Limitations imposed by optical turbulence profile structure and evolution on tomographic reconstruction for the ELT

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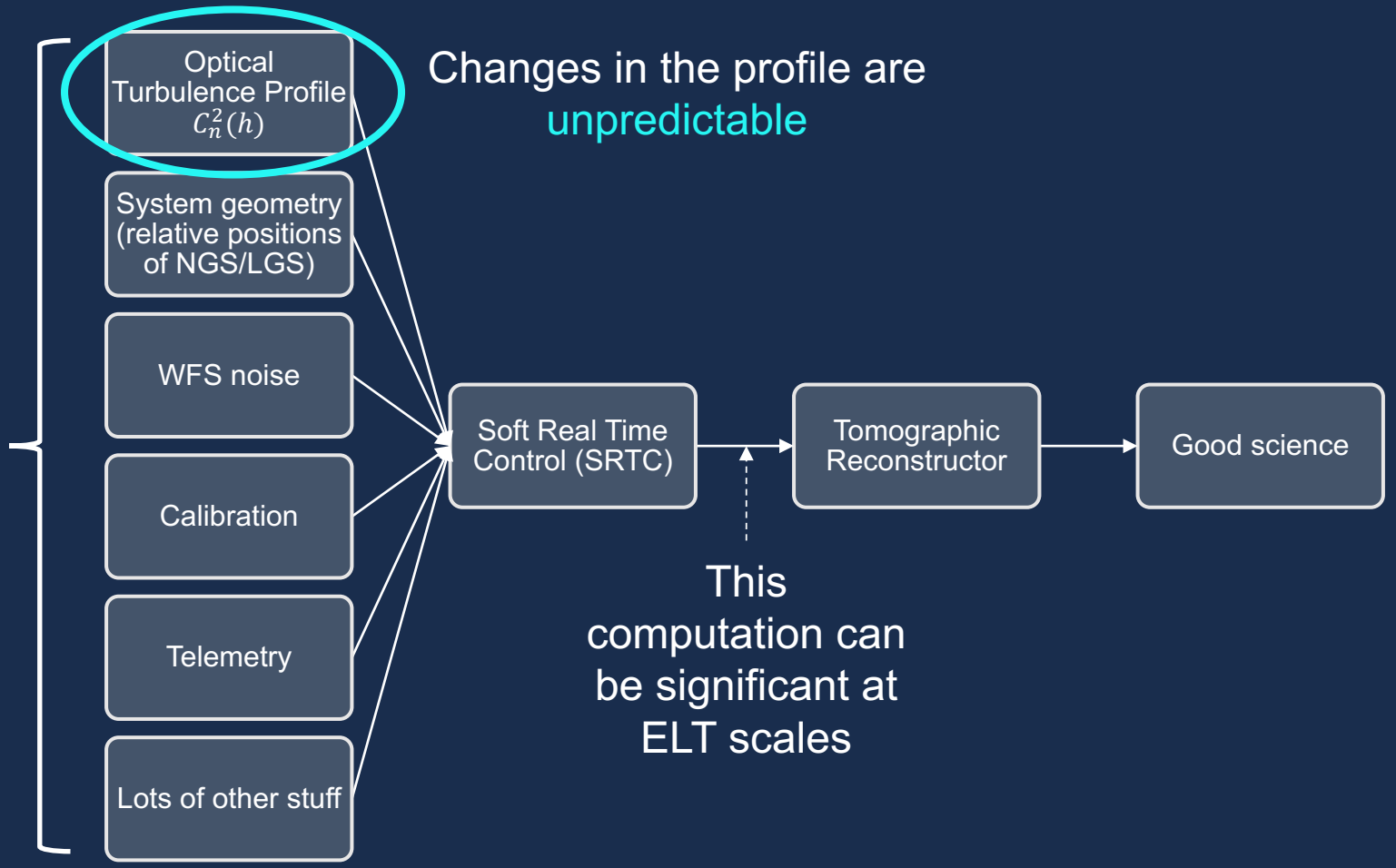
Motivation

If these change, the reconstruction matrix must be recomputed



Changes in the profile are unpredictable

This computation can be significant at ELT scales

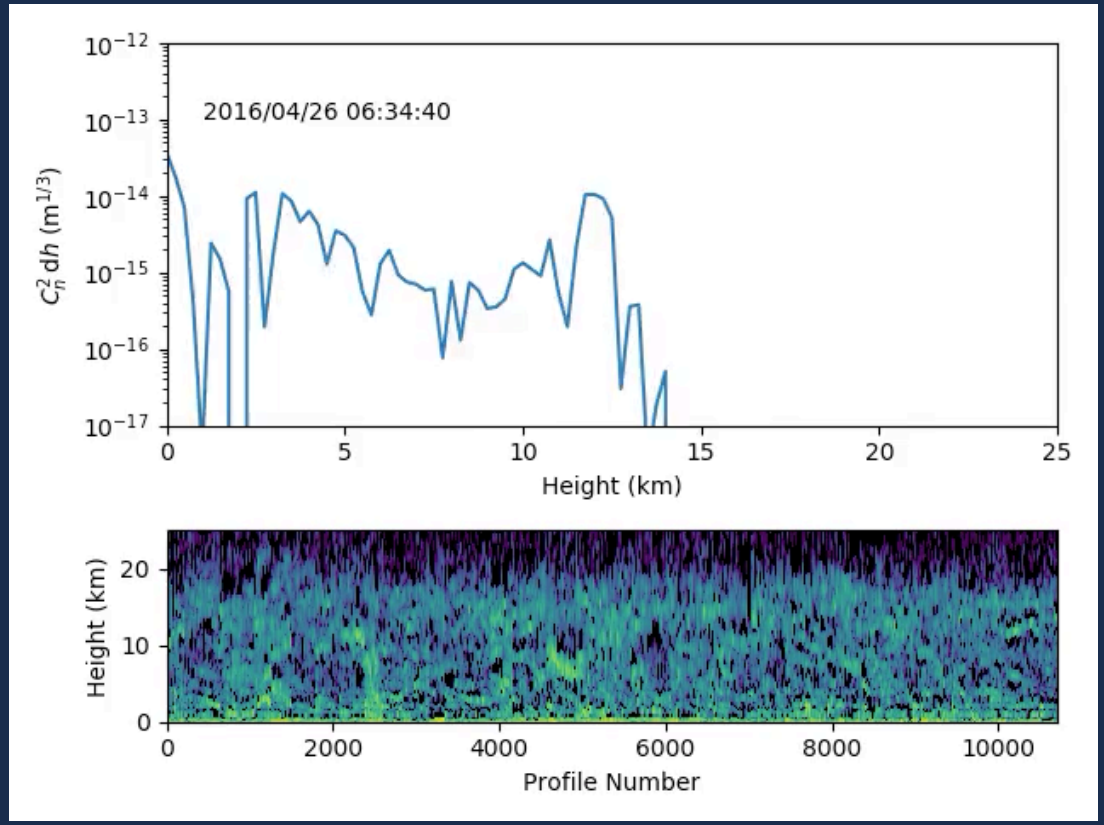
Motivation

- We focus on the changing turbulence profile, since its effects on tomographic reconstruction are unpredictable and largely unknown
- If the reconstruction profile is not matched to the true profile, there will be an increase in error
- Two questions:
  - How many layers are required to be reconstructed
  - How often should the reconstructor be optimised
- We use a fast Fourier domain tomographic AO simulation coupled to a large database of turbulence profiles to answer these questions

Method

- 2018A turbulence profiles from ESO Paranal
- Feed every profile into tomographic AO simulation to compute tomographic error
- Compare sub-optimal error to the optimal error:

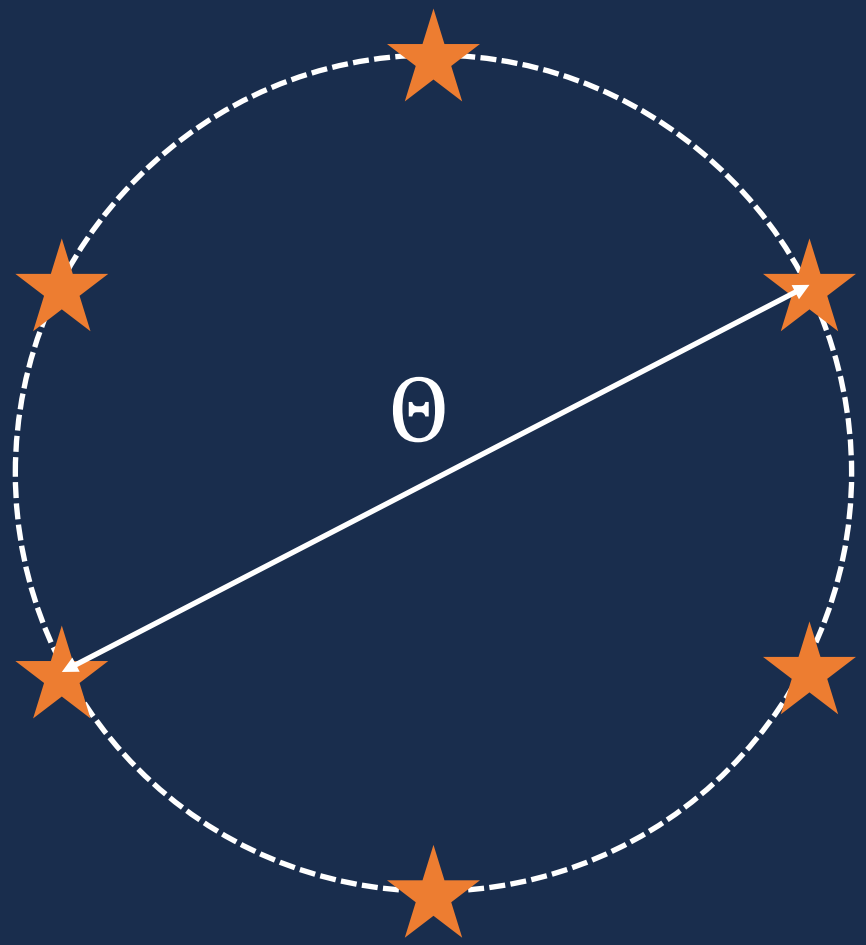
ESO Paranal Stereo-SCIDAR 2018A (10691 profiles)



$$E(N, t - t_{opt}) = \left[\sigma^2_{tomo}(N, t - t_{opt}) - \sigma^2_{tomo}(N = 100, t - t_{opt} = 0)\right]^{\frac{1}{2}}$$

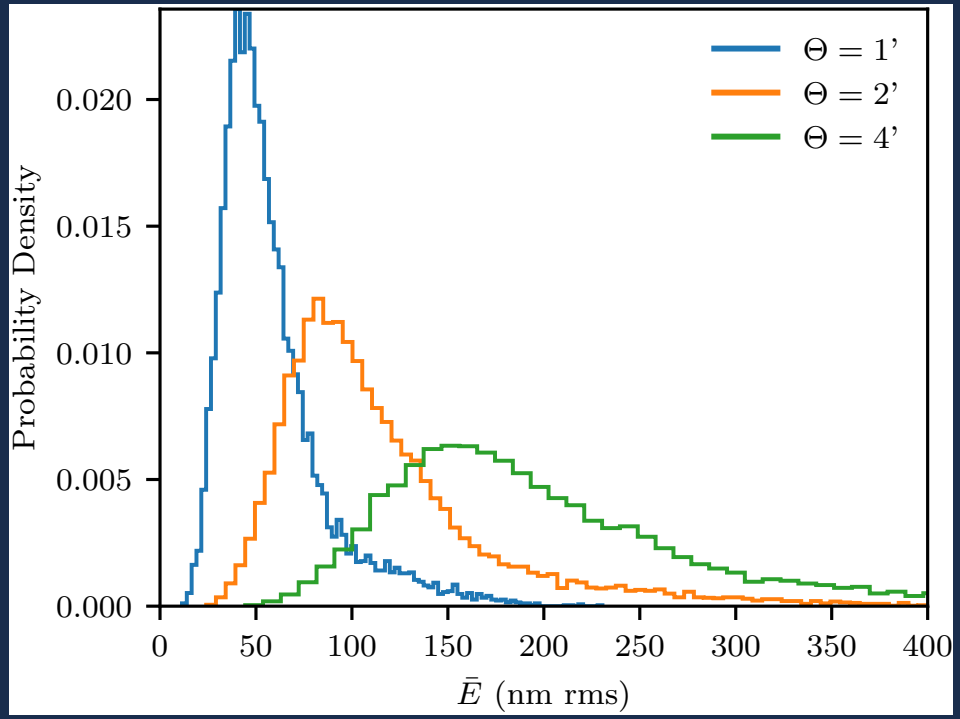
Simulation setup

- LAM Fourier code: simulation times of several seconds for a single turbulence profile at ELT scales
- ELT parameters:
  - D = 39.3m primary
  - 6 LGS in circular asterism
  - …
- LGS diameters:
  - 1’ (~LTAO)
  - 2’ (~MCAO)
  - 4’ (~MOAO)



Worst case

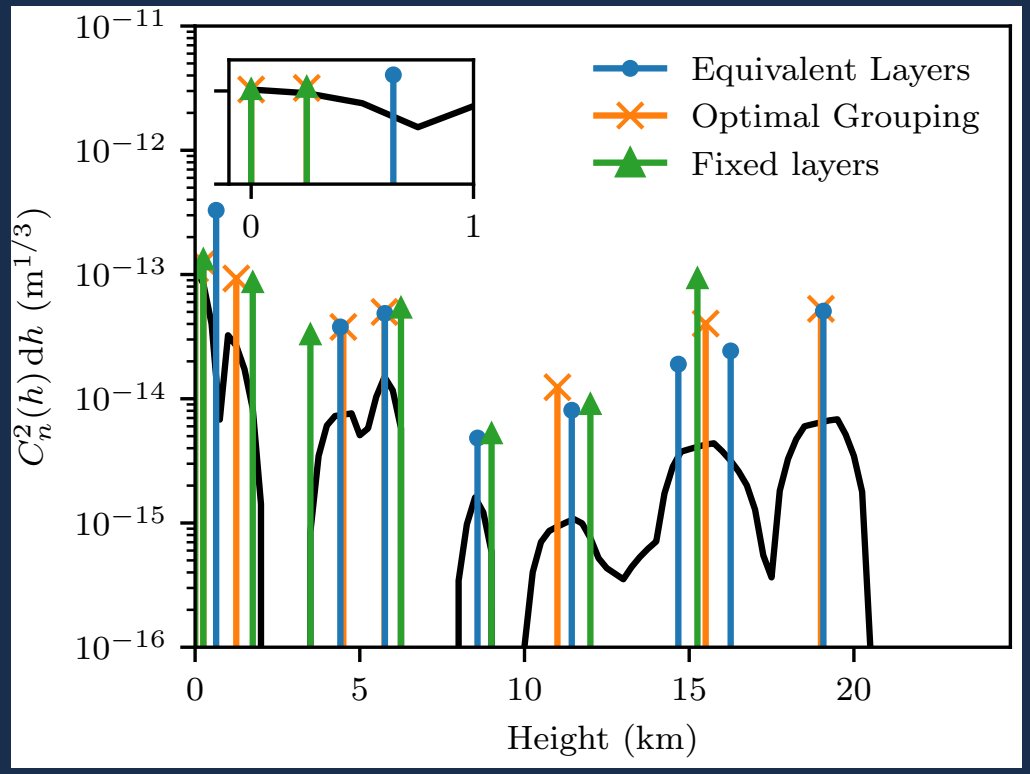
- We simulate a worst case situation for comparison
- Defined as the tomographic error using the ESO 35 layer profile as the optimisation profile
- If tomographic error is worse than this, we should not bother!



Θ (arcminutes)	E (nm rms) [median]
1	51
2	101
4	184

How many layers?

- Use 3 different methods to “compress” profile from 100 to N layers
  - Equivalent layers
    - Maintains isoplanatic angle (Fusco *et al* 1999)
  - Optimal grouping
    - Good in E2E simulation (Saxenhuber *et al* 2017)
  - Fixed layers
    - Altitude of layers the same for every profile in dataset, simple rebinning of $C_n^2(h)$



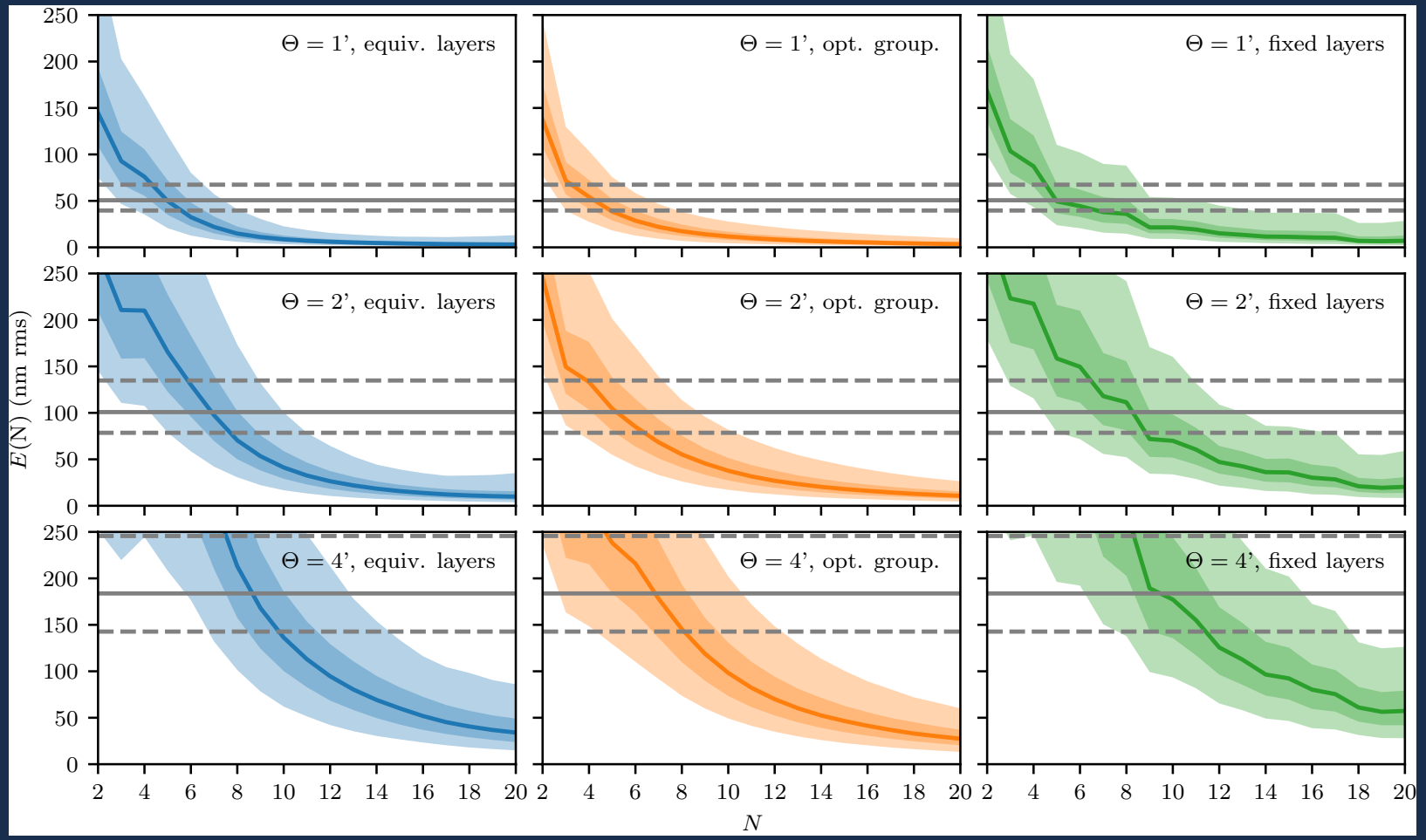
How many layers?

Solid line:
median

Darker shaded region:
interquartile range

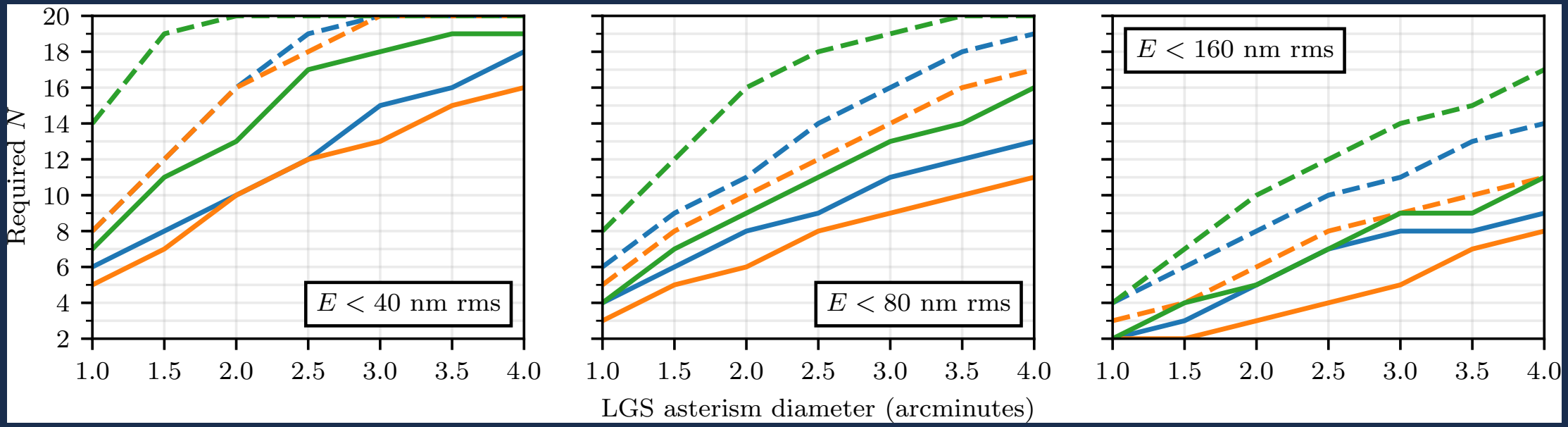
Lighter shaded region:
5th – 95th %ile range

Grey:
worst case +
interquartile range
(dashed)



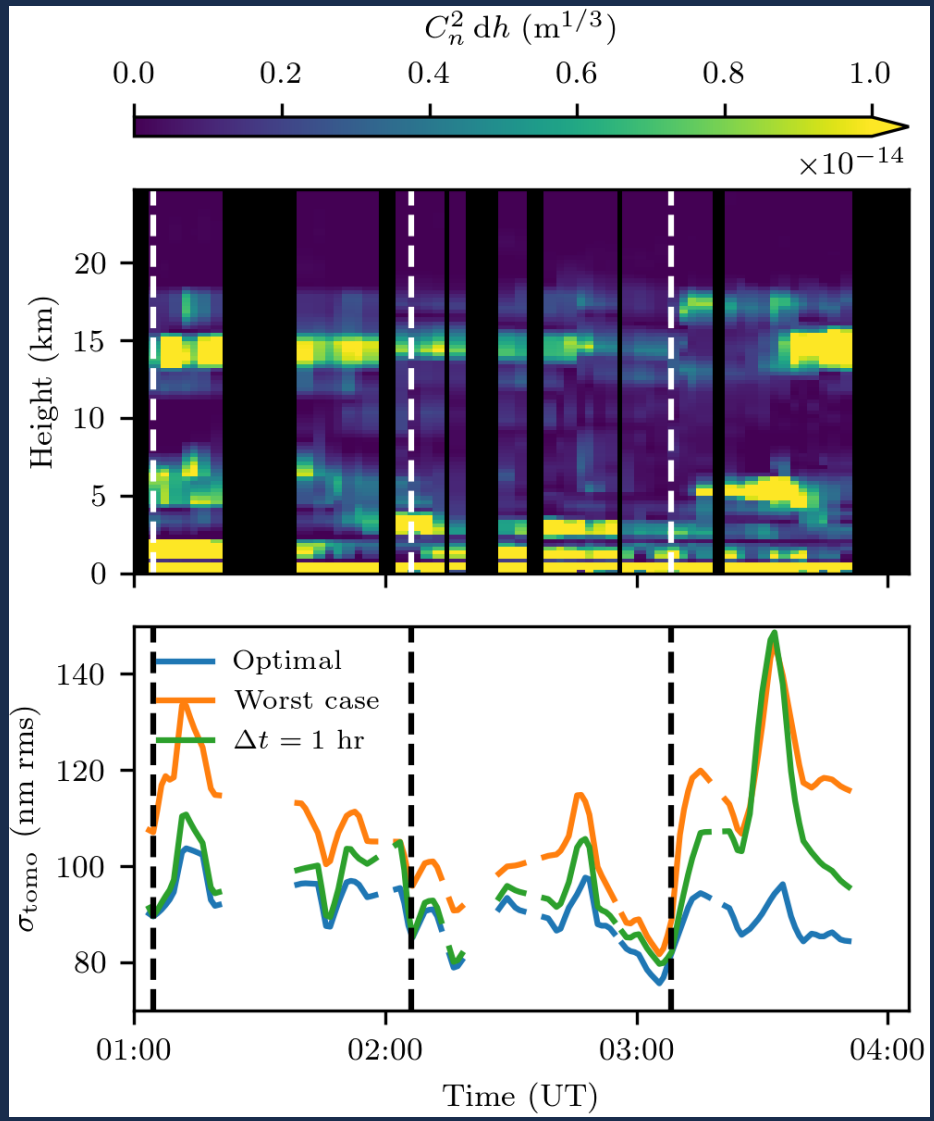
How many layers?

- Alternatively: how many layers are required to maintain an increase in error below some threshold?
  - Solid lines: 50% of profiles
  - Dashed lines: 95% of profiles



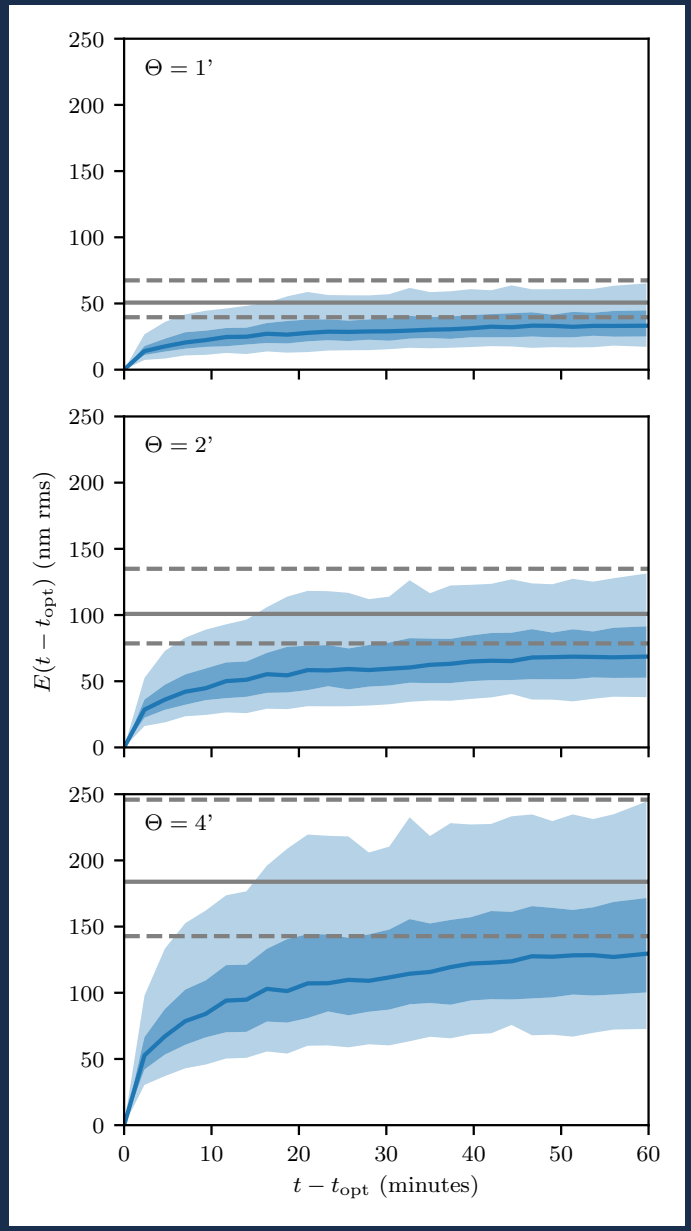
How often?

- Profile evolution over time can lead to rapid degradation of tomographic error
- Split the 2018A dataset into 1 hour chunks, optimise reconstructor once per hour



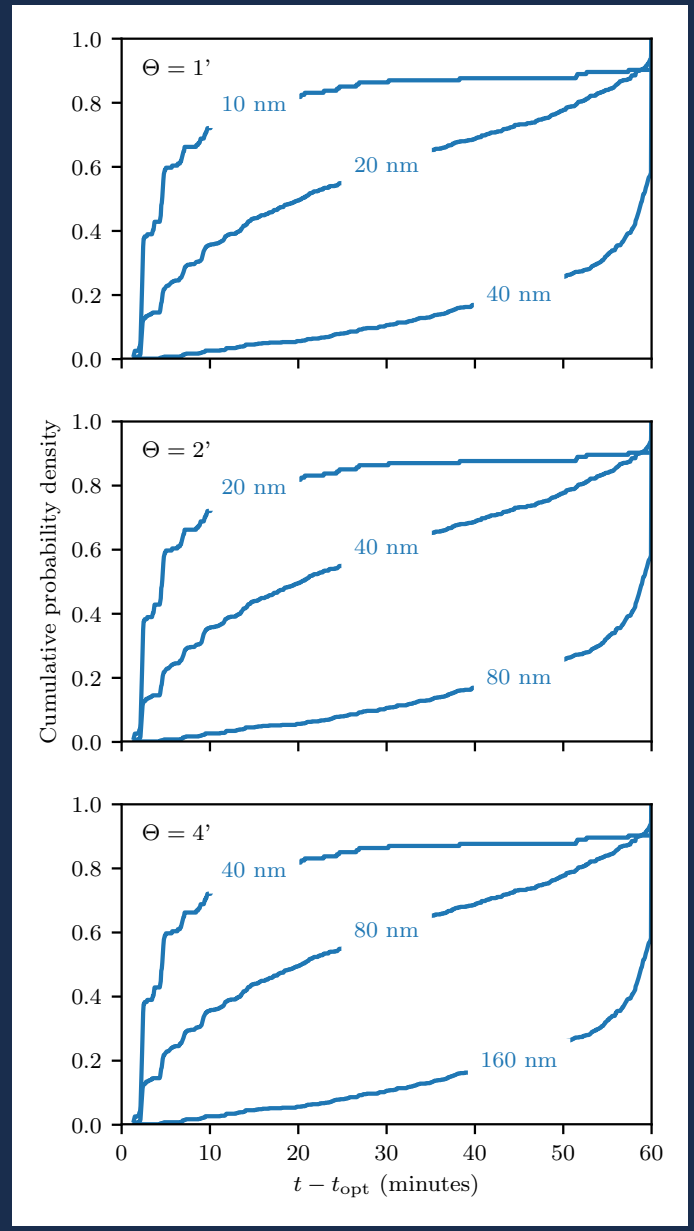
How often?

- Increase in error as a function of time since optimisation
- Most increase occurs in the first 20 minutes since optimisation
- Even after 1 hour, usually better than worst case



How often?

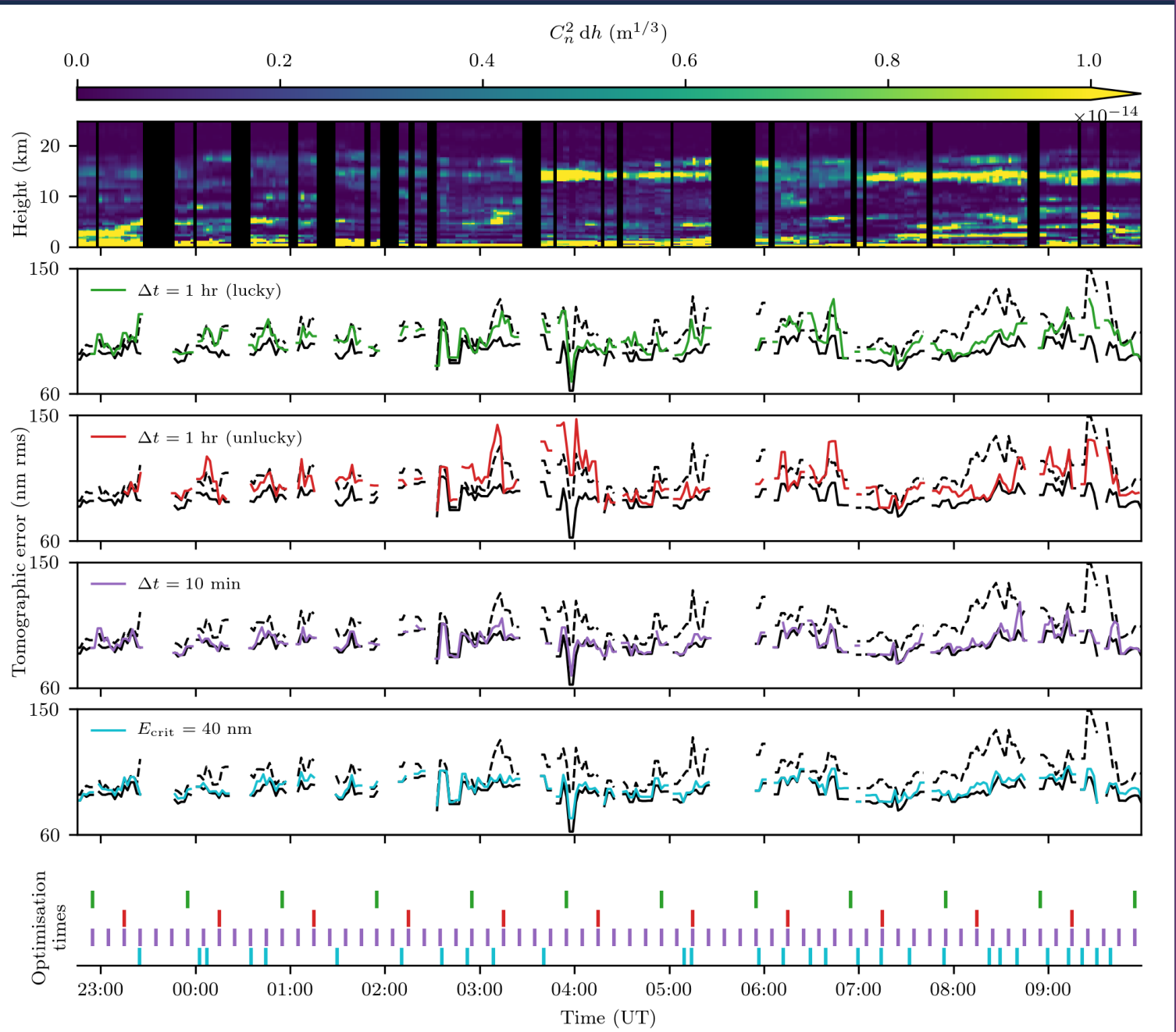
- How much time passes before we hit some threshold increase in tomographic error?
- Large spread in values for a given threshold
- What is the best optimisation period? Depends on tolerated error increase and desired robustness



Optimisation strategies

- Take two contrasting nights, one where the profile is variable and one where it is calmer
- Compute tomographic error across the night using different optimisation strategies
- Introduce strategy where the reconstructor is optimised when the tomographic error increase reaches some threshold. This means that the optimisation period changes depending on the state of the atmosphere
- Note: these results are only for $\Theta = 1$ arcminute

- Black: **optimal** (optimise on every profile)
- Dashed black: **worst case** (optimised on ESO 35 layer)
- Green: Δt **= 1 hour (lucky),** optimised once per hour at “lucky” times
- Red: Δt **= 1 hour (unlucky),** optimised once per hour at “unlucky” times
- Purple: Δt **= 10 minutes,** optimised every 10 minutes
- Cyan: E_{crit} **= 40 nm rms**, optimised when tomographic error increase above optimal is greater than 40 nm rms



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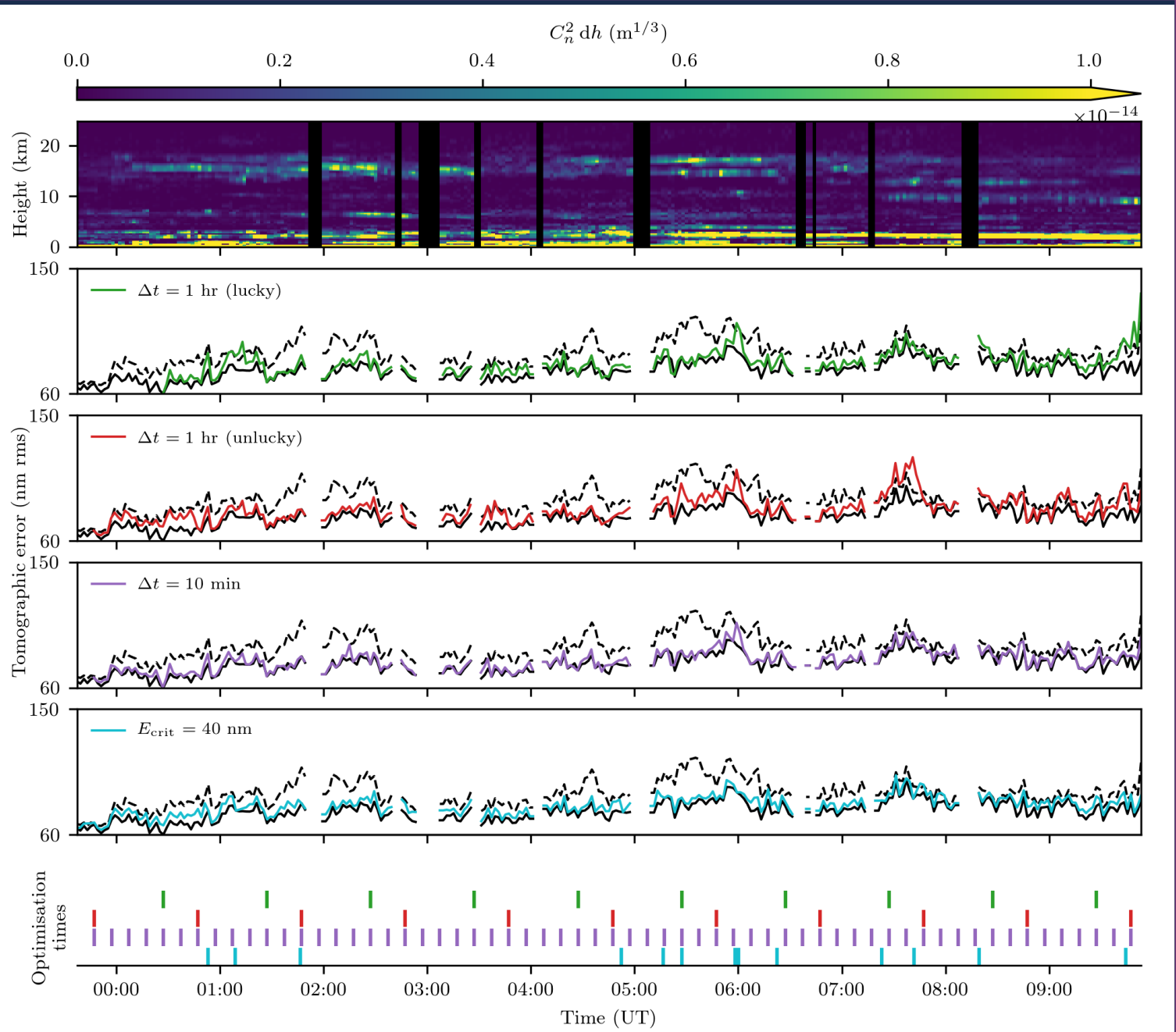

Conclusions

- Investigated the implications of suboptimal tomographic reconstruction on the tomographic error of an ELT-scale system
  - Only considering the changing turbulence profile, which is only one aspect constraining SRTC design
- How many layers required?
  - Depends on LGS asterism and tolerated error increase
  - Optimal grouping compression gives best results (not by much)
  - Additional layers will be required to operate to the same error tolerance 95% of the time as opposed to 50%
- How often should the reconstructor be updated?
  - Most increase in error happens in the first 20 minutes after optimisation
  - Error spikes on ~minute timescales can still happen
  - Maintaining near-optimal correction requires a short (<10 minutes) update period or a variable update period, where the increase in tomographic error is kept below a threshold

More info in the paper!

- O J D Farley *et al,* Limitations imposed by optical turbulence profile structure and evolution on tomographic reconstruction for the ELT, *Monthly Notices of the Royal Astronomical Society*, Volume 494, Issue 2, May 2020, Pages 2773–2784, https://doi.org/10.1093/mnras/staa795