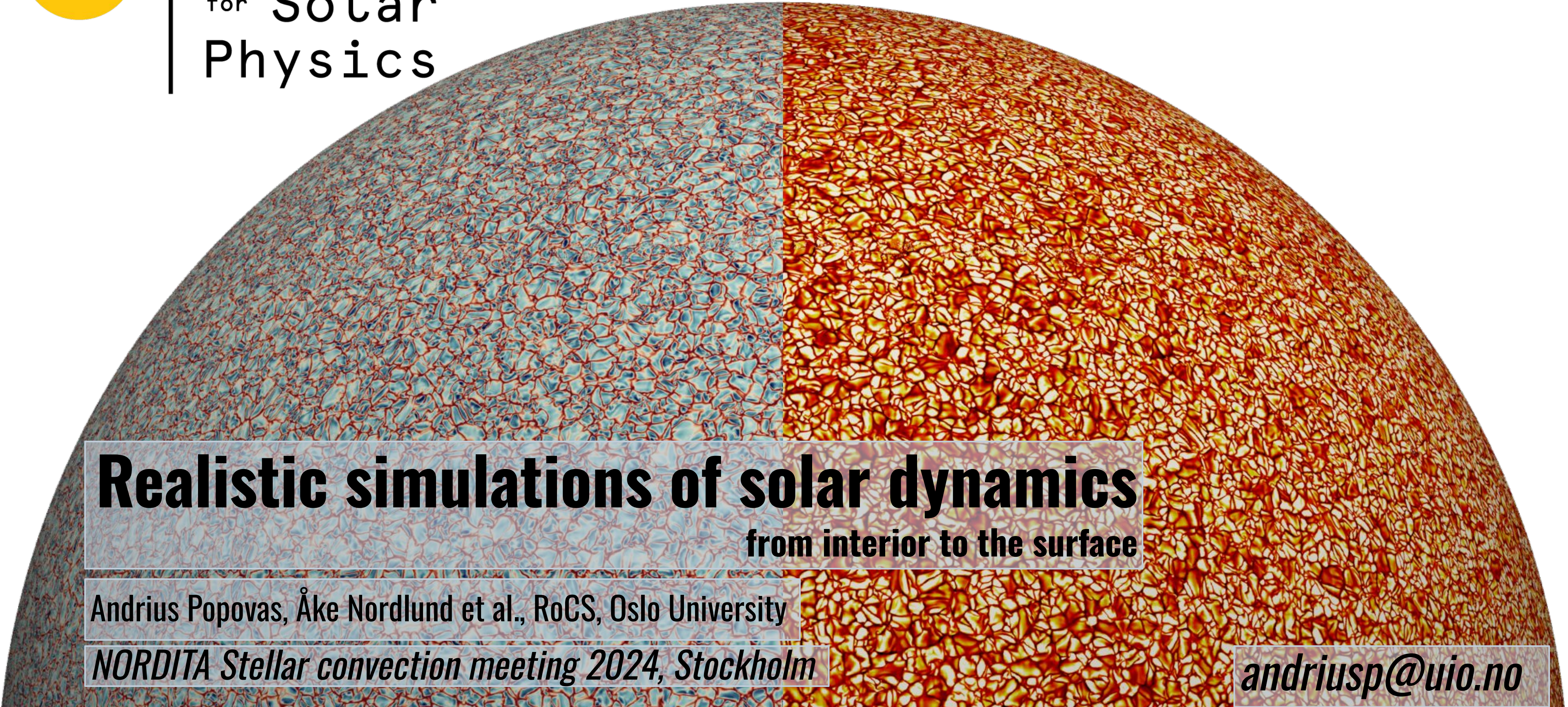
Rosseland Centre for Solar Physics

Realistic simulations of solar dynamics

from interior to the surface



Andrius Popovas, Åke Nordlund et al., RoCS, Oslo University

NORDITA Stellar convection meeting 2024, Stockholm

andriusp@uio.no

WHOLE
European Research Council
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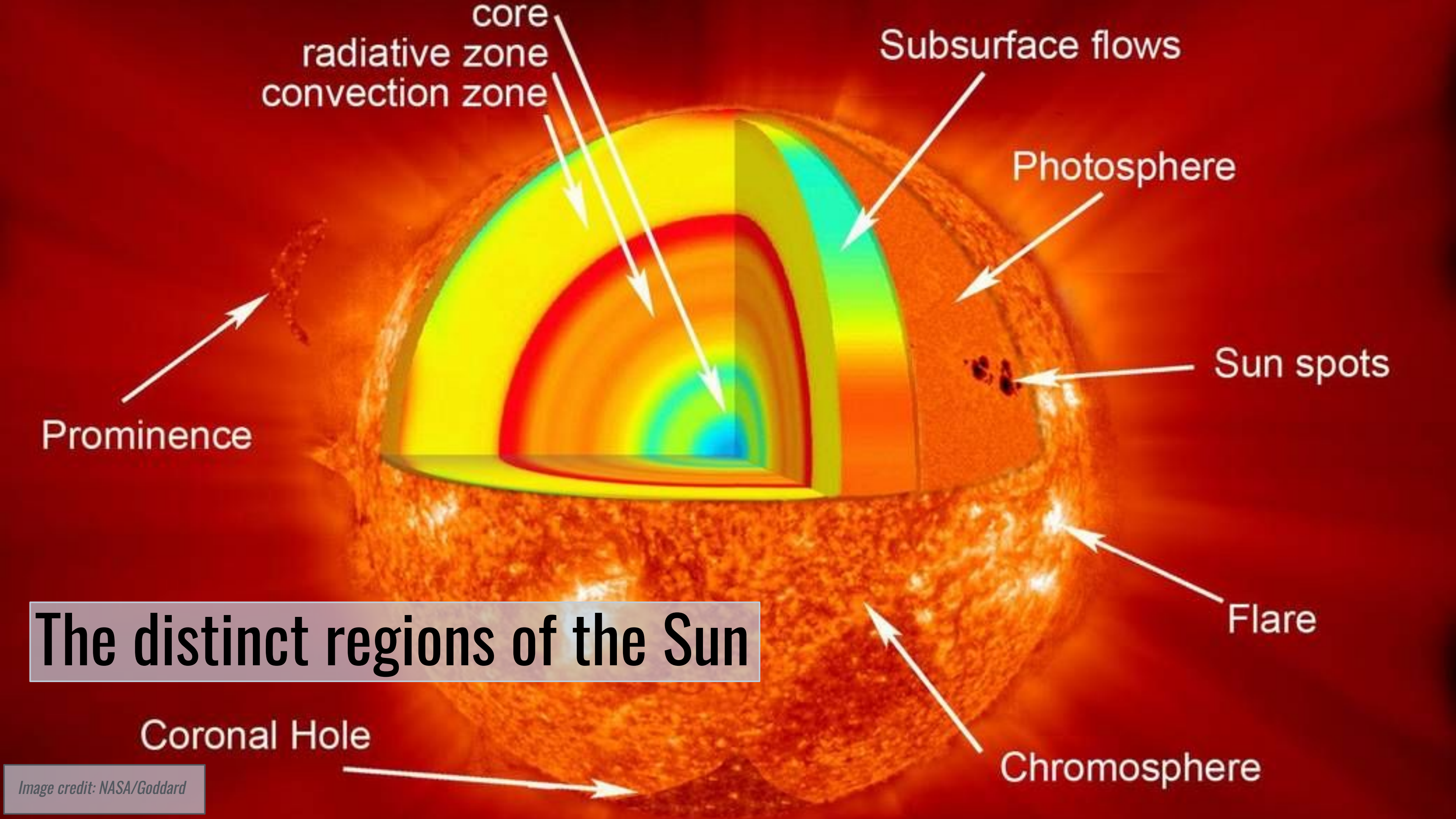
LUMI



The distinct regions of the Sun

Image credit: NASA/Goddard

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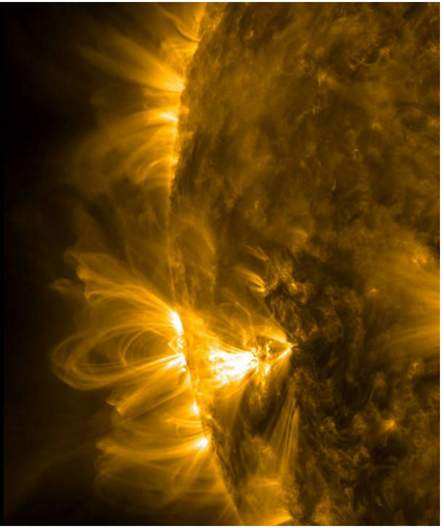
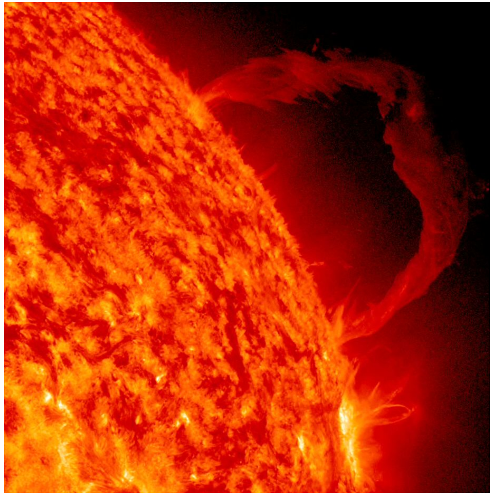
The scales in the Sun

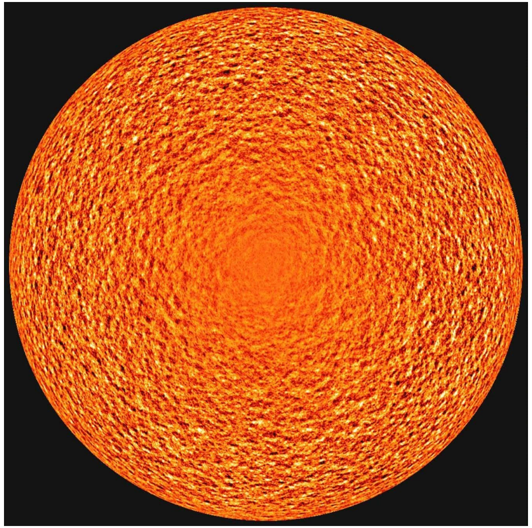
Image credit:
NASA/Solar Dynamics Observatory
SOHO/MDI/ESA
Luc Rouppe van den Voort



Coronal loops ~ 100 Mm
(Reale, 2014)

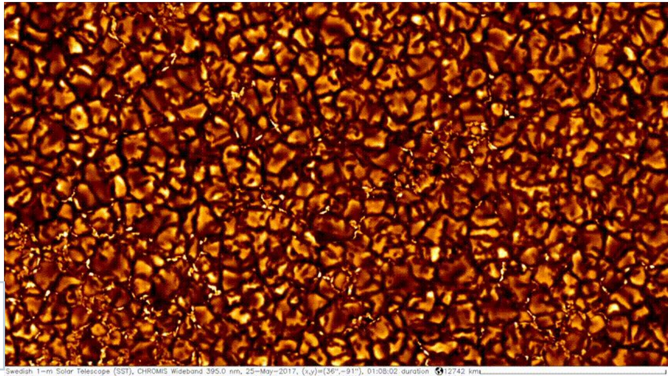


Prominences ~ 10 – 100 Mm
(Parenti, 2014)



Supergranulation ~ 30 – 50 Mm (Nordlund et al., 2009; Rincon & Rieutord, 2014)

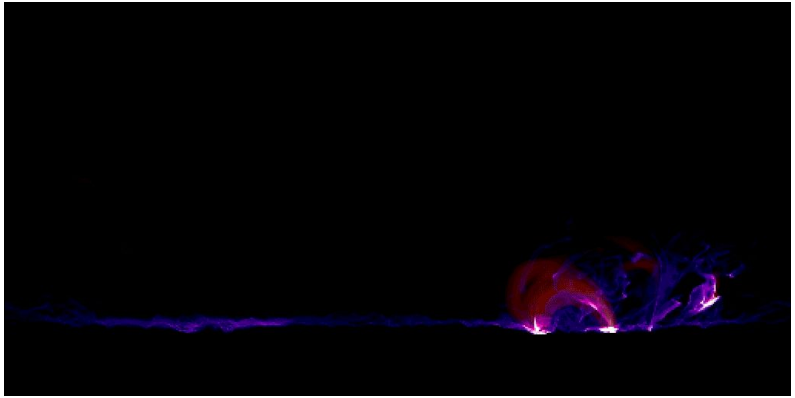
Pressure scale height through the convection zone varies ~ 5 orders of magnitude

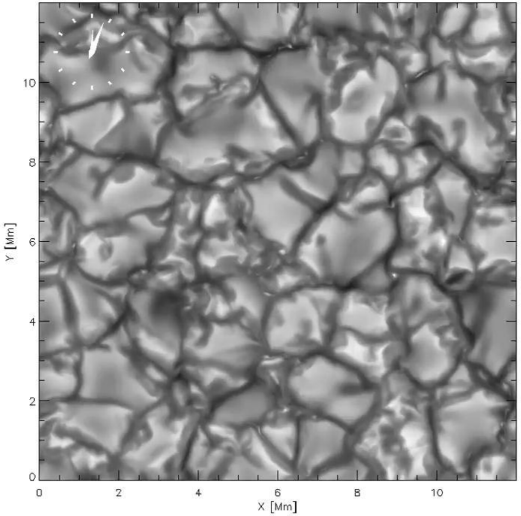


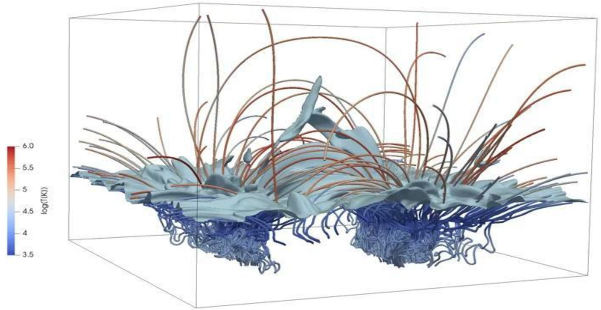
Surface convection cell size ~ 1 Mm

Surface simulations of the Sun

- ➢ Magnetic fields
- ➢ Investigations of spectral lines and chemical abundances
- ➢ Addition of chromosphere and corona
- ➢ Generation of waves
- ➢ Flux emergence
- ➢ Data-driven simulations



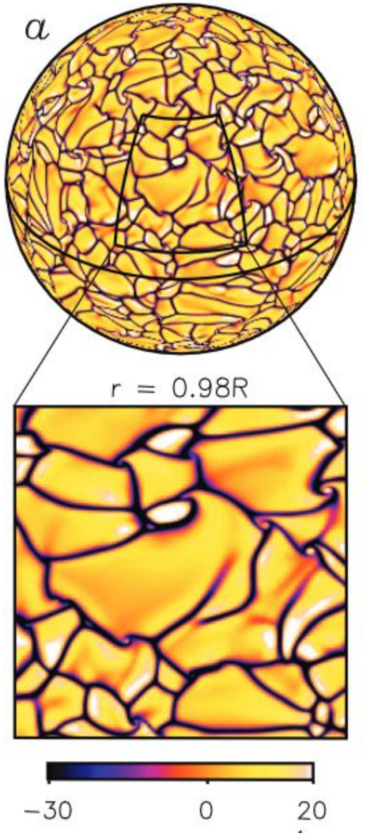


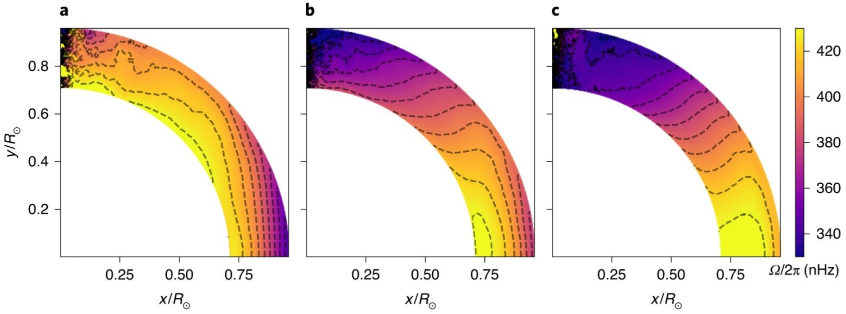


Video credit:
Carlsson et al. (2016)
Cheung et al., Nature Atronomy (2019)
Kohutova et al. (2020)

Solar interior simulations

- ➢ Coherent downflow structures associated with giant cells play a significant role in maintaining the differential rotation
  (Miesch et al., 2008)
- ➢ Successfully reproduced the solar differential rotation.
  (Hotta & Kusano 2021; Hotta et al., 2022)
- ➢ Magnetism and a near-surface shear layer may be necessary to accurately simulate the solar interior
  (Guerrero et al., 2022)





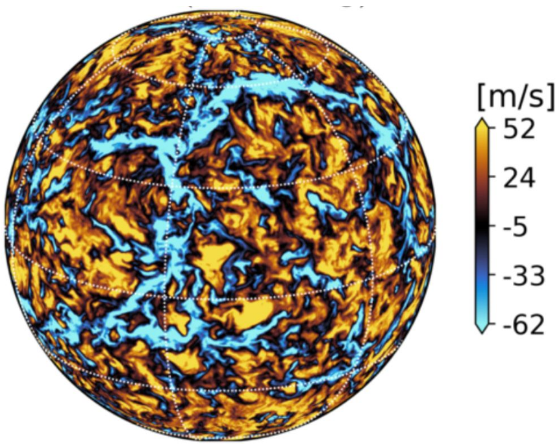
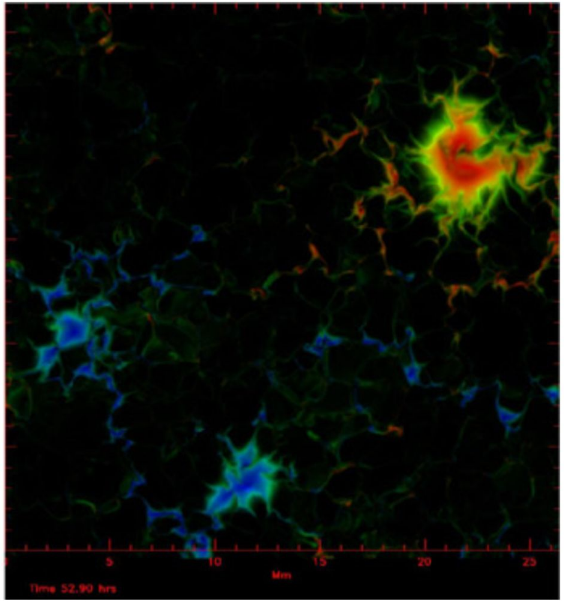


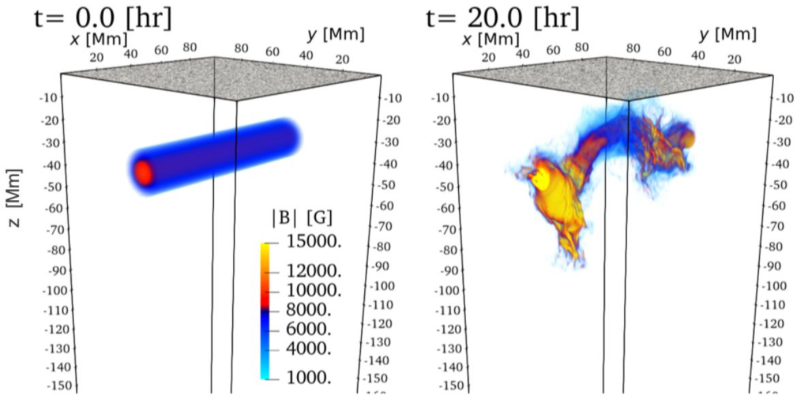
Image credit:
Miesch et al. (2008)
Hotta & Kusano (2021)
Guerrero et al., (2022)

Extended box simulations

Image credit:
Stein & Nordlund (2016)
Hotta et al. (2020)

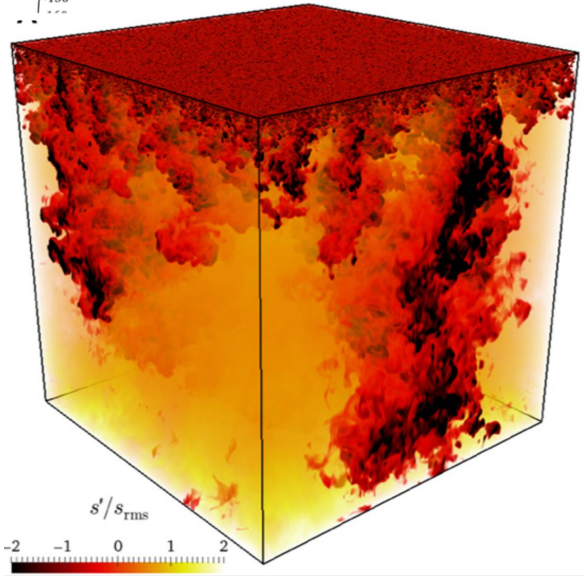


Magnetoconvection itself can produce the flux tubes that give rise to active regions
(Stein & Nordlund, 2012)



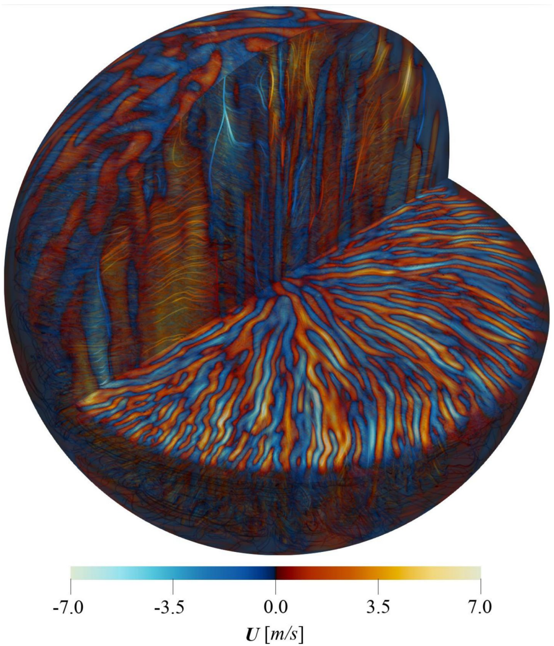
Indications that a deep simulation domain is needed for realistic flux emergence simulations
(Hotta et al., 2020)

Surface region has an unexpectedly weak influence on the deep convection zone
(Hotta et al., 2019)



Stellar interior simulations

- ➢ Large similarities between partially and fully convective stars when it comes to generating differential rotation and large-scale magnetism
  (Käpylä, 2021)
- ➢ Different $\Omega_\star$ results in different differential rotation profiles
  (Brun et al., 2017)
- ➢ The change in $\Omega_\star$ also lead to a transition in the nature of the dynamo processes (cyclical or not, *Brun et al., 2022*)



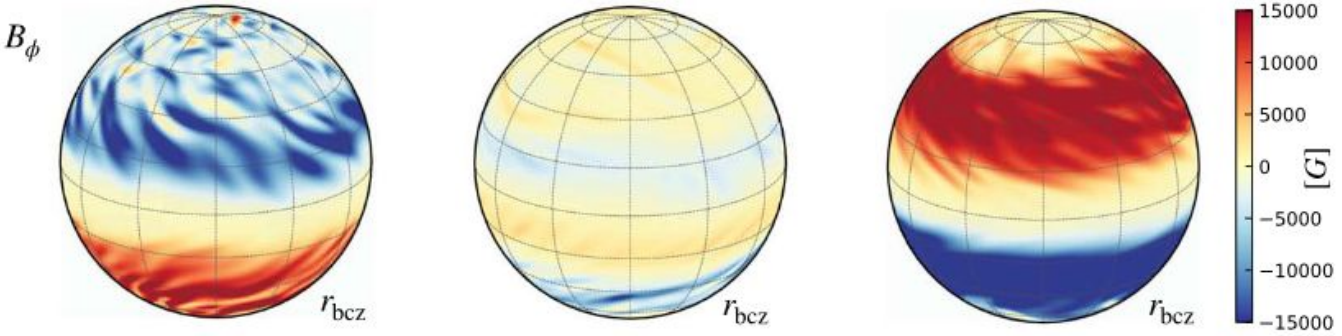


Image credit:
Käpylä (2021)
Brun et al. (2022)

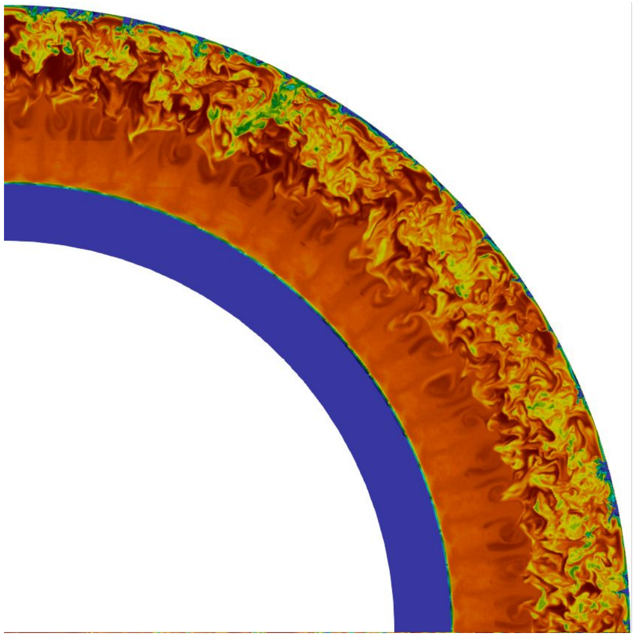
Challenges

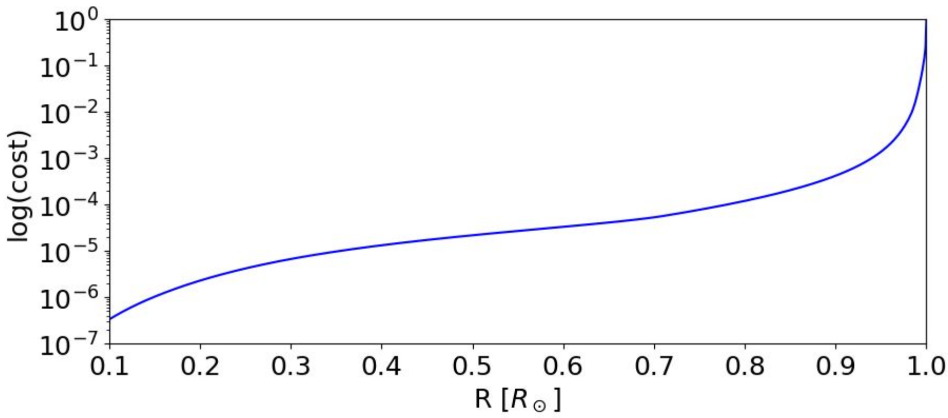
- ➢ Extreme computational cost.
- ➢ Modified partial differential equations ➪ incorrect sound wave propagation.
- ➢ Dynamo simulations fail to self-consistently generate sunspots *(Käpylä et al., 2023)*.
- ➢ Mismatch with observations (e.g. the 'convective conundrum').
- ➢ Dynamo simulations have upper boundaries too far below the surface.
- ➢ Cartesian boxes are not very suitable to maintain a spherical hydrostatic equilibrium.
- ➢ Spherical coordinates have singularities at the poles.
- ➢ Ad-hoc boundary conditions impose arbitrary artificial effects.

Global vs local timestep

➢ In the solar interior the scale height and local speed of sound varies with many orders of magnitude ➪ Global timestep unfeasible.

➢ In the photosphere and above – supersonic turbulence, shocks and magneto-acoustic waves ➪ Global timestep prohibitively expensive.





We take the speed of sound at the bottom of a patch and estimate how many updates it would take to get to one time unit. Then multiply this number by the total number of patches per layer. Lastly, this number is normalized by the total cost

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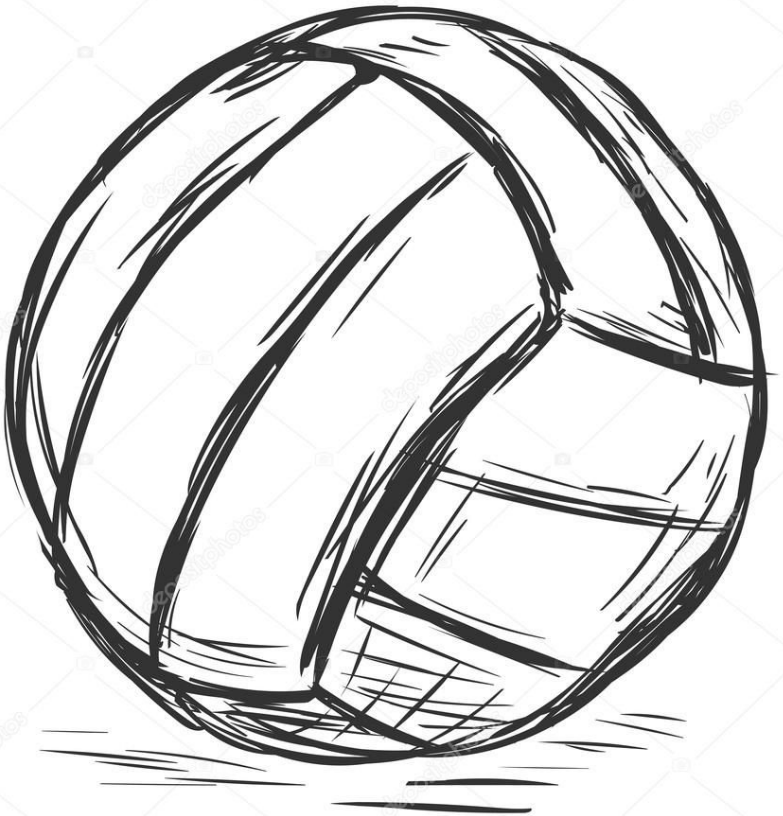
The **DISPATCH** framework

- ➢ *Local timesteps*
  - local Courant conditions ➪ great cost savings
- ➢ *Solver agnostic*
  - We are using an entropy-based HLLD Riemann solver *(Popovas, A&A submitted.)*
- ➢ *Nearest neighbour* communications
  - gives theoretically unlimited scaling
- ➢ *Curvilinear meshes*
  - We are using a Volleyball mesh decomposition
- ➢ Can use *Static & Adaptive Mesh Refinement*
  - local Courant conditions ➪ even greater cost savings
- ➢ *Flexible additional physics handling*
  - Can be very experiment-dependent

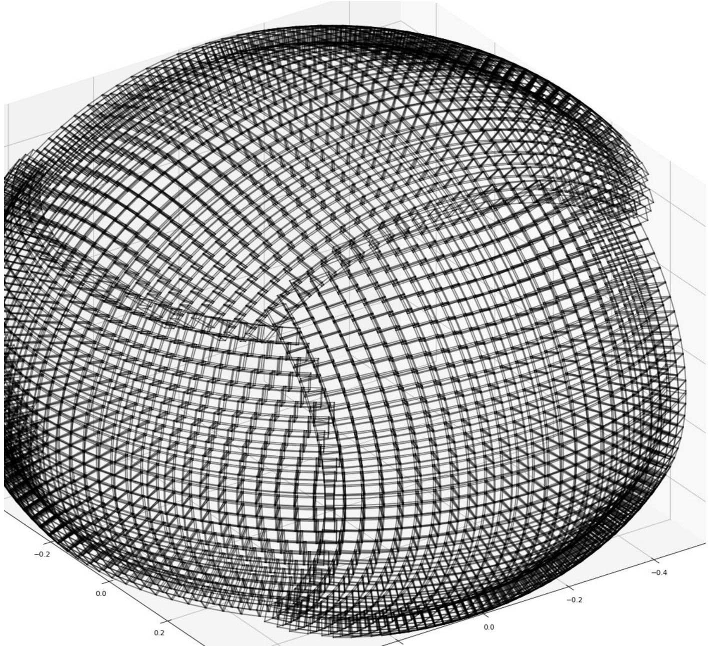
Nordlund, Ramsey, Popovas & Küffmeier, MNRAS 477, 624 (2018)

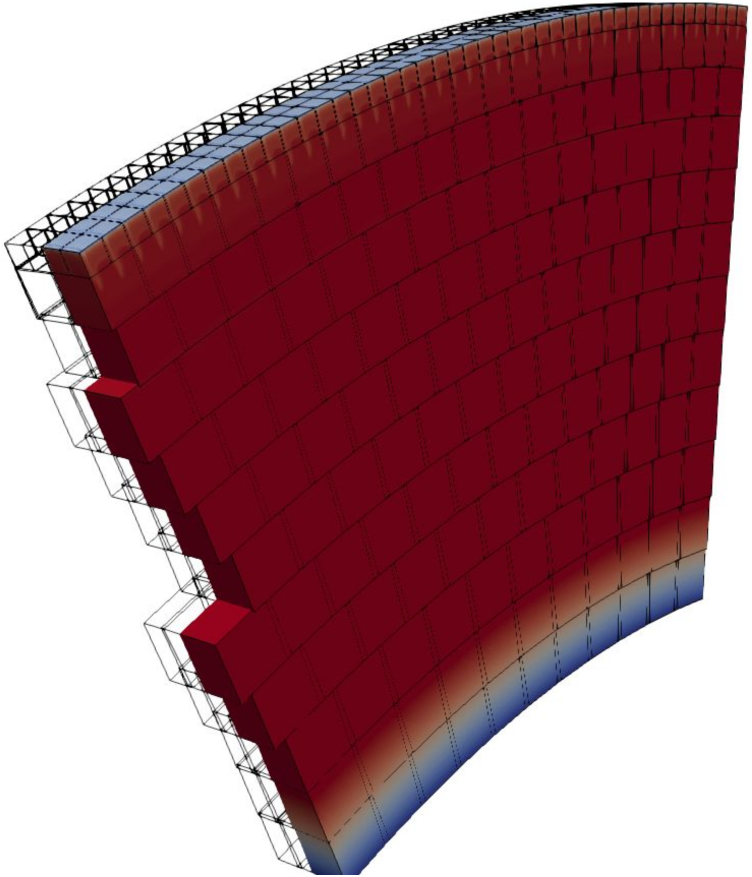
The ‘volleyball’ domain decomposition



The ‘volleyball’ domain decomposition

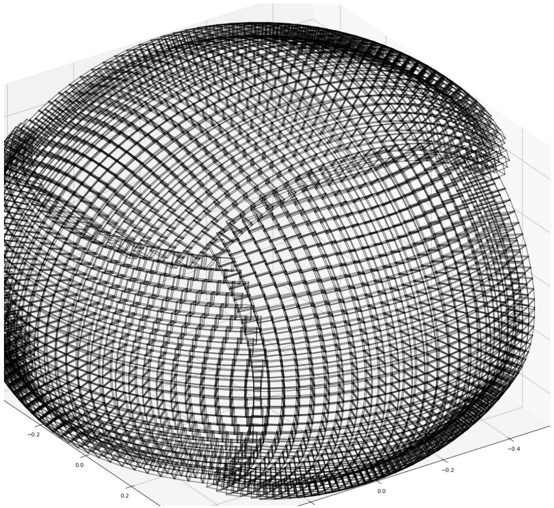
Locally Cartesian, globally - spherical, avoids singularity at the poles

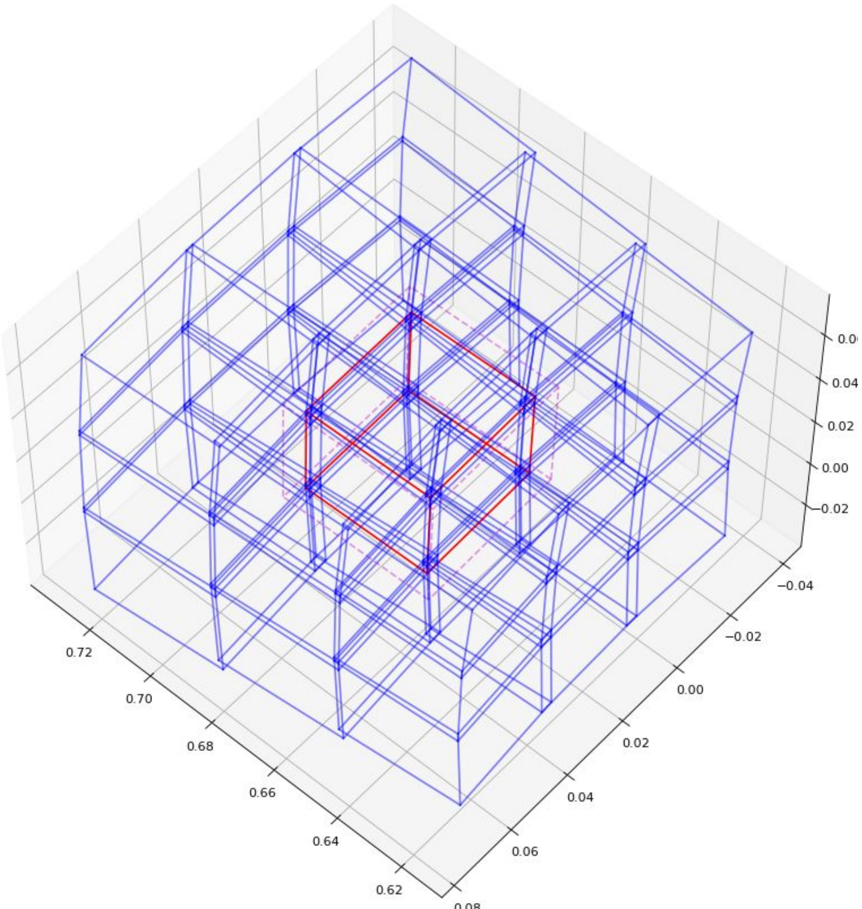




The ‘volleyball’ domain decomposition

Locally Cartesian, globally - spherical, avoids singularity at the poles



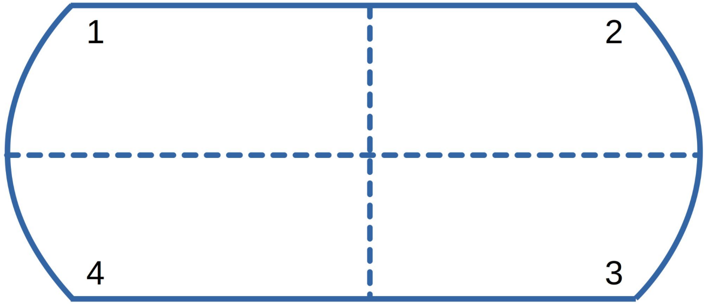


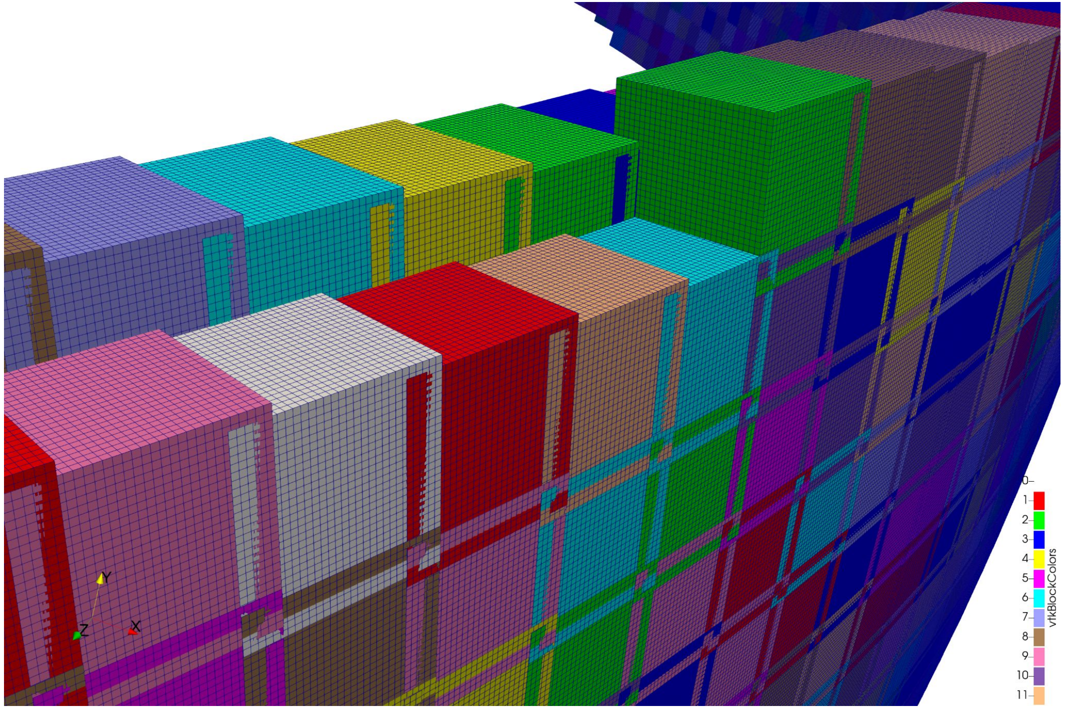
The ‘volleyball’ domain decomposition

Patches overlap with a slight angle

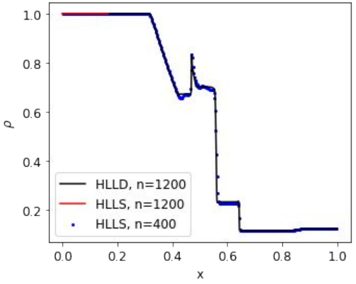
- ➢ *Large angles at seams*

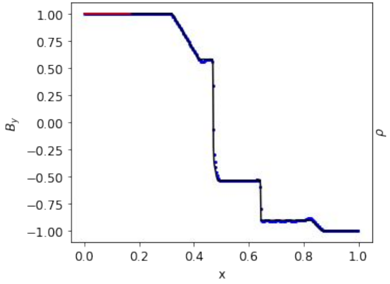
Simple MPI decomposition with good initial load balancing

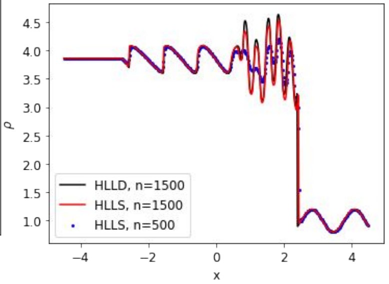




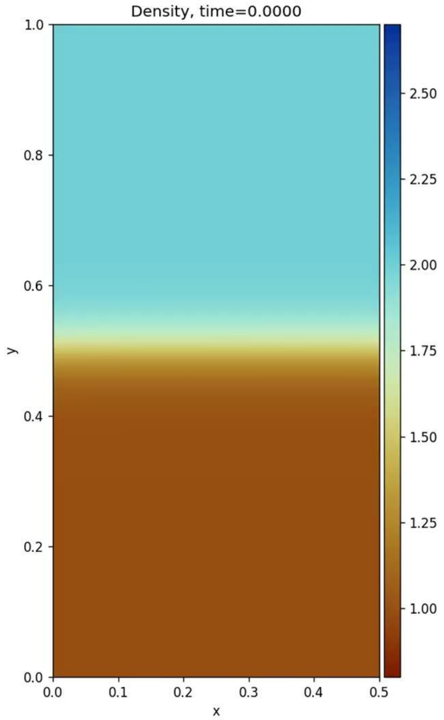
Experimental setup



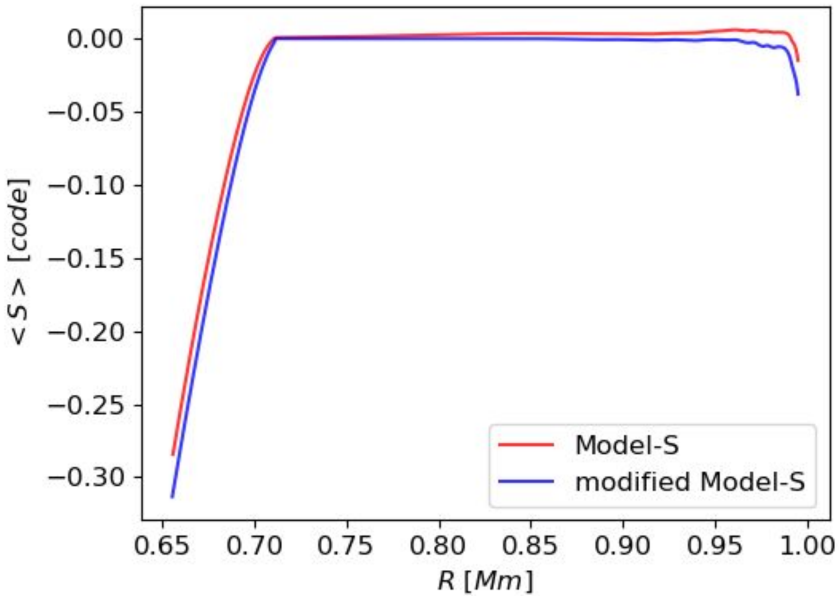


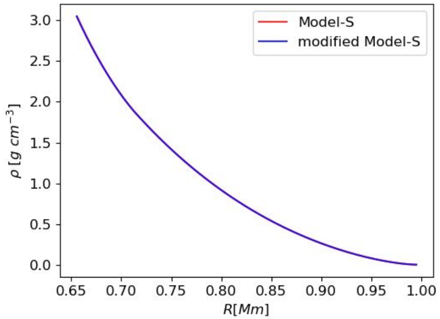


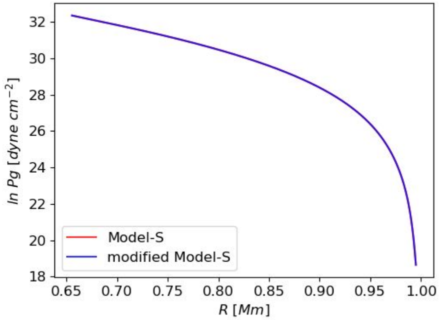
- ➢ JCD model-S *(Christensen-Dalsgaard et al., 1996)* as initial hydrostatic equilibrium
  - Modified with tabular equation of state
- ➢ Tabular equation of state (FreeEOS, *Irwin A, W, 2012)*
- ➢ Entropy-based HLLD Riemann solver *(Popovas, A&A submitted.)*
- ➢ Surface cooling driven convection
- ➢ Coriolis and centrifugal forces
- ➢ Radially dependent gravity
- ➢ Simulation domain 0.655-0.995 $R_\odot$ (now extended to 0.998 $R_\odot$)
- ➢ *Static mesh refinement*
- ➢ 600k patches (~4.5M after final refinement), 24^3 cells per patch
- ➢ 250 km smallest cell size (<70 km after max refinement) at 0.998 $R_\odot$

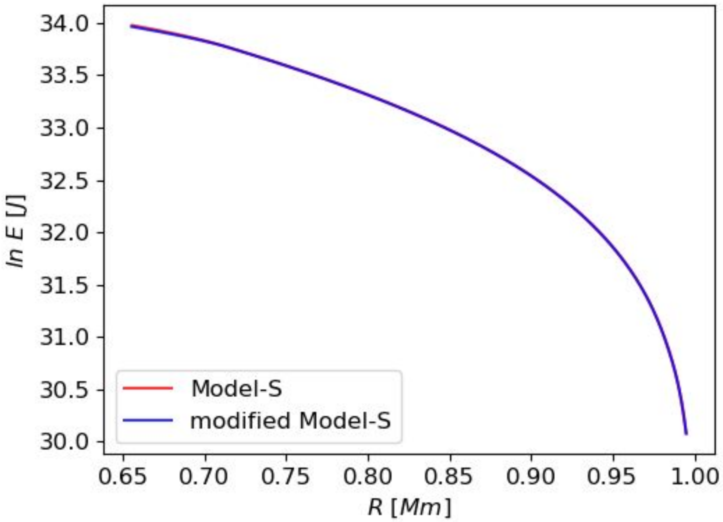


Initial hydrostatic equilibrium



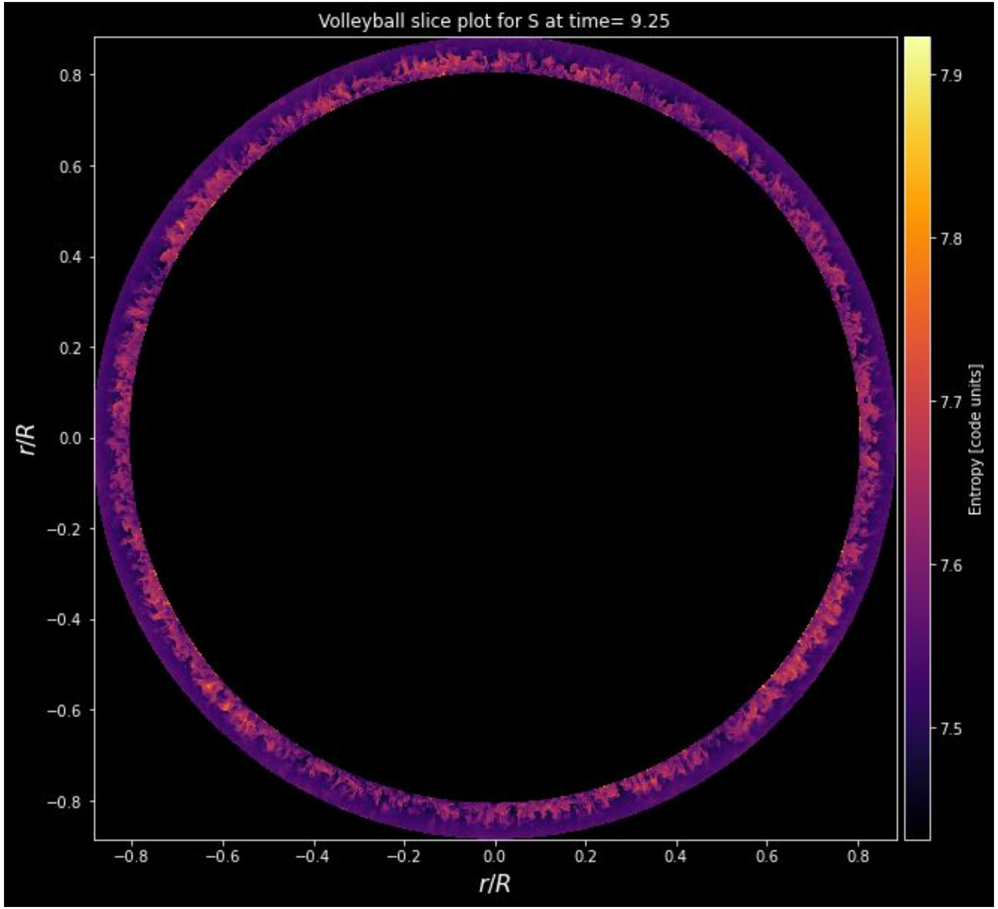


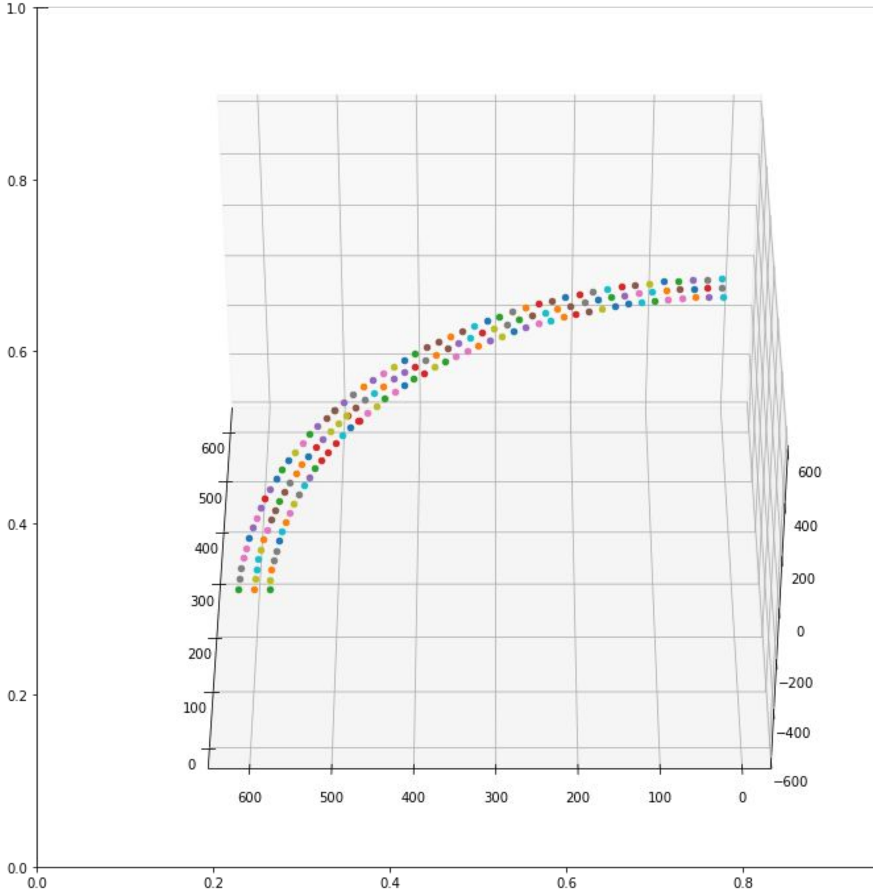




Entropy shifted by 8.254×10^7

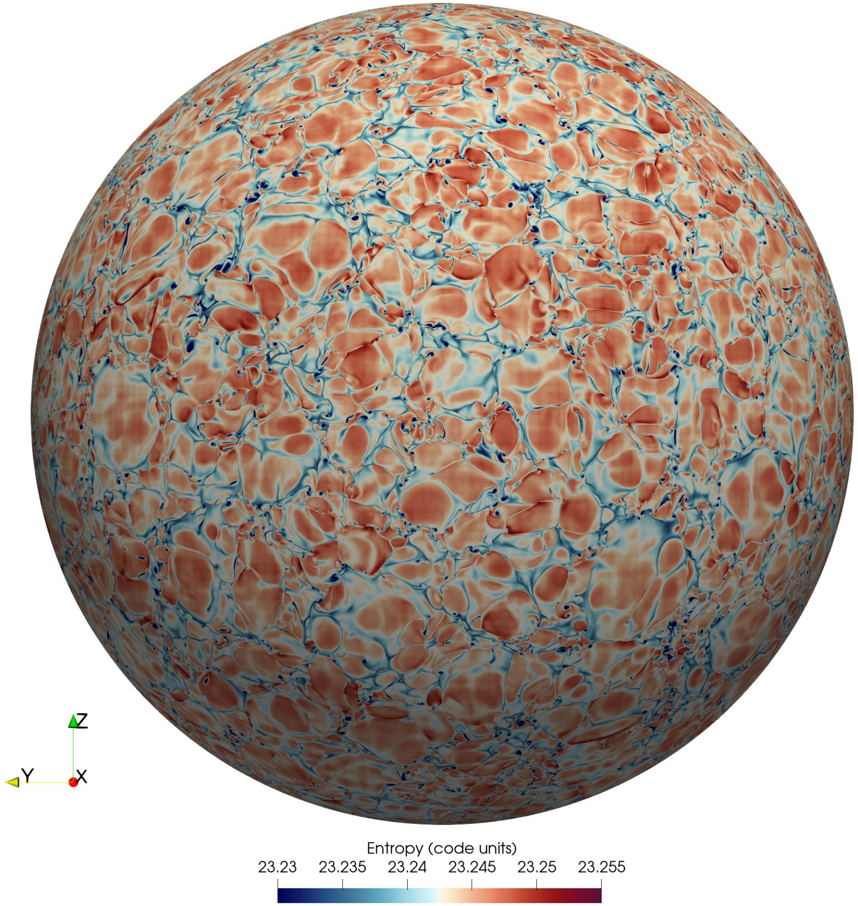
Simulations 2 years ago

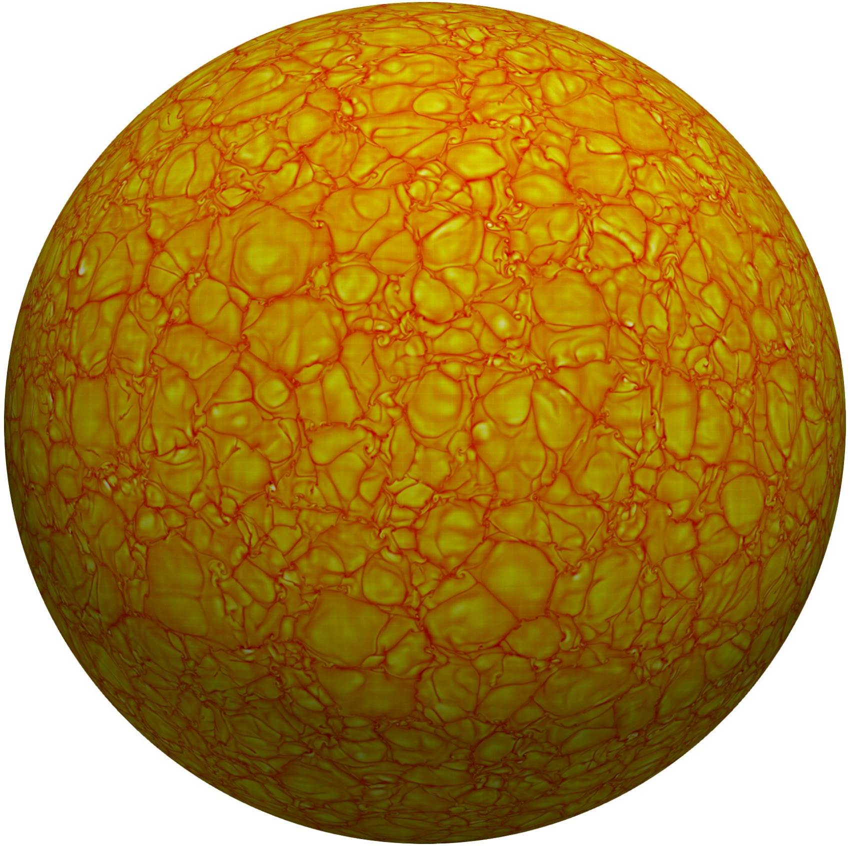




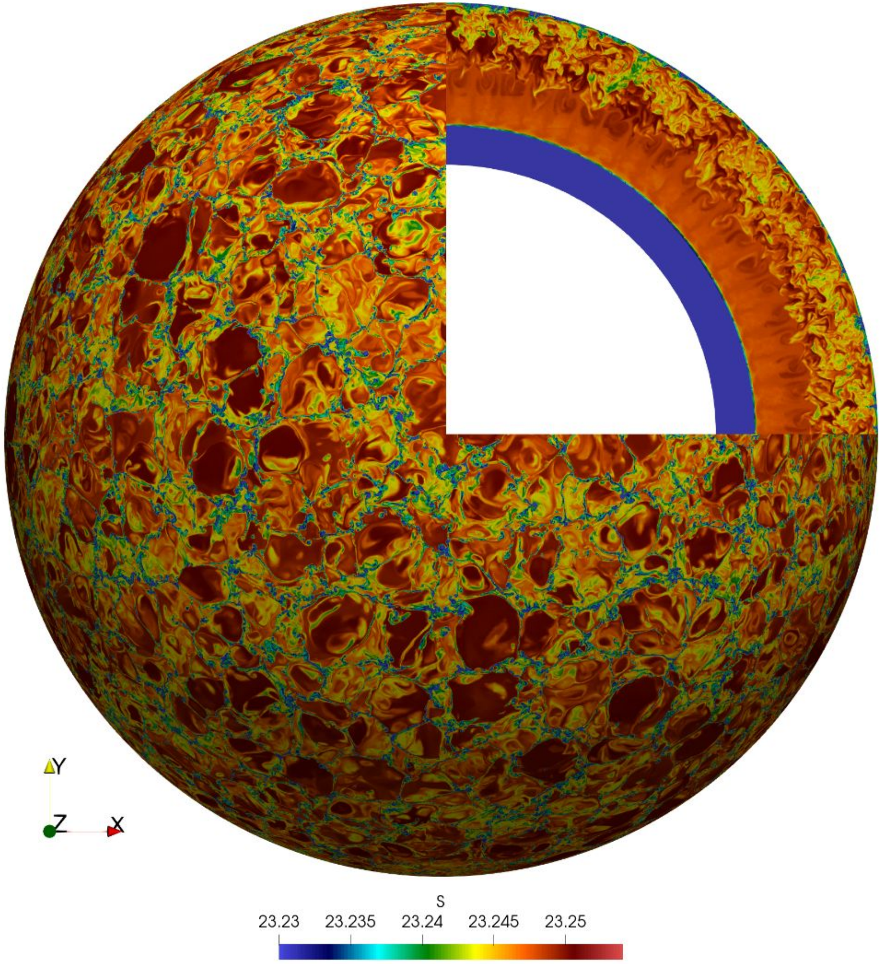
Simulations 1.5 years ago

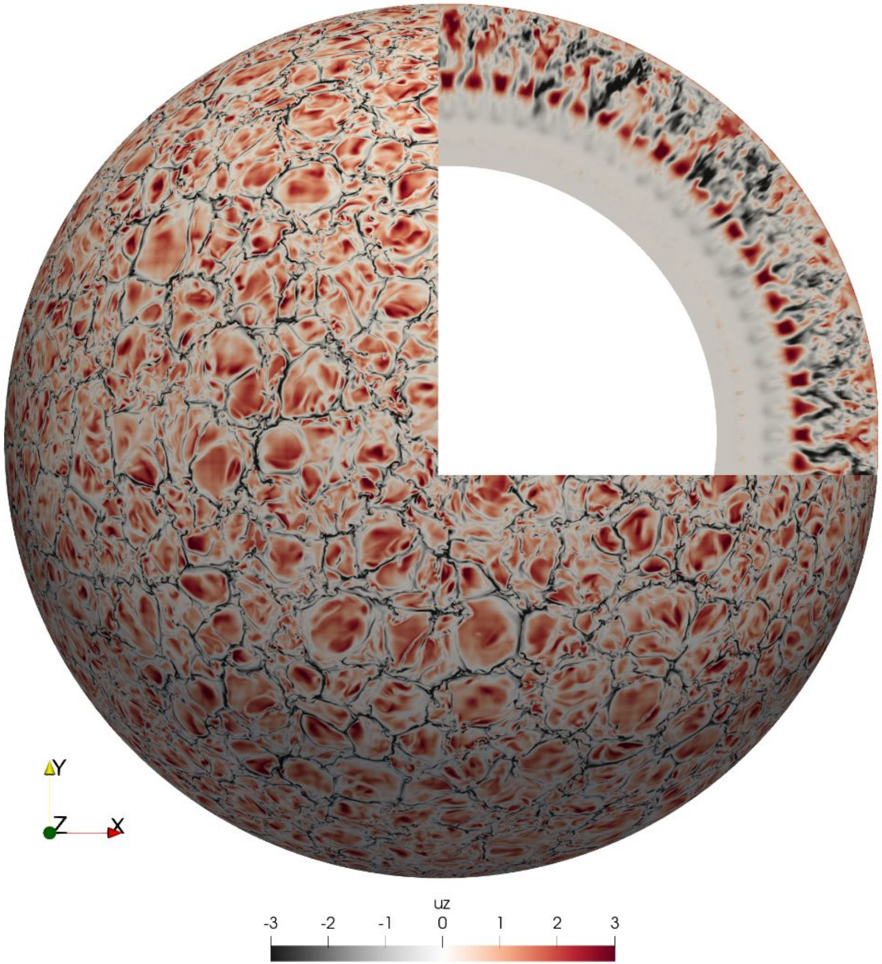
Time: 48.250000 (h)





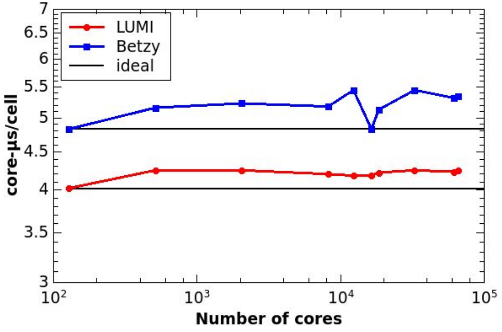
Simulations 1 year ago

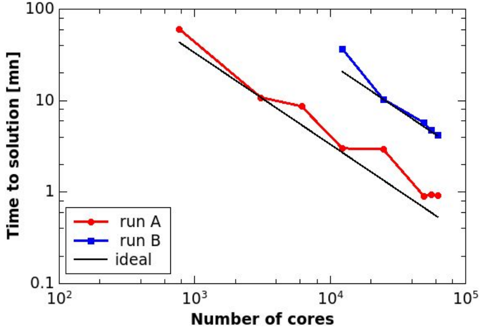




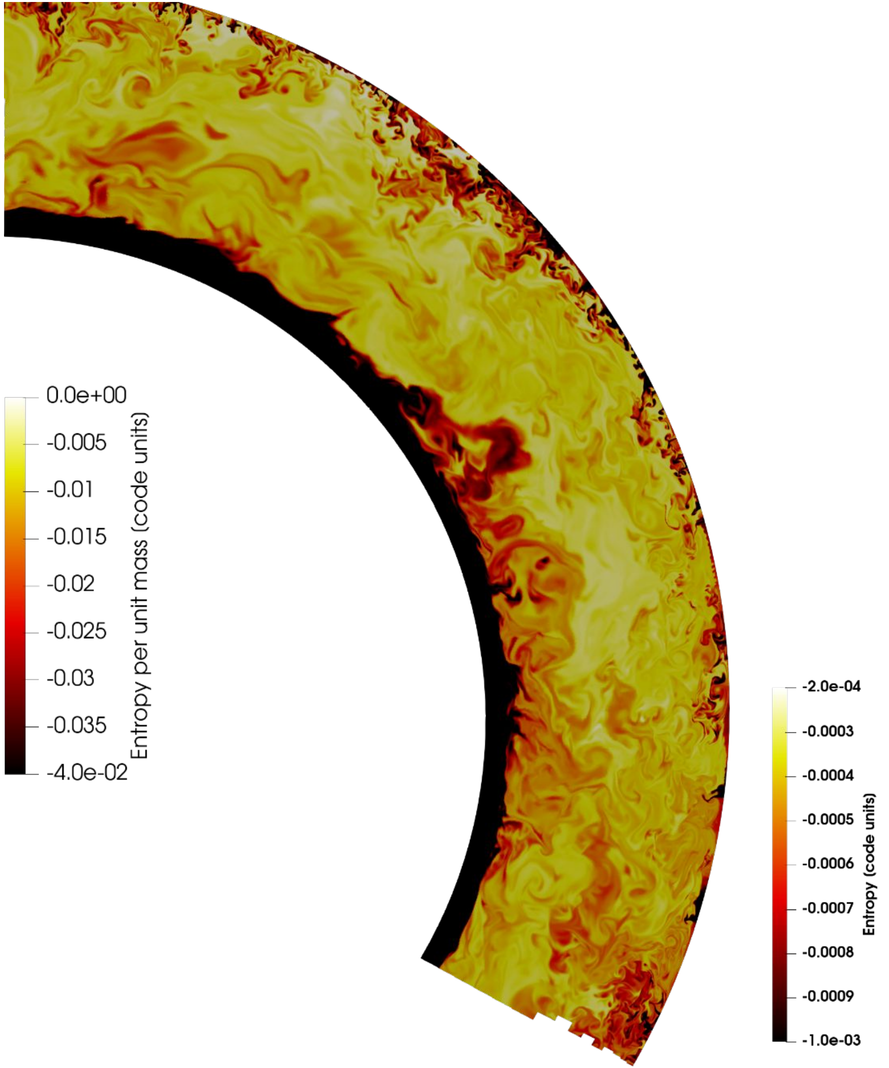
EuroHPC Extreme Scale Access

- ➢ 167 million CPU hours granted by EuroHPC
- ➢ Great software stack
- ➢ Good technical support
- ➢ Easy to start working with
- ➢ Very high oversubscription ➪ long queue time

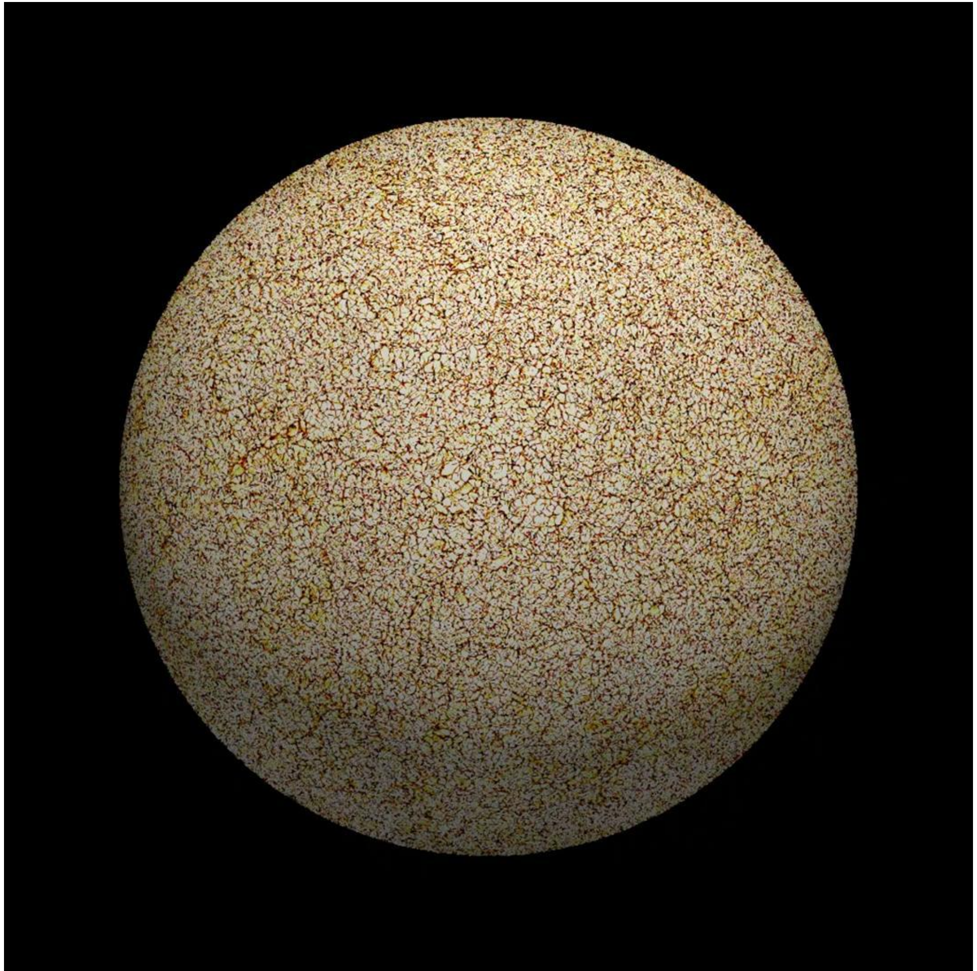




Simulations in progress



Simulations in progress



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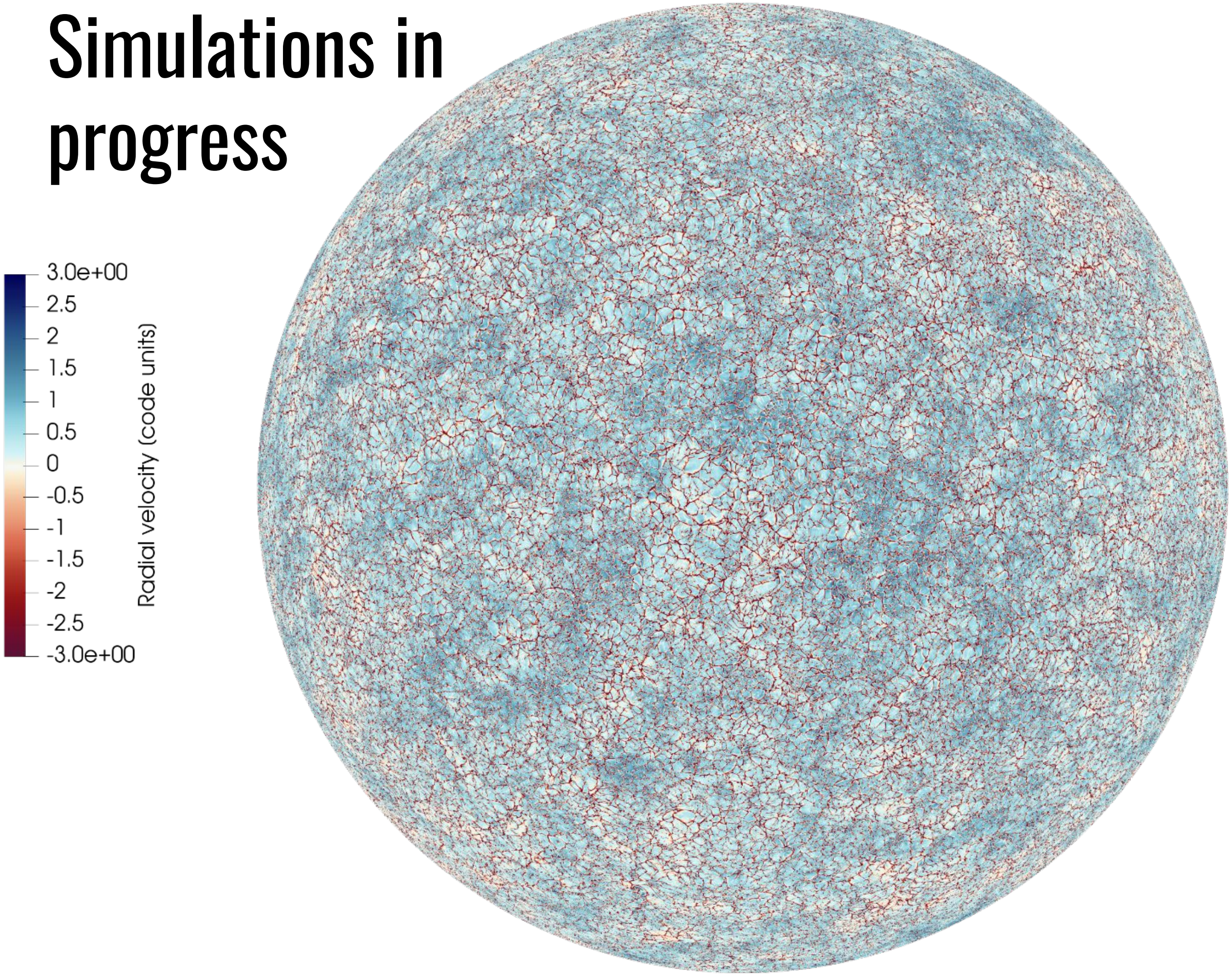
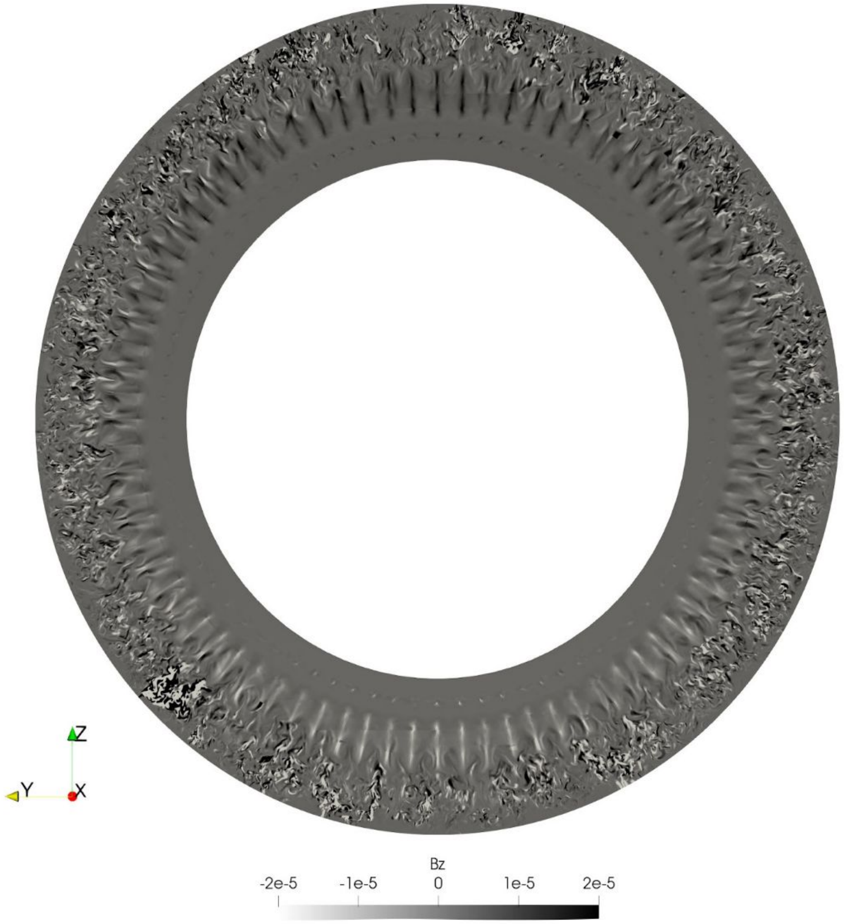
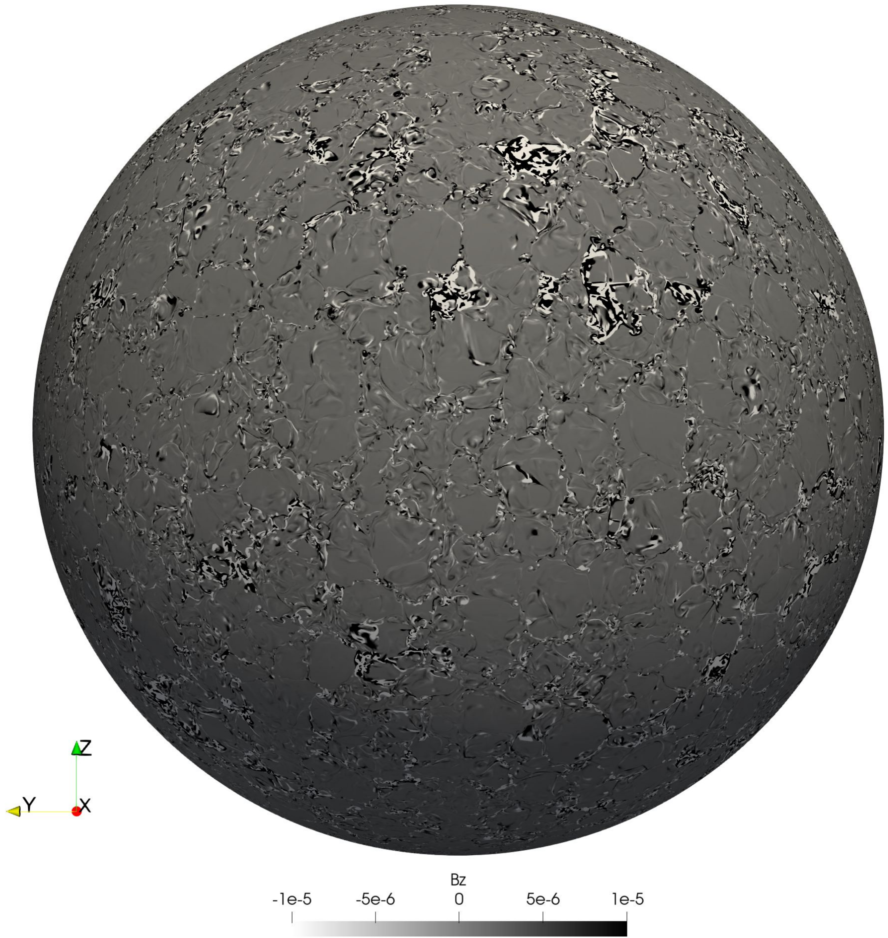
Simulations in progress



Simulations in progress

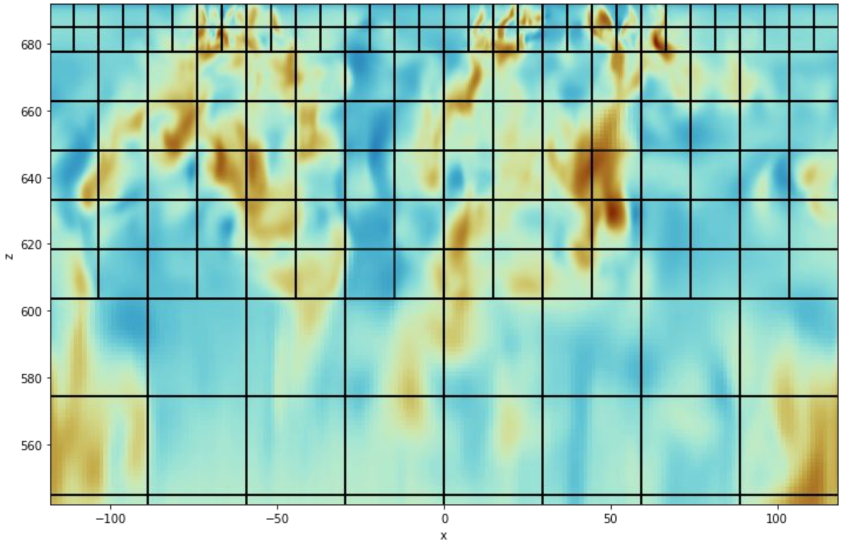
Simulations in progress

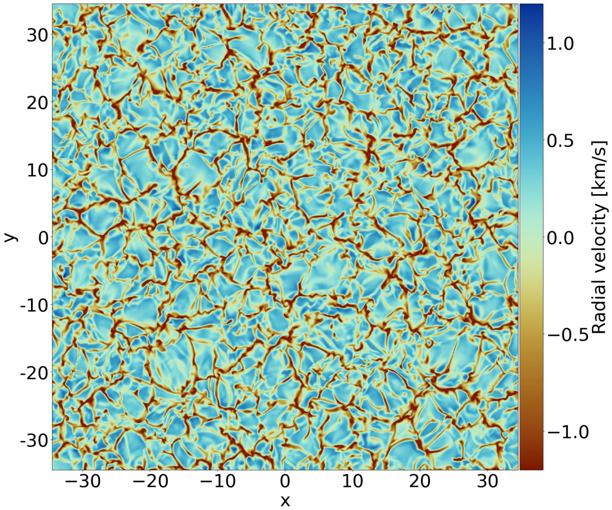




Next steps (short term)

- ➢ Ramp up the resolution, smallest cell size <70km
- ➢ Study near-surface convection morphology
- ➢ Local magnetic dynamo
- ➢ Expand the simulation into the photosphere
- ➢ Use short characteristics radiative heat transfer with multi-frequency opacities (Blue opacity package)
- ➢ Fully self-consistent magnetic flux emergence?





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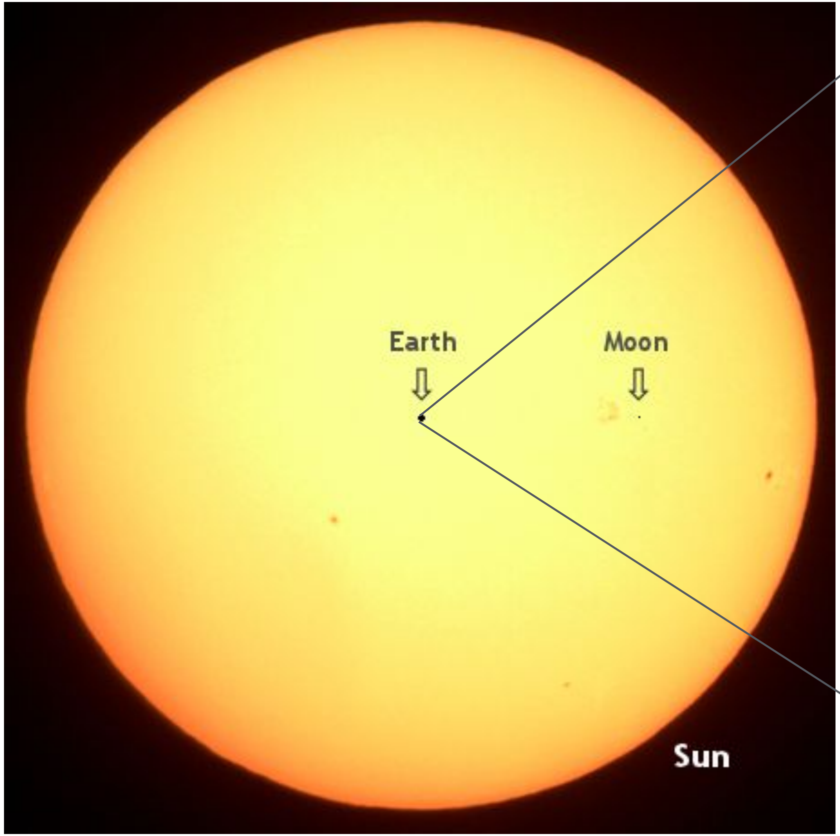
The smallest cell size



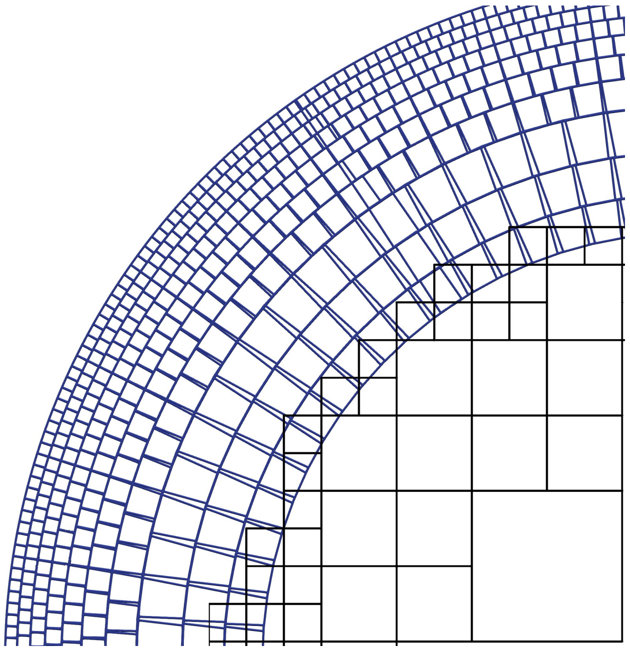
65 km x 65 km

Next steps: looking outwards

- Expand towards chromosphere and corona
- Short-duration, focused simulations
- Part of additional physics modules (e.g. Spitzer conductivity) already available in DISPATCH
- Use zoom-in techniques to focus on targets-of-interest in the photosphere and above

Next steps: looking inwards

- ➢ Prolonged simulations for helioseismology studies (p-mode waves)
  - No c_s reduction and no anelastic approximation ➪ *waves should propagate correctly*
- ➢ Add a "core"
  - Constant in time entropy per unit mass profile



Next steps: in a more distant future

Setup can be adapted to other stars and planets*:

- ➢ Adjust the initial hydrostatic equilibrium
- ➢ If necessary: amend/extend the equation of state and opacities
- ➢ Adjust the required resolution / cost per layer
- ➢ Collaborations welcome!

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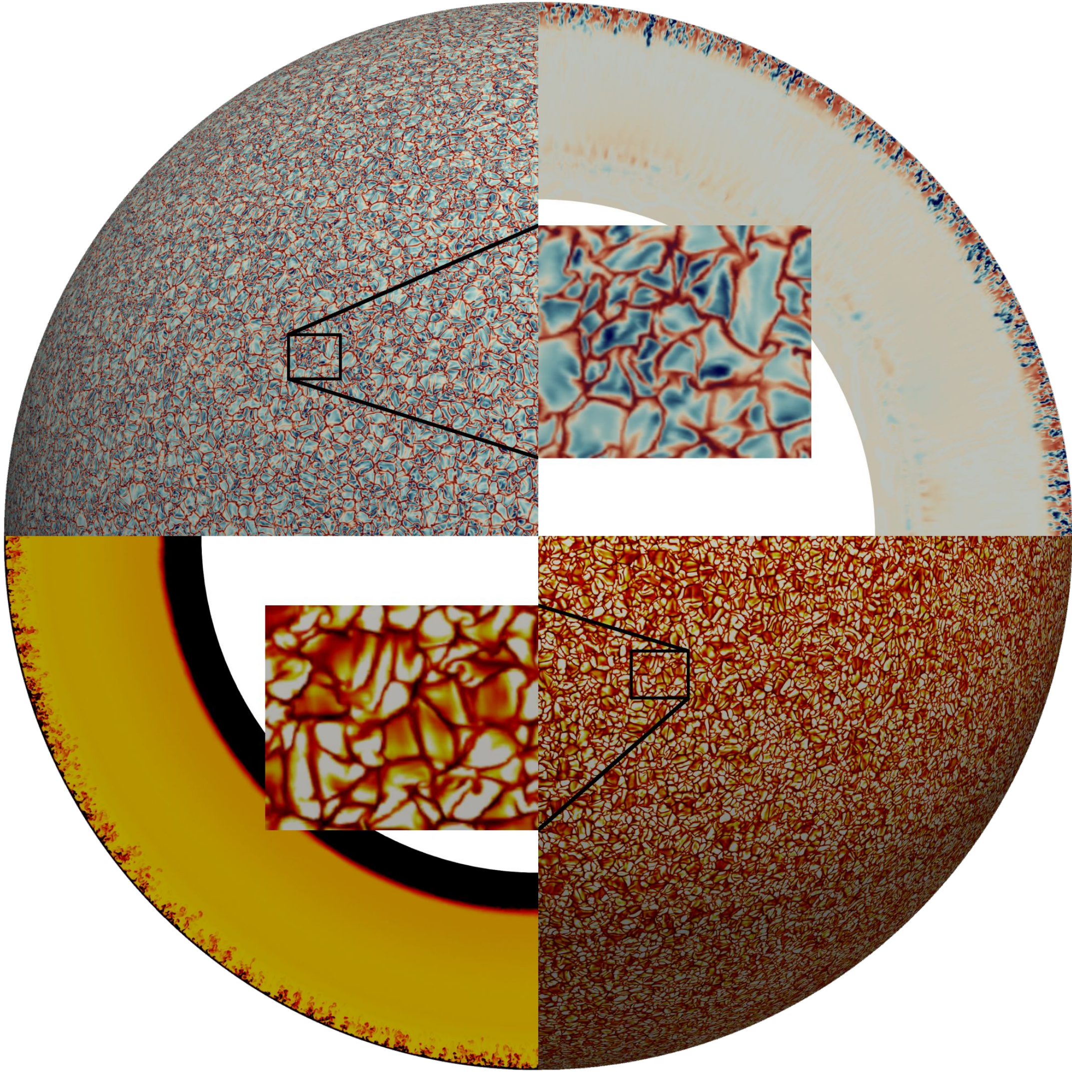
Thank you

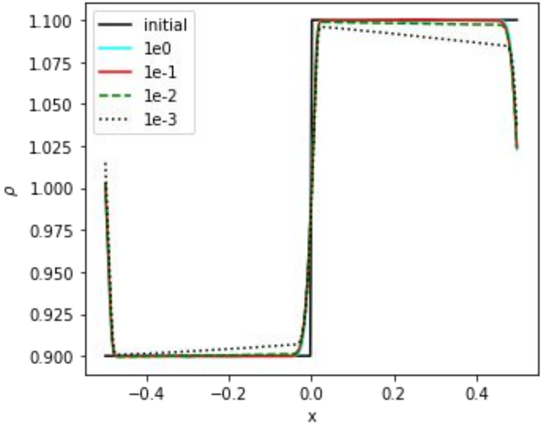


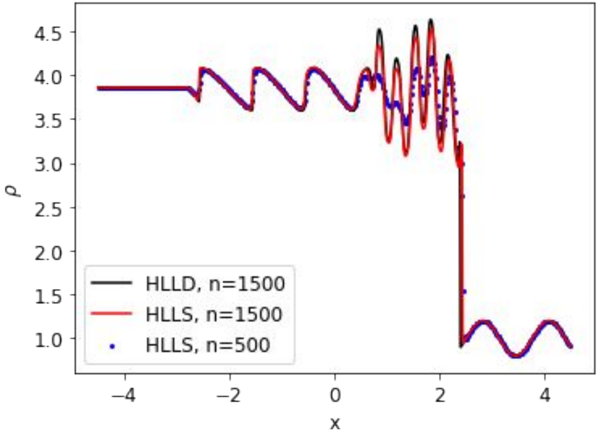
andriusp@uio.no

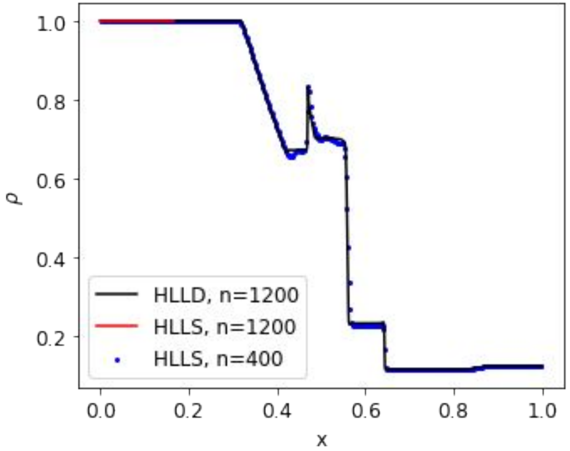
Approximate entropy based HLLD solver

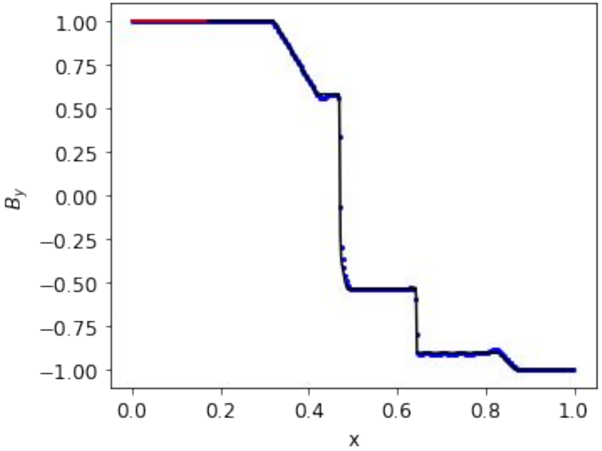
Popovas (A&A, submitted)

- *Entropy wave*
- *Shu & Osher shocktube*
- *Brio & Wu shocktube*
- *Kelvin-Helmholtz instability*
- *Rayleigh-Taylor instability*
- *MHD blast*
- *Orszag-Tang vortex*
- *Current sheet*
- *Gresho vortex*
- *Magnetic field loop advection*
- *Magnetic rotor*









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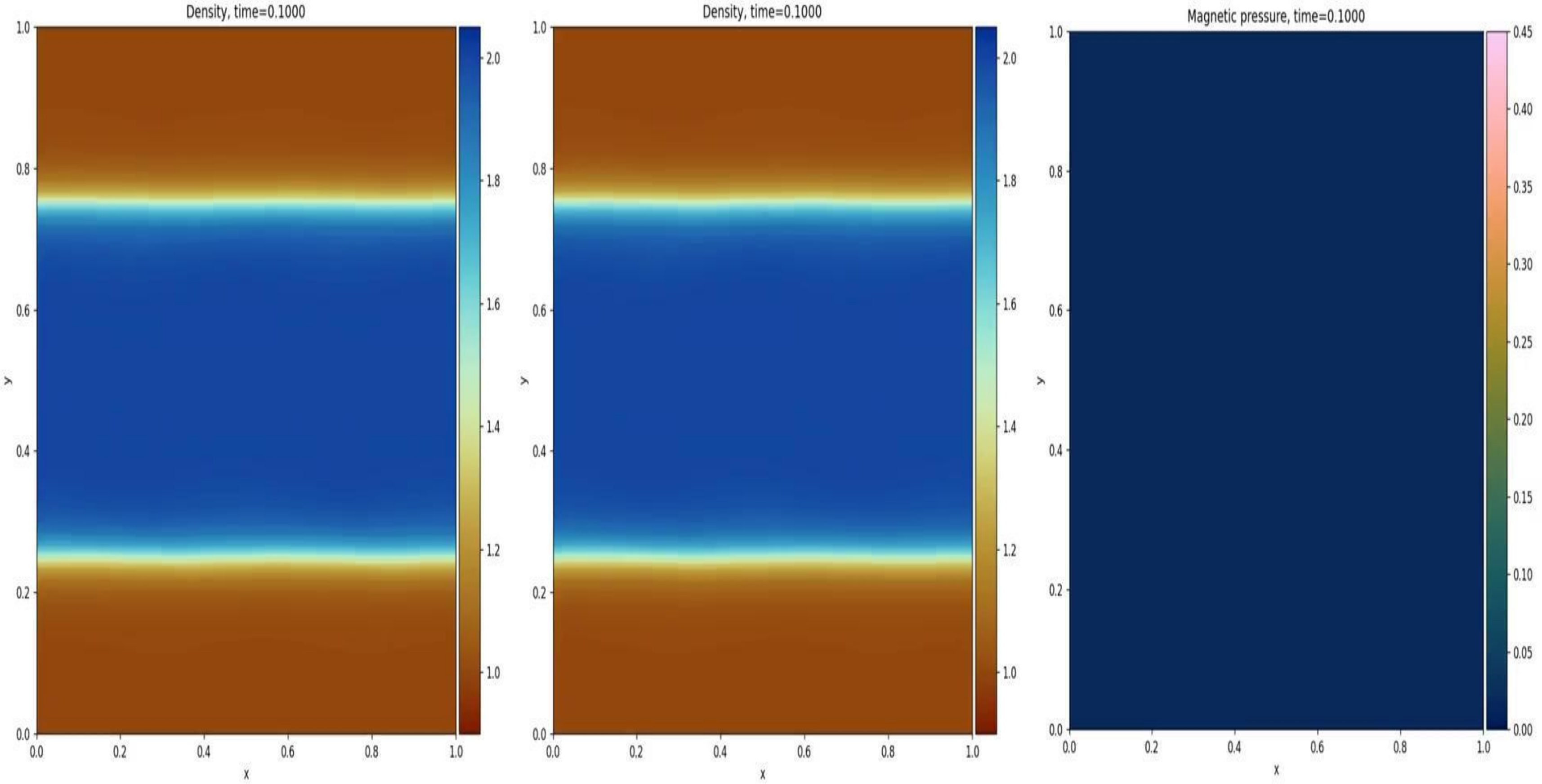
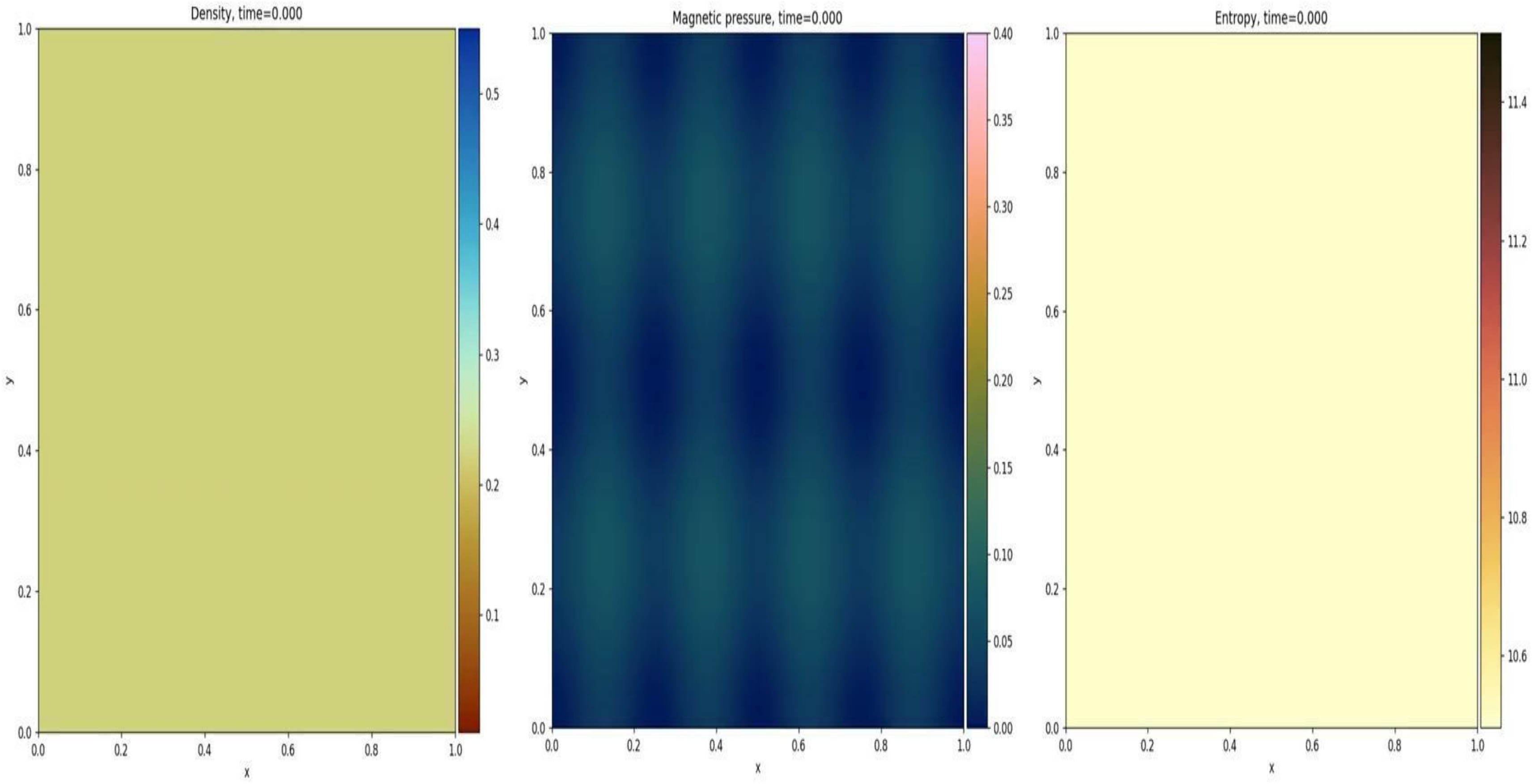
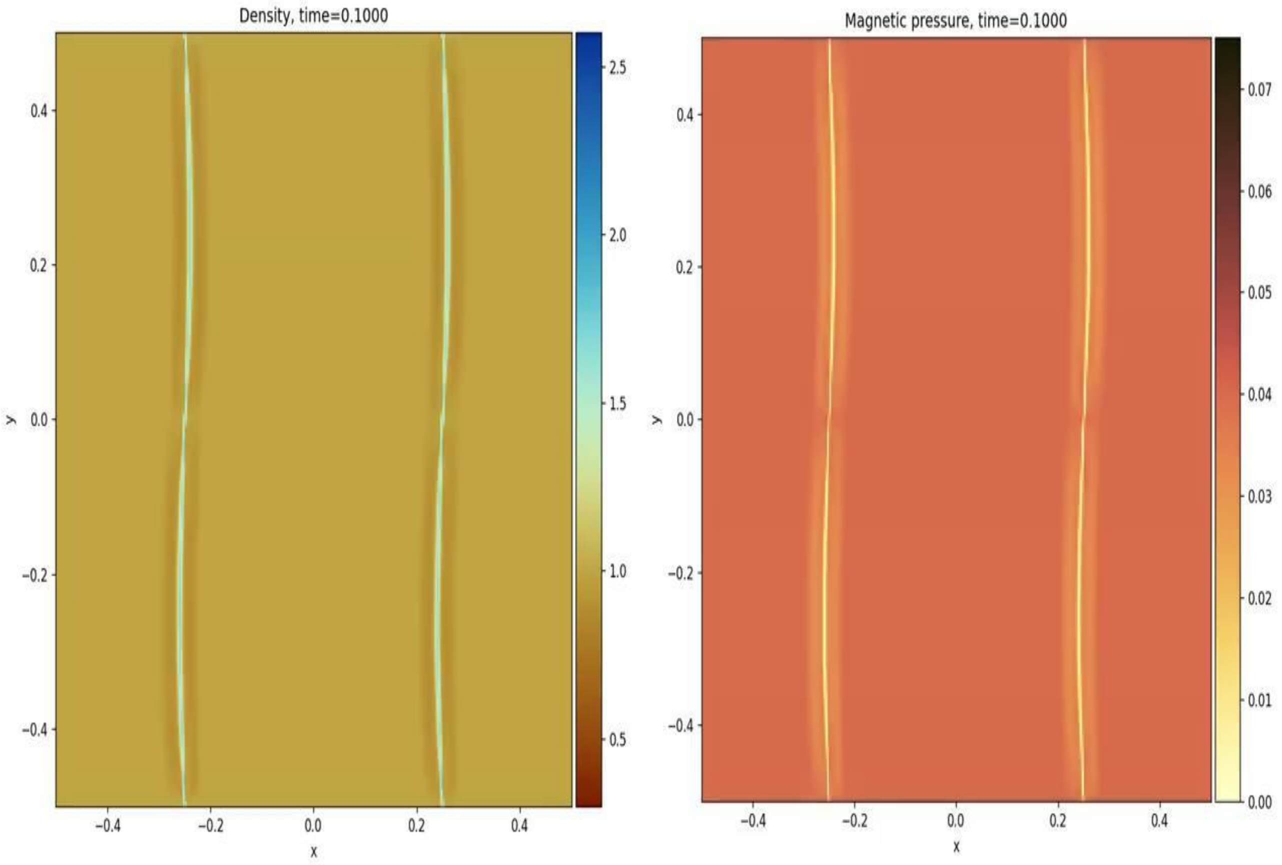
Approximate entropy based HLLD solver



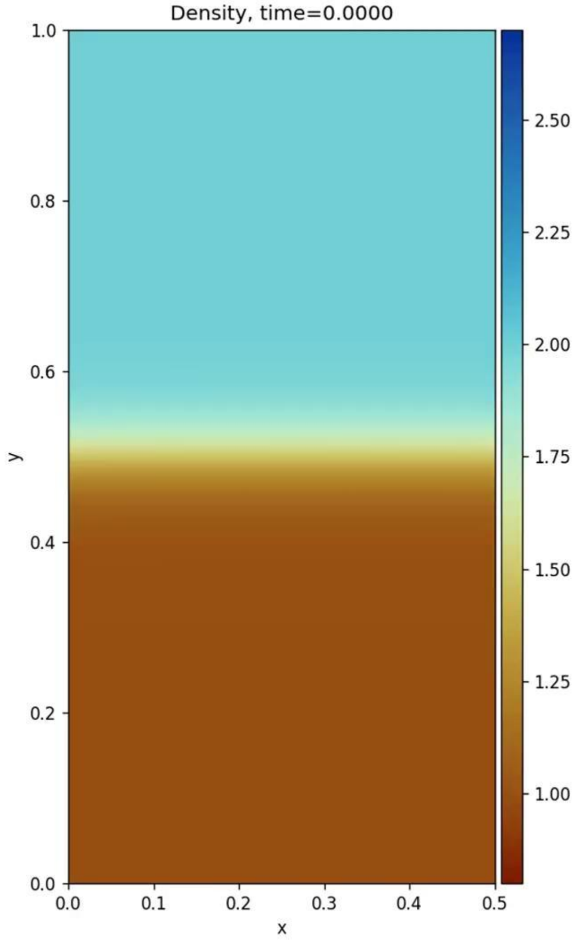
Approximate entropy based HLLD solver



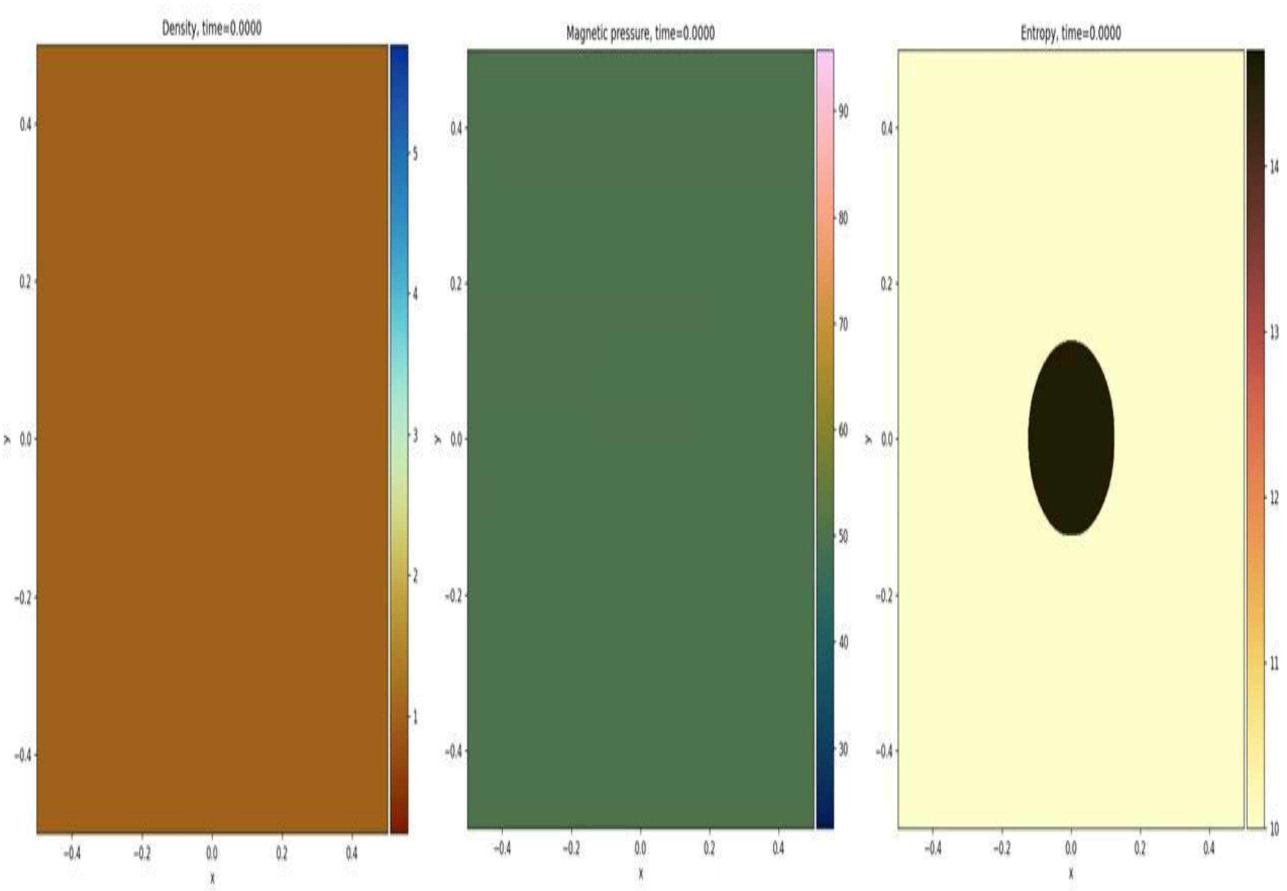
Approximate entropy based HLLD solver



Approximate entropy based HLLD solver

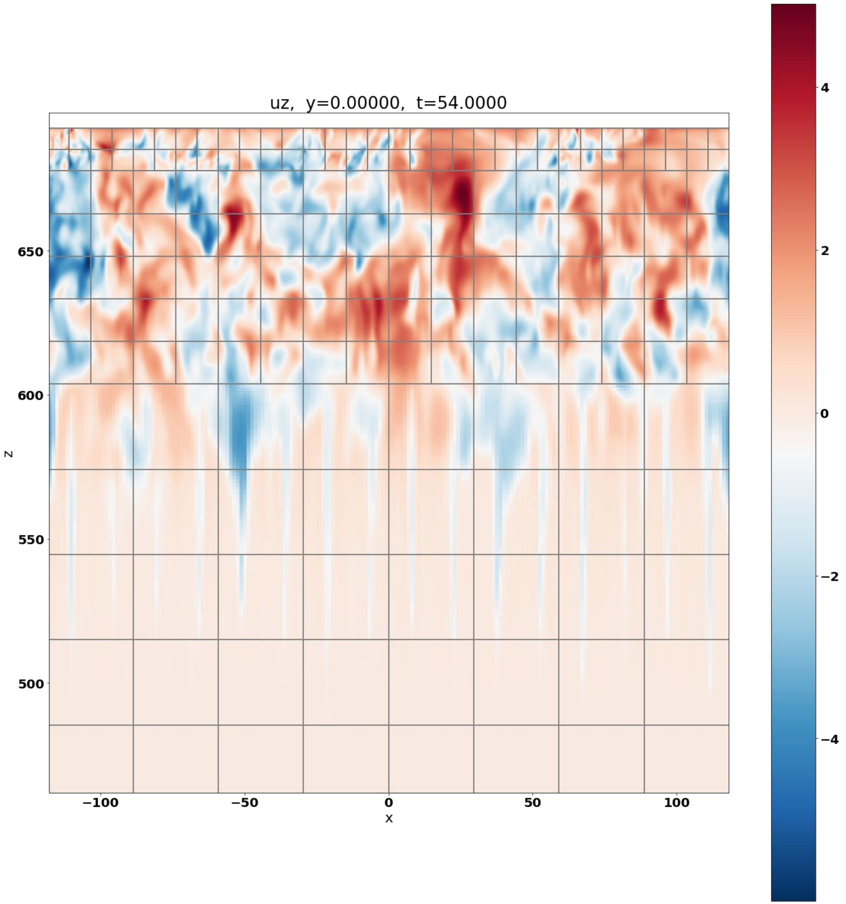


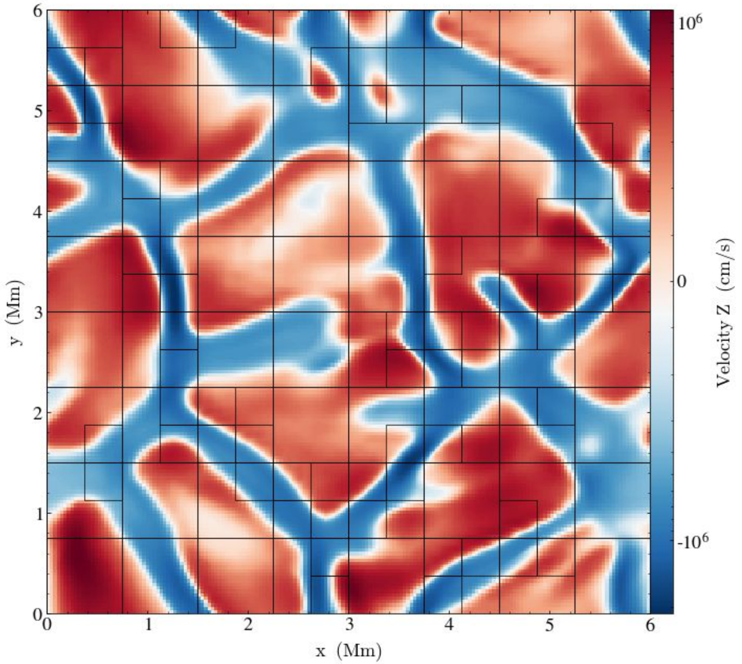
Approximate entropy based HLLD solver



R C S

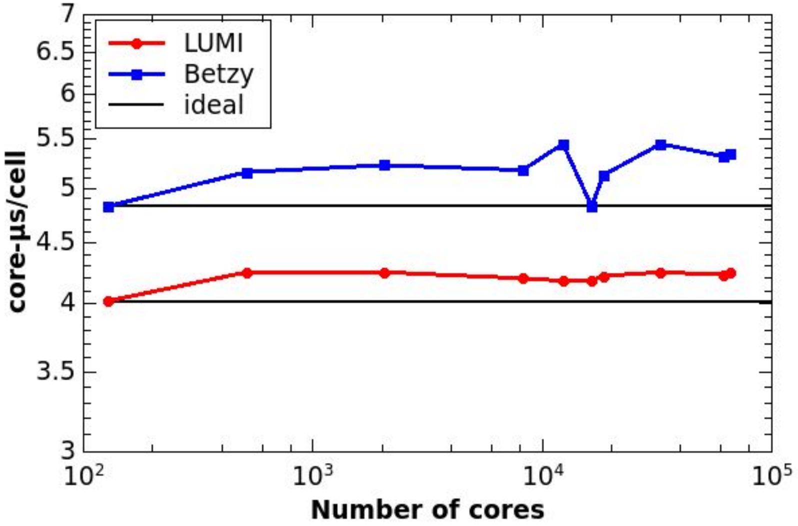
Mesh refinement





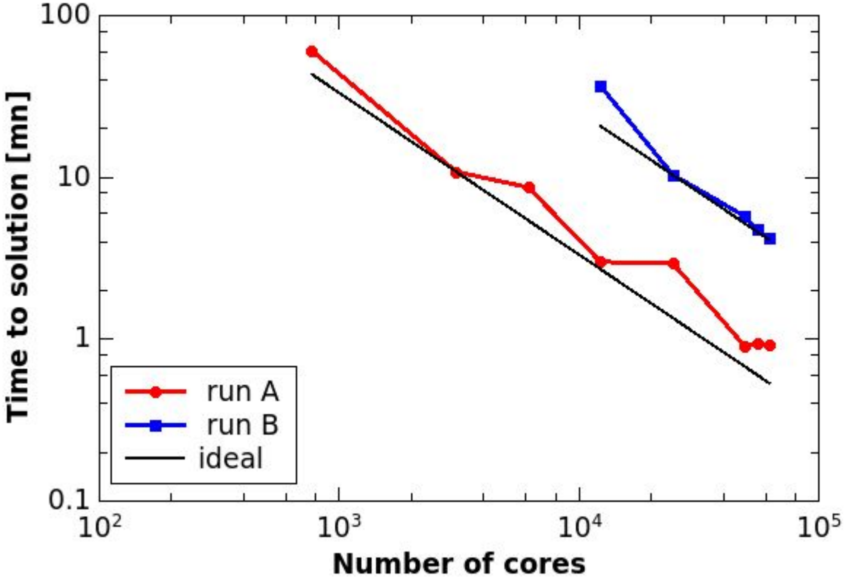
R C S

Weak scaling (LUMI and Betzy)



Nodes	Cores	MPI ranks	core-µs/cell (Betzy)	core-µs/cell (LUMI)	Efficiency (LUMI)
1	128	2	4.83	4.02	1.0
4	512	8	5.16	4.25	0.95
16	2,048	32	5.23	4.25	0.95
64	8,192	128	5.18	4.20	0.96
96	12,288	192	5.45	4.18	0.96
128	16,384	256	4.83	4.18	0.96
144	18,432	288	5.13	4.22	1.0
256	32,768	512	5.45	4.25	0.95
480	61,440	960	5.32	4.23	0.95
512	65,536	1024	5.35	4.25	0.95

Strong scaling (LUMI)



Nodes	Cores	MPI ranks	time-to-solution (A) [mn]	time-to-solution (B) [mn]
6	768	6	60.6	—
24	3,072	24	10.85	—
48	6,144	96	8.68	—
96	12,288	96	3.01	36.8
192	24,576	384	2.95	10.4
384	49,152	384	0.91	5.75
432	55,296	864	0.94	4.75
486	62,208	1944	0.92	4.19