Hunting for newborn hot Jupiters around young active stars

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A Cameron (StAndrews) & **the MaTYSSE consortium**

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- hunting for exoplanets : motivation, techniques & limitations

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- hot Jupiters around young forming Sun-like stars

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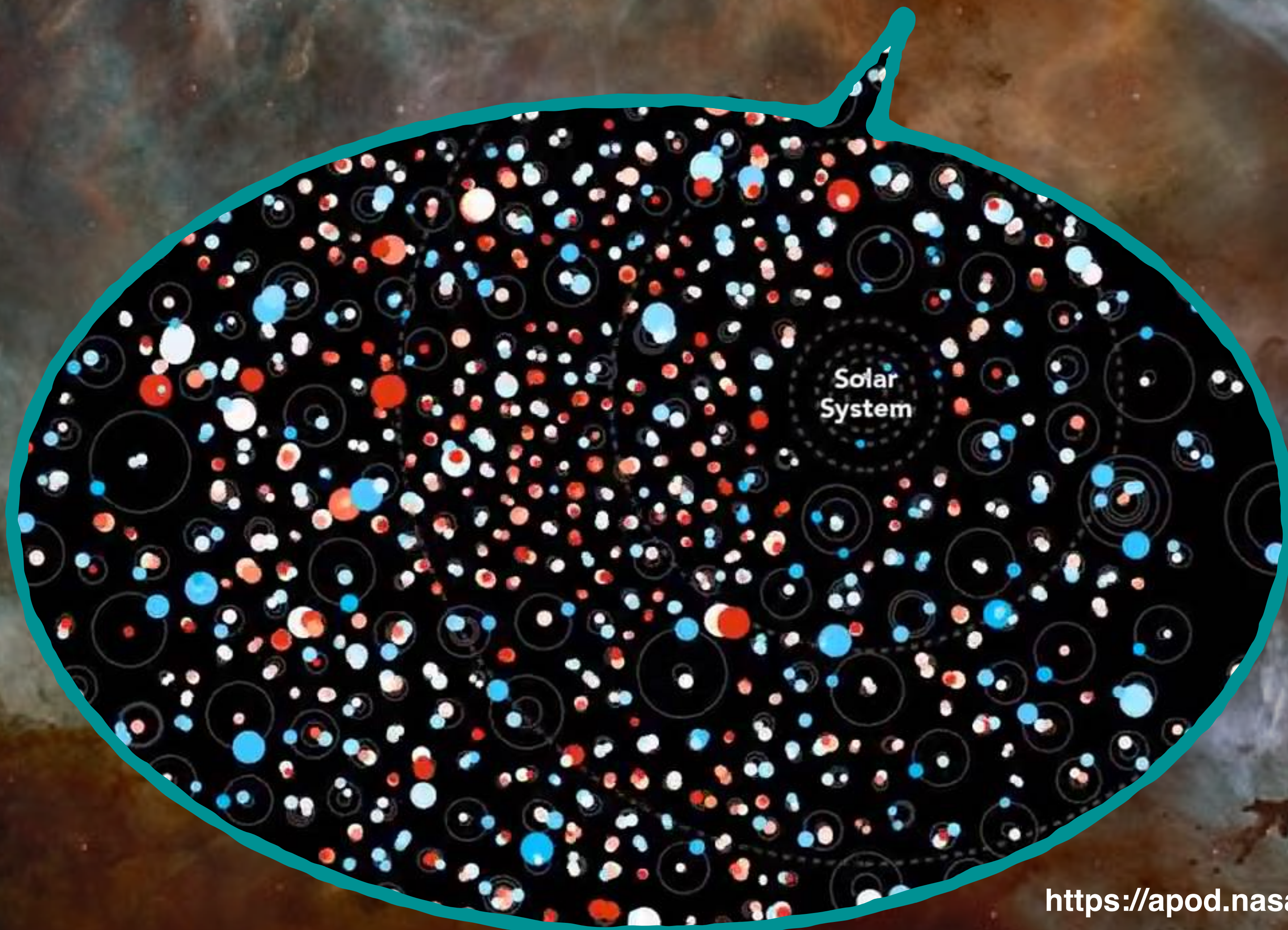
- what are hot Jupiters and what do we know about them?
- hot Jupiters around young forming Sun-like stars
- future prospects with SPIRou @ CFHT

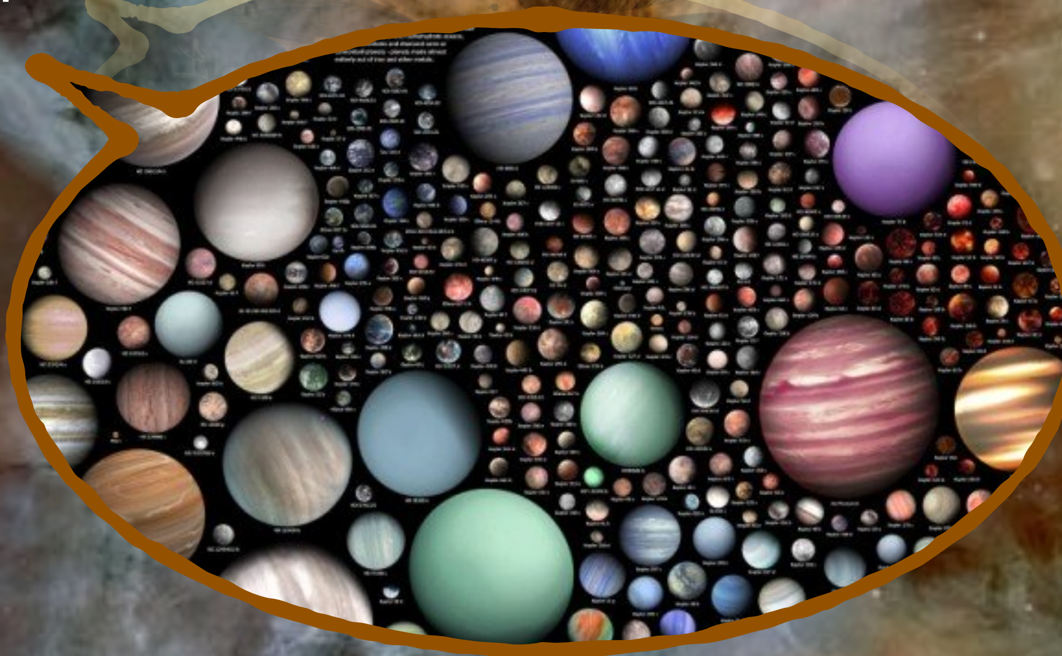
Hunting for exoplanets

- a quest for origins

origins of the Solar System & origins of life

  - study planets / satellites within the Solar System
  - detect & study worlds outside the Solar System





https://apod.nasa.gov/apod/ap151205.html

Hunting for exoplanets

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- unveiling the invisible
  technically tricky & only possible since last two decades
  several techniques to reveal distant exoplanets
  - imaging / velocimetry / photometry / micro-lensing / astrometry

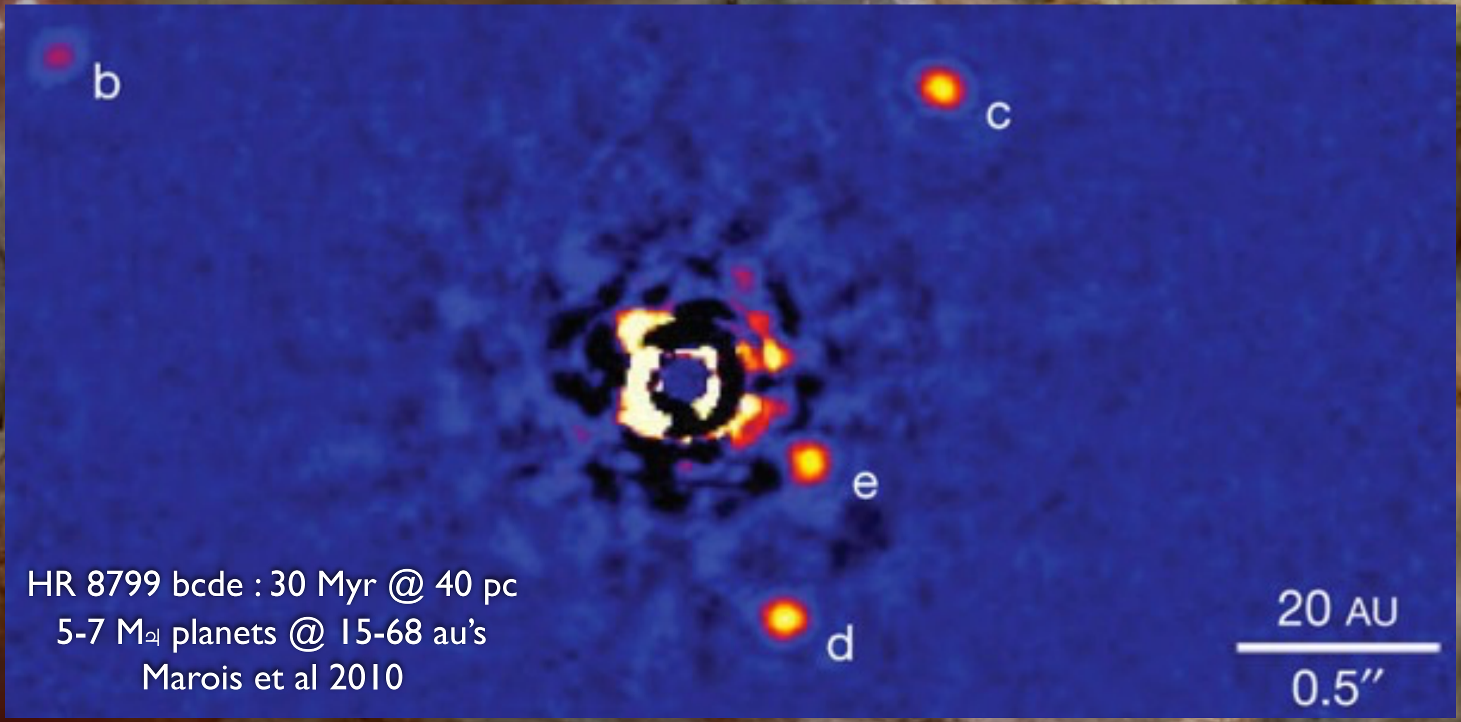
Hunting for exoplanets

- direct imaging

  extreme flux contrast : 5-9 orders of magnitude

  tiny angular separation : 1 au @ 10 pc = 0.1” (atmospheric turbulence > 0.5”)

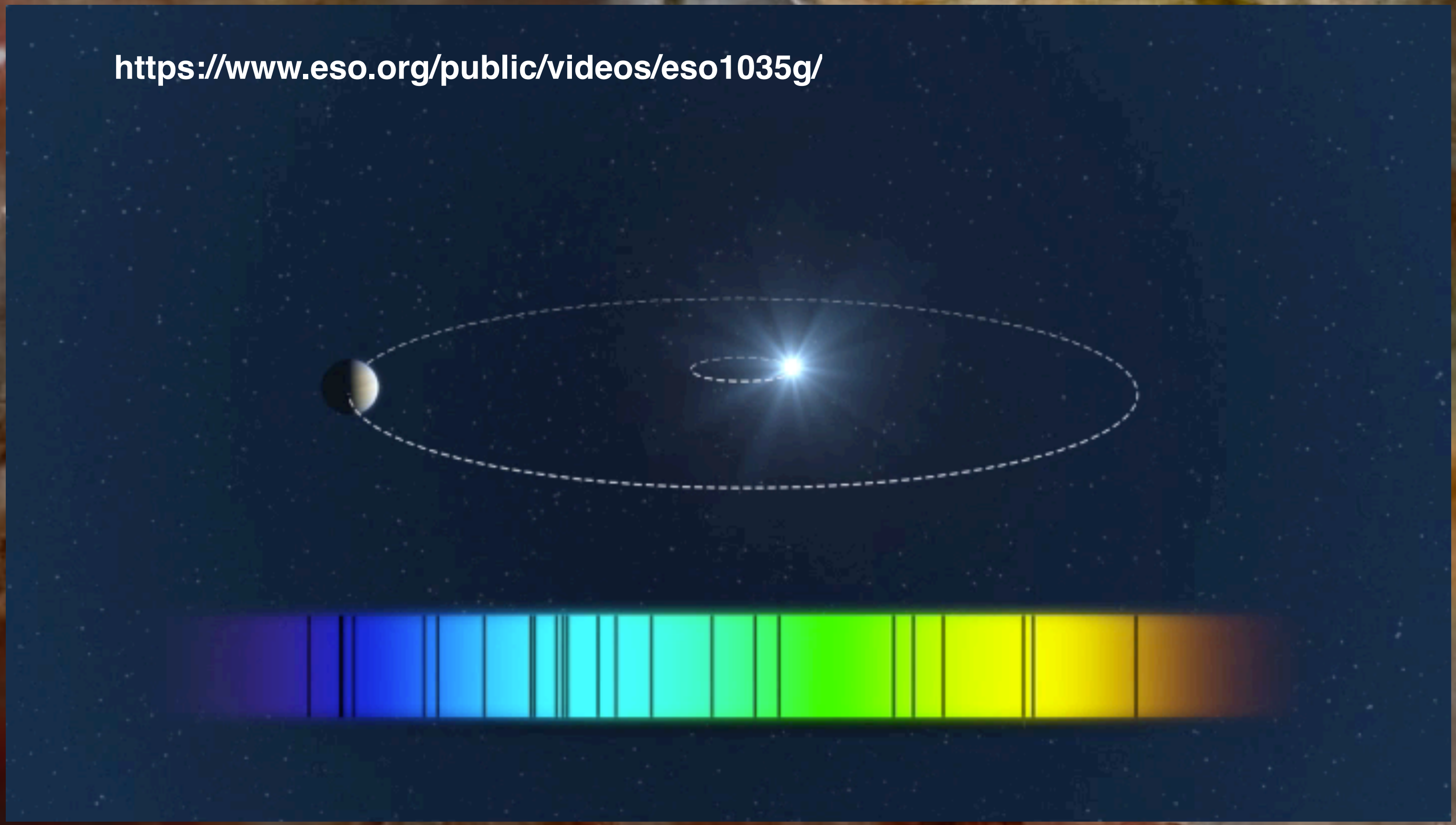
  - detect a candle next to a lighthouse from a distance of ~2 000 km
  - coronography / adaptive optics / interferometry
  - few detections of distant young giant planets, eg HR 8799



HR 8799 bcde : 30 Myr @ 40 pc
5-7 M♃ planets @ 15-68 au’s
Marois et al 2010

Hunting for exoplanets

- high-precision velocimetry
  detect & measure the reflex motion of the host star through the Doppler effect
  radial velocity (RV) signal yields planet mass (m sin i w/ i: orbit tilt wrt line of sight)
  e.g. Jupiter on the Sun: 13 m/s — Earth on the Sun: 0.08 m/s
  - extreme precision required: 1 m/s = 3 10^{-9} x speed of light
  - thermally stable (~0.01 K) evacuated spectrographs
  - very stable wavelength reference
  - HARPS @ 3.6m ESO telescope at La Silla (Chile)
  - most reliable technique & hundreds of planets detected



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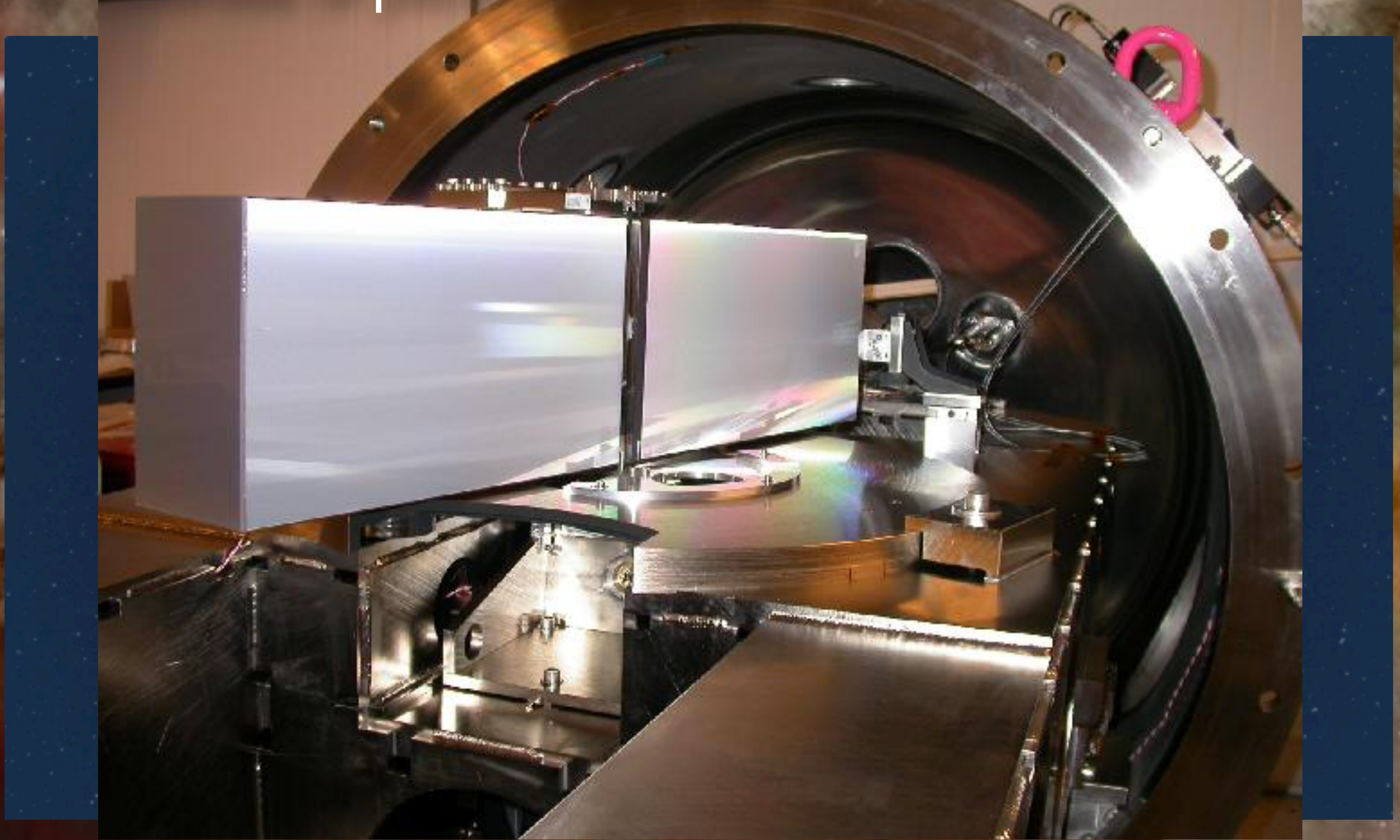
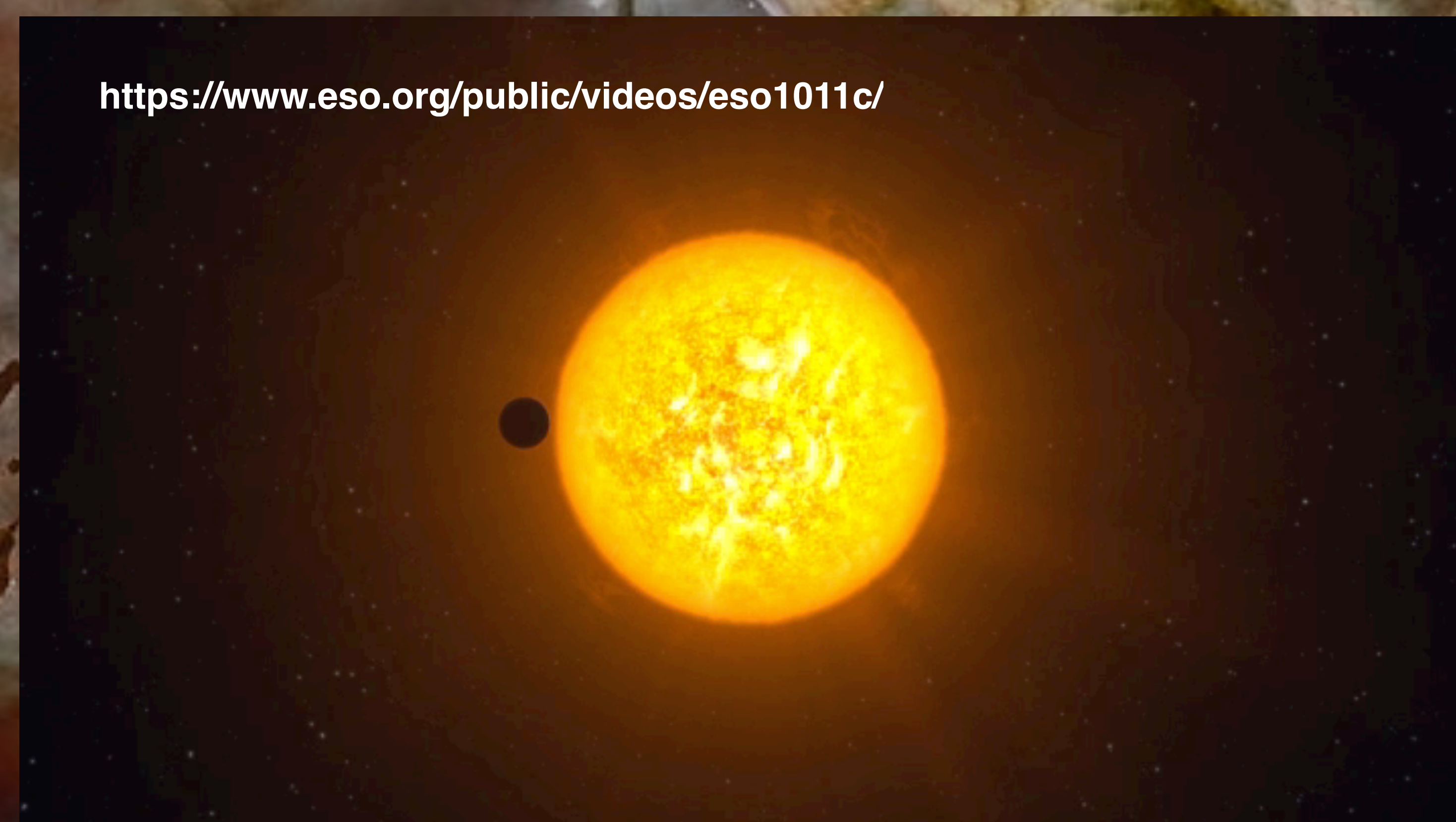


Hunting for exoplanets

- photometric transits

  detect & measure the partial occultation of the star by a close-in planet
  gives access to the planet radius (wrt the stellar radius)
  e.g. Jupiter on the Sun: 1% = 10 mmag — Earth on the Sun: 0.008% = 80 ppm

  - very high photometric precision (a few tens of ppm)
  - best from space (CoRoT, MOST, KEPLER, TESS, PLATO)
  - needs confirmation w/ velocimetry to validate planet
  - radius + mass yields average bulk density & composition
  - thousands of planets & hundreds of systems detected with KEPLER



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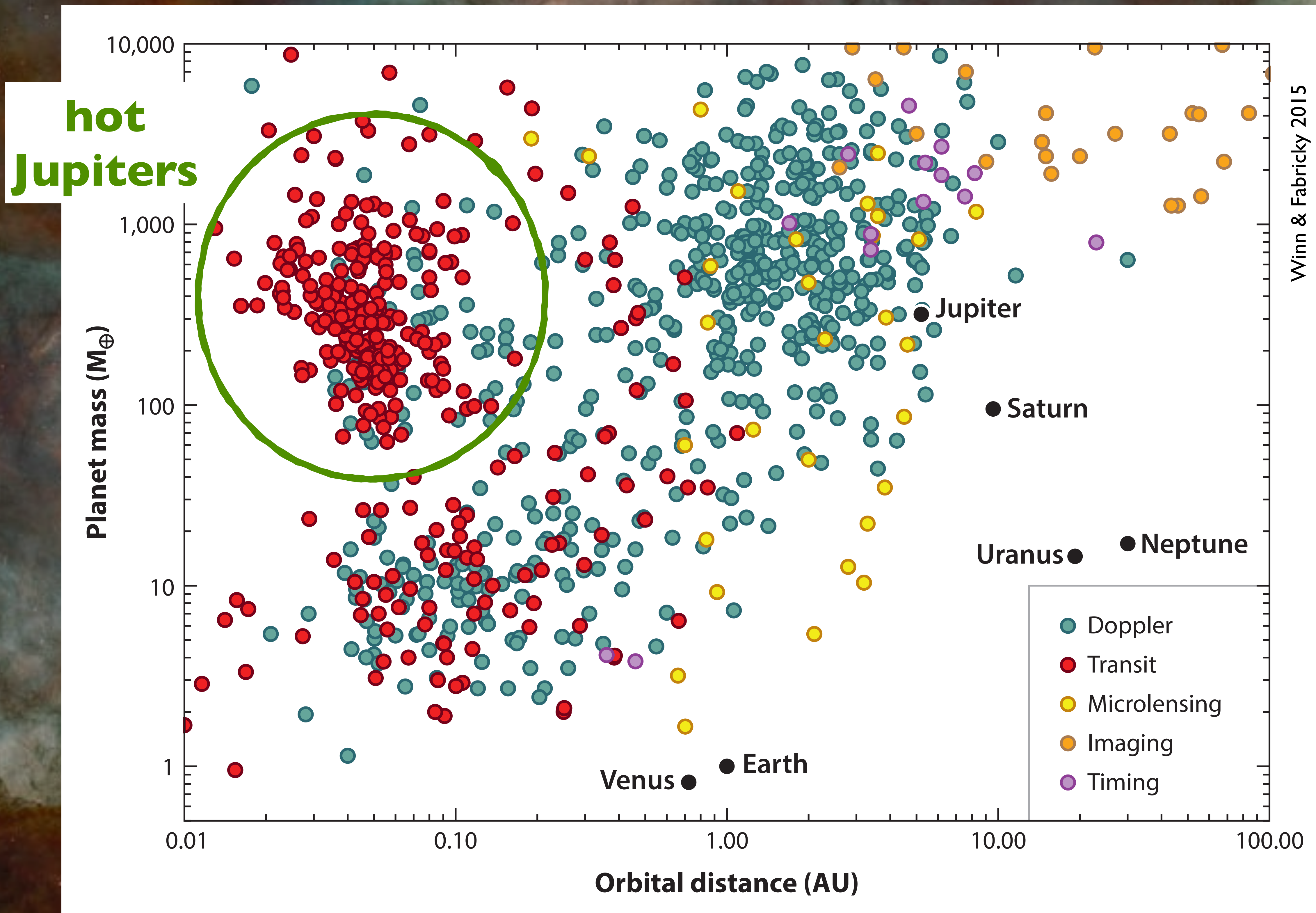
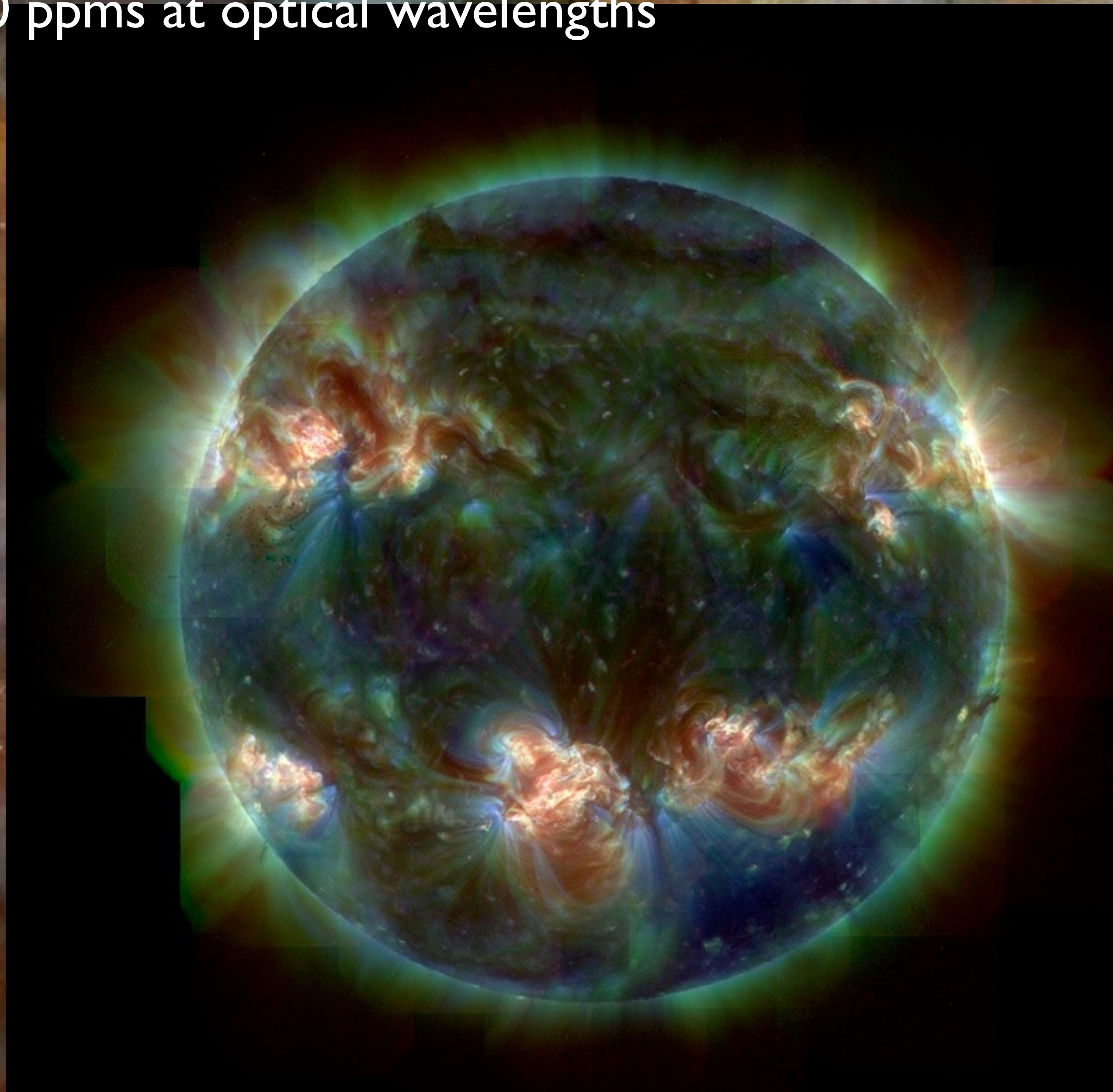


Hunting for exoplanets

- pollution by stellar activity

  stellar magnetic fields generates spots & plages at the surface of the host star
  impacts RVs & photometry on timescales of days to months & years (rotation, cycle)
  chromatic signature from activity as opposed to achromatic signature from planet

  - activity of the Sun: a few m/s and 100 ppms at optical wavelengths
  - distort / drown signal from planet :(
  - need to model & filter-out activity



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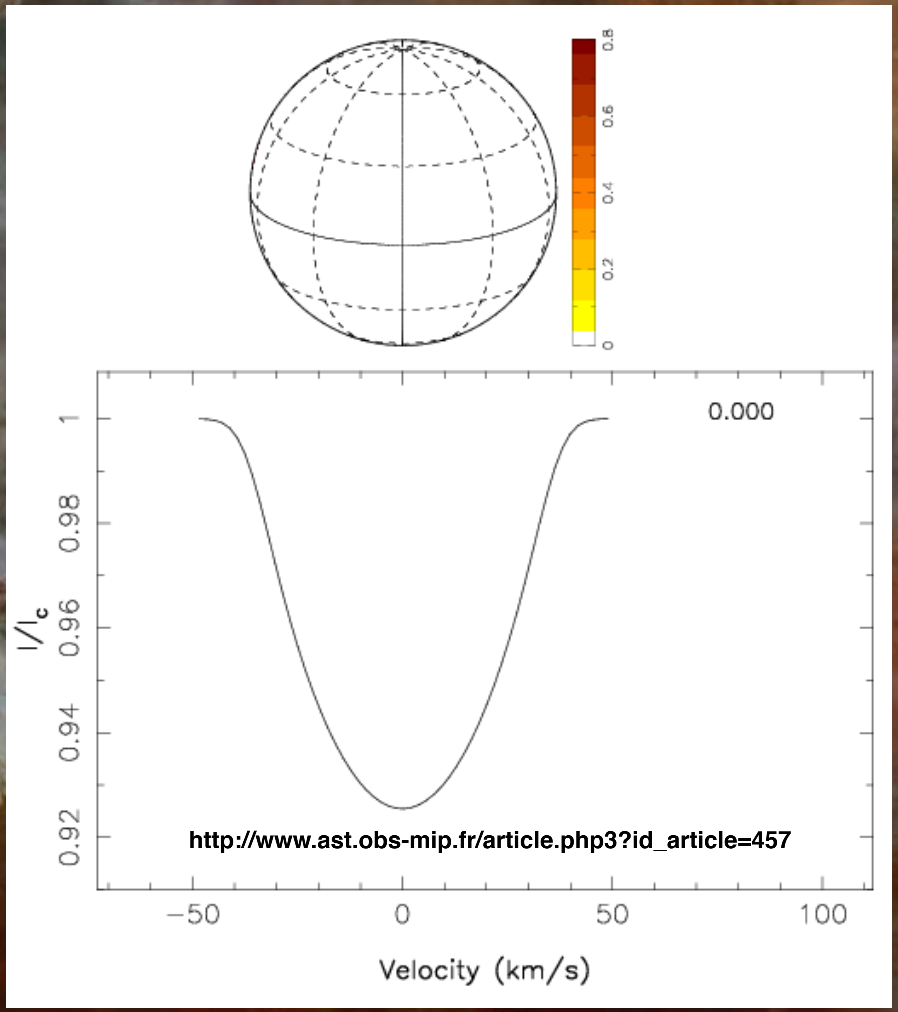

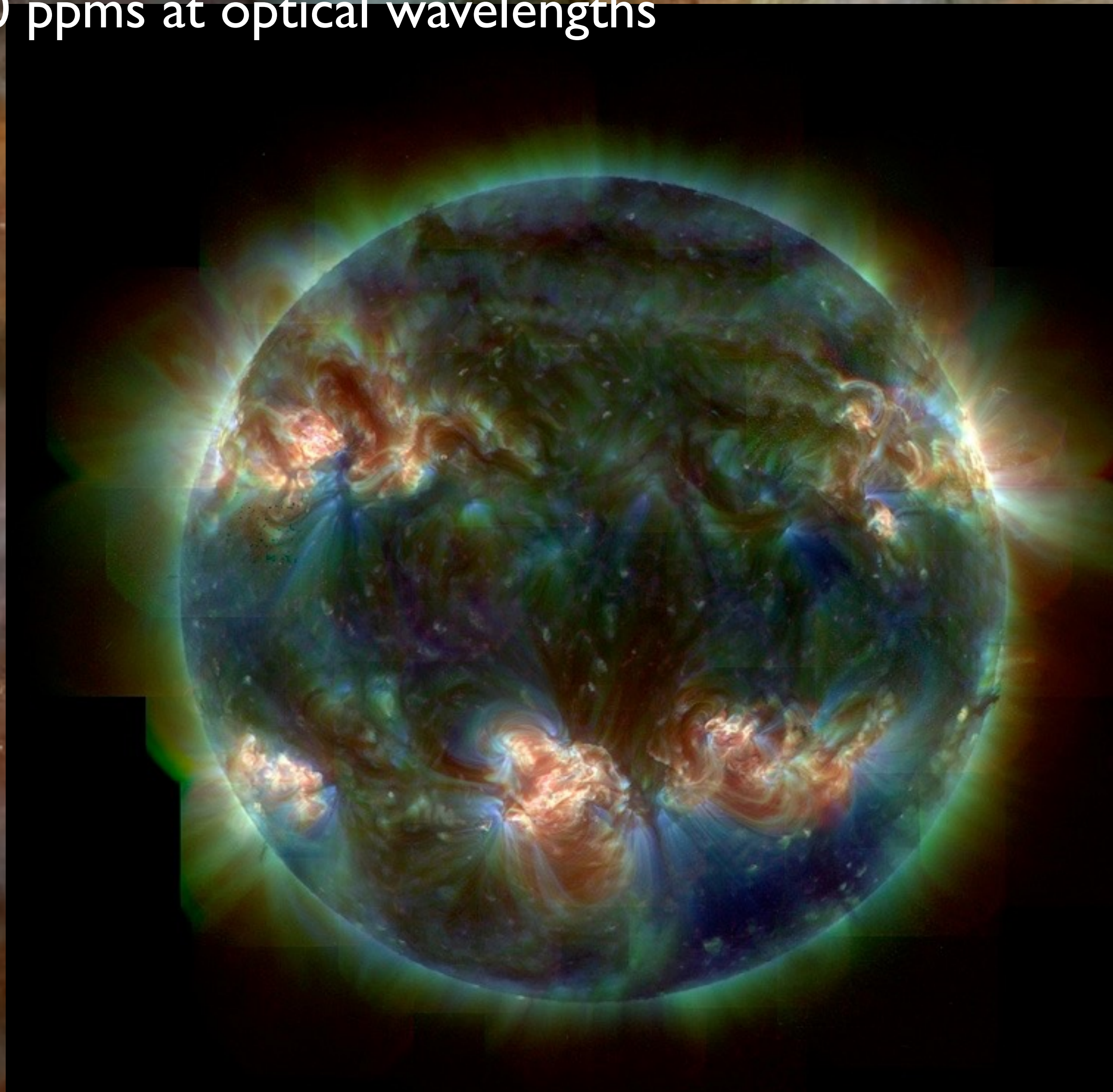

Properties of hot Jupiters

- what is a hot Jupiter ?

  close-in giant gaseous planet at a distance of <0.5 au from its host star
  - orbital period < 10 d and mass > 0.2 $M_{♃}$
  - large RV signal, typical semi amplitude of ~100 m/s or more
  - large photometric transit depth of a few %

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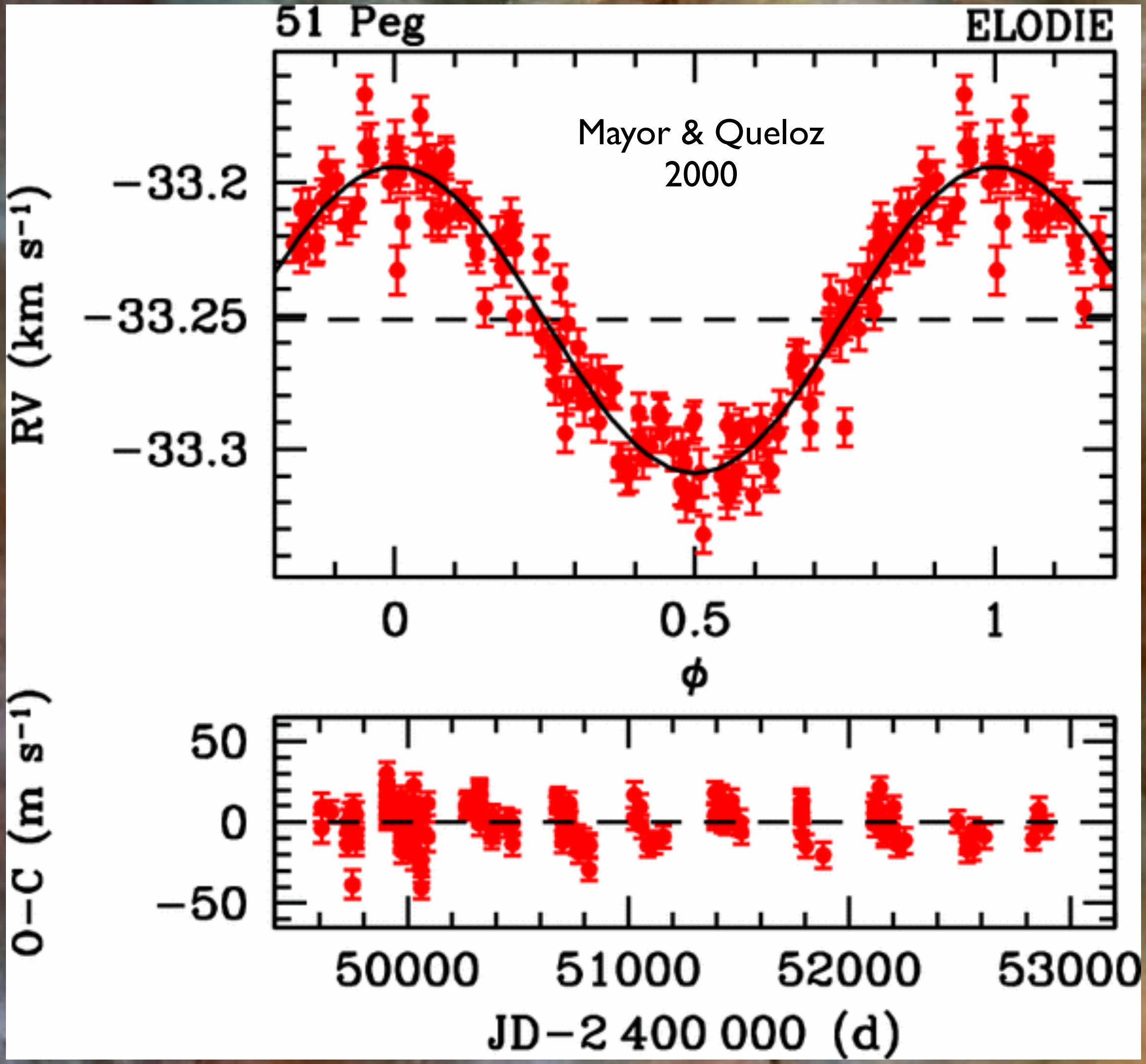
  easiest to detect thanks to their large RV signal
  51 Peg b (Mayor & Queloz 1995)
  HD 209458 b (Mazeh et al 2000)



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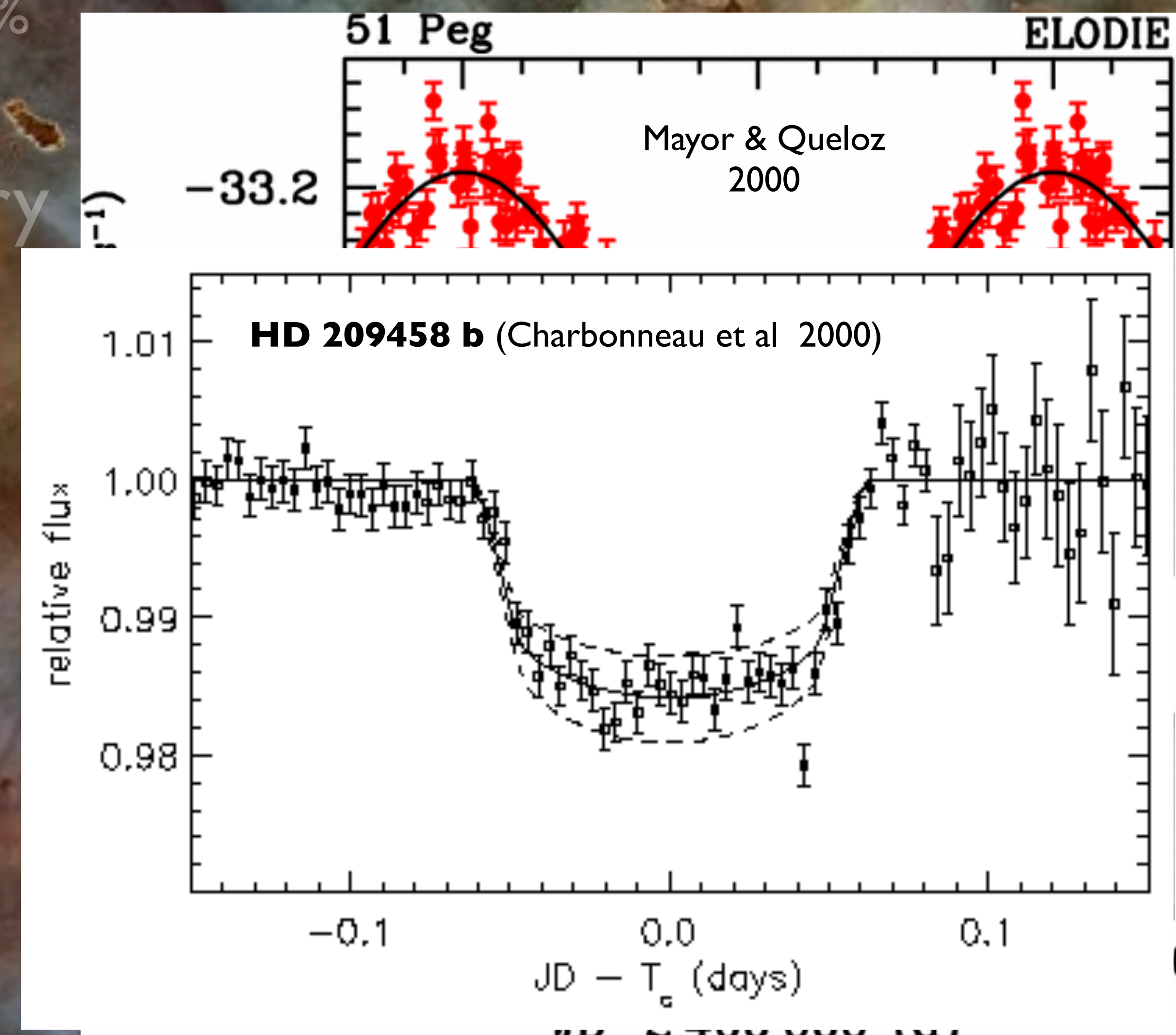

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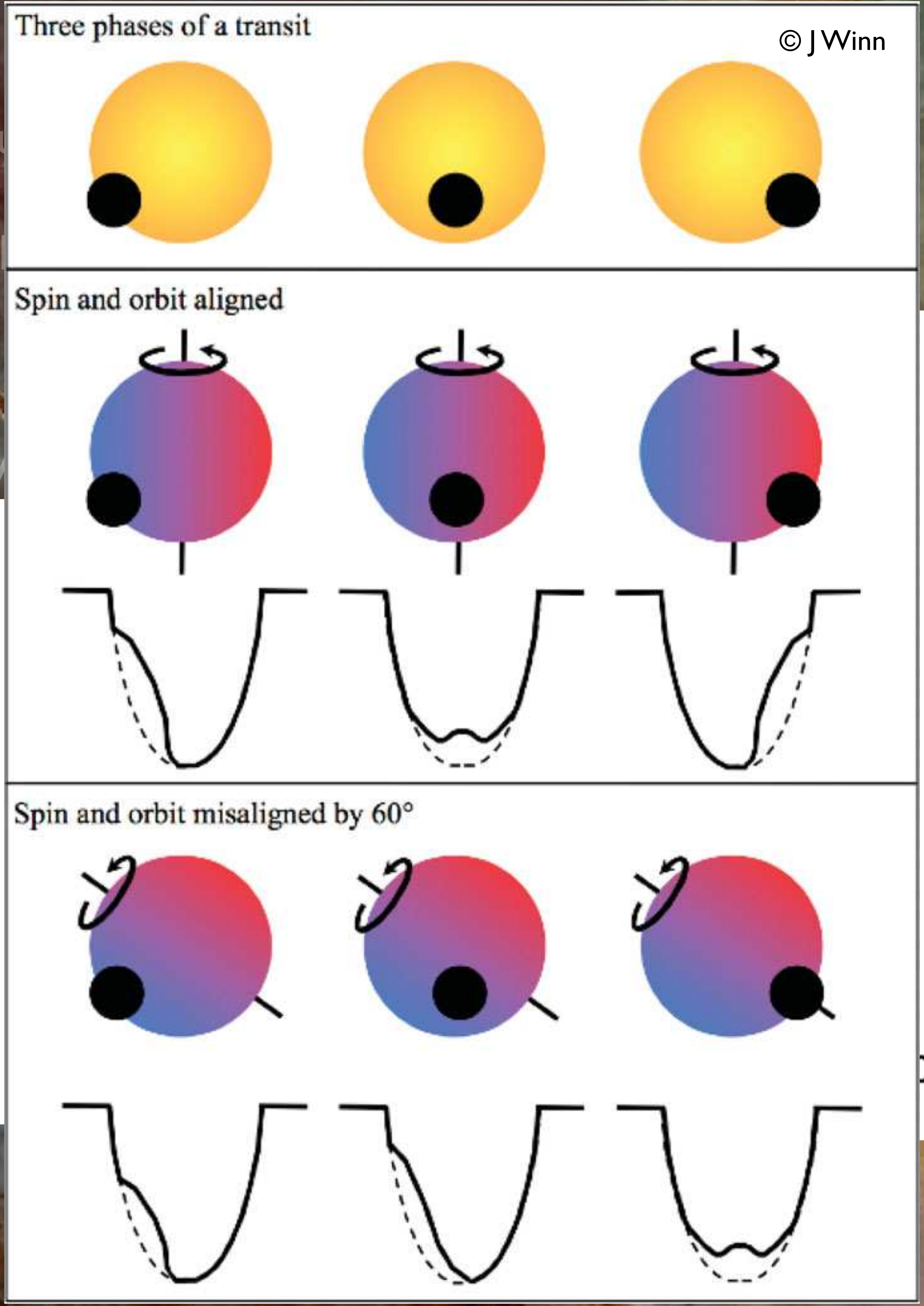
RV transit signal

Rossiter McLaughlin effect

- tilt of orbital axis to spin axis
- coplanar orbit for HD 209458 b



Properties of hot Jupiters

- occurrence rate of hot Jupiters

  only ~1% of mature Sun-like stars host hot Jupiters (eg Wright et al 2012)
  less for low-mass stars / M dwarfs
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  - most show prograde orbits, sometimes retrograde
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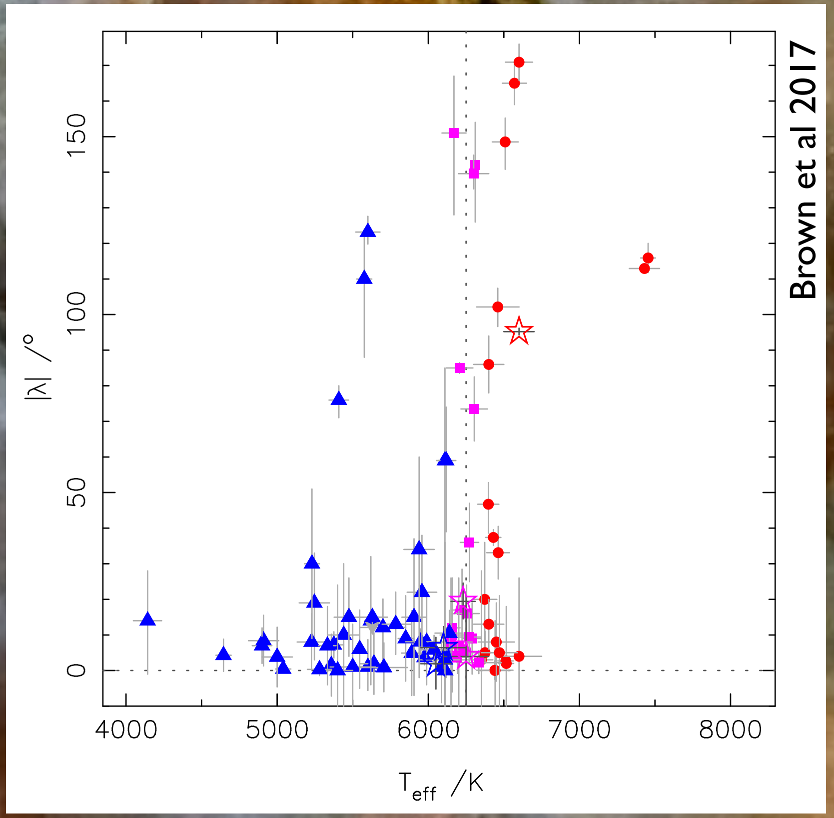

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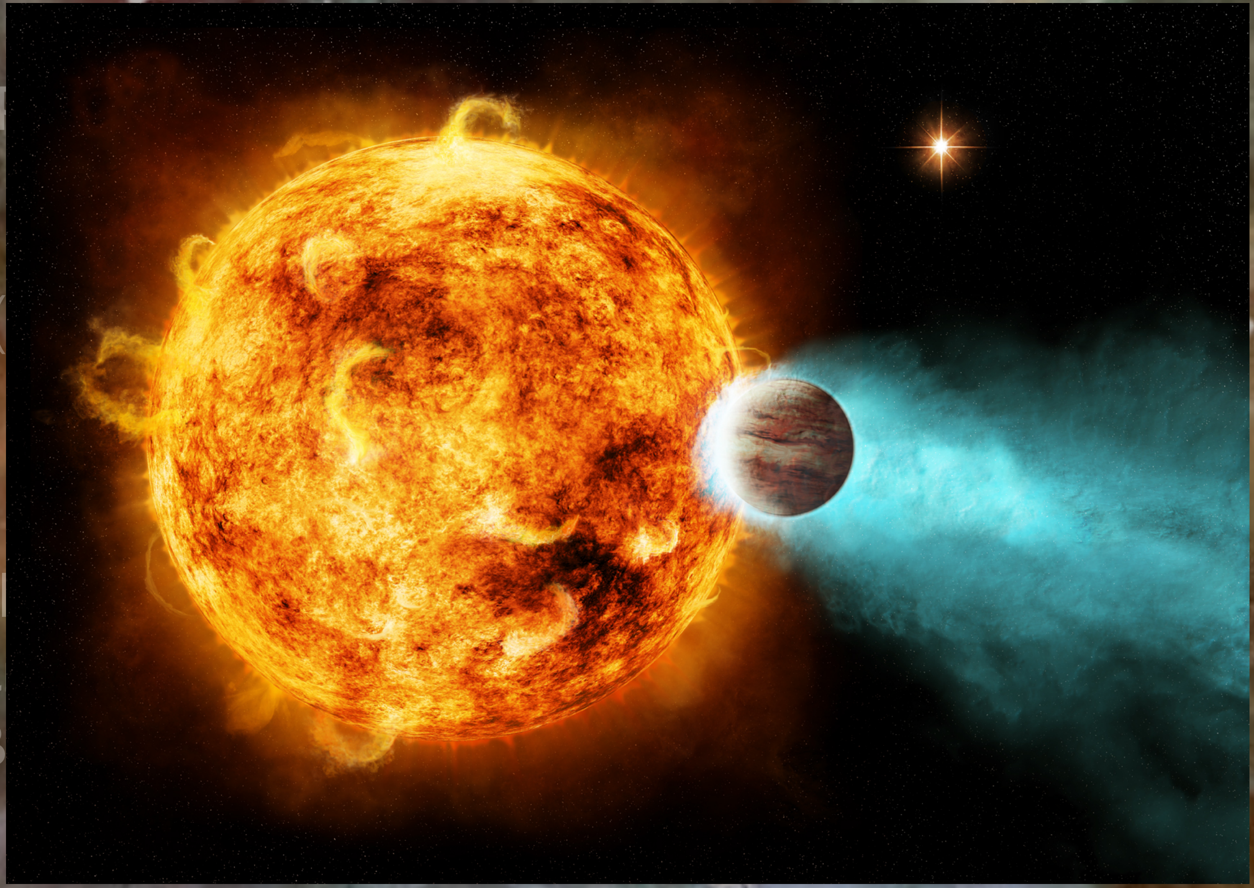

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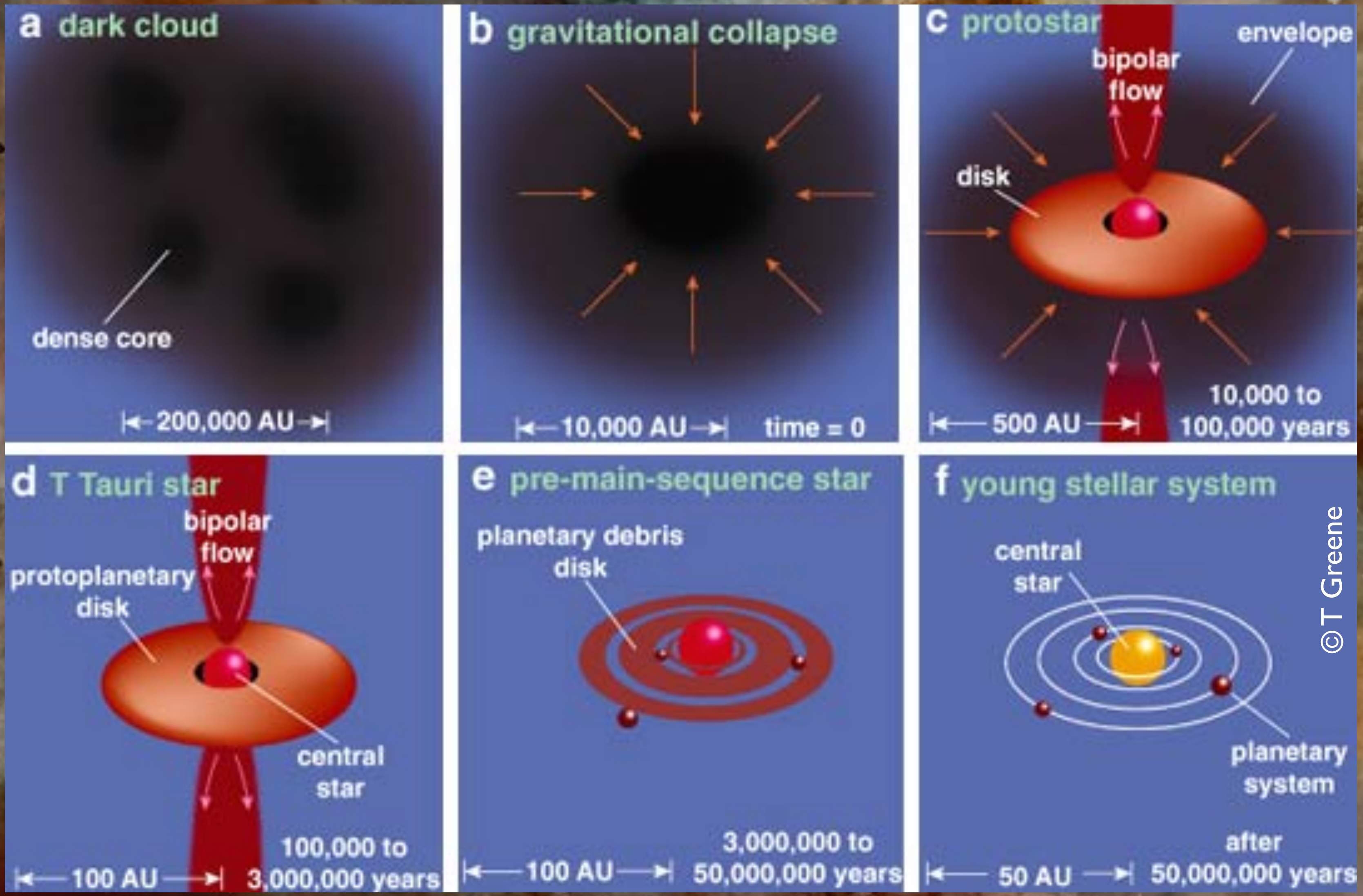
Formation of hot Jupiters

- star / planet formation
  dark cloud collapsing on its own weight, forming accretion disc
  accretion disc yielding central star (T Tauri) and protoplanetary disc
  giant planets / hot Jupiters shape early planetary system architecture
  - ➻ key role in formation of planetary systems



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- in-situ formation ?
  not enough disc material to form hot Jupiters in situ
  giant planet first formed at several au's, then migrate inwards
  formed by accretion of smaller planets (Batygin et al 2016; Boley et al 2016) ?
    ➺ possible for hot Neptunes, unlikely to occur for hot Jupiters

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planet-planet / star-planet interaction

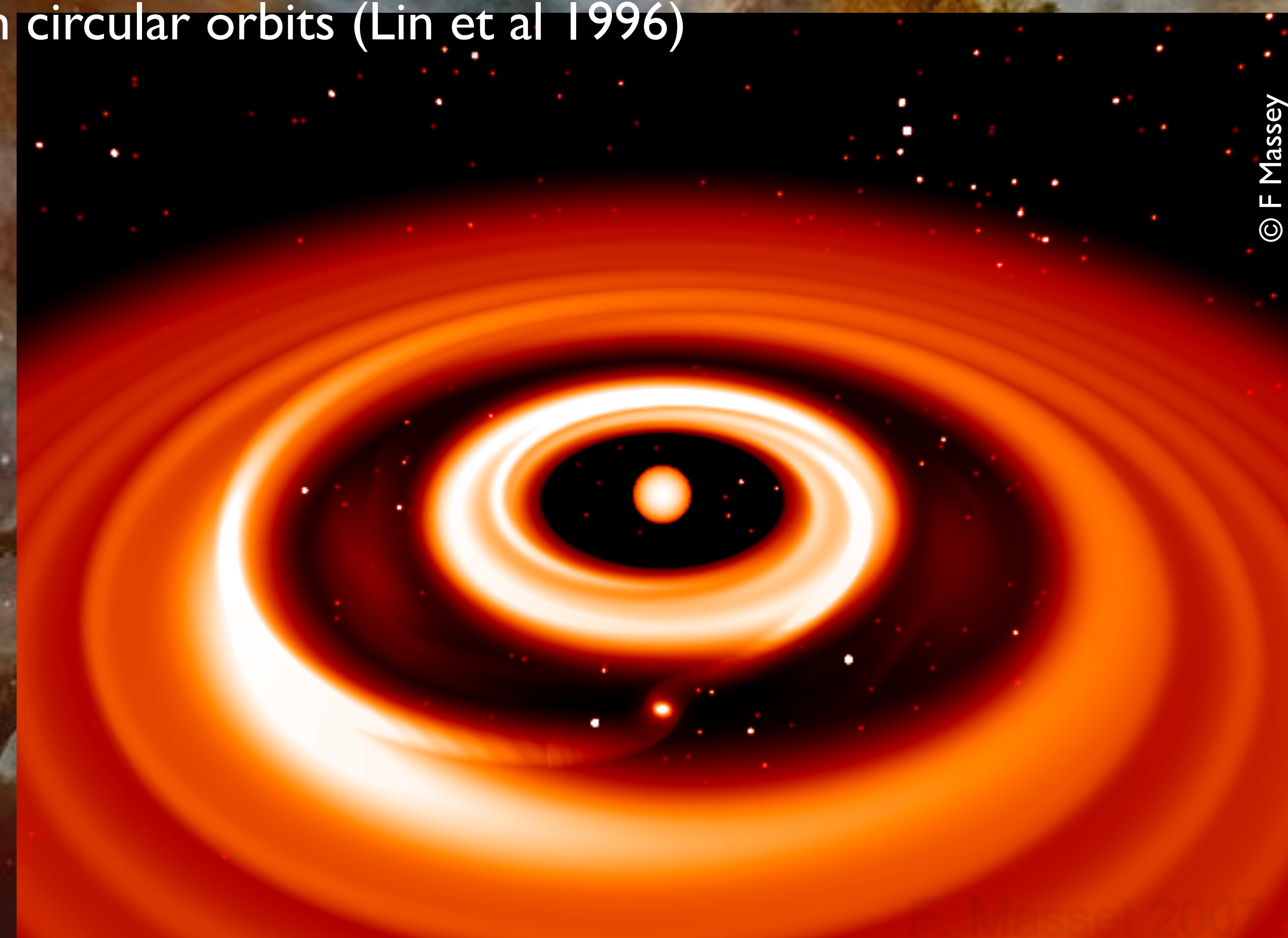
giant planet formed at several au's beyond ice line
kicked on elliptical orbit through gravitational interaction w/ nearby planet / star
orbit aligned & circularized through tidal effects with host star
➾ able to produce both aligned & misaligned hot Jupiters
➾ needs 100-1000 Myr to align & circularize orbits

Formation of hot Jupiters

- planet-disc interaction

  giant planet depletes co-orbital region & generate spiral density structures (wakes)
  differential torque from inner & outer wakes induces inward (type-II) migration
  hot Jupiters migrate on timescales of 0.01-0.1 Myr

  - generates hot Jupiters on circular orbits (Lin et al 1996)



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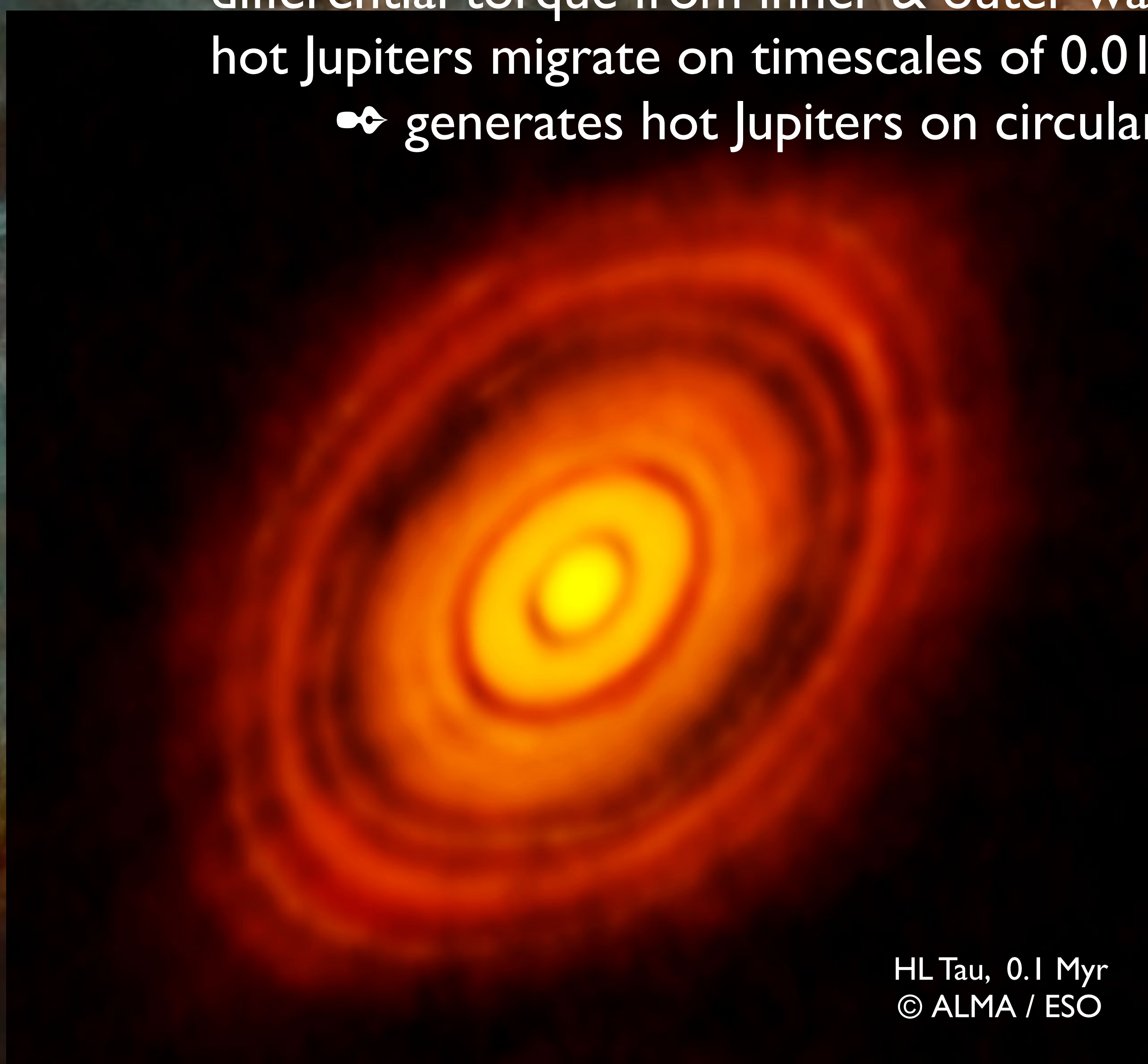

HL Tau, 0.1 Myr
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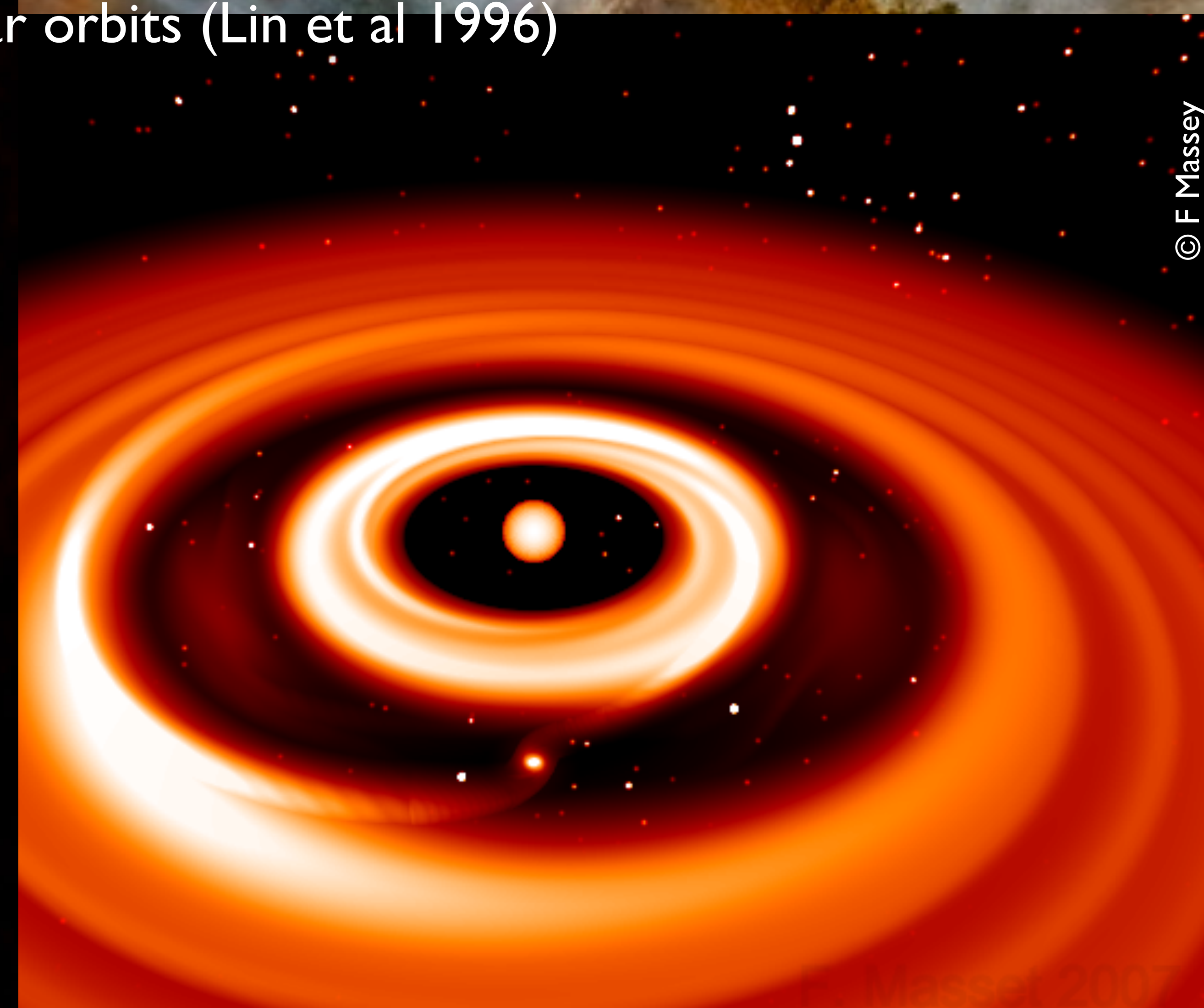

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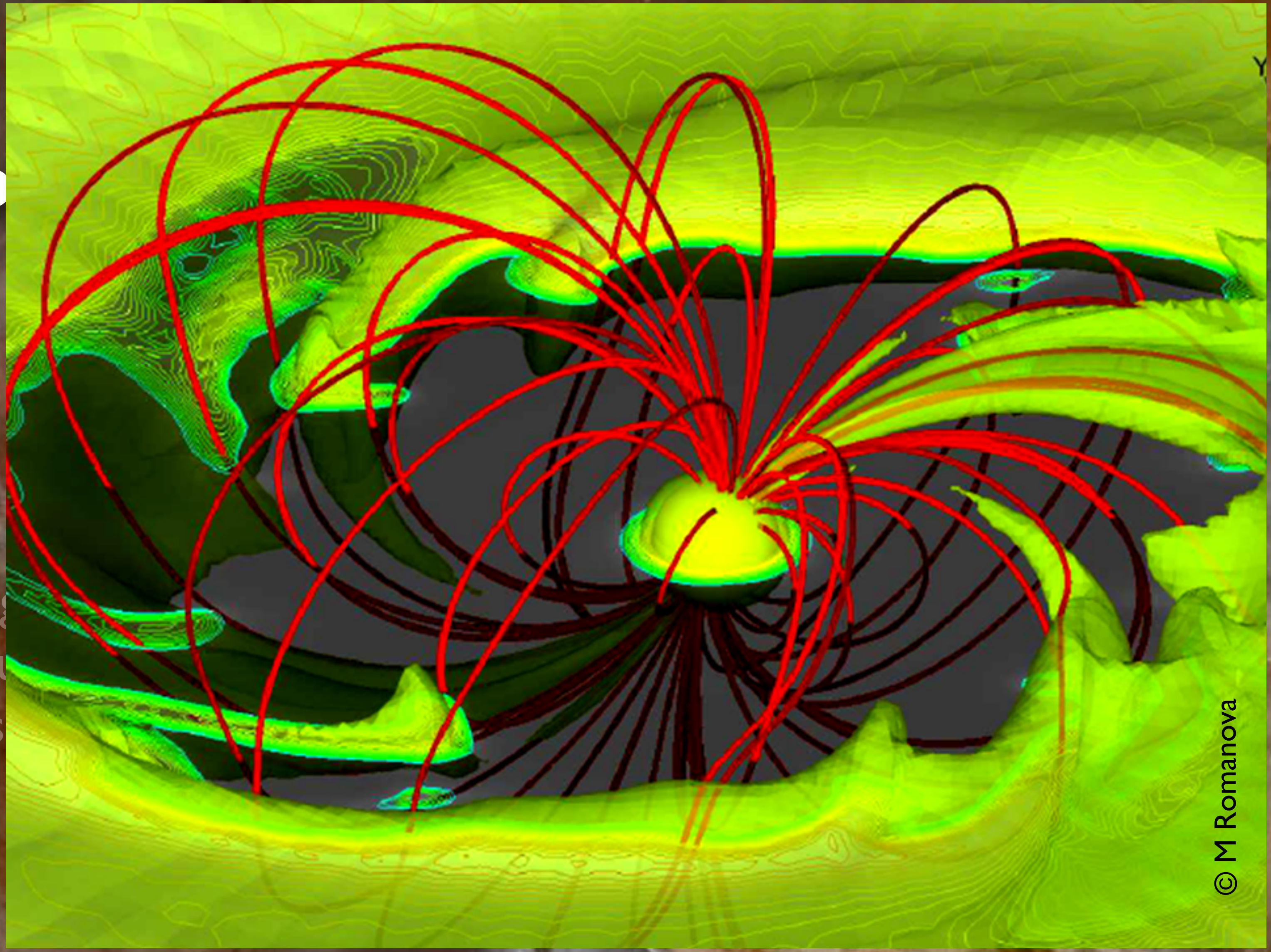

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magnetospheric gaps

host stars trigger strong large-scale dynamo magnetic fields
forces disc material into corotation w/i smallest of either Alfven / Kepler radius
disrupts the central disc regions, generate magnetospheric gap & accretion funnels
- stop planet migration at inner disc edge (Lin et al 1996)
- hot Jupiters survive if disc dissipates before field weakens

- validating hot Jupiter formation w/ young stars ?

Hot Jupiters around young stars

- T Tauri stars (TTSs)
  young Sun-like stars (0.5-15 Myr) no longer embedded in dust cocoon
  contraction not completed yet, w/ radii 3-1.2 $R_\odot$ for a 1 $M_\odot$ star
  either accreting from their discs (classical) or disc-free (weak-line)

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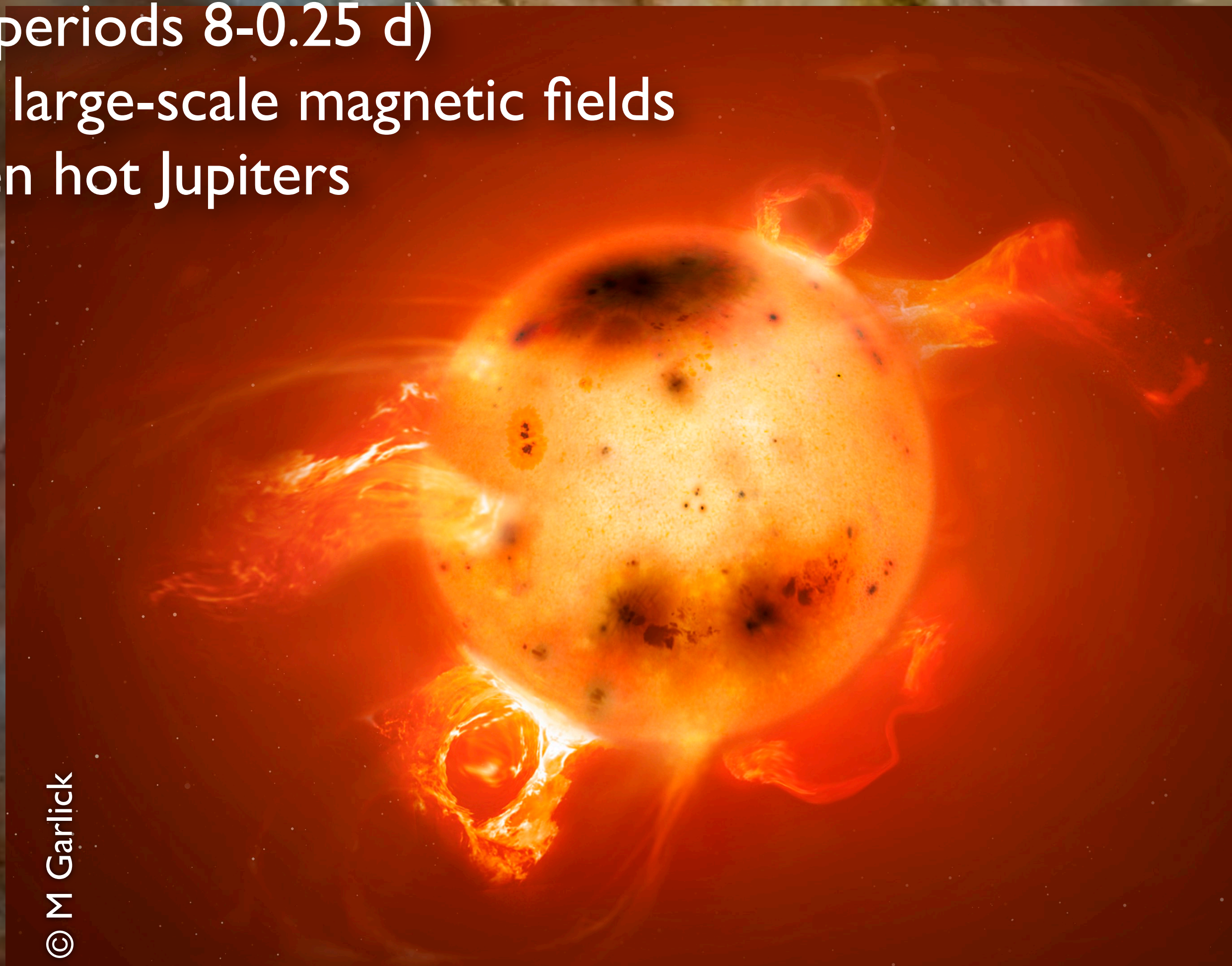
rotation & activity

rotation rates 3-100x faster than the Sun (periods 8-0.25 d)

- extremely active stars with strong large-scale magnetic fields
- very difficult to detect planets, even hot Jupiters



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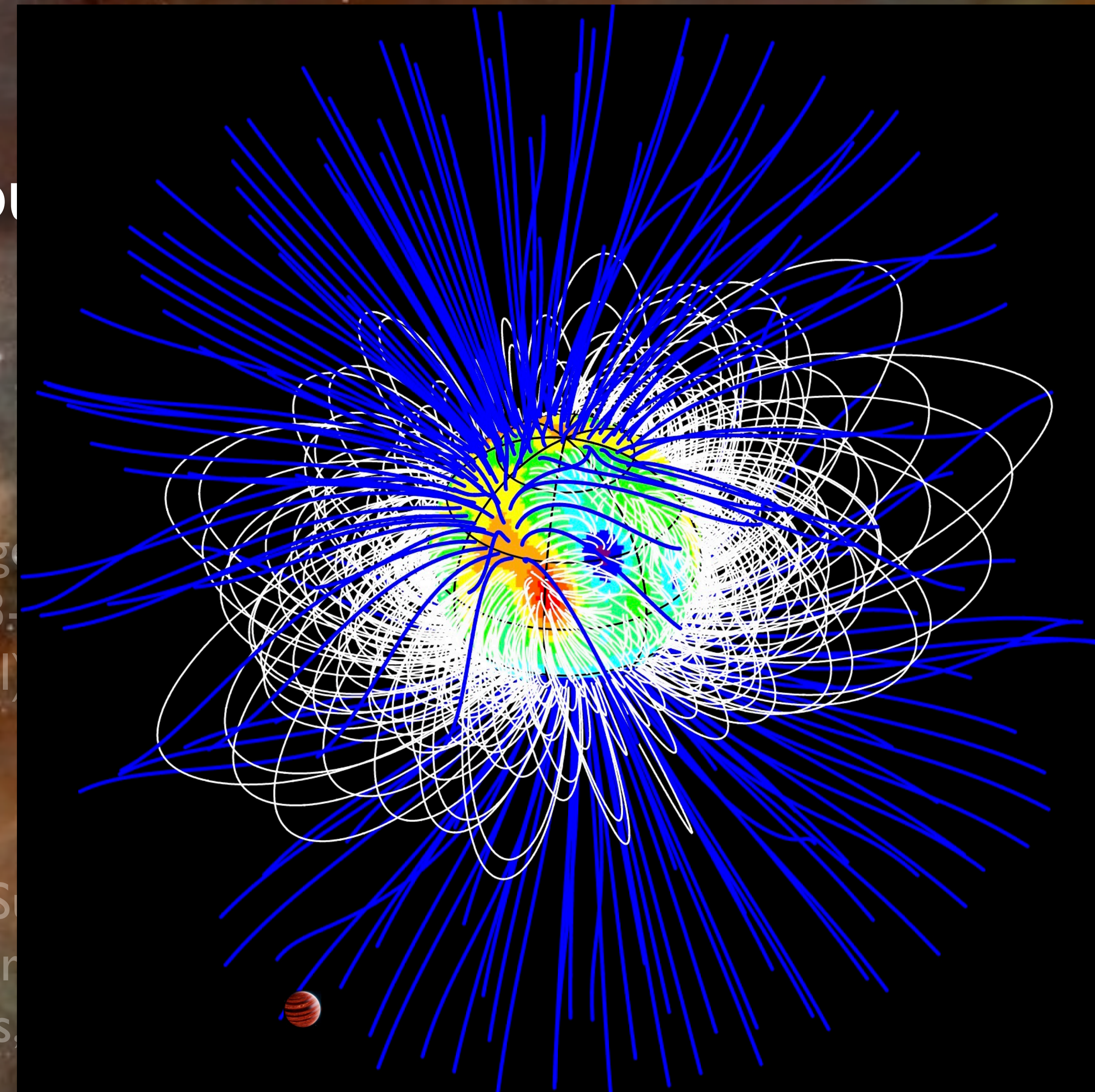


- the MaTYSSE programme
  spectropolarimetric monitoring of TTSs from CFHT (Hawaii) & TBL (Pic du Midi)
  model magnetic fields & activity w/ tomographic imaging
  search for potential hot Jupiters

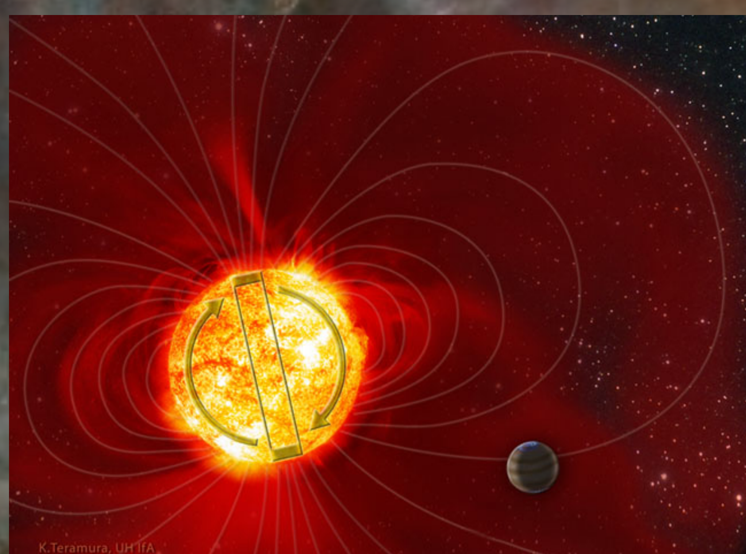
Hot Jupiters around young stars

pic du Midi 1953

Hot Jupiters around young stars

pic du Midi 1953

pic du Midi 2010



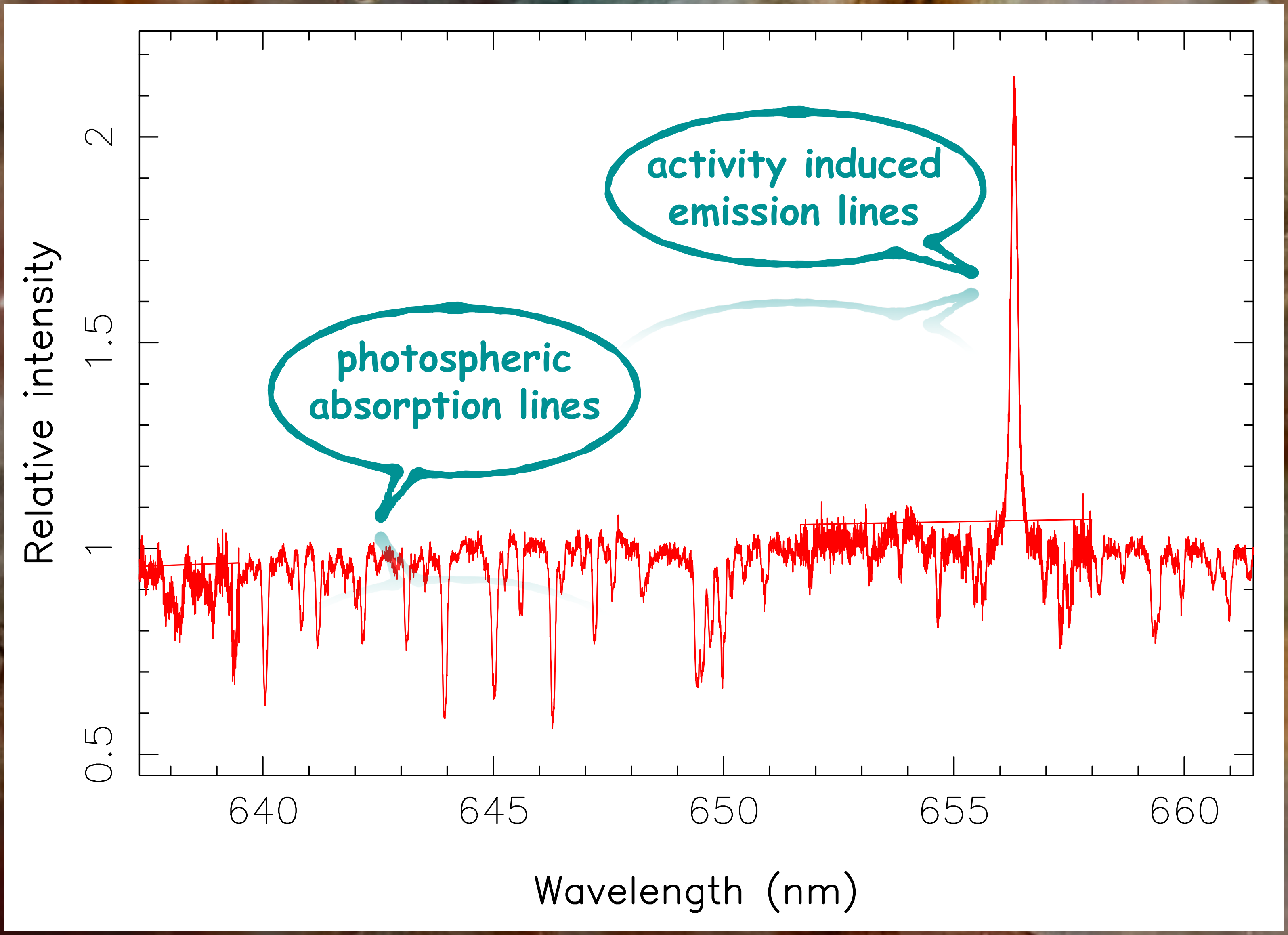
Hot Jupiters around young stars

- rotational modulation of spectral lines

  magnetic spots generate line profile variations & Zeeman signatures

  induce RV variations of several km/s, much larger than those from hot Jupiters

  - compute average line profiles from ~7000 spectral lines
  - monitor temporal variations / modulation of line profiles



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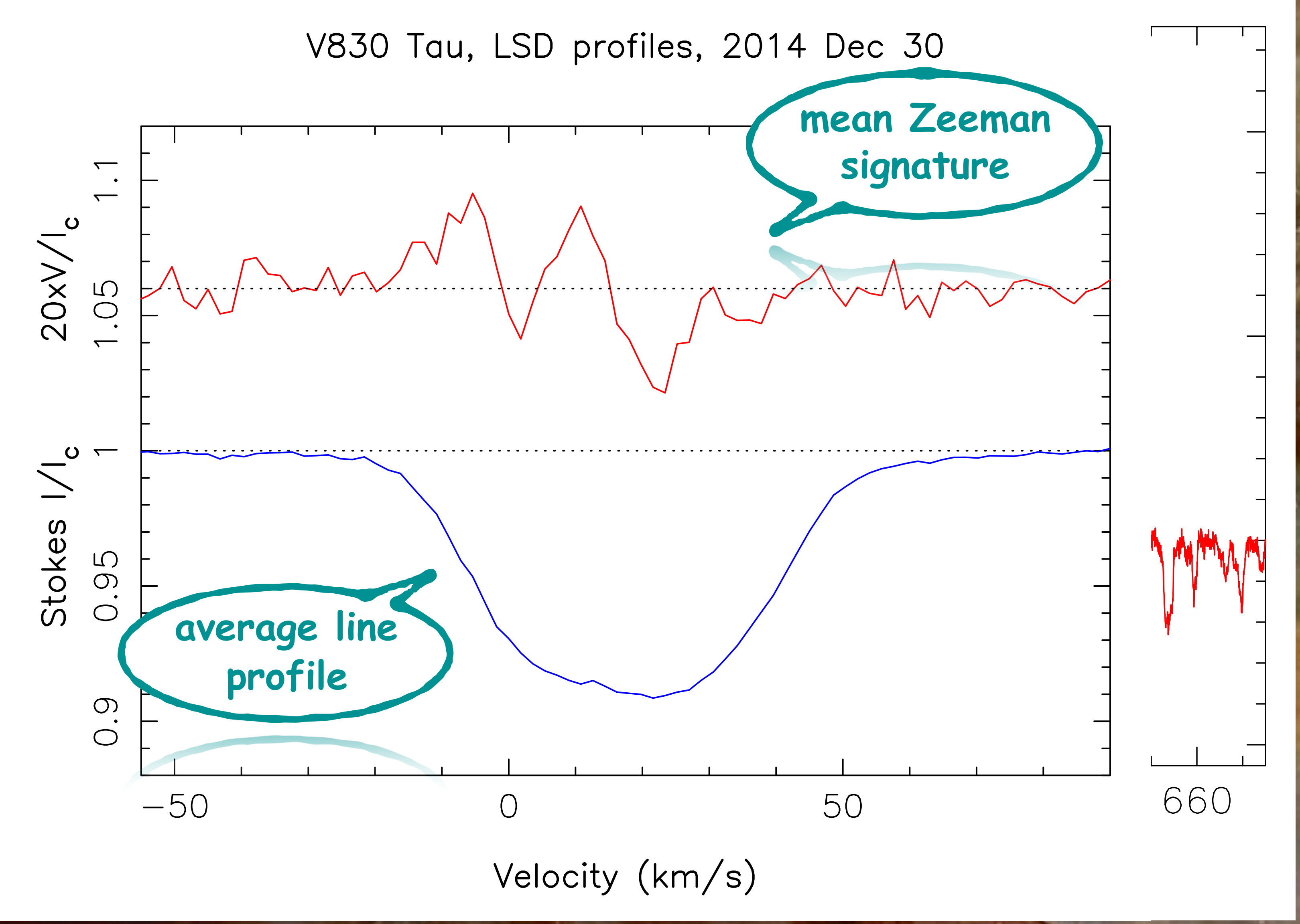

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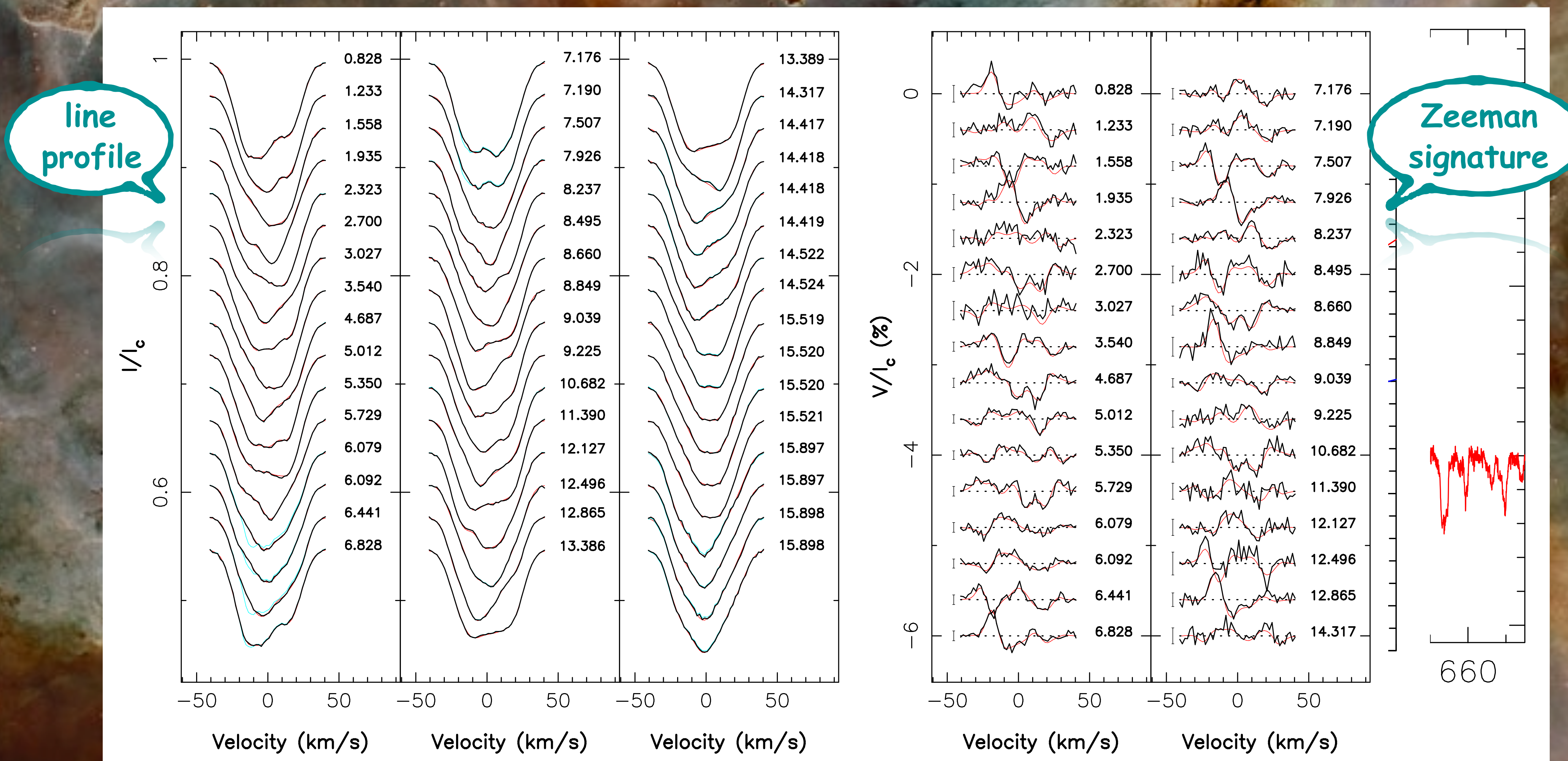
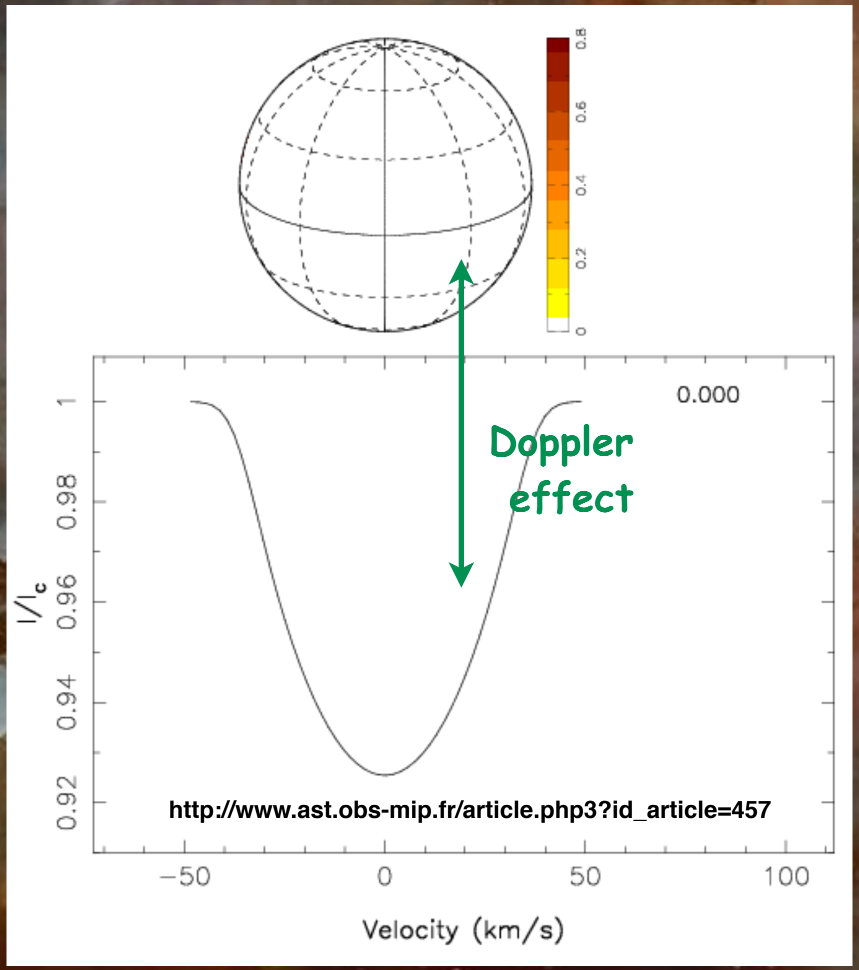


Hot Jupiters around young stars

- tomographic imaging

reconstruct 2D brightness & magnetic map from series of (1D) line profiles
use maximum entropy principle to infer simplest map compatible with data

- large fraction of the star covered with cool spots / warm plages
- large-scale field 2-3 orders of magnitude stronger than solar
- surface differential rotation shearing the surface
- temporal evolution of surface features
- use results to filter-out RV curves from "activity jitter"



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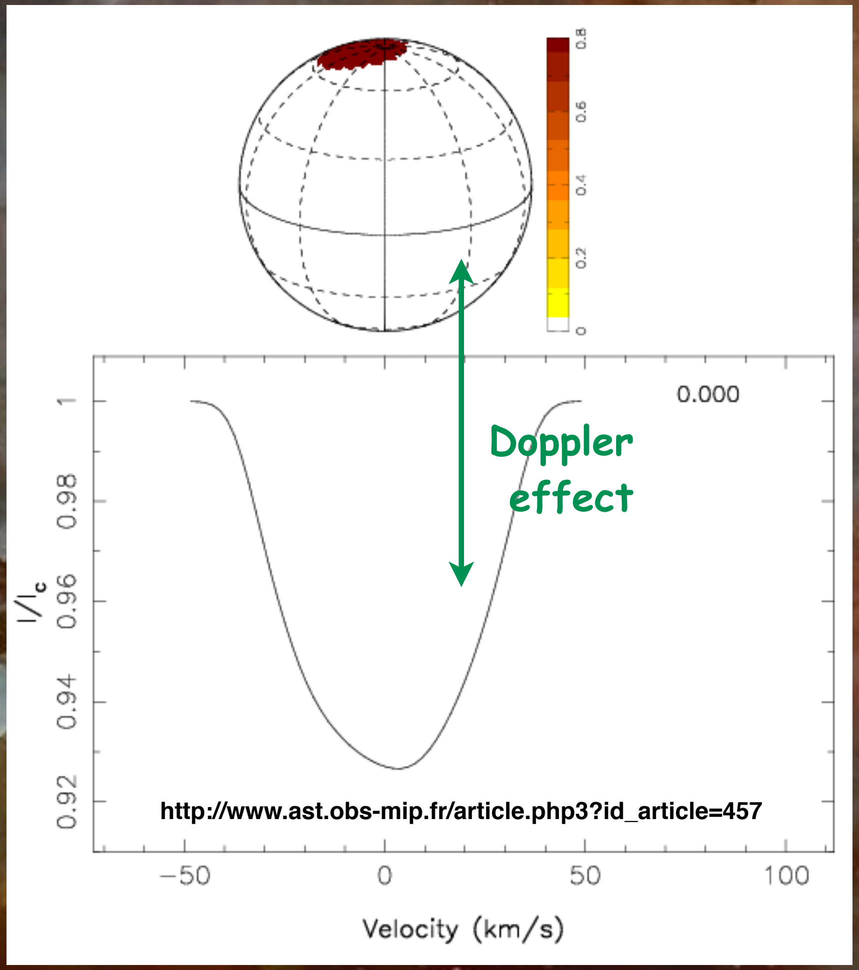

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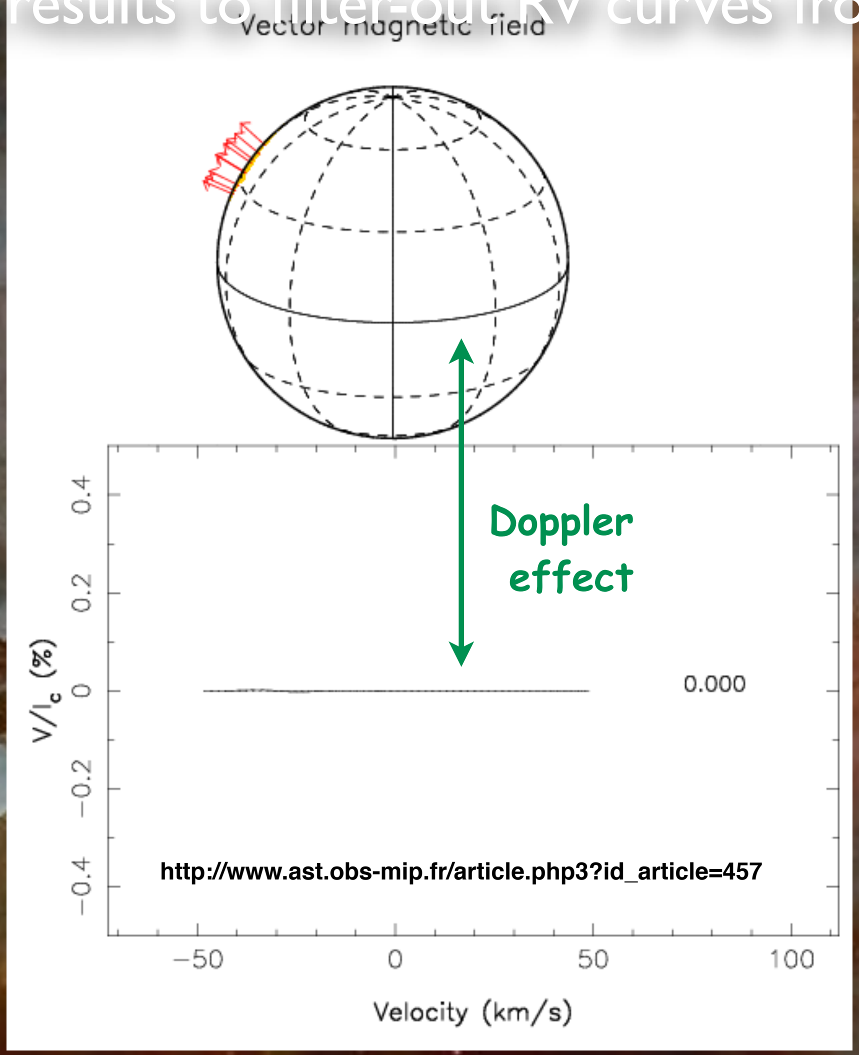

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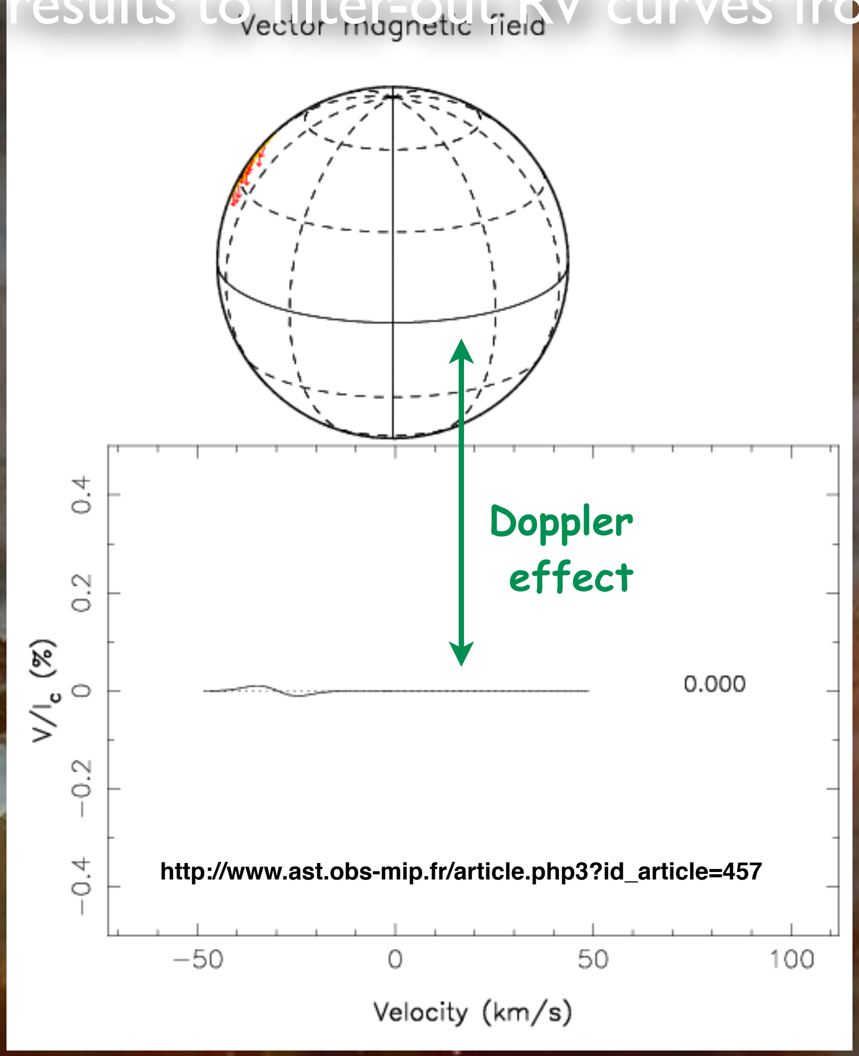

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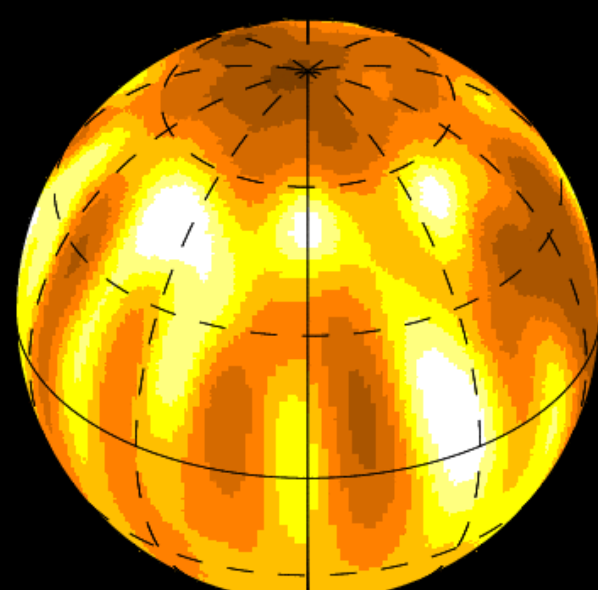
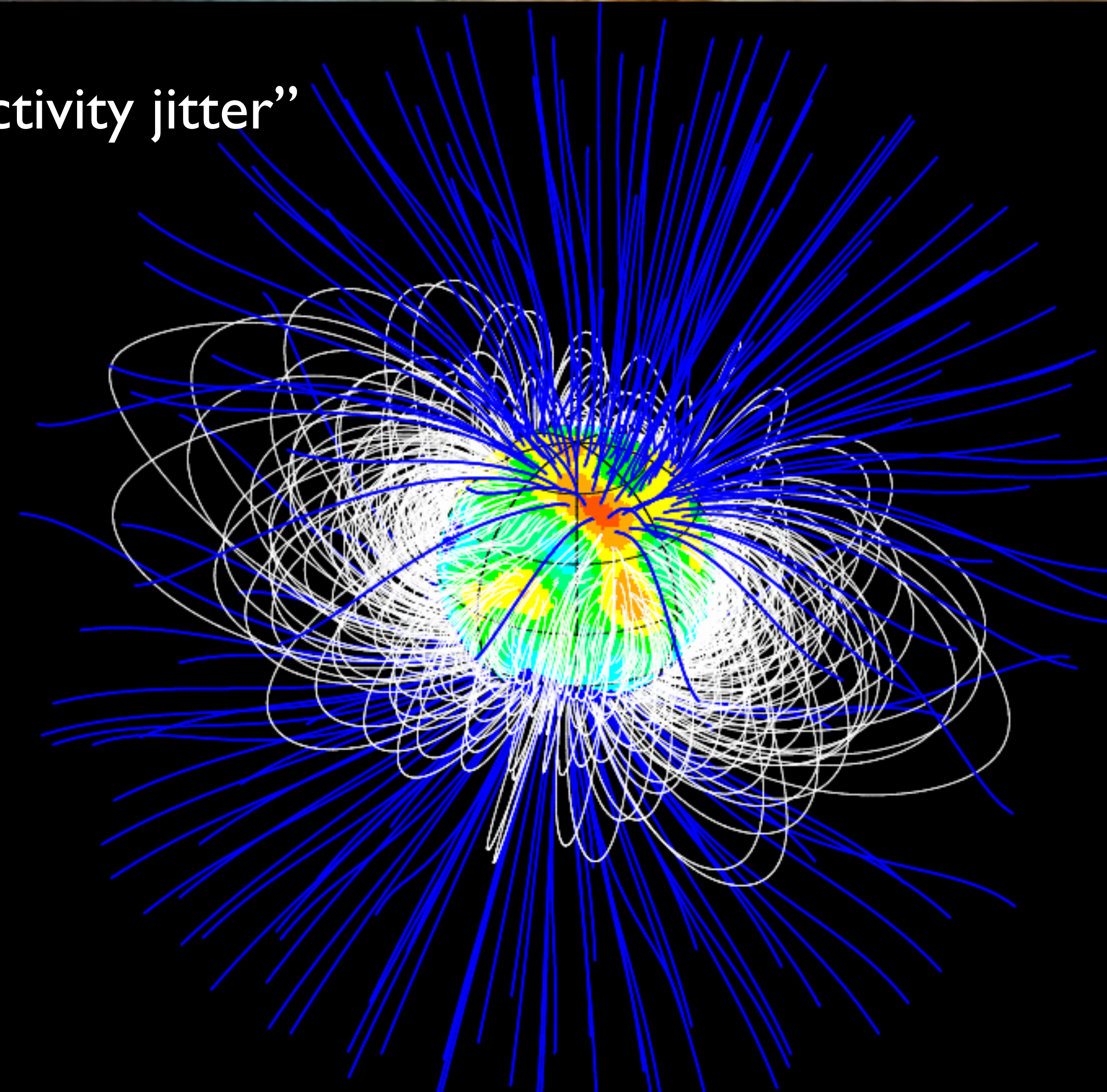
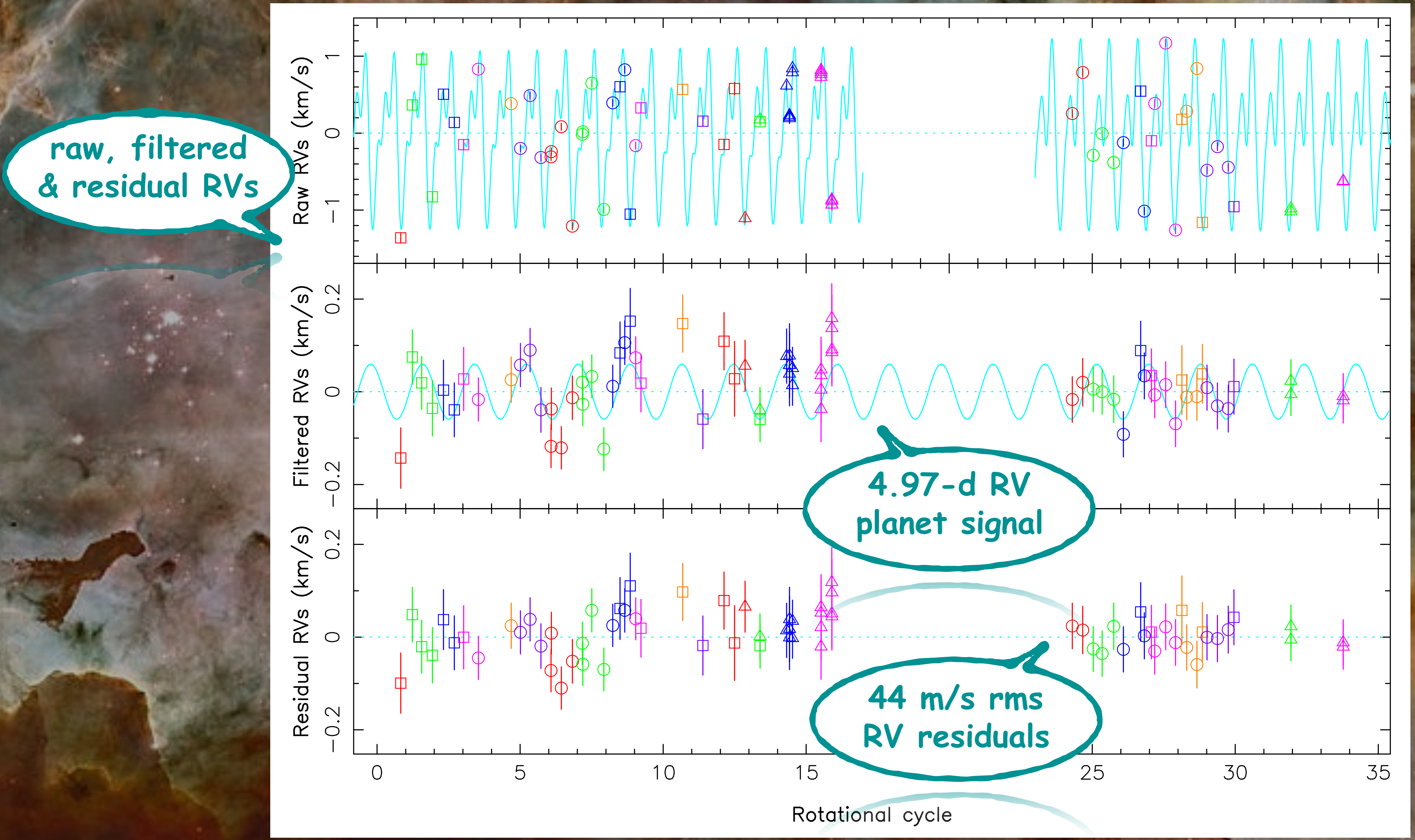




Hot Jupiters around young stars

- filtering RV curves from activity jitter w/ tomographic imaging
  youngest known hot Jupiter detected on ~2 Myr-old TTS V830 Tau
  planet RV signal ~20x smaller than activity jitter, small eccentricity



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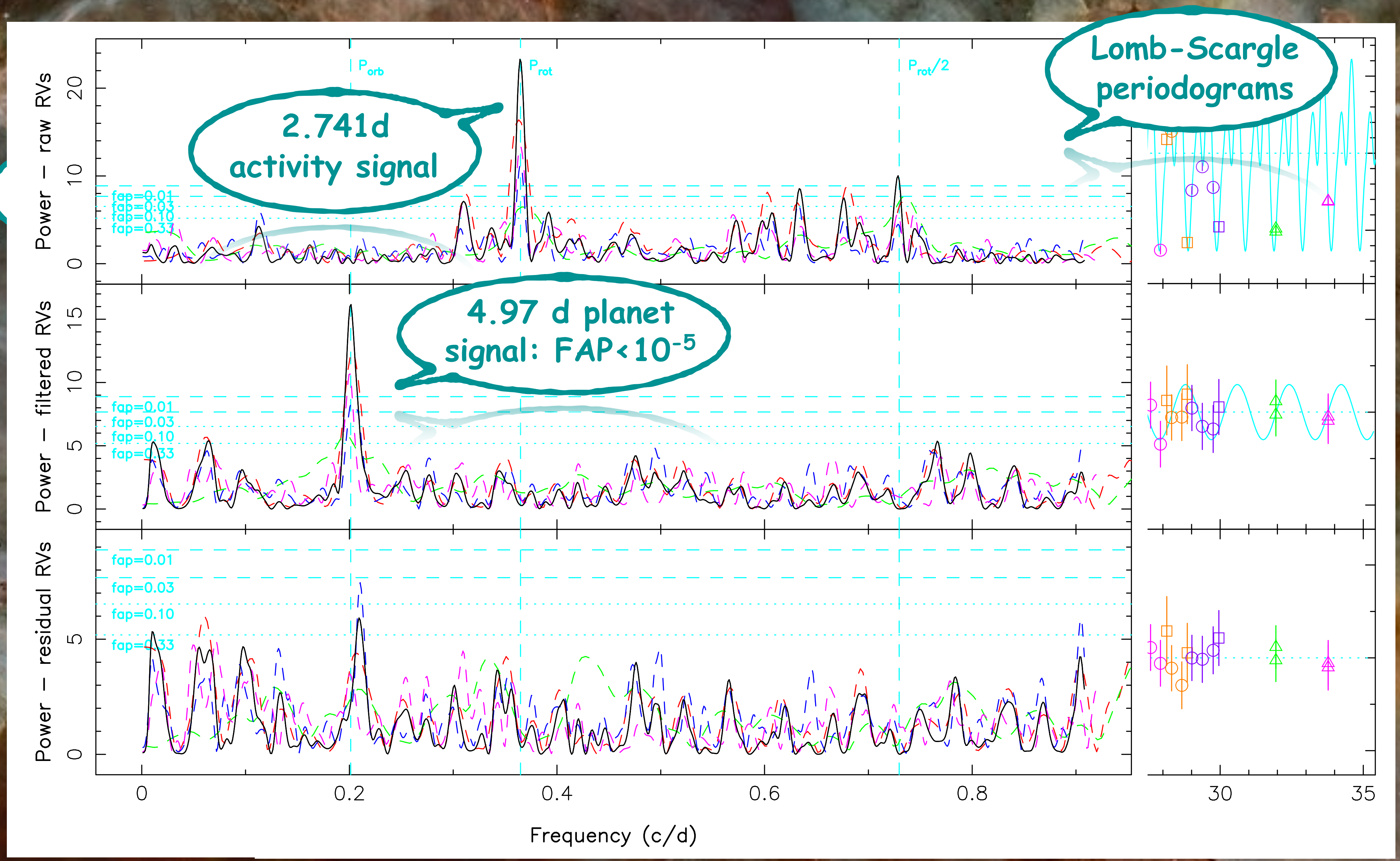

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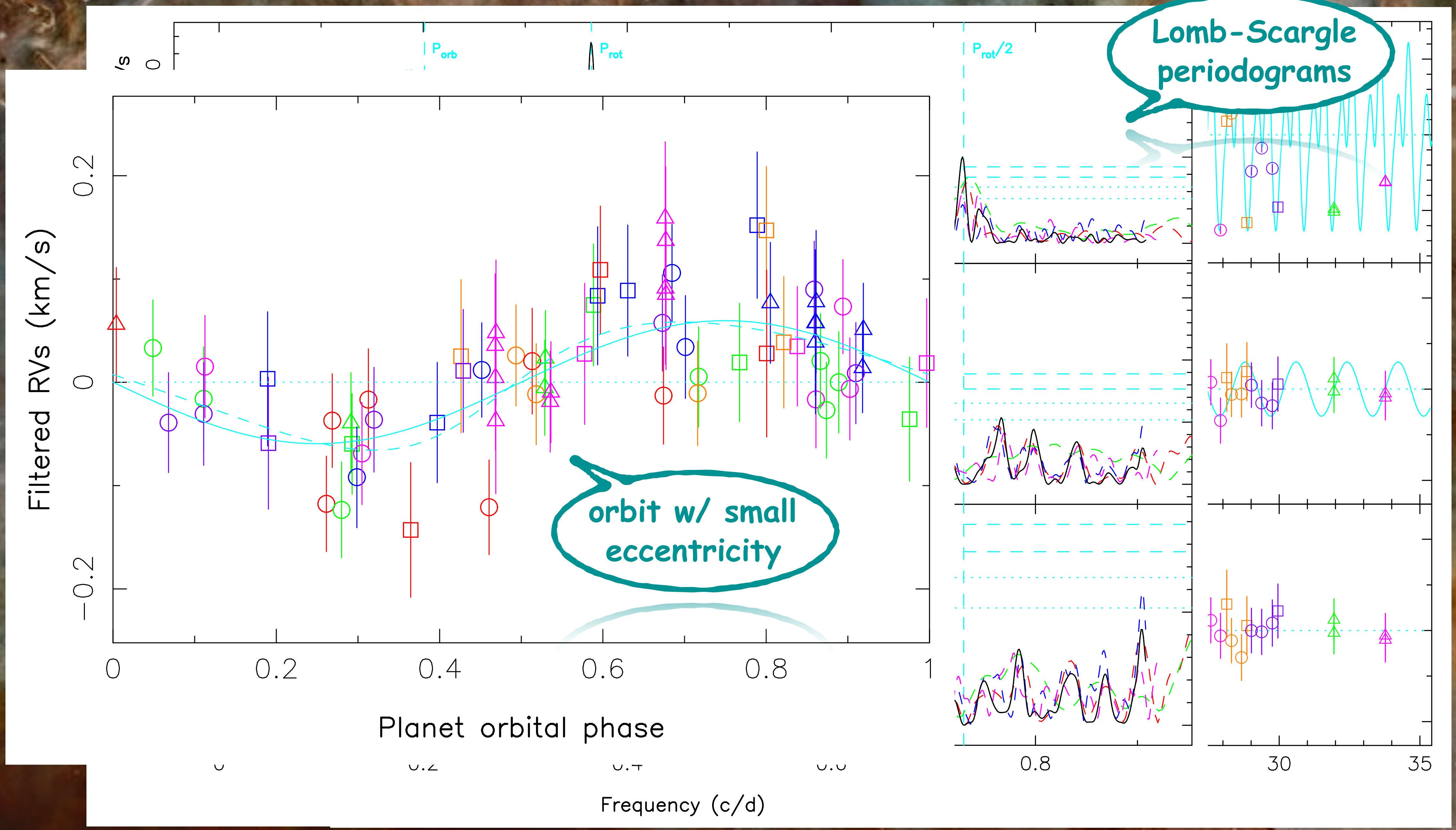

Hot Jupiters around young stars

- modeling activity using Gaussian Process Regression (GPR)

  model activity as correlated noise, eg a Gaussian process (GP) of known covariance

  assume pseudo-periodic covariance function (eg Haywood et al 2014)

  - reproduces rotational modulation & spot evolution

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- covariance function
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subtract planet signal & model activity for given set of GP parameters
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MCMC simulation

derive posterior distributions of planet & GP parameters at the same time

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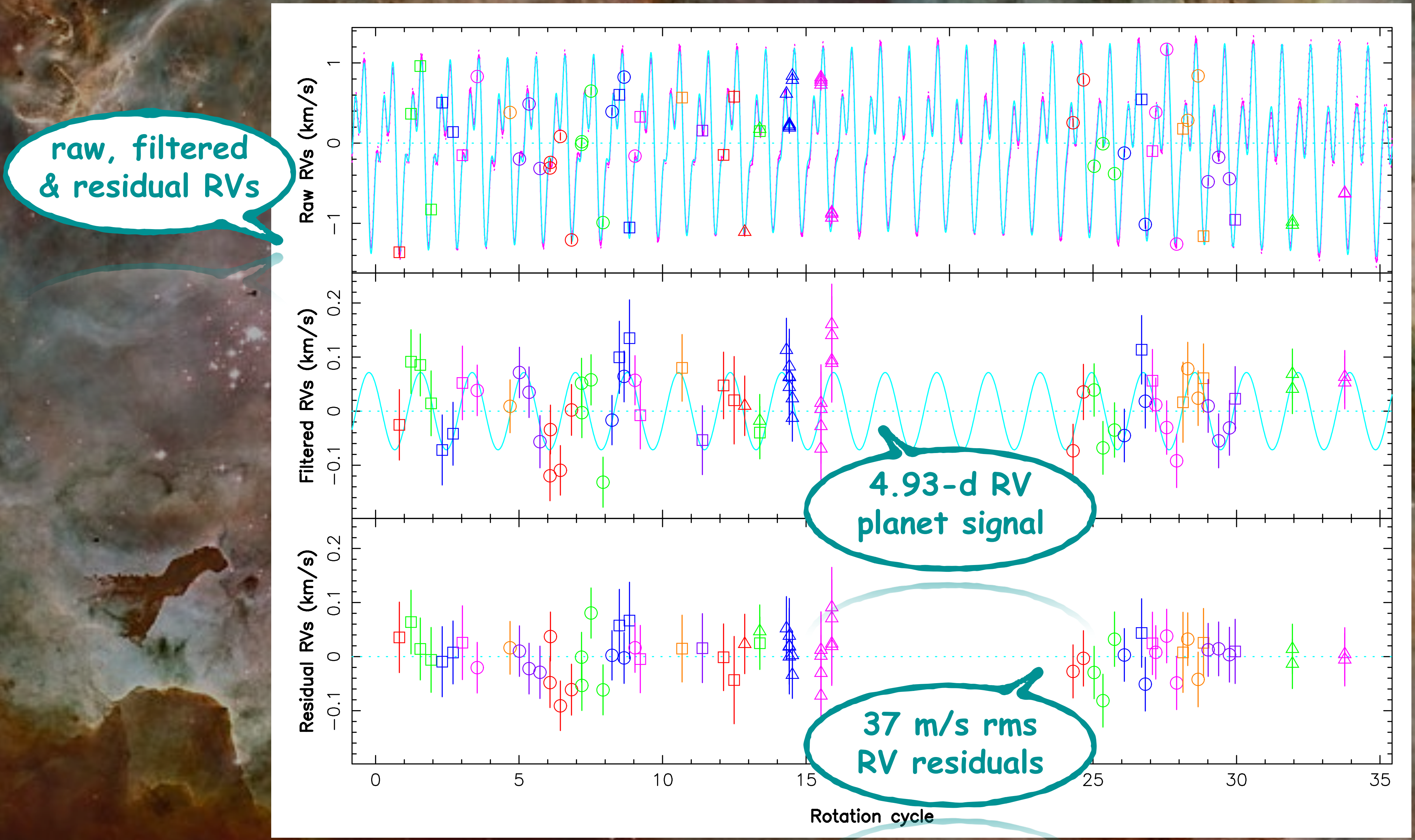
  - posterior distributions on planet (& GP) parameters



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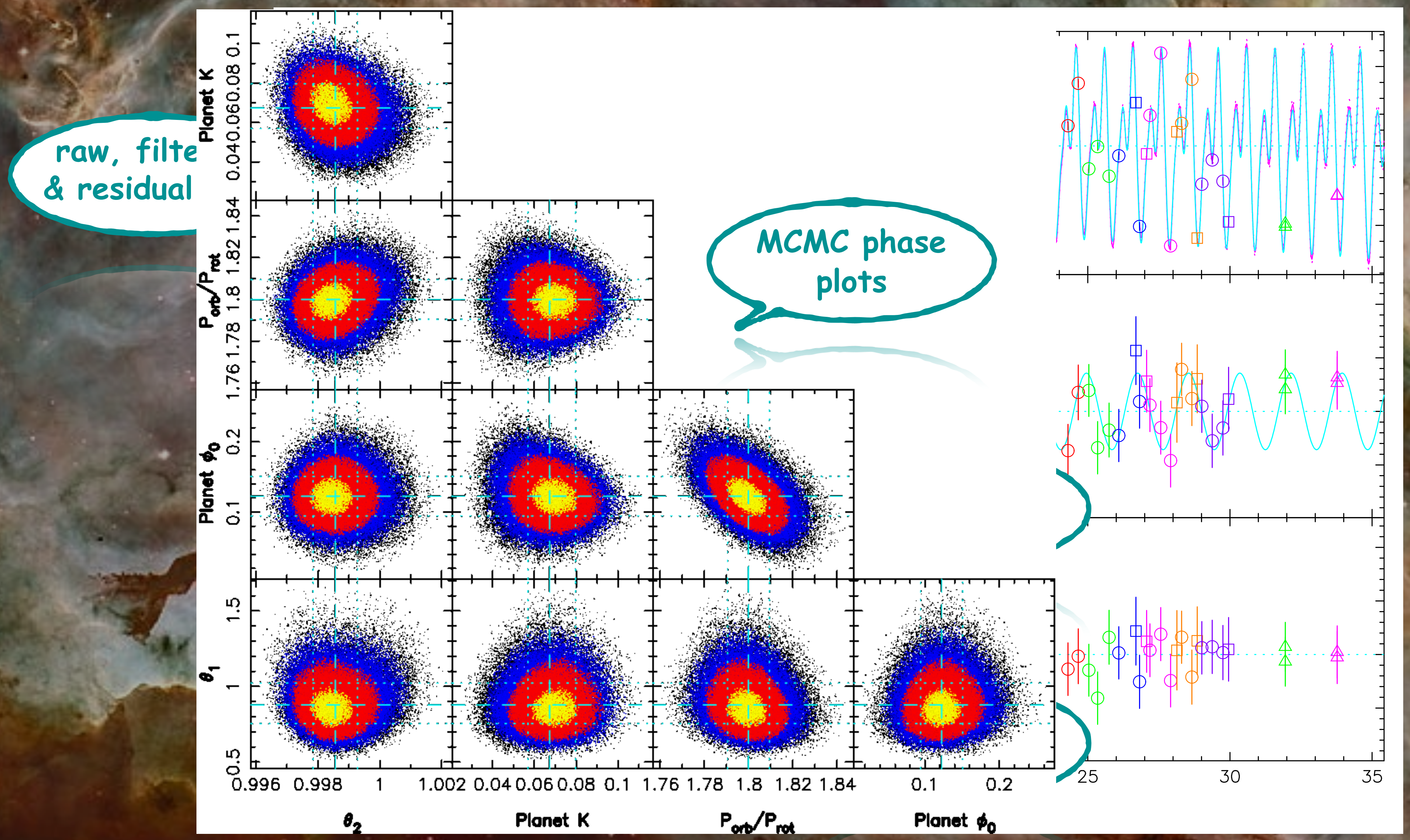

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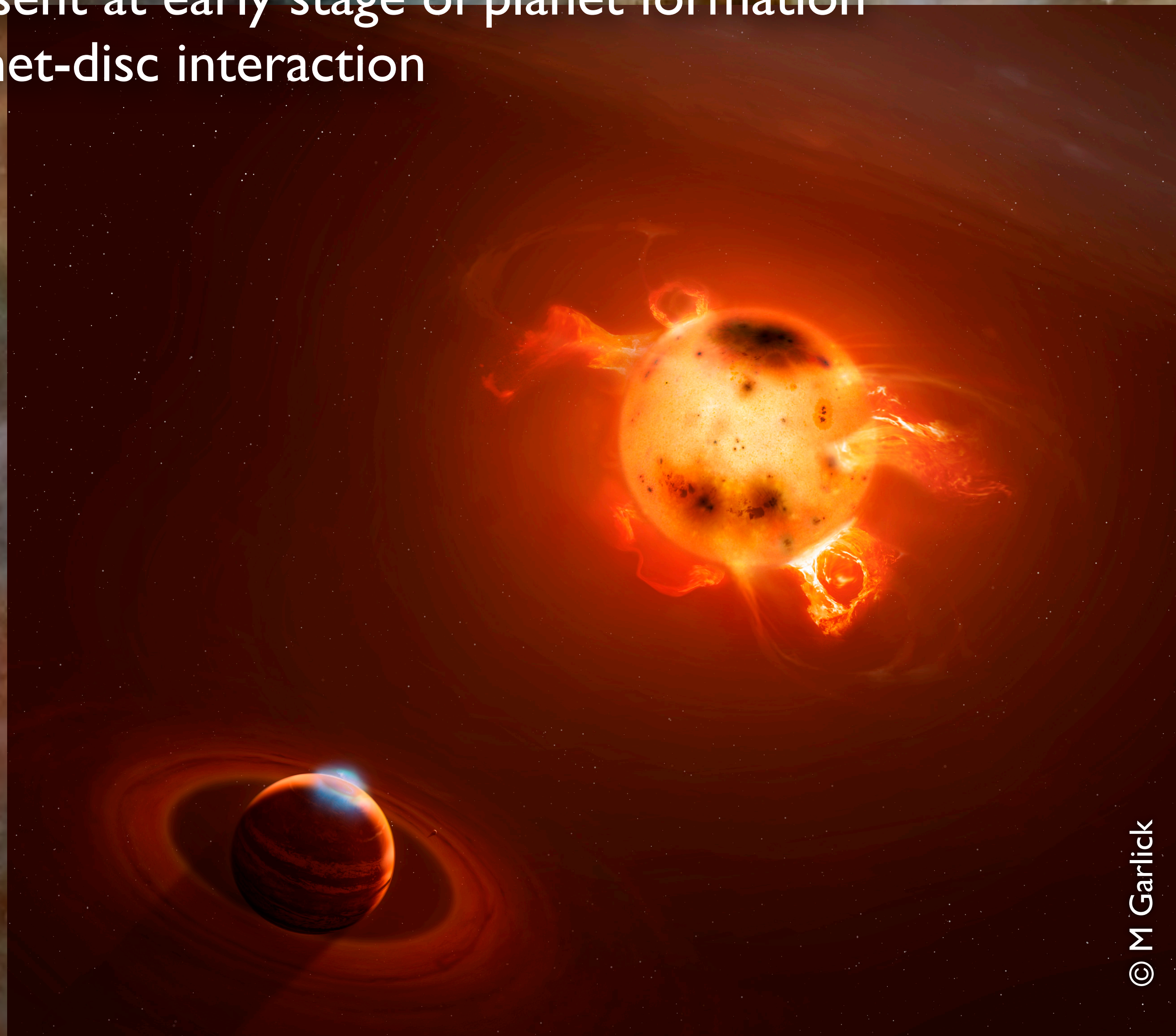

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- open questions
  - more frequent than on mature stars?
  - role of magnetic fields on planet survival?
  - impact on early architecture of planetary systems?
  - temperature / luminosity of newborn planets?
  - io-Jupiter like star-planet interactions?
  - transiting planets?

Future prospects

- characterize newborn hot Jupiters
  - new extensive monitoring campaign about to begin for both stars
  - multi wavelengths observations, including nIR spectroscopy & radio (LOFAR)
  - high-precision photometry with Kepler / K2 to detect potential transit
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SPiRou

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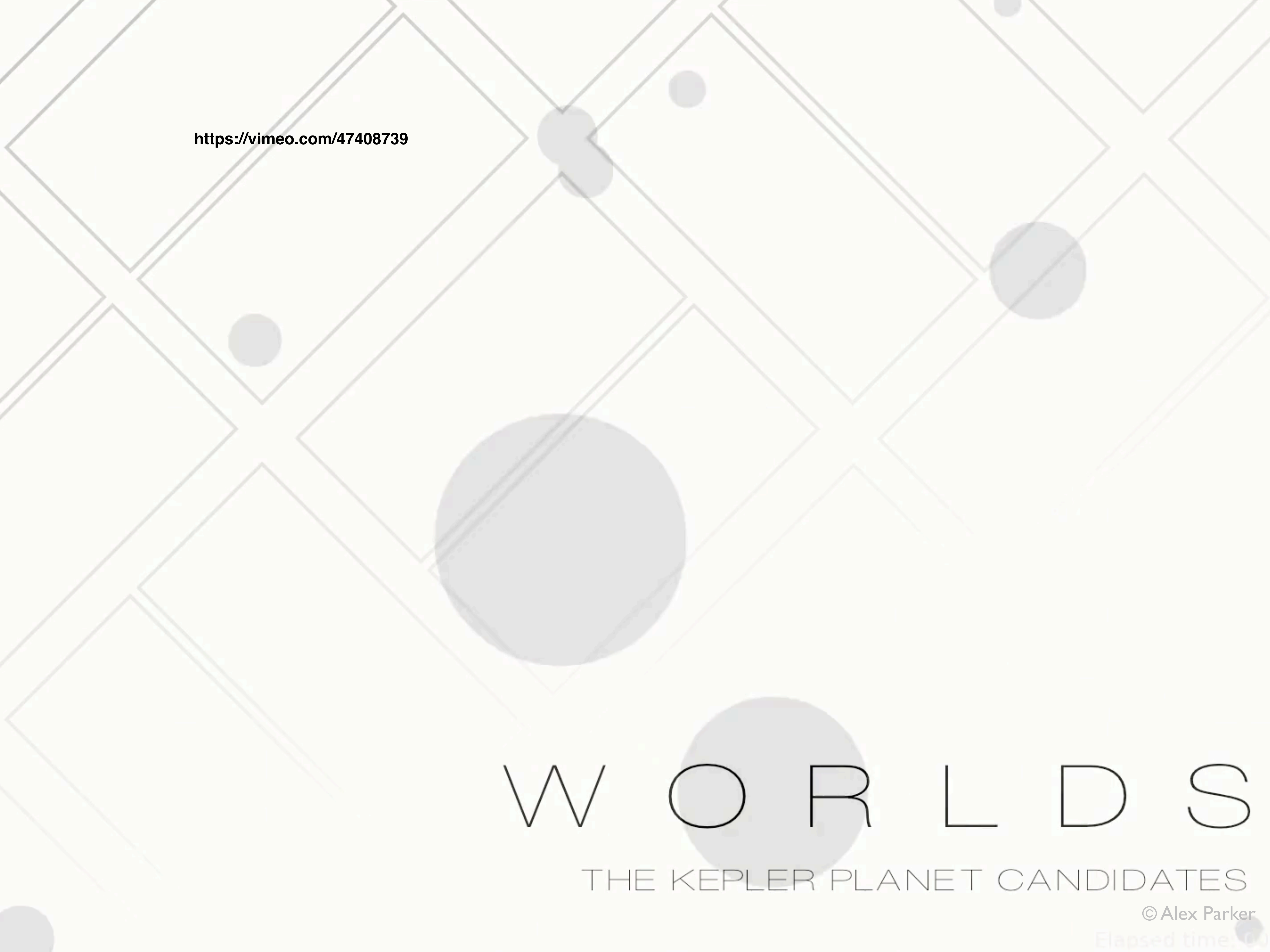
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