Learned Exascale Computational Imaging (LEXCI) overview

ExCALIBUR Programme Workshop

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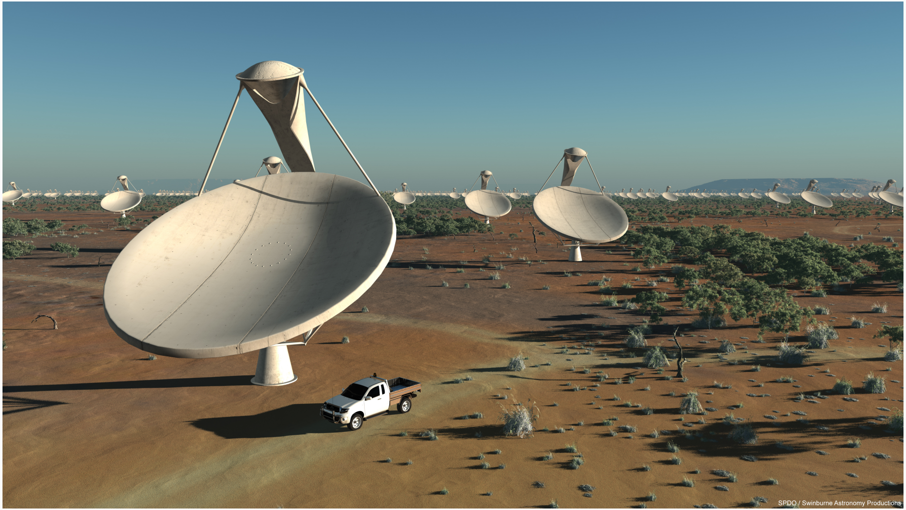
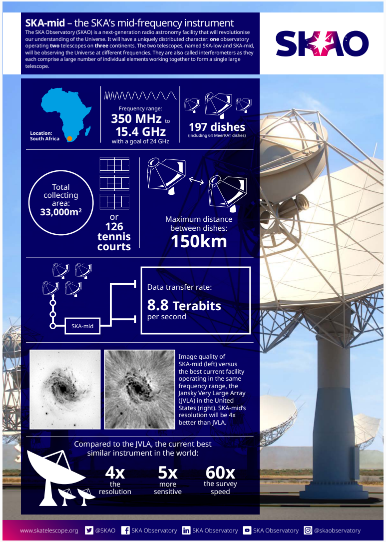
July 2022

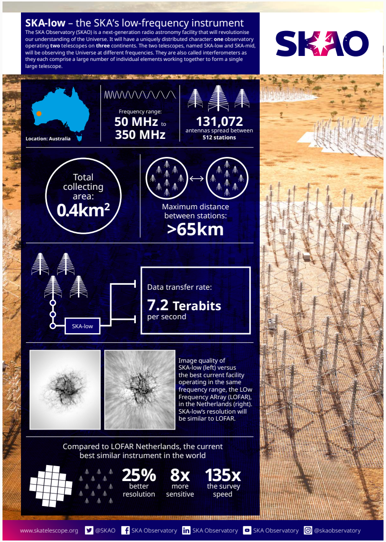
Canonical application: Square Kilometre Array (SKA)



SKA sites



SKA-mid – the SKA's mid-frequency instrument
The SKA Observatory (SKAO) is a next-generation radio astronomy facility that will revolutionise our understanding of the Universe. It will have a uniquely distributed character: one observatory operating two telescopes on three continents. The two telescopes, named SKA-low and SKA-mid, will be observing the Universe at different frequencies. They are also called interferometers as they each comprise a large number of individual elements working together to form a single large telescope.
SKAO
Location: South Africa
Frequency range:
350 MHz to 15.4 GHz
with a goal of 24 GHz
197 dishes
(including 64 MeerKAT dishes)
Total collecting area: 33,000m²
or 126 tennis courts
Maximum distance between dishes:
150km
SKA-mid
Data transfer rate:
8.8 Terabits
per second
Image quality of SKA-mid (left) versus the best current facility operating in the same frequency range, the Jansky Very Large Array (JVLA) in the United States (right). SKA-mid's resolution will be 4x better than JVLA.
Compared to the JVLA, the current best similar instrument in the world:
4x the resolution
5x more sensitive
60x the survey speed
www.skatelescope.org
@SKAO
SKA Observatory
SKA Observatory
SKA Observatory
@skaobservatory

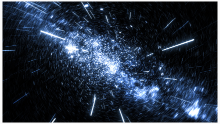


SKA-low – the SKA's low-frequency instrument
The SKA Observatory (SKAO) is a next-generation radio astronomy facility that will revolutionise our understanding of the Universe. It will have a uniquely distributed character: one observatory operating two telescopes on three continents. The two telescopes, named SKA-low and SKA-mid, will be observing the Universe at different frequencies. They are also called interferometers as they each comprise a large number of individual elements working together to form a single large telescope.
SKAO
Location: Australia
Frequency range:
50 MHz to 350 MHz
131,072
antennas spread between 512 stations
Total collecting area:
0.4km²
Maximum distance between stations:
>65km
SKA-low
Data transfer rate:
7.2 Terabits
per second
Image quality of SKA-low (left) versus the best current facility operating in the same frequency range, the LOw Frequency ARray (LOFAR), in the Netherlands (right). SKA-low's resolution will be similar to LOFAR.
Compared to LOFAR Netherlands, the current best similar instrument in the world
25% better resolution
8x more sensitive
135x the survey speed
www.skatelescope.org
@SKAO
SKA Observatory
SKA Observatory
SKA Observatory
@skaobservatory

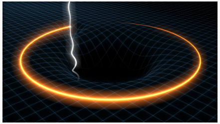
Next-generation of radio interferometry rapidly approaching

Next-generation of radio interferometric telescopes will provide orders of magnitude improvement in sensitivity and resolution.

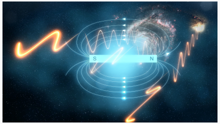
Unlock broad range of science goals.



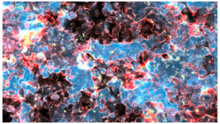
Dark energy



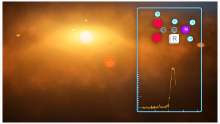
General relativity



Cosmic magnetism

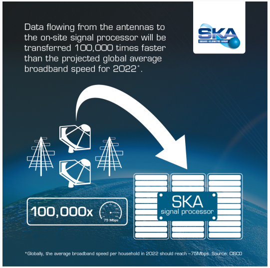


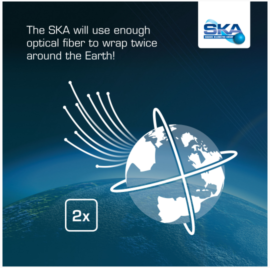
Epoch of reionization



Exoplanets

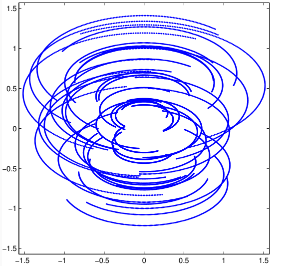
SKA poses a considerable exascale computational imaging challenge





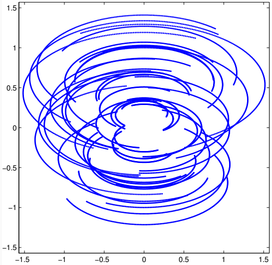
Radio interferometric telescopes acquire "Fourier" measurements

"Fourier"
Measurements
$\Rightarrow$



Radio interferometric telescopes acquire “Fourier” measurements

“Fourier” Measurements $\Rightarrow$



Interferometric imaging is an exascale computational inverse imaging problem:

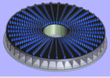
Recover an image from noisy and incomplete “Fourier” measurements.

LEXCI application domains more broadly

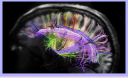
Learned Exascale Computational Imaging (LEXCI)

Radio Interferometry
e.g. MWA, SKA

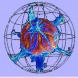
Optical Interferometry
e.g. SPIDER



Medical Imaging
e.g. Diffusion MRI



Seismic Imaging
e.g. Mantle Plumes



Computer Graphics
e.g. Inverse Rendering

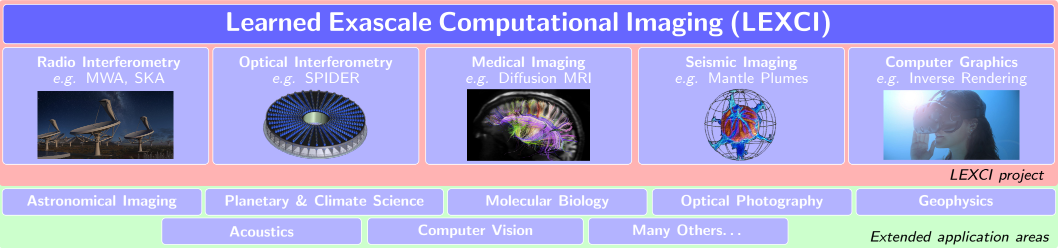
LEXCI project

Astronomical Imaging | **Planetary & Climate Science** | **Molecular Biology** | **Optical Photography** | **Geophysics**

Acoustics | **Computer Vision** | **Many Others...**

Extended application areas

LEXCI application domains more broadly



Partners

- Radio interferometry: Prof. Melanie Johnston-Hollitt (Curtin), Dr Luke Pratley (Toronto)
- SPIDER: Prof. Ben Yoo (UC Davis)
- Medical Imaging: Prof. Gary Zhang (CMIC, UCL)
- Seismic Imaging: Prof. Ana Ferreira (Earth Sciences, UCL)
- Computer Graphics & Virtual Reality: Kagenova
- (ExCALIBUR Benchmarking for AI for Science at Exascale; BASE)

Classical approach to computational inverse imaging

Classically, inverse imaging problems solved by **variational regularization**, where an optimization problem is posed that includes data fidelity and regularization terms:

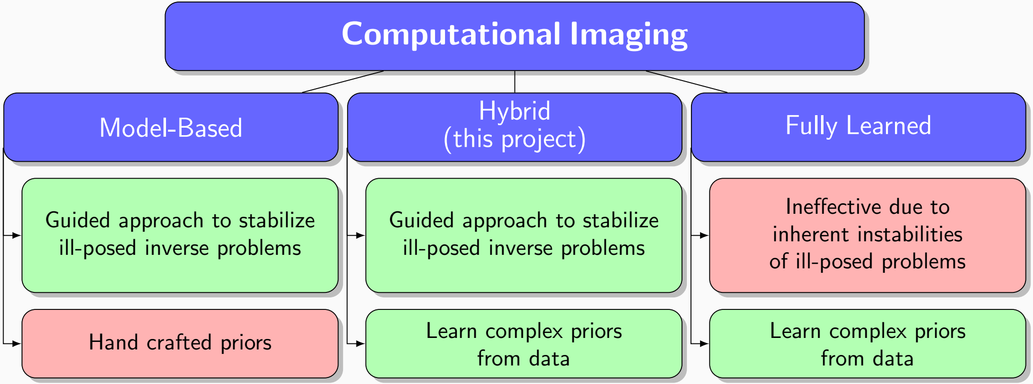
$$\arg\min_{\boldsymbol{x}} \|\boldsymbol{y} - \boldsymbol{\Phi}\boldsymbol{x}\|_2^2 + \lambda\, f(\boldsymbol{x}).$$

for observational model $\boldsymbol{\Phi} : \mathbb{R}^N \rightarrow \mathbb{R}^M$, data $\boldsymbol{y}$ and underlying image $\boldsymbol{x}$.

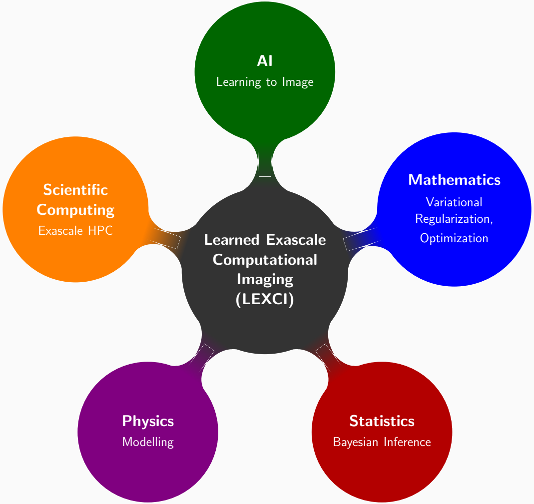
Regularization functional $f : \mathbb{R}^N \rightarrow \mathbb{R}$ encodes prior knowledge.

Typically **model-based regularizers** are used, *e.g.* $f(\boldsymbol{x}) = \|\boldsymbol{\Psi}^\dagger \boldsymbol{x}\|_1$ to promote sparsity in some dictionary $\boldsymbol{\Psi} : \mathbb{R}^D \rightarrow \mathbb{R}^N$.

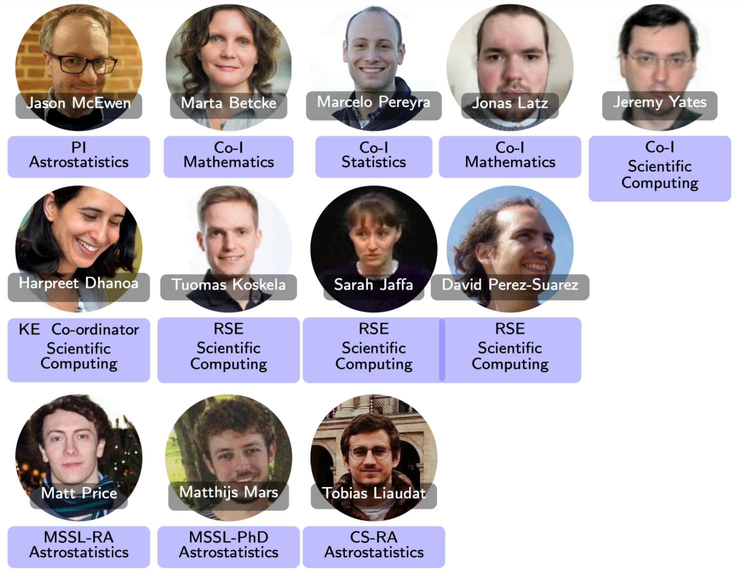
LEXCI hybrid approach



Cross-cutting research areas



LEXCI team


Jason McEwen
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Marcelo Pereyra
Co-I
Statistics
Jonas Latz
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Jeremy Yates
Co-I
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Scientific
Computing
Tuomas Koskela
RSE
Scientific
Computing
Sarah Jaffa
RSE
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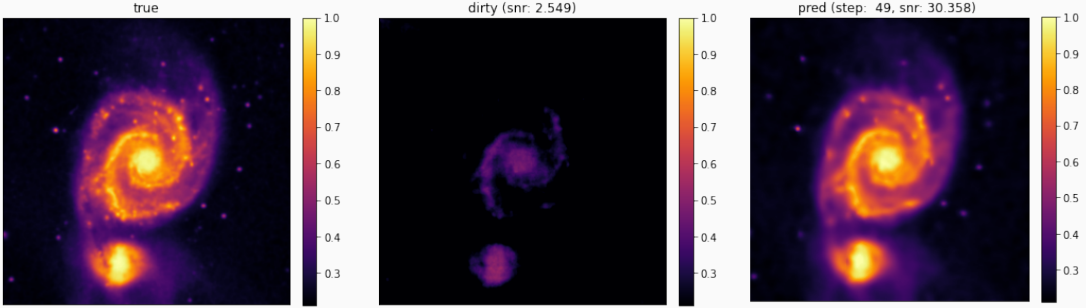
Computing
David Perez-Suarez
RSE
Scientific
Computing
Matt Price
MSSL-RA
Astrostatistics
Matthijs Mars
MSSL-PhD
Astrostatistics
Tobias Liaudat
CS-RA
Astrostatistics

Computational strategy

- Hybrid deep learning (data-driven) & model-based approach
- Big data and big compute BUT moderate size models embedded in iterative algorithms
- **Training and prototyping in Python** on current-generation hardware
- **Imaging (production) in C++** on **exascale** hardware
- **Computing paradigms**
  - Data partitioning algorithms
  - Distributed compute, storage & memory
  - Stochastic distributed algorithms
  - Parallelized & distributed uncertainty quantification
  - Exploit mixed-precision arithmetic

Excellent preliminary results



Events

- ▷ Traditional conference in 2023: *Computational Inverse Imaging*
- ▷ Unconference in 2024: *Applying LEXCI software to cross-cutting problems across domains*

Public open-source codes

PURIFY code

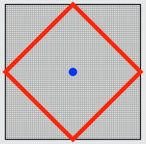
https://github.com/astro-informatics/purify

Next-generation radio interferometric imaging

PURIFY is a highly distributed and parallelized open-source C++ code for radio interferometric imaging, leveraging recent developments in the field of variational regularization and convex optimisation.

SOPT code

https://github.com/astro-informatics/sopt



Sparse OPTimisation

SOPT is a highly distributed and parallelized open-source C++ code for variational regularization and convex optimisation.