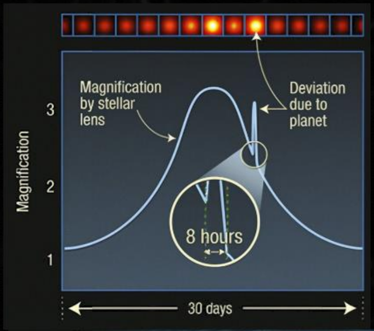
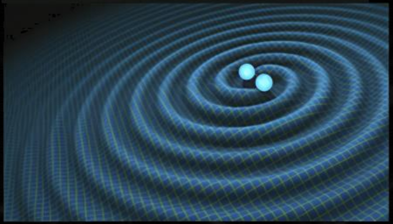
Astronomical Video Imaging

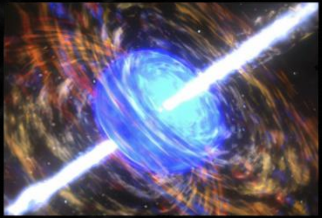
Emmanuel Bertin

Transient astronomy

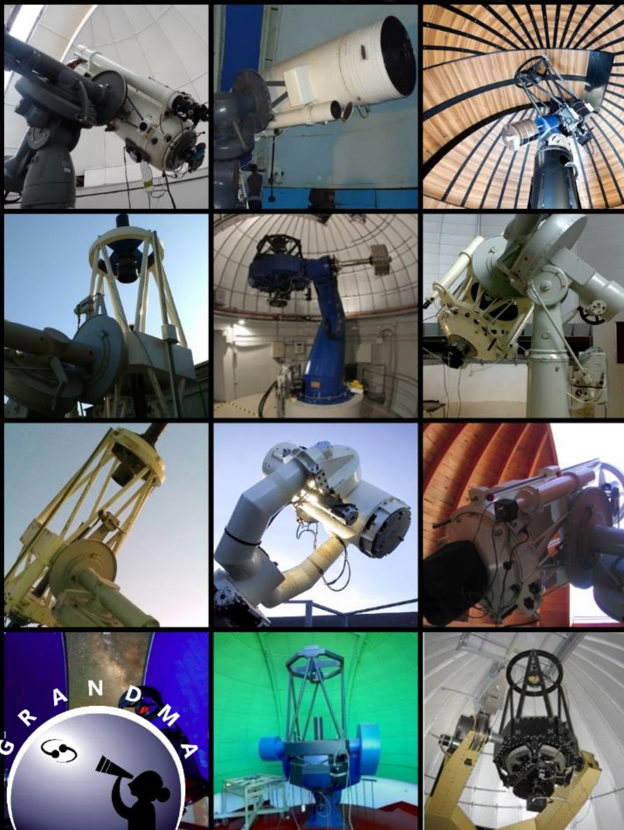


IPAC/Caltech





DanceCam



- EB, S.Bialek, H.Bouy, J.-C. Cuillandre, S.Fabbro, O.Lai, J.-P. Rivet
- Funding IDEX “Cosmic-DANCe” / INSU national projects / NTCO-Create
- Leverage new technologies to improve the efficiency of (small) survey telescopes
- Time domain astronomy

Potential benefits of deep sky video imaging

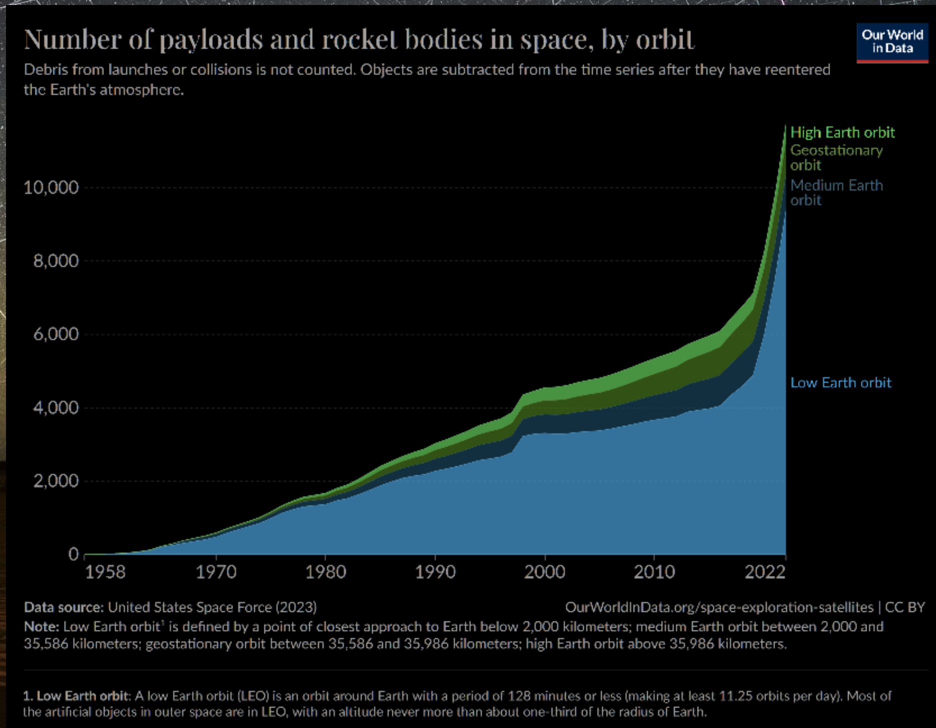
- Ultra-short readout time (Electronic shutter)
    - CCDs: 2s-80s (10-60%)
- No shutter action required
- No guiding required
- No de-rotator required

- Digital stacking
    - MegaCam: 25% of exposures are non-sidereal guided

- Real-time monitoring
    - Photometry
    - Turbulence profile

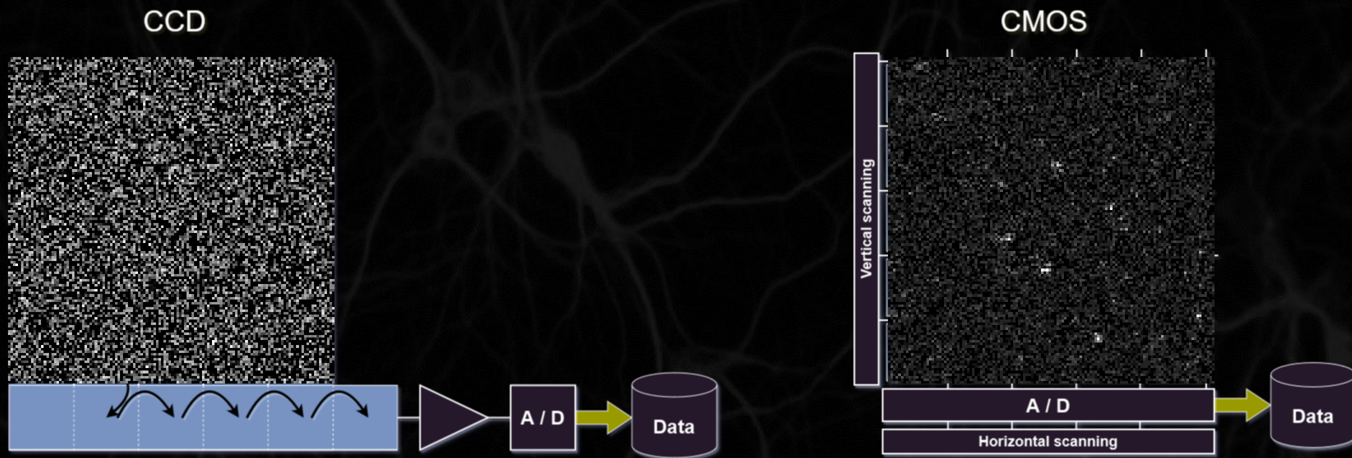
- Lucky imaging
- Mitigate the impact of temporal artifacts
- Mitigate blurring effects from the atmosphere

Satellite constellations

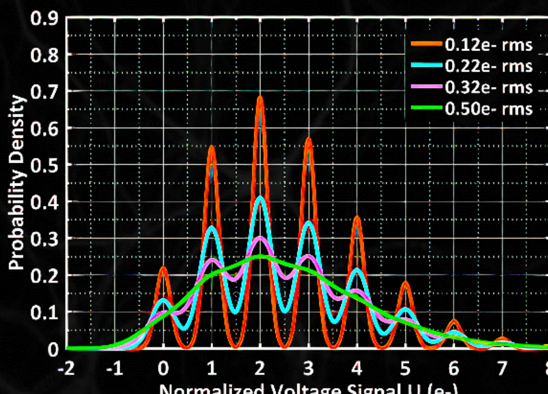


Joshua Rozells

CMOS vs CCD sensors



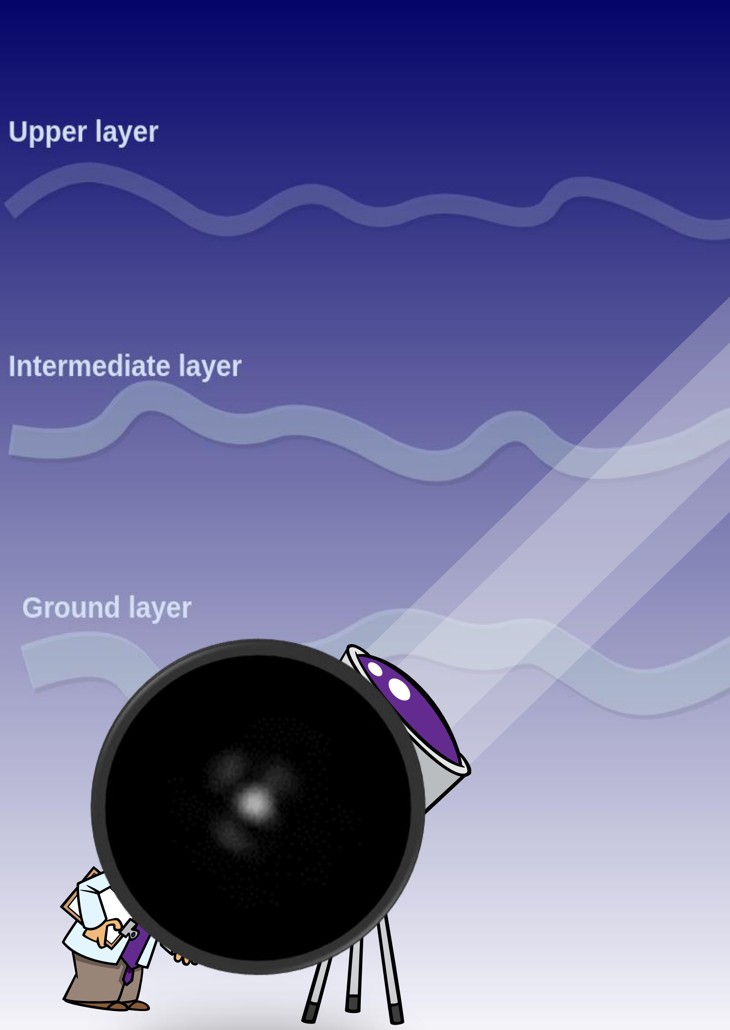
- CMOS: charges are converted to voltage at every pixel.
- Modern CMOS detectors allow ~20fps full-frame acquisition at sub-e$^-$ readout noise.
- Suitable for contemporary science (Betoule et al. 2023).
- Readout noise and QE in the NIR steadily improving.



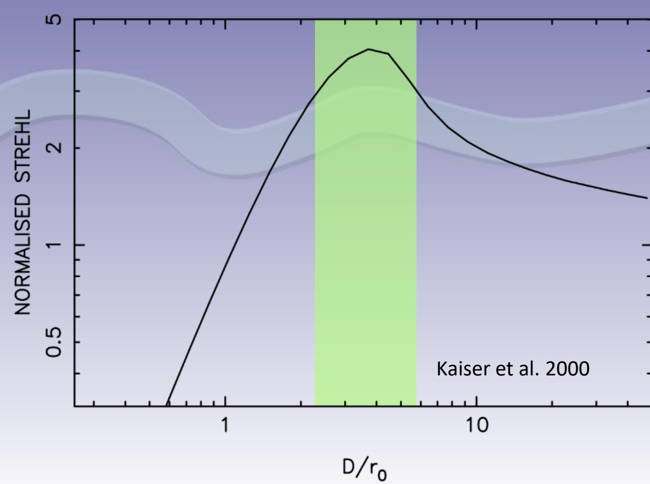
Gigajot technologies

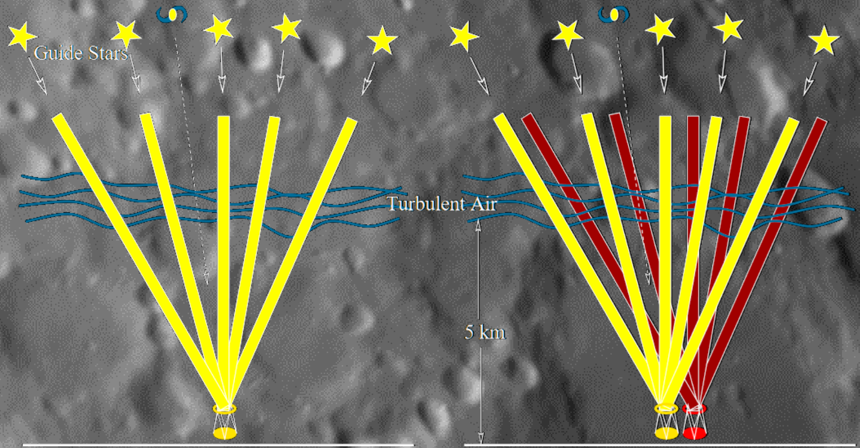
A low orbit satellite

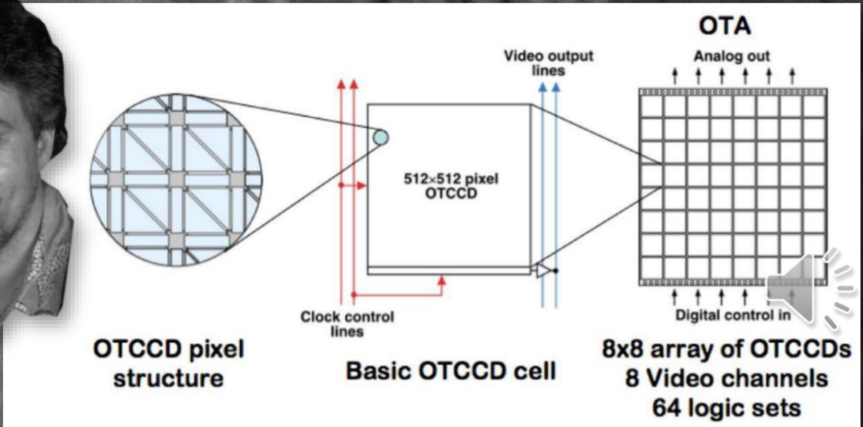
A more distant object



e.g., HRCam@CFHT (McLure et al. 1989)
GravityCam@NTT (MacKey et al. 2018)





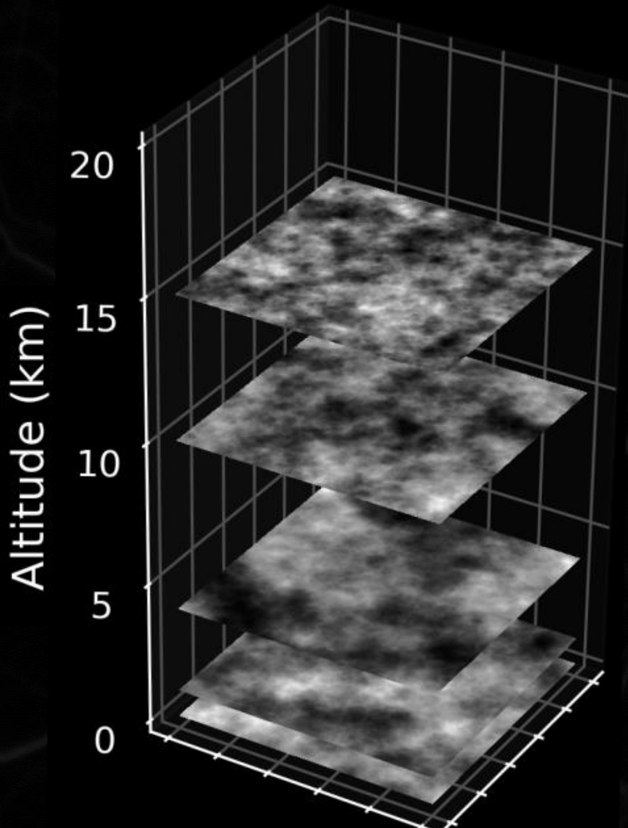


Kaiser, Tonry & Luppino 2000

Requirements

- An excellent <1m telescope in a good observing site, with excellent wide-field correction and low obstruction ✔
- A large SCMOS camera ✔
- A high speed image acquisition system (~1GB/s) ✔
- A good forward model

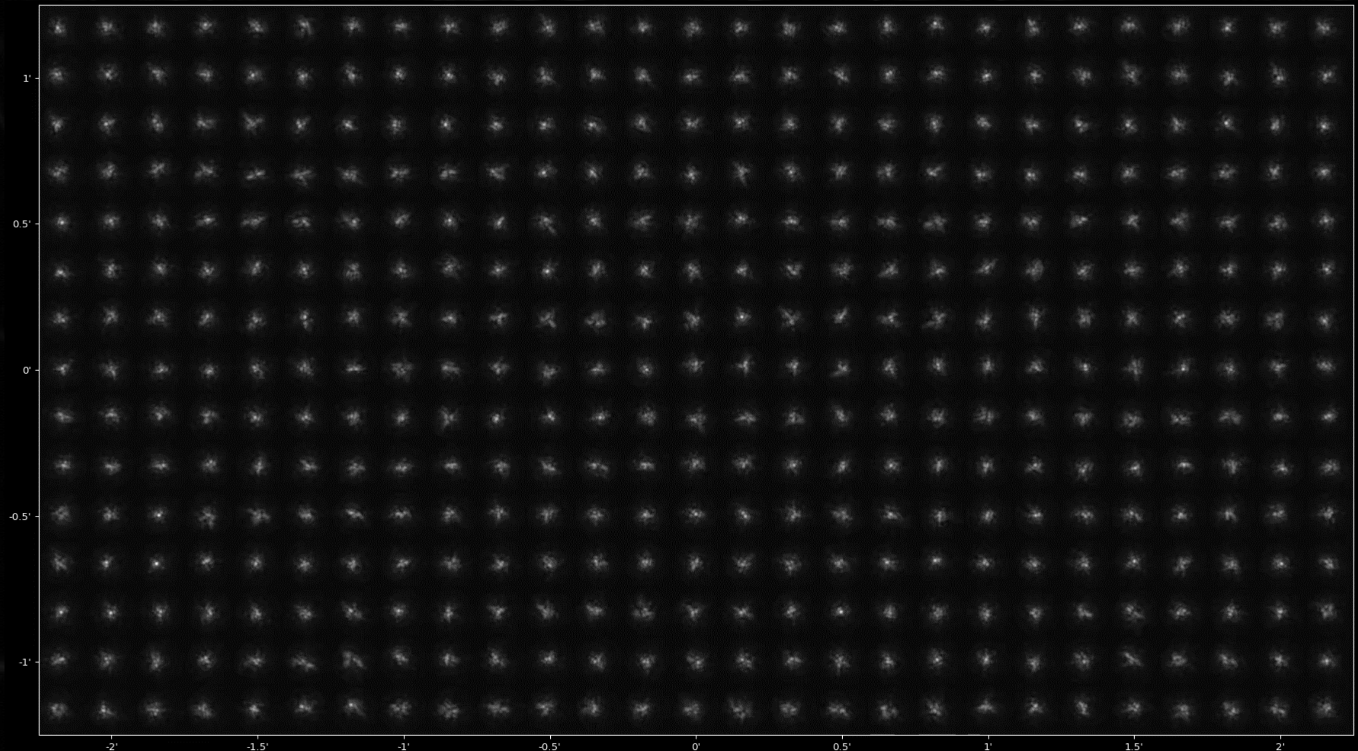
Propagation through the atmosphere



- Stochastic model with a modified von Kármán spectrum
- Frozen field approximation
- Centrimetric resolution
- Fresnel light propation using the angular spectrum representation
  - Instrument pupil and aberrations
  - Stars twinkle!
- Implementation in PyTorch 2
  - Batch FFTs and tensor folding/unfolding
  - 10^5 PSFs/s on a fast GPU

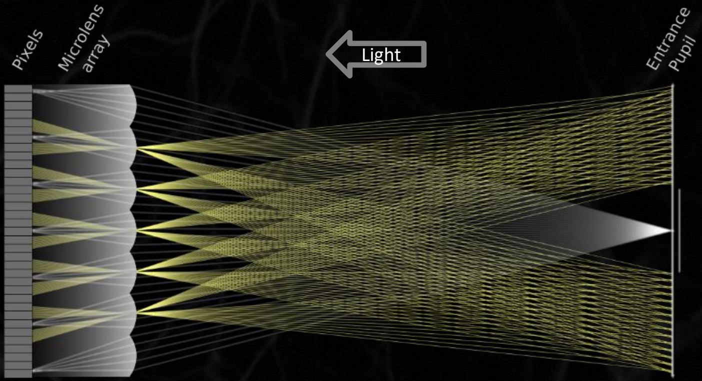
PSF rendering example

0.7” seeing over 5 turbulent layers / r band / 40” diameter / 30% obstruction

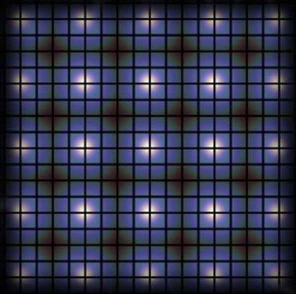


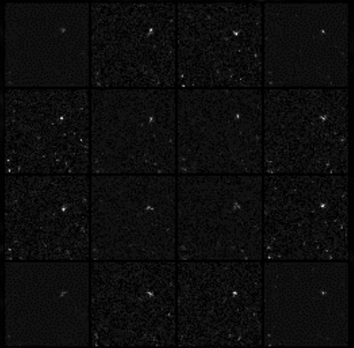
Dealing with larger pupils

- Extend iso-kinetic area around “guide-stars”
- Pupil splitting with a light-field camera design (e.g., Ng 2006)?
  - Abbe diffraction limit for an F/4 beam:
  - 2µm@400nm
  - 4µm@800nm
- Or rely on holographic-like reconstruction?

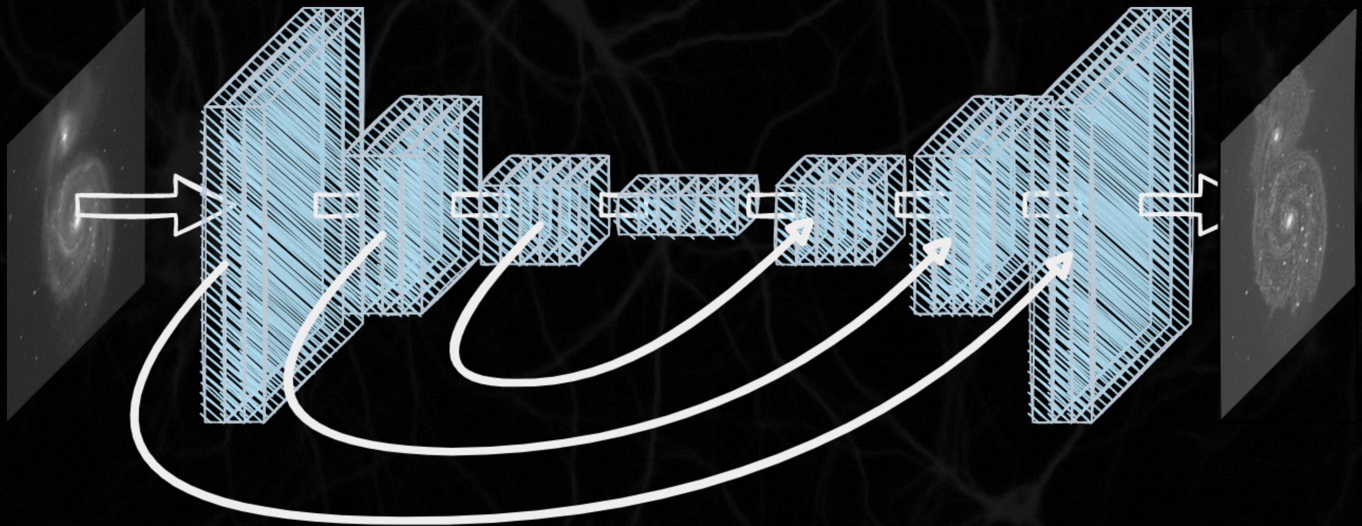


4m-class



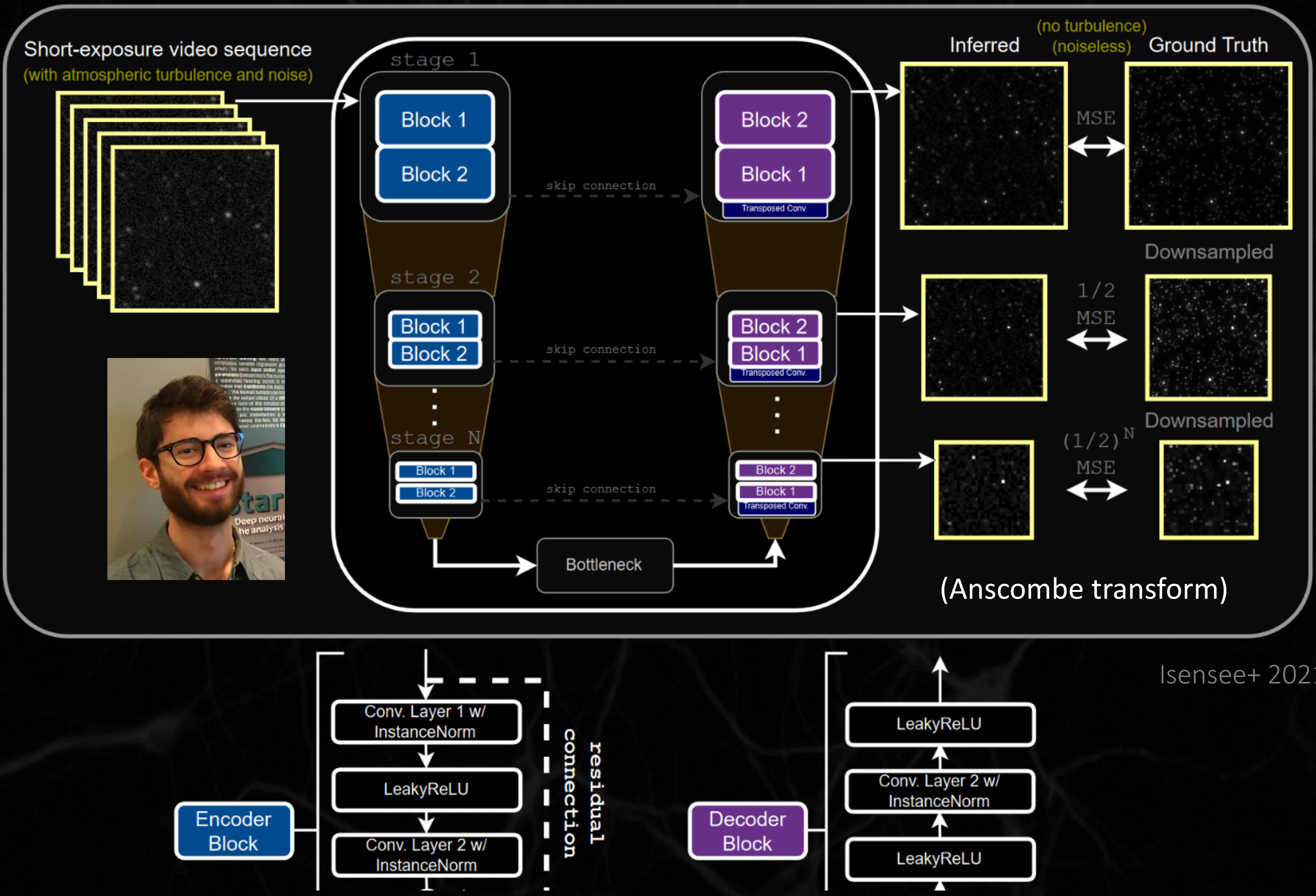


Deep learning approach: U-Net regressors



e.g., Ronneberger et al. 2015

DanceNet

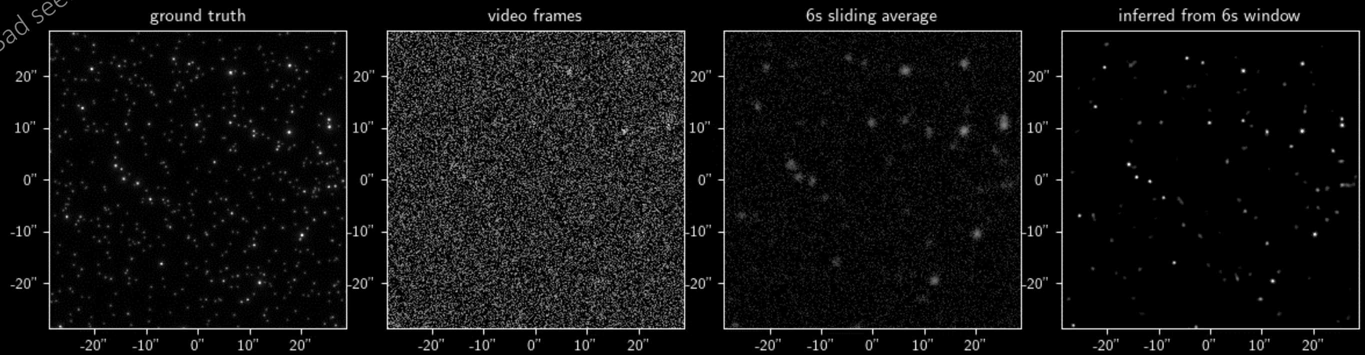


(Anscombe transform)

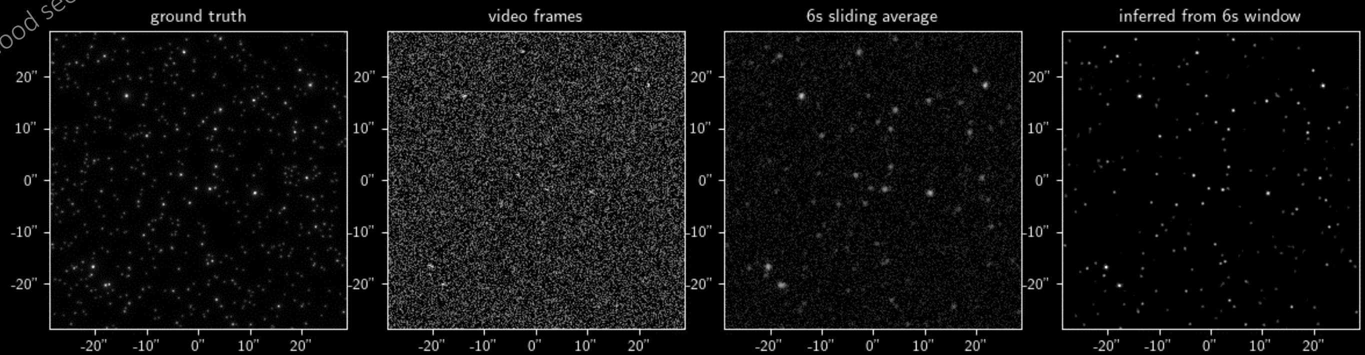
Isensee+ 2021

Inference test results

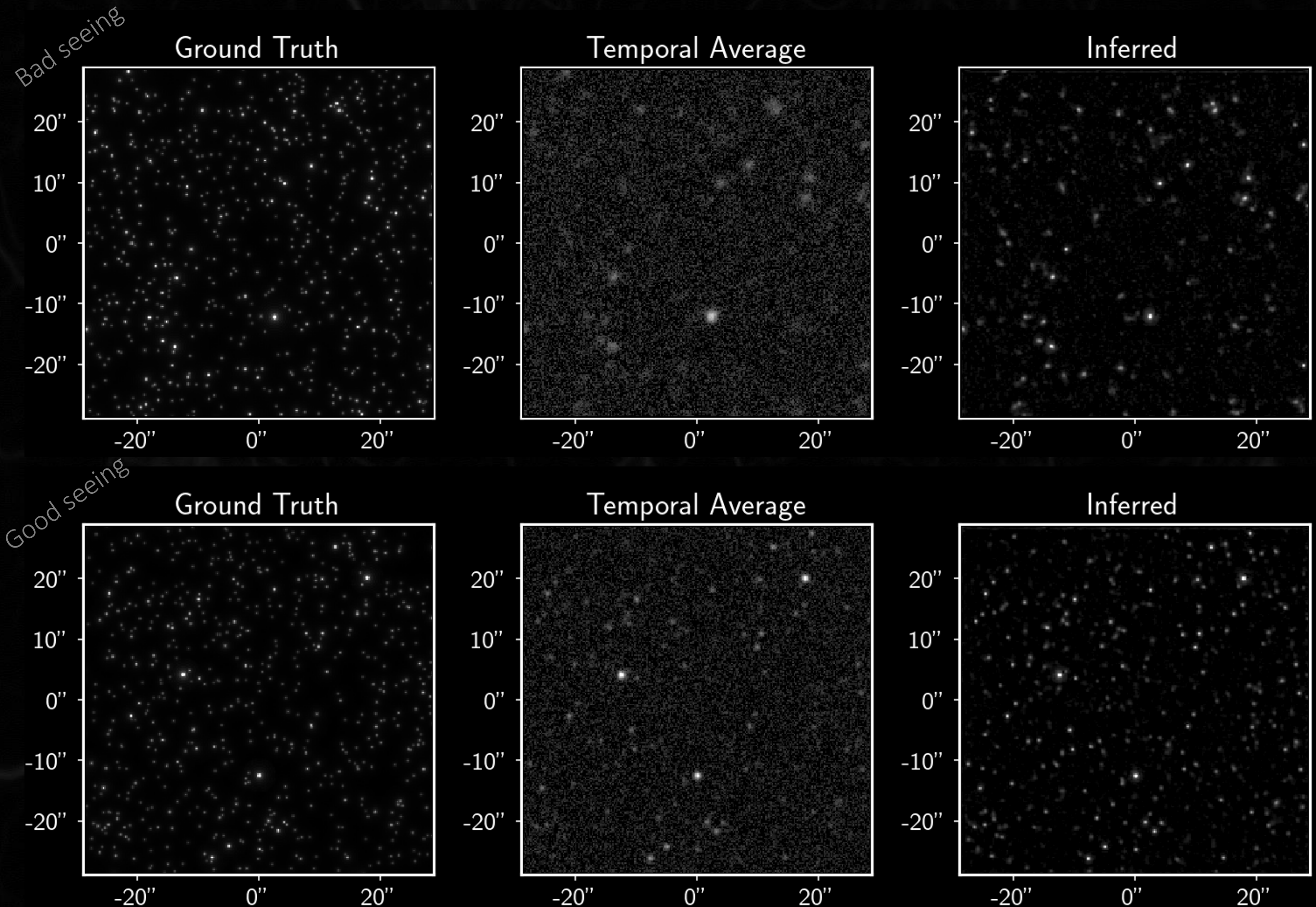
Bad seeing



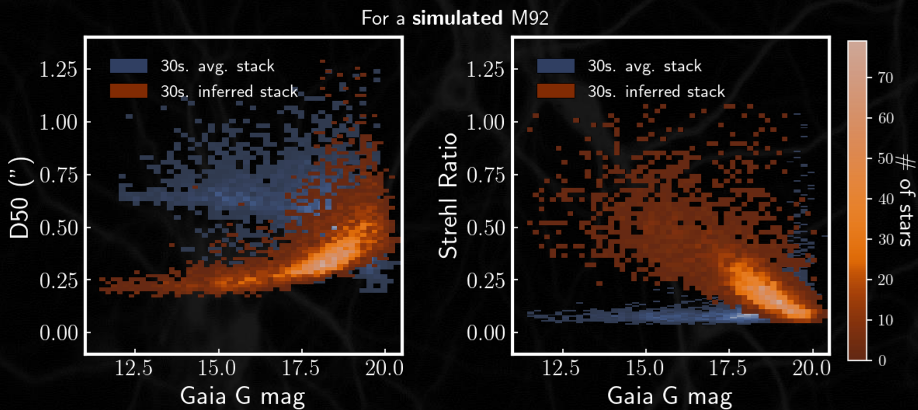
Good seeing

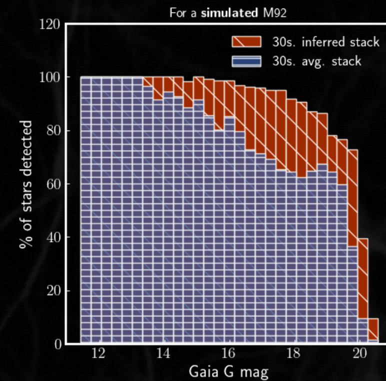


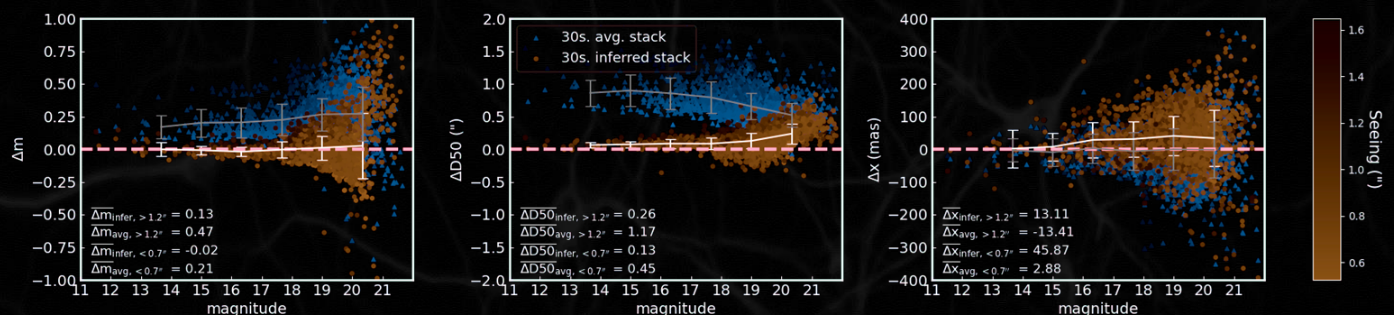
Inference test results (stacked)



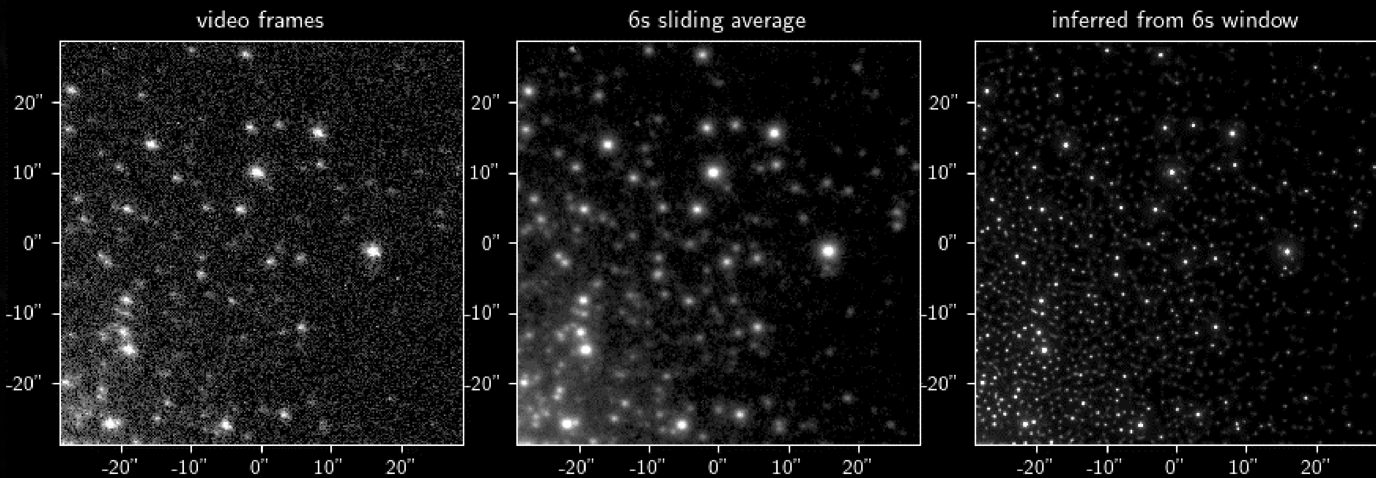
Validation on synthetic data



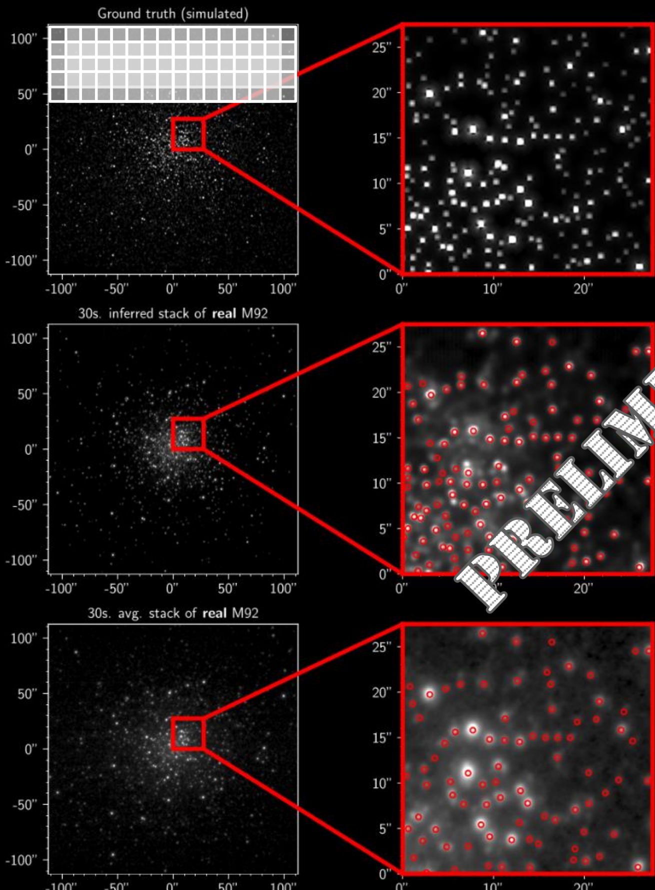




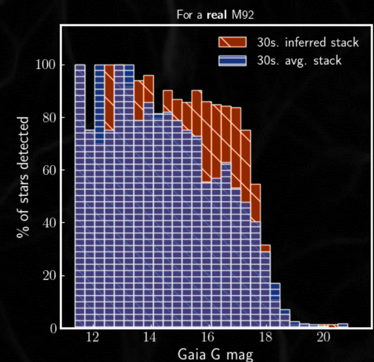
Real data

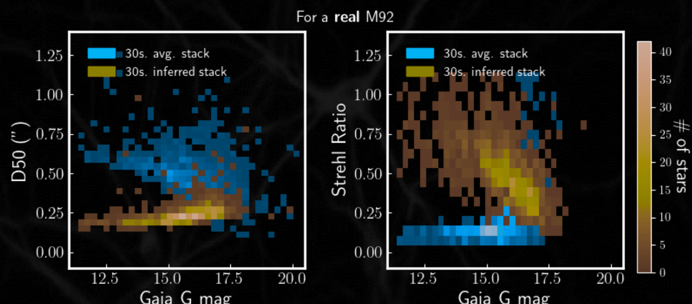

video frames
6s sliding average
inferred from 6s window
20"
10"
0"
-10"
-20"
-20"
-10"
0"
10"
20"

Real data



Sliding Hann window
(Pielawski & Wählby 2020)





Lessons learned

- High cadence (video) imaging carries a lot of potential for wide-field imaging
  - Hardware performance steadily improving
  - Data storage still an issue
- A forward modeling approach with deep learning appears to be a viable solution to mitigate the effects of atmospheric turbulence
  - Already beneficial in crowded star fields
  - More generative models?
  - Extend angular and temporal reach
  - External priors?
  - Manage transient artifacts
  - Atmospheric turbulence tomography?
- Combine with GLAO?

Conclusion

- High cadence (video) imaging has the potential to solve a number of issues in astronomical wide-field imaging
- “Classical” Deep Learning models such as U-Nets already have the ability to tackle wide-field imaging problems that involve the time dimension
  - E.g., tiled image sequences
  - Performance may be limited by the angular and temporal reach of the neural network inputs
  - Can be used on a large variety of data without transfer learning
  - Forward modeling is key: knowledge of the physical and instrumental processes
  - GPUs required to reach the required data rate
  - It can be advantageous to integrate the forward modeling process directly within the ML framework
    - Generate samples on the fly
    - Benefit from batch processing, GPU acceleration and JIT compilation of Python code
    - ML frameworks integrate nicely in existing (Python) pipelines and mature enough to be used in production
  - Uncertainties can be modelled by sampling the posterior distribution (at least approximately)
    - Still computationally prohibitive in most cases
- Visualization critical for qualitative assessment of performance
  - Must be interactive and remote-capable

Thank you

Extra slides

Comparison with blind deconvolution