The team

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- **Obs. Paris**: E. Huby, P. Baudoz
- Collaborators at **ESO** (J. Girard, J. Milli, M. Kasper, H.-U. Käufl), **CEA Saclay** (E. Pantin), **U. Leiden** (M. Kenworthy, F. Snik), **Keck** (B. Femenia, P. Wizinowich), **U. Arizona** (P. Hinz)
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

OUTLINE

history and technology development
commissioning & on-sky performance
scientific results
image processing with machine learning
future projects
HISTORY AND TECHNOLOGY DEVELOPMENT
Five Years of Harvest with the Vortex Coronagraph

The Birth of a Concept

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

Advantages:
- Inner working angle
- Clear 360° discovery space
- Achromaticity

Rouan et al. (2000)

Mawet et al. (2005)
THE VORTEX CORONAGRAPH IN A NUTSHELL

- vortex phase mask
- Lyot stop
- coronographic image plane

Perfect on-axis cancellation for a circular aperture

On-axis vortex

No vortex/ off-axis
IMPLEMENTATIONS OF THE VORTEX PHASE MASK

- scalar vortex
  - helical piece of glass
- vector vortex
  - liquid crystal polymers
  - subwavelength gratings
  - photonic crystals
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

OPTIMIZING THE GRATING DESIGN

L band. Period = 1.42 \mu m, angle = 3.00^\circ

Delacroix et al. (2013)
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

MANUFACTURING DIAMOND AGPM @ UPPSALA

1. diamond coated with Al and Si layers (sputtering)
   - thick Al layer
   - thin Si layer
   - thin Al layer

2. e-beam pattern transferred with solvent-assisted moulding
   - soft stamp replicated from e-beam
   - apply stamp
   - ethanol bath
   - baking

3. reactive ion etching
   - Al etching
   - Si etching
   - Diamond etching

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Vargas Catalan et al. (2016)
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

SETTING UP THE « YACADIRE » BENCH @ MEUDON
ANGUISH...
AFTER SOME TUNING . . .

Peak rejection

<table>
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<th>août-10</th>
<th>nov-10</th>
<th>févr.-11</th>
<th>juin-11</th>
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<th>juil-12</th>
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2 µm
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

BLISS!
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

BEST PERFORMANCE IN THE LAB - 2017 UPDATE

- dedicated test bench (VODCA) now available at ULiège
- 10+ science-grade L-band AGPMs etched & tested
- broadband rejection up to 1500 : 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 work remains to be done
- now exploring higher topological charges
  - less sensitive to tip-tilt, at the expense of larger IWA

work in progress
COMMISSIONING & ON-SKY PERFORMANCE
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPHS

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 $2\lambda/D$ from F0V
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
pointing errors create asymmetric « donut »

central obstruction changes the expected behavior of the donut

need modeling to infer pointing error from image (QACITS algorithm)

can be used to control pointing at low frequency
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

CLOSED-LOOP CENTERING CONTROL

- fully automated vortex operations with QACITS validated on NIRC2
  - includes acquisition & calibration
- ensures consistent centering and data quality
- rms jitter $\sim 0.02 \lambda/D$ (@ 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. (in prep)
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

IMPROVEMENT IN DETECTION LIMITS @ NIRC2

- obvious gain in $3-10 \frac{\lambda}{D}$ region ($0.25'' - 0.8''$)
- vortex transmission detrimental @ $1-2 \frac{\lambda}{D}$

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

- NACO (1h54, 83deg, L=3.4)
- NIRC2 (30min, 168deg, L=5.2)
- LMIRCam (1h20, 96deg, L=5.2)

5-sigma sensitivity [Δmag]

angular separation [arcsec]
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

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?
brown dwarf around Sco-Cen A0 star

177 mas, $\Delta L = 4.3$

only detected with aperture masking so far

recovered with NIRC2+vortex during commissioning
In the TW Hya system, as inferred from the dust gaps' positions, the presence of planets accreting mass is indicated by the patterns of the dust gaps. The color axis represents the mass and the mass accretion rate of these planets. The models show that for a protoplanet forming a circumplanetary disk, the most significant brightness is observed near-infrared bands. Assuming an age of 7 Myr, the results predict respective planet masses of 2.3, 1.6, 1.5, and 1.2 as calculated from the Zhu maps. Constraints on actively accreting protoplanets show that, for instance, planets with masses of 0.05 could be bright enough in scattered light.

Dust sculpting the gaps at 88 au reveals the potential for protoplanets to be dynamically active, with the youngest assumed age of 10 Myr predicting the highest masses: 2.3, 1.6, 1.5, and 1.2. These limits on the accretion rate of the planet with infrared photometry alone imply respective planet masses of 0.3, 0.2, 0.1, and 0.03. The deep coronagraphic observations of TW Hya, which we denote as gap 4, respectively, may be sculpting the gaps at thermal emission from the circumplanetary disk. Dusty, on the other hand, is the radius of Jupiter, would have to be accreting at a runaway accretion phase. Without additional observations, it is challenging to place unambiguous upper limits for both the mass of protoplanets and constrain their mass accretion rates. The lack of knowledge regarding the detection limits of these observations in the modeled brightness of circumplanetary disks do not allow us to set upper limits for both the mass of protoplanets and their accretion rates. The deep coronagraphic observations presented here provide tantalizing evidence that massive protoplanets may be sculpting features in the dust.
protoplanet with circumplanetary disk truncated at \( \sim 1R_{\text{Jup}} \) presently accreting at a rate insufficient to form a Jupiter-mass planet

Ruane et al. (2017)
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. (submitted)
MWC758: YET ANOTHER 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$_{\text{Jup}}$
  - not purely photospheric emission
- conclusion: accreting protoplanet or disk feature?
  - no polarized disk emission there!

Reggiani et al. (submitted)
MWC758: 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\textsubscript{Jup})
  - inner planet? might explain one spiral, but not all three

Reggiani et al. (submitted)
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

HOW TO BETTER EXPLOIT THE DATA?

- interesting science at 1-3 $\lambda/D$
  - strongly affected by residual speckles
  - non-Gaussian noise
    - $\rightarrow$ more false positives
  - hard to validate candidates
- ADI-based techniques produce SNR, but do not inform on nature of the source
- machine learning can help
 MACHINE LEARNING IN A NUTSHELL

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

**Unsupervised**

- Clustering

**Supervised**

- Regression
- Classification

**Dimensionality reduction**

PC 1

PC 2
SUPERVISED LEARNING

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

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

- mapping function $f$ based on (deep) neural network

  - layers of neurons whose parameters can be tuned to approximate a complex function

  - DNN can be trained with labeled datasets

- problem: need labels & large training sample!
SUPERVISED DETECTION OF EXOPLANETS

1. generation of labeled data
   - Input cube, N frames
   - $k$ SVD low-rank approximation levels
   - $k$ residuals, back to image space
   - $X$ : MLAR samples
   - $0 \ldots 1$ : Labels

2. training the DNN
   - Convolutional LSTM layer
     - kernel=(3x3), filters=40
   - 3d Max pooling
     - size=(2x2x2)
   - Convolutional LSTM layer
     - kernel=(2x2), filters=80
   - 3d Max pooling
     - size=(2x2x2)
   - Dense layer
     - units=128
   - ReLU activation + dropout
   - Output dense layer
     - units=1
   - Sigmoid activation

3. prediction
   - Input cube
   - MLAR patches
   - Trained classifier
   - Probability of positive class
   - Binary map
   - Probability threshold = 0.9

Gomez Gonzalez et al. (submitted)
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

LABELED DATASET

Labels: \( y \in \{ c^-, c^+ \} \)
SUPERVISED DETECTION OF EXOPLANETS

1. generation of labeled data

2. training the DNN

3. prediction

$X$ and $y$ to train/test/validation sets

- Convolutional LSTM layer
  - kernel=(3x3), filters=40

- 3d Max pooling
  - size=(2x2x2)

- Convolutional LSTM layer
  - kernel=(2x2), filters=80

- 3d Max pooling
  - size=(2x2x2)

- Dense layer
  - units=128

- ReLU activation + dropout

- Output dense layer
  - units=1

- Sigmoid activation

Input cube, $N \times P_{ann}$

$0 \ldots 1$

$k$ SVD low-rank approximation levels

$k$ residuals, back to image space

$X$ : MLAR samples

$y$ : Labels

MLAR patches

Trained classifier

Probability of positive class

Binary map

Probability threshold = 0.9

Gomez Gonzalez et al. (submitted)
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

TEST WITH INJECTED COMPANIONS (SPHERE/IRDIS)

ADI-PCA 2 PCs

ADI-PCA 4 PCs

ADI-PCA 8 PCs

S/N=3.2

S/N=5.9

S/N=1.3

S/N=2.7

MLAR patches of 4 fake companions
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

ROC CURVES

- Separation
  - \(2 - 3 \lambda/D\)

- Contrasts
  - \(2.9 \times 10^{-5}\)
  - to \(1.4 \times 10^{-4}\)
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

M3 (folded)

6 arcsec
AN APODIZED LYOT STOP

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

courtesy G. Ruane, AJ Riggs
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

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

Images:
- no vortex
- simple vortex
- vortex + apodized Lyot
FIVE YEARS OF HARVEST WITH THE VORTEX CORONAGRAPH

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
direct imaging of several RV planets
potential to detect temperate rocky planets
characterization with high-res LM-band IFS
A VORTEX UPGRADE FOR SPHERE?

- goal: open the 1-3 $\lambda/D$ parameter space
  - increase number of detections
  - access a few RV planets

- need to identify main limitations to FQPM performance
  - component degradation?
  - effect of dead actuators?
  - low-order wavefront aberrations?

- K-band AGPM performance being evaluated
THANKS FOR YOUR ATTENTION

AND NOW ... GAME ON!