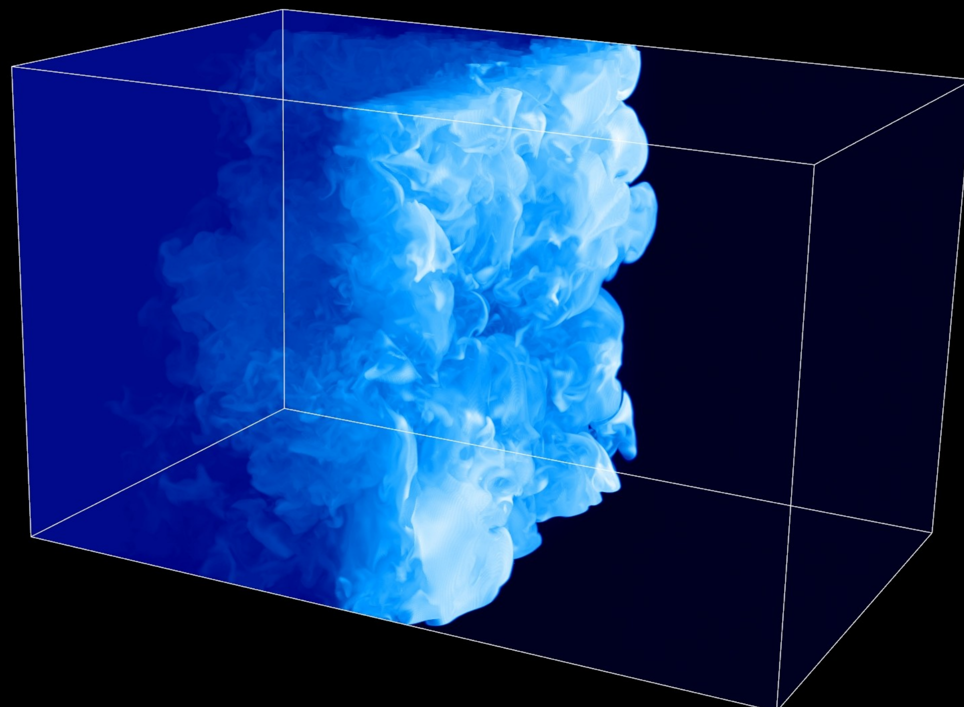
The development of neutrino-driven convection in core-collapse supernovae: 2D vs 3D



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Ringberg workshop

Max-Planck-Institut für Astrophysik

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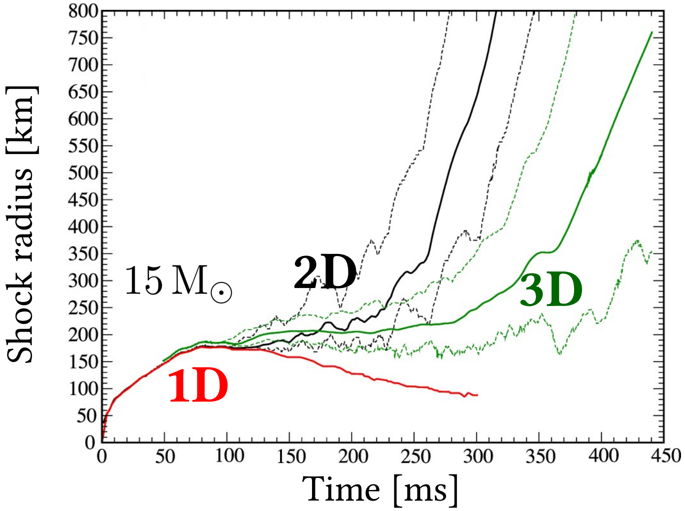
- Explosions are often harder to achieve in 3D compared to 2D.

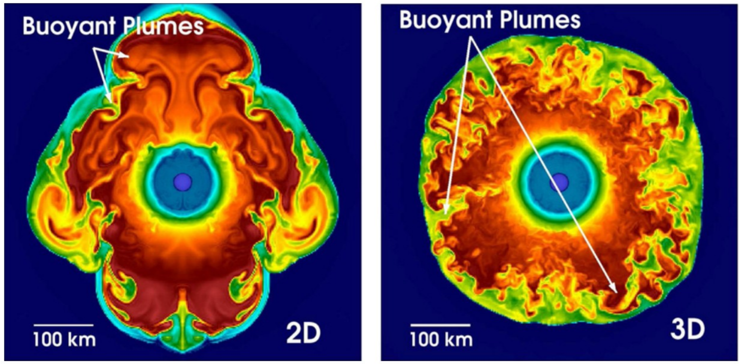
  (Hanke+ 2013, Takiwaki+ 2014, Melson+ 2015b, Lentz+ 2015, ...)

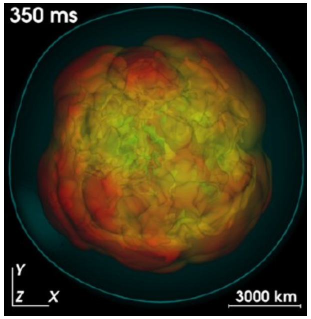


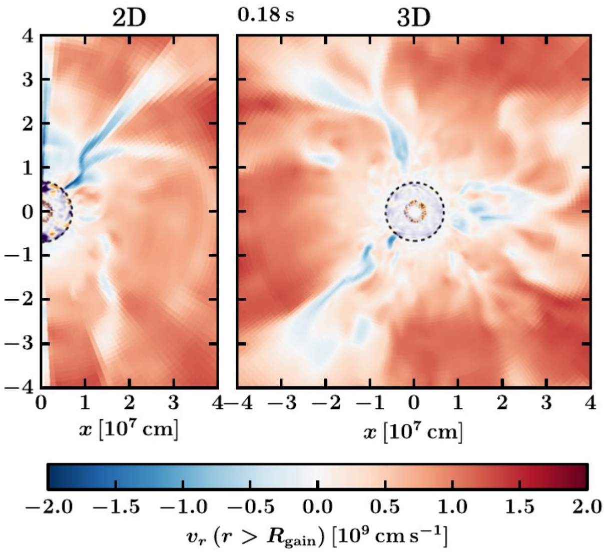
(Lentz+ 2015)

- Various reasons proposed to explain the discrepancies: buoyant bubble properties, turbulent energy cascade, ...

  (Hanke+ 2012, Murphy+ 2013, Couch 2013, Couch & O'tt 2015, Abdikamalov+ 2015, ...)





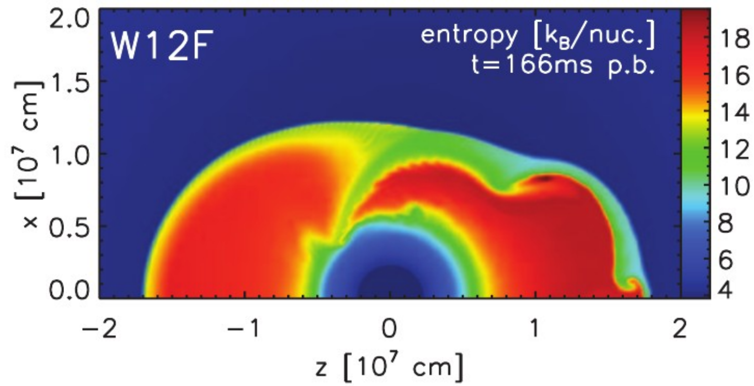


- Differences in the accretion and outflow dynamics may foster 3D explosions.

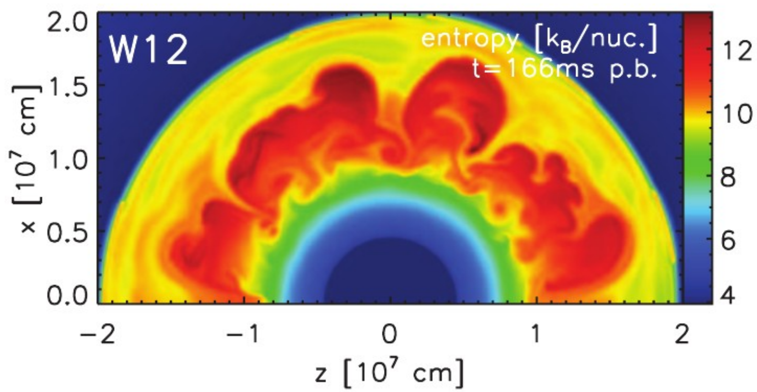
  (Melson+ 2015a, Müller 2015)

(Melson+ 2015a)

Standing Accretion Shock Instability (SASI)



Neutrino-driven convection



(Foglizzo+ 2006)

Linear regime

- ☑ neutrino heating in the gain region
- ☑ spatial scale: l ~ 5-6
- ☑ may be stabilized by advection *(Foglizzo+ 2006)*

$$\chi \equiv \int_{\mathrm{gain}} \frac{\mathrm{Im}\left(\omega_{\mathrm{BV}}\right)}{v_r} dr \simeq \frac{t_{\mathrm{adv}}}{t_{\mathrm{buoy}}}$$

linearly unstable if: $\chi > \chi_{\mathrm{crit}}$

Nonlinear regime

- May be triggered by a large amplitude perturbation even if linearly stable

(Scheck+ 2008, Fernández+ 2014)

$$\frac{\Delta\rho}{\rho} \equiv \left(\frac{\langle|v_r|\rangle}{\langle g\rangle t_{\mathrm{adv}}}\right)_{\mathrm{gain}} \sim \mathcal{O}\left(1\%\right)$$

Outline

- Is a perturbation with a large amplitude sufficient to trigger self-sustained convection?

- Is 2D necessarily more favourable to CCSNe than 3D?

Idealized model of the gain layer

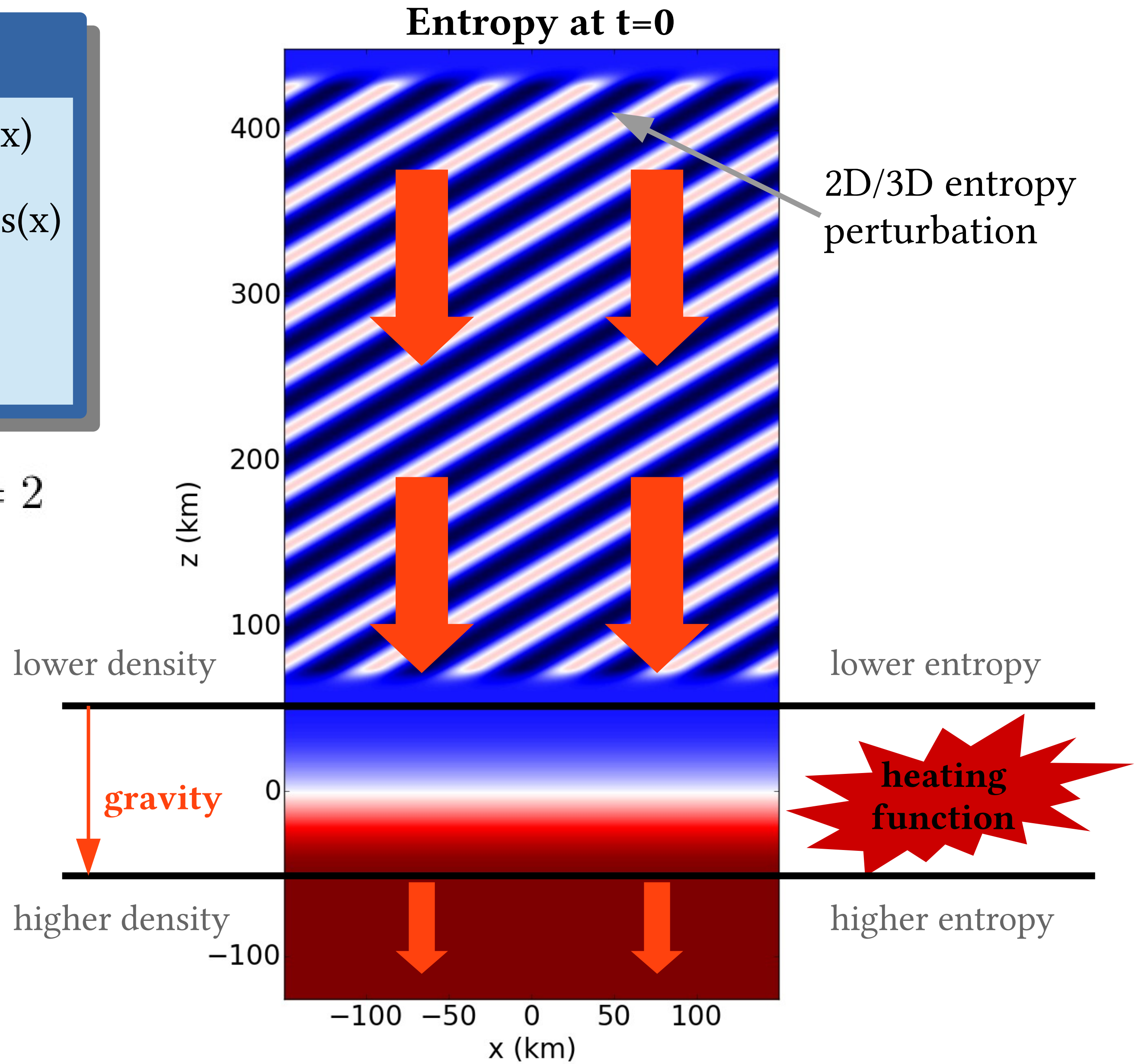
Physics

- ☑ Heating function: $H = H_0\,(\rho/\rho_0)\,s(x)$
- ☑ Gravitational acceleration: $g = g_0\,s(x)$
- ☑ No shock wave (no SASI)
- ☑ No cooling process.

linearly unstable if: $\chi > \chi_{\rm crit} = 2$

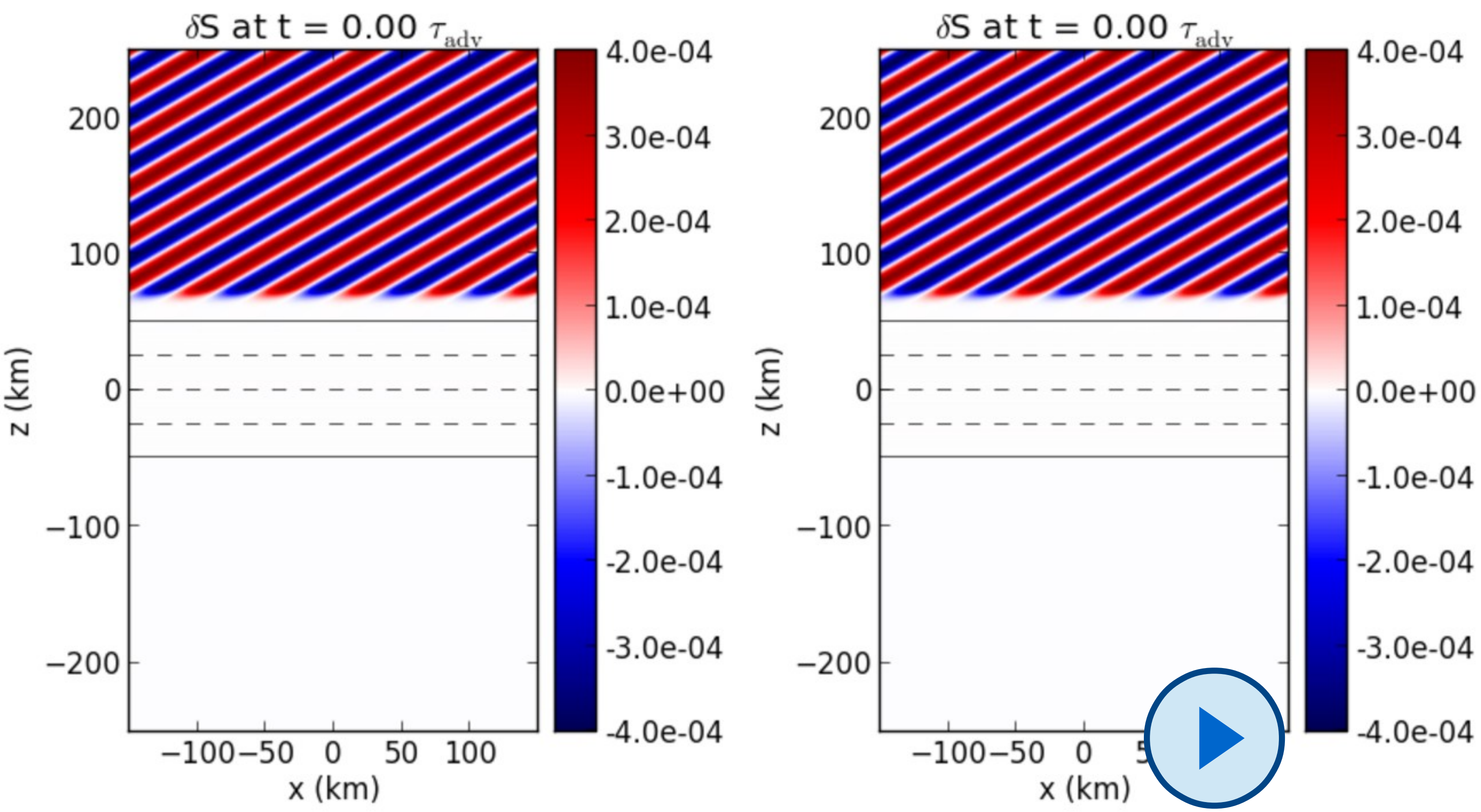
Parametric simulations with RAMSES

- ☑ $\chi_0 = \chi(t{=}0) \approx t_{adv}/t_{buoy}$
- ☑ $\Delta\rho/\rho$ perturbation strengh.



Linear instability threshold

entropy contrast $\delta S = S - \langle S(z) \rangle$

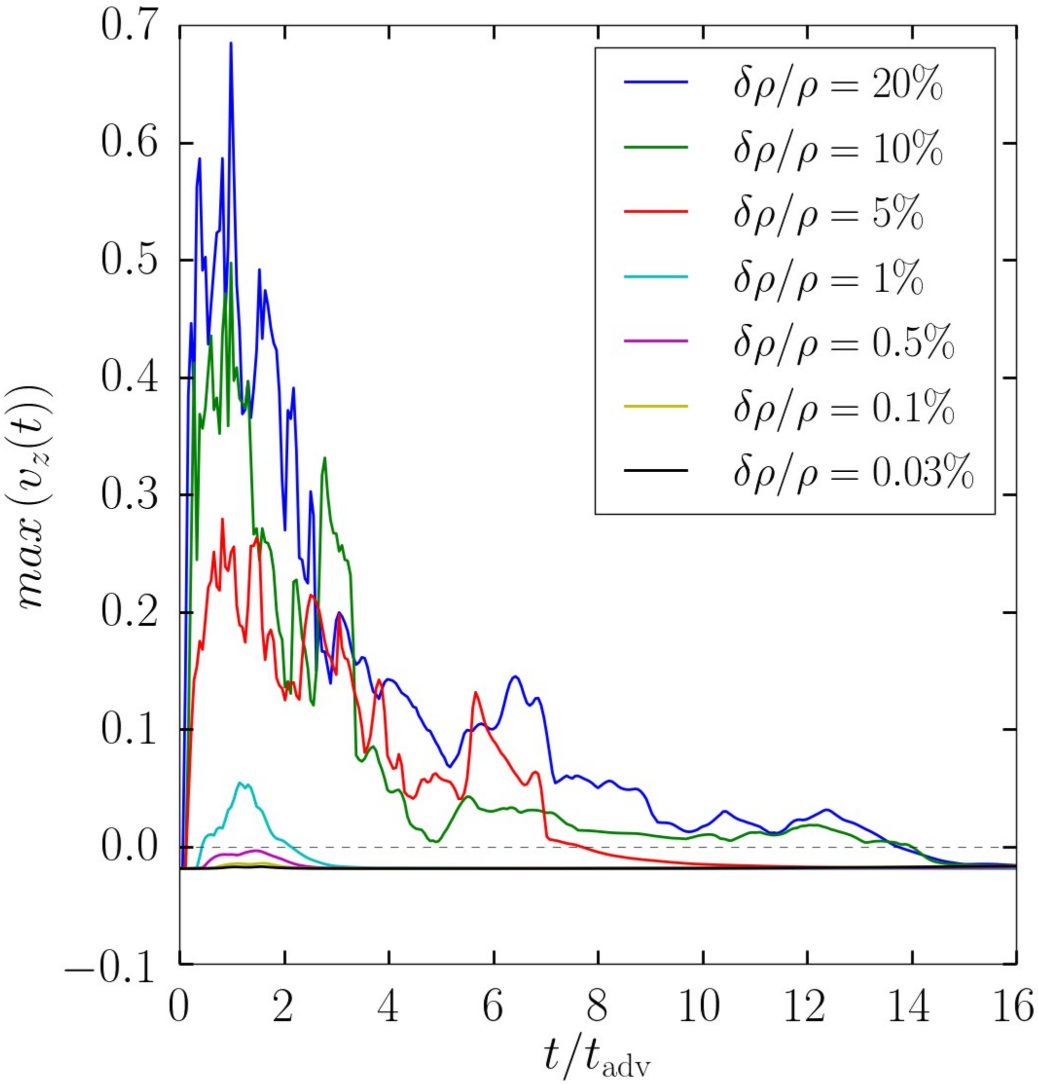


2D
$\chi = 1.5$
$\Delta\rho/\rho = 0.1$ %

$\chi_{crit} = 2$

2D
$\chi = 5.0$
$\Delta\rho/\rho = 0.1$ %

$\chi_0 = 1.5$



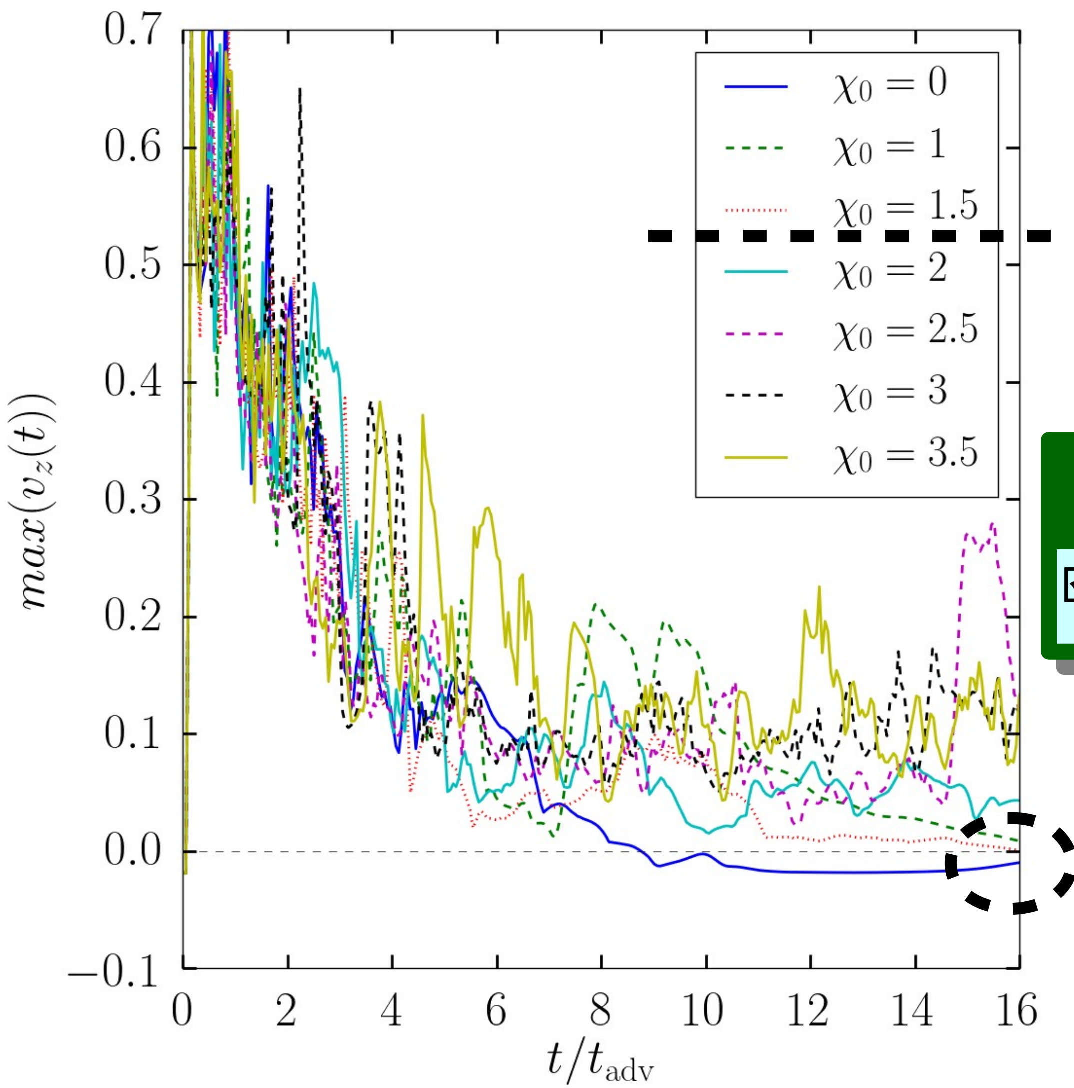
(t_{adv} ~ 20 ms)

$\chi_{crit} = 2$

Nonlinear threshold

☑ A buoyant bubble does not necessarily lead to the development of turbulent convection.

$\delta\rho/\rho$ = **30 %**



$\chi_{\rm crit} = 2$

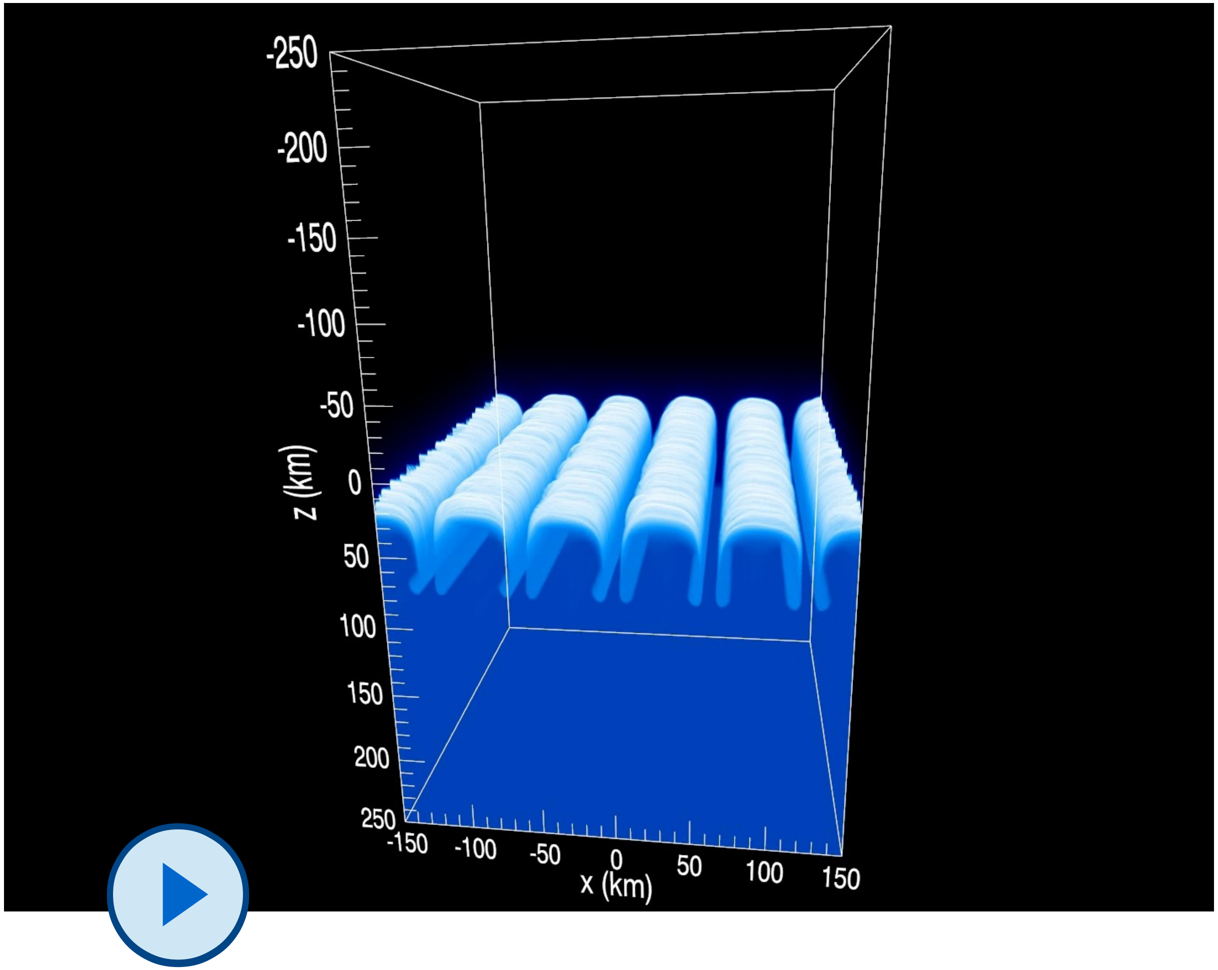
Nonlinear threshold

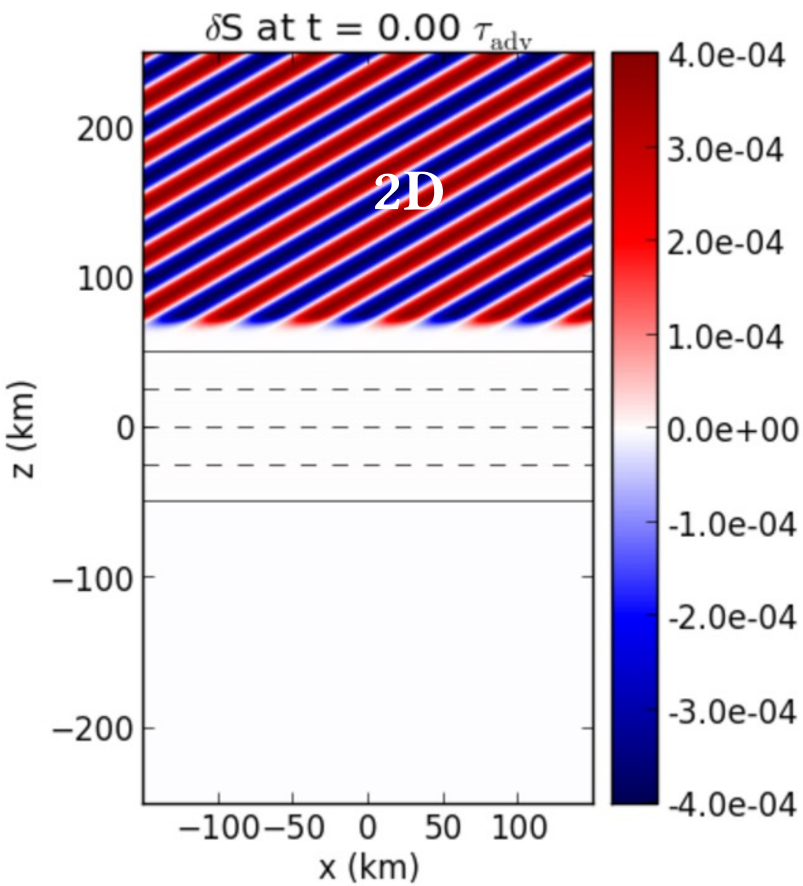
☑ The linear threshold holds in nonlinear cases

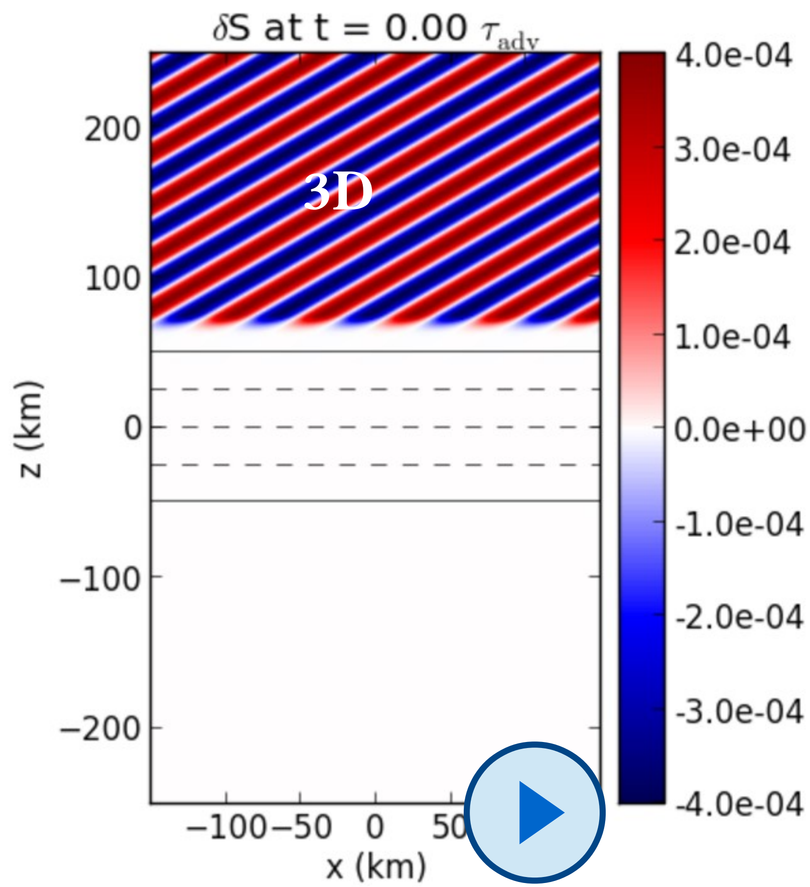
Outline

- Is a perturbation with a large amplitude sufficient to trigger self-sustained convection?

- Is 2D necessarily more favourable to CCSNe than 3D?


-250
-200
-150
-100
-50
0
50
100
150
200
250
z (km)
-150
-100
-50
0
50
100
150
x (km)



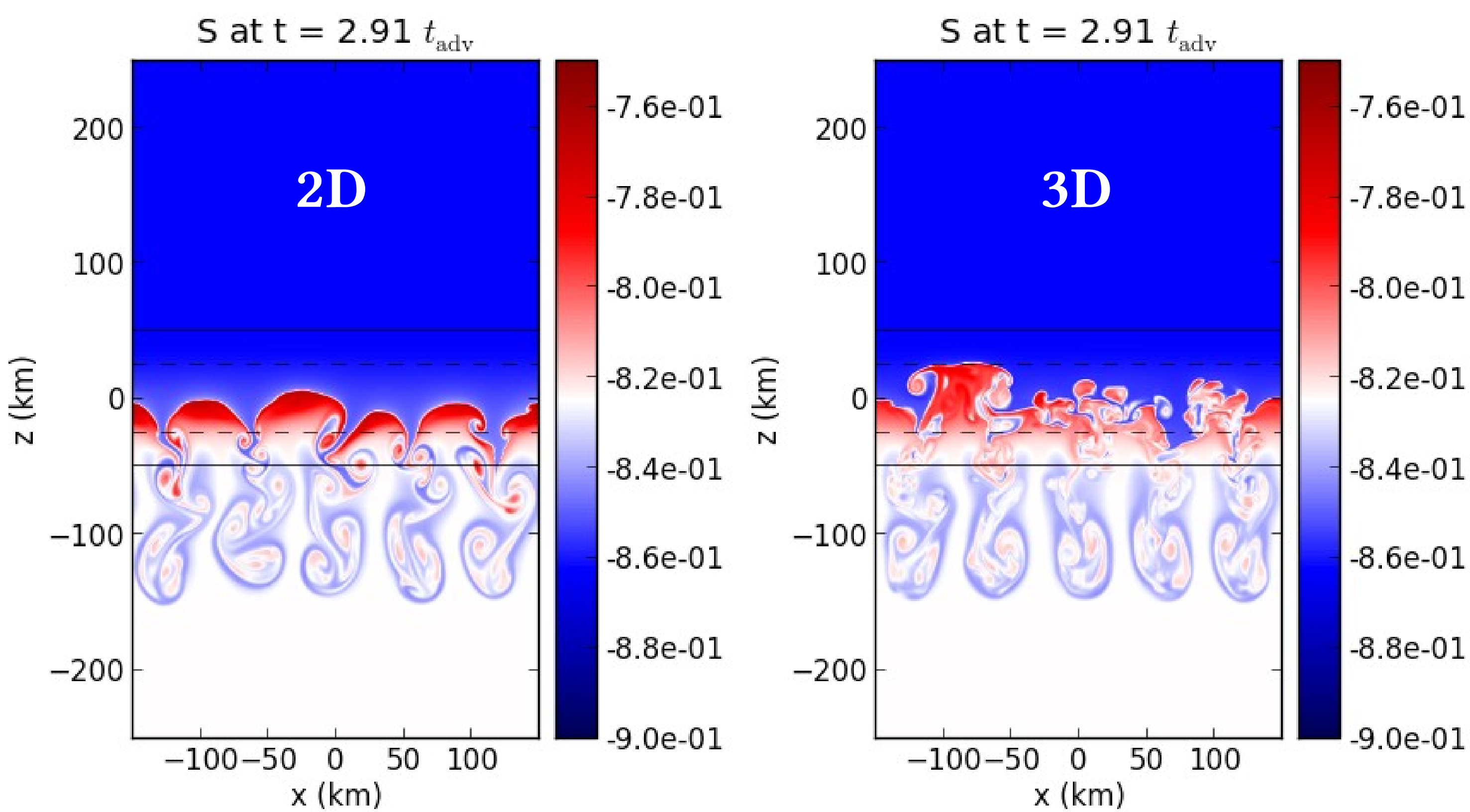


2D
$\chi = 5$
$\Delta\rho/\rho = 0.1$ %

3D
$\chi = 5$
$\Delta\rho/\rho = 0.1$ %

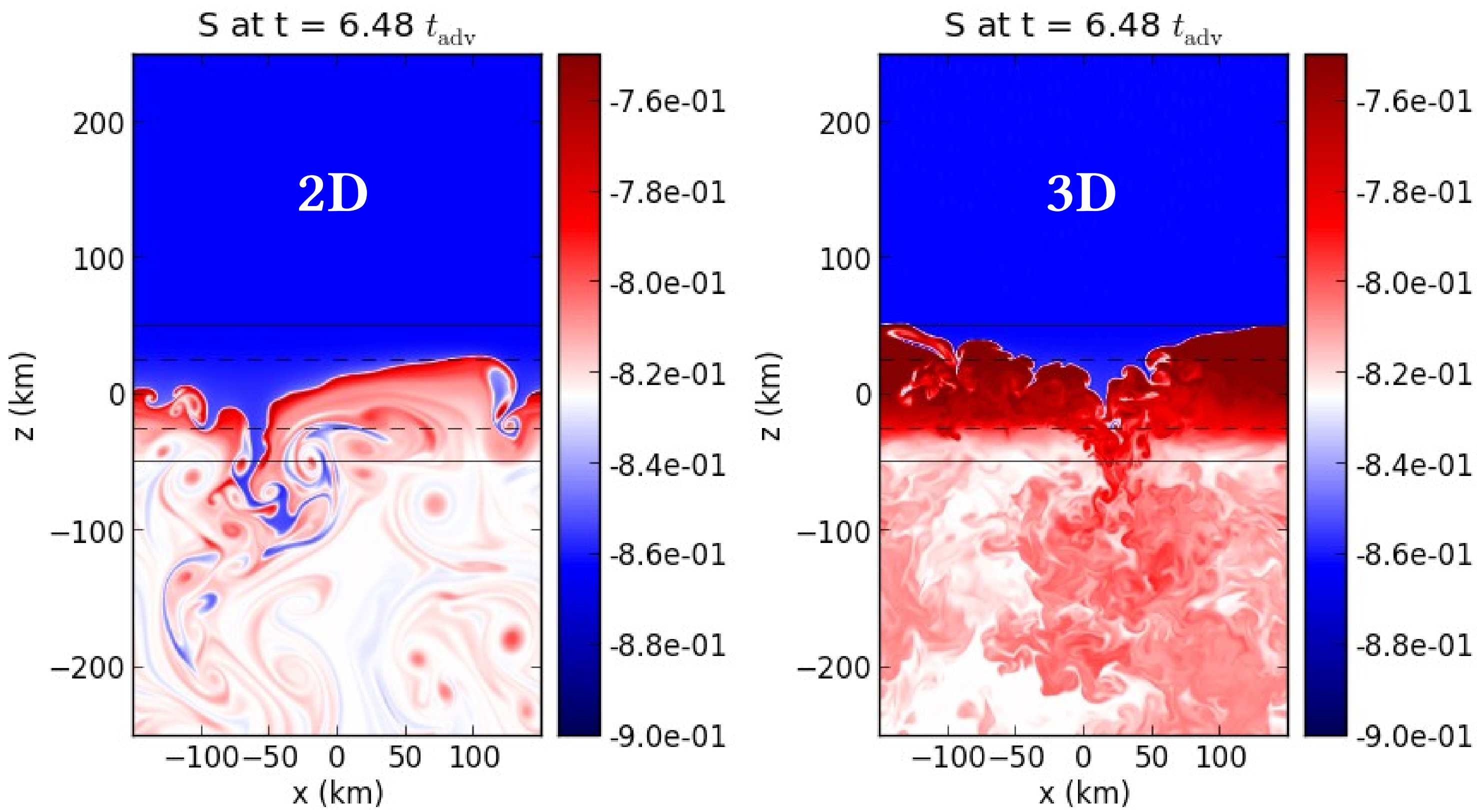
In which case does a buoyant bubble rise faster against advection?

In 2D or in 3D?



Neutrino-driven convection

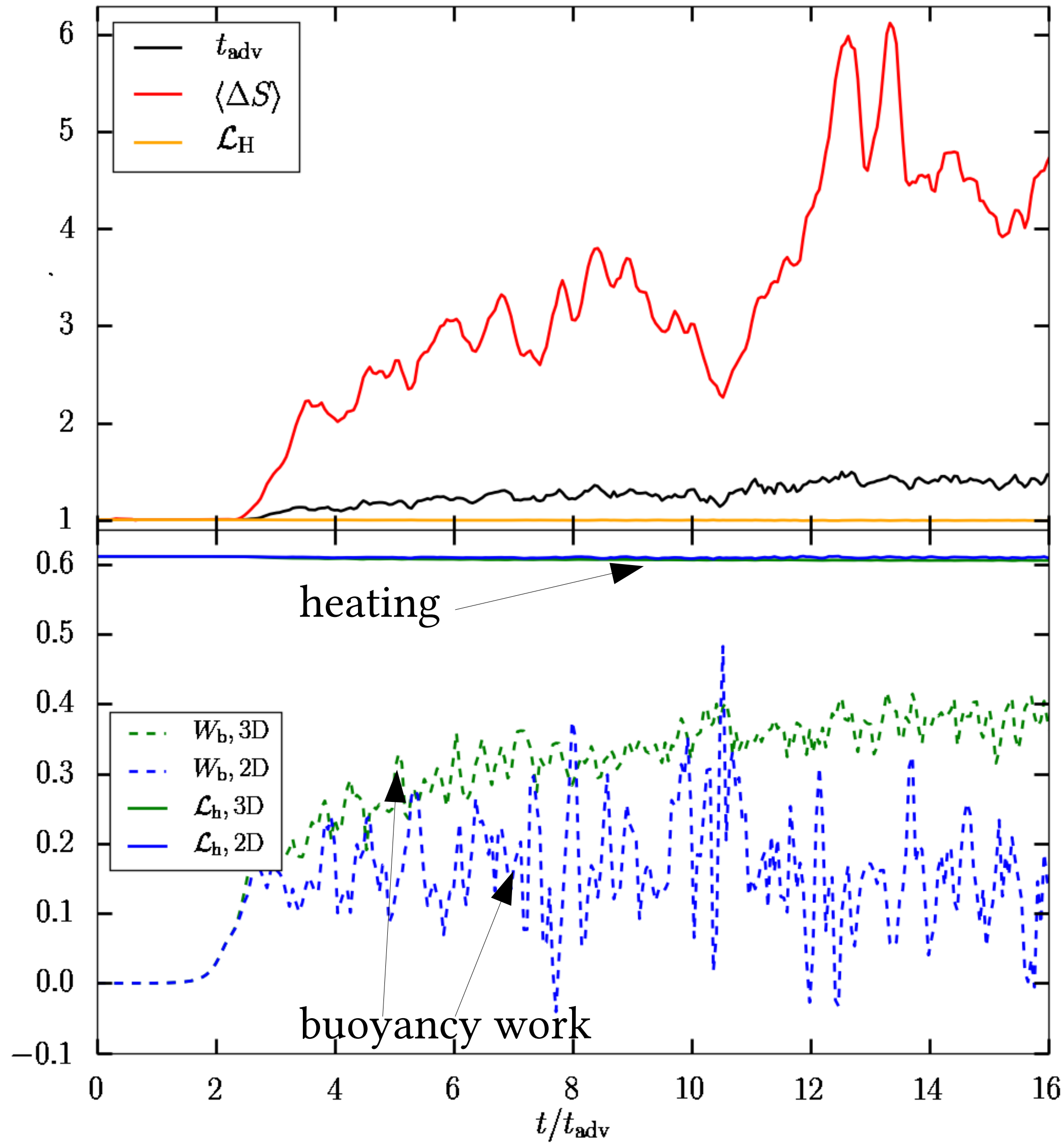
☑ Faster rising buoyant bubbles in 3D.



Neutrino-driven convection

- ☑ **Greater flow deceleration** due to small scale turbulent mixing **in 3D**.
- ☑ Residency time in the gain layer reduced due to large scale vortices in 2D.

3D/2D



heating

sources

entropy gap: x5

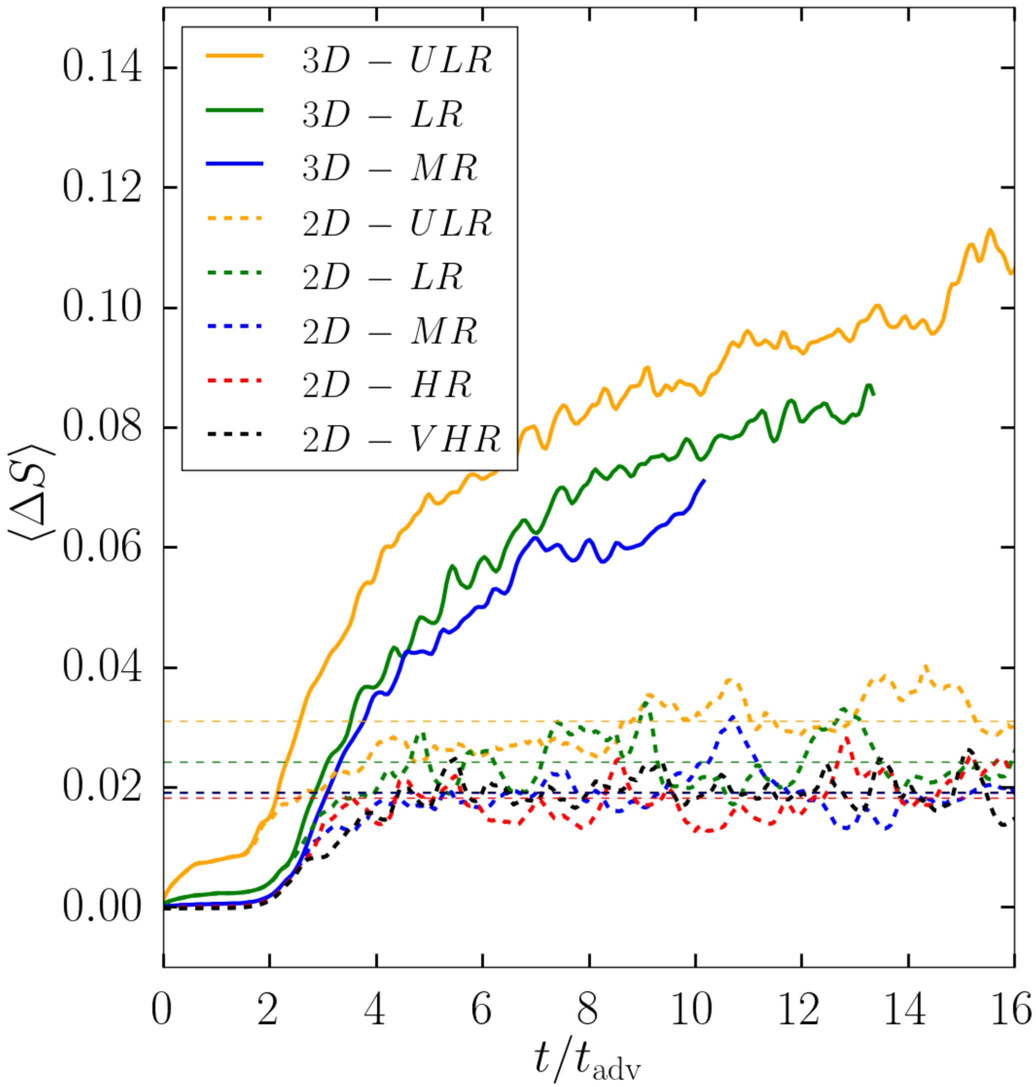
advection timescale: x1.5

heating rate: ~x1

~dissipation *(Murphy & Meakin 2011)*

Dimensionality and resolution

mean entropy in the gain layer



$\chi = 5$
$\Delta\rho/\rho = 0.1\ \%$

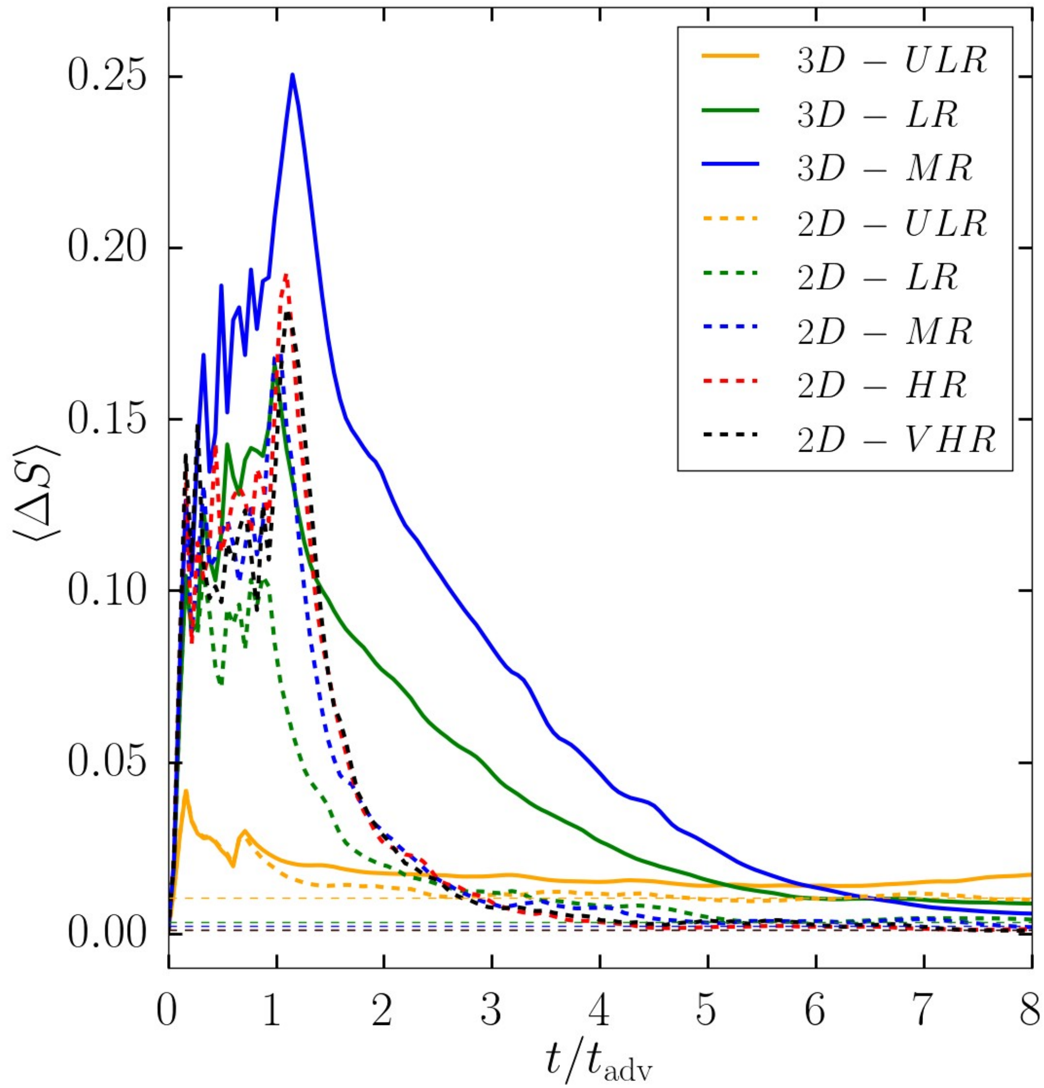
vertical cells in the gain layer

ULR	32
LR	64
MR	128
HR	256
VHR	512

Linear instability regime

- Heating increases in a runaway process **only** in 3D.
- Earlier rise of buoyant bubbles in low resolution cases.

mean entropy in the gain layer



$\chi = 1.5$

$\Delta\rho/\rho = 30\ \%$

vertical cells in the gain layer

ULR	32
LR	64
MR	128
HR	256
VHR	512

Nonlinear instability regime

- Convection triggered by large amplitude perturbations is more vigorous with increasing dimensionality and resolution.
- The decay timescale increases with dimensionality and resolution.

Conclusion

- An idealized model is employed to challenge our understanding of the dynamics in the gain region.
- A buoyant bubble does not lead to fully developed convection unless the linear instability criterion is satisfied.
- In 3D buoyant bubbles rise faster against advection.
- In 3D a more efficient turbulent mixing increases the efficiency of the heating in a runway process which may foster the onset of the explosion compared to 2D.
- The impact of the perturbations on the dynamics is stronger with increasing dimensionality and resolution.

(Kazeroni, Krueger, Guilet & Foglizzo 2017, in prep.)