

Instrumentation for high resolution spectra of exoplanets

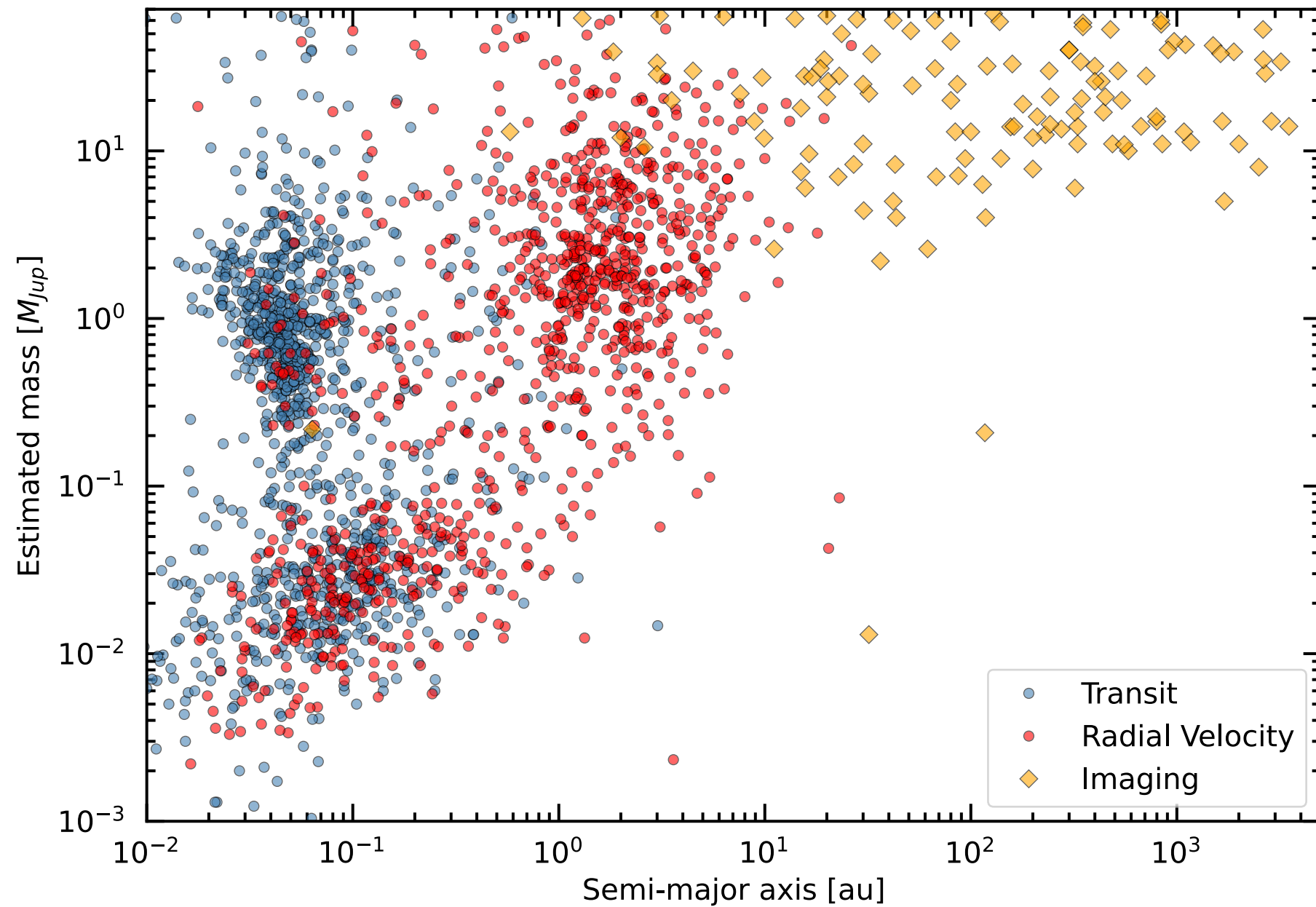
Arthur Vigan

Laboratoire d'Astrophysique de Marseille (LAM)
Centre National de la Recherche Scientifique (CNRS)



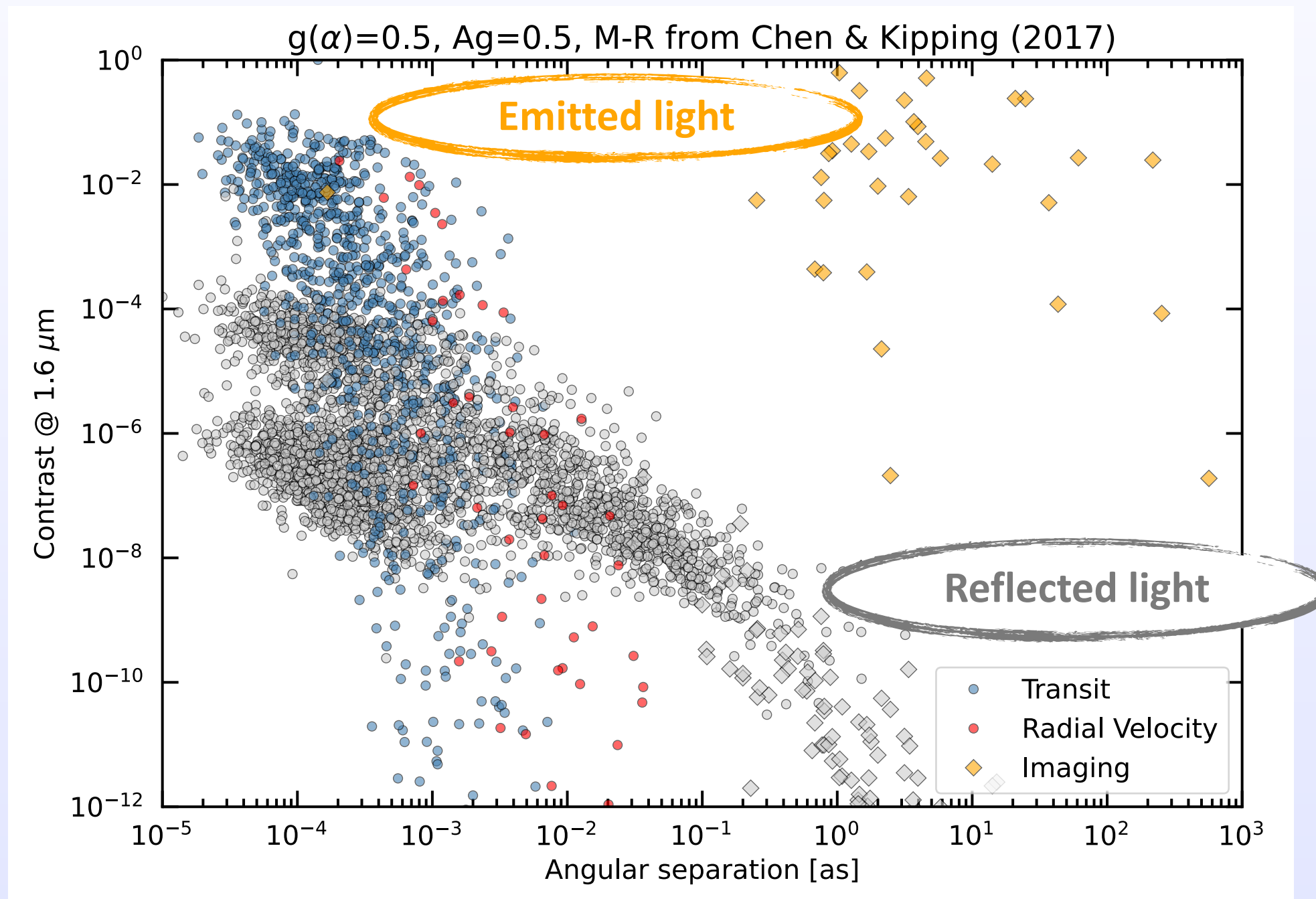
Direct planet detection: the challenge

Physical units



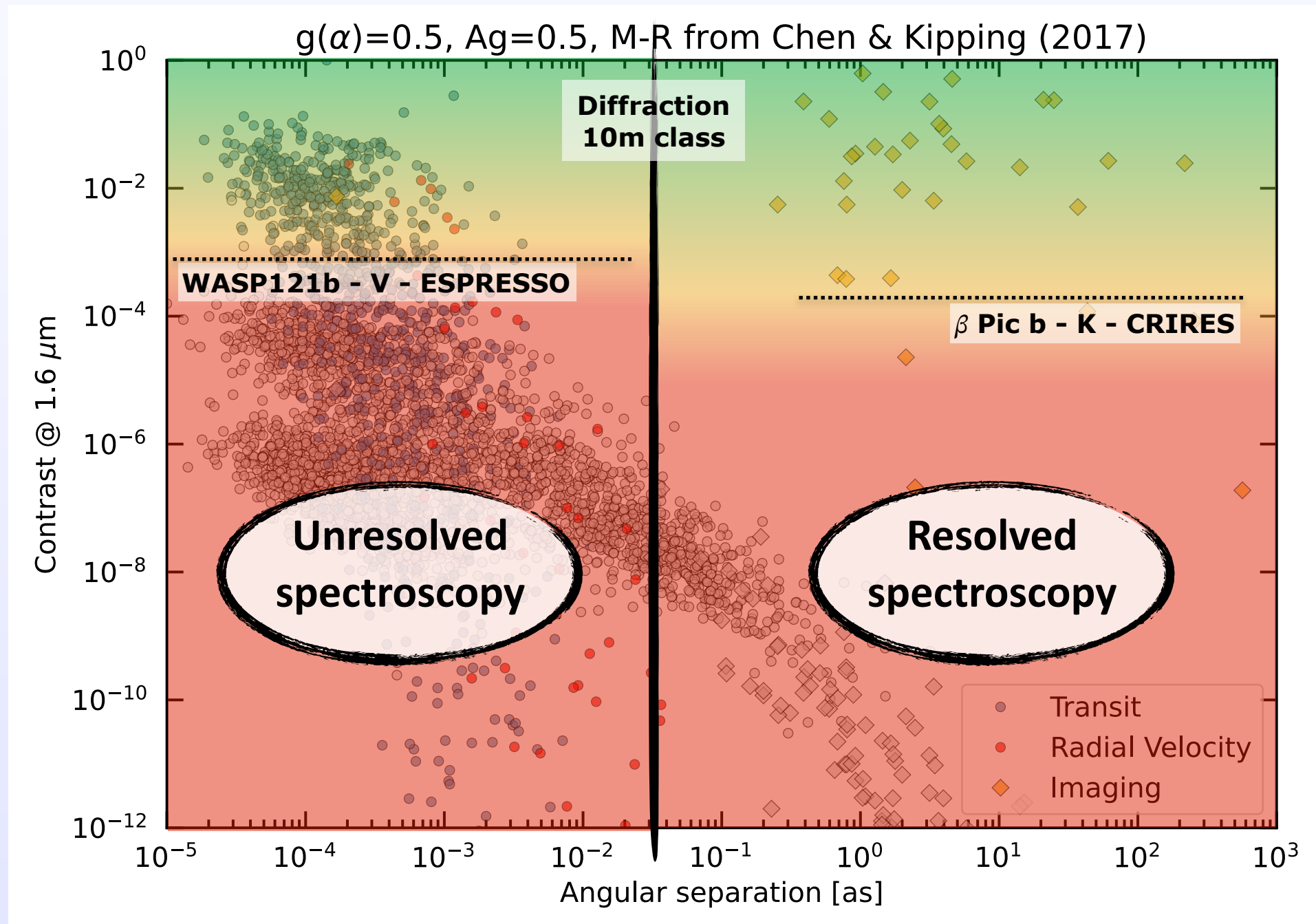
Direct planet detection: the challenge

Observables



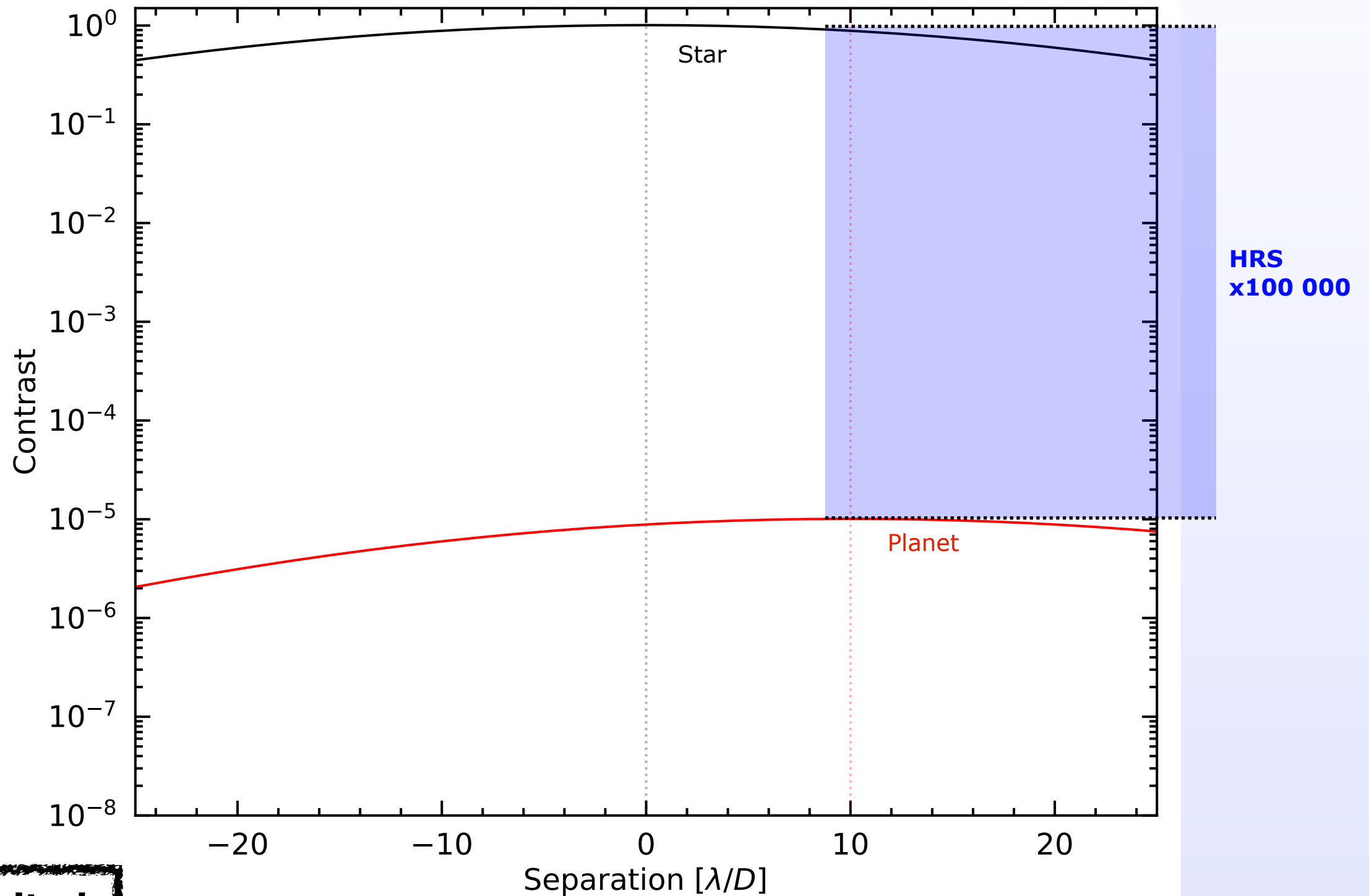
Direct planet detection: the challenge

Observables



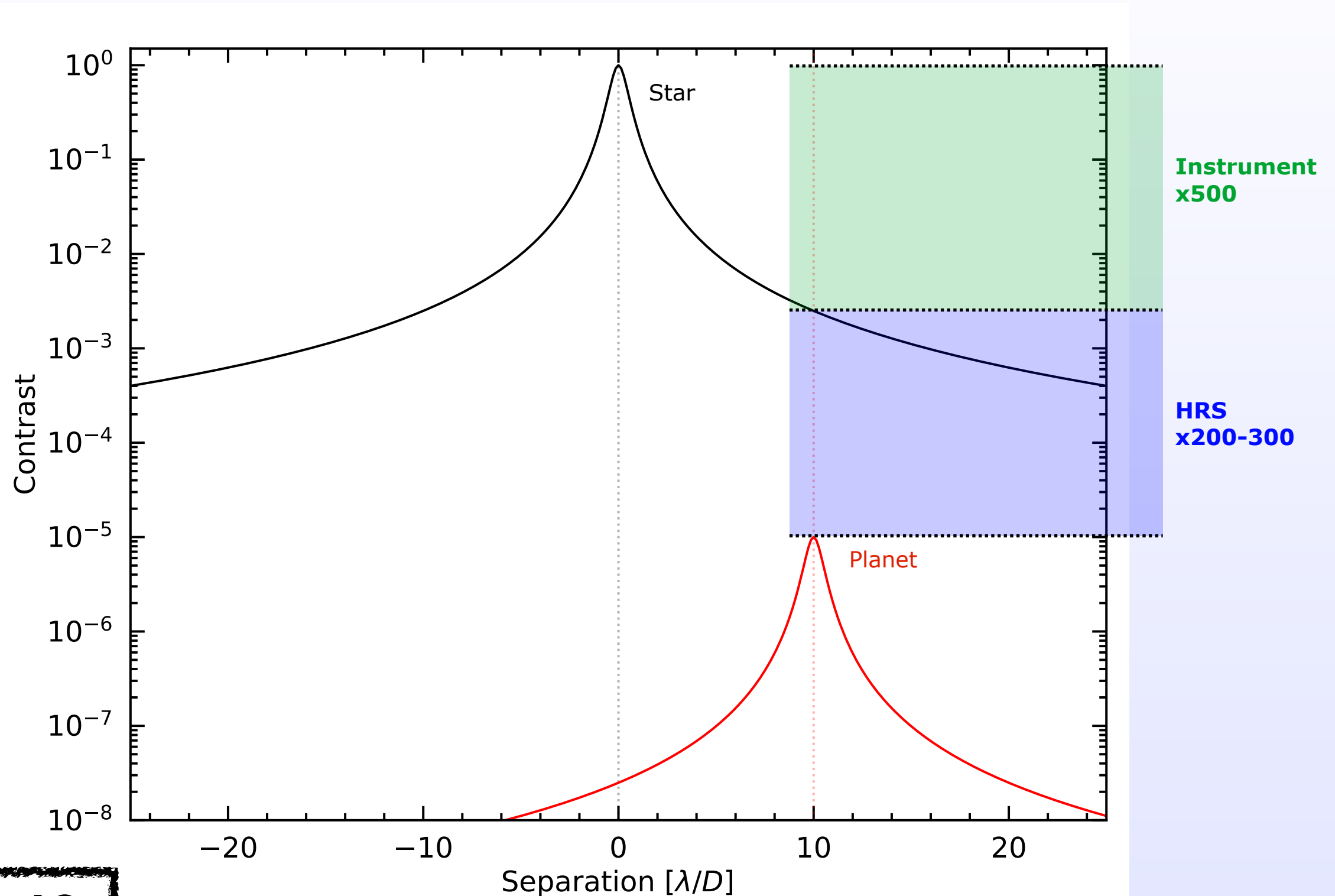
Hoeijmakers et al. (2024)
Landman et al. (2024)

From unresolved...



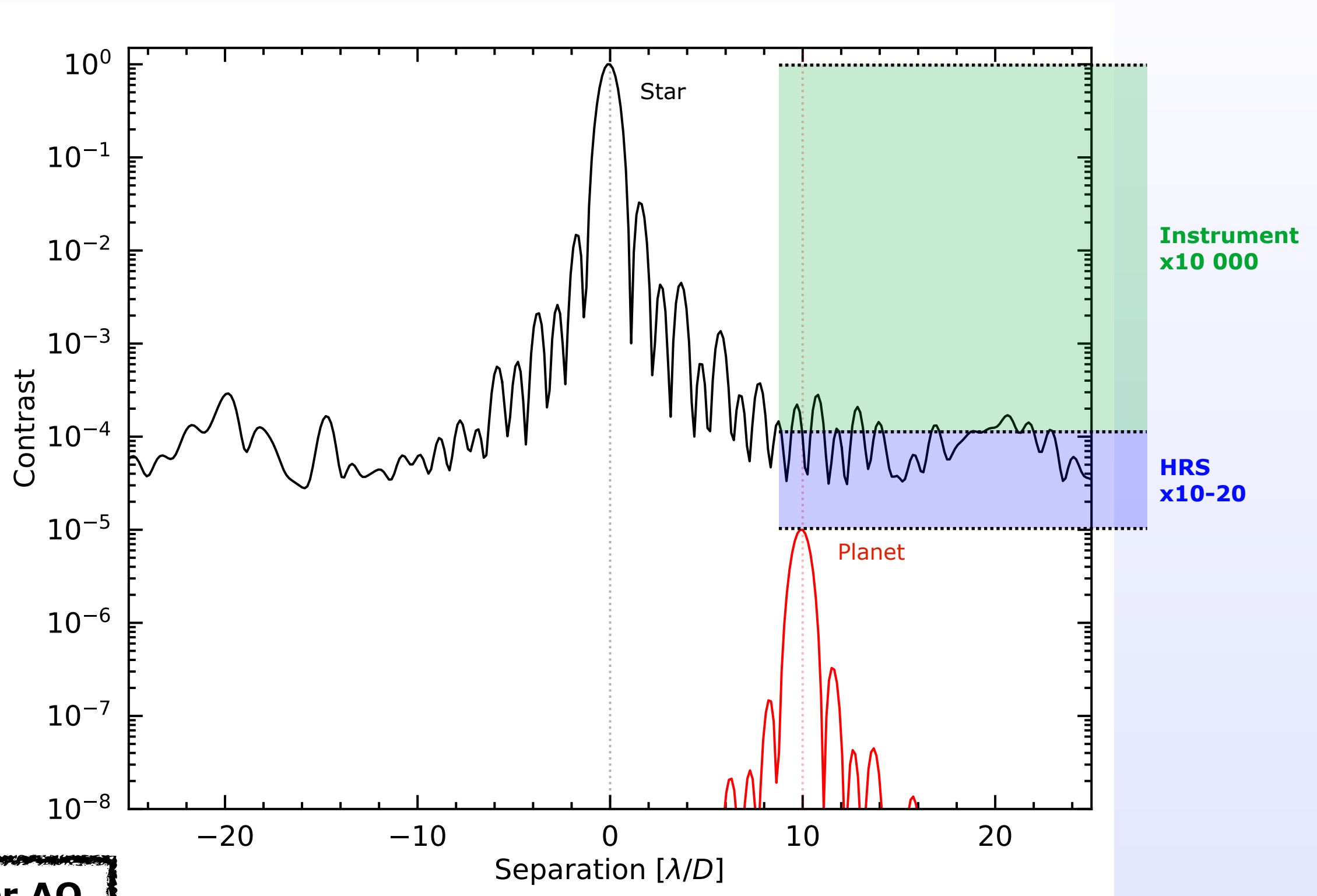
Seeing-limited

... to resolved spectroscopy



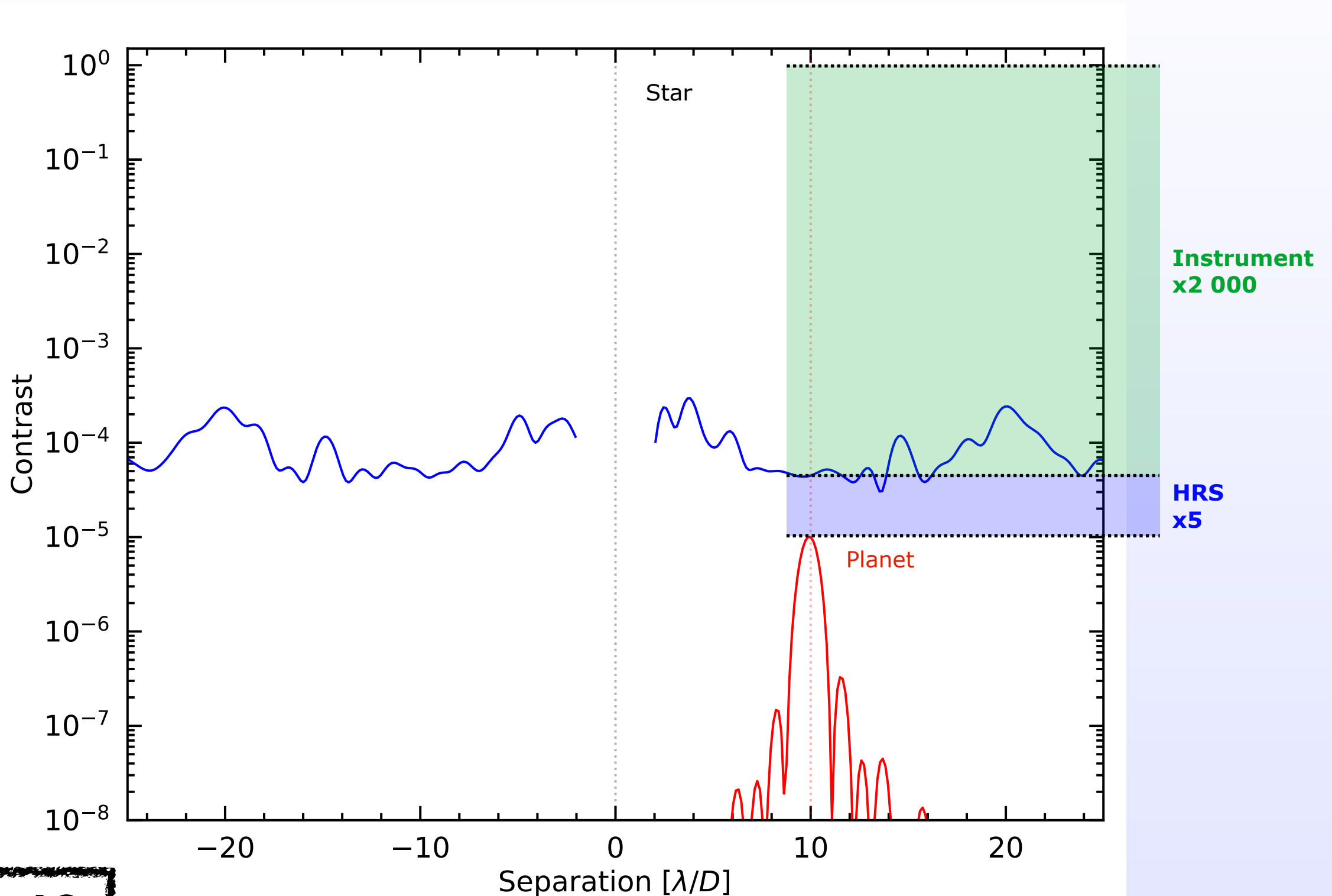
Low-order AO

... to resolved spectroscopy



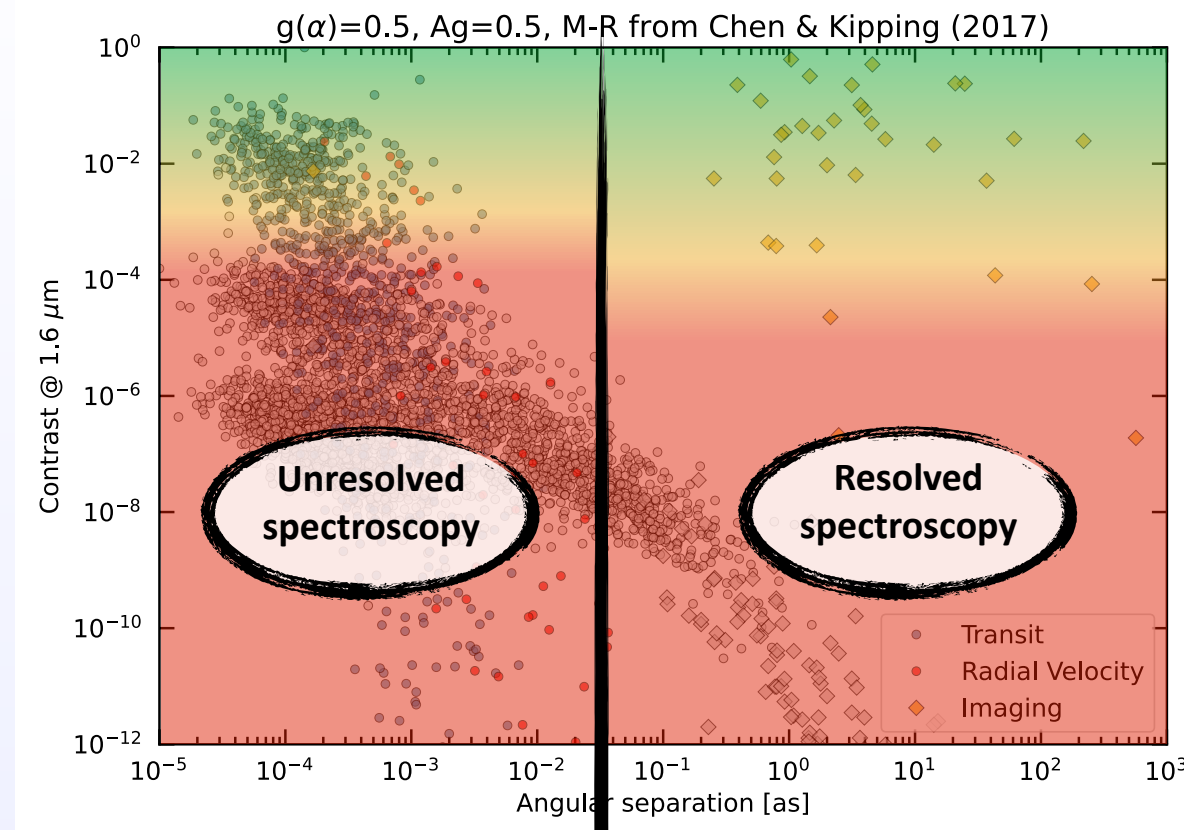
High-order AO

... to resolved spectroscopy



**High-order AO
+ coronagraphy**

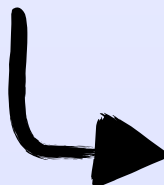
What sort of instrumentation do you need?



- Collect as many photons as possible from the unresolved system



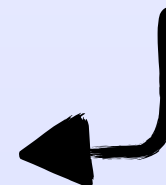
Big telescope



- Resolve the system
- Collect as many photons as possible from the planet
- Reject as many photons as possible from the star



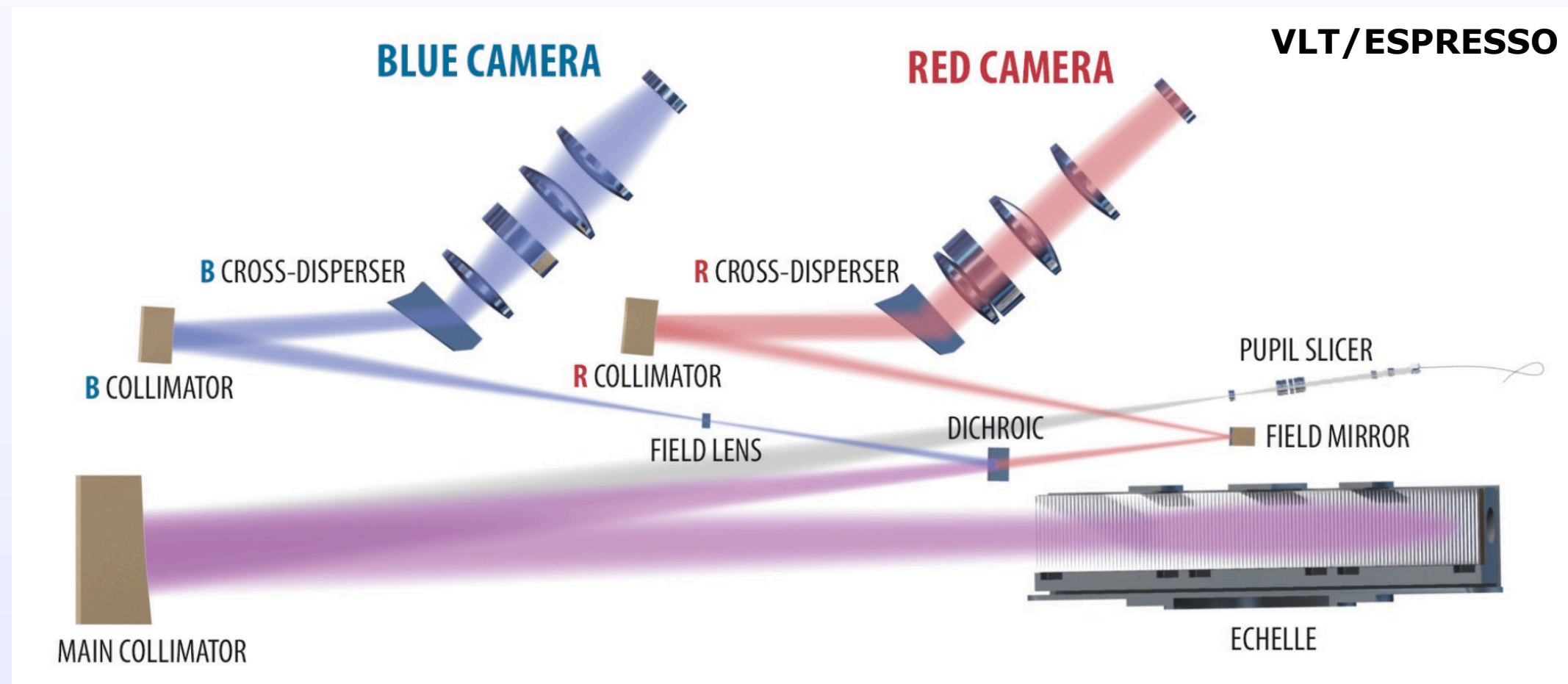
Big telescope + AO + coronagraphy



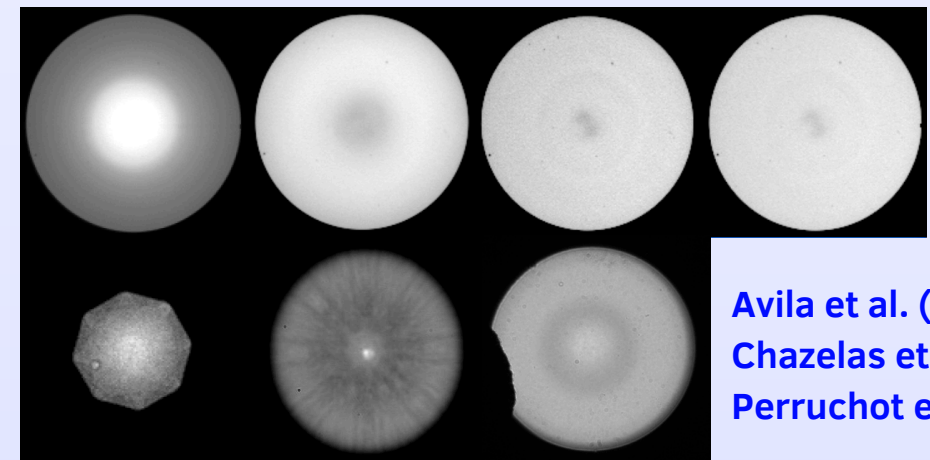
High-resolution spectrograph

Unresolved high-resolution spectroscopy

- Targeting fast-moving companions $\rightarrow$ km/s
- Any good cross-dispersed echelle spectrograph with stable PSF will do



- Optimised to search for planets $\rightarrow$ highly stable
- Usually fibre-fed with large MMF (not always: CRIRES)
 - Scrambling and/or octagonal fibers to reduce modal noise and increase stability
- In most cases seeing-limited (not always: CRIRES, NIRPS)



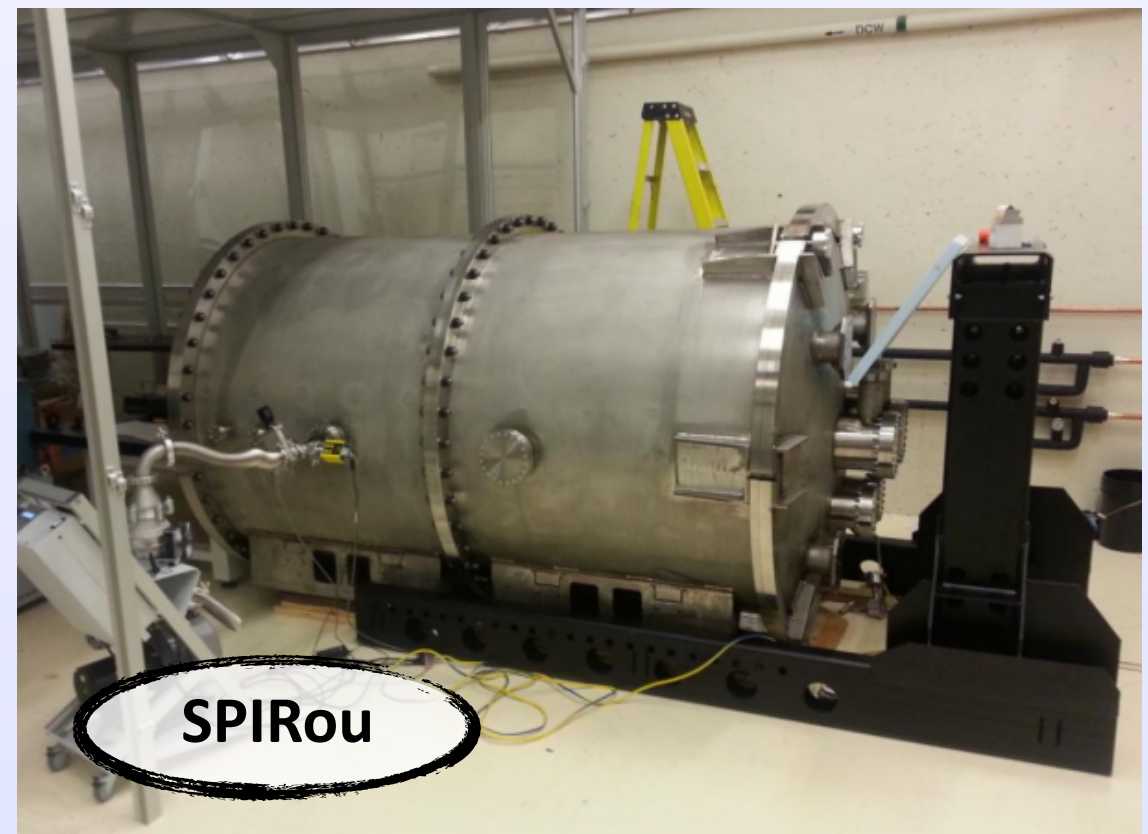
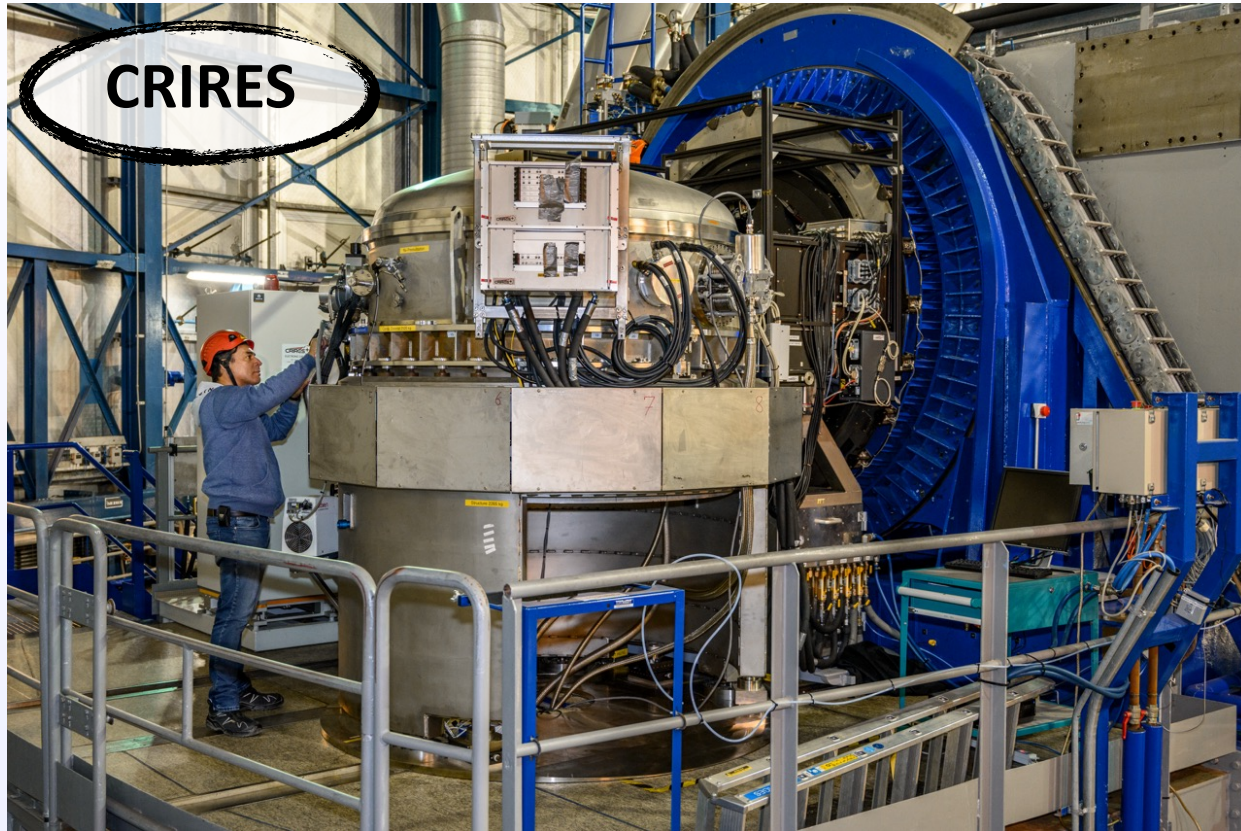
Avila et al. (2010)
Chazelas et al. (2010)
Perruchot et al. (2011)

Unresolved high-resolution spectroscopy



And certainly others...

Seeing-limited spectrographs



From unresolved to resolved spectroscopy

$$R = \frac{\lambda}{\Delta\lambda} = \frac{\lambda A d_{\text{col}}}{r \phi D_{\text{Tel}}}$$

Angular dispersion

Diameter of collimated beam on disperser

Anamorphic factor

Angular slit width

Telescope diameter

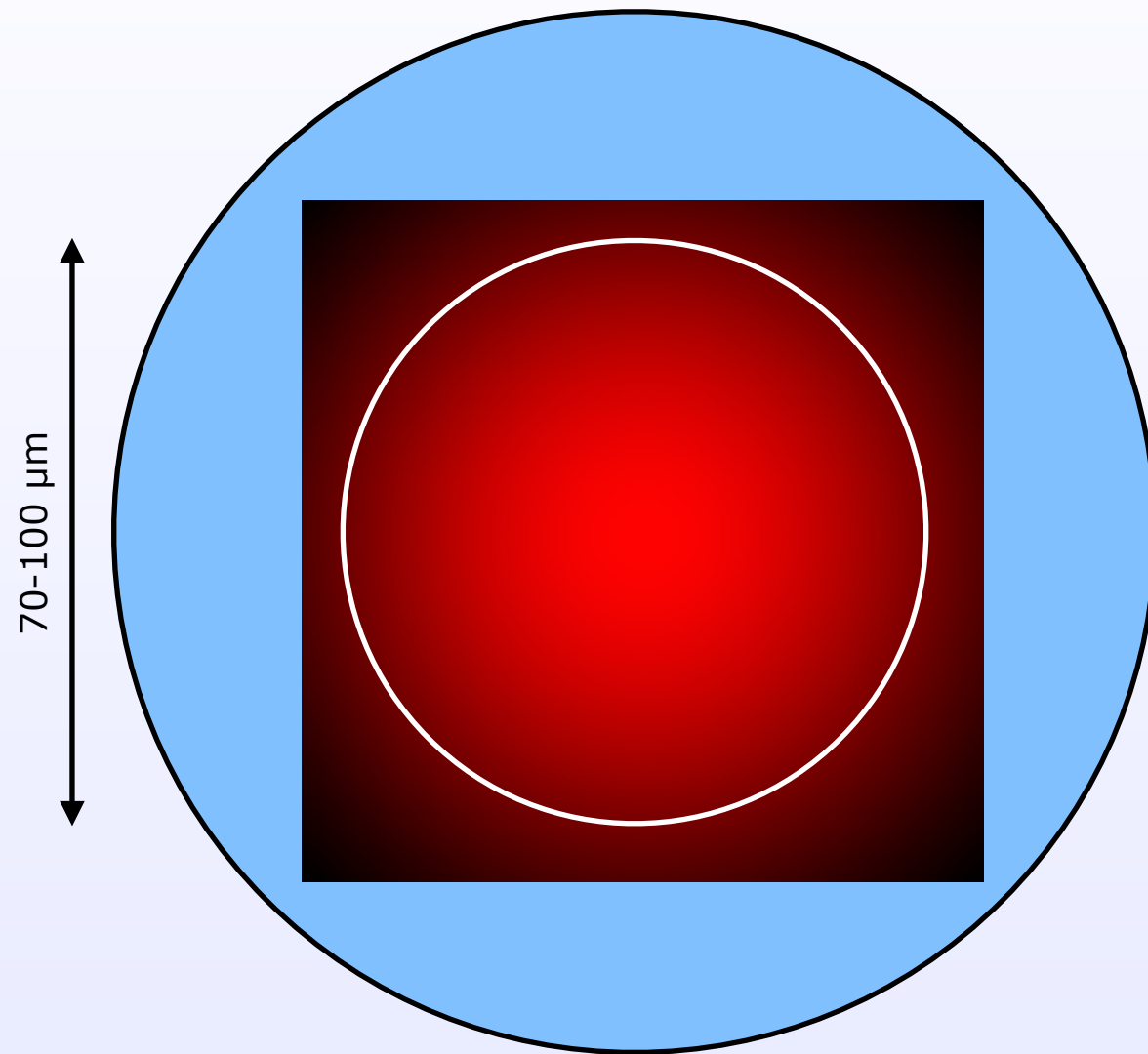
Diffraction limit

$$\phi \simeq \frac{\lambda}{D_{\text{Tel}}}$$

$$R = \frac{A d_{\text{col}}}{r}$$

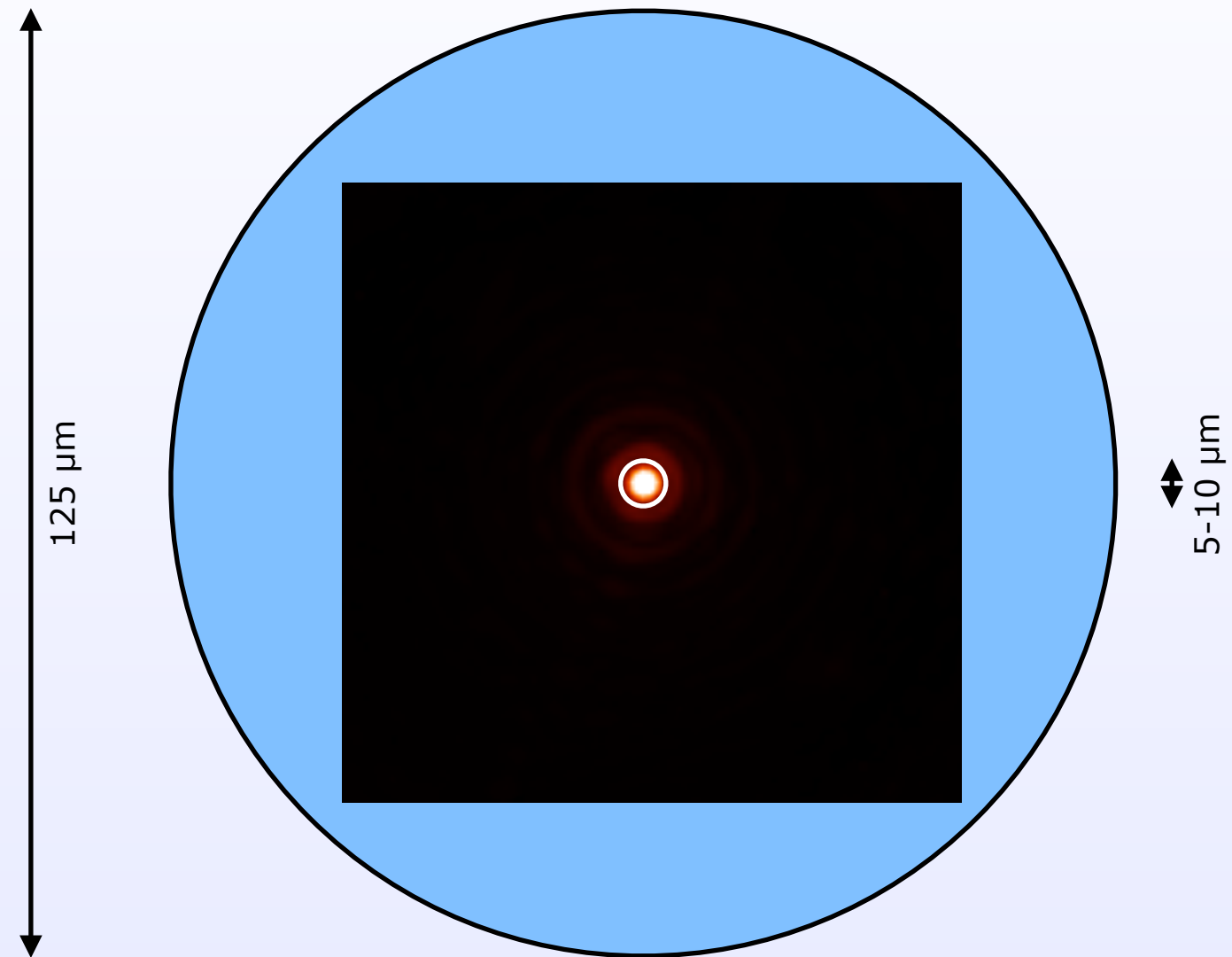
Independent of telescope and slit sizes!

From unresolved to resolved spectroscopy



Multi-mode fiber

0.5" to 1.0" on-sky



Single-mode fiber

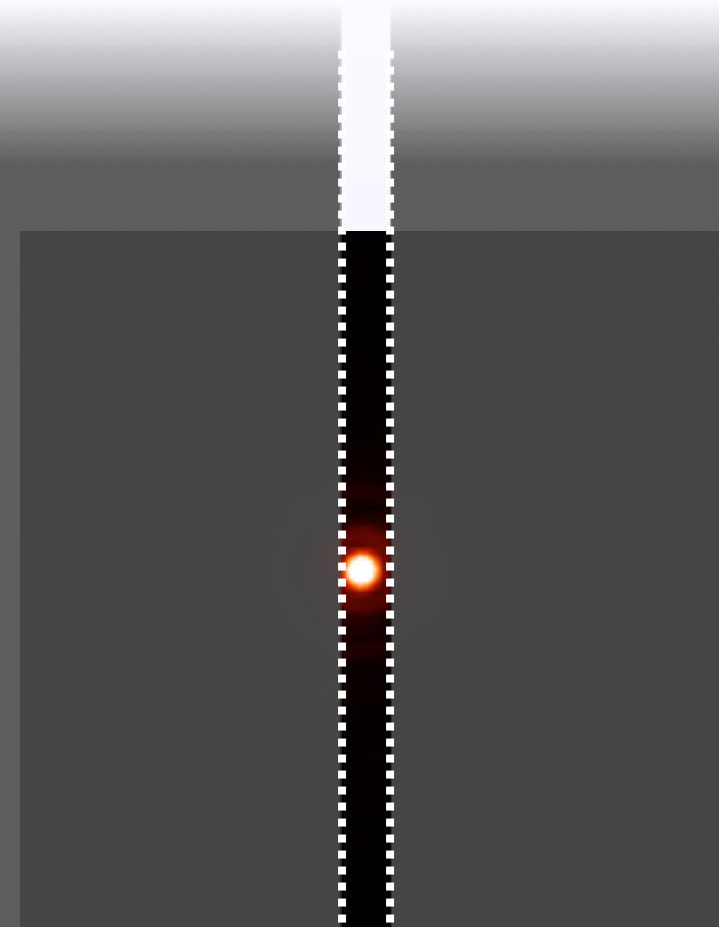
1 λ/D on sky
e.g. 0.04" in H band

From unresolved to resolved spectroscopy



Wide slit

0.5" to 1.0" on-sky



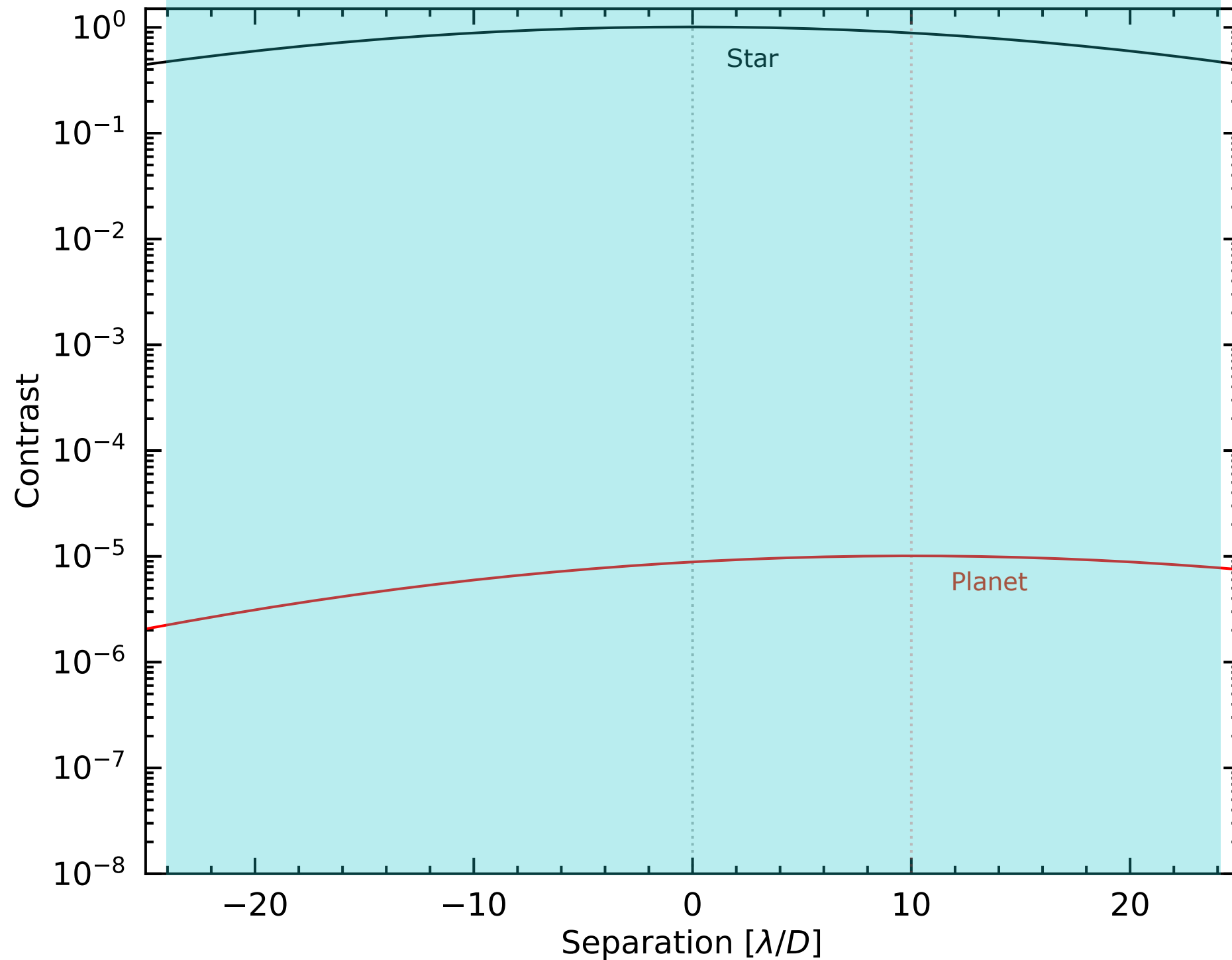
Narrow slit

1 λ/D on sky
e.g. 0.04" in H band

Seeing-limited spectrographs

Multi-mode fiber

Seeing-limited



Diffraction-limited spectrographs

Low-order AO

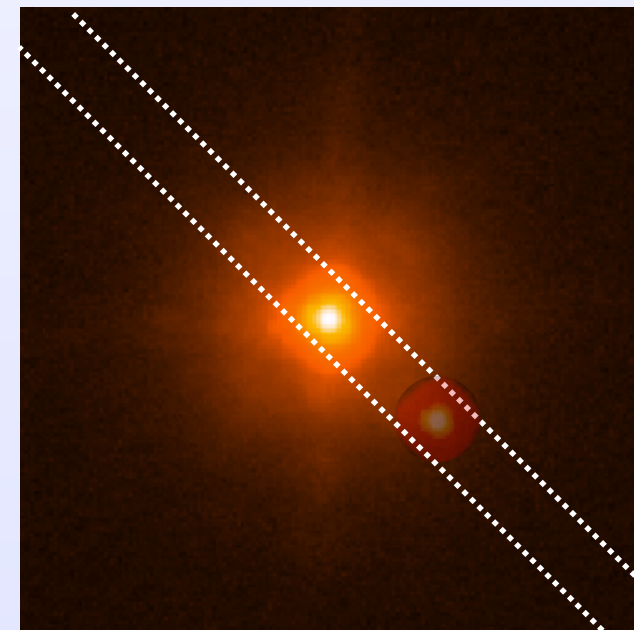
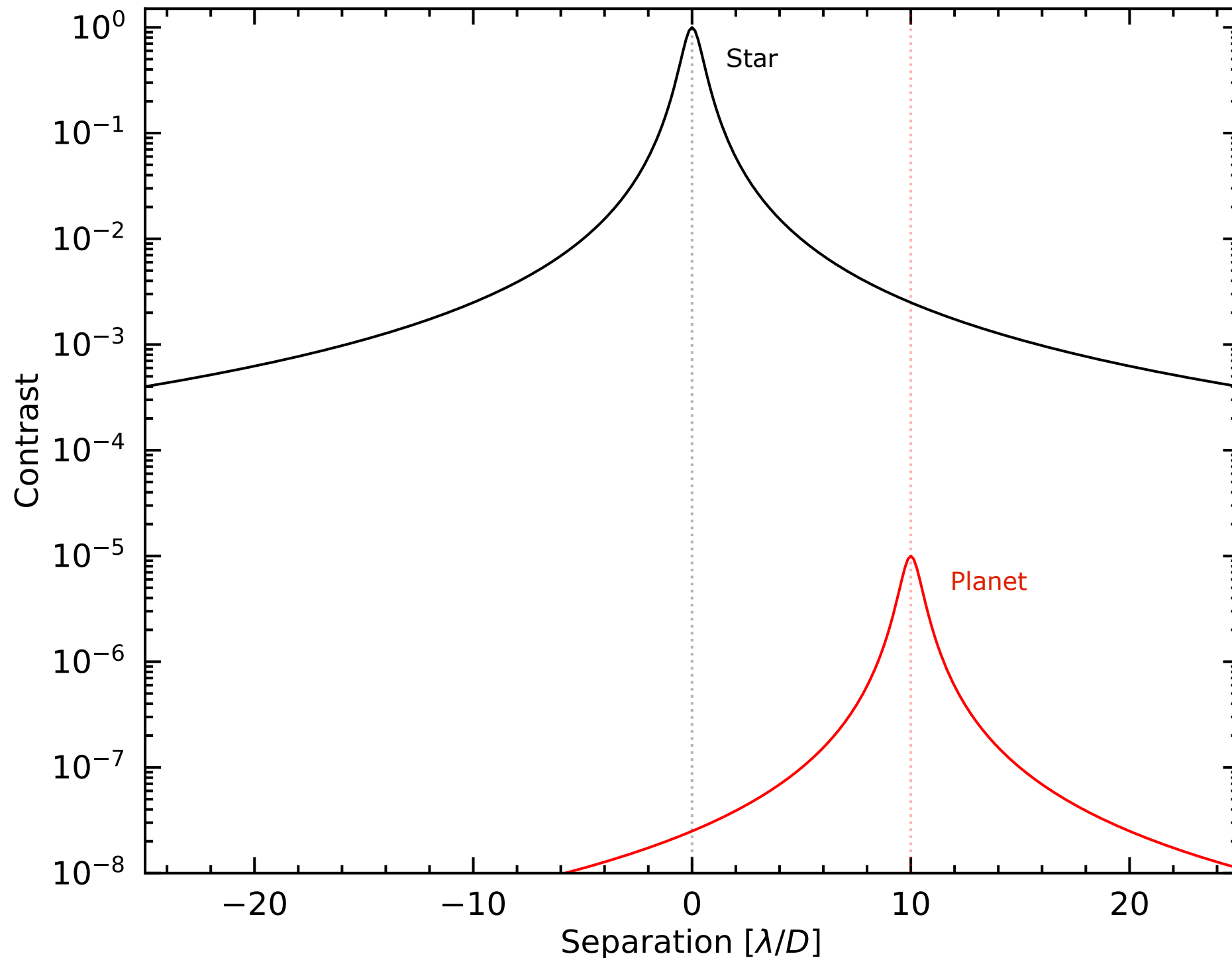
2000s

Shack-Hartmann WFS

~150 actuators

Sr = 40-50% (H)

NaCo, **CRIRES**,
SINFONI, **OSIRIS**



First results in resolved high-res. spectroscopy

Low-order AO

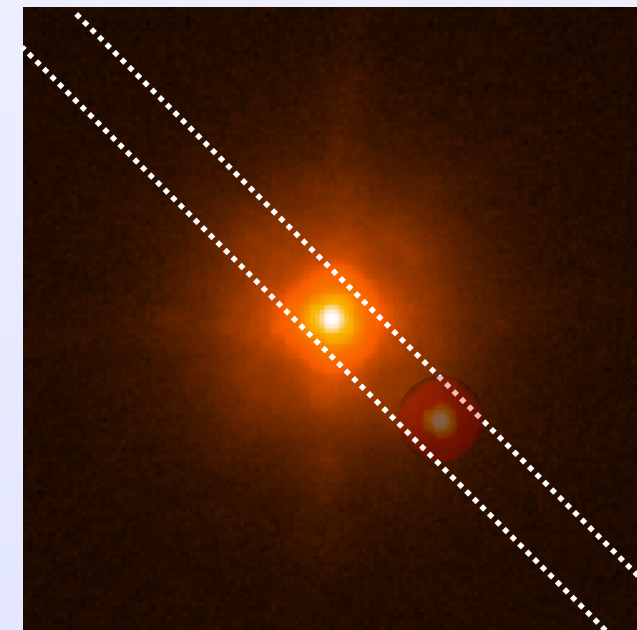
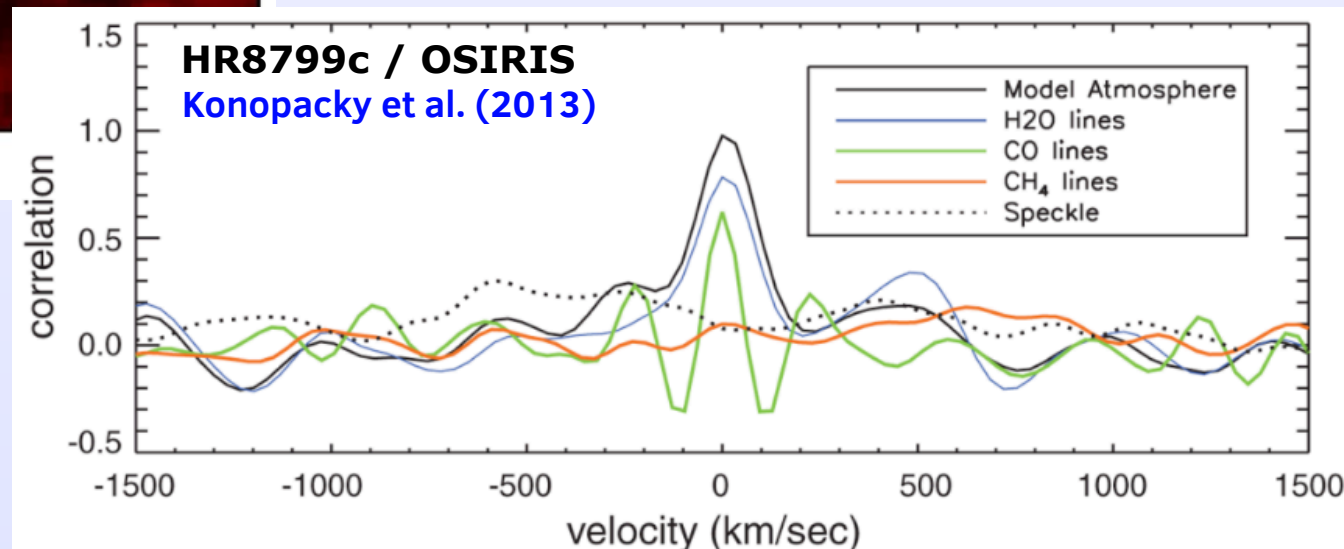
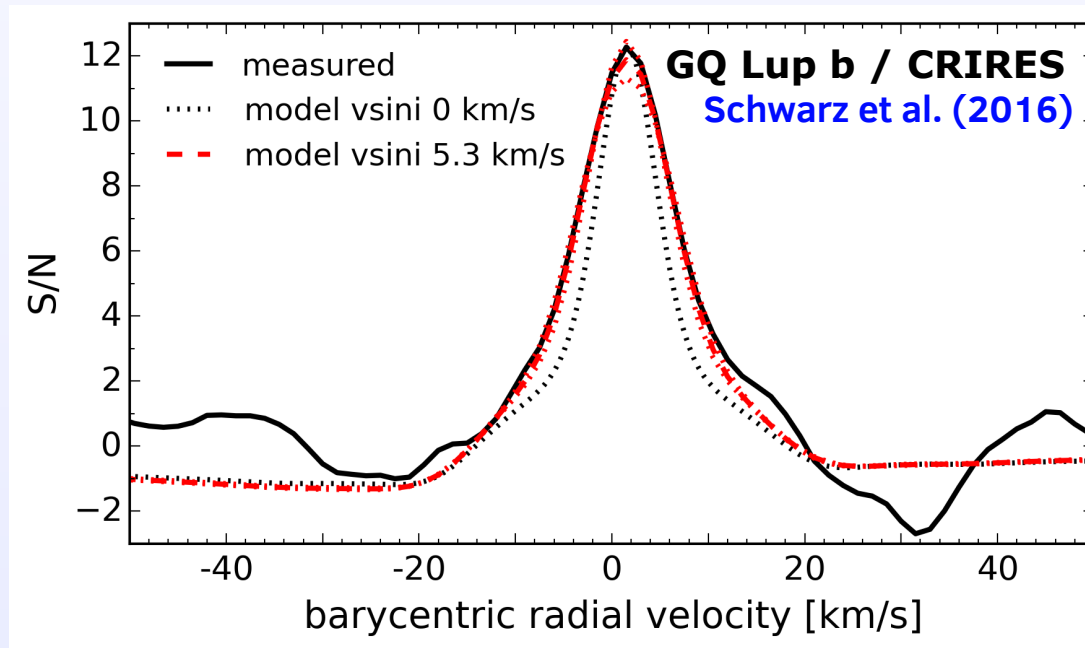
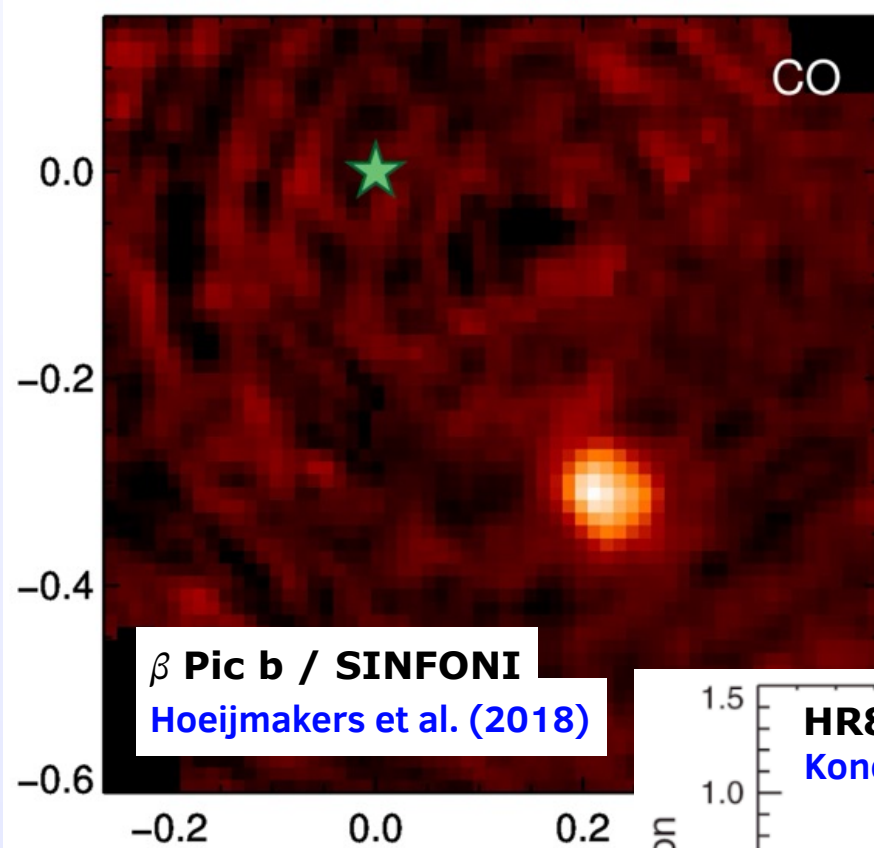
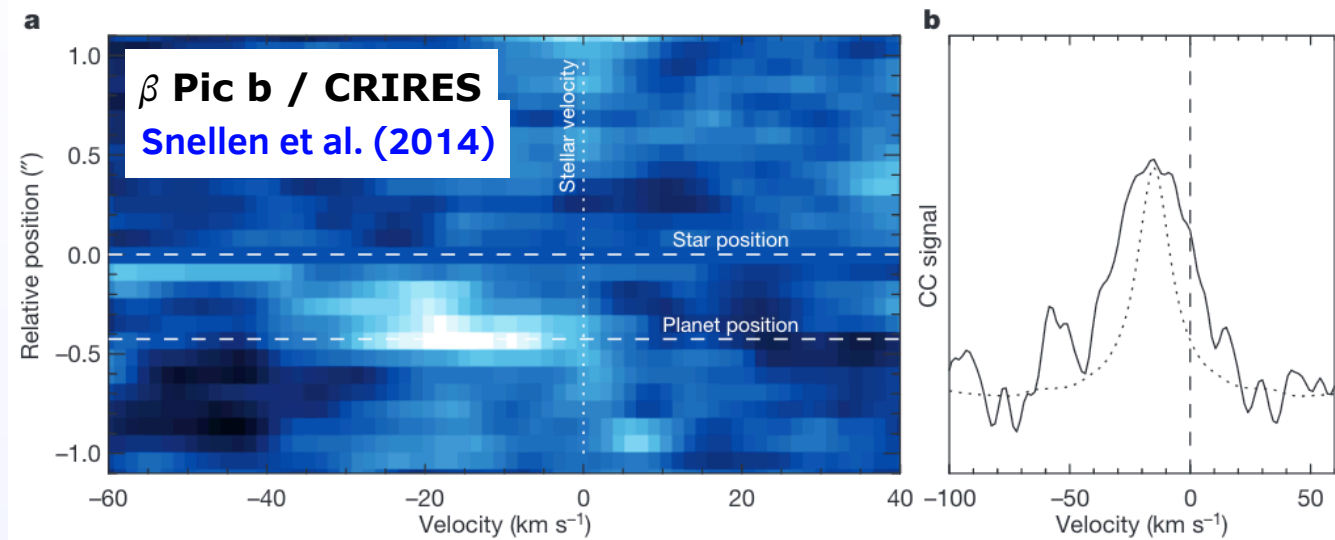
2000s

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NaCo, **CRIRES**,
SINFONI, **OSIRIS**



Diffraction-limited spectrographs

Low-order AO

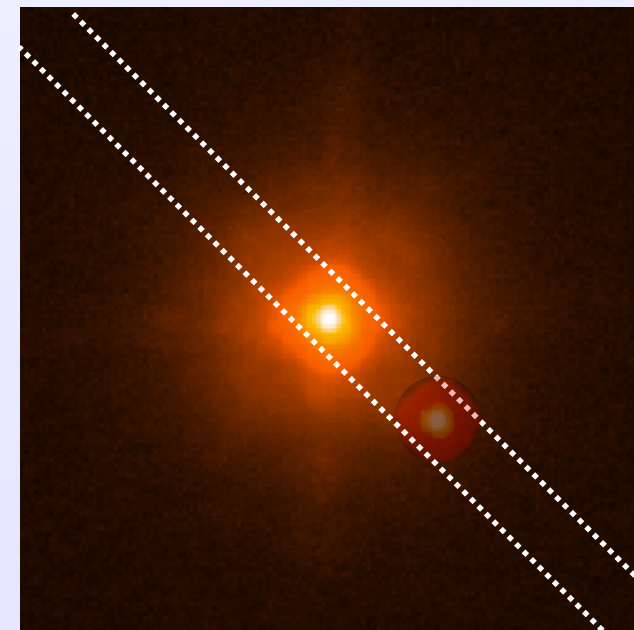
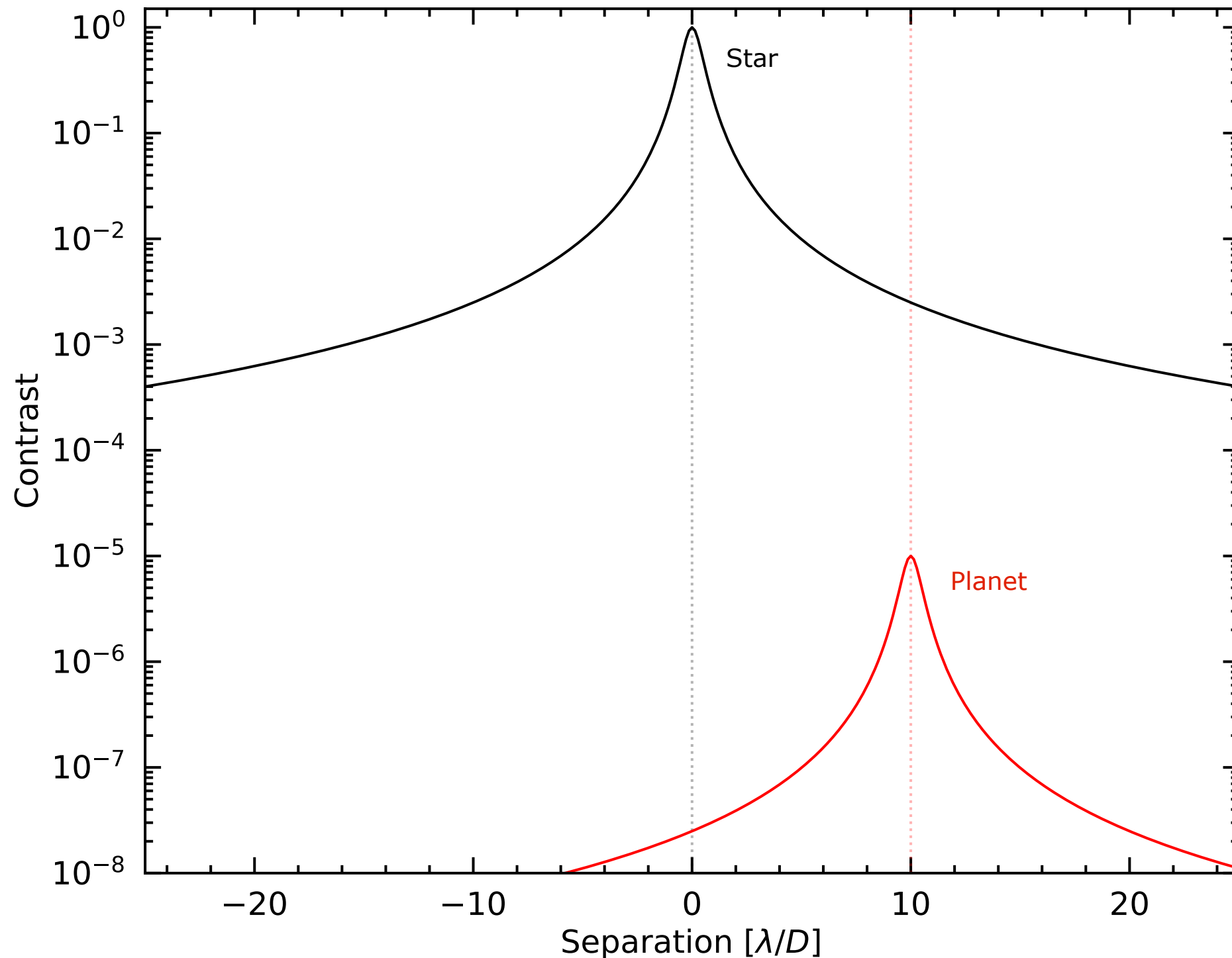
2000s

Shack-Hartmann WFS

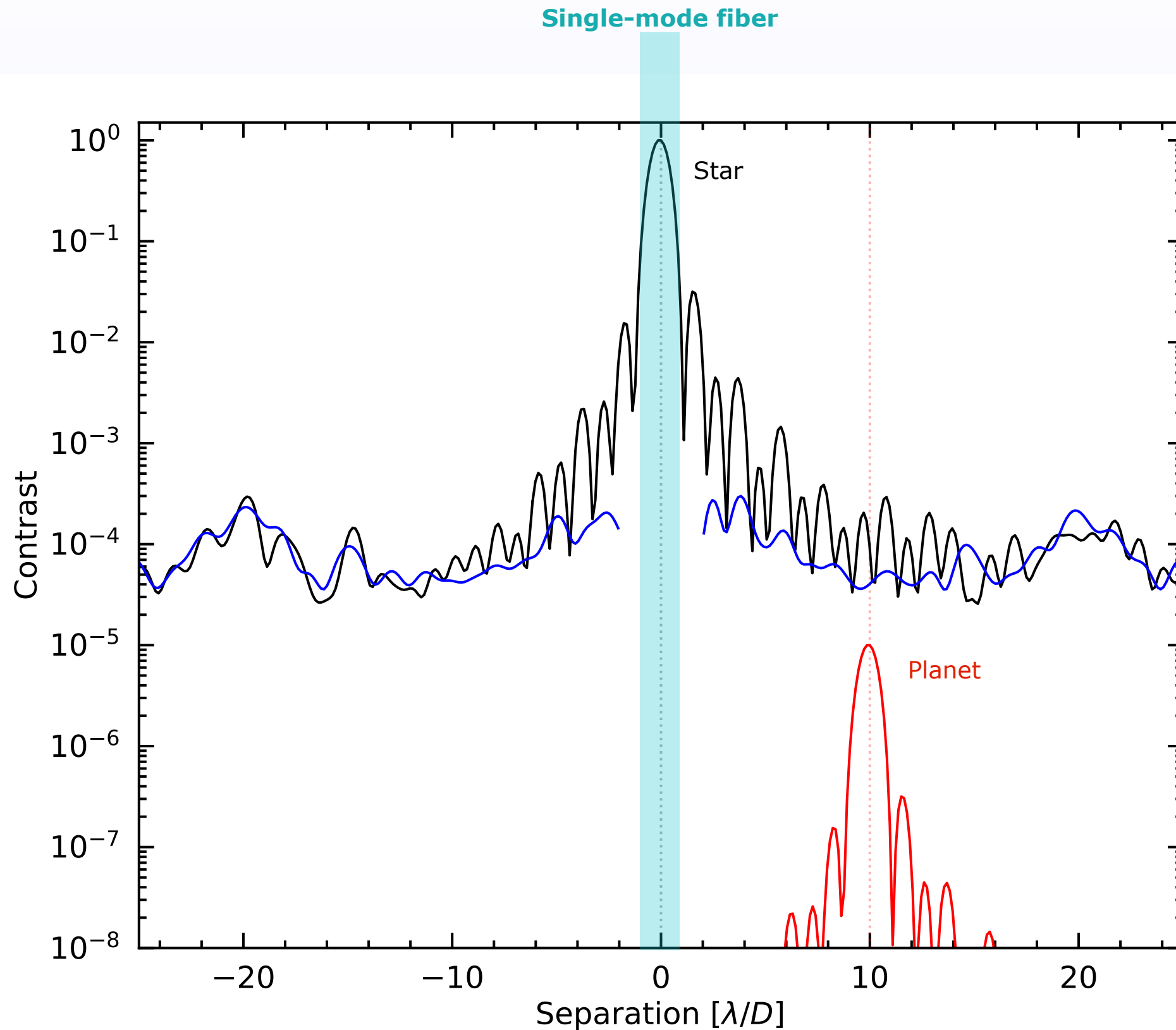
~150 actuators

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NaCo, **CRIRES**,
SINFONI, **OSIRIS**



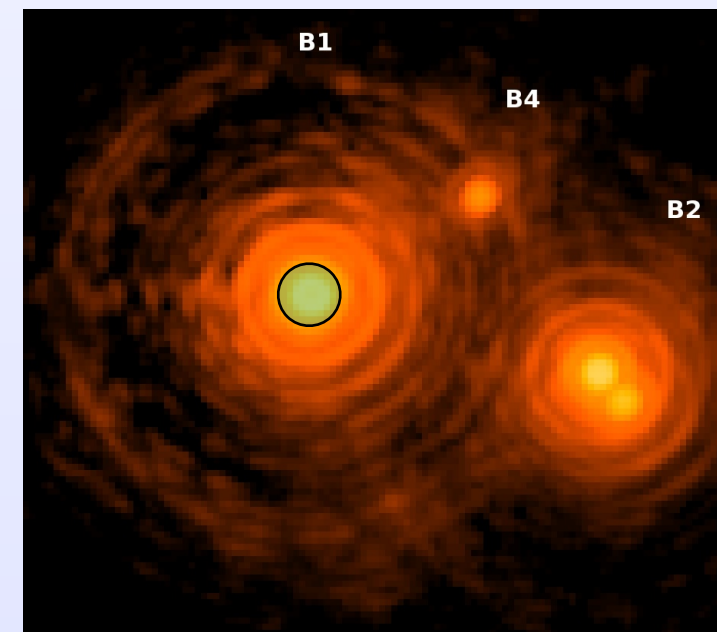
Diffraction-limited spectrographs



High-order AO

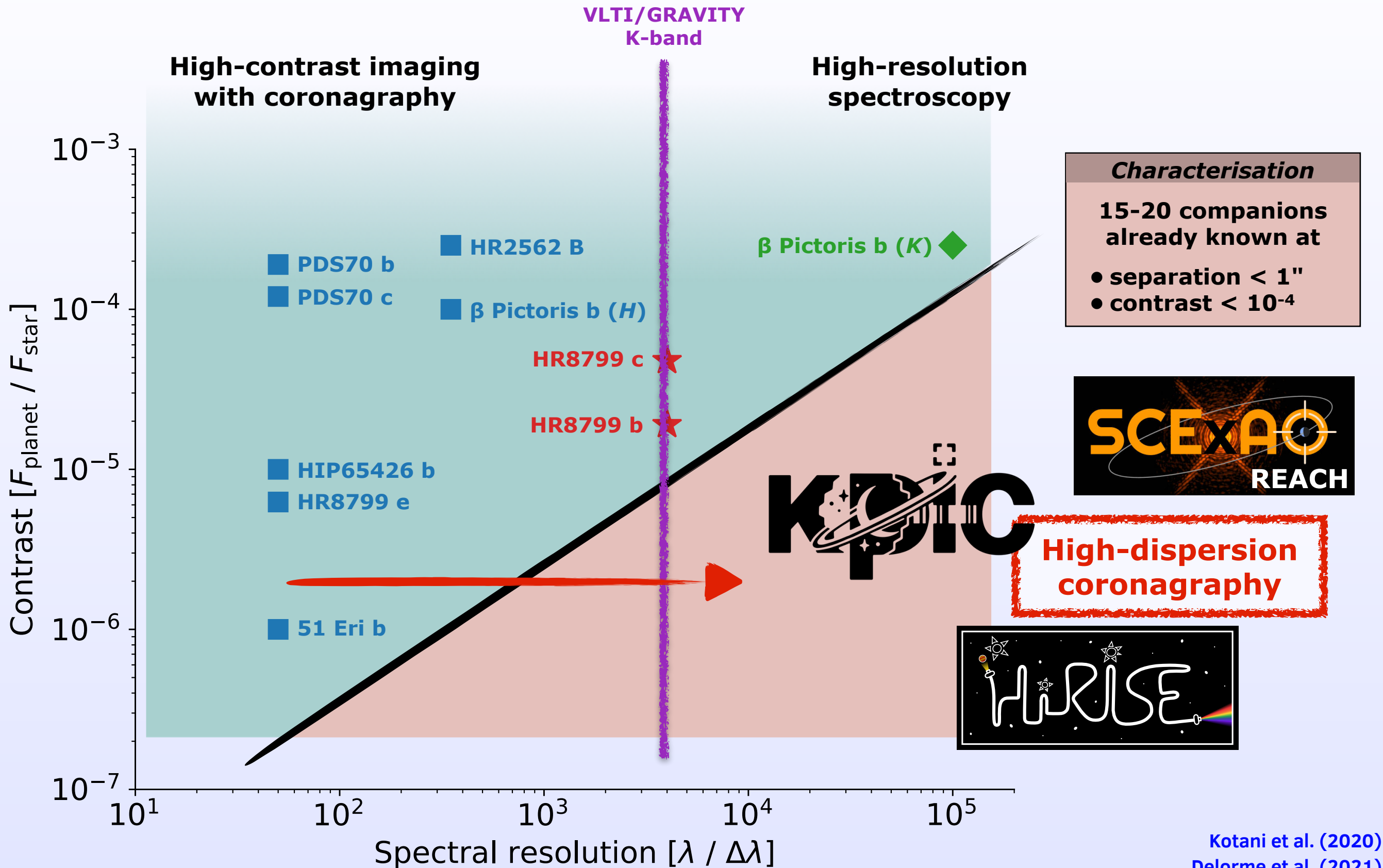
Since 2010s
SHWFS or PyWFS
> 1000 actuators
 $S_r > 80\%$ (H)
+ coronagraphy !

LBT, **SPHERE**, **GPI**,
SCExAO



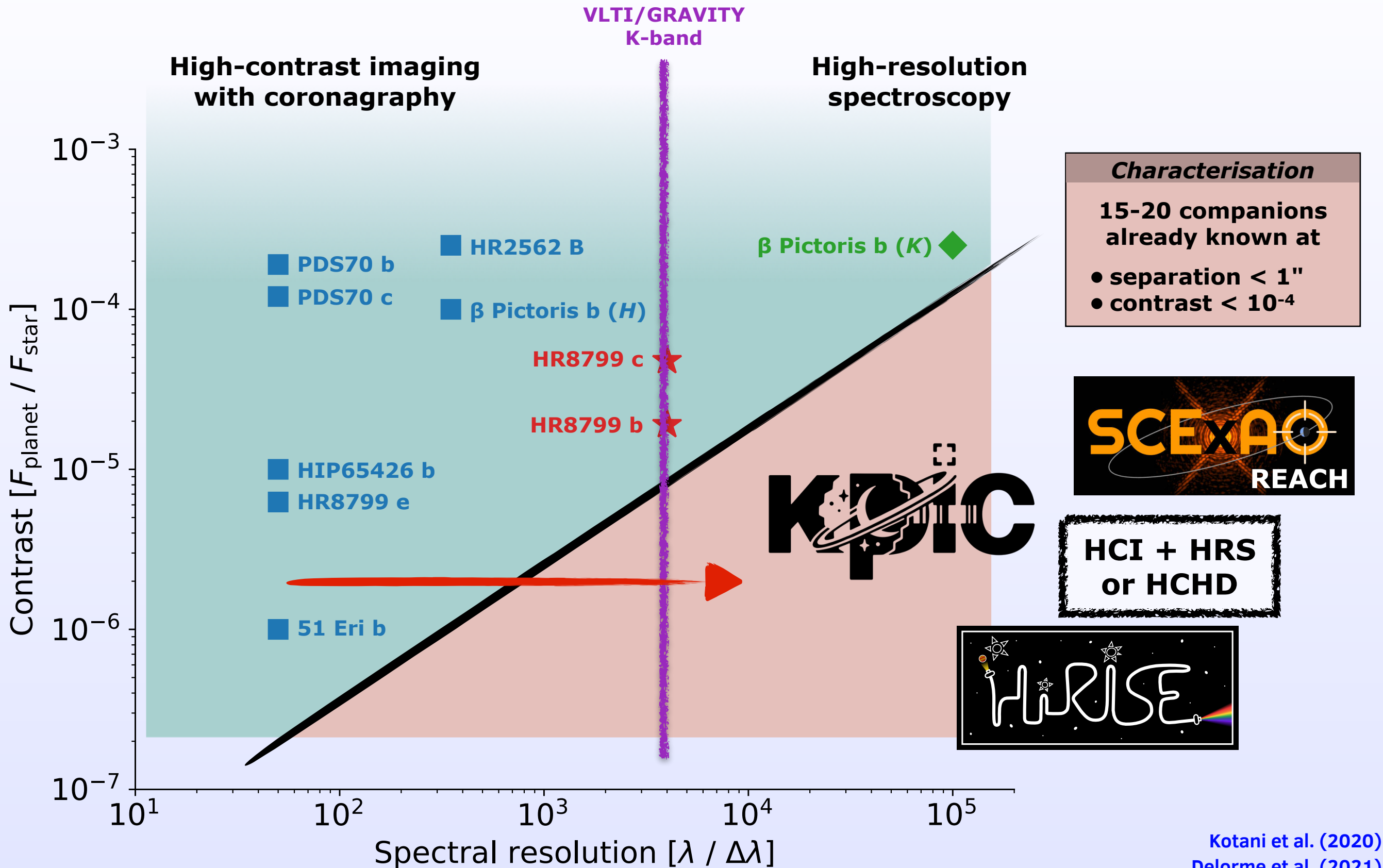
And more recently: KPIC, MagAO-X, ...

Resolved exoplanet spectroscopy in ~2017



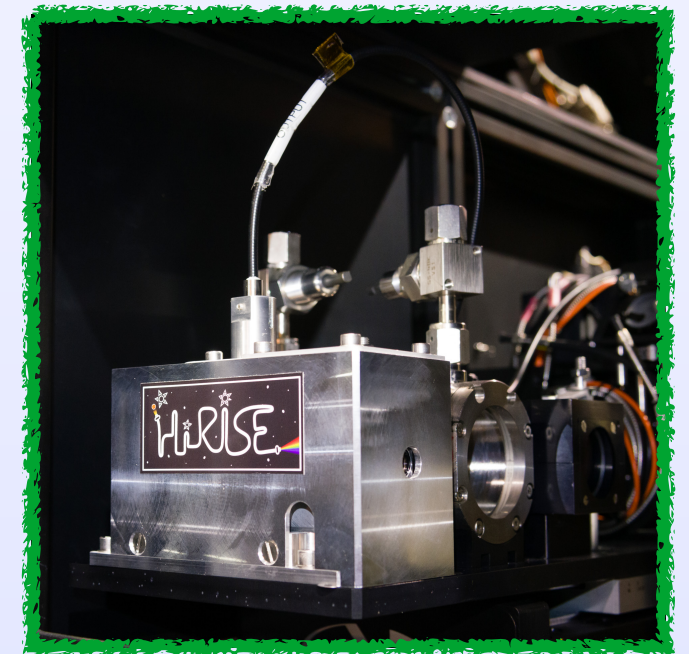
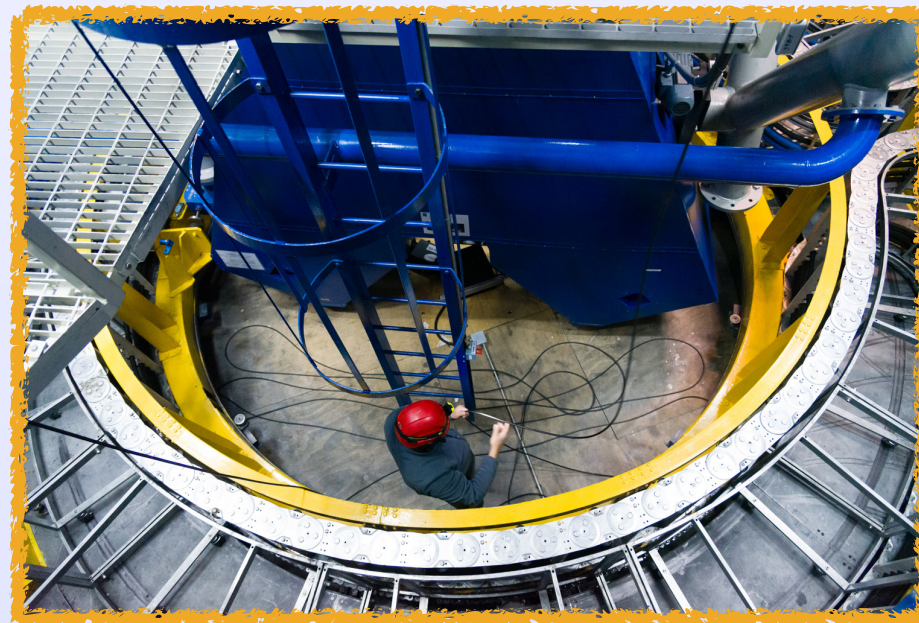
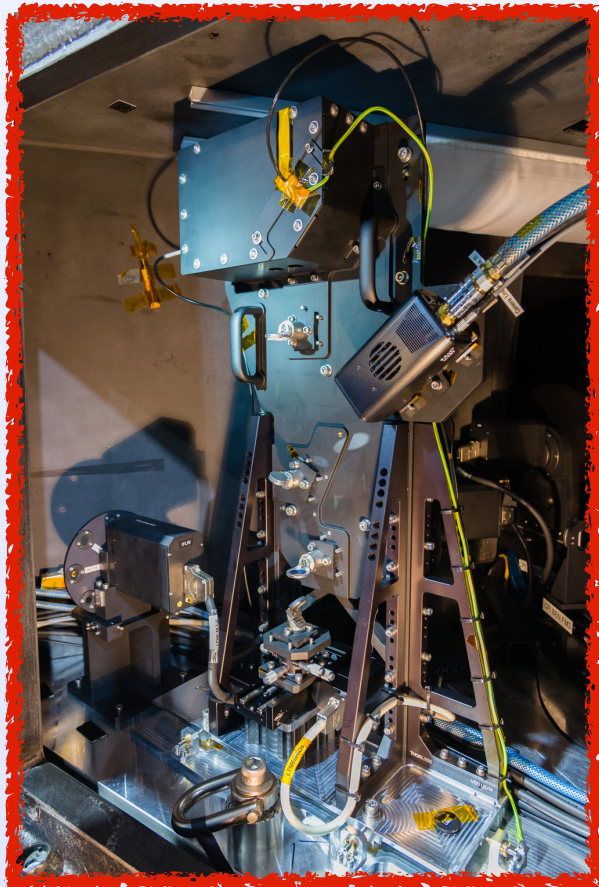
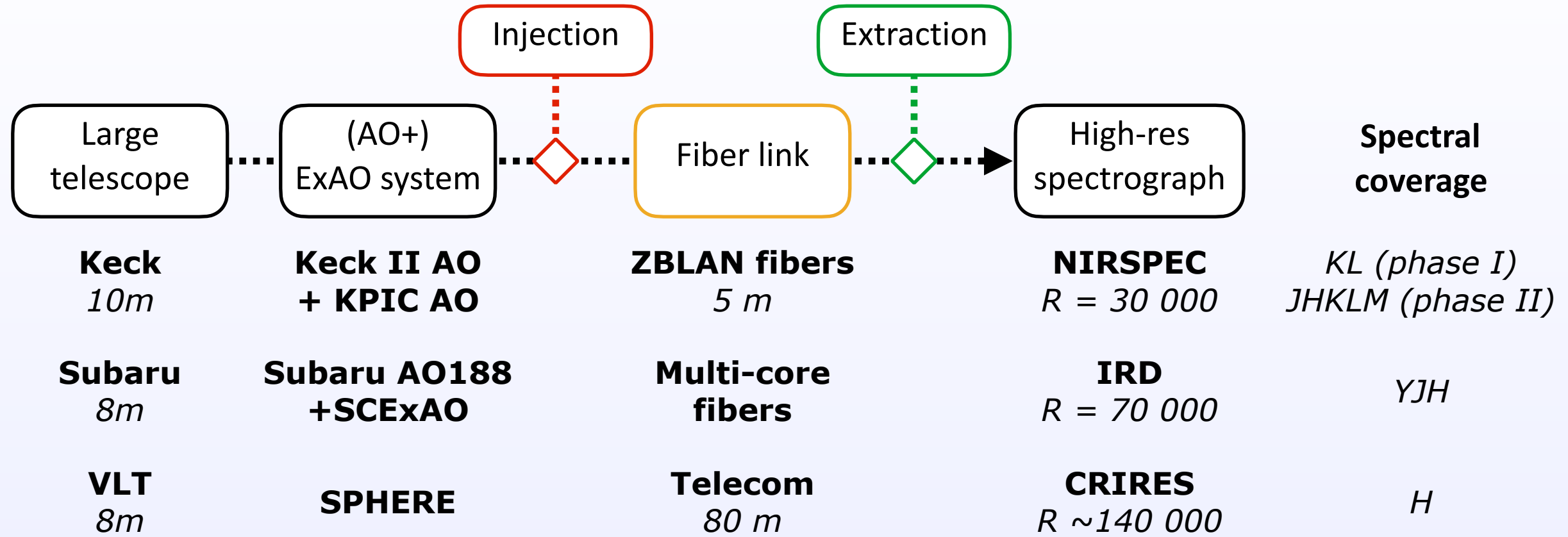
Kotani et al. (2020)
 Delorme et al. (2021)
 Vigan et al. (2024)

Resolved exoplanet spectroscopy in ~2017



Kotani et al. (2020)
Delorme et al. (2021)
Vigan et al. (2024)

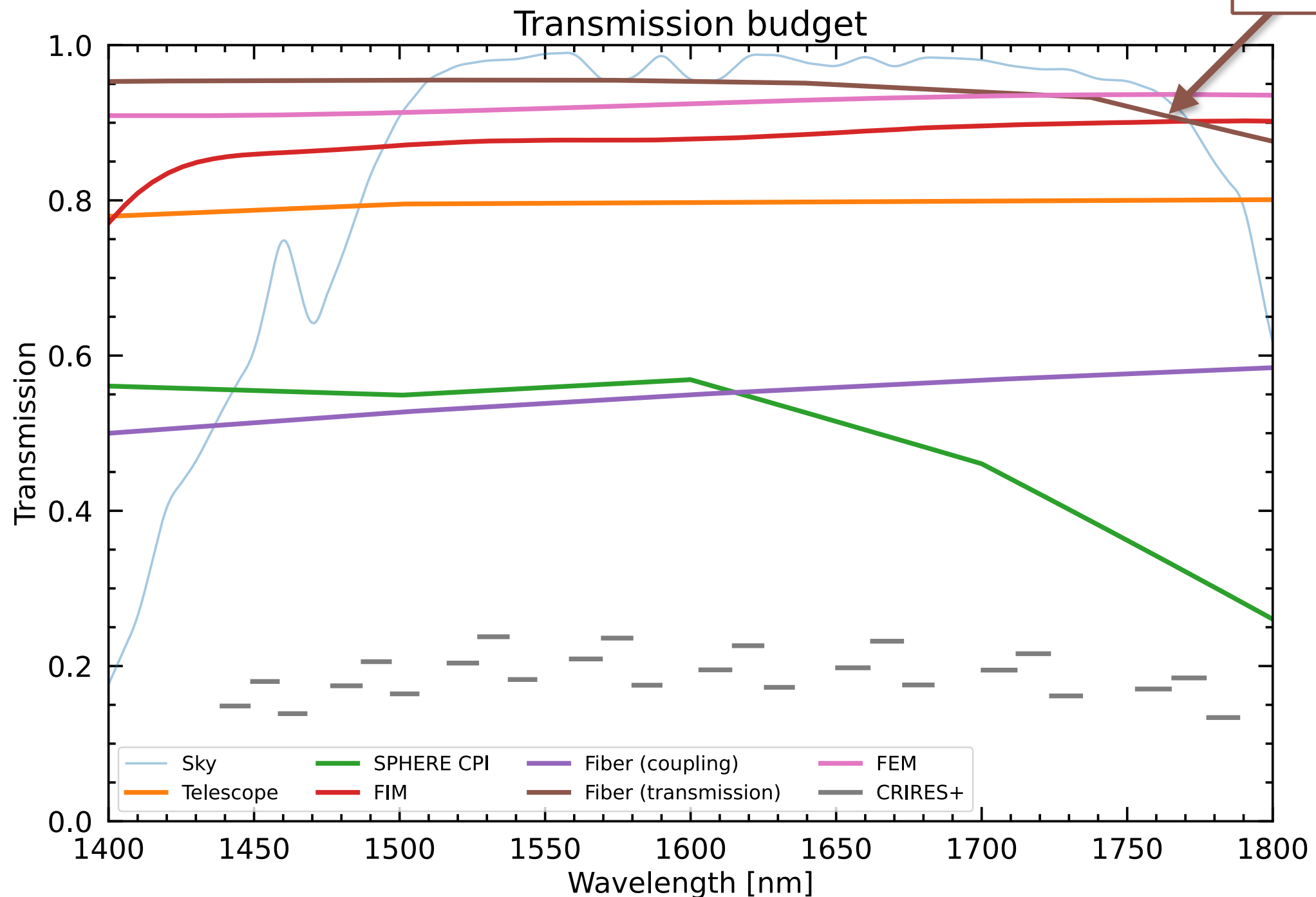
HCI+HRS: First generation of instruments



Kotani et al. (2020)
Delorme et al. (2021)
Vigan et al. (2024)

HCI+HRS: Technical challenges

Overall challenge = end-to-end transmission

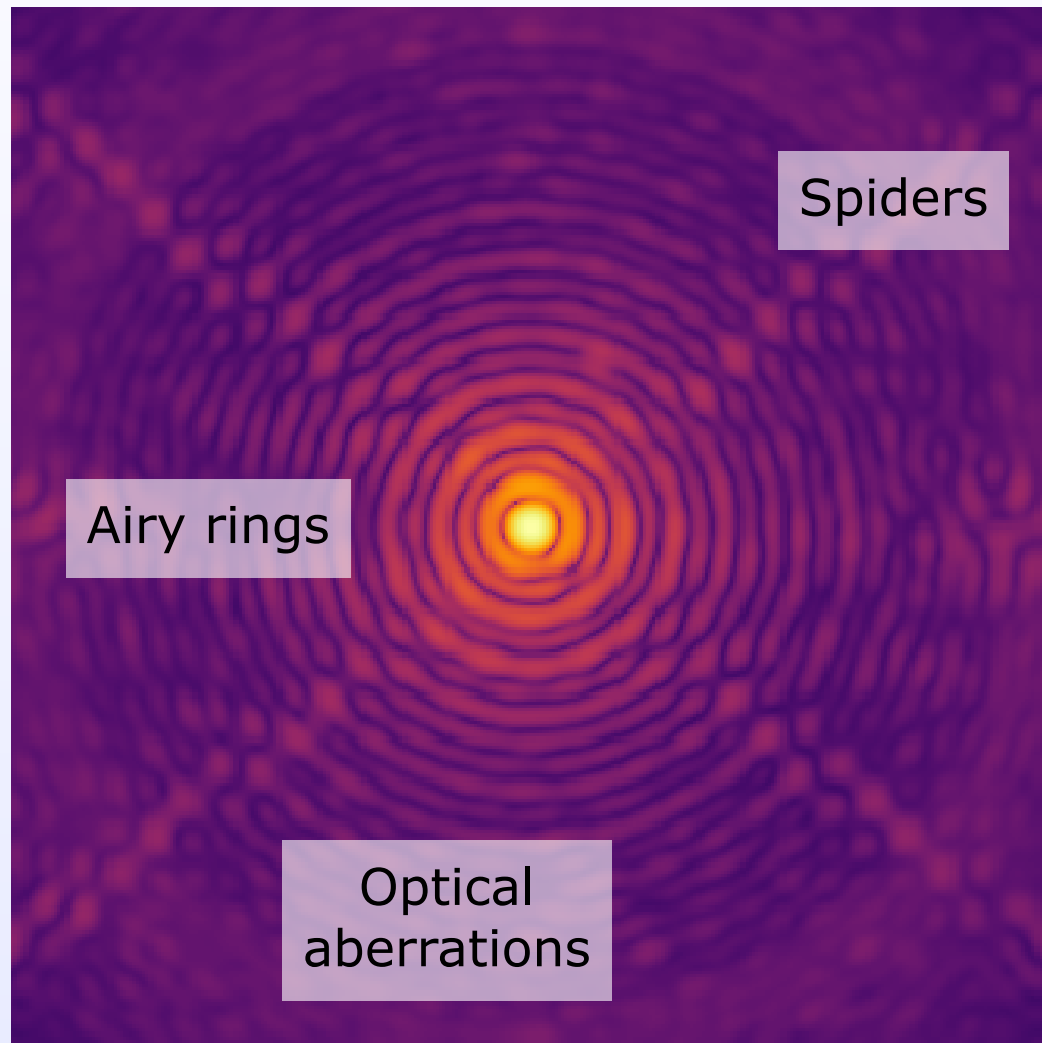


Fibers

Otten et al. (2021)

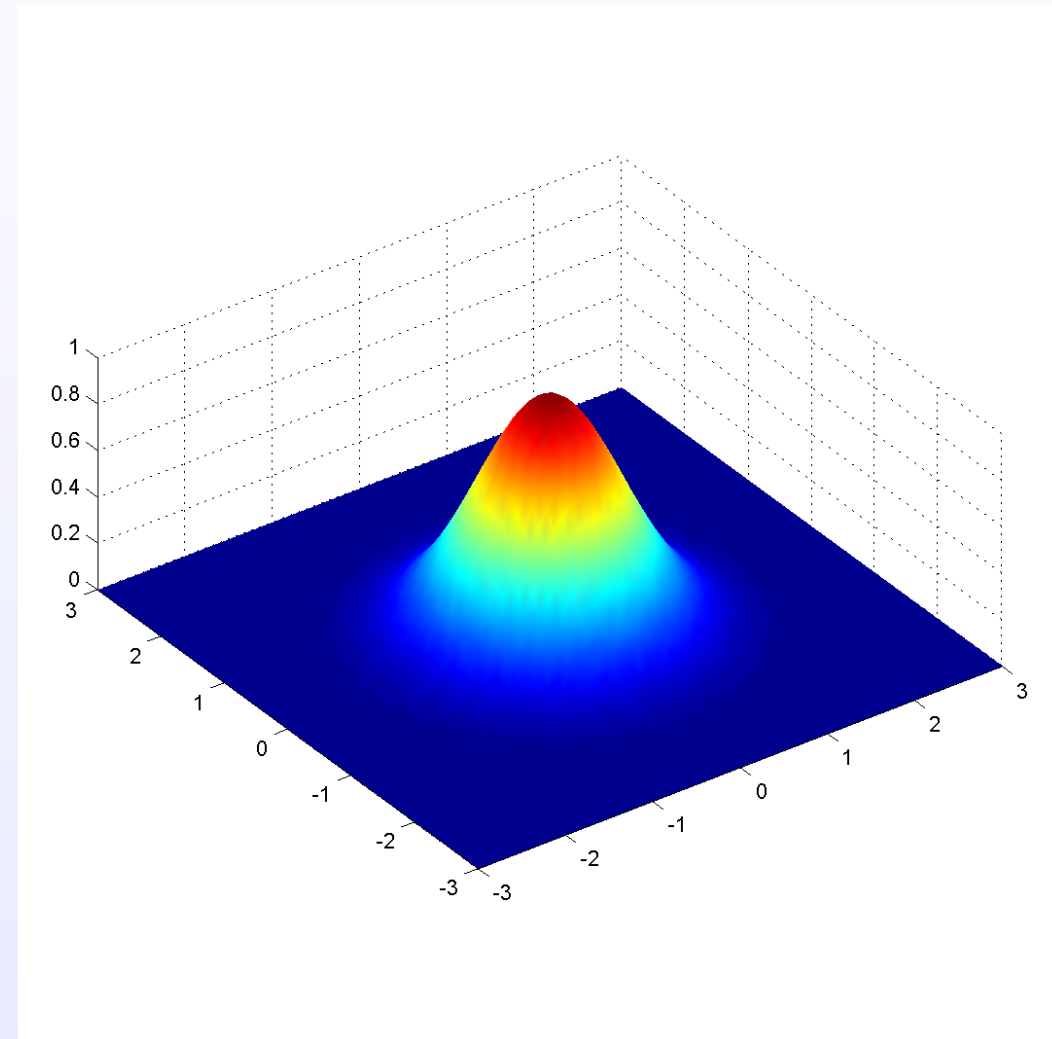
Single-mode fiber coupling

Telescope PSF



- Obstructed pupil + spiders
- Complicated pattern

Single mode fiber



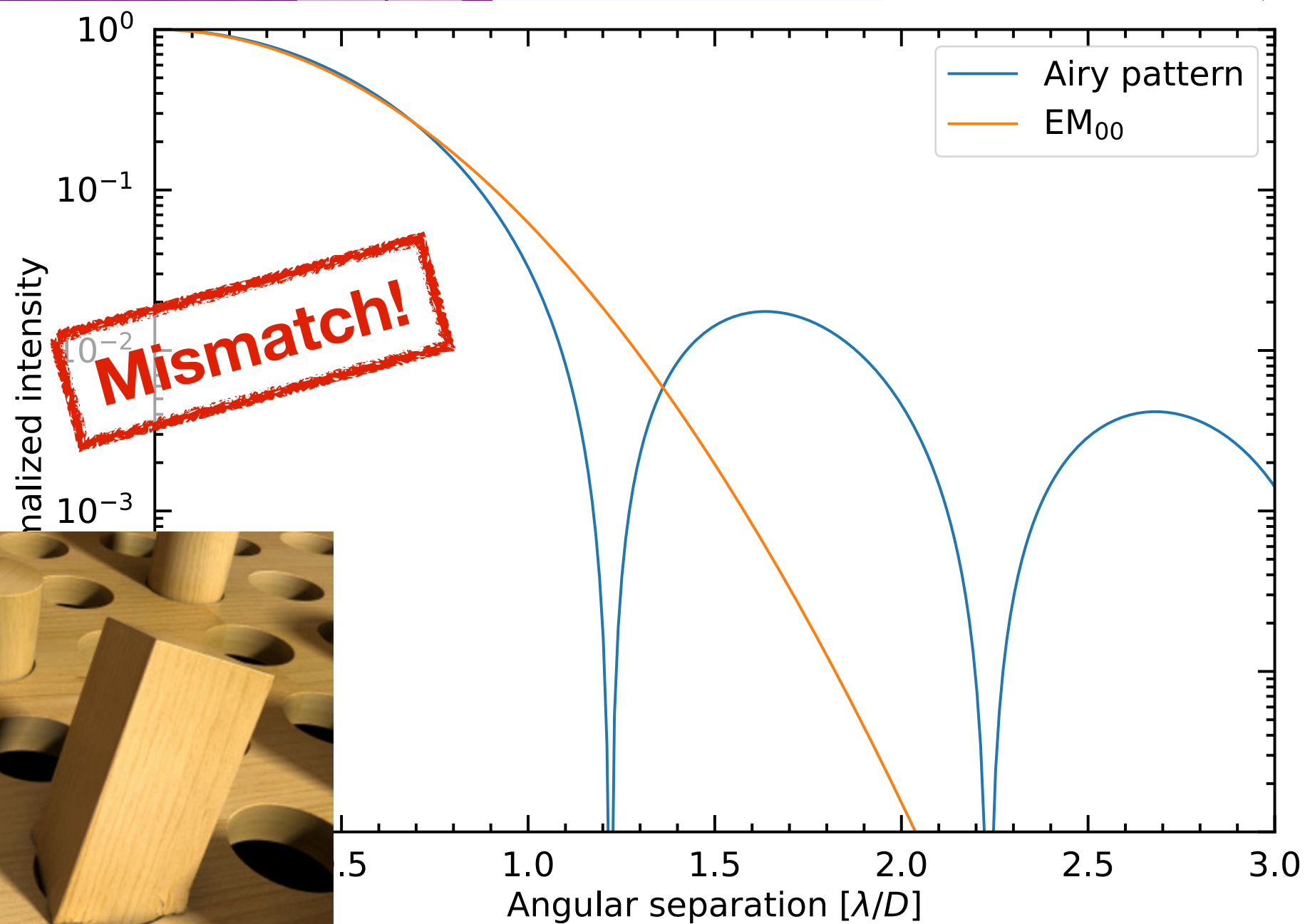
- Quasi-Gaussian EM_{00} mode

Single-mode fiber coupling

Telescope PSF

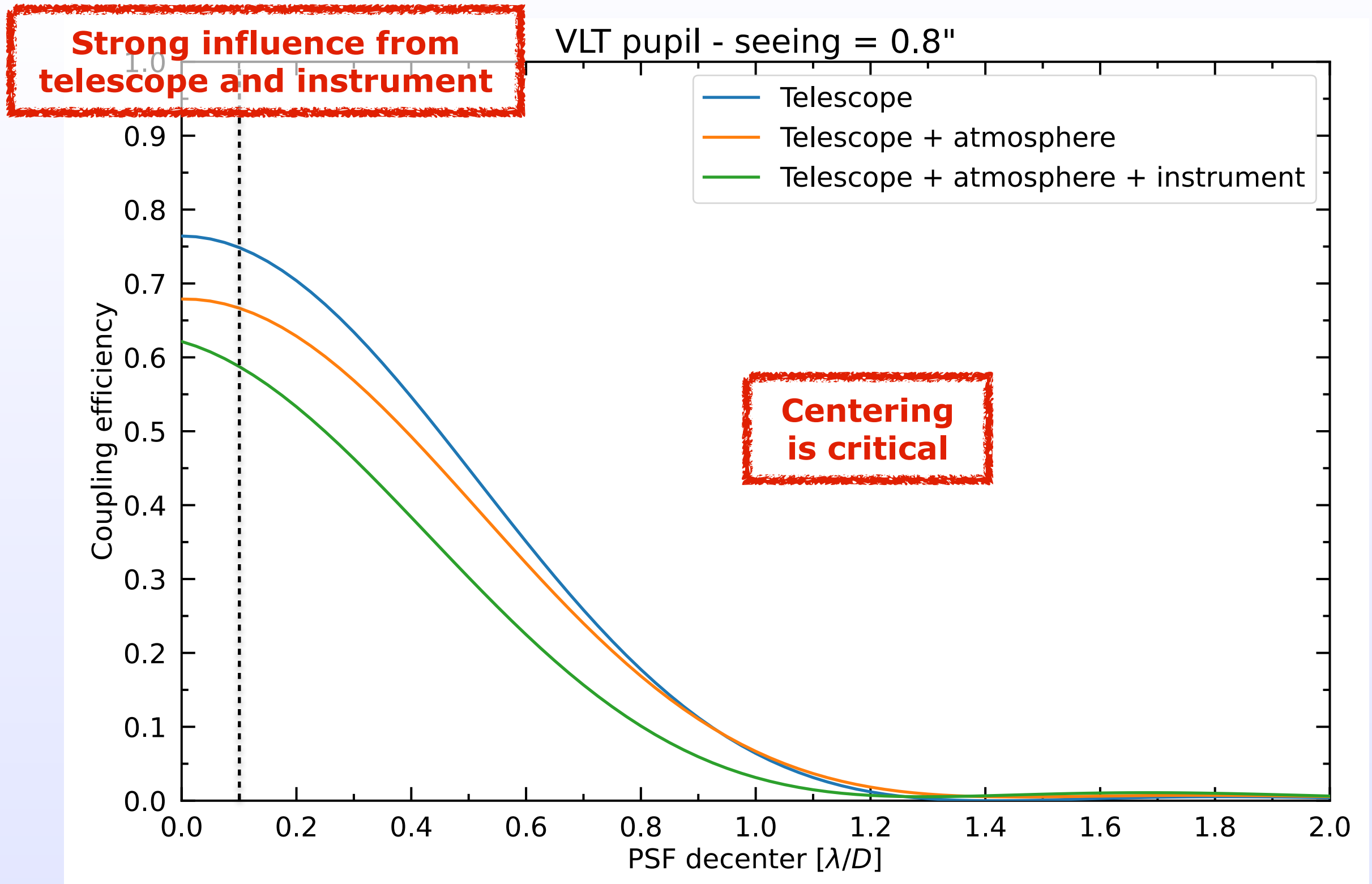
Single mode fiber

Airy rings

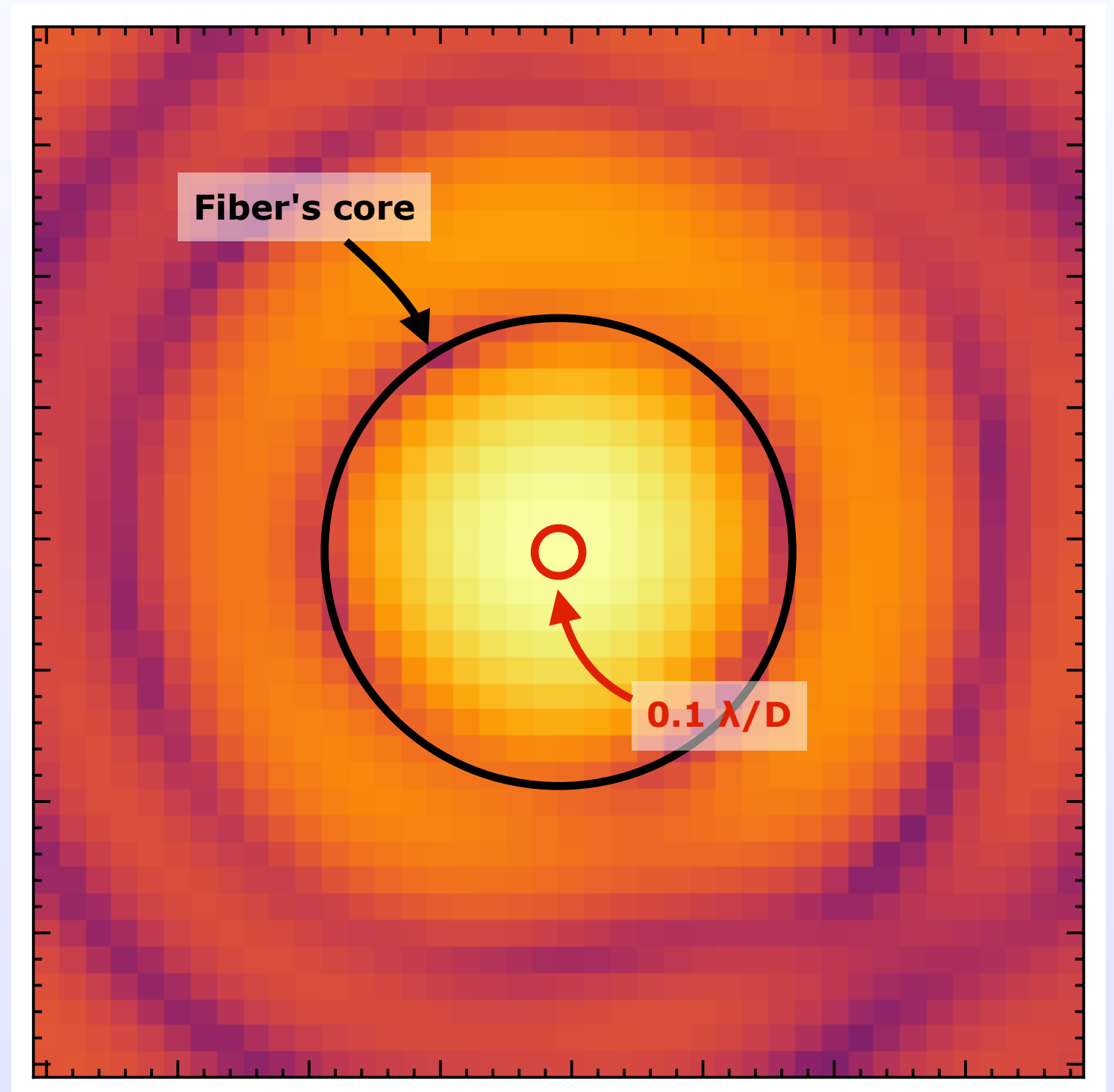
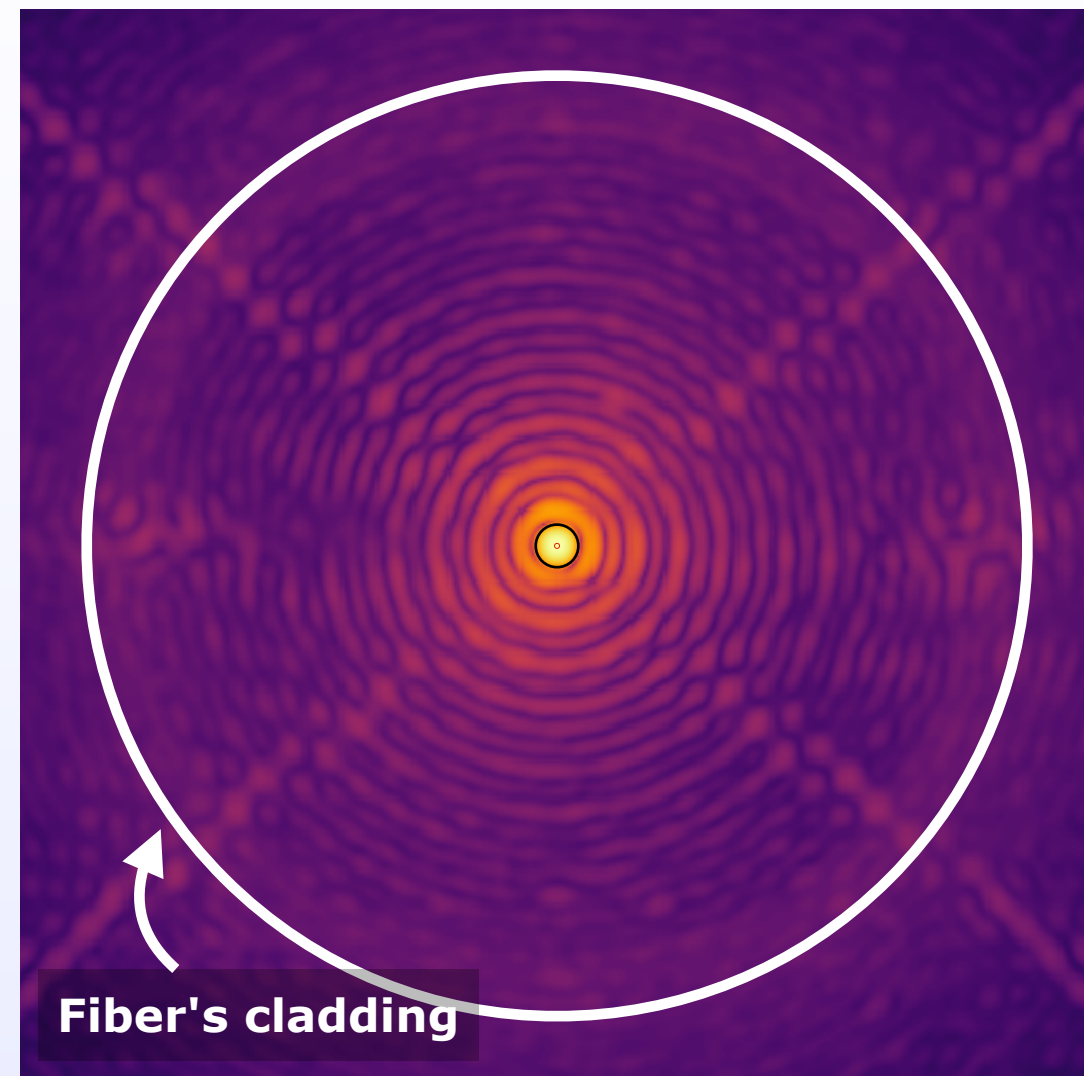


M_{00} mode

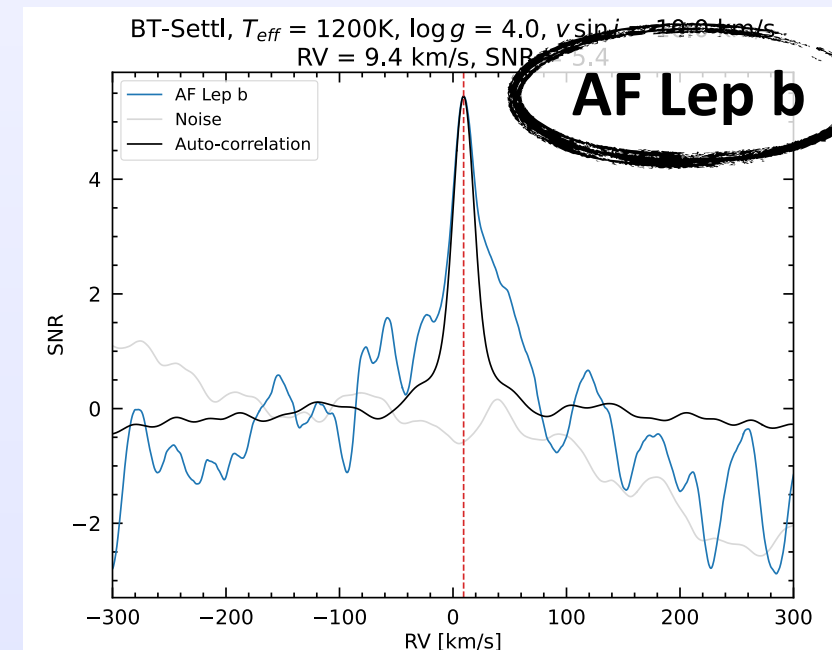
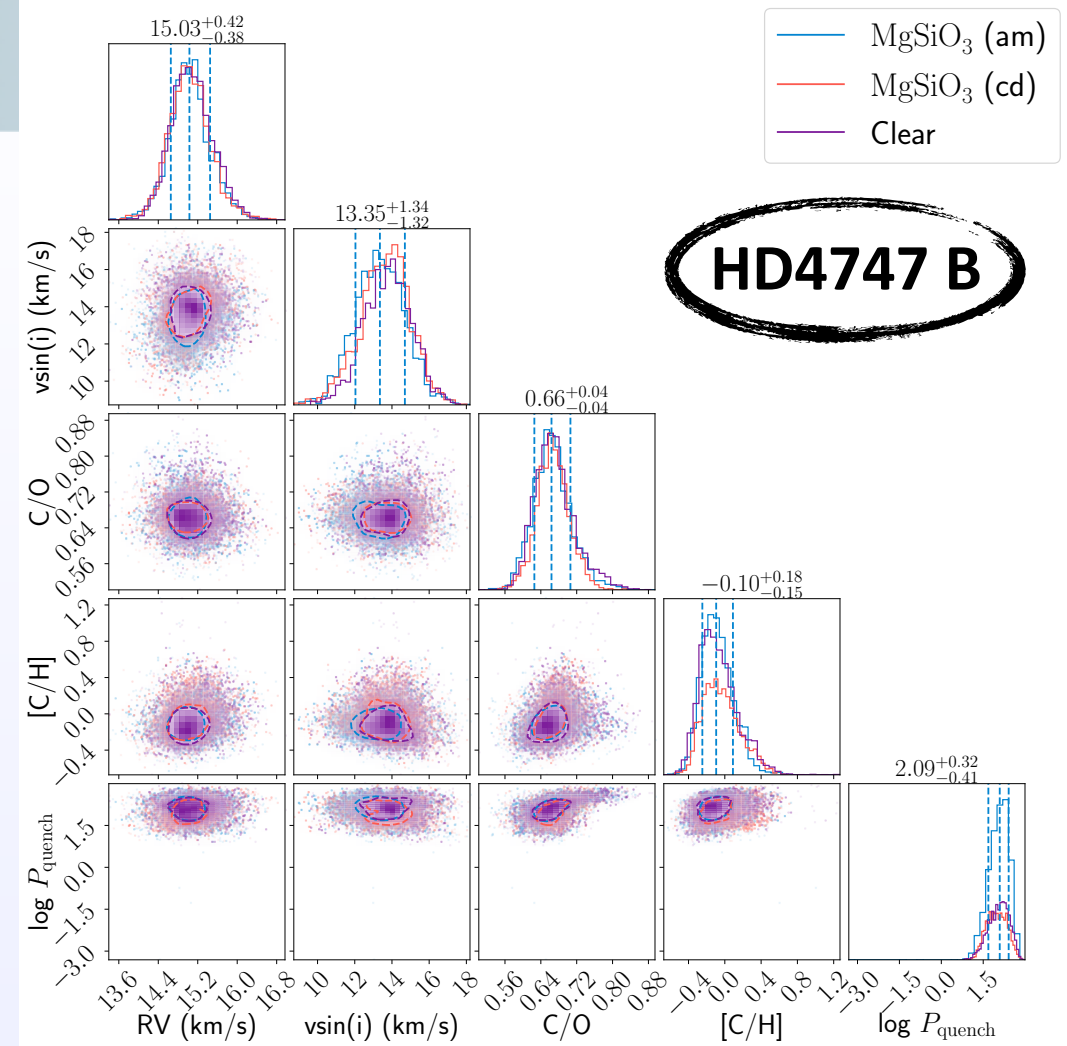
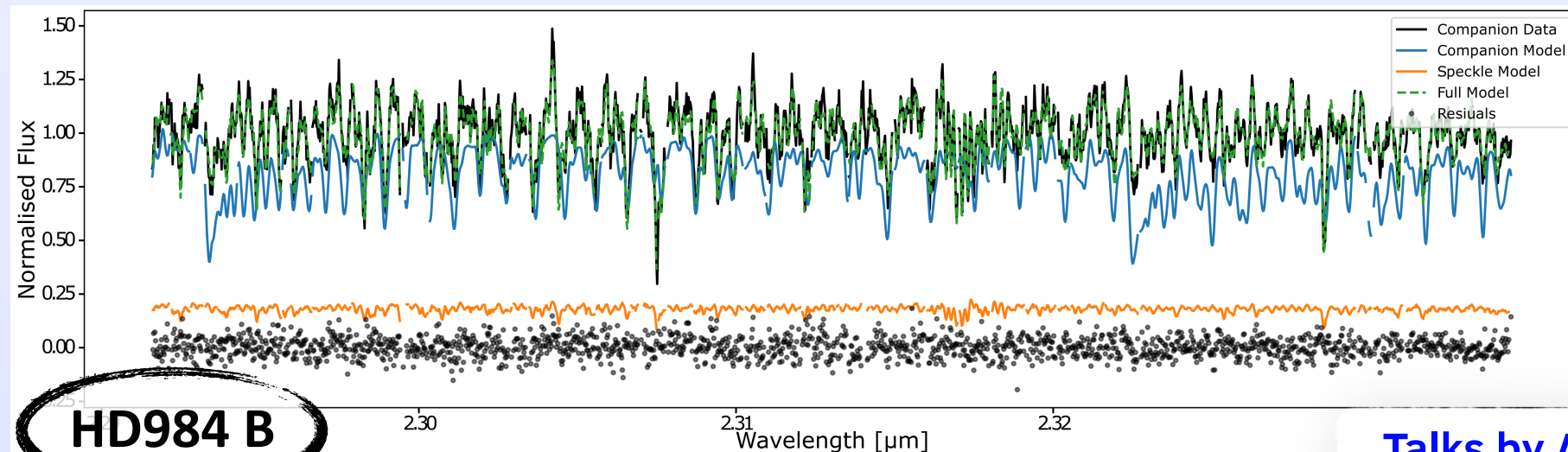
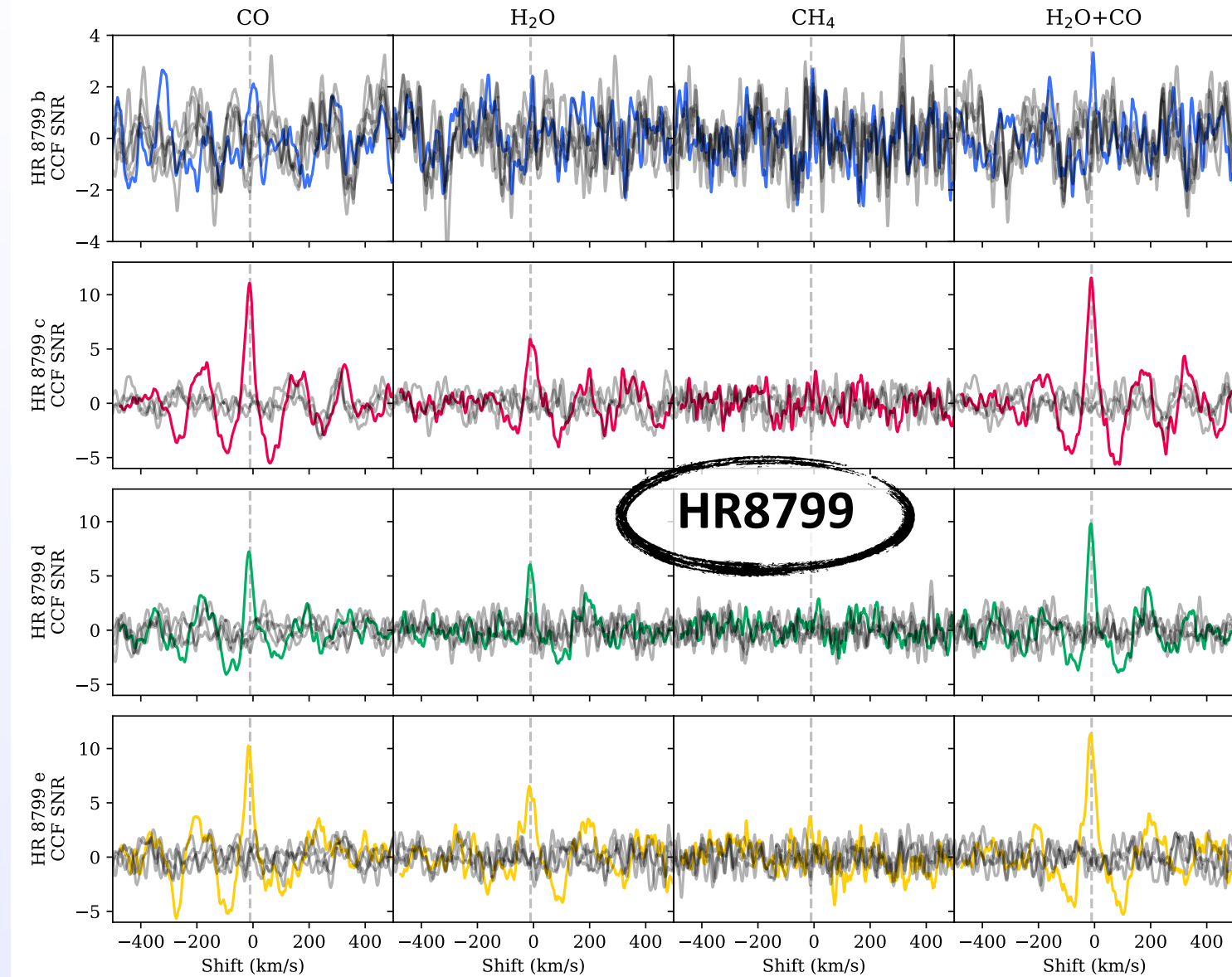
Single-mode fiber coupling



What does $0.1 \lambda/D$ represent?



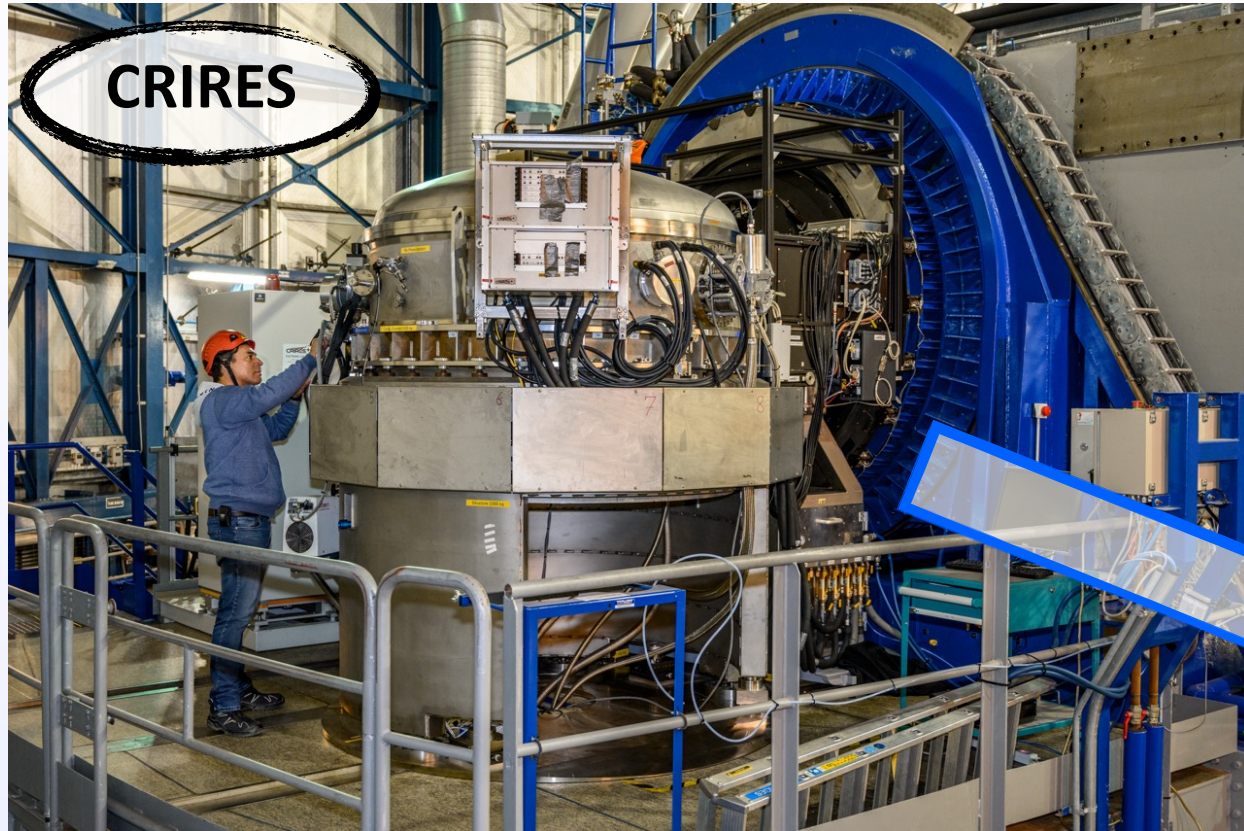
HCI+HRS: First results



Wang et al. (2021)
Xuan et al. (2022, 2024)
Costes et al. (2024)
Denis et al. (in prep.)

Talks by Allan Denis, Jean Costes, Sam de Regt

HCI+HRS: What's next?



Slit-fed seeing limited spectrograph

7 m³, 6 tons

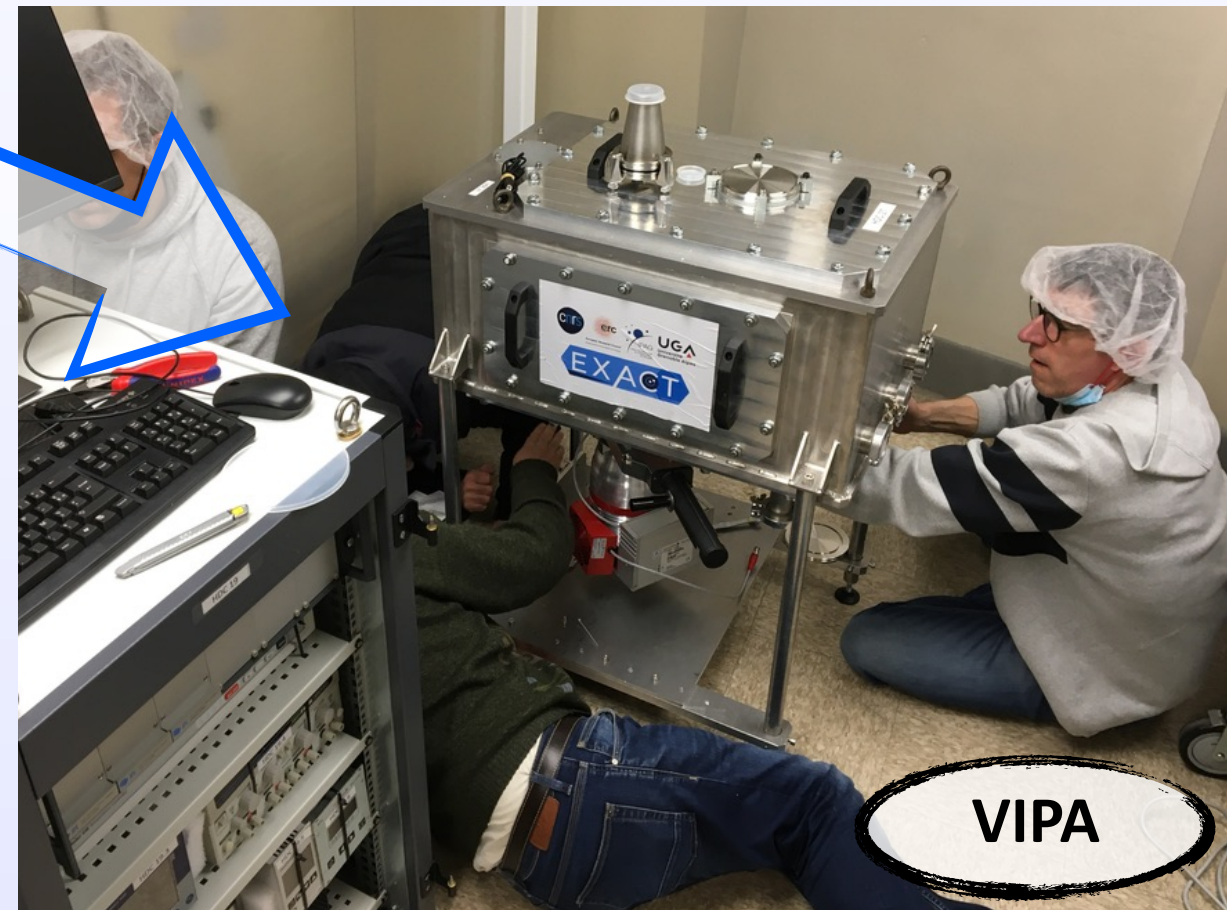
R = 100 000

11" slit

50% of H band with 3 Hawaii-2RG detectors

Transmission: ~20% in H band

Compact spectrographs!



Monomode diffraction-limited spectrograph

0.2 m³, 0.05 tons

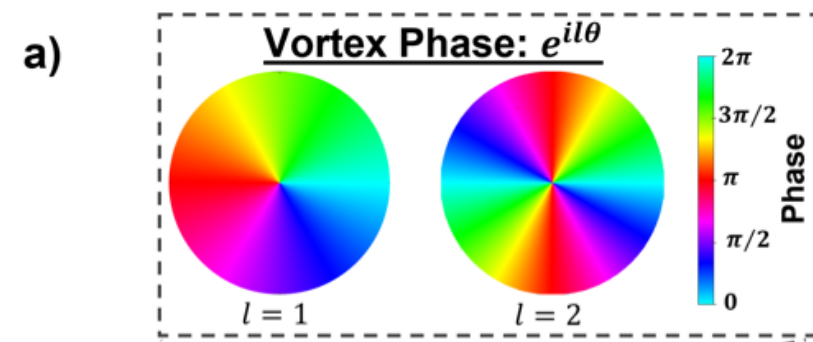
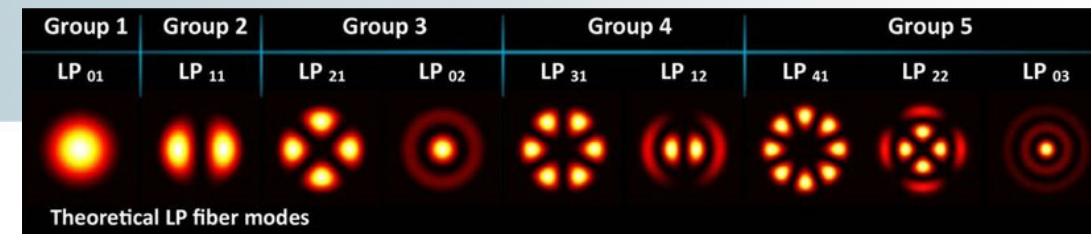
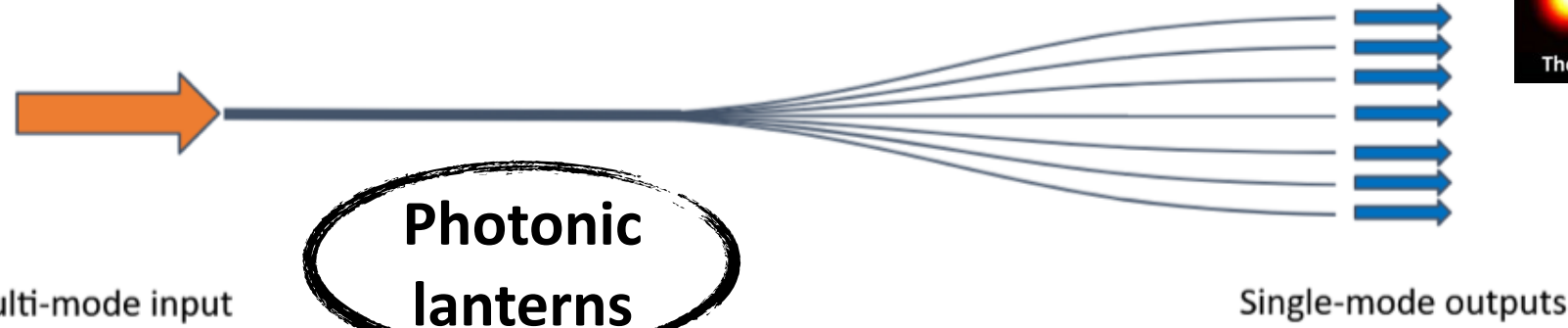
R = 80 000

1 λ/D spaxel

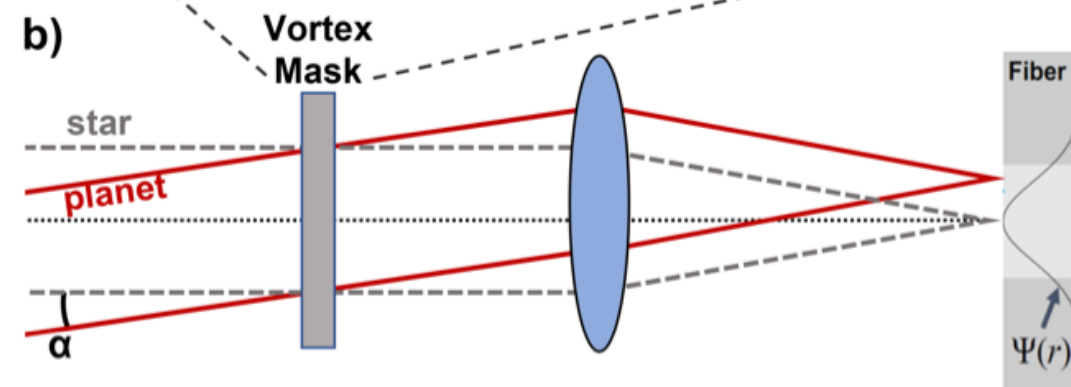
100% of H band with 1 Hawaii-2RG detector

Transmission: ~50% in H band

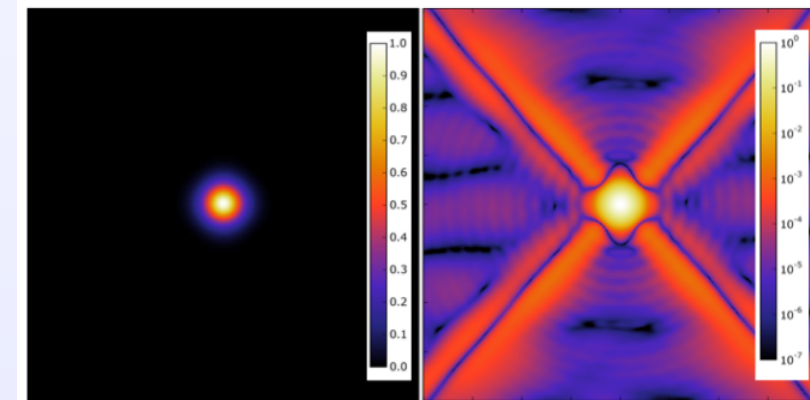
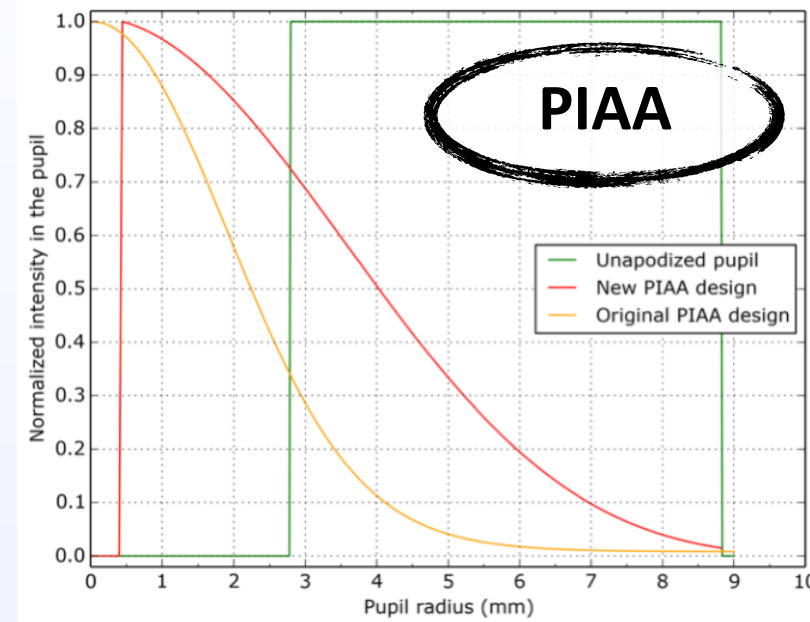
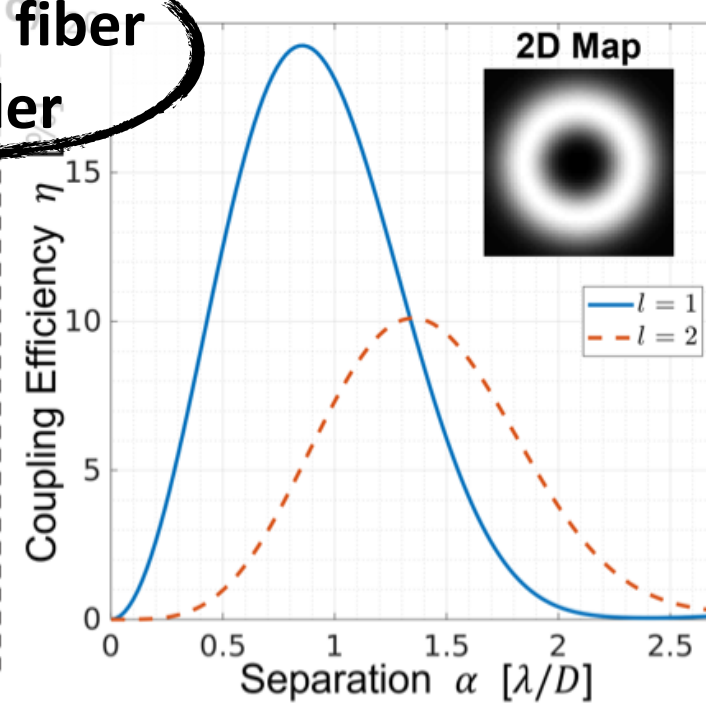
HCI+HRS: What's next?



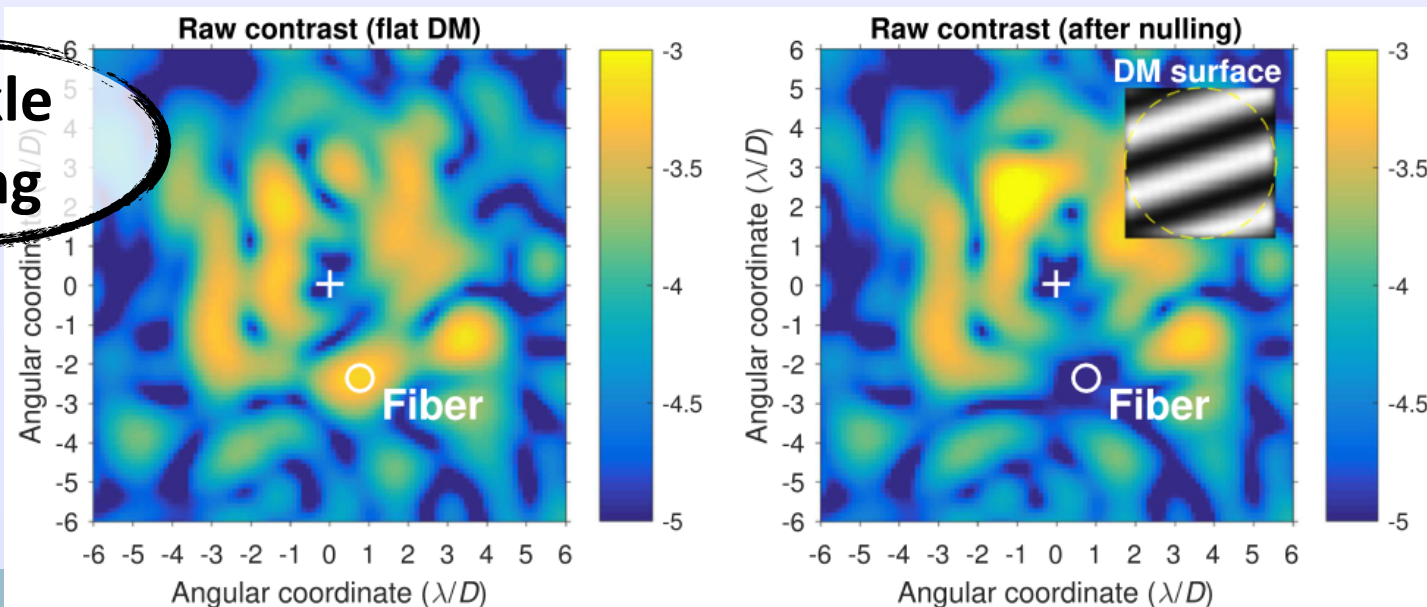
Vortex fiber nuller



Companion Coupling Efficiency Into Fiber



Speckle nulling



- Lallemant et al. (2023)
- Ruane et al. (2018, 2019)
- Echeverri et al. (2019, 2023)
- Guyon (2003)
- Jovanovic et al. (2017)
- Mawet et al. (2017)
- Xin et al. (2023)

Upcoming facility instrumentation

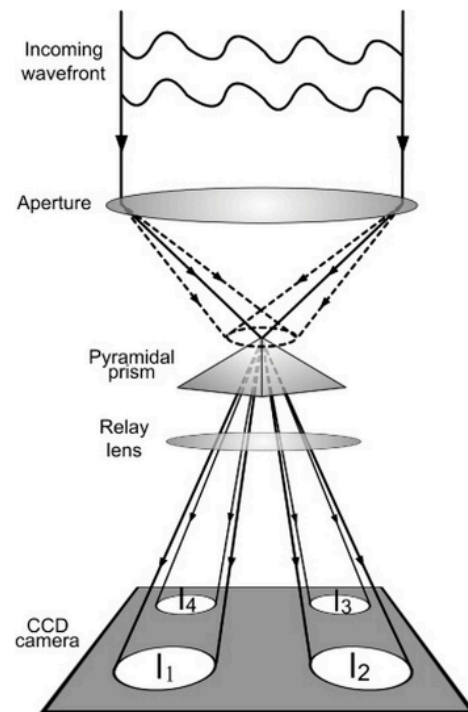
- KPIC phase II → better AO, wider spectral coverage, increase transmission, ...
- VLT/ASGARD/BIFROST → $R = 25\,000$ around He I, Pa β , Pa γ
- SAXO+ → 2nd stage AO in SPHERE, will benefit HiRISE
- HISPEC → new fiber-fed spectro for Keck II, with KPIC-like capabilities
- RISTRETTO → visible ExAO for Proxima Cen b (visitor instrument for VLT)

Upcoming facility instrumentation

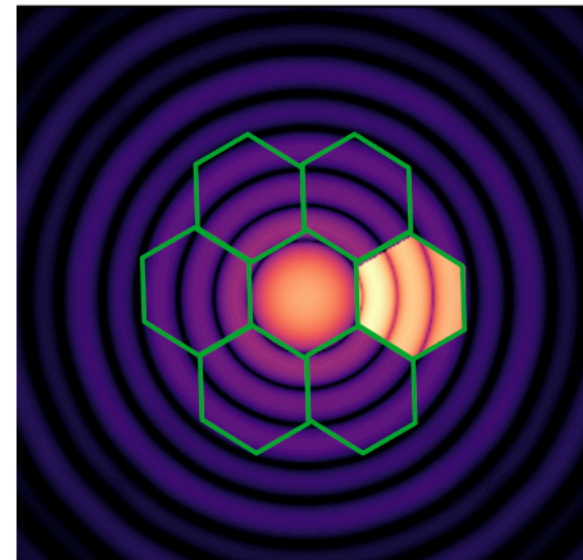
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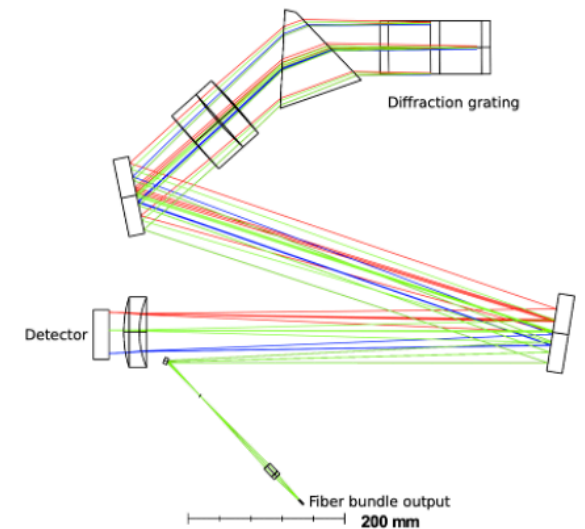
VLT-UTx
8-m primary mirror



XAO system based on near-IR
Pyramid wavefront sensor



7-spaxel coronagraphic
IFU & single-mode fibers



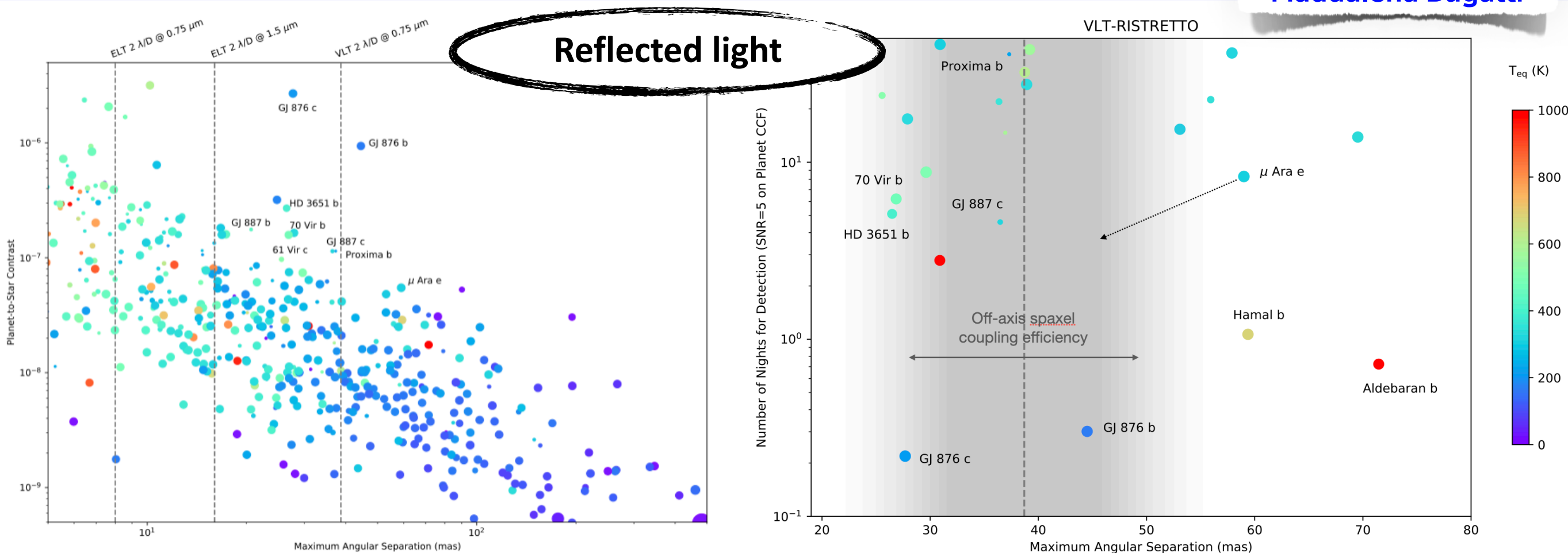
Visible high-resolution
spectrograph

Lovis et al. (2016)
Lovis et al. (2022)
Chazelas et al. (2024)

Upcoming facility instrumentation

- KPIC phase II → better AO, wider spectral coverage, increase transmission, ...
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Talk by
Maddalena Bugatti



→ Spectrograph in procurement phase, but still a long way to go for the AO...

Lovis et al. (2016)
Lovis et al. (2022)
Chazelas et al. (2024)

ELT instrumentation

What's next?



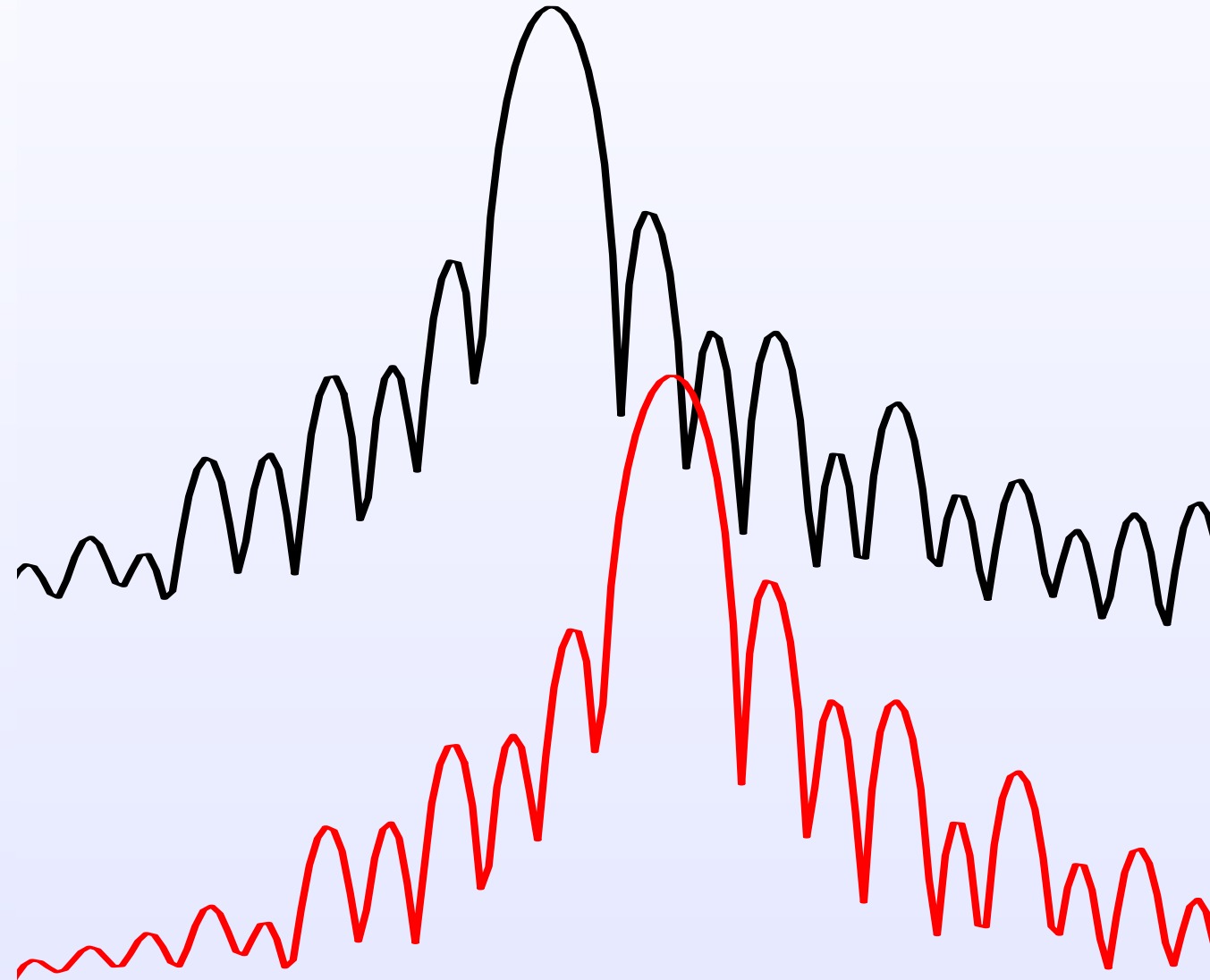
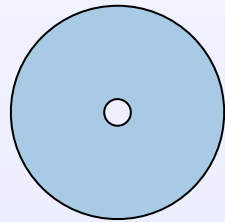
What's next?



European ELT instrumentation

- Geometrical gain just because of telescope diameter: x4-5 for "free"

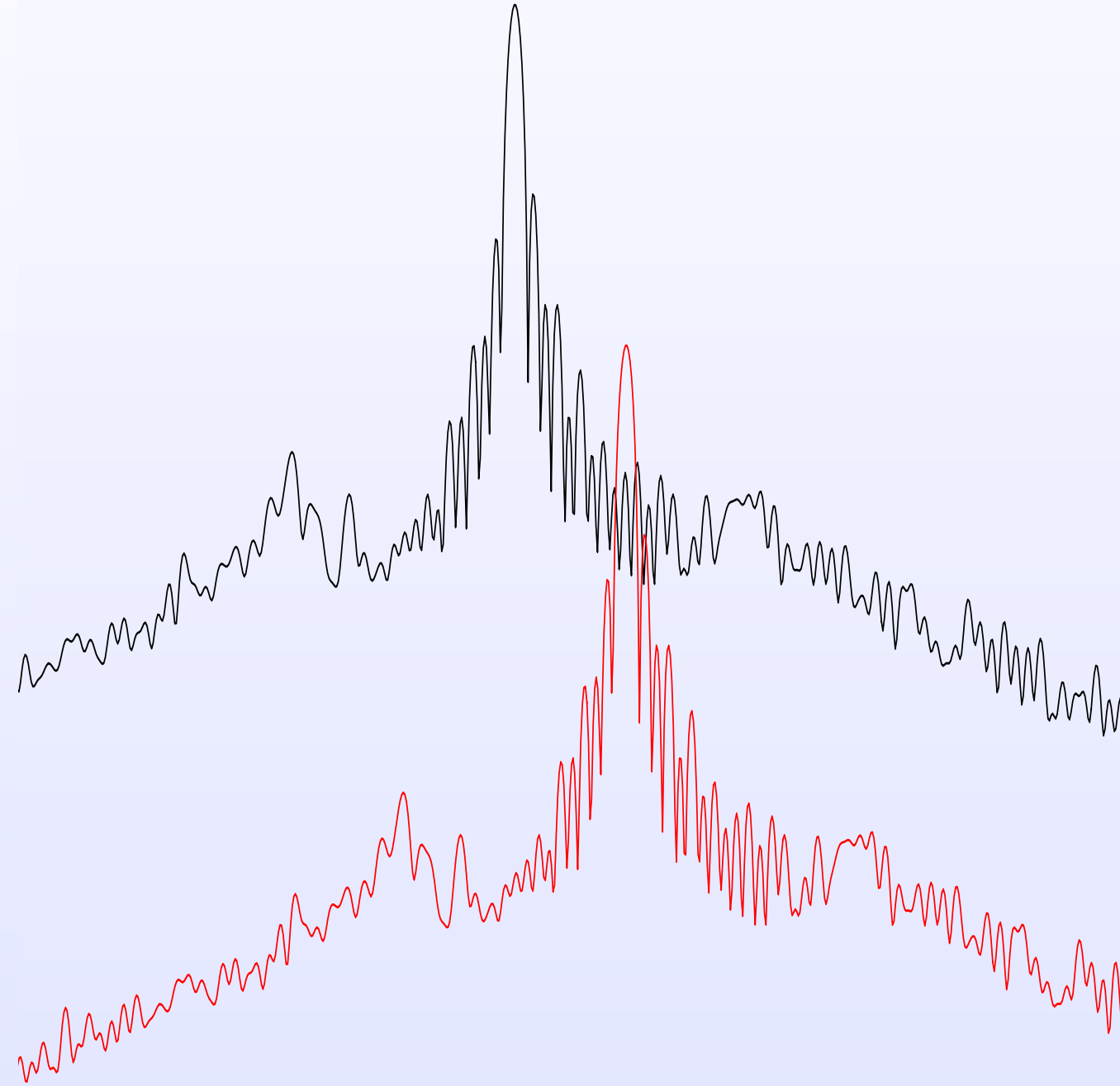
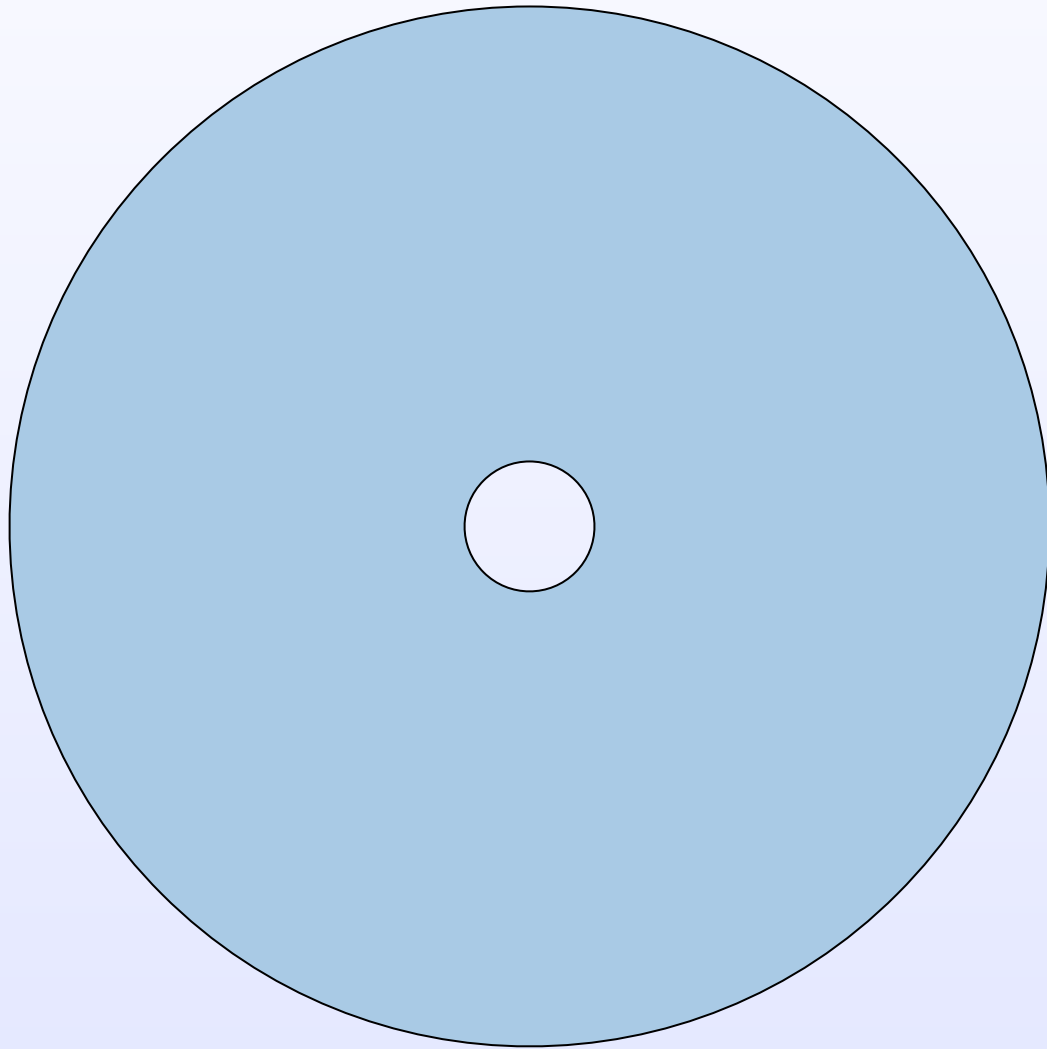
8 m



European ELT instrumentation

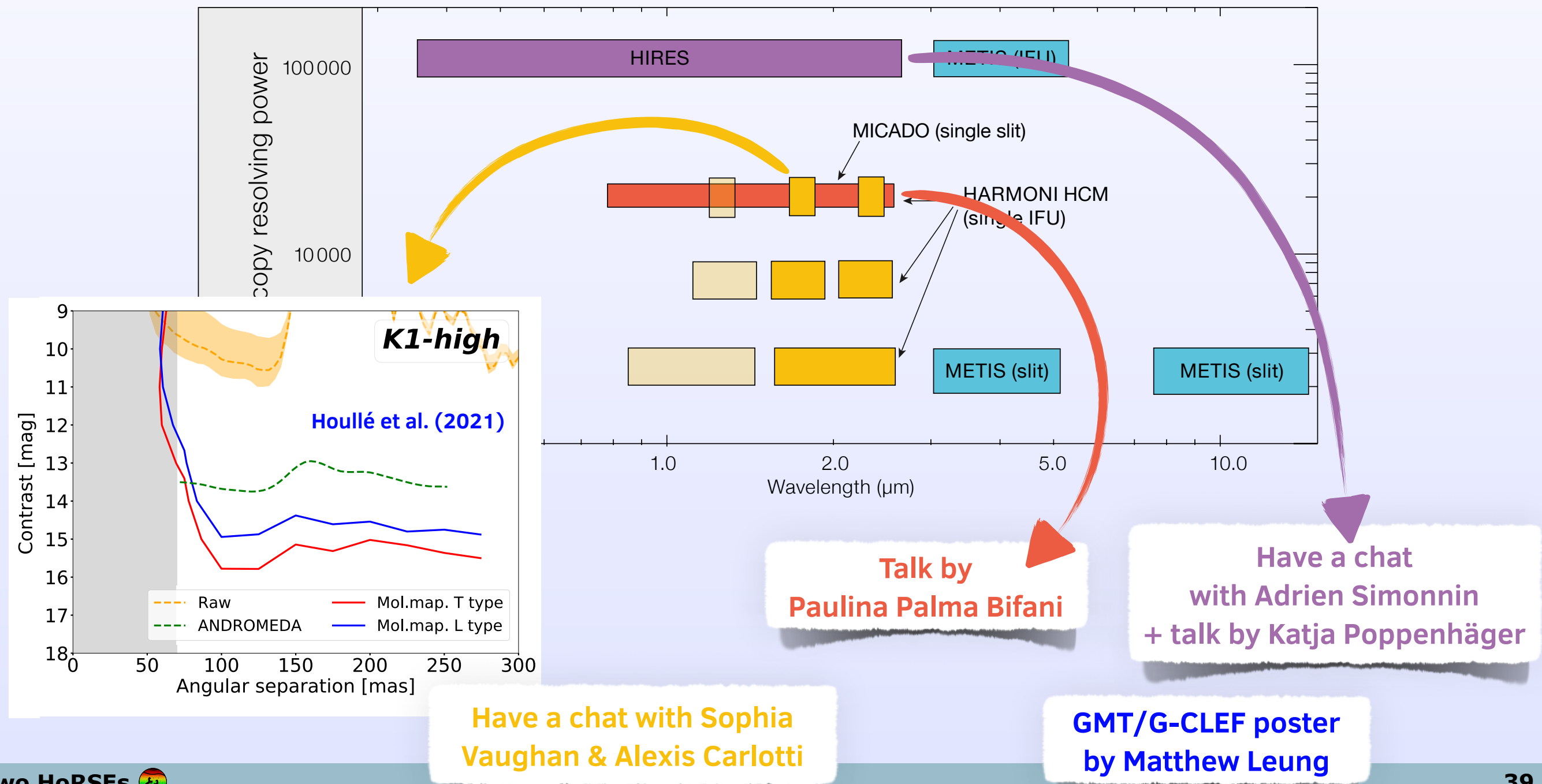
- Geometrical gain just because of telescope diameter: x4-5 for "free"

39 m



European ELT instrumentation

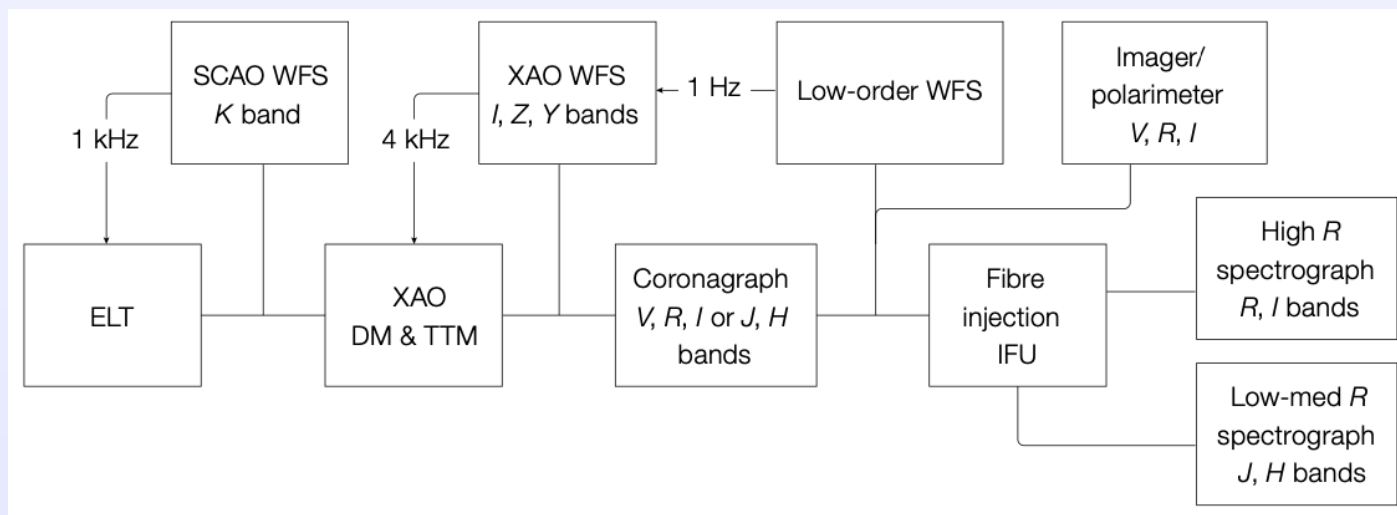
- Geometrical gain just because of telescope diameter: x4-5 for "free"
- European ELT
 - AO by default!
 - All instruments include spectroscopic capabilities + some high-contrast



European ELT instrumentation

- Geometrical gain just because of telescope diameter: x4-5 for "free"
- European ELT
 - AO by default!
 - All instruments include spectroscopic capabilities + some high-contrast
- Planetary Camera & Spectrograph (2nd generation)
 - Extreme AO + coronagraphy
 - 0.6-1.8 μm @ $R = 5, 10\,000$ (IFU), 100 000 (fiber-fed)
 - Still a lot of R&D to make this real!

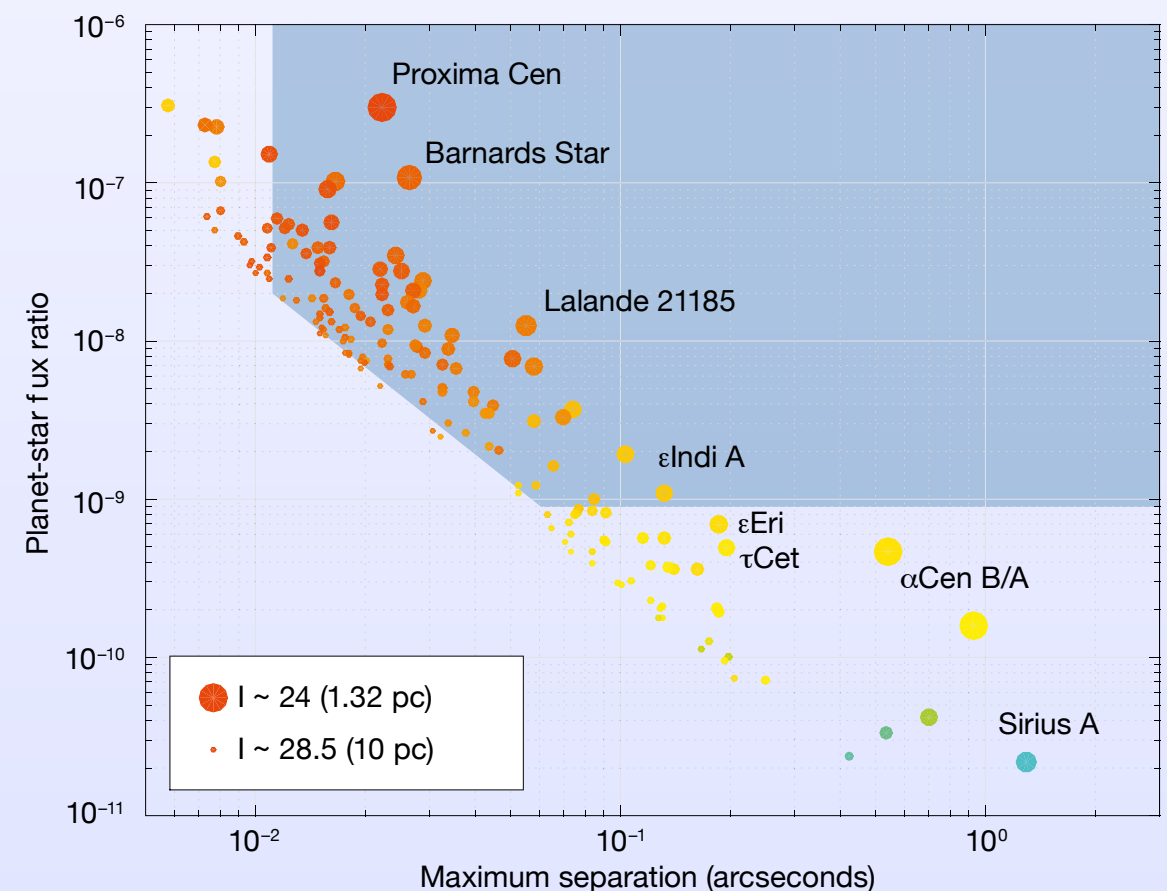
Talk by
Giulia Roccetti



With 20h observations:

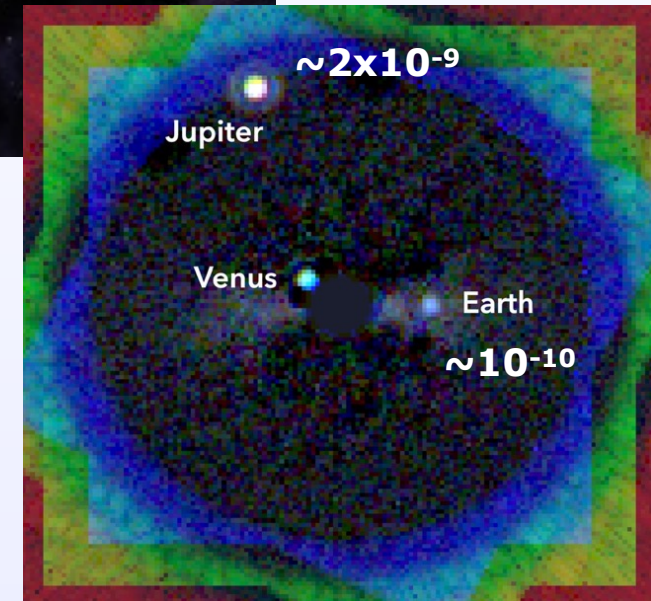
→ ~10 Earths, >20 Neptunes, >70 Jupiters

Kammerer et al. (in prep.)



What about space?

- Star: G2V @ 10 pc, $V=4.8$
- Planet: 10^{-10} contrast
- Telescope + instrument:
 - 6m, unobstructed pupil
 - 30% transmission
- $T_{\text{exp}} = 1$ day



How many photons per bin at $R = 100\,000$ in reflected light in V band?

~ 0.5 photons/day 🥲

But do we really need $R = 100\,000$ in space for telluric planets?

**What kind of future high-resolution
instrumentation do we need? For what science?**

Thanks for your attention