# *Applying*

# ***Modern Imaging Techniques***

# *to* ***Old Hubble Data***


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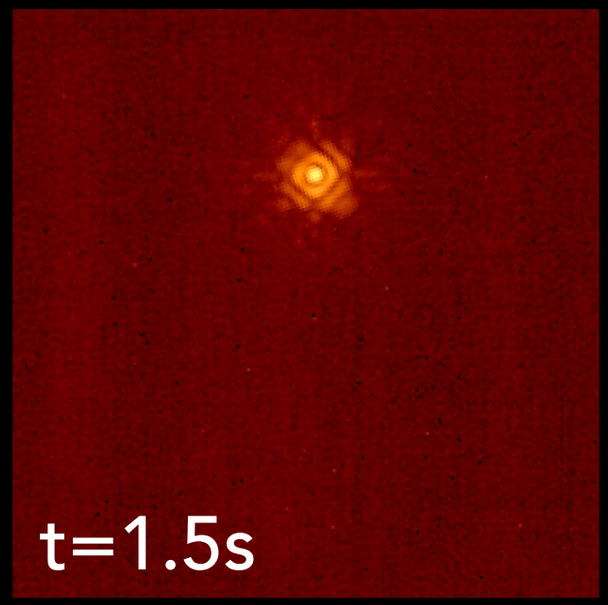
E. Serabyn, R. Soummer, C. Stark, N. Wallack, S. Wolff

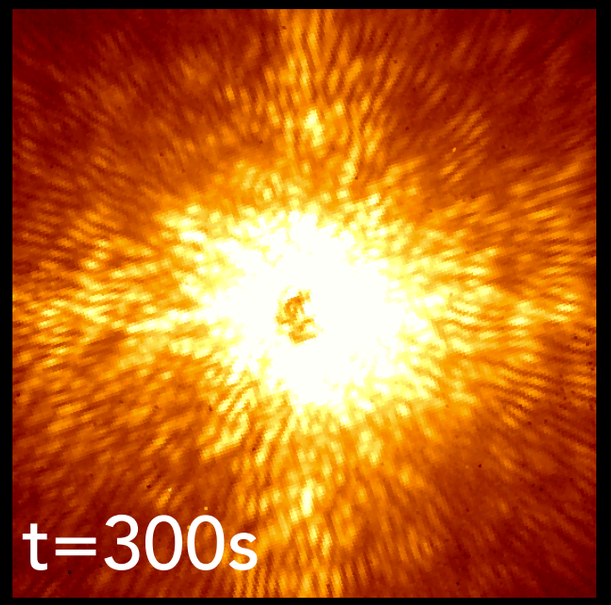
# High-Contrast Imagers

## *Photon-Killing Machines*

on ground-based telescopes

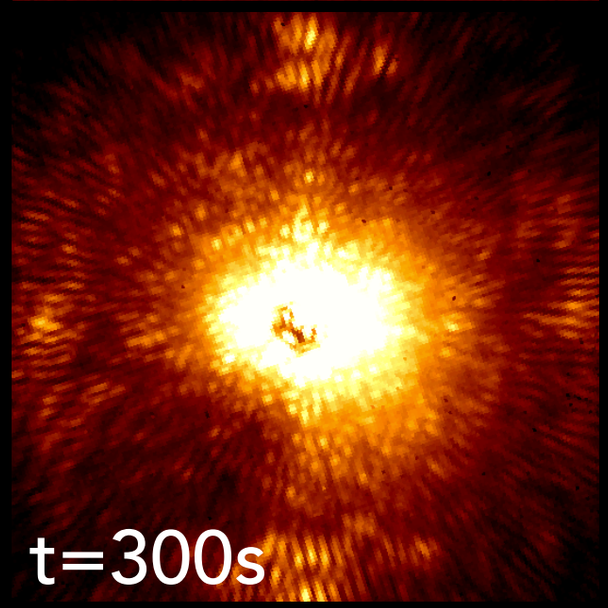
Adaptive Optics

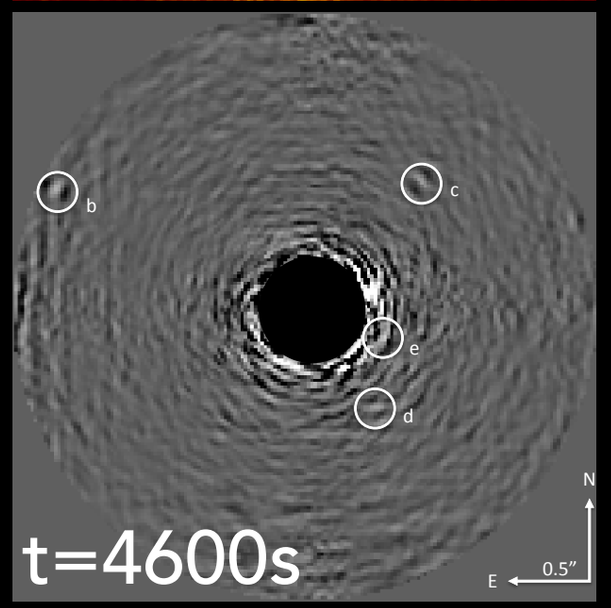



Coronagraph

Wavefront Control




Star-light (PSF) Subtraction

Oppenheimer et al. 2013

# PSF Subtraction Techniques

## *Quasi-static aberrations*

t ~ exposure time

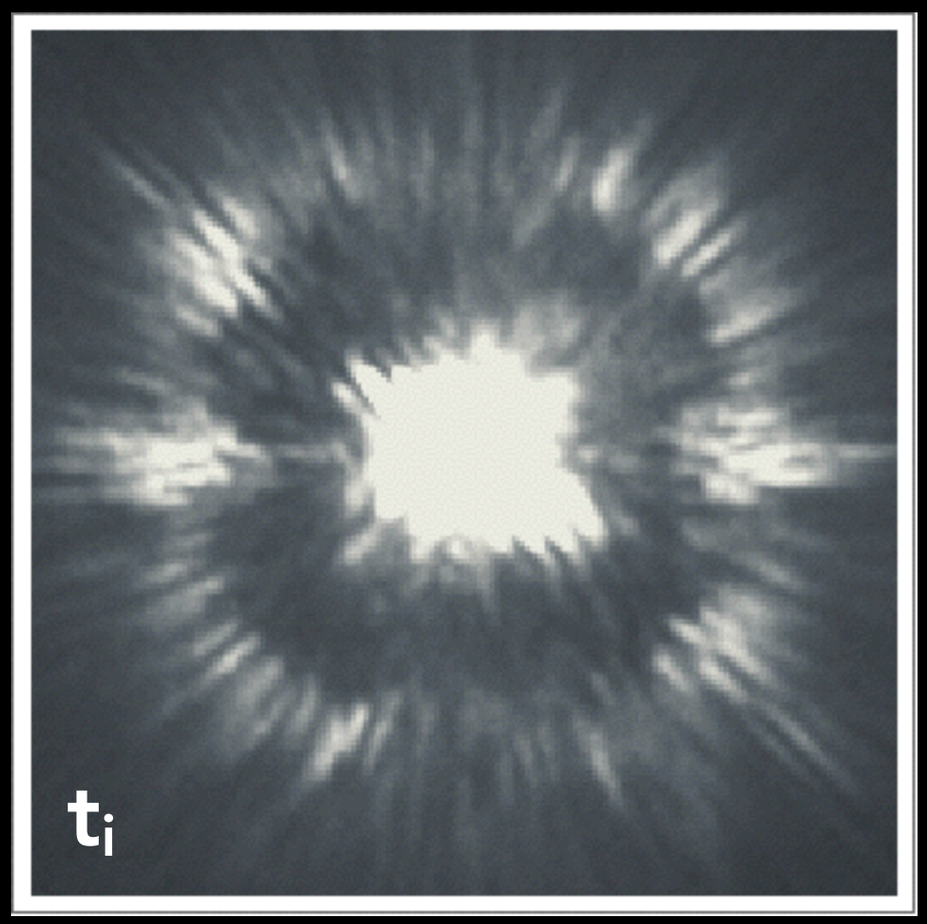
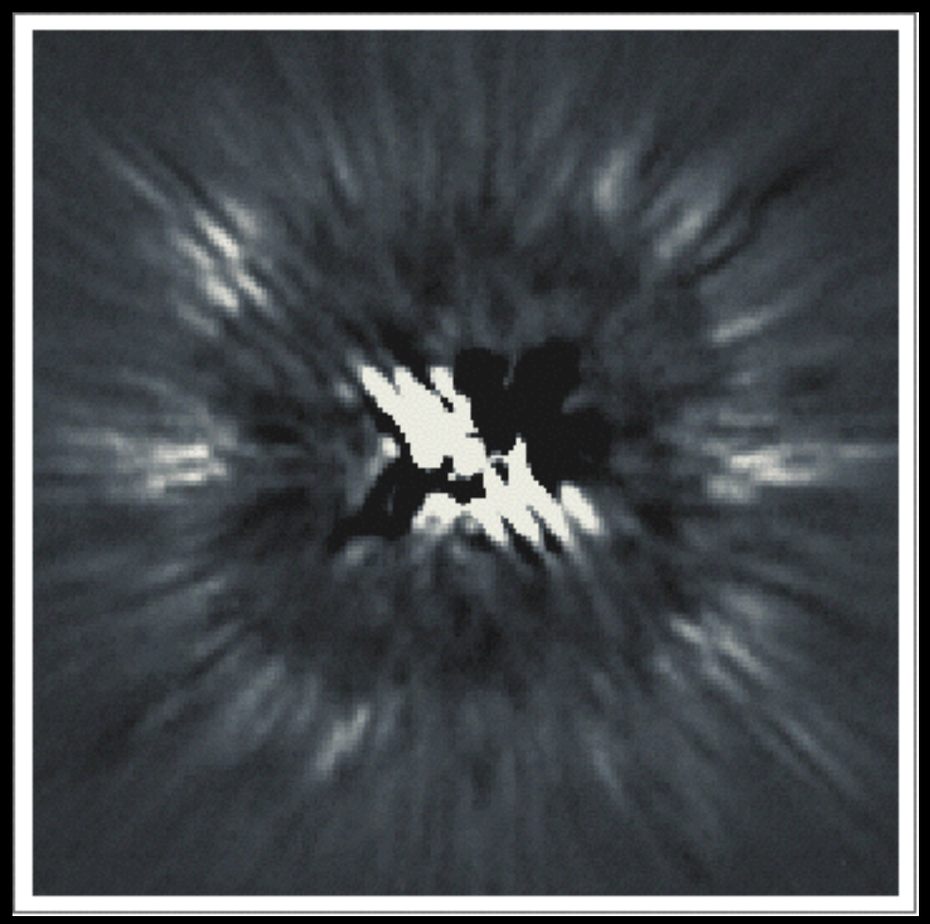




Image subtraction

~~$w_i t_i << t_2$~~

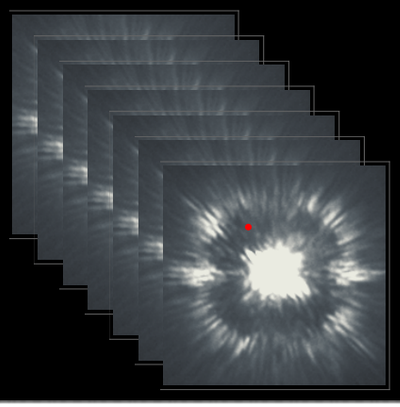


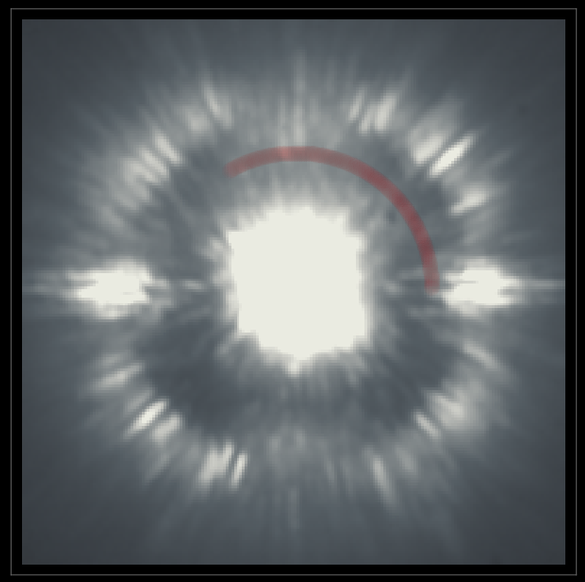
# PSF Subtraction Techniques

## *Angular Differential Imaging*

*"Let the sky rotate"*

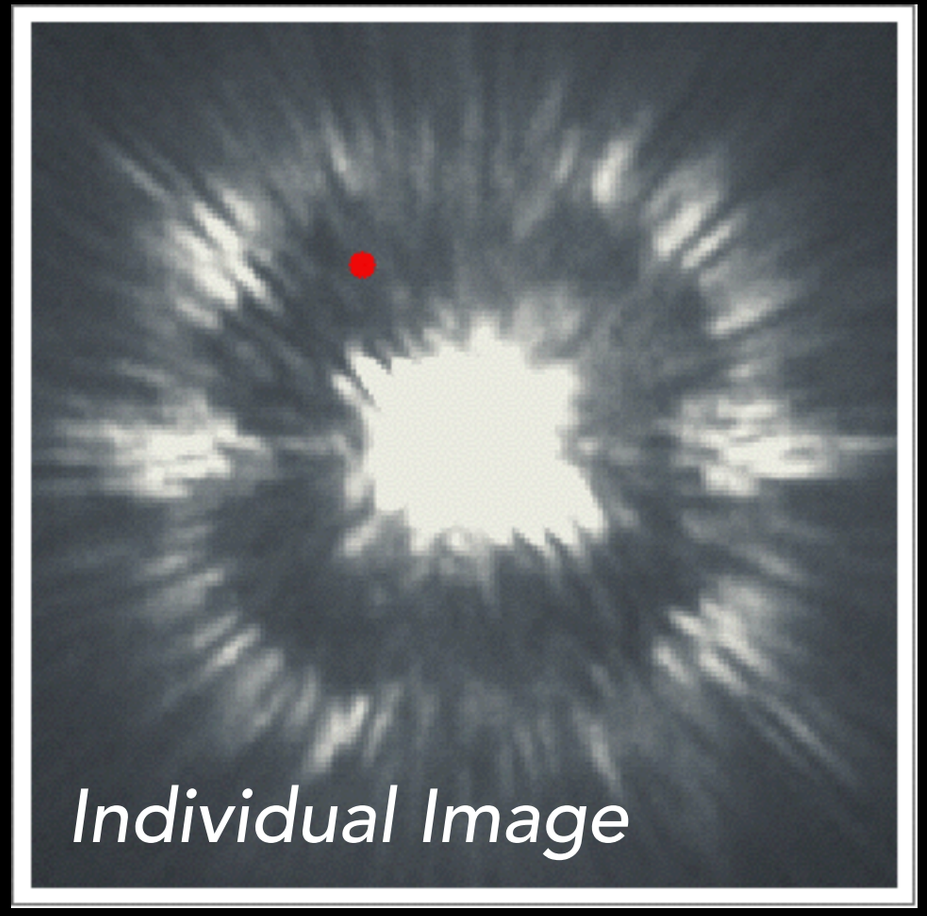
*PSF library*

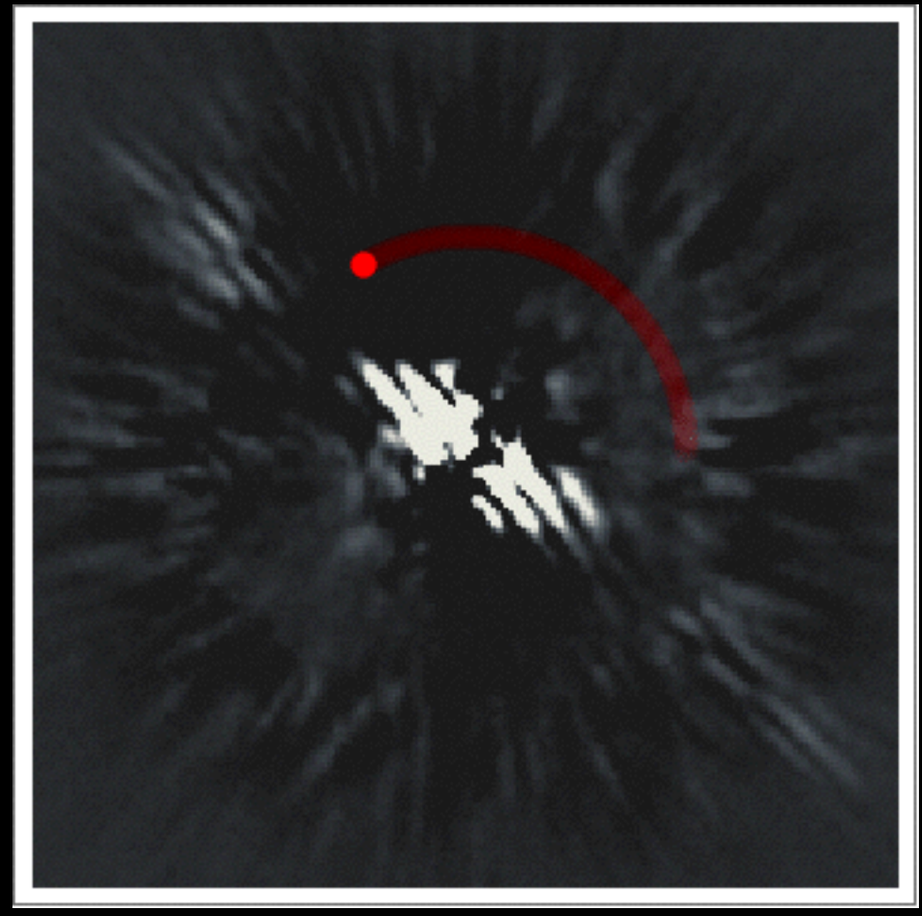




**Median**

**Image subtraction w. median of $t_i$**



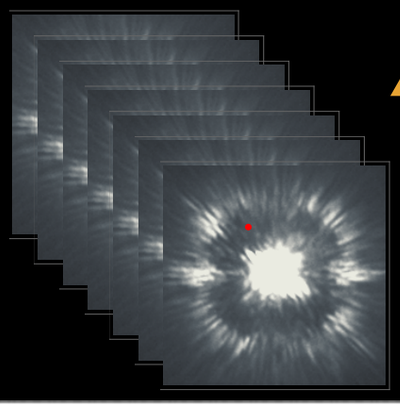



Marois et al. 2006

# PSF Subtraction Techniques

## *Angular Differential Imaging*
## *Advanced Algorithms*

*PSF library*



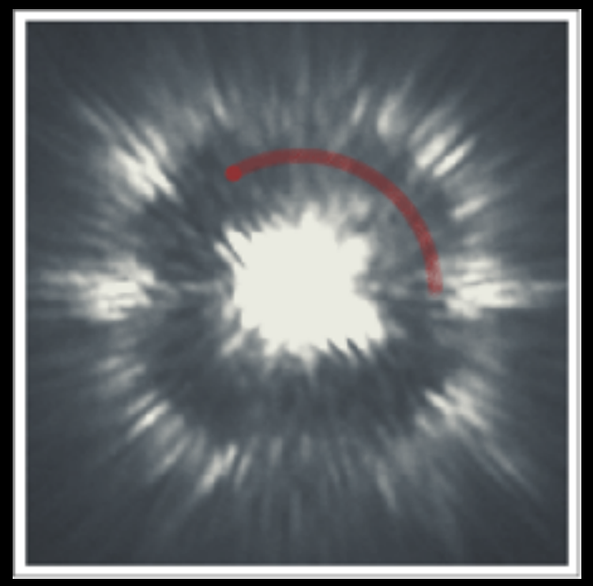
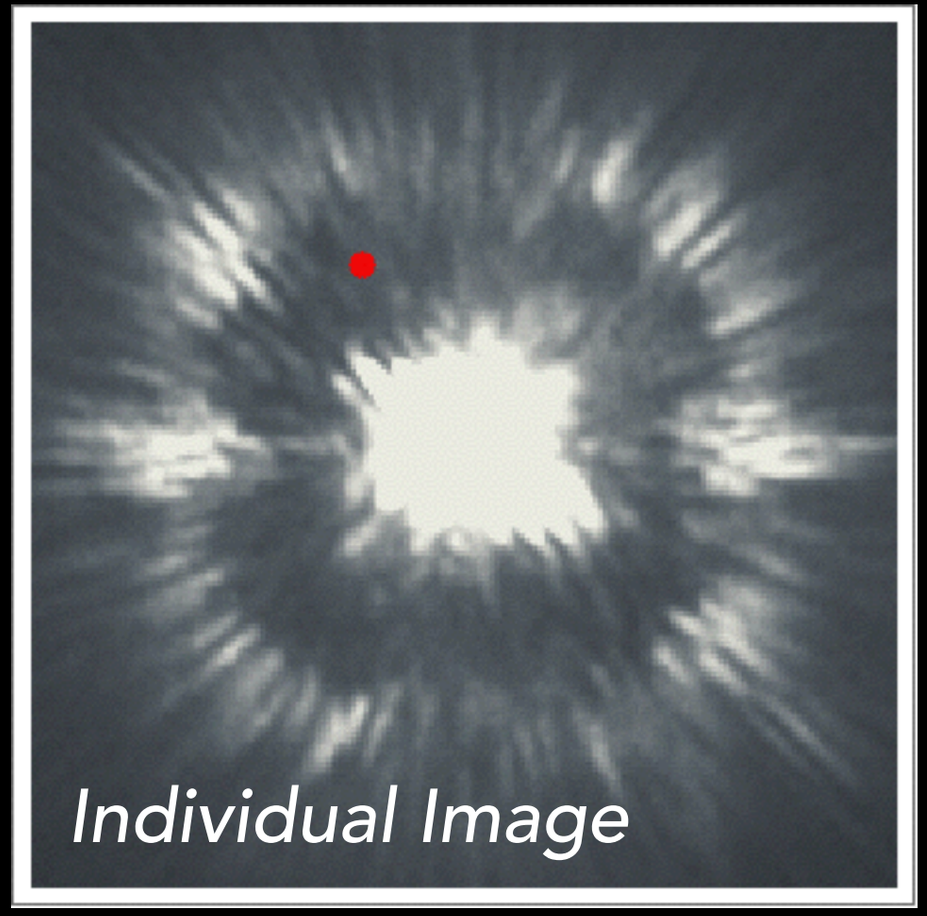


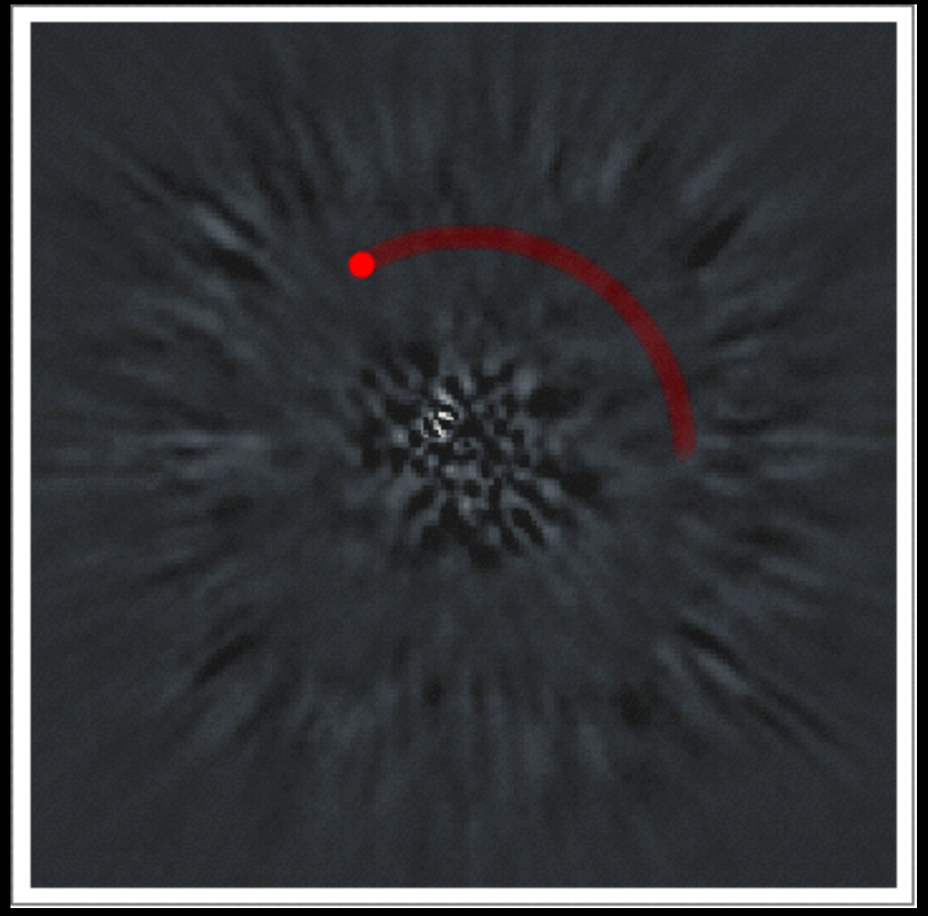
Image subtraction
ADI + LOCI / PCA




**Linear Comb.**

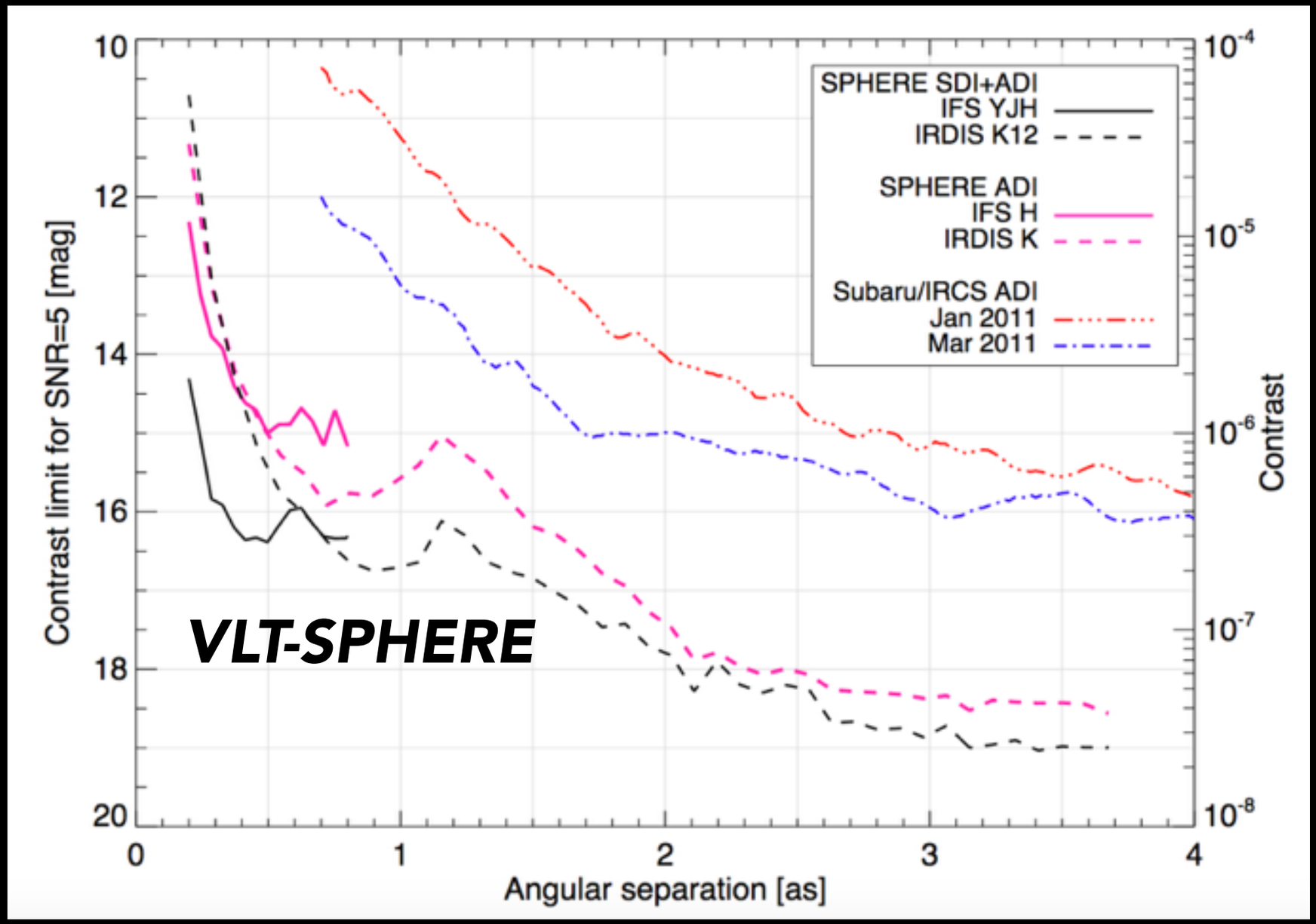
$$\min_{\{c_k\}} ||T - \sum_{k}^{K} c_k R_k||^2$$

Lafrenière et al. 2007
Soummer et al. 2012
Amara & Quanz 2012



# PSF Subtraction Techniques

## *State-of-the-art: $2 \times 10^{-7}$ at 1''*



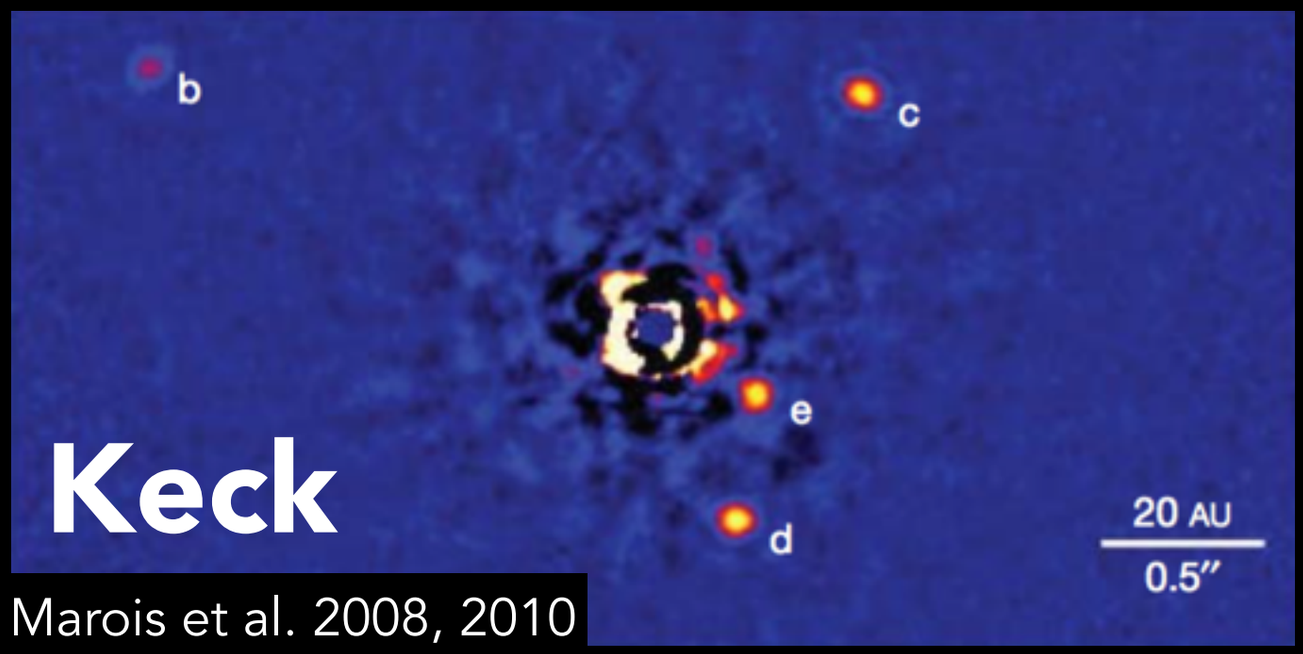

**Sirius A:**

*No 6 $M_{Jup}$ planet beyond 1 AU*

Vigan et al. 2015

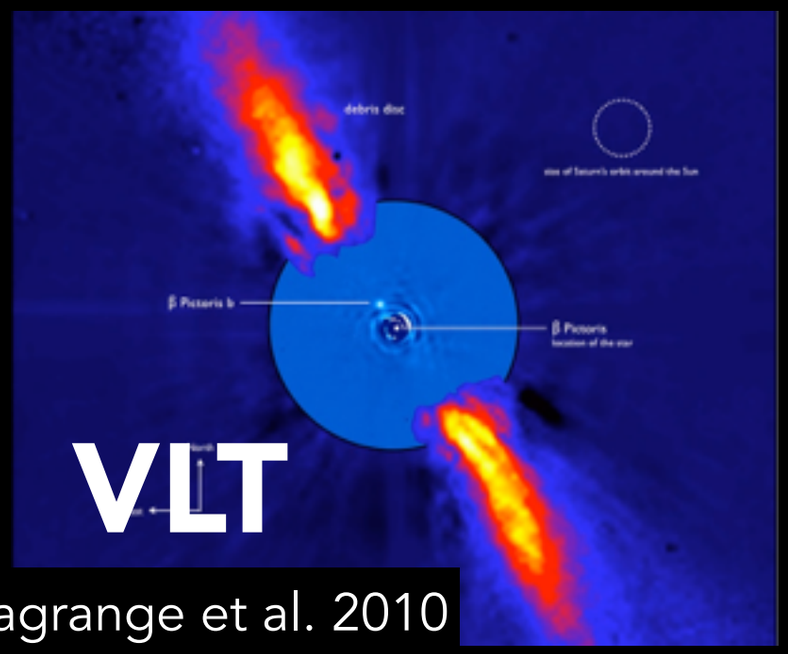
# Exoplanet gallery

HR 8799 b, c, d, e



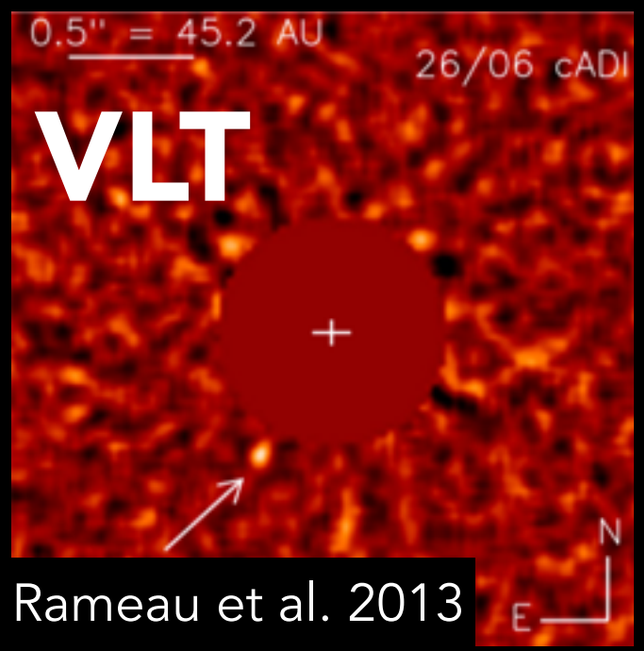

Marois et al. 2008, 2010

beta Pic b



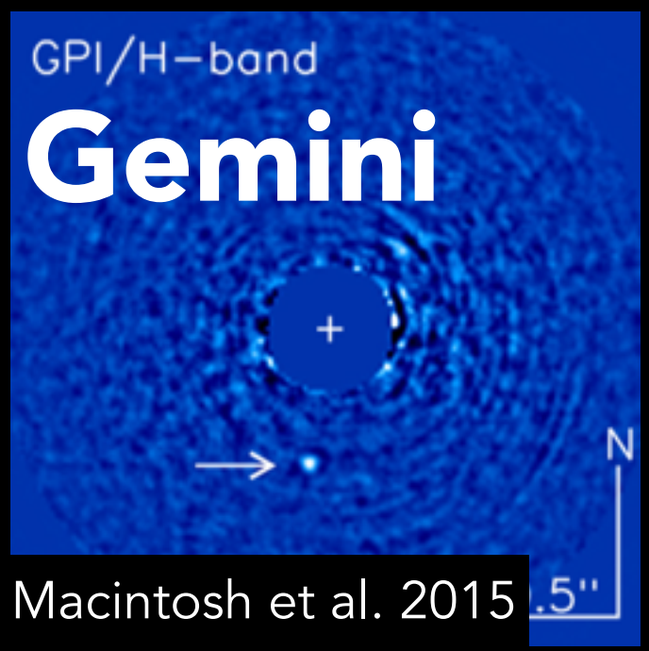

Lagrange et al. 2010

HR 95086 b



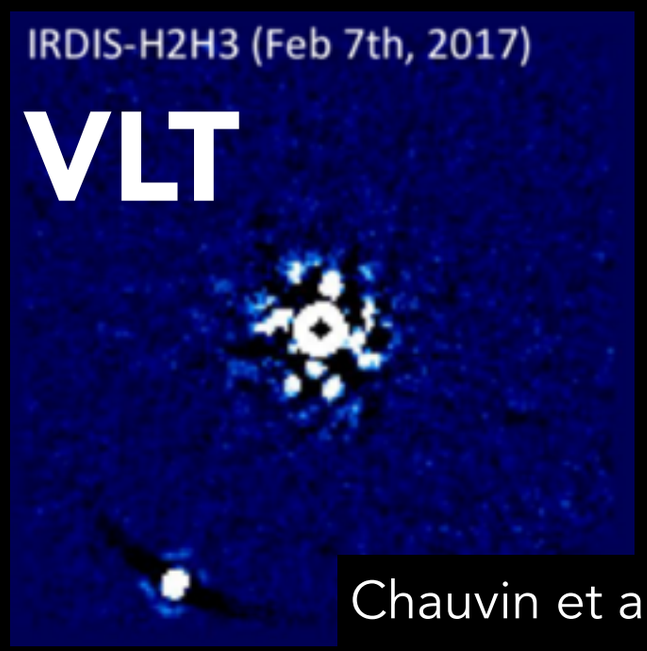

Rameau et al. 2013

51 Eri b




Macintosh et al. 2015

HIP 65426

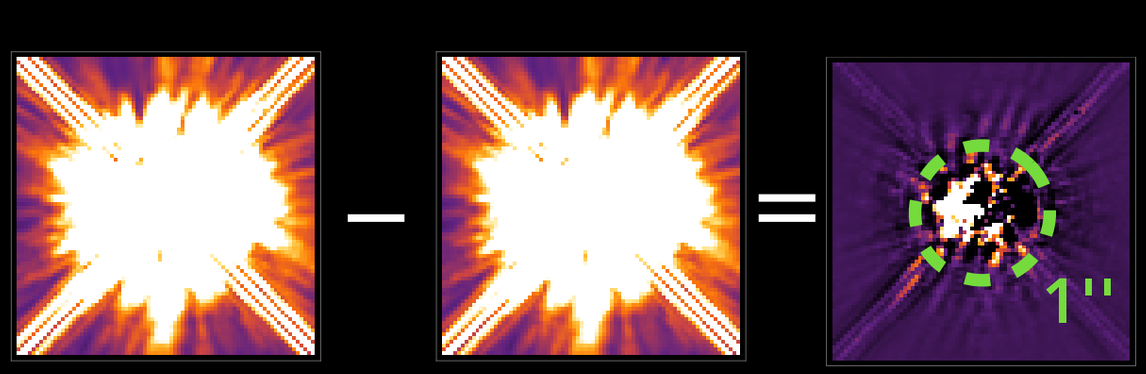



Chauvin et al. 2017

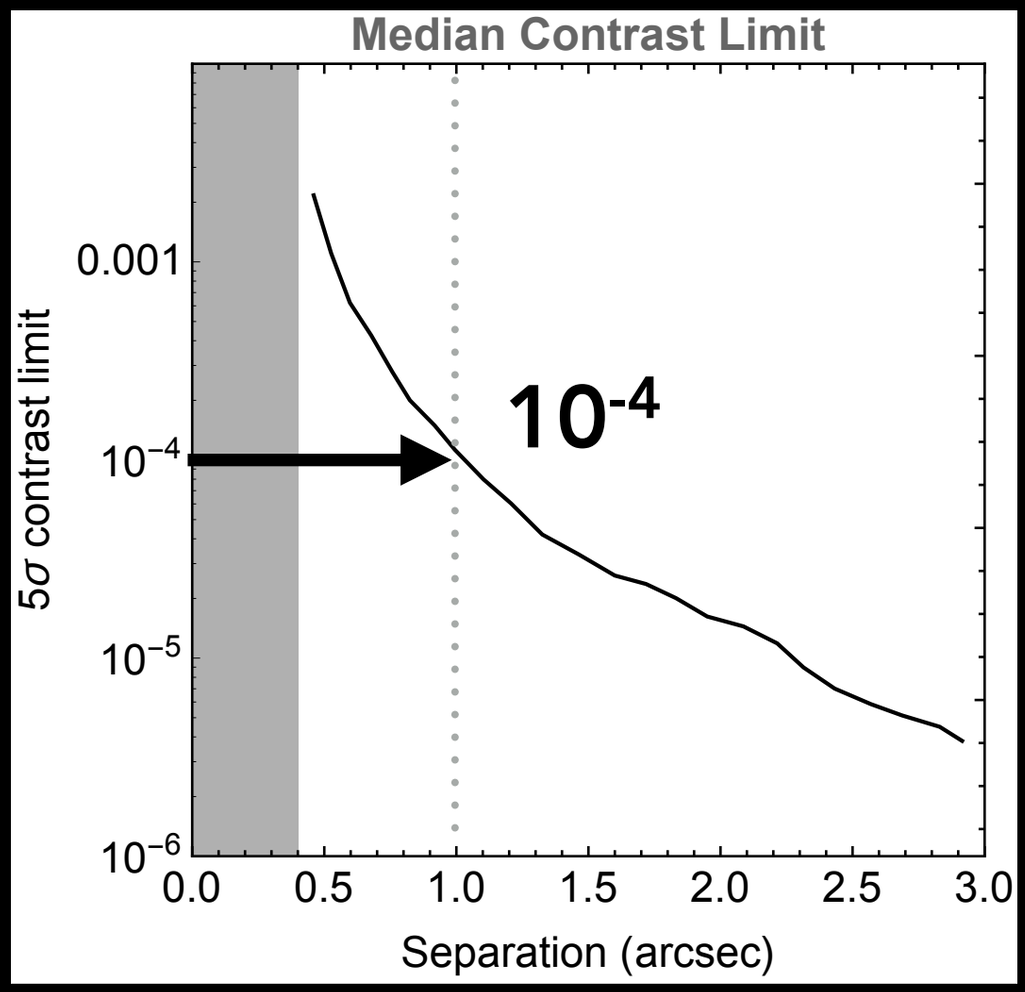
# Imaging techniques for HST

## Basic differential Imaging

"A minus B"



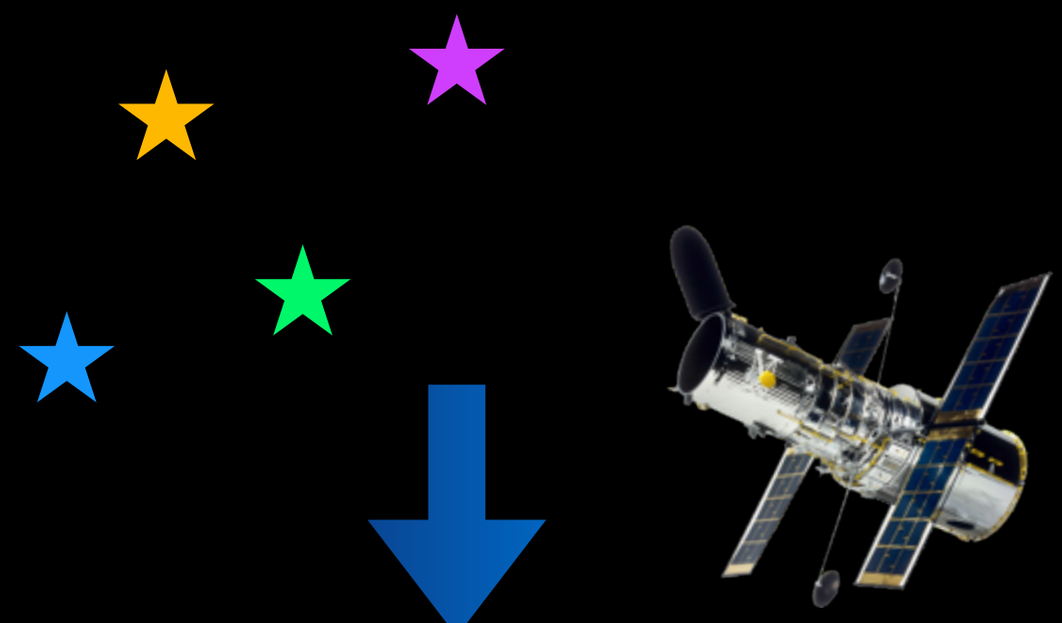

*Telescope Roll Image*
*Reference star Image*



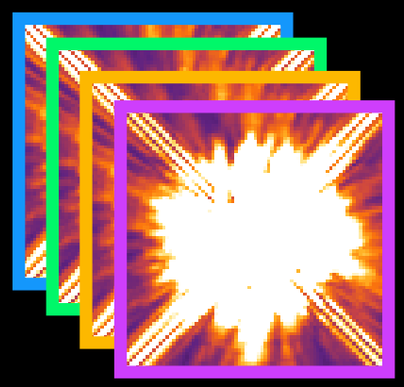

Lowrance et al. 2005

# Imaging techniques for HST

## Planet Surveys

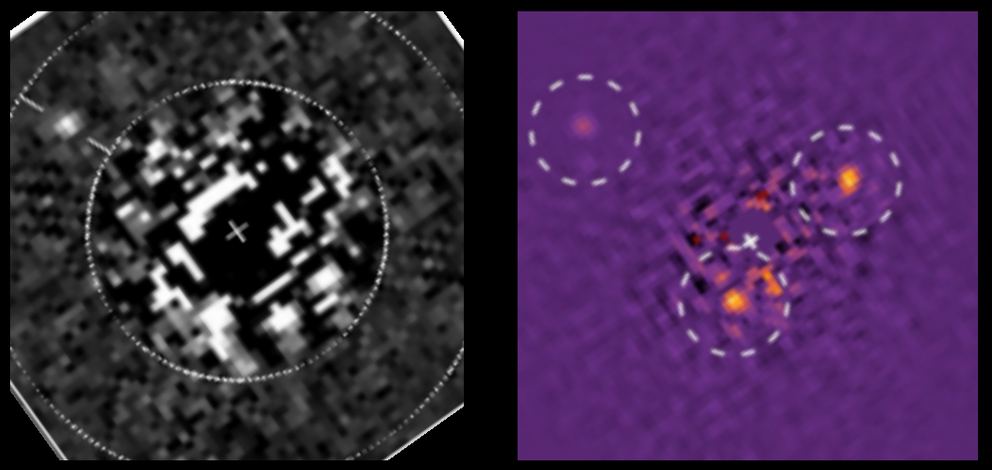


## Self-calibrating programs



## HR8799 RE-Discoveries

1998 HST data

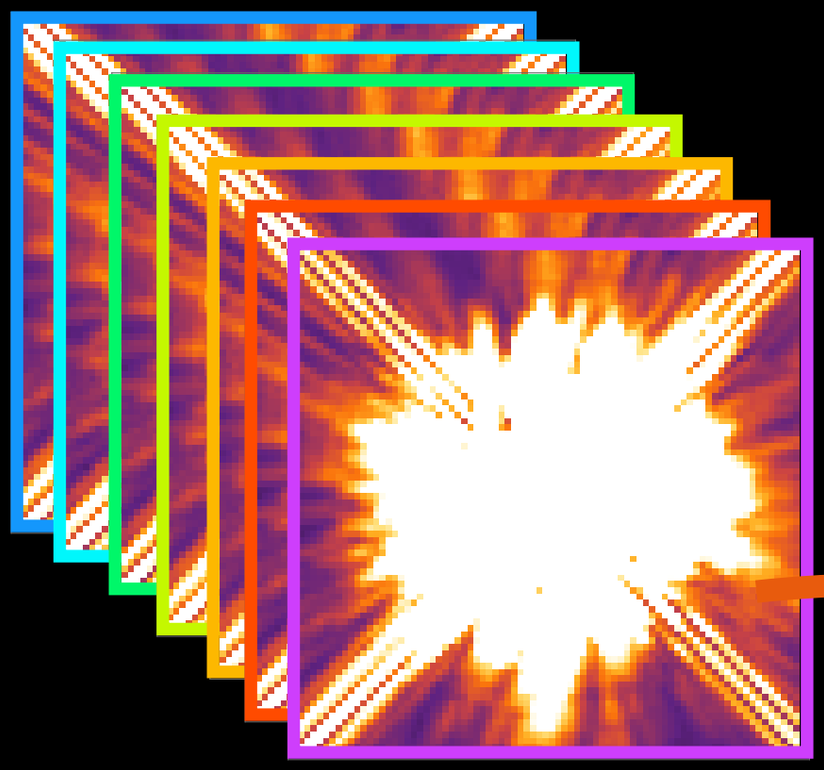


## 200 PSFs (23 survey stars)

Lafrenière et al. 2009
Soummer et al. 2011

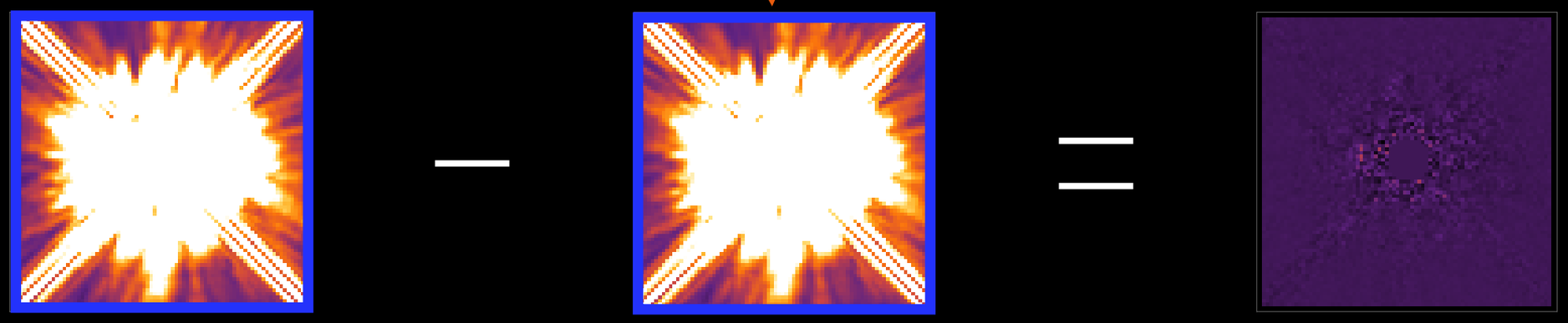
# Reference PSF libraries

## *Multi-Reference stars Differential Imaging*



Using the Whole Archive:
A lifetime of temporal variations

$$\min_{c_k} ||T - \sum_{k}^{n} c_k R_k||^2$$

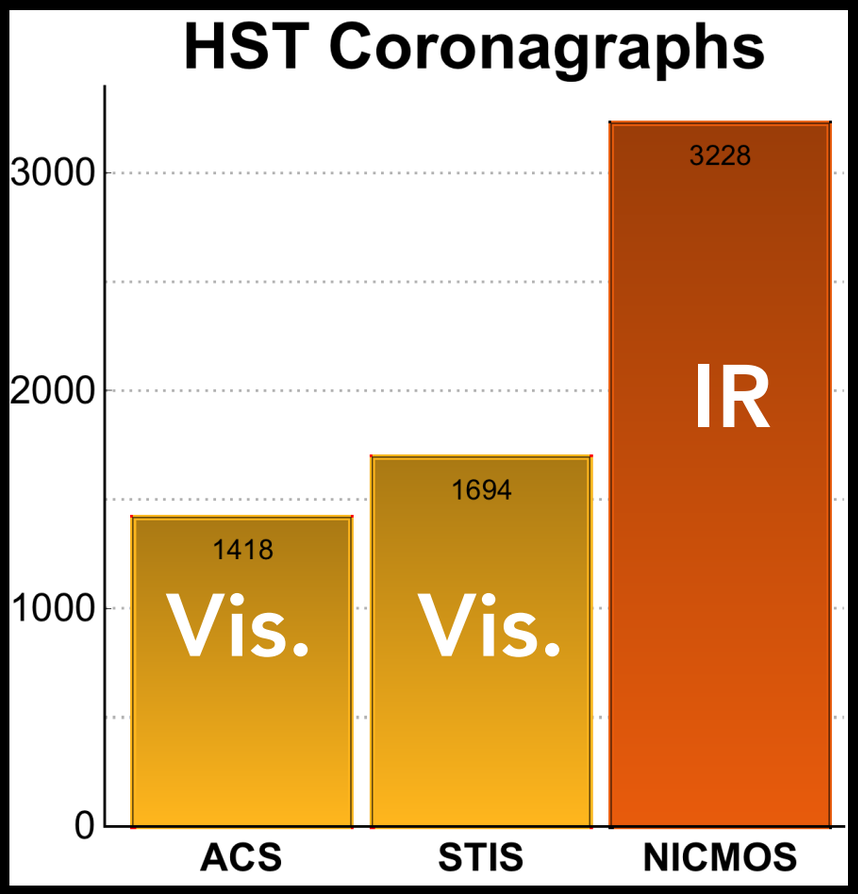


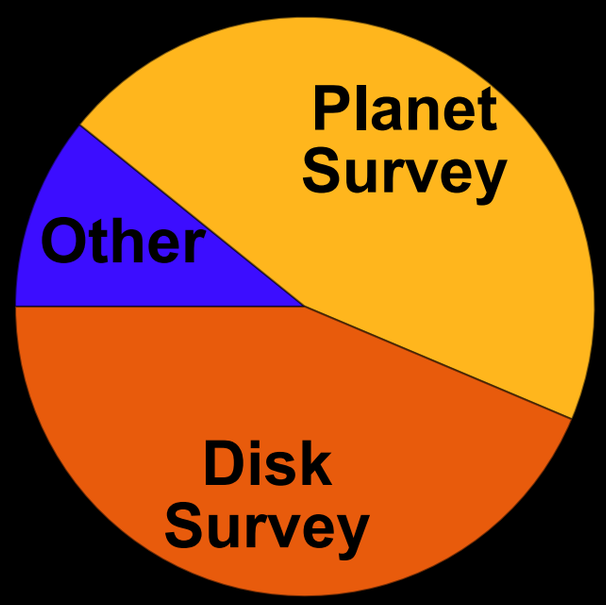
# The ALICE Program

**A**rchival **L**egacy **I**nvestigations of **C**ircumstellar **E**nvironments

PI: R. Soummer

Apply on the whole **NICMOS** archive



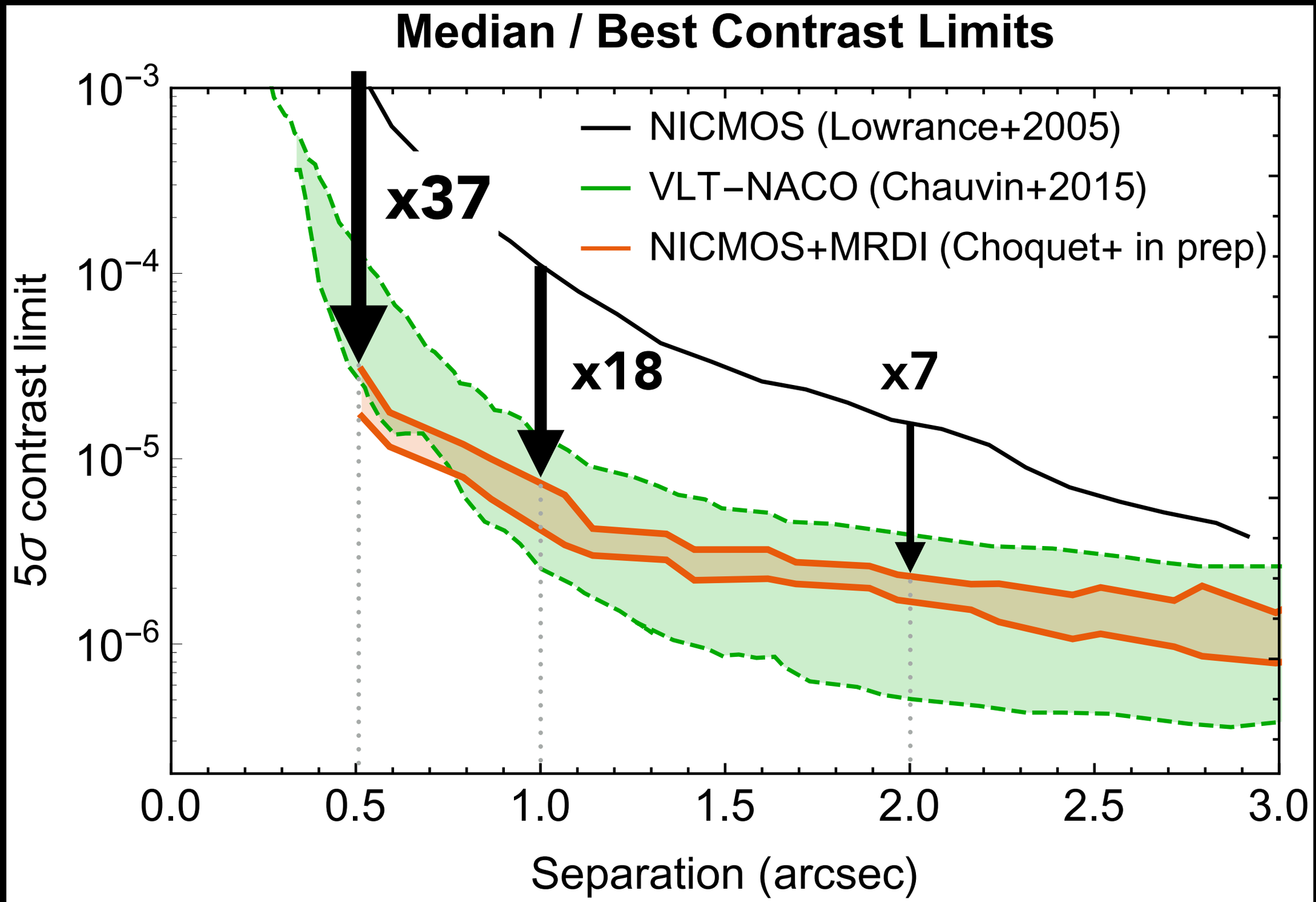




**MRDI libraries:**

~800 PSFs

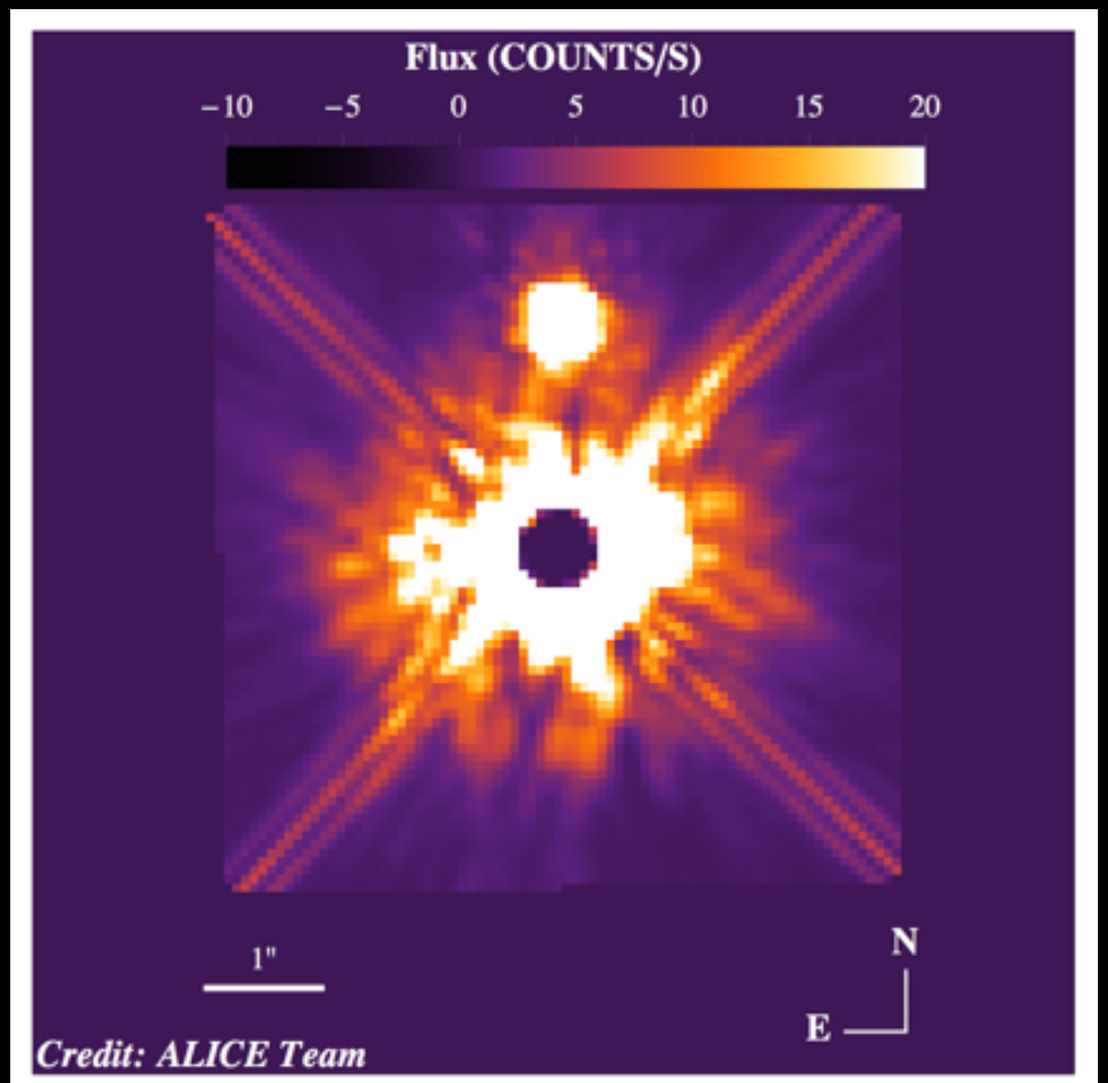
Choquet et al. 2014

# ALICE Contrast limits

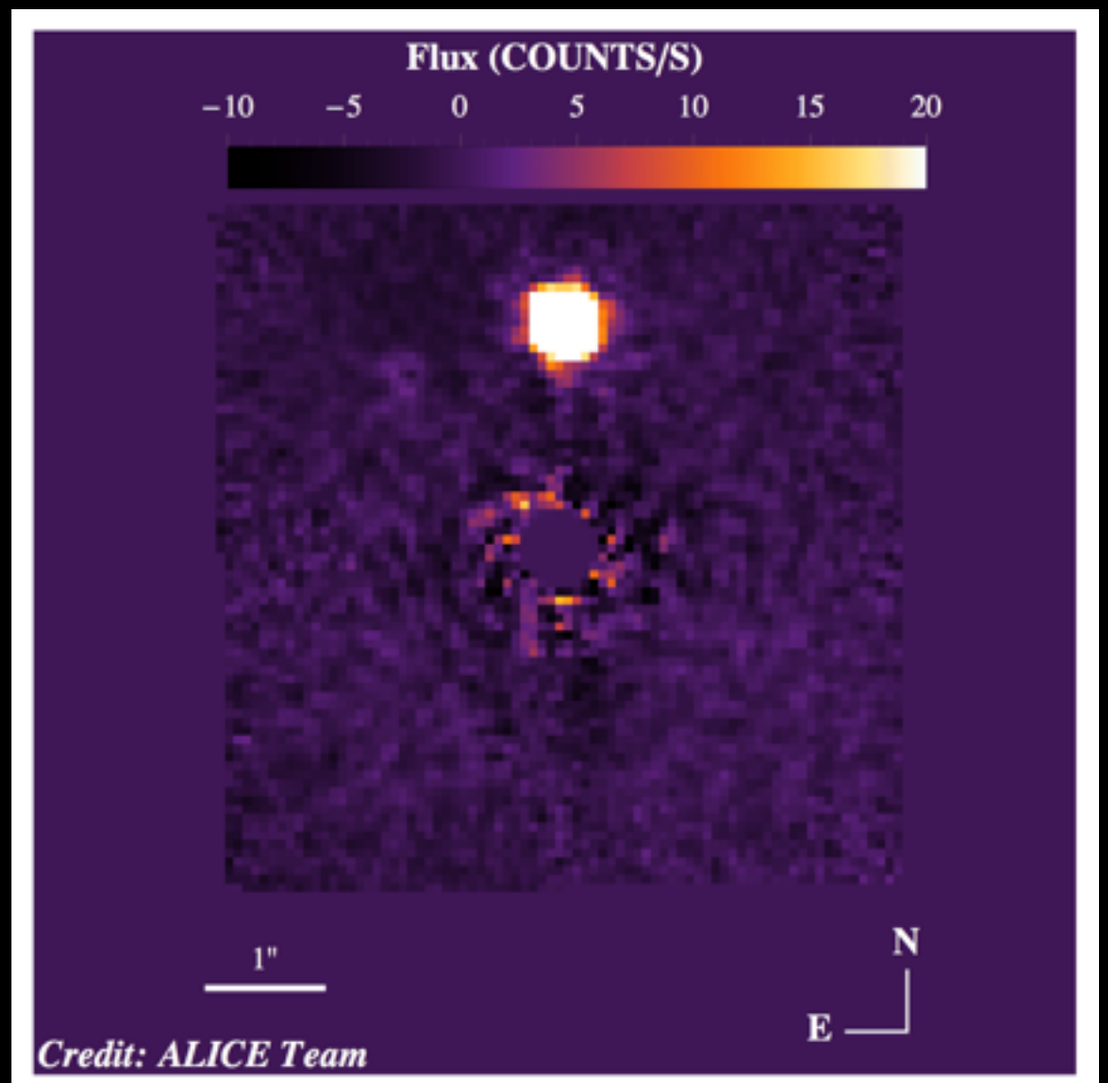


# The ALICE Program

## Raw




## Processed



# ALICE Data are Public!

https://archive.stsci.edu/prepds/alice/

Hagan et al. 2018

Barbara A. MIKULSKI ARCHIVE FOR SPACE TELESCOPES

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About MAST | Getting Started

## Archival Legacy Investigations of Circumstellar Environments (ALICE)

Primary Reference Document

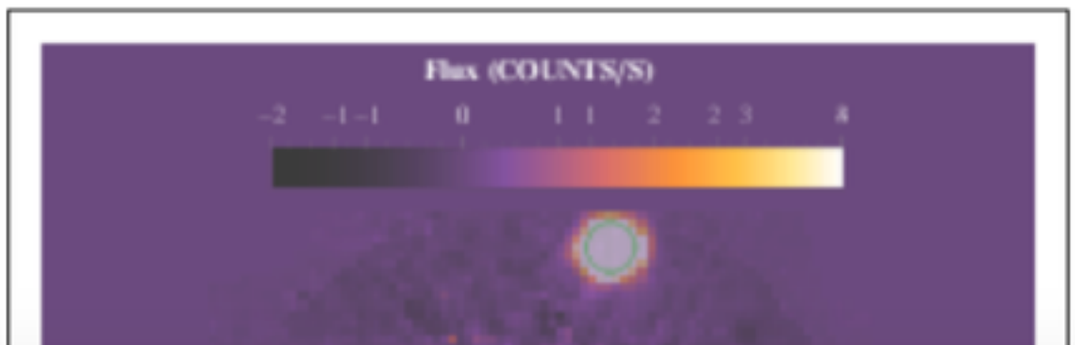
See also (hover for titles):

Soummer et al. (2012), *ApJL*, 755, 28
Choquet et al. (2016), *ApJL*, 817, 2
Debes et al. (2016), *JATIS*, 2a1010D
Milli et al. (2017), *A&A*, 597, 2
Soummer et al. (2014), *ApJL*, 786, 23
Mazoyer et al. (2016), *ApJ*, 818, 150
Choquet et al. (2015), *SPIE*, 9605, 1
Choquet et al. (2014), *SPIE*, 9143, 57
Soummer et al. (2011), *ApJ*, 741, 55
Milli et al. (2015), *A&A*, 577, 57
Rajan et al. (2015), *ApJL*, 809, 33
Choquet et al. (2017), *ApJL*, 834, 12
Choquet et al. (2014), *SPIE*, 9147, 51

Introduction | Data Products | Data Access

### Introduction

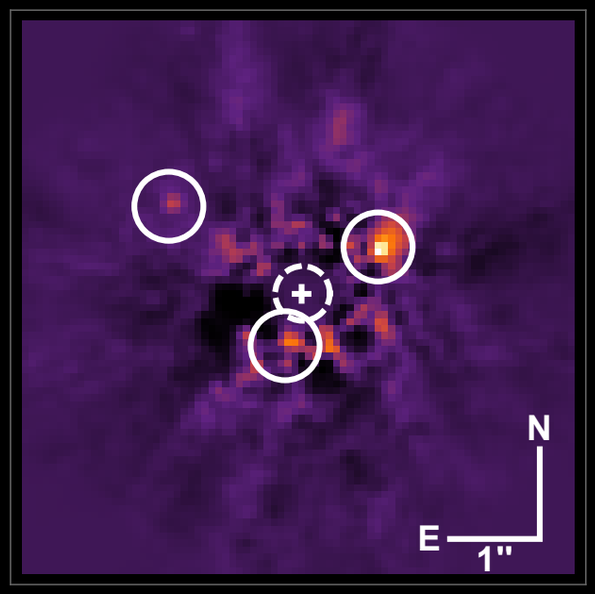
The HST NICMOS instrument has been used from 1997 to 2008 to perform coronagraphic observations of about 400 targets. Most of these were part of surveys looking for substellar companions or resolved circumstellar disks to young nearby stars, making the NICMOS coronagraphic archive a valuable database for exoplanets and disks studies. These data are complementary to ground-based high-contrast imaging observations in several ways, in particular due to HST's excellent sensitivity and to the great timeline between these observations and contemporary observations.



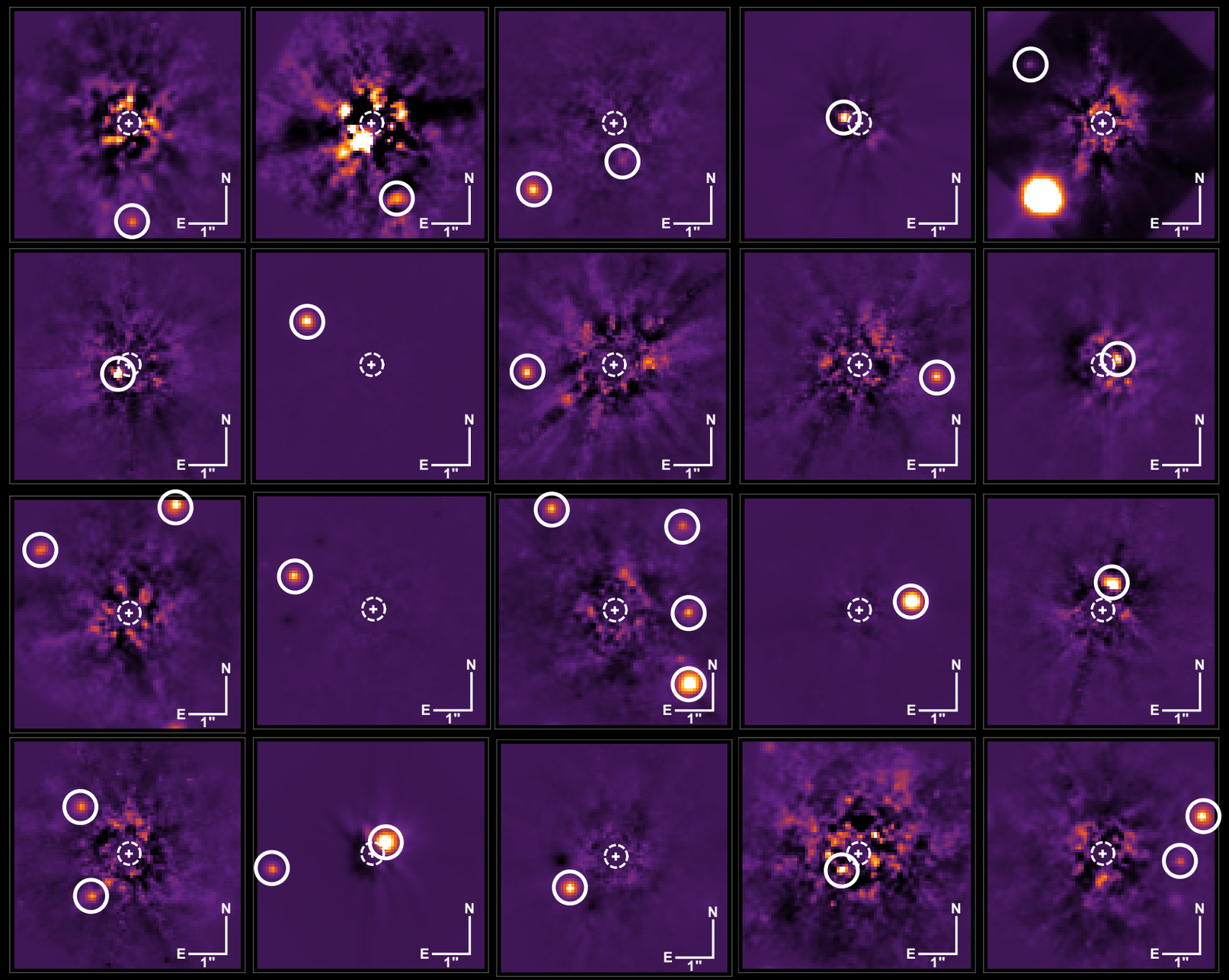

The ALICE program is an HST Legacy program aiming at revaluing the NICMOS

# ALICE Point Source Detections

## HR 8799's planets



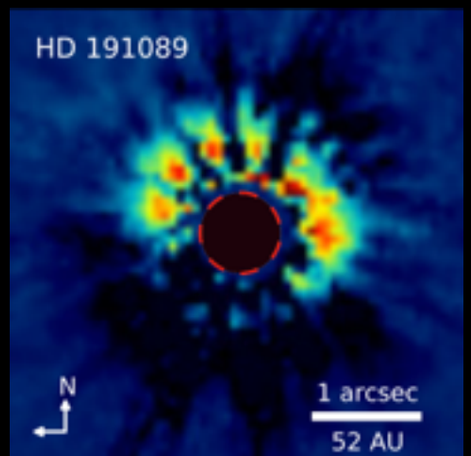

## New planet / BD candidates

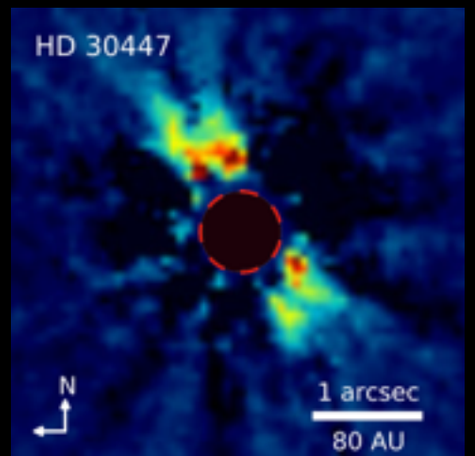


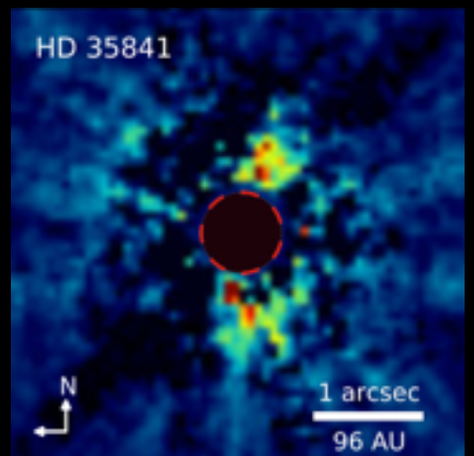

## Follow-up campaign @ Keck

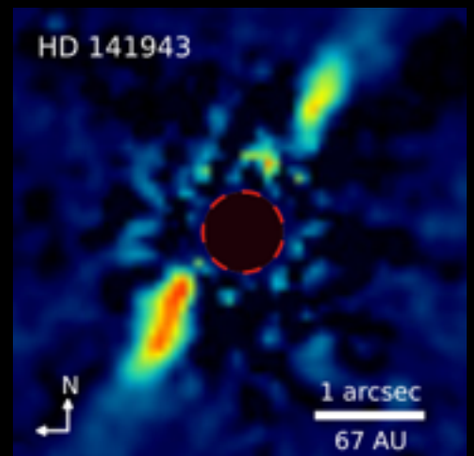
# New Debris Disks

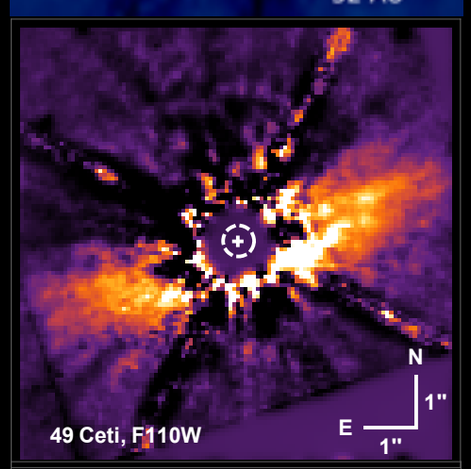
## First Images in scattered light

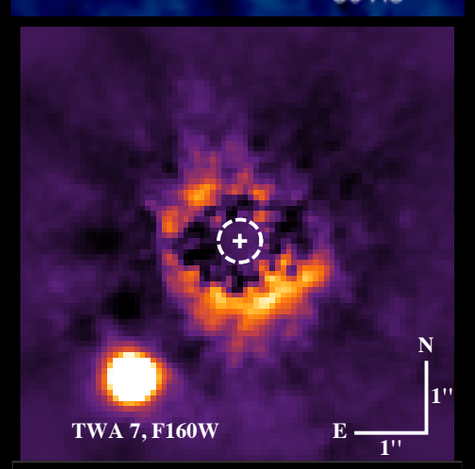


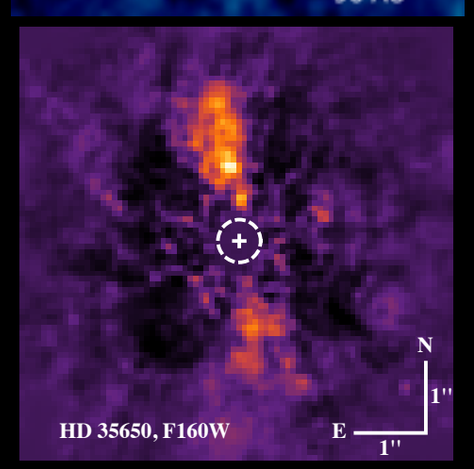



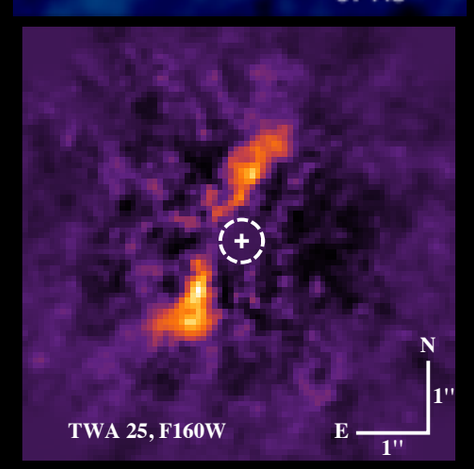



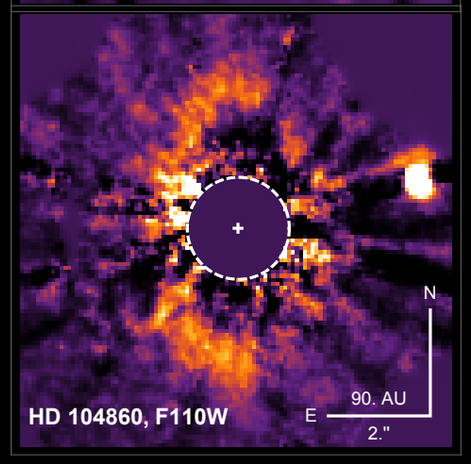



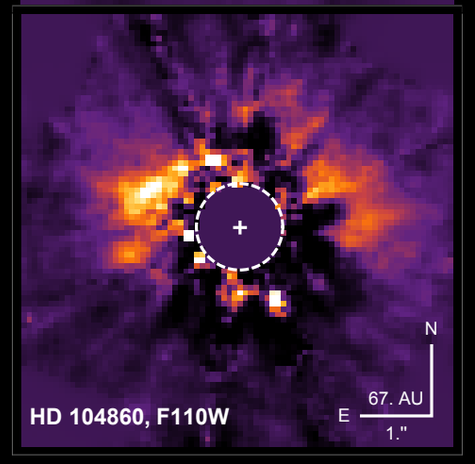



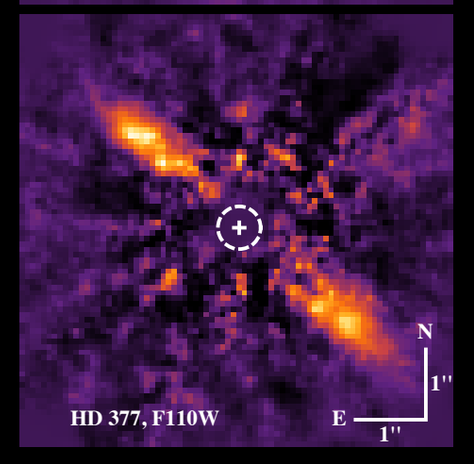



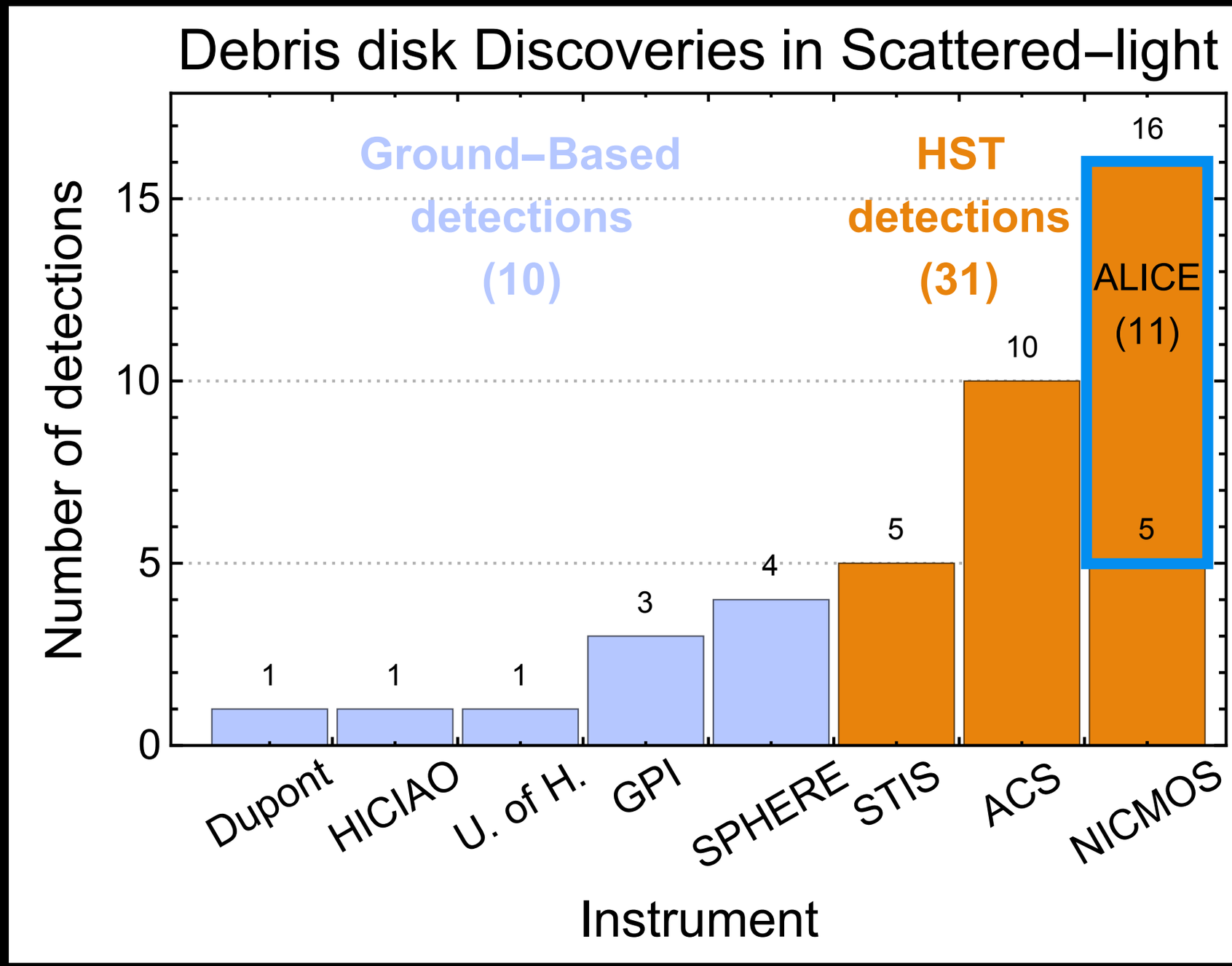




Soummer et al. 2014
Choquet et al. 2016
Choquet et al. 2017
Choquet et al. 2018

# ALICE Debris Disks Detections



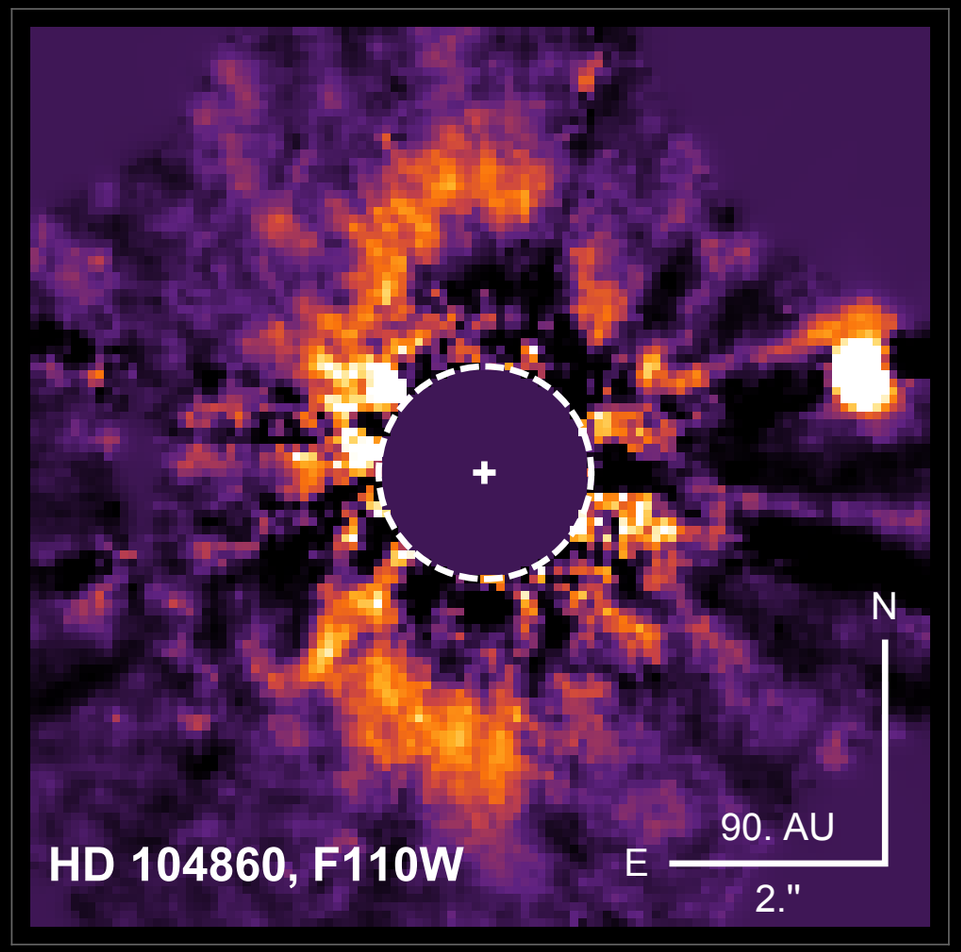


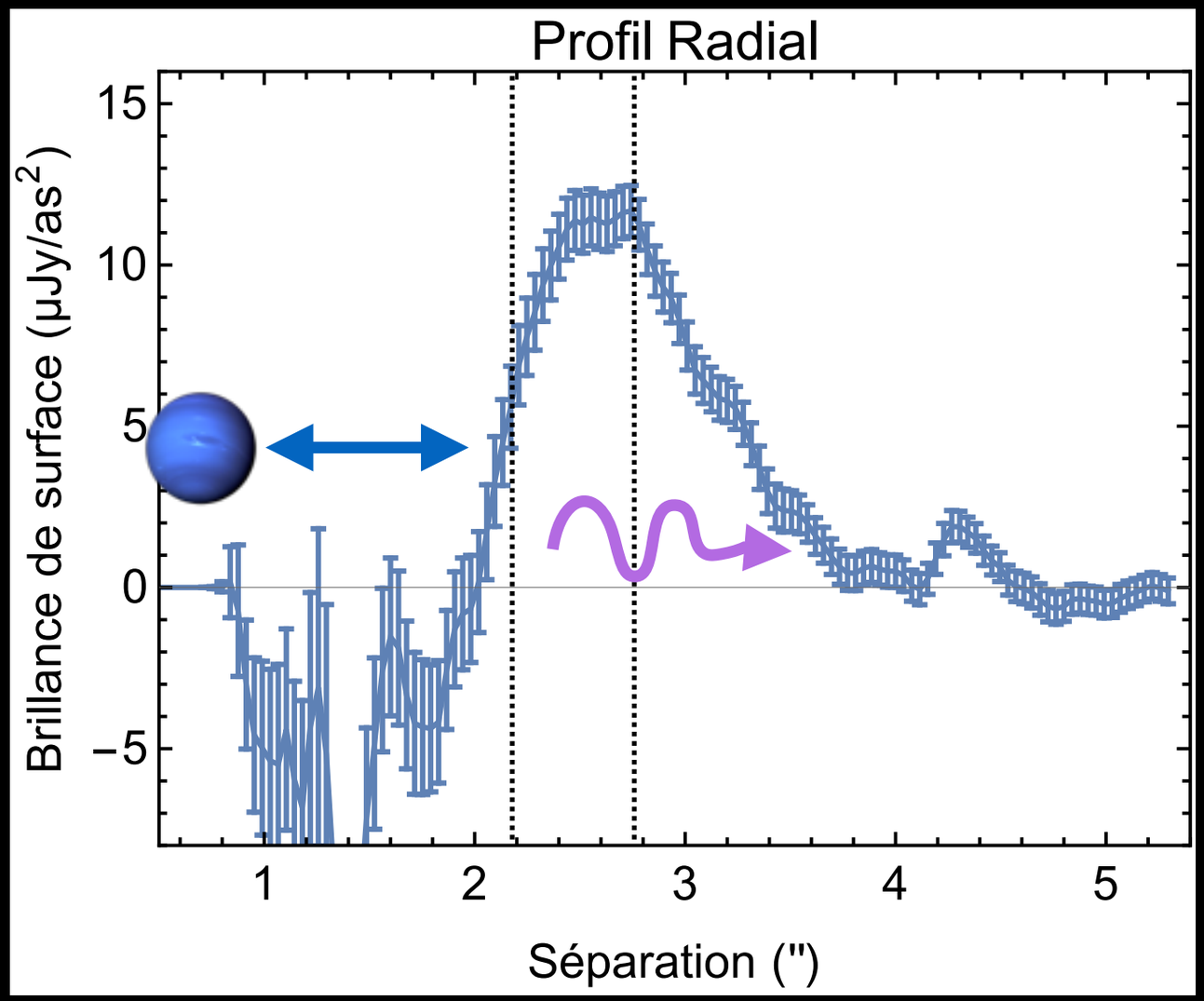
**HST rules!**

Choquet et al. 2018

# Disk characterization

## Constraints on the dynamics

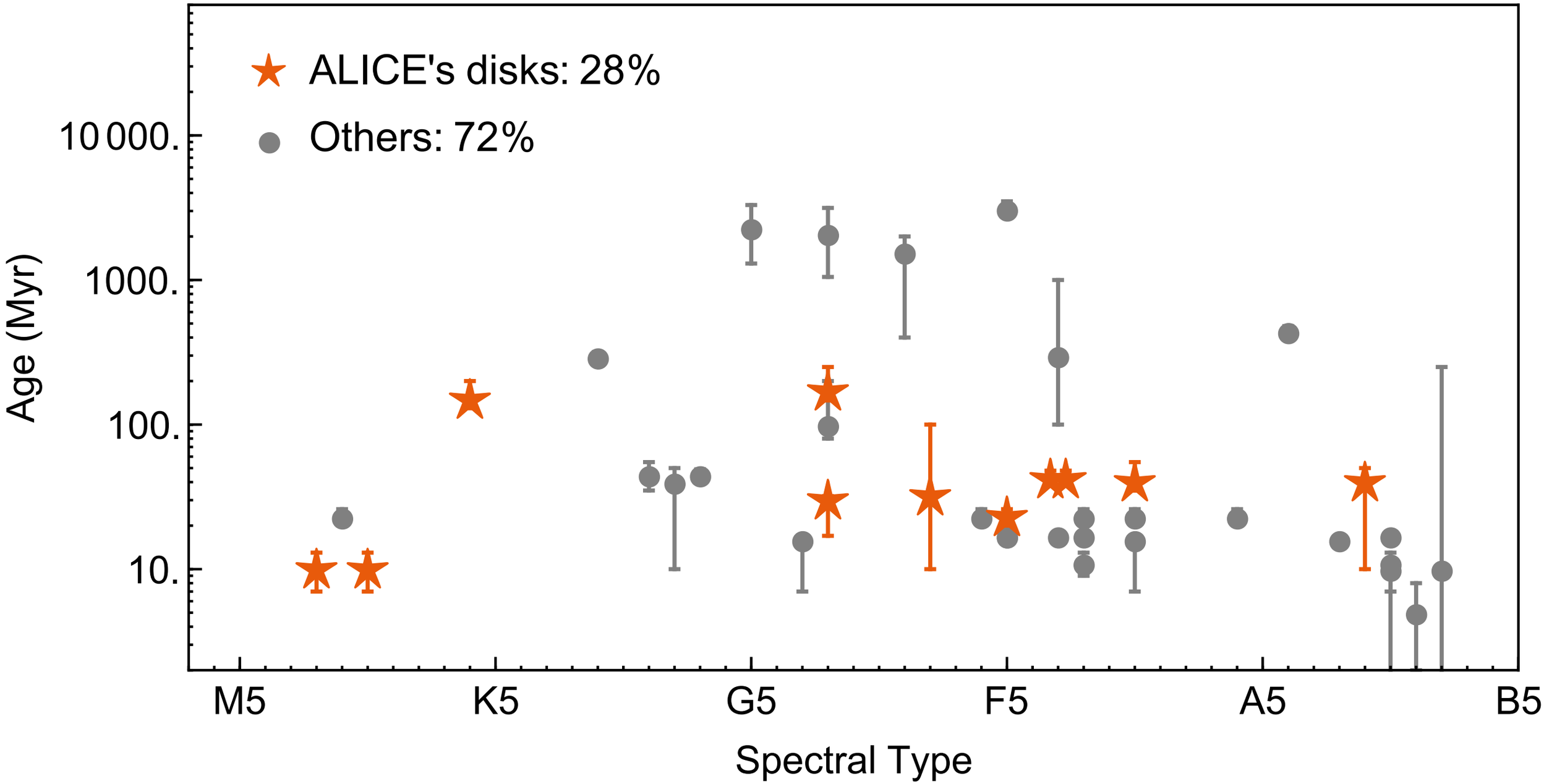



**ω ~10% : excludes H2O ice grains and grains < 1μm**

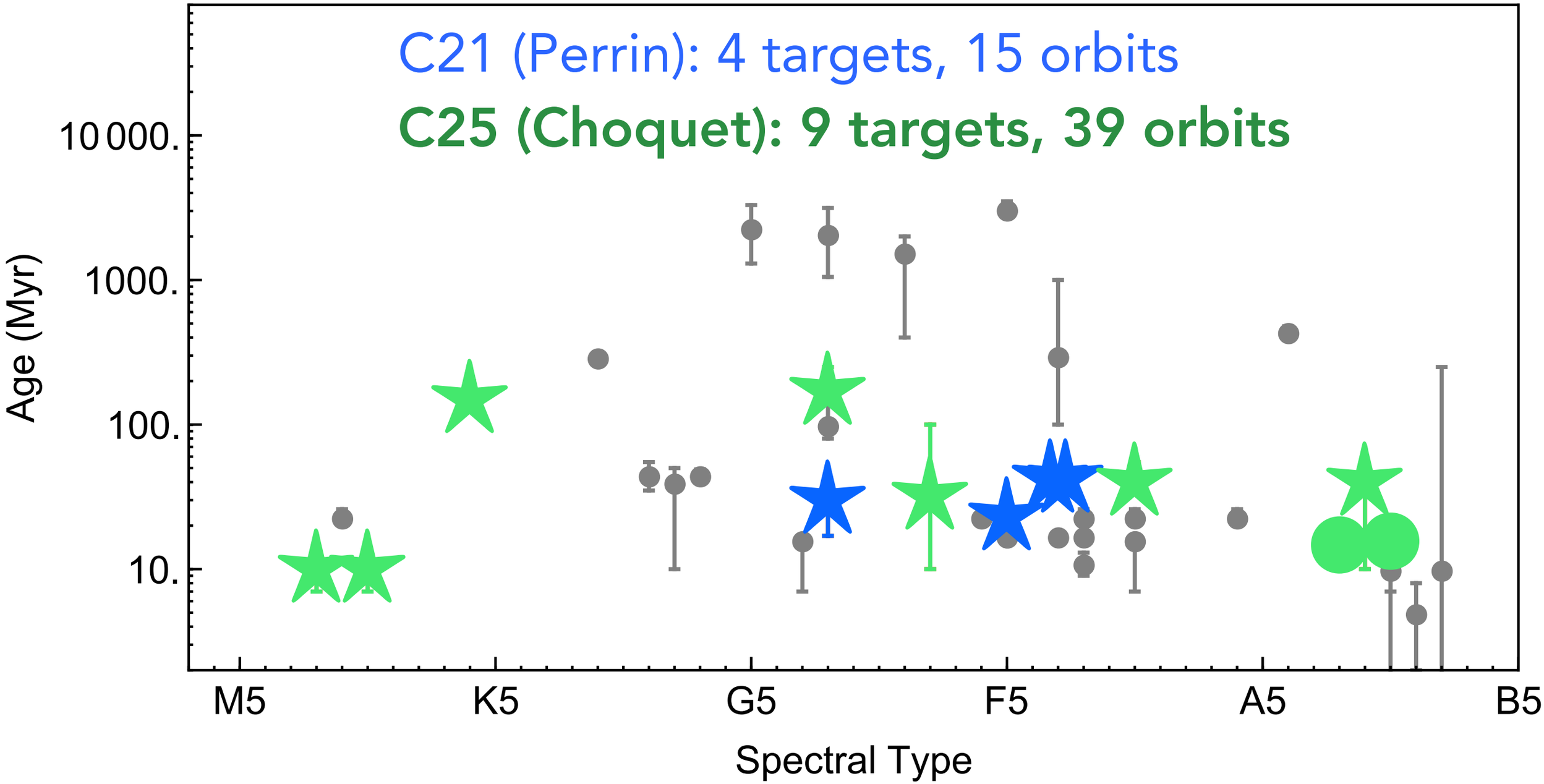
Choquet et al. 2018

# Debris Disks in Scattered-Light



# HST-STIS visible-light programs

*near-IR + visible color* *... across spectral types*

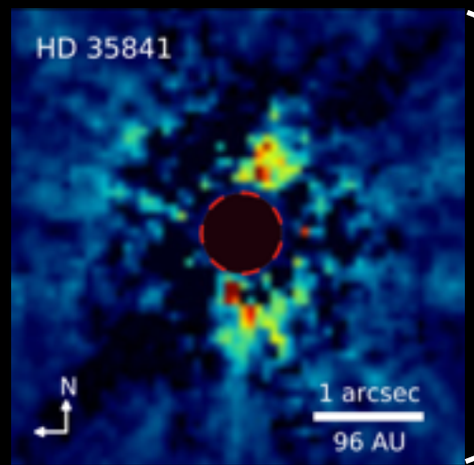


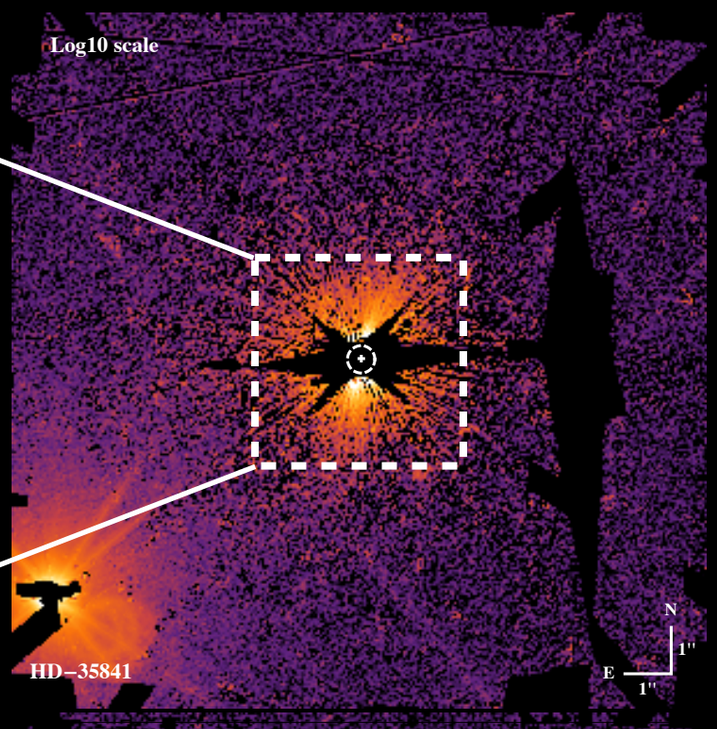
# C21: Blown-out Particles Halo

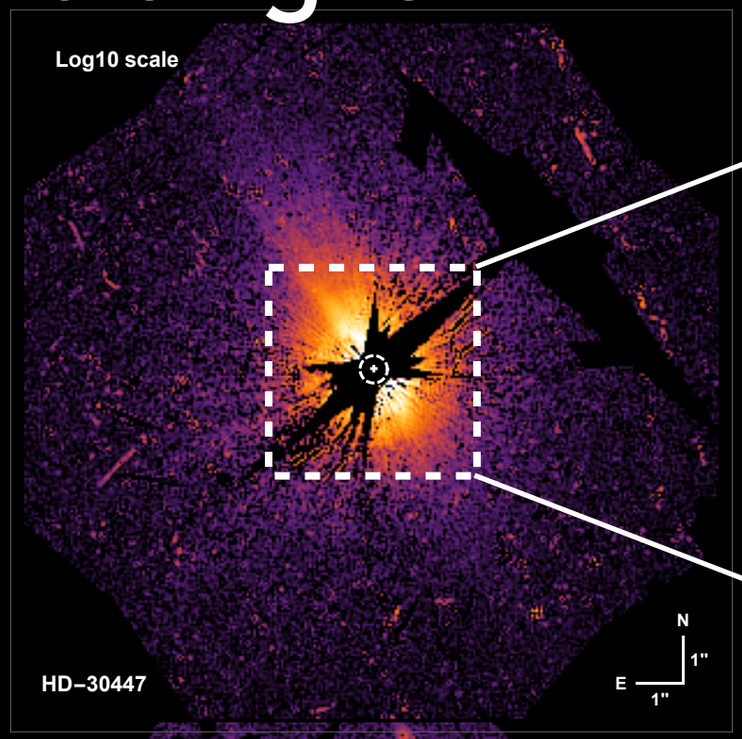
## NICMOS near-IR

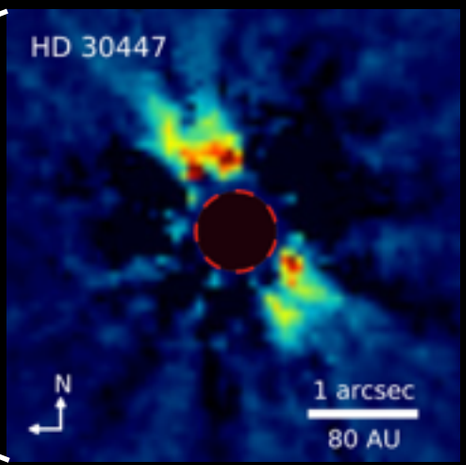
## STIS - visible-light

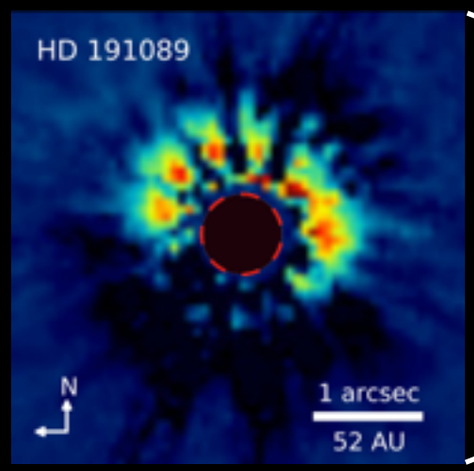
## NICMOS near-IR

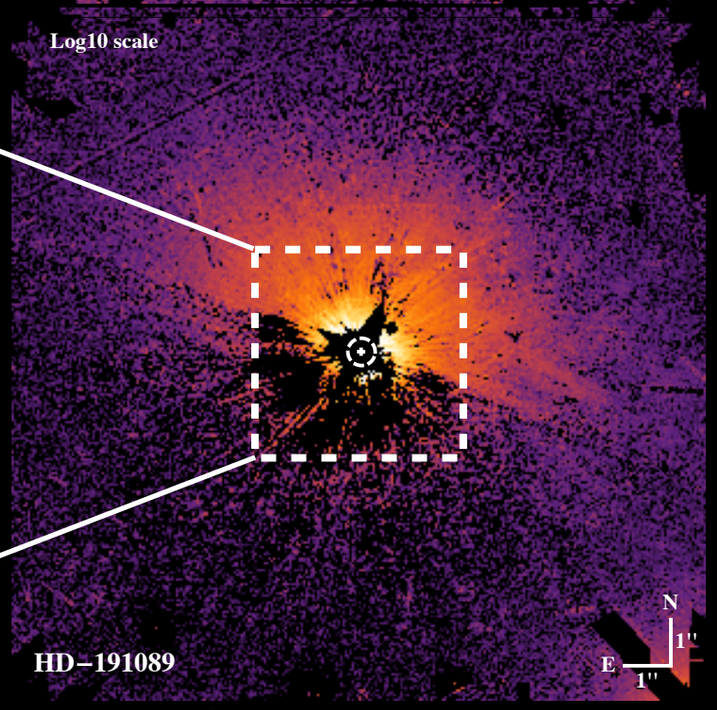


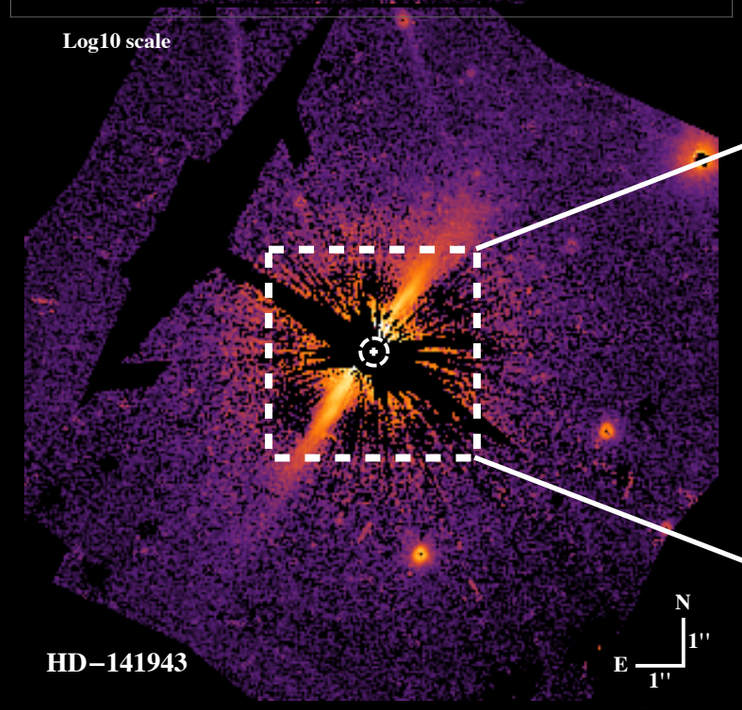



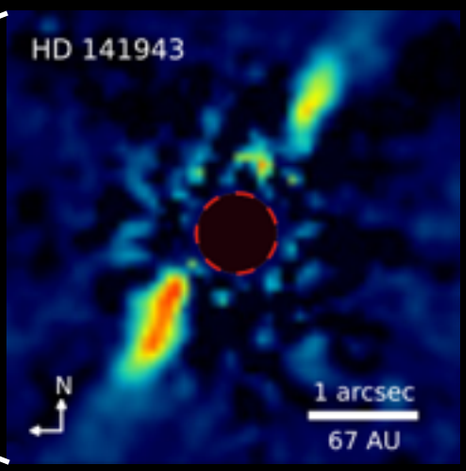



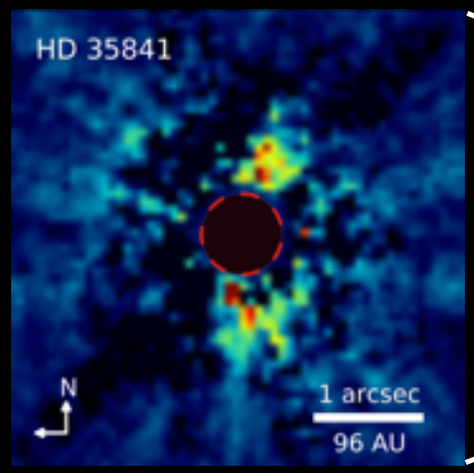

Esposito et al. in prep, Ren et al in prep, Perrin et al. in prep

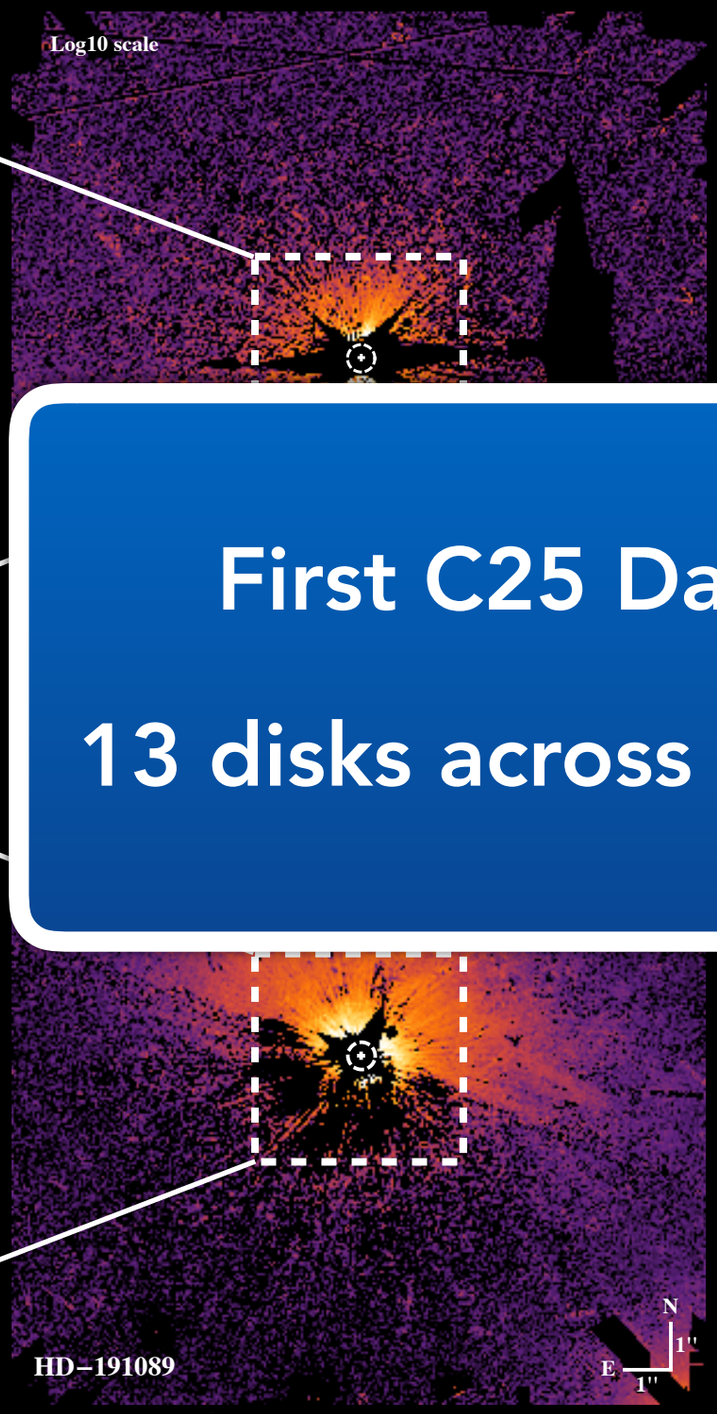
# C21: Blown-out Particles Halo

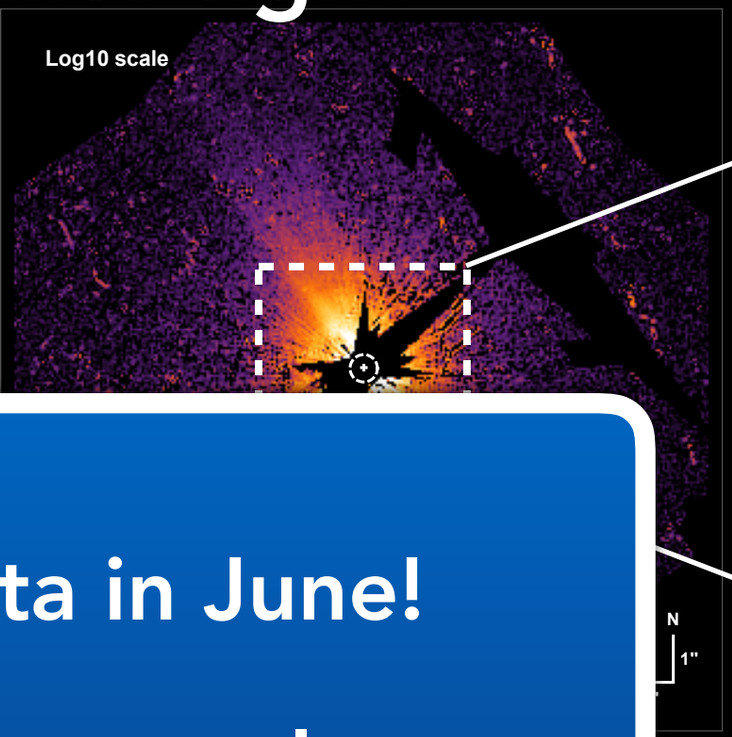
NICMOS near-IR

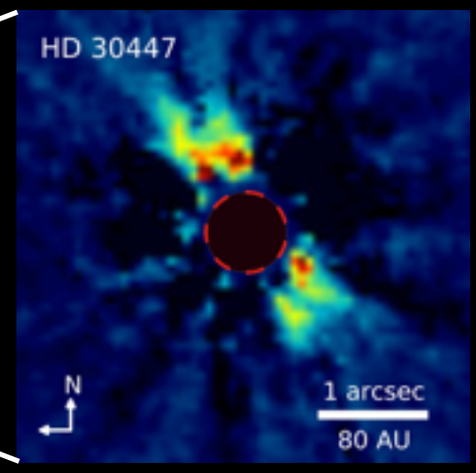
STIS - visible-light

NICMOS near-IR



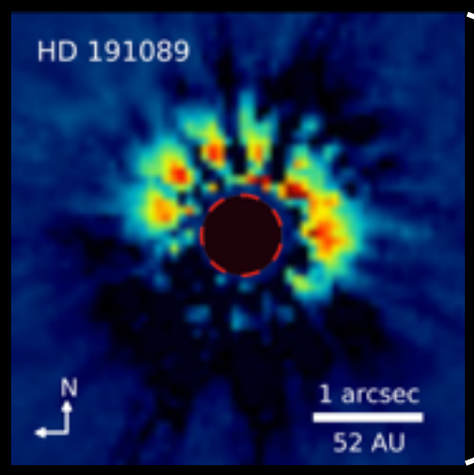



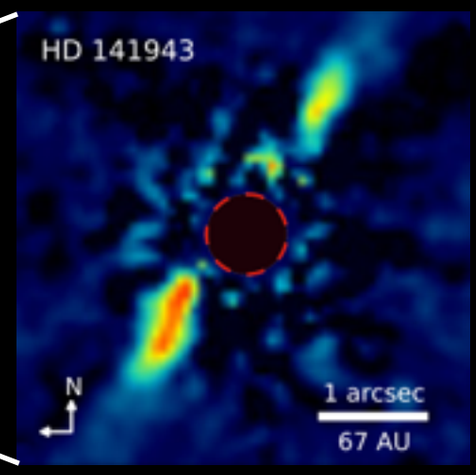




**First C25 Data in June!**

**13 disks across spectral types**



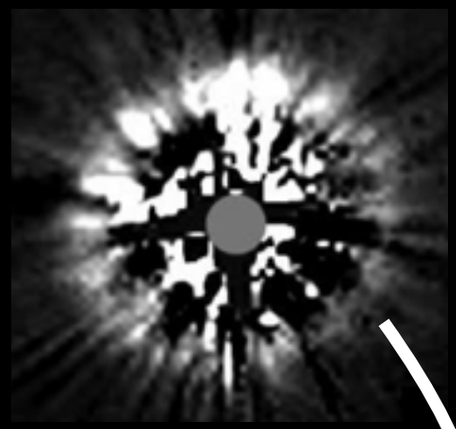




Esposito et al. in prep, Ren et al in prep, Perrin et al. in prep

# Conclusion & Prospects

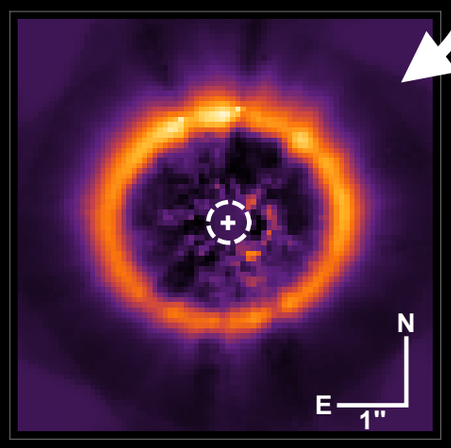
## MRDI

Classical



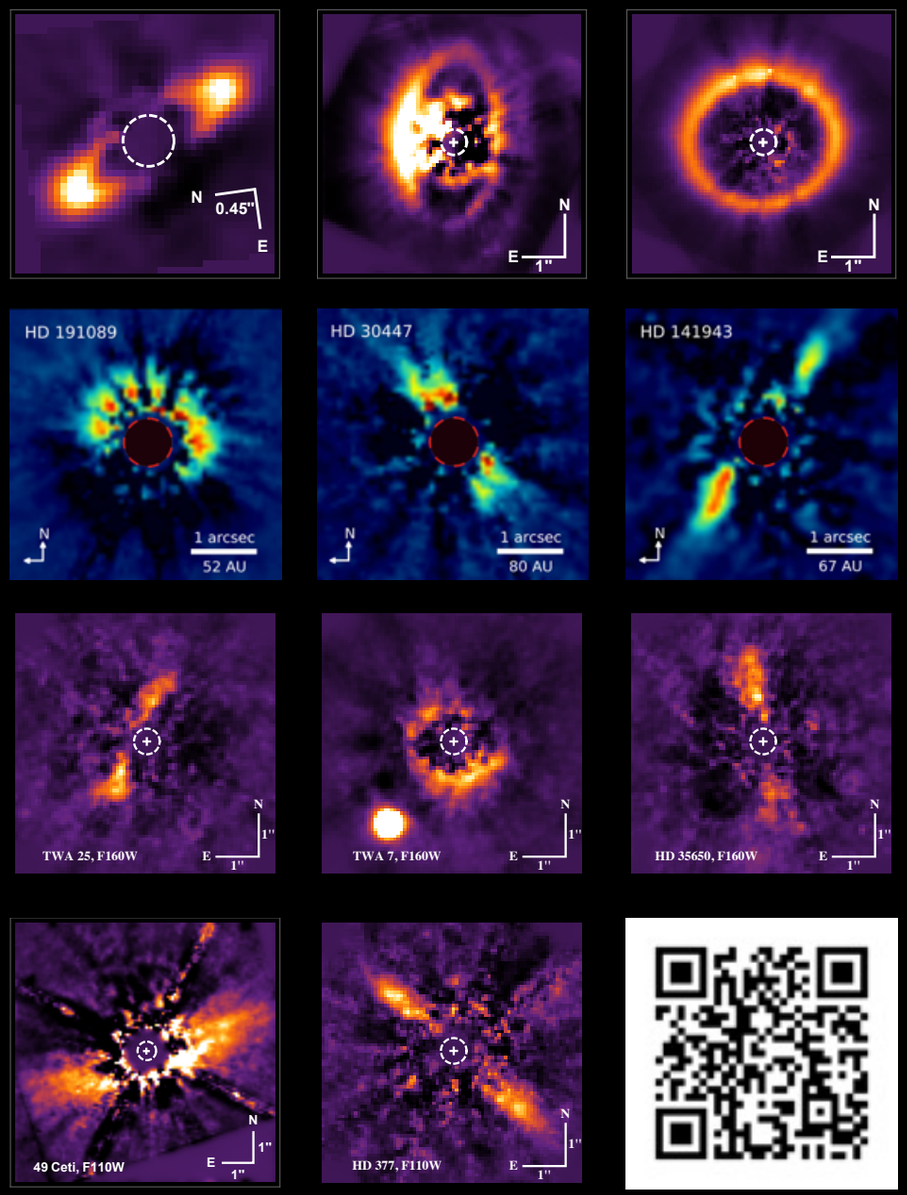
x30

Advanced




$10^{-5}$

## ALICE




https://archive.stsci.edu/prepds/alice/

## JWST

**No archive yet!**

Telescope rolls

Reference stars

Dither patterns

# Thanks