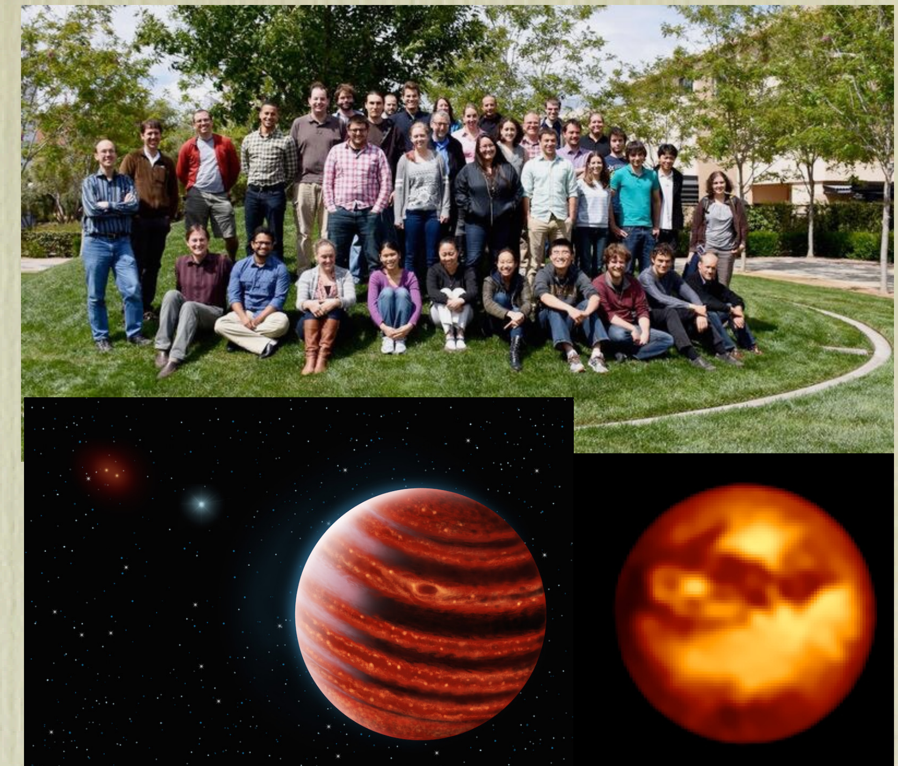
Processing and Data Analysis with AO Instruments Challenges & Perspectives



Franck Marchis (SETI Institute)
AAS Conference, NOAO Workshop, Kissimmee, FL
Jan 6 2016

Contributors: Bin Yang (ESO), Erik Hom (U. of Mississippi), Jennifer Patience (ASU), Jean-Baptiste Ruffio (Stanford U.), Marshall Perrin (STSCI) & GPIES consortium

Outline

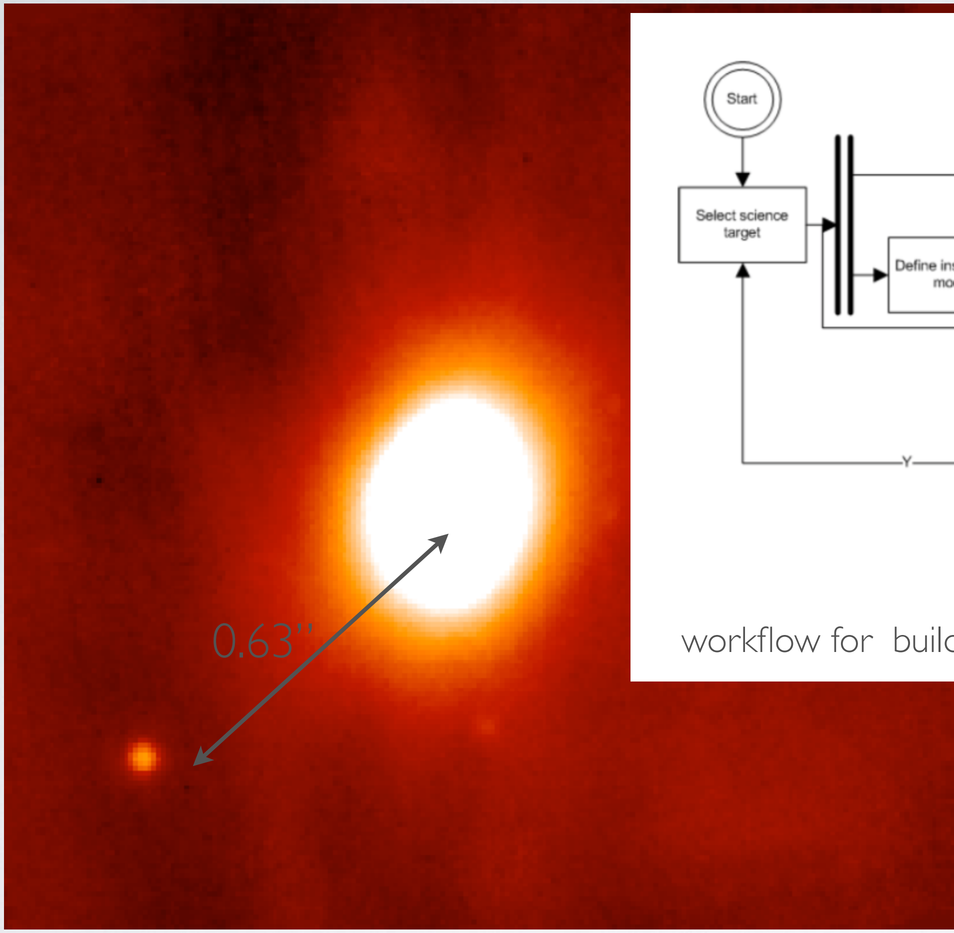
An inspirational quote? *"Data processing is without doubt the most fascinating part of astronomy. In the future people will cherish those algorithms and admire those who created them." F. Marchis, Kissimmee, FL*

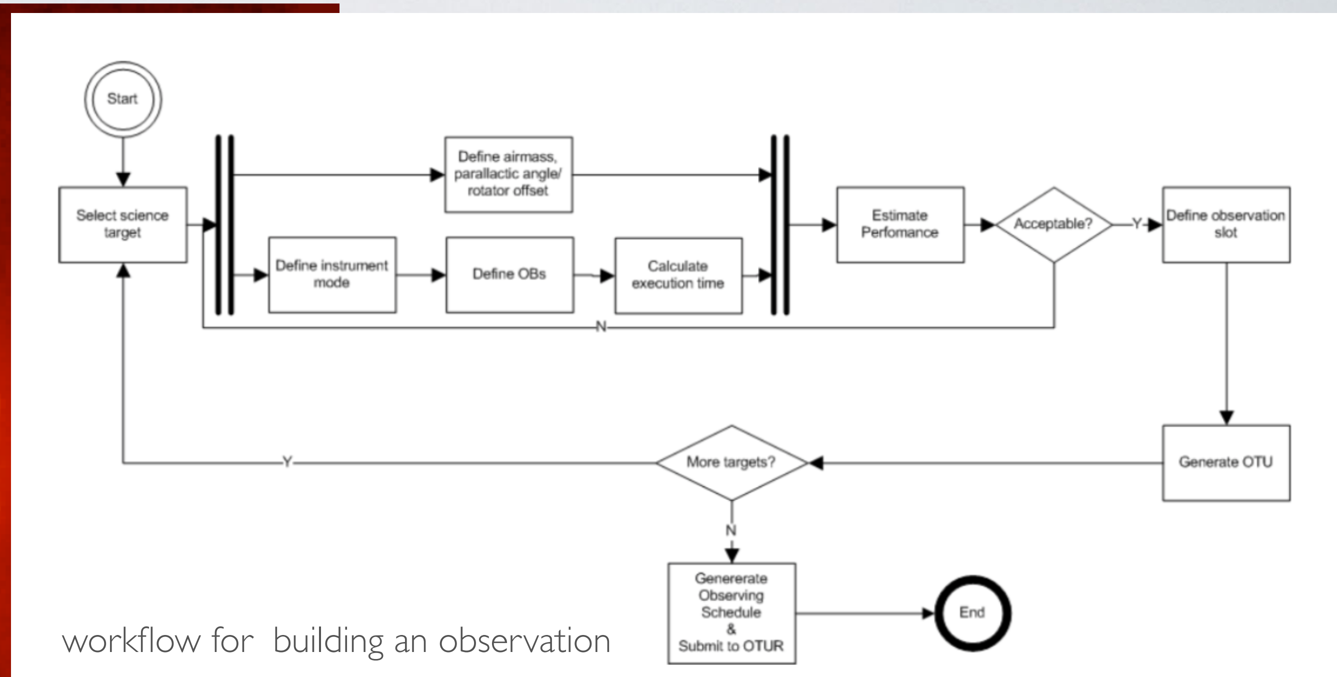
Not really...

but efficient and well understood data processing is part of the job...

- Detection & Photometry of moons around asteroids
- The power of deconvolution to improve image sharpness
- Modern pipelines for modern instruments: the GPI case

SEARCH FOR COMPANIONS AROUND ASTEROIDS





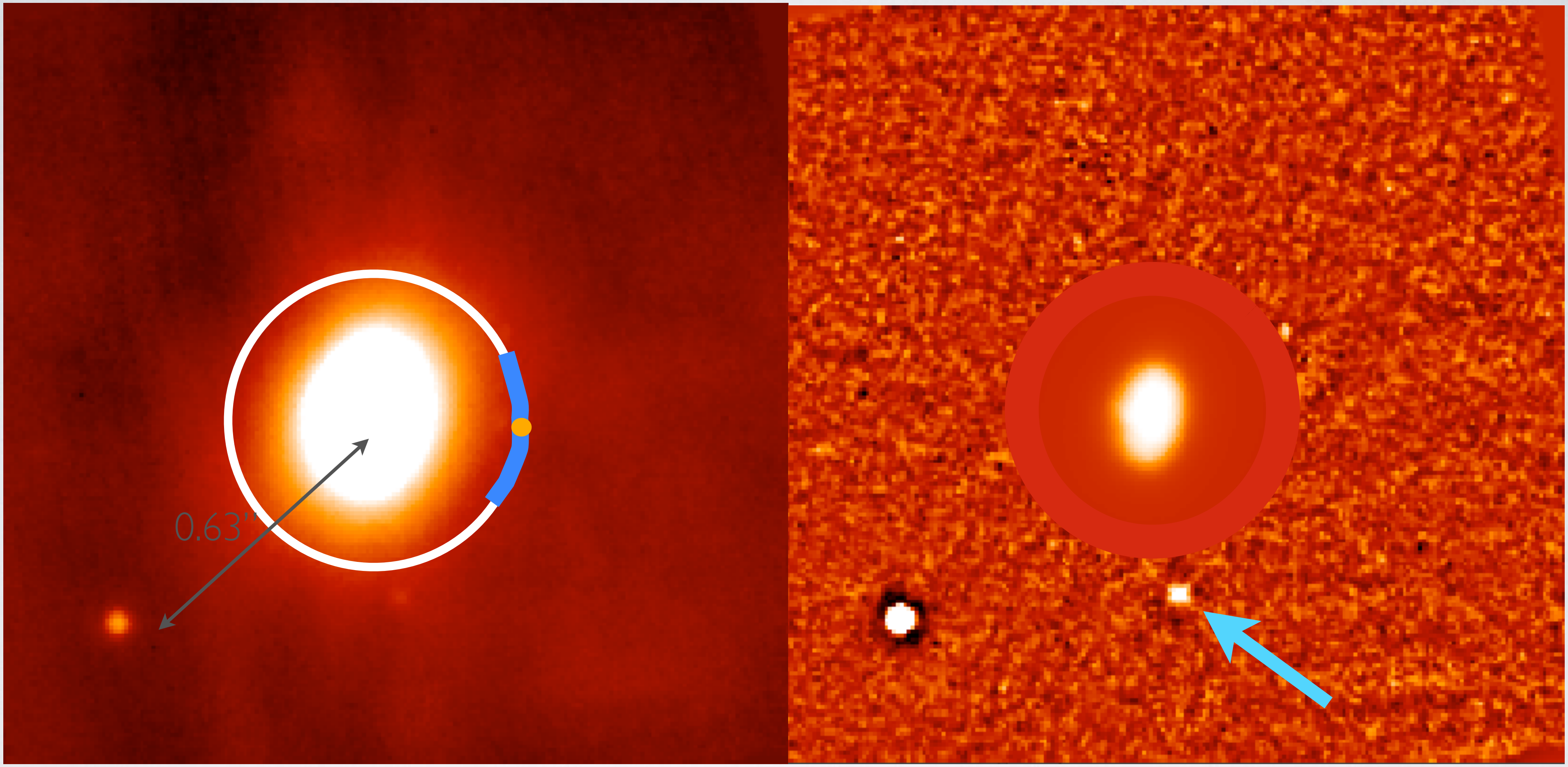
workflow for building an observation

VLT/SPHERE AO observations of (130) Elektra with IFS and IRDIS (Dec 30 2014)

Complex instrument => Well-defined **data reduction pipeline** (Pavlov et al. 2008)

- Master Calibration product (bias/flat/badpix from observing run, wavelength cal from arc lamps)
- Calibrated Science frame (e.g. individual exposure with cosmic removed)
- Science product (e.g. combined and selected science frames)
- Data quality control (quantitative information about the data, e.g. FWHM, contrast curve, photometric quality…)

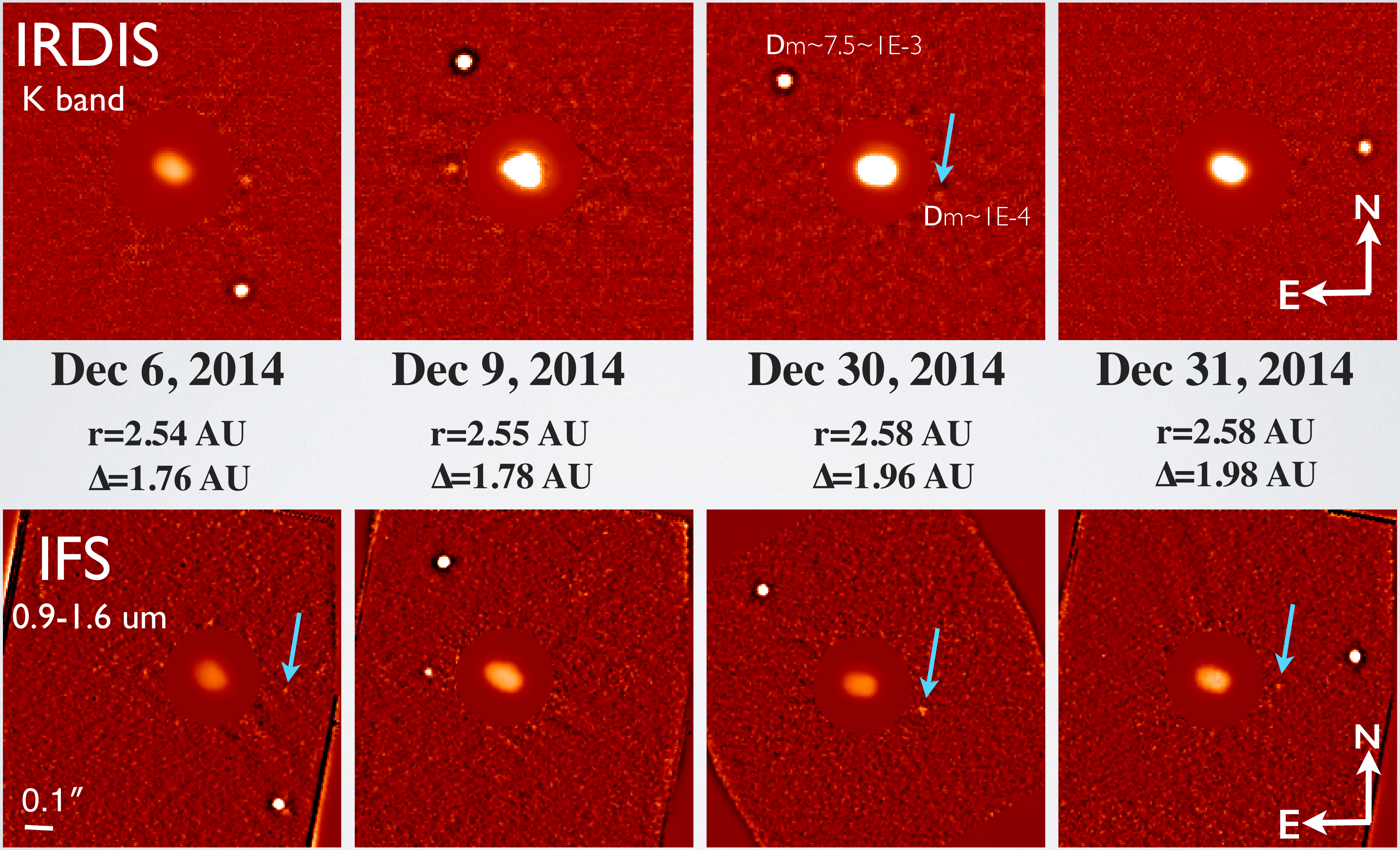
SEARCH FOR COMPANIONS AROUND ASTEROIDS



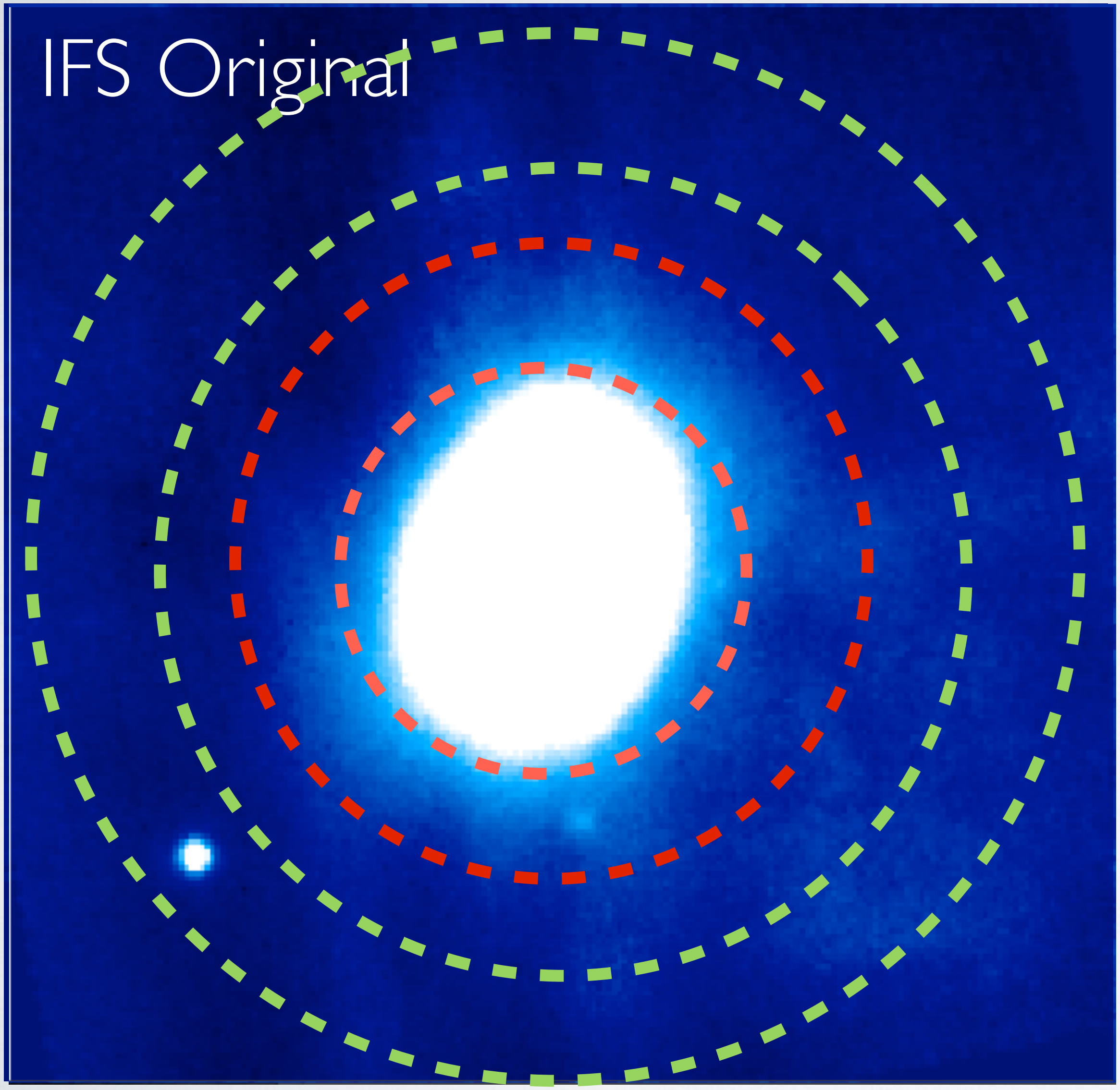
Data Analysis: Satellite buried in the halo of the primary?
Wahhaj et al. (2013) method

1. Image divided in a series of annuli centered on the primary
2. For each point, the background is calculated over an arc (blue) 3-5 times the PSF of the satellite
3. Halo is gone!
4. Moons are here!

DISCOVERY OF A NEW MOON



PHOTOMETRIC ERROR ESTIMATE

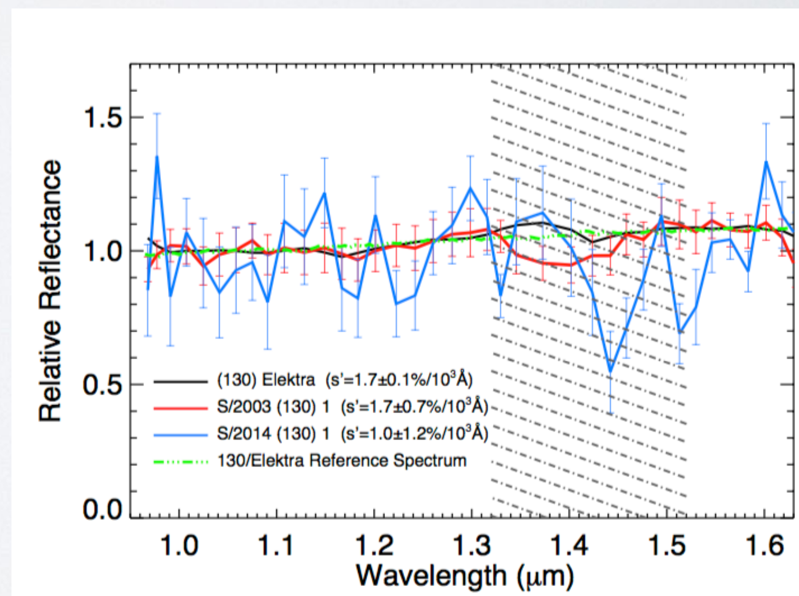


Yang et al. 2016

- Gaussian point sources inserted in IFS data (FWHM = FWHM of PSF)
- 200 random positions on the image
- Strong sources (10x sat flux) to estimate the systematic loss flux
- Weak sources to estimate the random error

Results:

- PSF fitting yields smaller photometric uncertainties for good quality data
- aperture photometry gives better result if poor AO correction (high airmass, poor seeing)



Deconvolution:Image Formation Process

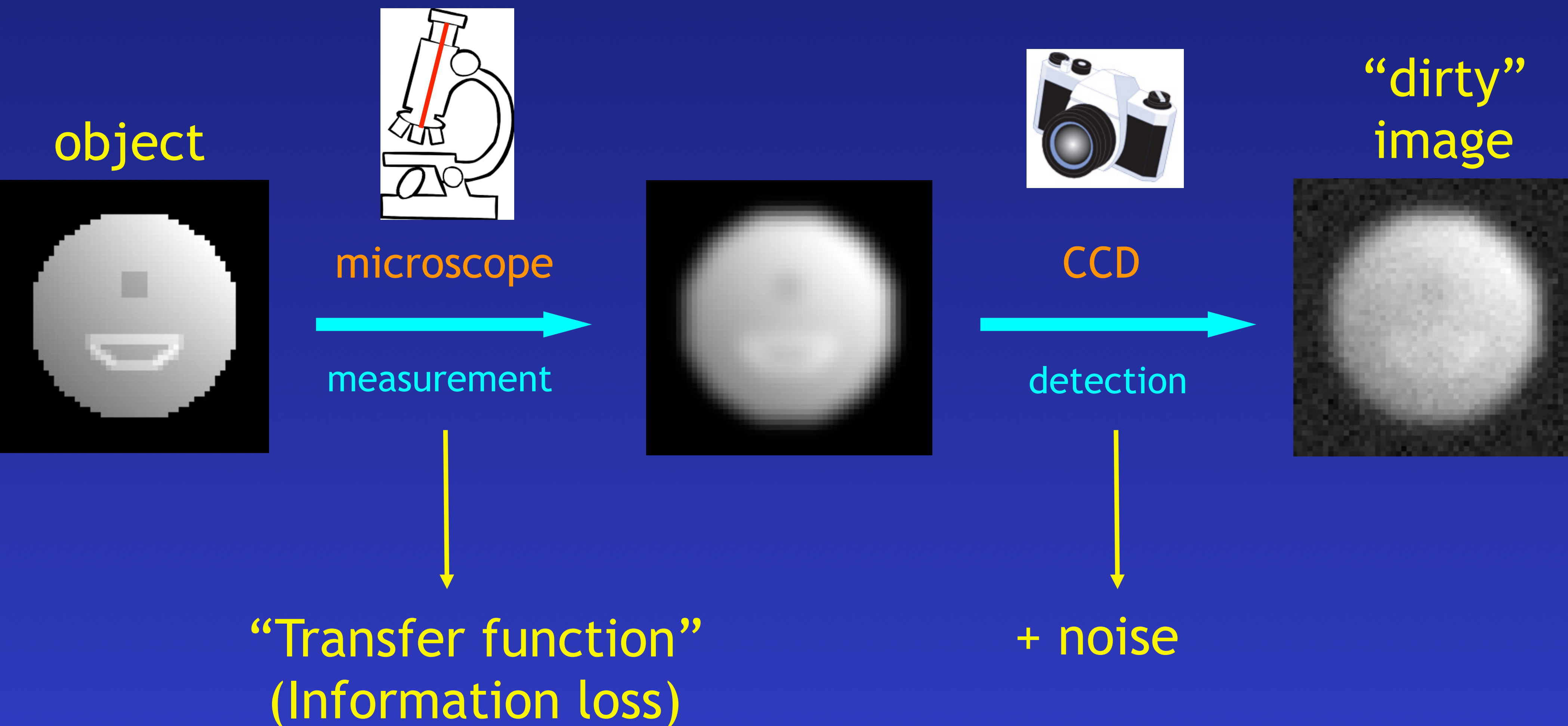


Image Formation Equation

Information degradation →

Object • Transfer Function + noise = Image

$$O \bullet T + \mathbb{N} = I$$

T

Bonjour, je suis Erik

Bonjour, ___ ___ Erik

Banjoer, ___ ___ Arin

N

Deconvolution: Go Backwards

Invert: $$O \bullet T + \mathbb{N} = I$$ (solve for O)

$$O = \frac{I - \mathbb{N}}{T}$$

? : stochastic

limited bandwidth

"ill-posed" problem

not enough info

"ill-conditioned" problem

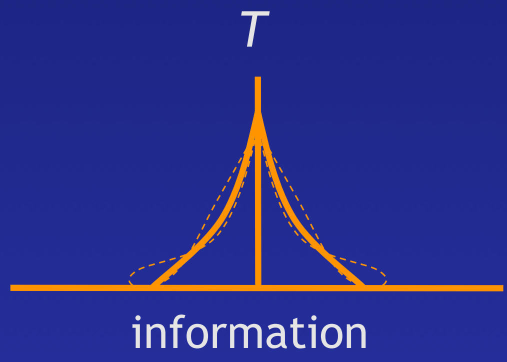
math: hard to solve

Deconvolution: Go Backwards

…a more complicated (realistic) scenario

$$O = \frac{I - \mathbb{N}}{T\ ?}$$

T may not be known:
"myopic deconvolution"
SR>20%



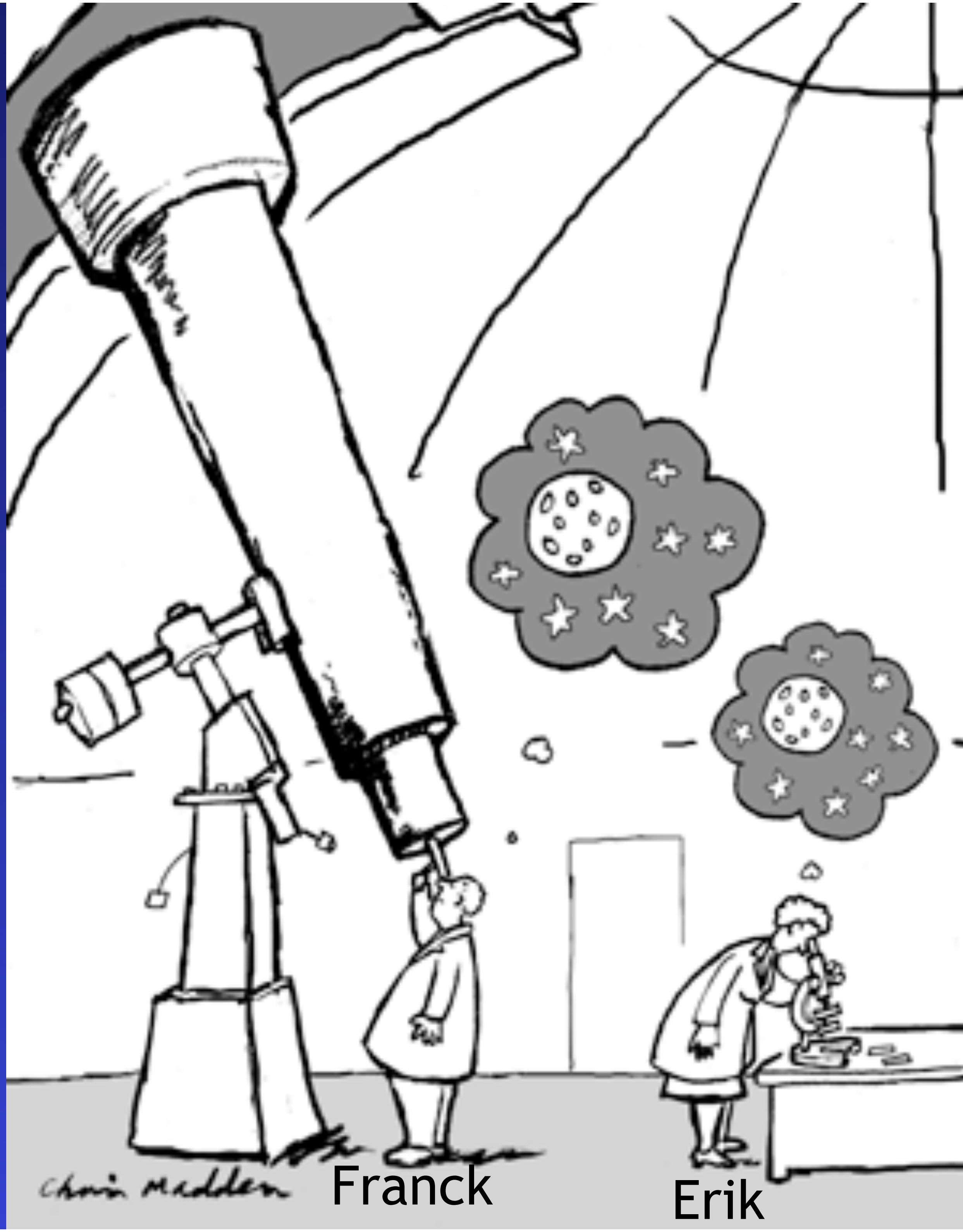
Bonjour, je suis Erik ----------→ Banjoer, ___ ___ Arin

Regularizations

- -Is this French?
- -Messenger speaks French?
- -Poor speller?

If use wrong *T* to invert, may get really wrong answer:
e.g., "Erin <u>plays</u> <u>the</u> Banjo"

AI
DA



A Robust Solution…

MISTRAL Developed by:
Theoretical Optics Group, ONERA (France)
To post-process adaptive optics images

Vol. 21, No. 10/October 2004/J. Opt. Soc. Am. A 1841

MISTRAL: a myopic edge-preserving image restoration method, with application to astronomical adaptive-optics-corrected long-exposure images

Laurent M. Mugnier, Thierry Fusco, and Jean-Marc Conan

Office National d'Études et de Recherches Aérospatiales, Optics Department, B.P. 72, F-92322 Châtillon cedex, France

- Excellent "photometry" (intensities recovered to within 5-10% accuracy)
- Minimal but effective assumptions –> minimal artifacts

Wanted:

- To extend the MISTRAL approach to 3D microscopy
- Capability of deconvolving multiple image frames simultaneously

Problem:

- MISTRAL is "*classified*" (argh!)

Solution:

➡ Build from scratch?

AIDA: an adaptive image deconvolution algorithm with application to multi-frame and three-dimensional data

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We describe an adaptive image deconvolution algorithm (AIDA) for myopic deconvolution of multi-frame and three-dimensional data acquired through astronomical and microscopic imaging. AIDA is a reimplementation and extension of the MISTRAL method developed by Mugnier and co-workers and shown to yield object reconstructions with excellent edge preservation and photometric precision [J. Opt. Soc. Am. A **21**, 1841 (2004)]. Written in Numerical Python with calls to a robust constrained conjugate gradient method, AIDA has significantly improved run times over the original MISTRAL implementation. Included in AIDA is a scheme to automatically balance maximum-likelihood estimation and object regularization, which significantly decreases the amount of time and effort needed to generate satisfactory reconstructions. We validated AIDA using synthetic data spanning a broad range of signal-to-noise ratios and image types and demonstrated the algorithm to be effective for experimental data from adaptive optics–equipped telescope systems and wide-field microscopy.

OCIS codes: 100.1830, 100.3020, 100.3190, 010.1080, 180.0180, 180.6900.

- AIDA v1.3 released on Oct 14 2013 - we need developers....
- Code and tutorial available on Google code https://code.google.com/p/aida-deconvolution/

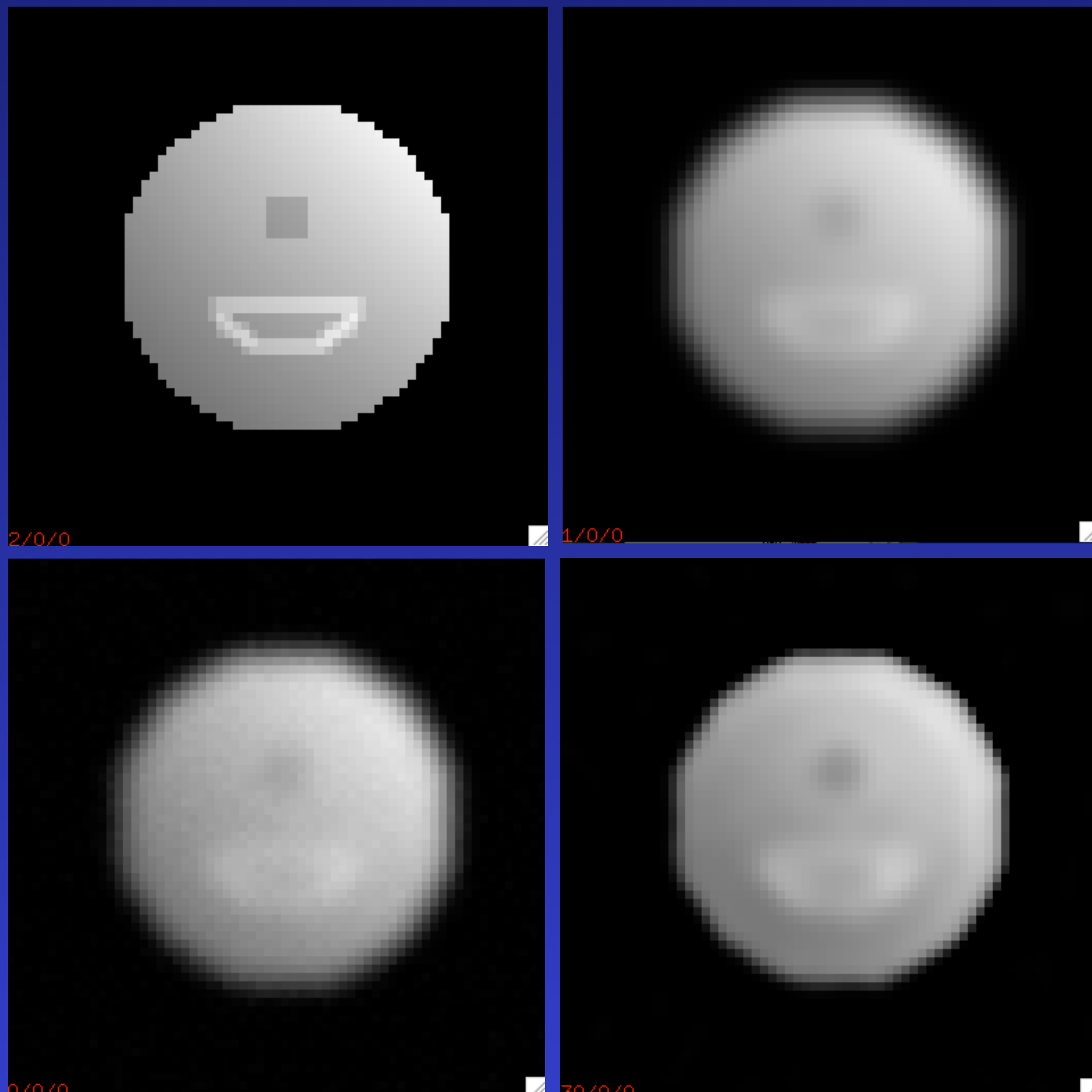
AIDA:
Adaptive Image Deconvolution Algorithm

- Written in Numerical Python with calls to a robust constrained conjugate gradient optimizer (LLNL)
- Runs >15 times faster than MISTRAL
- **Free**; meant for open source development
- Automatic estimation of regularization hyperparameters; an additional order of magnitude speed up
- Handles multi-frame data (e.g., 1 object, N variable transfer functions)
- Handles 3D image data

$I_{max}/\sigma_{noise} \sim 100$

object

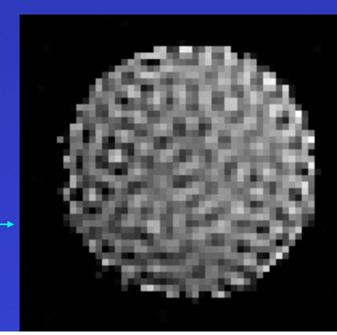
blurred



blurred
+ noise

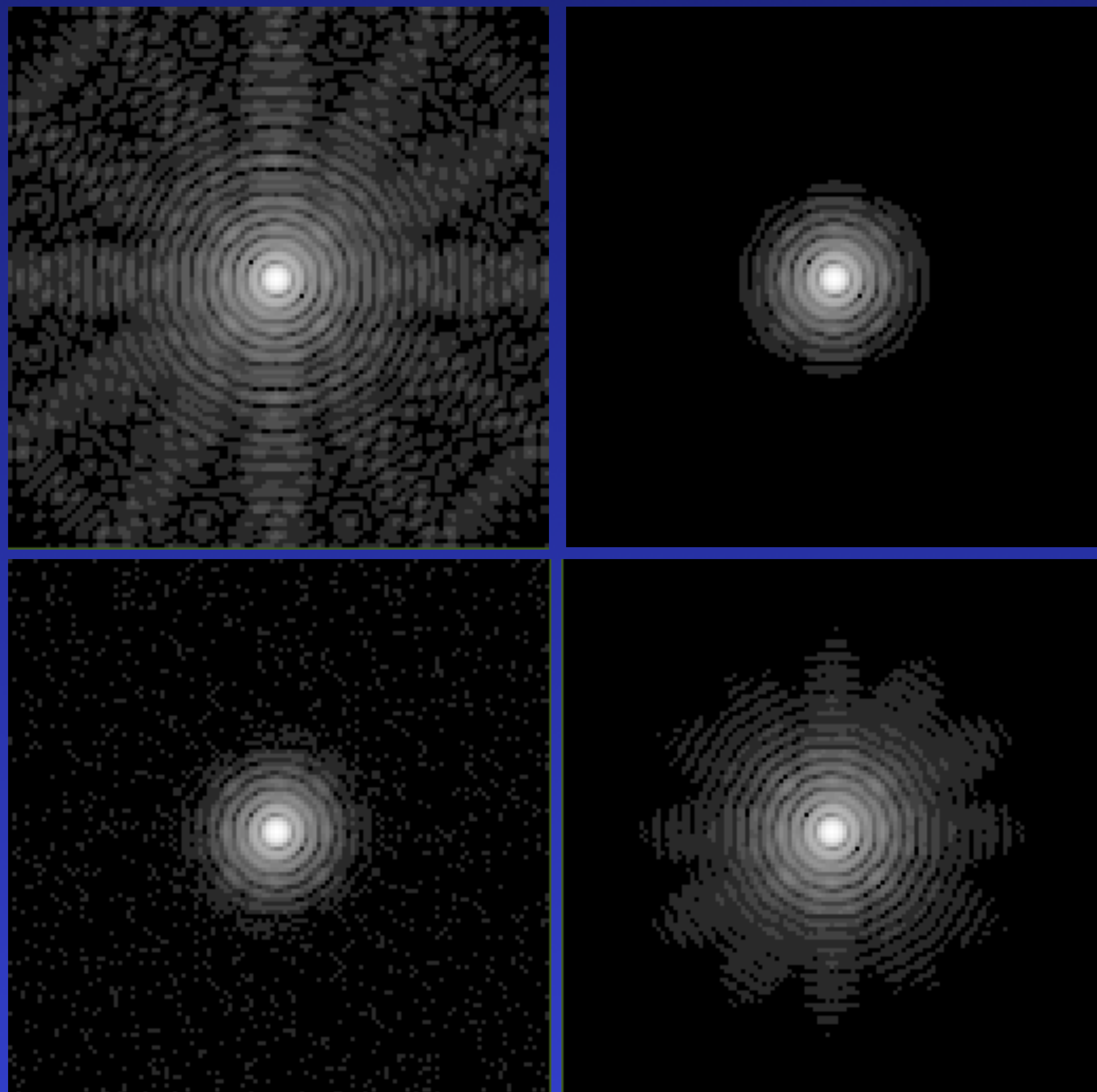
AIDA
decon

Least squares only



AIDA automatically balances max-likelihood estimation and object regularization

$I_{max}/\sigma_{noise} = 100$



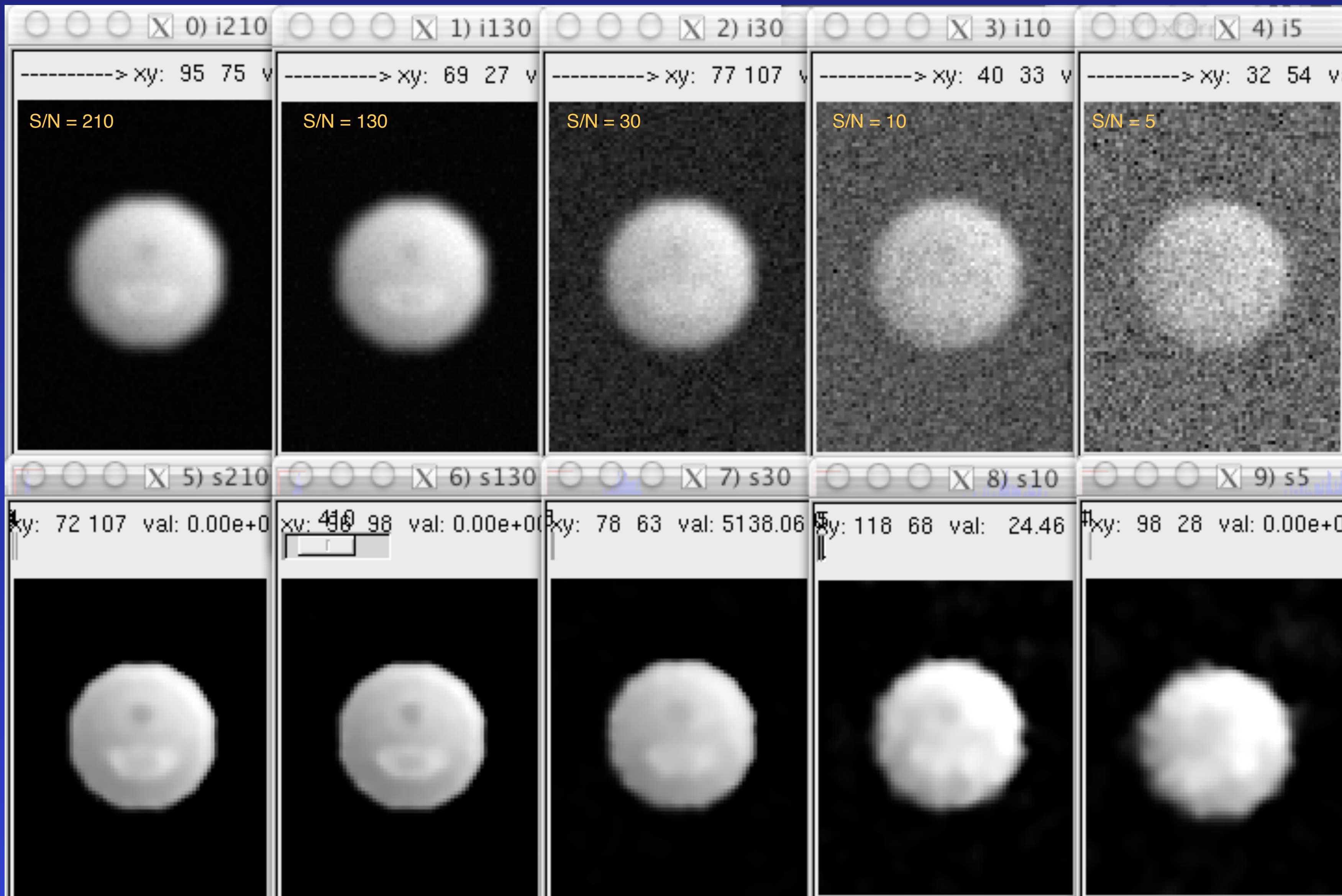
object_{FT}

blurred_{FT}

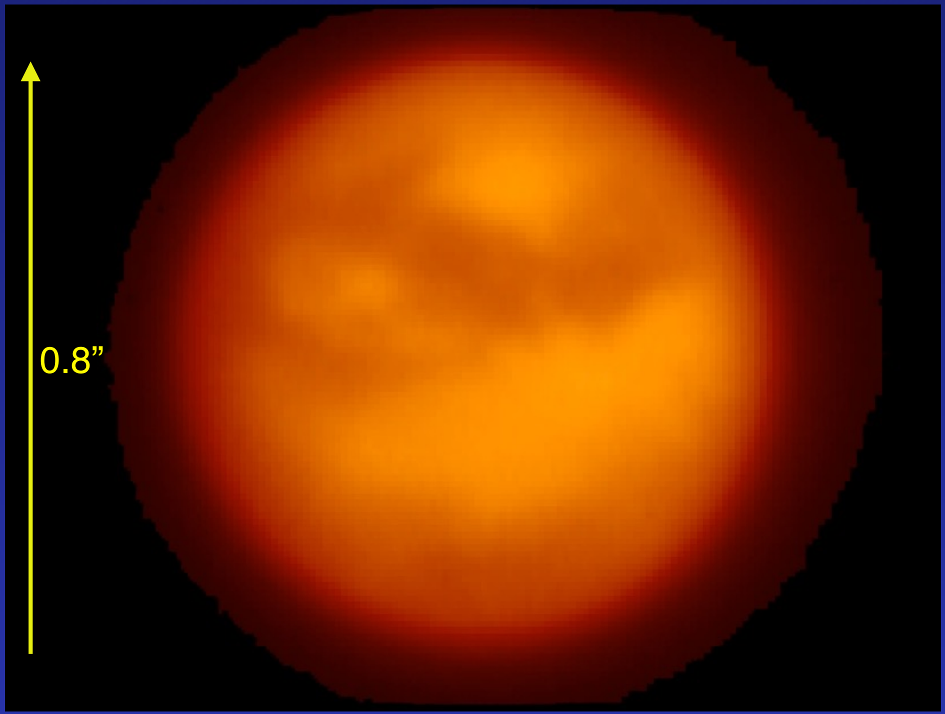
$(\text{blurred} + \text{noise})_{FT}$

decon_{FT}

Photometric accuracy better than 10% (SNR>30) and no artifacts

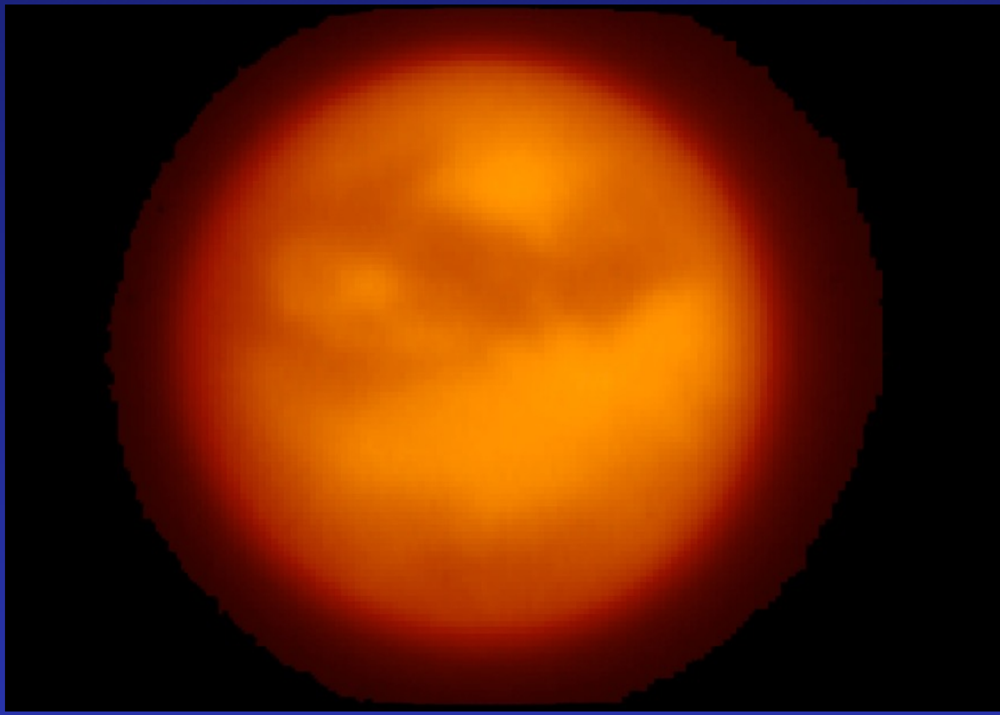


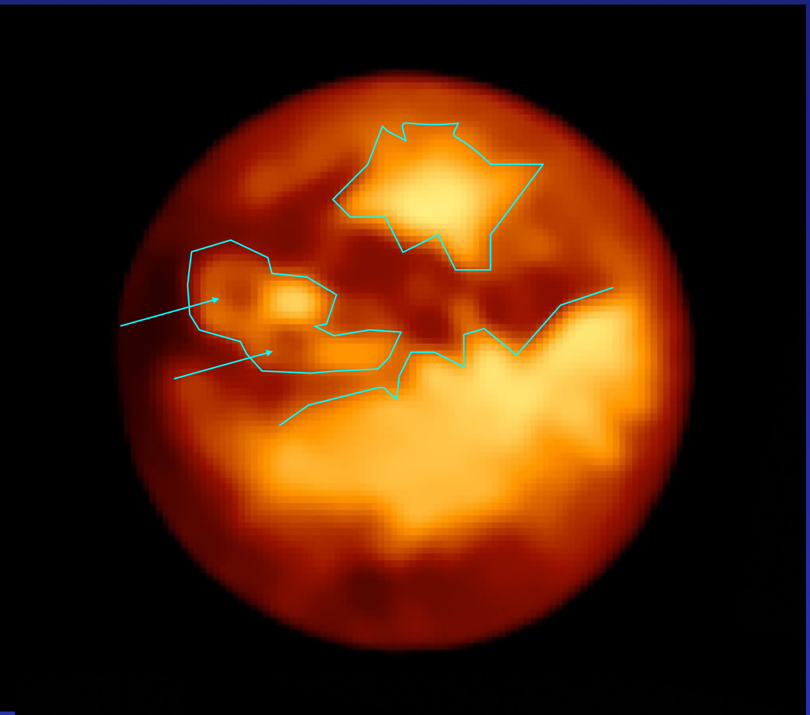
Titan (Moon of Saturn)



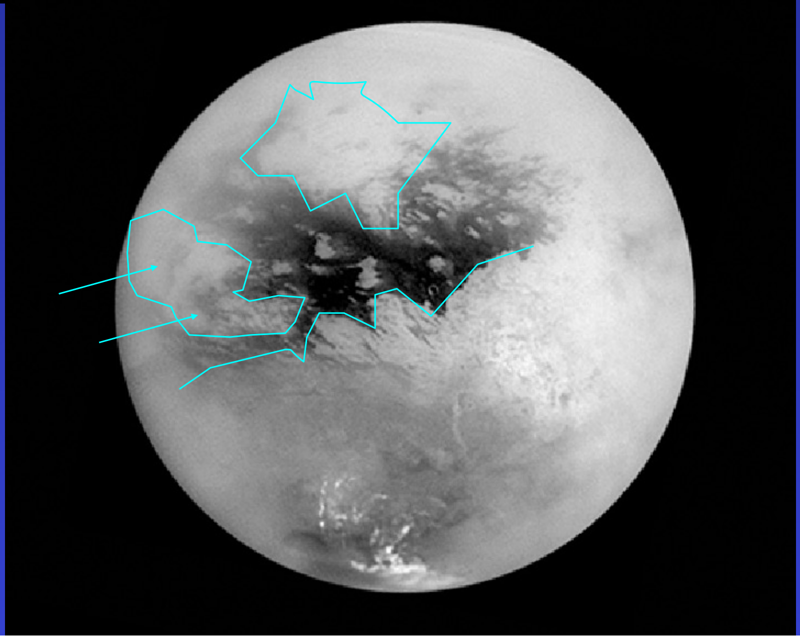
NIRC 2 Keck Telescope
Adaptive optics image in narrow band filter at 2.06 um (January 15 2005)
SR~30%

Titan (Moon of Saturn): AIDA Deconvolved

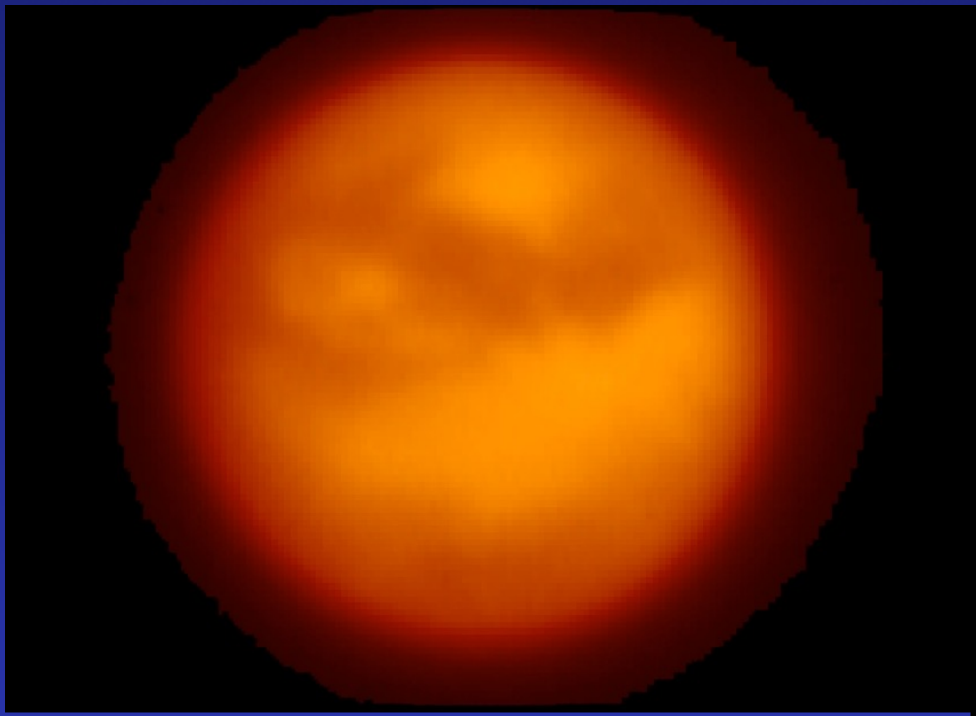


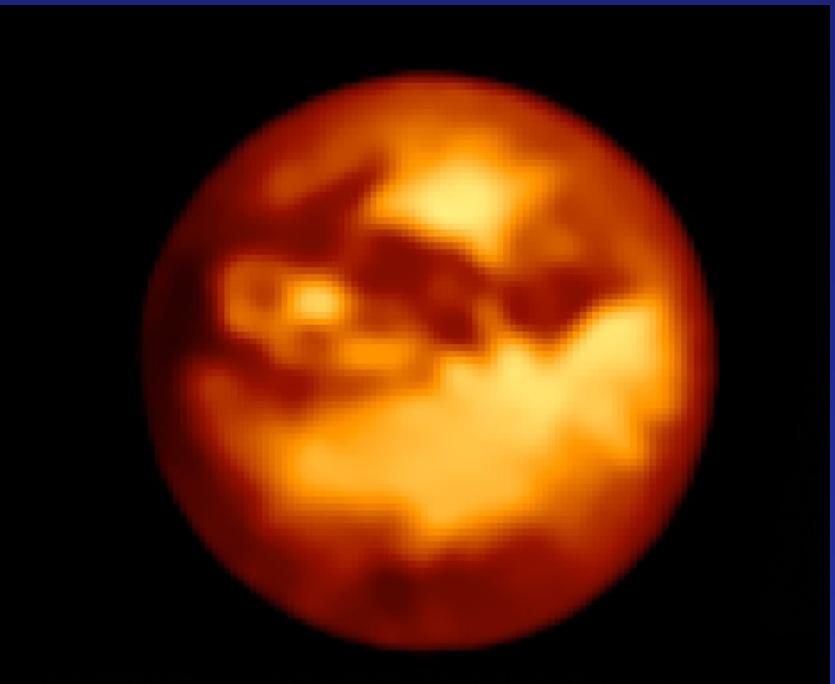


Cross-validation:
Cassini-Huygens
satellite flyby image

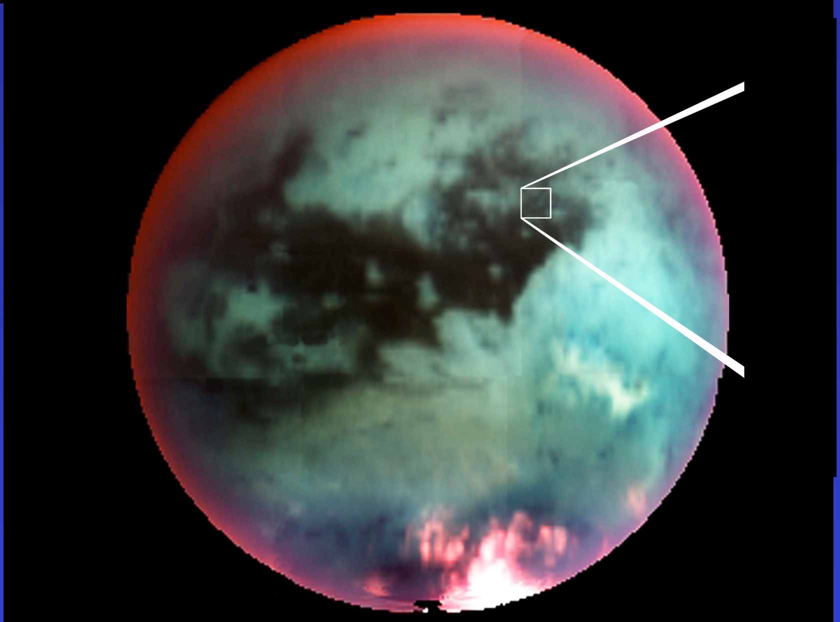


Titan (Moon of Saturn): AIDA Deconvolved



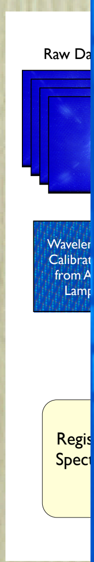


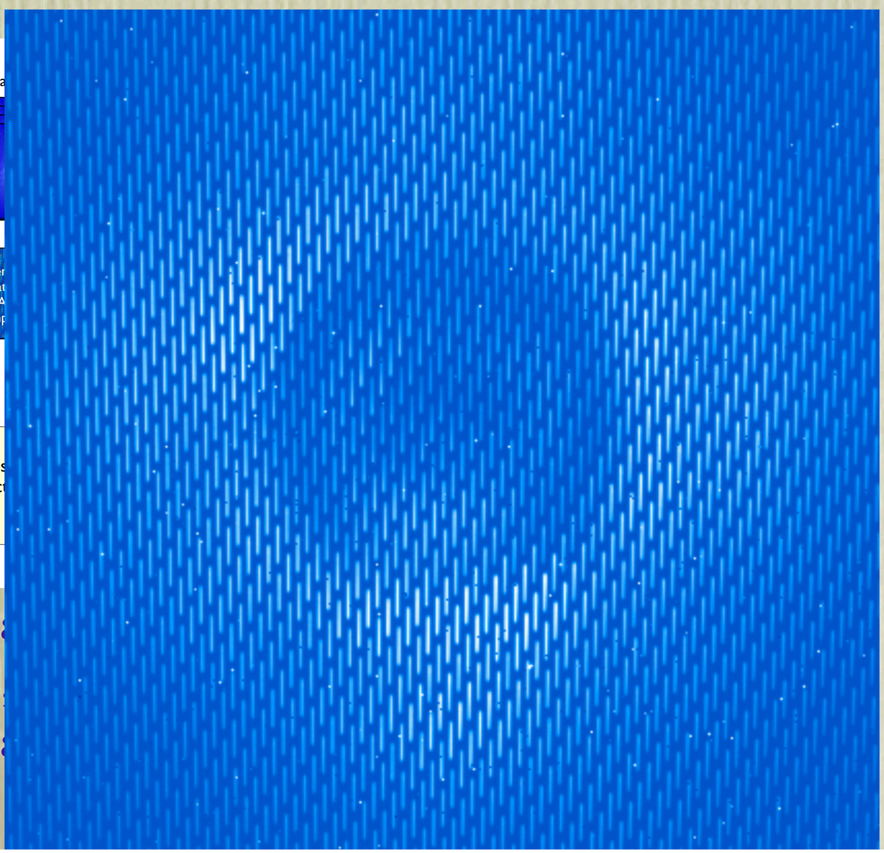
Today AIDA is used by astronomers and biologists alike…

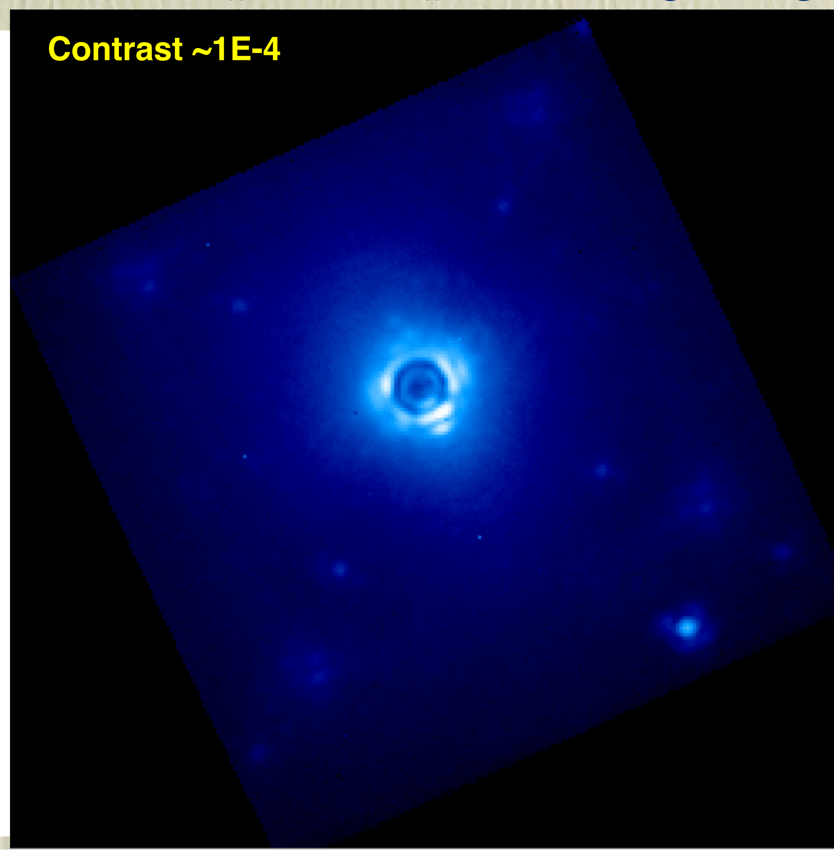


GPI Data Pipeline

- GPI (PI: B. Macintosh) a planet hunter (first light in 2013), now available. GPIES (600 nearby young stars in 890h) currently in progress
- Open source IDL Software (Perrin et al. 2014; Maire et al. 2010) to transform GPI raw data into calibrated cubes in spectroscopy and polarization modes at the telescope (Quicklook) and in your office.
- Current version v 1.3.0 + Tutorials on http://docs.planetimager.org/pipeline/







Dat
field
Dat
PSF

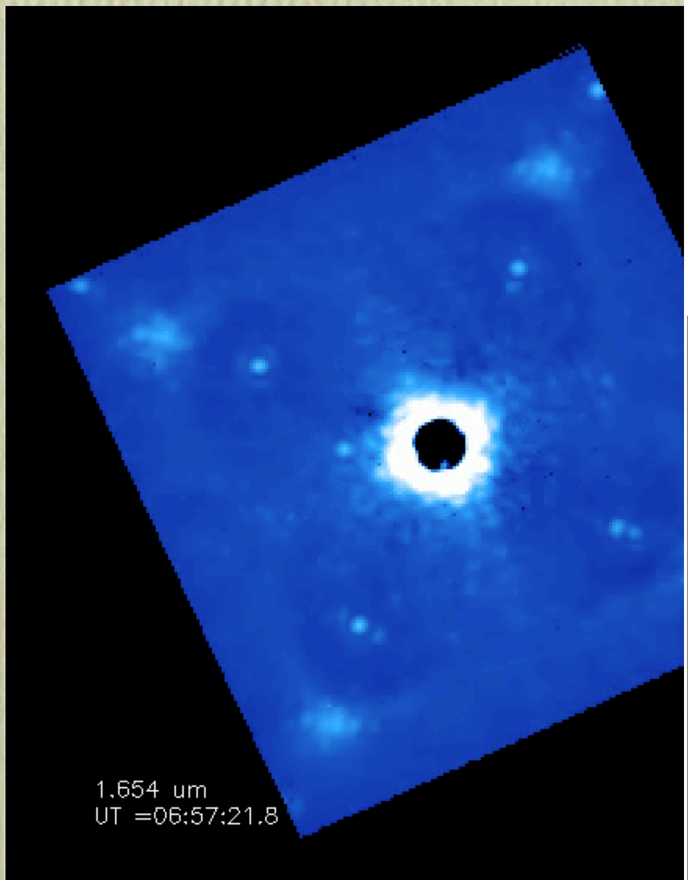
GPI Data Pipeline

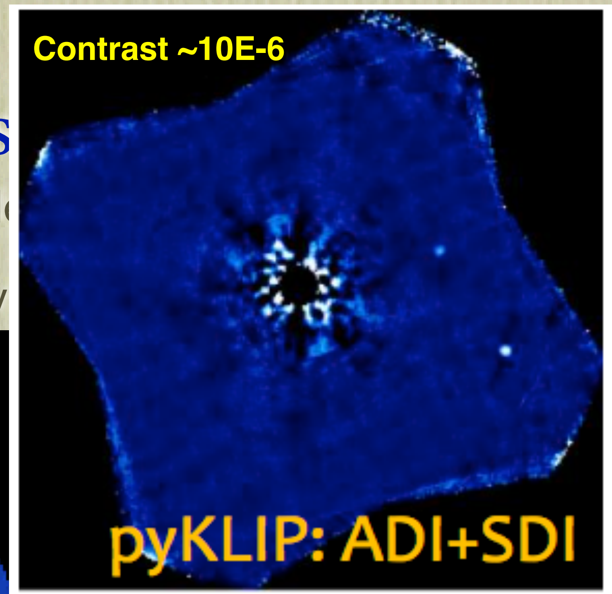
GPI Pipeline Papers Series in SPIE (2014)

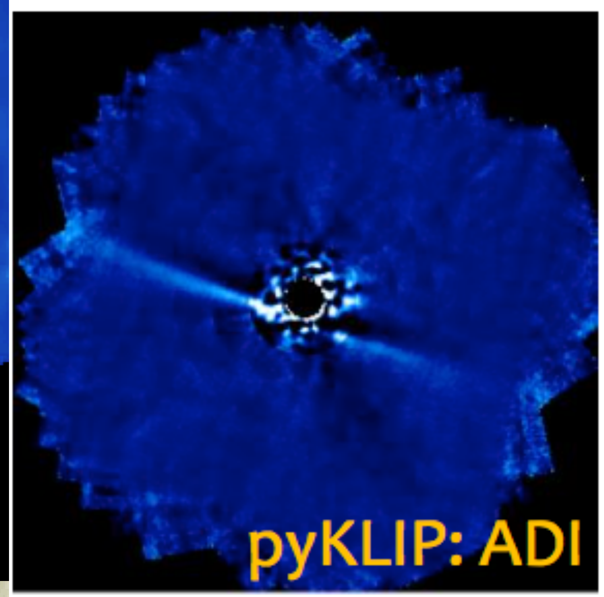
- Paper I: Overview of the GPI data analysis pipeline (Perrin et al., paper #9147-3)
- Paper II: Detector Performance and Calibration (Ingraham et al., paper #9147-286)
- Paper III: Empirical Measurement and Applications of High-Resolution Microlens PSFs (Ingraham et al., #9147-282)
- Paper IV: Wavelength Calibration and Flexure Correction for the IFS (Wolff et al., #9147-279)
- Paper V: Astrometry and Distortion (Konopacky et al., #9147-306)
- Paper VI: Photometric and Spectroscopic Calibration for the IFS (Maire et al., #9147-307)
- Paper VII: On-sky Polarimetric Performance (Wiktorowicz, Max et al., #9147-305)

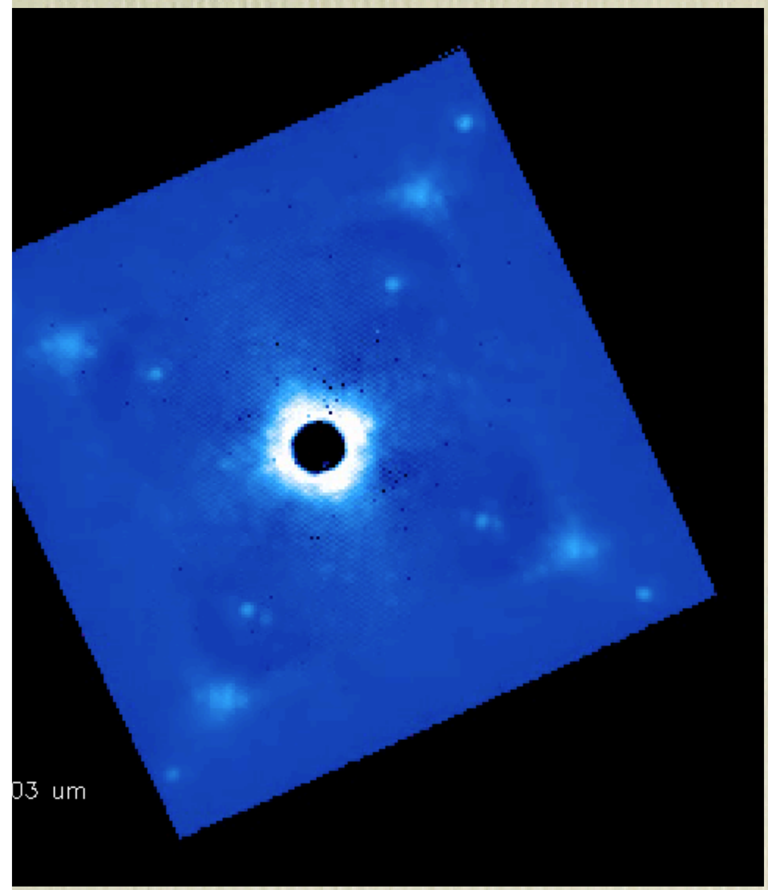
GPI Data Analysis

- Time/wavelength depend enhance planet detection
  - One wavelength slice ov avelength slices form the datacube







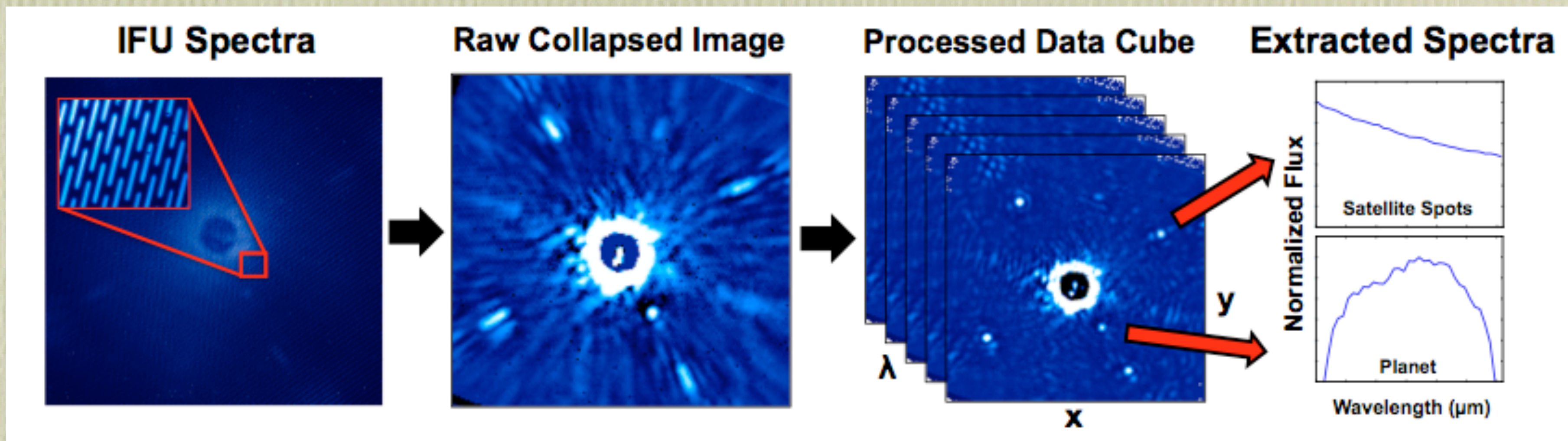


pyKlip - a python library for PSF subtraction (Wang et al., 2015)

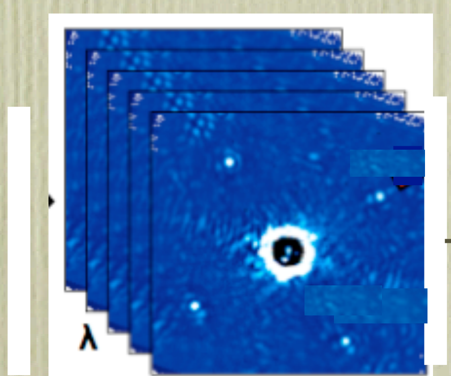
- Implementation of KLIP (Soummer et al. 2012) in a fast parallelized code
- Capable of running ADI, SDI, ADI+SDI with spectral template to optimize PSF subtraction
- Insert fake planets in raw data
- Available on BitBucket https://bitbucket.org/pyKLIP/pyklip

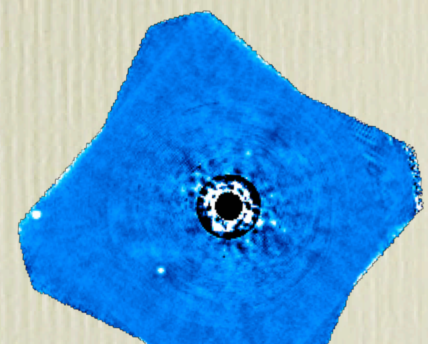
GPIES Data Processing

- **GPIES Data Cruncher - flow of data**



- **GPI Data Cruncher takes data cubes to make final reduced & PSF subtracted images**





Input: Raw IFU data + calibration

Automated Data processing system "Data Cruncher" (lead: Wang)

Data analysis: pyKLIP (Wang et al. 2015) cADI (UdeM), TLOCI (Marois et al. 2014)

Quality checked: MySQL DB

Output: final image on Dropbox, contrast curve, updated wiki

Perspectives

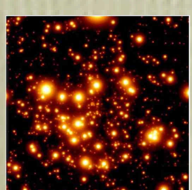
"Data processing is without doubt the most fascinating part of astronomy. In the future people will cherish those algorithms and admire those who created them." F. Marchis, Kissimmee, FL

Not really... but efficient and well understood data processing is part of the job...

- Robust pipelines are key to increase the **scientific return of modern AO instruments** (e.g. 12 peer-reviewed publications for GPI and 23 for SPHERE in less than a year)

- Best pipelines are those made by the instrument builders and improved with **contributions** and **feedbacks** from observers (you!).

- Don't reinvent the wheel. A lot of **well-documented** and **efficient** pipelines already exist. They can be adapted to your needs.



- **AO PSF variability** is less a problem today but it is still here. Derive the errors on your measurements using your pipeline with simulated images.

Challenges

- New ideas and new concepts for AO data analysis for exoplanet detection
  - ✳ Myopic detection algorithm based on analytical model of AO coronograph (Ygouf et al. 2014)
  - ✳ forward modeling PSF (Pueyo, 2016)
  - ✳ Machine learning?
- Manageable pipelines despite the complexity of future instruments (e.g NGAO, MIKADO for E-ELT, ERIS for TMT)