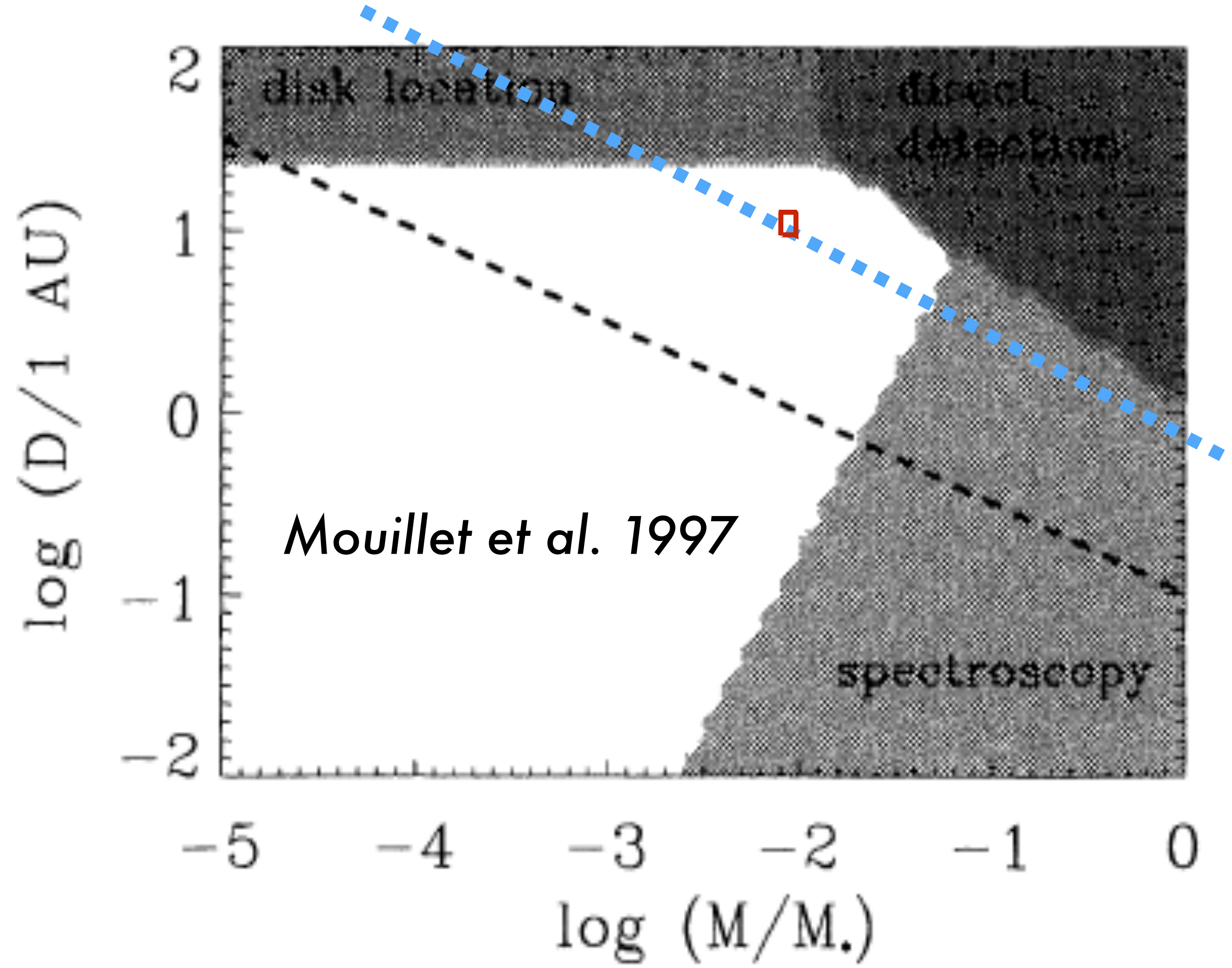
Physical properties & origins

Toward a consistent picture?

Warp & belts

It works

➥ M. Keppler's poster



F.E.B.

Slightly eccentric orbits still possible (e < 0.17). Need lower bounds on the eccentricity

➥ H. Beust's talk

Physical properties & origins

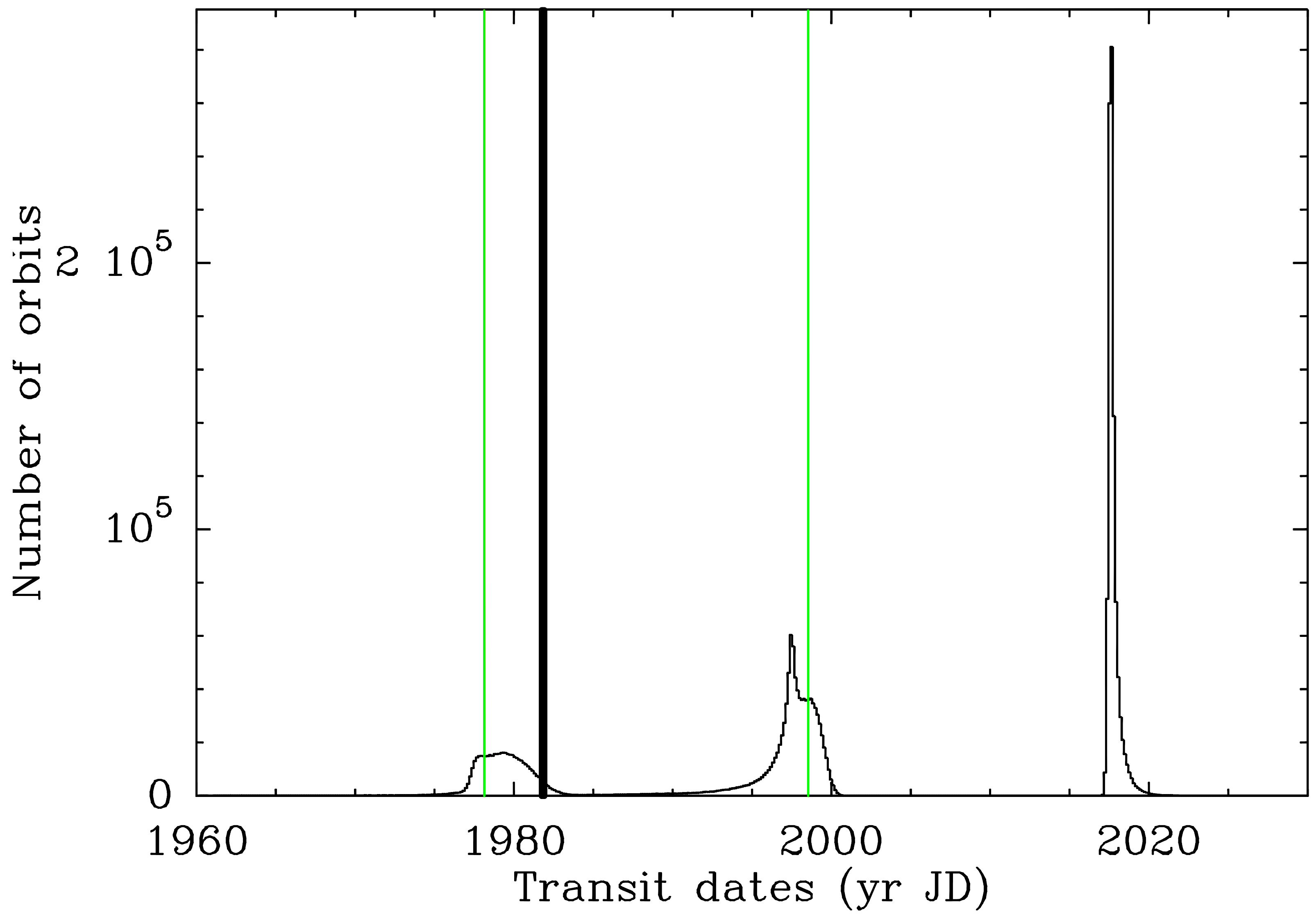
Toward a consistent picture?

Transit event

It works

➥ H. Le Cavelier's talk

H. Beust, priv. com.



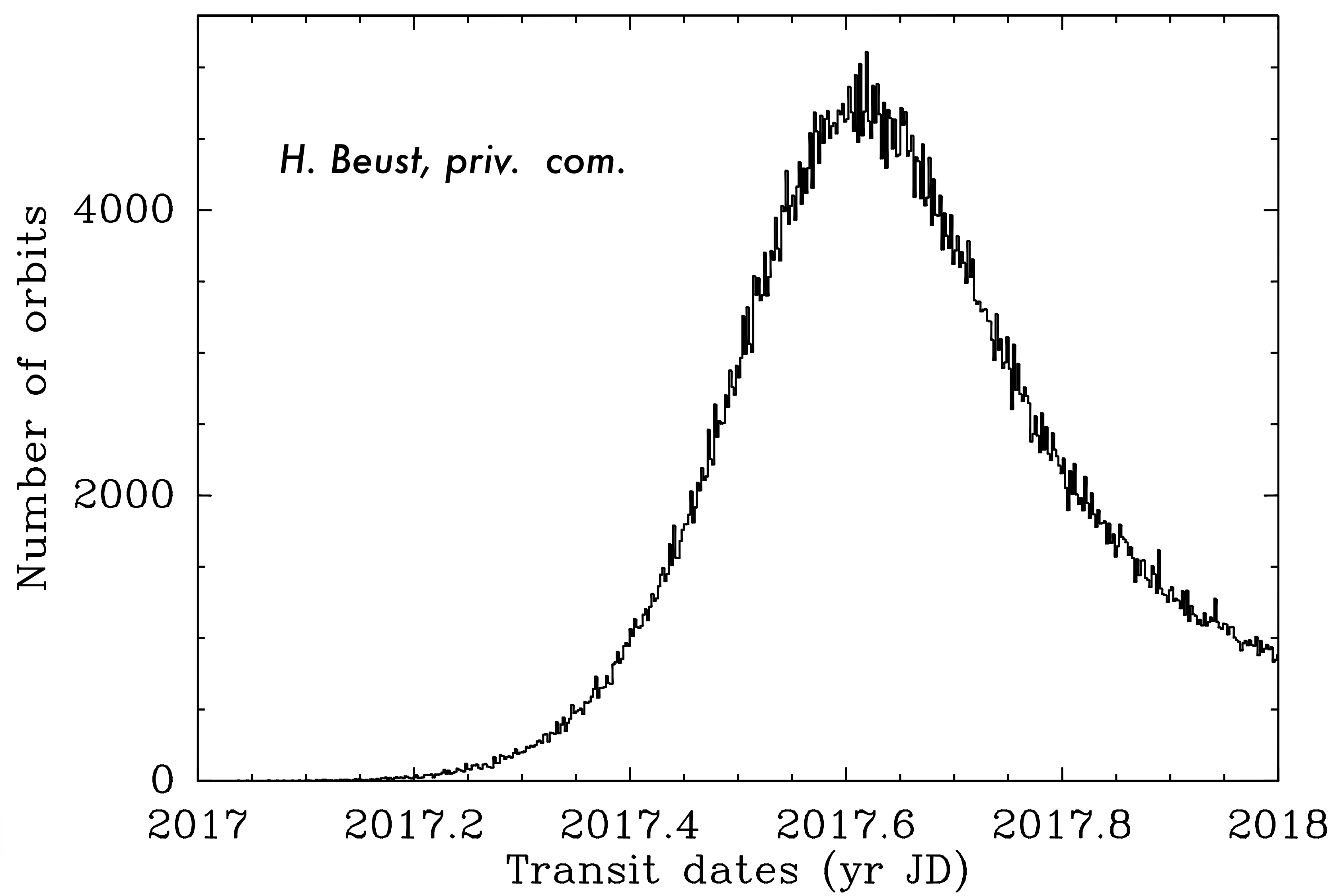
Physical properties & origins

Toward a consistent picture?

Transit event

But 2-4% of chances to transit

➥ H. Le Cavelier's talk



What can we do next?

Additional astrometric measurements

With GPI & SPHERE:

1/ Constraints on the eccentricity → F.E.B. model

2/ Inner disk structures vs planet orbit

3/ Constraints on the inclination → « next » transit

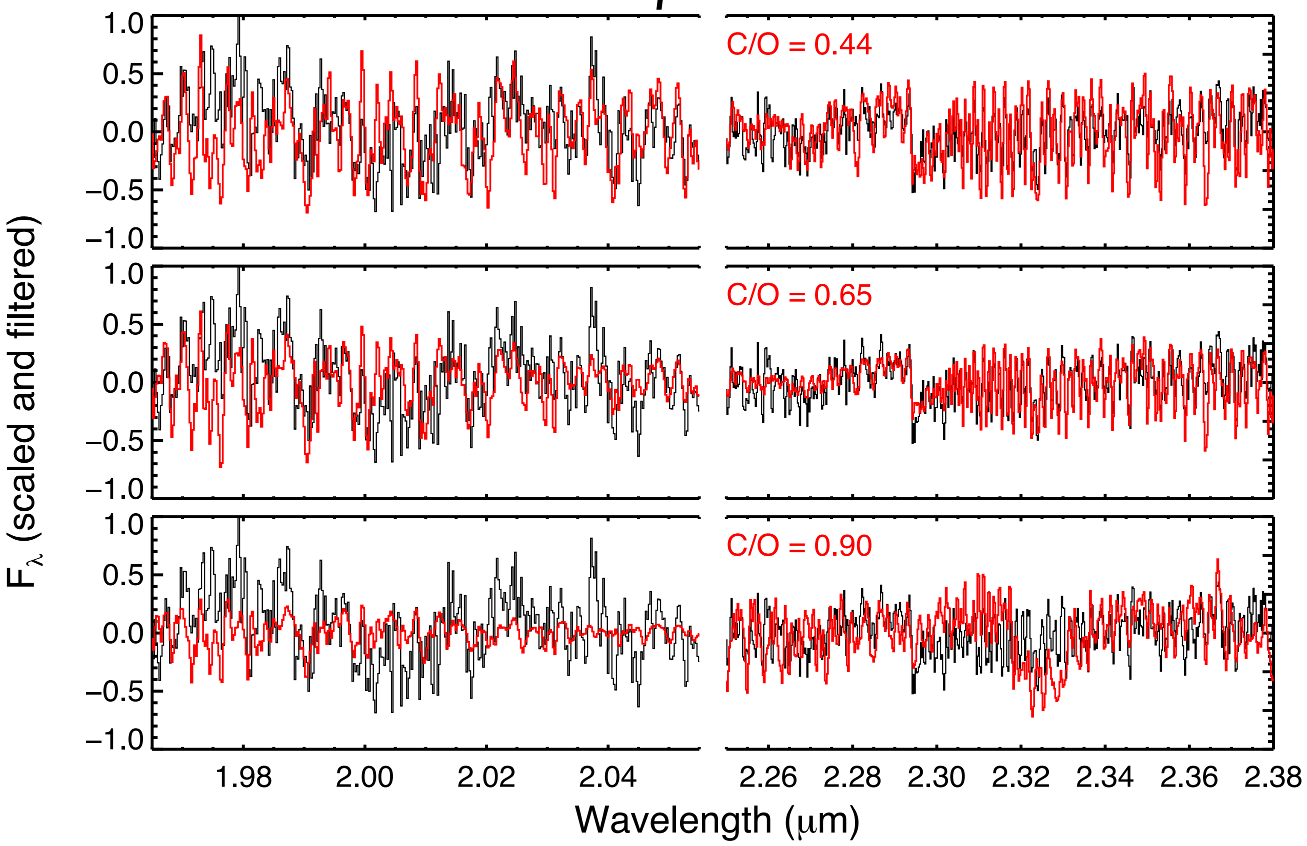
4/ Additional planets by direct imaging

+ Increased baseline for the R.V. → dynamical mass & additional planets

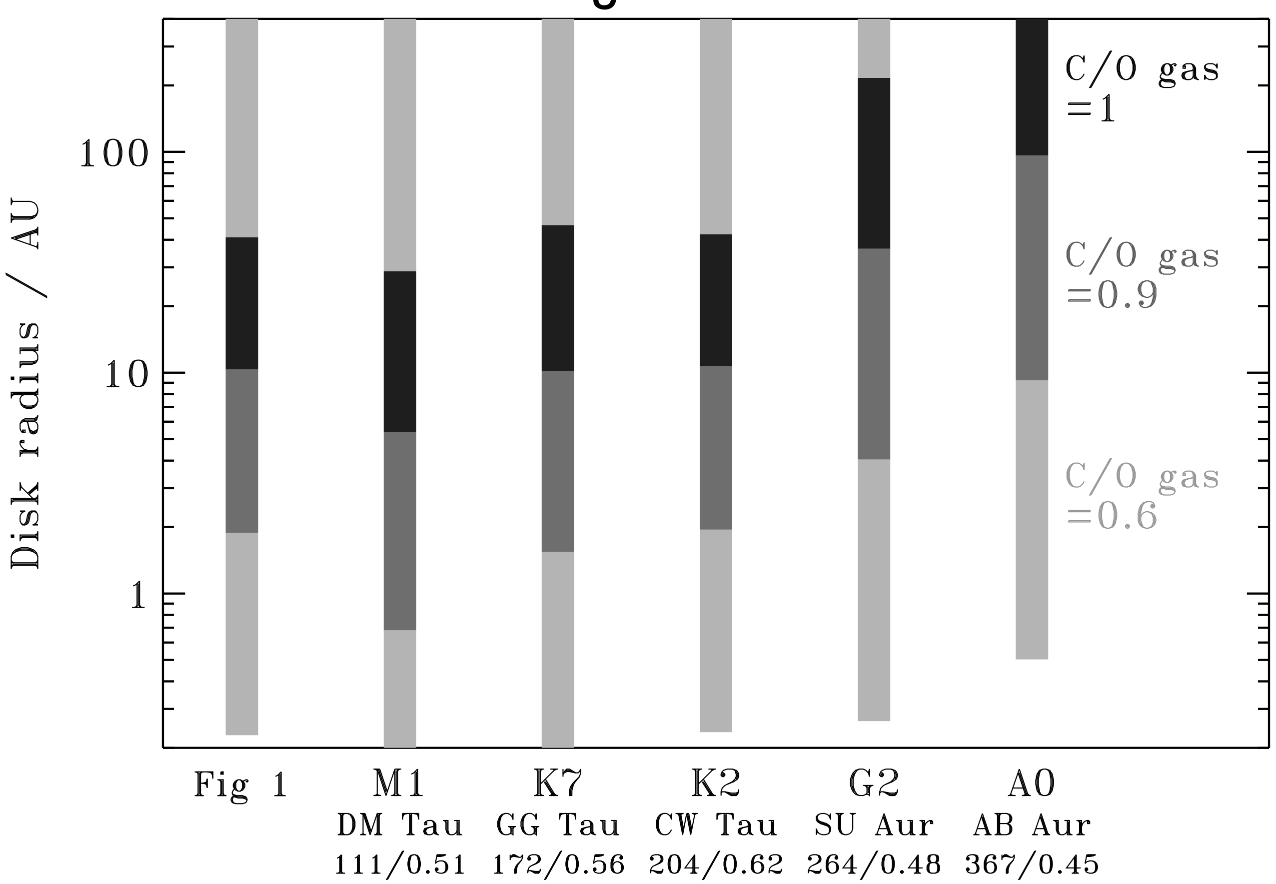
What can we do next?

Determining the atmospheric abundances

Konopacki et al. 2013



Oberg et al. 2011

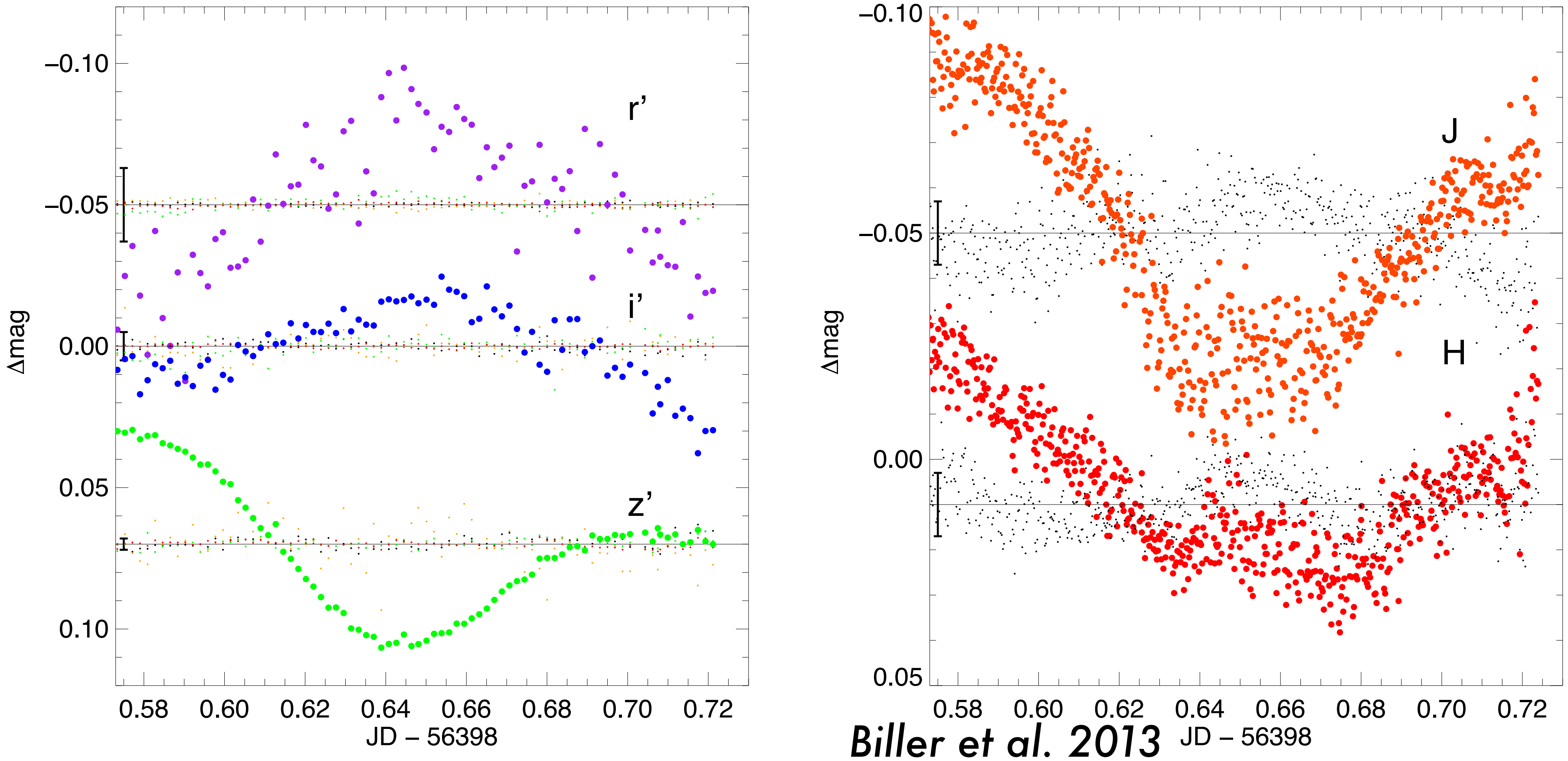


Instruments: VLT/SINFONI, Keck/OSIRIS

But we might be limited by errors in atmospheric models.

What can we do next?

Surface inhomogeneities & 3D atmospheric structure

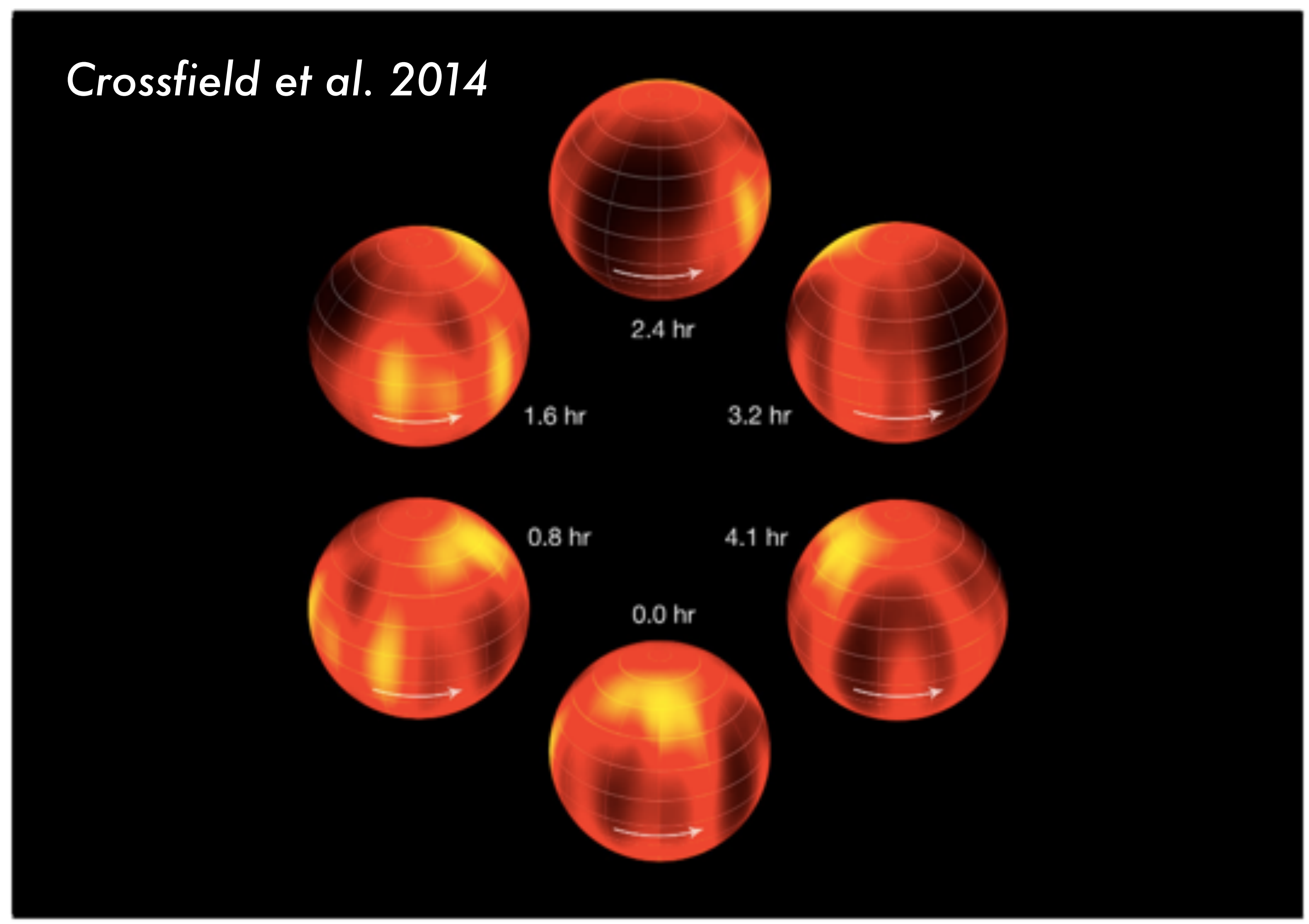


Biller et al. 2013

Multi-λ lightcurves (with the IFS go GPI and SPHERE) :
spots and/or holes in the cloud deck vs different atmospheric pressure

What can we do next?

Surface inhomogeneities & 3D atmospheric structure



➥ J. Birkby's talk

Doppler imaging :

One of the most promising target for the E-ELT (ELT-HIRES, ELT-MIR)

What can we do next?

and polarization fraction, SED > 5 μm, new spectra, additional epoch with CRIRES+...

+ repeat the measurements !

Conclusions

Detailed portrait of ß Pictoris b since 2009

- Low-eccentricity orbit, with s.m.a. around 9 AU
- Not in the main disk
- Low-res spectra: similar to young early-L brown-dwarfs
- Dusty, low surface-gravity atmosphere
- Hot-start-like initial conditions, mass=10-15.5 MJup
- Rotation, follow the trend of solar-system planets
- C.A. more plausible than G.I., or need to stop inward migration+planet from growing

The planet properties fits with indirect hints (so far)

- F.E.B.
- Warp & belts
- Transit event of 1981

Lots of things remain to be learned!

- variability (weather, cloud deck structure)
- primordial enrichment (C/O, Fe/H)
- better constraints on the orbit
- and more (polarization fraction,...)

Conclusions

Detailed portrait of

- Low-eccentricity orbit, with s.m.a. around 9 AU
- Not in the main disk
- Low-res spectra similar to young early-L brown-dwarfs
- Dusty, low surface-gravity atmosphere
- Hot-start-like initial conditions, mass [illegible] MJ
- Rotation, follow the trend of solar-system planets
- C.A. more plausible than G.I., or need to stop inward migration+planet from growing

The planet properties fits with indirect hints (so far)

- F.E.B.
- Warp & belts
- Transit event of 1981

Lots of exciting things to attempt!

- variability (weather, cloud deck structure)
- primordial enrichment (C/O, Fe/H)
- better constraints on the orbit
- and more (polarization fraction,...)

Thank you

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