Fast-Cadence High-Contrast imaging: the SFADI speckle-free method

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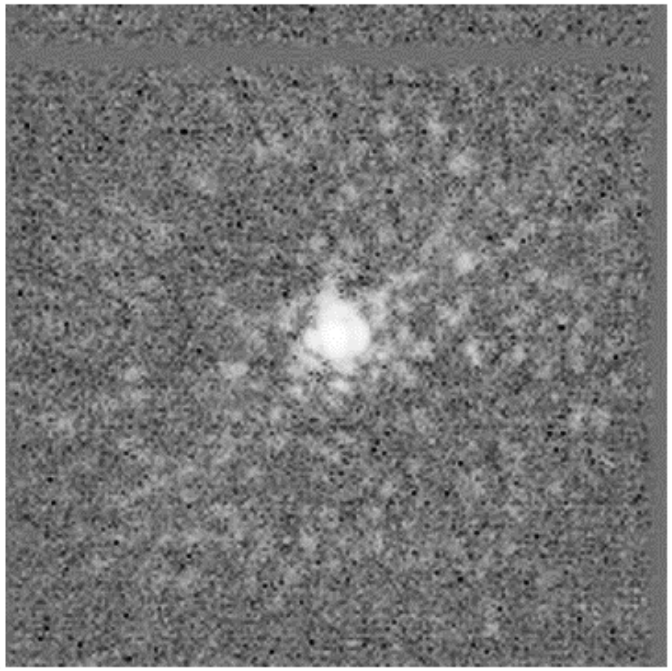
Fast cadence imaging at kHz rate

Advantages of Fast Cadence Imaging

(learned from ForeRunner@LBT experiment, Pedichini+ 2017, Stangalini+ 2017)

- **Speckles freezing**: speckles lifetime is 2-5ms.
- Pure **sky background areas among the speckles**.
- Accurate **peak alignment for jitter compensation** (up to **300Hz**).
- **Measurement of frame-by-frame core flux variation** for normalization and weighted average.
- **Frames-by-frames selection** to reject elongated, or fragmented peaks (note: **only ~10% frames**)
- → **Spatial Lucky Imaging**:
  no "best frames", but **best pixels** in each frame



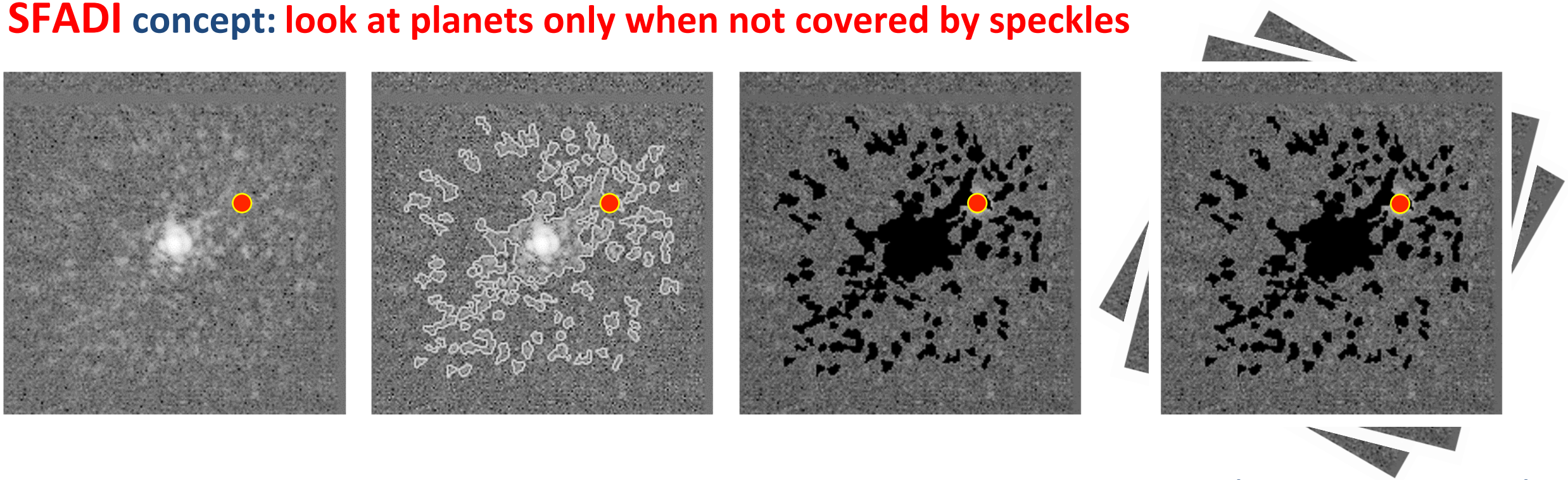
ForeRunner 1ms single frame,

630 nm, 20 min exp, avg seeing 1.2″

SFADI (Speckle-Free ADI) Spatial Lucky Imaging

Li Causi et al. 2017, ApJ, 849:85

SFADI concept: look at planets only when not covered by speckles



A: kHz frames acquisition
No usual PSF concept, PSF very different on each frame made of speckles spread onto a zero background.

B: Speckles identification
NOTE: planets < 10^{-3} are not identified, because lower than noise in single frames.

C: Speckles suppression
Speckles flagged as «bad pixels». Planets are imaged only when not covered by speckles.

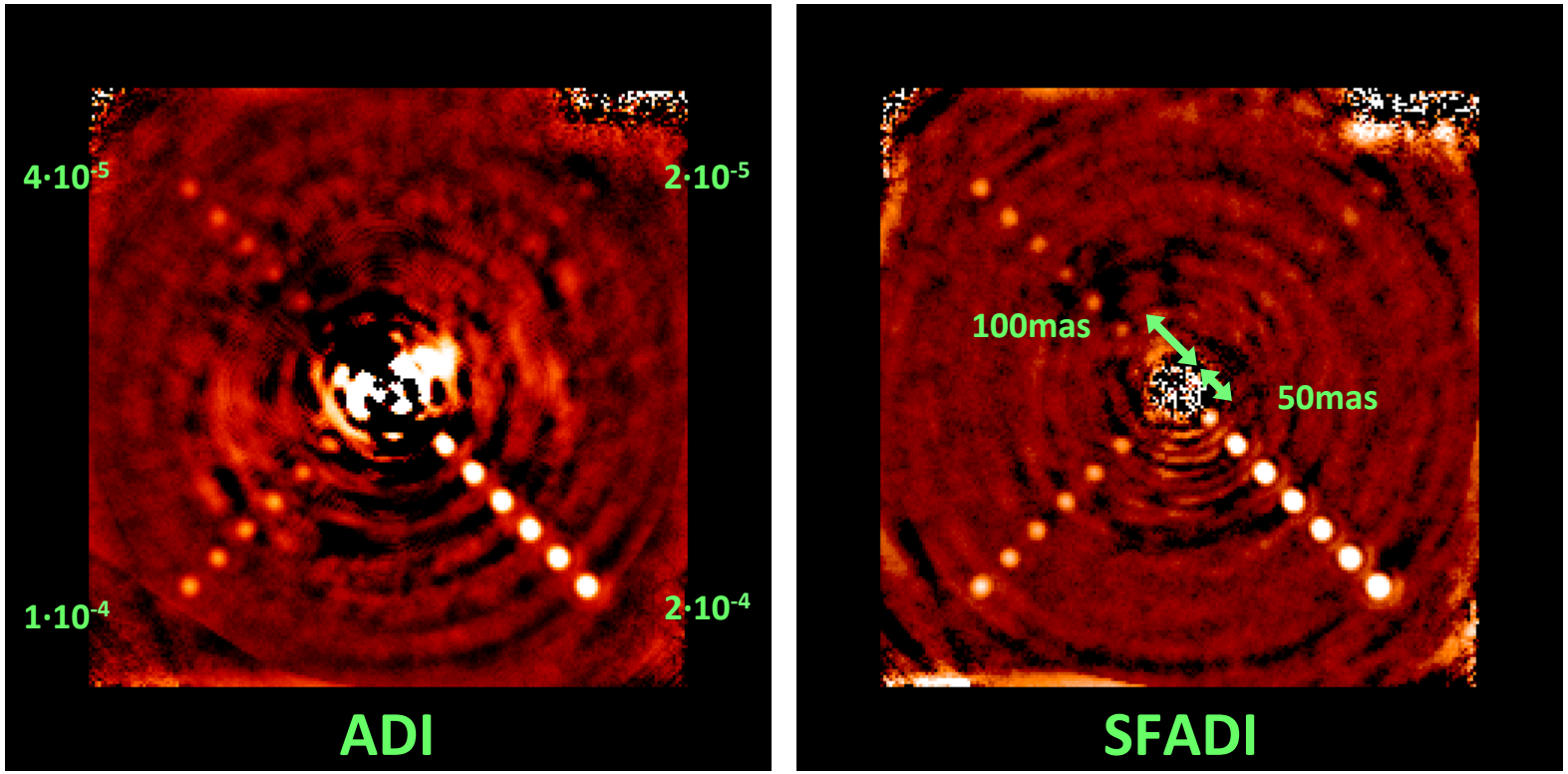
D: ADI (un-masked pixels only)
Standard ADI is performed, for un-masked pixels only, to remove the false background structure due to unperfect speckle suppression.

SFADI (Speckle-Free ADI): performances

Li Causi et al. 2017, ApJ, 849:85

ADI vs SFADI:

10^6 Forerunner frames - 1.2'' seeing – No Coronagraphy
$2{\cdot}10^{-5}$, $4{\cdot}10^{-5}$, 10^{-4}, and $2{\cdot}10^{-4}$ contrast planets



NOTE:

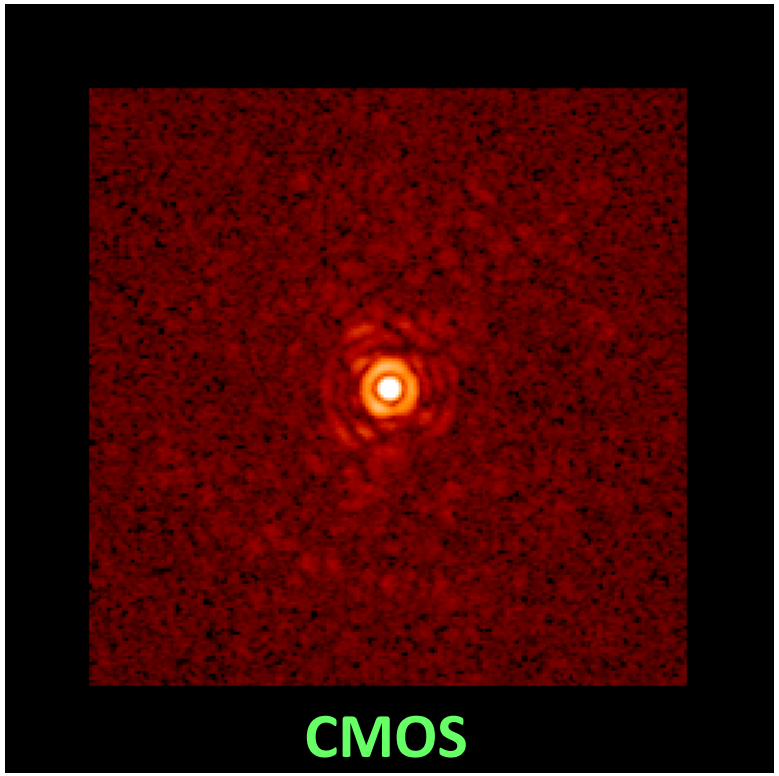
- Very clean and uniform residual
- ADI here is done after jitter correction by peak alignment at 1 KHz frame-rate
- Still not at photon limit ($2{\cdot}10^{-6}$) but SHARK-VIS (10 times more sensitive) will approach it in good seeing

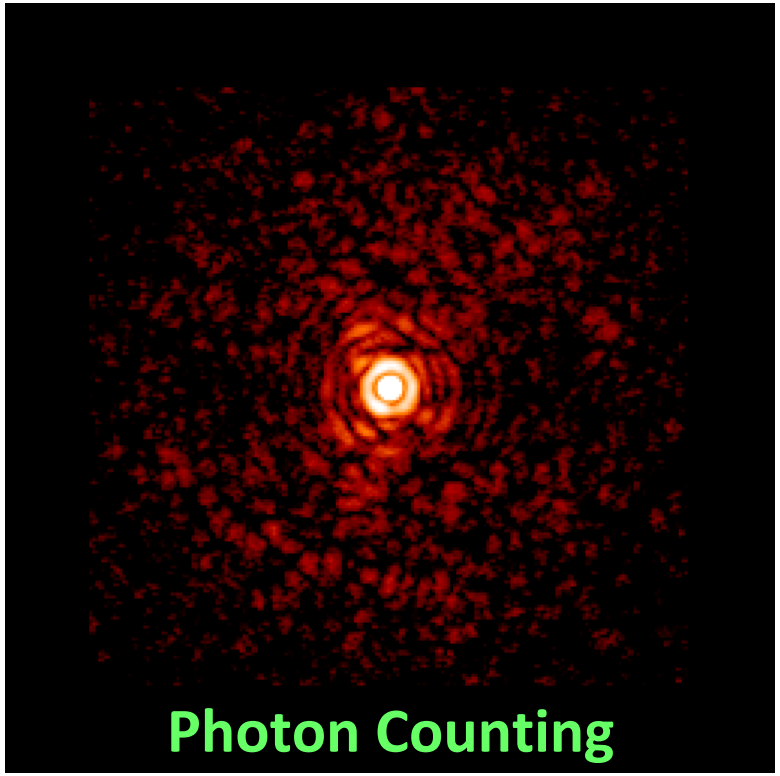
SFADI (Speckle-Free ADI): performances

Li Causi et al. 2017, ApJ, 849:85

CMOS vs. no noise Photon Counting:

1 KHz frame SOUL simulations (SHARK Simulator Code, Stangalini+ 2016)





NOTE:

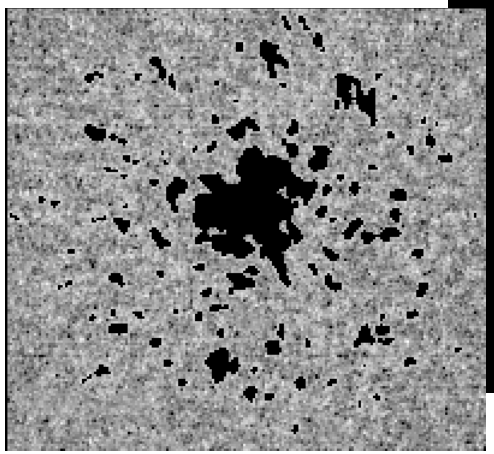
- **Noise-free Photon Counting detectors allow better speckles identification and masking**

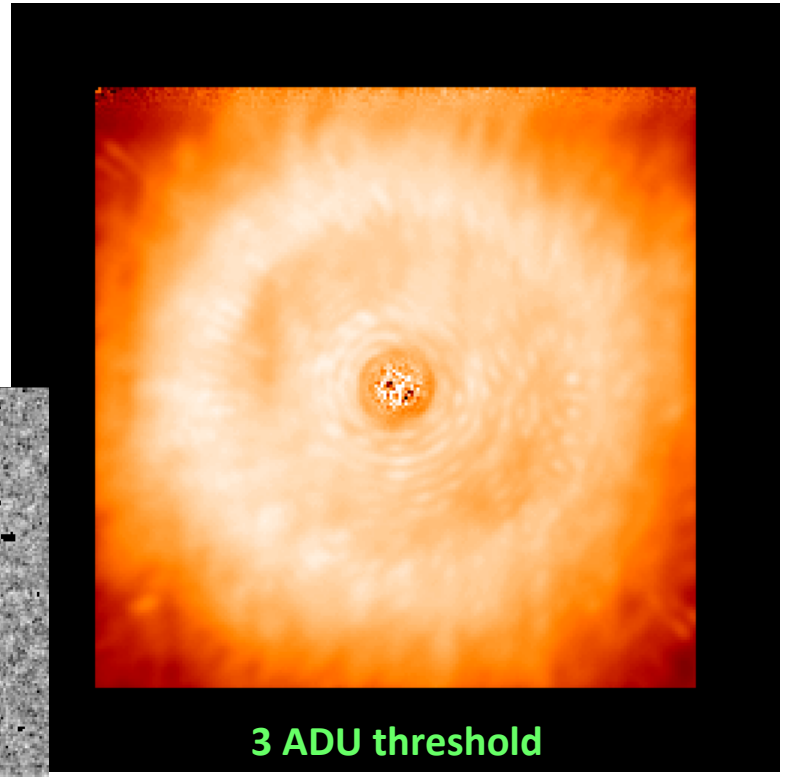
SFADI (Speckle-Free ADI): performances

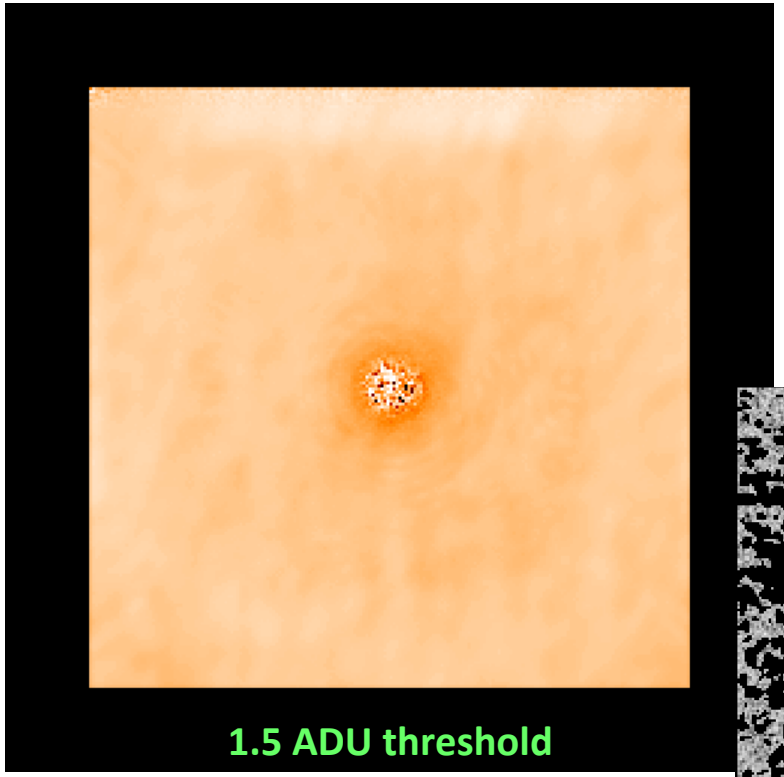
Li Causi et al. 2017, ApJ, 849:85

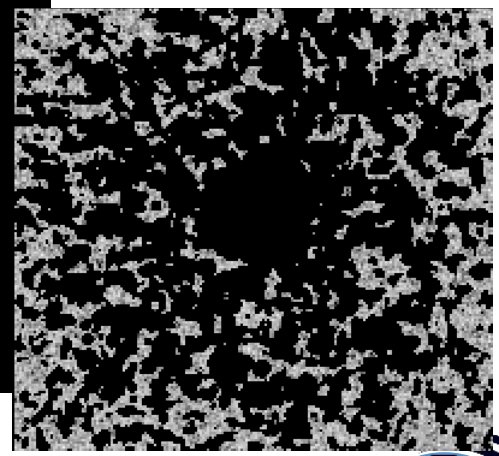
Speckle identification powered by SWAMIS (De Forest and Lamb 2007): follow speckles evolution

Median stack of speckle-masked frames







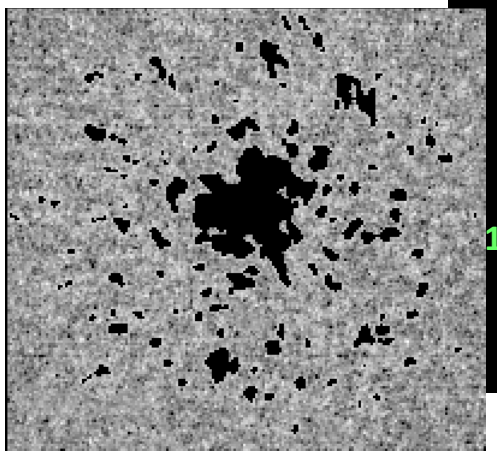


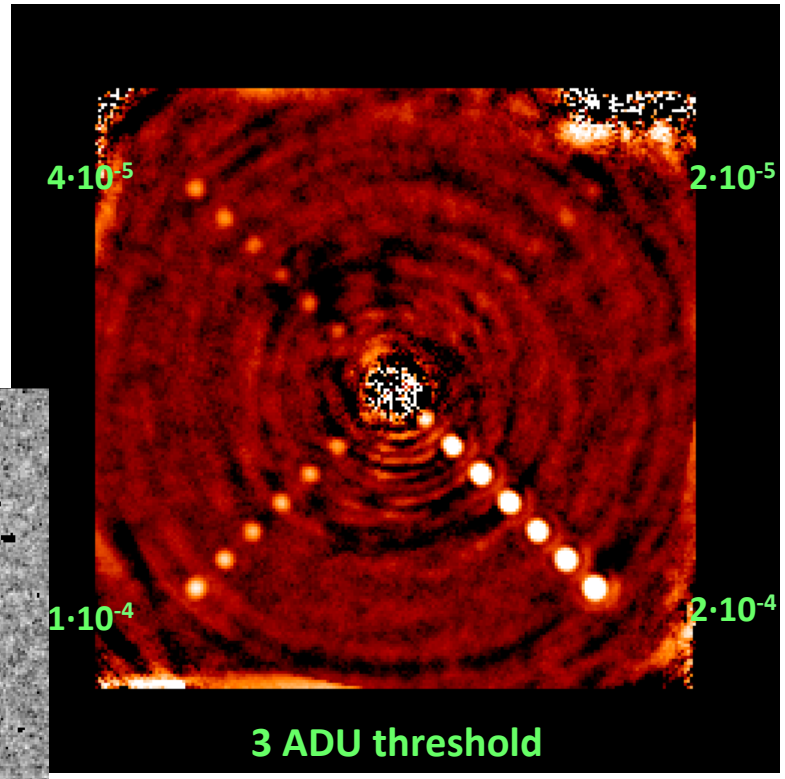
SFADI (Speckle-Free ADI): performances

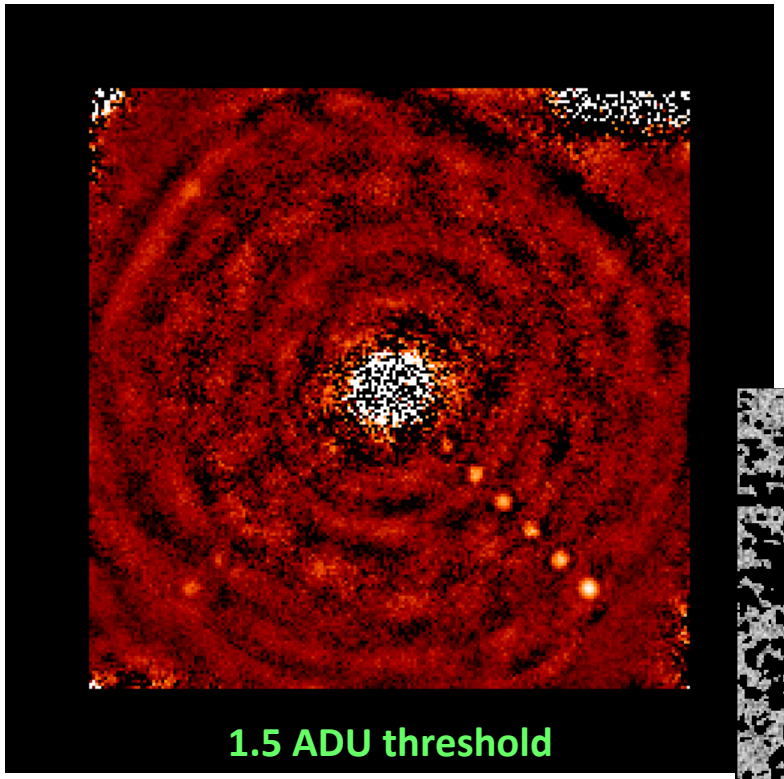
Li Causi et al. 2017, ApJ, 849:85

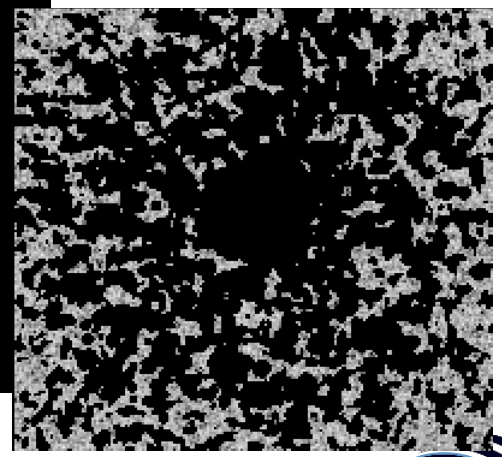
SFADI wrt SWAMIS threshold:

10^6 Forerunner frames
$2{\cdot}10^{-5}$, $4{\cdot}10^{-5}$, 10^{-4}, and $2{\cdot}10^{-4}$ contrast planets





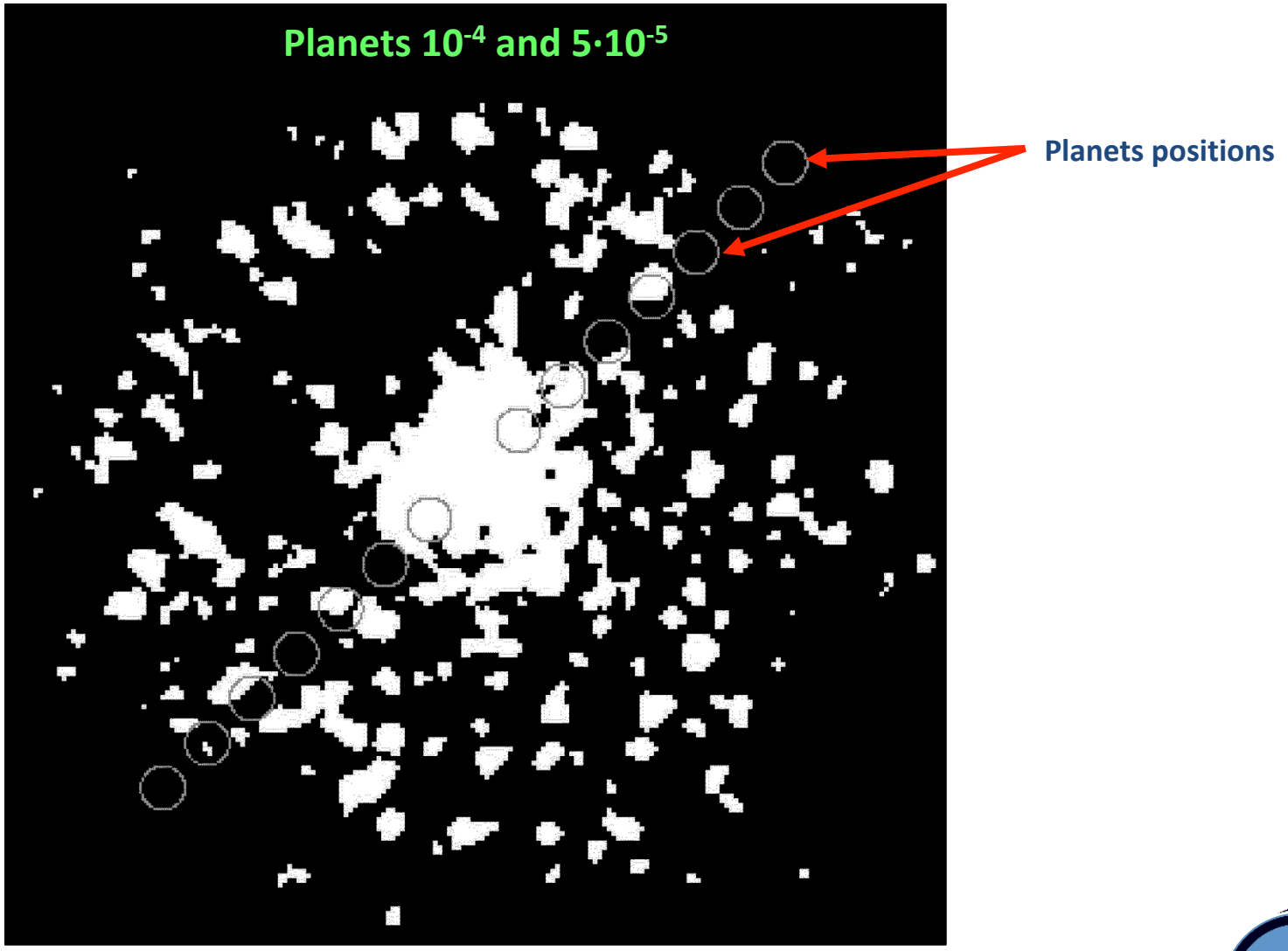




SFADI (Speckle-Free ADI): performances

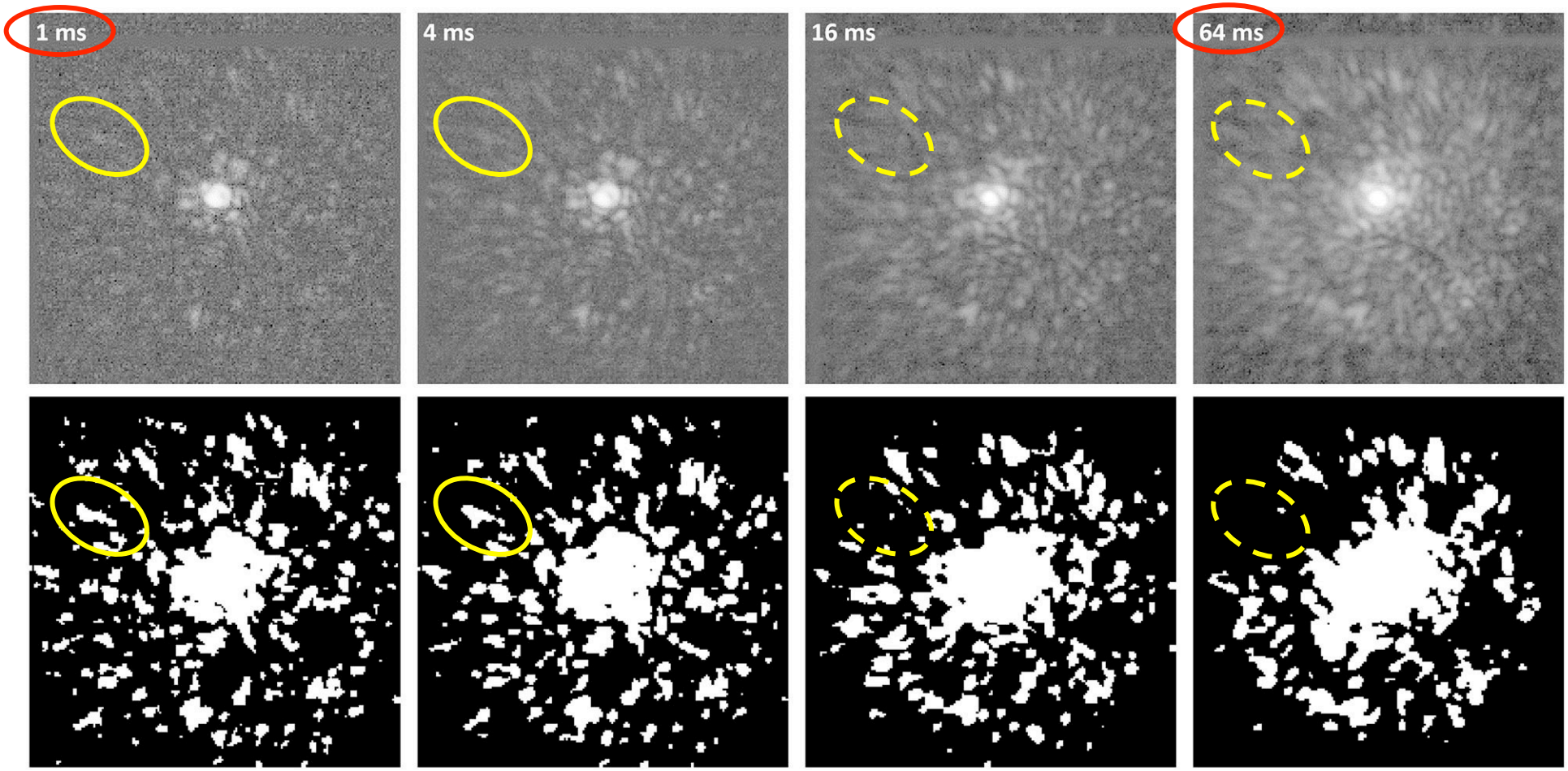
Li Causi et al. 2017, ApJ, 849:85

Planets are not masked if they are fainter than 10^{-3} because they are not detectable in single frames:
< 1 photon /pixel / frame in central pix



SFADI (Speckle-Free ADI): KHz rate mandatory!

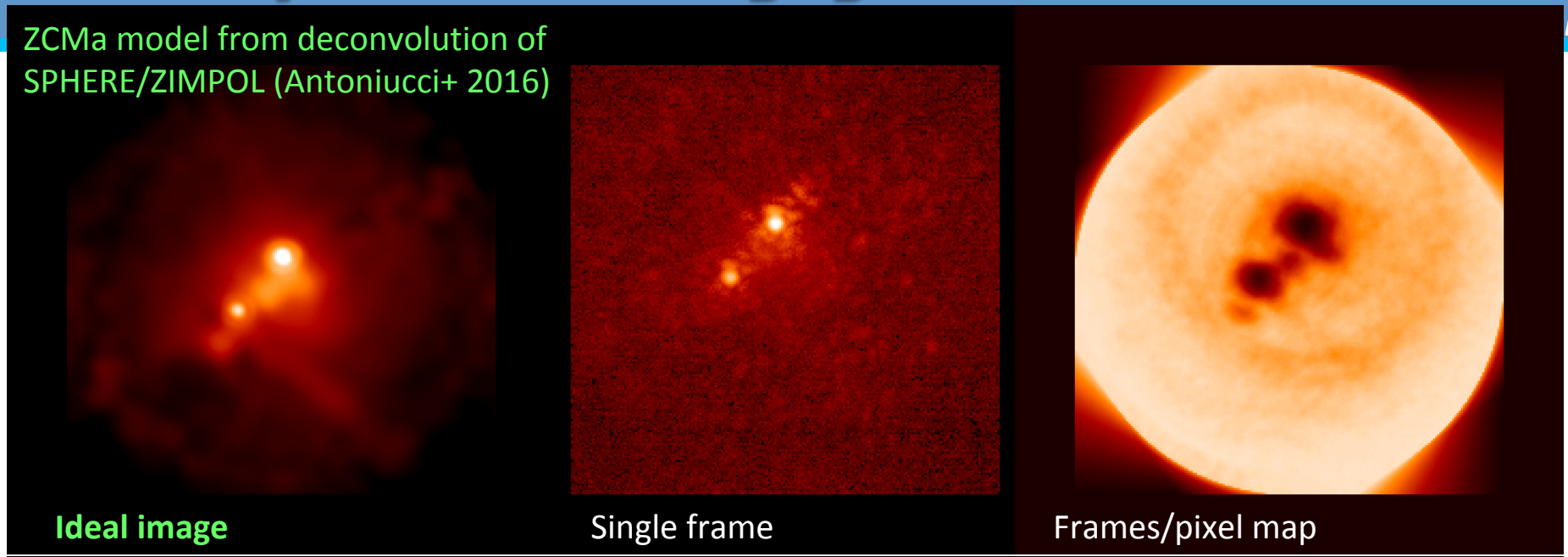
Li Causi et al. 2017, ApJ, 849:85

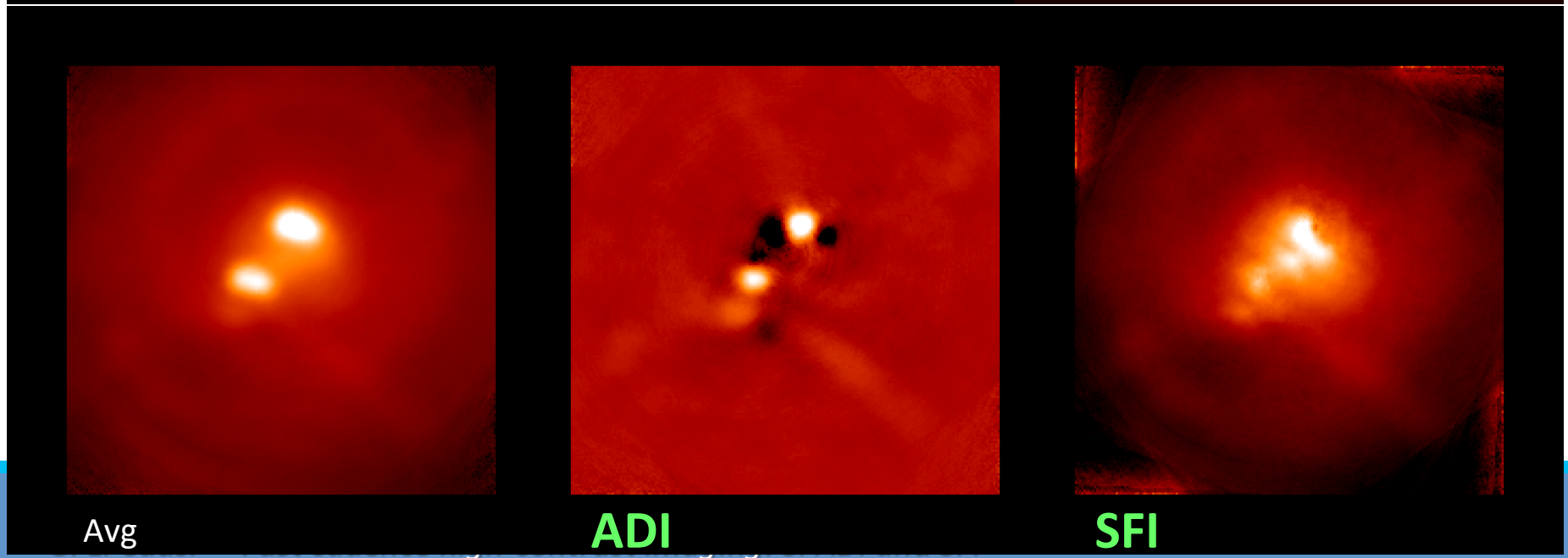


KHz rate is mandatory: speckles degradation with increasing frame exposure from 1 ms to 64 ms

SFI (Speckle-Free Imaging): extended sources

Li Causi et al. 2017, ApJ, 849:85





SFI = SFADI without subtraction of median PSF

NOTE:

- No Self Subtraction issues
  → **HCI on extended sources**
- No need of FoV rotation
- Allows for quick HCI (seconds or minutes)

Fast cadence yields Huge Data

Huge data (4.5 Gb per minute of acquisition in Forerunner sequence) **needs fast processing**

- **SWAMIS code optimization by** D. Lamb & S.J. Van Kooten

Code changes	What it does	Time in all.dat for 1000 images (seconds)	Total run time (seconds)	incremental difference	cumulative difference	cumulative fractional difference
original		357,0	382,0			
mem=>1001	Keep images in memory	333,0	355,0	24,0	24,0	93,3%
uniqvec if nelem>5000	Limit the number of times an expensive subroutine	309,0	328,0	-289,1	48,0	86,6%
byteneg	Disregard negative pixels, output in byte format	249,0	261,0	60,0	108,0	69,7%
inline	Rewrite in C	19,9	23,6	229,1	337,1	5,6%

11x
speed factor
wrt published SWAMIS code

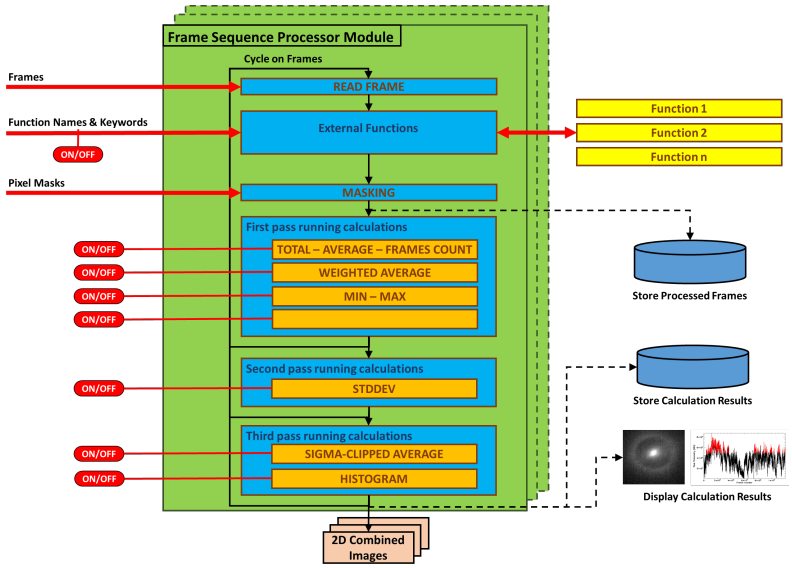
With such optimization we can now compute the speckle masks for 10^6 200x200 pix frames in a few hours.

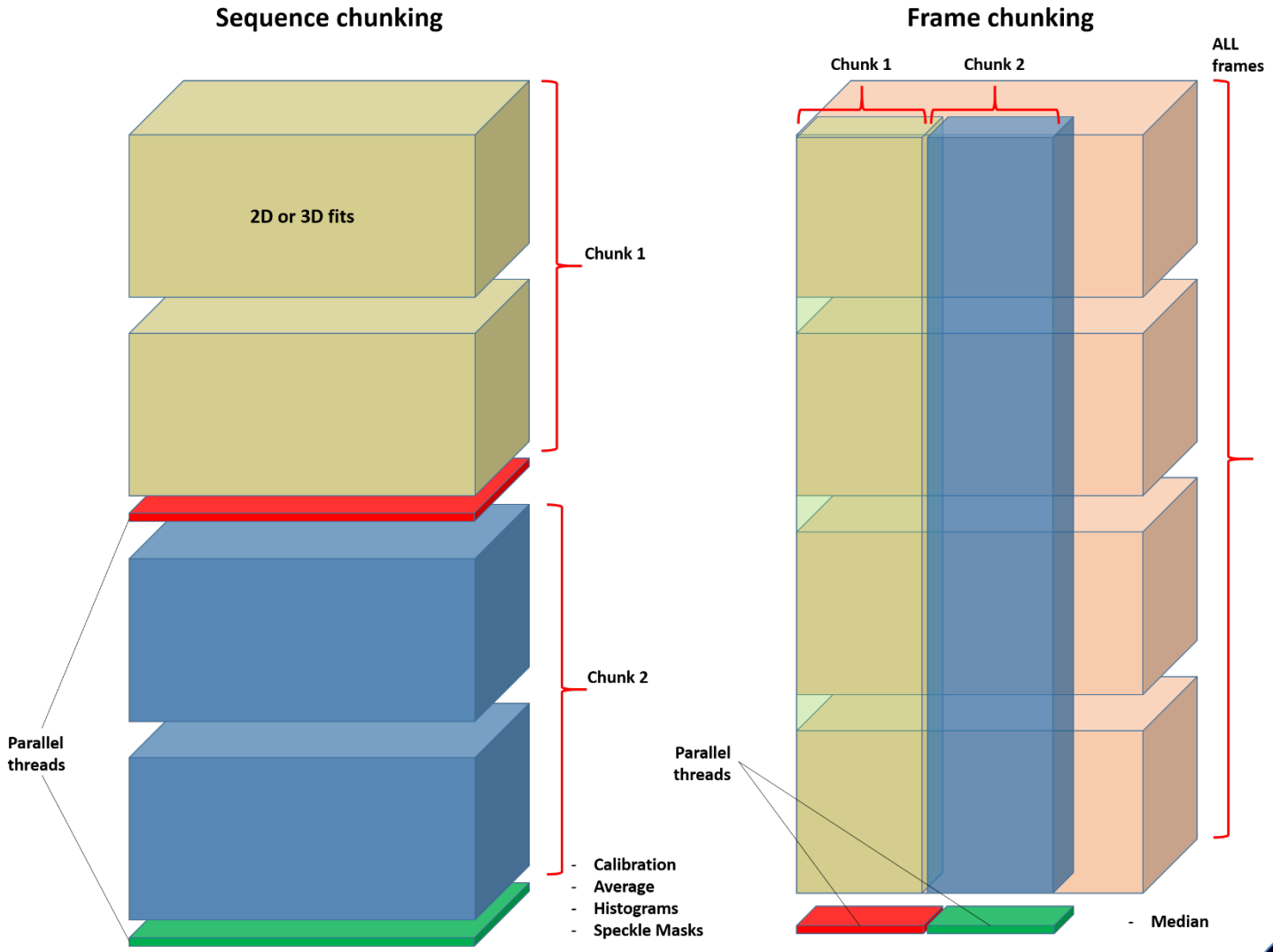
Latest tests on a 12-cores PC: 24x speed factor!

Fast cadence implementation

Huge data (4.5 Gb per minute of acquisition in Forerunner sequence) **needs fast processing**

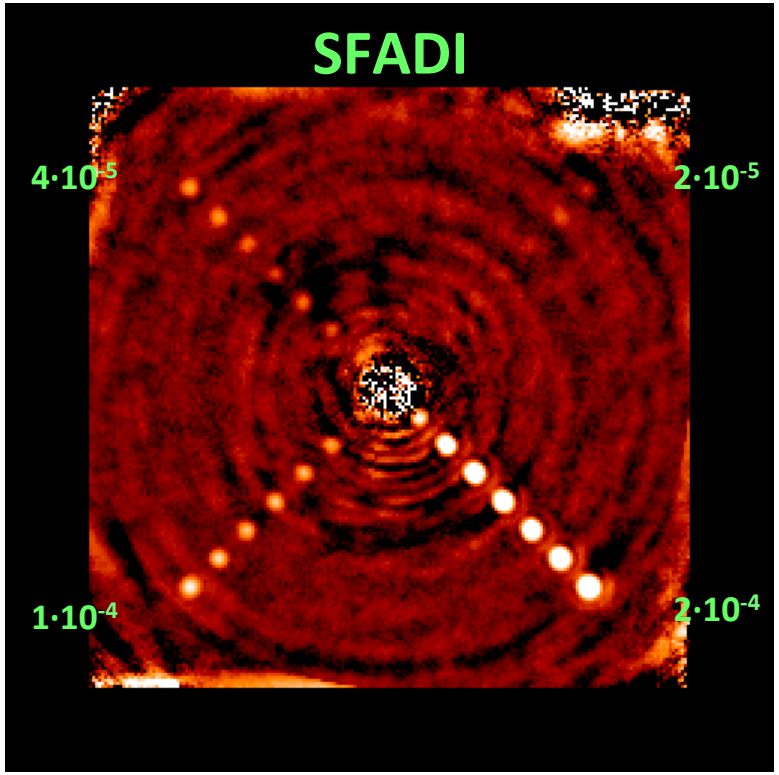
- **Multi-Threading by**
  - **Sequence chunking (vertical)**
  - **Frame chunking (horizontal)**

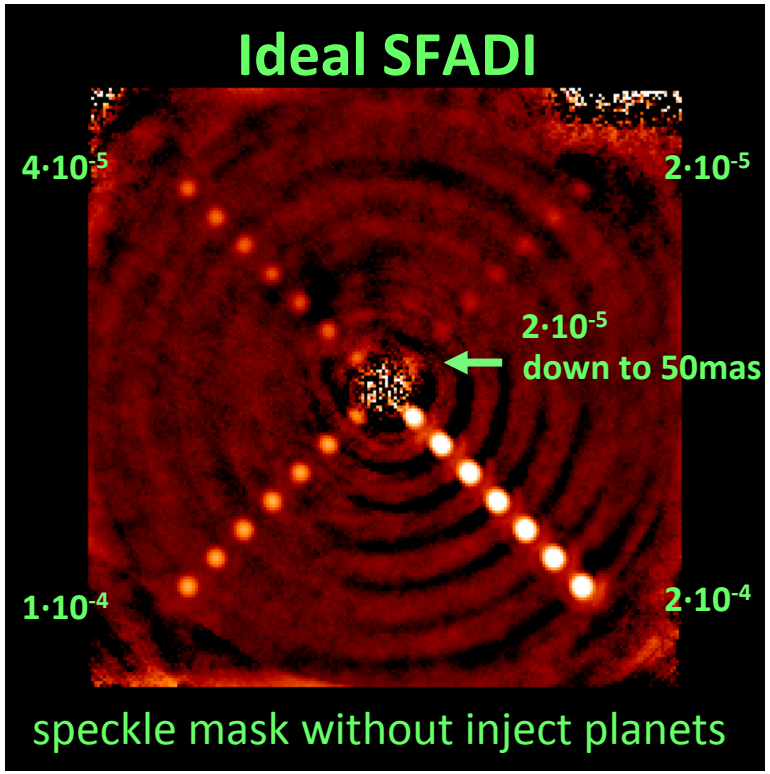




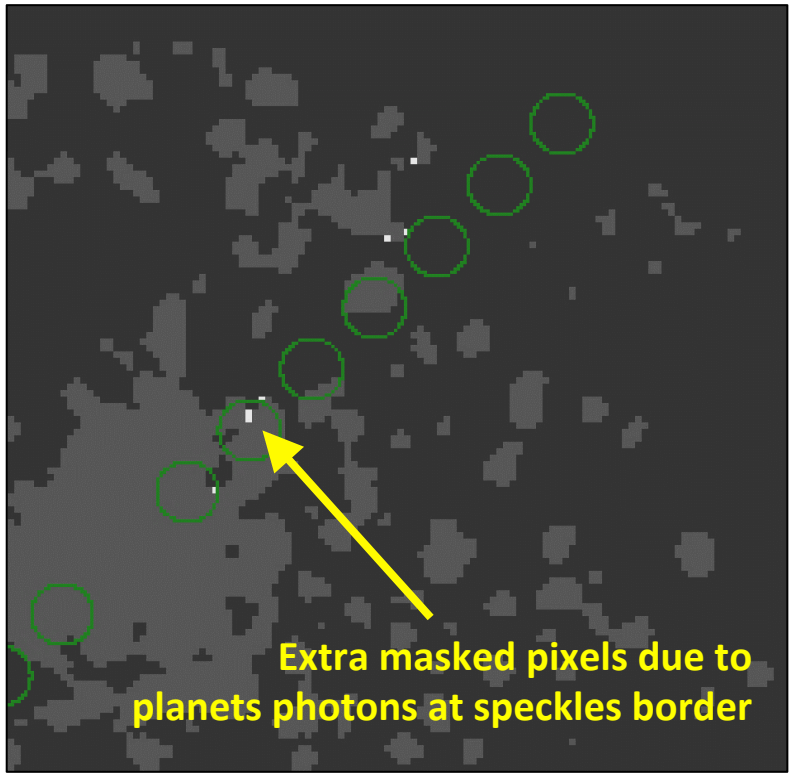
What next with SFADI ?

Can we improve the SFADI method ? → Yes





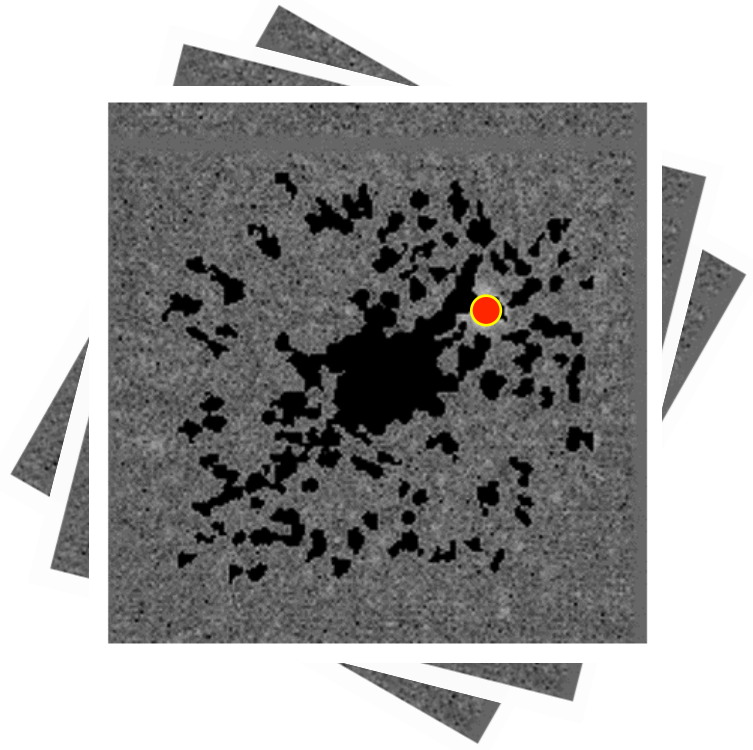
We find a 2x to 3x planets attenuation
even if planets are not masked in single frames



Correcting this effect will led us to reach < 1·10-5 in ForeRunner data
…some recent ideas …work in progress, stay tuned

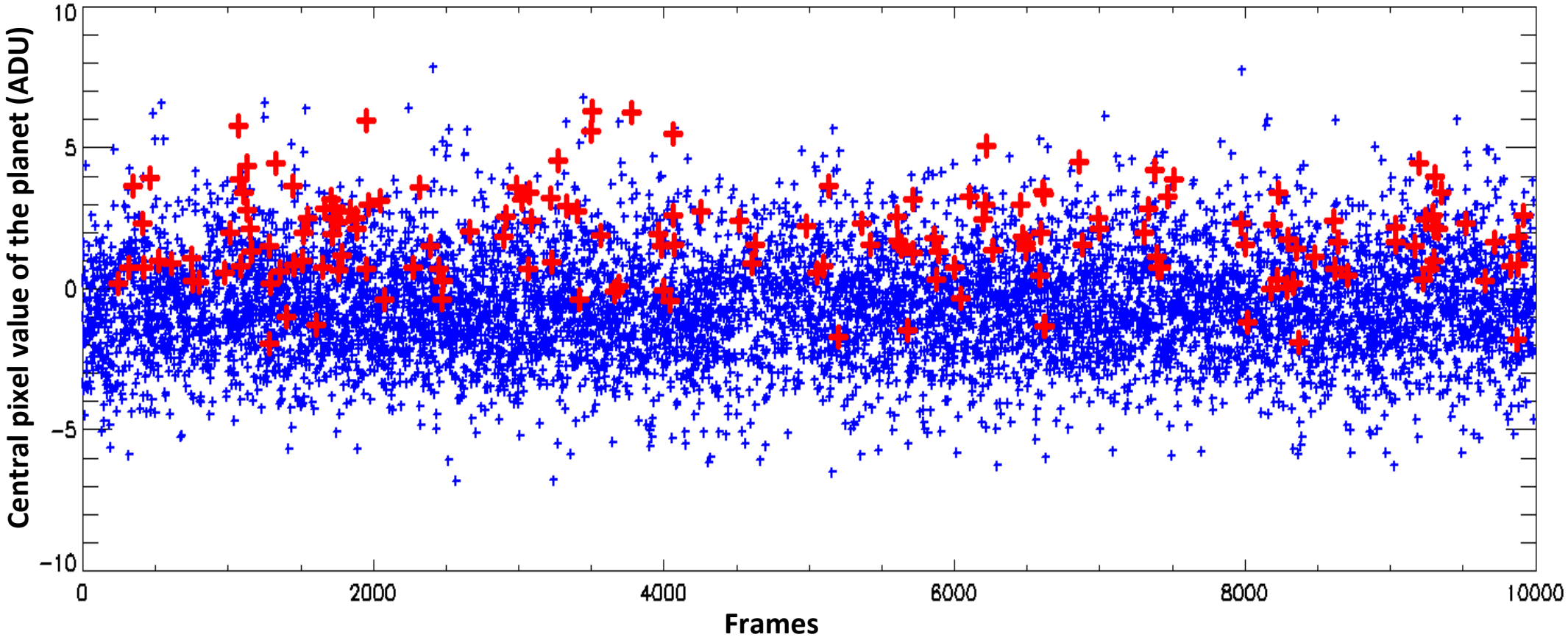
Fast Imaging CONCLUSIONS

- KHz frame rate is mandatory
- Post facto residual jitter compensation
- Individual speckles identification with exclusion of affected pixels
  → Spatial Lucky Imaging → SFADI & SFI
- Exclusion of frames with distorted / fragmented peaks
  → Temporal Lucky Imaging
- Enlarging HCI to Extended Sources
- …possibility of many more techniques (RQA, MFBD, etc…)
  → do not miss next presentation!



Planet's residual attenuation effect...

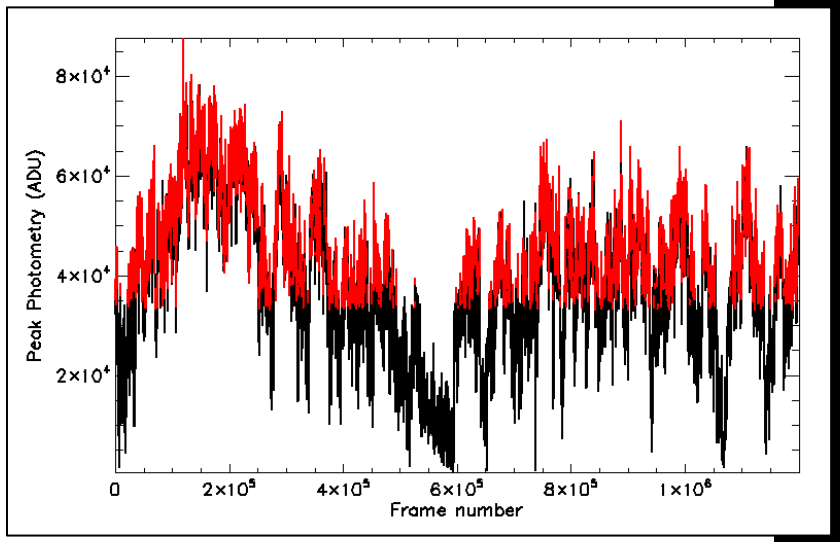
Sublte residual attenuation effect:

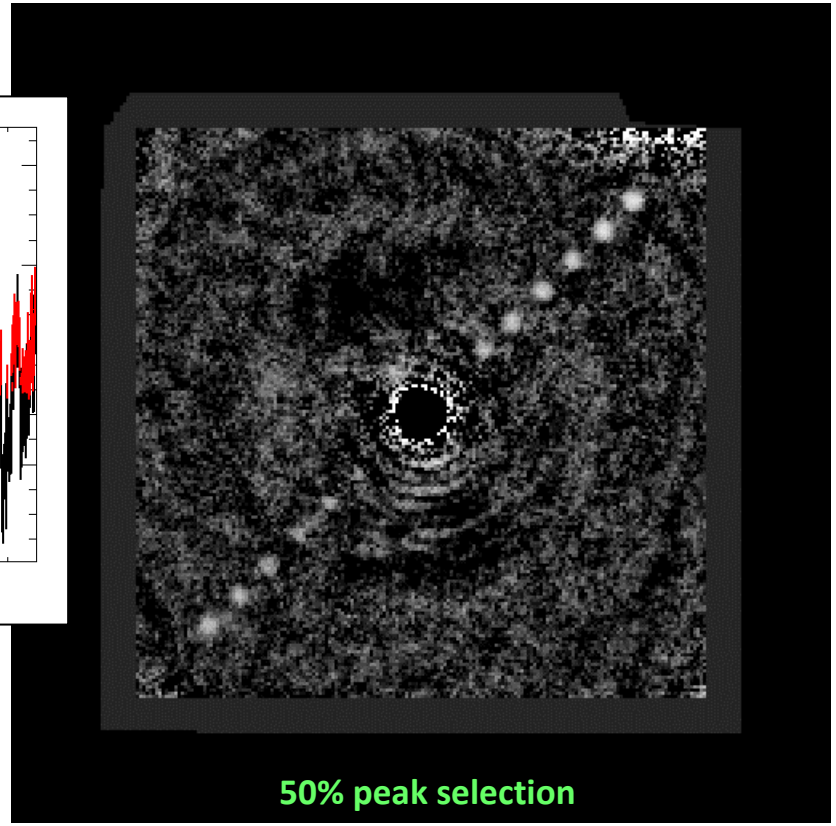


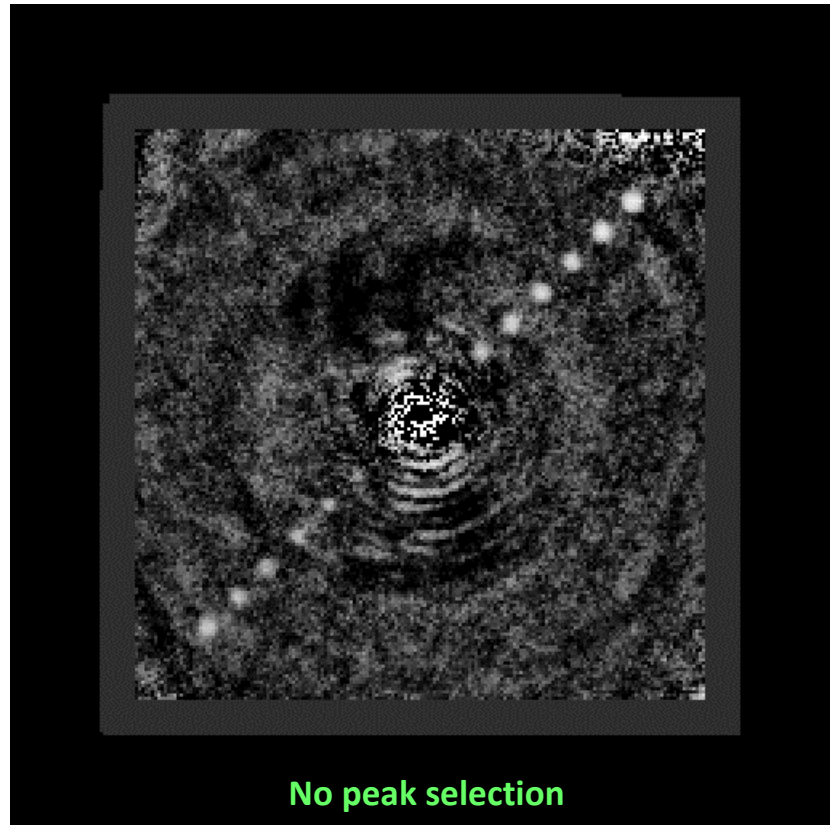
SFADI (Speckle-Free ADI): performances

Li Causi et al. 2017, ApJ, 849:85

KHz Fast Imaging is not only lucky imaging: excluding frames with lower peak photometry does not improve the results.
But we do exclude all frames with distorted or fragmented peaks.



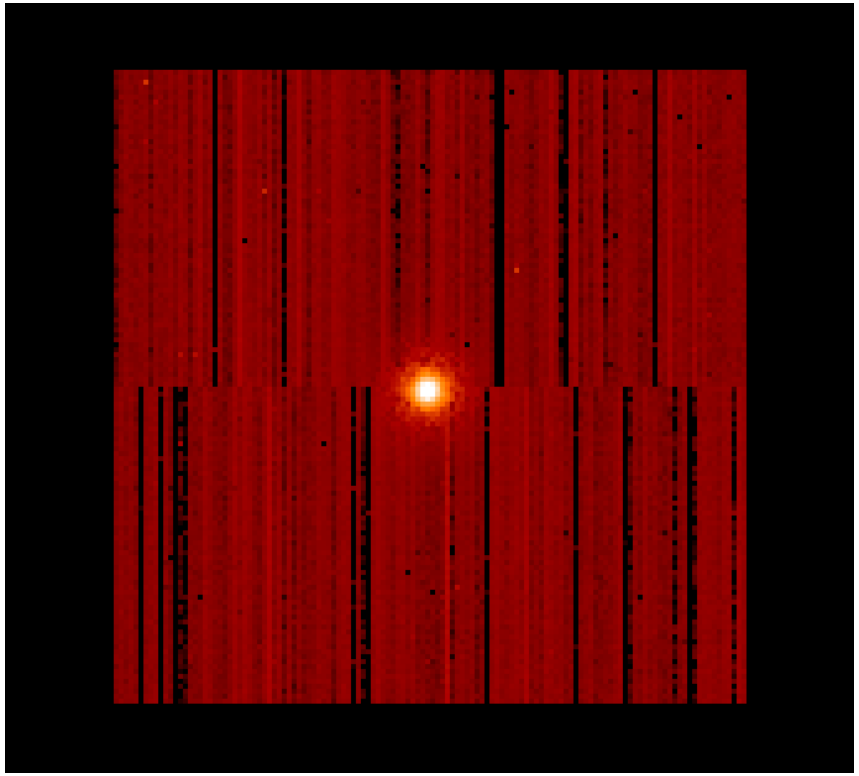




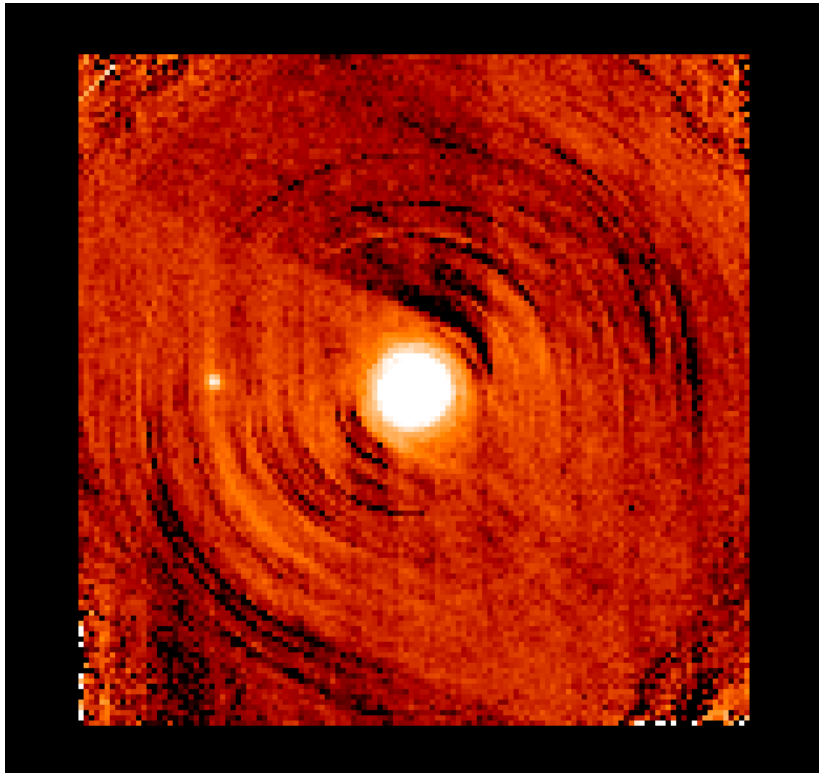
Testing sensitivity at SHARK-VIS testbench

Master Bias subtraction:

$6 \cdot 10^{-4}$ physical spot in 1 minute



Avg of Master Bias subtracted frames

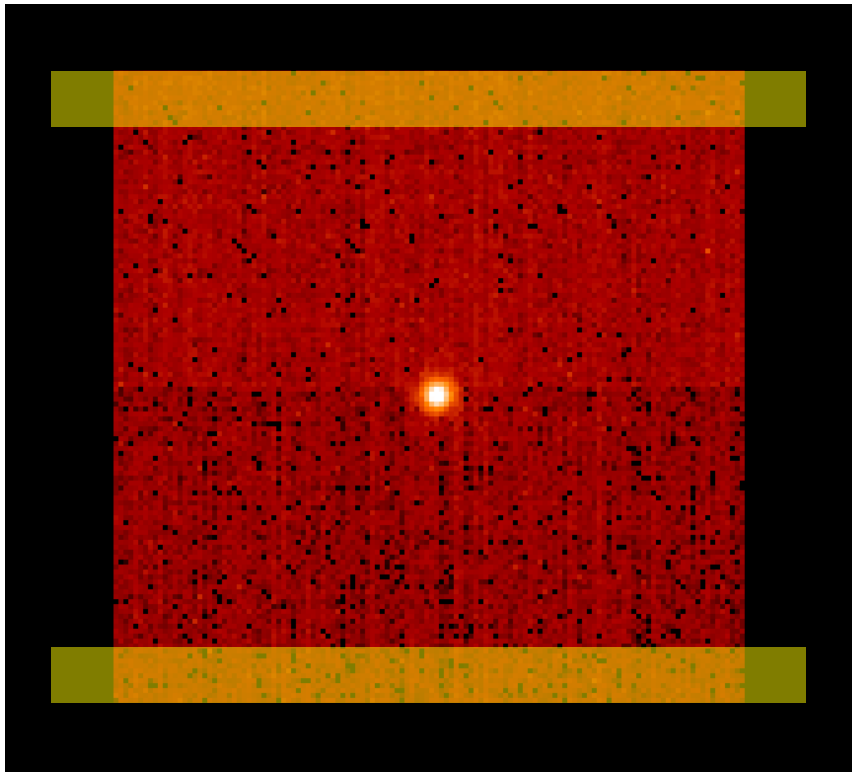


Avg after de-rotation

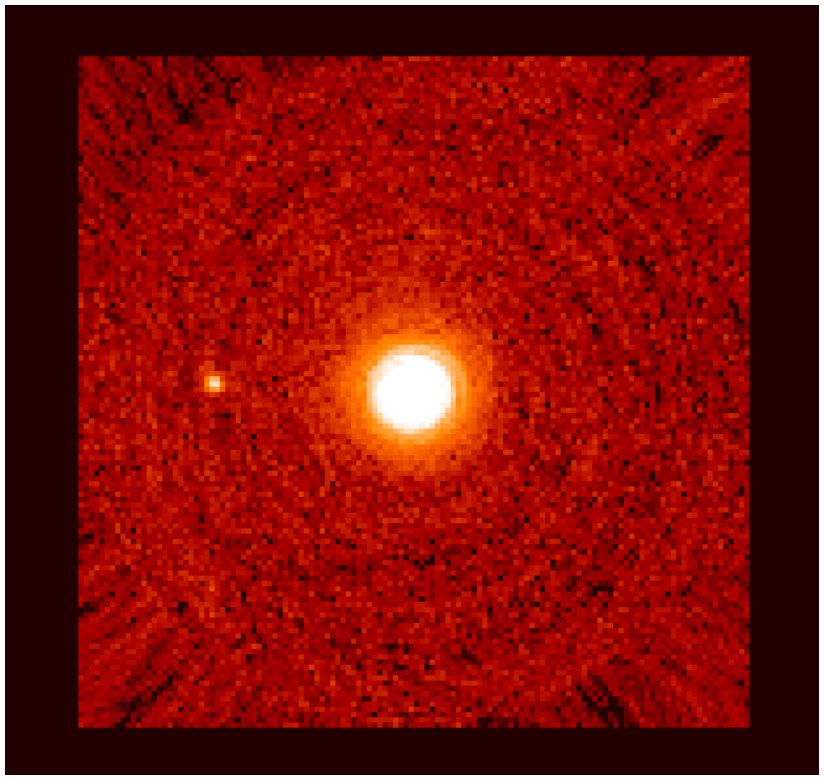
Testing sensitivity at SHARK-VIS testbench

Frame by frame reference rows subtraction:

$6 \cdot 10^{-4}$ physical spot in 1 minute



Frame with upper and lower reference rows

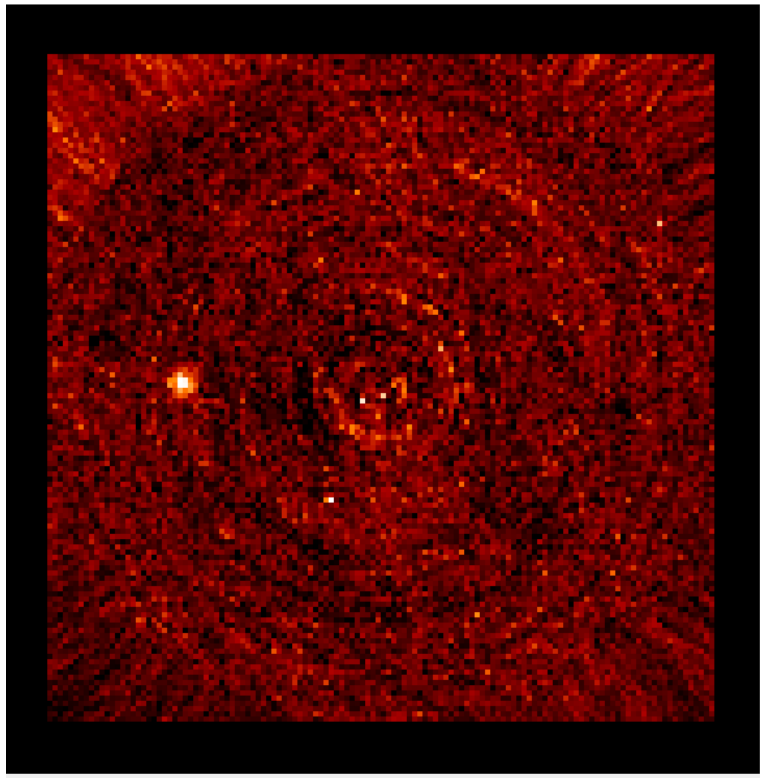


Avg after de-rotation

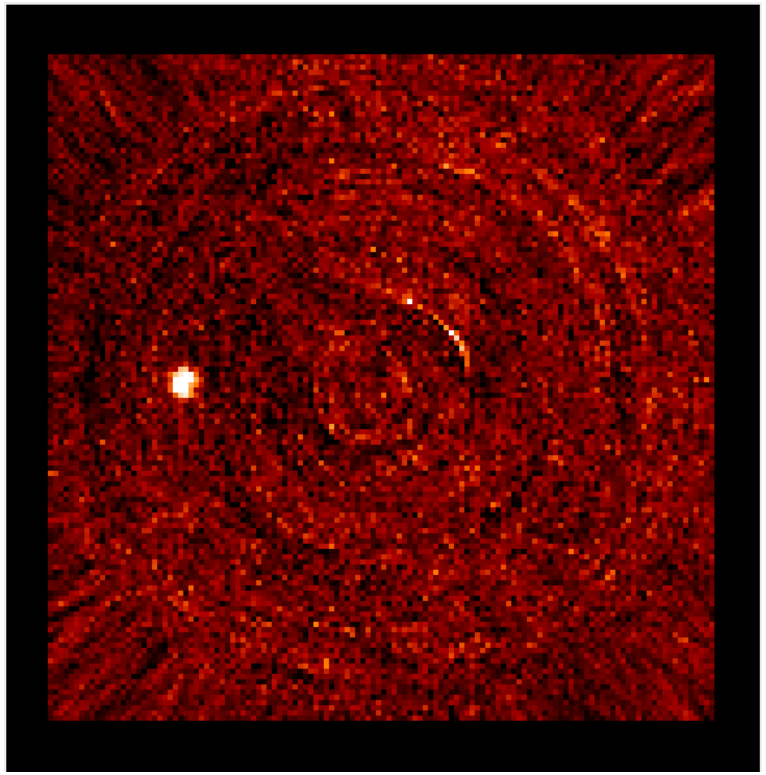
Testing sensitivity at SHARK-VIS testbench

Fast vs Slow readout mode for Zyla CMOS:

$5 \cdot 10^{-5}$ physical spot in 1 minute



Fast readout: $6 \cdot 10^{3}$ frames in 1 sec, SNR=7.0

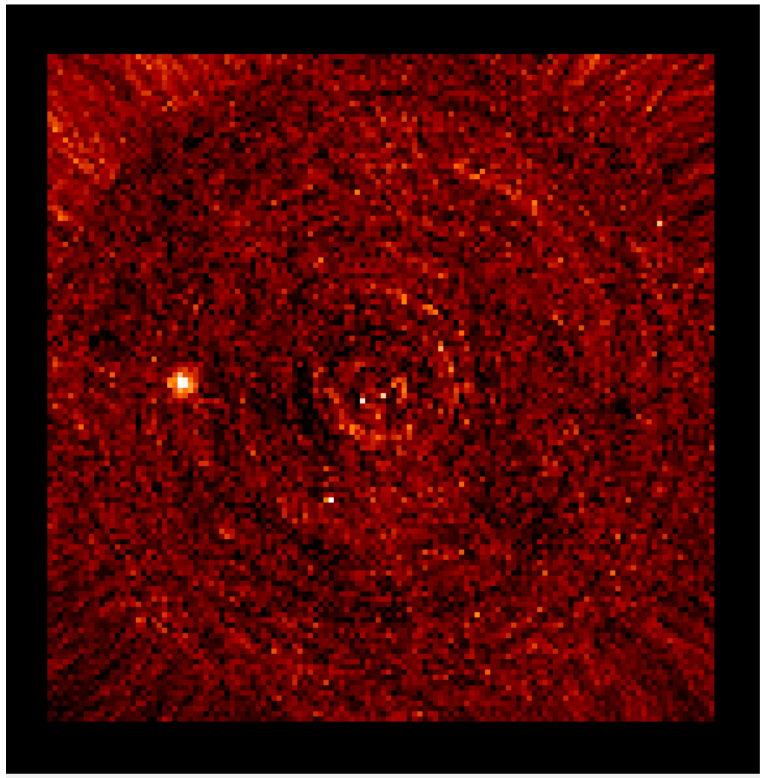


Slow readout: $4 \cdot 10^{3}$ frames in 1 sec, SNR=10.5

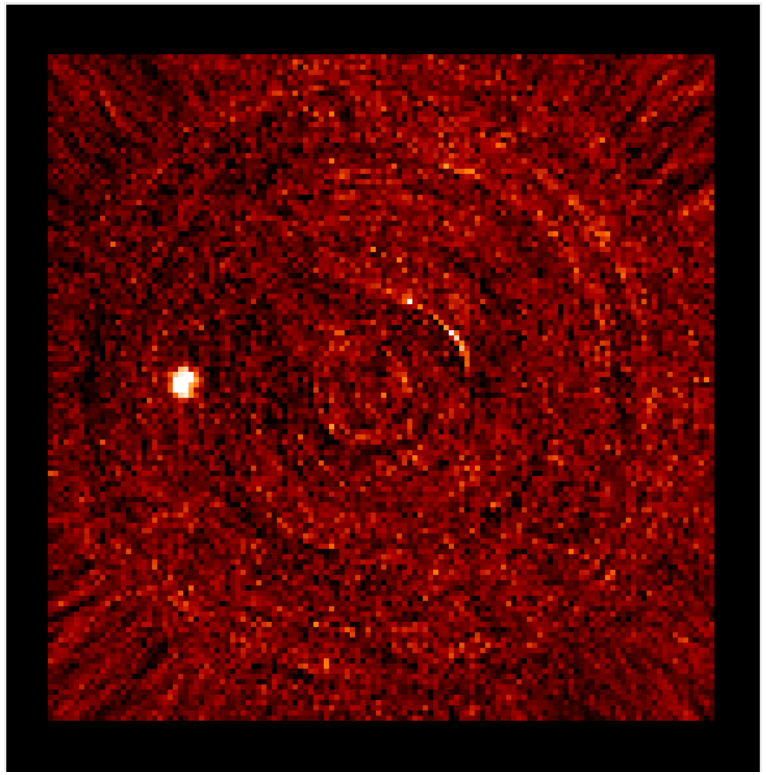
Testing SFADI at SHARK-VIS testbench

Speckle will soon be introduced by means of a rotating phase mask to test the SFADI in the lab – WORK IN PROGRESS!

$5 \cdot 10^{-5}$ physical spot in 1 minute



Fast readout: $6 \cdot 10^{3}$ frames in 1 sec, SNR=7.0



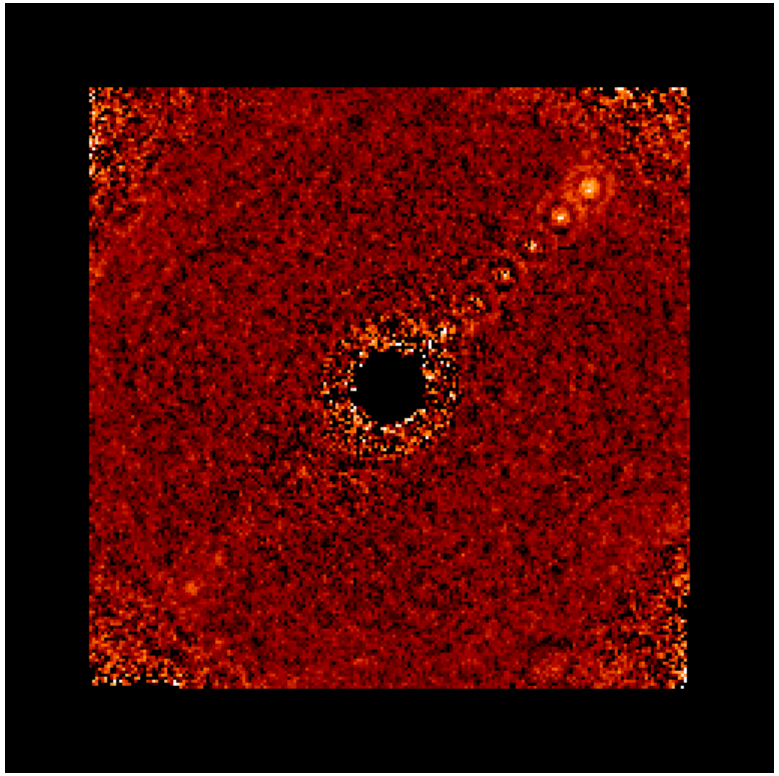
Slow readout: $4 \cdot 10^{3}$ frames in 1 sec, SNR=10.5

SFADI (Speckle-Free ADI): performances

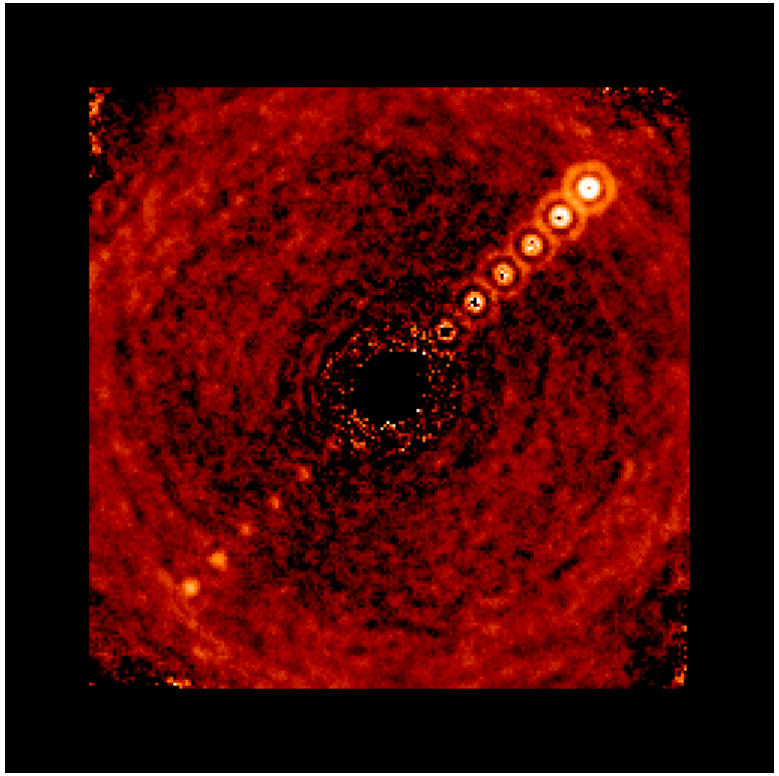
Li Causi et al. 2017, ApJ, 849:85

SFADI performance with CMOS vs. EMCCD

SFADI results on 1 sec simulated frames at 1kHz
10^{-3} (first quadrant) and **10^{-4}** (third quadrant) contrast planets



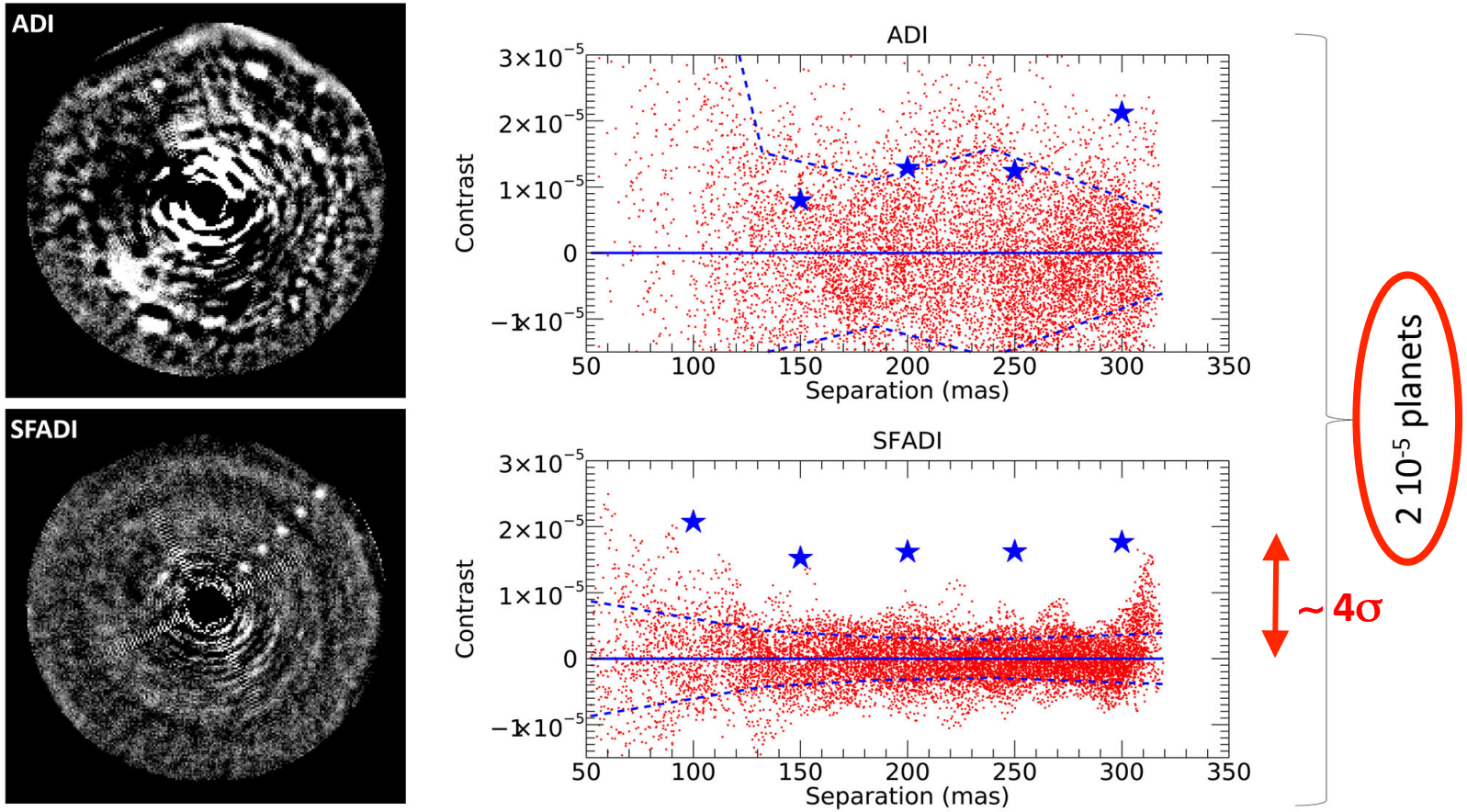
Zyla 5.3 CMOS



First Light Ocam2k EMCCD

SFADI (Speckle-Free ADI): performances

Li Causi et al. 2017, ApJ, 849:85

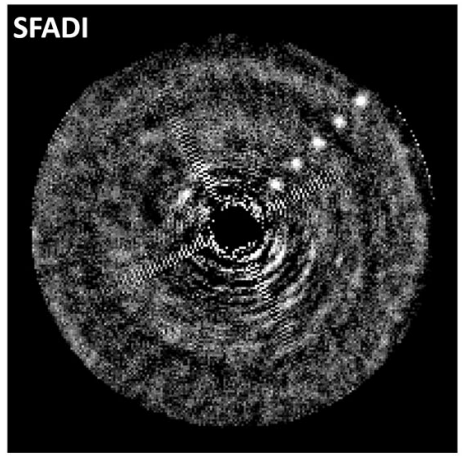


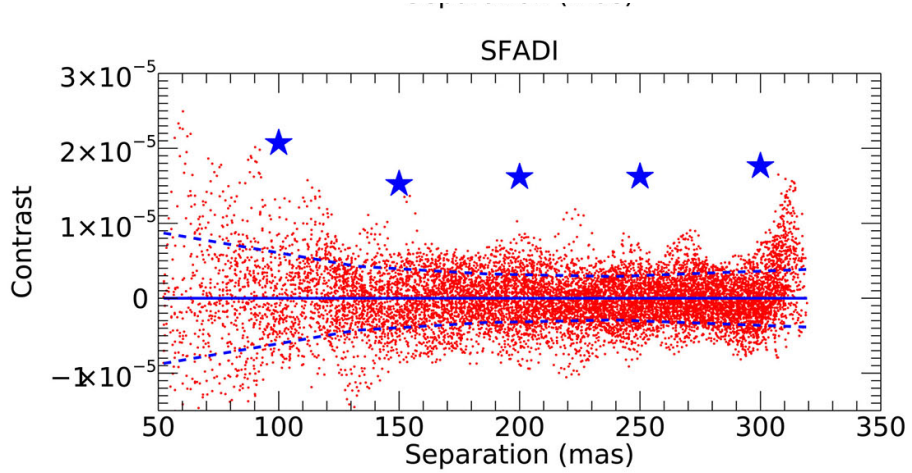
SFADI vs ADI for 2 10^{-5} contrast planets injected on real 1.2 million frames with SHARK-VIS Forerunner@LBT

SFADI (Speckle-Free ADI): need of kHz rate

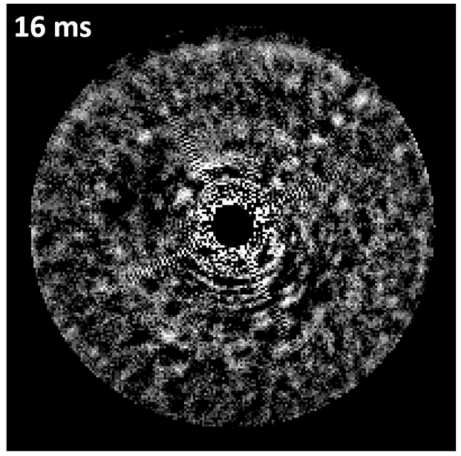
Li Causi et al. 2017, ApJ, 849:85

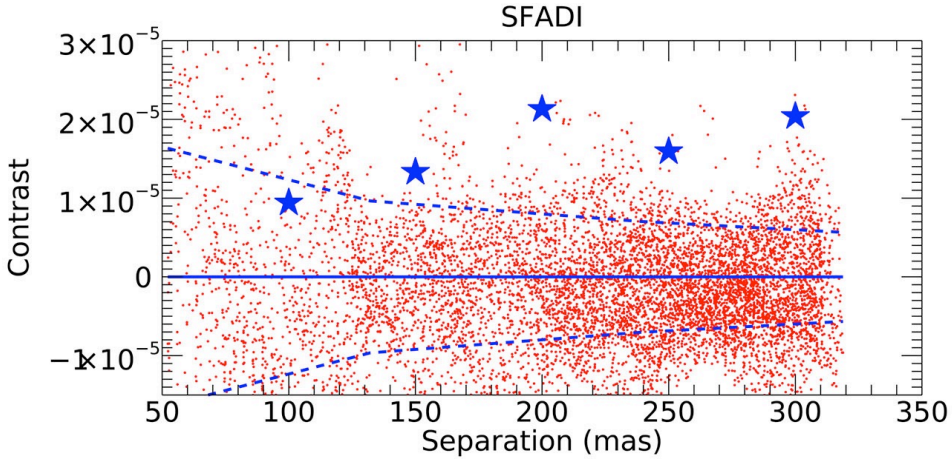
DIT 1 ms





DIT 16 ms

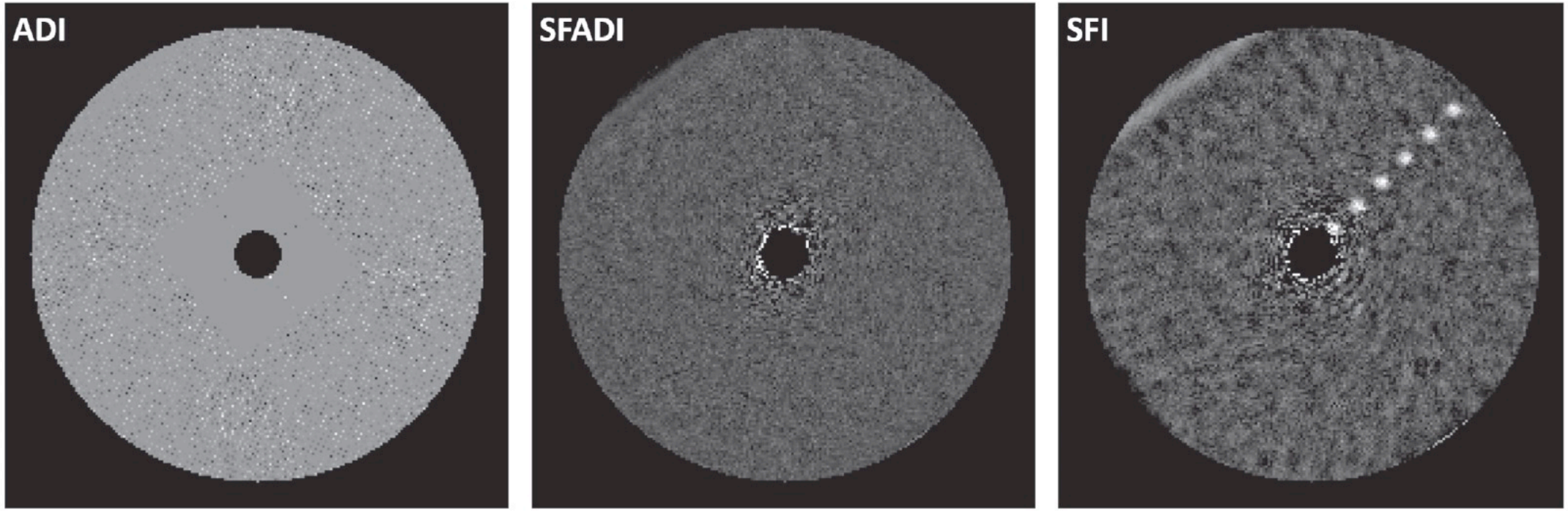




SFADI degradation for 16ms frame exposure with respect to 1ms for 2 10^{-5} planets.

SFI (Speckle-Free Imaging): no field rotation

Li Causi et al. 2017, ApJ, 849:85



ADI, SFADI and SFI comparison for 5 seconds of aquisition of 5 10^{-4} planets.