AO modeling and PSFs

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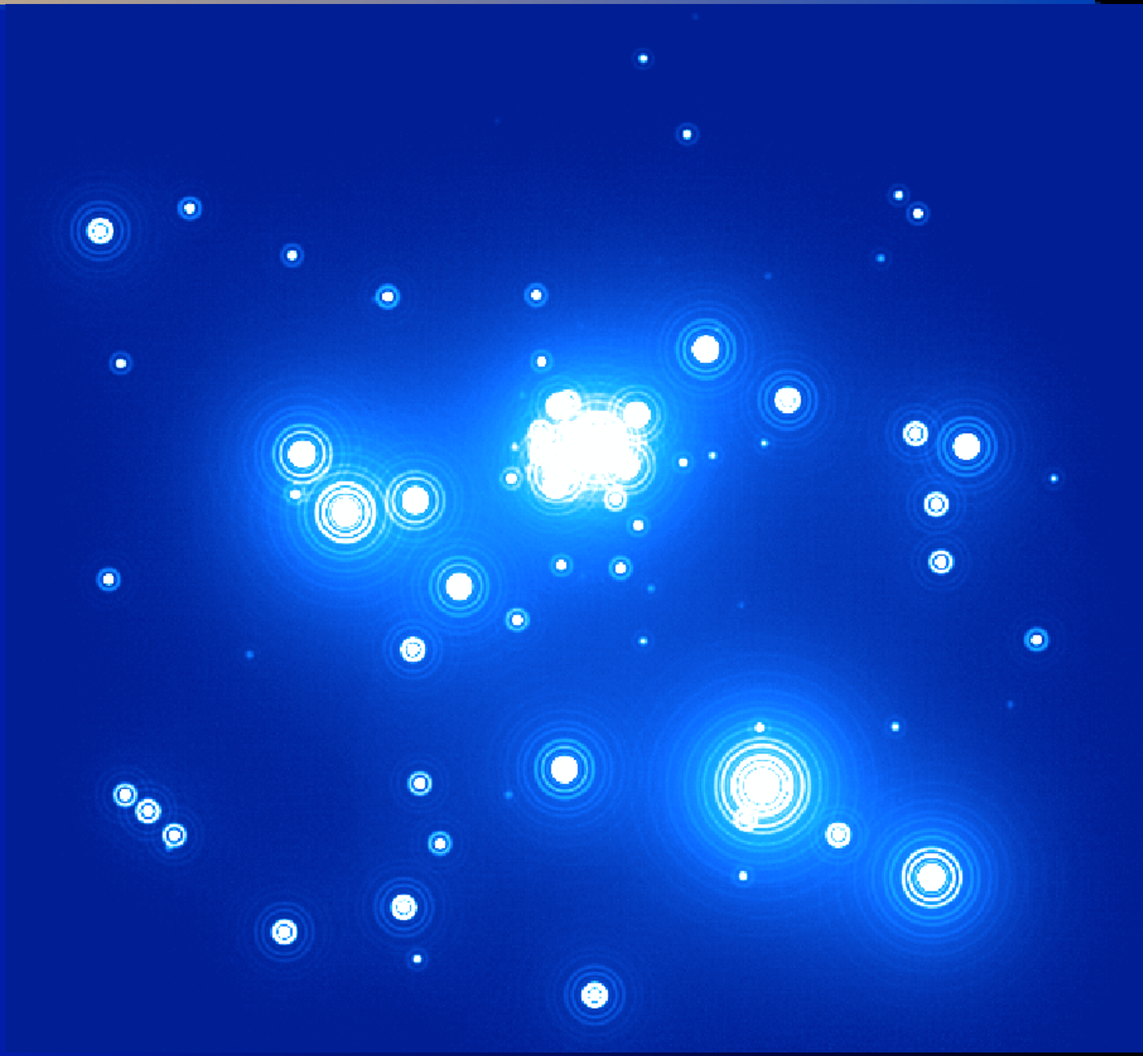
ESO

Why AO simulations ?

- AO designer : Guidance on HW choices
  - How many actuators, subaps, laser powers, …
  - Tolerancing (mis-alignments, jitters, component imperfections)
  - What errors dominate, sensitivity analysis (to physical parameters, like r0, Cn2, Na profile…)
  - Development and testing of new algorithms
- Astronomer / user:
  - AO & Instrument definition and optimization
    - AO type (SCAO, GLAO, MCAO,…)
    - Instrument pixel scale, wavelength range,…
  - AO system performance requirement definition
    - Simulate science observation and see if you can extract what you want from the data
  - Simulated observations to prepare data reduction pipeline
  - Exposure time calculator
- "Debugger" of a real AO system in the lab / sky
  - Does system reach simulated simulated perf. If not, why ?
  - Allow to better understand AO system & telescope environment

Astronomical simulations

- Use AO simulated PSFs to generate astronomical observation → verify that astronomical science goals can be reached with that level of AO correction



Simulated K band image of a young Star forming region in the LMC. Exposure time=25 hours
Calamida et al., DRM report, 2010

Kinds of simulation / analysis tools

- Error budgets / Analytic (without PSF)
  - Lump Error budget & analytical rms wavefront error
  - Identify error sources, calculate associated error, add effects in quadrature
- Getting PSFs is more important now, because new metrics are not as simple to analytically handle as Strehl
  - Ensquared Energy (→ Spectroscopic applications)
  - PSSn (Point Source Sensitivity – normalized → ELTs)
  - Contrast (XAO)
- Semi-analytic (Fourier) codes provide infinitely long PSFs
  - Some approximations needed (esp. LGS aspects)
  - Excellent to cover a large parameter space in short amount of time
  - Results then refined / confirmed with E2E codes.
- End to End
  - Pretty much as refined as can be
  - Need cluster / super server to run

What is included in the simulations ?

- By "default", AO simulations analyze:
  - Atmosphere
  - AO system
  - Telescope
- Usually, no "instrument" (except in XAO)
- Provides PSF (long exp)
  - Basic coronography option
- E2E, in addition, can provide:
  - Short exposure PSF @ loop rate (i.e. temporal behavior)
  - Short exposure Phase residual → could be sent to instrument model

Fourier methods

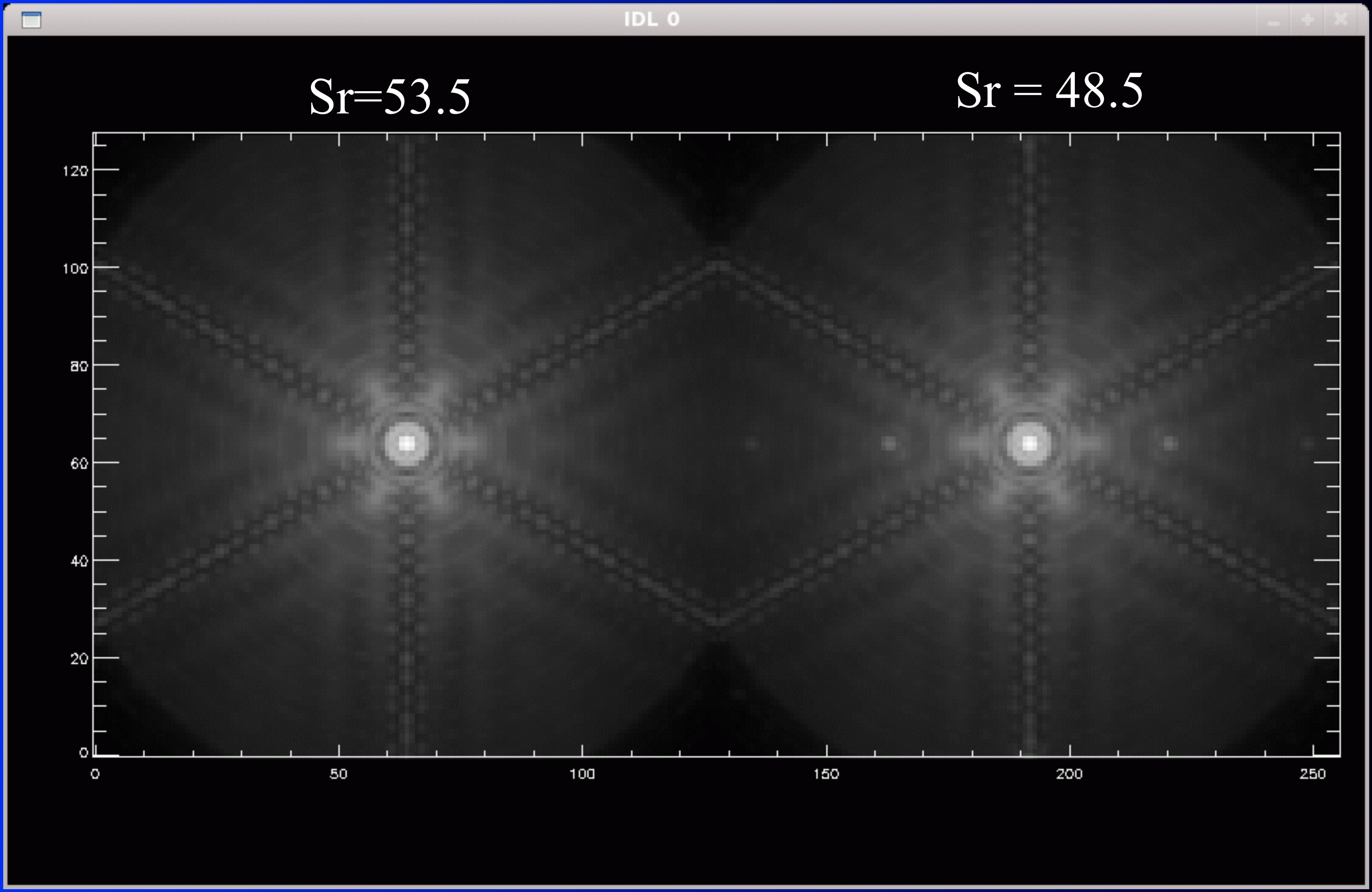
- Analytical / Semi-analytical (with PSF output)
  - E.g. PAOLA, Cibola, Fourier based codes
    - Calculate filter functions for input phase
    - Calculate or simulate the effect of this filter on phase → AO PSF
    - Approximations can be used to address cone effect
  - Pro: fast, accurate, allow simulation of GLAO, Tomographic AO, provide long exposure "smooth" PSFs, no residual speckles
  - Con: Some errors difficult to model, correlations of error not necessarily well modeled
    - Limitations caused by LGSs (cone effect – beam overlap – finite pupil) because these models are Fourier based…
- Heavily used in "first stage" of project (large parameter space analysis)

Fourier example: LTAO PSFs

- Calculated @ ONERA (Fusco et al), semi-analytic (Fourier)
- 39m telescope, LGSs @ 1' (radius), 6LGS
- 40 layers simulated, 7 reconstructed
- Different wavelengths available:
  - 0.8, 1.0, 1.2, 1.6, 2.2, 10.0 um
  - On-axis
  - With and without telescope WFE (very preliminary error budget)
  - Seeing=0.67 @ 30 degrees
- Contain some "reasonable" TT jitter (±3mas rms for LTAO)
- → More realistic than @ phase A (but also less perf)

ATLAS PSFs by ONERA / K band

Fusco et al.



Without telescope

With telescope

What can we simulate in E2E?

- Pretty much any AO system can be simulated:
  - SCAO, GLAO,LTAO, MCAO, MOAO,XAO,…
- Mostly atmosphere, but telescope effects can be added
  - For example time series provided to instru. consortia have been added for SCAO
  - E-ELT Telescope simulations uses different simulation tools, results included as phase screen time series into E2E
- Each loop step is simulated
- ESO tool: Octopus (software & cluster)

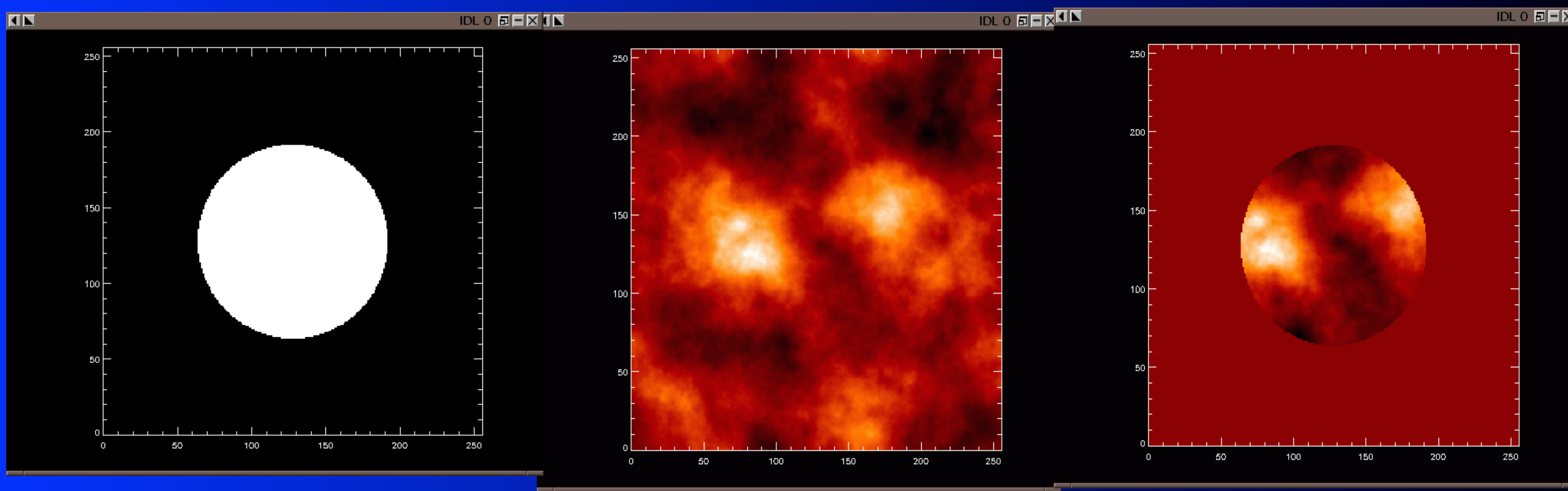
Closer to the physics: End to end models

- Analytic / Semi-analytic codes have roughly dimensioned system
- Now need deeper analysis, for example:
  - Non linear effects in WFS
  - WFS dynamic range, pixel size, FOV, diffraction effects,…
  - DM stroke, IFs, hysteresis, effect of dead actuators,…
  - Tolerances (alignment errors, displacements…)
  - Spatial filtering for aliasing reduction
  - Loop stability and optimization
  - New control algorithms (Kalman, Predictive,…)
  - Segmentation/co-phasing effects on WFS
  - Speckle subtraction schemes
  - […]
- "Monte Carlo" methods, since input (phase) is random

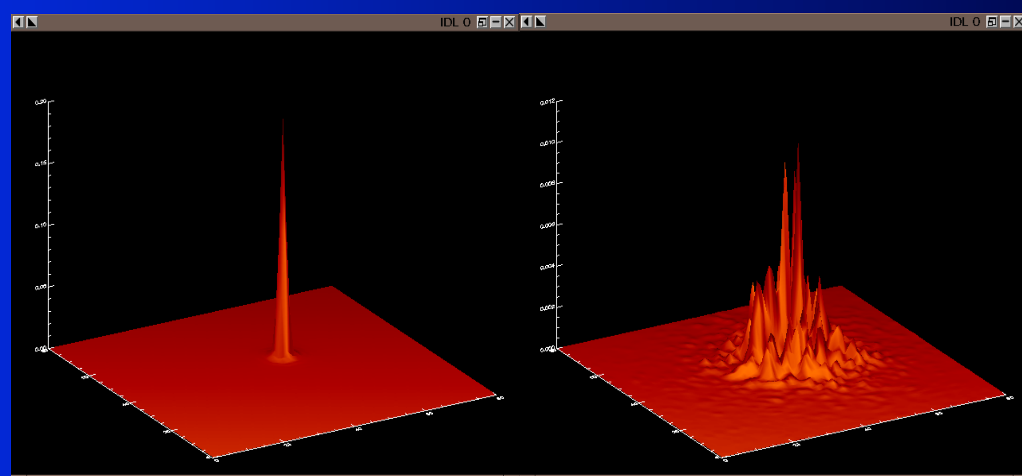
End to end models

- Simulate as close as possible to the physics
  - Phase screens for atmosphere
  - FFTs to get WFS measurement (to include diffraction)
  - Centroiding process
  - Interaction matrix creation from measurements (if required by reconstructor)
  - Temporal evolution simulated by moving phase screens
  - PSF calculated from residual phase by FFT
- In principle very accurate
- Relatively easy to take new effects into account
  - No need for analytical formula, just need to modify phase
- Heavy numerically → slow
- Huge amount of work has gone into optimizing these codes (TMT MAOS, yao, Octopus, ONERA,...) to be as fast as possible

Getting a PSF



FFT

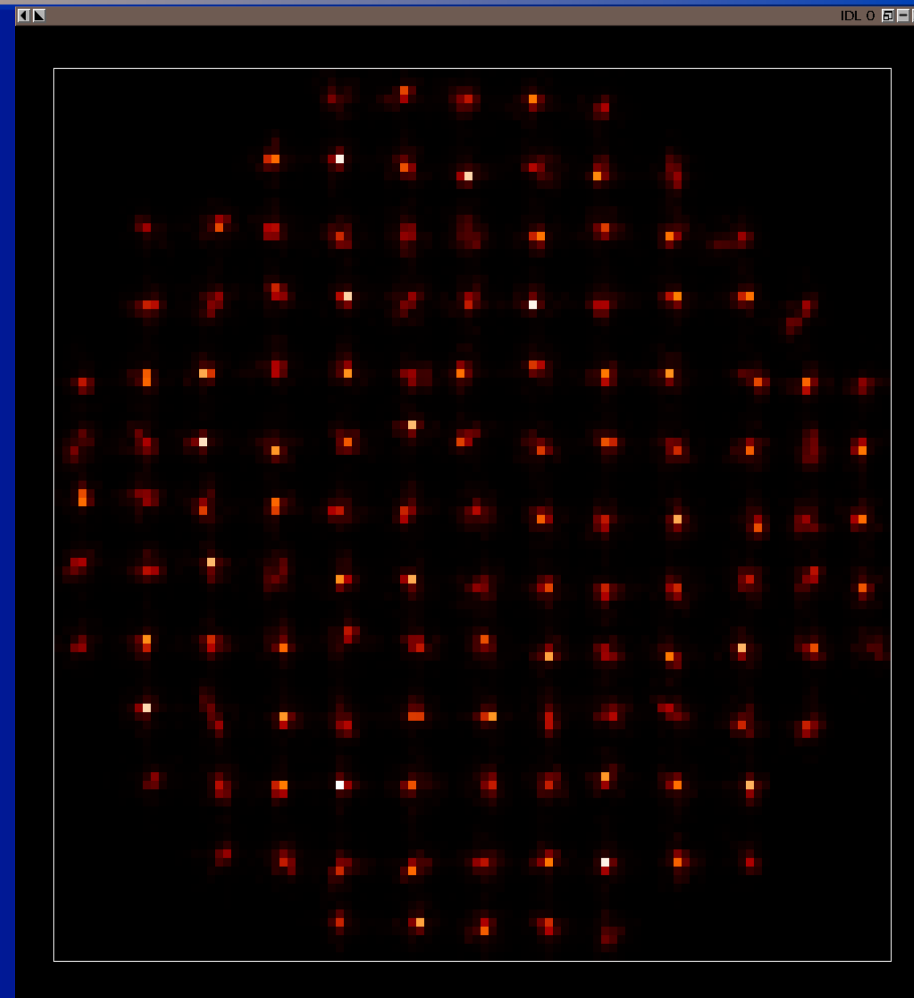


Airy pattern
(no phase screen)

Speckle pattern
(with phase screen)

Wavefront sensor

- SH or curvature can be modeled
- Cut phase screen into sub-apertures
- FFT -> SH PSF = SH speckles are taken into account
- Add noise (photon, RON, sky, dark...)
- Threshold
- Compute centroids
- Output measurement vector



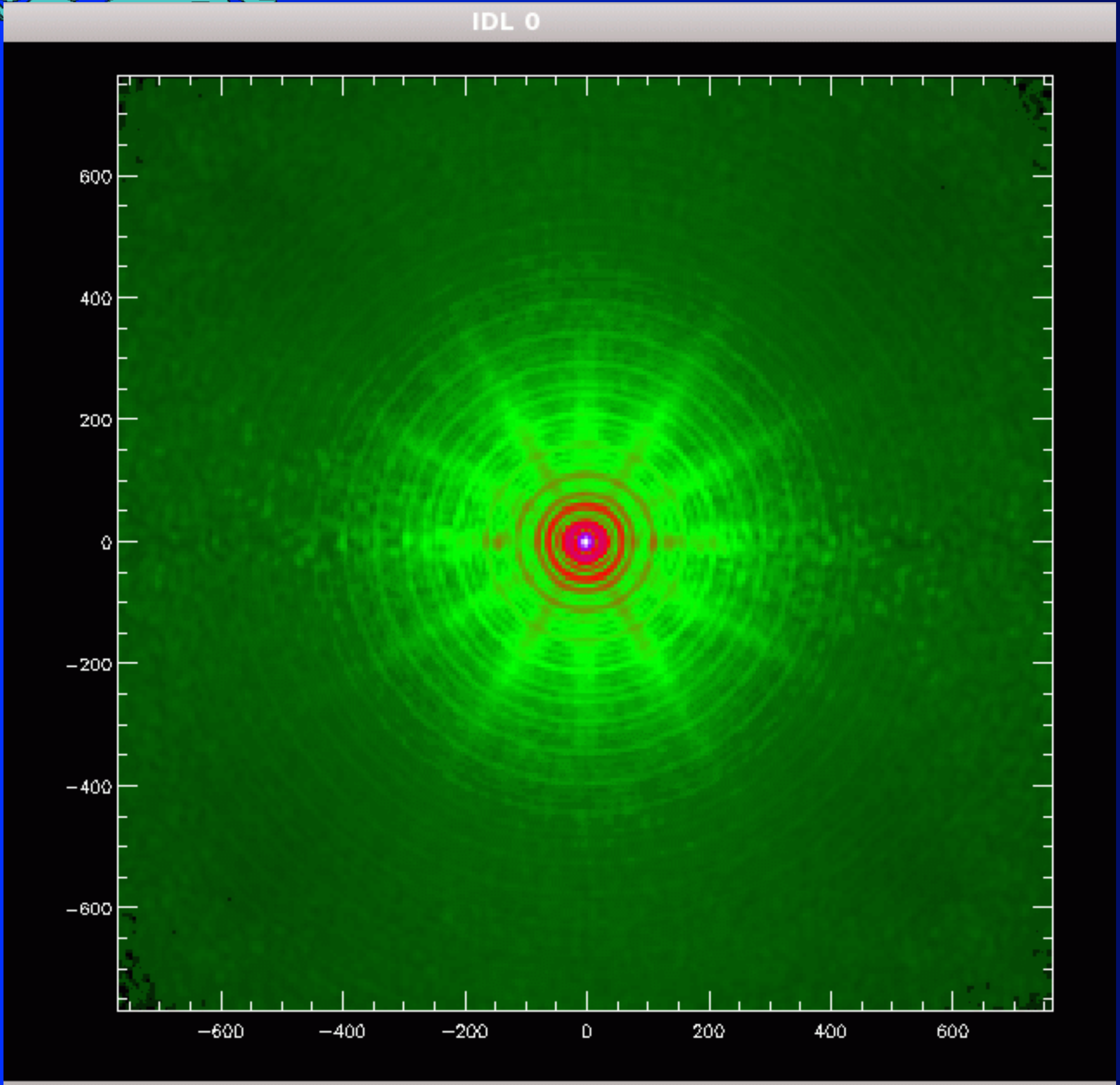
- At each step errors (e.g. flat field or novel treatments (eg WCOG, spatial filtering) can be added.
- For MCAO, WFSs can be cloned to look at different stars

Closed loop / temporal evolution

Temporal behavior:

- Shift phase screens
- Propagate screens
- New WFS measurement
- IM # measurements -> c
- New DM commands: $c_n = c_{n-1} + g\ c$ (g:gain)
- New DM shape
- Atm. phase - DM shape = Residual phase
- Long exposure PSF = Sum(Short exposure corrected PSF)

LTAO PSF, Atm only

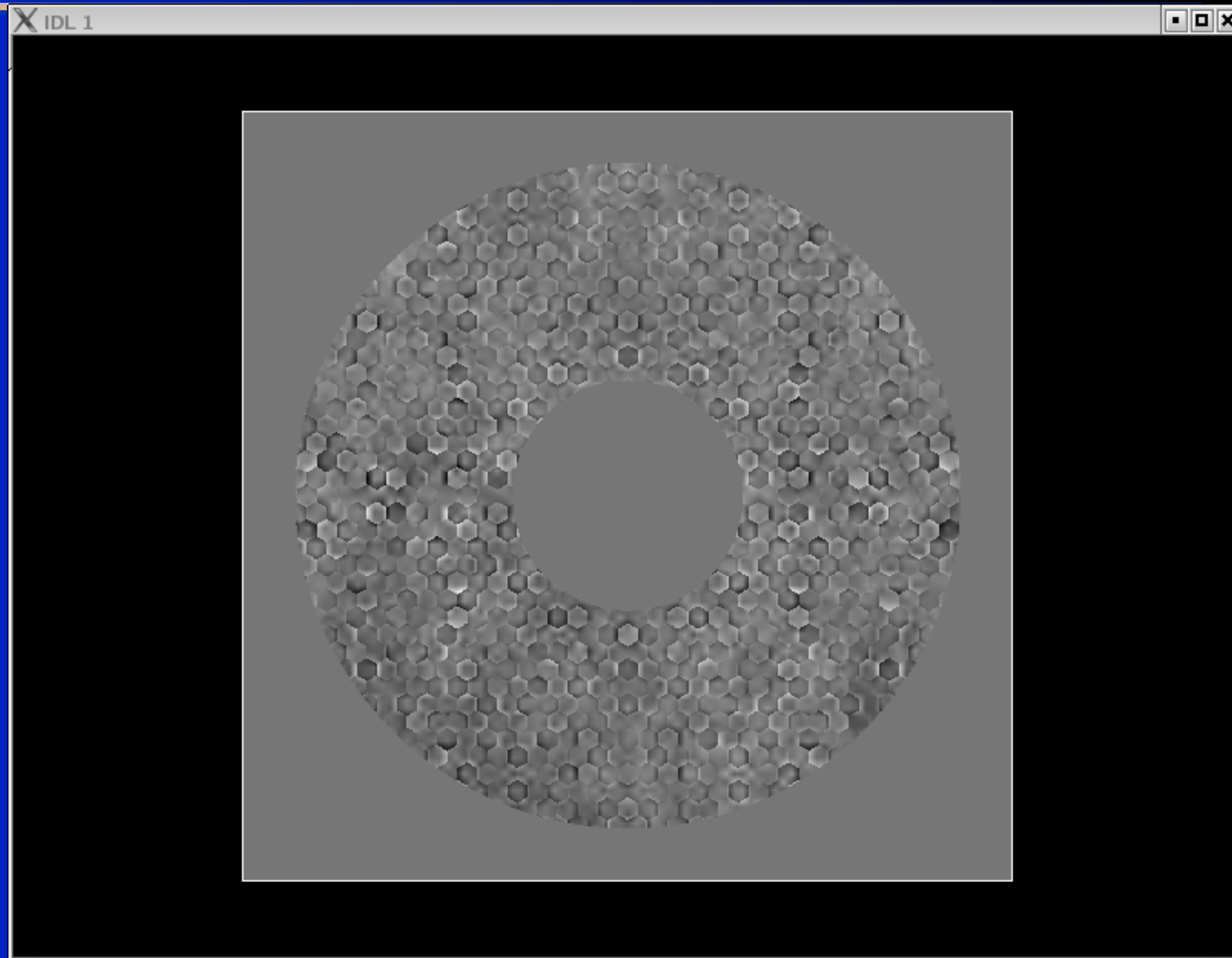


5.9 mas / pixel
Axis in mas
Stretch: ^0.2
K-band
8s integration
(4000it@500Hz)

Circular pupil here,
No segmentation

LGS symmetry seen here, not primary

Interaction with (a more complex) telescope



How the AO corrects a particular mode of the segmented telescope
→Only high spatial frequency modes remain, due to segment imperfection (exaggerated in this case)

Parallelization

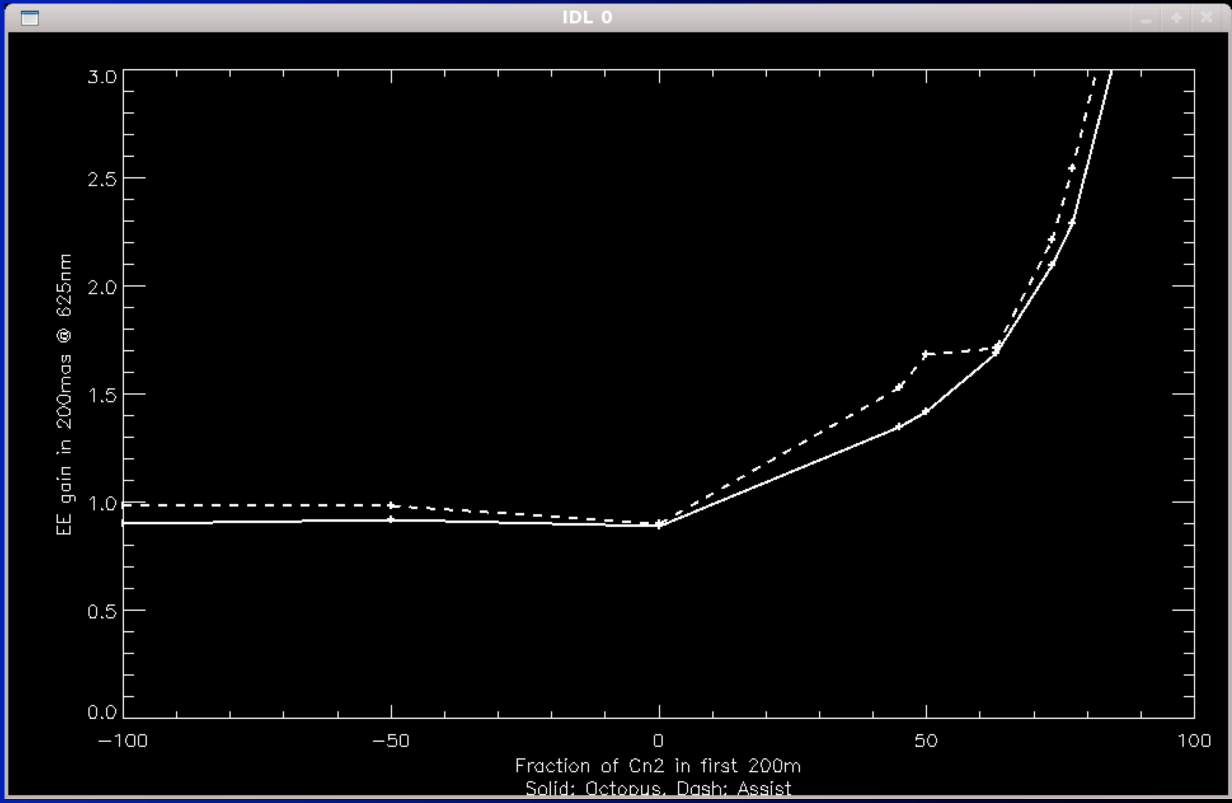
End to End simulations can be numerically heavy: clusters, GPUs, parallelism, …

Simulation validation

- How do we know simulations are correct ?
- Software against software
  - Classic paper, Rigaut, Ellerbroek & Northcott, Appl. Opt, **36**, 1997
- Lab experiments & integration in lab
  - Lab experiment used to validate simulation results
  - Need to simulate the lab experiment & its particularities
  - Some “extra” effects, specific to lab environment are likely
- Sky
  - Analyze AO system post-facto, and understand its real life limitation (e.g. van Dam et al, 2004).
  - This validates simulation AND AO system

Lab validation of Octopus

Here, a lab "bench" is set up
With the sole purpose of
validating
System performance
→ Controlled environment
→ Known input (phase
screens) to know output.



GALACSI WFM (for MUSE), on ASSIST. EE in 200 mas gain vs. Cn2 profile used on the bench

Using E2E simulated PSFs for “astronomers”

- One problem with E2E PSFs: residual speckles
  - Run simulation @ 500Hz – 1kHz
  - Takes forever (6h – 2days for 1 point)
  - → only some seconds (1-10-100) of data can be simulated “easily”
  - → Residual speckles are still visible on the PSFs
- Science data: 20min-80h.
  - No speckles at all, very smooth PSF
- Total number of PSFs can be parallelized, so producing cubes of PSFs is “easy”. Long ones: not so much.

How to solve speckle problem in E2E?

- Use analytic simulated PSFs as “fitting” functions
  - Fudge analytic simul to get same “result” metric as E2E (Strehl, EE,…).
  - Assume image structure is “roughly” the same as E2E
- Use PSFs from lab
  - May also be limited in time span (limited phase screens)
- Use radial averages
  - Assumes centro-symmetric PSF (not true for tomography)
- Use ad-hoc fitting functions (splines,…) to fit E2E PSF
  - May be difficult to say what is speckle, what is PSF structure
- OR: play with the E2E model
  - Some tricks can be applied to reduce speckles, like:
  - uncorrelated phase screens to accelerate convergence (but lose time info)
  - Simplify E2E to accelerate code to run many more iterations
  - […]

Conclusions

- Different tools are available to generate AO PSFs
  - Each have their limitations:
  - Analytic: slightly less accurate (but probably good enough ?), smooth PSF, infinite exposure time, some approximations
  - E2E: residual speckles due to short integration time, but more “effects” included, more precise. Overkill ? Or necessary ?
  - “Massaging” PSFs may be necessary
- How accurate do the PSFs need to be ?
  - What criterion to say “this PSF is good for our use” ?
- What and how do you want to use the PSFs ?
  - May dictate which kind of PSF is used
- There are many tools. Choose the right one !
  - There will be work associated to get the PSFs you want