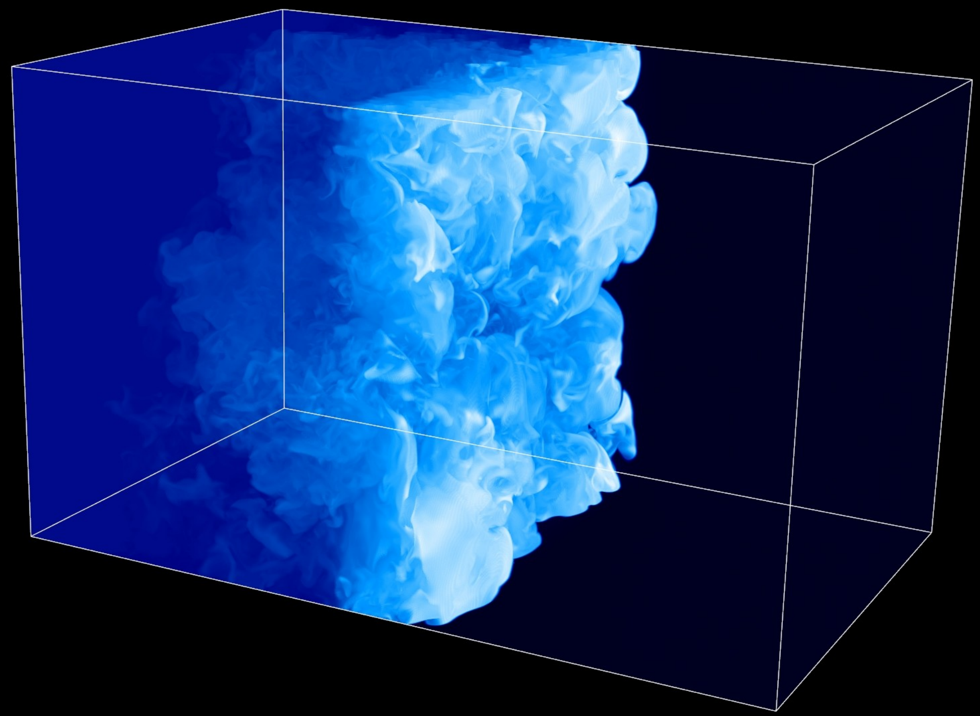
The development of neutrino-driven convection in core-collapse supernovae: 2D vs 3D



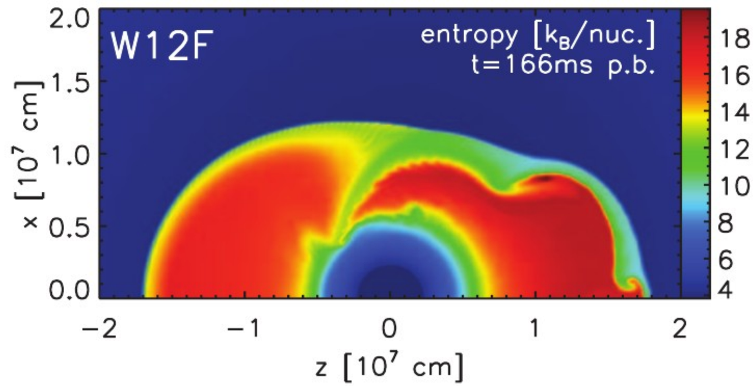
Rémi Kazeroni

B. Krueger, J. Guilet, T. Foglizzo

CoCoNuT Meeting

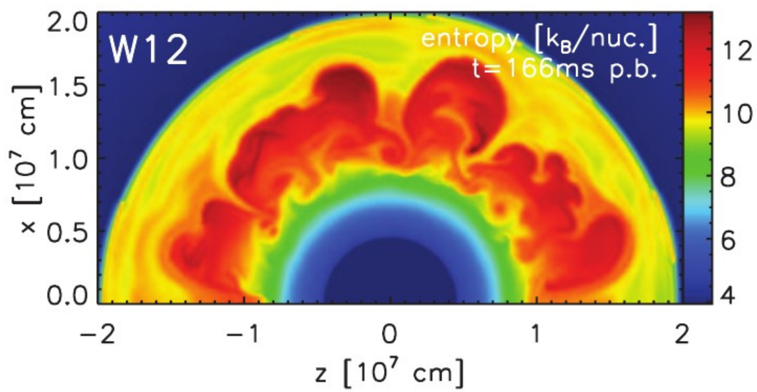
October 25, 2017

Standing Accretion Shock Instability (SASI)



Neutrino-driven convection

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)*

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

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

Nonlinear regime

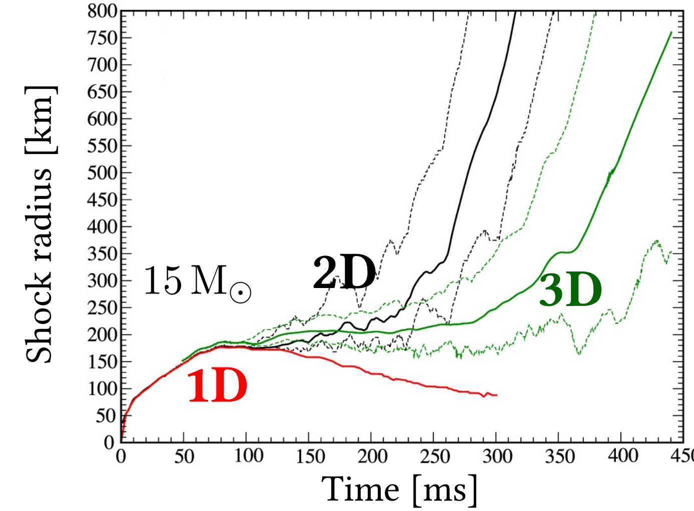
- May be triggered by a large amplitude perturbation even if linearly stable

(Scheck+ 2008, Fernández+ 2014)

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

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

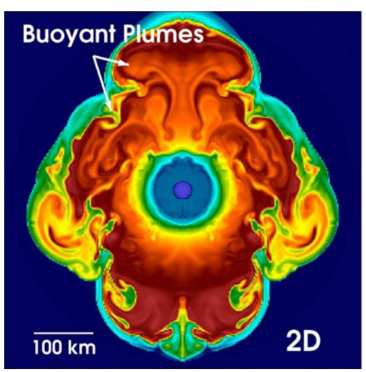
  (Hanke+ 2013, Takiwaki+ 2014, Melson+ 2015b, Lentz+ 2015, ...)

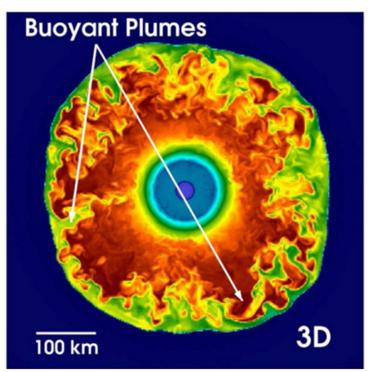


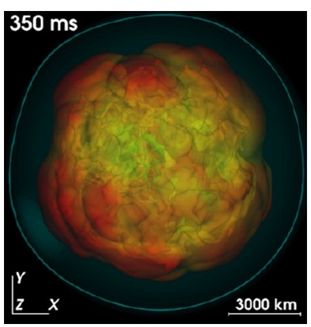
(Lentz+ 2015)

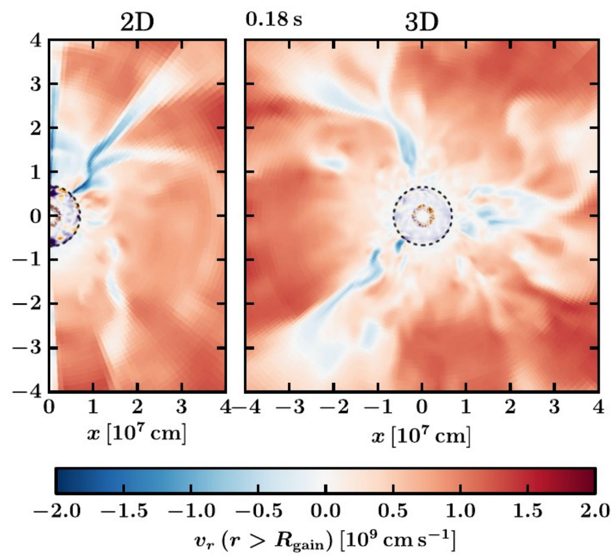
- Various reasons proposed to explain the discrepancies: buoyant bubble properties, turbulent energy cascade, ...

  (Hanke+ 2012, Murphy+ 2013, Couch 2013, Couch & Ott 2015, Abdikamalov+ 2015, ...)









(Melson+ 2015a)

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

  (Melson+ 2015a, Müller 2015)

Idealized model of the gain layer

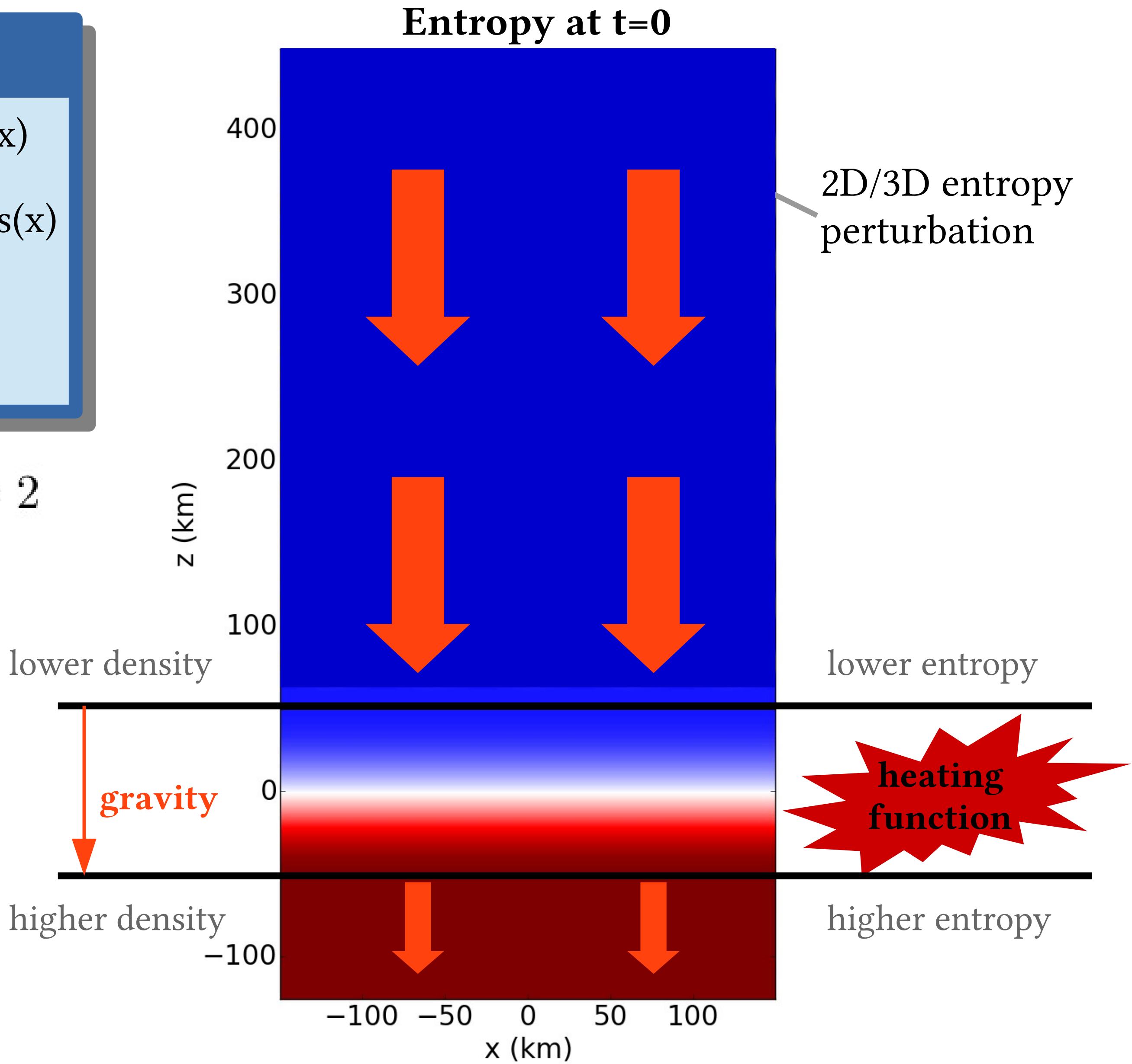
Physics

- ☑ 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: $\chi > \chi_{\mathrm{crit}} = 2$

Parametric simulations with RAMSES

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



Outline

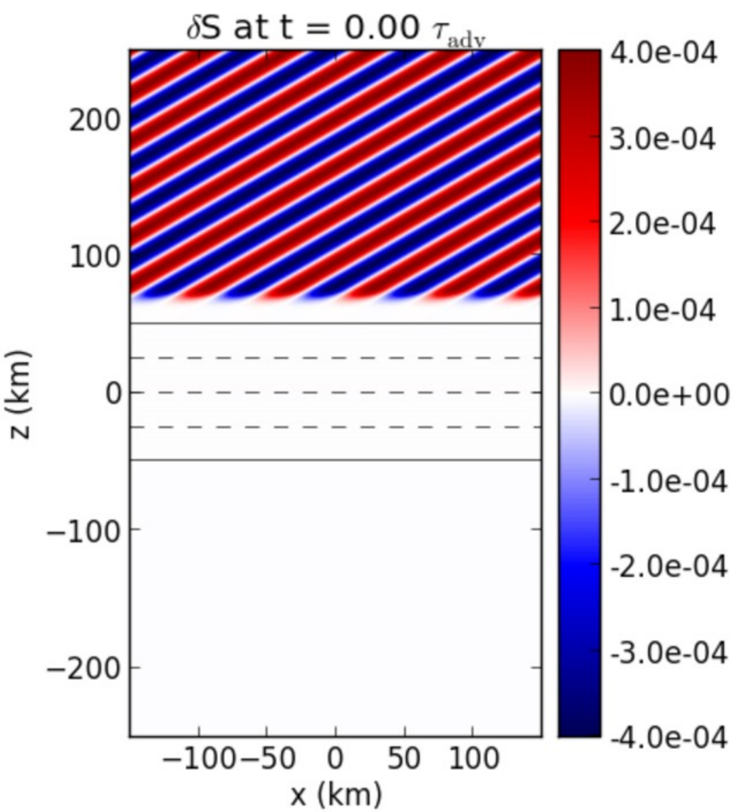
- Is a perturbation with a large amplitude sufficient to trigger self-sustained convection?

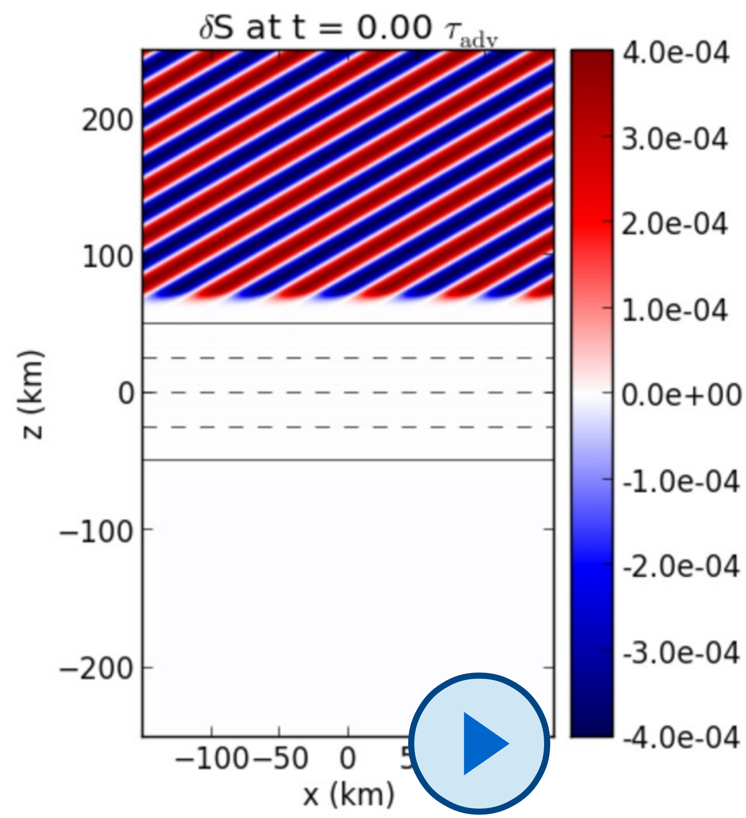
- Is 2D necessarily more favourable to CCSNe than 3D?

- What is the impact of the numerical resolution?

Linear instability threshold

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





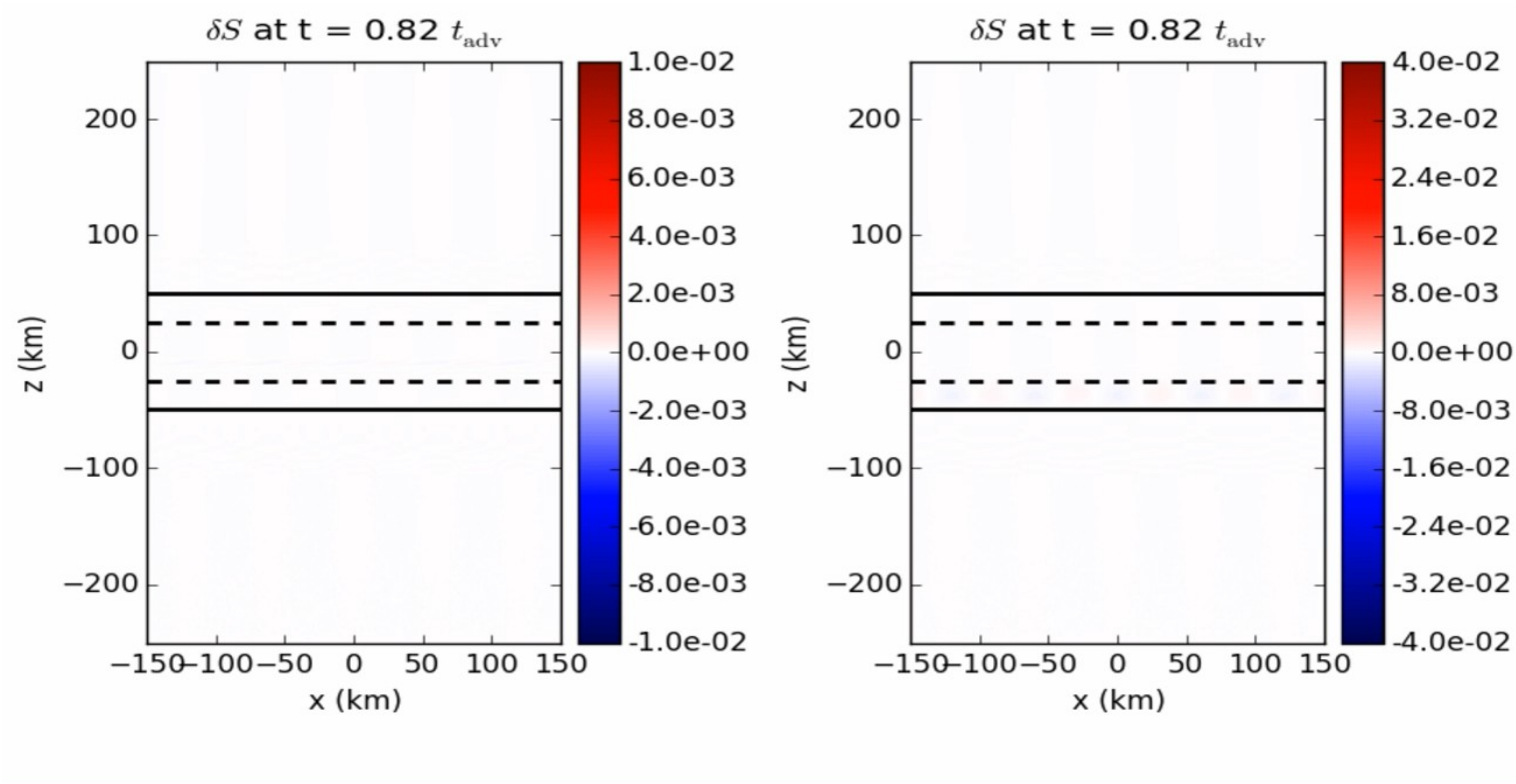
2D
$\chi = 1.5$
$\delta\rho/\rho = 0.1$ %

$\chi_{crit} = 2$

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

Linear instability threshold

entropy contrast δS = S - <S(z)>

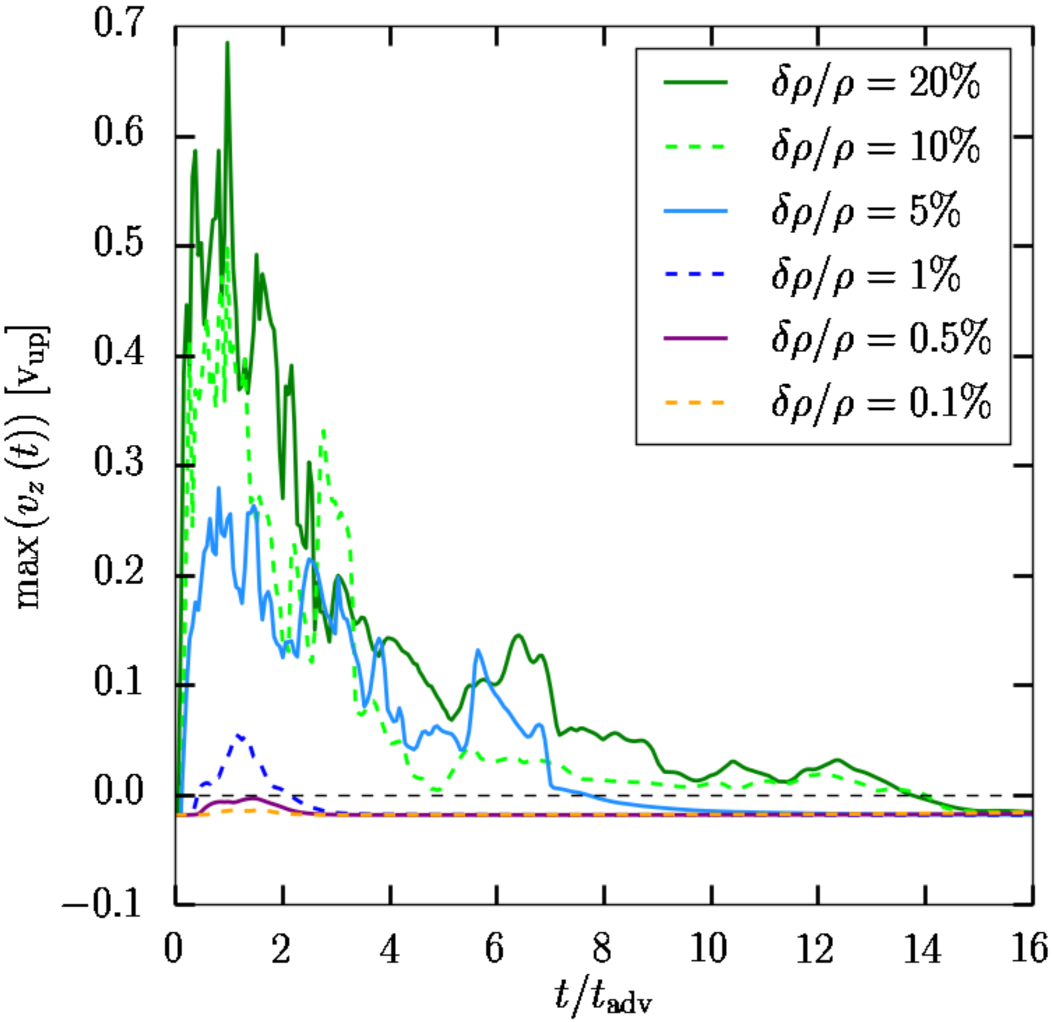


2D
$\chi = 1.5$
$\delta\rho/\rho = 0.1\ \%$

$\chi_{crit} = 2$

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

χ_0 = 1.5



(t_{adv} ~ 20 ms)

χ_{crit} = 2

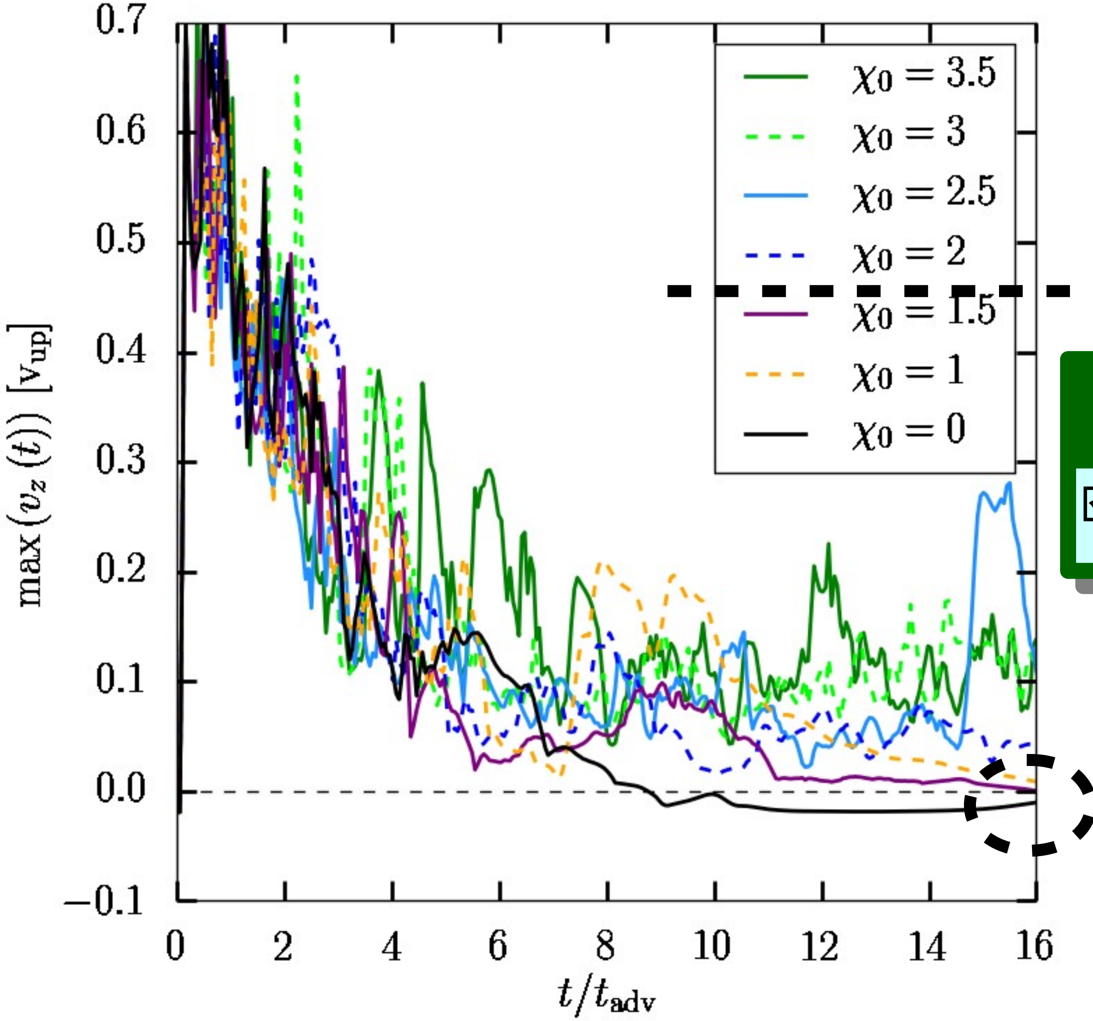
Nonlinear threshold

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

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

(Scheck+ 2008)

δρ/ρ = **30 %**



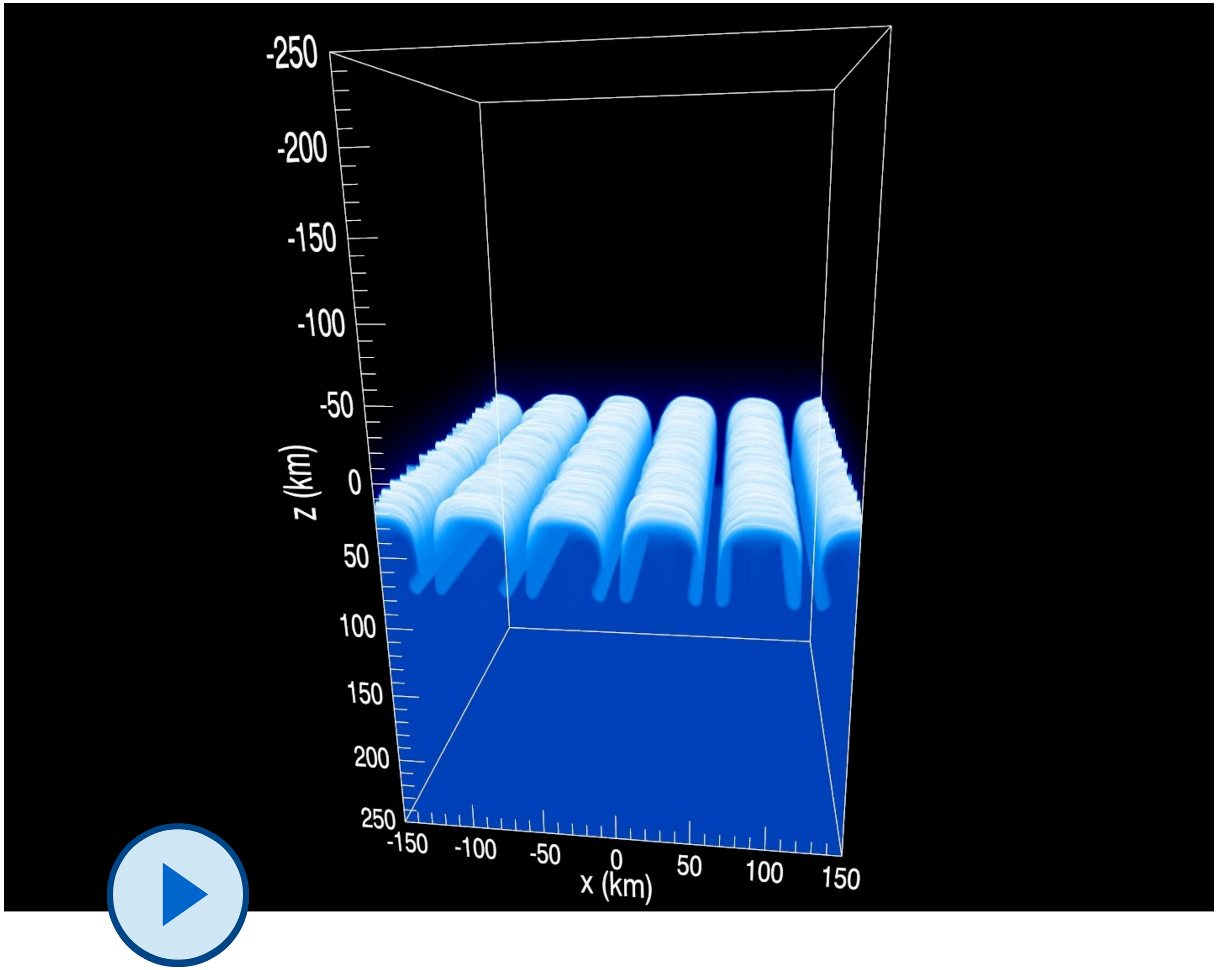
$\chi_{crit} = 2$

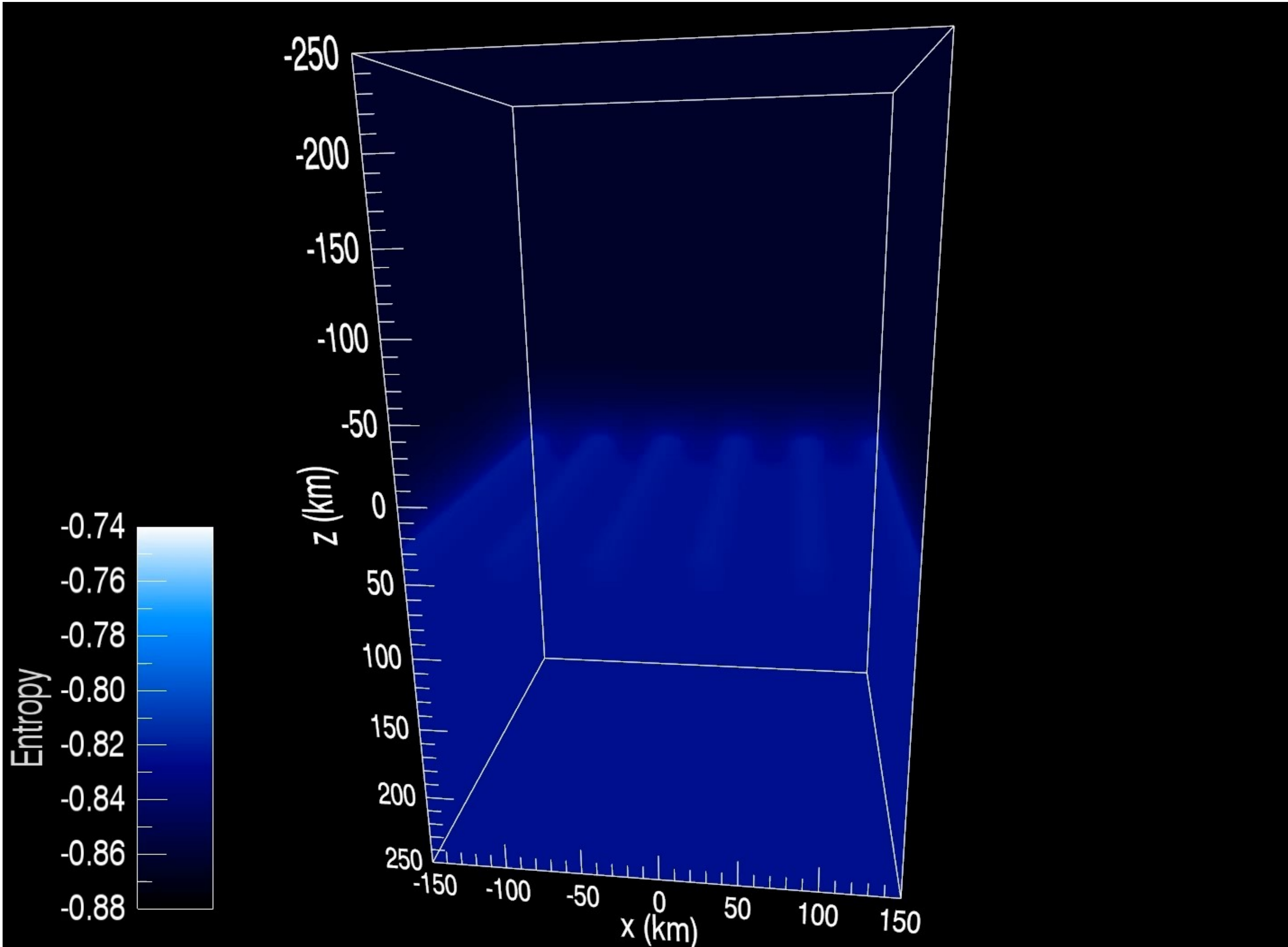
Nonlinear threshold

☑ The linear threshold holds in nonlinear cases

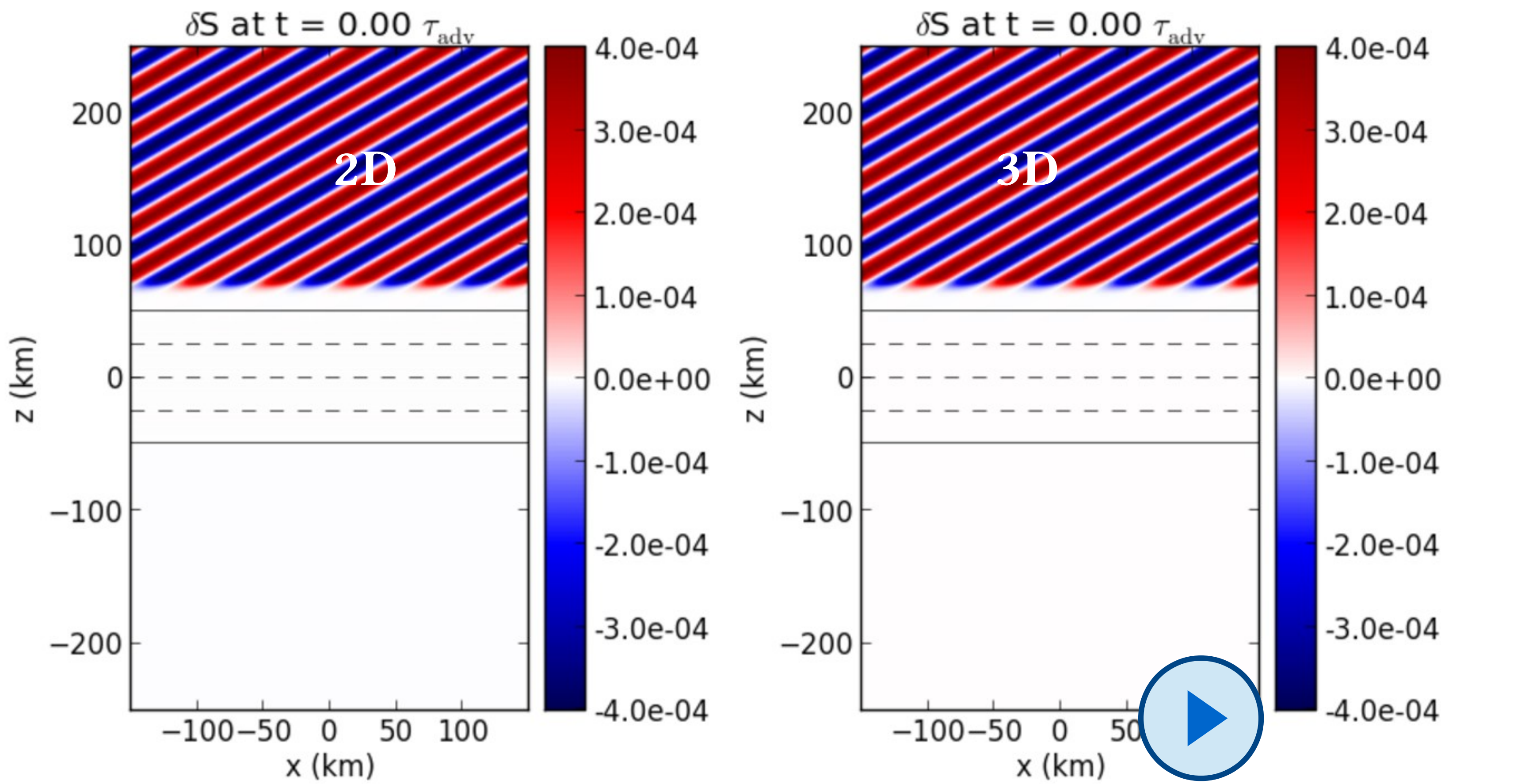
Outline

- Is a perturbation with a large amplitude sufficient to trigger self-sustained convection?
- Is 2D necessarily more favourable to CCSNe than 3D?
- What is the impact of the numerical resolution?


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


Entropy
-0.74
-0.76
-0.78
-0.80
-0.82
-0.84
-0.86
-0.88
z (km)
-250
-200
-150
-100
-50
0
50
100
150
200
250
x (km)
-150
-100
-50
0
50
100
150

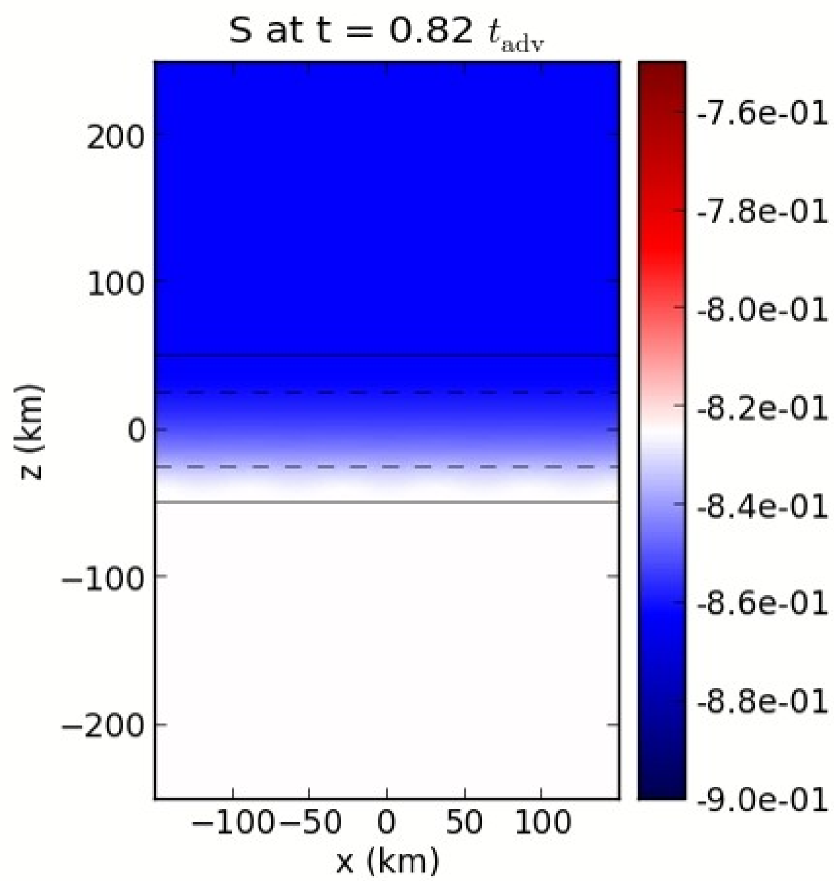
What are the differences between 2D & 3D? Linear instability regime

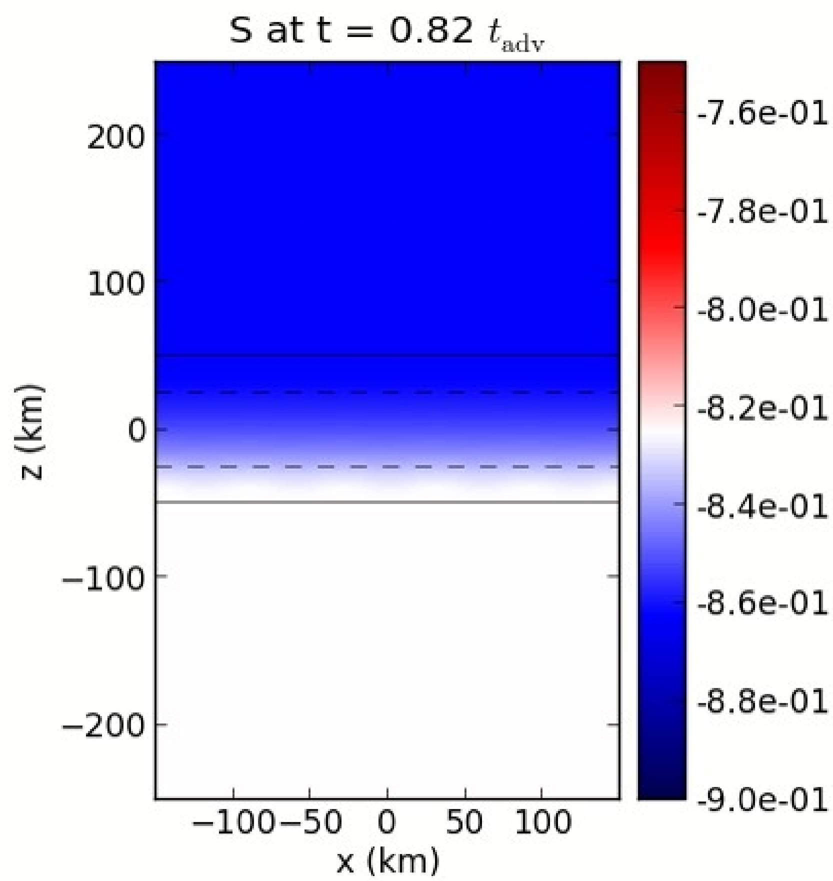


2D
$\chi = 5$
$\delta\rho/\rho = 0.1$ %

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

What are the differences between 2D & 3D?

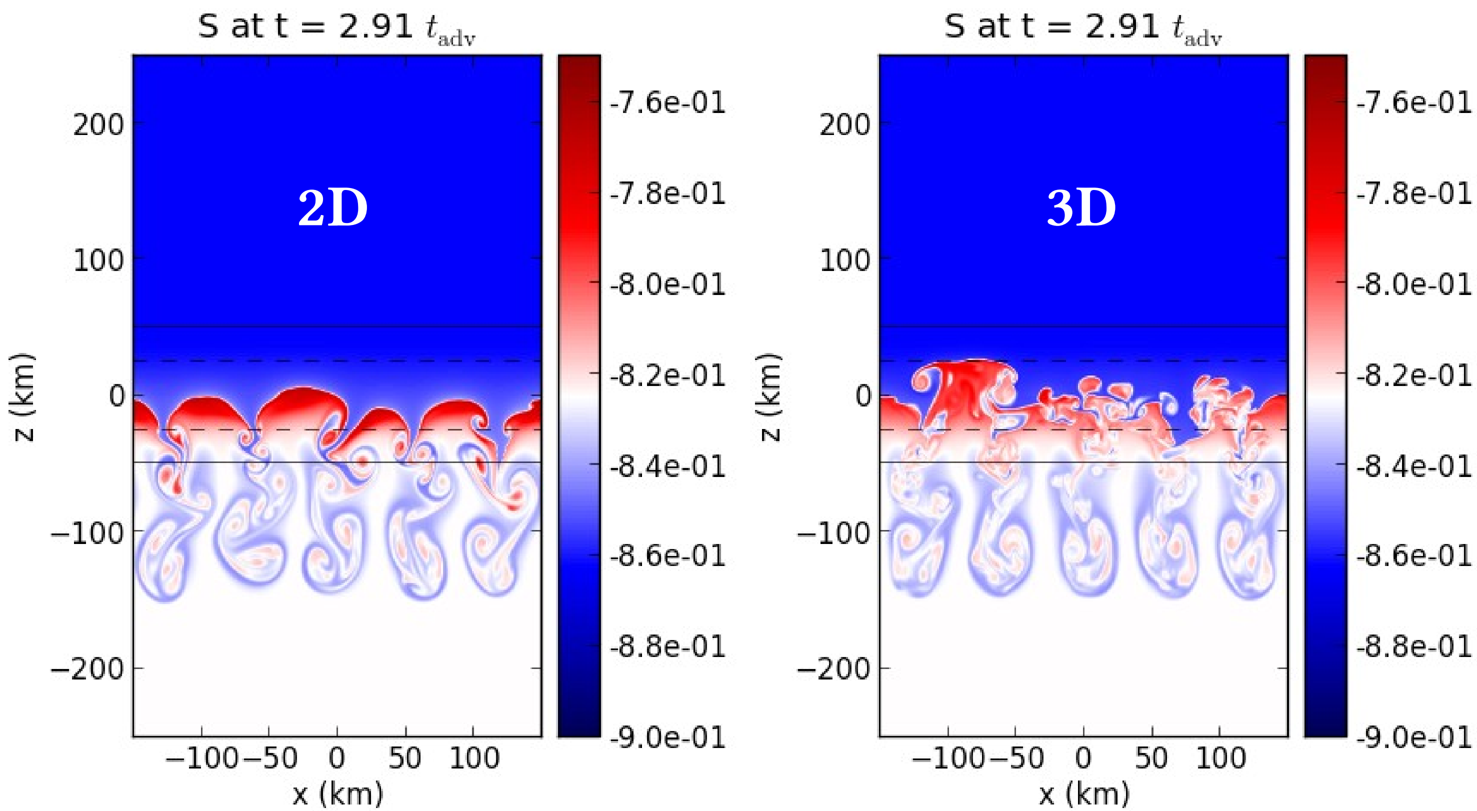




2D
$\chi = 5$
$\delta\rho/\rho = 0.1$ %

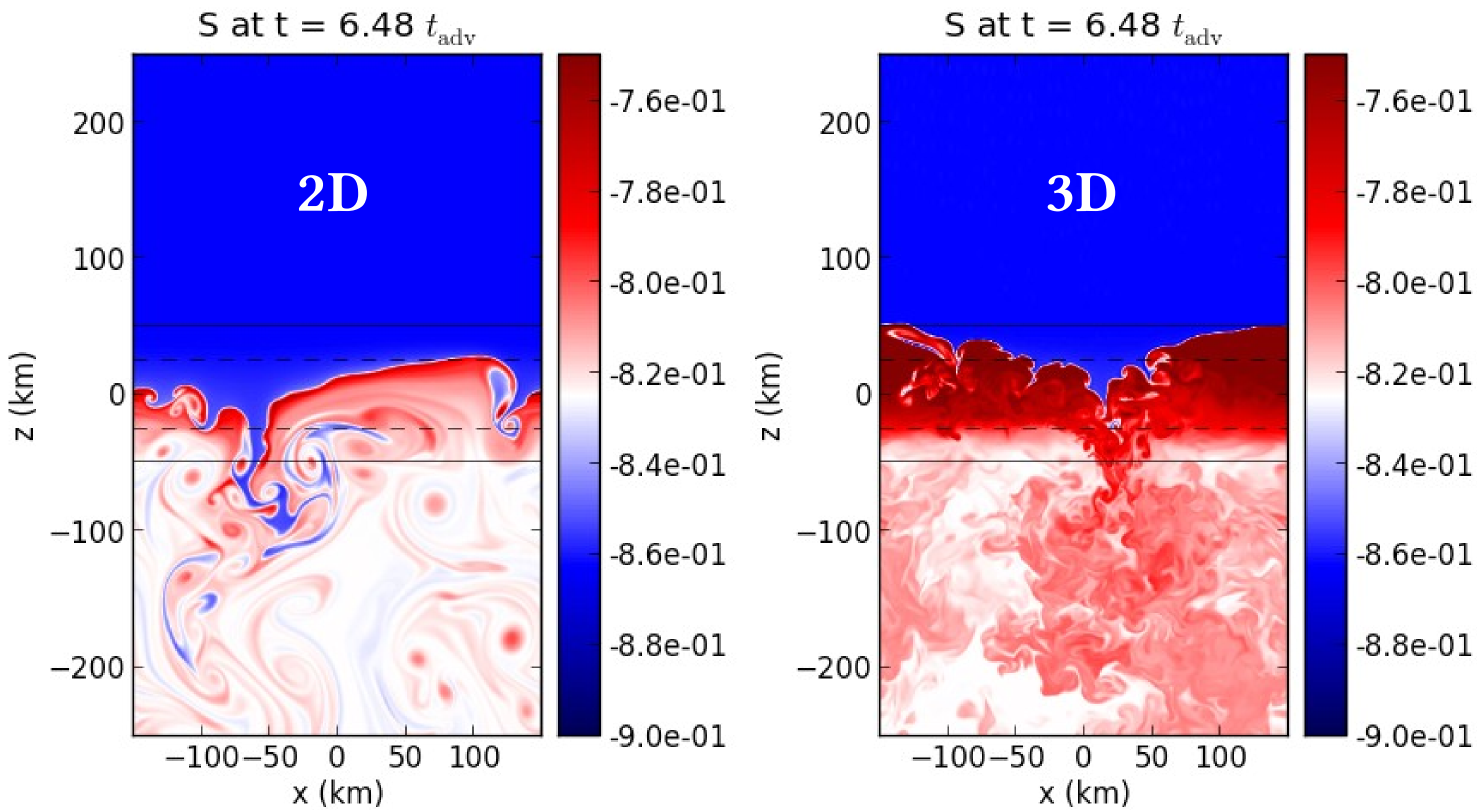
3D
$\chi = 5$
$\delta\rho/\rho = 0.1$ %

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



Neutrino-driven convection

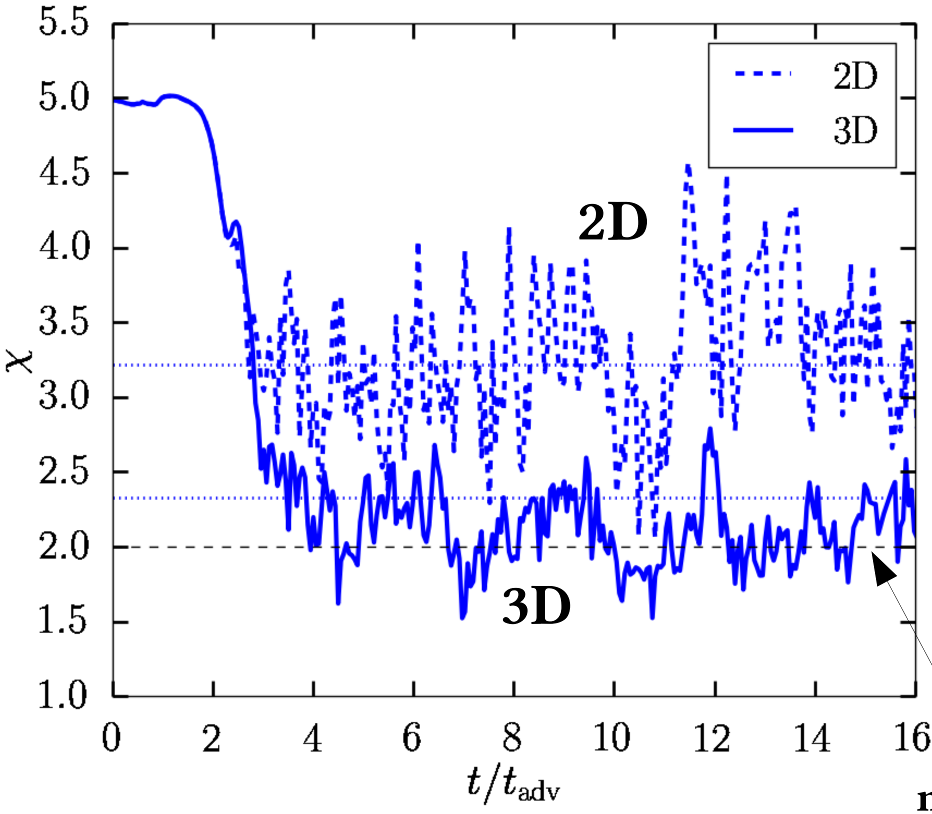
- ☑ Faster rising buoyant bubbles in 3D.
- ☑ Consistent with results on RT the instability and RT mixing during the explosion *(Young+ 2001, Cabot 2006, Hammer+ 2010, ...)*



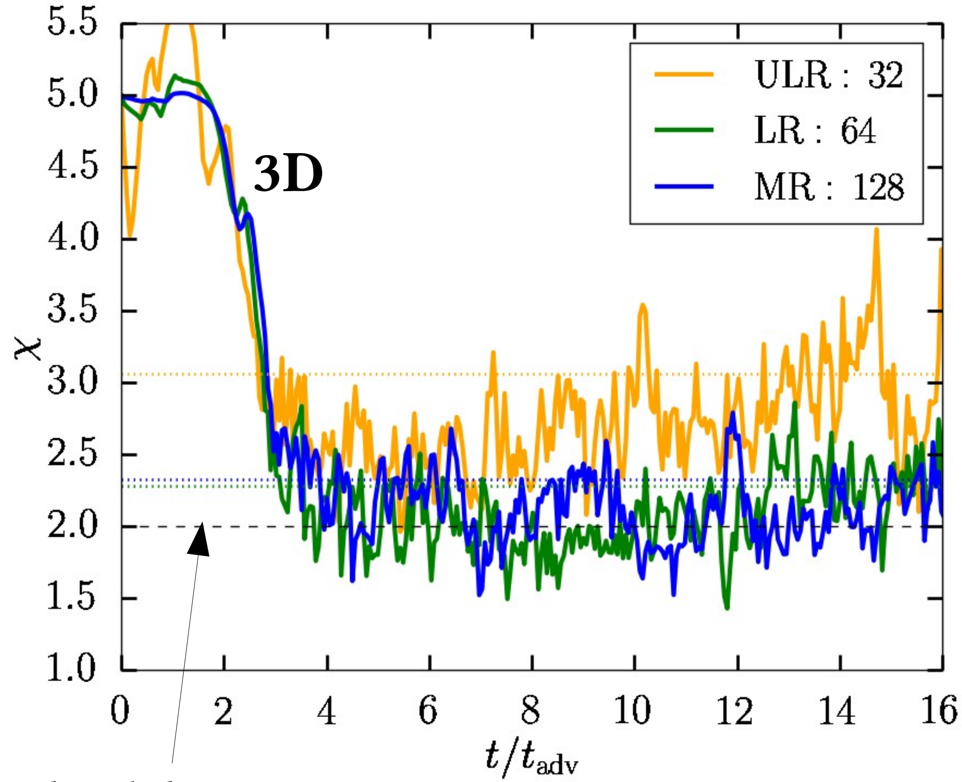
Neutrino-driven convection

- ☑ **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.

2D & 3D



Numerical resolution

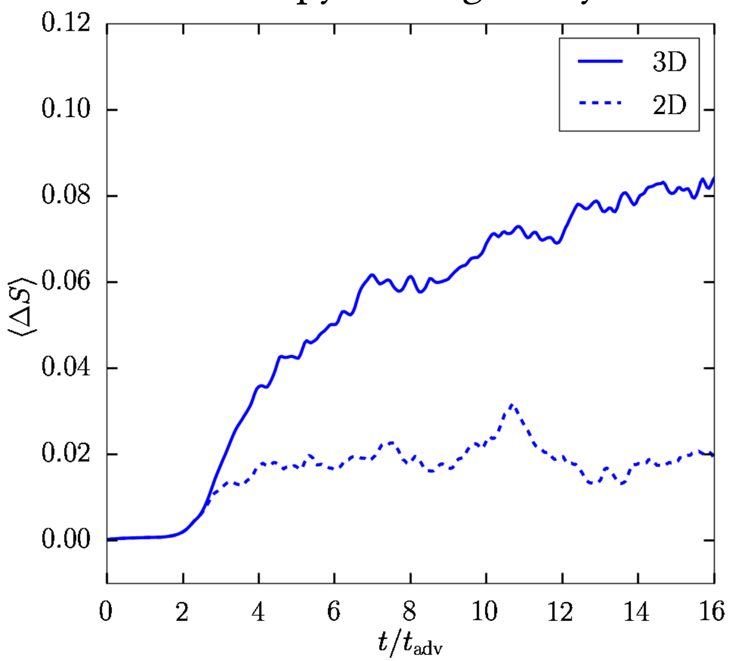


marginal stability

Neutrino-driven convection

☑ 3D and higher numerical resolution bring the flow closer to the marginal stability.

mean entropy in the gain layer



$$\frac{\partial(\rho S)}{\partial t} + \nabla.(\rho S\vec{u}) = \frac{\rho\dot{q}}{T} + \frac{\rho\epsilon}{T}$$

Heating rate — Turbulent dissipation

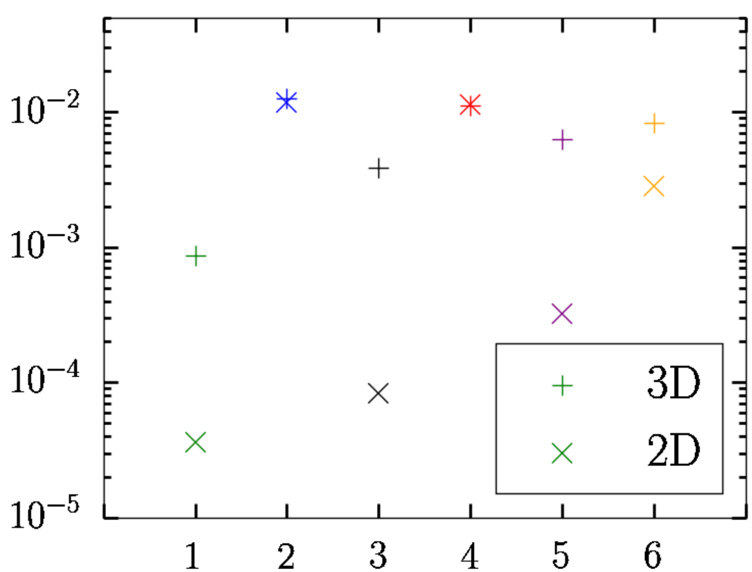
1 **2** **3** **4** **5**

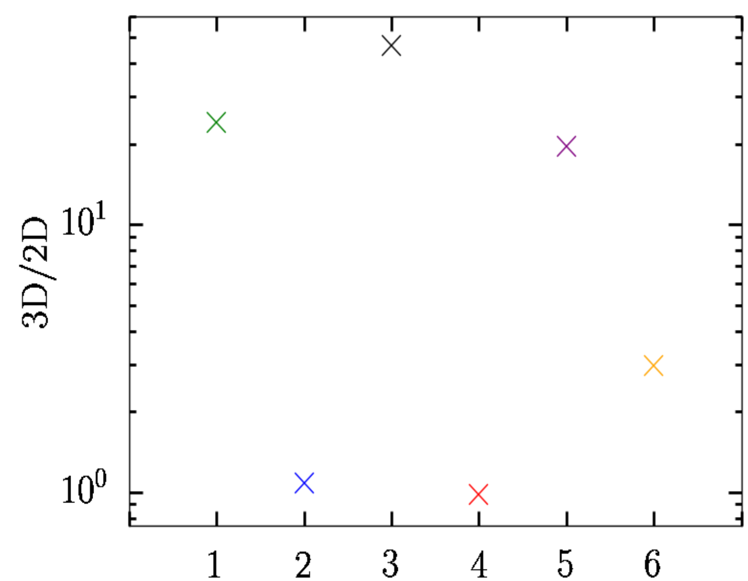
$$\frac{\partial\bar{\rho}\tilde{S}}{\partial t} + \nabla.\left(\bar{\rho}\tilde{v}\tilde{S}\right) + \nabla.\left(\overline{\rho v'' S''}\right) = \overline{\left(\frac{\rho\dot{q}}{T}\right)} + \overline{\left(\frac{\rho\epsilon}{T}\right)}.$$

$?? \sim W_b$

Buoyancy work **6**

(see also Murphy & Meakin 2011, Mabanta & Murphy 2017)





Outline

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

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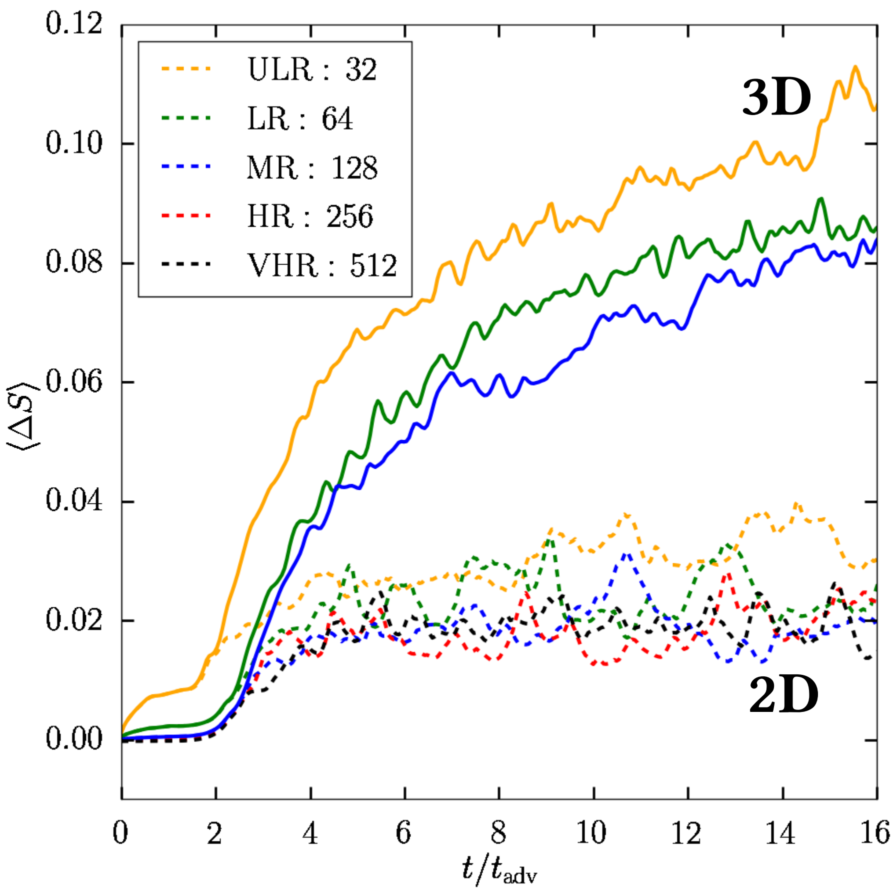
- What is the impact of the numerical resolution?

Resolution study

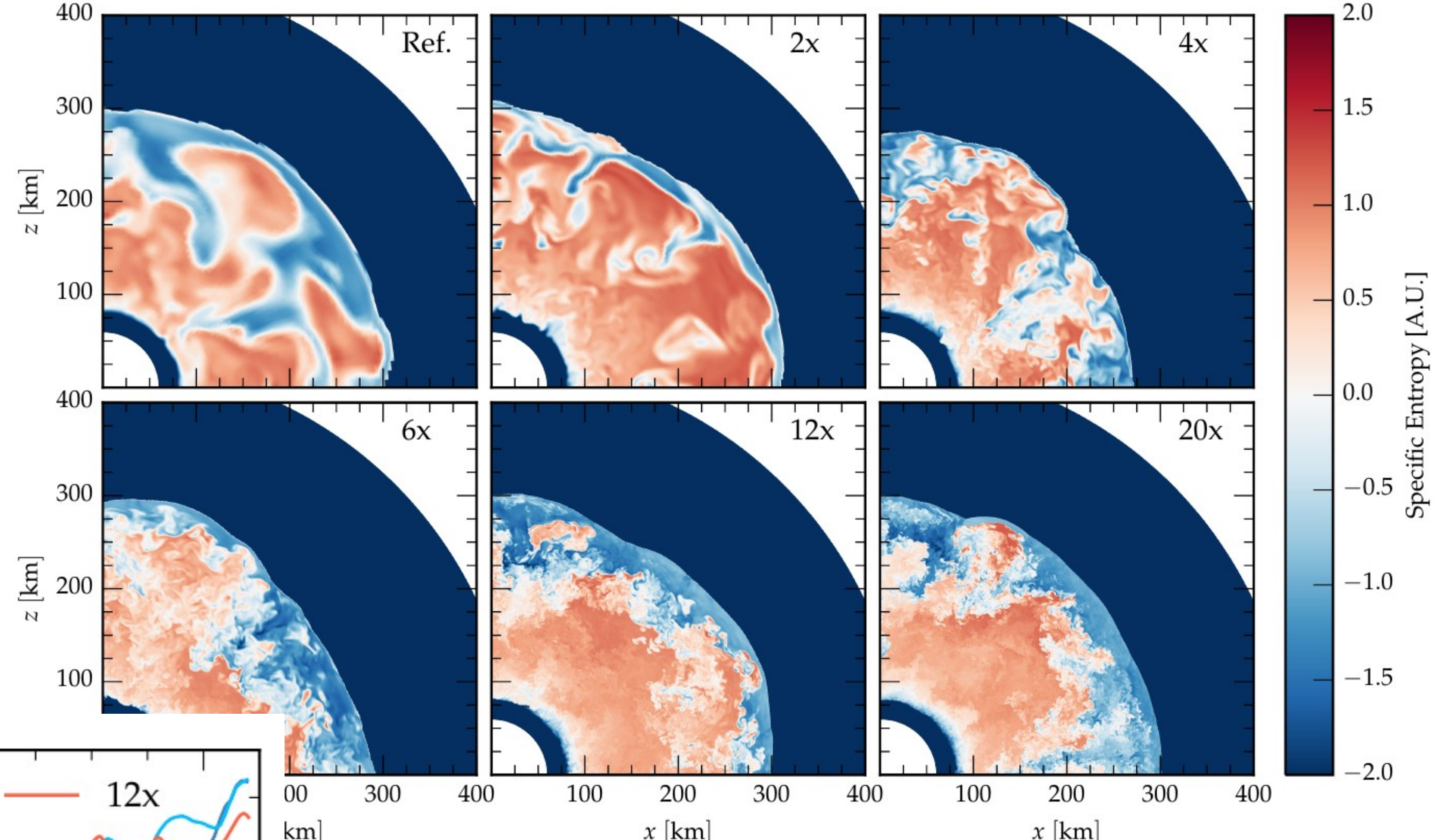
mean entropy in the gain layer



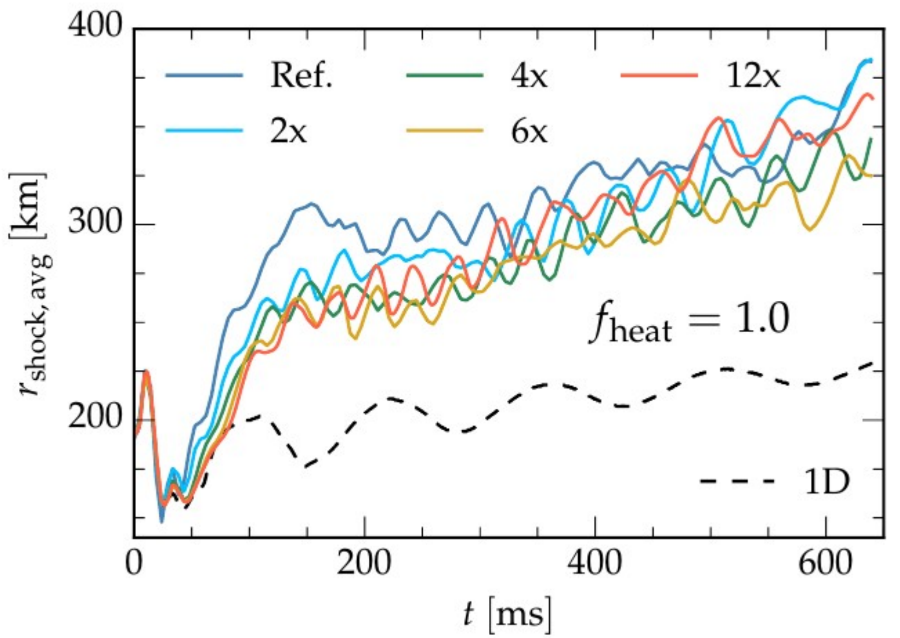
$\chi = 5$
$\delta\rho/\rho = 0.1\ \%$

Linear instability regime

- Heating increases in a runaway process **only** in 3D.
- No strong impact of resolution

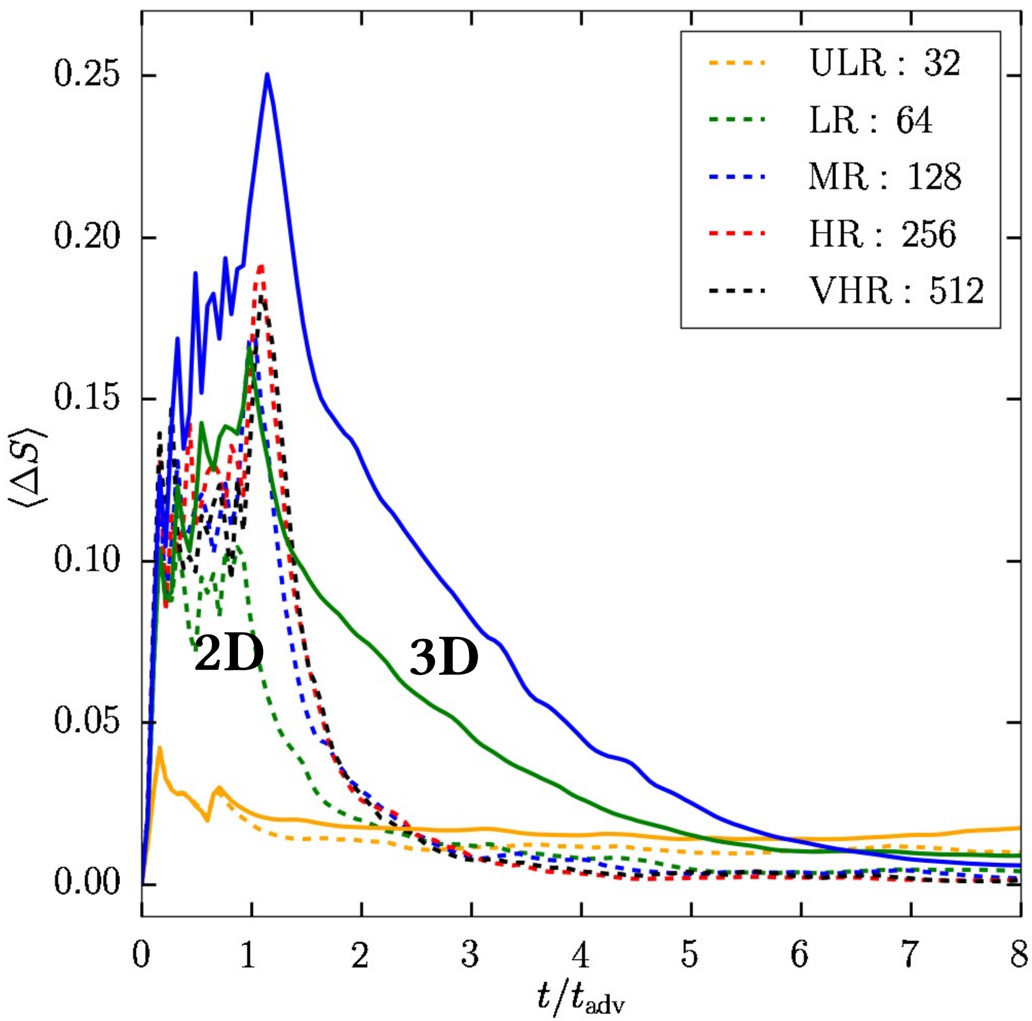


(Radice+ 2016)



- No clear impact on the shock radius

mean entropy in the gain layer



$\chi = 1.5$
$\delta\rho/\rho = 30$ %

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.

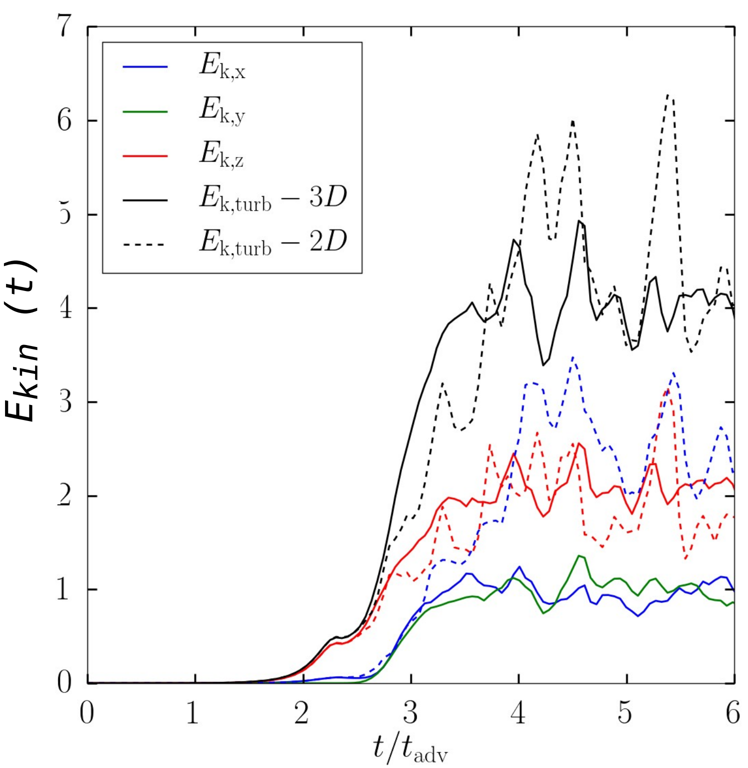
Conclusion

- 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, in prep.)

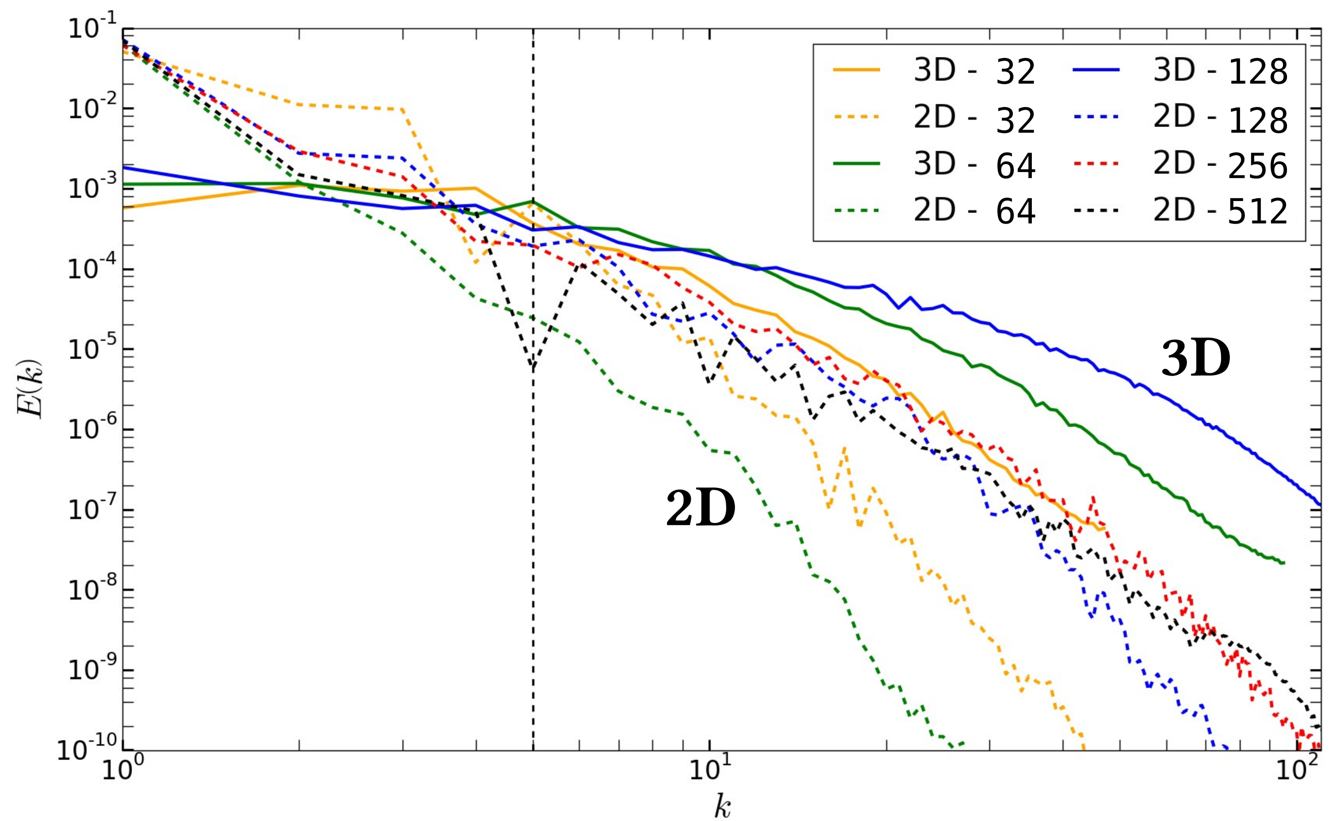
What are the differences between 2D & 3D?

turbulent kinetic energy



(see also Murphy & Meakin 2011, Murphy+ 2013)

turbulent energy spectrum



(see also Hanke+ 2012, Abdikamalov+ 2015, Radice+ 2016, ...)