The VORTEX team

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- ***U. Uppsala***: M. Karlsson, P. Forsberg, P. Piron, E. Vargas Catalan
- ***Caltech/JPL***: D. Mawet, E. Serabyn, K. Matthews, G. Ruane, AJ Riggs, E. Choquet, M. Bottom, H. Ngo, R. Jensen-Clem
- ***Obs. Paris***: E. Huby, P. Baudoz
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OLIVIER ABSIL

SIX YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

OUTLINE

history and technology development

commissioning & on-sky performance

selected scientific results

image processing with machine learning

future projects

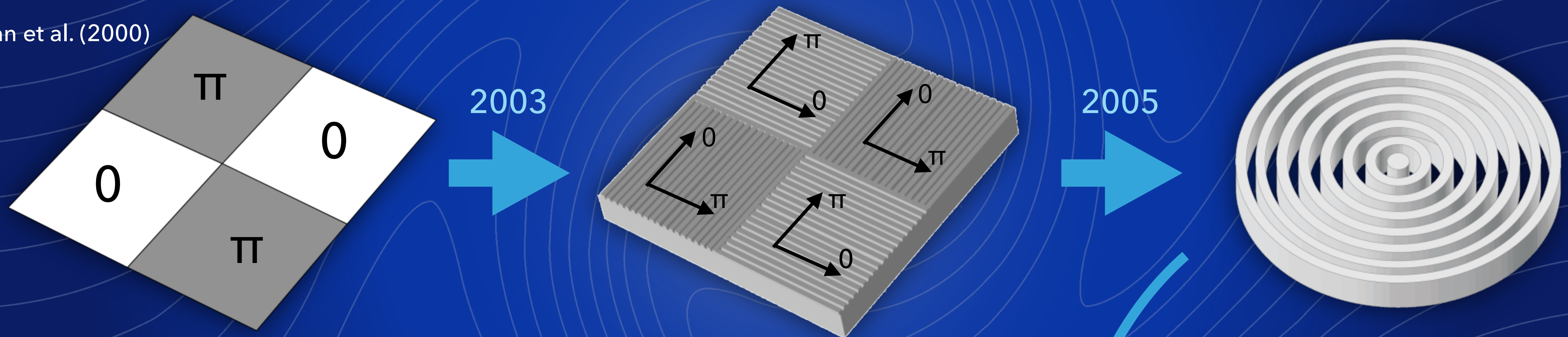
VORTEX

HISTORY AND TECHNOLOGY DEVELOPMENT

THE BIRTH OF A CONCEPT

- FQPM → sub-wavelength grating → annular groove phase mask

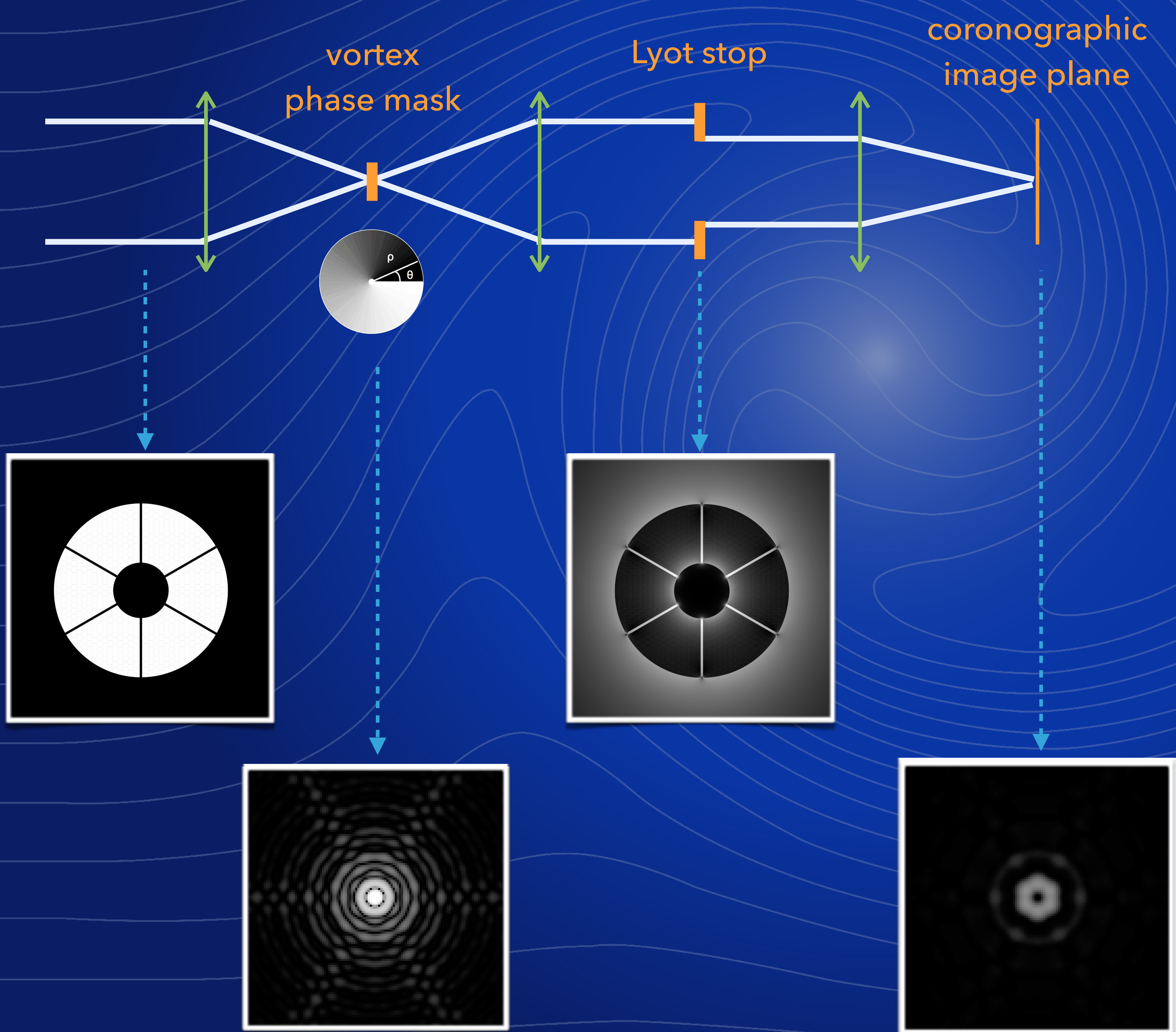
Rouan et al. (2000)



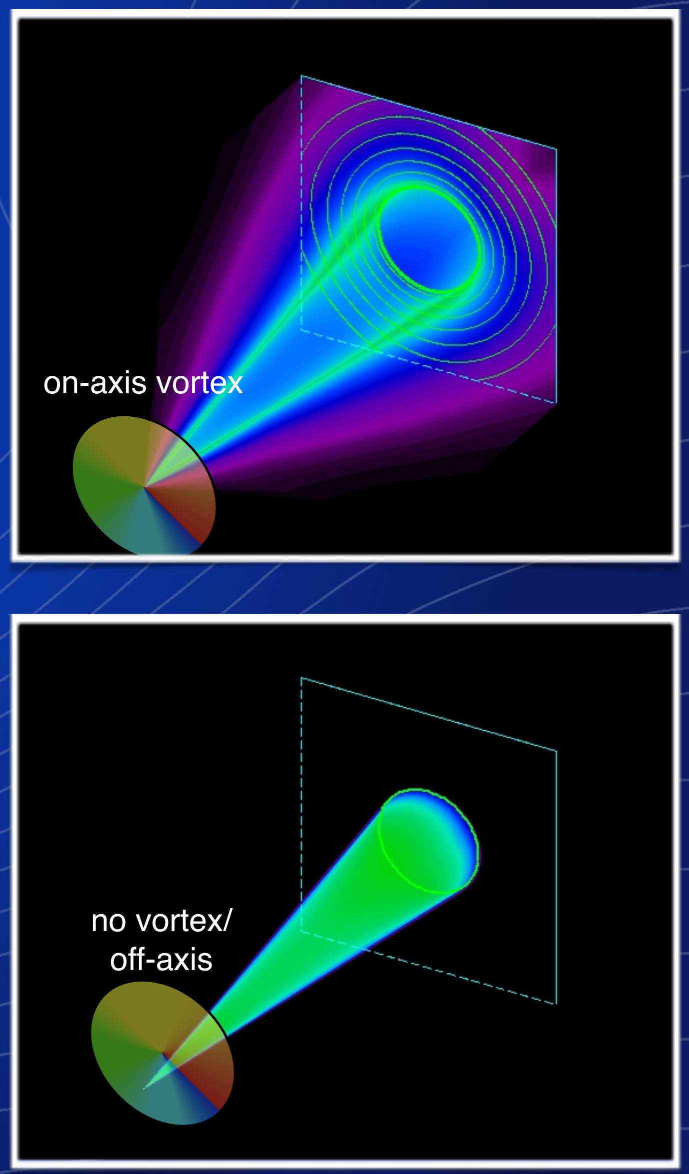
Mawet et al. (2005)

- advantages:
  - inner working angle
  - clear 360° discovery space
  - achromaticity

THE VORTEX CORONAGRAPH IN A NUTSHELL

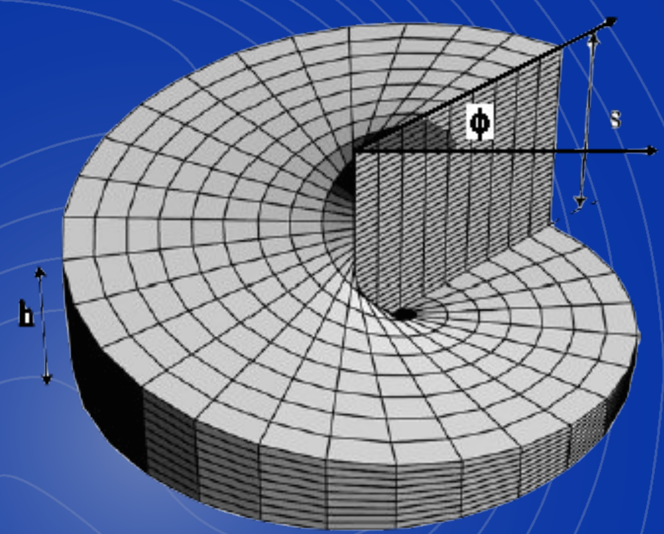


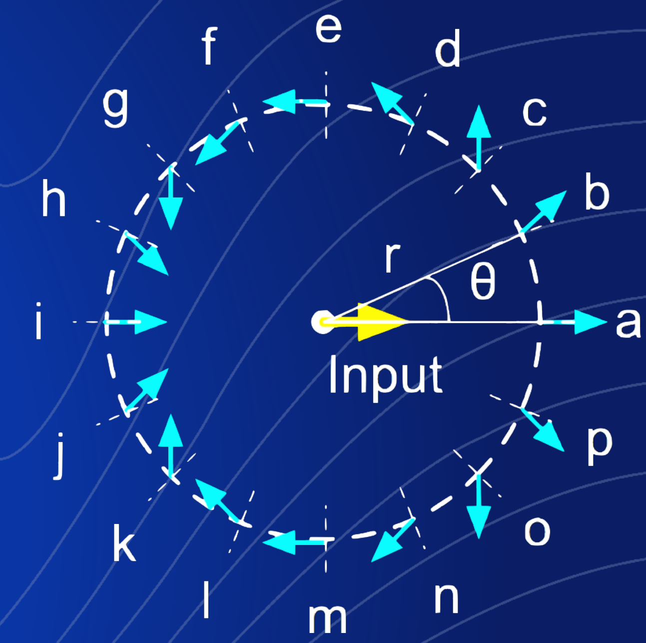
perfect on-axis cancellation
for a circular aperture



IMPLEMENTATIONS OF THE VORTEX PHASE MASK

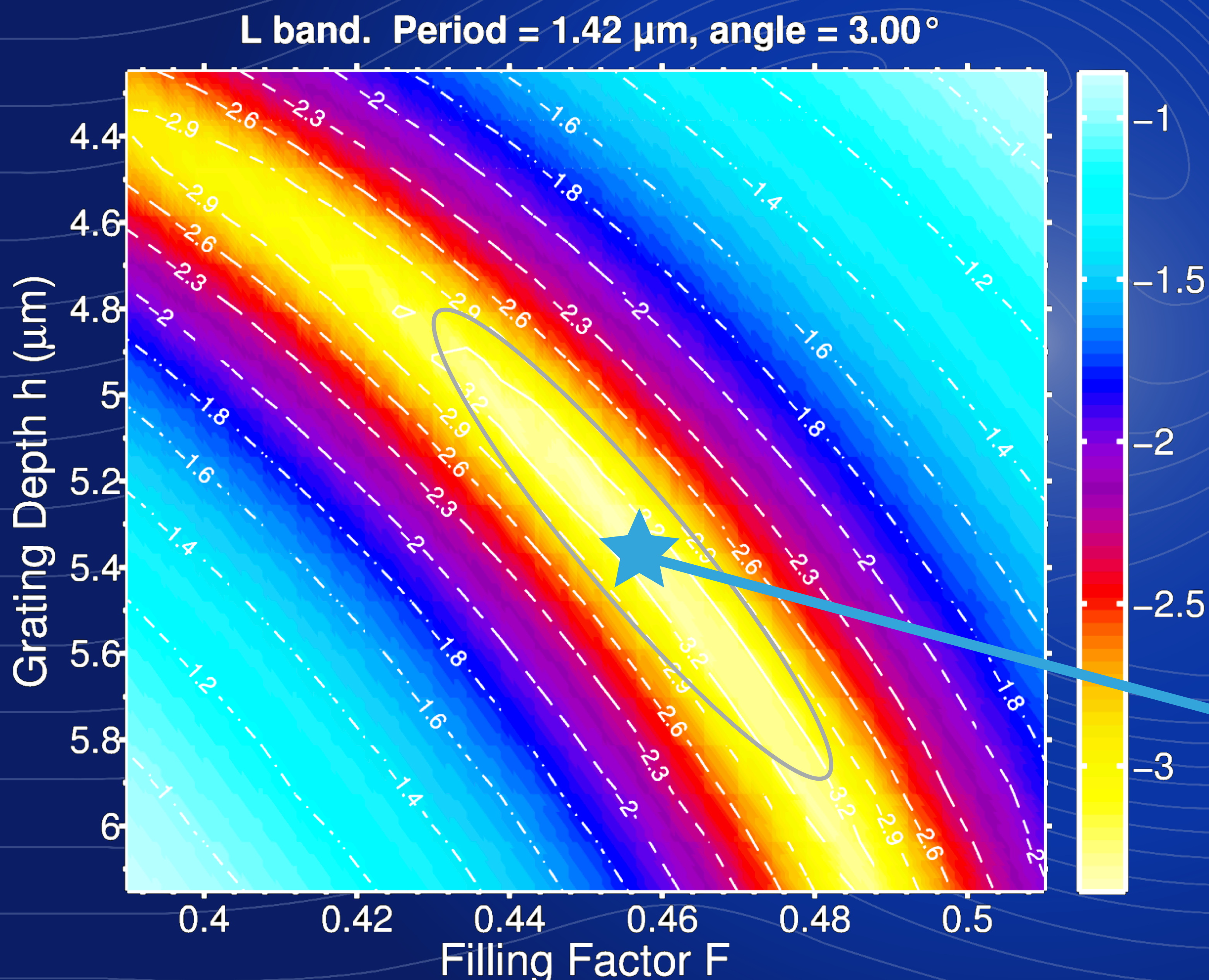
- scalar vortex
  - helical piece of glass
- vector vortex
  - liquid crystal polymers
  - subwavelength gratings
  - photonic crystals

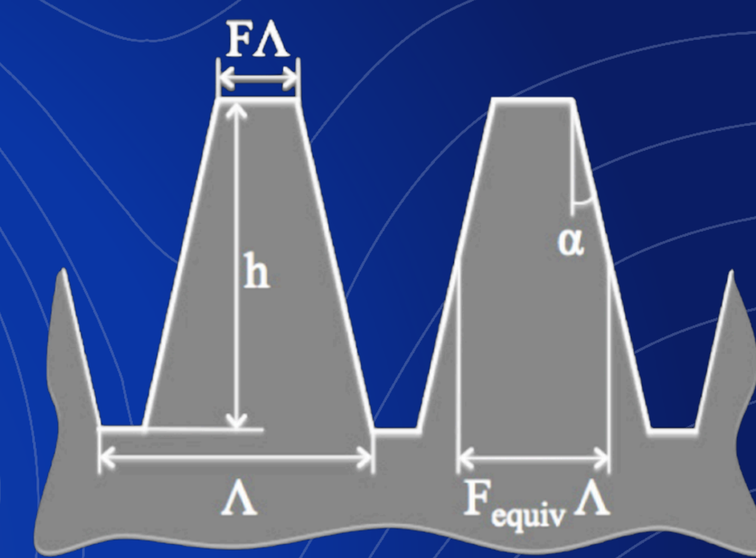


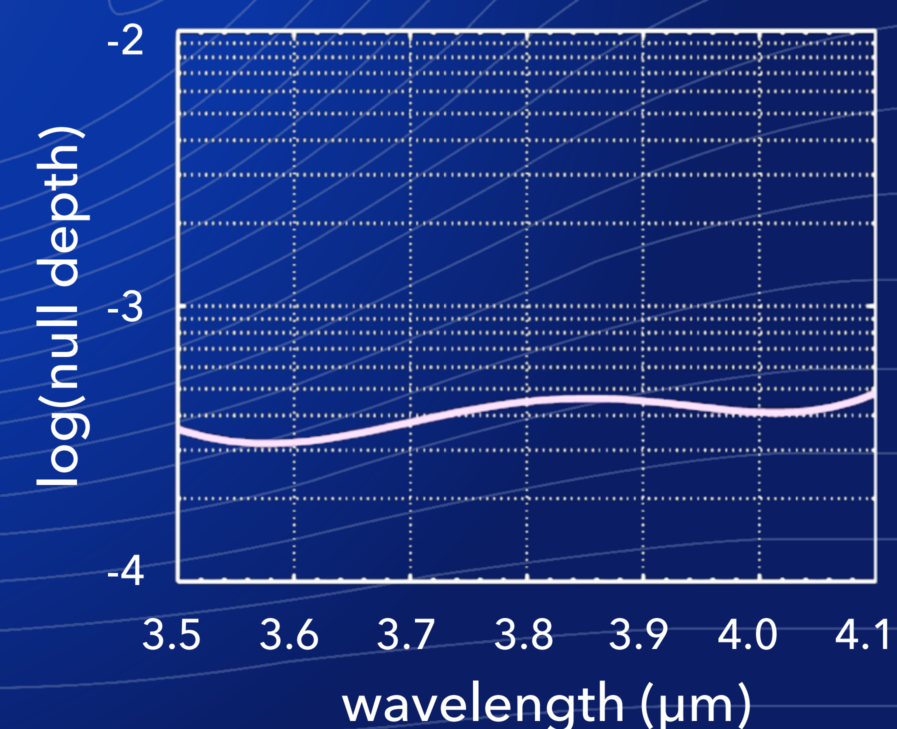


Annular Groove Phase Mask

OPTIMIZING THE GRATING DESIGN





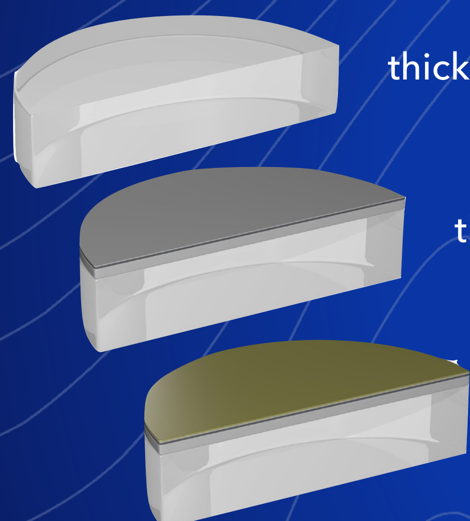


Delacroix et al. (2013)

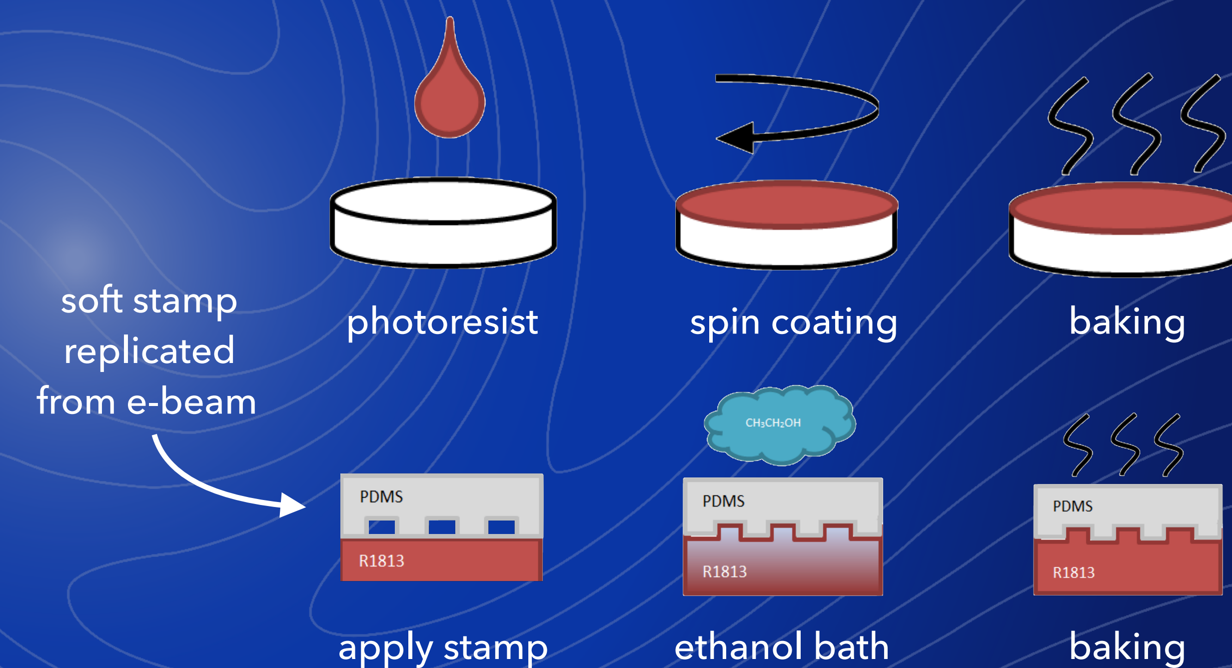
MANUFACTURING DIAMOND AGPM @ UPPSALA

Vargas Catalan et al. (2016)

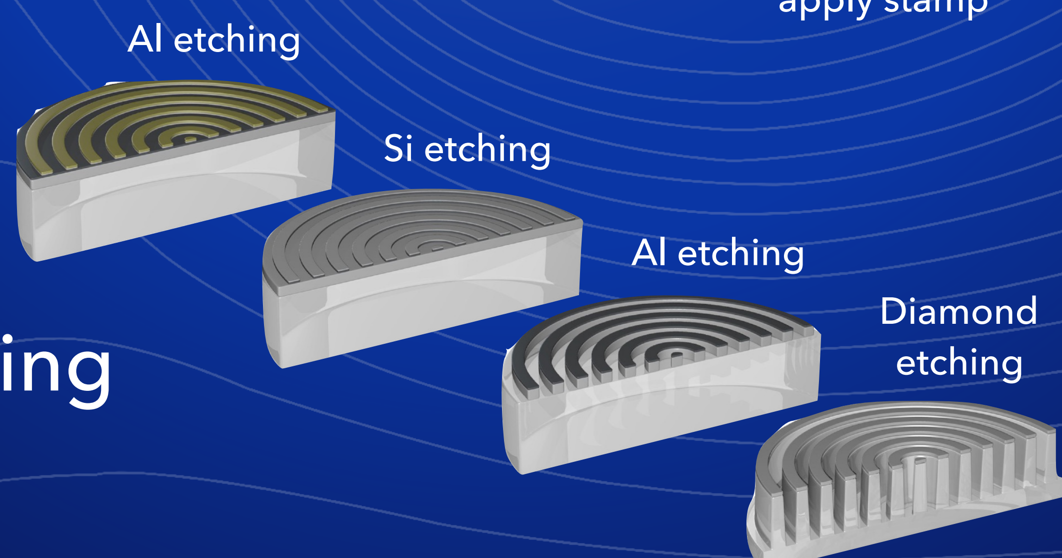
1. diamond coated with Al and Si layers (sputtering)

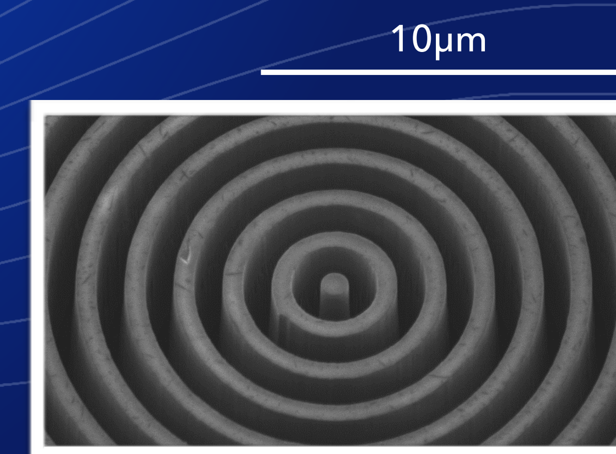


2. e-beam pattern transferred with solvent-assisted moulding

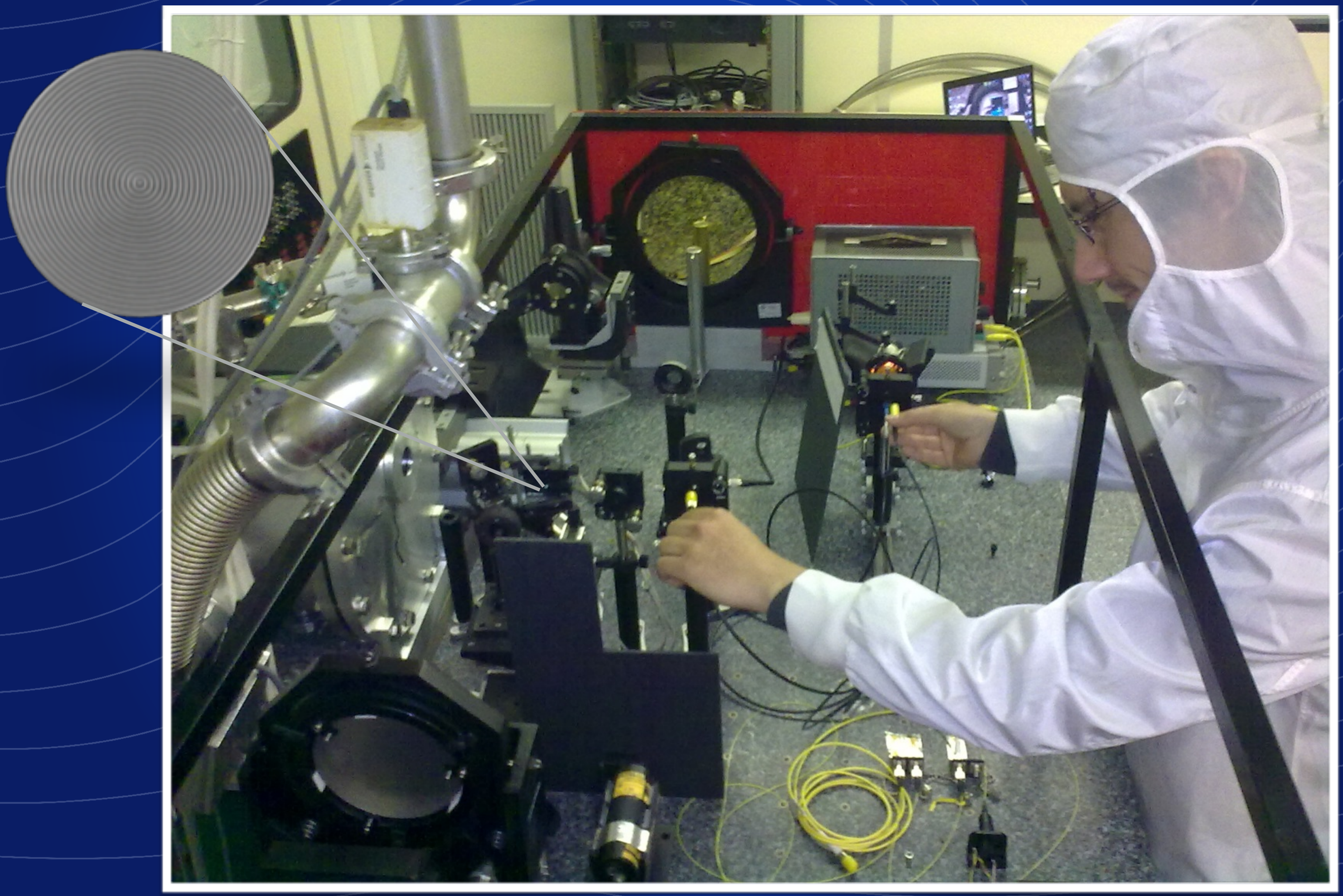


3. reactive ion etching



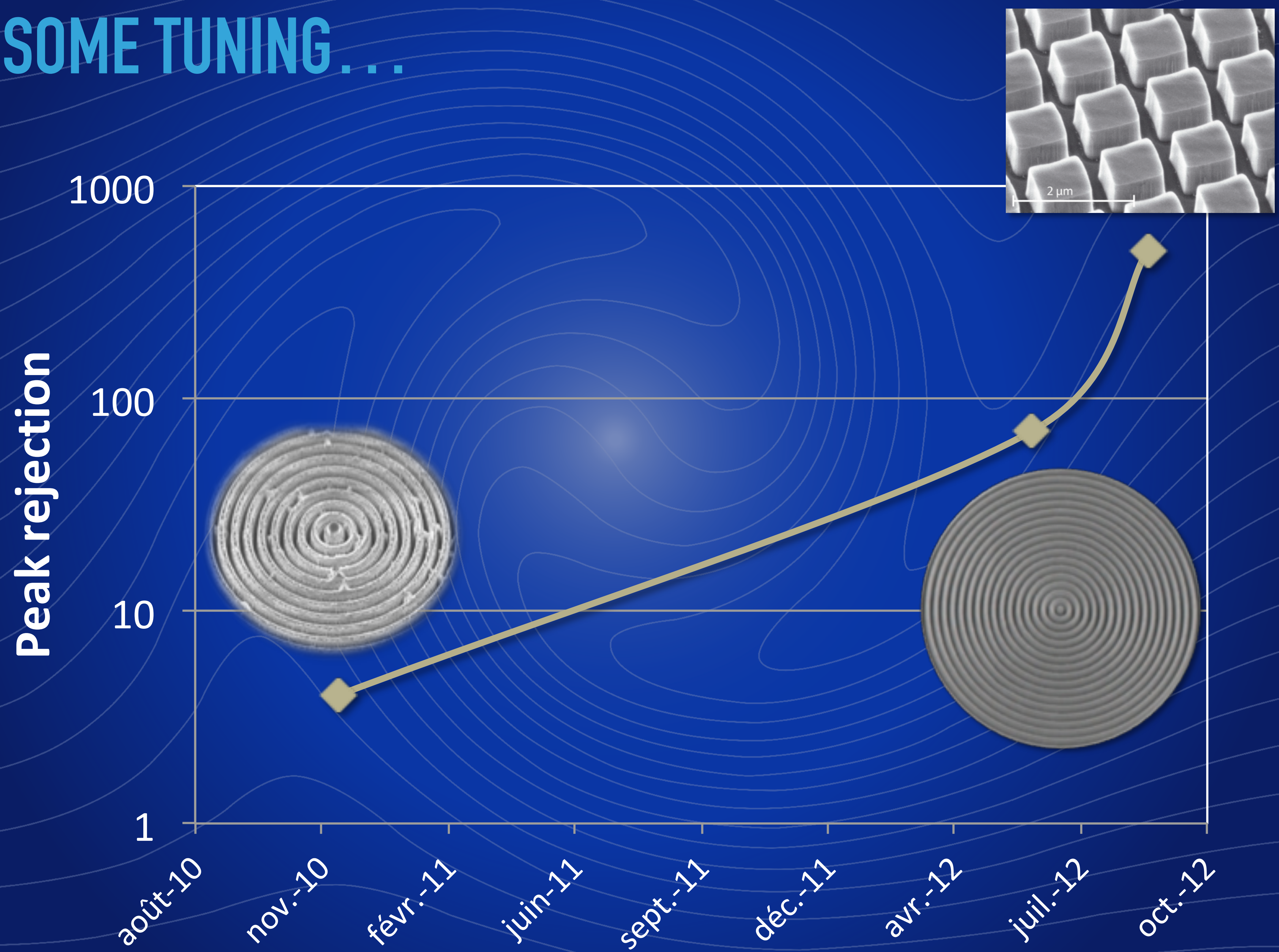


SETTING UP THE « YACADIRE » BENCH @ MEUDON

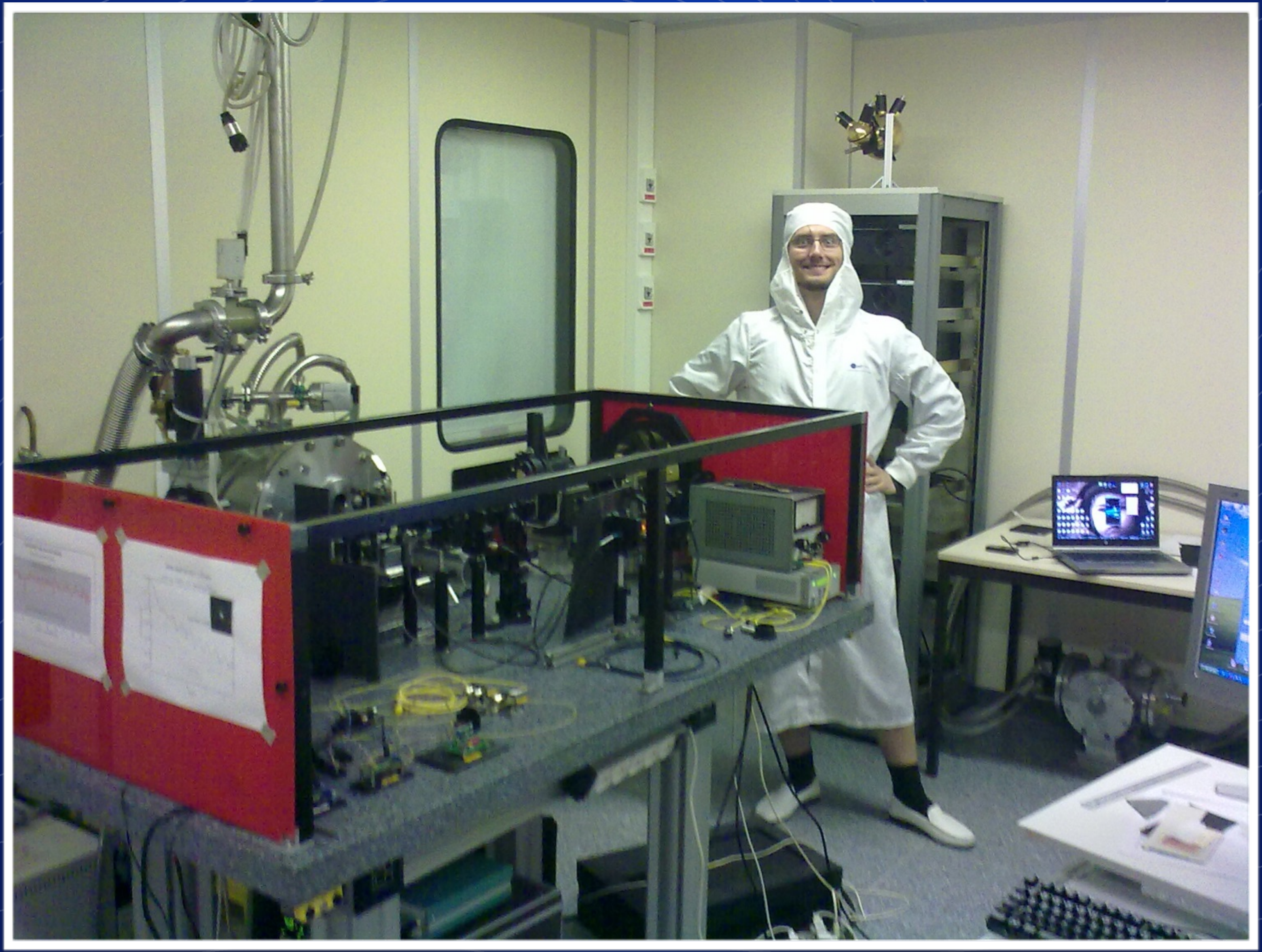


ANGUISH...

AFTER SOME TUNING…

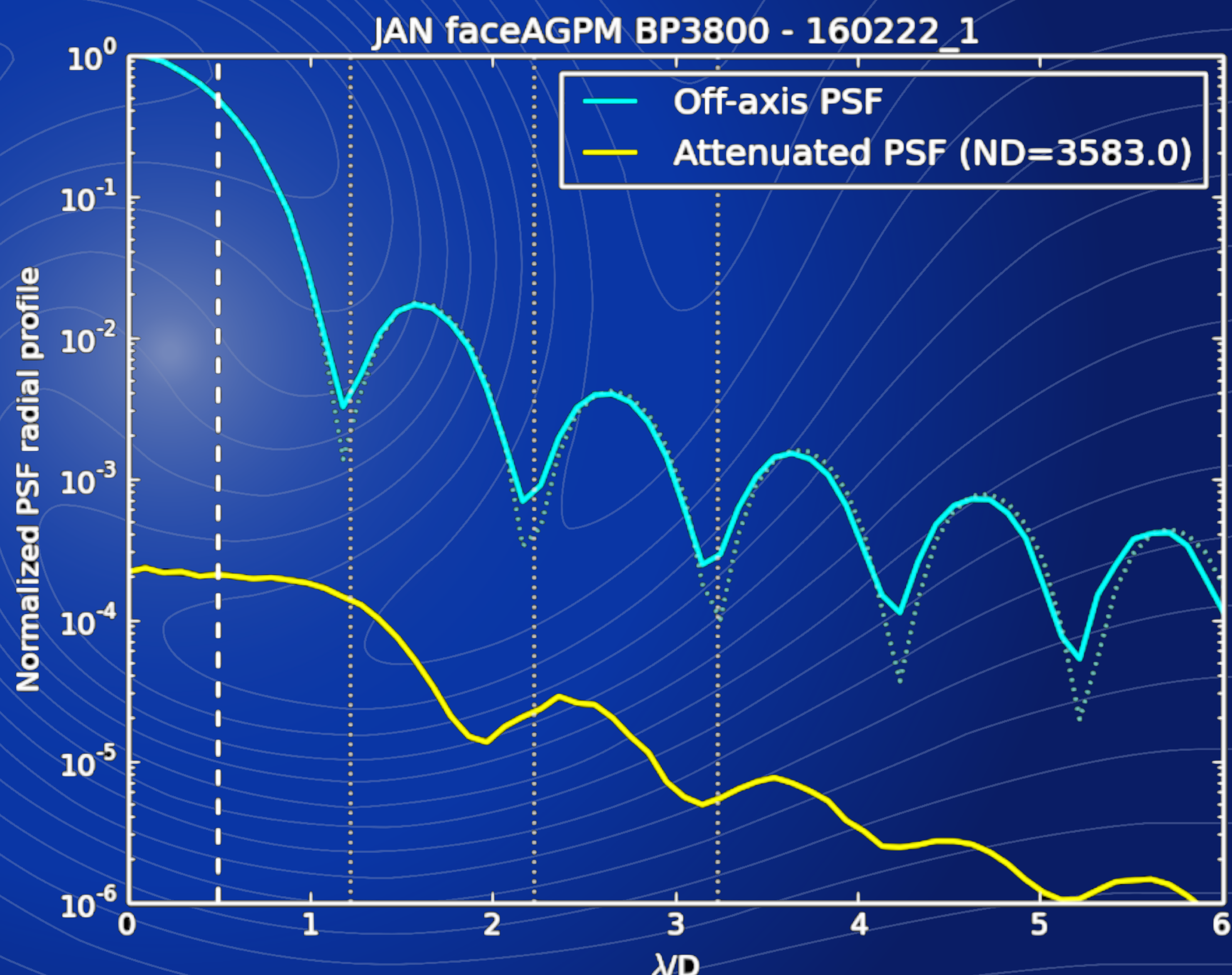


BLISS!



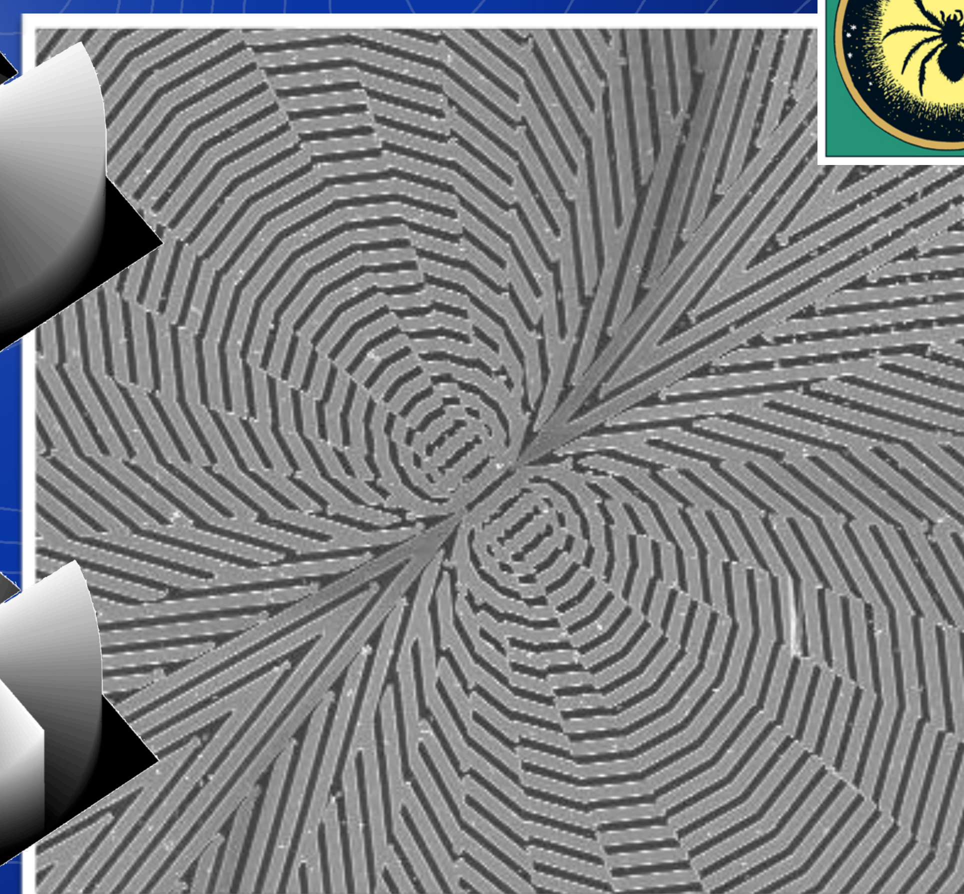
BEST PERFORMANCE IN THE LAB - 2018 UPDATE

- dedicated test bench (VODCA) now available at ULiège
- 10+ science-grade L-band AGPMs etched & tested
- broadband rejection up to 2500 : 1



EXTENDING THE CONCEPT

- AGPM first developed for thermal infrared (L, M, N bands)
  - excellent performance on ~30% bandwidth
- manufacturing tests for H-K bands promising, but more work needed
- now exploring higher topological charges
  - less sensitive to tip-tilt, at the expense of larger IWA



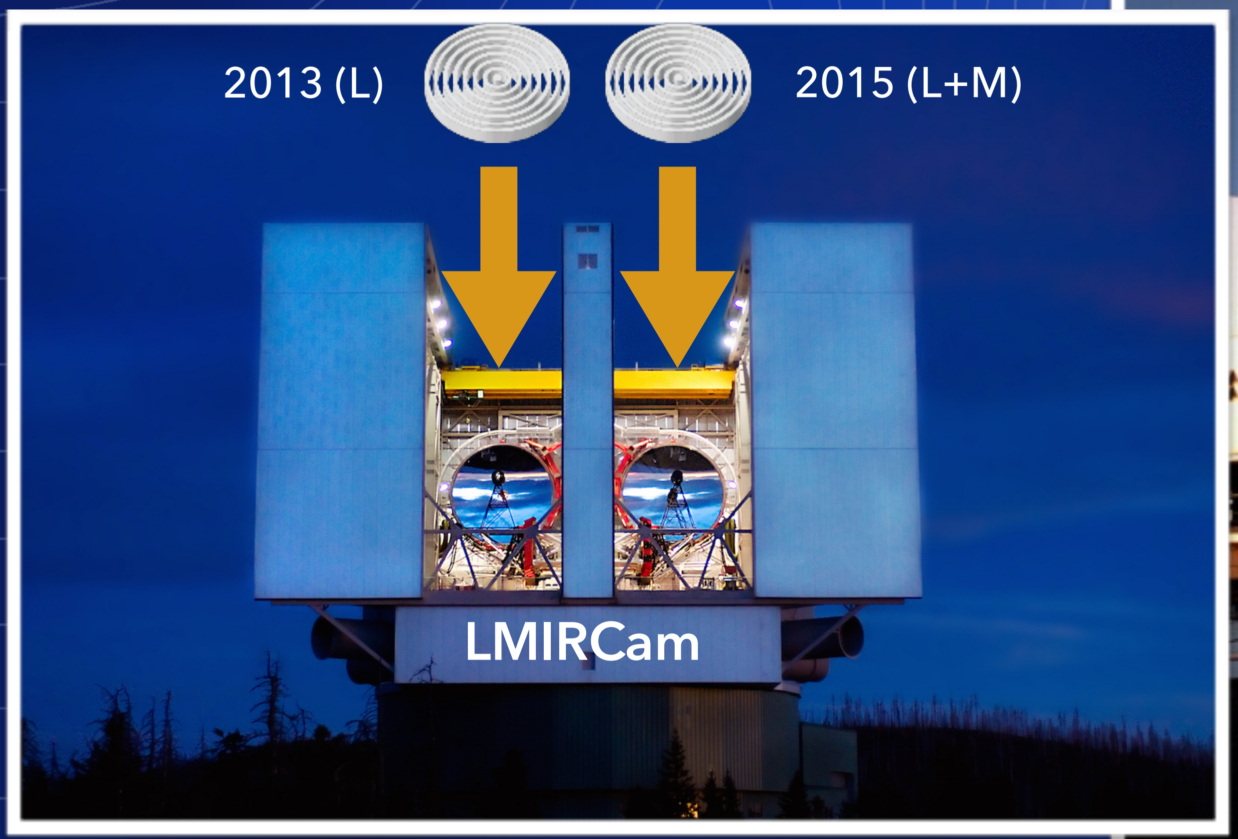
charge-4 vortex, work in progress

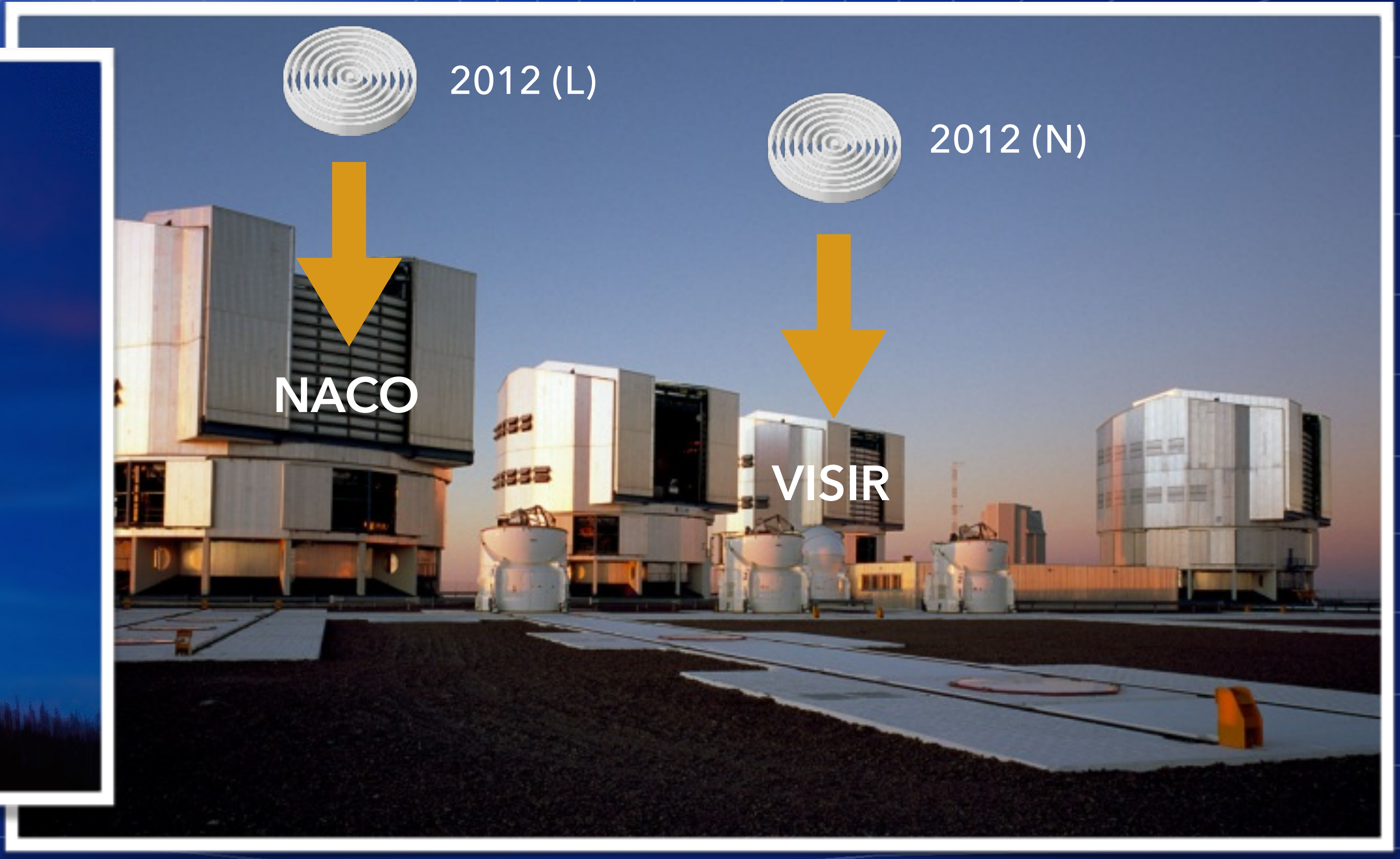
VORTEX

COMMISSIONING & ON-SKY PERFORMANCE

INSTALLATION AND COMMISSIONING

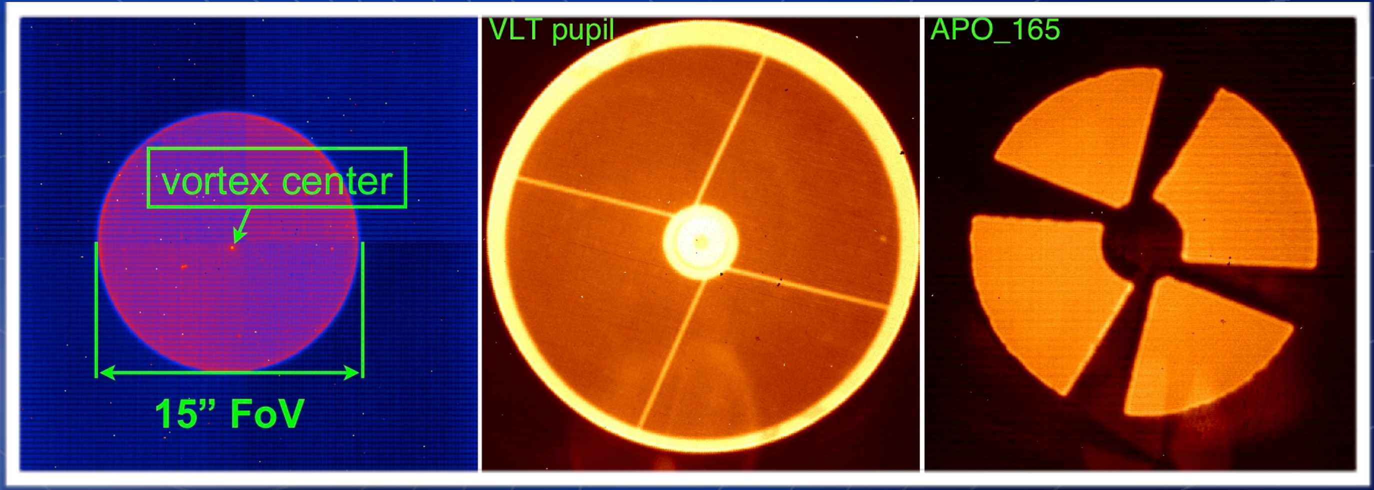
- piggyback on existing coronagraphic IR cameras
- very short commissioning phase (1-2 nights)



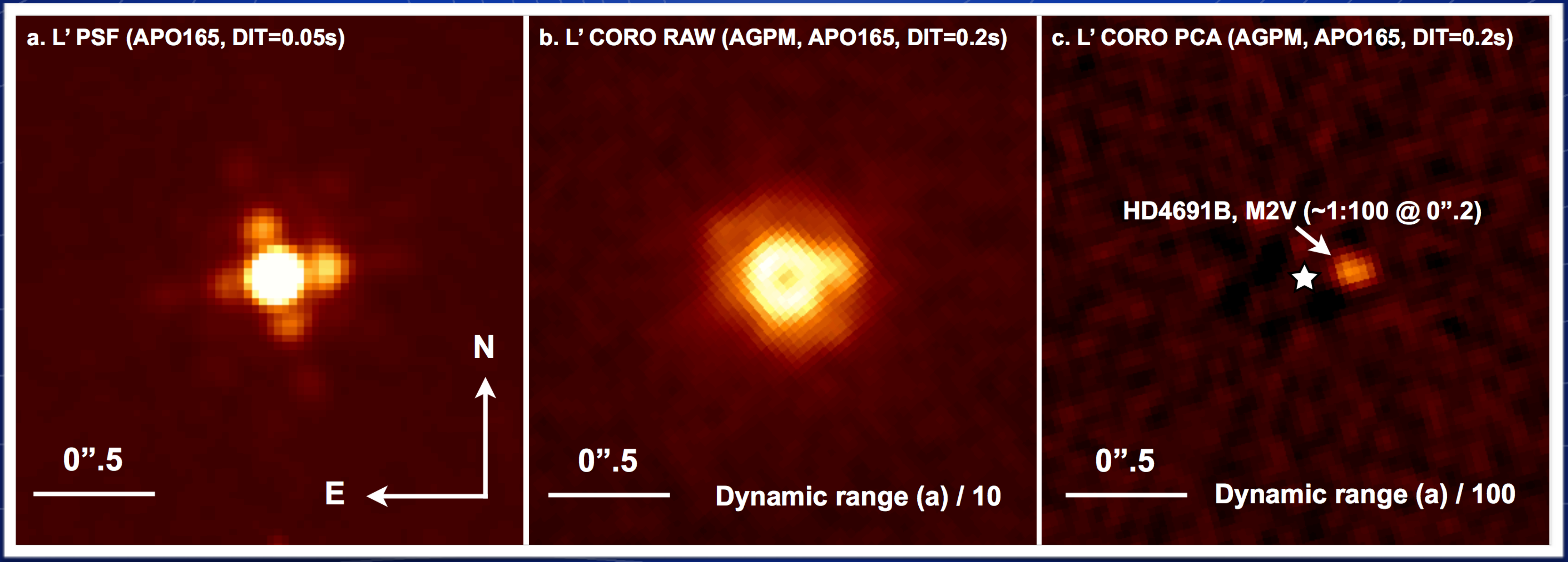


AGPM FIRST LIGHT @ NACO (DEC 2012)

- worked out of the box with available Lyot stops
- serendipitous discovery of M2V at 2λ/D from F0V

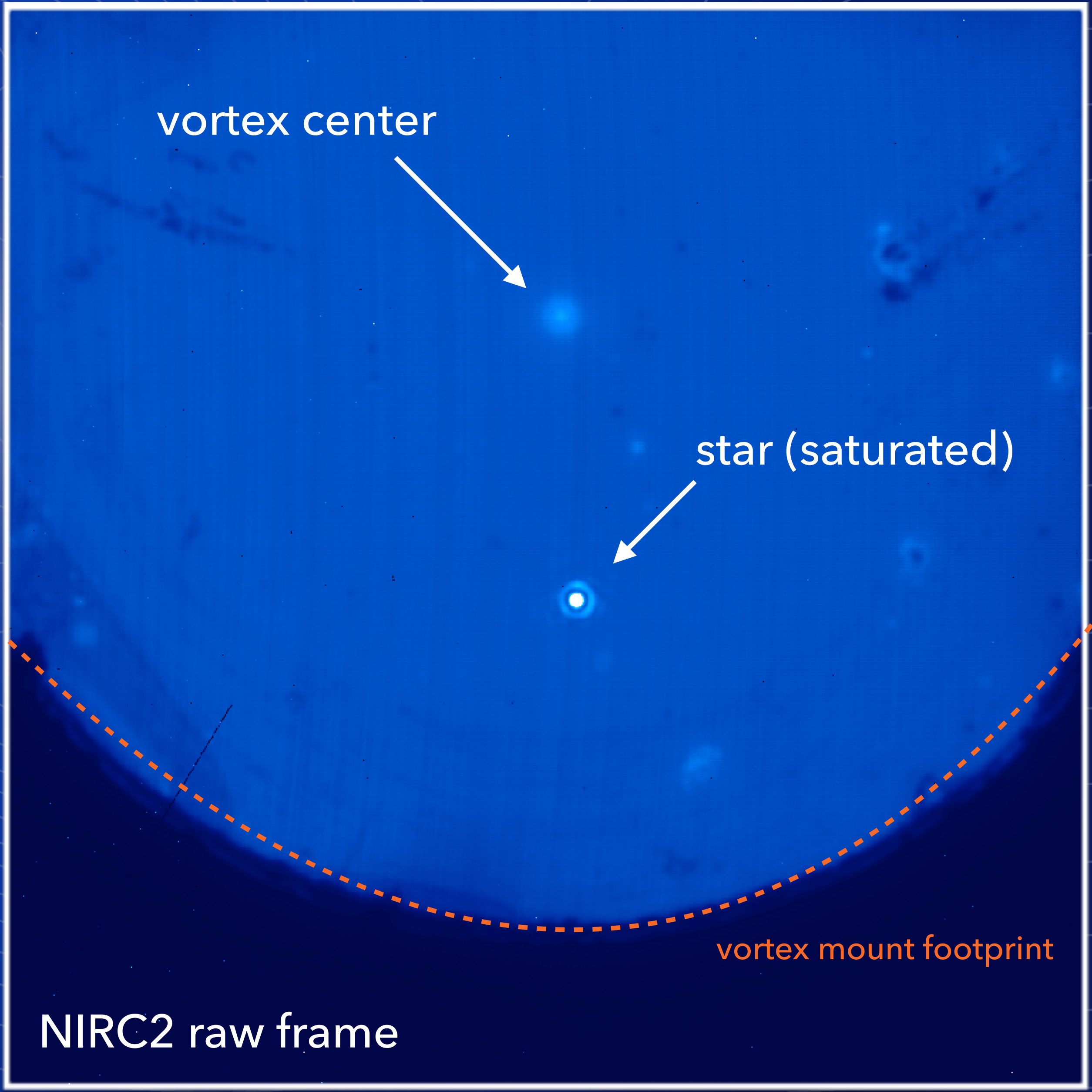


Mawet et al. (2013)



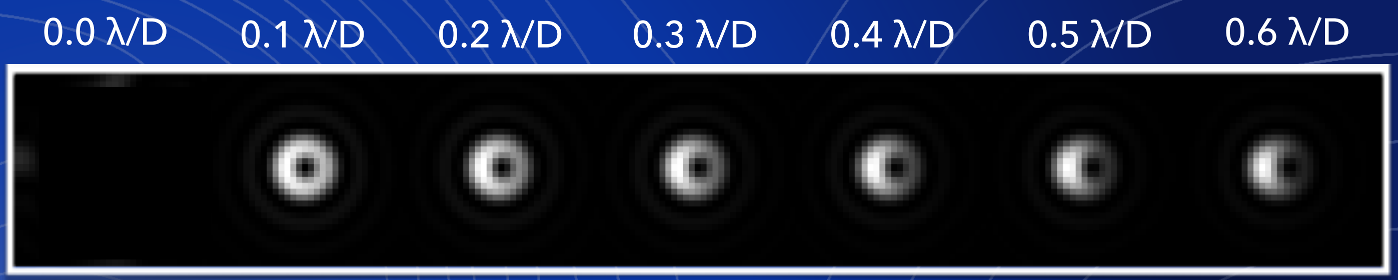
ON-SKY OPERATIONS: THE VORTEX GLOWS!

- thermal emission outside pupil partly diffracted inside pupil by vortex
- seen in all instruments (vortex upstream cold stop)
- removed by background subtraction
- useful for centering



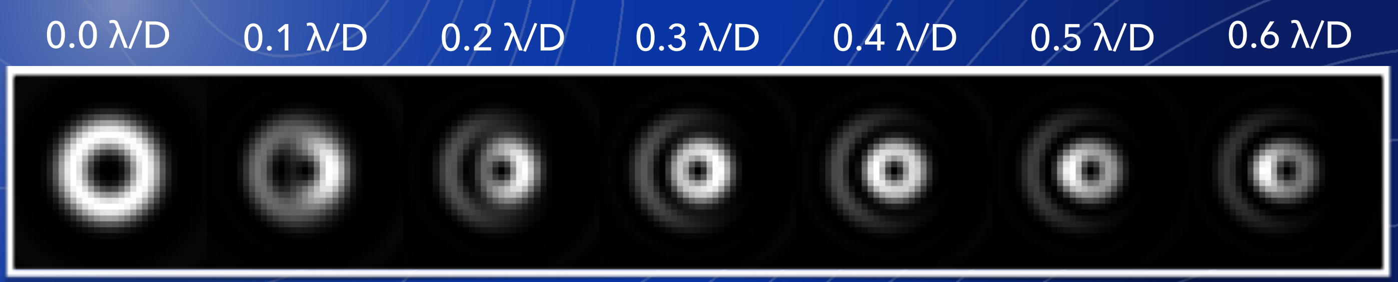
ON-SKY OPERATIONS: ACQUISITION & CENTERING

- pointing errors create asymmetric « donut »



w/o central obstruction

- central obstruction changes the expected behavior of the donut



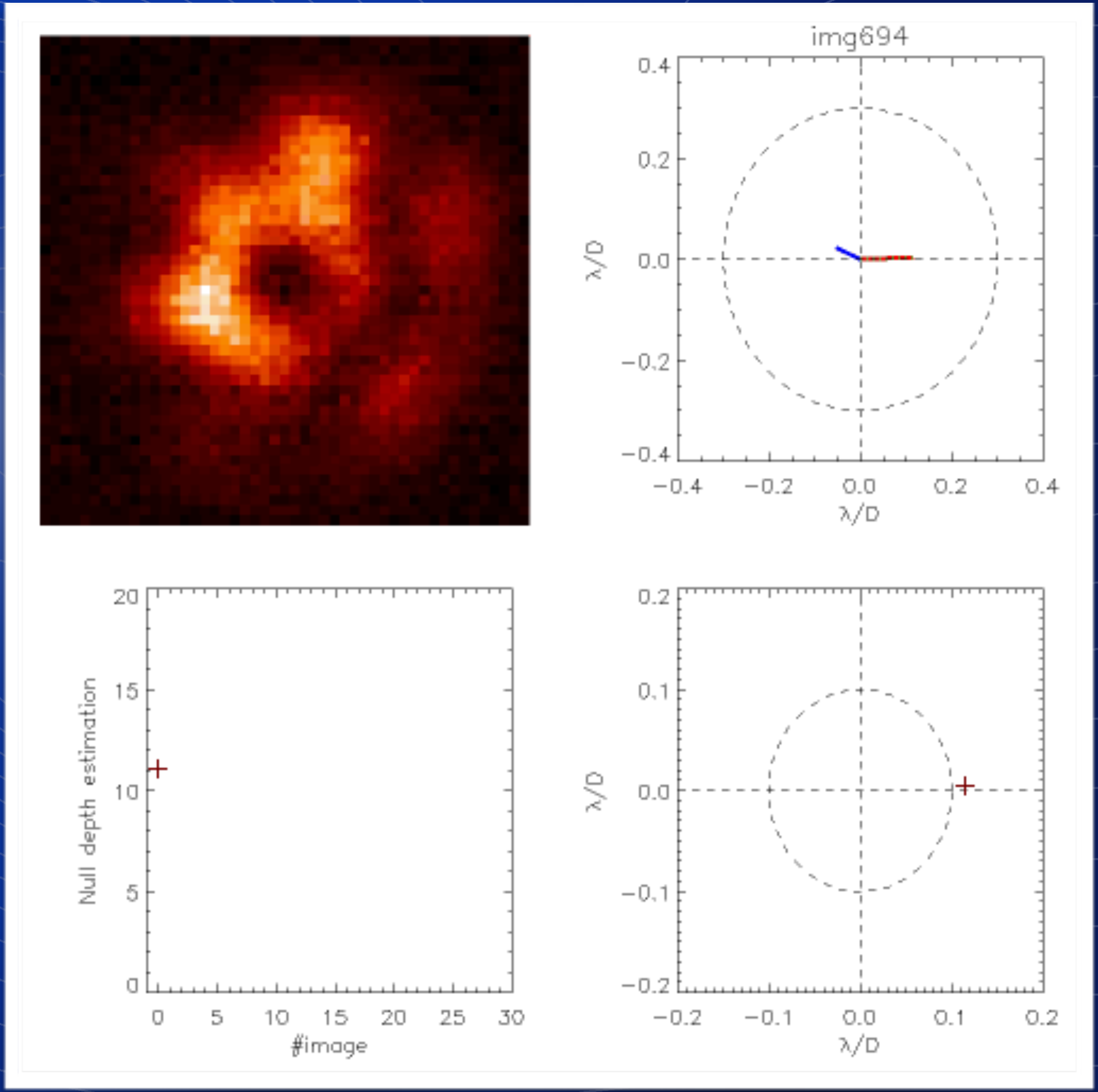
w/ central obstruction

- need modeling to infer pointing error from image (QACITS algorithm)
- can be used to control pointing at low frequency

Huby et al. 2015

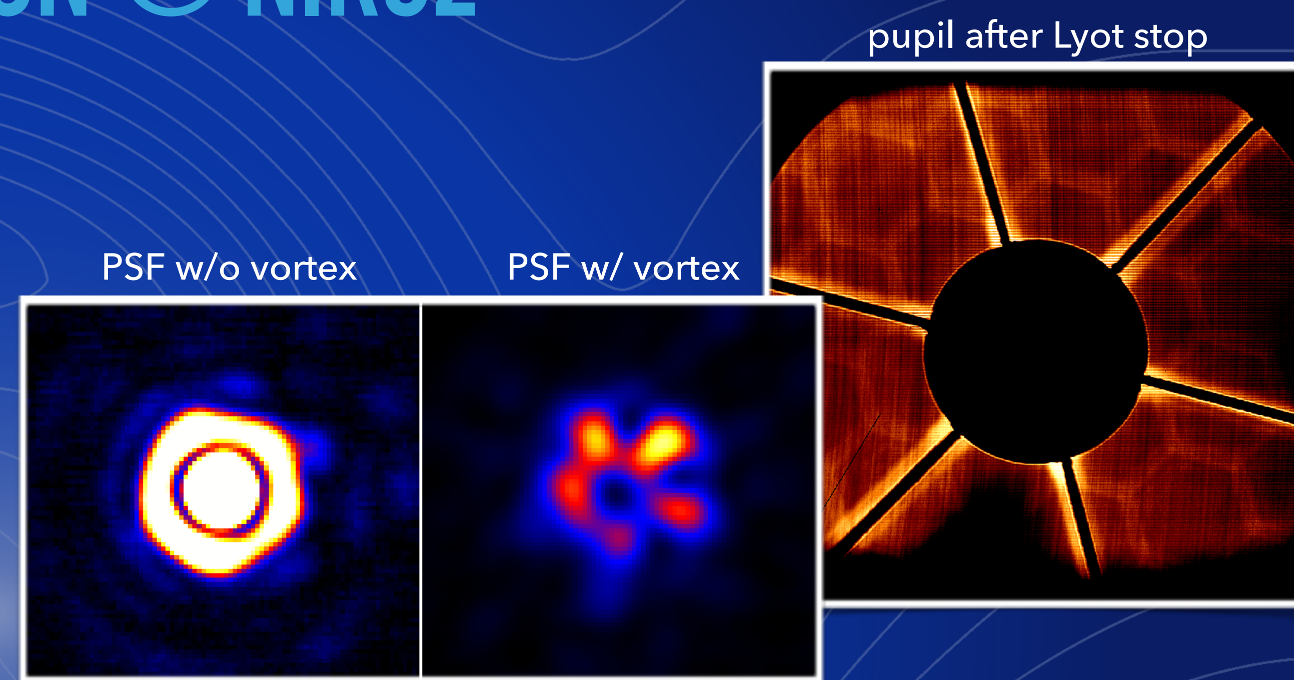
CLOSED-LOOP CENTERING CONTROL

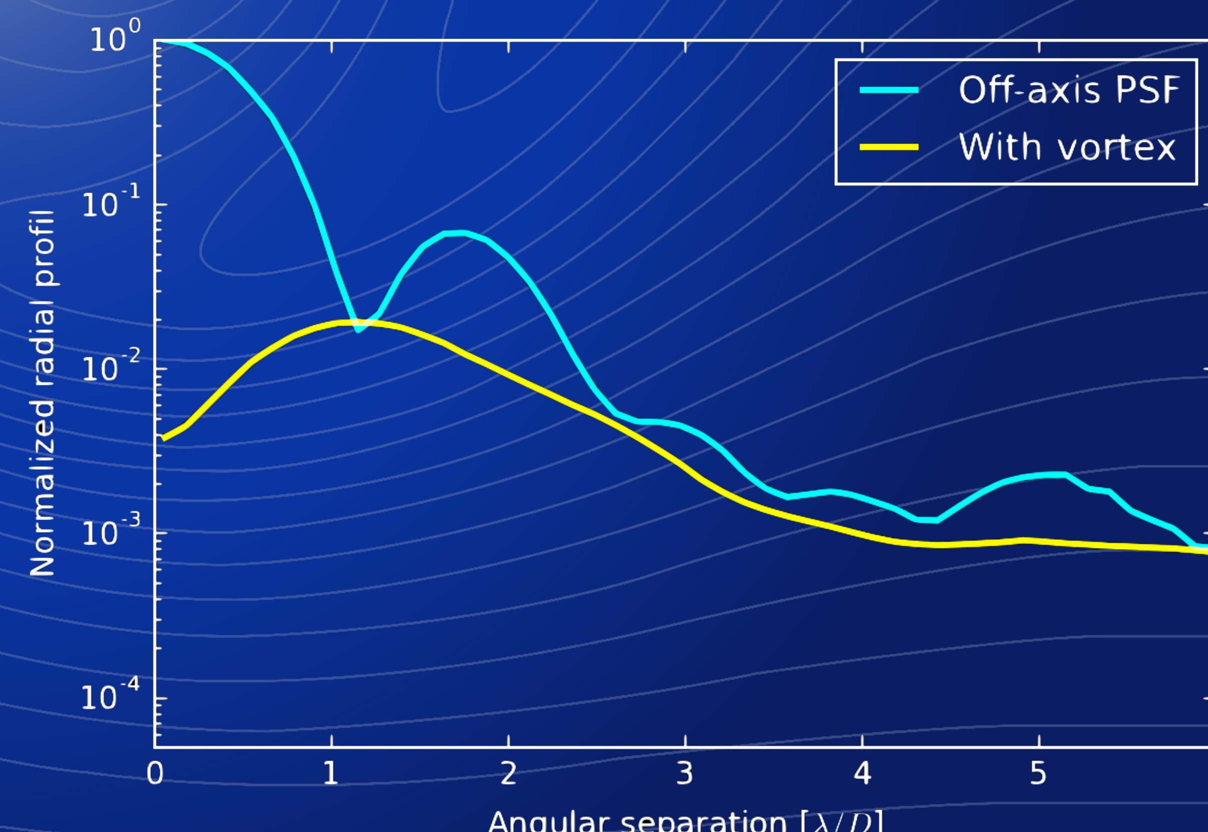
- fully automated vortex operations with QACITS validated on NIRC2
  - includes acquisition & calibration
- ensures consistant centering and data quality
- rms jitter ~ 0.02 λ/D (2 mas) @ 0.03 Hz

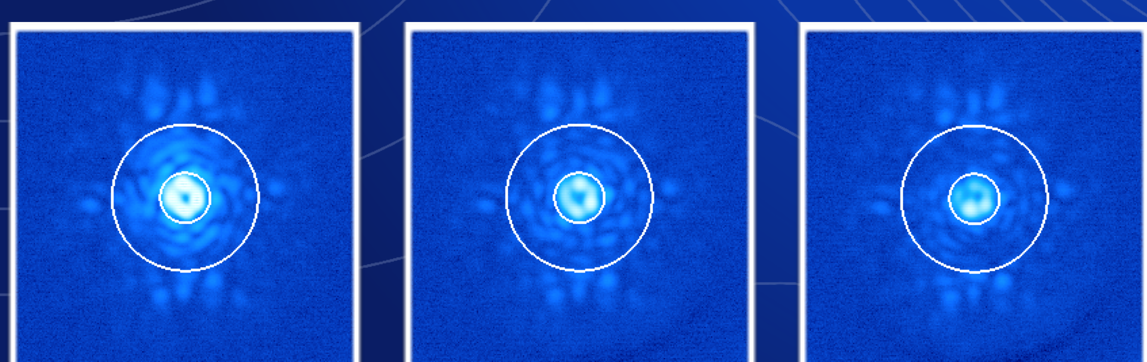


ON-SKY STARLIGHT CANCELLATION @ NIRC2

- on-sky extinction limited by
  - pupil geometry / Lyot stop
  - AO residuals
  - non-common path aberrations
- daytime speckle nulling helps reduce NCPA … but NIRC2 upgrade needed!



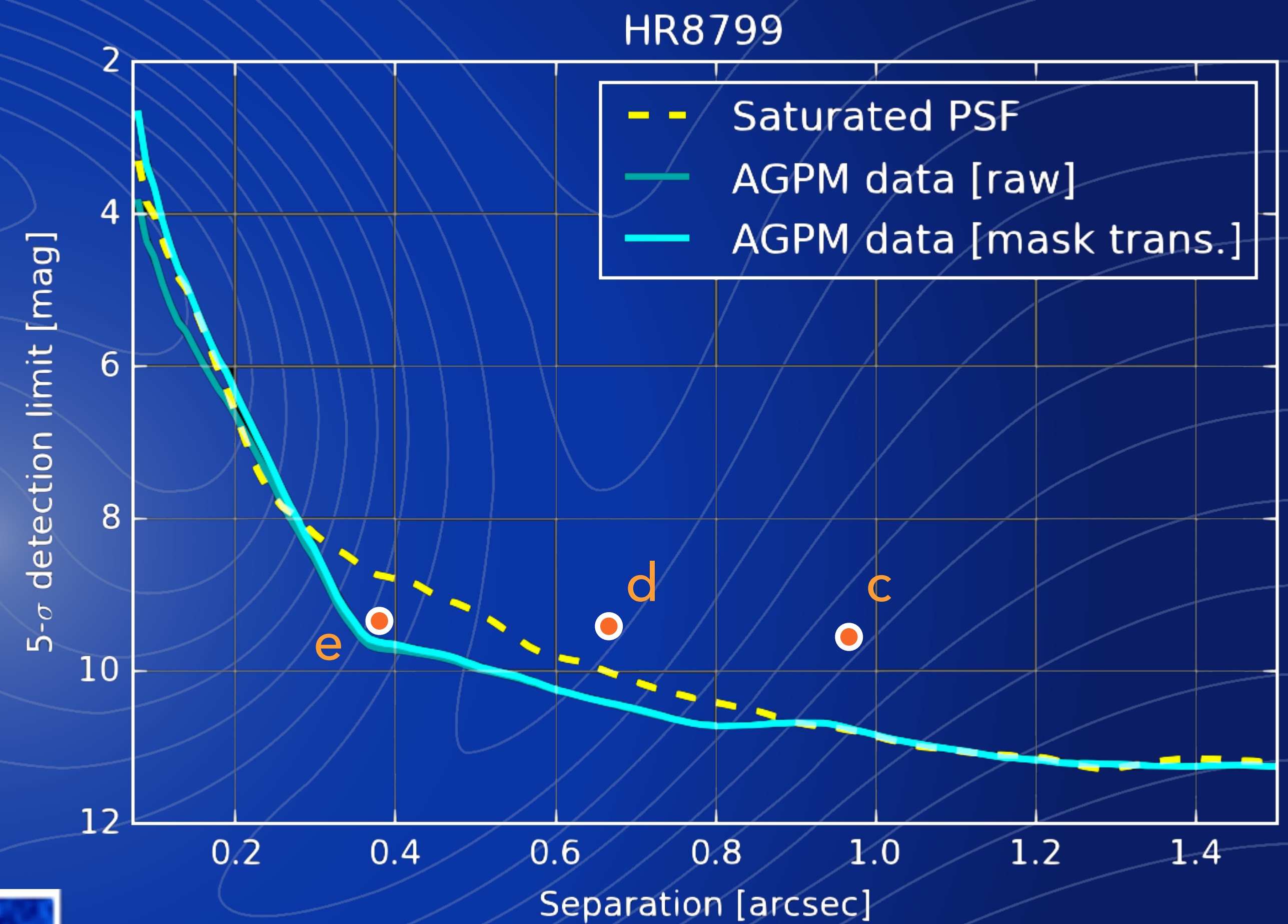


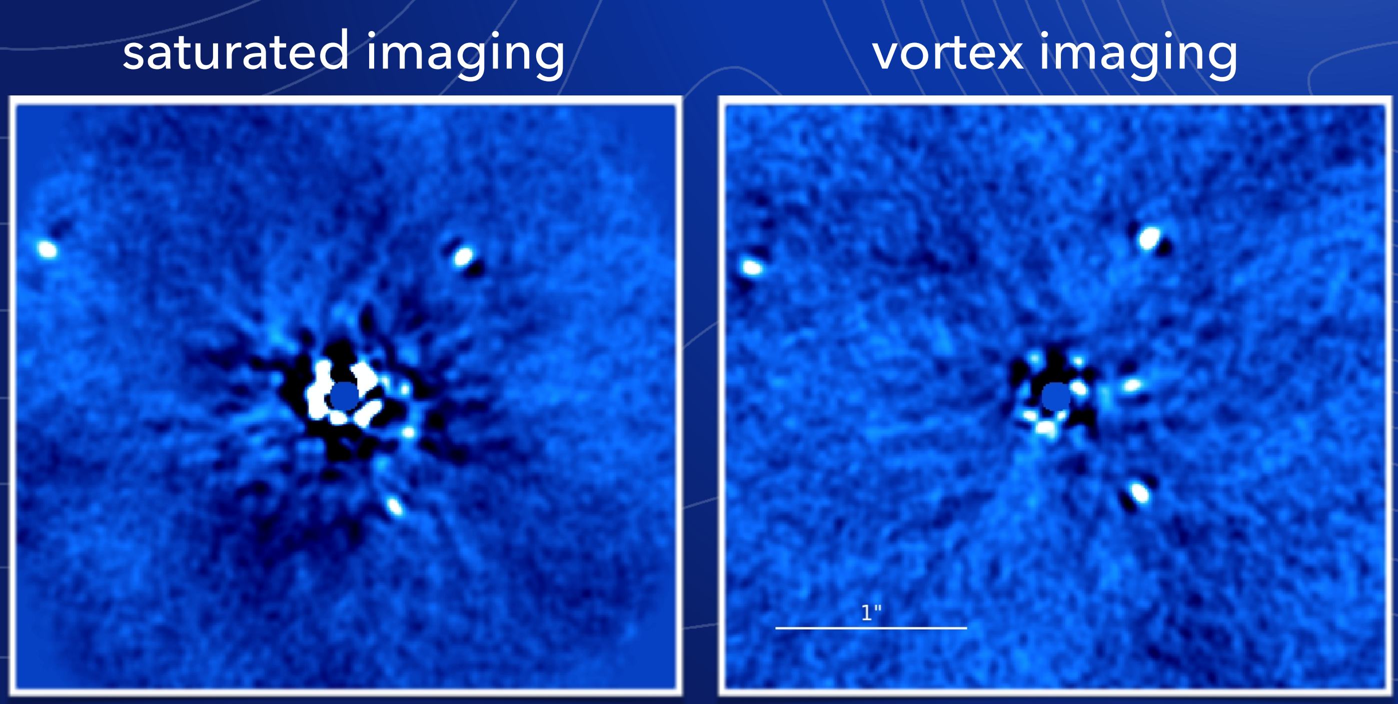


Bottom et al. 2016

IMPROVEMENT IN DETECTION LIMITS @ NIRC2

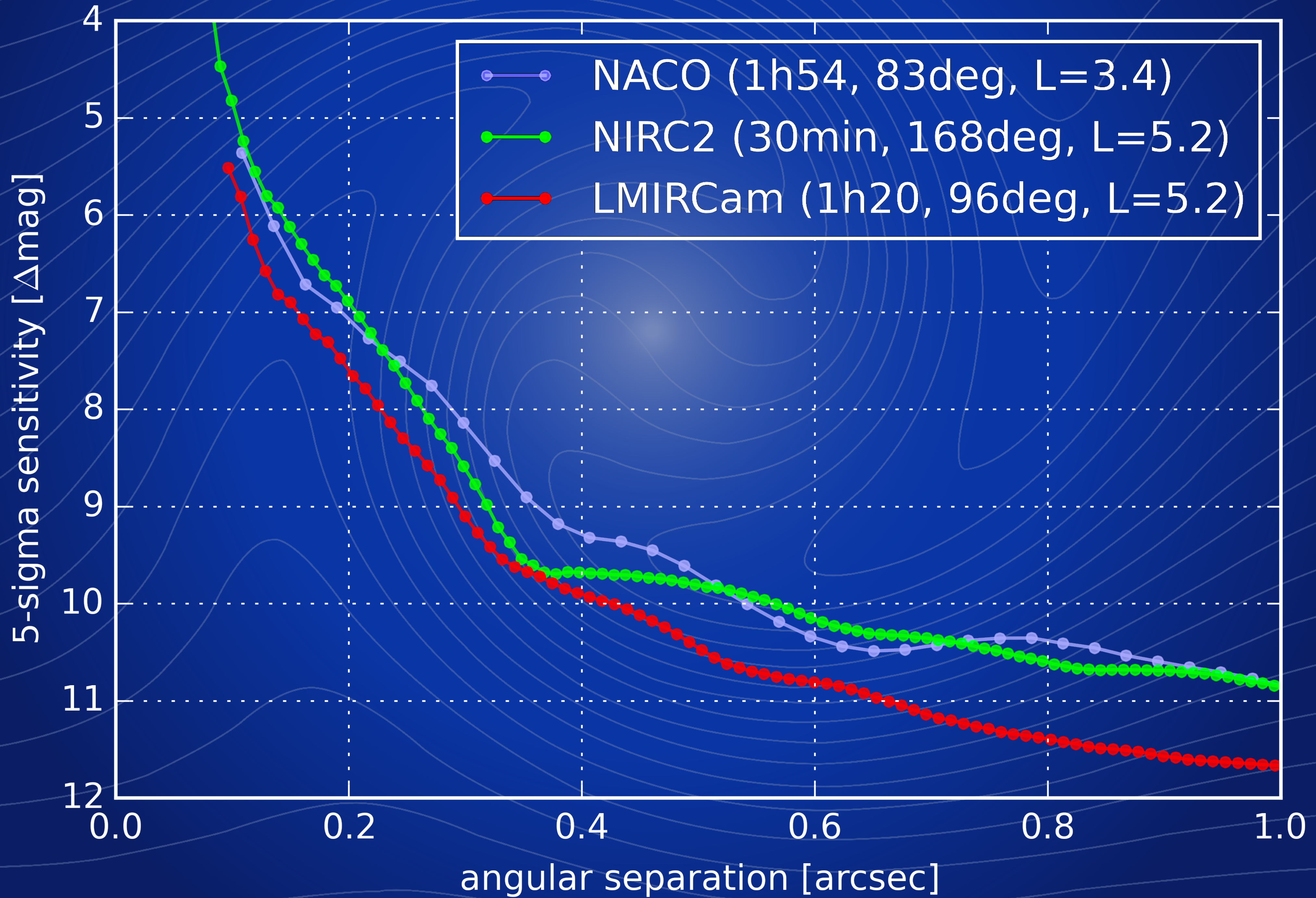
- obvious gain in 3–10 λ/D region (0.25" – 0.8")
- vortex reduces throughput @ 1-2 λ/D





comparison based on two HR8799 data sets with similar integration time and parallactic angle rotation, processed using a standard PCA-ADI algorithm

VORTEX PERFORMANCE ON VARIOUS INSTRUMENTS

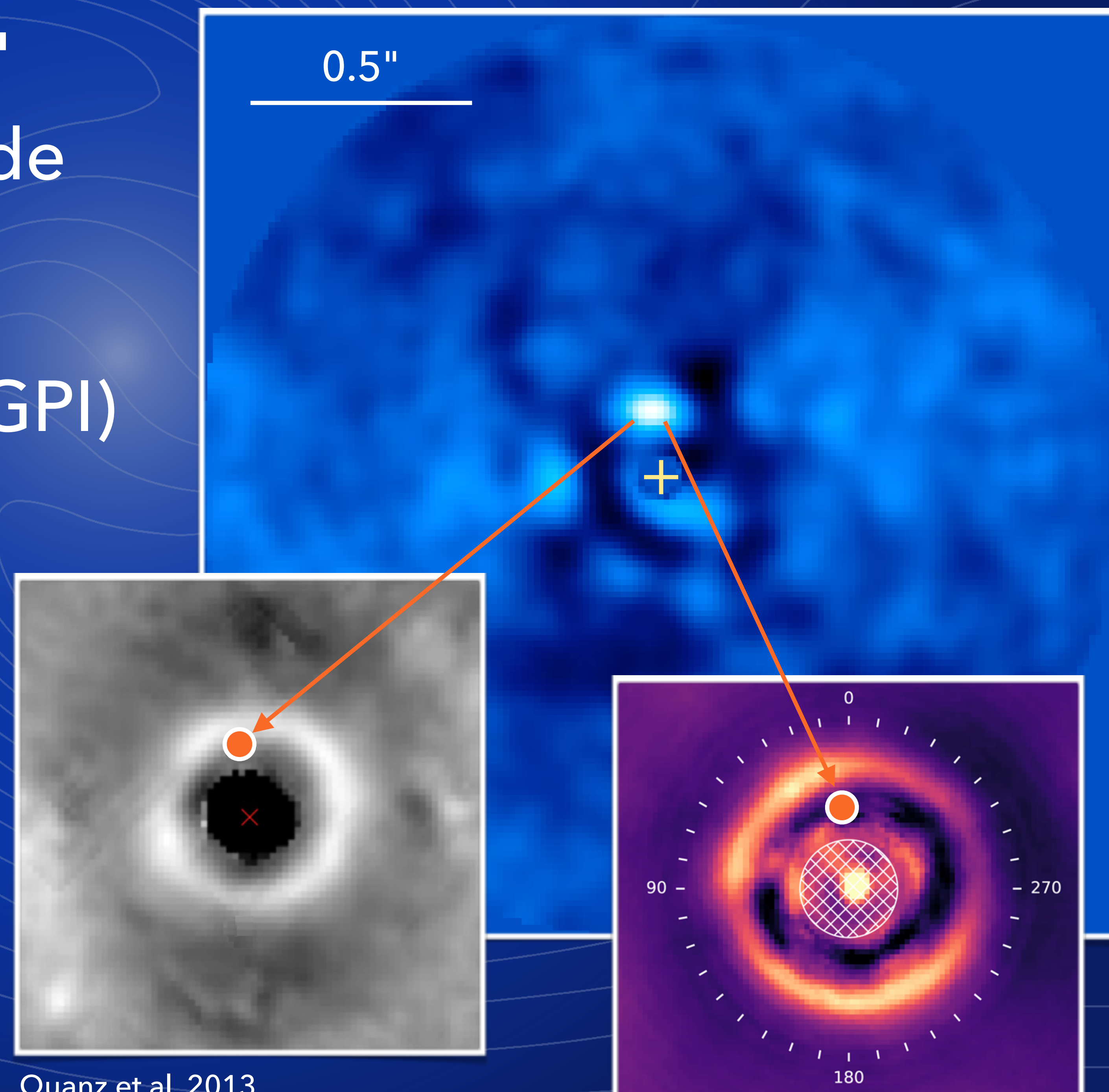


SELECTED SCIENTIFIC RESULTS

EARLY SCIENCE @ VLT/NACO: HD 169142

- point-like source at 0.15" from Herbig Ae star, inside H-band PDI inner cavity
- not detected at J band (GPI) nor H-K bands (MagAO)
- possible explanations
  - accreting protoplanet?
  - disk feature?

Biller et al. 2014, Reggiani et al. 2014



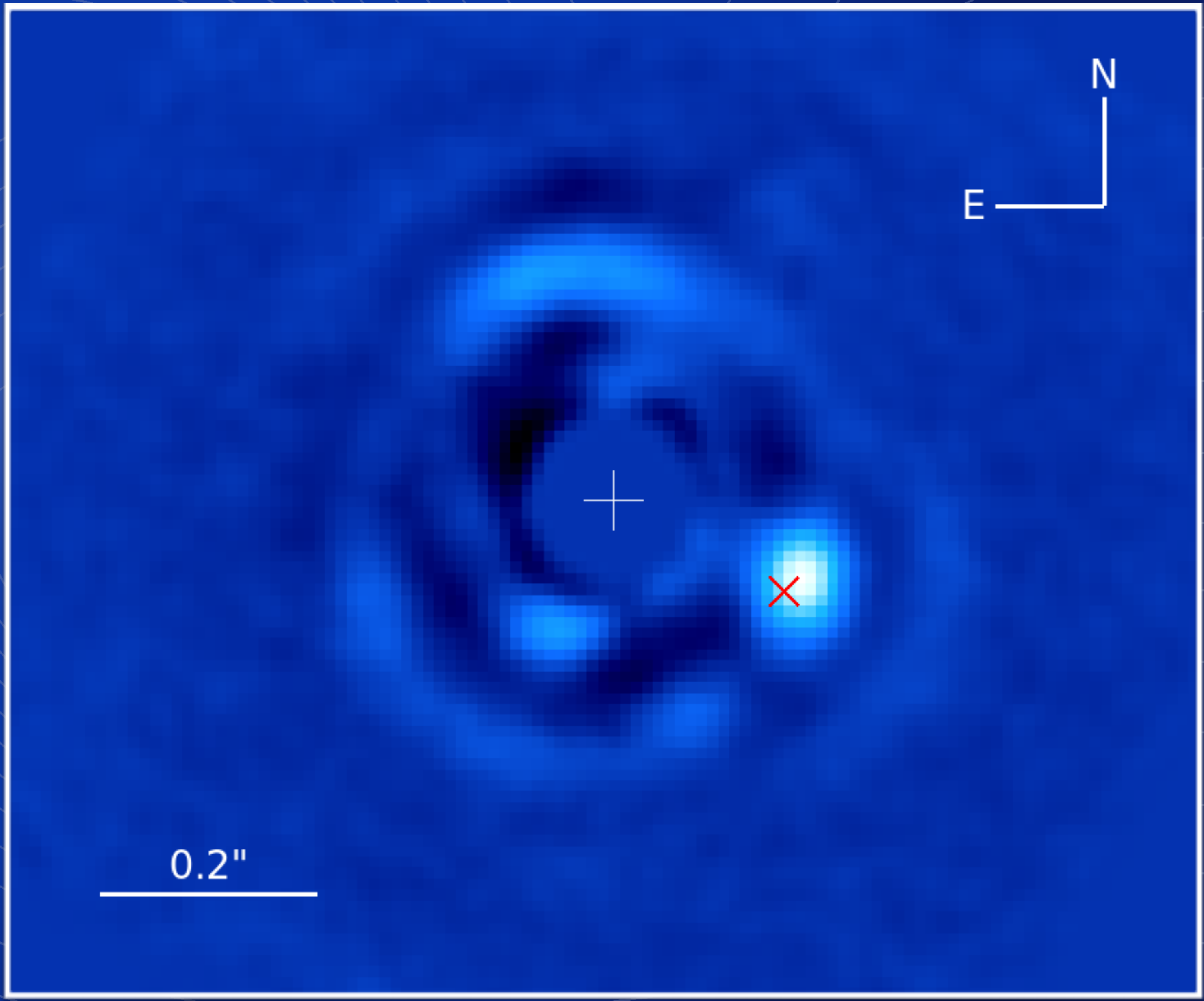
Quanz et al. 2013

Ligi et al. 2018

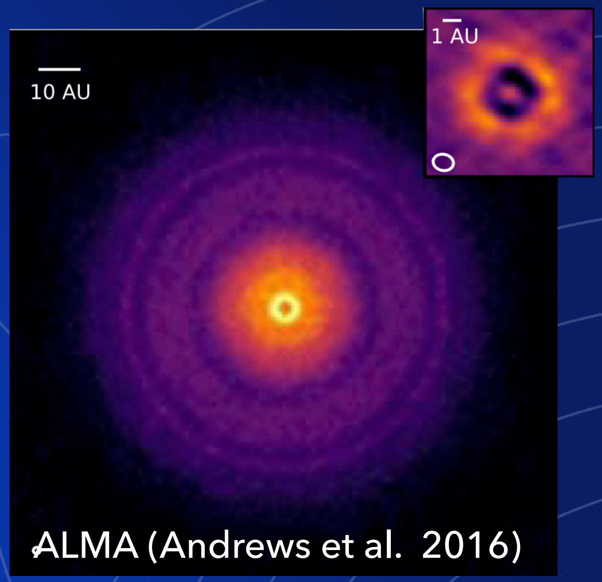
FIRST LIGHT @ KECK/NIRC2: HIP 79124

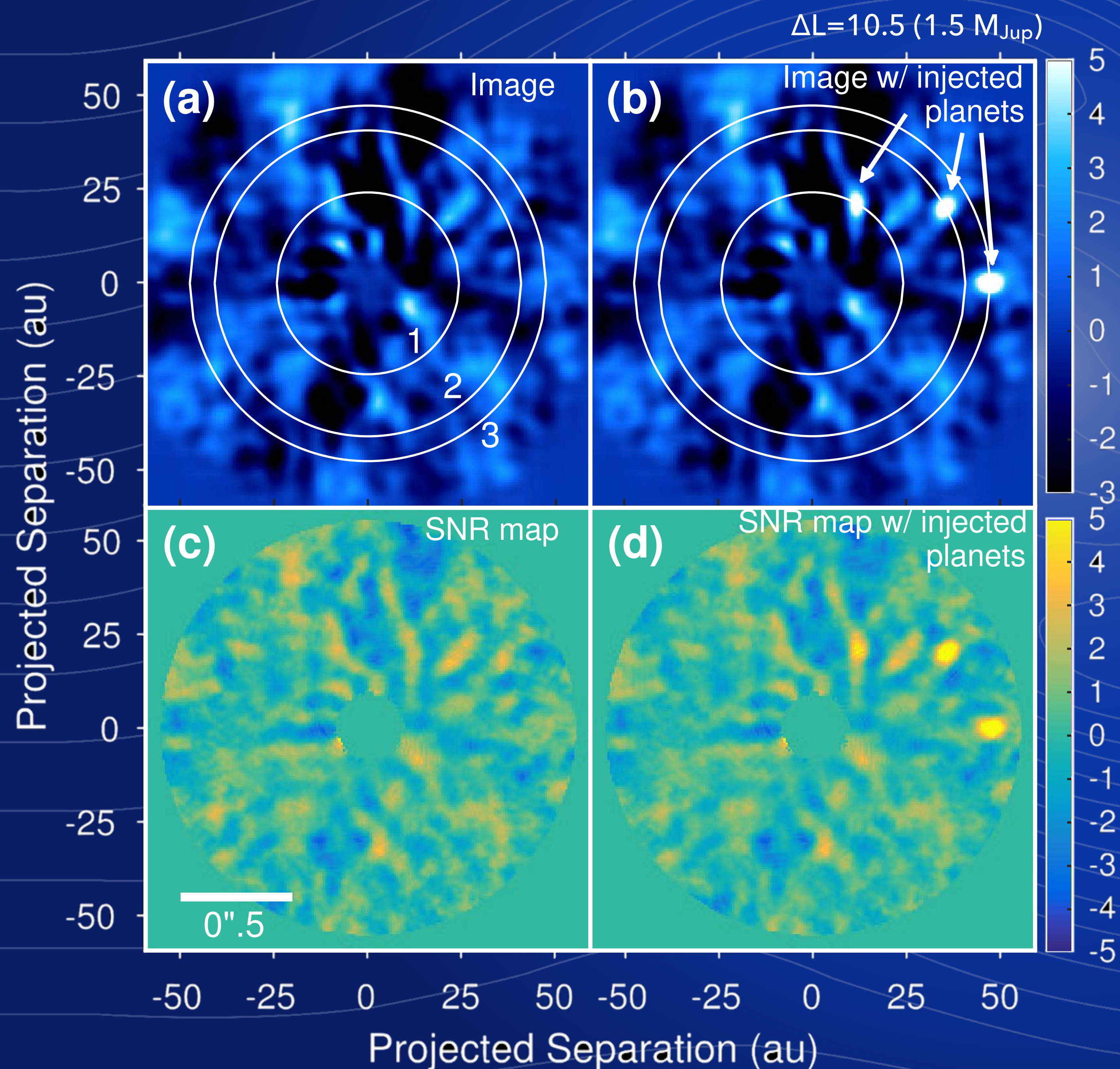
- brown dwarf around Sco-Cen A0 star
- 177 mas, ΔL=4.3
- only detected with aperture masking so far
- recovered with NIRC2+vortex during commissioning

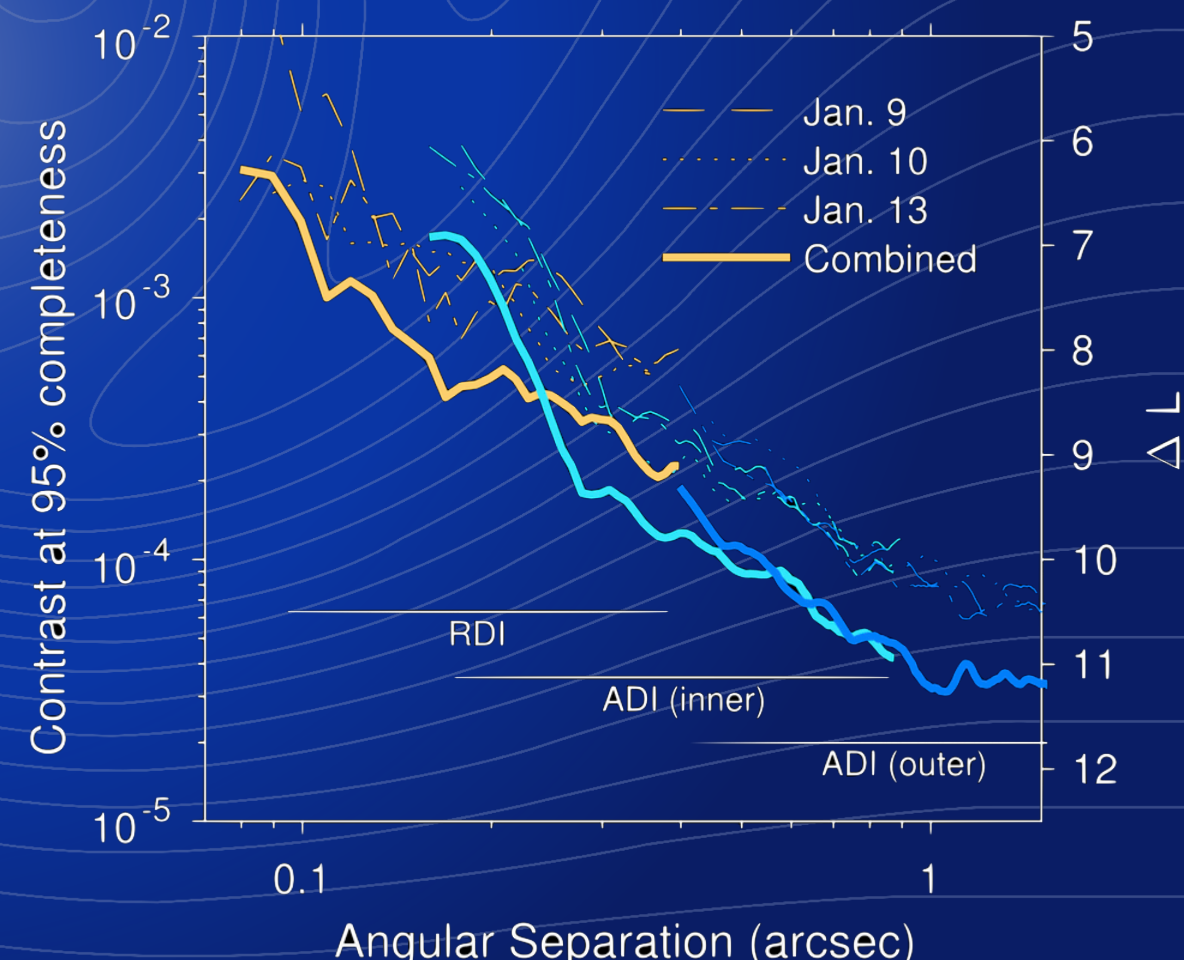
Serabyn et al. (2017)



KECK CORONAGRAPHIC DEEP FIELD: TW HYA



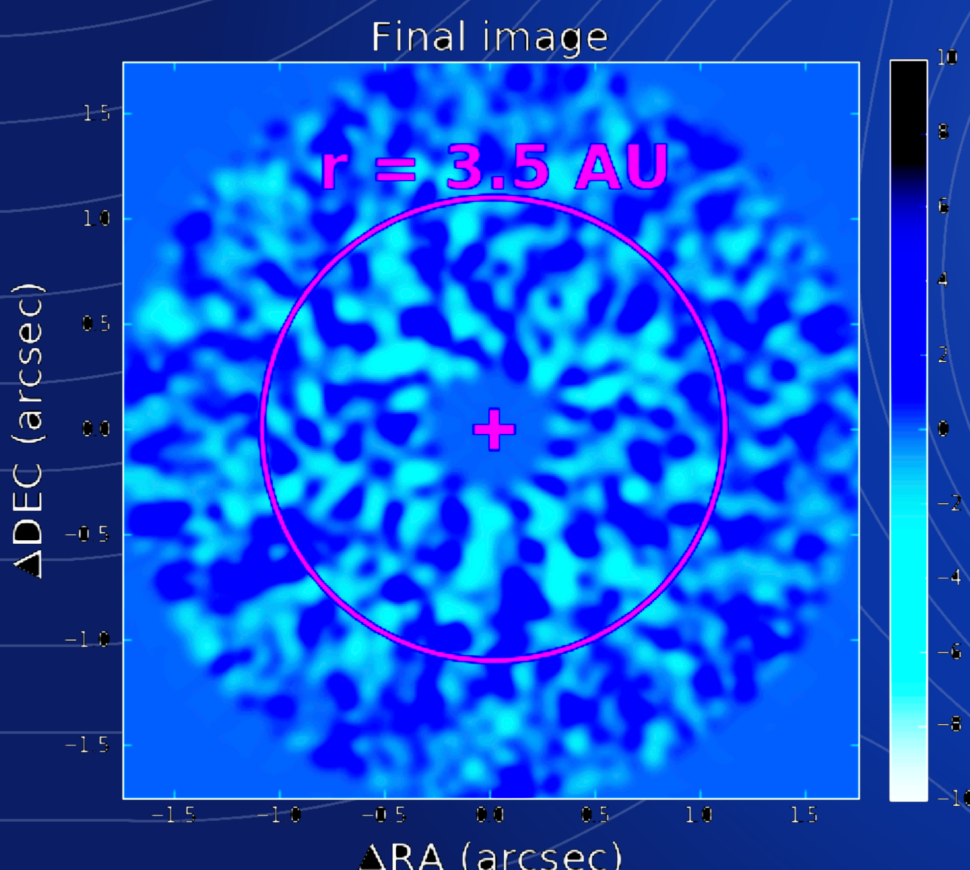


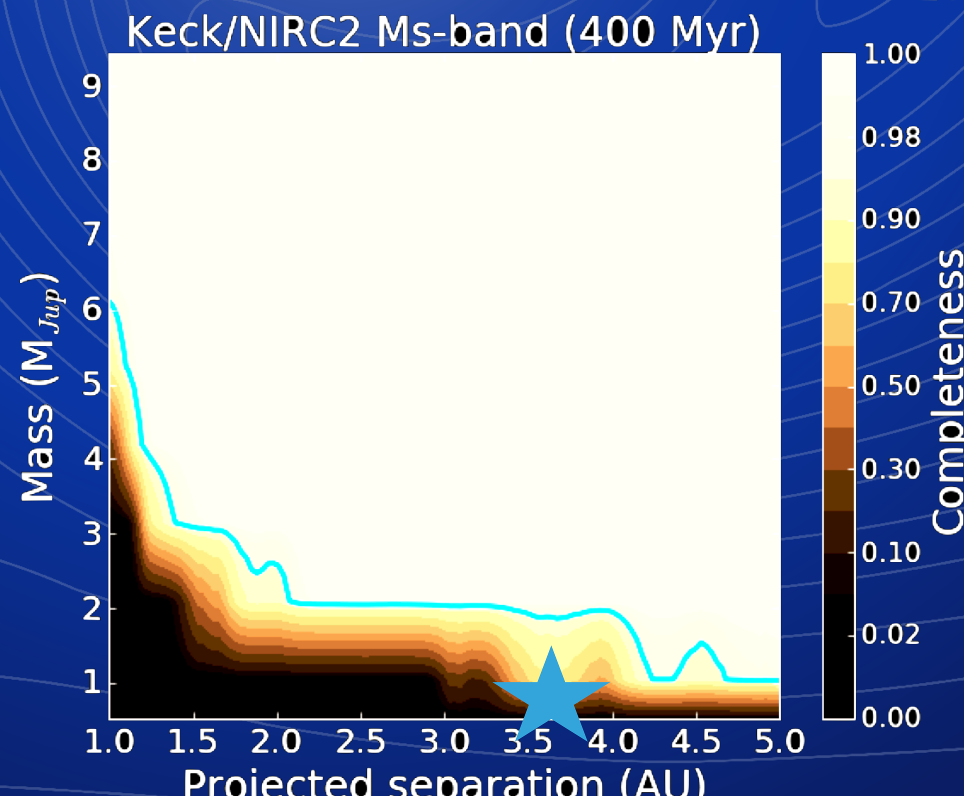


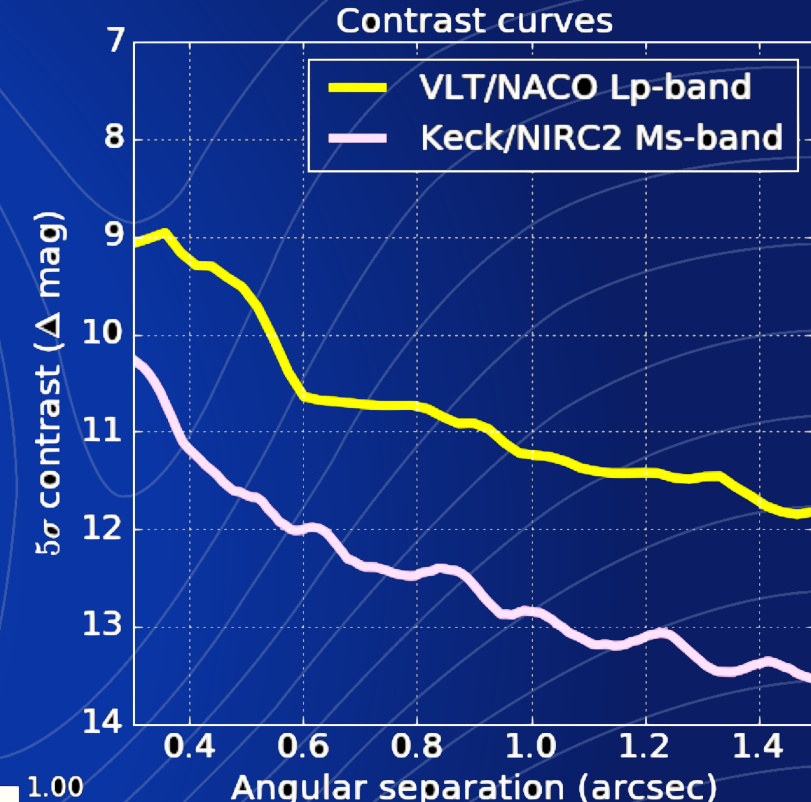
Ruane et al. (2017)

KECK CORONAGRAPHIC DEEP FIELD: EPS ERIDANI

- 0.8 MJup companion would have been detected if eps Eri was 200 Myr old



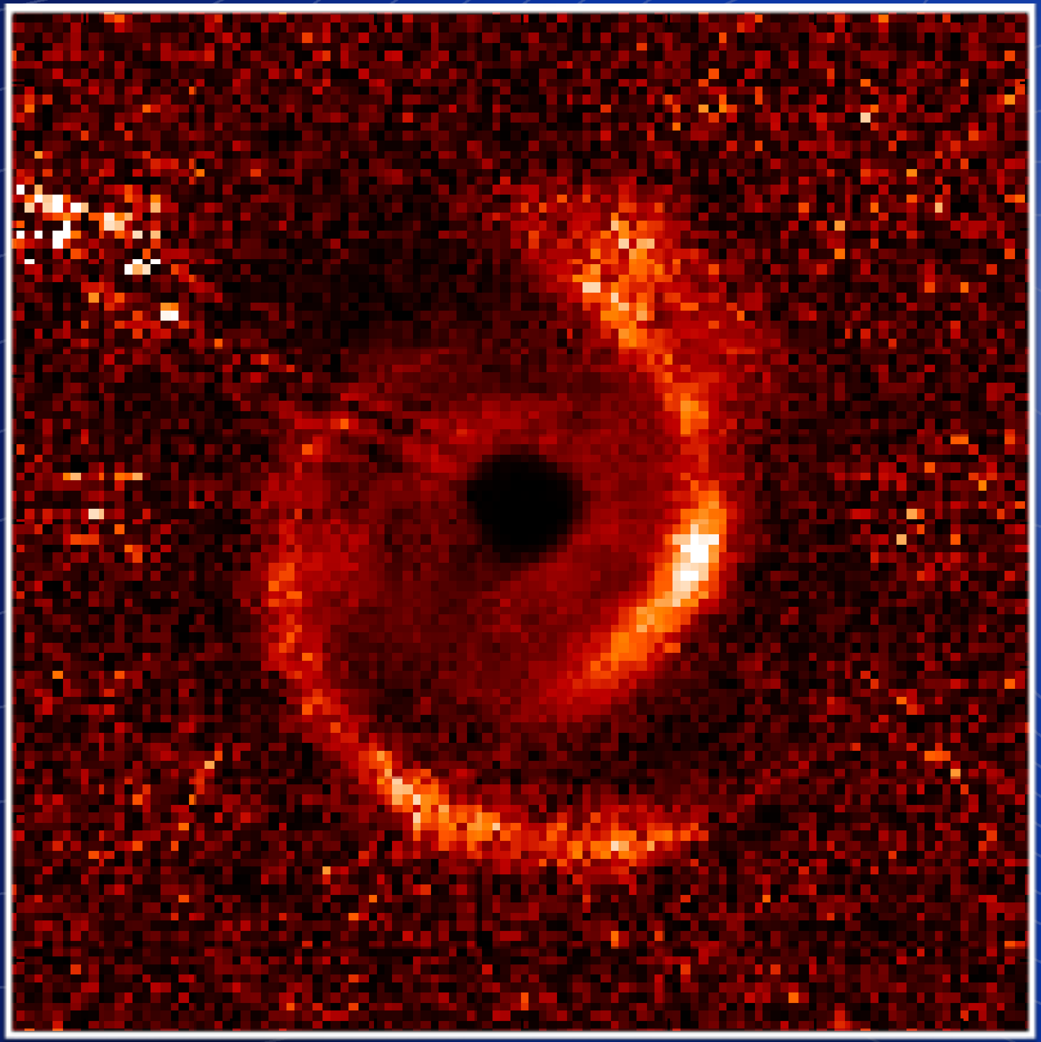




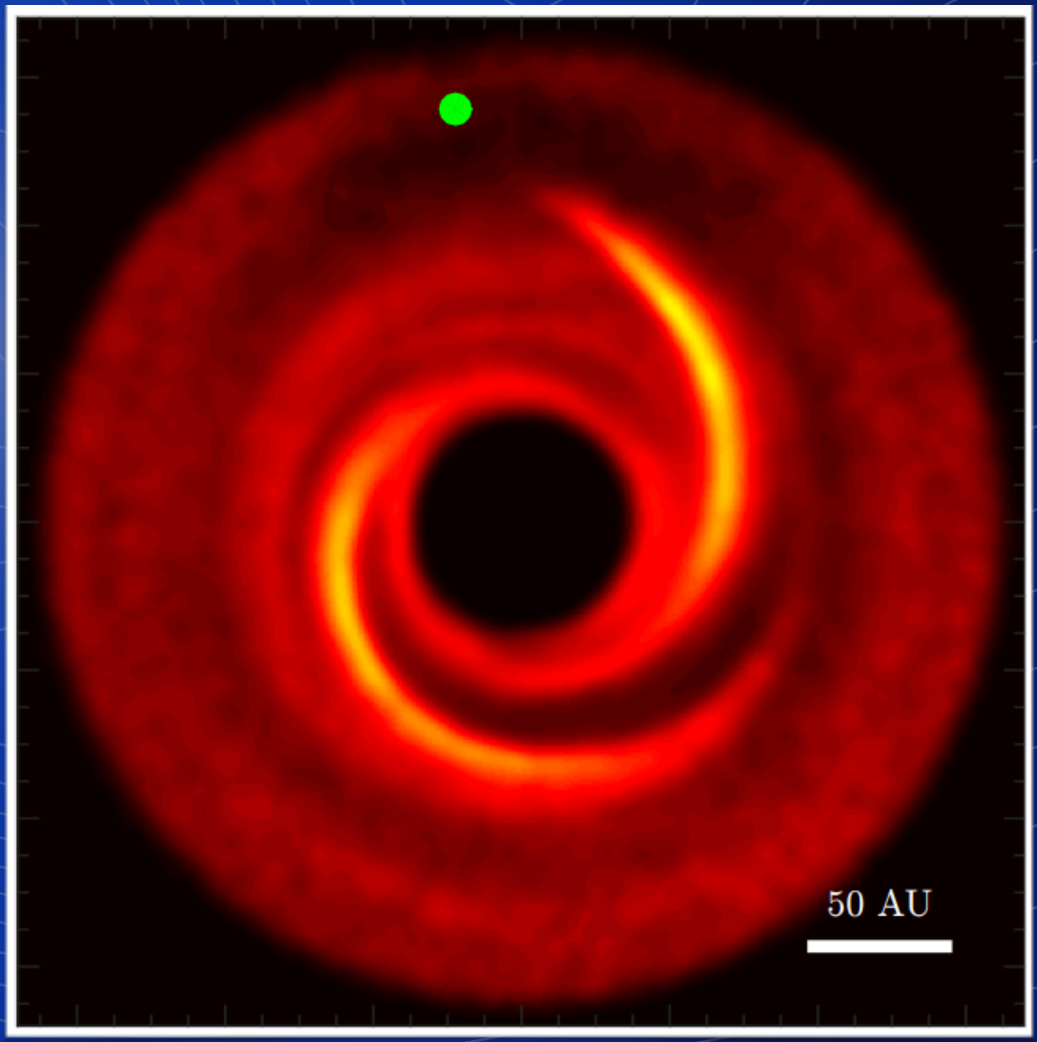
Mawet et al. (in press)

TRANSITION DISK SURVEY (NIRC2 & NACO)

SPHERE/IRDIS Y band polarimetry (Benisty et al. 2015)

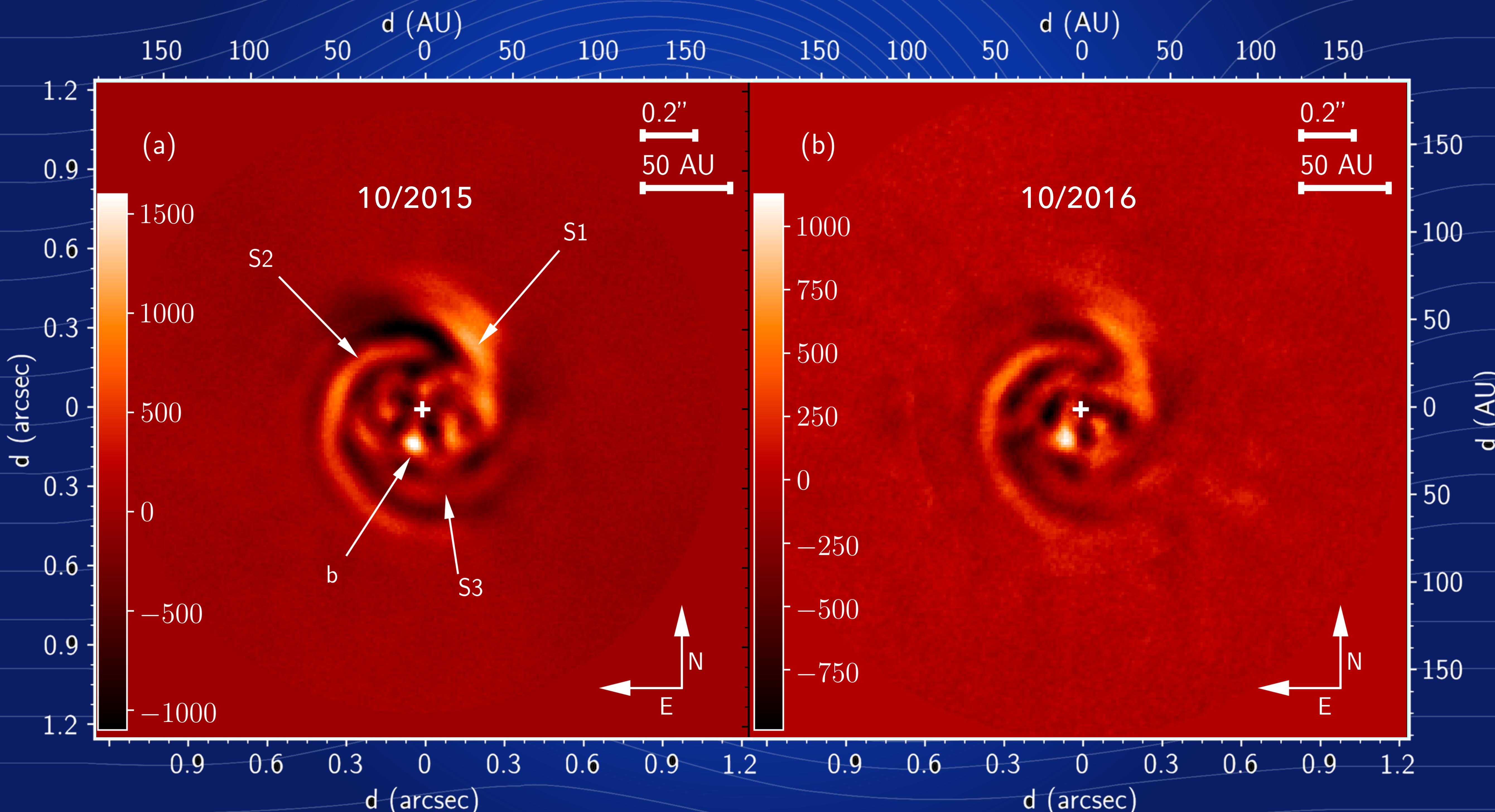


Protoplanet prediction (Dong et al. 2015)



goal: search for protoplanets at the origin of disk structures

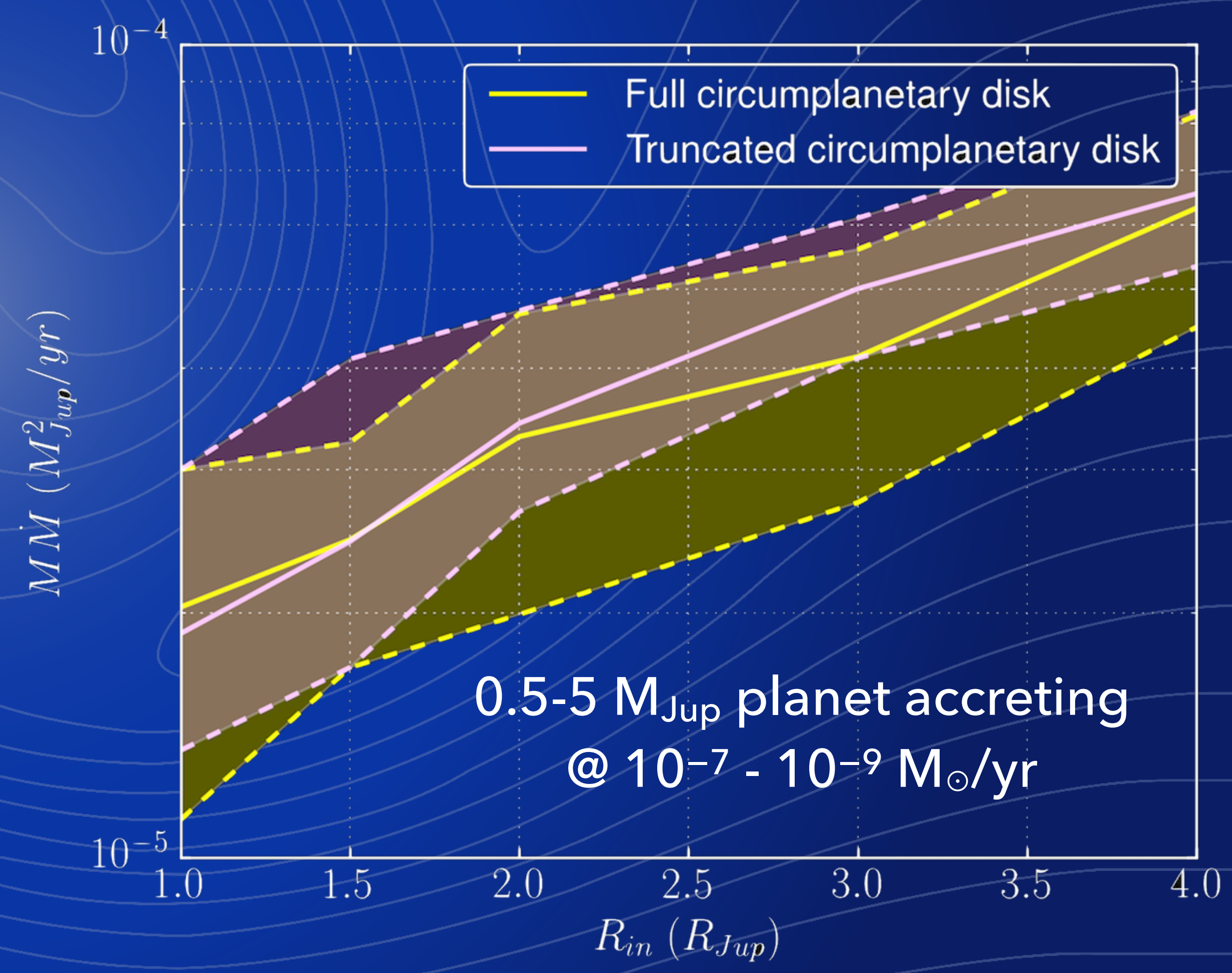
THE KECK/NIRC2 + VORTEX VIEW OF MWC758



Reggiani et al. 2018

MWC758B: A DISK-SCUPLTING PROTOPLANET CANDIDATE?

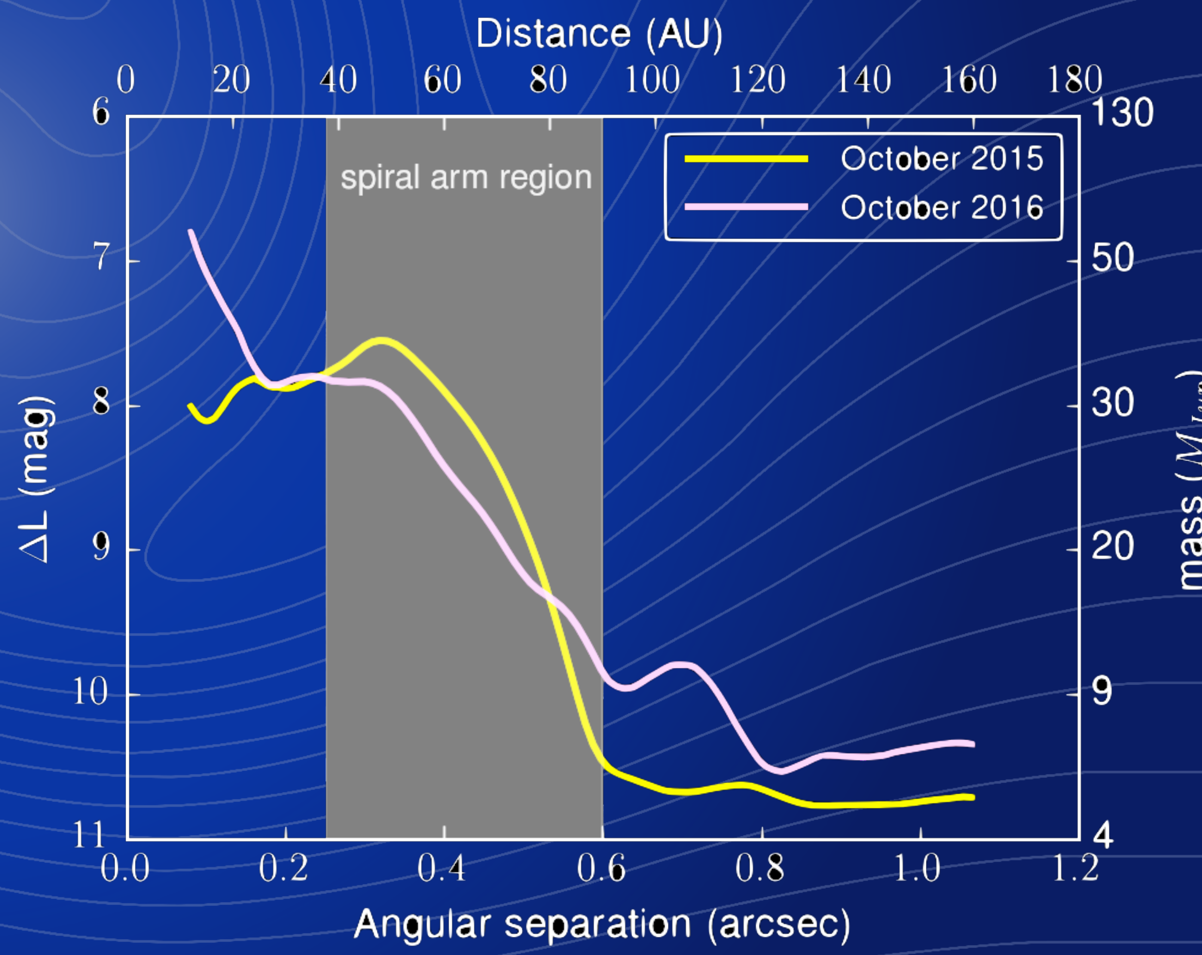
- main properties
  - 0.1'' separation (20 au), $\Delta L = 7$
  - two epochs: PA difference consistent with Keplerian rotation in 1 yr
- low probability for bckg star
- companion? needs to be <6 M_{Jup}
  → not purely photospheric emission
- conclusion: accreting protoplanet or disk feature?
  - no polarized disk emission there!



Reggiani et al. 2018

MWC758B: ORIGIN OF THE SPIRALS?

- now three spiral arms to reproduce with models
- driven by protoplanet?
  - outer planet? most likely explanation based on models, but strong constraints from observations (< 6 M_{Jup})
  - inner planet? might explain one spiral, but not all three

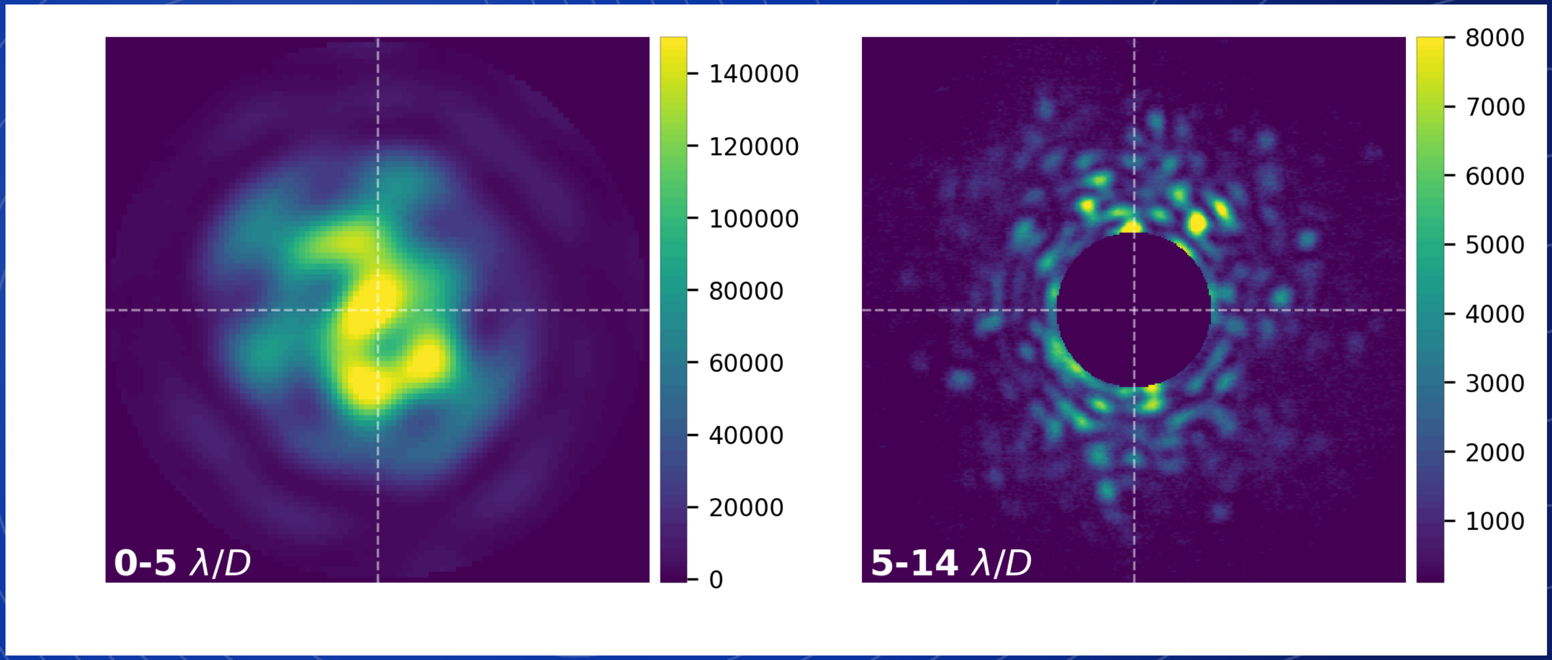


Reggiani et al. 2018

HOW TO BETTER EXPLOIT THE DATA?

- interesting science at 1-3 λ/D
  - strongly affected by residual speckles
  - non-Gaussian noise –> more false positives
  - hard to validate candidates

NIRC2+vortex image sequence



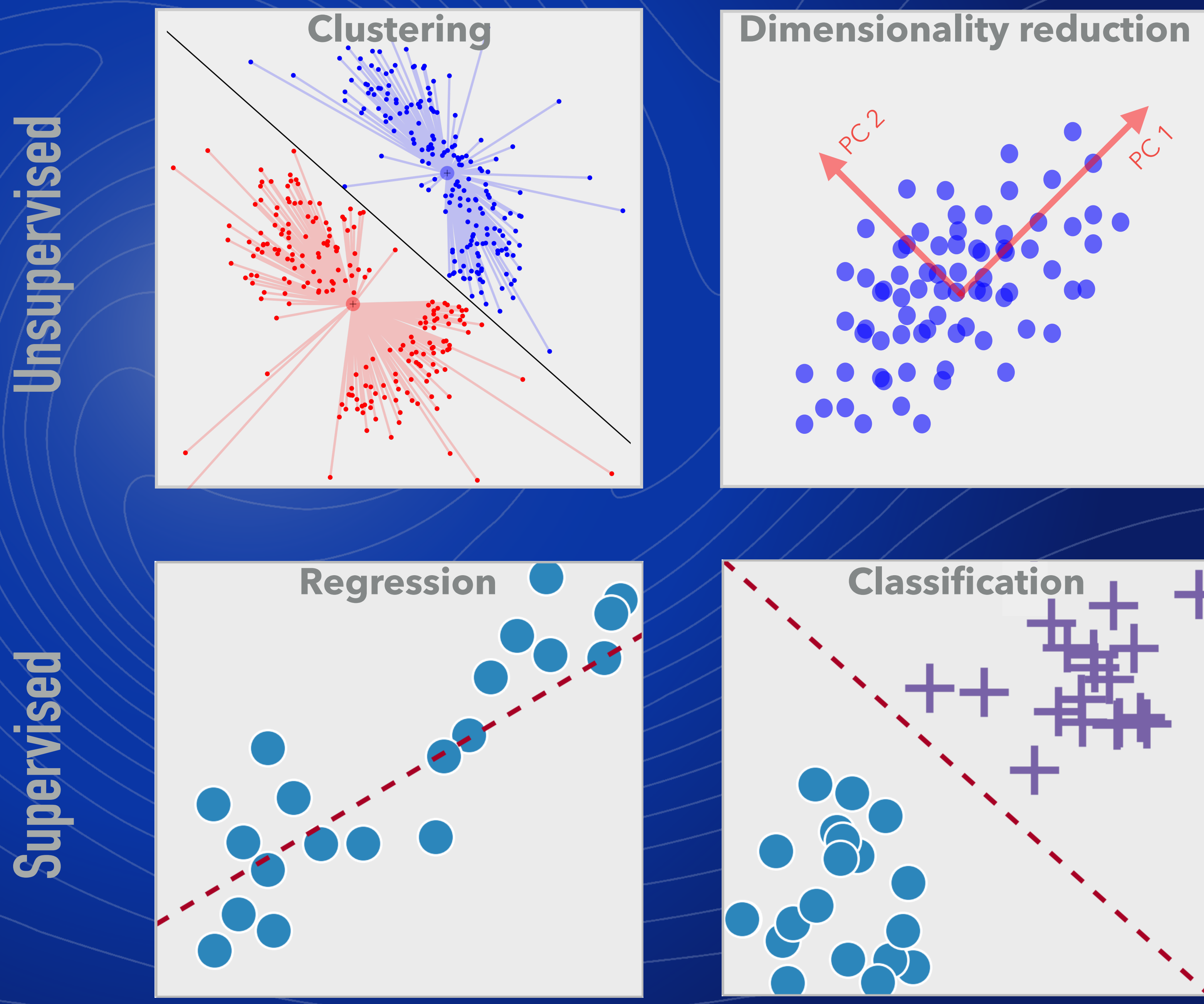
- ADI-based techniques produce SNR maps, but do not inform on nature of the candidates
- machine learning can help

VORTEX

IMAGE PROCESSING WITH MACHINE LEARNING

MACHINE LEARNING IN A NUTSHELL

- construction of algorithms that can learn from, and make predictions on data



SUPERVISED LEARNING

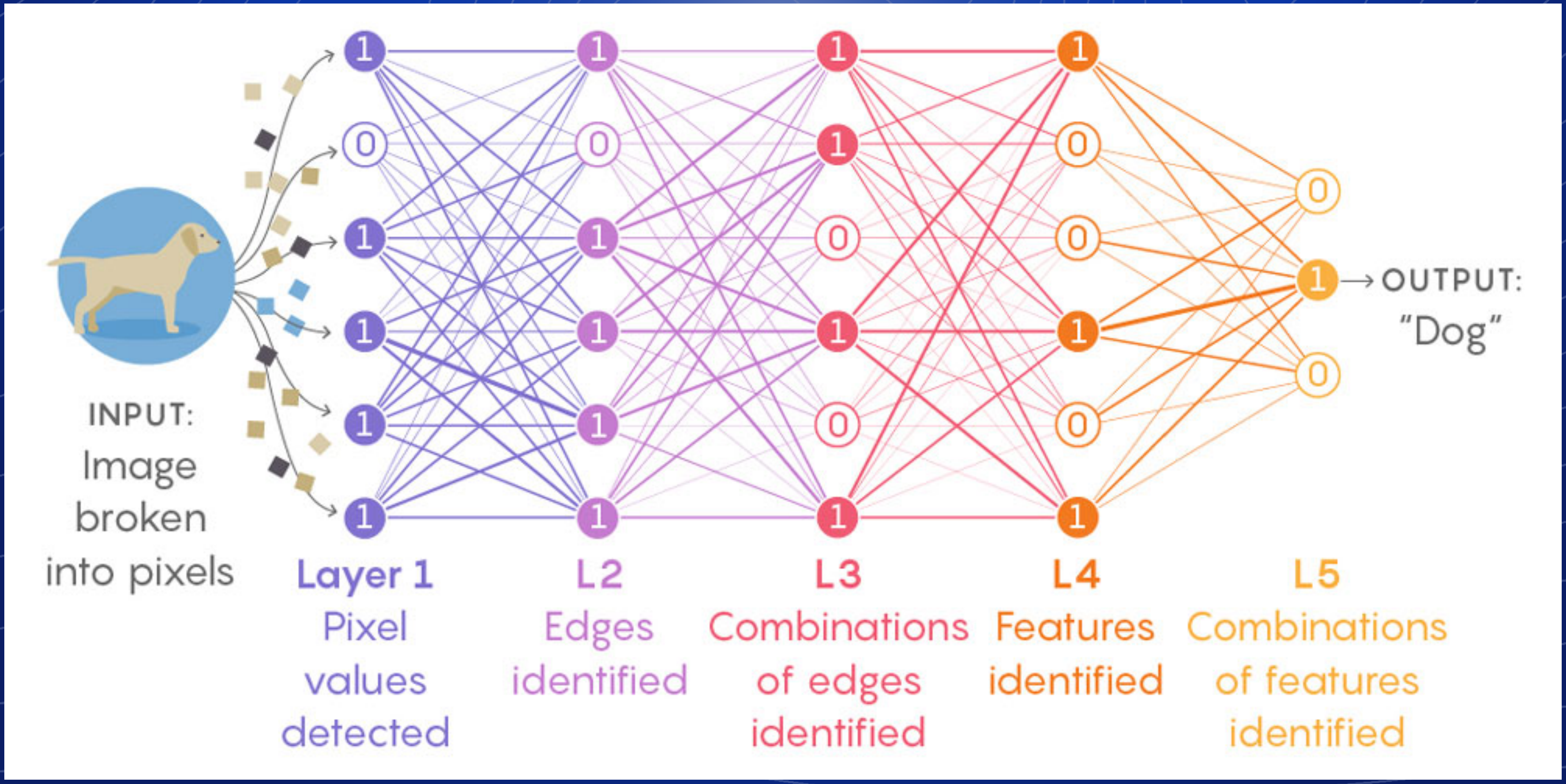
- goal: learn function f mapping input samples $\mathcal{X}$ to labels $\mathcal{Y}$ given a labeled dataset $(x_i, y_i)_{i=1,\ldots,n}$:

$$\min_{f \in \mathcal{F}} \frac{1}{n} \sum_{i=1}^{n} \mathcal{L}(y_i, f(x_i)) + \lambda \Omega(f)$$

- mapping function f can be based on a (deep) neural network

DEEP NEURAL NETWORKS

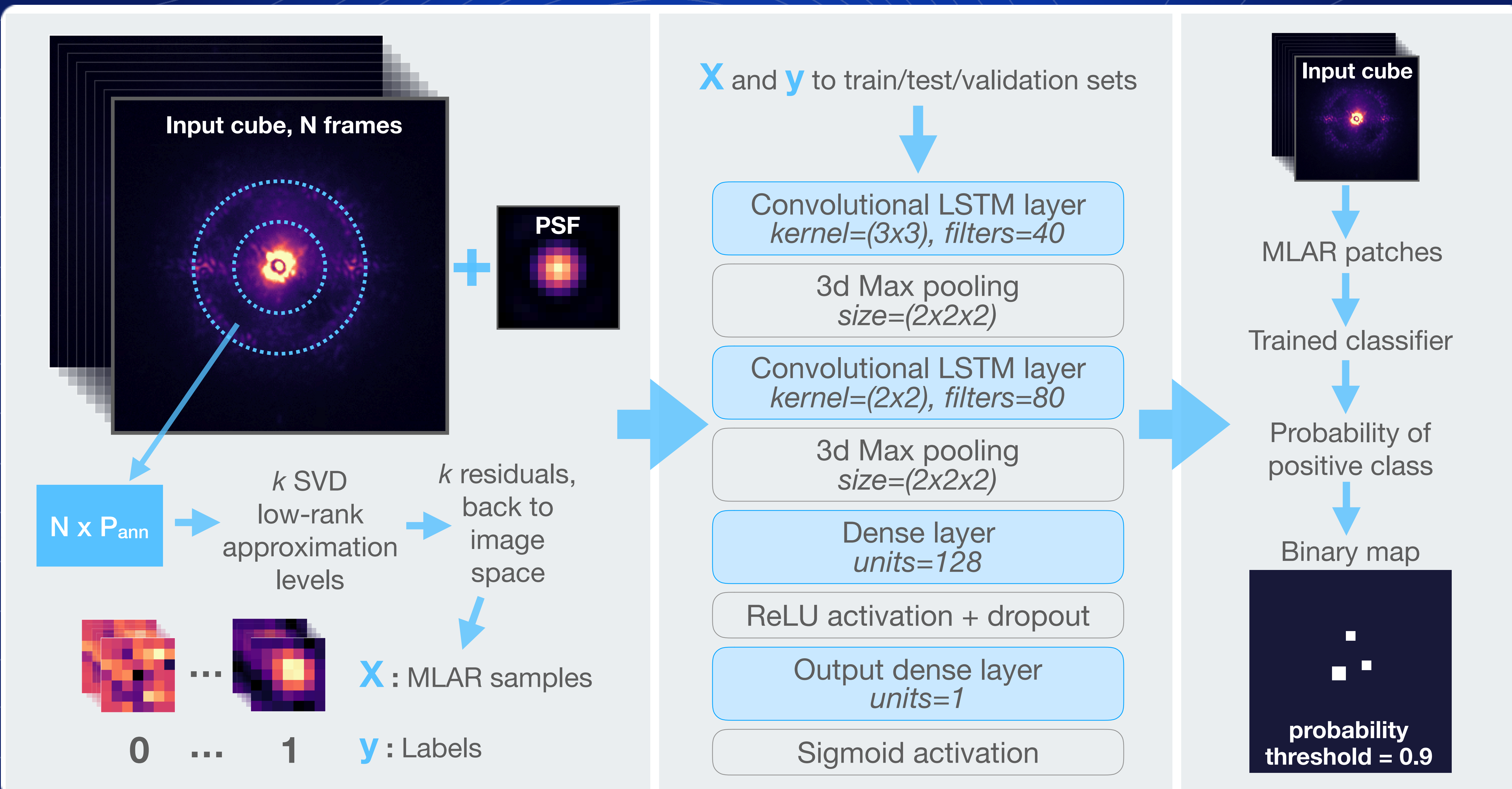
- DNN can be trained with labeled data set
  - main challenge in HCI is to build the labeled data set



SUPERVISED DETECTION OF EXOPLANETS

Gomez Gonzalez et al. 2018

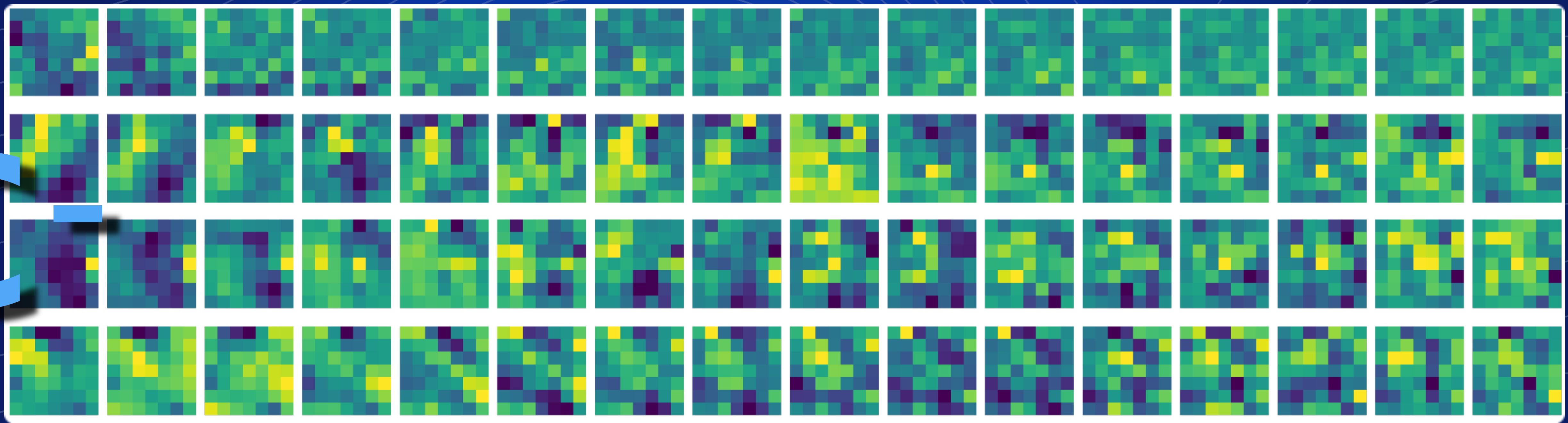
1. generation of labeled data
2. training the DNN
3. prediction



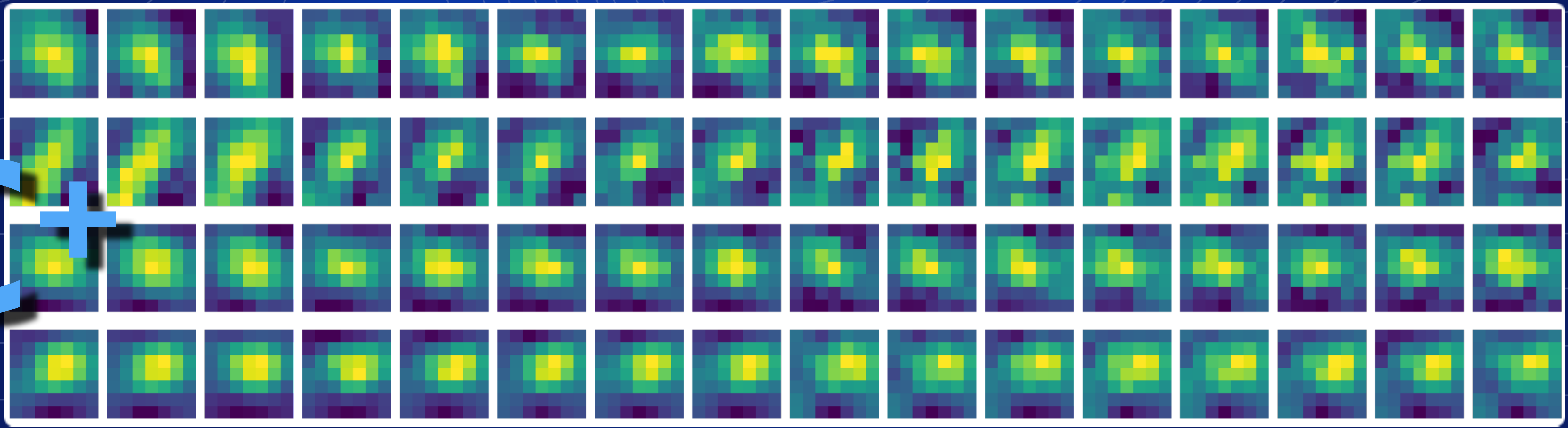
LABELED DATASET

Labels: $y \in \{c^{-}, c^{+}\}$

c^{-}



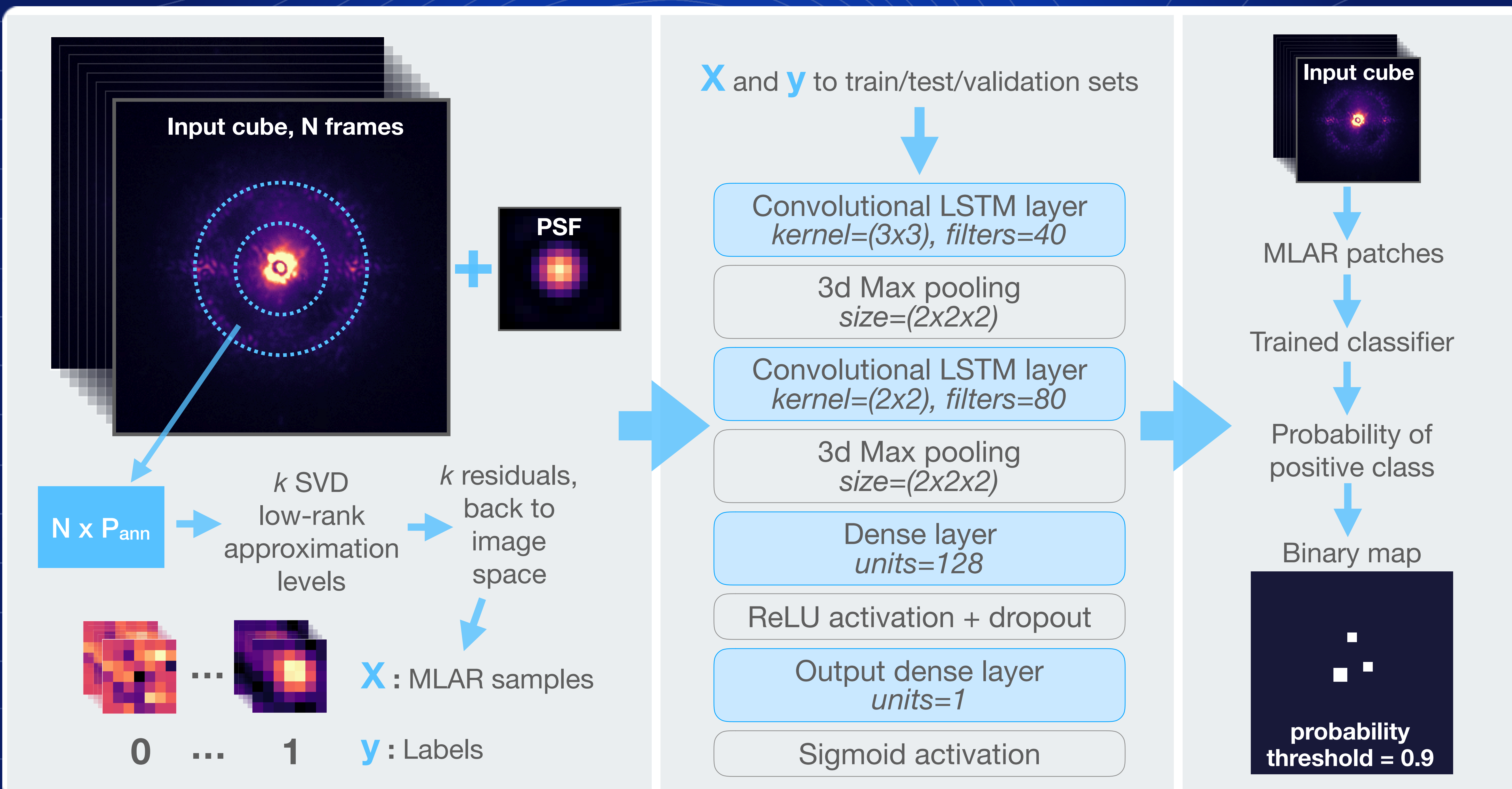
c^{+}



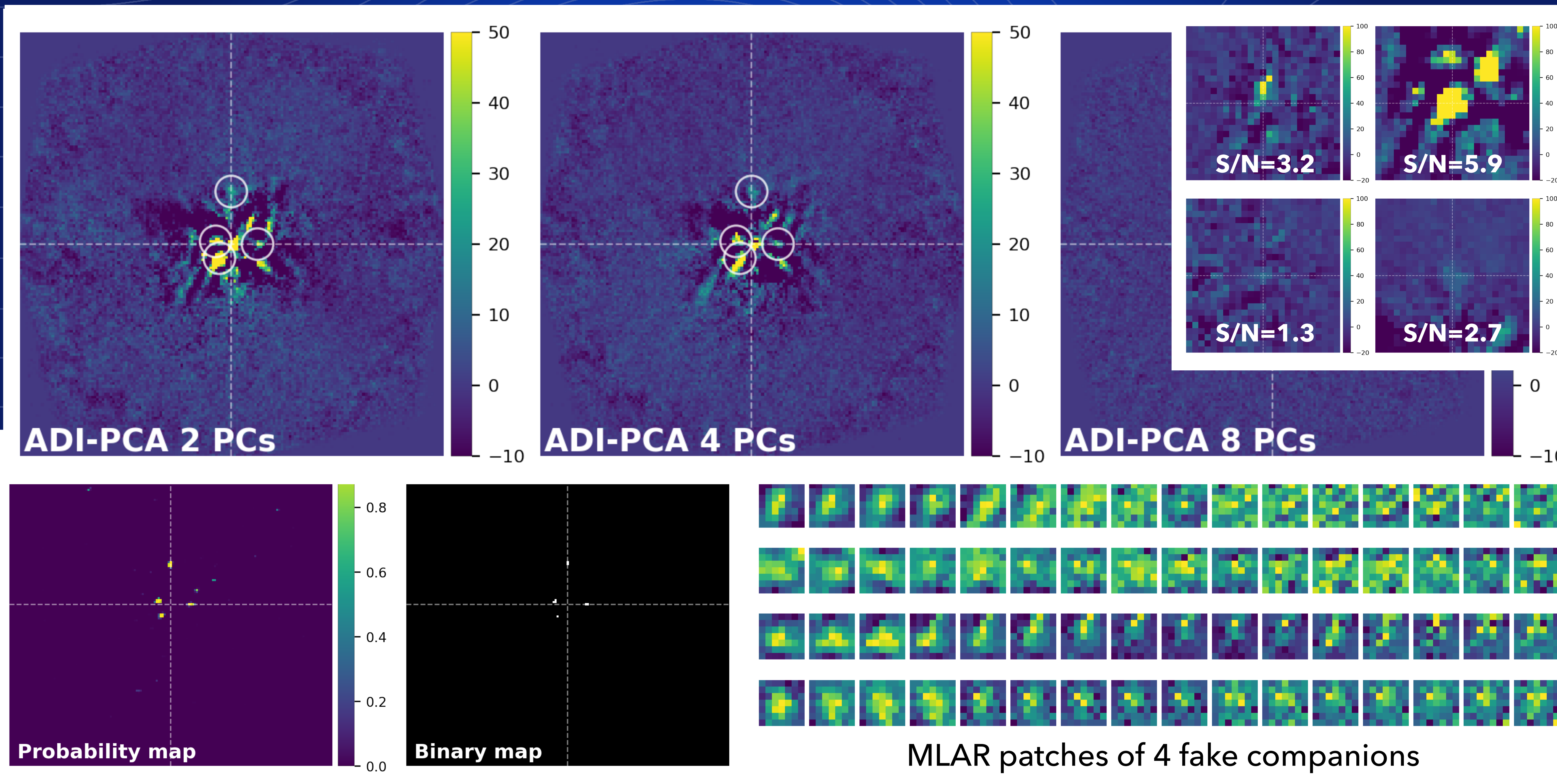
SUPERVISED DETECTION OF EXOPLANETS

Gomez Gonzalez et al. 2018

1. generation of labeled data | 2. training the DNN | 3. prediction



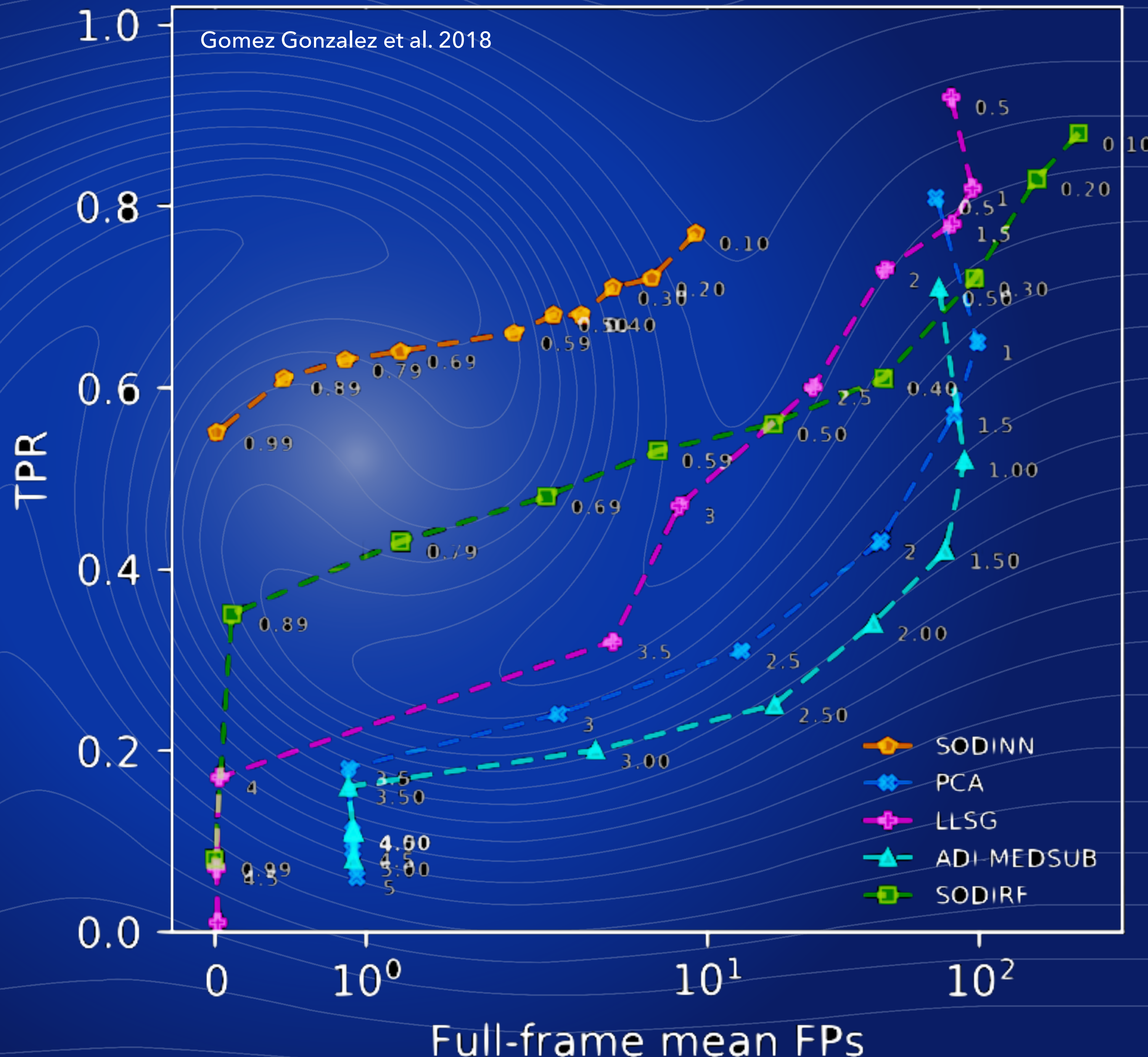
TEST WITH INJECTED COMPANIONS (SPHERE/IRDIS)



Gomez Gonzalez et al. 2018

ROC CURVES

- Separation
  - ✳ 2 - 3 λ/D
- Contrasts
  - ✳ 2.9×10^{-5} to 1.4×10^{-4}



VORTEX

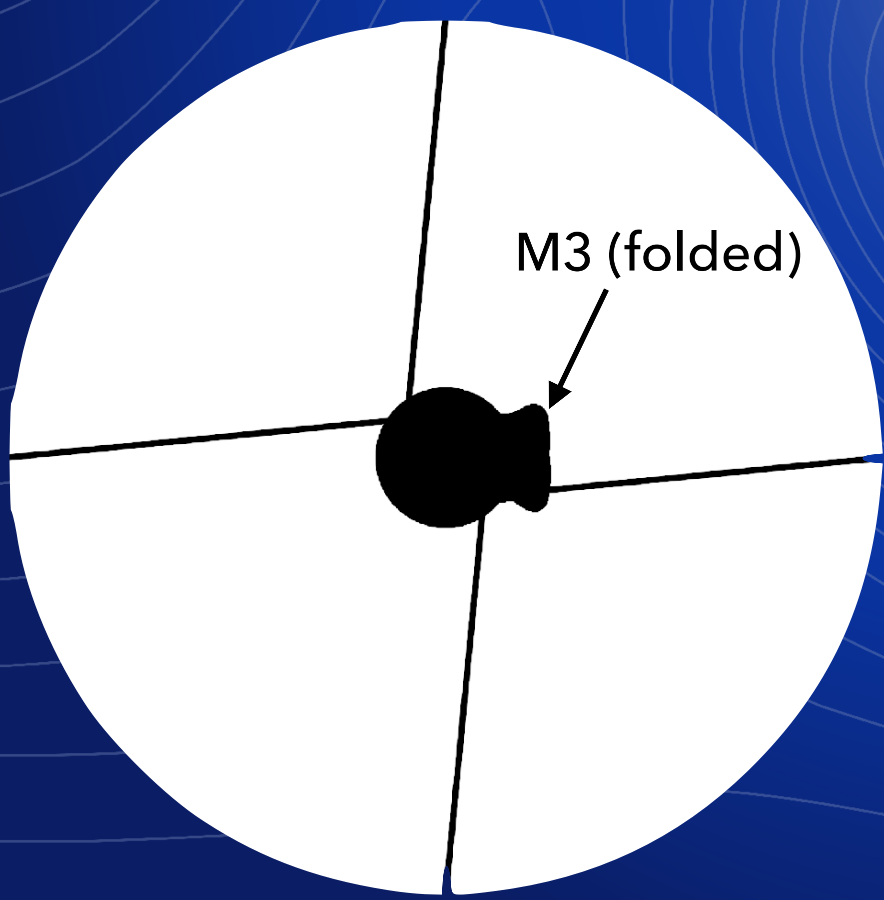
FUTURE PROJECTS

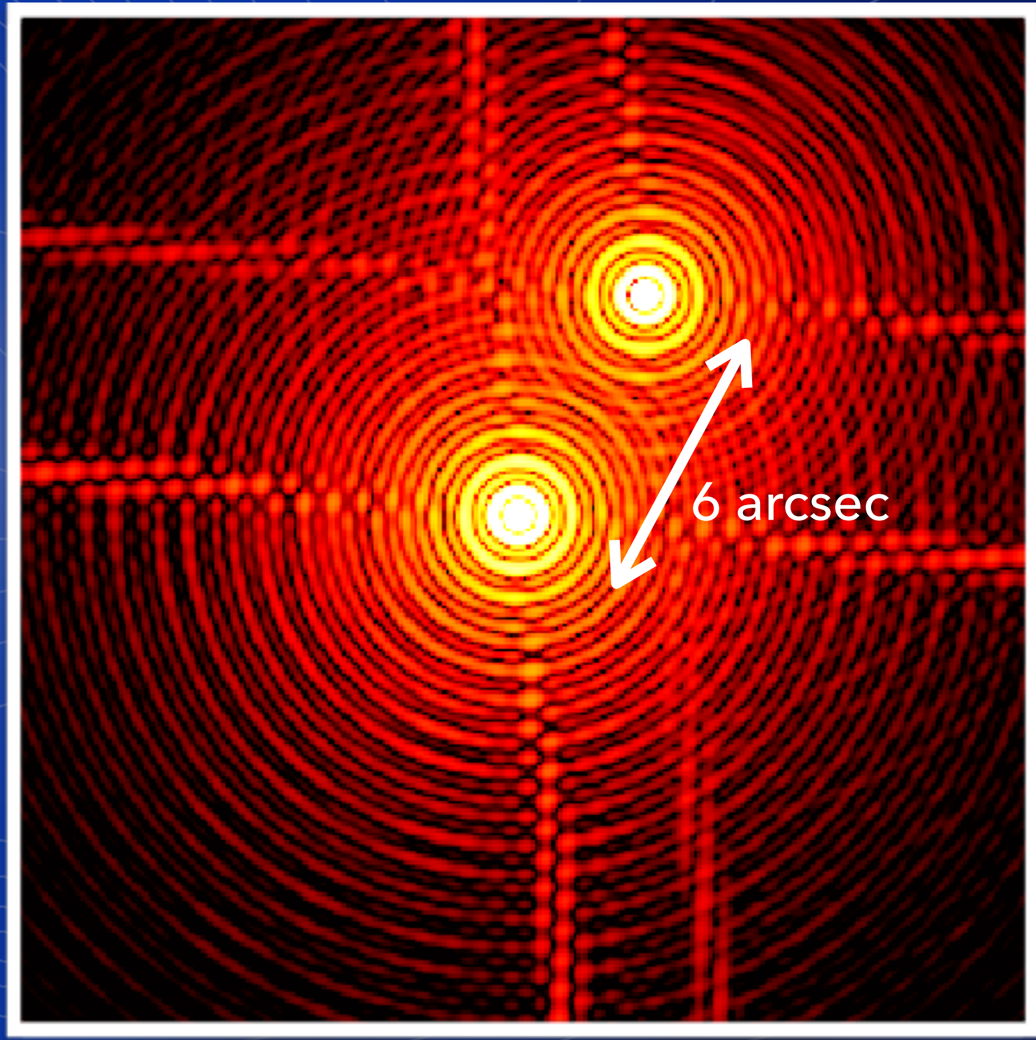
NEAR – NEW EARTH IN THE ALPHA CENTAURI REGION

- ESO project funded by Breakthrough Watch
  - what? search for rocky planets around α Cen A&B
  - how? refurbish VISIR and put it behind UT4+AOF
  - when? 100h observing campaign in mid-2019
- vortex team contribution
  - provide optimized AGPM for 10-12.5μm filter
  - design optimized Lyot stop
  - develop closed-loop pointing control with QACITS

NEAR LYOT STOP: TWO CHALLENGES

- binary target star
  - need to dim secondary star
- complicated pupil



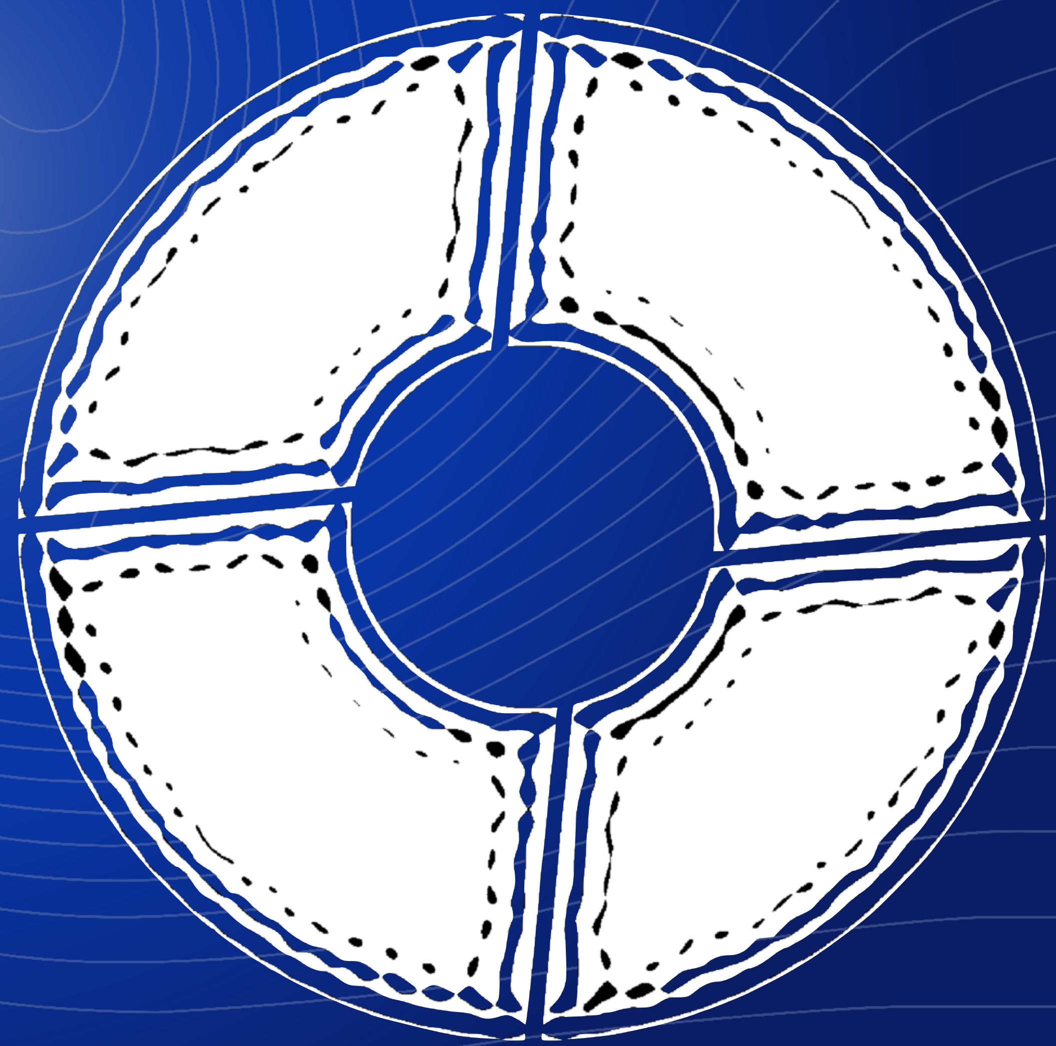


AN APODIZED LYOT STOP

- shaped-pupil: induce dark hole from 3″ to 8″ around B

Lyot stop

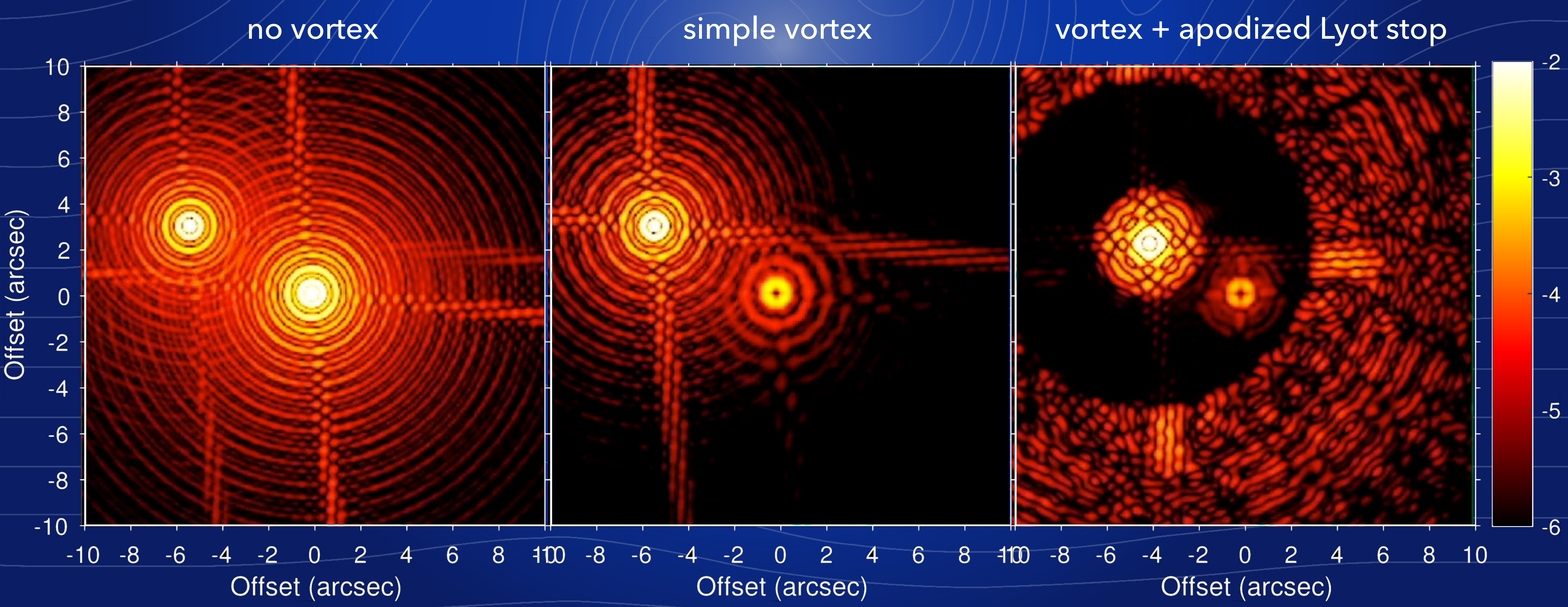
apodized Lyot stop



courtesy G. Ruane, AJ Riggs

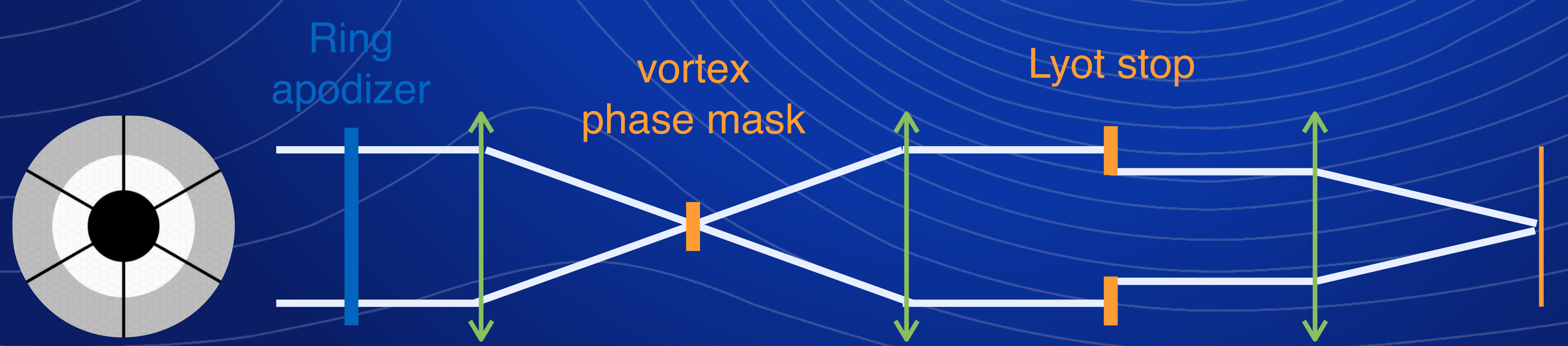
NOTIONAL IMAGES OF ALPHA CENTAURI SYSTEM

- habitable zone at 0.8″ - 1.1″ (A) or 0.5″ - 0.65″ (B)
- contrast around 10^{-6} for 2 $R_\oplus$ planet

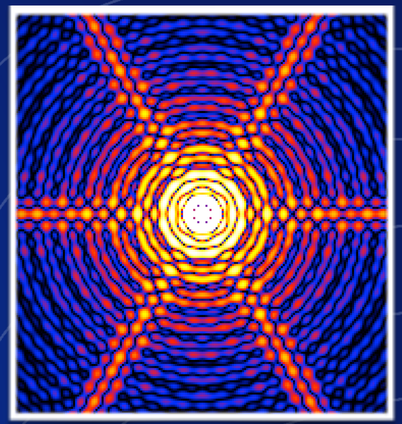


NEXT STEPS: VLT/ERIS AND ELT/METIS

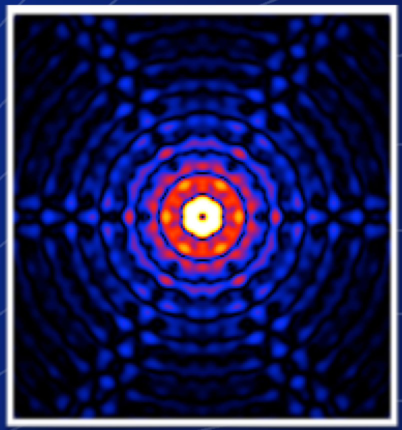
- ERIS: L & M band AGPMs
  - standard vortex coronagraph with simple Lyot stop
- METIS: L, M & N band AGPMs
  - ring-apodized vortex coronagraph: cancels diffraction from huge central obstruction



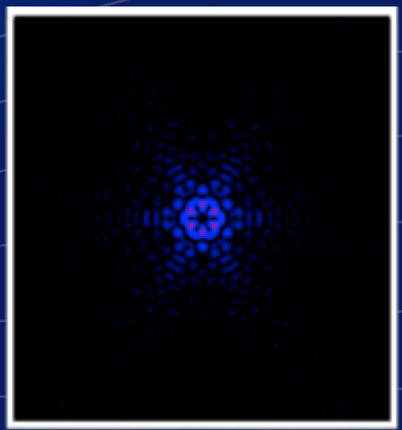
ELT



ELT+VC

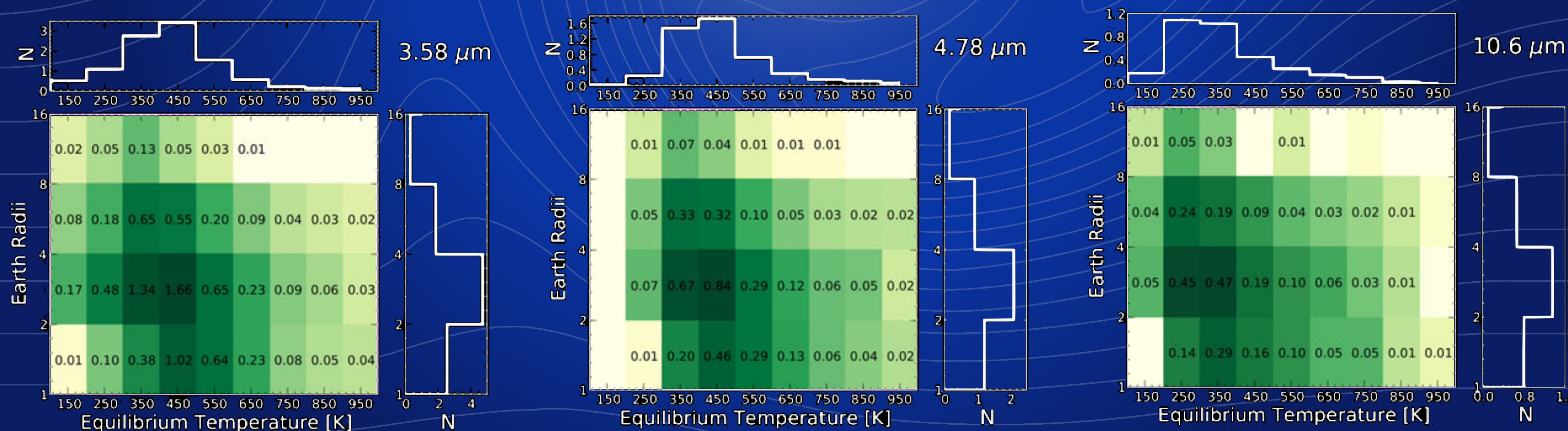


ELT+RAVC



METIS SCIENCE HIGHLIGHTS

- direct imaging of several RV planets
- potential to detect temperate rocky planets
- characterization with high-res LM-band IFS



Quanz et al. (2015)

CAN MACHINE LEARNING DO EVEN MORE FOR HCI?

fast adaptive optics

- problem = lag in AO loop
- speed limited by hardware & photons
- predictive control, **requires model**

deep learning = key to building fast, robust models

non-common path aberrations

- science camera to measure wavefront
- inverse problem, **requires model**
- approximate and fast, or complex and slow

VORTEX

KEEP LIGHT SPINNIN'