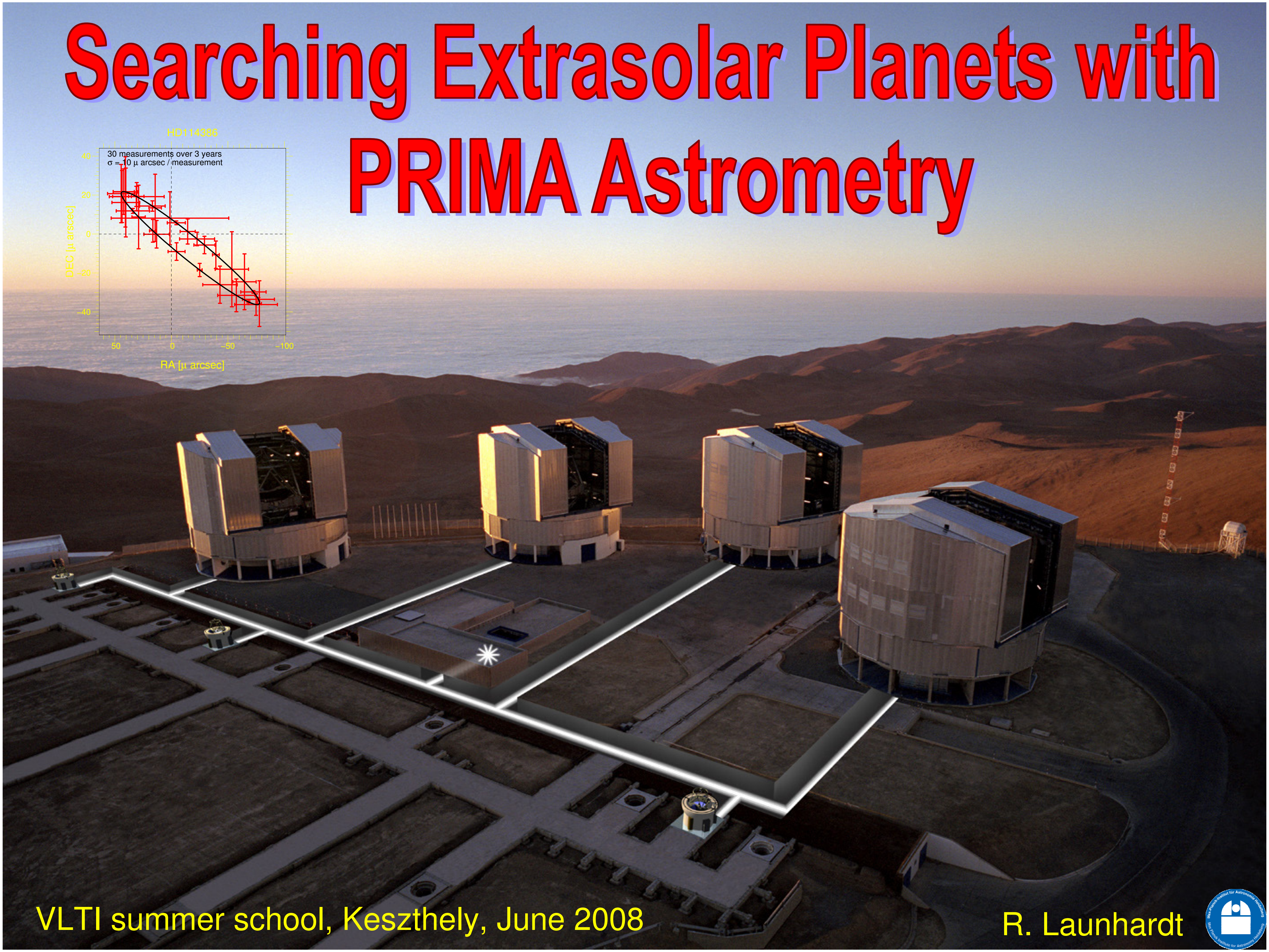
Searching Extrasolar Planets with PRIMA Astrometry



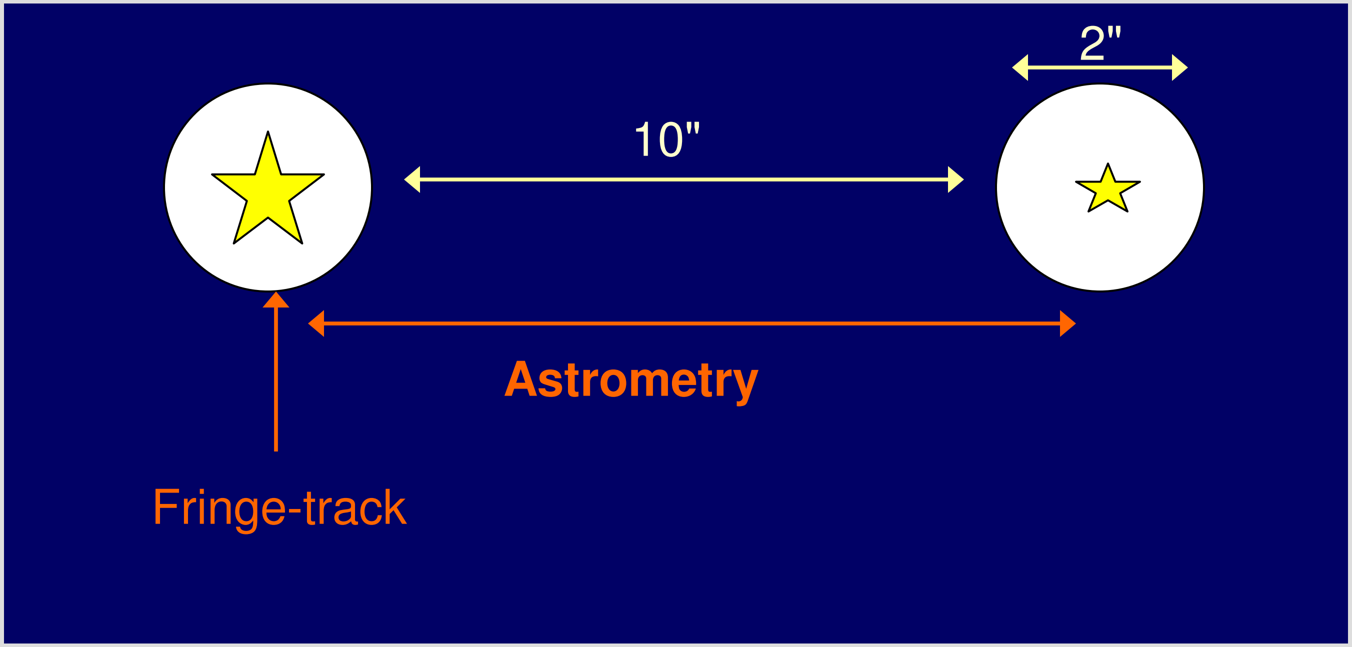
VLTI summer school, Keszthely, June 2008

R. Launhardt

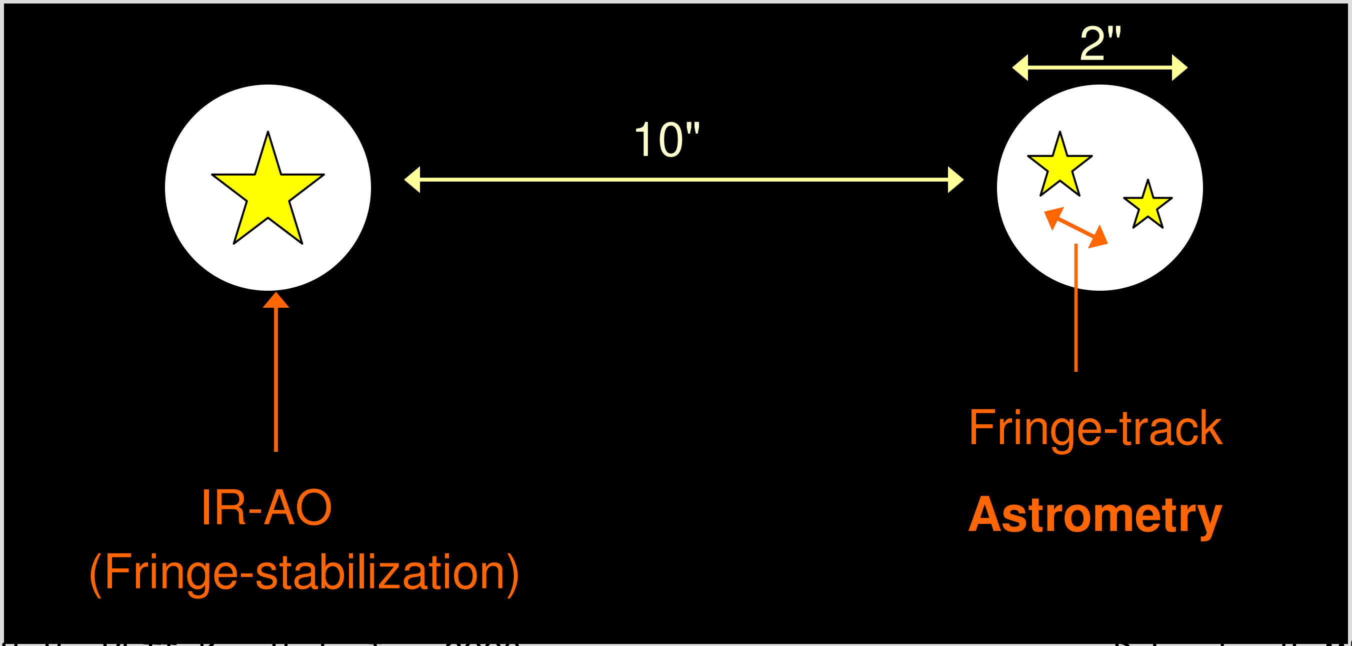
Outline:

1. Exoplanets
2. Astrometry
3. The ESPRI project

PRIMA:



Gravity:



1. Exoplanets

Why do we care for Giant Planets around other stars?

1. **Are we alone in the universe?**
2. Where are they?
   (Most likely on rocky planets with atmospheres in habitable zones)
3. Where do we search for life?
   (Best around stars that have formed giant planets and allow stable orbits for rocky planets in the habitable zone)
4. How many and which stars have such planetary systems?

=> Find out where the big planets are!

Challanges of observing extrasolar planets

1. Planets don‘t produce any light of their own, except when young
2. They are lost in the blinding glare of their host stars
3. They are an enormous distance from us

Planet search methods

Direct

Detect light from the planet

- Direct imaging
- Differential spectroscopy

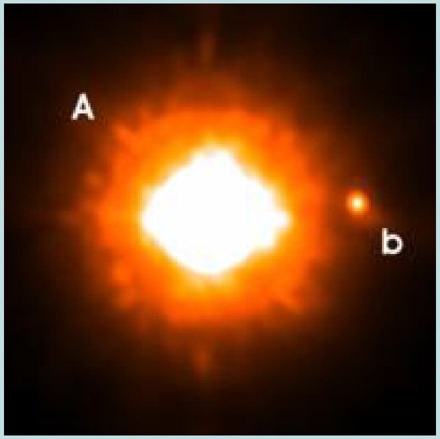
Indirect

Measure signal from another body (e.g., host star) and infer the existence of a planet

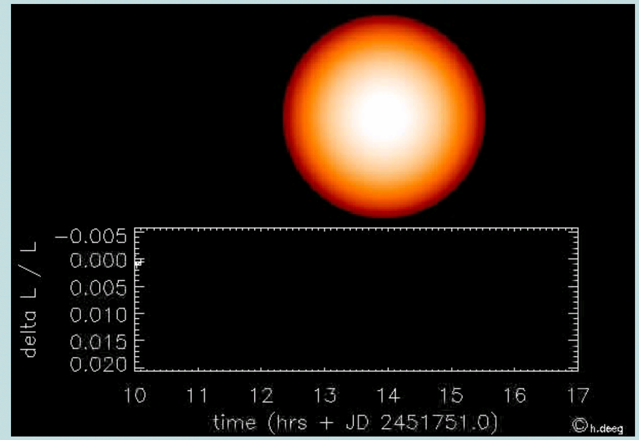
- Radial velocity
- Astrometry
- Gravitational Microlensing
- Transit photometry

Planet search methods *(incomplete!)*

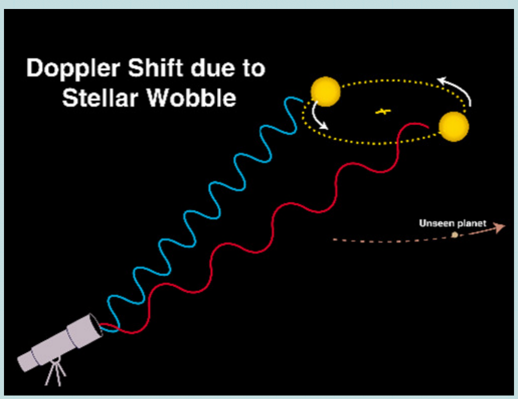
Direct Imaging → Sphere



Transit photometry → Corot



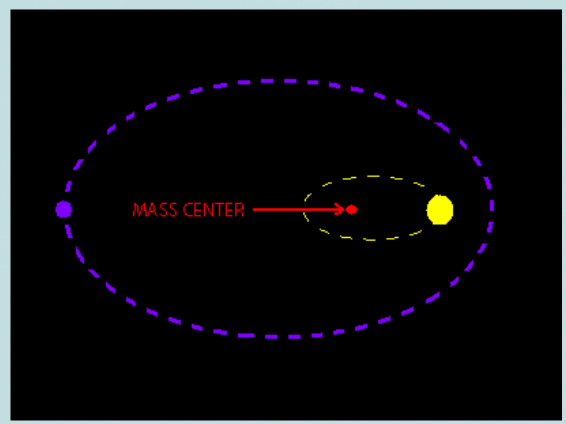
Doppler Spectroscopy → HARPS



1-D

(z)

Astrometry → PRIMA

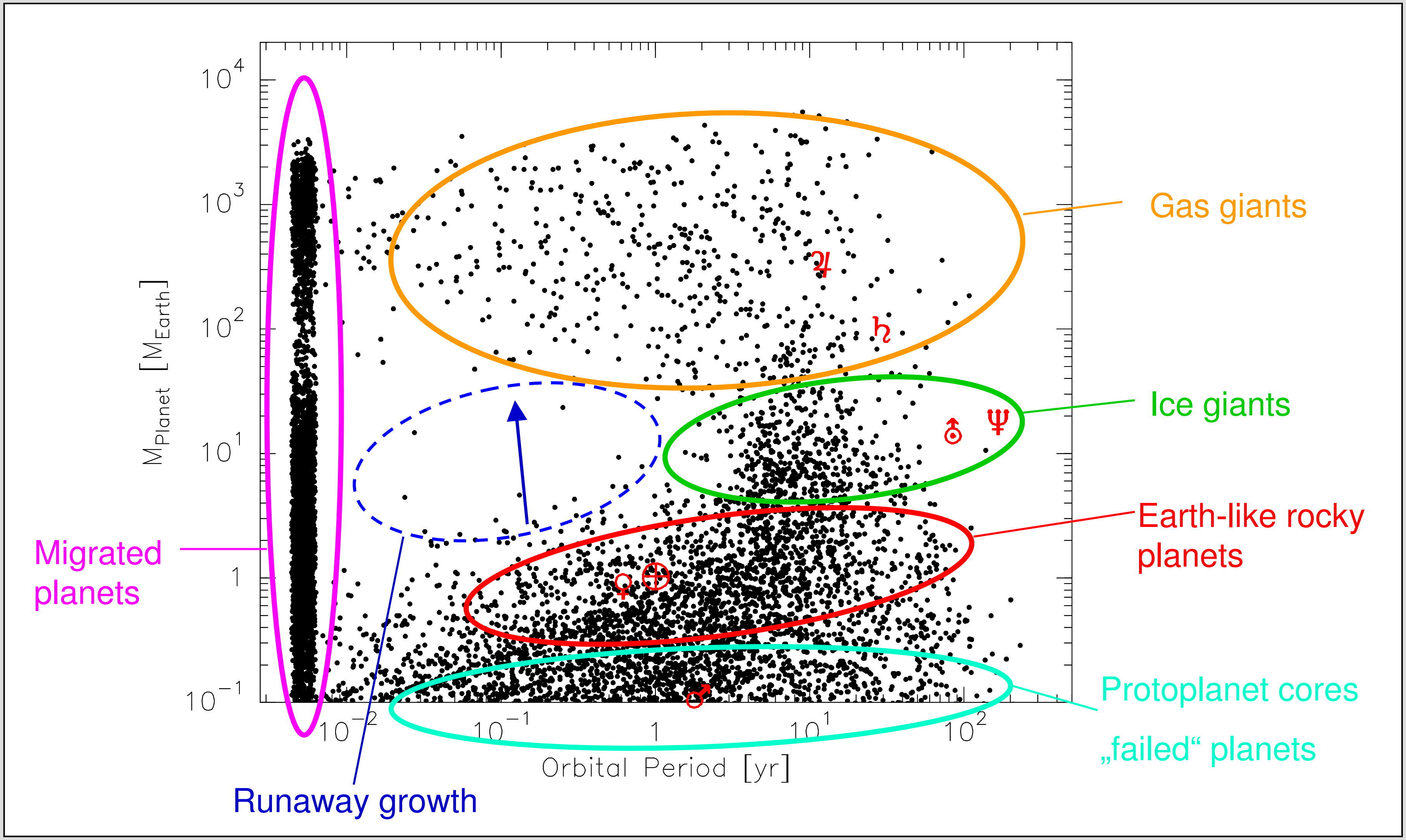


2-D

x,y

Planet detection space

Planet population synthesis, Ida & Lin 2008; host star mass 1 M_{sun}



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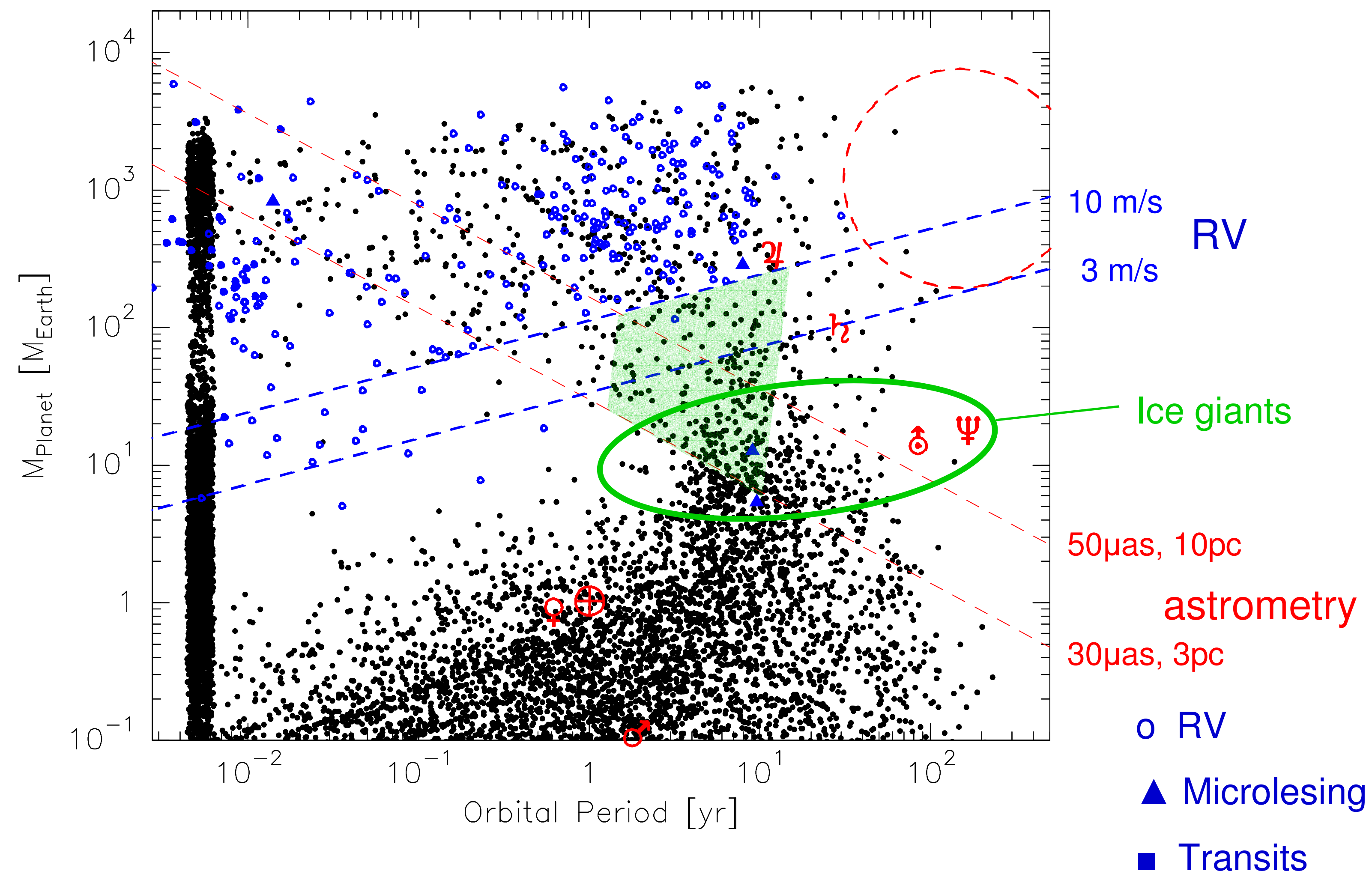


Astrometry vs. RV

Astrometry:

$\rho = (G/4\pi^2)^{1/3}\, m_p / m_*^{2/3}\, P^{2/3} / D$

RV:

$K = m_p \sin i / (m_* + m_p)^{2/3}\, (2\pi G/P)^{1/3} f(e)$

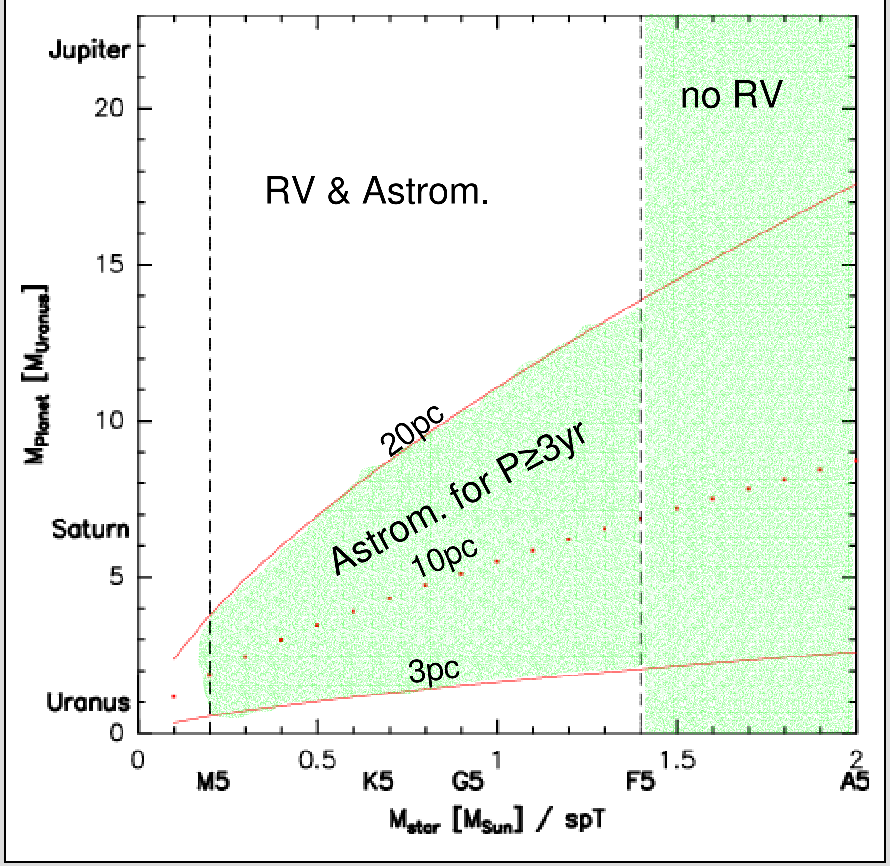
$\longrightarrow\ D \sim P^{1/3} K/\rho$

$\rho > 50\mu as$ & $K < 10 m/s$

For $P \geq 3yr$,

astrometry is always better at D<20pc,
RV is better at D>20pc

Astrometry detection domain for P≥3yr:



➡ In ESPRI, we chose 15 pc as distance limit for nearby stars

Astrometry detection space – other aspects

- Astrometric signal $\propto D^{-1}$

  → promising potential to characterize the ***most nearby*** *systems*

- Astrometry does not depend on narrow and stable spectral lines

  → Observe ***young stars*** (active, broad and unstable lines)

  → Stars more ***massive*** than 1.4 M_{Sun} (few and broad lines)

- Astrometry is 2-D

  → all orbital parameters, ***true planet mass***, no *sin i* ambigouity

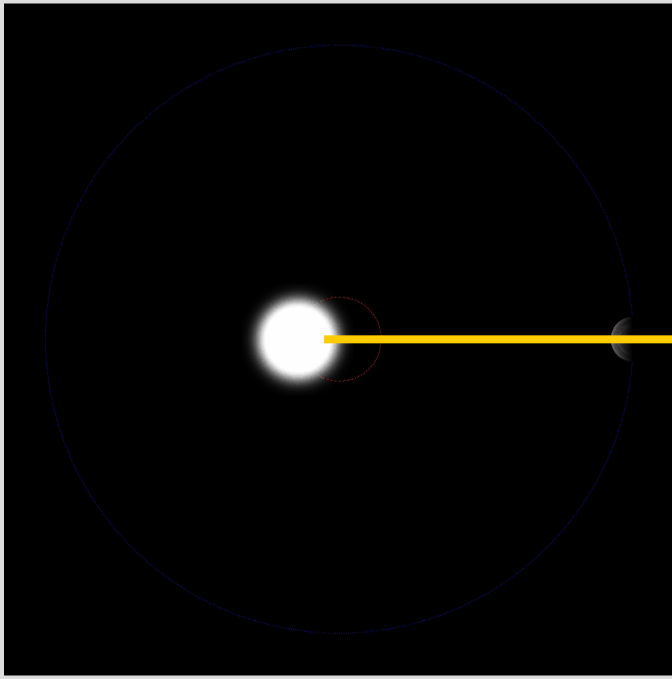
Exoplanet detection

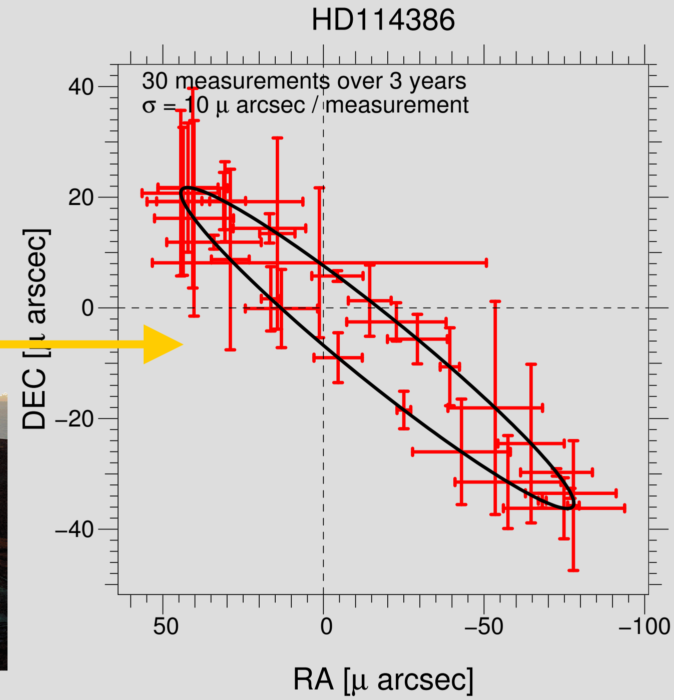
Summary

- Planetary systems around other stars do exist.
- Models of planet formation → predict where and how to search.
- RV: most successful technique so far,
  but: other techniques are emerging.
- Astrometry: measure true planet masses (no *sin i* ambiguity)
  detect lower-mass planets in longer-period orbits than RV
- Astrometric measurement accracy:
  100 µarcsec: get signal from a few planets („*scratch on the surface*")
  10 µarcsec: find the ice giants (out of reach for RV, *new science*)
- Earth-like rocky planets are out of reach for ground-based astrometry

2. Astrometry

Searching for planets with astrometry





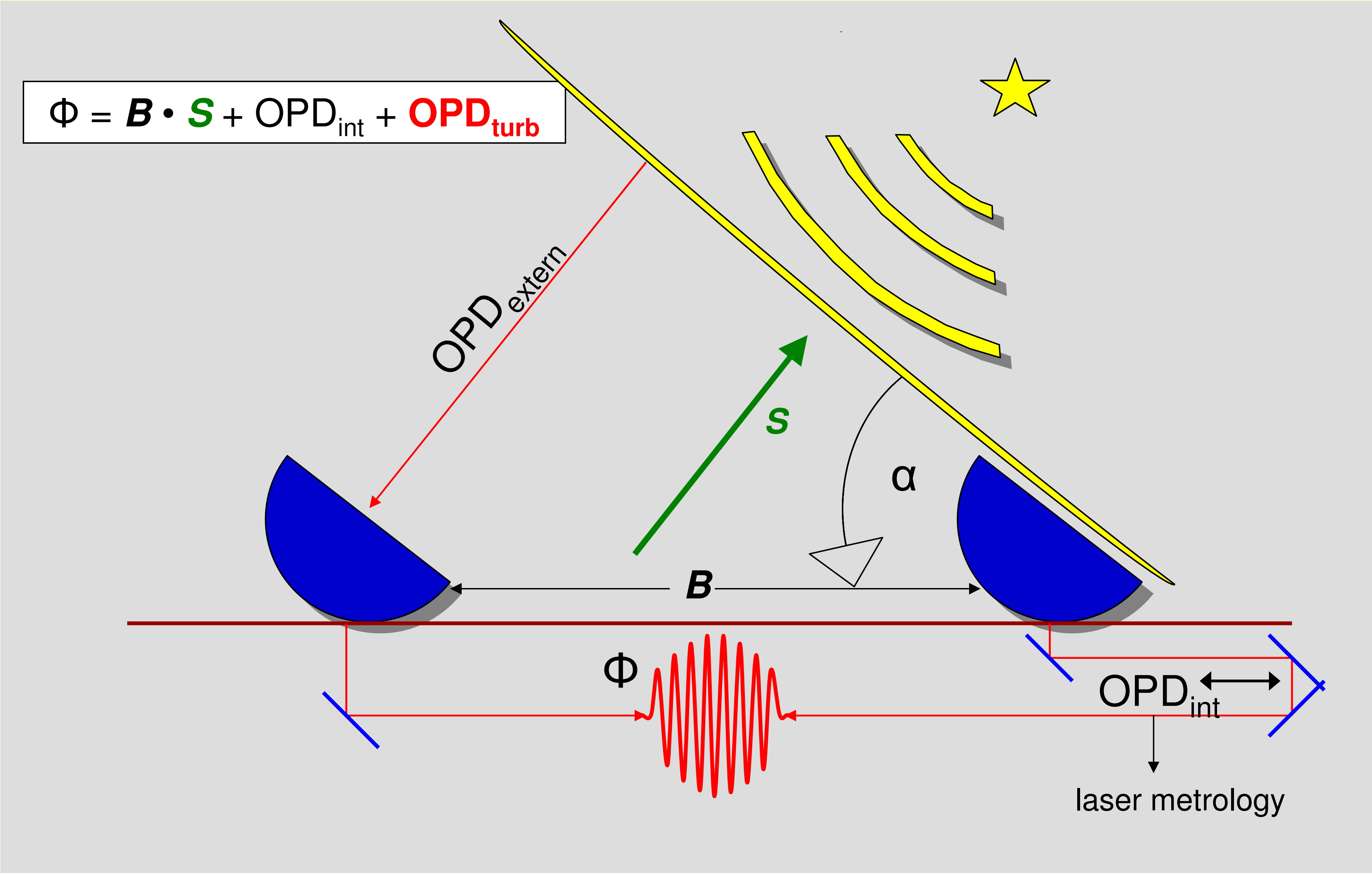
Example:

Astrometric signal of Jupiter on the Sun when viewed from 10 pc:

$$\boldsymbol{\rho}\ [\text{arcsec}] \approx \mathbf{m_2} / \mathbf{m_1} \cdot \mathbf{a}\ [\text{AU}] / \mathbf{D}\ [\text{pc}]$$

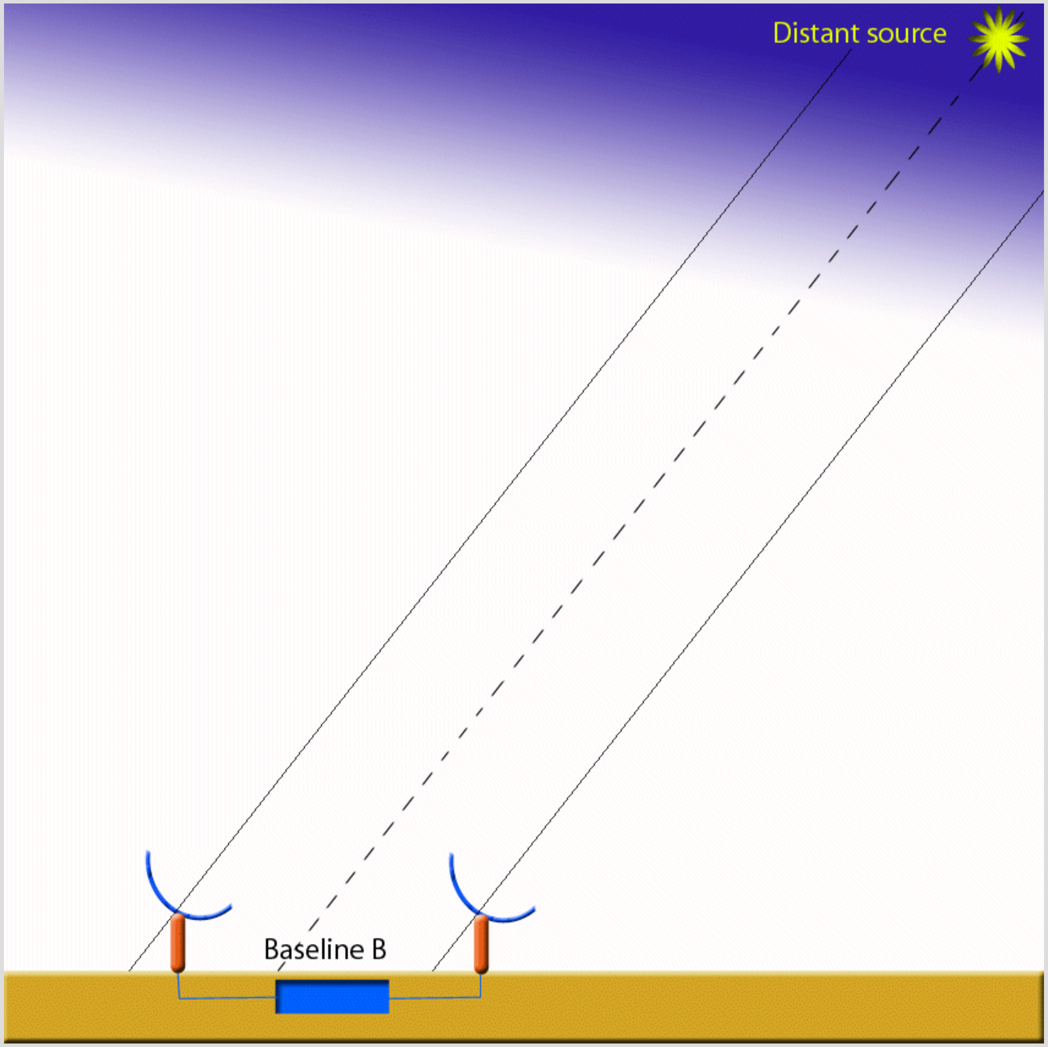
$\Rightarrow$ 1 R_{Sun} or 0.5 mas

Position measurement with an interferometer



➡ **Astrometric observable: Delay = *F*(OPD,Φ)**

Atmospheric anisoplanatism



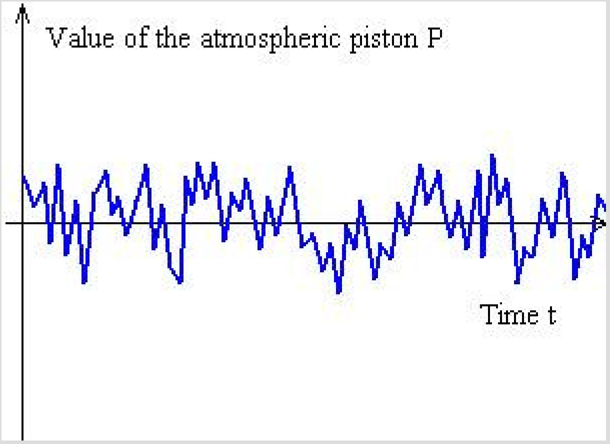
Atmospheric turbulence

⇩

Piston fluctuations

⇩

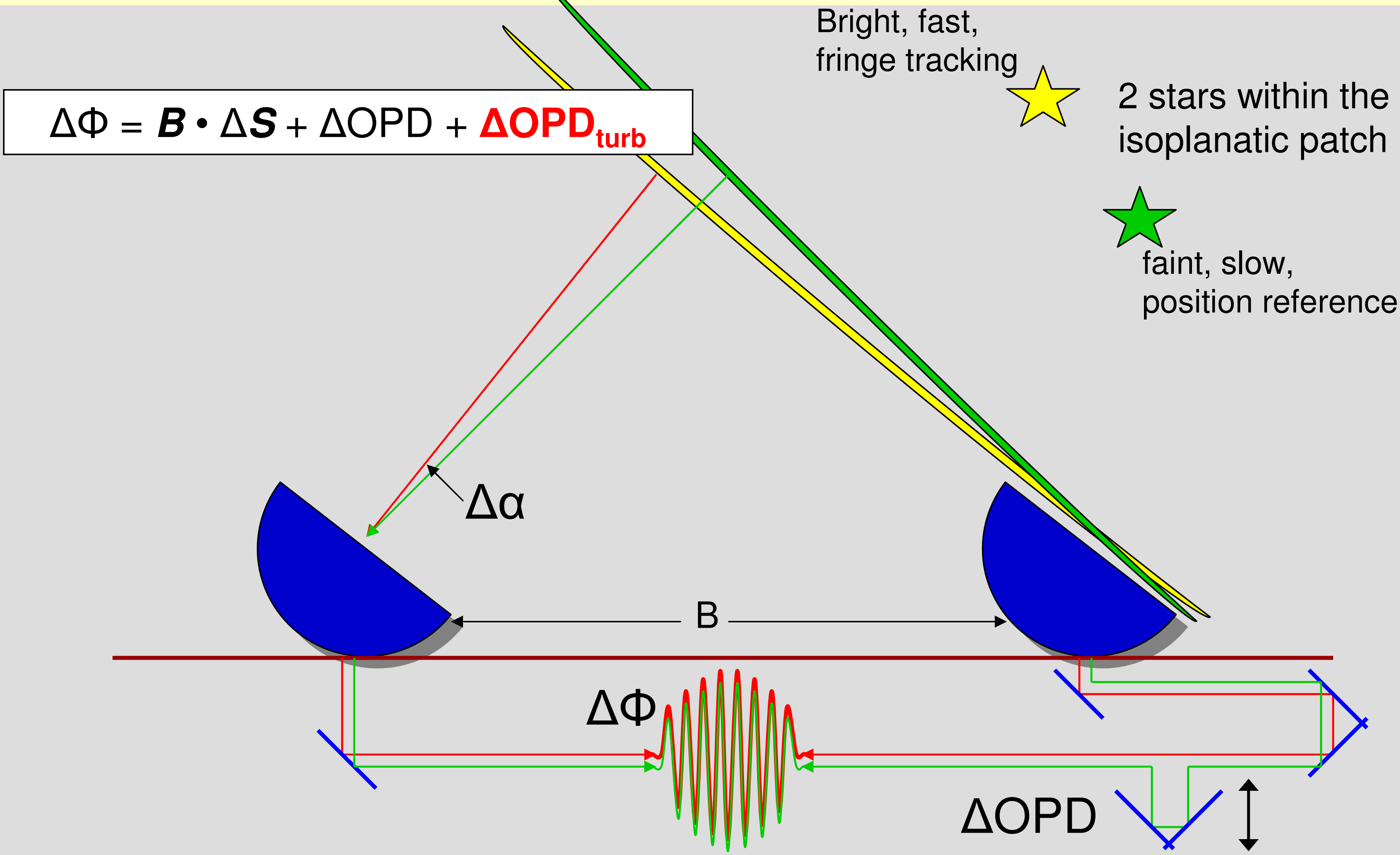
Measured position vector ***S*** fluctuates



But:

Fluctuations are correlated within the isopistonic angle

Narrow-angle astrometry



The double purpose of phase-referencing

- **Fringe-tracking:**

  When the bright star delivers enough photons to measure its fringe phase within the atmospheric coherence time, this information can be used to adjust the OPD of the fainter star in real time. Thus, one can coherently integrate on the faint star without smearing the fringes, i.e., the sensitivity of the interferometer is improved by several magnitudes.

  („*Adaptive Optics in phase space*")

- **Differential delay astrometry:**

  Within the isoplanatic angle, the phase difference between the two stars is no longer affected by atmospheric turbulence

  => the angular separation can be measured with high accuracy

  („*Stable local coordinate system*")

Narrow-angle astrometry

Observables: Laser ***metrology*** (ΔOPD_{int})
Differential Group ***delay*** from FSU

- *Calibration of instrumental, atmospheric, and astrometric effects.*
- *Baseline*

Final measurement result: ***1-D*** projected (onto baseline) ***angular separation*** between the centers of light of two stars

- *Source selection*
- *Observing strategy (baseline rotation)*
- *Astrometric fitting*

Scientific goal: ***2-D position time series*** of one star's center of mass

From angular separations to orbit solutions

- **Time series of calibrated 1-D angular separations:**

  => Result of *PM* & *P* of both stars & 1 companion (13 parameters)

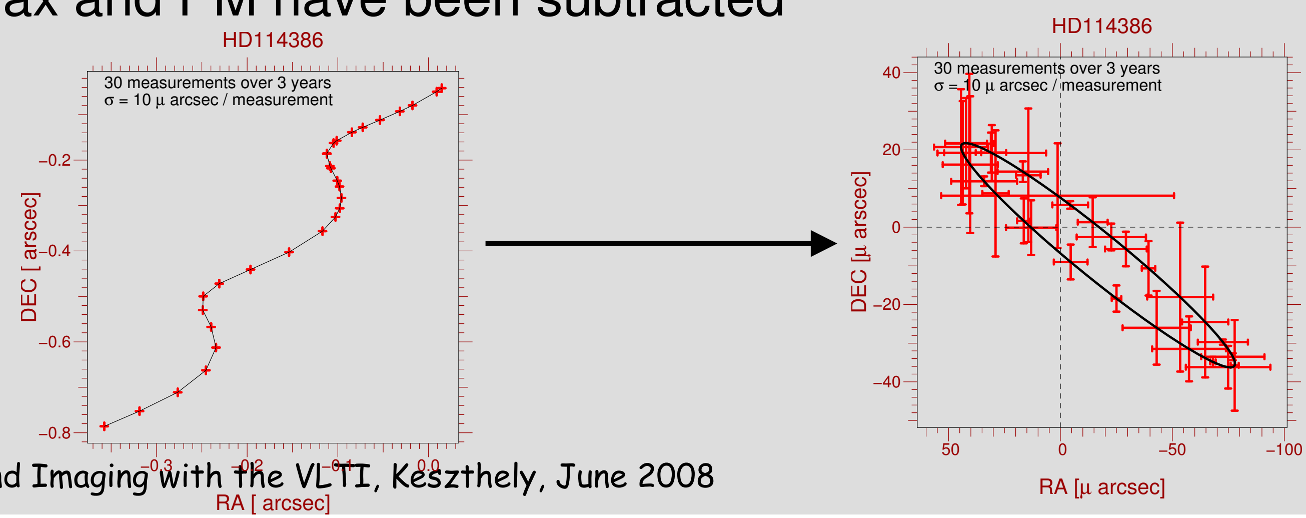
  (=> talk by Sabine Reffert)

- *Proper motion: 1000 mas / yr (known to 1 mas/yr accuracy)*

  Parallax: 100 mas (known to 1 mas accuracy)

  Planet: 0.1 mas

- The data must be fitted for a combined solution for all parameters
- The planet orbit (if exisiting) becomes visible only in residuals after parallax and PM have been subtracted



Astrometry with an interferometer

Summary

- An **dual-star interferometer** can measure the **differential delay** between two stars in the isoplanatic angle

  => **angular separation**

- **Fringe-tracking** on the bright star **increases sensitivity** on the fainter star => more sources observable

- **Exoplanets** can be inferred from the evolution of angular separation by solving simultaneously for parallaxes, proper motions, and orbits

3. ESPRI

Exoplant Seach with PRIMA

Goal

Perform astrometric **E**xoplanet **S**earch program

with **PRI**MA@VLTI

Consortium proposes to ESO

Agreement with ESO

Build **D**ifferential **D**elay **L**ines

and

Develop **A**strometric **O**peration and **S**oftware Tools

Science preparation

Target selection

Reference star search

Preparatory science, modeling

Target & Ref-star characterization

Reward

GTO with PRIMA and 2 ATs

The Consortium

&


Project kick-off in Geneva, Feb. 2004

Pls:

D. Queloz (Geneva)

Th. Henning (HD)

A. Quirrenbach (HD)

Project Manager:

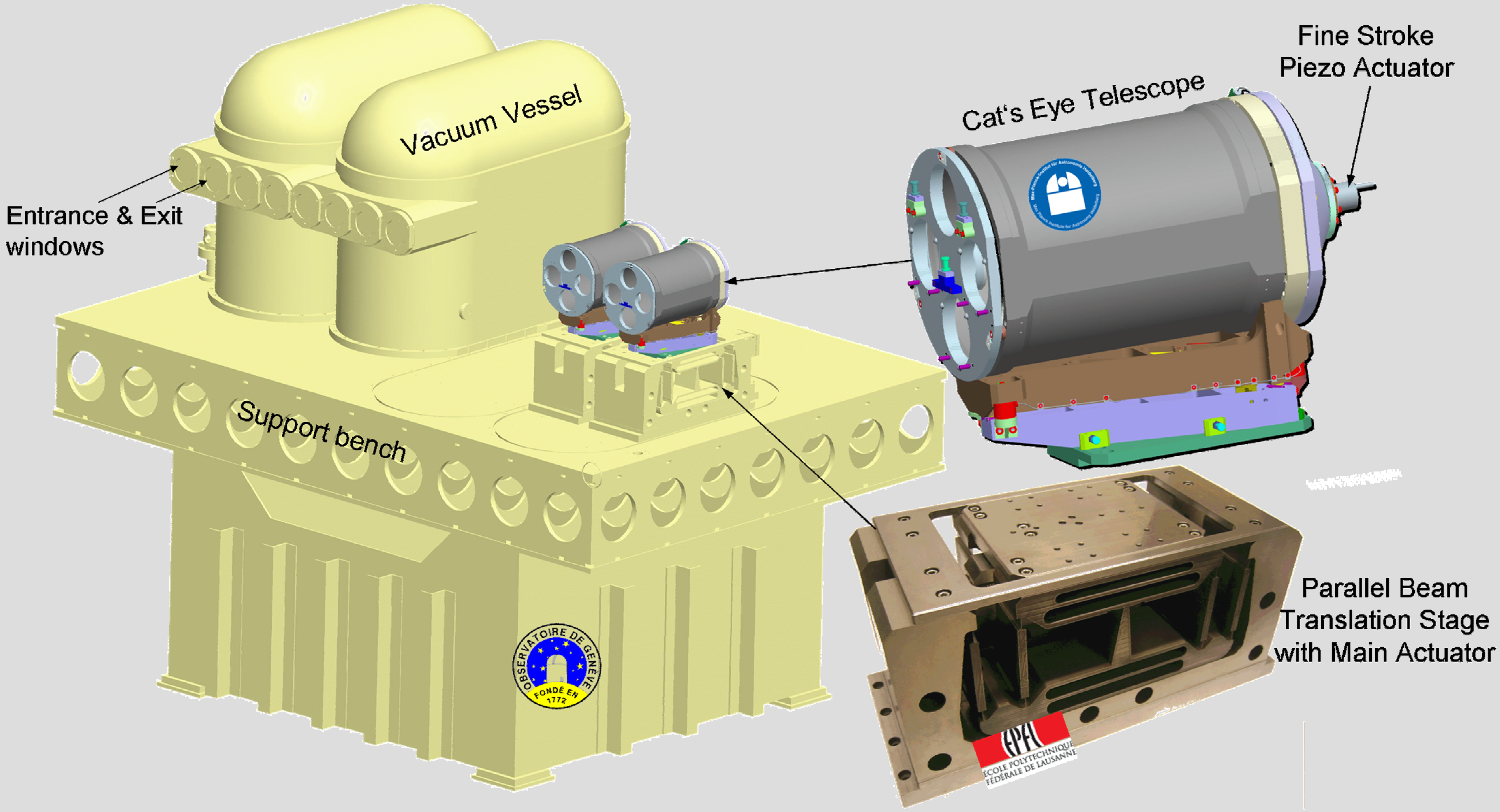
F. Pepe (Geneva)

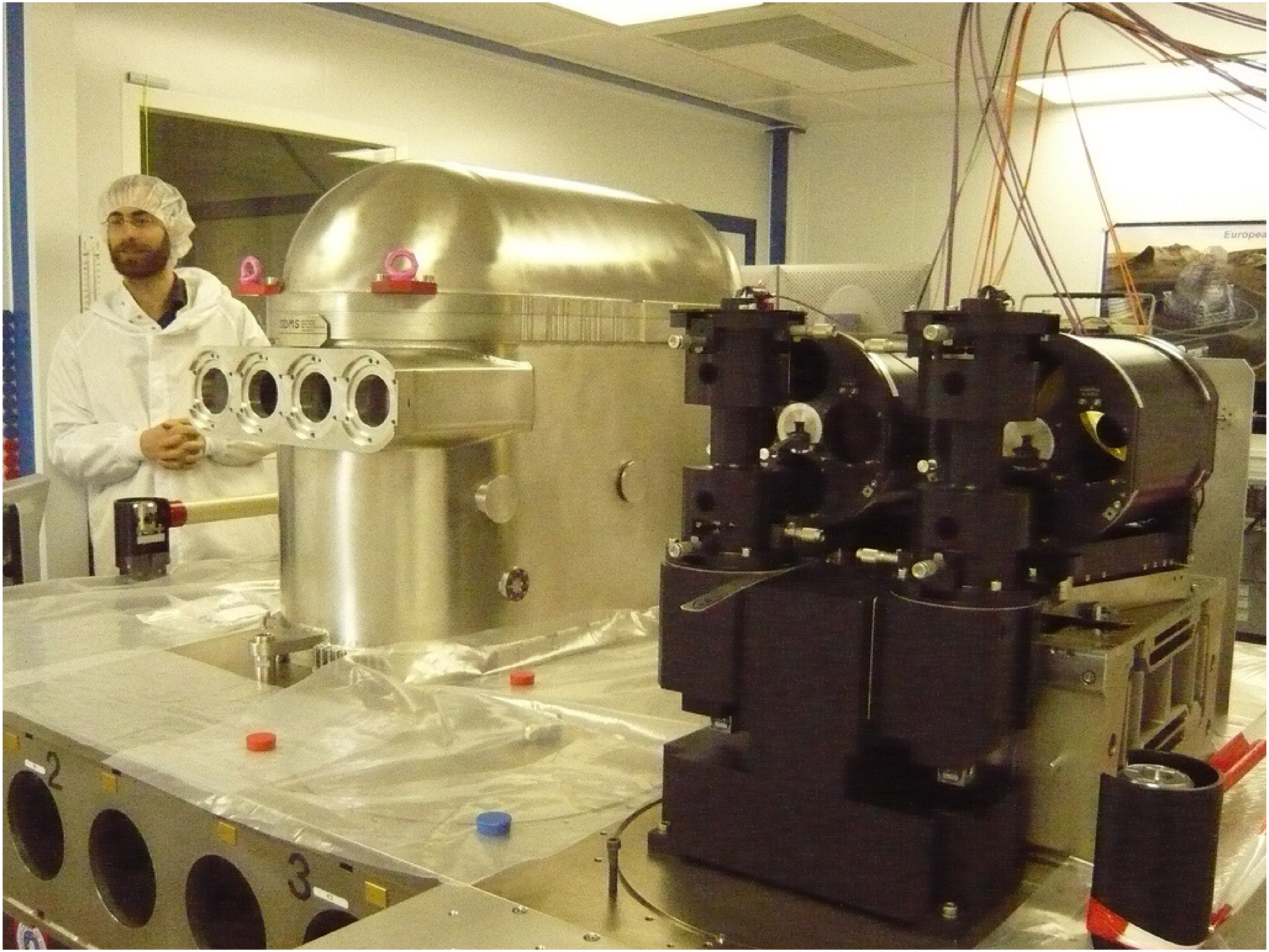
Project Scientist:

R. Launhardt (HD)

Plus 37 more people in Heidelberg (MPIA and LSW), Geneva, Lausanne, Neuchatel

Differential Delay Lines




SDMS
2
3

Software Developments

Observation Preparation Software
(APES)
D. Segransan (Geneva)

Interactive tool (java GUI) for creating narrow-angle astrometric observing runs with PRIMA

Astrometric Data Reduction Software
(ADRS)
N. Elias (Heidelberg)

Fully automatic:
- Online pipeline
- Offline pipeline („morning after")

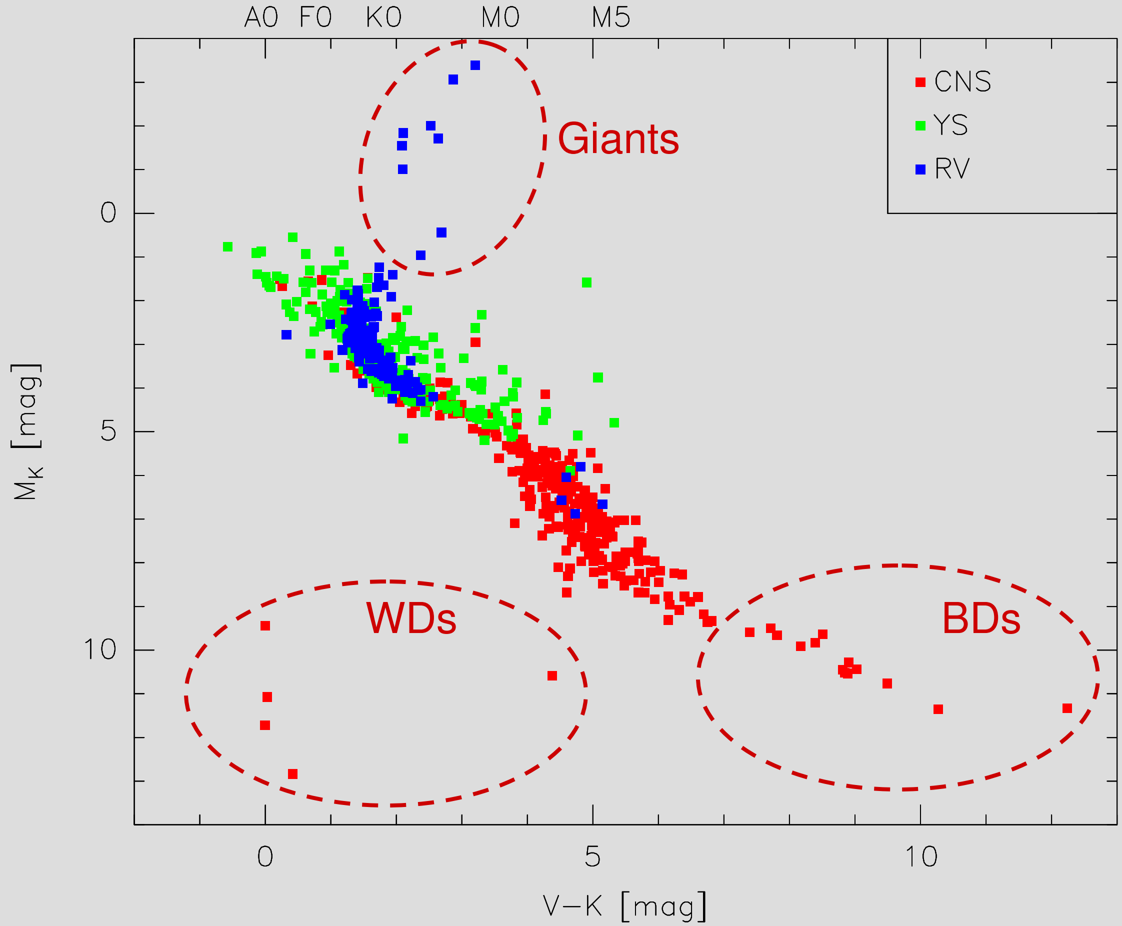
Run by ESO:
- Data Analysis Facility (new CoCo every 6 month)

Not distributed:
- Interactive expert tool

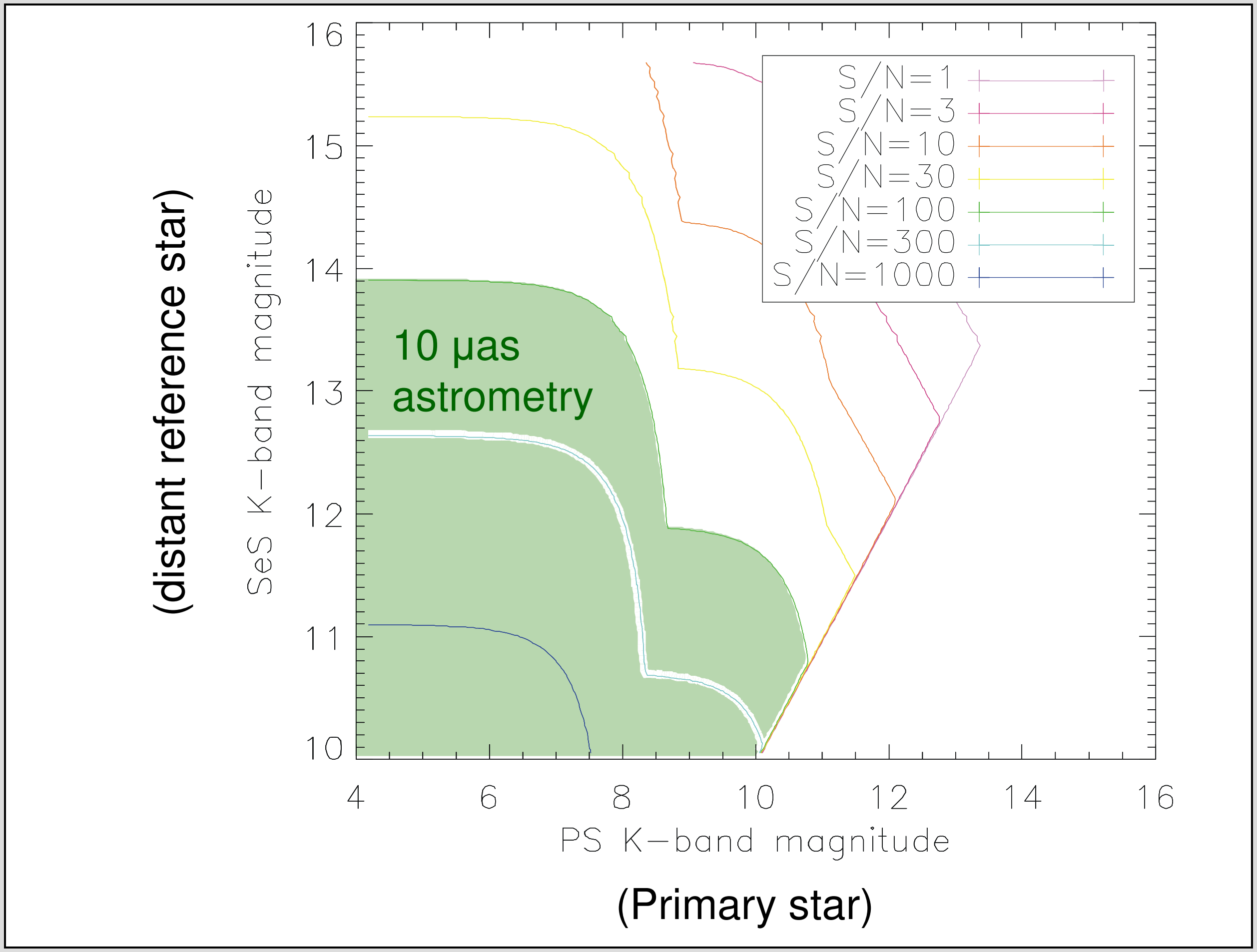
ESPRI – Science program

- One large and coherent program: **ESPRI**
- Two sub-surveys:
  - Characterizing known planetary systems
  - Planet search as function of mass and time
- Target groups:
  - Stars with RV planets
  - Nearby MS stars of any spT D≤15pc
  - Young stars a < 300Myr D≤100pc
- Specific science:
  - Planet masses; Orbit inclinations; New long-period planets
  - Saturns and Uranuses with P>2yr
  - Jupiters with P ≈1-5 yr

Target List – HR diagram



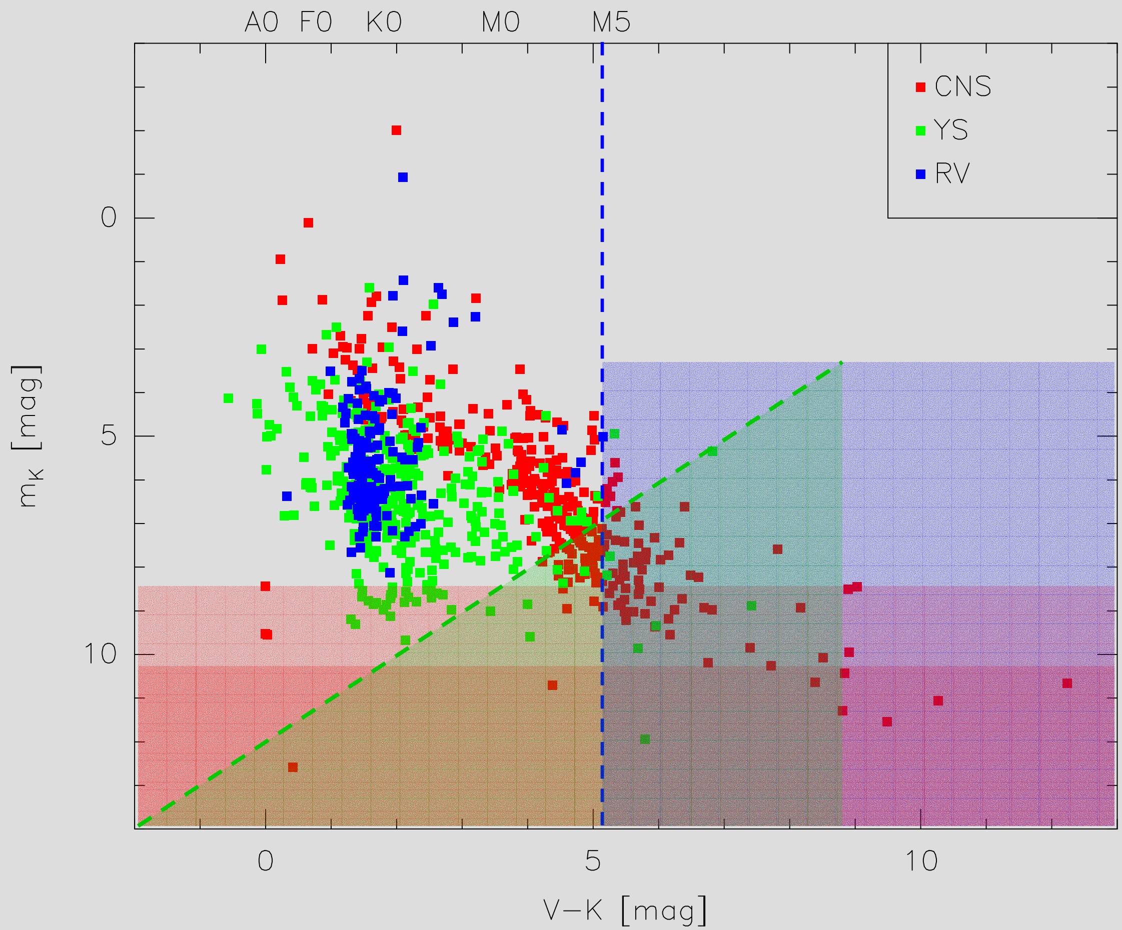
PRIMA with ATs - Limiting magnitudes



Priority 1: PS ≤ 8mag, SES ≤ 14mag, Δ≤10"

Priority 2: PS 8-10mag, but with SES < 12mag, Δ≤20“ (lower astrometric accuracy)

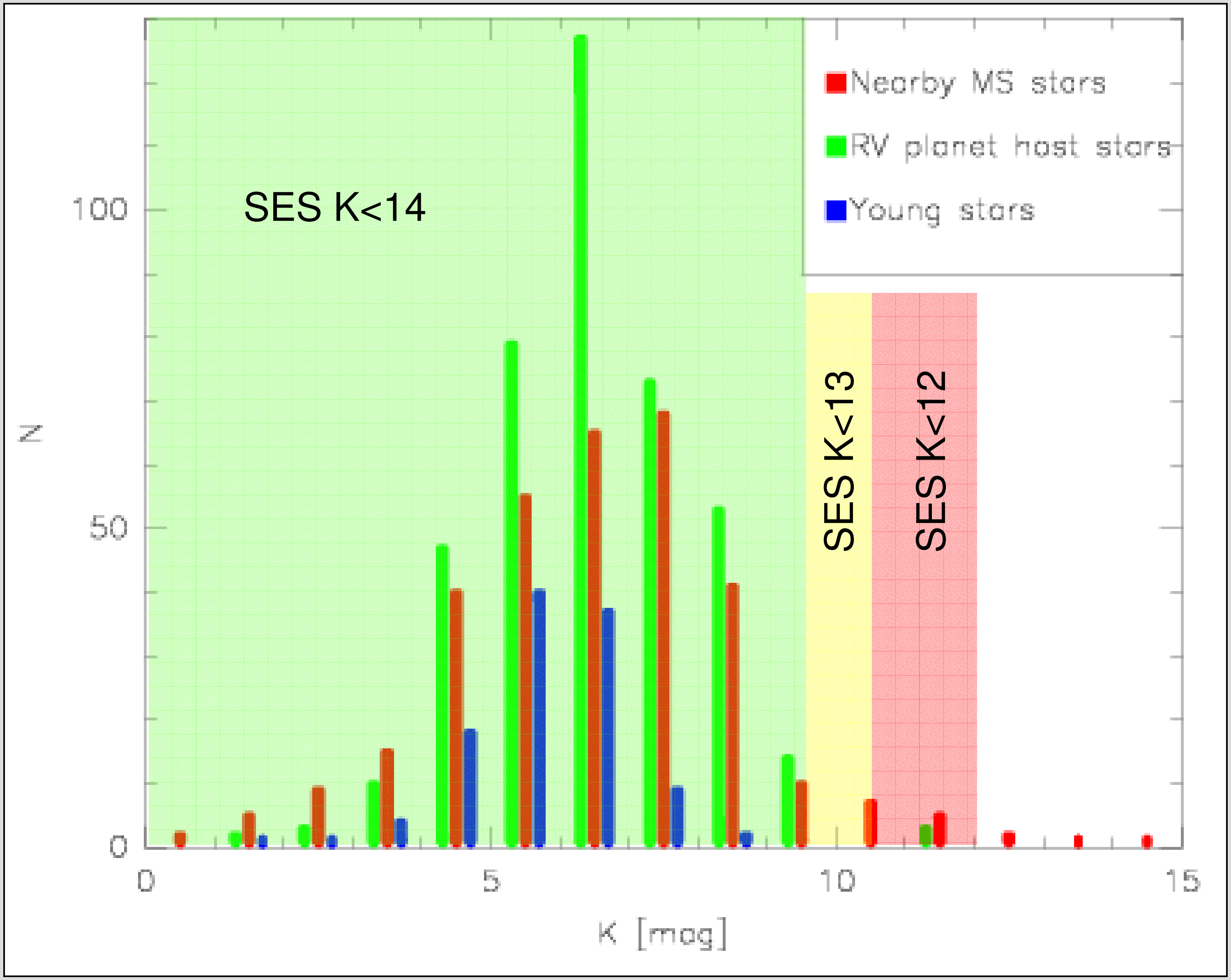
Target List – col-mag diagram



- Too faint for fringe-tracking
- Too low mass to form planets?
- PS too faint for STRAP, need external guide star

➢ WDs, BDs, and stars later M6 are too faint for fringe-tracking.

Target List – magnitudes



Logged in as: Launhardt, Ralf => logout

- List unclassified PS
- List qualified PS
- List disqualified PS
- List all PS
- Basic search
- Advanced search

Search result primary stars

N°	Name	RA	Decl	Groups	Sp.T.	Age	Distance	Ss	V
1	HD 261557	06:39:31.380	03:19:11.200	YS	K3 V		60.241 (+7.099 | -5.745)	0	☐
2	HD 26923	04:15:28.860	06:11:13.600	YS	G0 IV		21.186 (+0.496 | -0.474)	0	☐
3	HD 26913	04:15:25.850	06:11:59.700	YS	G5 IV		20.894 (+0.514 | -0.490)	0	☐
4	HD 26756	04:14:25.590	14:37:30.300	YS	G5 V		45.641 (+2.808 | -2.501)	0	☐
5	HD 2638	00:29:59.930	-05:45:48.400	RV	G5		53.706 (+4.198 | -3.631)	0	☐
6	HD 260655	06:37:11.270	17:33:50.400	CNS	M0 V		9.843 (+0.233 | -0.223)	0	☐
7	HD 26965	04:15:17.640	-07:38:40.400	CNS	K1 V		5.044 (+0.021 | -0.021)	0	☐

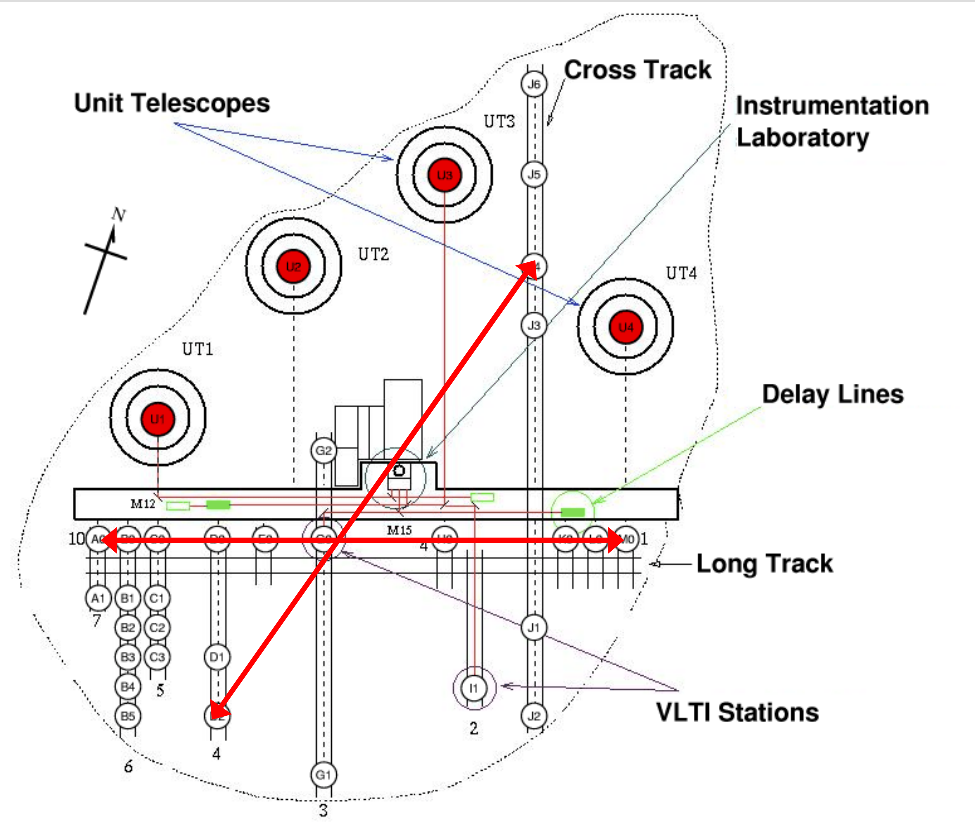
reset invert export

- **AS**trometric **T**arget and **R**eference star **I**nteractive **D**atabase
- http://www.mpia-hd.mpg.de/ASTRID/
- THE database for ESPRI target and reference stars
- Accessible via guest account (to be requested)

Strategy

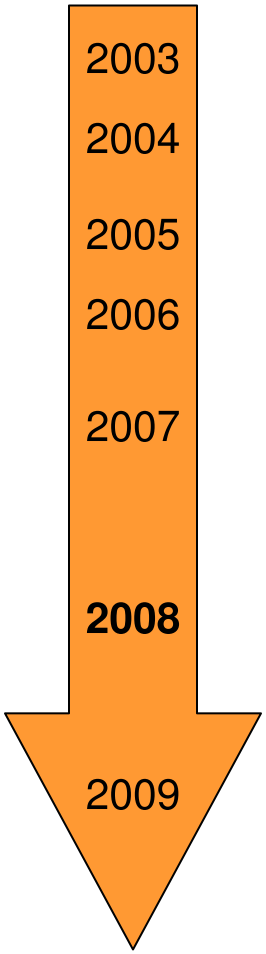
- ≈ 100 stars
- One data point: 45-60 min => 6 – 10 data points per night
- 2nd dimension by re-visit at other hour angle
- 20 – 60 data points per star
- 2-week observing runs every 2-3 months
- 2009 + 3-5 years
- First science: orbit inclinations for massive RV planets

Baselines



- Longest baselines: 200m
- Delay line restrictions
  => work with 150m
- Work with 1, max 2 baselines
- N-S baseline gives best rotation, but lose northern stars (=> summer)
- E-W baseline rotates less, but also works for northern targets (=> winter)

Timeline



- ❑ Sep 2003…….. Proposal to ESO
- ❑ Feb 2004…….. Kick-off
- ❑ Apr 2005…….. Preliminary Design Review
- ❑ Jul 2006……… DDL Final Design Review
- ❑ Apr 2007…….. PAOS Final Design Review
- ❑ Oct 2007…… Cat's tests at MPIA
- ❑ Nov 2007……. DDL integration in Geneva
- ❑ Apr 2008 ……. PAE
- ❑ **Jul 2008……… AIV on Paranal**
- ❑ Nov 2008…….. Commisioning
- ❑ Oct 2009…….. Start astrometric observations
- ❑ **2009 – 2012 … Planet Search Program**

Summary

ESPRI - Summary

- => **E**xoplanet **S**each with **PRI**MA
- Ground-based narrow-angle astrometry with PRIMA and ATs
- Timeline: 2009 – 2013
- Trend analysis and empirical post calibrations of a priori unknown systematics are intrinsic parts of data reduction strategy
- Anticipated accuracy of 10µas may be reached after 1-2 yr
- GTO exoplanet program of consortium: ≈100 stars
- Other exciting science cases (binaries, …):
  Not covered by our GTO

Links

- http://planetquest.jpl.nasa.gov
- http://exoplanet.eu
- http://www.mpia-hd.mpg.de/PRIMA-DDL
  http://www.espri-planet.com
- http://www.eso.org/projects/vlti/instru/prima/index_prima.html