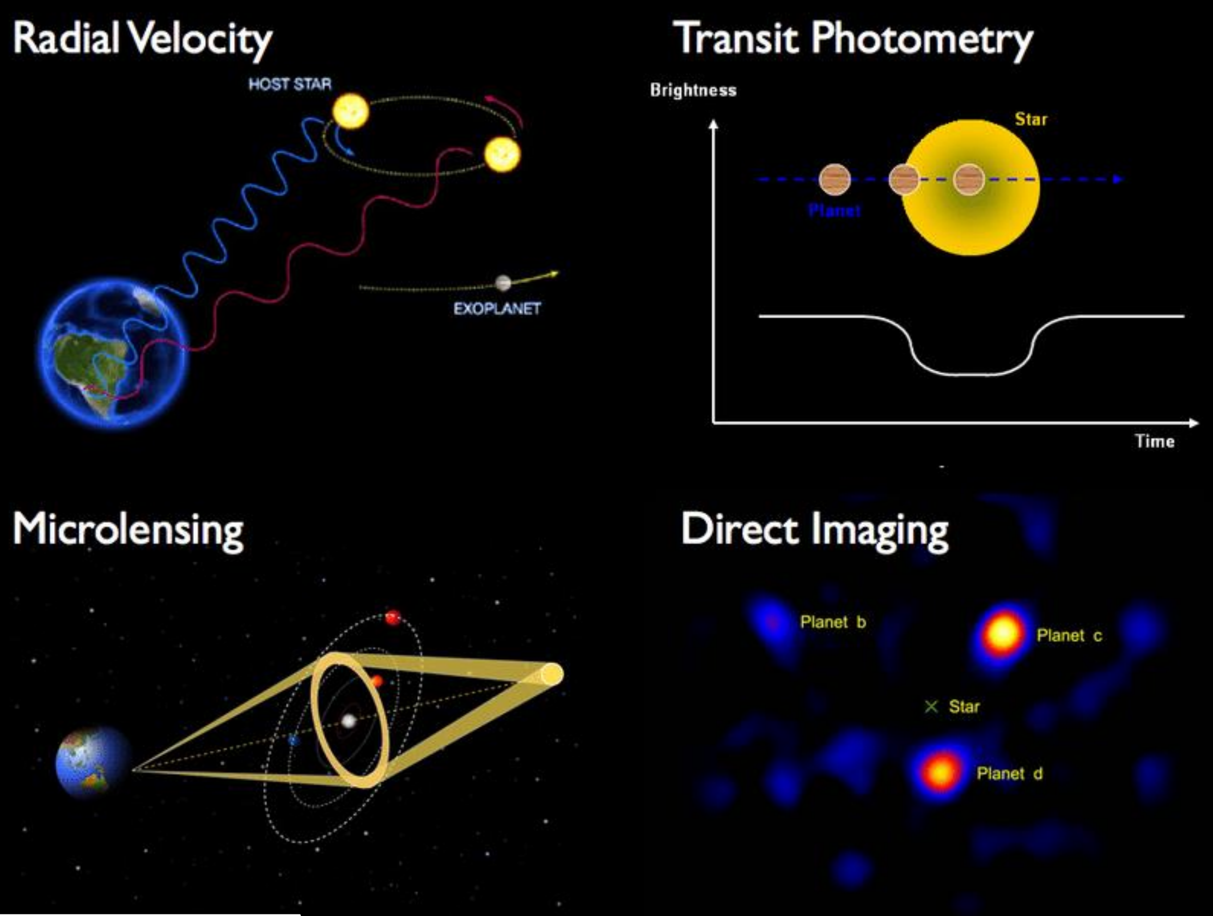
MKIDs: A novel detector technology for high-contrast imaging of exoplanets

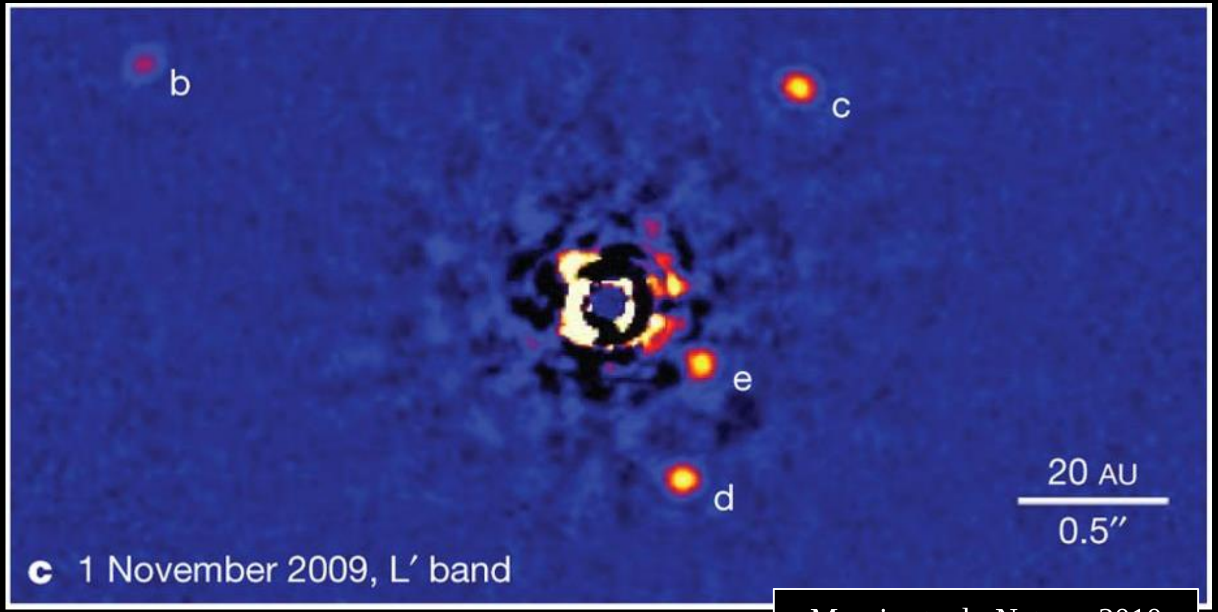
September 2nd 2019

Gerhard Ulbricht

Dublin Institute for Advanced Studies, School of Cosmic Physics, Dublin, Ireland

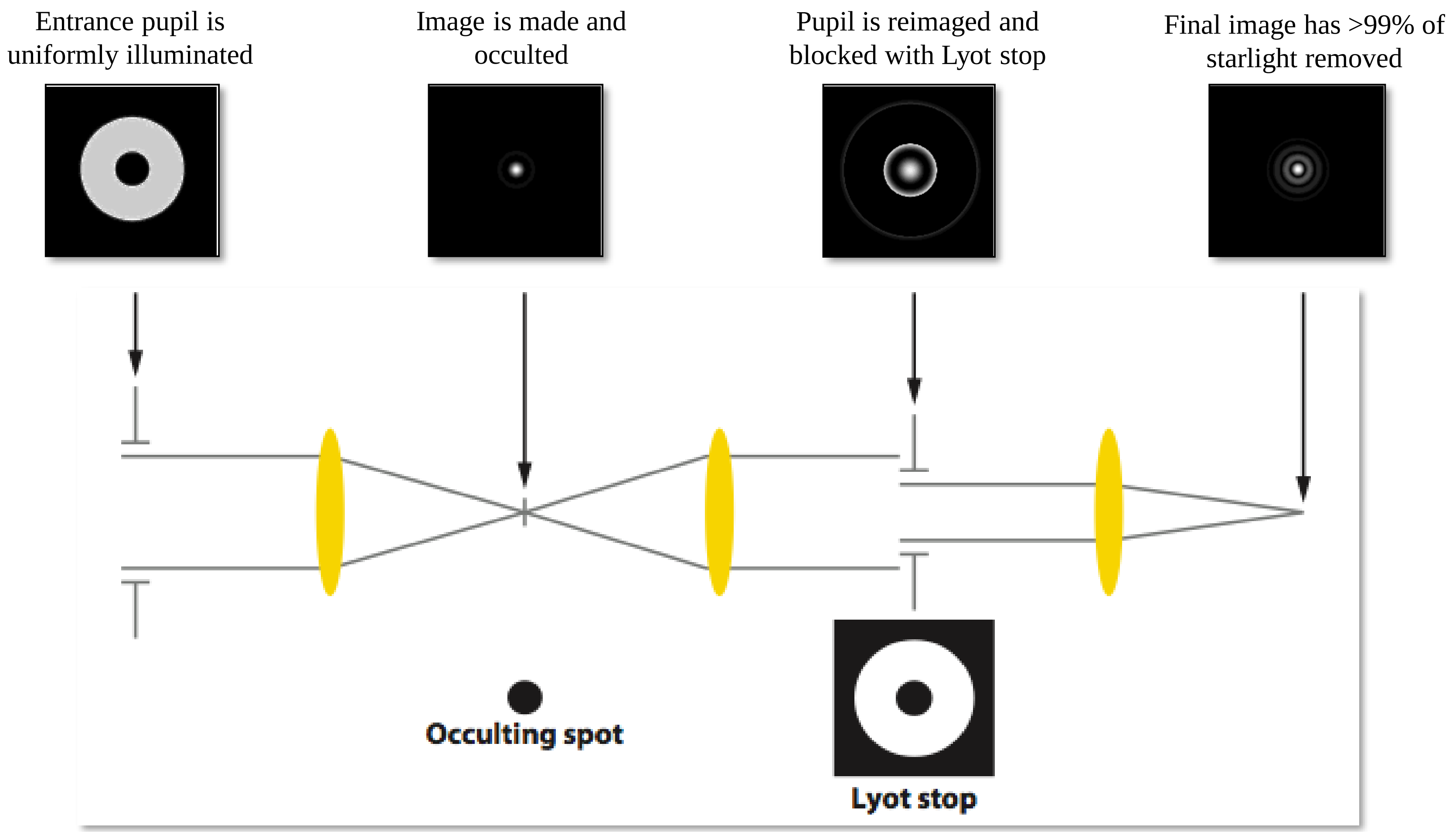


NASA Ames / N. Batalha



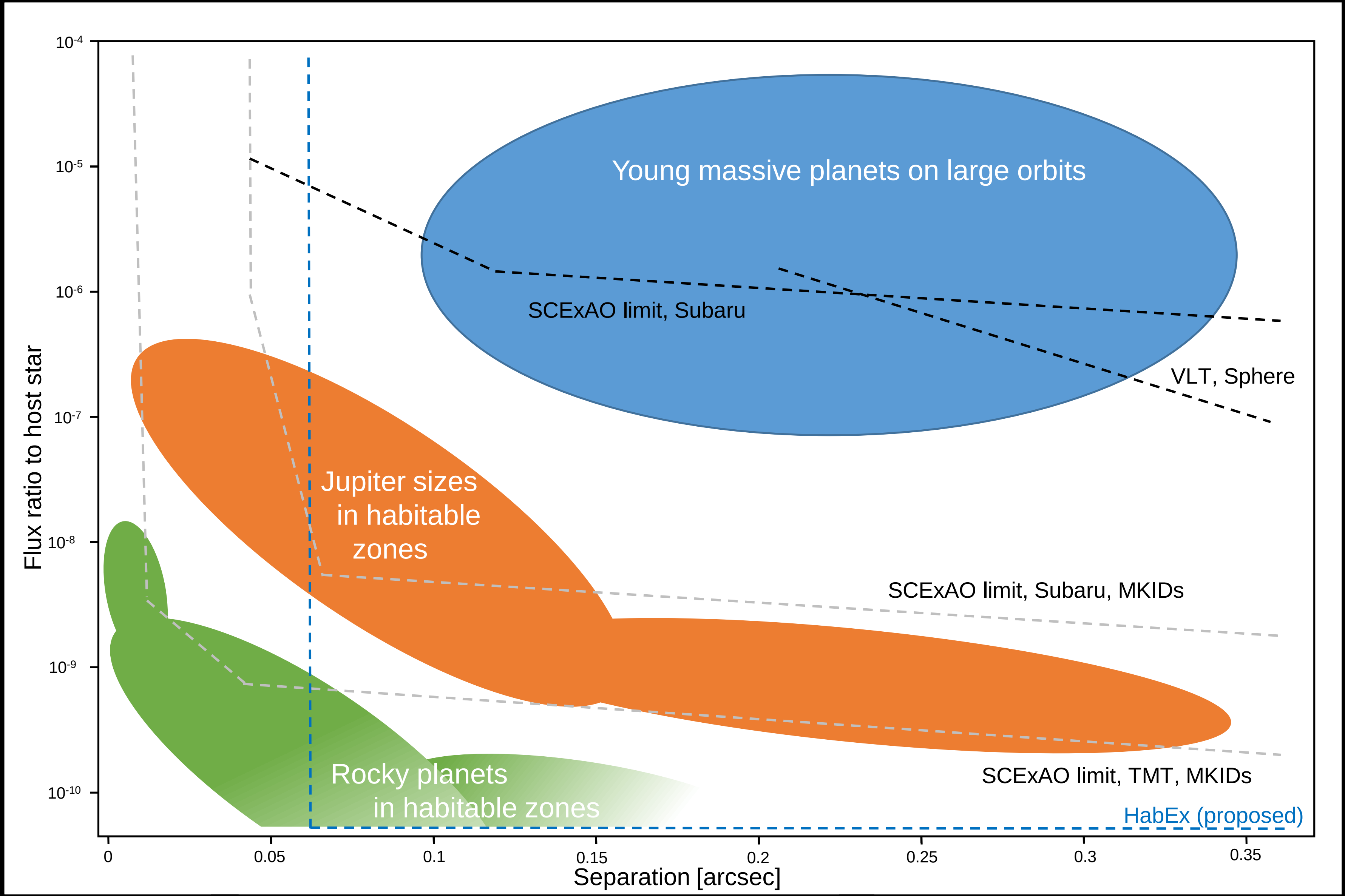
Marois et. al., Nature, 2010

- Direct imaging is the most powerful method to investigate exoplanetary atmospheres.
- It’s main challenges are the inner working angle and the achievable contrast ratio.
- For smaller working angles atmospheric speckles are the most important limitation.

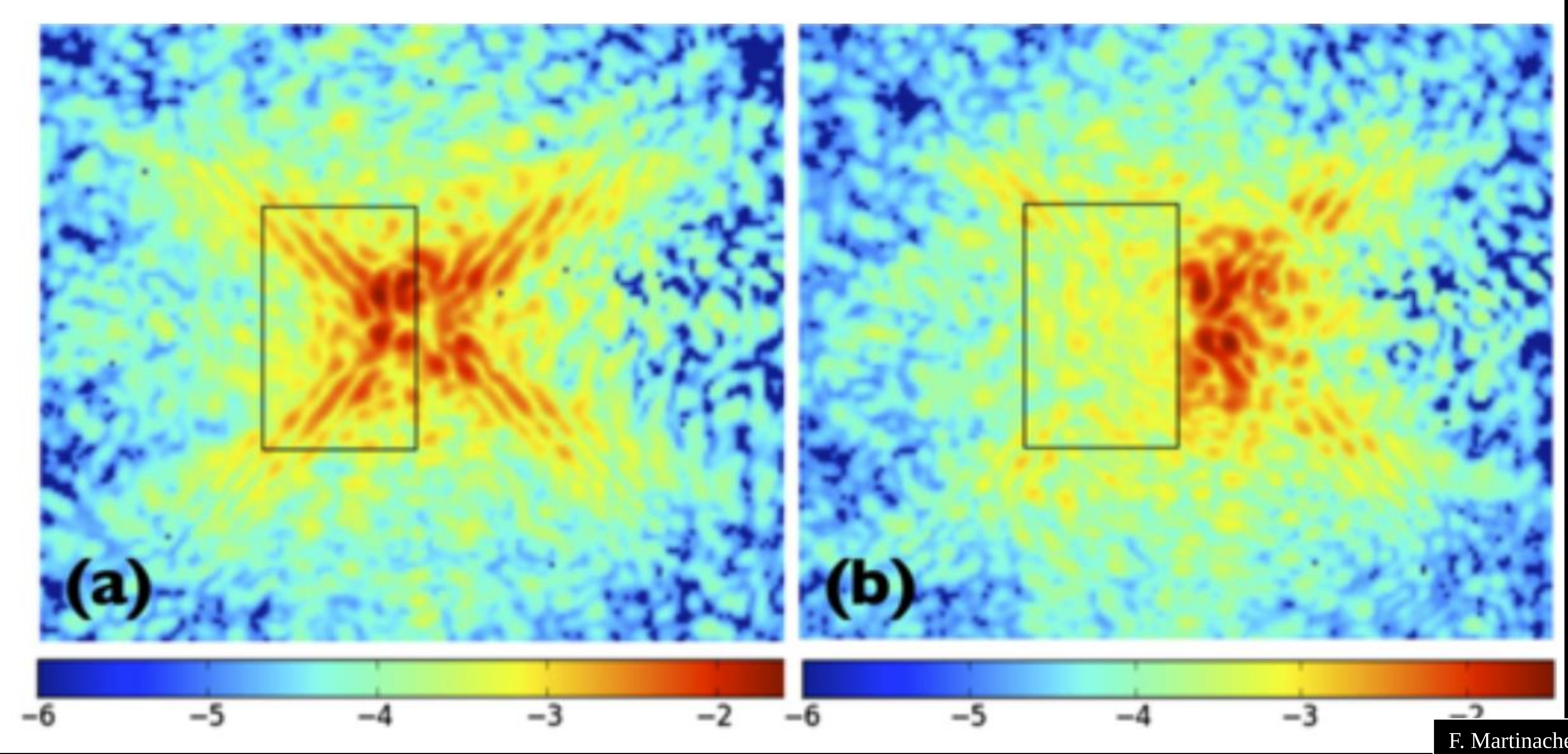


Adapted From Oppenheimer & Hinkley (2009) and Sivaramakrishnan et al. (2001)

- Requires extreme adaptive optics system with 70% - 90% Strehl ratio.

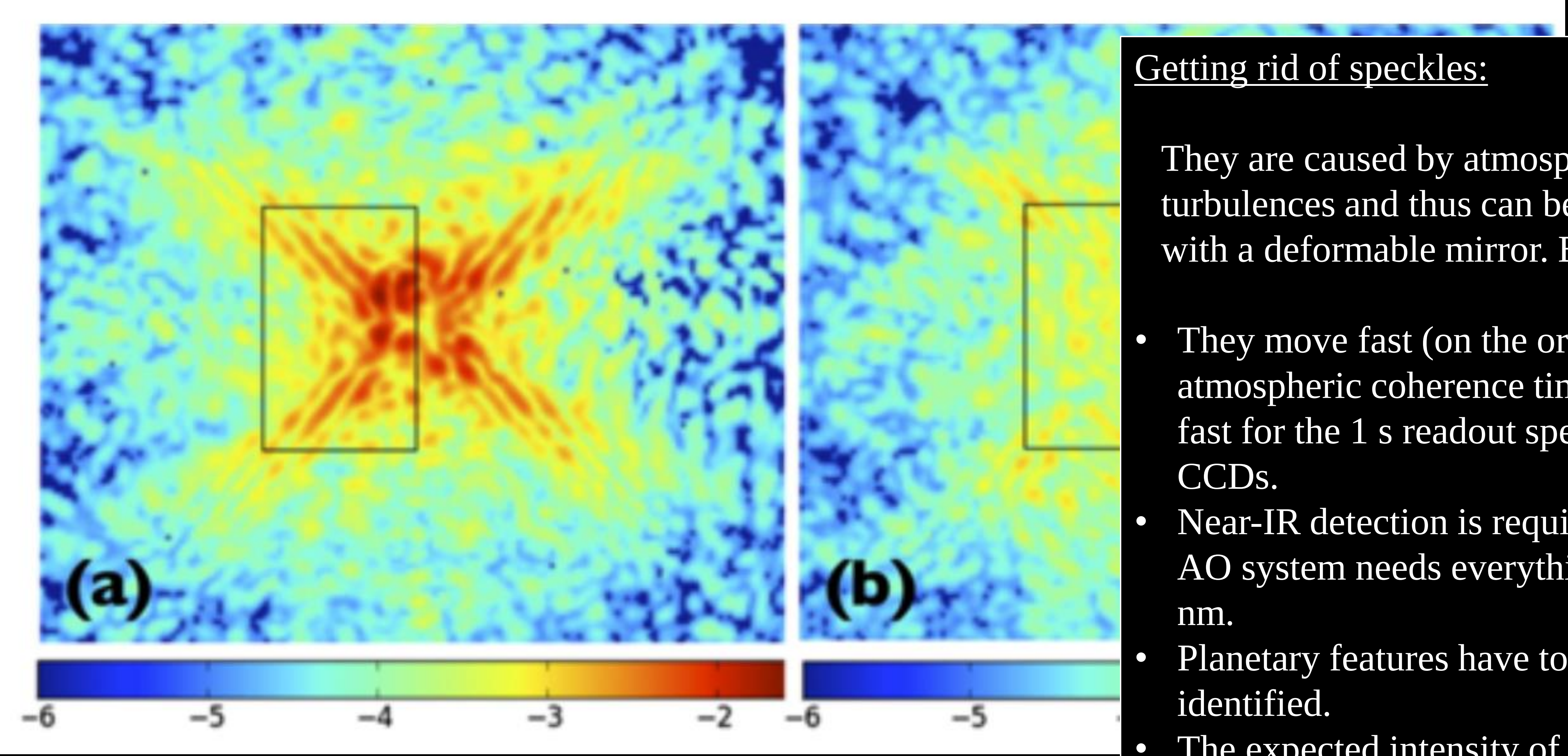


- Expected contrast ratios only rough estimates for stars within 20 pc.
- Data from the HabEx Interim report, 2018 (HabEx: 4 m mirror with star shade).
- Contrast ratio is most important to improve.
- But angular resolution is also important.
- Very promising as pathfinder for 40 m class telescopes: Habitable zones of nearby M-dwarfs require extreme angular resolution but contrast could be up to 10^{-8}.



F. Martinache et al., 2012

Speckles are the main limitation for contrast ratio at small angles.



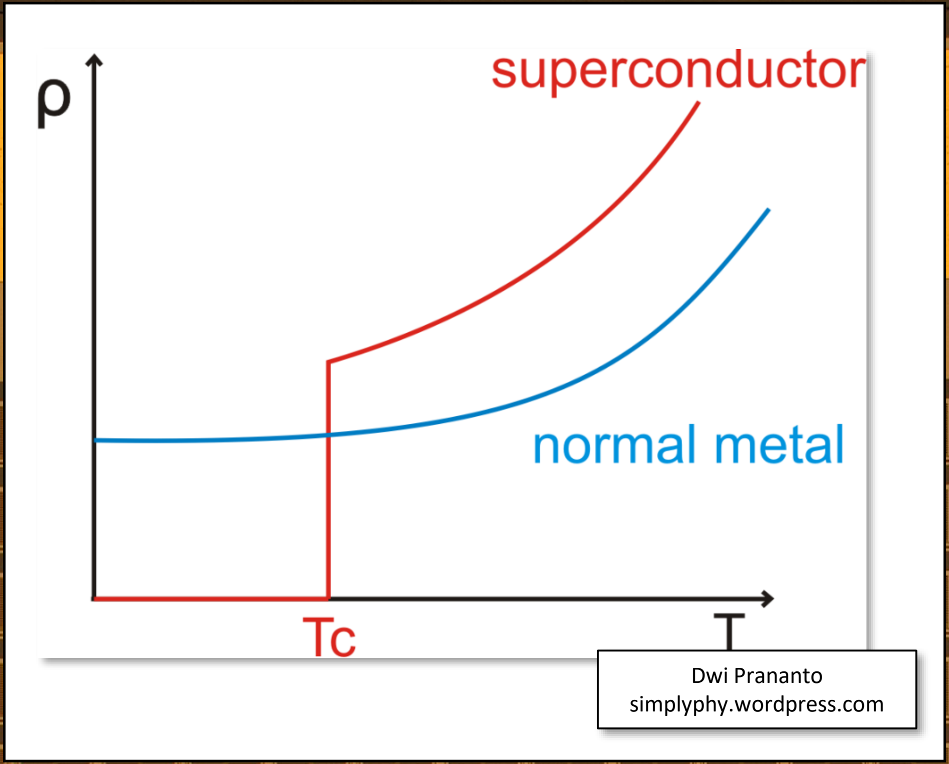
<u>Getting rid of speckles:</u>

They are caused by atmospheric turbulences and thus can be nulled with a deformable mirror. But:

- They move fast (on the order of atmospheric coherence time), too fast for the 1 s readout speed of CCDs.
- Near-IR detection is required as the AO system needs everything < 800 nm.
- Planetary features have to be identified.
- The expected intensity of planetary features is very small.

Speckles are the main limitation for contrast ratio at small angles.

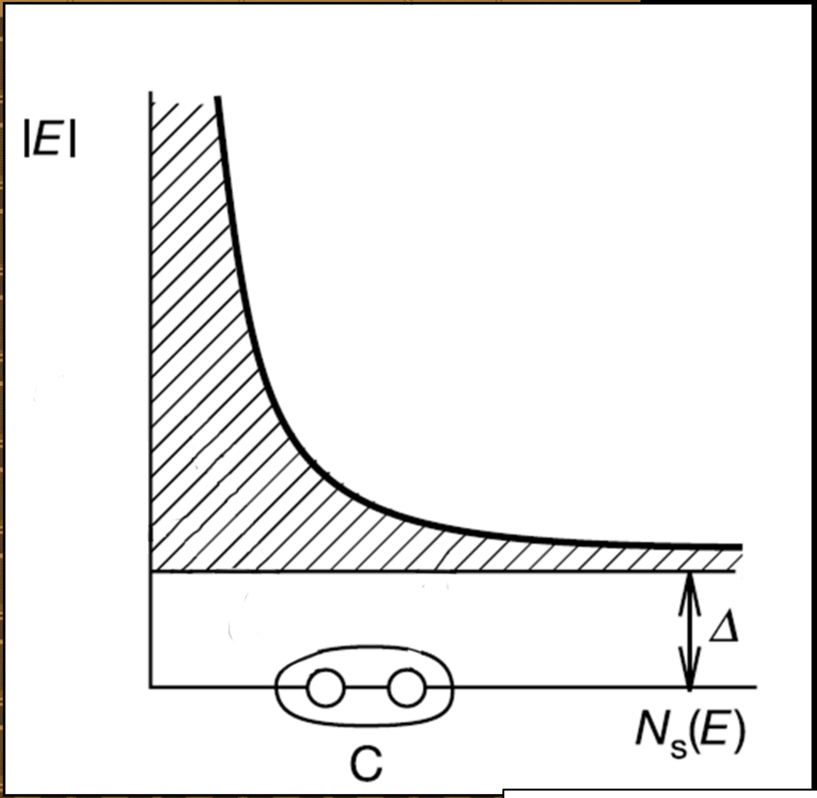
MKID operation principle



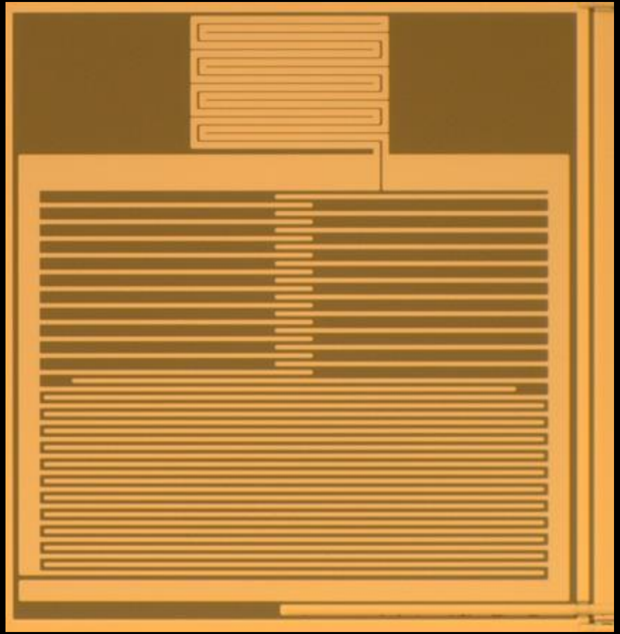
Dwi Prananto
simplyphy.wordpress.com

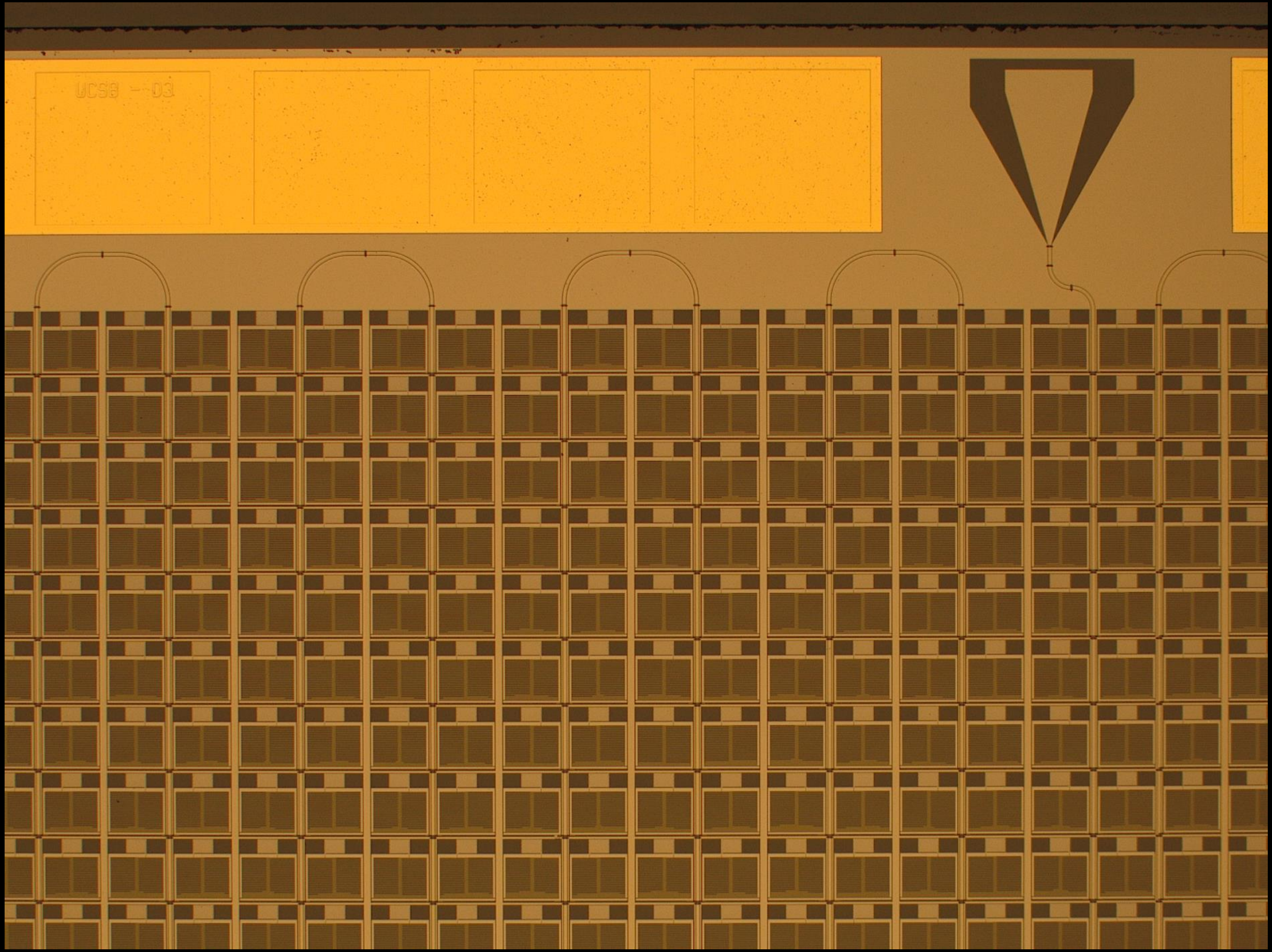
An MKID is not a semiconductor (like CCDs) but a **superconductor**.

- Band gap 4 orders of magnitude smaller compared to Si!



P. Day et. al., Nature 425, 817



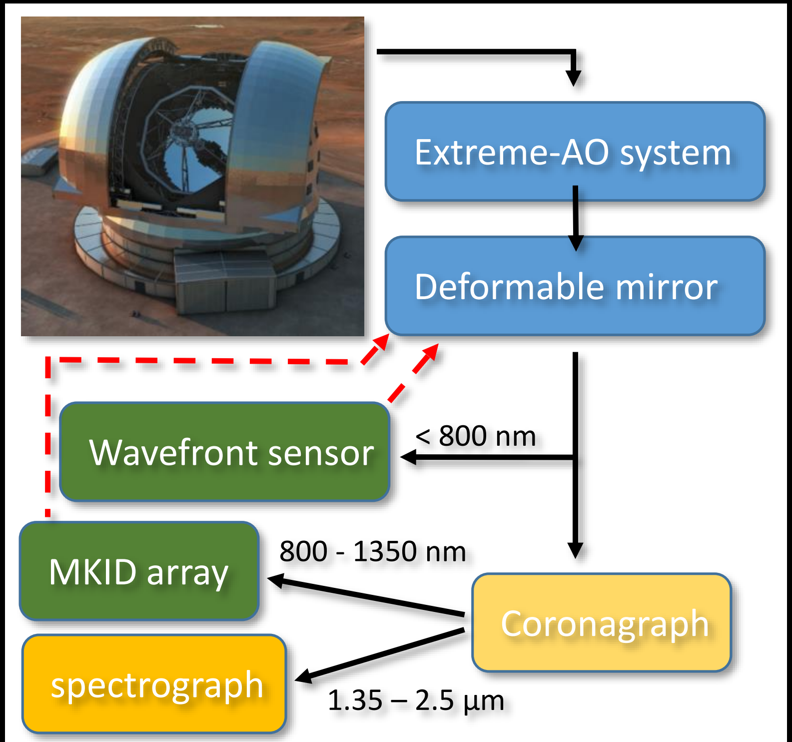


An MKID is not a semiconductor (like CCDs) but a **superconductor**.

This enables:

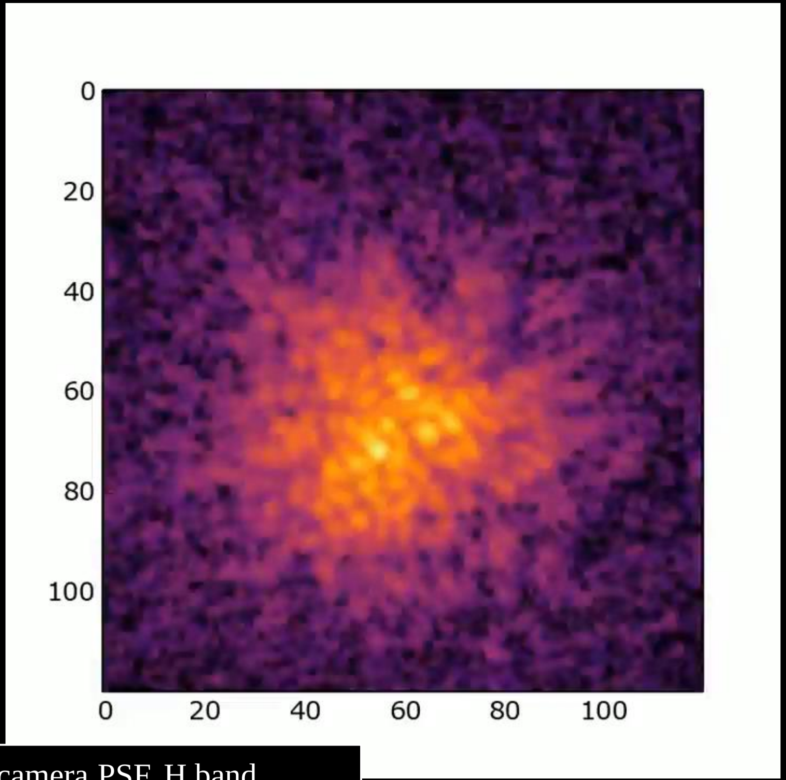
- Low sensitivity threshold and big bandwidth,
  0.5 – 2.5 µm is possible.
- Single photon counting (below ~ 5 µm).
- Single photon energy resolution for speckle identification.
- Very fast readout speeds up to 1 MHz time resolution / 10 kHz count rate.
- Practically no dark noise!

Why MKIDs for high contrast imaging?

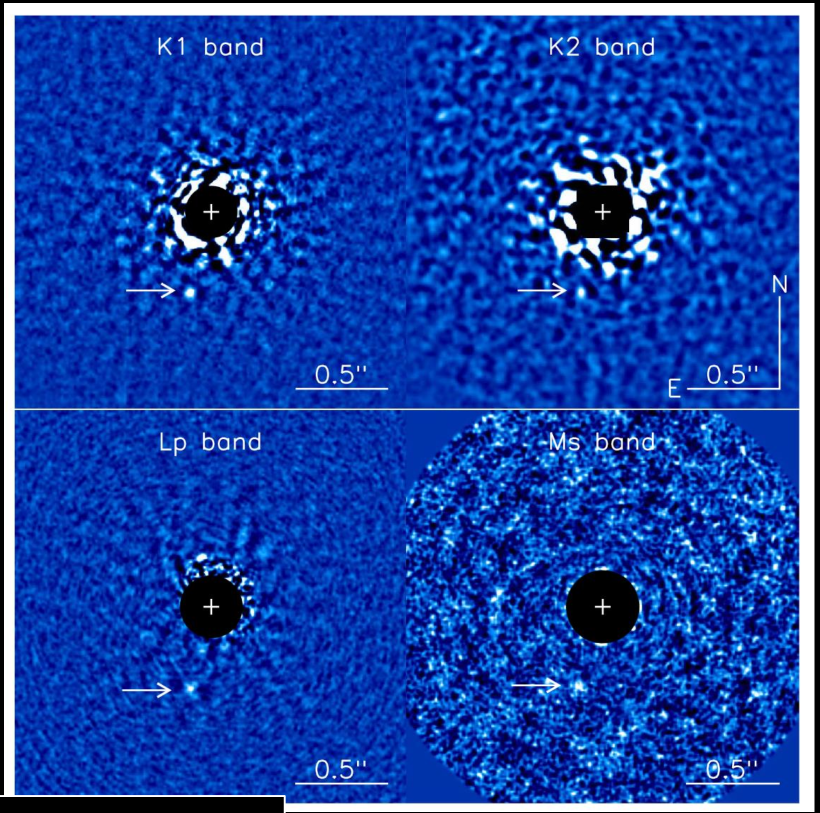


The DM feedback loop requires near-IR sensitivity.
→ MKIDs sensitive up to 2.5 µm

Speckles evolve on a timescale of 0.6 D/v = **0.1 – 1 s**
(D: telescope aperture, v: mean wind speed)
→ MKIDs readout speed: 1 – 10 kHz



IR camera PSF, H band
SCExAO team, Youtube, 12.3. 2017

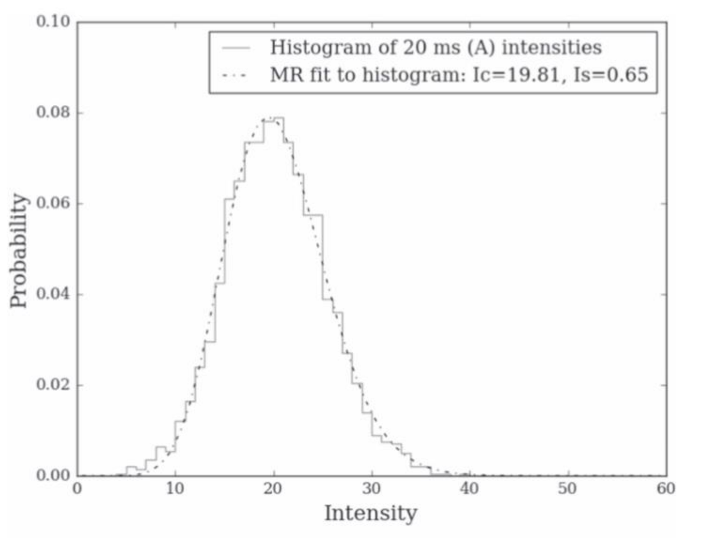


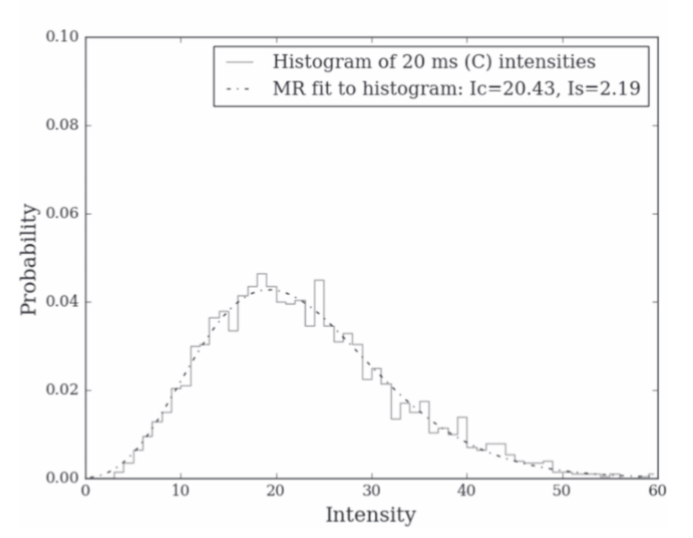
51 Eri b (2-10 M_{jup})
A. Rajan et al., 2017

Low brightness of exoplanets requires a high SNR.
→ MKIDs are practically noise-free

Microwave Kinetic Inductance Detectors (MKIDs)

Separate speckles from exoplanets.

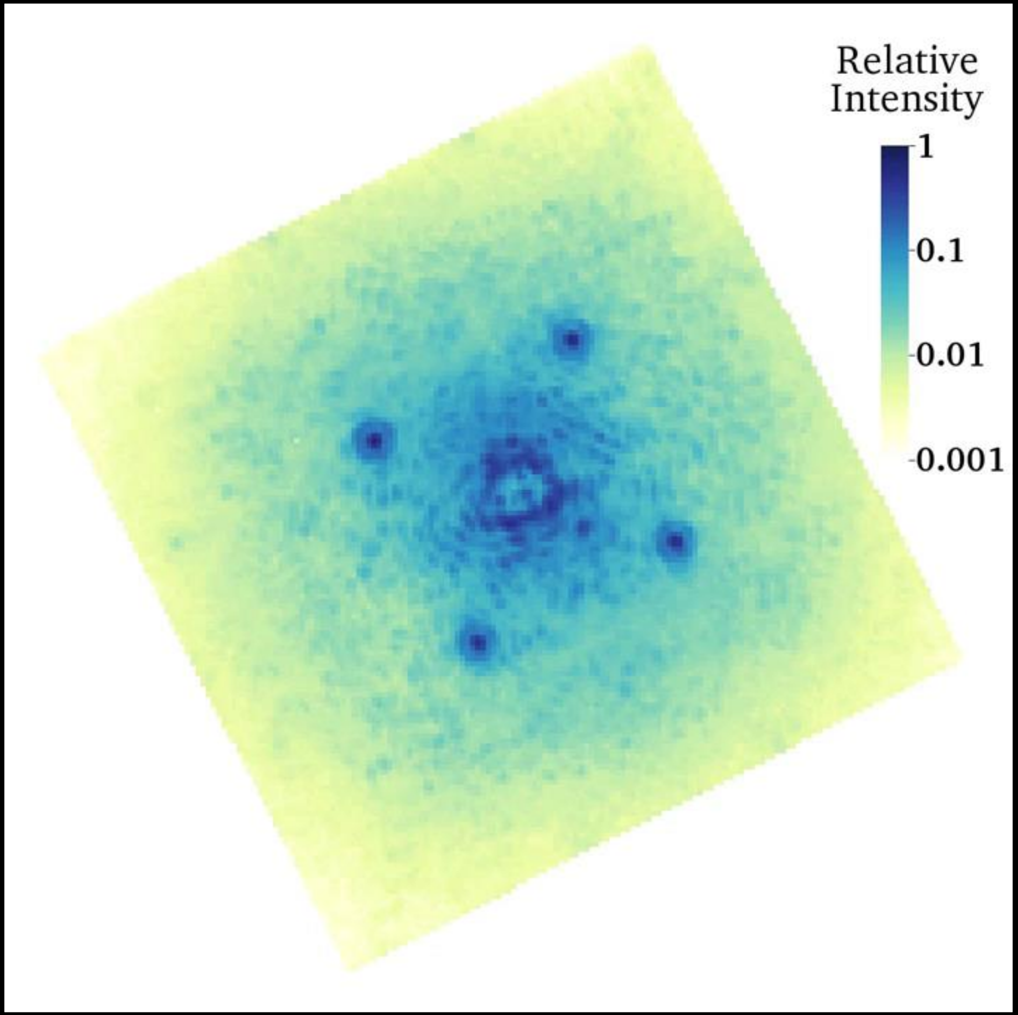




Left: 32 Peg Ab (a stellar companion).
Right: Artificial speckles.
Intensity is photons per 20 ms.
Meeker et. al., PASP, 2018

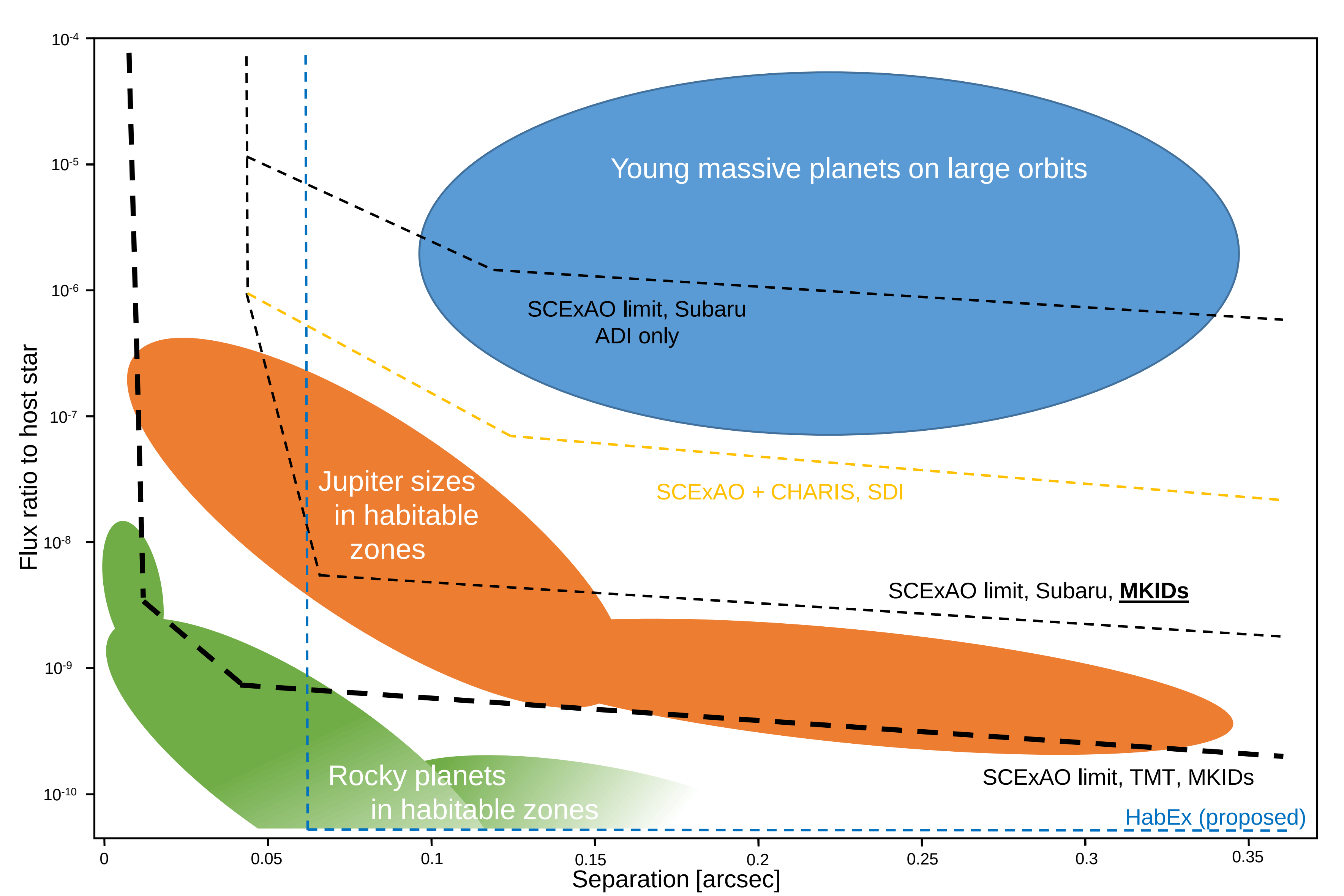
Due to their photon counting capability and low noise MKIDs allow Stochastic Speckle Discrimination (SSD) to distinguish between speckles and planetary features.

Apart from just suppressing speckles, it can be difficult to distinguish between them and real features, especially for disks.



Double start system observed with CHARIS, J – K band
Tim Brandt, SCExAO, 8.5.2017

MKID's single pixel energy resolution allows to use the chromatic nature of speckles to identify planetary features.

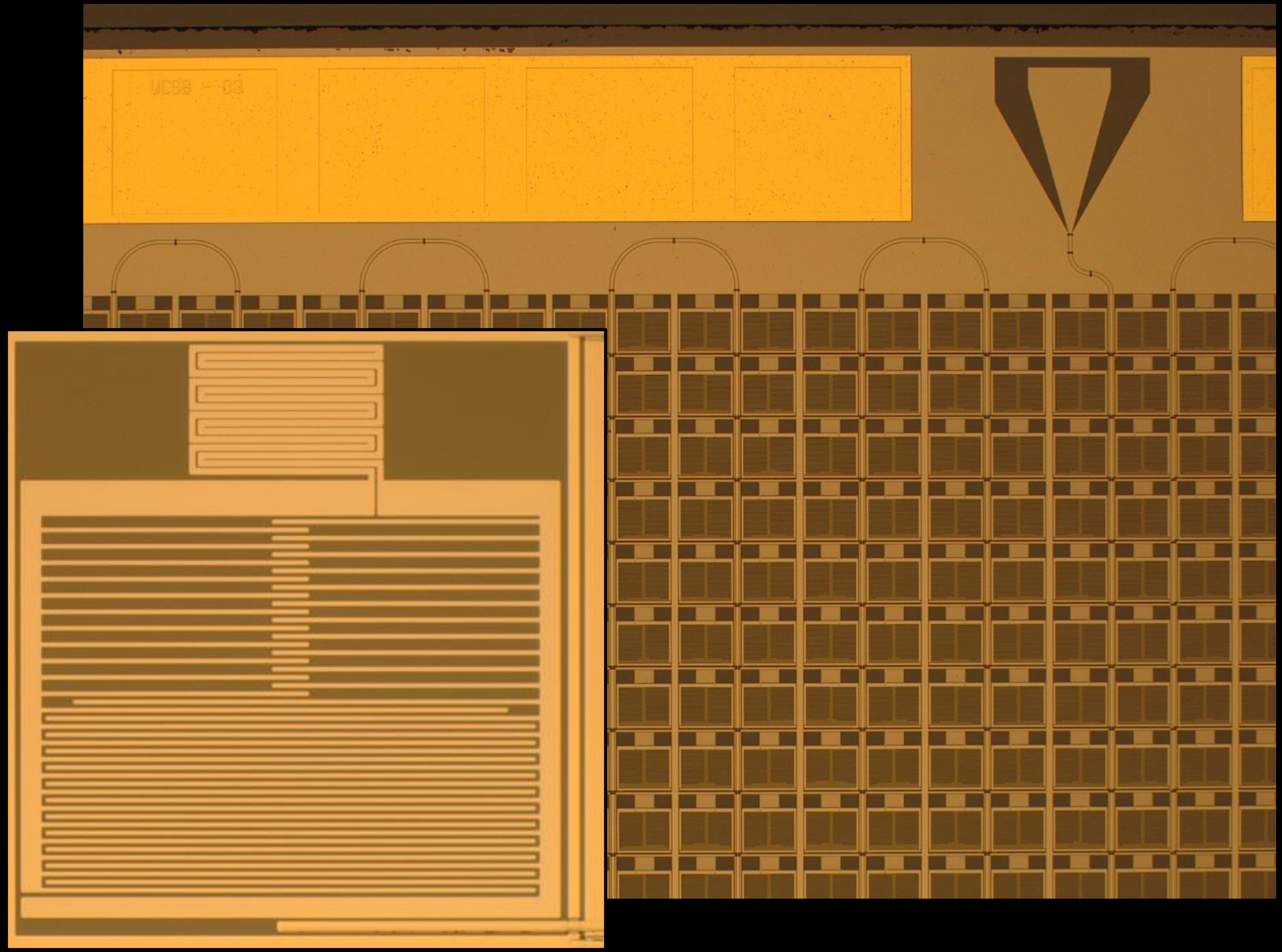


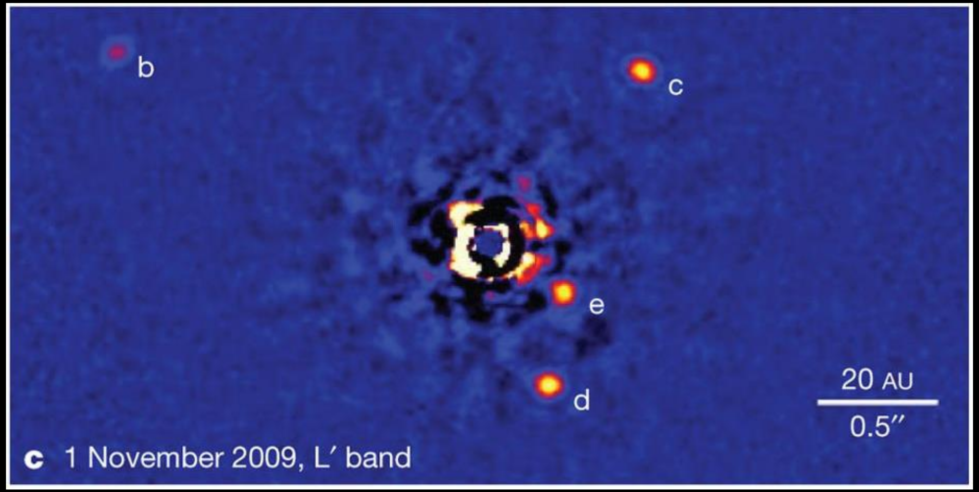
Prediction of contrast ratio improvements (1.2 µm, around an $m_J = 3$ star):

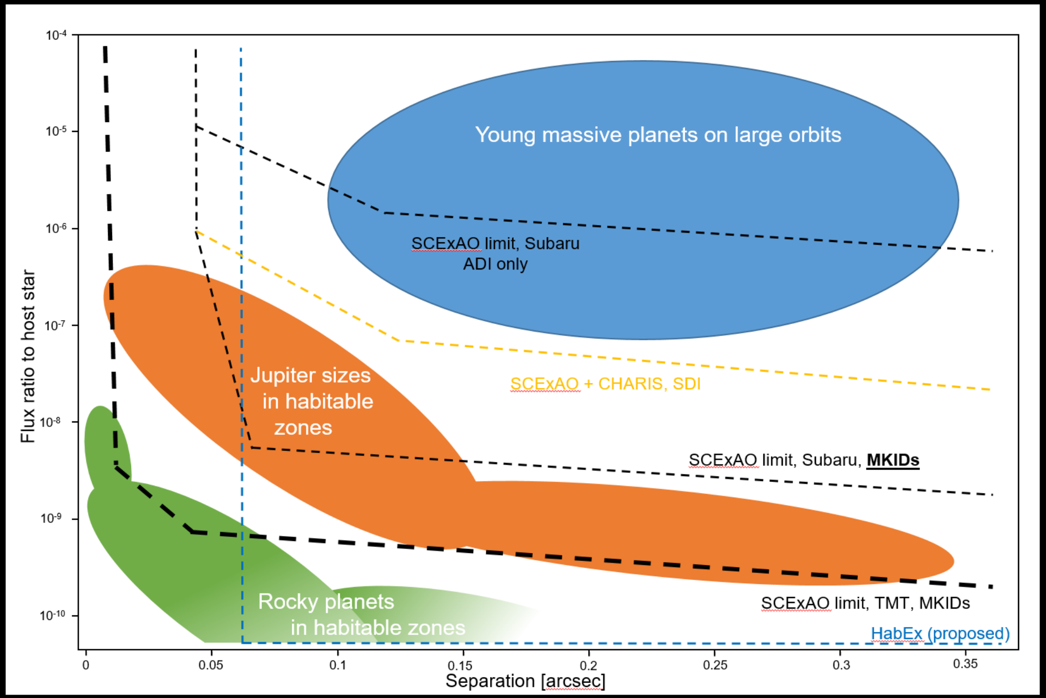
- Spectral differential imaging (SDI): ~ factor 10 – 100
- No dark counts & better SNR in the near-IR: ~ factor of 10
- Real-time speckle suppression at a few hundred Hz: ~ factor of up to 10
- Stochastic speckle identification: Hard to predict.

➔ Obviously most interesting on 40 m class telescopes!

Summary:




b
c
e
d
20 AU
0.5″
c 1 November 2009, L′ band


Young massive planets on large orbits
SCExAO limit, Subaru ADI only
Jupiter sizes in habitable zones
SCExAO + CHARIS, SDI
SCExAO limit, Subaru, MKIDs
SCExAO limit, TMT, MKIDs
Rocky planets in habitable zones
HabEx (proposed)
Flux ratio to host star
Separation [arcsec]