Feasibility of Spectro-Polarimetric Detection of Atmospheric Components of Exoplanets

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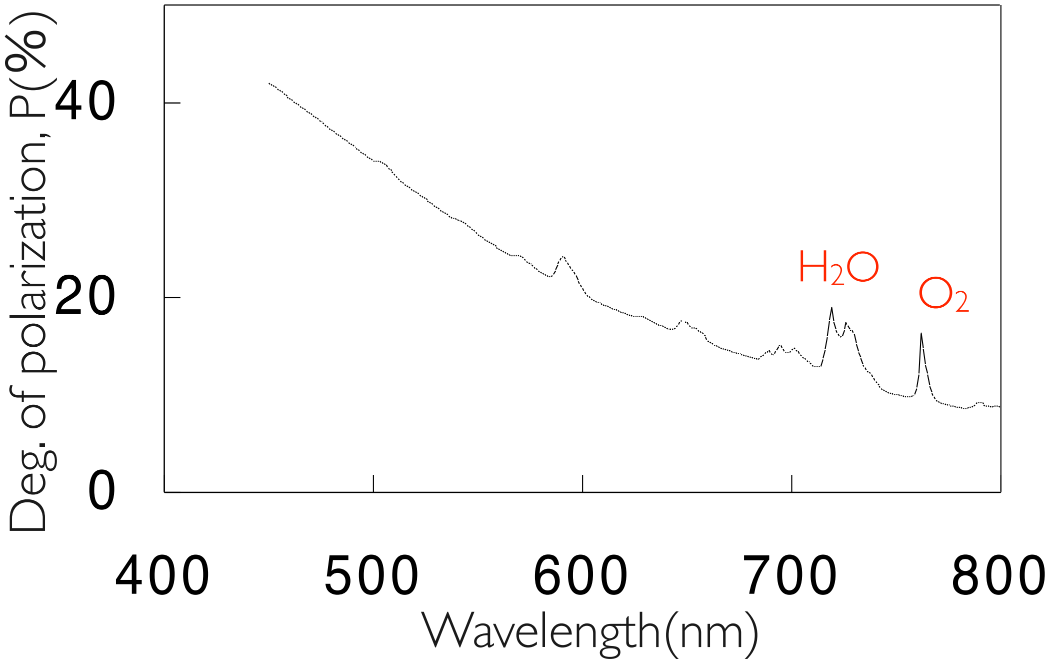
Polarimetry for planets

- Reflection makes polarization. Polarization of the reflected light from a planet has information of its atmosphere, clouds and surface.
- Polarimetry has been a powerful method to investigate Solar-System objects. For example, polarimetry for Venus (e.g., Lyot 1929) played a key role to identify H_2SO_4 hazes by determining the size and refractive index of the reflecting particles.
- As is for Solar-System planets, polarimetry for exoplanets may be a good diagnostic tool to know …
    - atmospheric composition
    - cloud/haze altitude (Stam 2004, 2008)
    - optical thickness of atmosphere ? (Takahashi+ 2013)
    - existence of a surface ocean ?? (McCullough 2006)

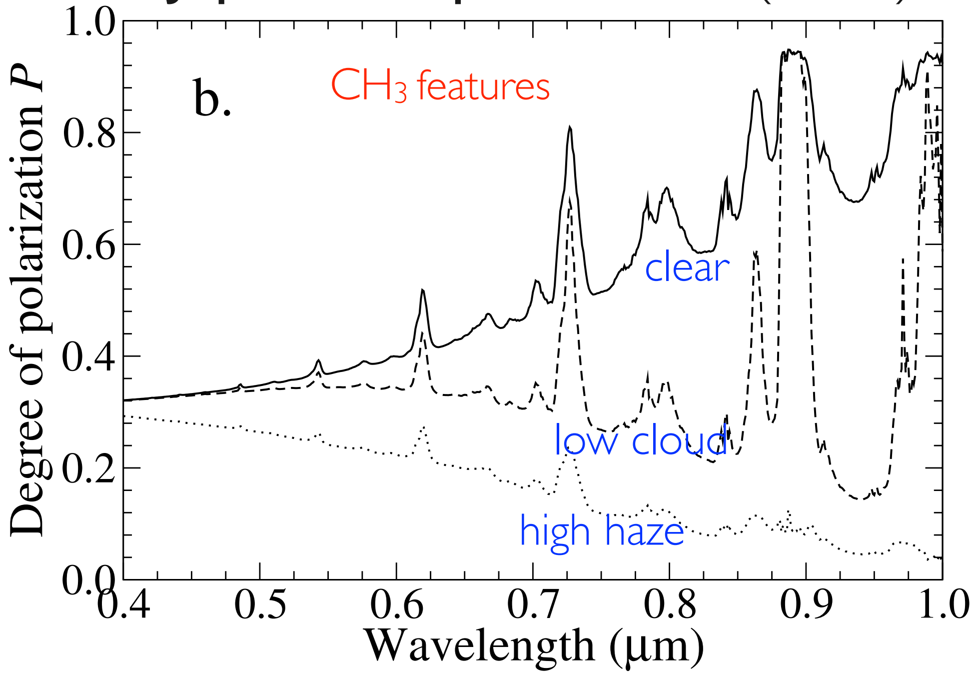
Pol. spectra of planets

- Model calculations

Earth-like planet, Stam(2008)



Jupiter-like planet, Stam(2004)



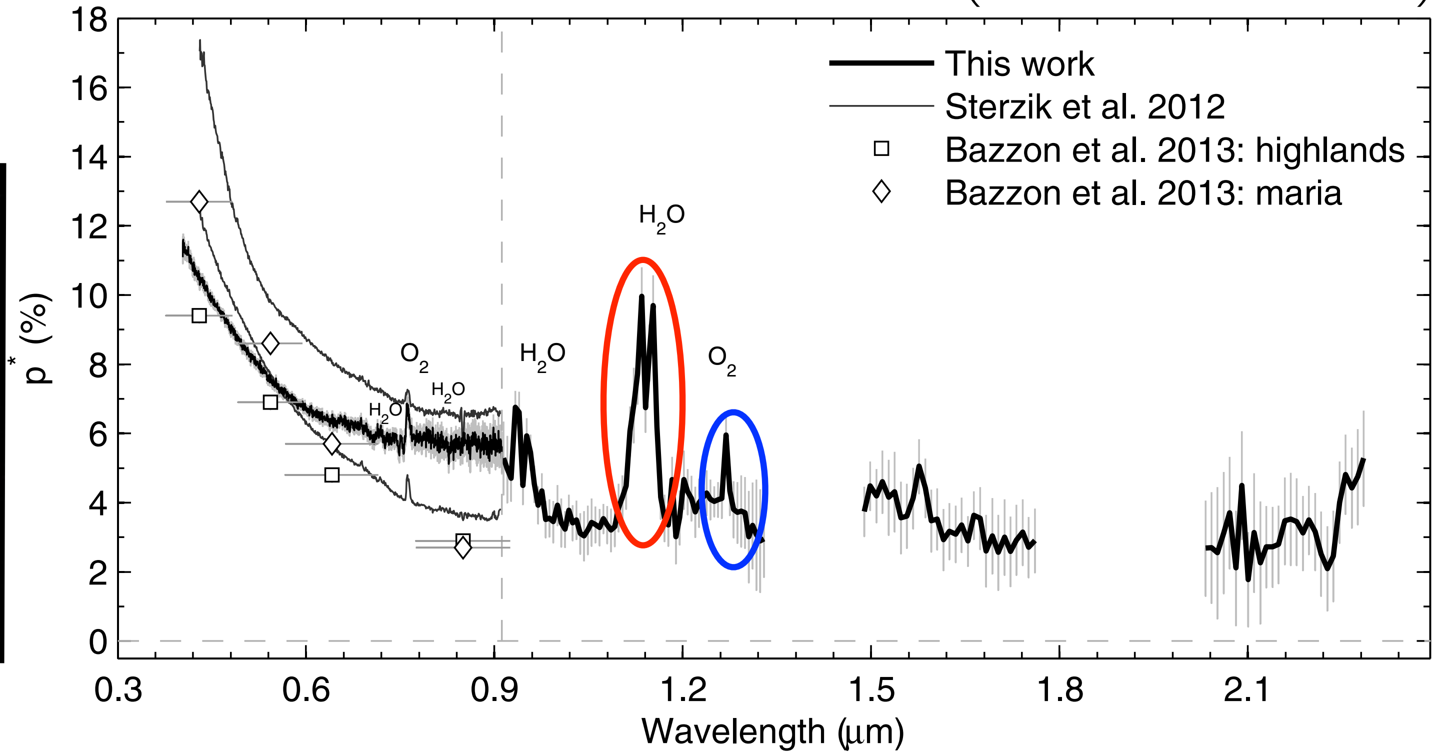
- The enhanced features are explained by the decrease in intensity of the multiply scattered component at the absorption wavelengths as compared with that at the continuum wavelengths.

- Pol spectra are sensitive to the clouds/haze altitude.

Pol. spectra of planets

- **Earthshine observations** (Sterzik+ 2012, Miles-Paez+ 2014).

(Miles-Paez+ 2014)



Enhanced features at molecular (H_2O, O_2) absorption wavelengths were confirmed by the observations.

➡Spectro-polarimetry seems to be a promising method to detect atmospheric molecules.

Benefits of polarimetry

- **Scientific points**
  - Polarization in planetary reflected light has information of its atmosphere, clouds and surface, which may not be obtained only by intensity observations.

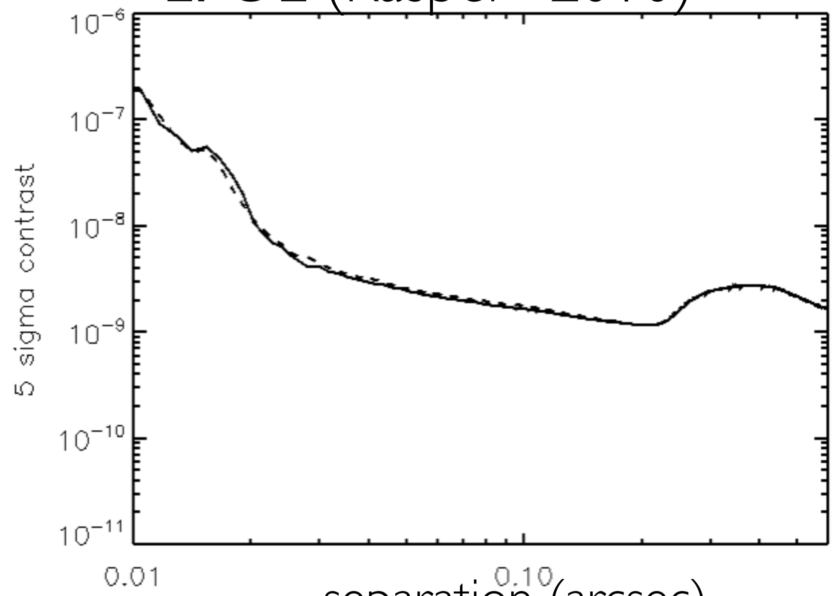
- **Technical points**
  - State of polarization is (almost) not affected by telluric transmission.
    - ➡ H_2O and O_2 may be detected through spectro-polarimetry even on the ground.
  - Polarimetric differential imaging (PDI) enhances contrast performance of an instrument and helps to detect planet signals.

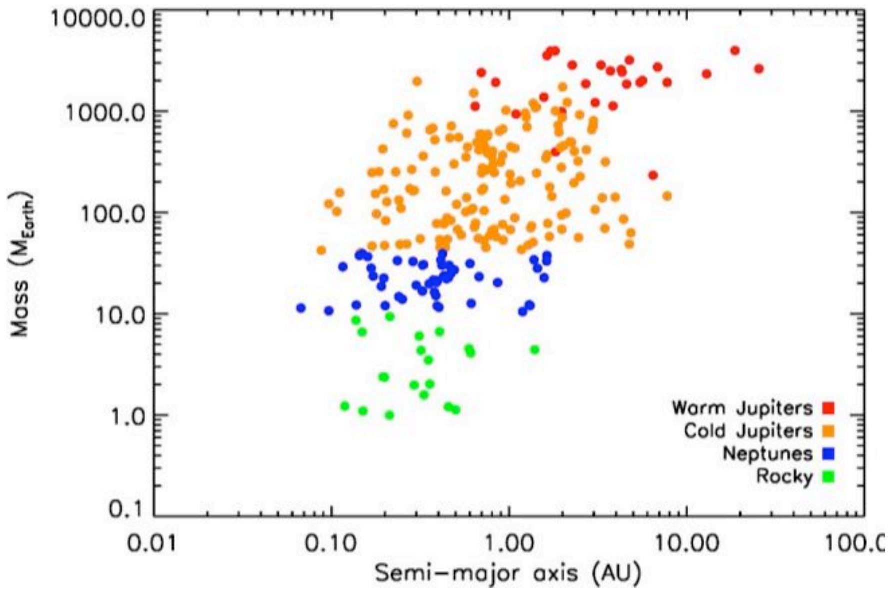
Polarimeter for ELTs

- E-ELT
  - **A visible polarimetric imager EPICS-EPOL is being studied** (Kasper+2010, Keller+ 2010).
  - **EPOL is designed to have a detection contrast of a few 10^{-9} at 0.1 arcsec.**
  - **A spectro-polarimetry option is also studied** (Rodenhuis+ 2012).

- TMT
  - No polarimeter has been proposed yet.

EPOL (Kasper+2010)



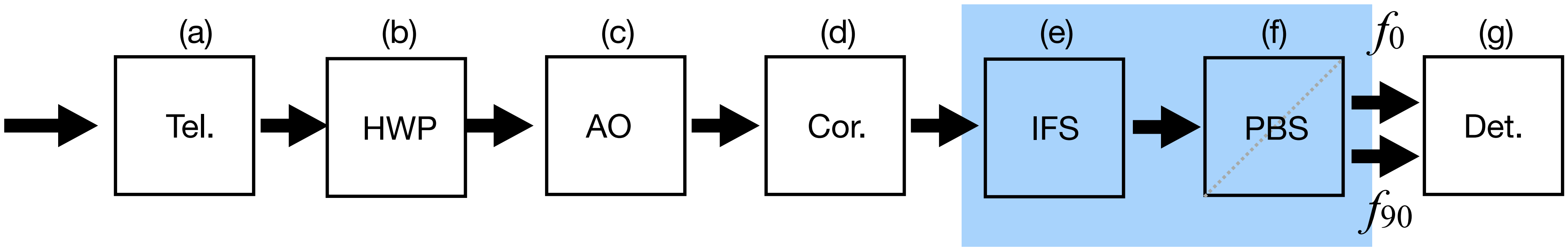


This study

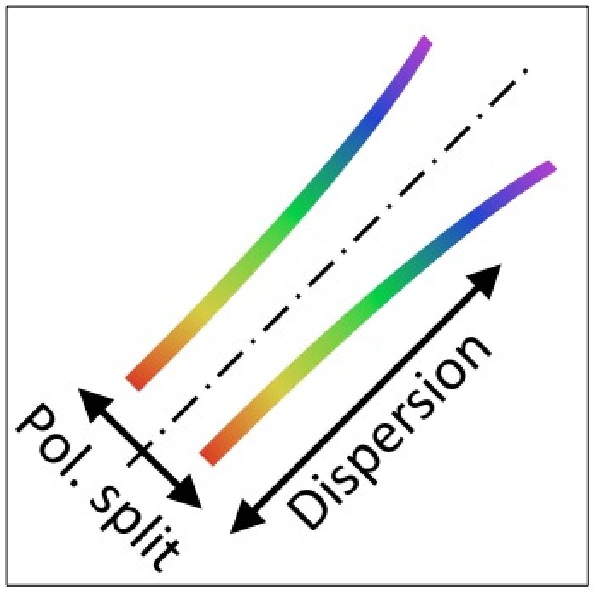
- **Motivation**
  - Spectro-polarimetry for reflected light from an exoplanet may be used to detect atmospheric compositions such as H_2O and O_2.
- **Aims**
  - We aim to evaluate the feasibility of the search for a spectro-polarimetric feature of H_2O vapor using a high-contrast polarimetric instrument on a ground-based extremely large telescope (ELT).
- **Methods**
  - Three types of errors are considered: (a) errors from different efficiencies between ordinary and extraordinary light beams, (b) errors caused by speckle noises, and (c) errors by photon noises from the leakage of the host star.
  - We estimate the number of planets for which feasible spectro-polarimetric observations will be possible.

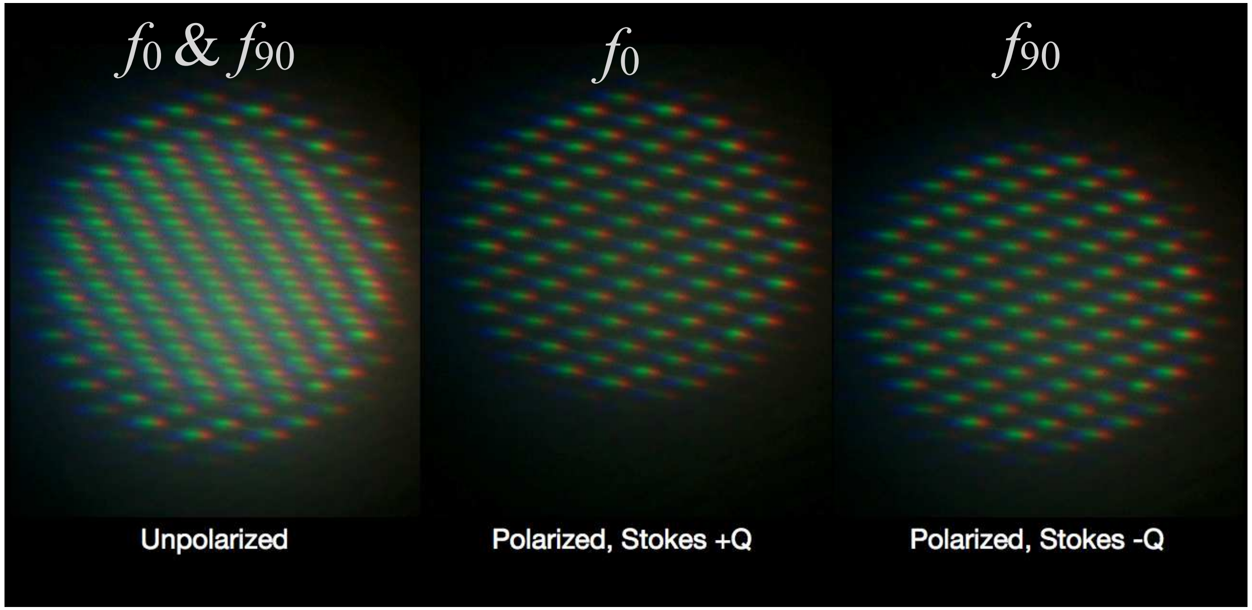
Hypothetical instrument

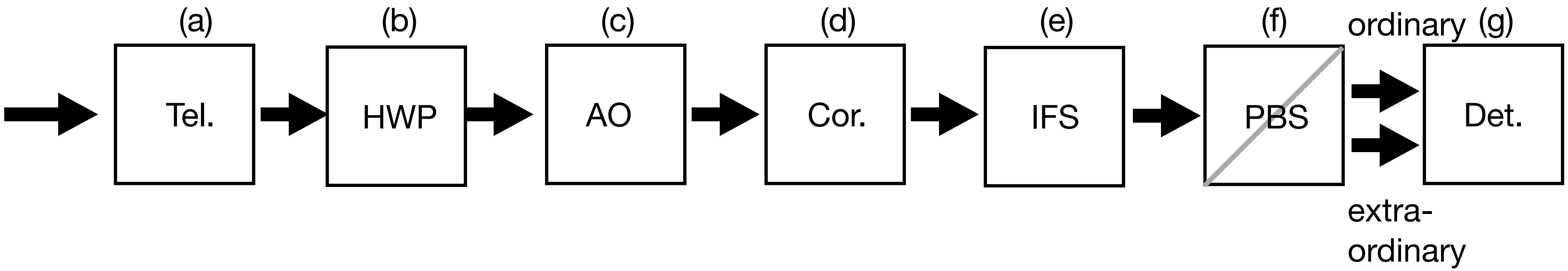
- EPOL(spectro-polarimetry mode)-like observing system is assumed.



EPOL spectro-polarimetry experiment (Rodenhuis+ 2012)






(a)
Tel.
(b)
HWP
(c)
AO
(d)
Cor.
(e)
IFS
(f)
PBS
ordinary
(g)
Det.
extra-
ordinary

Formulation of errors

- Degree of polarization:

$$P = \frac{F_0 - F_{90}}{F_0 + F_{90}}$$

replace F by f

F_0, F_{90} : true flux of the planet (ordinary and extra-ordinary)

- Measured flux:

$$\underbrace{\begin{pmatrix} f_0 \\ f_{90} \end{pmatrix}}_{\text{measured}} = \begin{pmatrix} r_0 F_0 \\ r_{90} F_{90} \end{pmatrix} + \underbrace{\begin{pmatrix} \epsilon_0 \\ \epsilon_{90} \end{pmatrix}}_{\text{offset error (speckle or photon noise)}}$$

total efficiency

$$r_\chi = \mathcal{I}_\chi \mathcal{T}_\chi k_\chi$$

inter-stellar trans.

telluric trans.

inst. efficiency

- Error terms:

$$\mathcal{E}_P = b_P^{\mathrm{eff}} + \frac{(\epsilon_0 - \epsilon_{90}) - (P + b_P^{\mathrm{eff}})(\epsilon_0 + \epsilon_{90})}{2\bar{r}\bar{F}}$$

Formulation of errors

- Error terms:

$$\mathcal{E}_P = \boxed{b_P^{\mathrm{eff}}} + \boxed{\frac{(\epsilon_0 - \epsilon_{90}) - (P + b_P^{\mathrm{eff}})(\epsilon_0 + \epsilon_{90})}{2\bar{r}\bar{F}}}$$

(a) Bias due to different efficiencies

$$b_P^{\mathrm{eff}} = -\frac{1}{2}\left(\frac{r_{90}}{r_0} - 1\right)(1 - P^2)(1 + \underline{A\bar{f}})$$

detector non-linearity

(b) Bias due to speckles

detection contrast (before PDI)

$$[b_P^{\mathrm{spec}}]_{\mathrm{typ}} \cong \sqrt{g^2 + (P + b_P^{\mathrm{eff}})^2}\frac{C_{\mathrm{det}}}{C_{\mathrm{p/s}}}$$

PDI gain
best: 0.05
worst: 1.0

planet-to-star contrast

(c) Random error due to photon noise

raw contrast

$$\sigma_P \cong \pm\frac{1}{\sqrt{\underline{2\bar{r}\bar{F}^*}}}\frac{\sqrt{C_{\mathrm{raw}}}}{C_{\mathrm{p/s}}}$$

star photon num.

Requirements

(a) Bias due to different efficiencies

$$b_P^{\mathrm{eff}} = -\frac{1}{2}\left(\frac{r_{90}}{r_0} - 1\right)(1-P^2)(1+A\bar{f}) \quad \Rightarrow \quad |b_P^{\mathrm{eff}}(\lambda_{\mathrm{cnt}}) - b_P^{\mathrm{eff}}(\lambda_{\mathrm{abs}})| \;<\; w \cdot \Delta P$$

pol feature (10%)

detection criteria (1/3)

(b) Bias due to speckles

$$[b_P^{\mathrm{spec}}]_{\mathrm{typ}} \cong \sqrt{g^2 + (P + b_P^{\mathrm{eff}})^2}\frac{C_{\mathrm{det}}}{C_{\mathrm{p/s}}} \quad \Rightarrow \quad [b_P^{\mathrm{spec}}(\lambda_{\mathrm{abs}})]_{\mathrm{typ}} \;<\; w \cdot \Delta P$$

(c) Random error due to photon noise

$$\sigma_P \cong \pm\frac{1}{\sqrt{2\bar{r}\bar{F}^*}}\frac{\sqrt{C_{\mathrm{raw}}}}{C_{\mathrm{p/s}}} \quad \Rightarrow \quad \sigma_P(\lambda_{\mathrm{abs}}) \;<\; w \cdot \Delta P$$

Calculation

- Using the derived error equations, the error values in polarization degree are calculated for the 2041 known planets.
- We extract planets for which the pol. feature by water vapor (ΔP=10% at λ_{abs}=1.12 μm) is detectable.
- Planet and star assumptions:

		Val.	unit	ref
$P(\lambda_{cnt})$	pol deg at continuum	0.1		Miles-Paez+ 2014 (Earthshine x3)
ΔP	pol deg feature strength	0.1		Miles-Paez+ 2014 (Earthshine x3)
λ_{abs}	absorption wavelength	1.12	μm	Miles-Paez+ 2014
$\Delta\lambda$	wavelength width of the	0.05	μm	Miles-Paez+ 2014
μ	absorption intensity depth	0.5		Turnbull+ 2005
α_p	phase angle	90	deg	
p	geometric albedo	0.25		Montanes-Rodriguez+ 2005
r_p	planet radius	var	km	Estimated from mass: Weiss et al. (2013) and Weiss & Marcy (2014)
m^*	stellar apparent magnitude	var	mag	SIMBAD
d	distance of the system from Earth	var	pc	Exoplanet.eu or SIMBAD

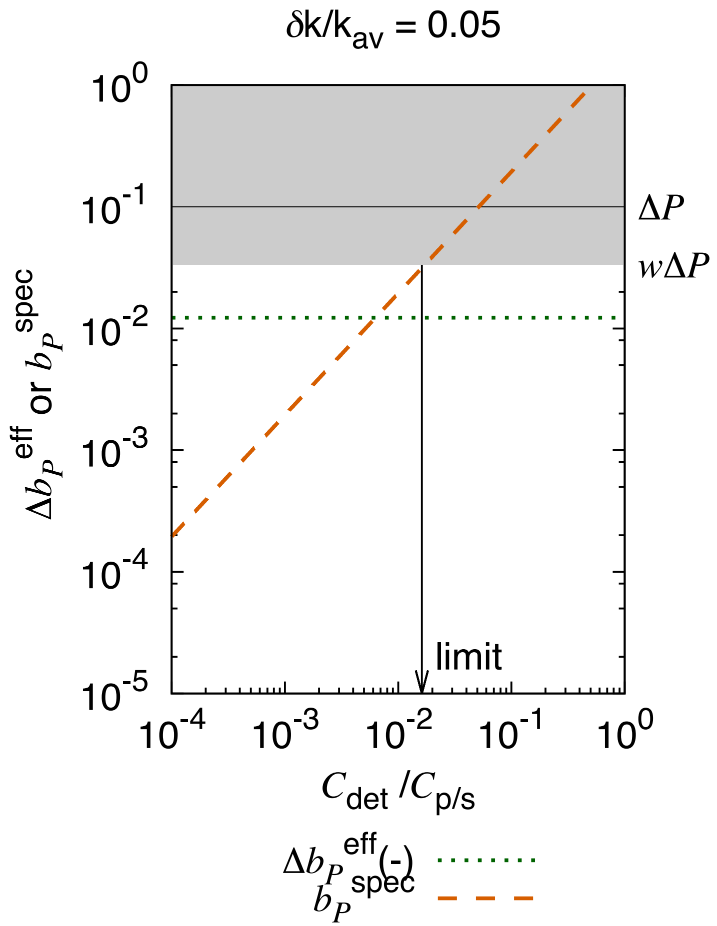
Calculation

- Other setting

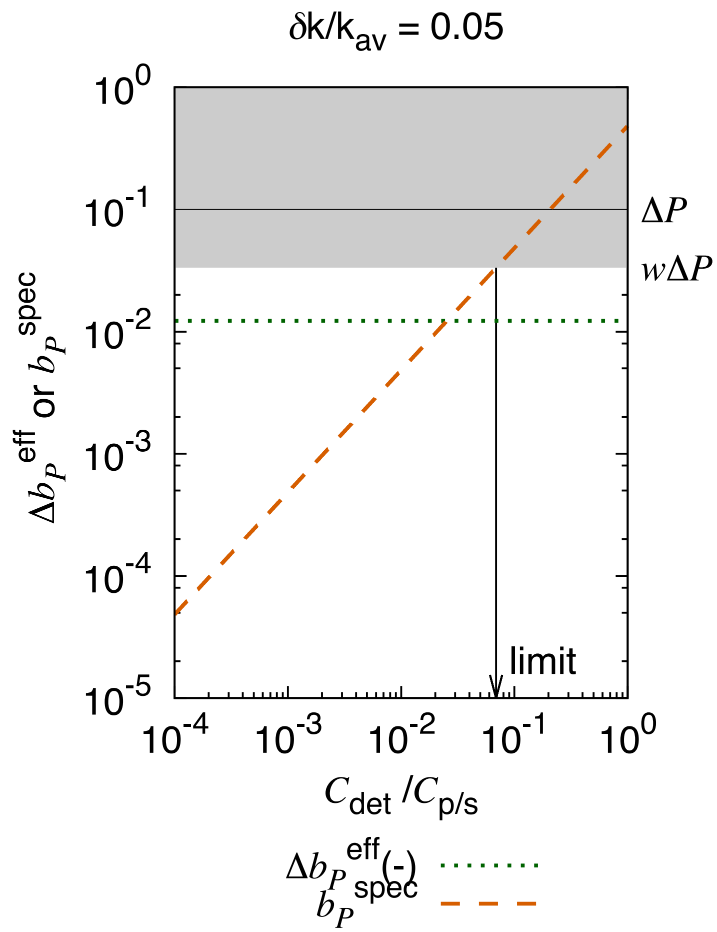
		Val.	unit	ref
T_{abs}	telluric transmittance at abs. wave.	0.7		GEMINI-S data
Δt	exp time	15	h	
D	telescope diameter	39	m	E-ELT
C_{raw}	raw contrast	10^{-6} @0.1”		EPICS
C_{det}	detection contrast wo PDI	10^{-9} @0.1”		EPICS-IFS
k_{av}	inst efficiency: $(k_0 + k_{90})/2$	0.1		
$\Delta k/k_{av}$	inst pol	0.05		
$\Delta T/T_{av}$	pol by telluric transmission	5×10^{-5}		Bailey+ 2008
$\Delta I/I_{av}$	inter-steller pol.	0.01		
w	detection definition	1/3		

Bias

g = 1.0 (No PDI gain)



g = 0.05 (Best PDI gain)



Speckle errors limit the detectability.

$C_{det} < C_{p2s}$ / 100 (g=1.0) or $C_{det} < C_{p2s}$ / 10 (g=0.05) is necessary.

Observable planets

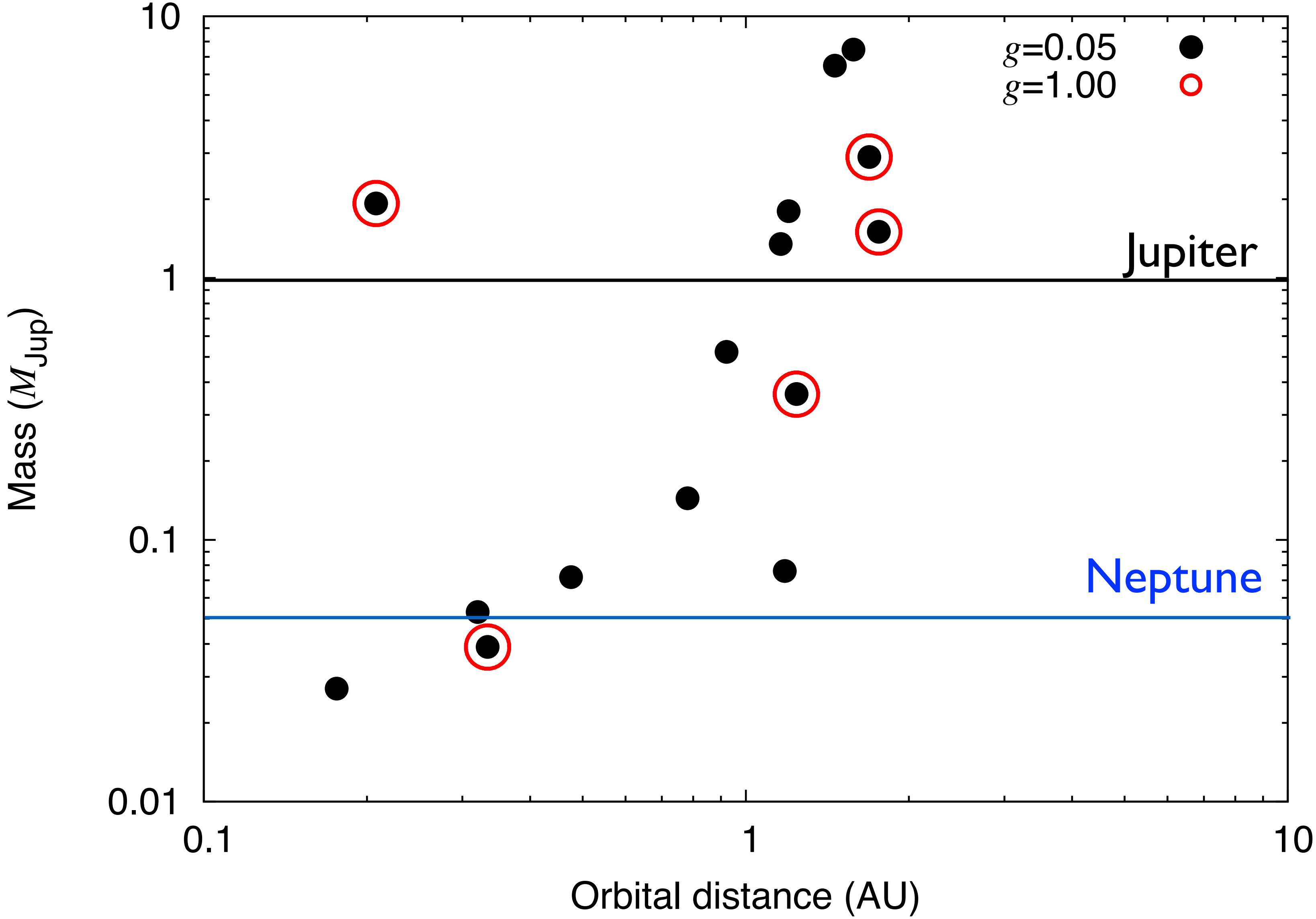
Planet	m* (J mag)	d (pc)	Spect. type	Mass(M_Jup)	Est. R_p (km)	Est. type	flux (erg / s /cm^2)	a_p (AU)	In/Outside of snow line ?	θ_p (arcsec)	σ_P	ΔP/σ_P	Δb_P	ΔP/Δb_P	SL (AU)
55 Cnc f	4.6	12.3	K0IV-V	0.14	56460	E2	1.30E+06	0.78	I	0.063	0.019	5	0.012	9	2.21
61 Vir d	3.3	8.5	G5V	0.07	37607	E2	4.78E+06	0.48	I	0.056	0.01	10	0.015	7	2.44
Aldebaran b	-2.1	20.4	K5III	6.47	73097	E1	3.18E+08	1.46	I	0.071	0.002	62	0.015	7	3.45
GJ 682 c	**6.5**	**5.1**	**M3.5V**	**0.03**	**22509**	**E3**	**8.60E+08**	**0.18**	**I**	**0.035**	**0.029**	**4**	0.021	5	0.20
Gl 785 b	4.1	8.9	K1V	0.05	32227	E2	3.91E+06	0.32	I	0.036	0.015	7	0.033	3	1.64
Gliese 876 b	5.9	4.7	M4 V	1.93	41457	E1	4.62E+05	0.21	I	0.044	0.007	15	0.005	19	0.30
Gliese 876 e	5.9	4.7	M4 V	0.04	29984	E2	1.80E+05	0.33	O	0.071	0.02	5	0.005	21	0.30
HD 113538 b	6.4	15.8	K9V	0.36	99429	E2	8.98E+04	1.24	O	0.078	0.029	3	0.005	21	0.92
HD 176051 b	3.9	15.0		1.50	84965	E1	8.60E+08	1.76	?	0.117	0.017	6	0.007	14	0.92
HD 192310 c	4.1	8.8	K3V	0.08	42025	E2	3.06E+05	1.18	I	0.134	0.032	3	0.009	11	1.73
HD 27442 b	**2.6**	**18.1**	**K2 IV a**	**1.35**	**59975**	**E1**	**2.02E+07**	**1.16**	**I**	**0.064**	**0.014**	**7**	0.022	5	3.89
HD 60532 c	**3.7**	**25.7**	**F6IV-V**	**7.46**	**79813**	**E1**	**8.60E+08**	**1.58**	**I**	**0.061**	**0.026**	**4**	0.028	4	5.60
HD 62509 b	-0.5	10.3	K0IIIb	2.90	57459	E1	1.76E+07	1.69	I	0.163	0.004	28	0.008	13	5.83
alf Ari b	0.1	20.2	K2III	1.80	66913	E1	7.31E+07	1.20	I	0.059	0.004	24	0.025	4	6.08
μ Ara d	4.2	15.3	G3IV-V	0.52	50881	E1	2.37E+06	0.92	I	0.060	0.028	4	0.025	4	3.15
Average	**3.5**	**12.9**		**1.65**	**55653**		**2.01E+08**	**0.97**		**0.1**	**0.017**	**12**	**0.0**	**10**	**2.58**

Red: detectable for g=1.0

- g= 0.05 (best) → 15 planets (inside of snow lime: 12)
- g= 1.0 (worst)→ 5 planets (inside of snow line : 2)

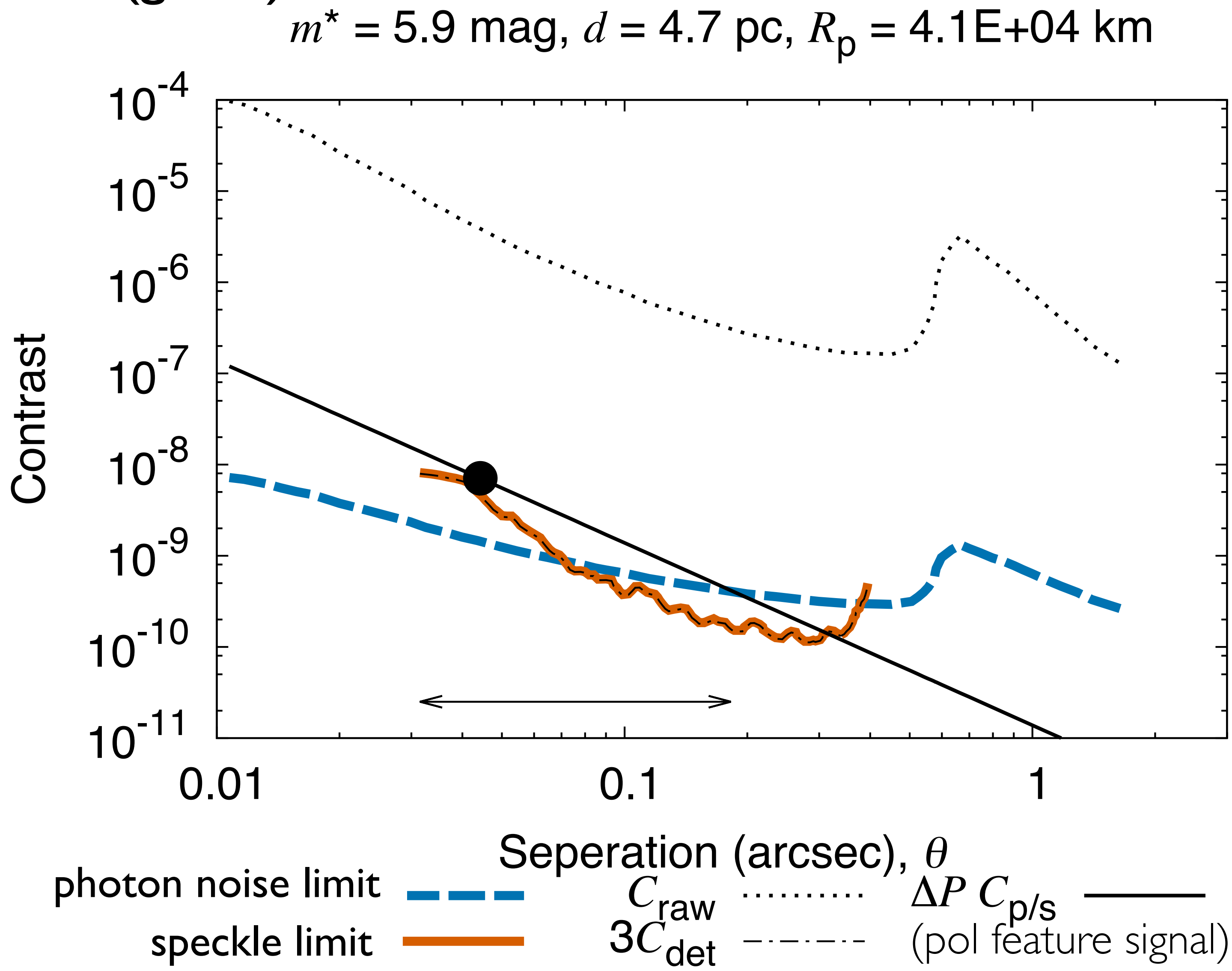
Observable planets

- Exposure time = 15h



Contrast vs. seperation

- **Gliese 876b (g=1.0)**



Summary

- Spectro-polarimetry for reflected light from an exoplanet may allow ground-based observers to detect atmospheric compositions such as H_2O and O_2.

- We evaluated the feasibility of the search for a spectro-polarimetric feature of H_2O vapor ($\Delta P=10\%$) by considering (a) errors from different efficiencies between ordinary and extraordinary light beams, (b) errors caused by speckle noises, and (c) errors by photon noises from the leakage of the host star.

- We predict that several known planets including a mini-Neptune are observable in principle assuming an EPICS-IFS-like detection contrast before PDI.

- It is worth beginning to study for a future high-contrast spectro-polarimeter for TMT.