The Role of Convection in Basin Modeling: Lessons from the Perth Basin*

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Abstract

The thermal state of the basin is fundamental for petroleum exploration. The classical assumption is that in a sedimentary basin heat is transferred through conduction. Yet reservoirs are by nature zones of high permeability in between barriers of low permeability. Such conditions can also trigger a different mode of heat transfer through convection, leading to significant difference in the temperature regime. As such fluid convection cells greatly modify the geometry of the isotherms and their transient nature makes them a complicated phenomenon to identify from temperature logs only. Indications for fluid convection can often be found in areas where thick units of high permeability are encountered such as the massive pre-salt reservoirs in Brazil. The Western Australian Geothermal Centre of Excellence (WAGCoE, 2008–2011) focused some its research on the role of convection in the Perth Basin and we are presenting here the methodology followed as well as some results which highlight the impact of basin convection for the petroleum industry.

Large scale models (basin scale) were constructed to study the existence of convection cells and constrain the parameter space for all values required to populate the most realistic 3D model. The numerical results from hydrothermal simulations at that scale were then used to generate boundary conditions at the lower scale (Perth metropolitan) and numerous models were run to understand the sensitivity of the main parameters identified in order to account for the large uncertainty around the geological data. Results show that convection can easily occur in various locations within the Perth Basin and that convective patterns create significant temperature changes compared to conductive scenarios. Convection cells are strongly pinned by the geological faults and a detailed 3D model is required to obtain realistic results. Numerical simulations proved very useful tool to estimate the spacing of convecting upwelling zones and also showed that convection homogenizes salinity within the aquifer, with convective flow rates similar to regional groundwater flow rates. The strong association of convection cells with faults and their persistent nature allow us to more reliably predict thermal regimes in areas that were previously returning large errors in classical conductive temperature inversions.

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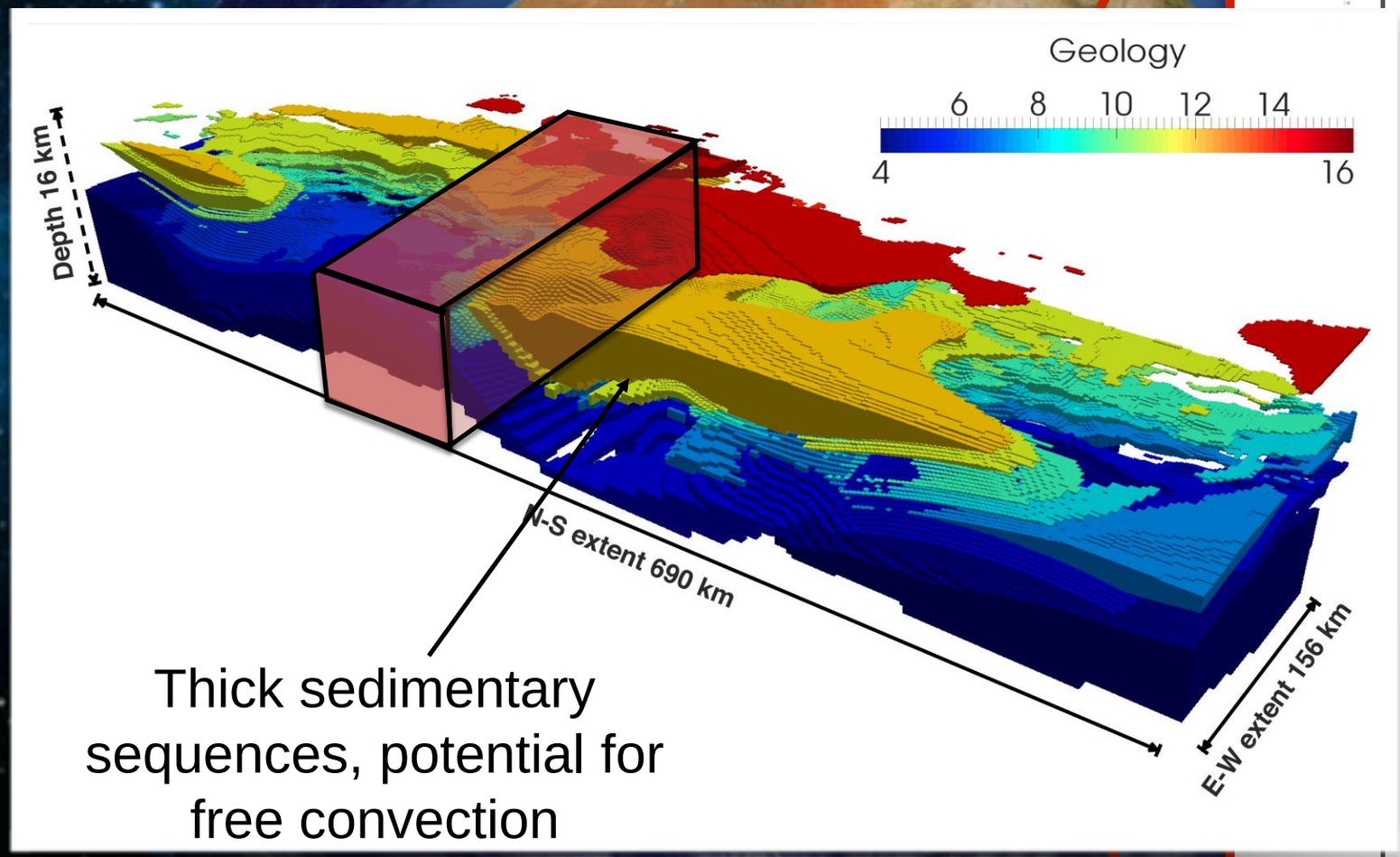
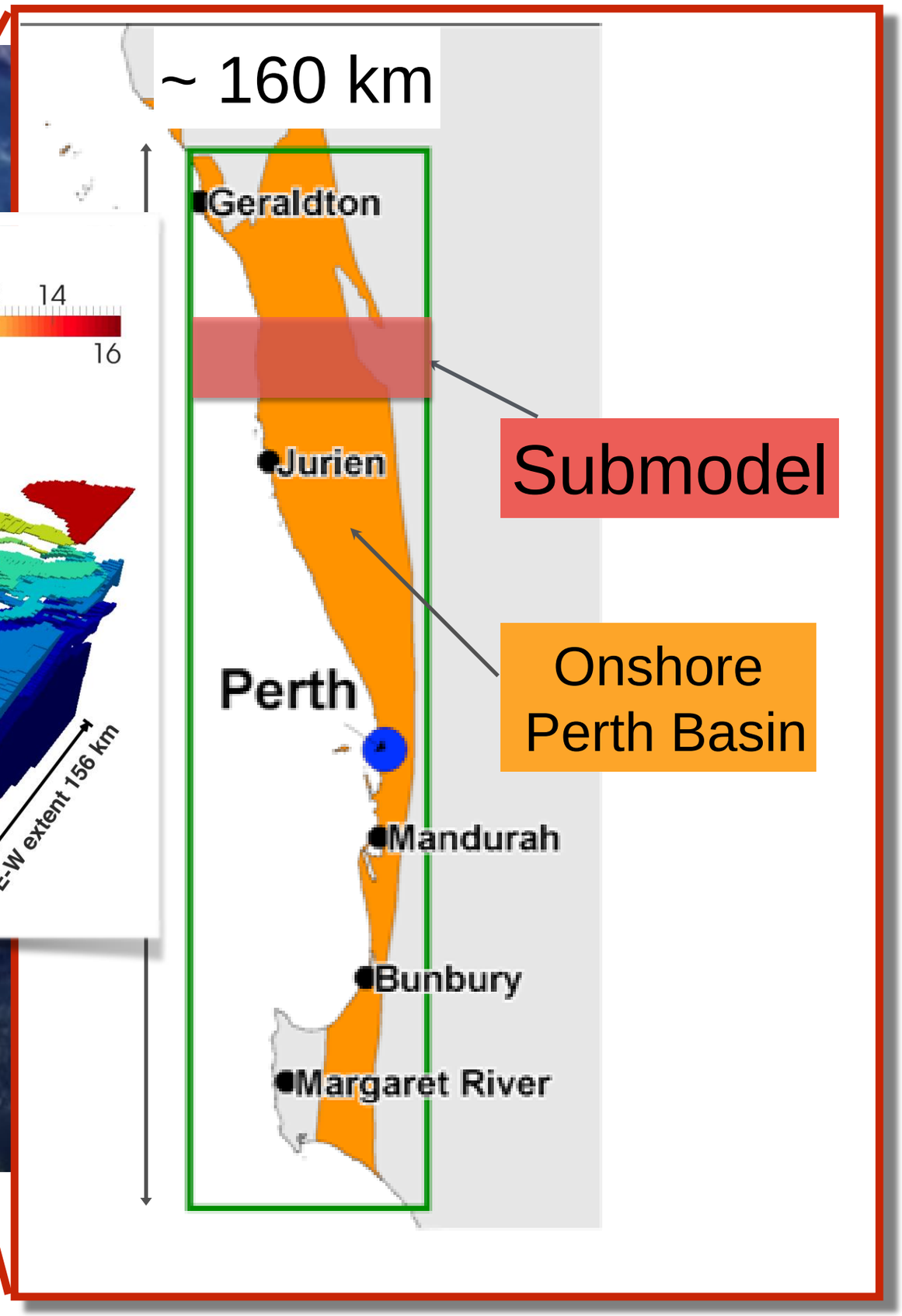
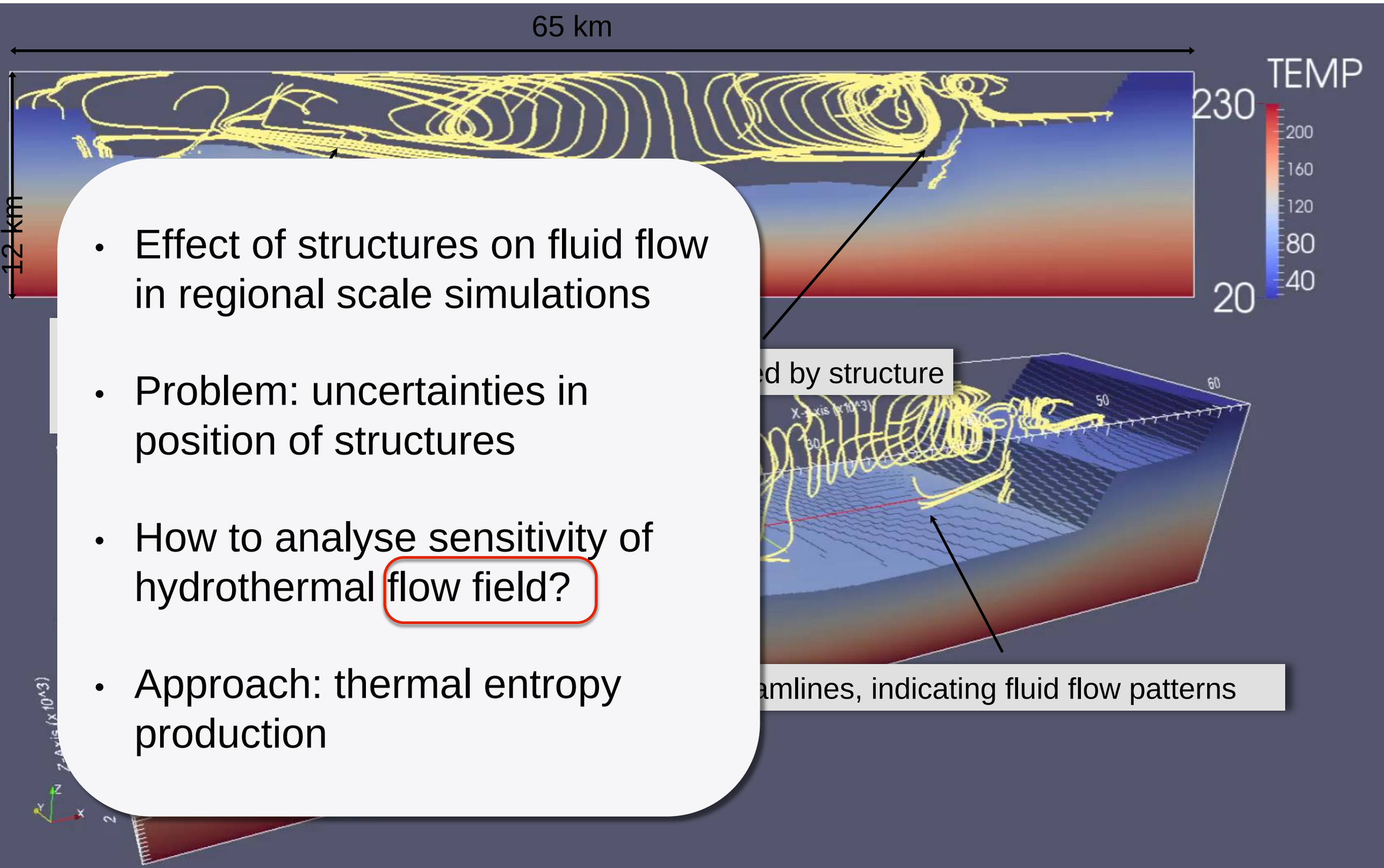


Thick sedimentary sequences, potential for free convection



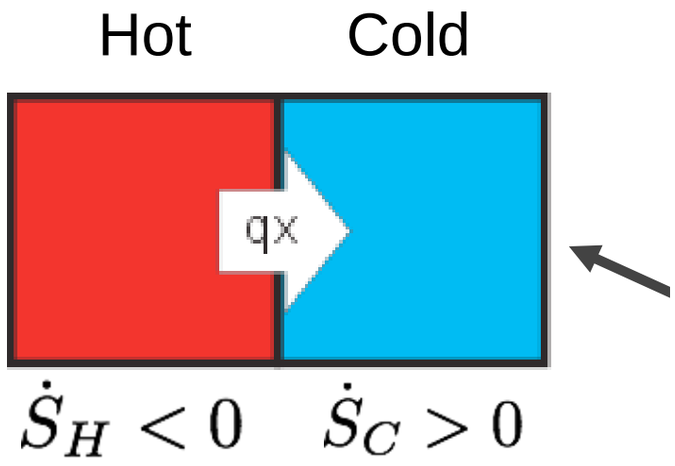
Control of Structures on Fluid Flow



- Effect of structures on fluid flow in regional scale simulations
- Problem: uncertainties in position of structures
- How to analyse sensitivity of hydrothermal flow field?
- Approach: thermal entropy production

Thermal Entropy Production in a convective flow field

$$\dot{S} \equiv \frac{dq}{T}$$



Fluid flow
(schematic)

Temperature field

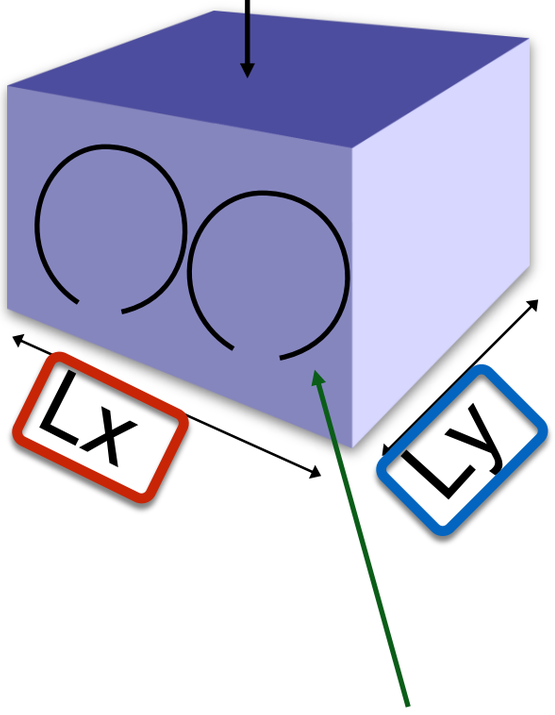
Specific entropy production

$$\dot{s} = \frac{k}{T^2}\vec{q} \cdot \nabla T$$

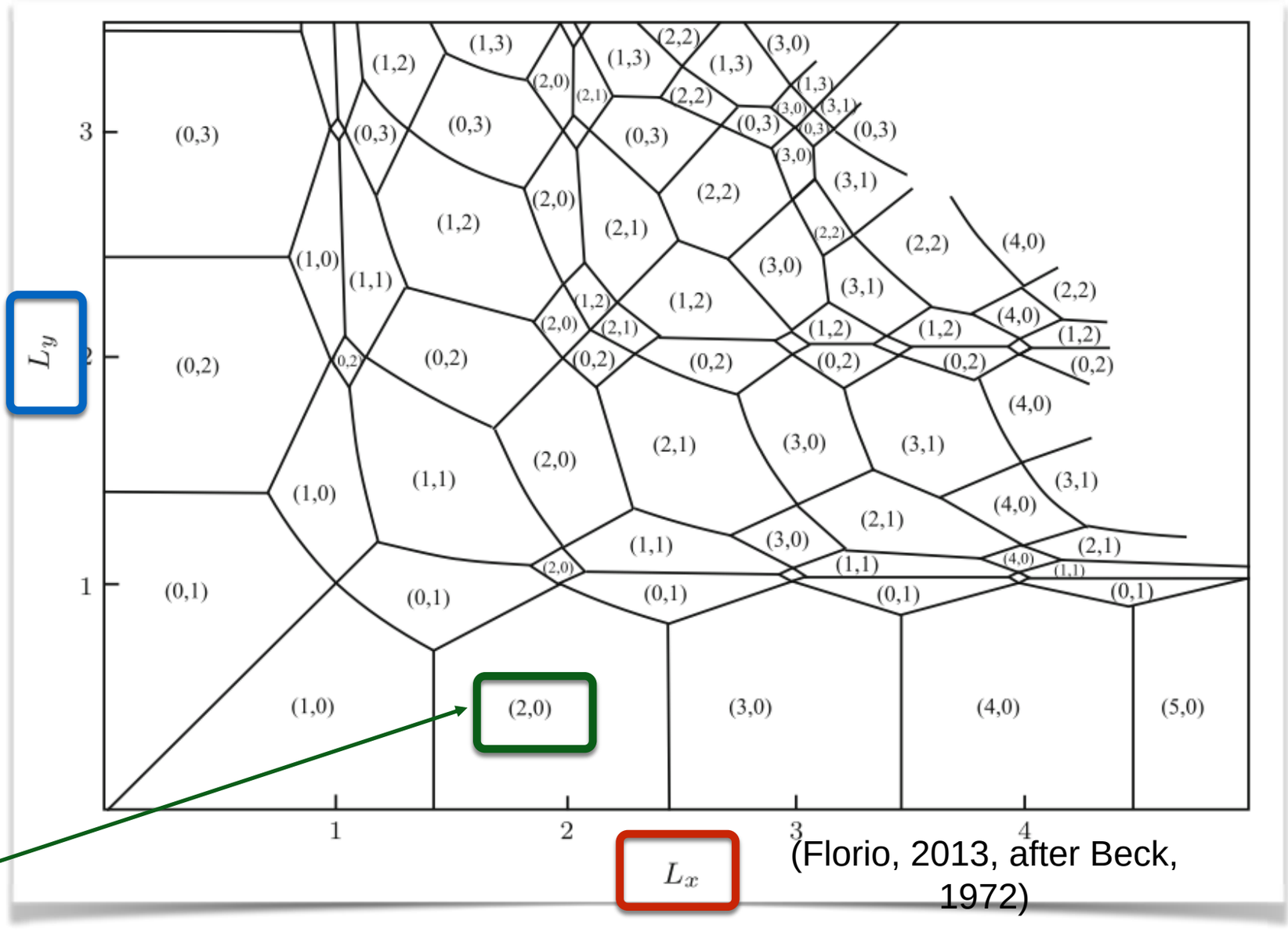
thermal

Convection in a box

North Perth Basin as a box, heated from below



Convection cells in each direction

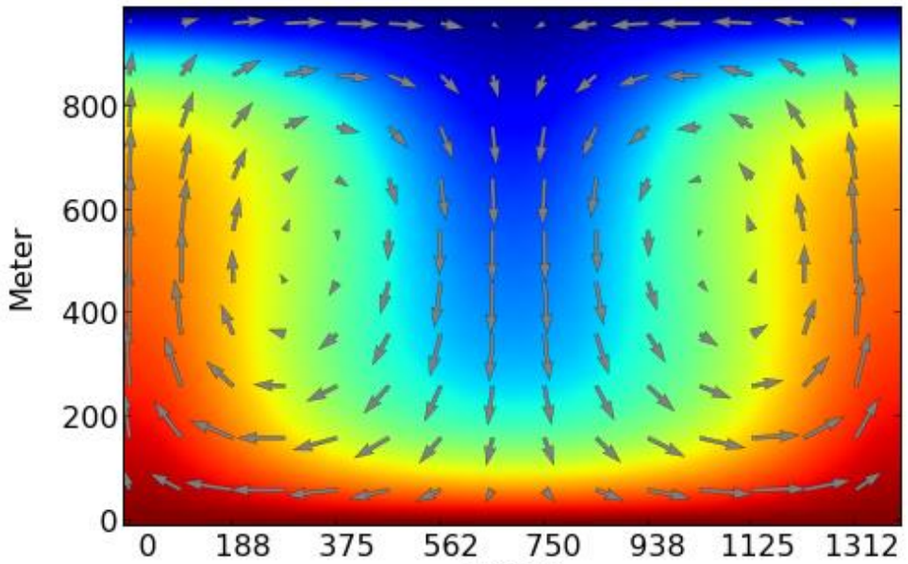


(Florio, 2013, after Beck, 1972)

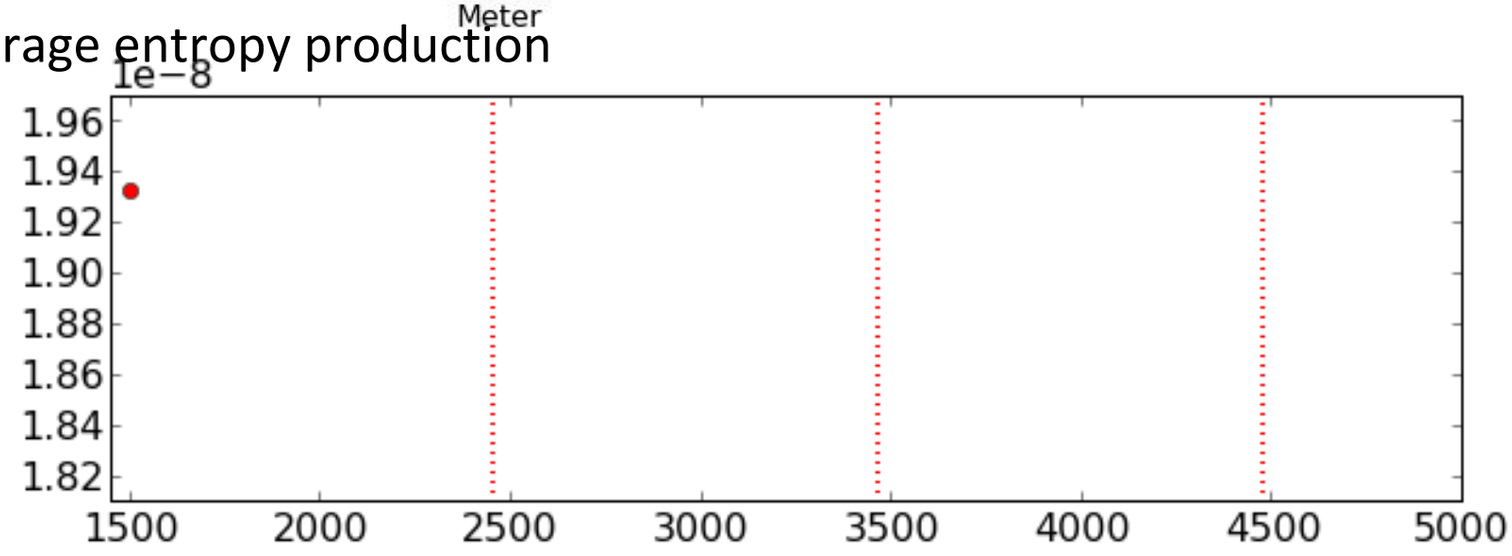
How is it related to thermal entropy production in the system?

Convection in a box

Temperature and flow field

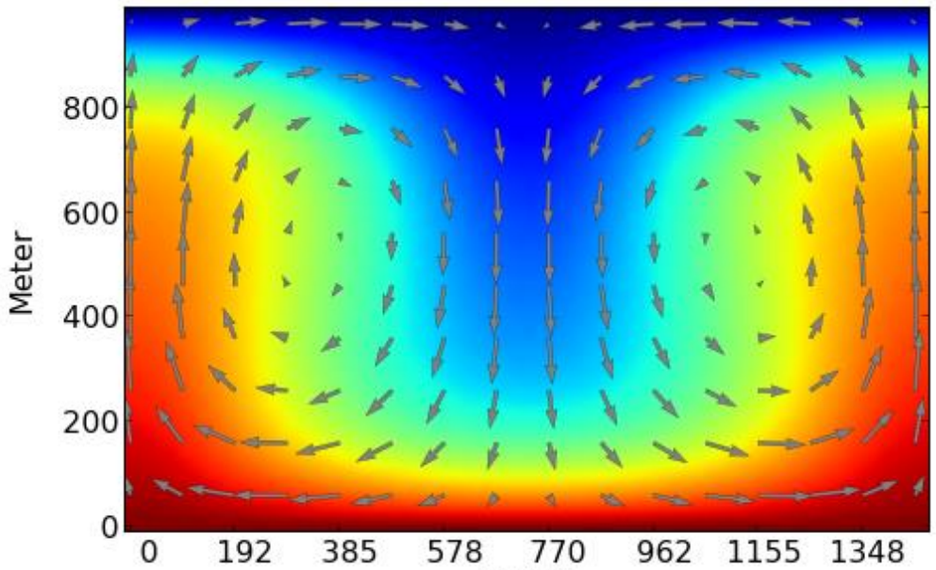


Average entropy production



Convection in a box

Temperature and flow field



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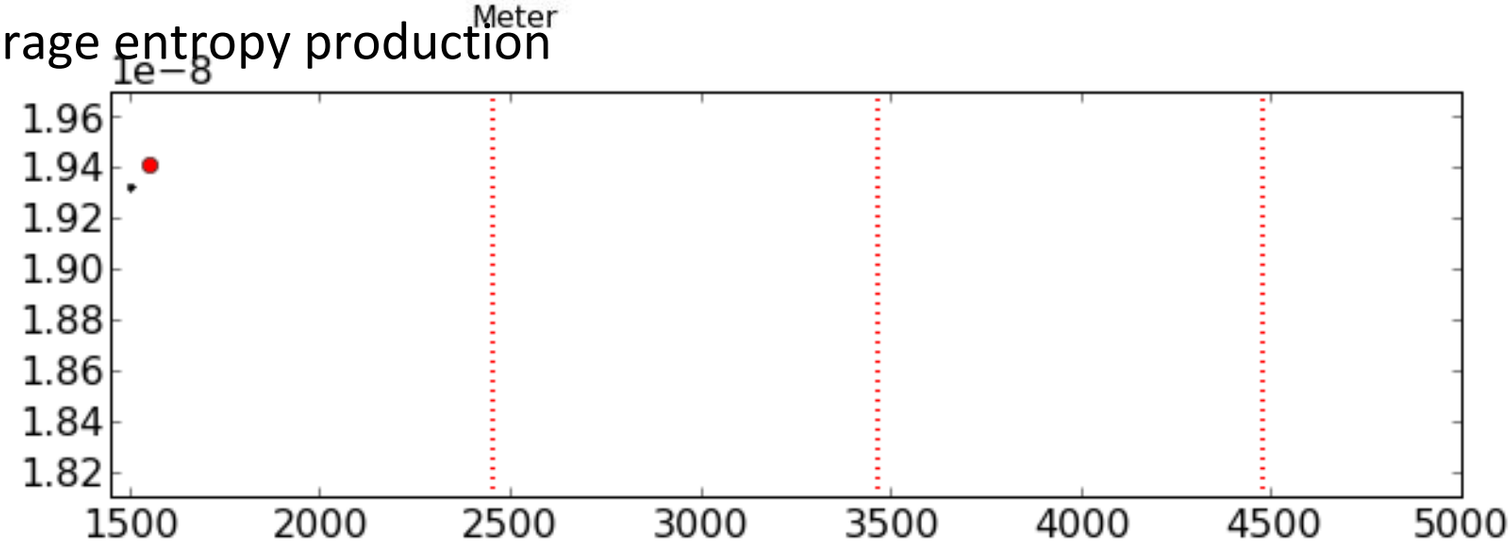
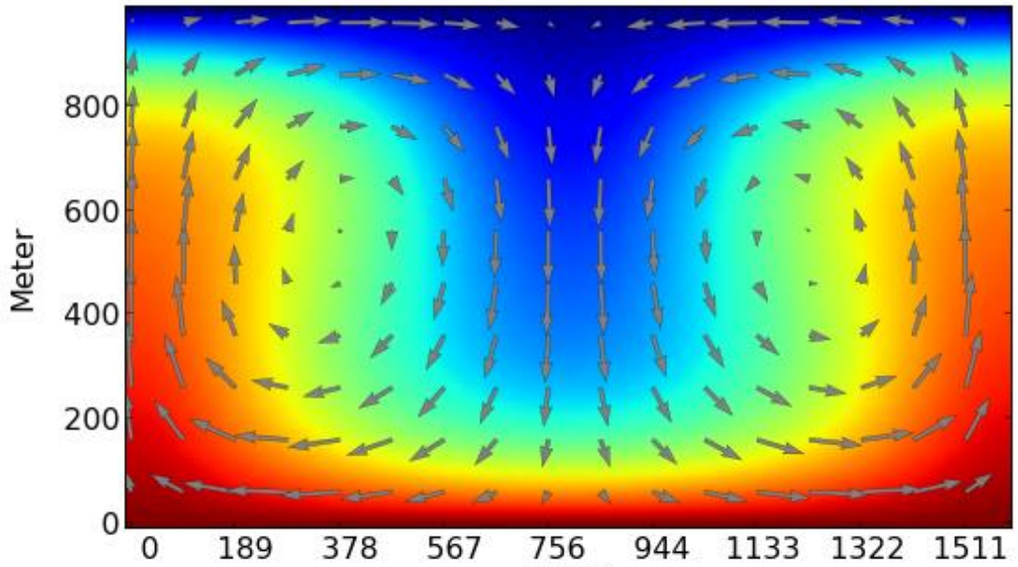


Convection in a box

Temperature and flow field



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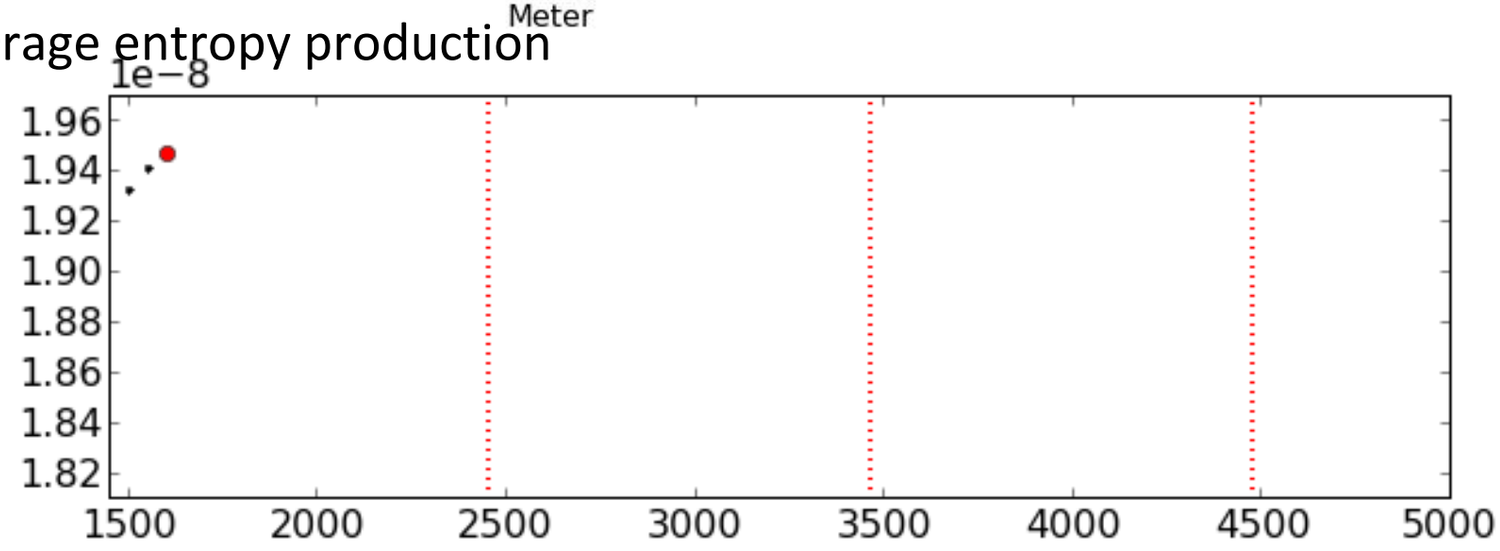
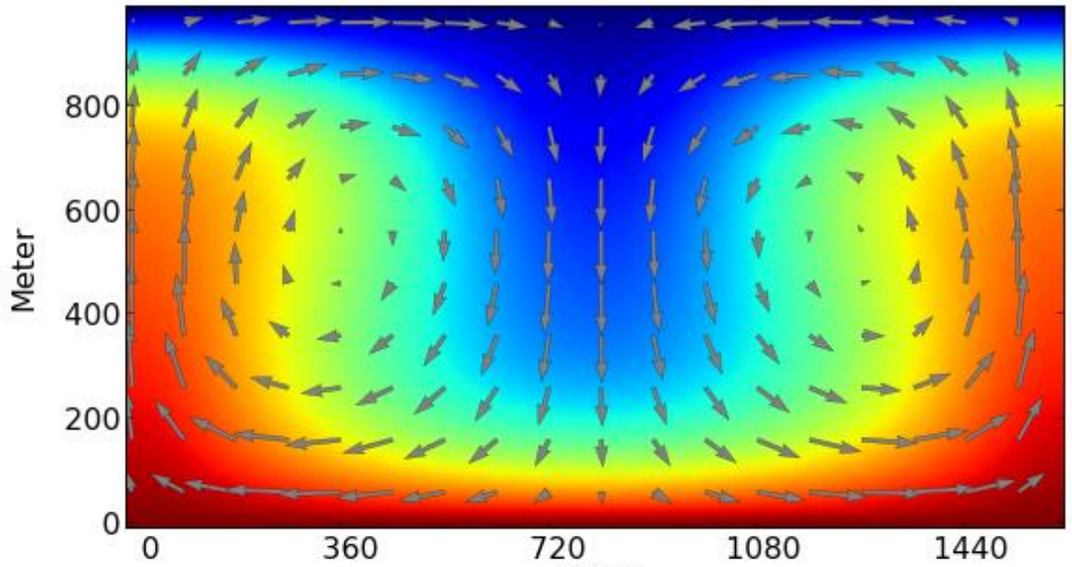


Convection in a box

Temperature and flow field



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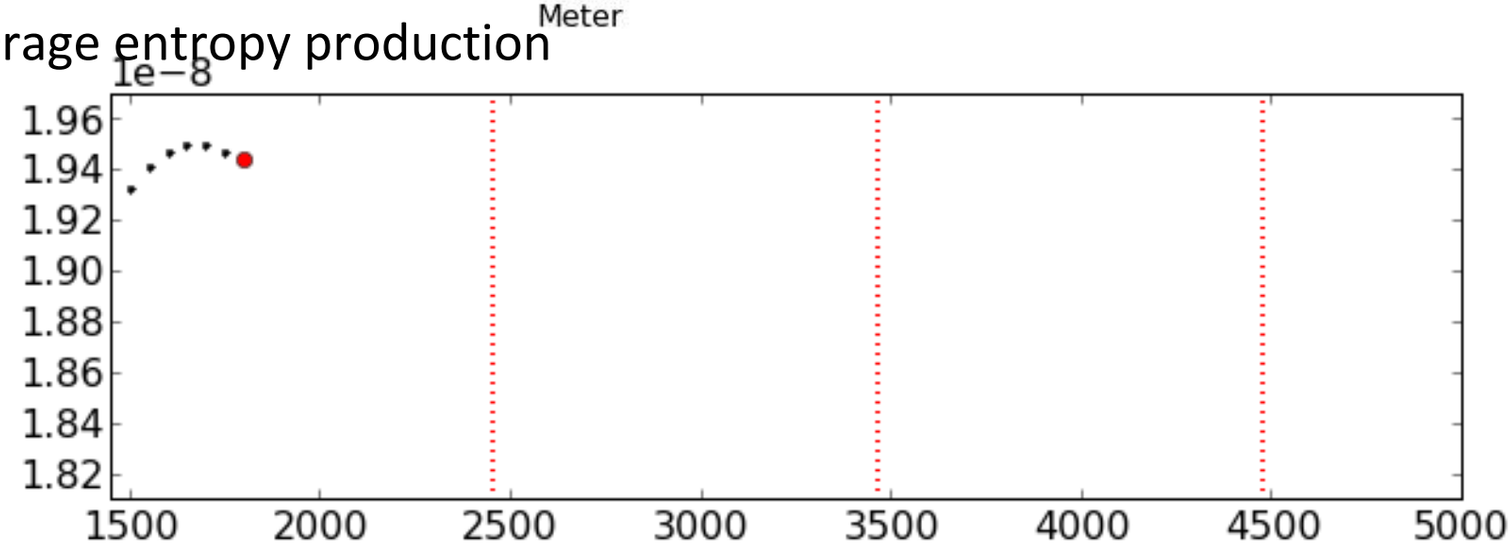
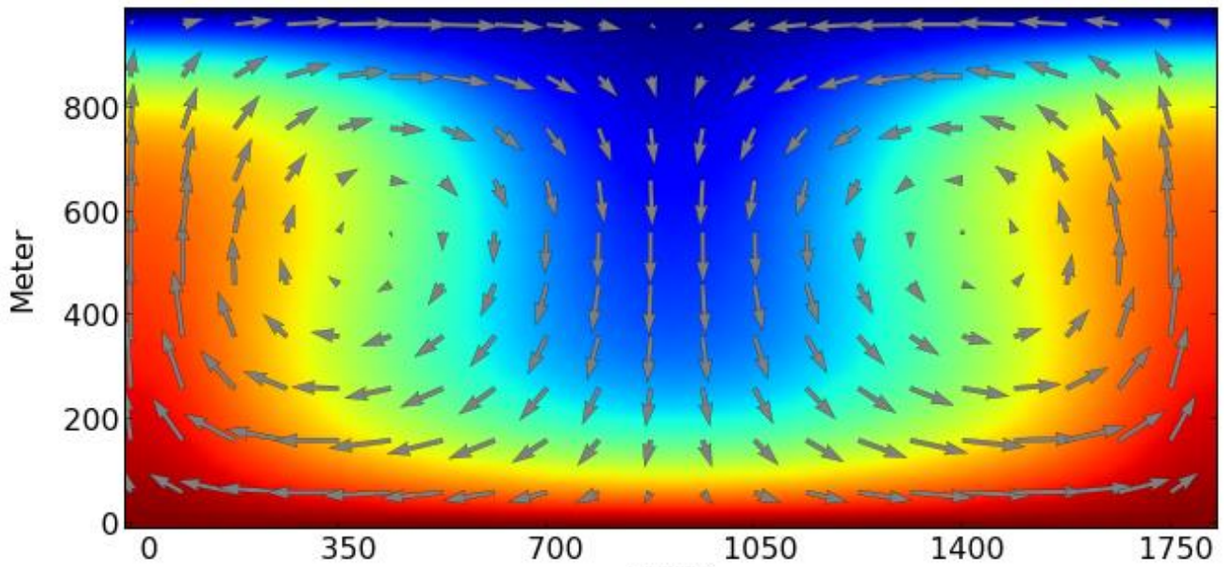


Convection in a box

Temperature and flow field



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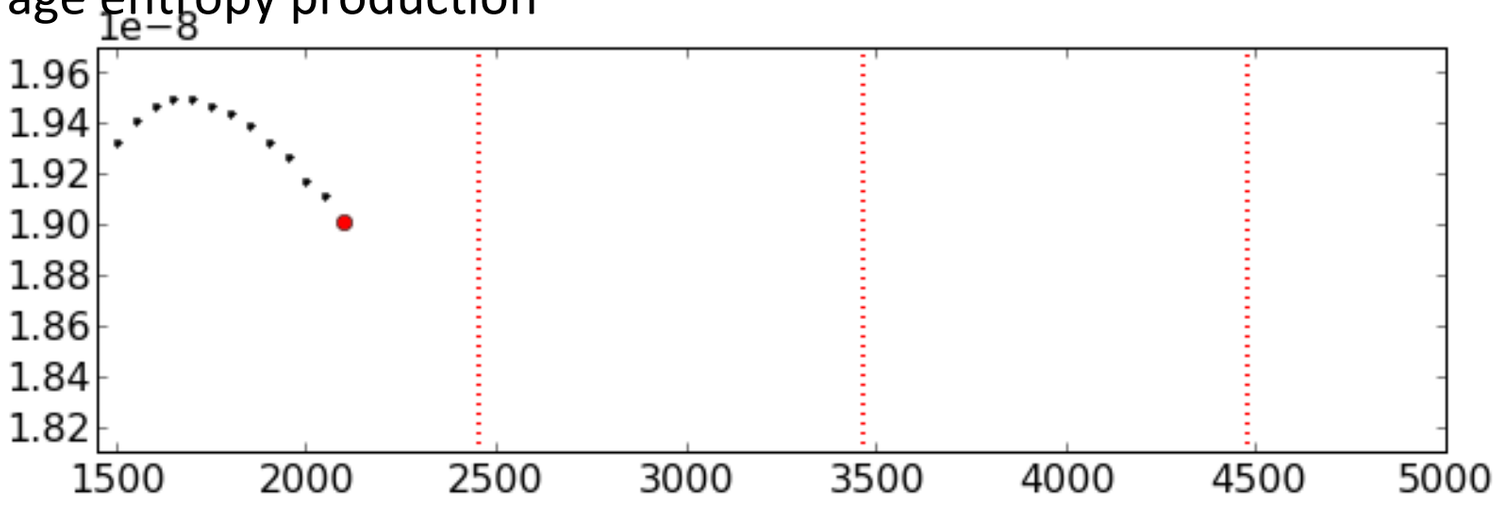
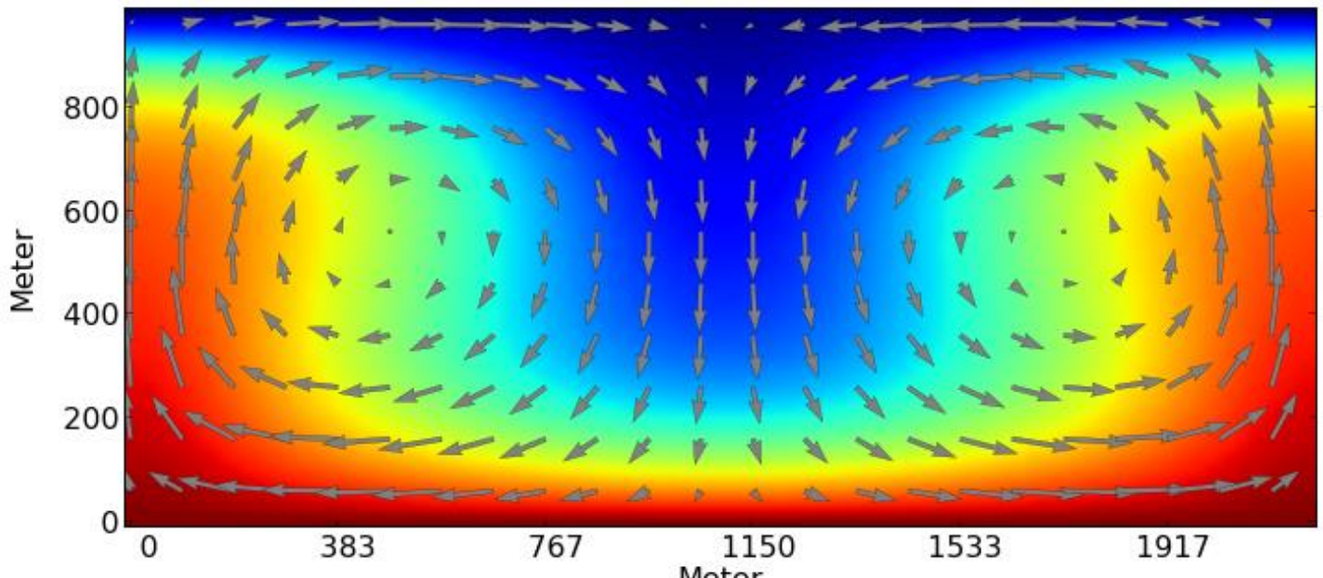


Convection in a box

Temperature and flow field



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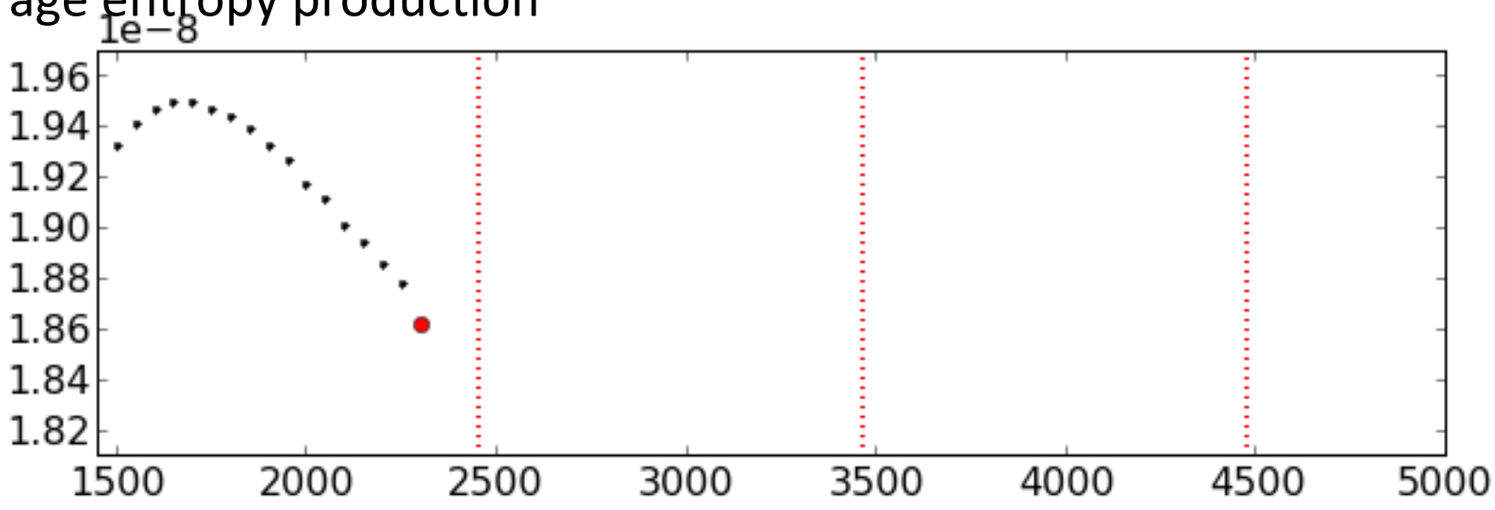
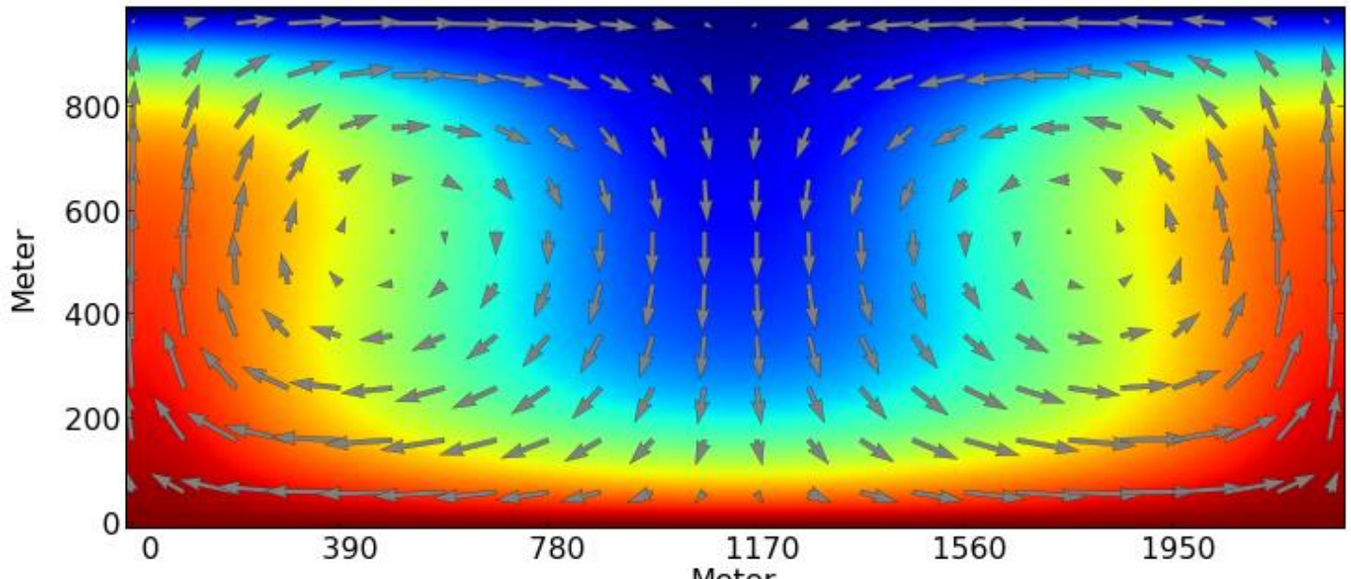


Convection in a box

Temperature and flow field



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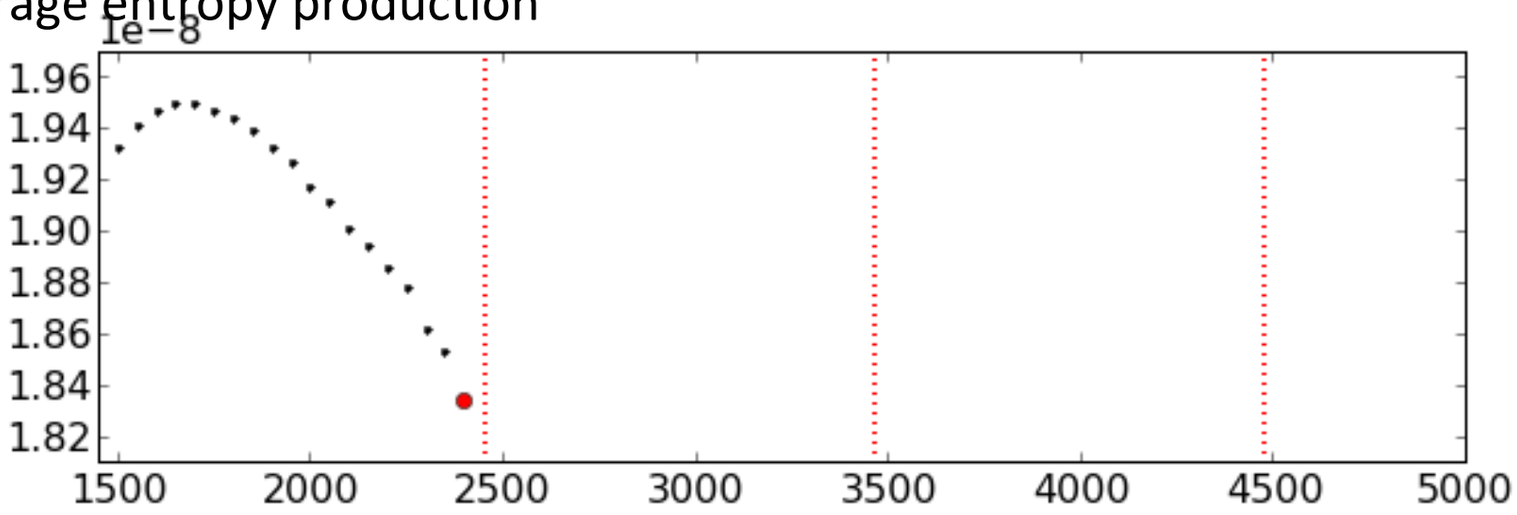
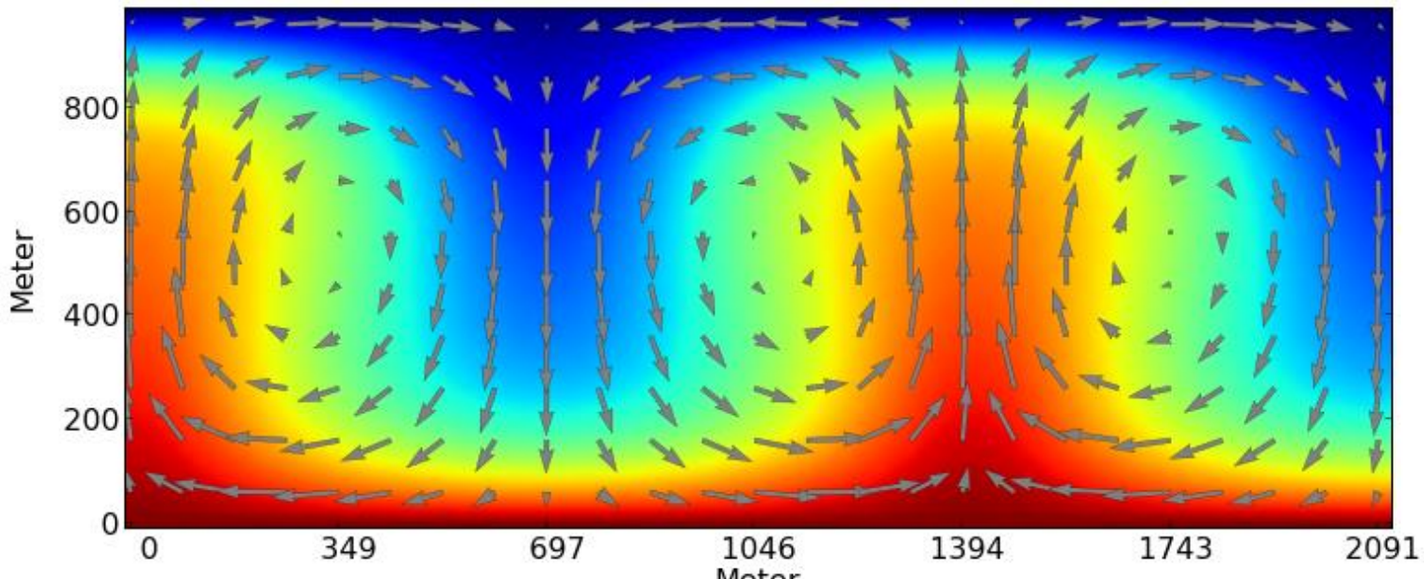


Convection in a box

Temperature and flow field



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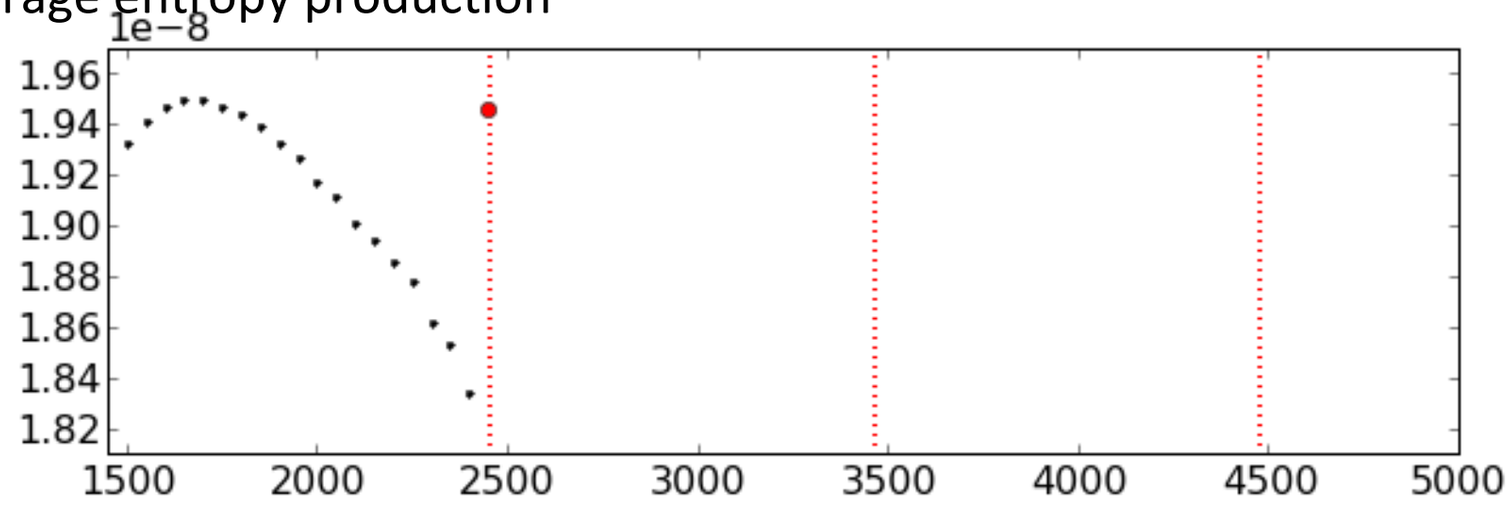
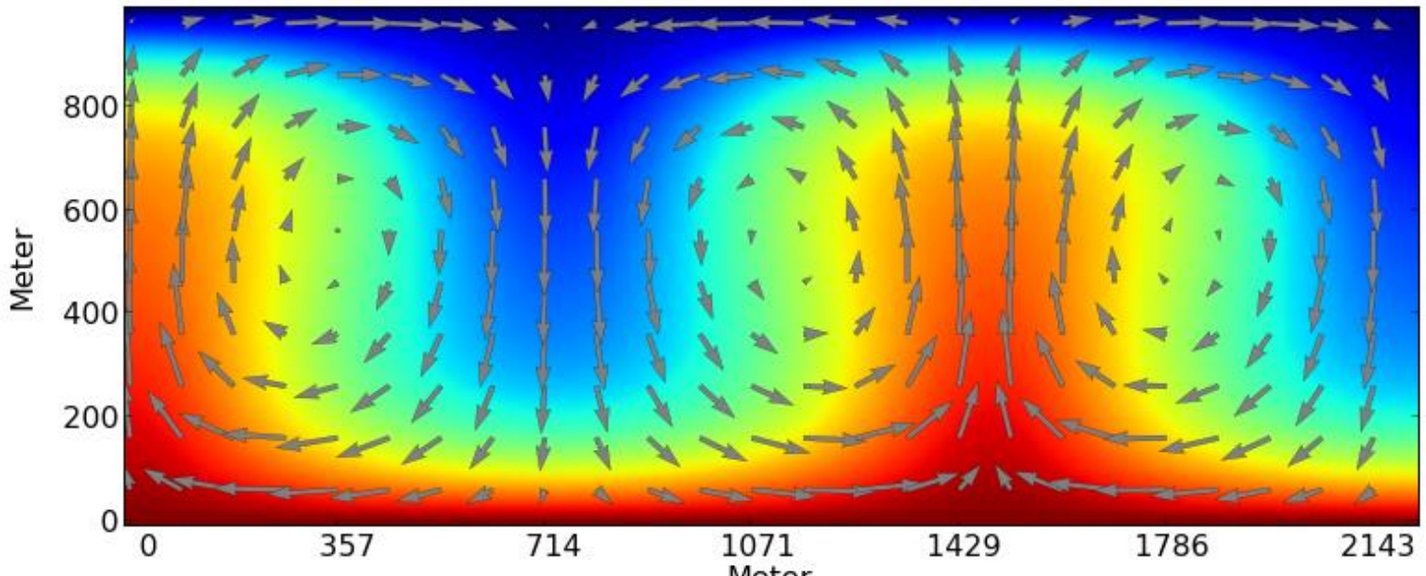


Convection in a box

Temperature and flow field



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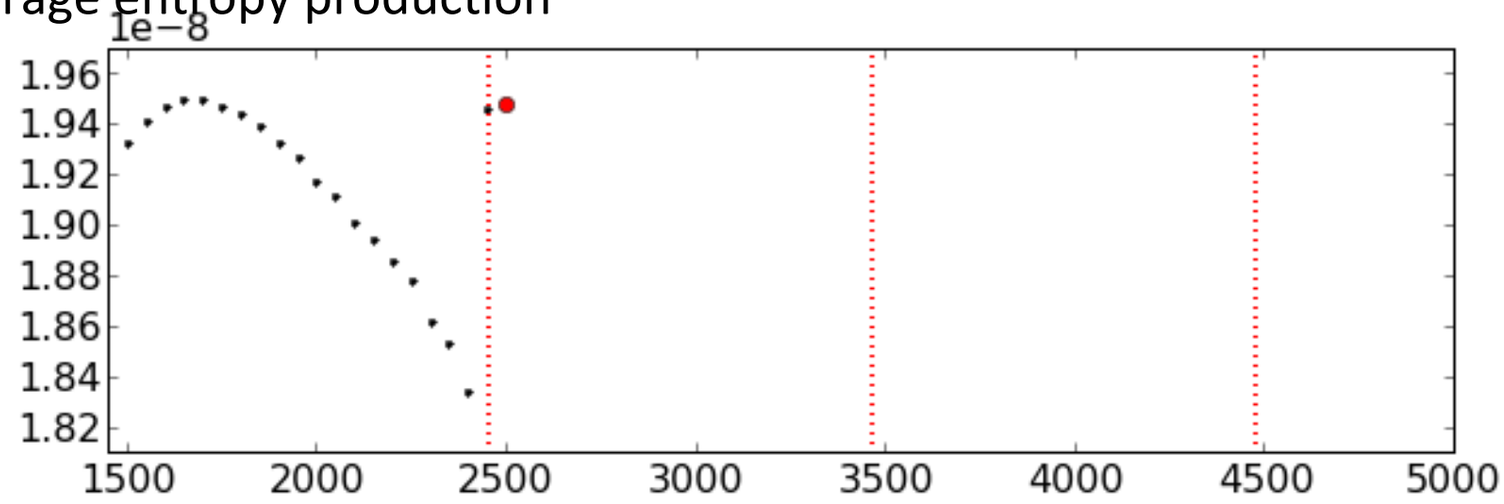
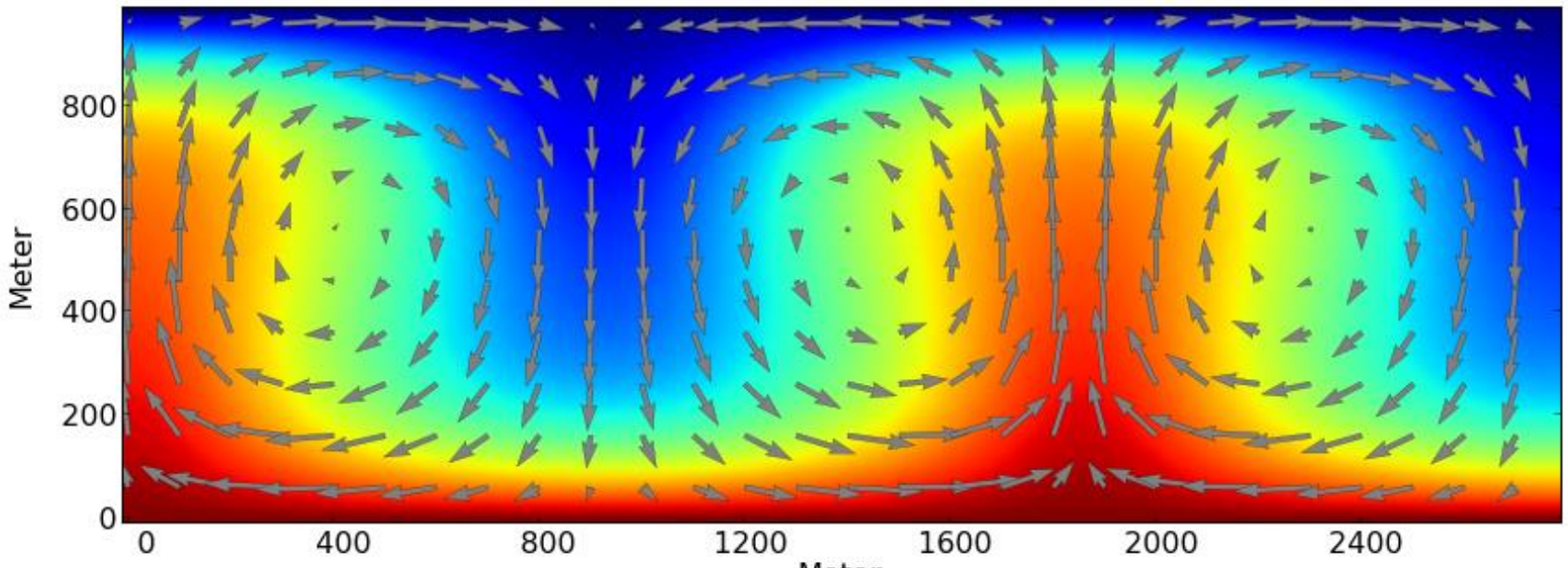


Convection in a box

Temperature and flow field



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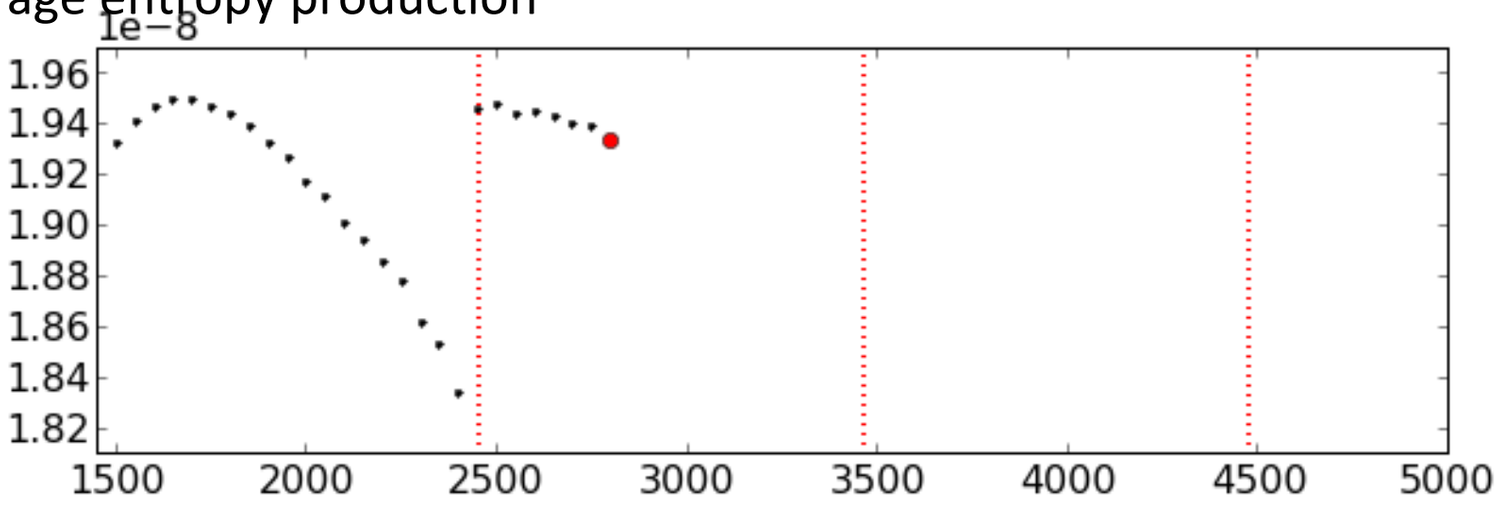

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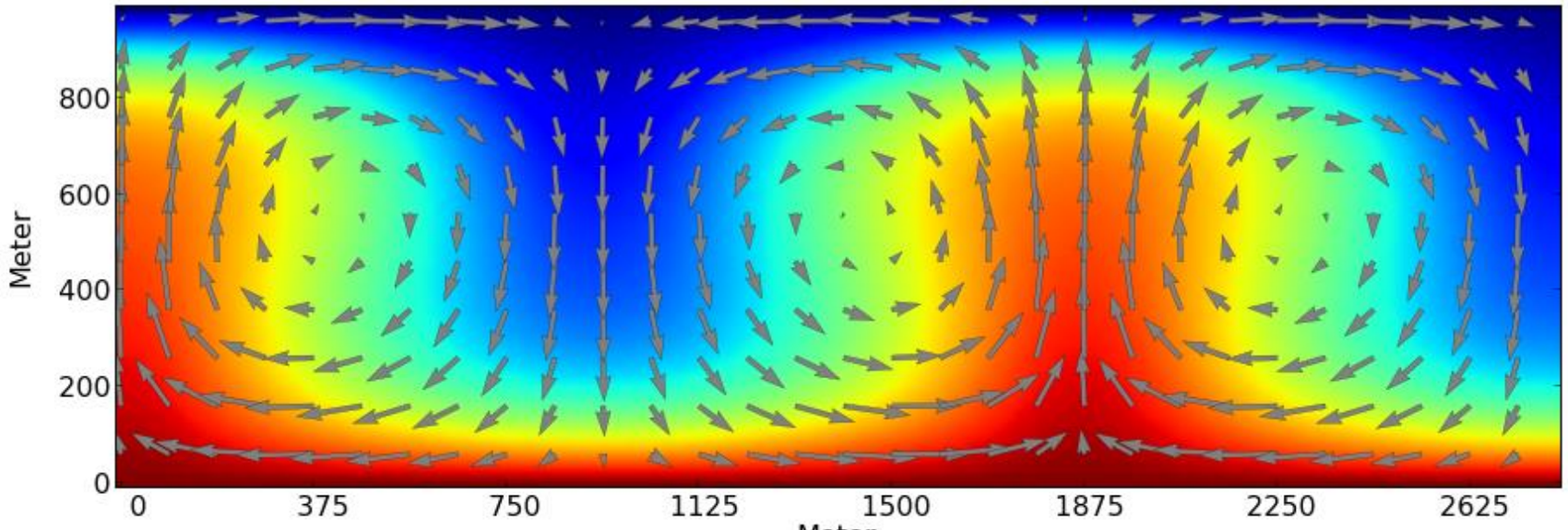

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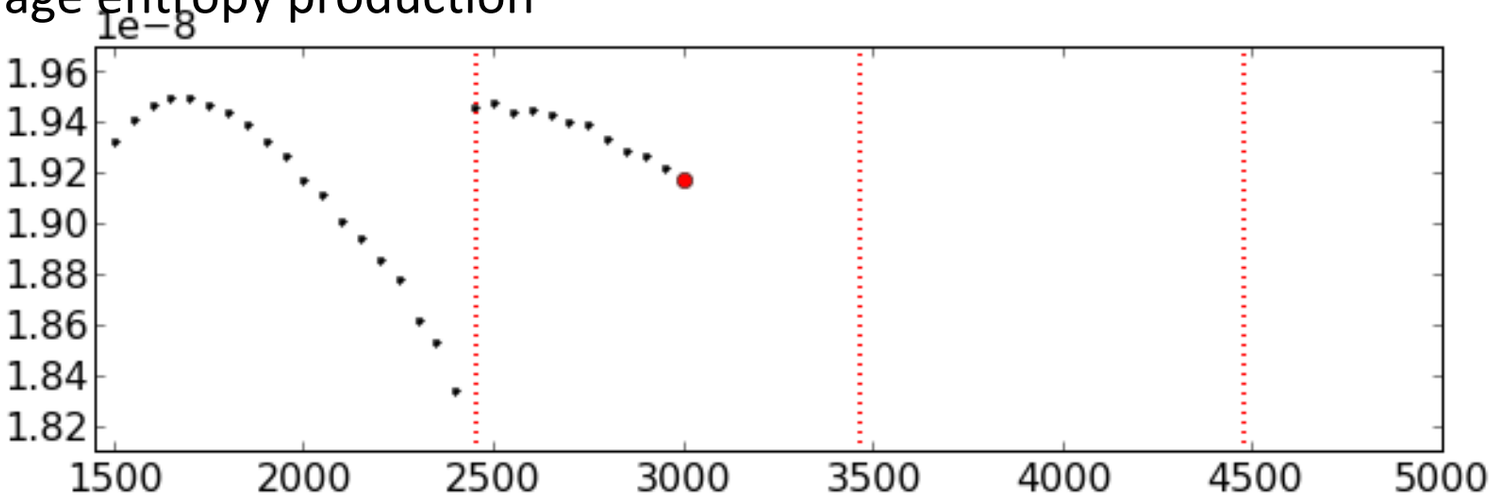

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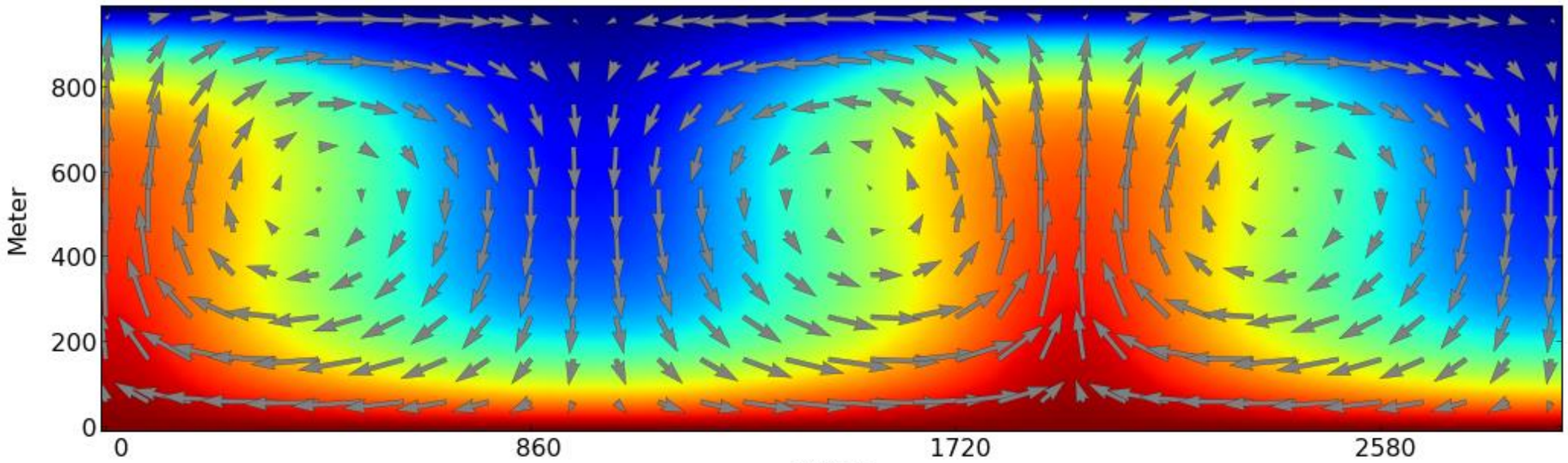

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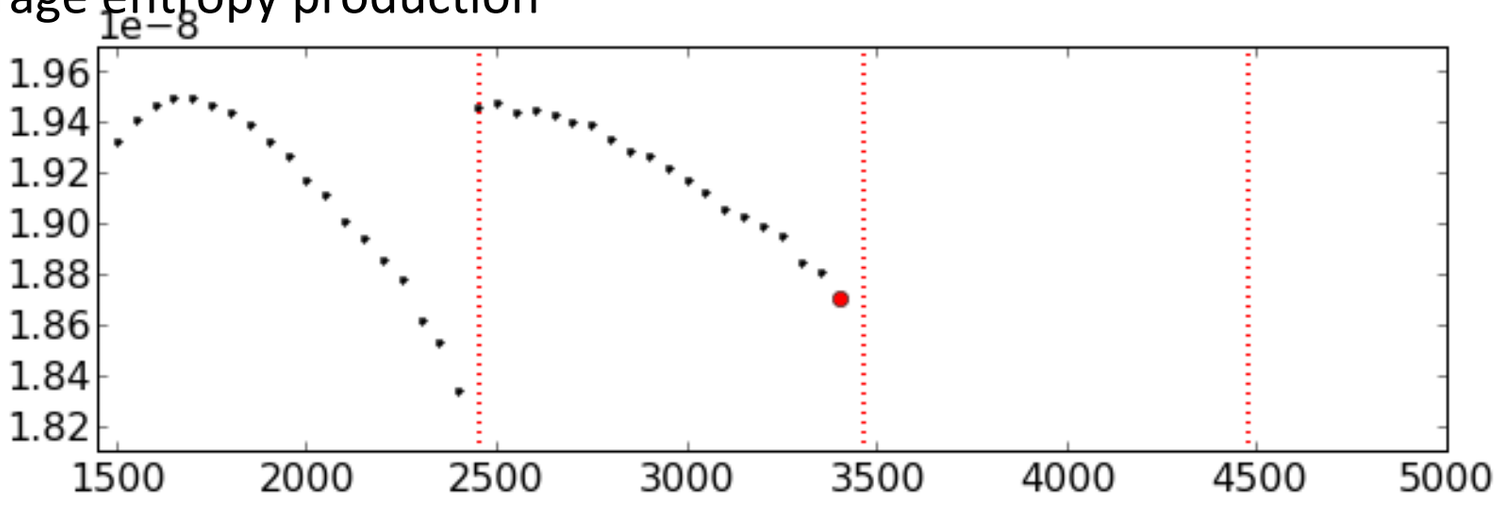

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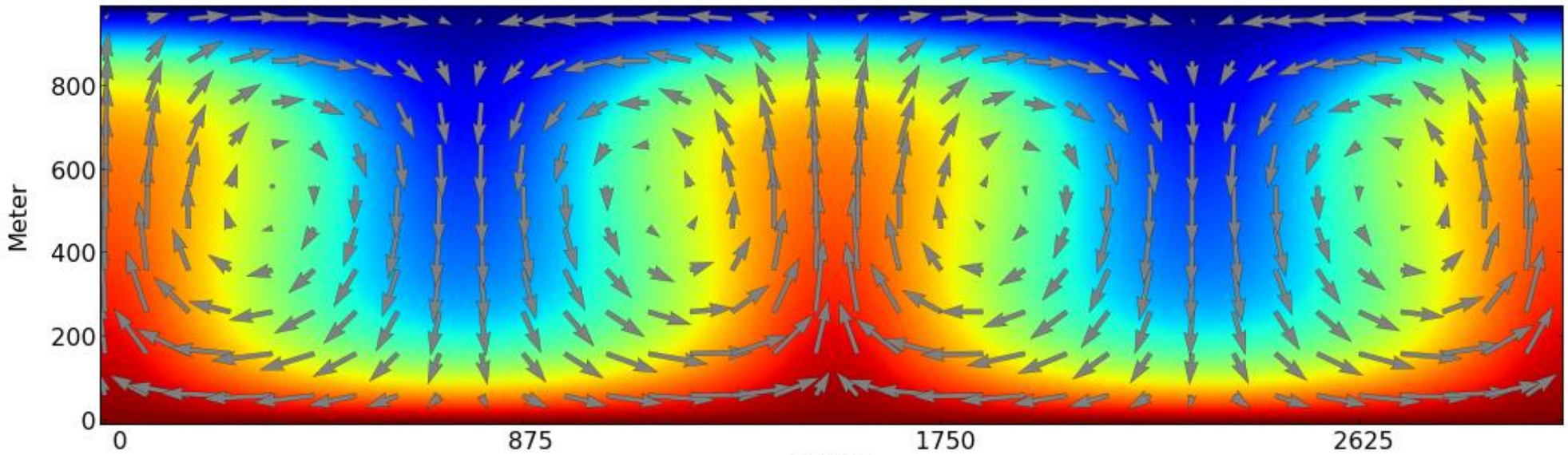
Temperature and flow field



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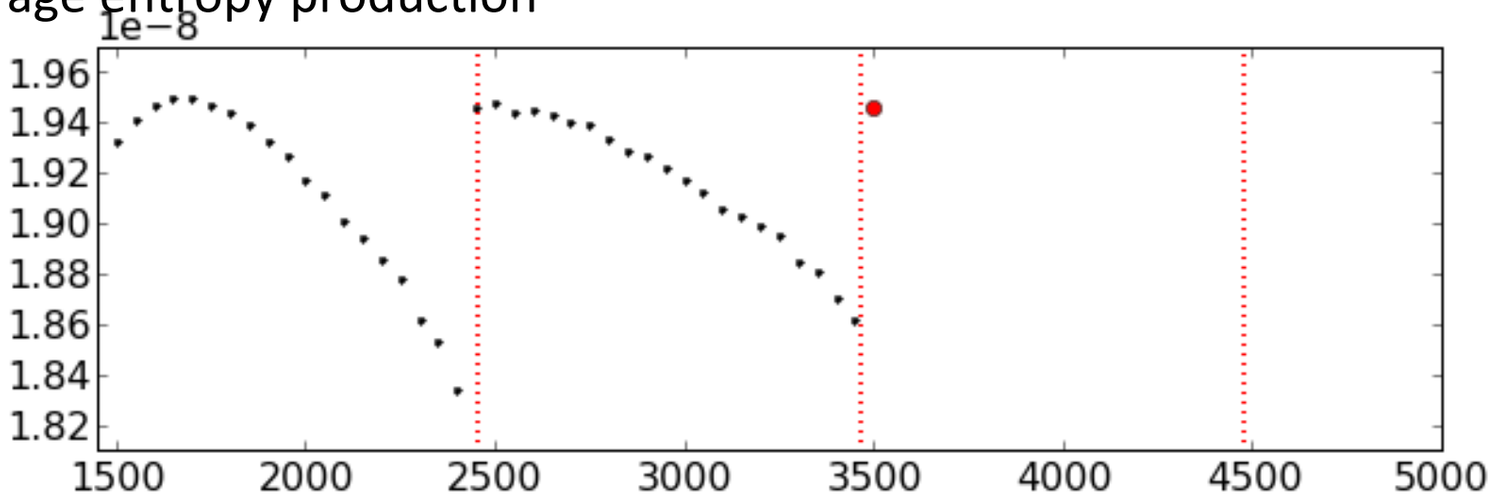

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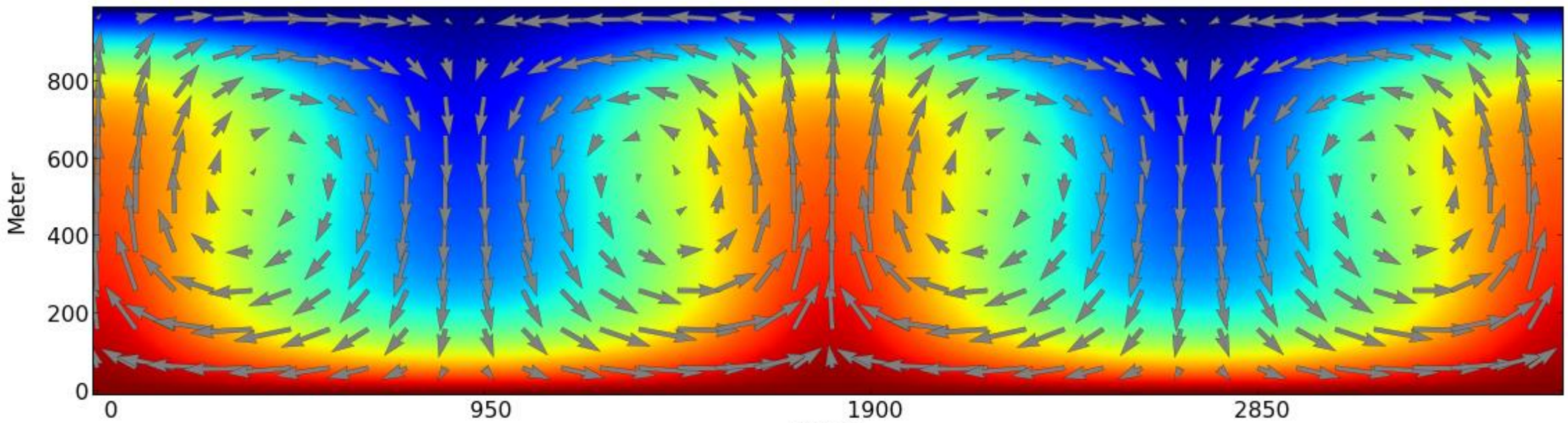
Temperature and flow field



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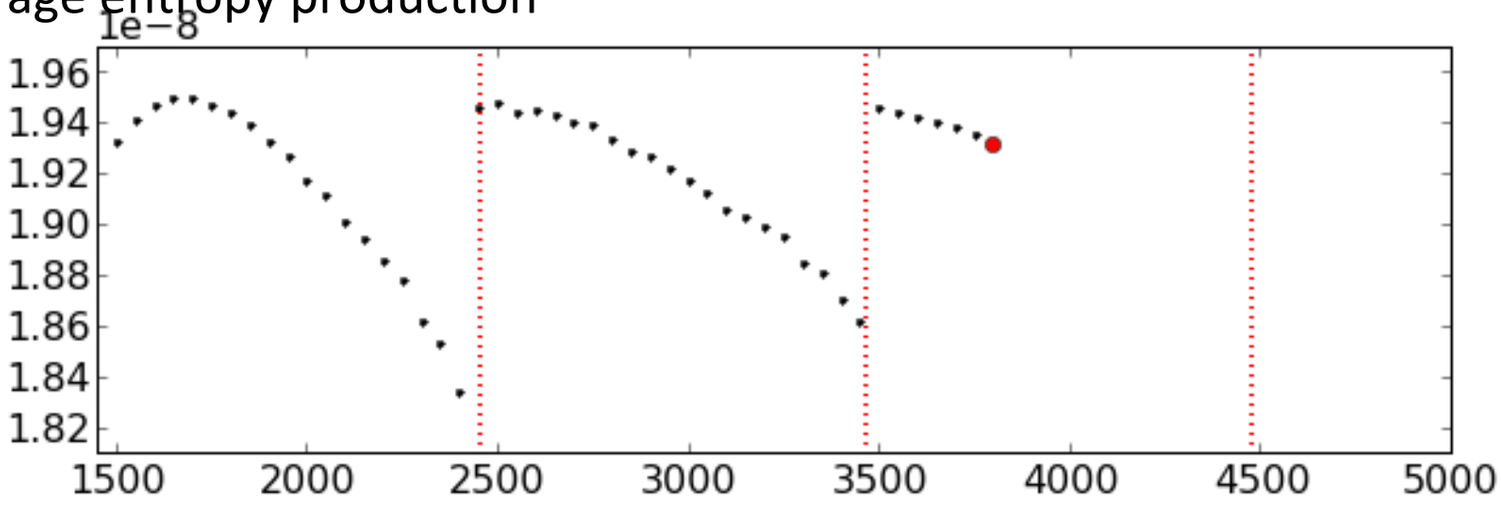
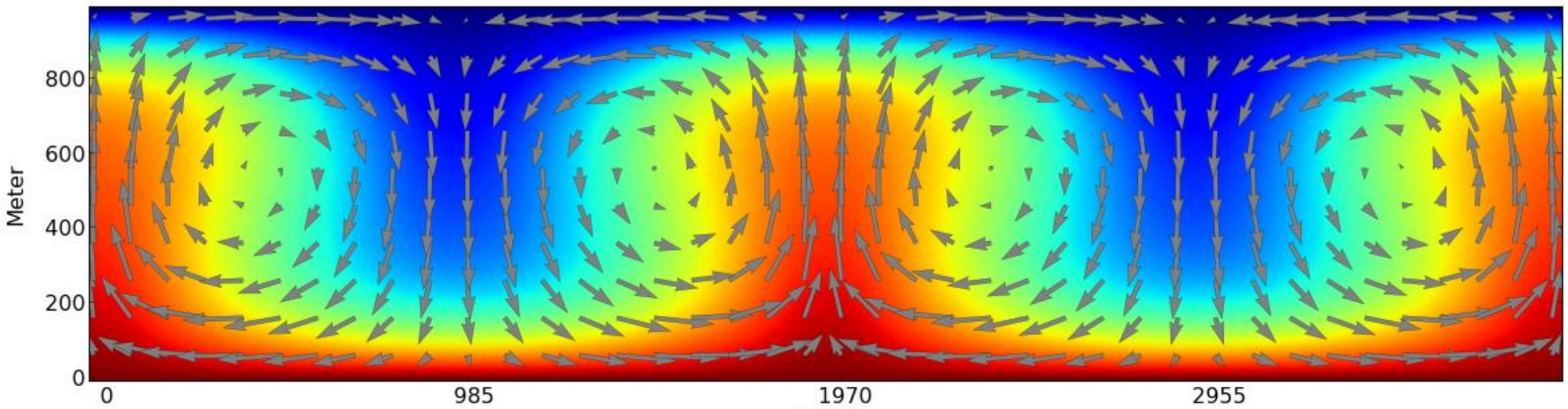


Convection in a box

Temperature and flow field



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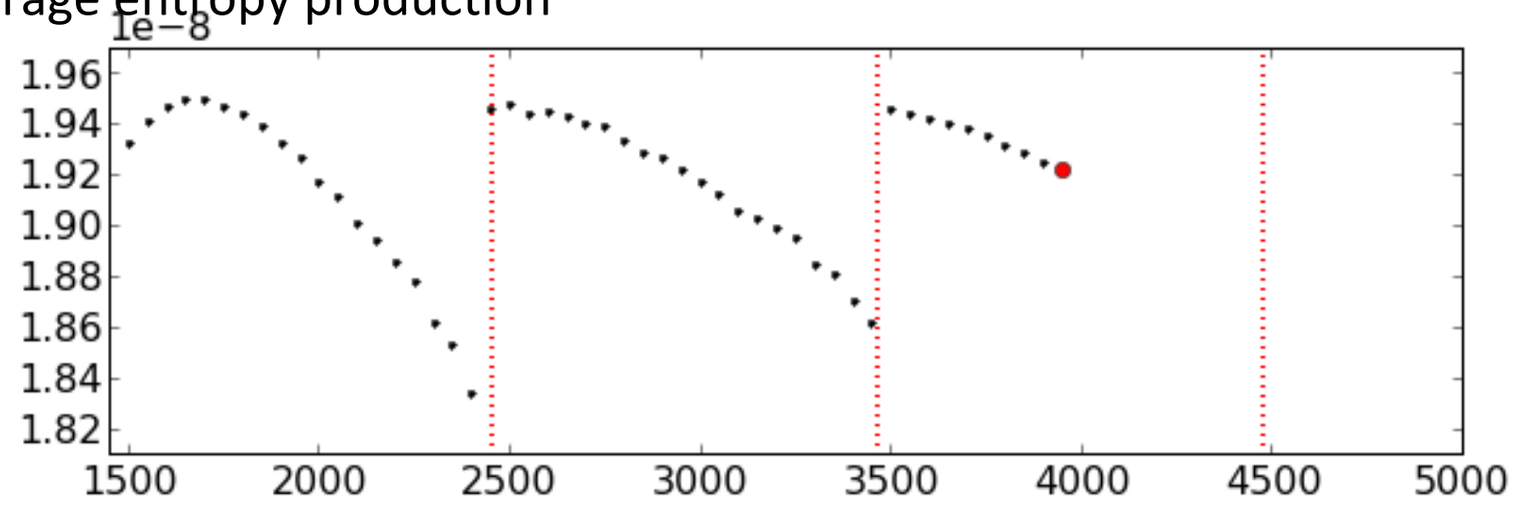
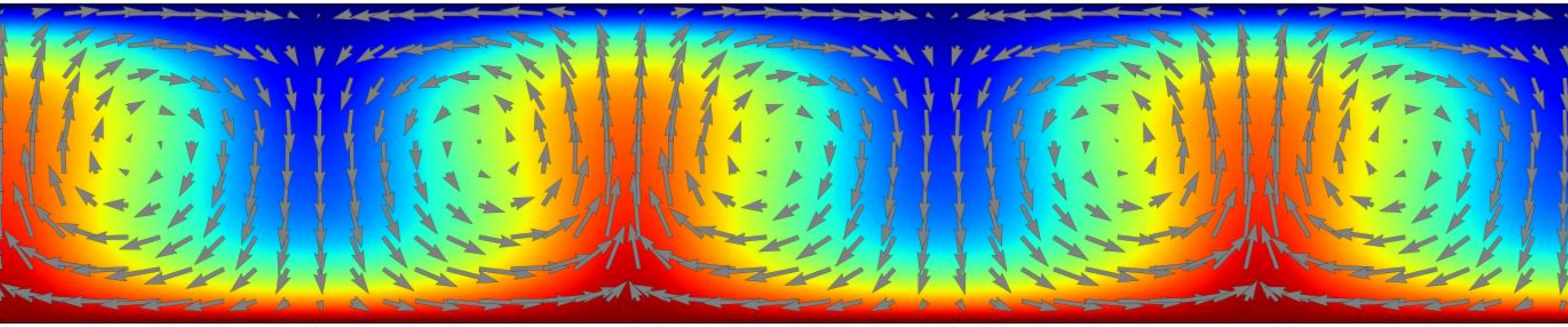
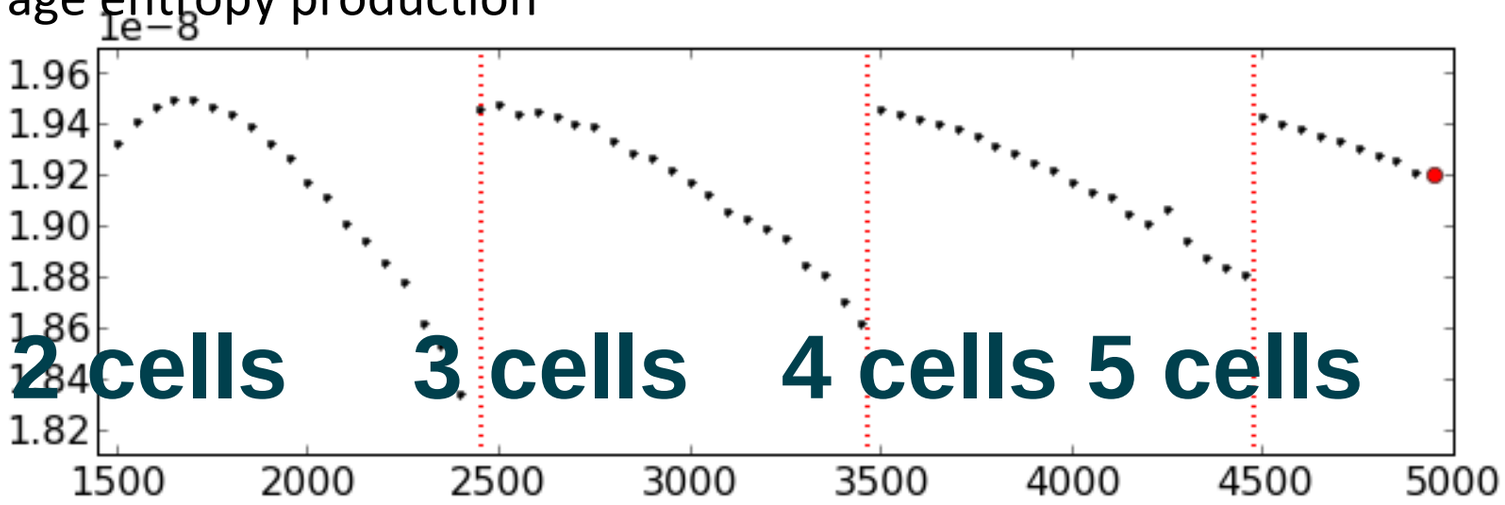


Convection in a box

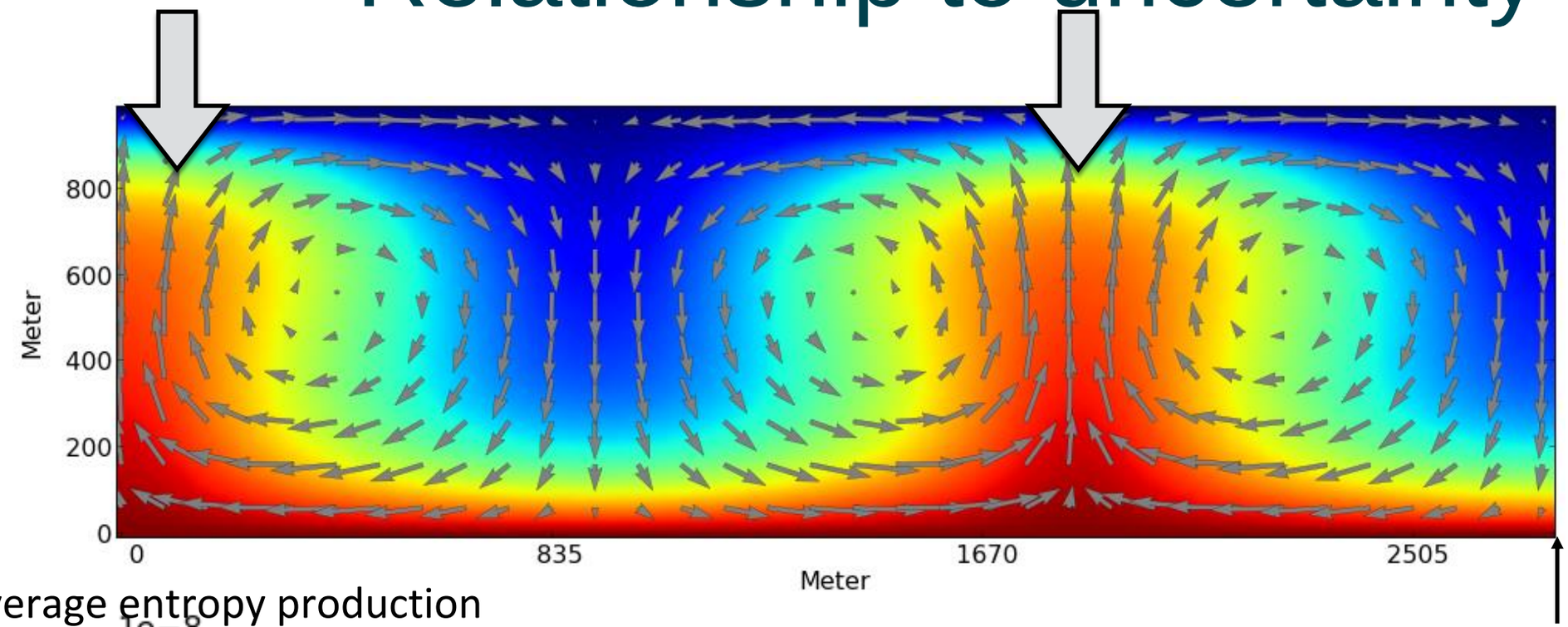
Temperature and flow field



Average entropy production



Relationship to uncertainty



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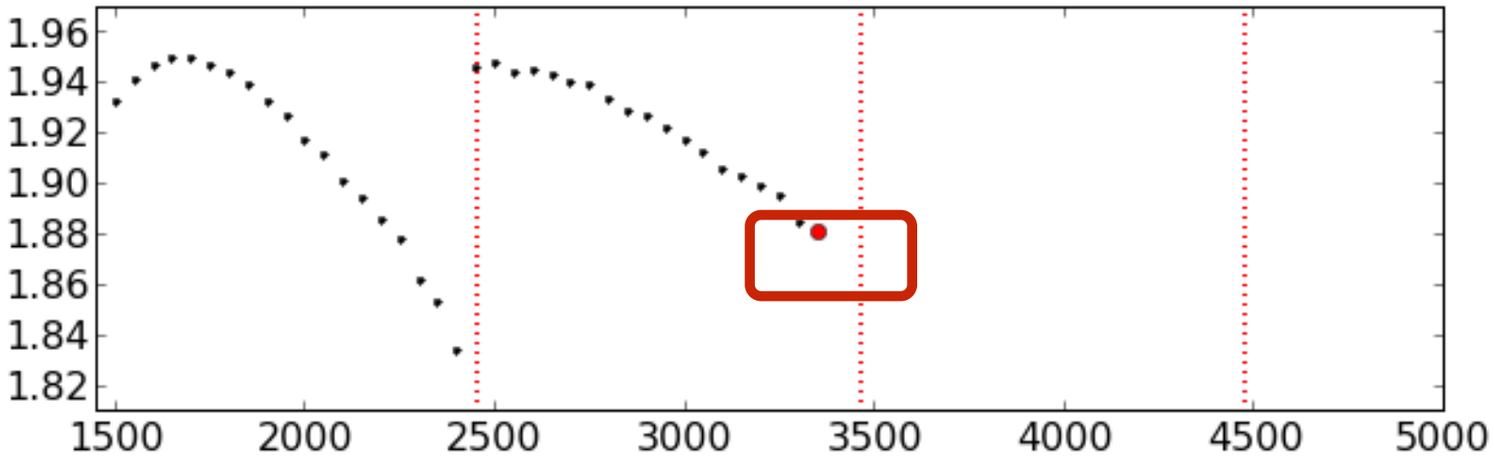

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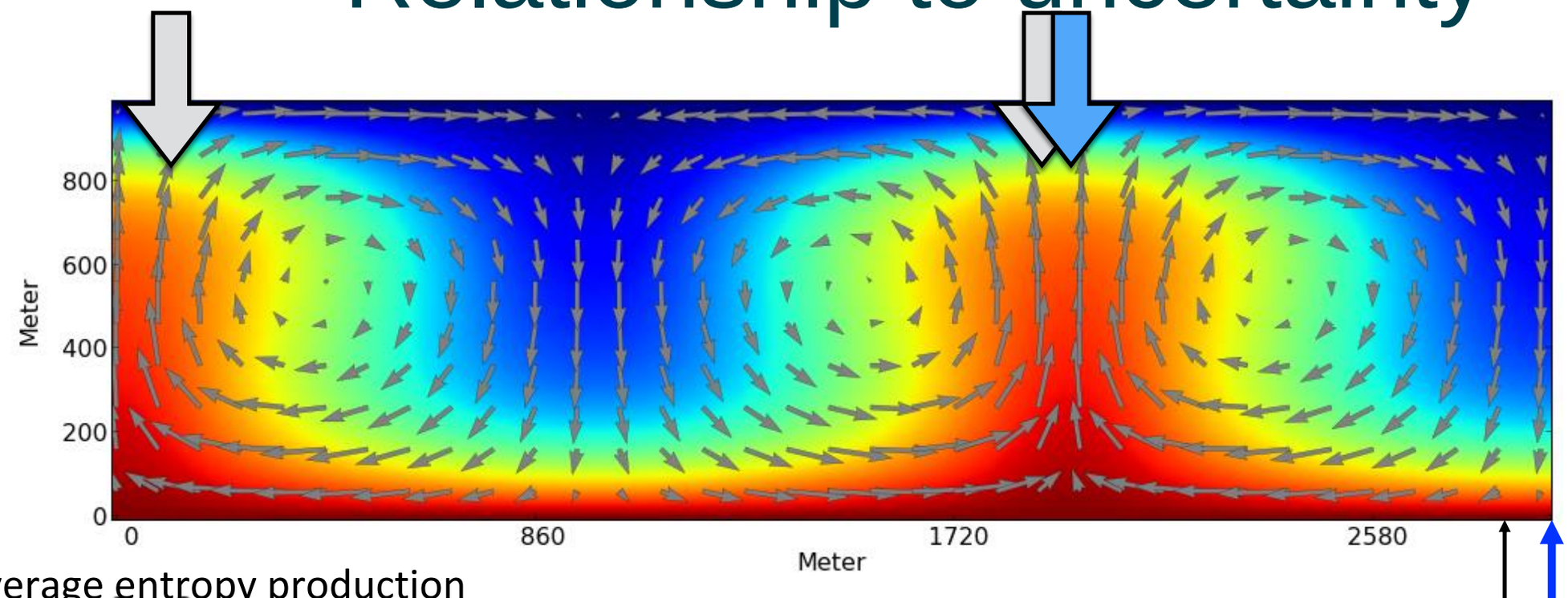

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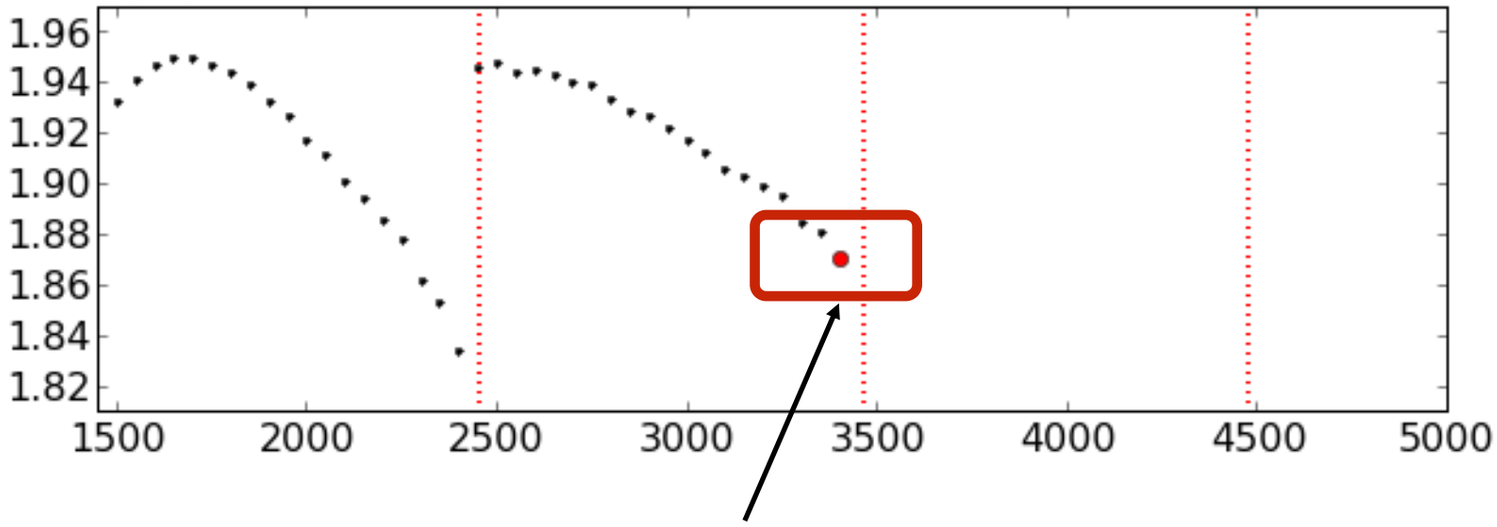
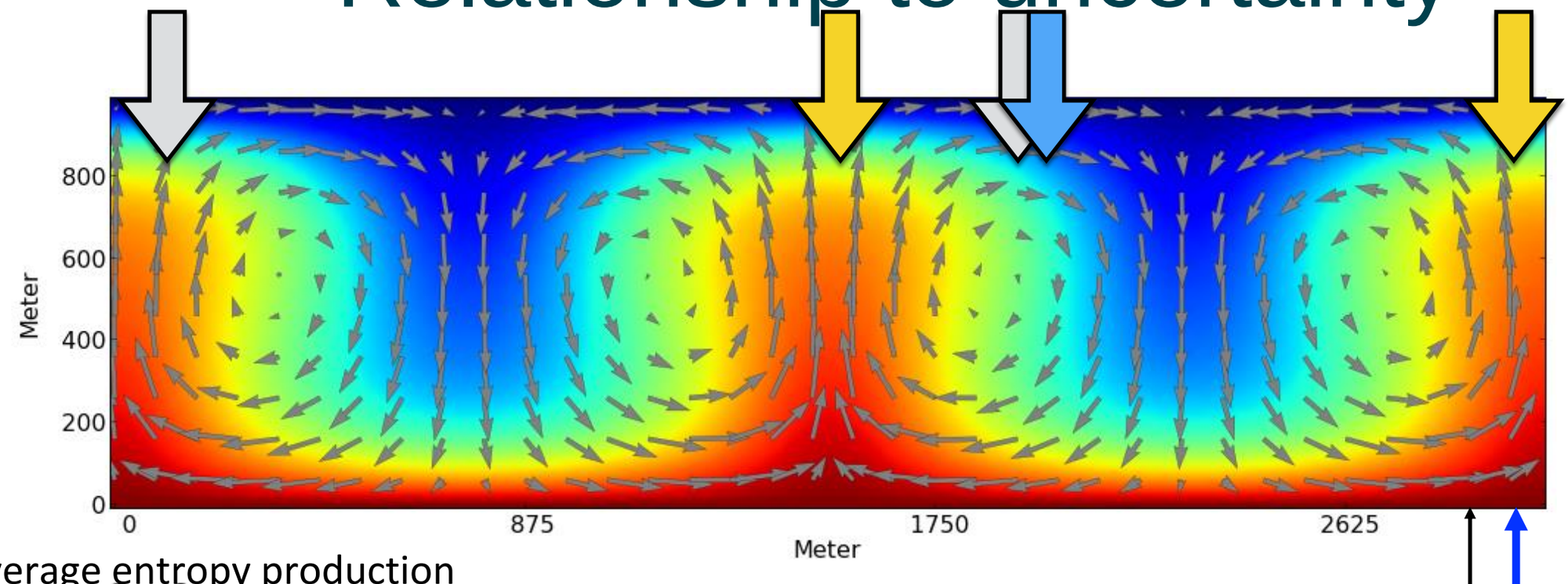
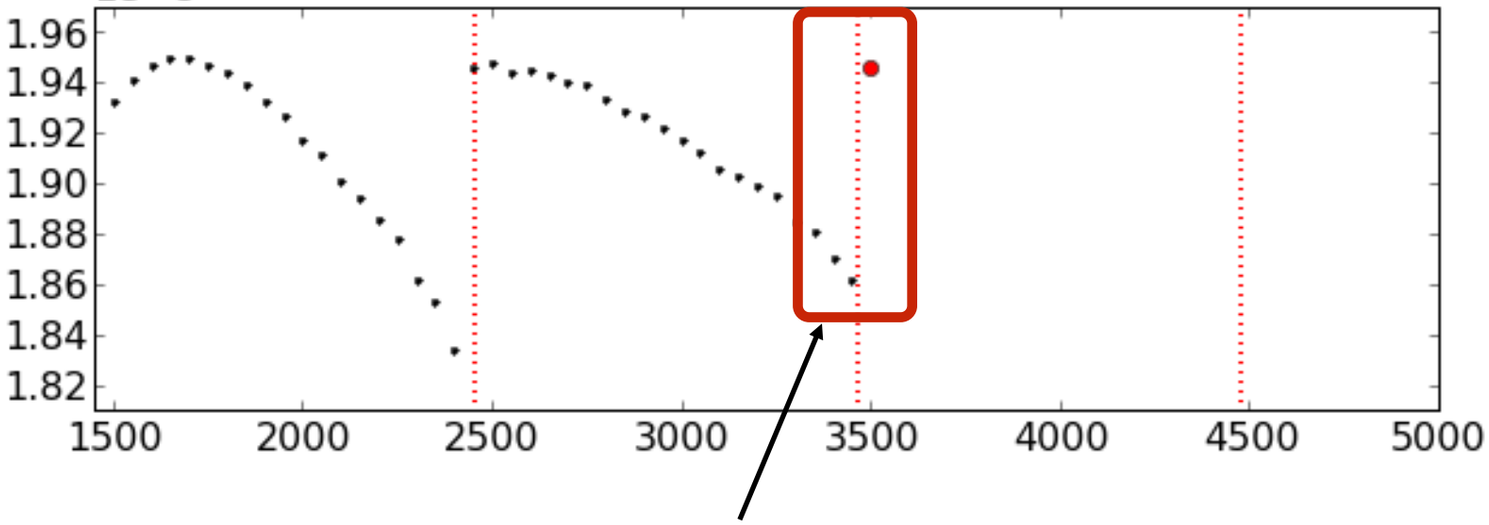


Small change with little effect

Relationship to uncertainty



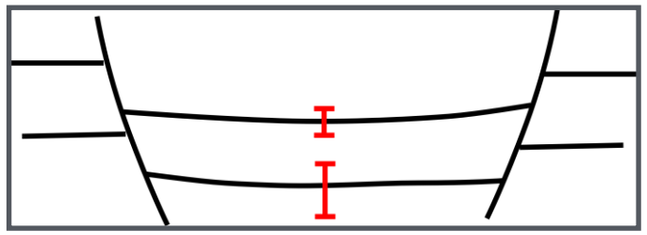
Average entropy production



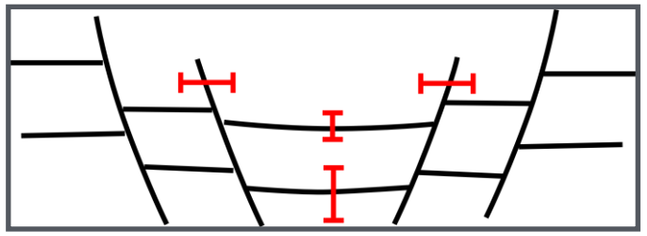
Same small change, significant effect, reflected in entropy production

Comparison of uncertainties

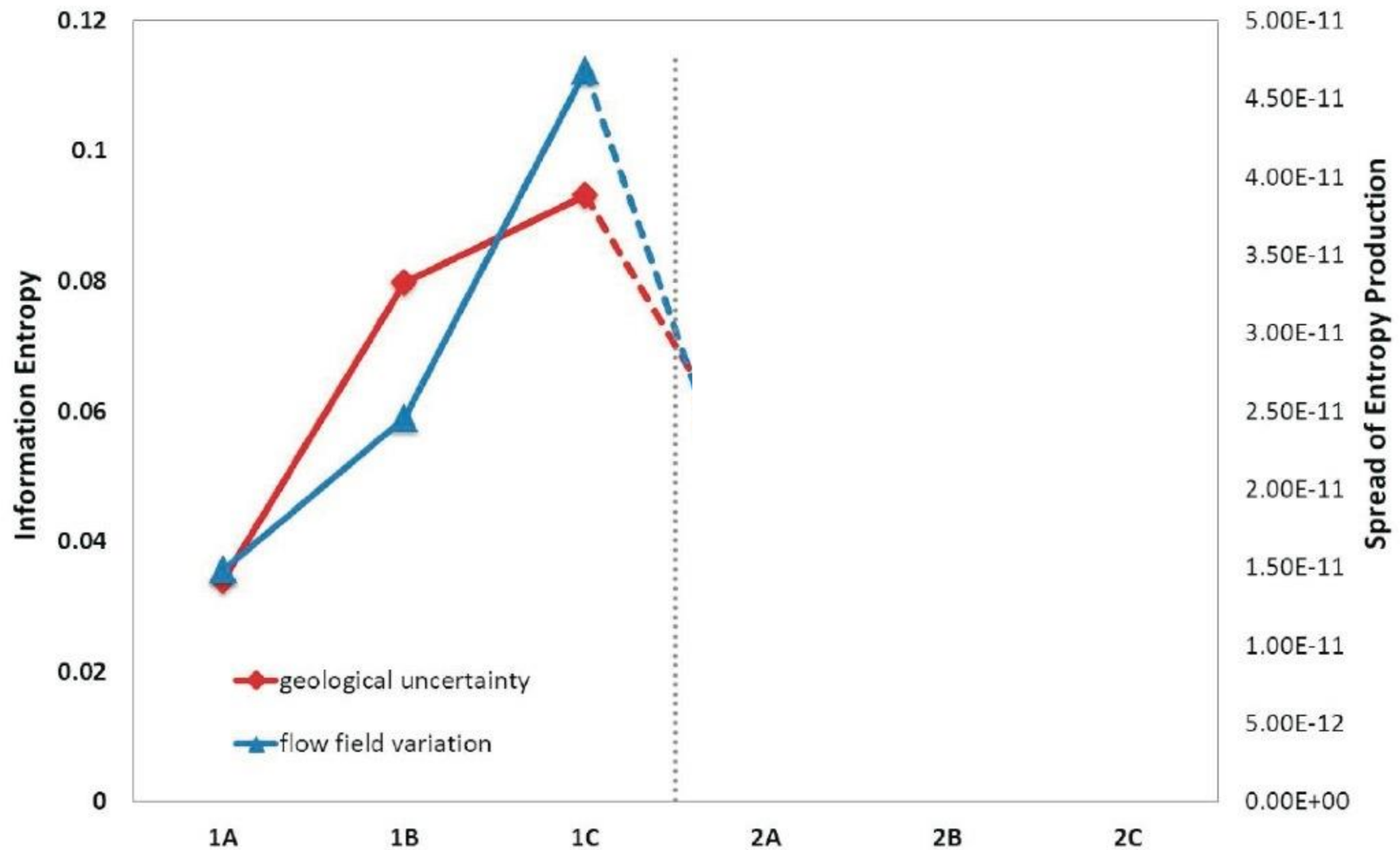
Depth uncertain



Additional faults



reduced data quality



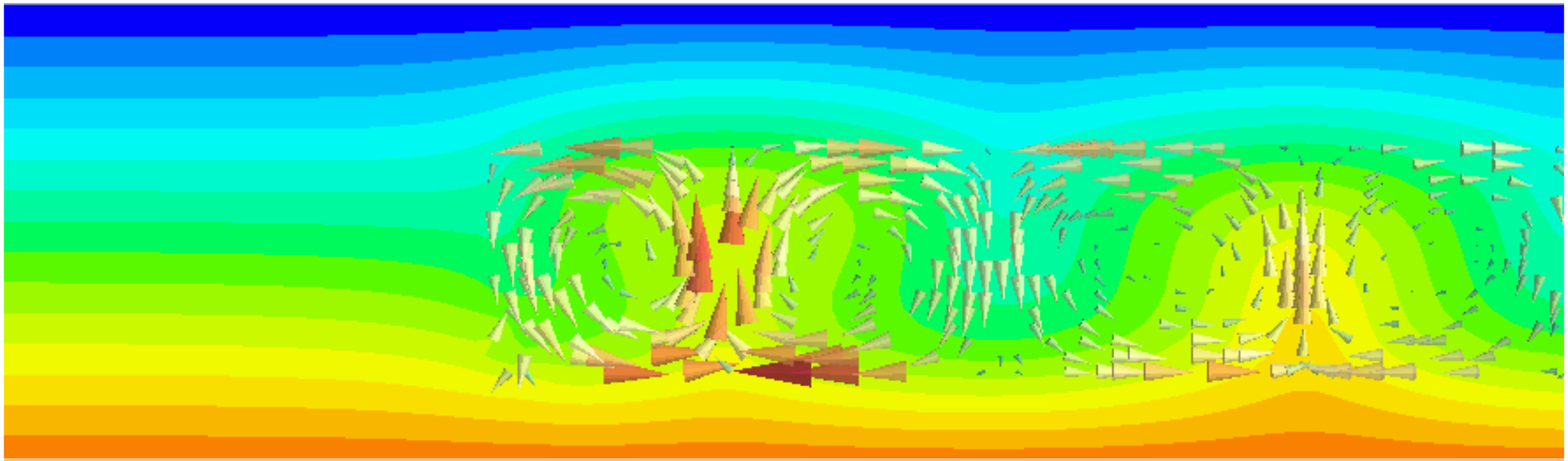
Summary + Conclusions

- Information Entropy describes uncertainty of geological structure and can be used for geometric uncertainty quantification
- Thick and permeable sedimentary sequences are prone to convection which introduces uncertainty in physics of heat trransfer
- Thermal entropy production is a measure of hydrothermal state of the system, related to heat transport mechanism
- It provides a valuable insight beyond temperature analysis
- Information and thermal entropy together can be used to (e.g. transitions between n cells -> n+1 cells)

Conclusion and Outlook

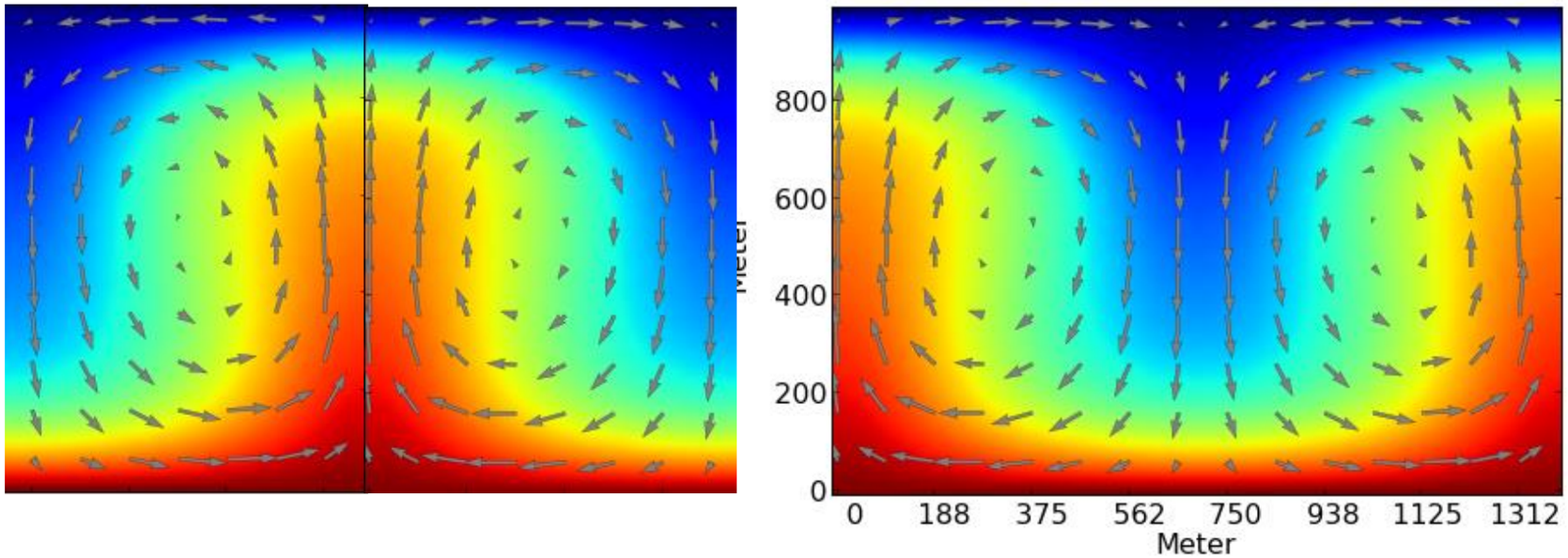
- Conclusion
  - Thermal entropy production as measure of hydrothermal state of the system, related to heat transport mechanism
  - Potentially a valuable insight beyond temperature analysis
    - Sensitive to changes in the overall configuration of convective system (e.g. transitions between n cells -> n+1 cells)
- Outlook
  - More detailed theoretical analysis of system
  - Effect of forced convection
  - Effect of boundary conditions (force/ flux)

Thank you for your attention!



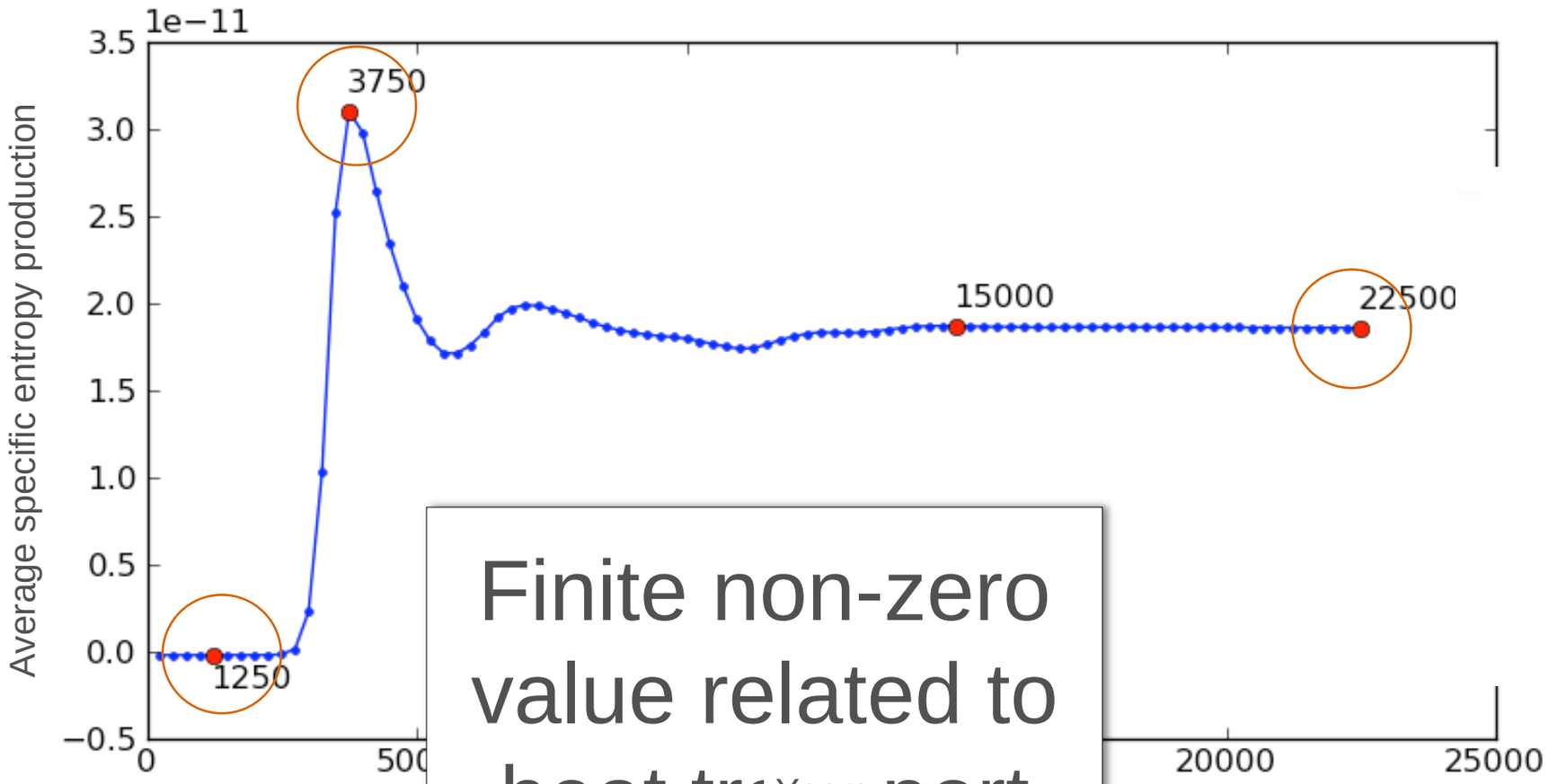
Florian Wellmann - wellmann@aices.rwth-aachen.de

Non-uniqueness of solution



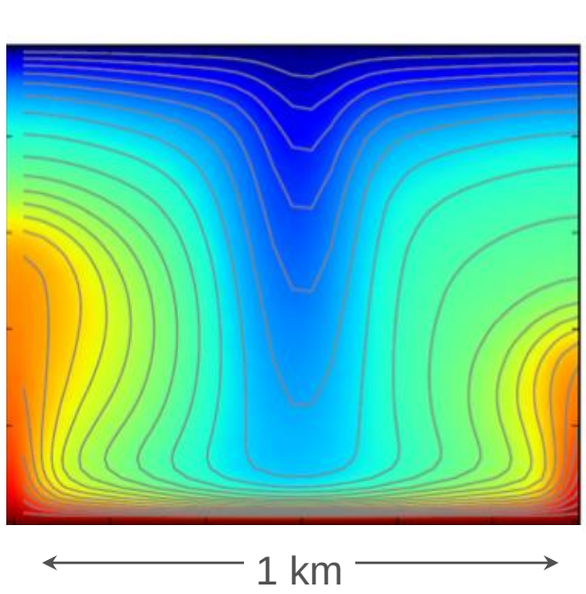
Entropy production during onset of convection

Entropy production during the onset of convection

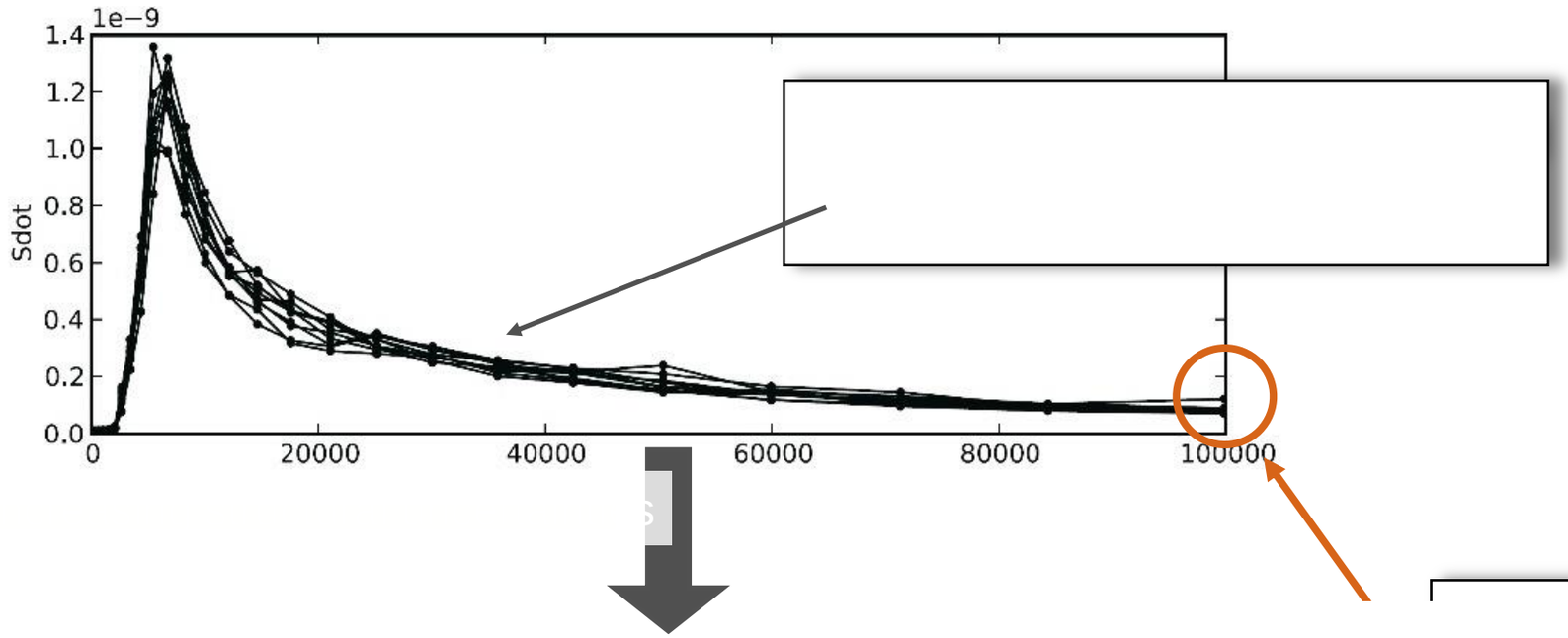


Finite non-zero value related to heat transport mechanisms

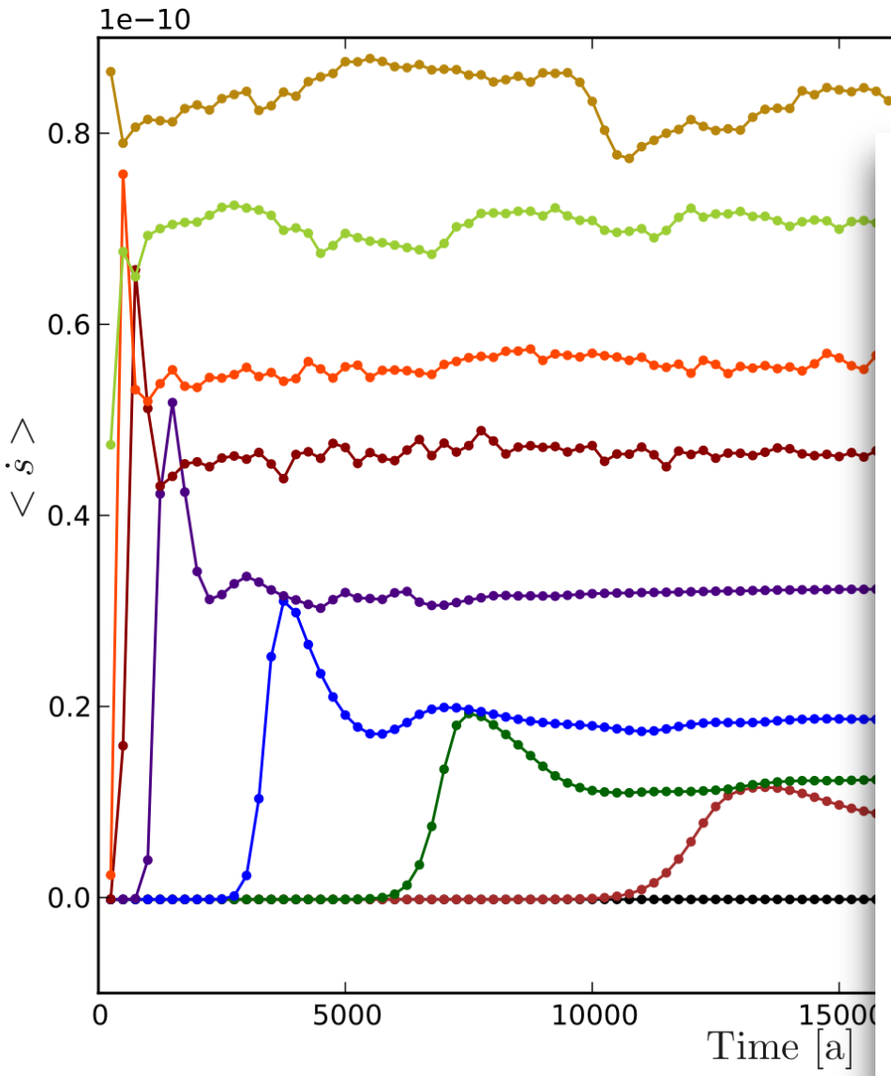
Temperature

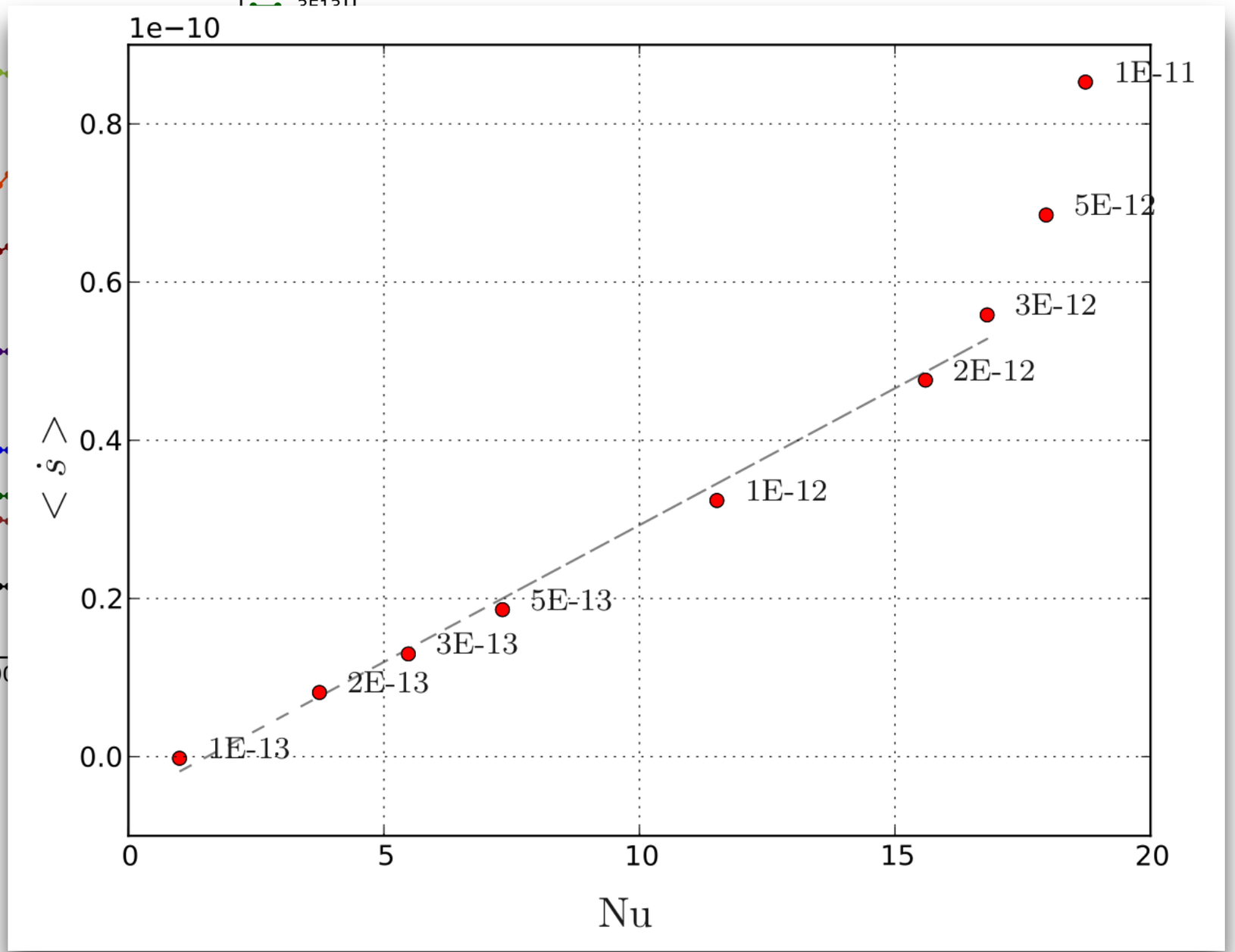


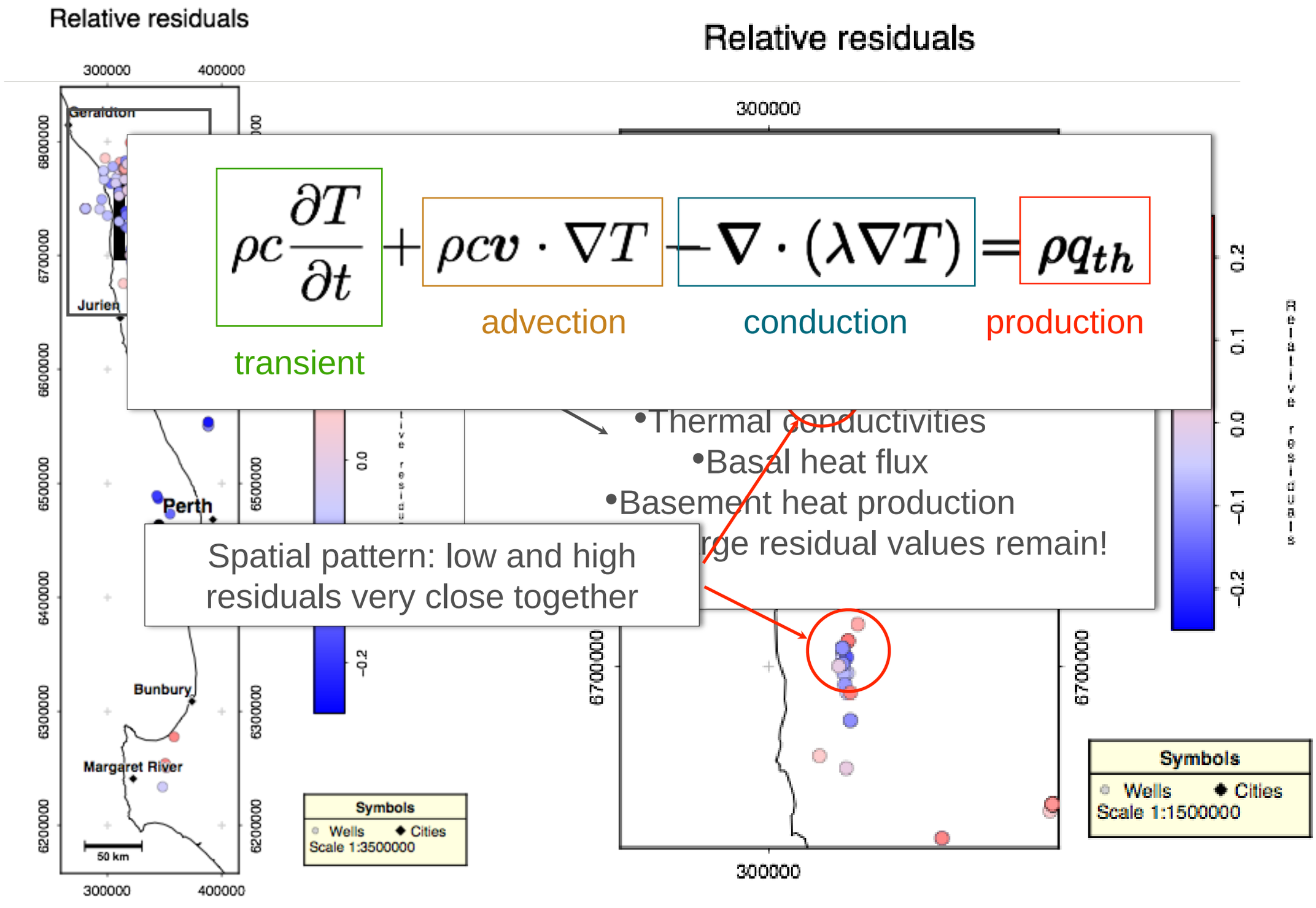
Testing influence of geological uncertainties on flow fields



Relationship between entropy production and heat transfer






Relative residuals
Relative residuals
300000
400000
Geraldton
Jurien
Perth
Bunbury
Margaret River
50 km
6800000
6700000
6600000
6500000
6400000
6300000
6200000
0.0
−0.2
Symbols
Wells
Cities
Scale 1:3500000
$\rho c \frac{\partial T}{\partial t} + \rho c \boldsymbol{v} \cdot \nabla T - \nabla \cdot (\lambda \nabla T) = \rho q_{th}$
transient
advection
conduction
production
•Thermal conductivities
•Basal heat flux
•Basement heat production
rge residual values remain!
Spatial pattern: low and high residuals very close together
0.2
0.1
0.0
−0.1
−0.2
Symbols
Wells
Cities
Scale 1:1500000

Application to Perth Basin study: two scenarios of structural uncertainty

Consideration of data quality: exact position uncertain (increasing with depth)

In total six ensembles: two scenarios, low, medium, high geological uncertainty each

Lateral fault position uncertain