Statistical inference and superstatistics for power grid modeling

Alessandro Lonardi

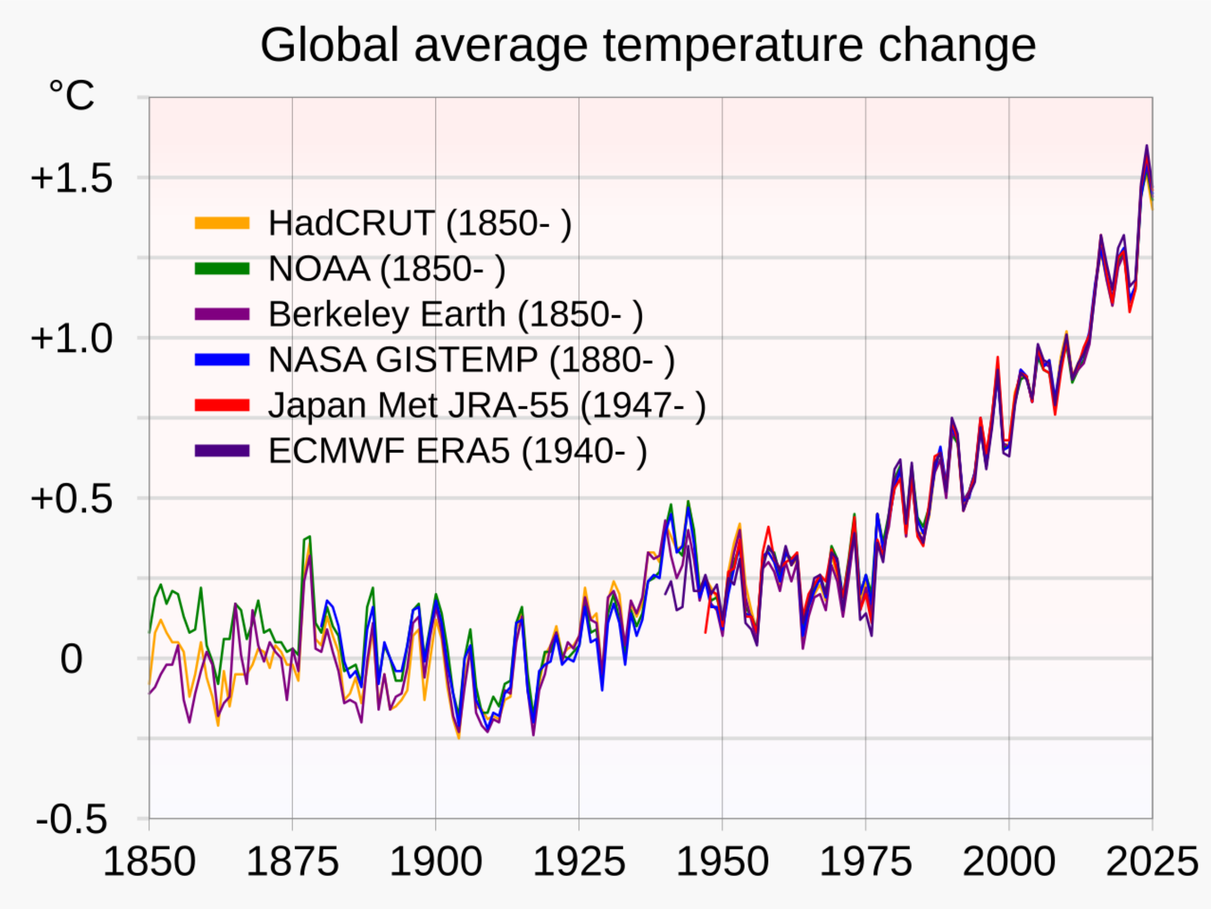
November 5, 2026

Queen Mary University of London

a.lonardi@qmul.ac.uk

aleable.github.io

Why does it matter?


Global average temperature change
°C
+1.5
+1.0
+0.5
0
-0.5
HadCRUT (1850-)
NOAA (1850-)
Berkeley Earth (1850-)
NASA GISTEMP (1880-)
Japan Met JRA-55 (1947-)
ECMWF ERA5 (1940-)
1850
1875
1900
1925
1950
1975
2000
2025



Coal mine, Wyoming, US



Oil well, Texas, US



Offshore gas platform, Hainan, China



Coal mine, Wyoming, US



Oil well, Texas, US



Offshore gas platform, Hainan, China

🔥🔥🔥



Coal mine, Wyoming, US

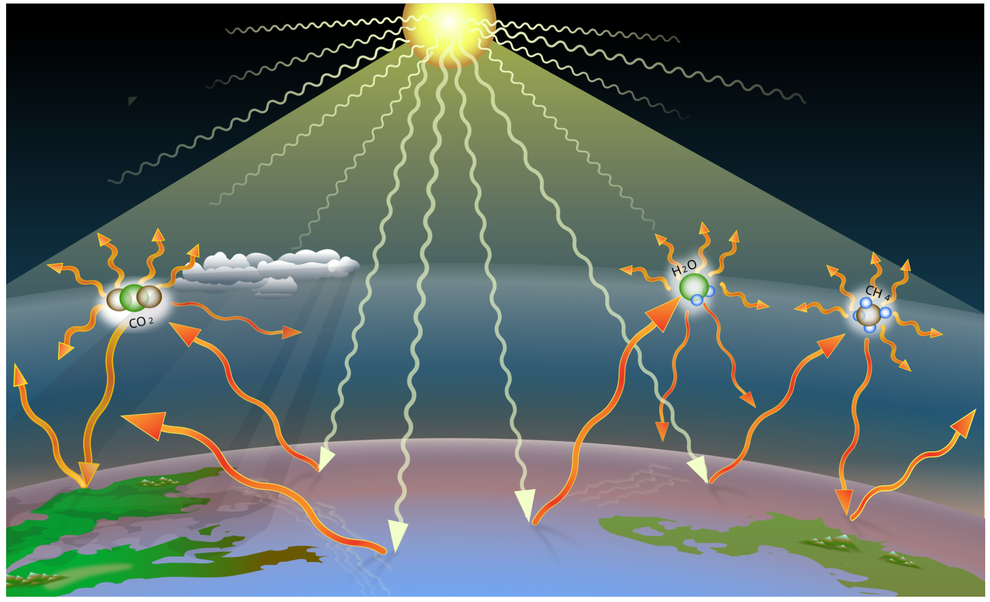


Oil well, Texas, US



Offshore gas platform, Hainan, China

🔥🔥🔥





Coal mine, Wyoming, US

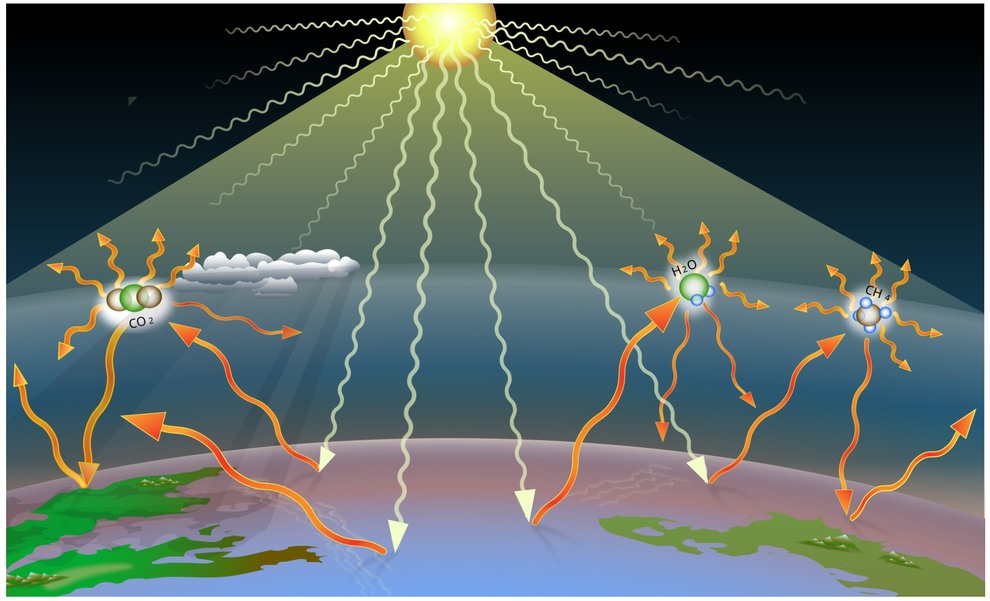


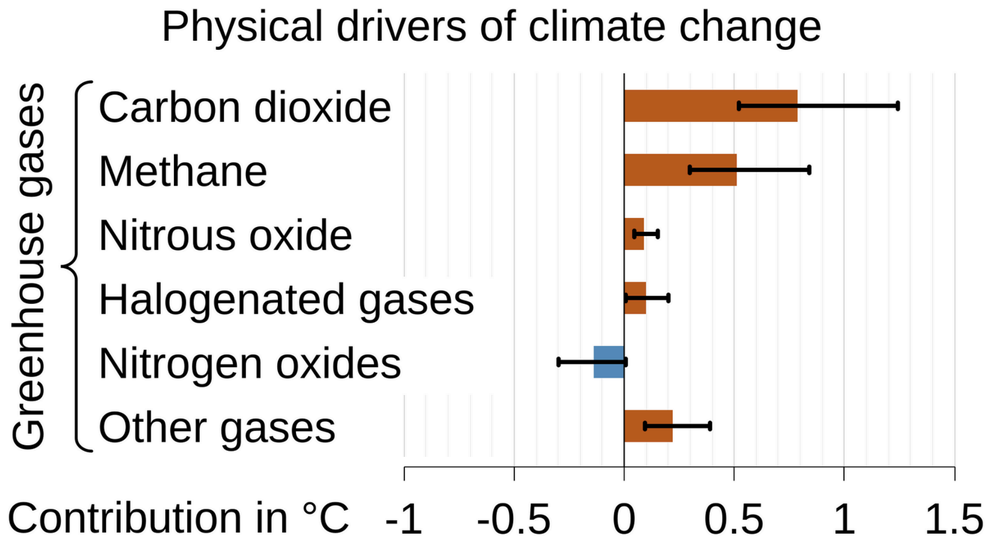
Oil well, Texas, US



Offshore gas platform, Hainan, China

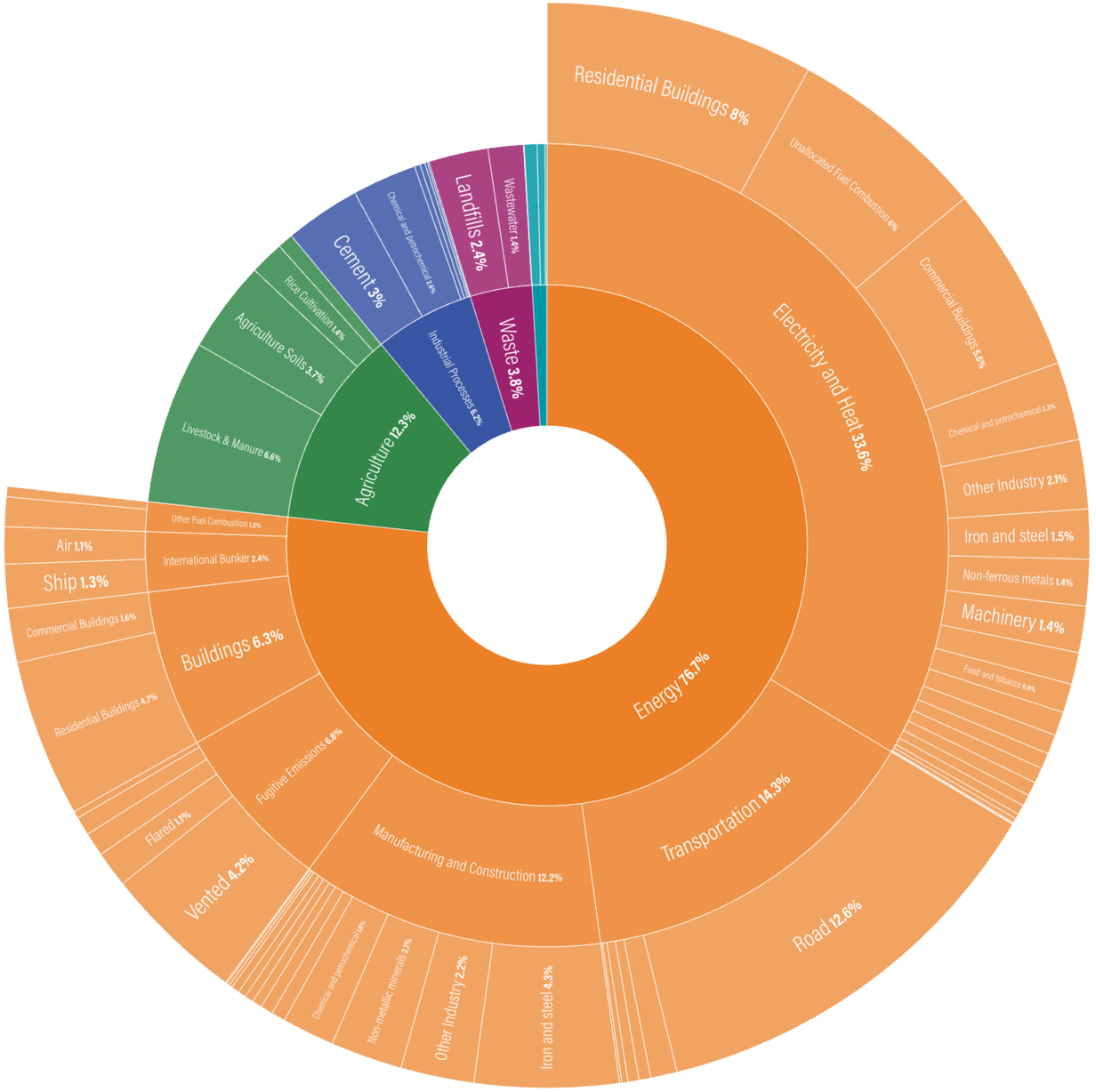
🔥🔥🔥





IPCC (2021)

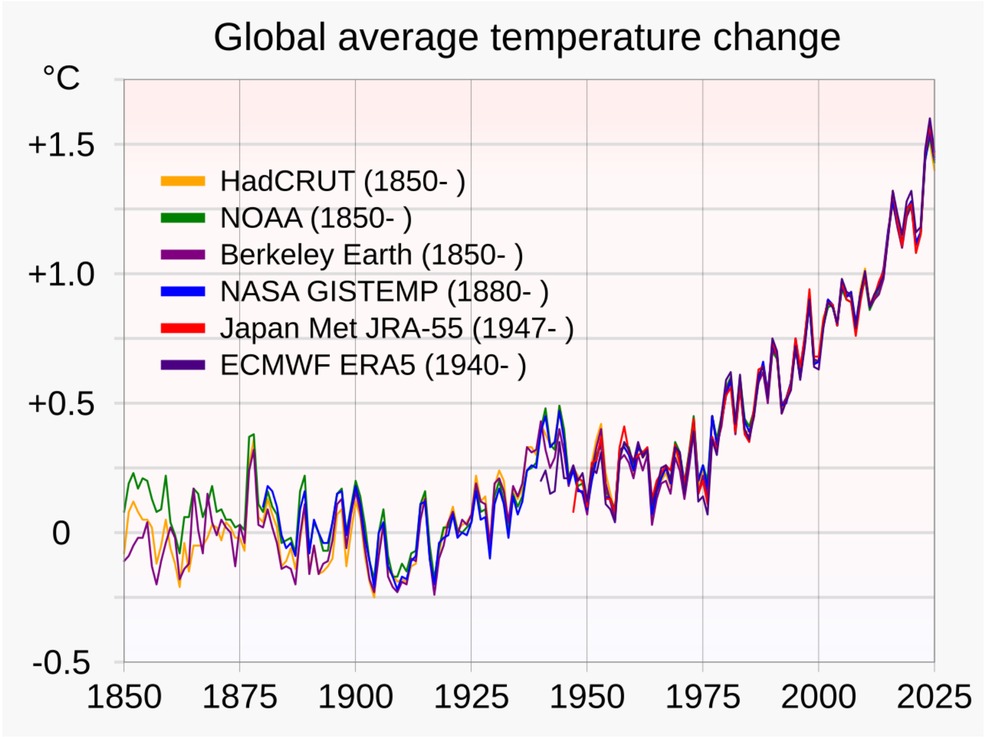
Global greenhouse gas emissions by sector and end use, 2023



World Resources Institute (2026)

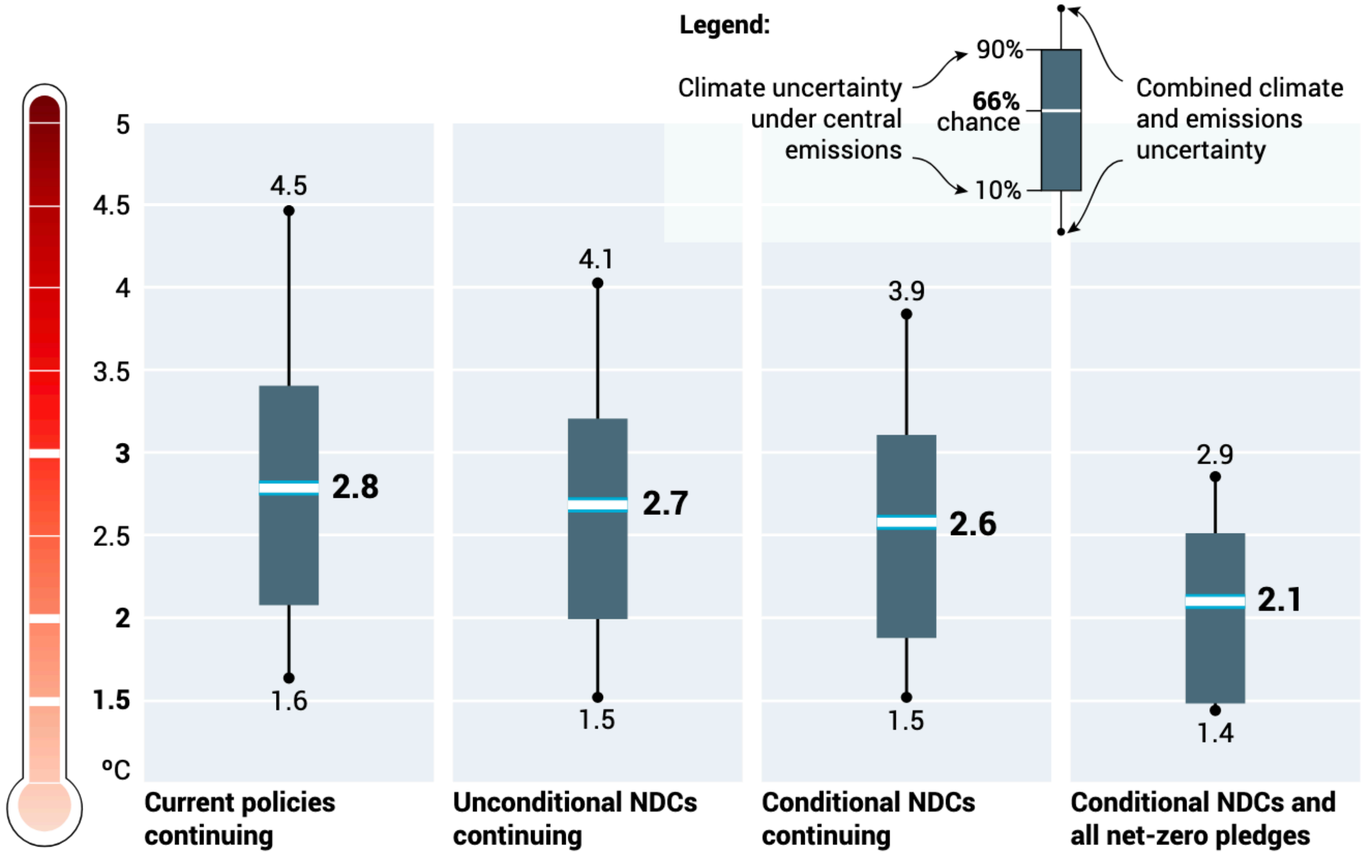
Increasing grid investment [helps] [...] holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C [2015 Paris Agreement: 1.5°-2.0°C; for 1.5°C, ~50% emission cut by 2030].

Adapted, United Nations Climate Change Conference, COP29 Global Energy Storage and Grids Pledge (2024)



Increasing grid investment [helps] [...] holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C [2015 Paris Agreement: 1.5°-2.0°C; for 1.5°C, ~50% emission cut by 2030].

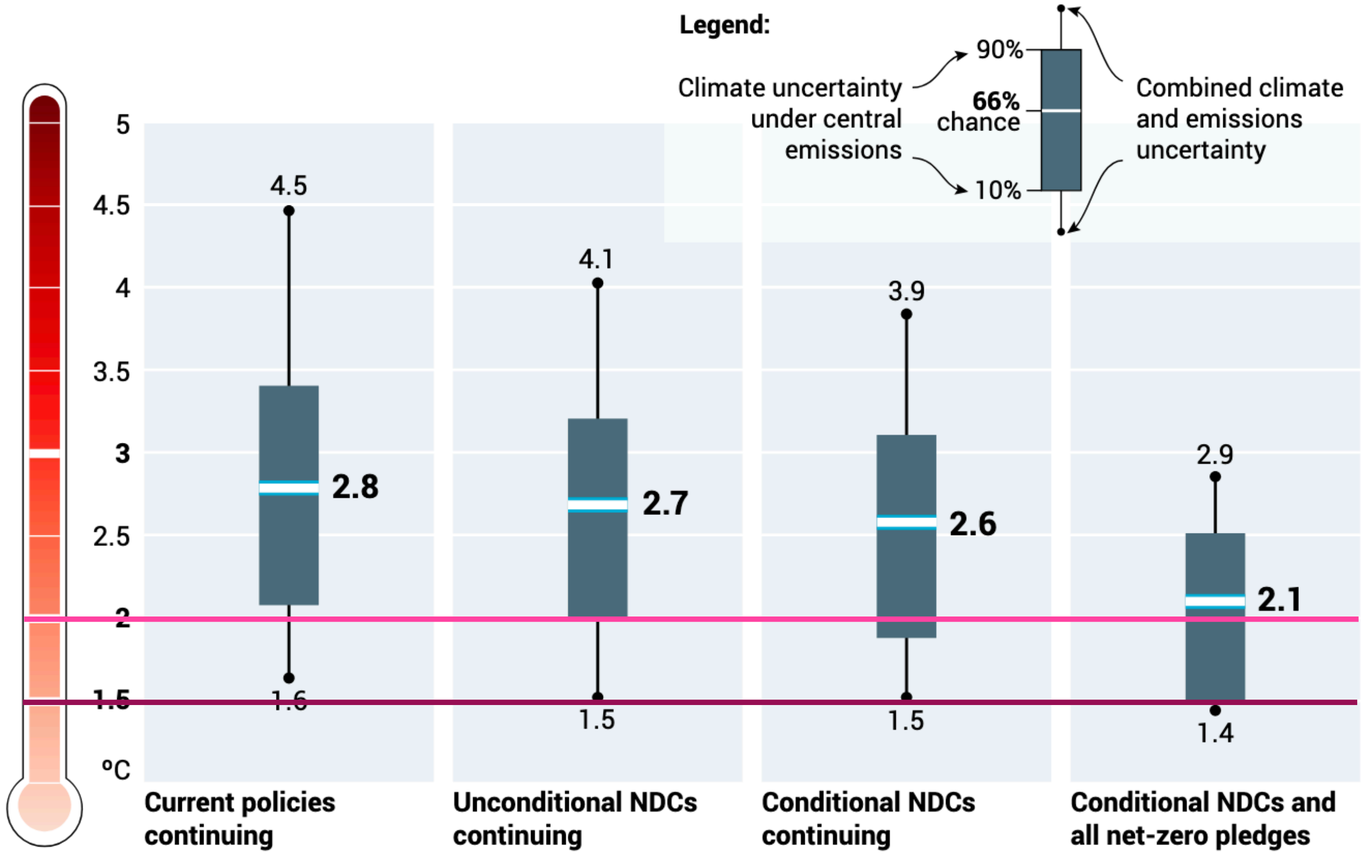
Adapted, United Nations Climate Change Conference, COP29 Global Energy Storage and Grids Pledge (2024)



Emissions Gap Report, 13 October 2026

Increasing grid investment [helps] [...] holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C [2015 Paris Agreement: 1.5°-2.0°C; for 1.5°C, ~50% emission cut by 2030].

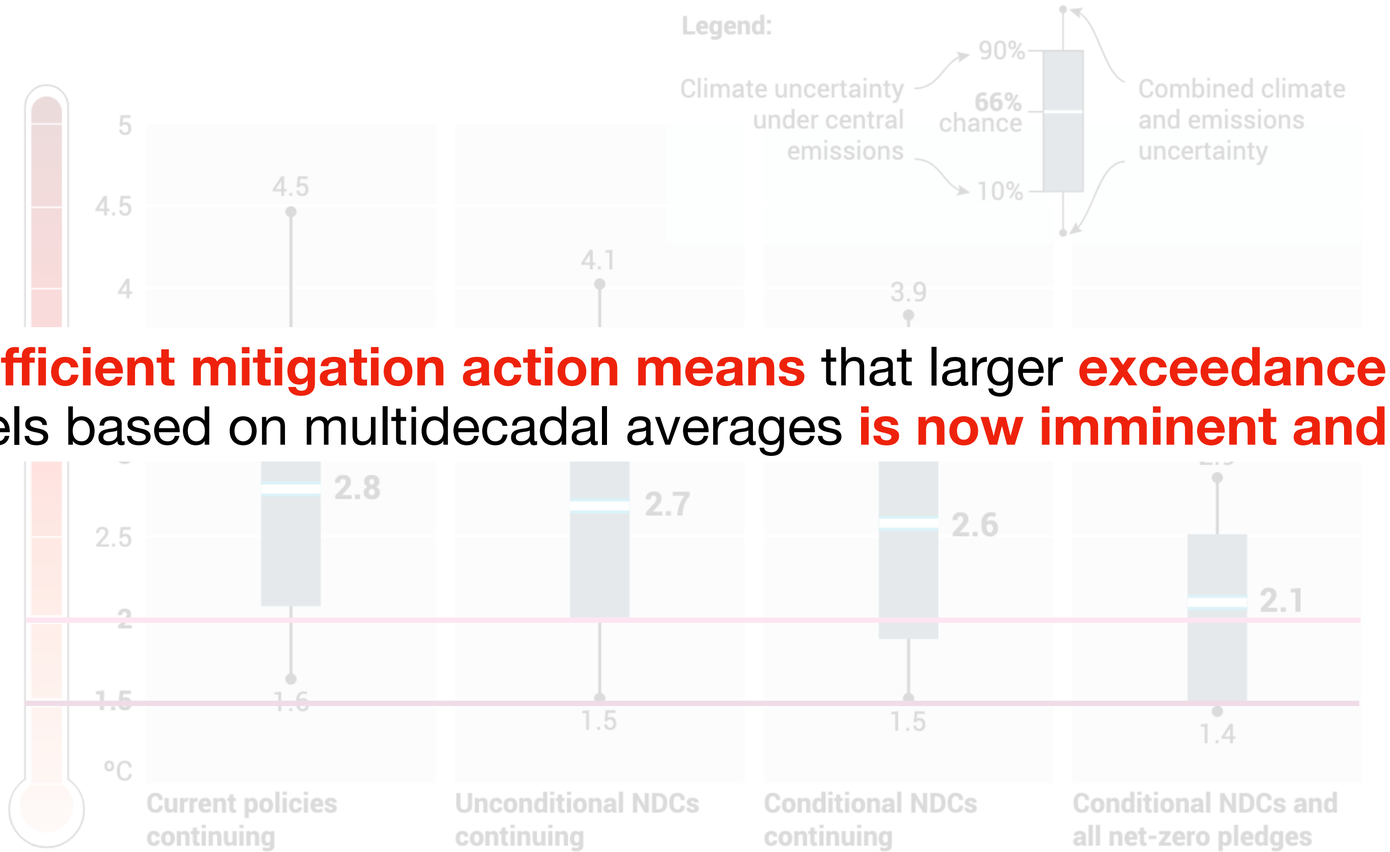
Adapted, United Nations Climate Change Conference, COP29 Global Energy Storage and Grids Pledge (2024)



Emissions Gap Report, 13 October 2026

Increasing grid investment [helps] [...] holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C [2015 Paris Agreement: 1.5°-2.0°C; for 1.5°C, ~50% emission cut by 2030].

Adapted, United Nations Climate Change Conference, COP29 Global Energy Storage and Grids Pledge (2024)



"Decades of **insufficient mitigation action means** that larger **exceedance of 1.5°C** above pre-industrial levels based on multidecadal averages **is now imminent and unavoidable**."

Emissions Gap Report, 13 October 2026

177 net-zero pathways by the year 2100 anticipate:

- Renewables to be 60% of primary energy supply (today ~14%)
- Electricity’s share of final energy increasing from about 20% to 50%

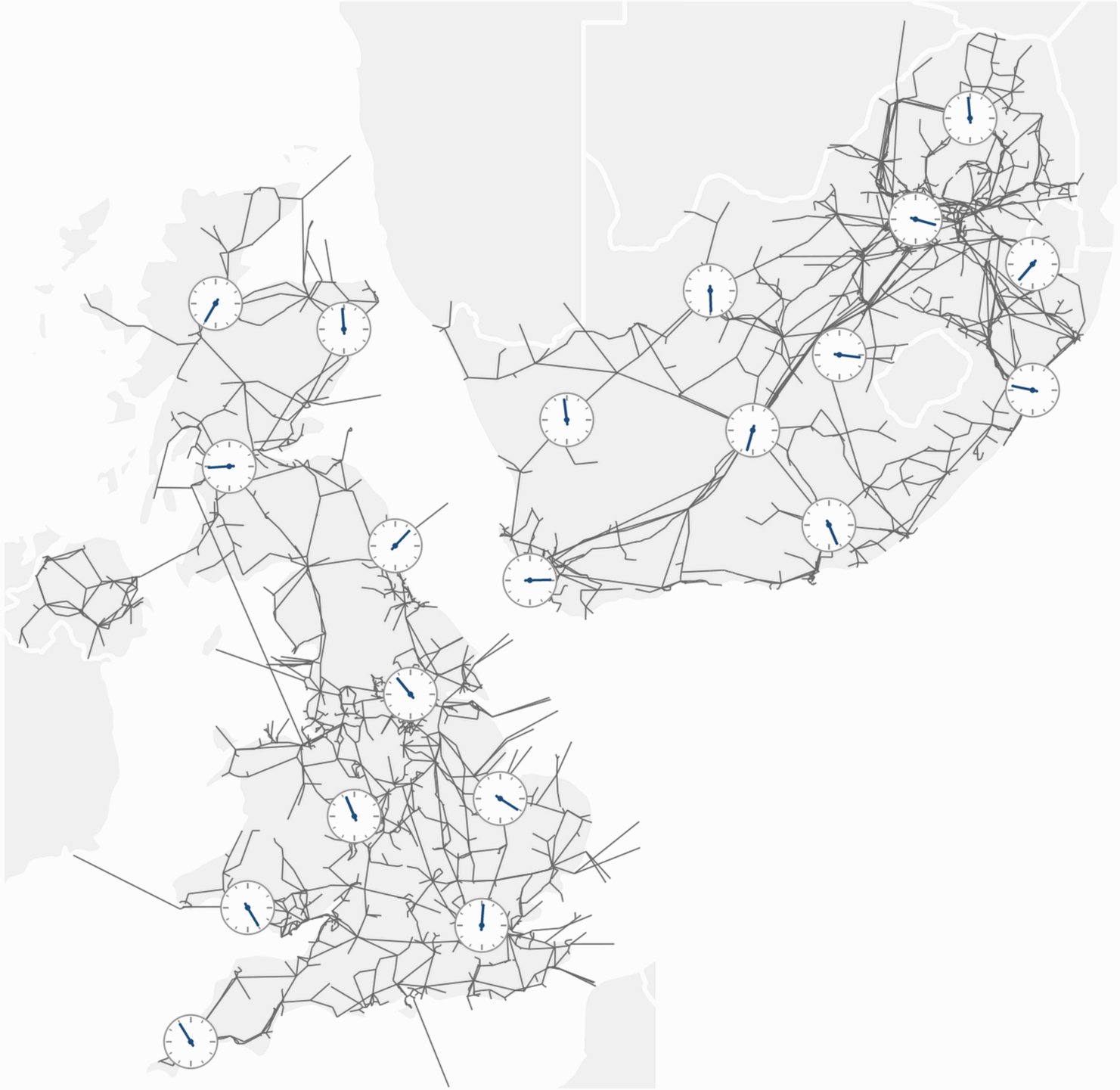
J. DeAngelo et al., *Nature Communications* (2021)

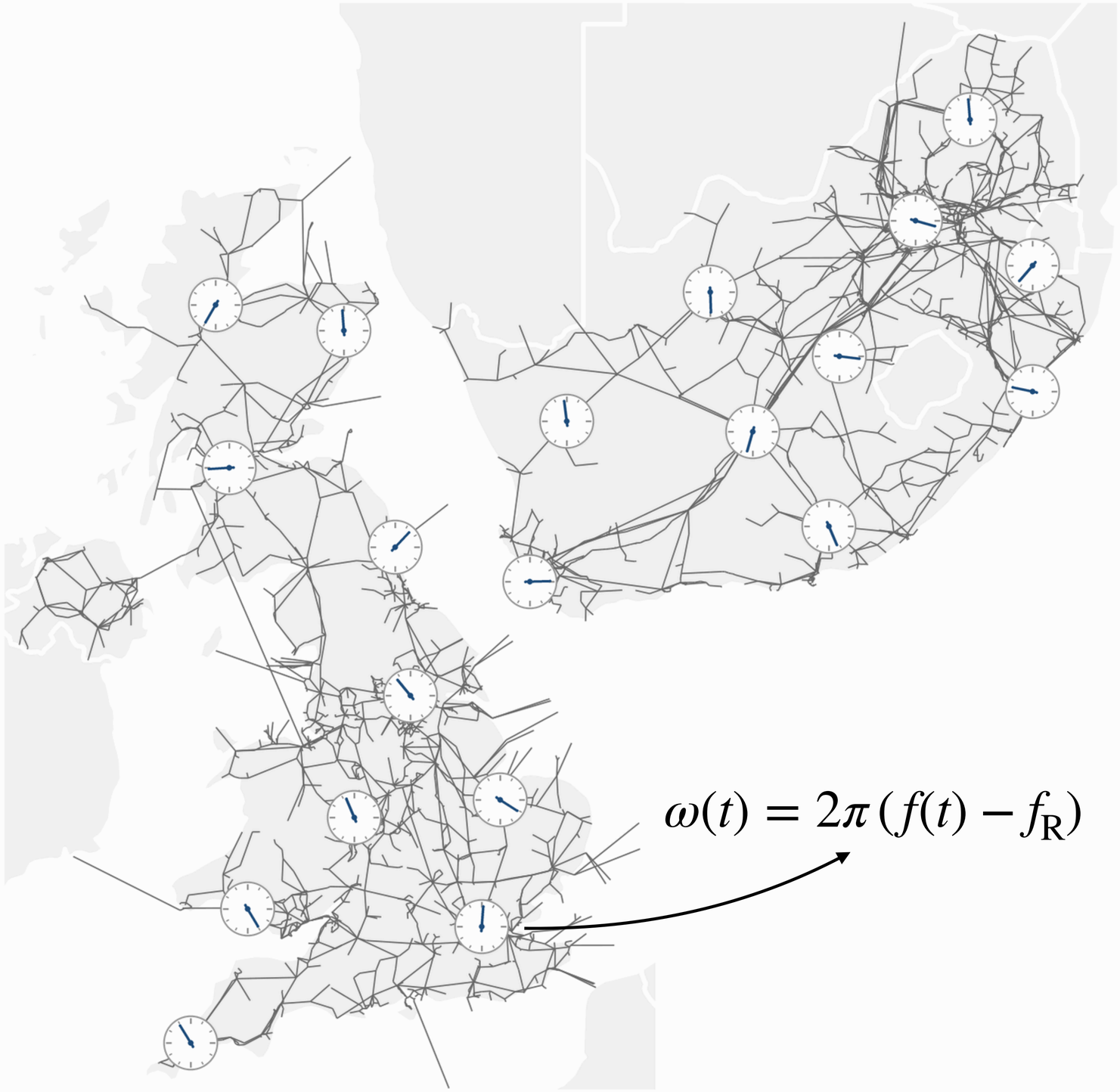
Let’s narrow down the scope: power grids

Let’s narrow down the scope: power grids

Goal: understand power grids better with physics and statistics






$\omega(t) = 2\pi\,(f(t) - f_{\mathrm{R}})$

Many factors influence power grids…







My flat, London, UK

Many factors influence power grids…







My flat, London, UK



Seagreen Offshore Wind Farm, Scotland, UK

Many factors influence power grids…



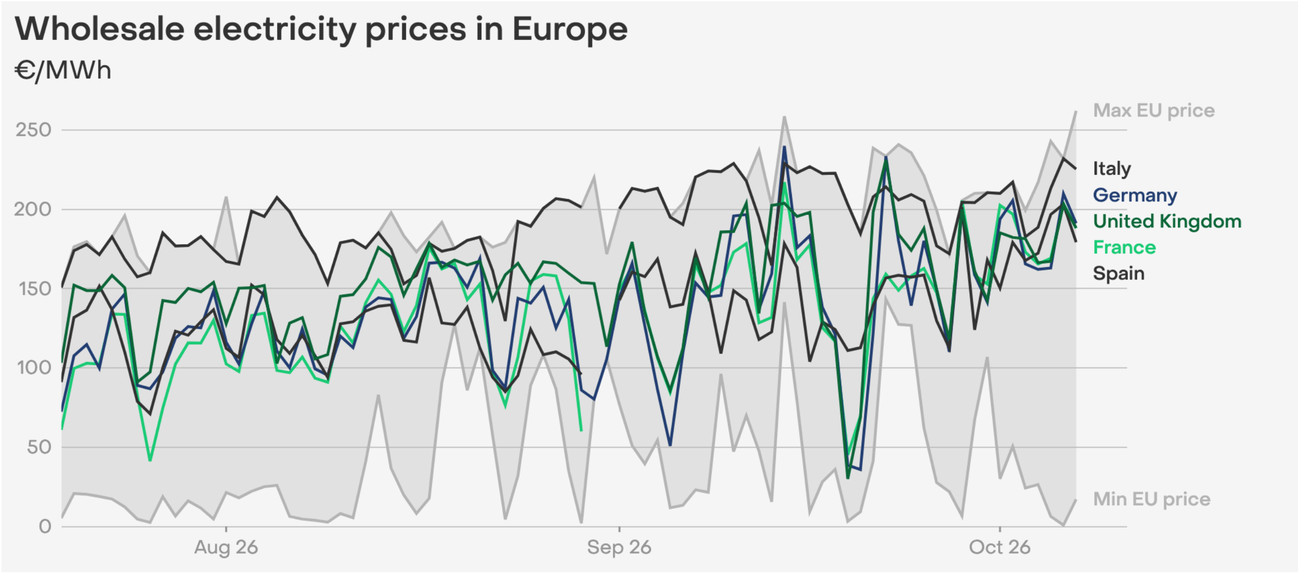




My flat, London, UK

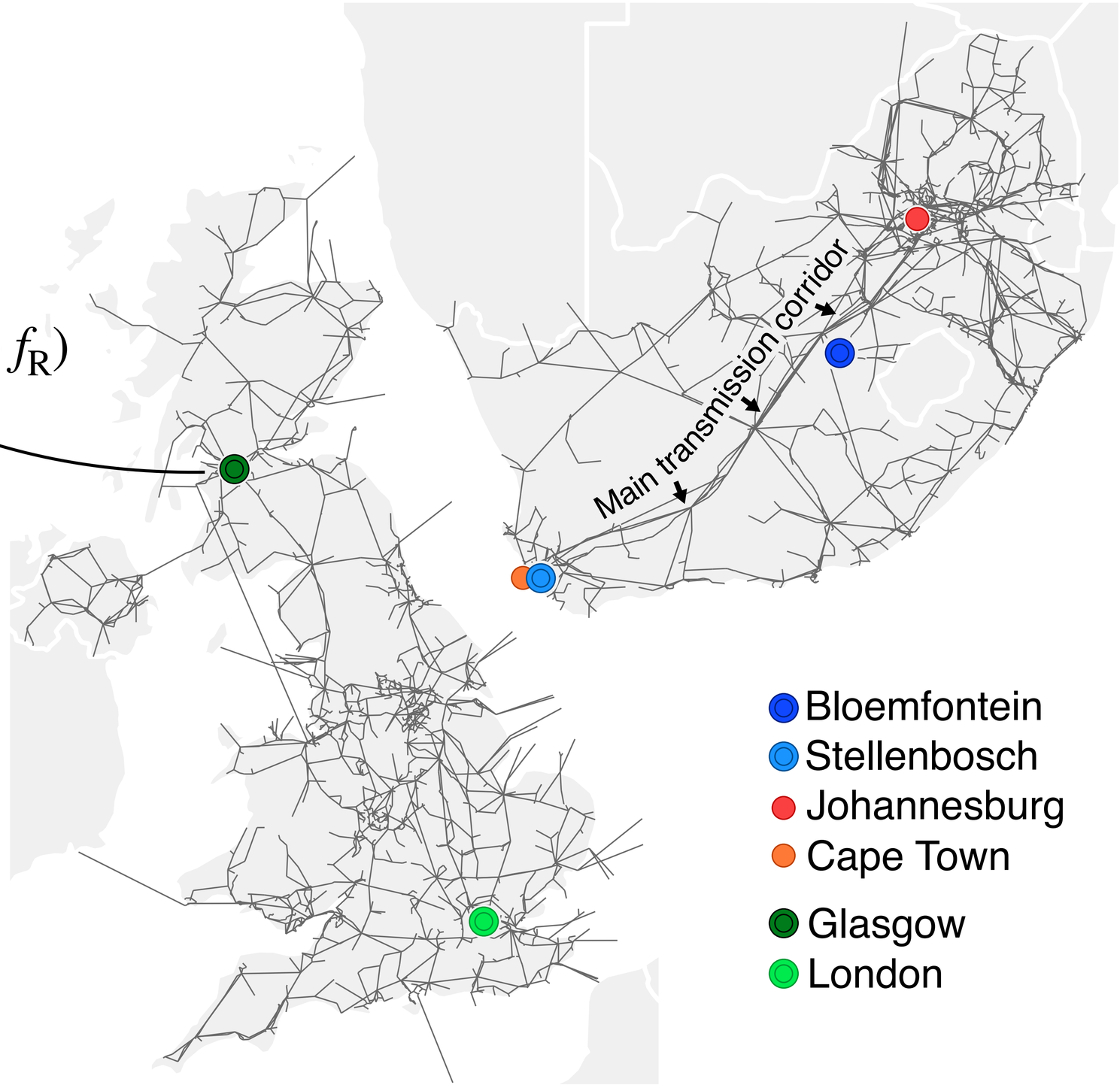


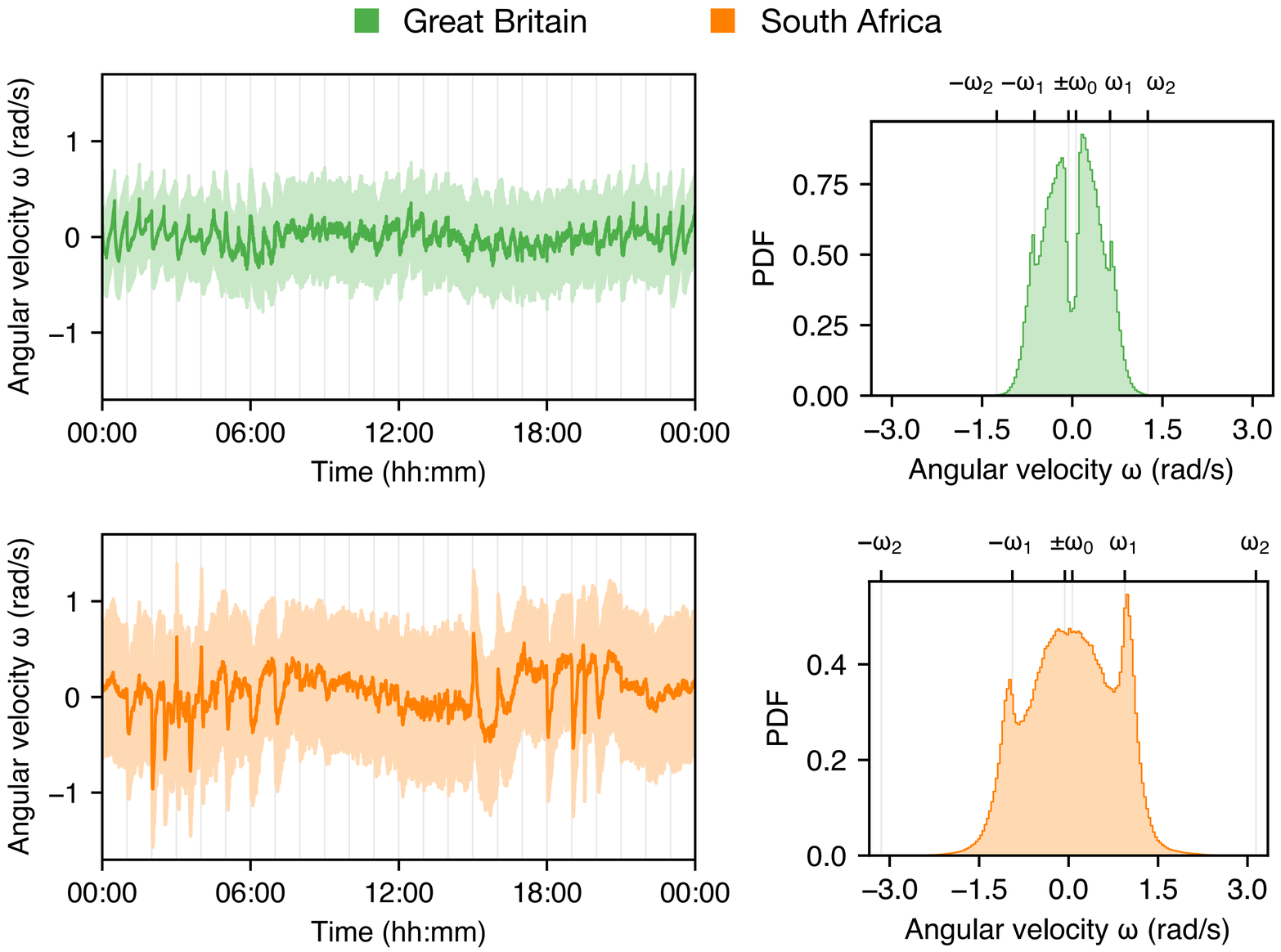
Seagreen Offshore Wind Farm, Scotland, UK

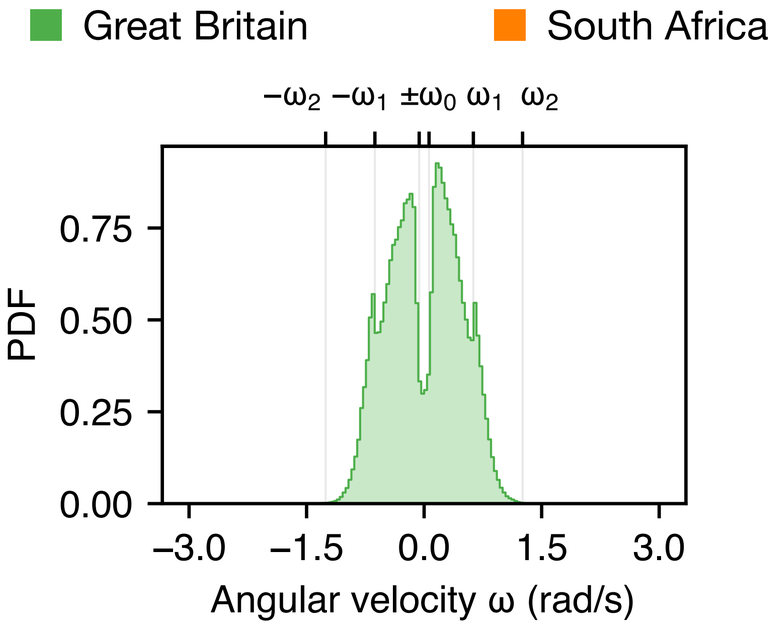


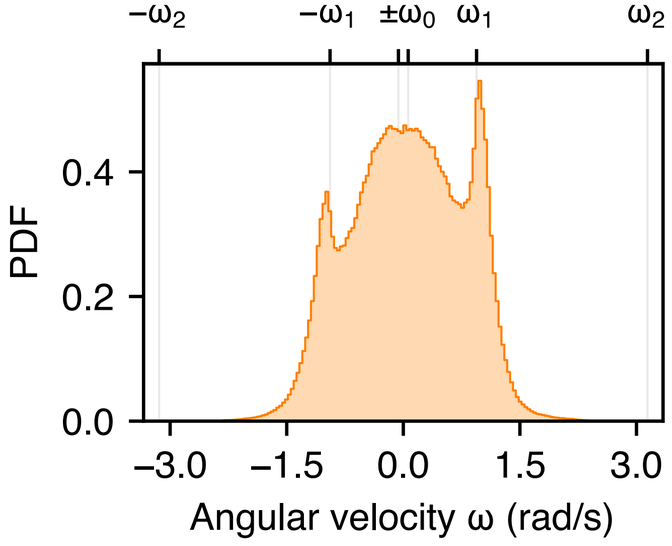
Frequency

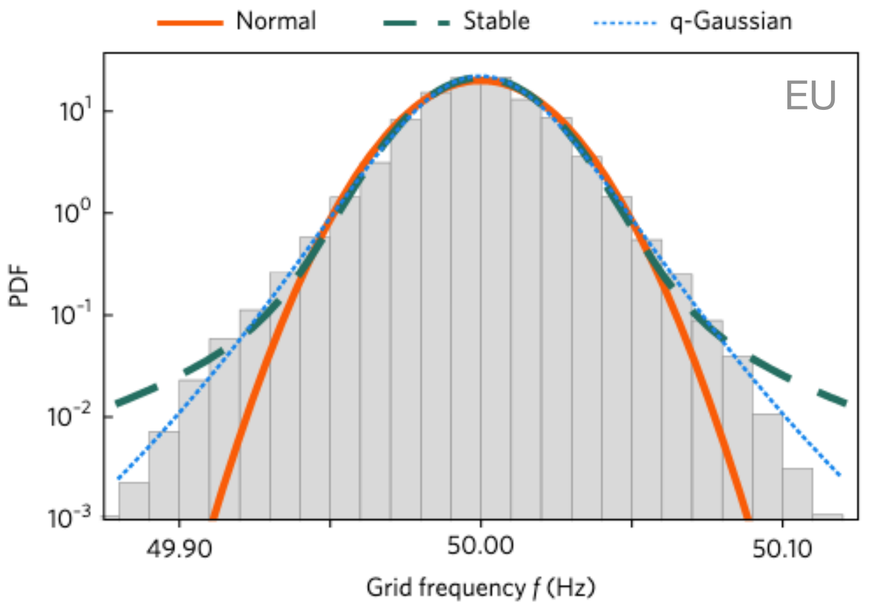
$$\omega(t) = 2\pi\,(f(t) - f_{\mathrm{R}})$$



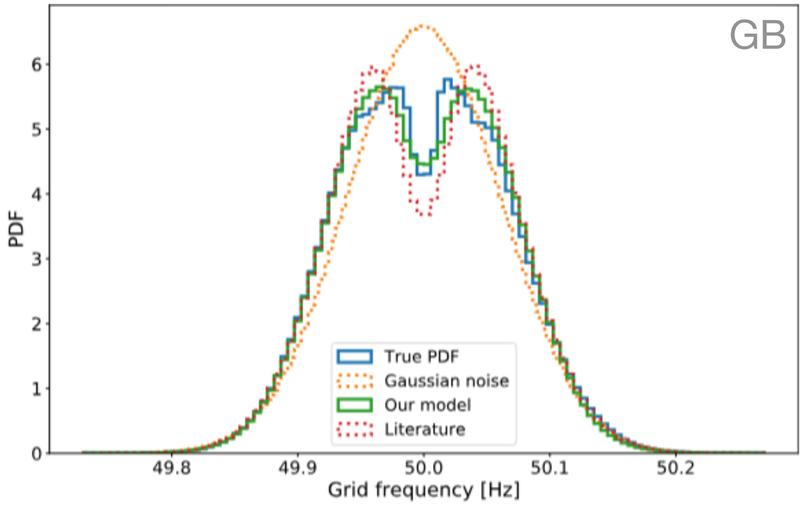

Great Britain
South Africa
Angular velocity ω (rad/s)
1
0
−1
00:00
06:00
12:00
18:00
00:00
Time (hh:mm)
−ω2 −ω1 ±ω0 ω1 ω2
PDF
0.75
0.50
0.25
0.00
−3.0
−1.5
0.0
1.5
3.0
Angular velocity ω (rad/s)
Angular velocity ω (rad/s)
1
0
−1
00:00
06:00
12:00
18:00
00:00
Time (hh:mm)
−ω2 −ω1 ±ω0 ω1 ω2
PDF
0.4
0.2
0.0
−3.0
−1.5
0.0
1.5
3.0
Angular velocity ω (rad/s)







B. Schäfer et al., *Nature Energy* (2018)



D. Kraljic, *IEEE Transactions on Power Systems* (2023)

Superstatistics

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = H(\omega) + P(t) + \epsilon\xi$$

Superstatistics

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = H(\omega) + P(t) + \epsilon\xi$$

$\epsilon > 0, \xi \sim \mathcal{N}(0,1)$

Superstatistics

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = H(\omega) + P(t) + \epsilon\xi$$

$\epsilon > 0, \xi \sim \mathcal{N}(0,1)$

$P(t)$ is the slow “superstatistical” variable

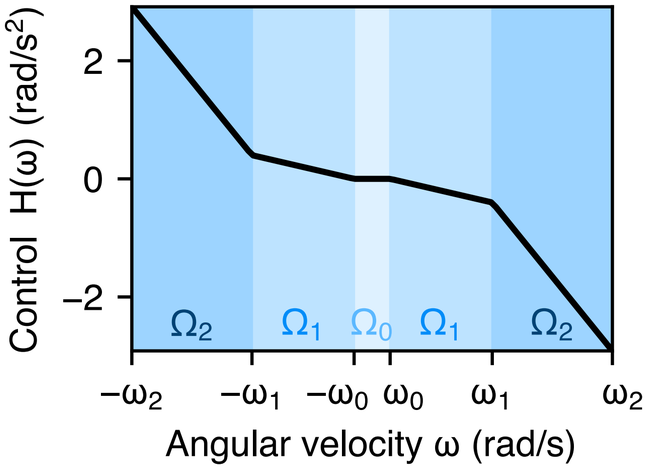
Superstatistics

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = H(\omega) + P(t) + \epsilon\xi$$

$\epsilon > 0, \xi \sim \mathcal{N}(0,1)$

$P(t)$ is the slow “superstatistical” variable

Nonlinear control



Superstatistics

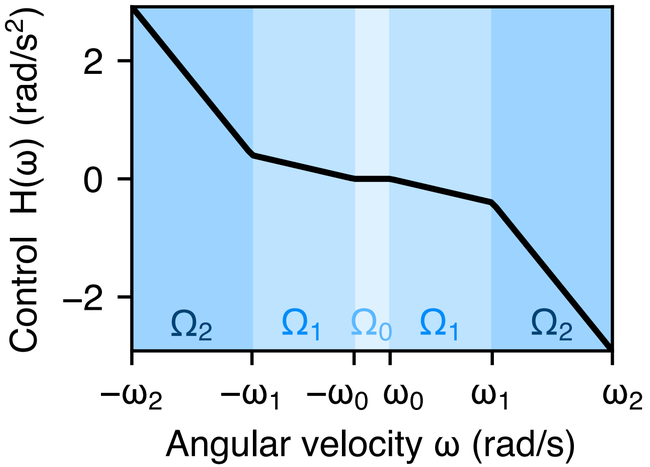
$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = H(\omega) + P(t) + \epsilon\xi$$

$\epsilon > 0, \xi \sim \mathcal{N}(0,1)$

$P(t)$ is the slow “superstatistical” variable $\longrightarrow$ $p(\omega) \propto \int p(\omega \mid P)p(P)\,\mathrm{d}P$

C. Beck, *Physical Review Letters* (2001)

Nonlinear control



Superstatistics

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} = H(\omega) + P(t) + \epsilon\xi$$

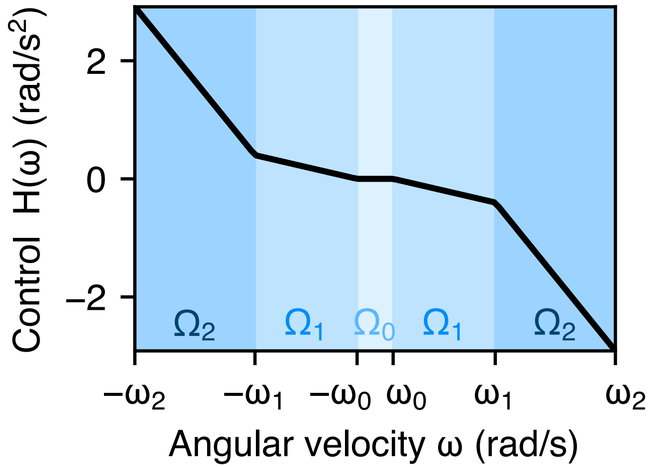
$$\epsilon > 0, \xi \sim \mathcal{N}(0,1)$$

$P(t)$ is the slow “superstatistical” variable $\longrightarrow$ $p(\omega) \propto \int p(\omega \mid P)p(P)\,\mathrm{d}P$

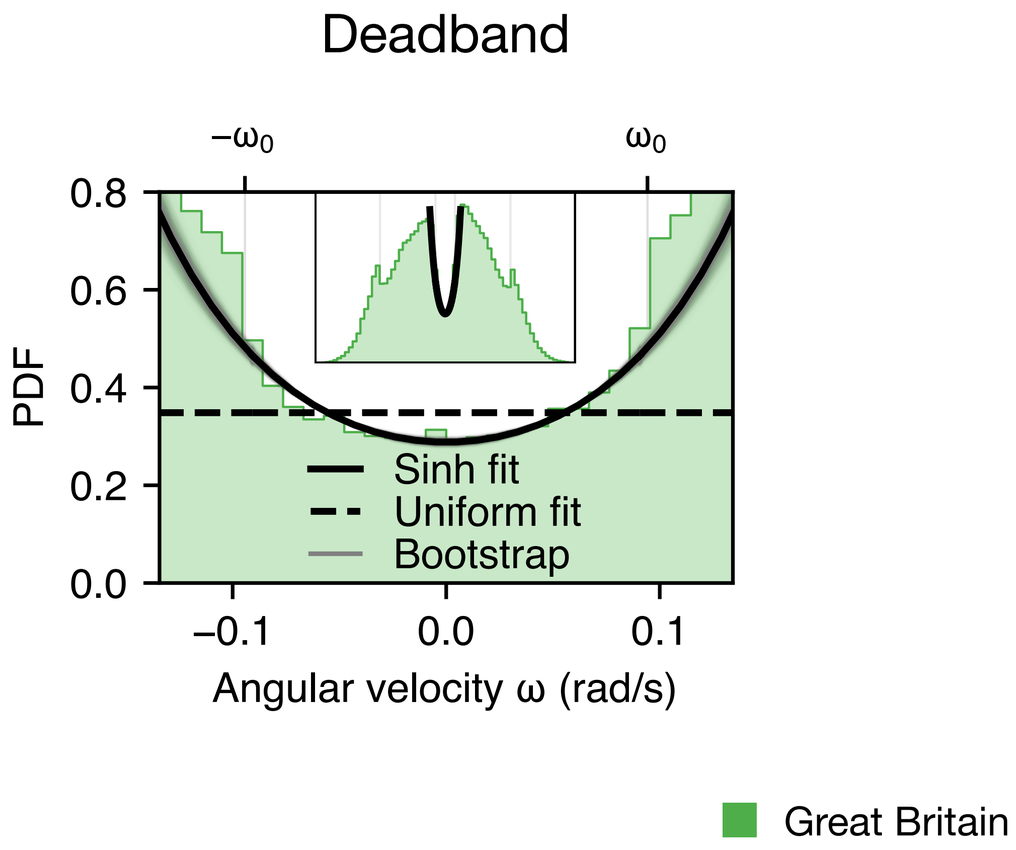
C. Beck, *Physical Review Letters* (2001)

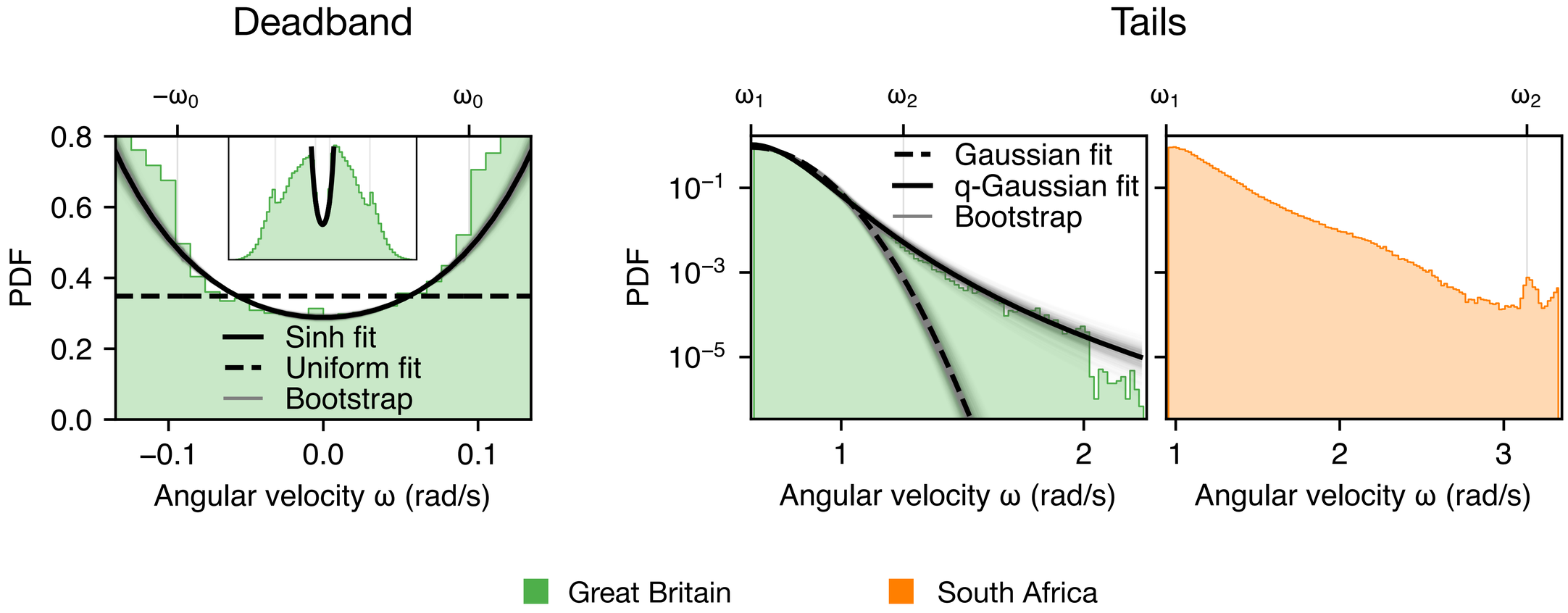
Nonlinear control

Latent variables



Statistical inference


Deadband
−ω0
ω0
0.8
0.6
0.4
0.2
0.0
PDF
Sinh fit
Uniform fit
Bootstrap
−0.1
0.0
0.1
Angular velocity ω (rad/s)
Great Britain


Deadband
Tails
−ω0
ω0
ω1
ω2
ω1
ω2
0.8
0.6
0.4
0.2
0.0
PDF
Sinh fit
Uniform fit
Bootstrap
−0.1
0.0
0.1
Angular velocity ω (rad/s)
10−1
10−3
10−5
Gaussian fit
q-Gaussian fit
Bootstrap
1
2
Angular velocity ω (rad/s)
1
2
3
Angular velocity ω (rad/s)
Great Britain
South Africa

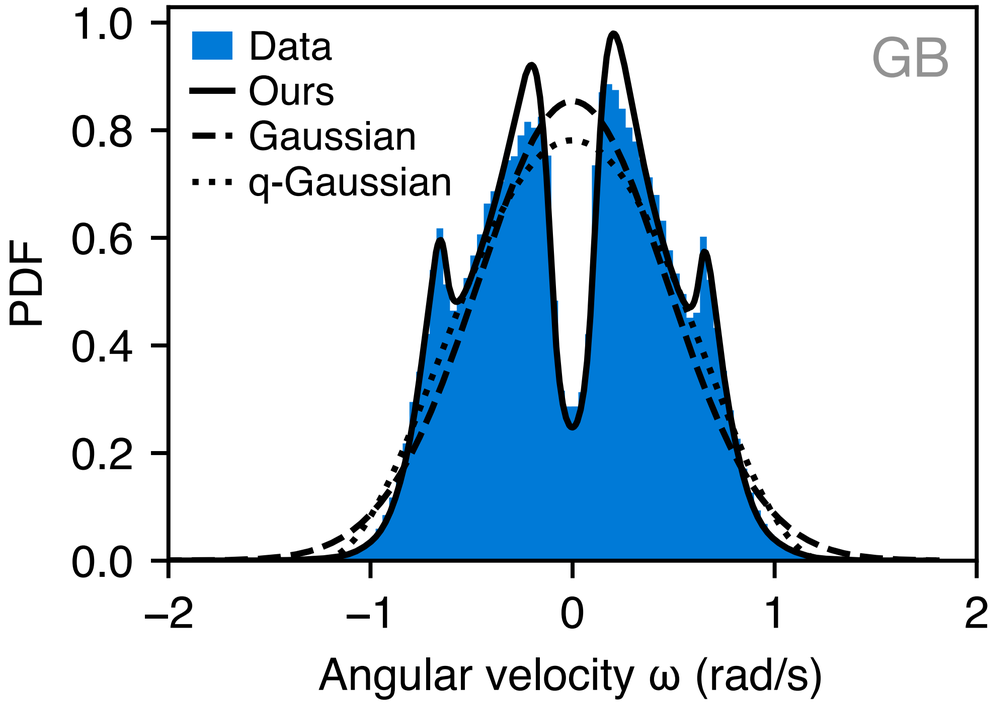
Inference algorithm

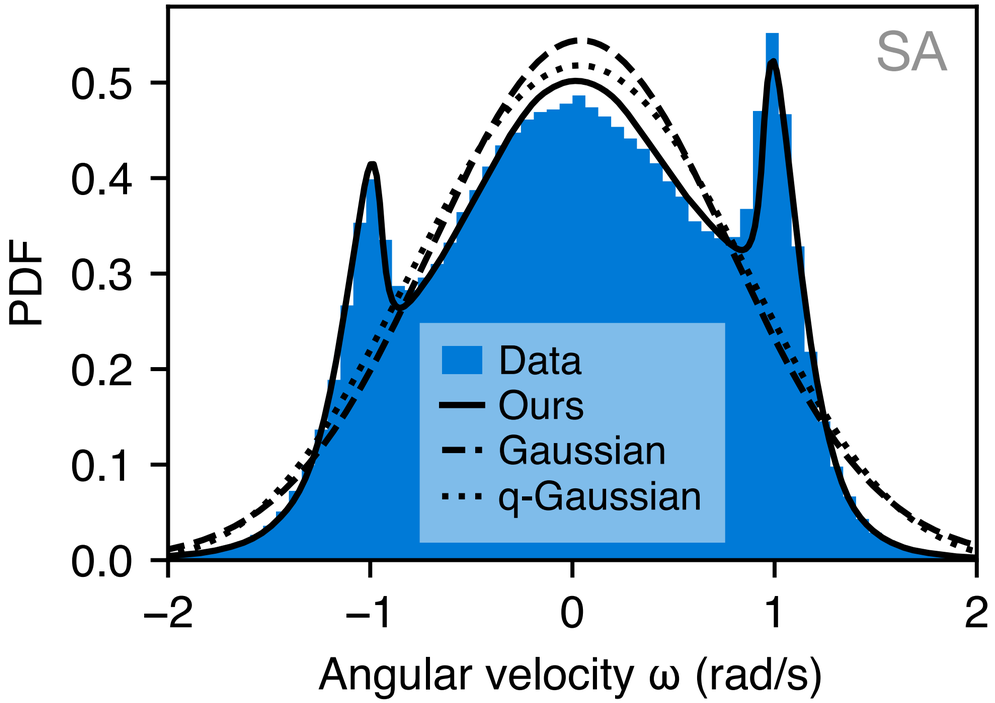
Discretization $\quad \boldsymbol{\Delta\omega} = \Delta t\,(\mathbf{H} + \mathbf{P}) + \sqrt{\Delta t}\,\epsilon\boldsymbol{\xi}$

Superstatistics $\quad \mathbf{P} = \mathbf{B}\tilde{\mathbf{P}}$

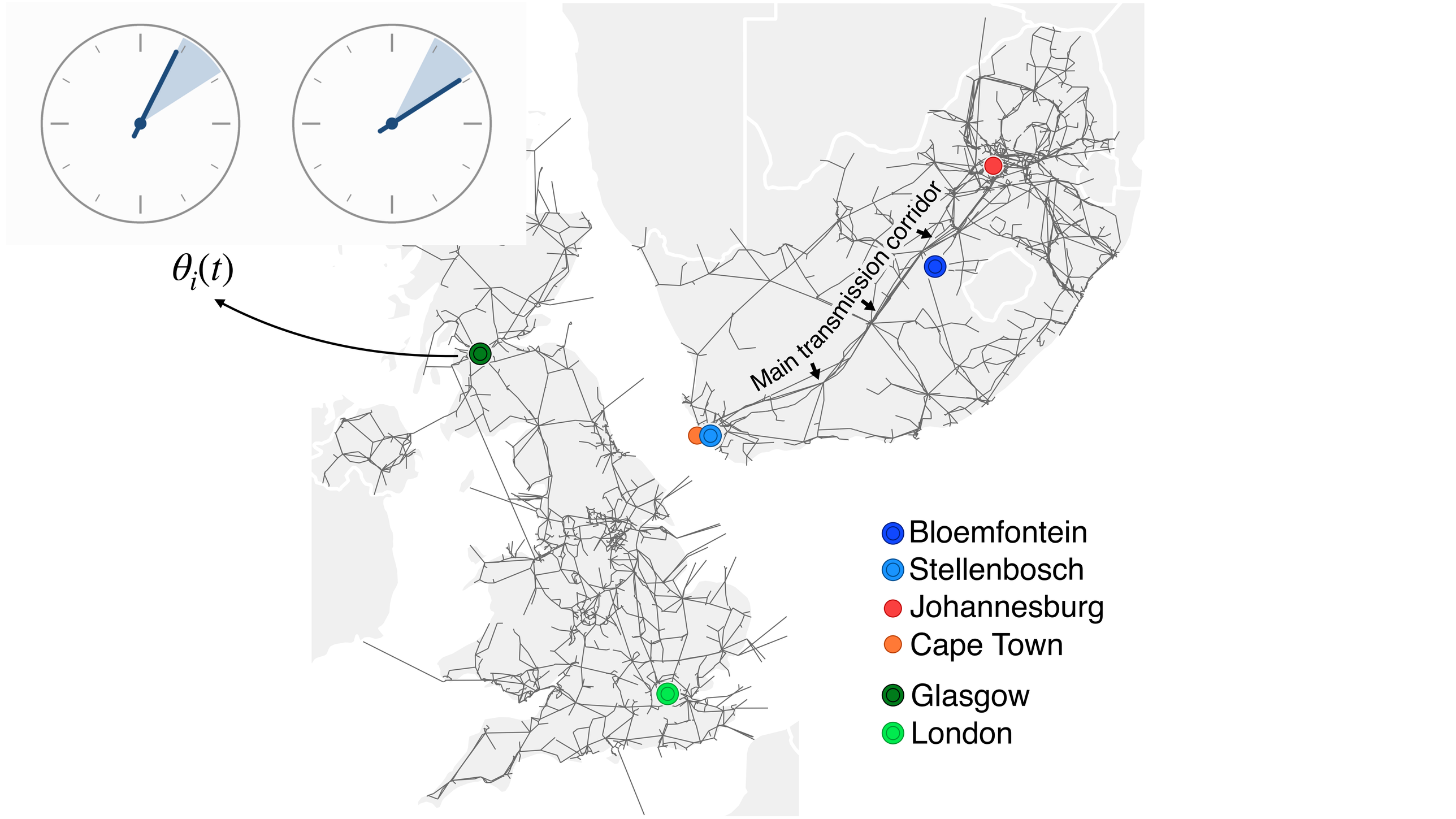
Likelihood $\quad p(\boldsymbol{\Delta\omega} \mid \tilde{\mathbf{P}}, \boldsymbol{\theta}) = \mathcal{N}(\Delta t\,(\mathbf{H} + \mathbf{B}\tilde{\mathbf{P}}), \epsilon^2 \Delta t\,\mathbf{I})$

Inference $\quad \min_{\tilde{\mathbf{P}} \in \mathbb{R}^M, \boldsymbol{\theta} \in \Theta} \mathscr{L}(\tilde{\mathbf{P}}, \boldsymbol{\theta})$


GB
Data
Ours
Gaussian
q-Gaussian
PDF
1.0
0.8
0.6
0.4
0.2
0.0
−2
−1
0
1
2
Angular velocity ω (rad/s)


SA
Data
Ours
Gaussian
q-Gaussian
PDF
0.5
0.4
0.3
0.2
0.1
0.0
−2
−1
0
1
2
Angular velocity ω (rad/s)

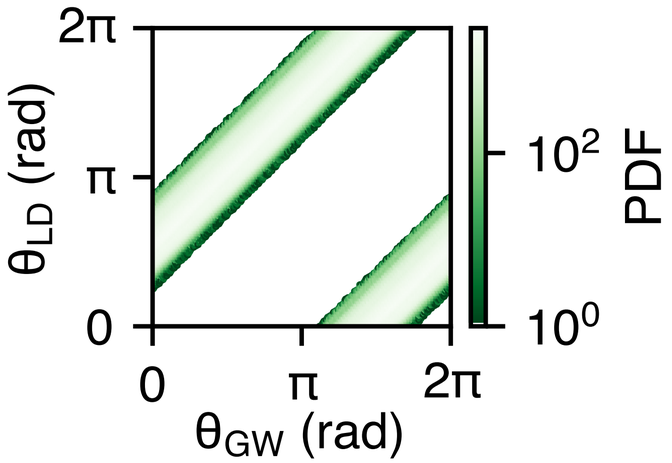
Phase angles

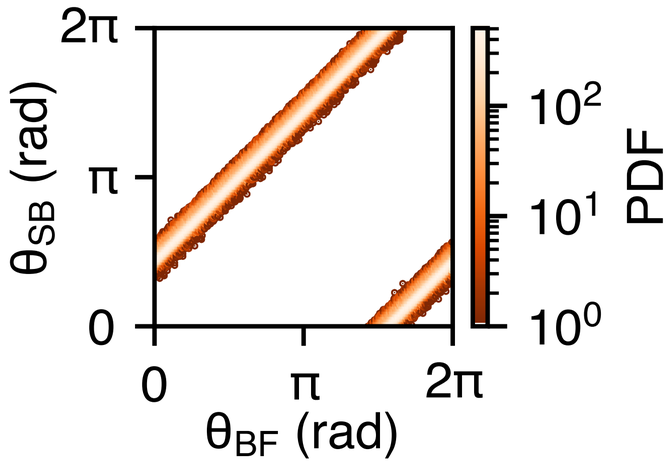

$\theta_i(t)$
Main transmission corridor
Bloemfontein
Stellenbosch
Johannesburg
Cape Town
Glasgow
London



Great Britain

South Africa





A reduced grid model for phase angles

$$\frac{\mathrm{d}^2x}{\mathrm{d}t^2} + \gamma\frac{\mathrm{d}x}{\mathrm{d}t} + \frac{\mathrm{d}V}{\mathrm{d}x} = \epsilon\xi$$

$$V(x) = -\delta x - 2\kappa\cos x$$

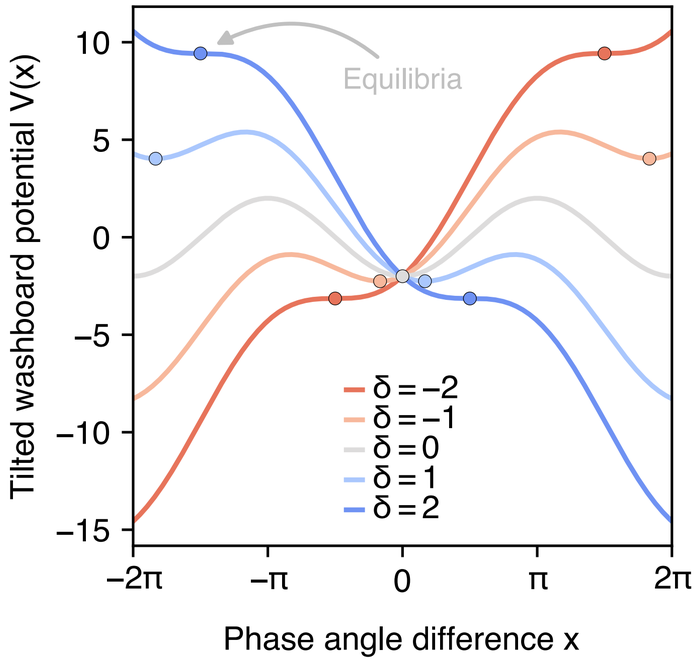
$$\epsilon > 0, \langle \xi(t)\,\xi(t')\rangle = 2\,\delta(t-t')$$

$$\gamma > 0$$

$$N = 2!$$

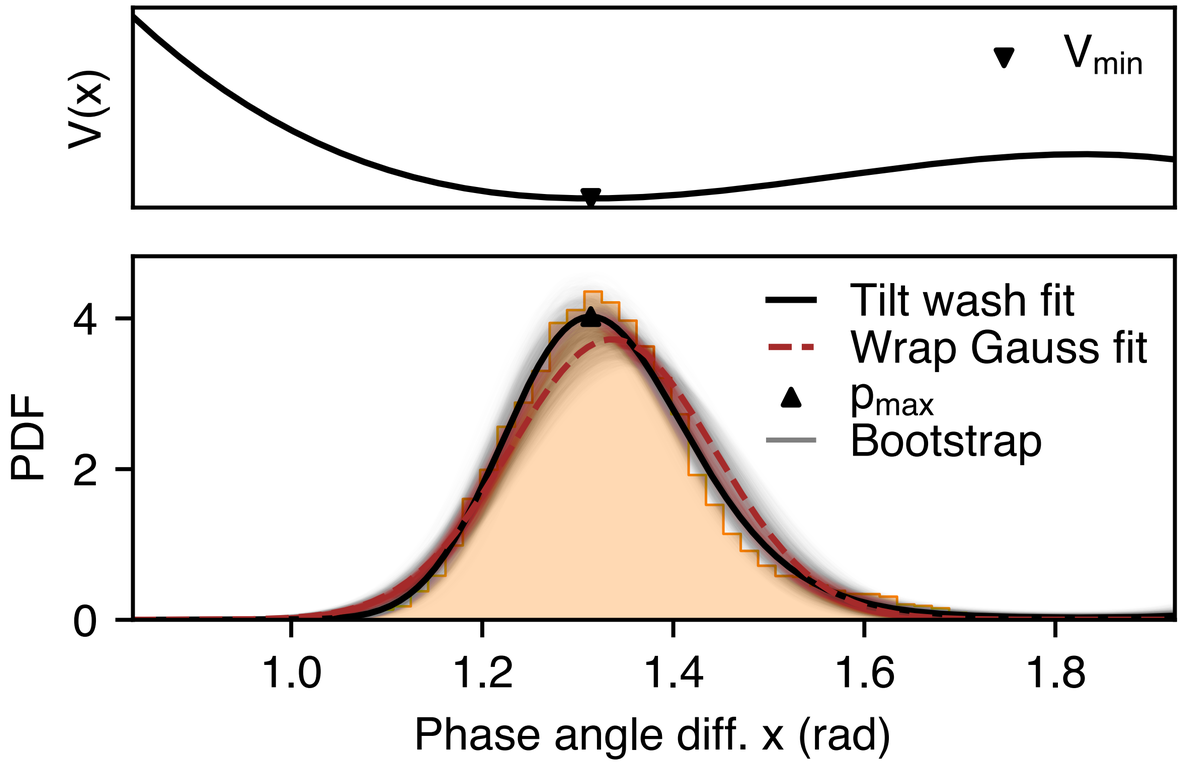
$$x(t) = \theta_{\mathrm{LD}}(t) - \theta_{\mathrm{GW}}(t)$$

$$x(t) = \theta_{\mathrm{SB}}(t) - \theta_{\mathrm{BF}}(t)$$



$$p(x) \propto e^{-\gamma V(x)/\epsilon^2}$$

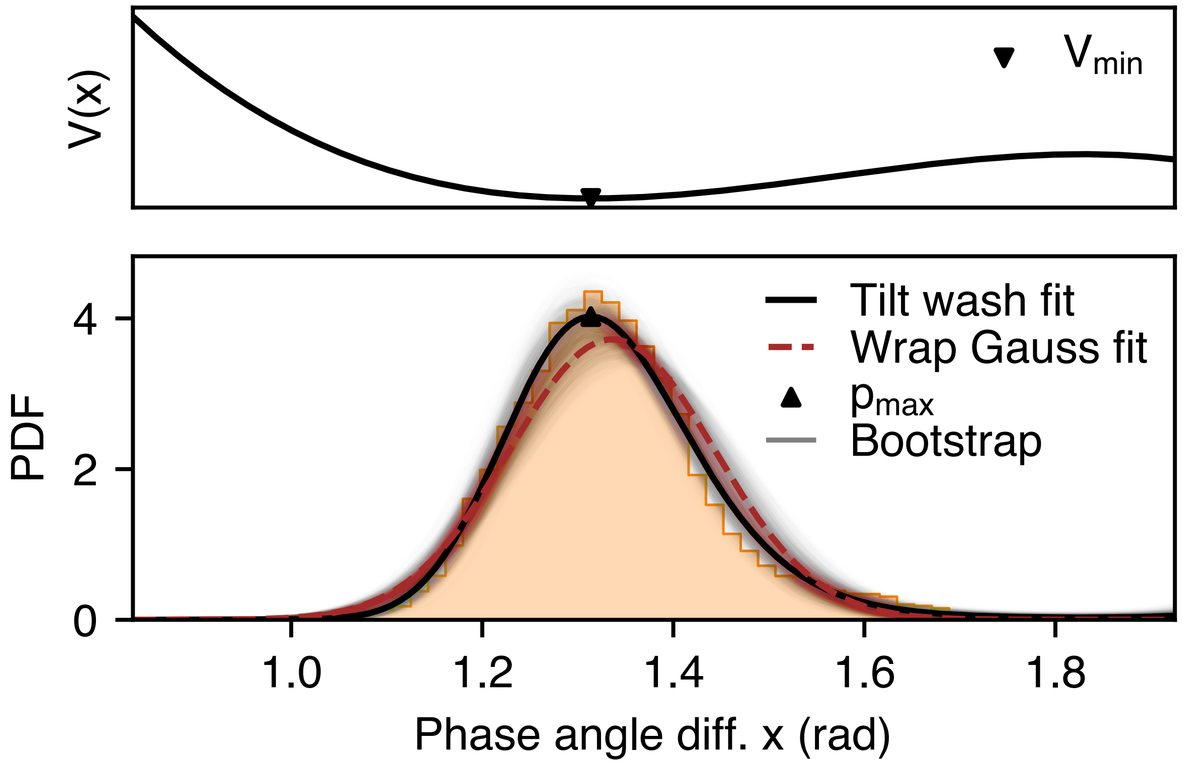
$$V(x) = -\delta x - 2\kappa \cos x$$



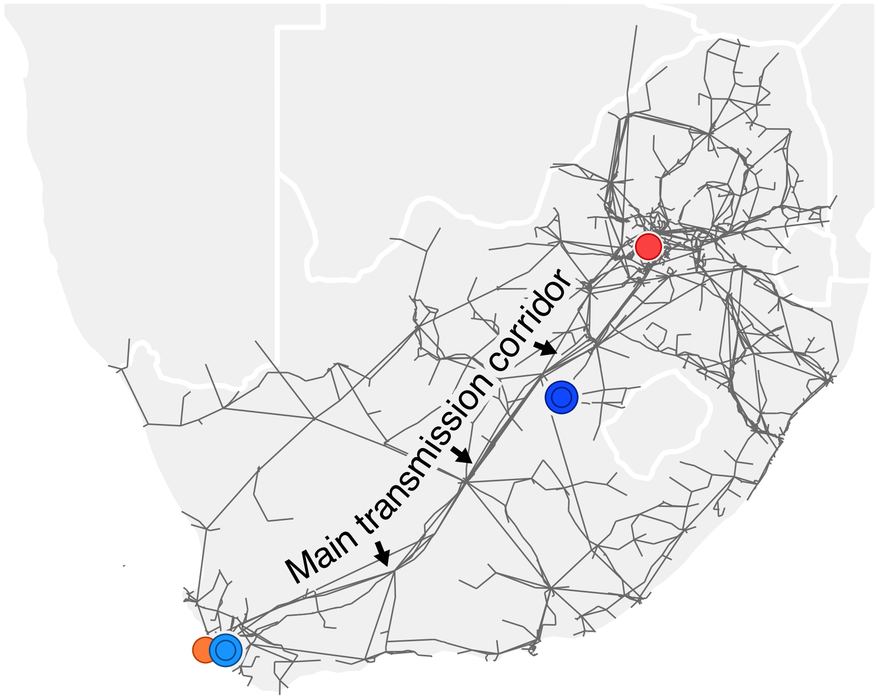
South Africa

$$p(x) \propto e^{-\gamma V(x)/\epsilon^2}$$

$$V(x) = -\delta x - 2\kappa \cos x$$



South Africa



Bloemfontein
Stellenbosch
Johannesburg
Cape Town

Takeaway: we can understand power grids better with physics and statistics

- Understanding the complexity of frequency and phase angle fluctuations in power grids, *PRX Energy*

Preprint	arXiv:2604.03133
Code (GitHub)	aleable/power-grid-complexity
Data (Zenodo)	10.5281/zenodo.19397526

- High-fidelity inference of power grid frequency distributions, *arXiv*

Preprint	arXiv:2607.28232
Code (GitHub)	aleable/power-grid-inference
Data (Zenodo)	10.5281/zenodo.21461024

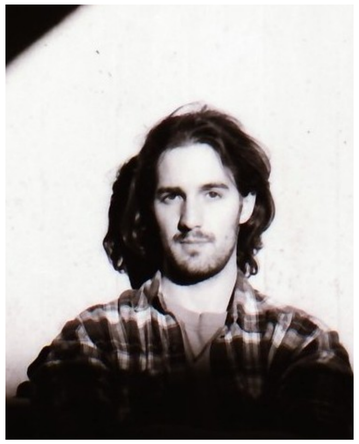
Slides, references, and more 👉



Wanru Hao
UK



Jacques Maritz
South Africa



Leonardo Rydin Gorjão
Netherlands / Norway



Christian Beck
UK



Benjamin Schäfer
Germany

Stability of the South African Power Grid: A data-driven statistical physics approach

UK Research and Innovation





Chantelle van Staden
South Africa



Cristina Trois
South Africa



Thank you!

Alessandro Lonardi

November 5, 2026

Queen Mary University of London

a.lonardi@qmul.ac.uk

aleable.github.io

References

- Global average temperature change: https://climate.metoffice.cloud/temperature.html
- Coal mine, Wyoming, US: https://www.theguardian.com/environment/2014/nov/10/-sp-the-real-story-of-us-coal-inside-the-worlds-biggest-coal-mine
- Oil well, Texas, US: https://en.wikipedia.org/wiki/Oil_well#/media/File:West_Texas_Pumpjack.JPG
- Offshore gas platform, Hainan, China: https://www.scmp.com/news/china/article/3273626/china-confirms-discovery-major-natural-gas-field-south-china-sea
- Physical drivers of climate change: https://commons.wikimedia.org/wiki/File:Physical_Drivers_of_climate_change.svg, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_SPM_final.pdf
- Greenhouse effect: https://commons.wikimedia.org/wiki/File:Greenhouse-effect-t2.svg
- Global greenhouse gas emissions by sector and end use: https://www.wri.org/data/world-greenhouse-gas-emissions-sector-2023-sunburst-chart
- Emissions Gap Report 2026: https://wedocs.unep.org/items/87c02cac-8da8-4c28-ba61-c846ee68ea70
- Wholesale electricity price: https://ember-energy.org/data/european-electricity-prices-and-costs/ (accessed 18th October 2026)