UNIVERSITY OF CAMBRIDGE
Department of Engineering

Whittle Laboratory

Desktop DNS

An open toolkit for turbomachinery aerodynamics

Andrew Wheeler
Whittle Laboratory
University of Cambridge
aw329@cam.ac.uk

ASME Turbo Expo 2023

2002

- LPT DNS at Re ~ 50,000
- 20 million solution points
- 1.5-3 months *

2023

- Same case ~ 4 hours on an Amazon Virtual Machine
- Around $40*USD* **

*V. Michelassi, W. Rodi, J. Wissink. “Analysis of DNS and LES of Flow in a Low Pressure Turbine Cascade with Incoming Wakes and Comparison with Experiments.” *Flow, Turbulence and Combustion* Vol. 69 No. 4 (2002): pp. 295– 330. DOI 10.1023/A:1027334303200.

** ‘p4d.24xlarge’ instance and current spot prices

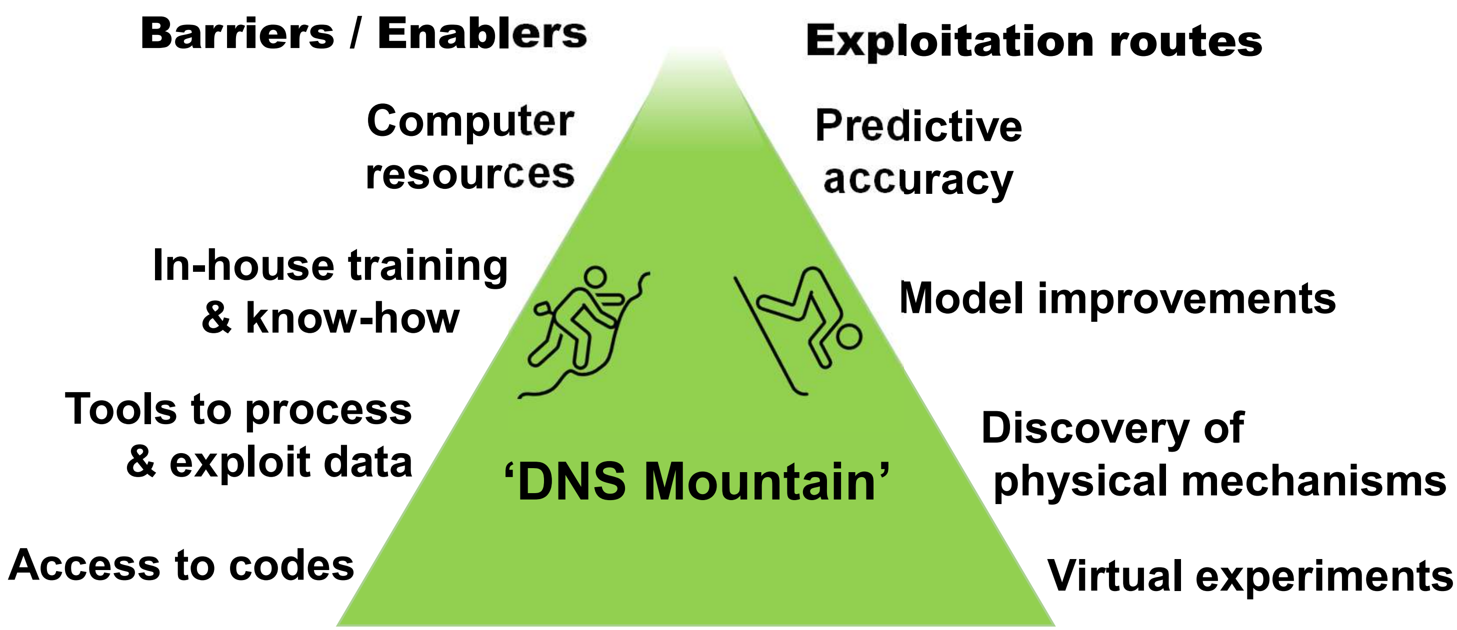
2002

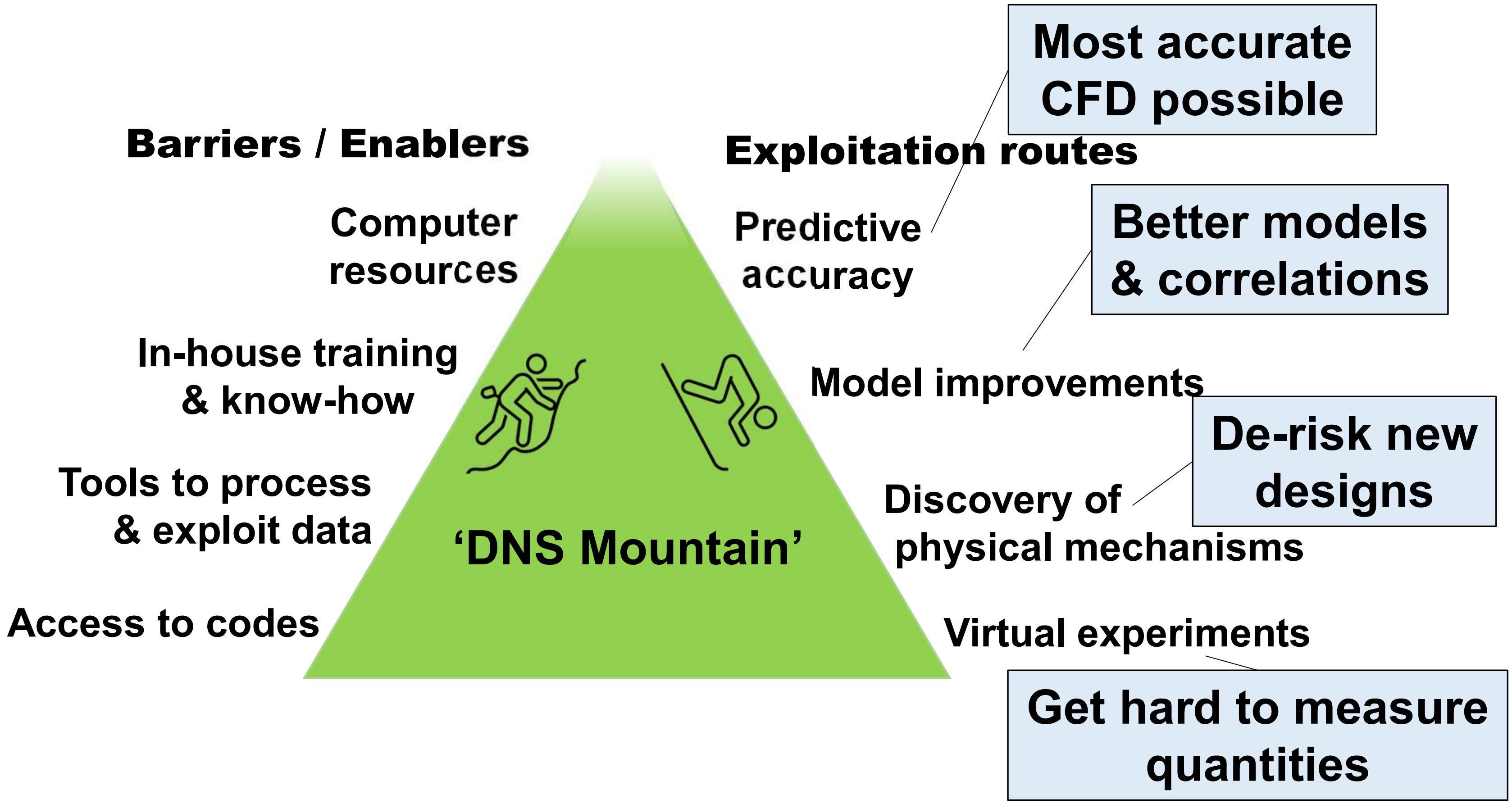
- LPT DNS at Re ~ 50,000
- 20 million solution points
- 1.5-3 months *

2023

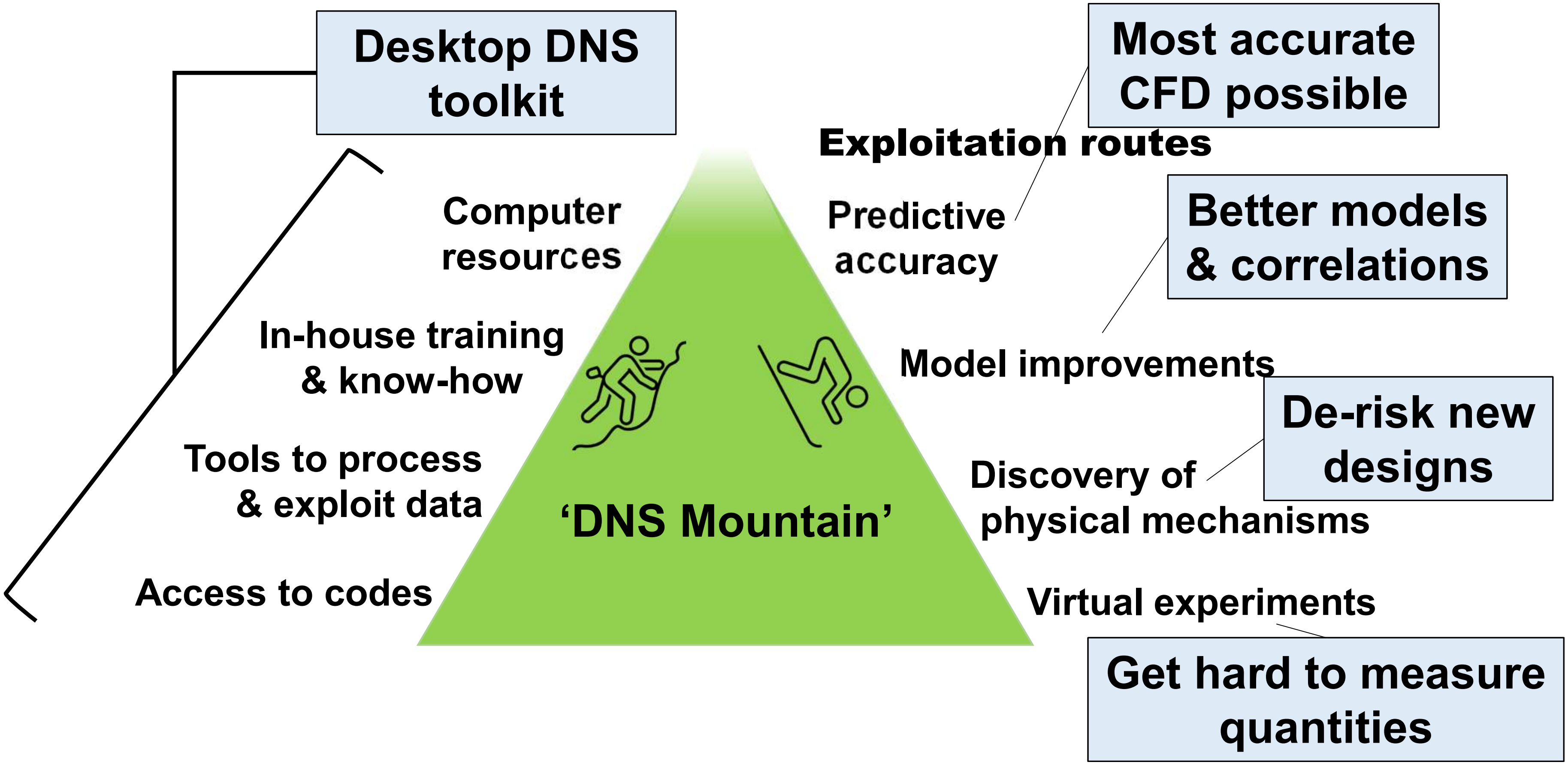
- Same case ~ 4 hours on an Amazon Virtual Machine
- Around $40*USD* **

Why don’t we make more use of DNS?


Barriers / Enablers
Exploitation routes
Computer resources
In-house training & know-how
Tools to process & exploit data
Access to codes
'DNS Mountain'
Predictive accuracy
Model improvements
Discovery of physical mechanisms
Virtual experiments



How do we overcome the DNS Mountain?



How do we overcome the DNS Mountain?

Easily accessible
- Virtual Machine in the cloud
- Powerful gaming PC
- Single compute node

Direct simulation of Navier Stokes
- No turbulence modelling
- High fidelity

Desktop DNS open toolkit

Publicly available for turbomachinery aerodynamicists to explore DNS

New toolkit draws on more than 10 years of DNS research

Access to codes

Training & know-how

Tools to process & exploit data

Computer resources

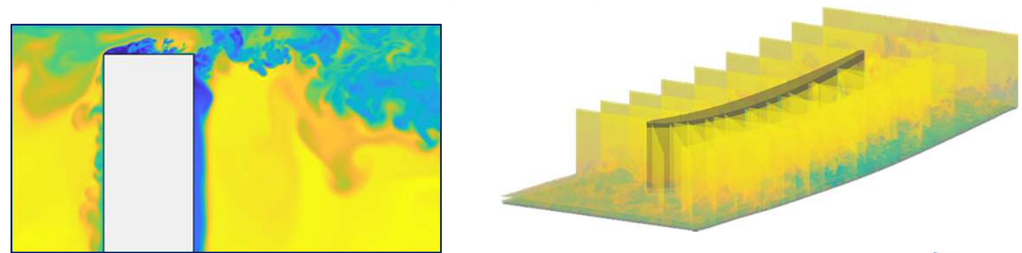
3DNS

Compressible Navier-Stokes

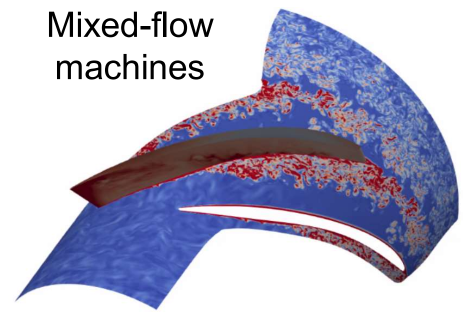
High order
4th order DRP, 4-stage Runge Kutta, characteristic multi-block interfaces

Low dispersion and dissipation error
skew-split differencing, 8th order filter

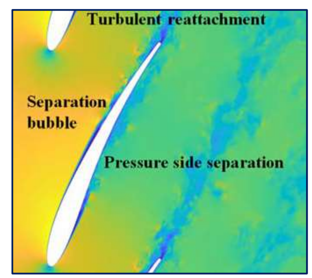
Compressor tip flows



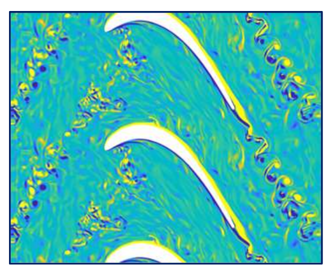
Mixed-flow machines



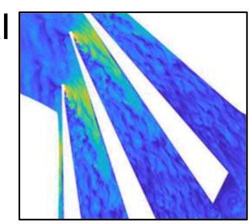
Low-Reynolds turbomachinery



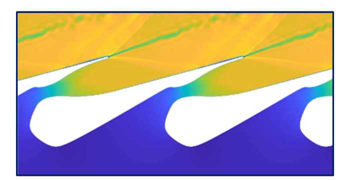
LPTs with wakes



Centrifugal machines



ORC turbines

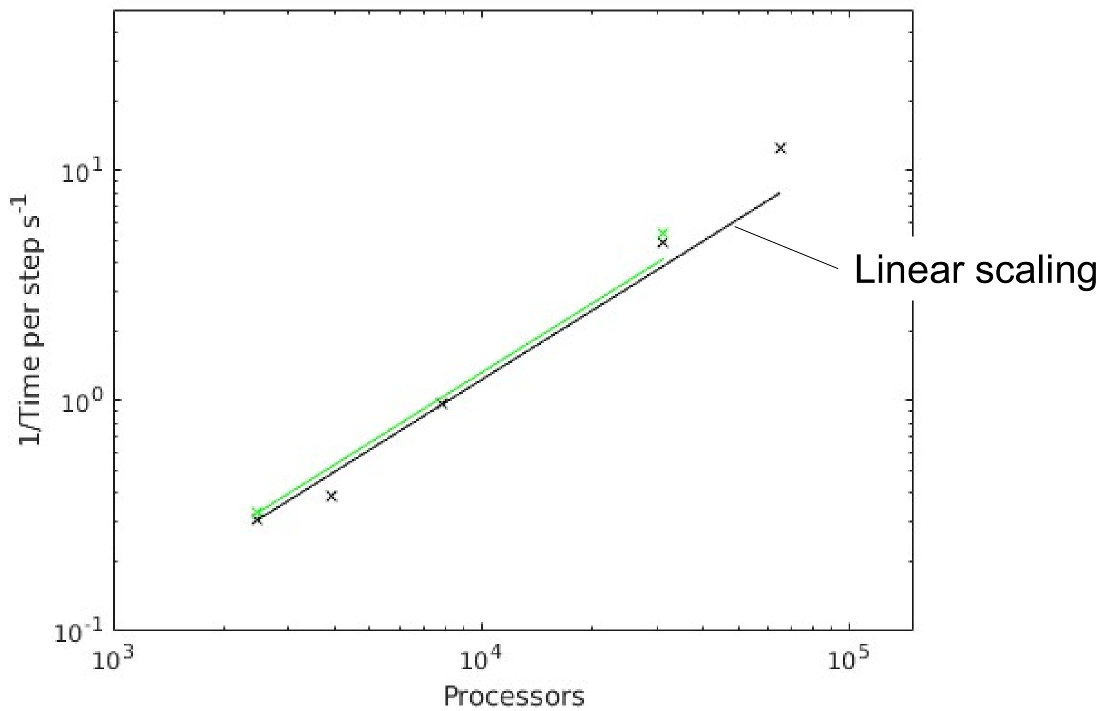


3DNS-cpu

- Optimized for running on large computer systems (10^4-10^5 processors)

- For ‘Desktop DNS’ need something more accessible

Strong scaling performance on HAWK

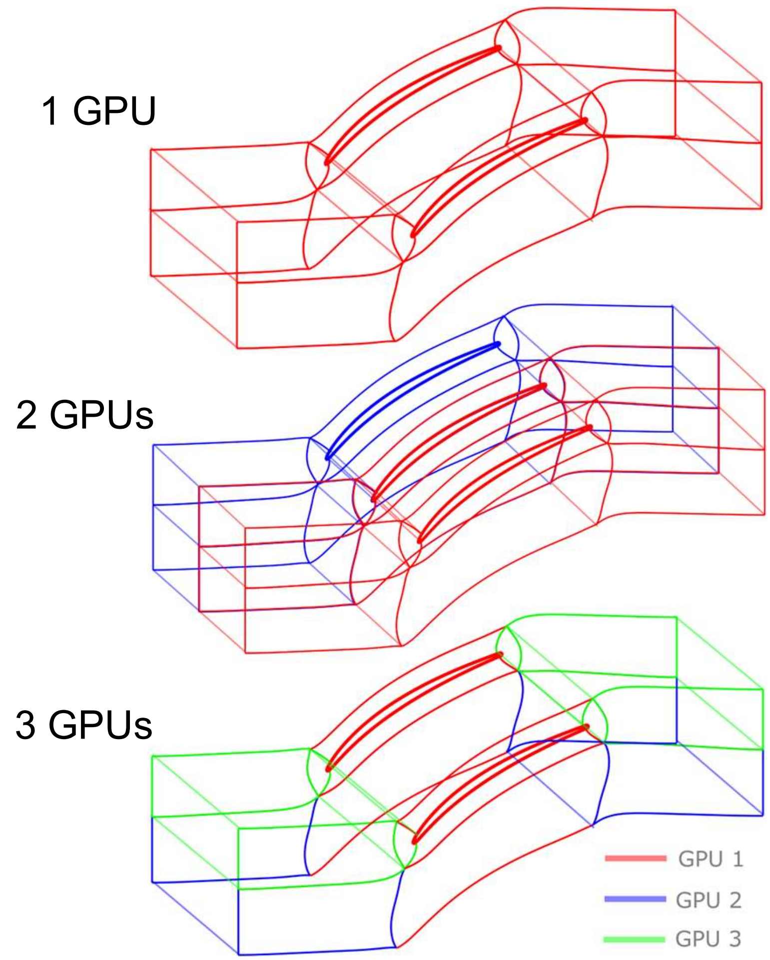


1.4 billion point multi-block mesh (9-blocks)

PRACE project PrcPA4748

3DNS-gpu

- Same high order algorithm as 3DNS-cpu
- MPI communication across GPUs and nodes
- Acceleration with OpenACC
- Multiple blocks on each GPU and/or multiple GPUs on each block
- Flexibility allows load-balancing of GPUs with large variations in block sizes

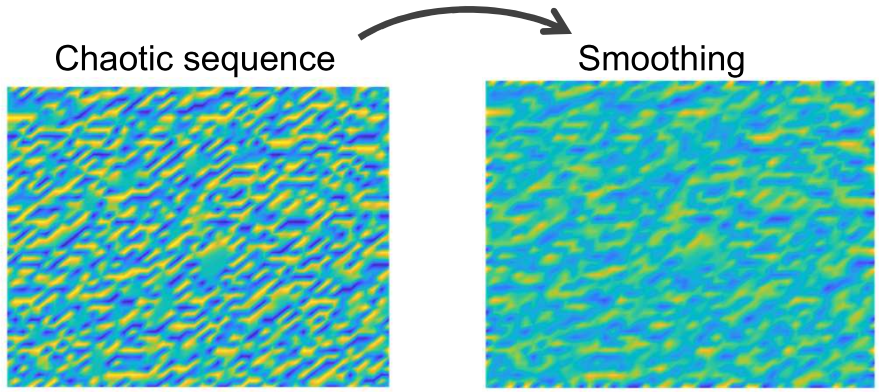


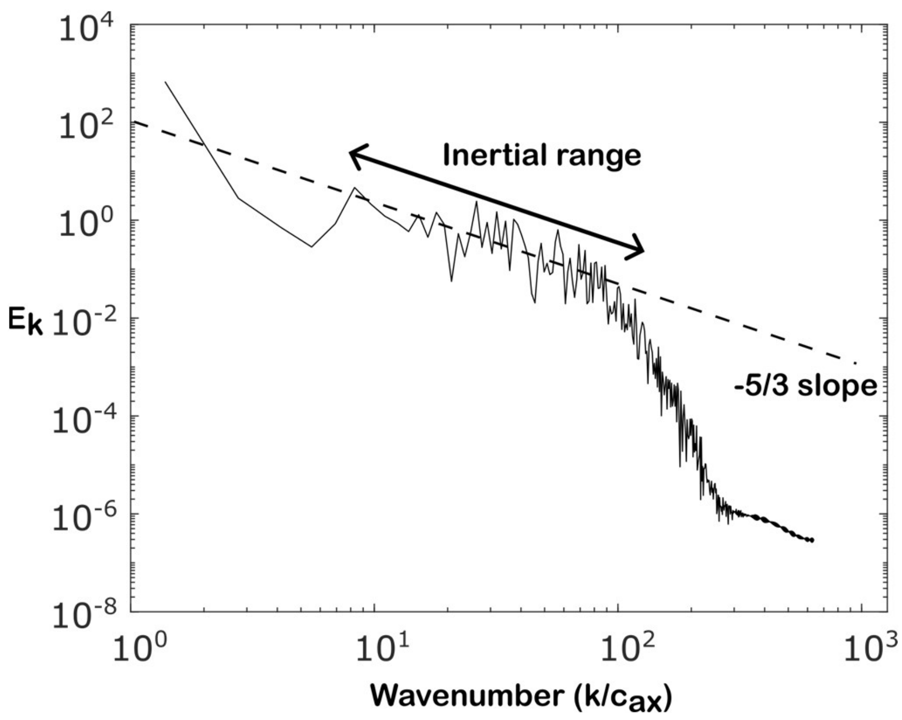
3DNS-gpu – inlet turbulence

- Filtered random number generators are expensive
- New way to generate turbulence using chaotic sequence

  $s_n = \sin(2 \pi s_{n-1})$

- Smoothing operation gives Gaussian correlation





3DNS-gpu – scaling performance

Strong scaling on 109M pt 9-block mesh

GPUs	Time per step (s)	Scaling Efficiency (%)
1	1.21	100
2	0.600	101
4	0.290	104

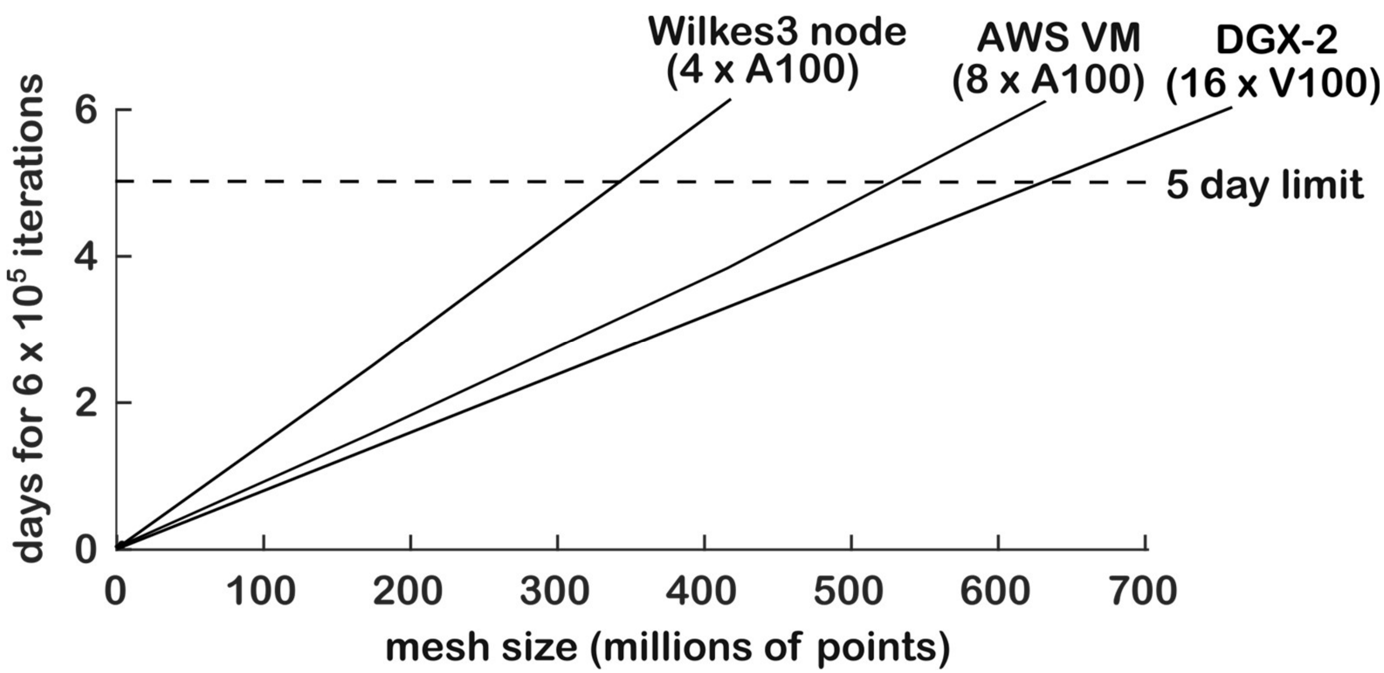
Weak scaling

GPUs	Mesh size (million points)	Time per step (s)	Scaling Efficiency (%)
1	109	1.21	100
4	436	1.16	104

Wilkes3 node
4 x NVIDIA A100
each with 80GB

thanks to Filippo Spiga

3DNS-gpu – public release runs in Amazon AWS



- Around 500 Million points can be run in 5 days on Amazon Cloud instance

Access to codes

Training & know-how

Tools to process & exploit data

Computer resources

Desktop DNS toolkit

- Public release of ***3DNS-gpu*** → Runs in the cloud
- Open toolkit for pre- and post-processing DNS → Step-by-step guide open source Jupyter Notebooks

Desktop DNS toolkit

- Public release of ***3DNS-gpu*** → Runs in the cloud
- Open toolkit for pre- and post-processing DNS → Step-by-step guide open source Jupyter Notebooks

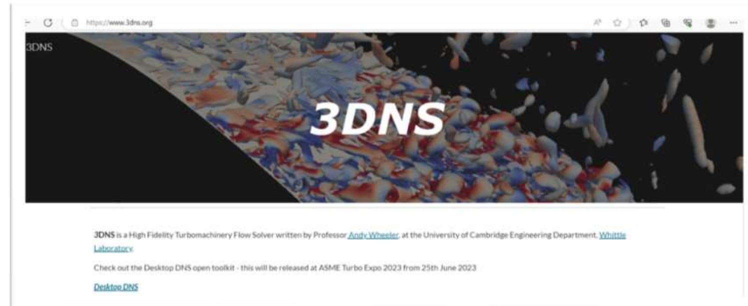
- **Public release limited to cascade geometries**
- **Some features disabled for public release – available on request**

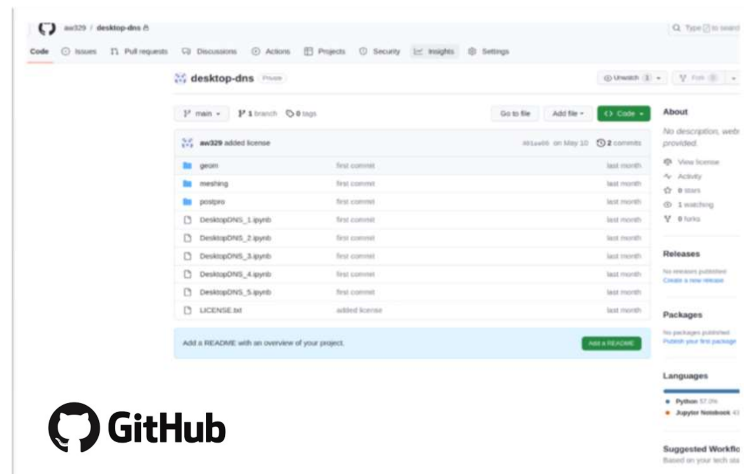
Desktop DNS toolkit

4 Jupyter notebooks:

1. Meshing and initial 2D simulation
2. 3D simulation, inlet turbulence, statistical convergence
3. Mesh sensitivity, statistics gathering, entropy budget analysis
4. RANS modelling

[3dns.org](3dns.org)





Access to codes

Training & know-how

Tools to process & exploit data

Computer resources

3DNS 3DNS

https://www.3dns.org

Sharing https://www.3dns.org to cambridgelectures.cloud.panopto.eu Stop sharing Share this tab instead

3DNS

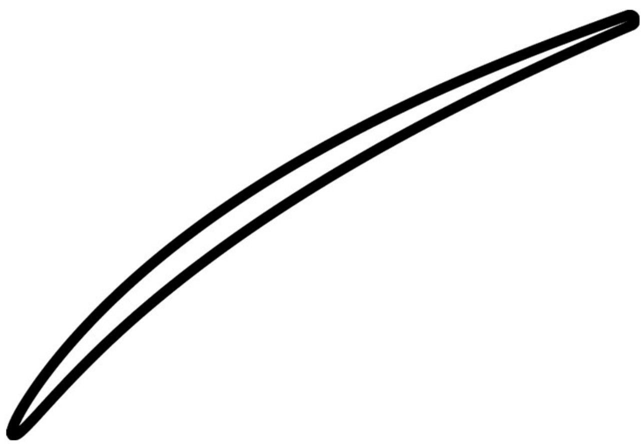
3DNS is a High Fidelity Turbomachinery Flow Solver written by Professor Andy Wheeler, at the University of Cambridge Engineering Department, Whittle Laboratory.

Check out the Desktop DNS open toolkit - this will be released at ASME Turbo Expo 2023 from 25th June 2023

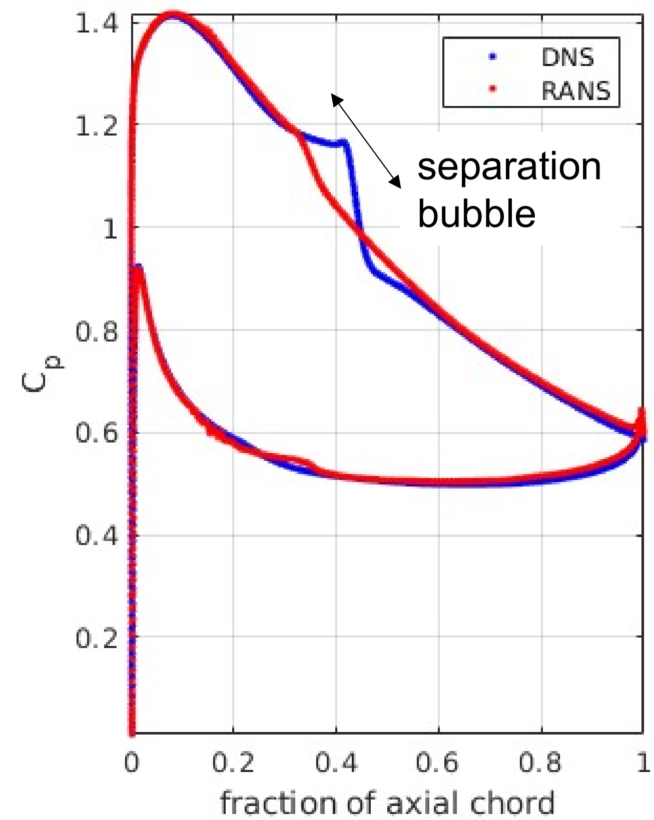
Desktop DNS

Desktop DNS - compressor cascade test case

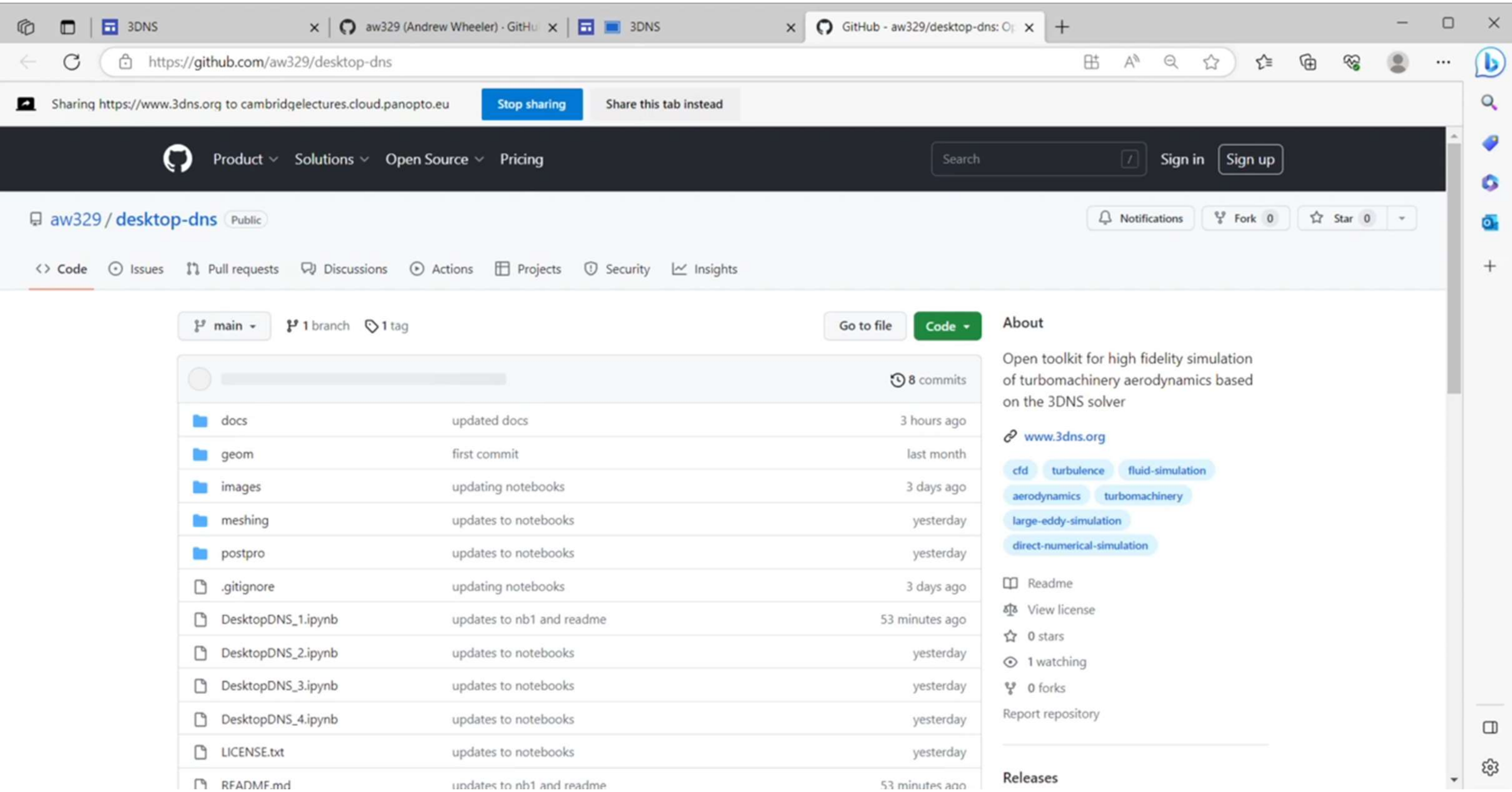
Industry standard Controlled Diffusion design*



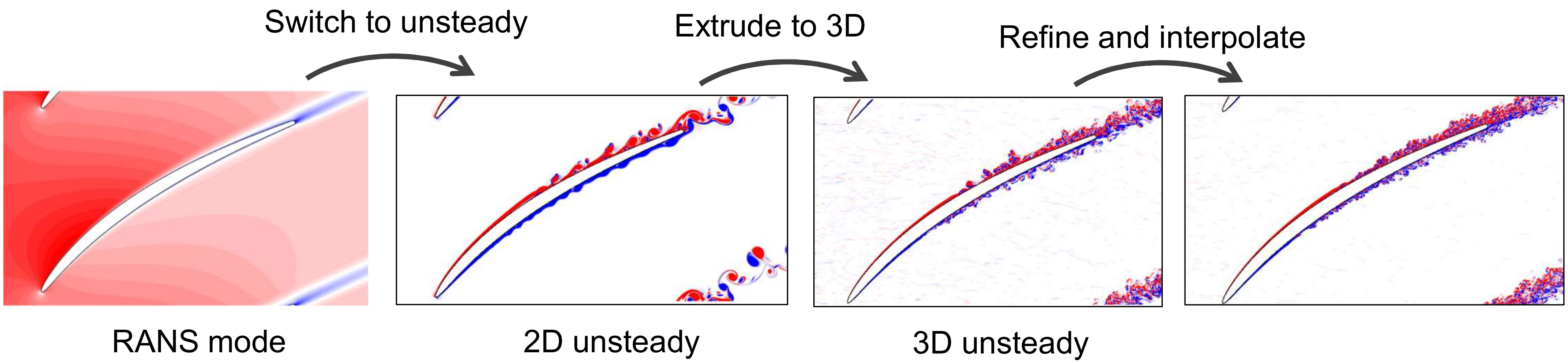
s/c_{ax}	α_{in}	α_{exit}	Re_{in}	M_{in}	Tu_{in}
0.72	50.2°	25.2°	2.33×10^5	0.2	0.4%



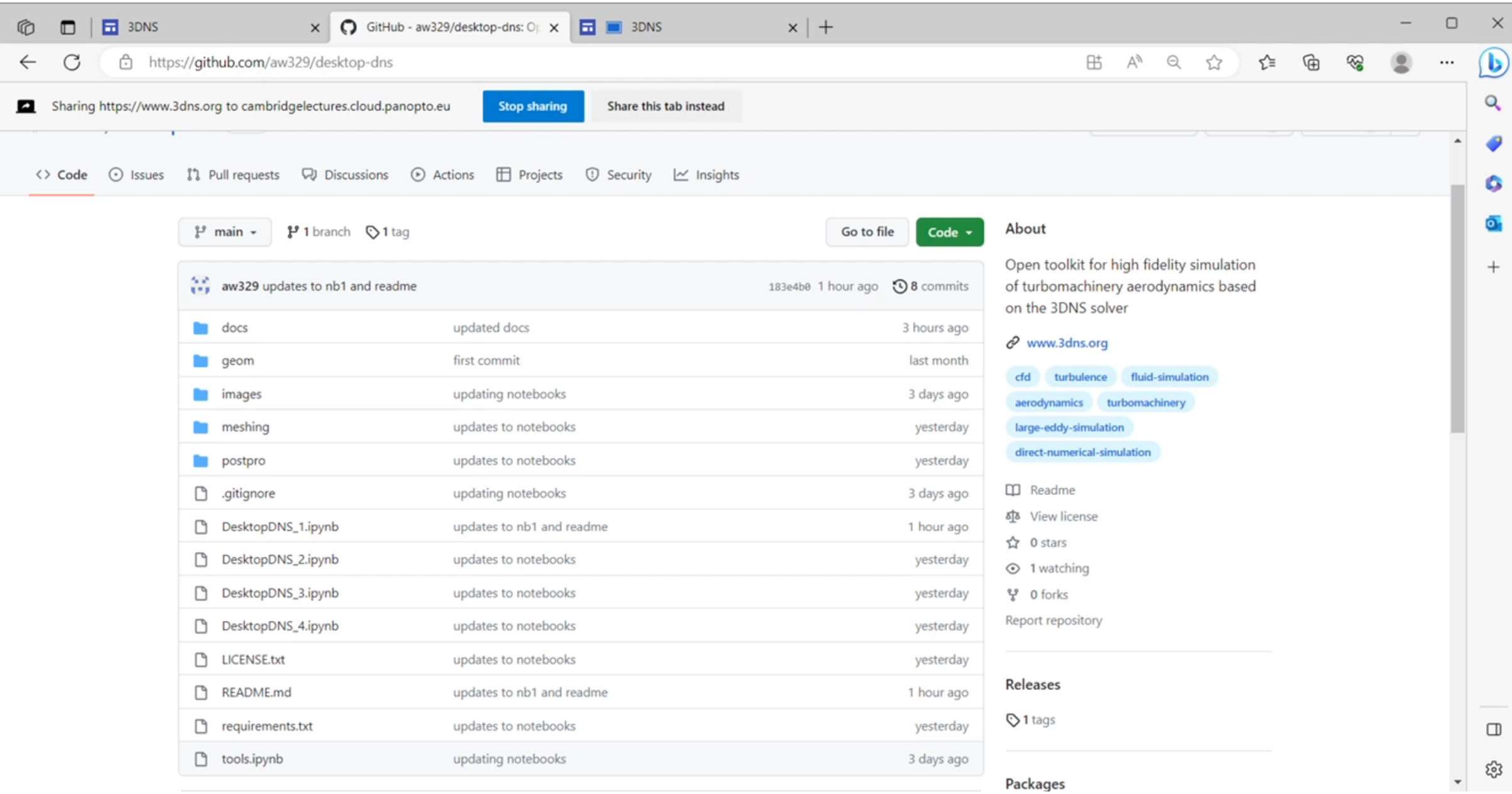
*Profile provided by Alistair Senior (Whittle Lab)


3DNS
aw329 (Andrew Wheeler) · GitHu
3DNS
GitHub - aw329/desktop-dns: O
https://github.com/aw329/desktop-dns
Sharing https://www.3dns.org to cambridgelectures.cloud.panopto.eu
Stop sharing
Share this tab instead
Product
Solutions
Open Source
Pricing
Search
Sign in
Sign up
aw329 / desktop-dns
Public
Notifications
Fork 0
Star 0
Code
Issues
Pull requests
Discussions
Actions
Projects
Security
Insights
main
1 branch
1 tag
Go to file
Code
8 commits
docs updated docs 3 hours ago
geom first commit last month
images updating notebooks 3 days ago
meshing updates to notebooks yesterday
postpro updates to notebooks yesterday
.gitignore updating notebooks 3 days ago
DesktopDNS_1.ipynb updates to nb1 and readme 53 minutes ago
DesktopDNS_2.ipynb updates to notebooks yesterday
DesktopDNS_3.ipynb updates to notebooks yesterday
DesktopDNS_4.ipynb updates to notebooks yesterday
LICENSE.txt updates to notebooks yesterday
README.md updates to nb1 and readme 53 minutes ago
About
Open toolkit for high fidelity simulation of turbomachinery aerodynamics based on the 3DNS solver
www.3dns.org
cfd
turbulence
fluid-simulation
aerodynamics
turbomachinery
large-eddy-simulation
direct-numerical-simulation
Readme
View license
0 stars
1 watching
0 forks
Report repository
Releases

Desktop DNS – meshing refinement



- Establishing flow on a coarse mesh and then successively interpolating to speed-up transients and determine mesh requirements


3DNS
GitHub - aw329/desktop-dns: O
3DNS
https://github.com/aw329/desktop-dns
Sharing https://www.3dns.org to cambridgelectures.cloud.panopto.eu
Stop sharing
Share this tab instead
Code
Issues
Pull requests
Discussions
Actions
Projects
Security
Insights
main
1 branch
1 tag
Go to file
Code
aw329 updates to nb1 and readme
183e4b0 1 hour ago
8 commits
docs updated docs 3 hours ago
geom first commit last month
images updating notebooks 3 days ago
meshing updates to notebooks yesterday
postpro updates to notebooks yesterday
.gitignore updating notebooks 3 days ago
DesktopDNS_1.ipynb updates to nb1 and readme 1 hour ago
DesktopDNS_2.ipynb updates to notebooks yesterday
DesktopDNS_3.ipynb updates to notebooks yesterday
DesktopDNS_4.ipynb updates to notebooks yesterday
LICENSE.txt updates to notebooks yesterday
README.md updates to nb1 and readme 1 hour ago
requirements.txt updates to notebooks yesterday
tools.ipynb updating notebooks 3 days ago
About
Open toolkit for high fidelity simulation of turbomachinery aerodynamics based on the 3DNS solver
www.3dns.org
cfd
turbulence
fluid-simulation
aerodynamics
turbomachinery
large-eddy-simulation
direct-numerical-simulation
Readme
View license
0 stars
1 watching
0 forks
Report repository
Releases
1 tags
Packages

Desktop DNS – determining solution quality

$$\underbrace{\rho \frac{Ds}{Dt} + \nabla \cdot \left(\frac{q}{T}\right)} = \frac{\phi}{T} + \dot{S}_N + \theta$$

irreversible entropy flux

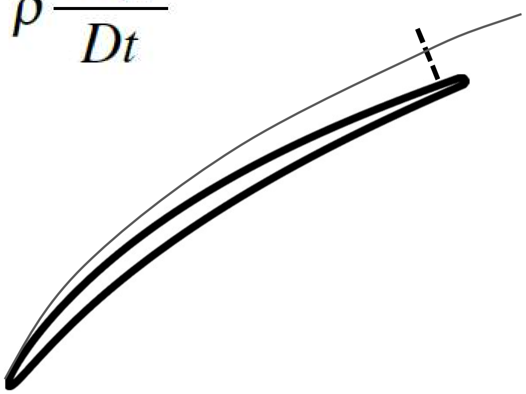
‘resolved’ dissipation – i.e. due to computed velocity gradients

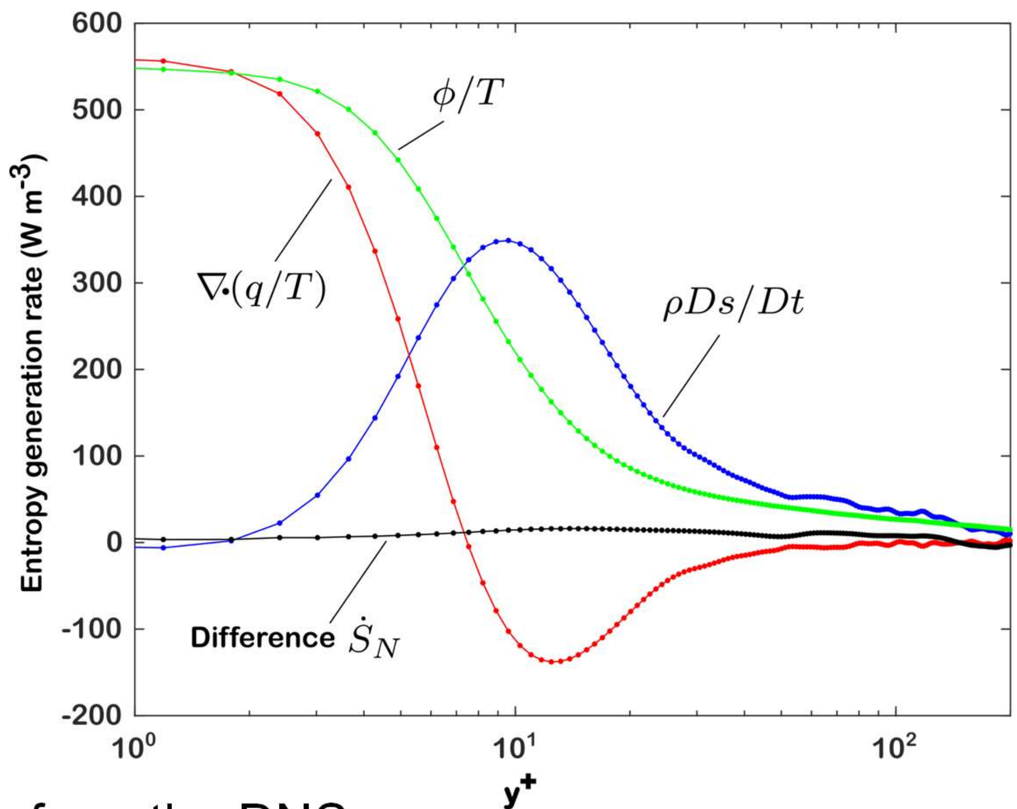
numerical dissipation

thermal term ≈ 0

Desktop DNS – entropy generation rate

$$\underbrace{\rho\frac{Ds}{Dt}+\nabla\cdot\left(\frac{q}{T}\right)}_{\rho\frac{Ds_{irr}}{Dt}}=\frac{\phi}{T}+\dot{S}_N$$





- Extracting the true loss mechanisms from the DNS
- Numerical dissipation (S_N) can be determined

651M point mesh

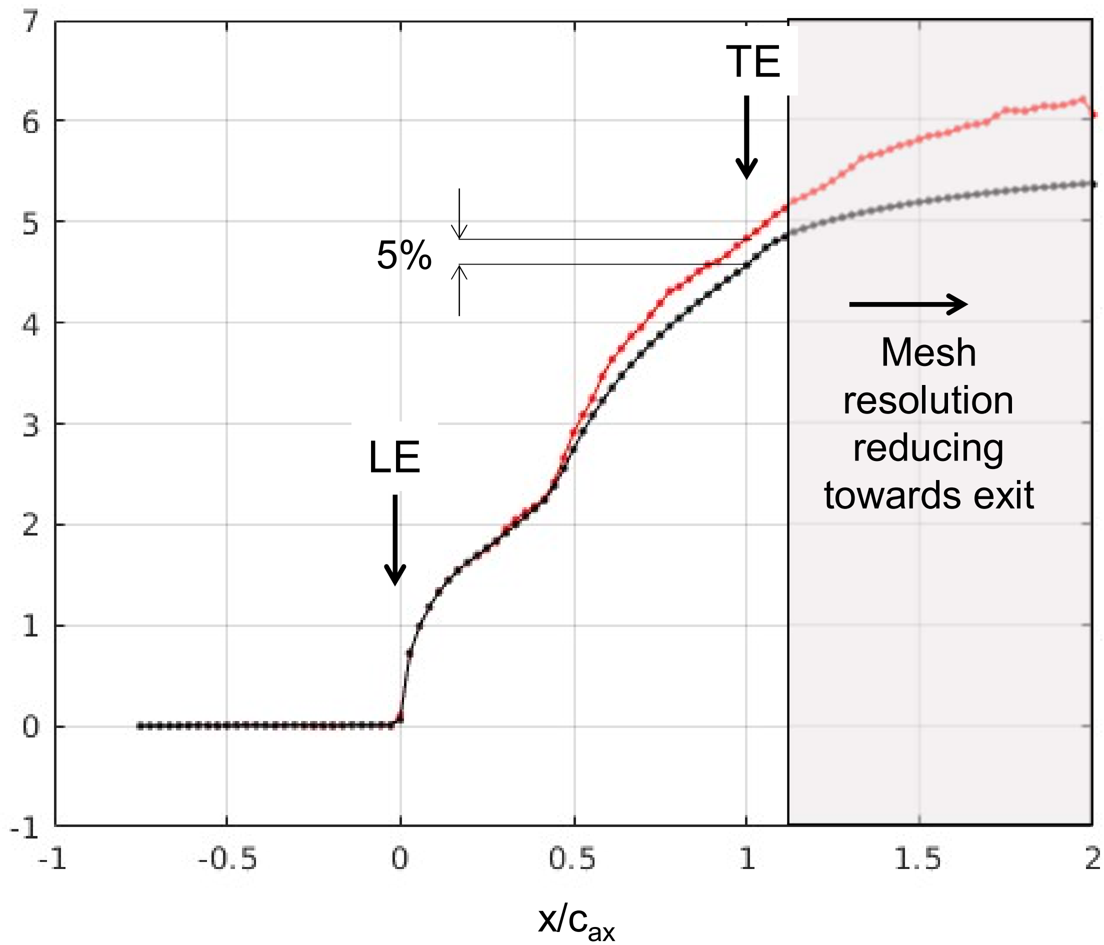
Desktop DNS – entropy rise

Entropy flux

$$\Sigma_{flux} = \int_{\Omega} \frac{Ds}{Dt} d\Omega$$

Resolved dissipation

$$\Sigma_{res} = \int_{\Omega} \frac{\phi}{T} d\Omega$$



651M point mesh

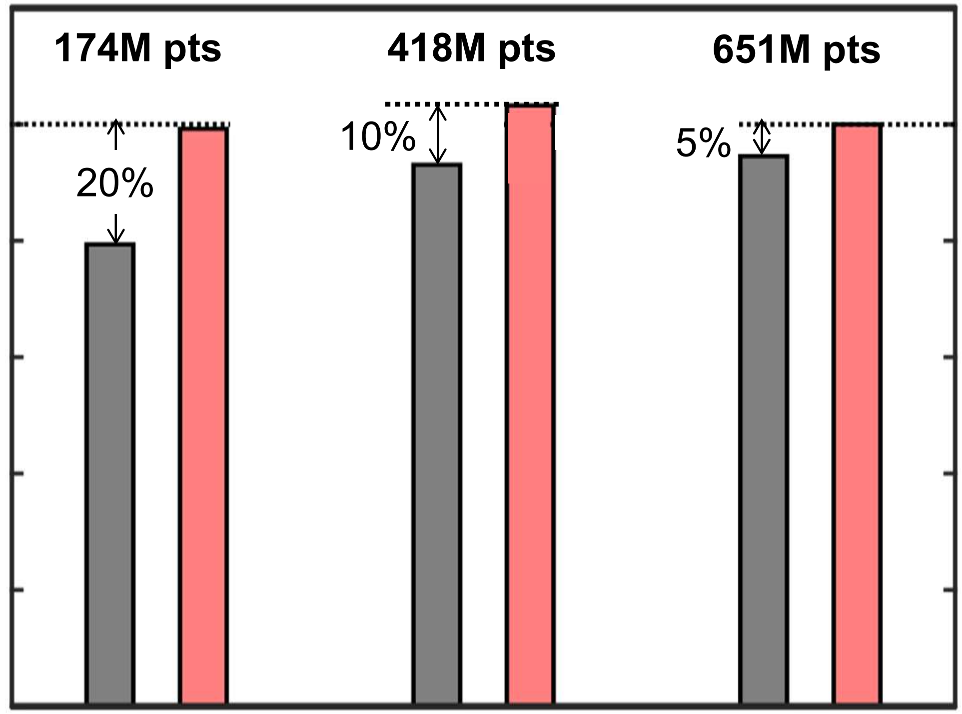
Desktop DNS – quality checks using entropy budget

Entropy flux

$$\Sigma_{flux} = \int_{\Omega} \frac{Ds}{Dt} d\Omega$$

Resolved dissipation

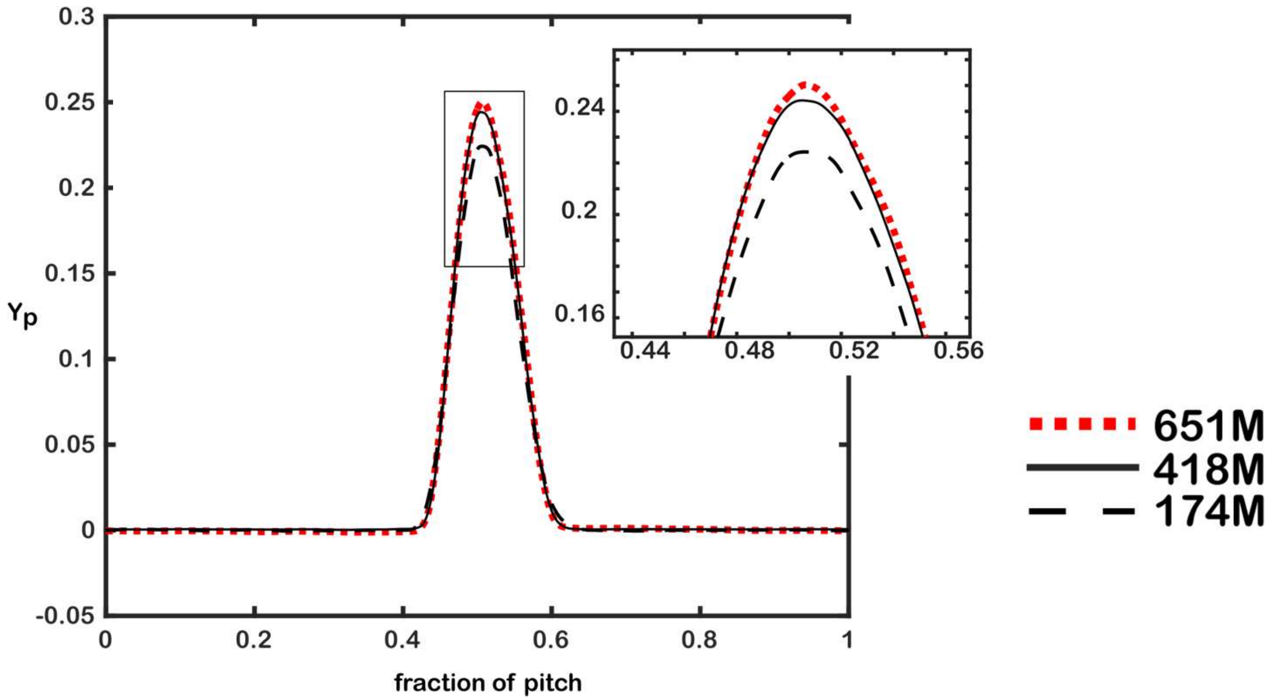
$$\Sigma_{res} = \int_{\Omega} \frac{\phi}{T} d\Omega$$



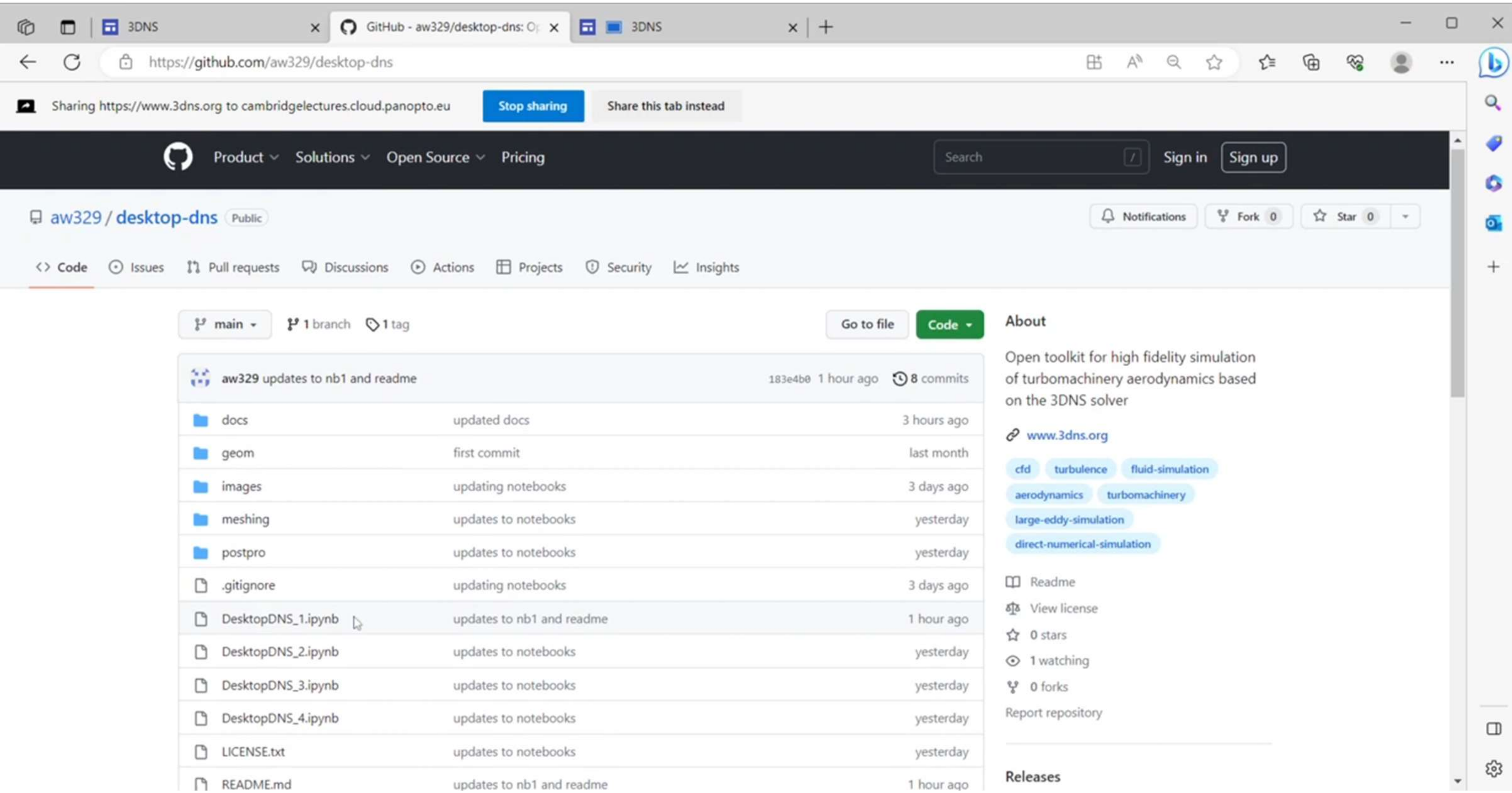
integration to x/c_{ax}=1.1

- Loss (entropy flux) less sensitive than resolved dissipation
- Little advantage in increasing resolved dissipation above 90%

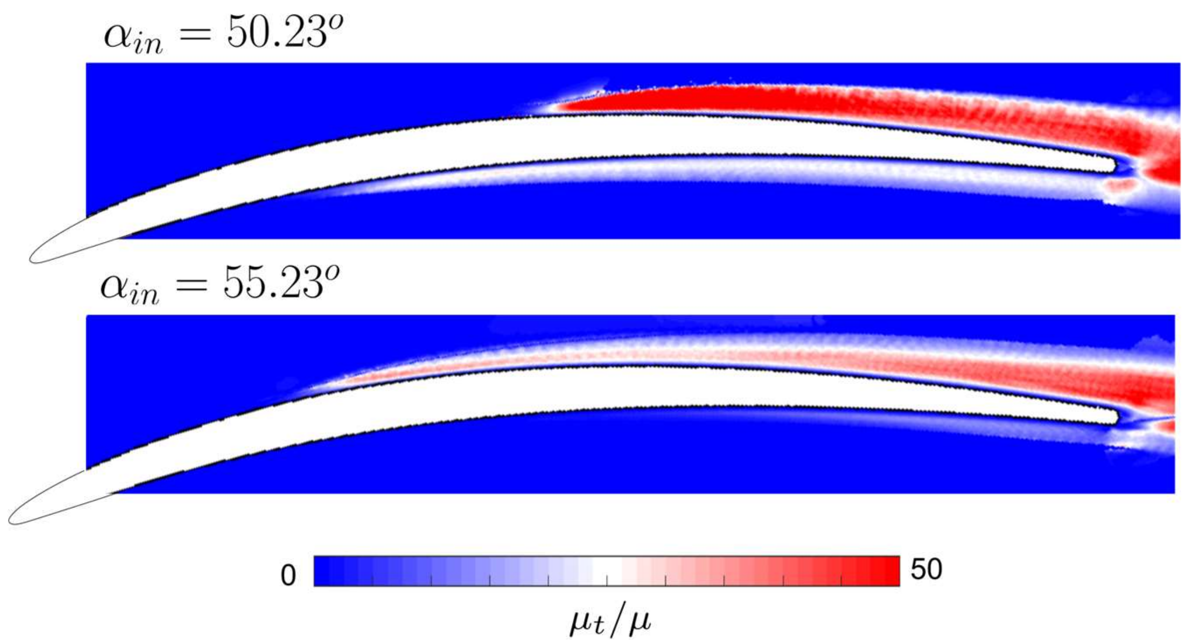
Desktop DNS – mesh sensitivity



- Mesh convergence achieved with 418M point mesh (90% resolved dissipation)


3DNS
GitHub - aw329/desktop-dns: O
3DNS
https://github.com/aw329/desktop-dns
Sharing https://www.3dns.org to cambridgelectures.cloud.panopto.eu
Stop sharing
Share this tab instead
Product
Solutions
Open Source
Pricing
Search
Sign in
Sign up
aw329 / desktop-dns
Public
Notifications
Fork 0
Star 0
Code
Issues
Pull requests
Discussions
Actions
Projects
Security
Insights
main
1 branch
1 tag
Go to file
Code
aw329 updates to nb1 and readme
183e4b0 1 hour ago
8 commits
docs | updated docs | 3 hours ago
geom | first commit | last month
images | updating notebooks | 3 days ago
meshing | updates to notebooks | yesterday
postpro | updates to notebooks | yesterday
.gitignore | updating notebooks | 3 days ago
DesktopDNS_1.ipynb | updates to nb1 and readme | 1 hour ago
DesktopDNS_2.ipynb | updates to notebooks | yesterday
DesktopDNS_3.ipynb | updates to notebooks | yesterday
DesktopDNS_4.ipynb | updates to notebooks | yesterday
LICENSE.txt | updates to notebooks | yesterday
README.md | updates to nb1 and readme | 1 hour ago
About
Open toolkit for high fidelity simulation of turbomachinery aerodynamics based on the 3DNS solver
www.3dns.org
cfd
turbulence
fluid-simulation
aerodynamics
turbomachinery
large-eddy-simulation
direct-numerical-simulation
Readme
View license
0 stars
1 watching
0 forks
Report repository
Releases

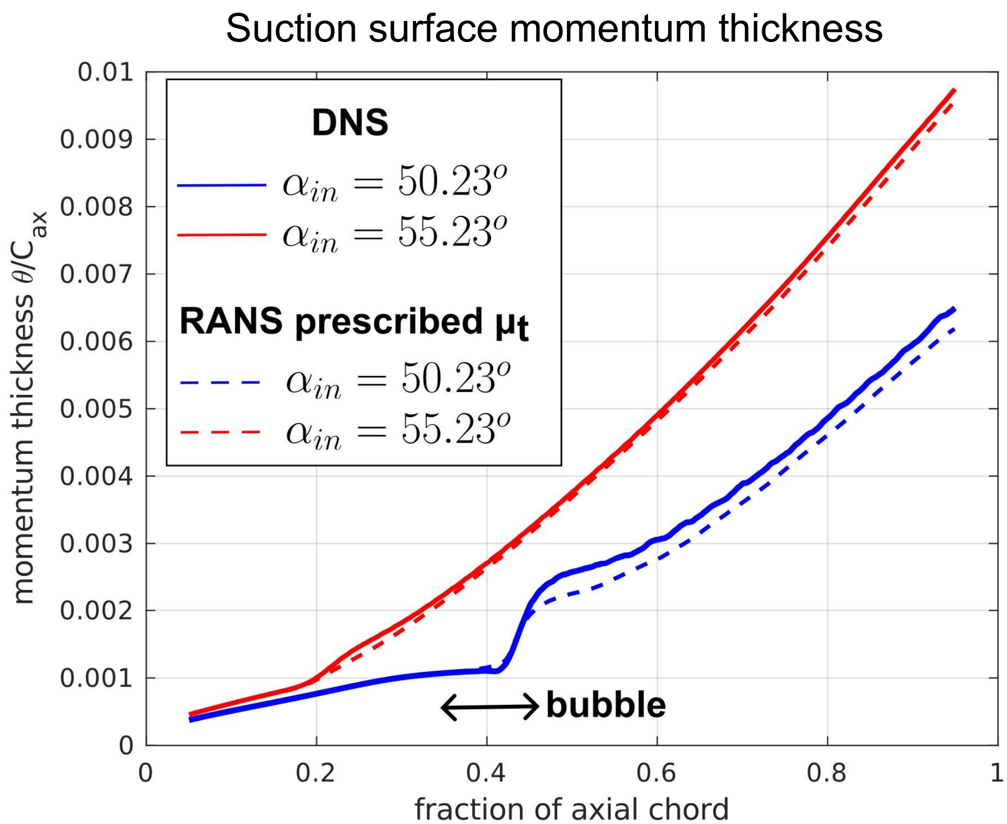
Desktop DNS – extracting eddy viscosity



- Optimum eddy viscosity minimizes the error in the Reynolds stress tensor*

*Michelassi et al, *J. Turbomach.* Vol. 137 No. 7 (2014)

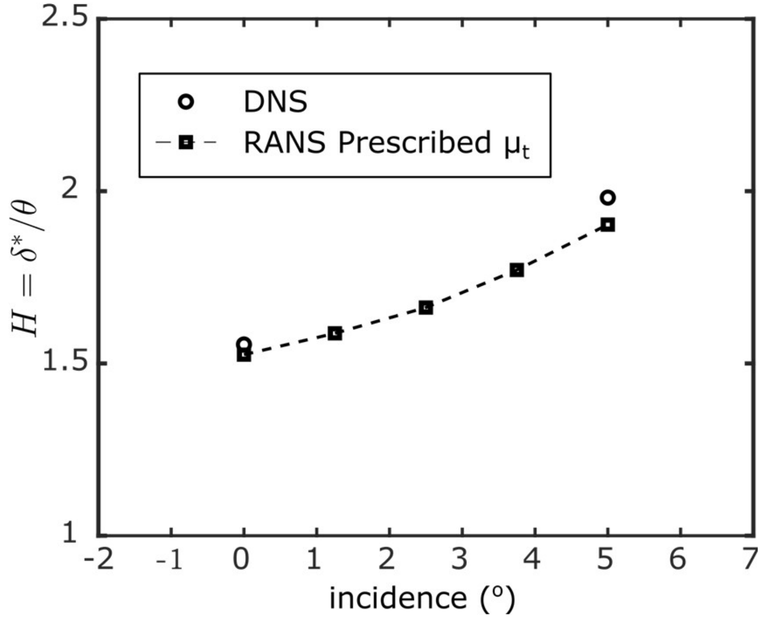
Desktop DNS – RANS modelling

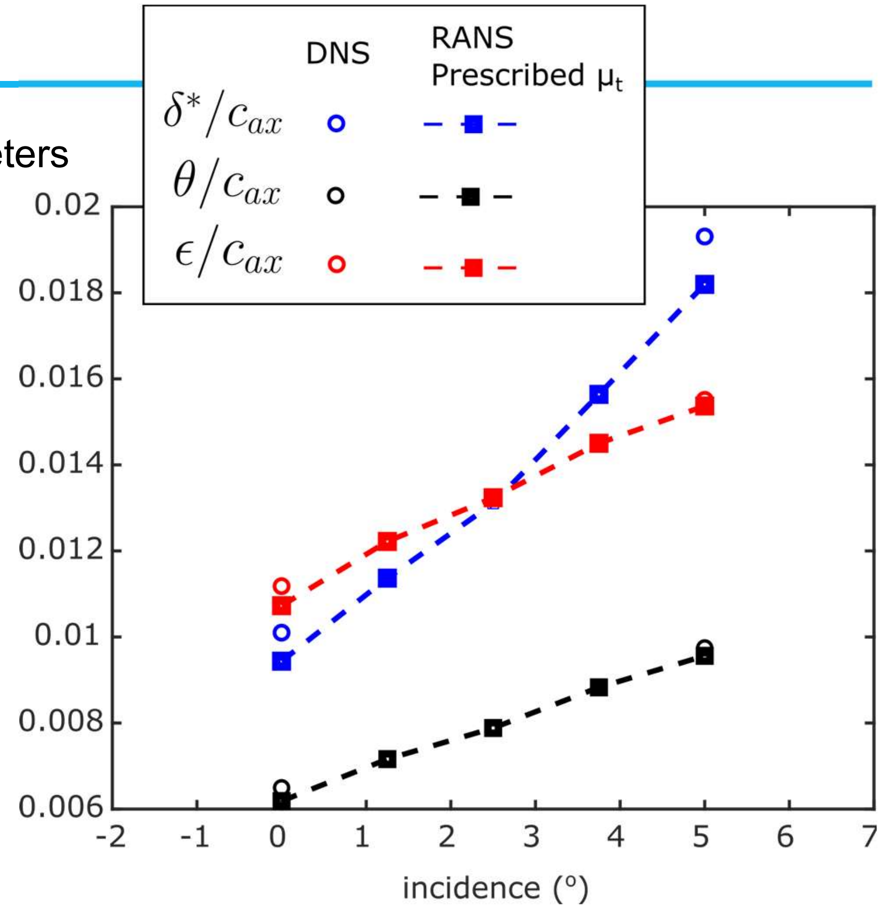


- Calibrated RANS captures effect of incidence

Desktop DNS – RANS modelling

Suction surface trailing-edge parameters





- Interpolating the eddy viscosity allows effects of incidence to be explored at low cost
- Possible to explore other parameters e.g. pitch-to-chord, diffusion style

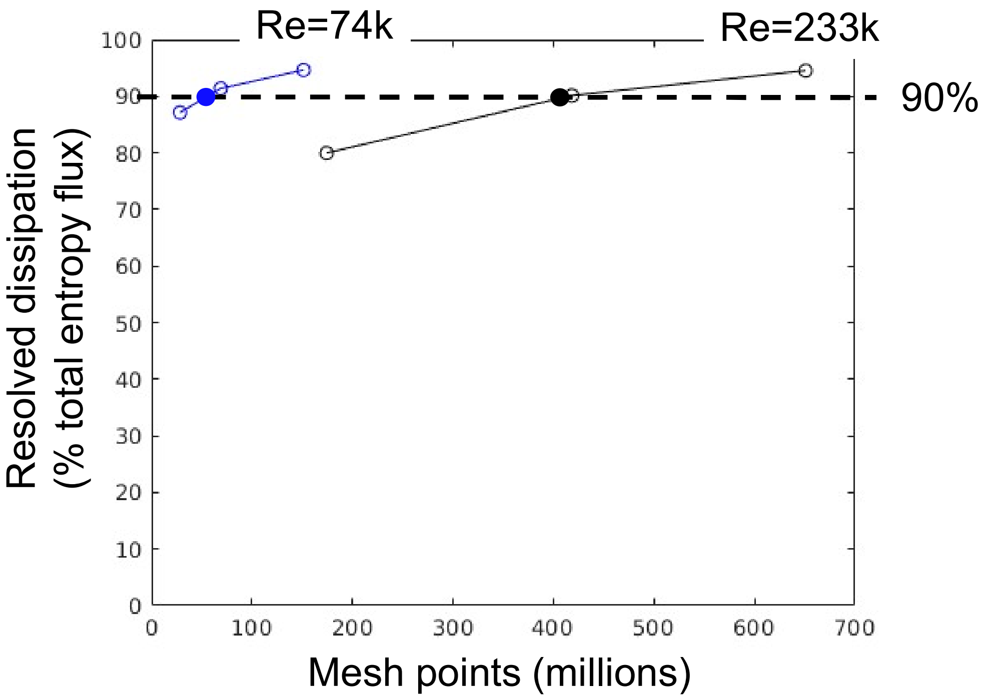
Access to codes

Training & know-how

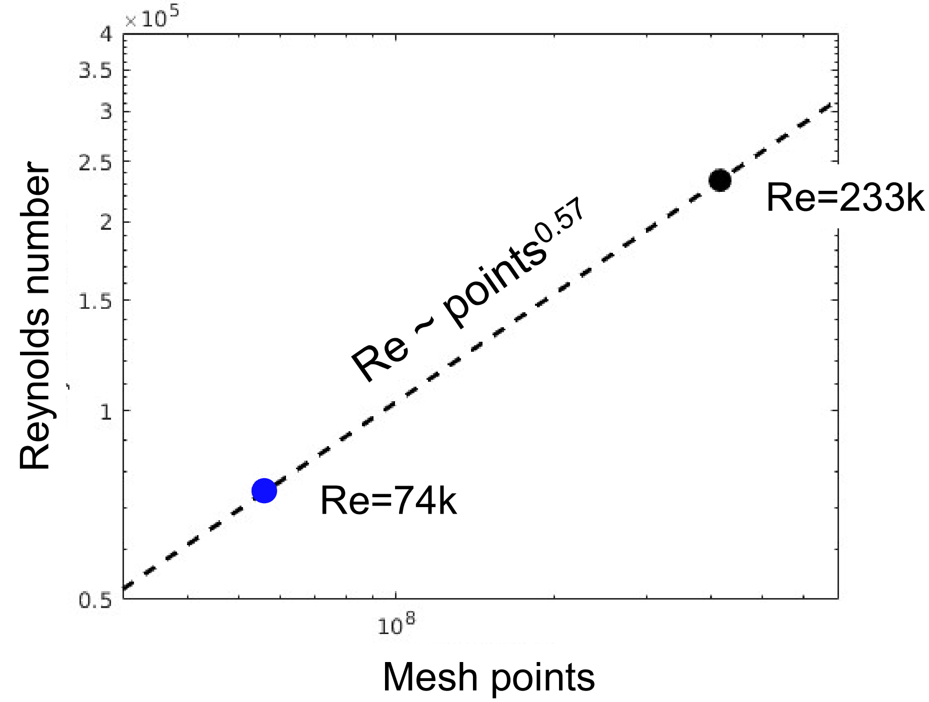
Tools to process & exploit data

Computer resources

Scaling with Reynolds number



Required points to achieve 90% threshold



- For this case achievable Re scales with points$^{0.57}$

Running DNS in the cloud – how much does it cost today?

Achievable Reynolds number and costs for cascade simulations

Mesh points ($x10^6$)	**Reynolds number**	**Compute time (hrs)**	**Cost on AWS***
30	50,000	6	$55
70	80,000	15	$140
150	130,000	33	$290
400	230,000	95	$840
650	300,000	147	$1300

- Performing a DNS to de-risk a new design is now relatively affordable

*approximate spot price on AWS
p4d.24xlarge instance (8 x A100 GPUs)
600,000 iterations, span=10% axial chord

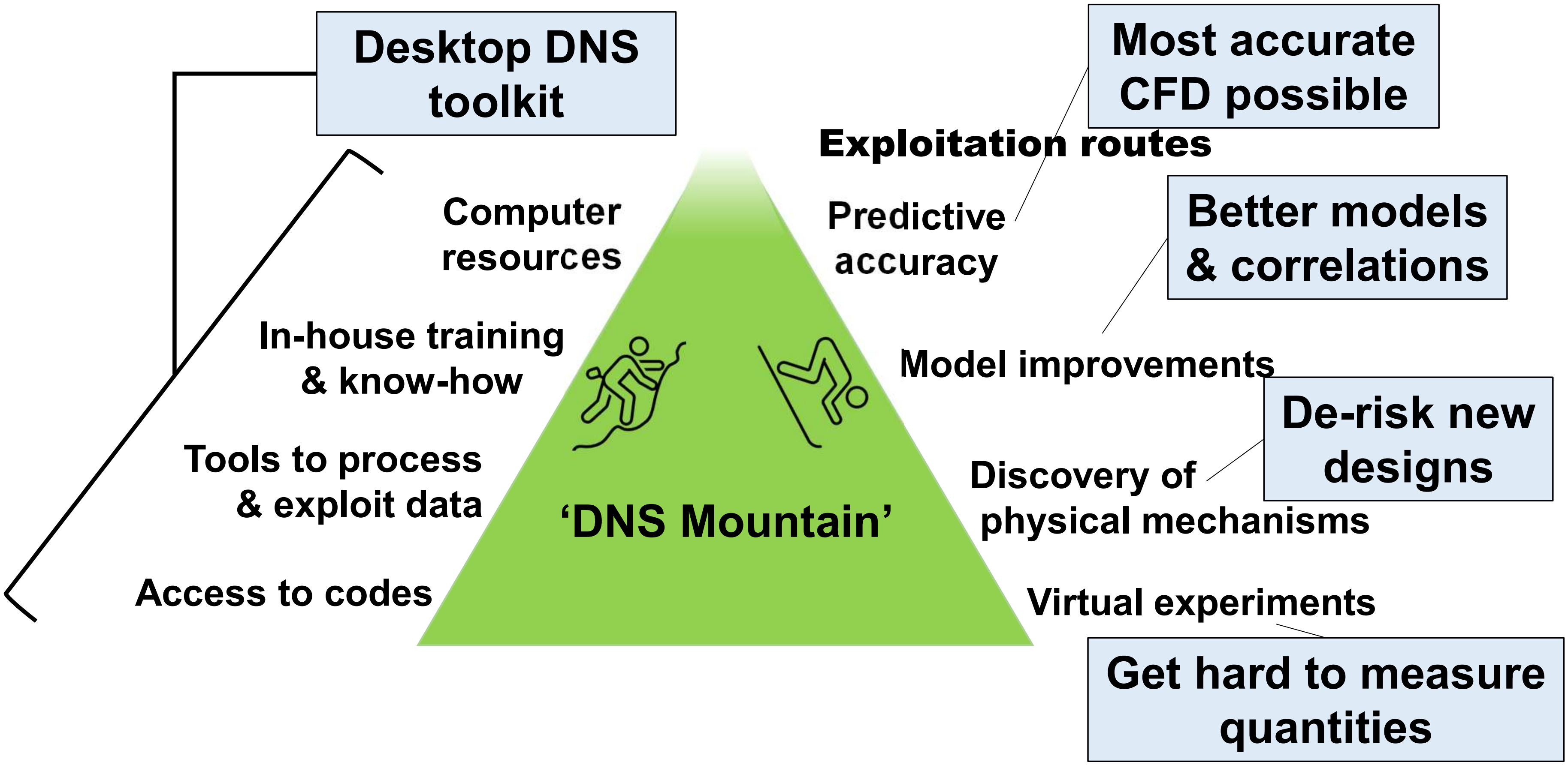
What might be possible in the next 5 years?

10 x increase in compute power every 5 years

Reynolds number
50,000
80,000
130,000
230,000
300,000

Compute time in 2028 (hrs)	Cost in 2028
0.6	$5.5
1.5	$14
3.3	$29
9.5	$84
14.7	$130

- Over next 5 years many engine components will be accessible with DNS
- Designers need tools and training to exploit this



- Follow links at 3dns.org for non-commercial use
- Get in touch for commercial use