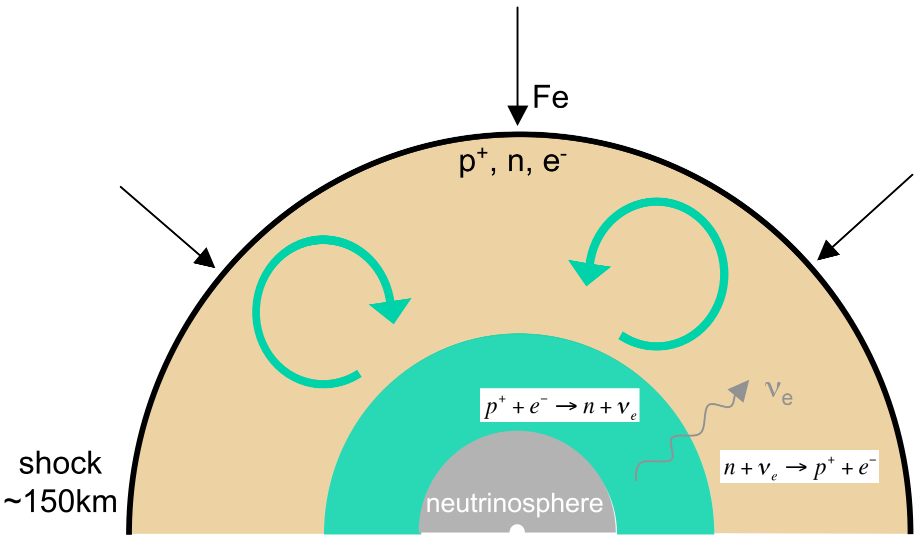
Identifying the mechanism at work behind SASI



T. Foglizzo, CEA Saclay
T. Yamasaki, J. Sato, J. Guilet (SAp) & MPA

Core collapse supernovae, before and after SASI

How far do we understand SASI, why bother ?

What is an advective-acoustic cycle ?

Are there alternative explanations for SASI ?

Some evidence for the AAC

Some misleading properties of advective-acoustic cycles
(that should not be considered as evidence against AAC)

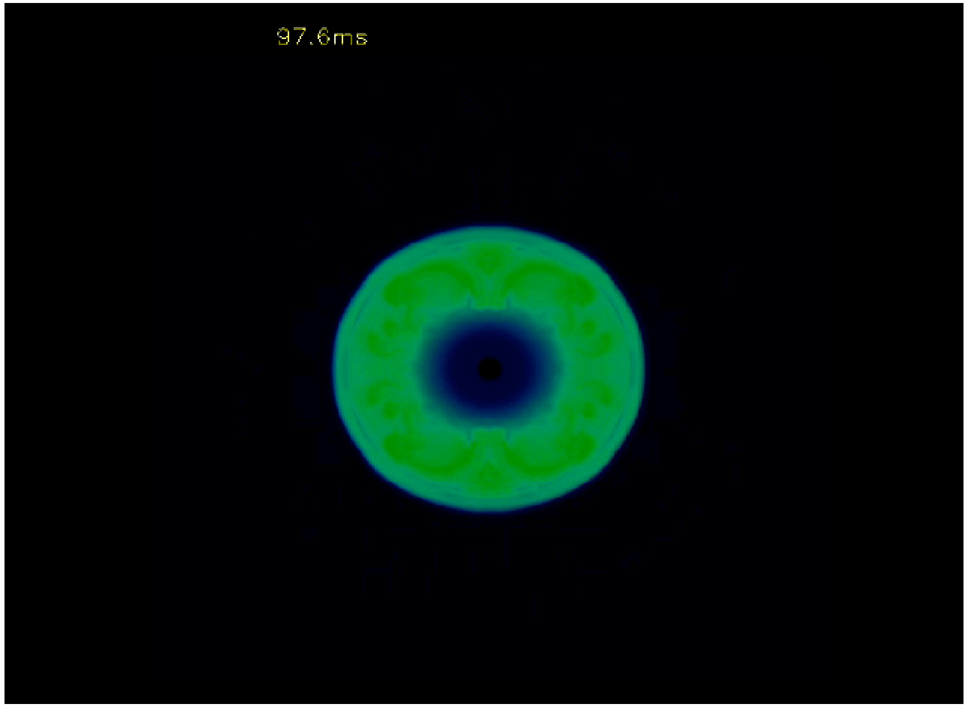
Perspectives

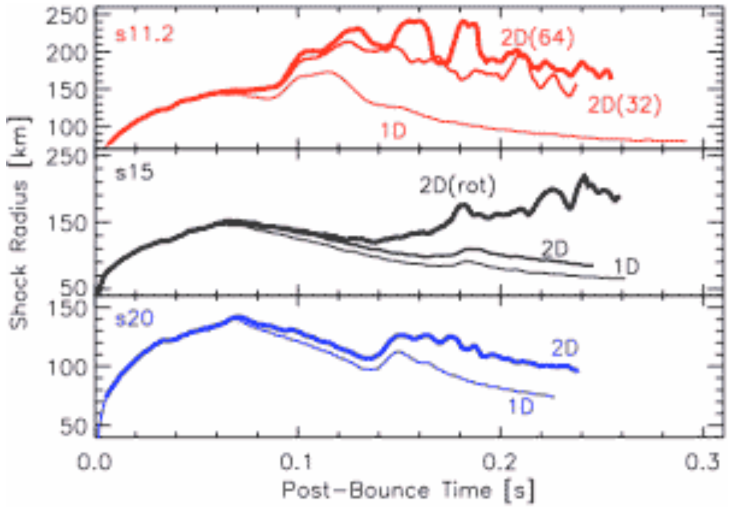
Core-collapse supernovae in 2003: « What was missing? »

VOLUME 90, NUMBER 24 PHYSICAL REVIEW LETTERS week ending 20 JUNE 2003

Improved Models of Stellar Core Collapse and Still No Explosions: What Is Missing?

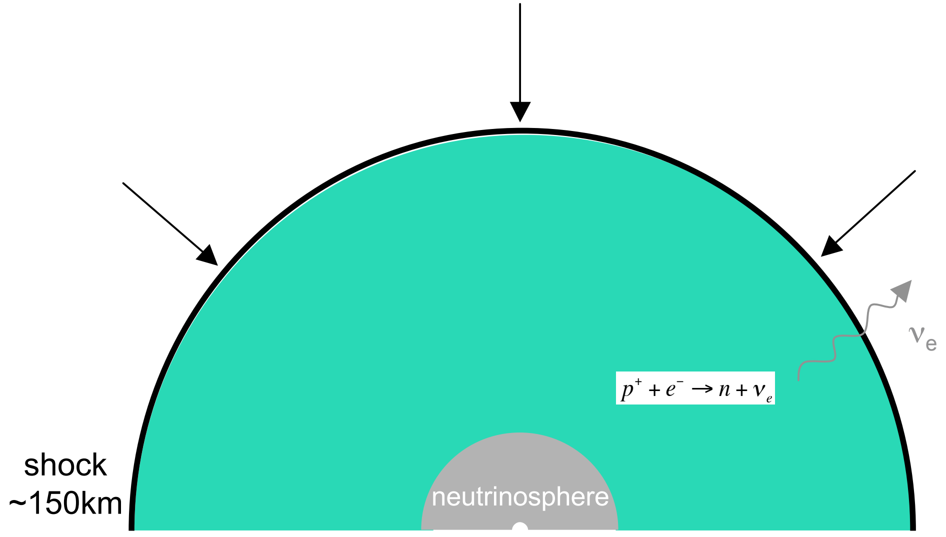
R. Buras, M. Rampp, H.-Th. Janka, and K. Kifonidis

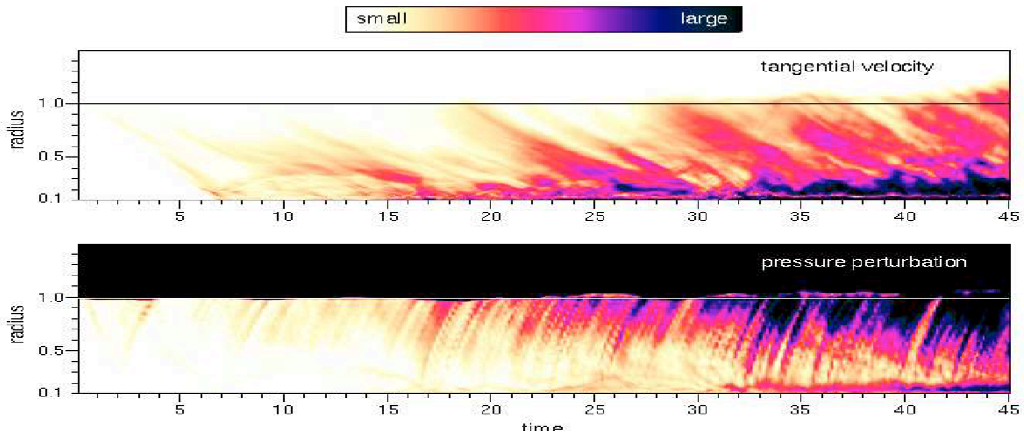




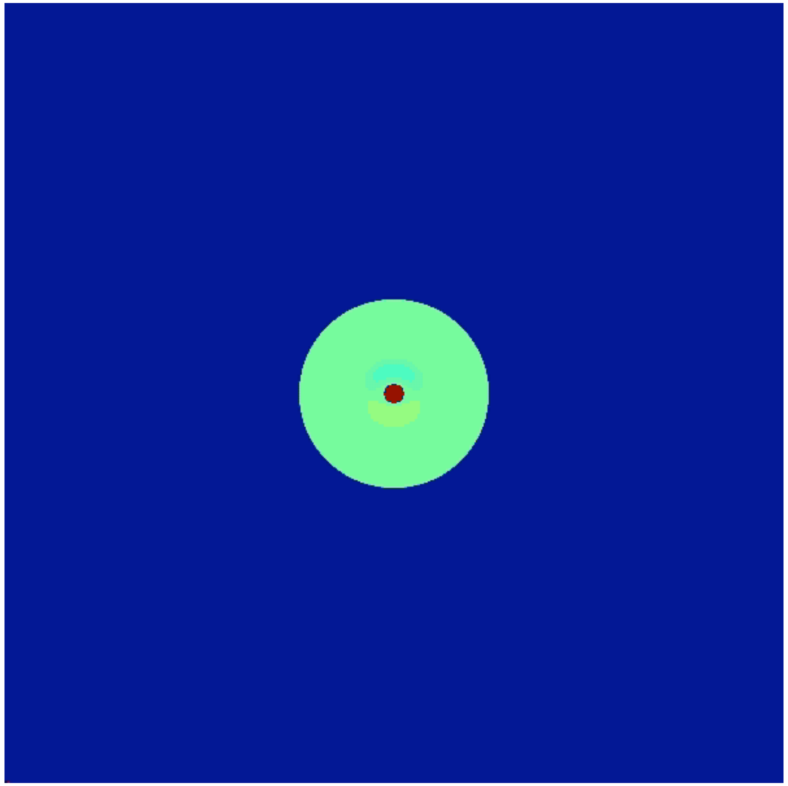
Buras et al. 03

Stationary Accretion Shock Instability : SASI





Blondin et al. 03

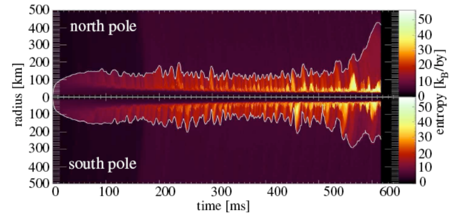


the mechanism of SASI must be fundamentally different from neutrino-driven convection
-> an advective-acoustic cycle ? (Blondin et al. 03, Galletti 05, Foglizzo et al. 07)

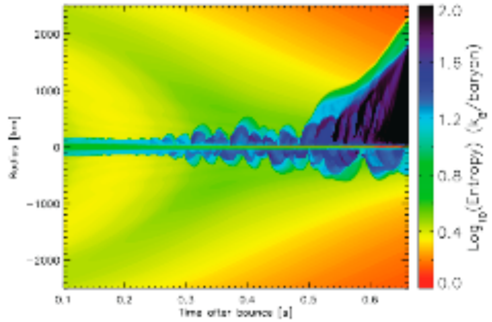
SASI in numerical simulations: ubiquitous since 2003

		initial setting	symmetry	SASI	ν-driven convection	NS g-modes
2003	Blondin et al.	stalled	2D axi.	X	-	-
2004	Scheck et al.	collapse	2D axi.	X	X	-
2006	Scheck et al.	collapse	2D axi.	X	X	-
	Burrows et al.	collapse	2D axi.	X	X	X
	Ohnishi et al.	stalled	2D axi.	X	X	-
	Blondin & Mezzacappa	stalled	2D axi.	X	-	-
2007	Blondin & Mezzacappa	stalled	3D	spiral	-	-
	Kotake et al.	stalled	2D axi.	X	X	-
	Burrows et al.	collapse	2D axi.	X	X	X
	Blondin & Shaw	stalled	2D eq.	spiral	-	-
	Fryer & Young	collapse	3D	X	X	?
2008	Scheck et al.	collapse	2D axi.	X	X	-
	Iwakami et al.	stalled	3D	X	X	-
-	Marek & Janka	collapse	2D axi.	X	X	weak
-	Ott et al.	collapse	2D axi.	X	X	?
-	Murphy & Burrows	collapse	2D axi.	X	X	?

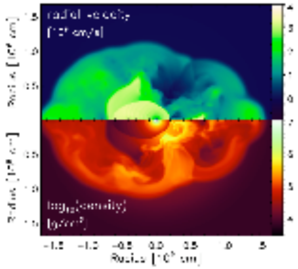
Some unexpected consequences of SASI



-successful explosion mechanism based on neutrino energy deposition, $15M_{sol}$ (Marek & Janka 08)

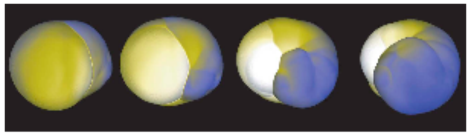


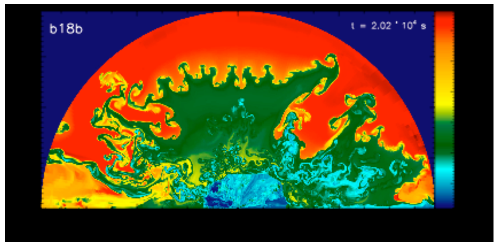
- new explosion mechanism based on acoustic energy, $11\text{-}25M_{sol}$ (Burrows et al. 06, 07, but see also Weinberg & Quataert 08)



- pulsar kicks (Scheck et al. 04, 06)

- pulsar spin (Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08)





- H/He mixing in SN1987A (Kifonidis et al. 06)

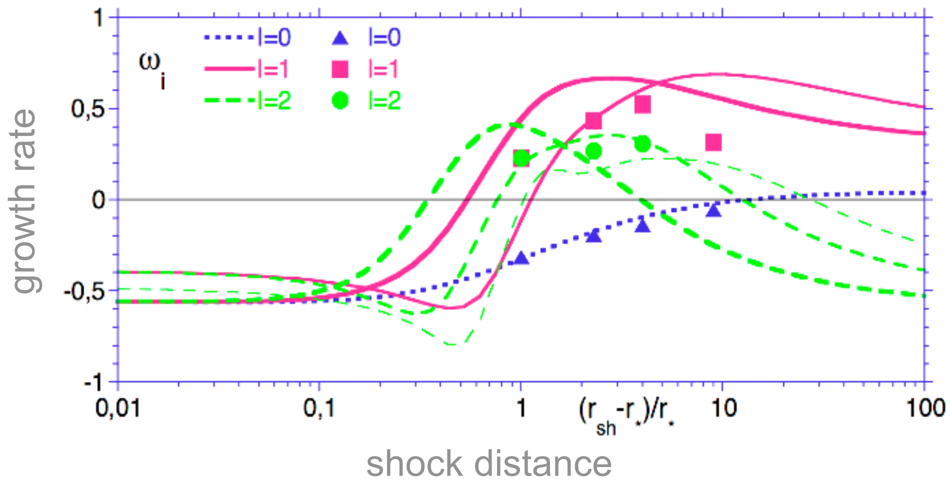
- Core collapse supernovae, before and after SASI
- How far do we understand SASI, why bother ?
- What is an advective-acoustic cycle ?
- Are there alternative explanations for SASI ?
- Some evidence for the AAC
- Some misleading properties of advective-acoustic cycles
  (that should not be considered as evidence against AAC)
- Perspectives

Should we trust the simulations of SASI ?

Although SASI is well recognized, different numerical simulations reach different conclusions about

- the explosion threshold: Marek & Janka 08
- the growth of the neutron star g-mode: Burrows et al. 06, 07
- the kick amplitude: Scheck et al. 04, 06
- the spiral mode of SASI even with a non rotating progenitor: Blondin & Mezzacappa 07

-> numerical methods and physical simplifications have to be compared carefully (e.g. Ott et al. 08)
-> Validation of the simulations of SASI in the linear regime (Blondin & Mezzacappa 06, Foglizzo et al. 07)



Do we understand SASI ?

Proposed instability mechanisms: neutrino driven convection
acoustic instability
advective-acoustic cycle

- SASI does not require negative entropy gradients, and can be disentangled from convection in the linear regime (Foglizzo et al. 06, Yamasaki & Yamada 07)

- what is the physical explanation supporting a purely acoustic instability ???

- what is the advective-acoustic cycle ? (Foglizzo & Tagger 00, Foglizzo 01, 02)

Beyond the comparison of timescales and eigenfrequencies, a WKB approach can fully characterize the instability of higher harmonics

Core collapse supernovae, before and after SASI

How far do we understand SASI, why bother ?

What is an advective-acoustic cycle ?

Are there alternative explanations for SASI ?

Some evidence for the AAC

Some misleading properties of advective-acoustic cycles
(that should not be considered as evidence against AAC)

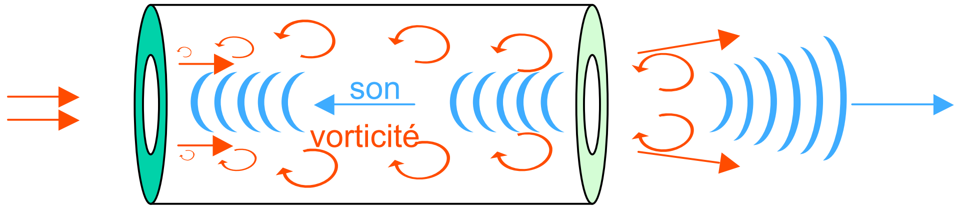
Perspectives

Aero-acoustic instabilities

- advected perturbations
- acoustic feedback

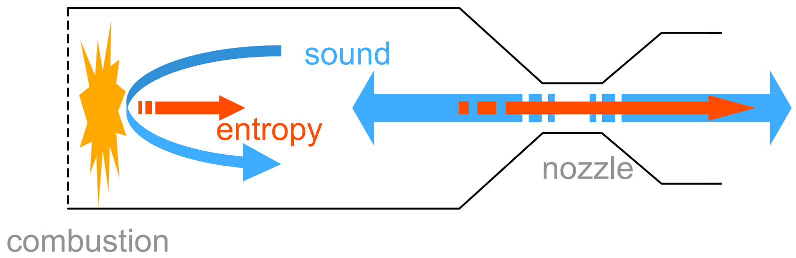
- vortical-acoustic cycle

whistling kettle
Chanaud & Powell (1965)



vibrations in Ariane 5
Mettenleiter, Haile & Candel (2000)

- entropic-acoustic cycle



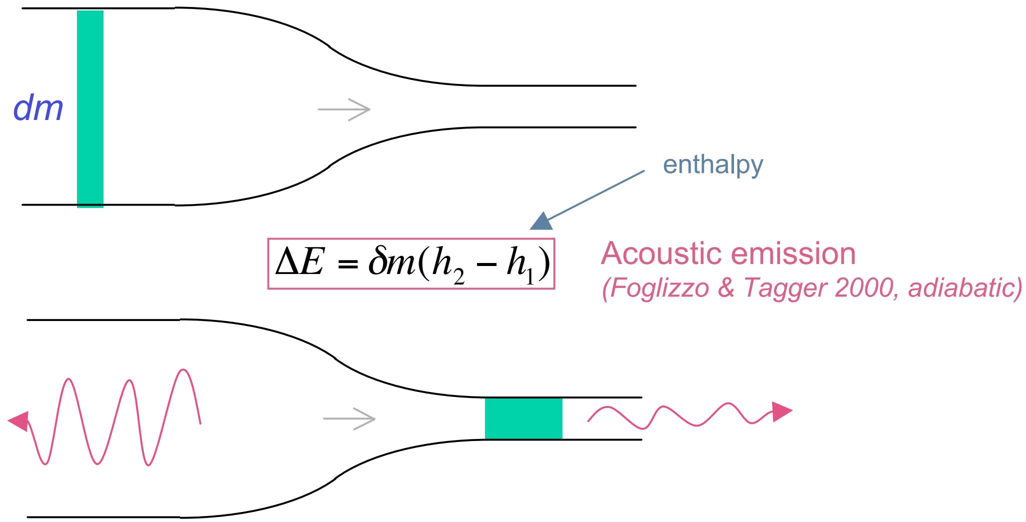
rumble instability of ramjets
Abouseif, Keklak & Toong (1984)

Advective-acoustic coupling: 2 types of acoustic feedback

advection of entropy

↓

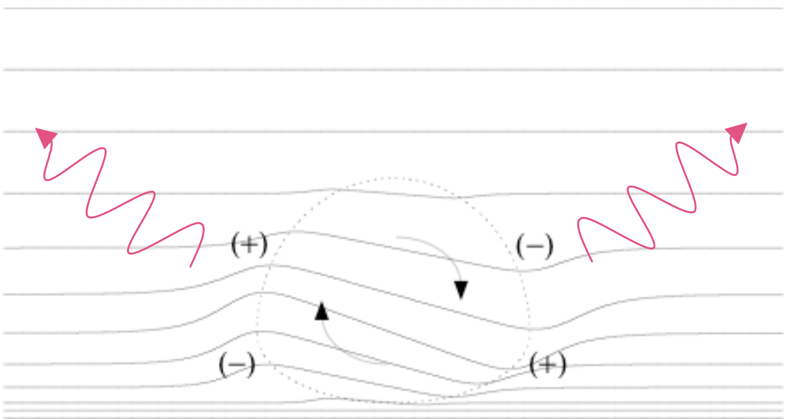
« entropic-acoustic cycle »



advection of vorticity

↓

« vortical-acoustic cycle »



Advective-acoustic coupling: analytic description

$$\left\{ \frac{\partial^2}{\partial r^2} + a_1 \frac{\partial}{\partial r} + a_0 \right\} \frac{\delta p}{p} = \frac{b_0}{1 - M^2} \delta S_R e^{i\omega \int_R^r \frac{dr}{v}}$$

Equation of acoustic waves

Source

$$\delta K \equiv r^2 v \cdot \left(\nabla \times \delta w \right) + l(l+1) c^2 \frac{\delta S}{\gamma} = 0$$

$$b_0 \equiv \frac{\Delta}{vc^2} \frac{\partial}{\partial r} \left[\frac{c^2}{\Delta} \left(v \frac{\partial \log M^2}{\partial r} - i\omega \right) \right]$$

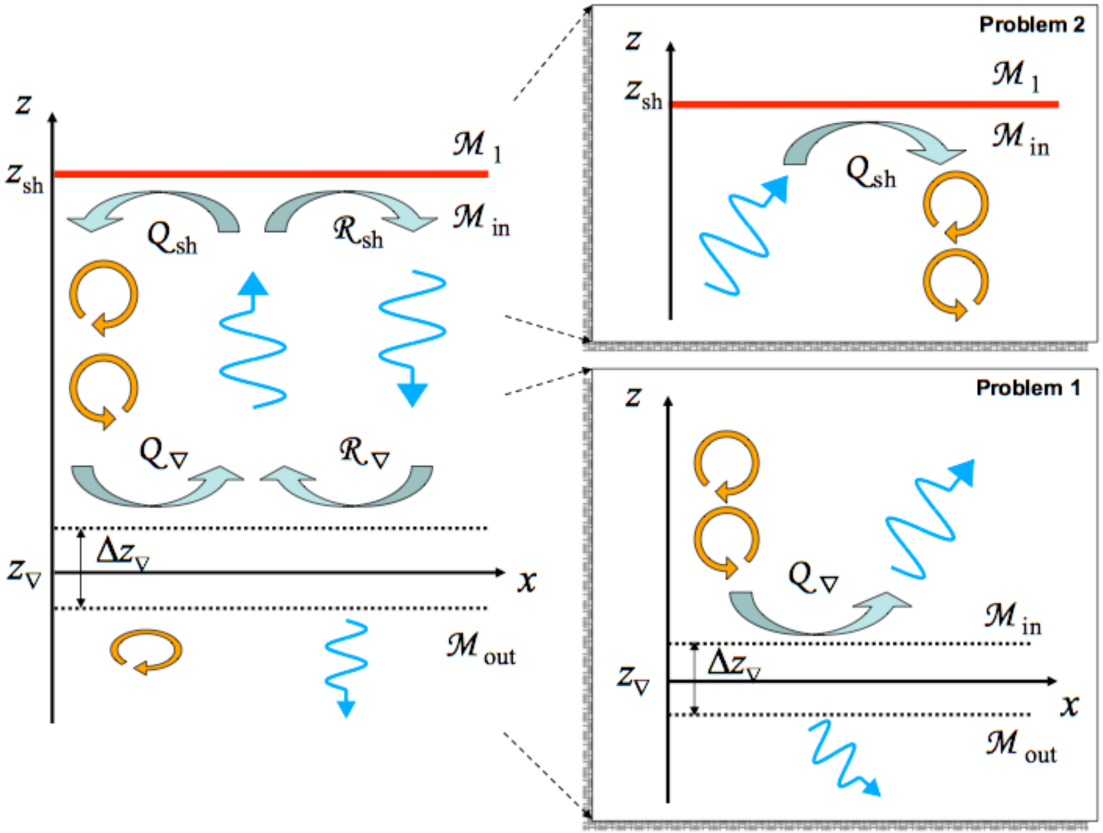
$$\Delta \equiv \omega^2 + 2i\omega \frac{\partial v}{\partial r} + l(l+1) \frac{v^2}{r^2}$$

$$b_0 \approx \frac{i\omega}{v} \frac{\partial \log c^2}{\partial r} \qquad \frac{\omega r}{v} >> 1$$

$$b_0 \approx -\frac{\partial \log c^2}{\partial r} \frac{\partial \log M^2}{\partial r} \qquad \frac{\omega r}{v} << 1, \quad l = 0$$ entropic-acoustic

$$b_0 \approx \frac{\partial \log M^2}{\partial r} \frac{\partial \log}{\partial r} \left(\frac{v}{rc^2} \right) \qquad \frac{\omega r}{v} << 1, \quad l \geq 1$$ vortical-acoustic

The simplest example of a 2D advective-acoustic cycle



-> see the movies by J. Sato (2008)

Core collapse supernovae, before and after SASI

How far do we understand SASI, why bother ?

What is an advective-acoustic cycle ?

Are there alternative explanations for SASI ?

Some evidence for the AAC

Some misleading properties of advective-acoustic cycles
(that should not be considered as evidence against AAC)

Perspectives

SASI as a purely acoustic cycle ?

Blondin & Mezzacappa 06

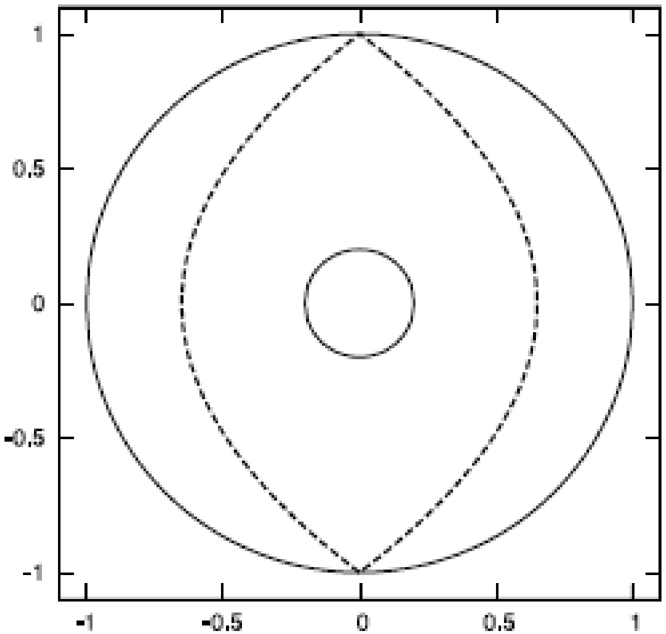
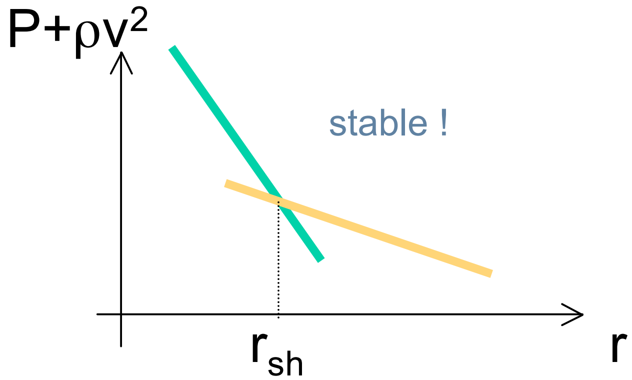
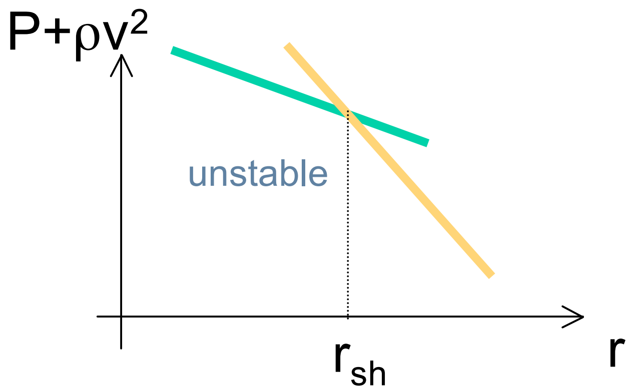


FIG. 6.—Example of a round-trip path (*dashed line*) for which the acoustic travel time is $\tau = 2\pi/\omega_I = 10.5$ for the T^4 model with $R_s/r_* = 5$. The outer circle marks the spherical accretion shock, and the inner circle is the surface of the accreting star with a radius of $r_* = 0.2$.





Nobuta & Hanawa 1994

Laming 07: frequency domain of validity ?

Core collapse supernovae, before and after SASI

How far do we understand SASI, why bother ?

What is an advective-acoustic cycle ?

Are there alternative explanations for SASI ?

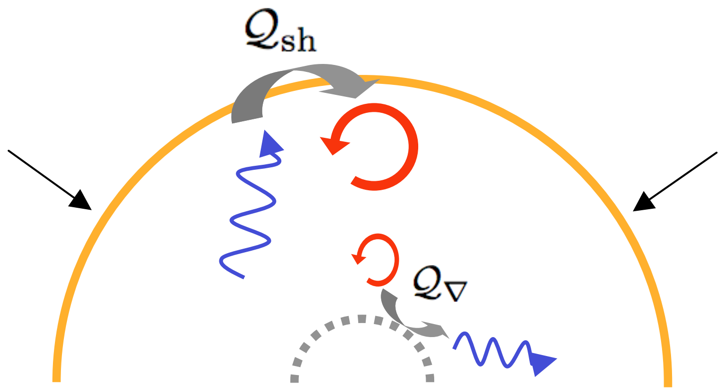
Some evidence for the AAC

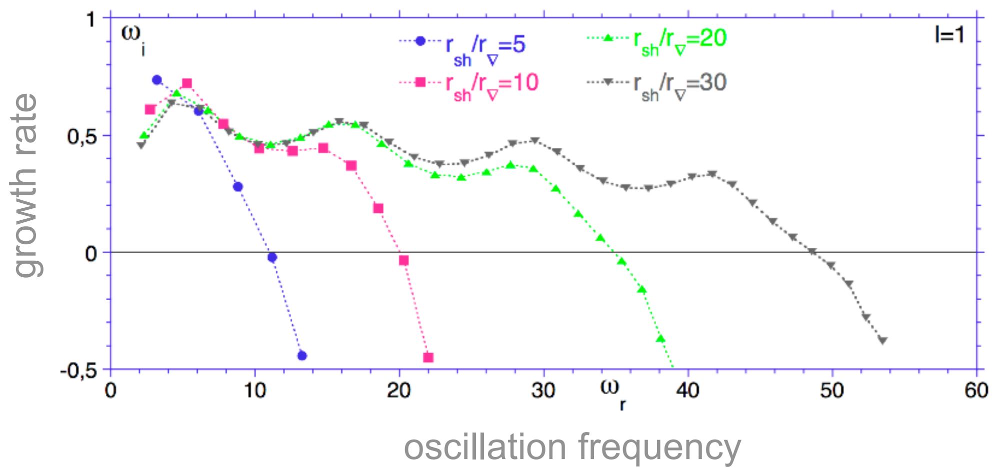
Some misleading properties of advective-acoustic cycles
(that should not be considered as evidence against AAC)

Perspectives

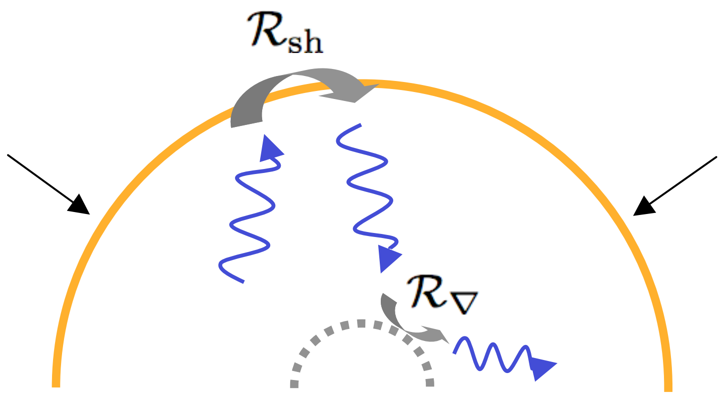
Advective-acoustic cycle in a decelerated, cooled flow

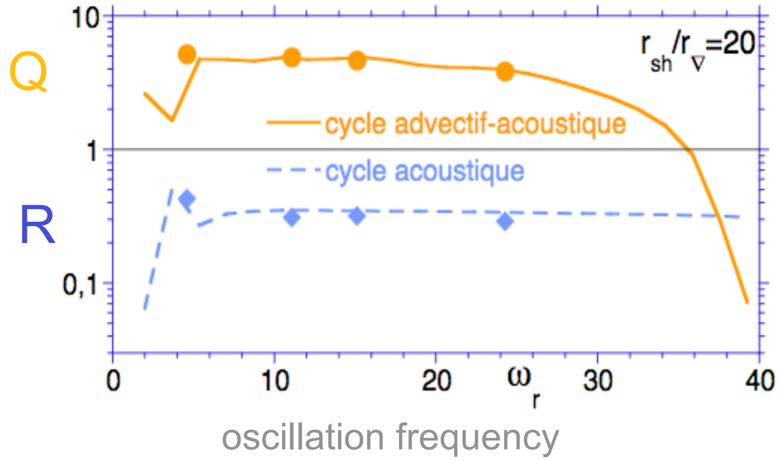
Foglizzo et al. 2007



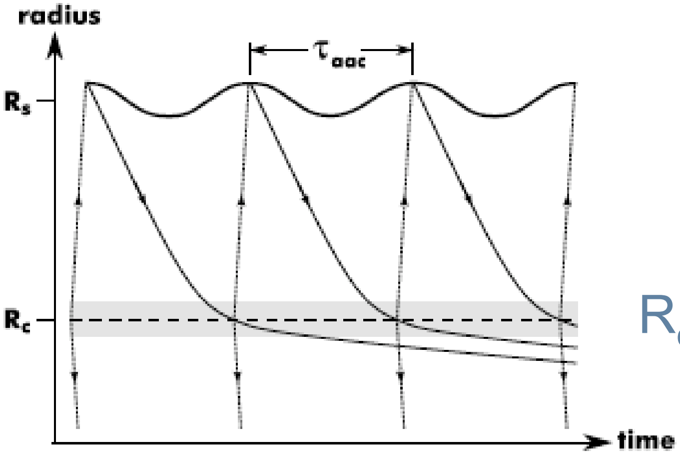


Unstable advective-acoustic cycle,
Stable acoustic cycle

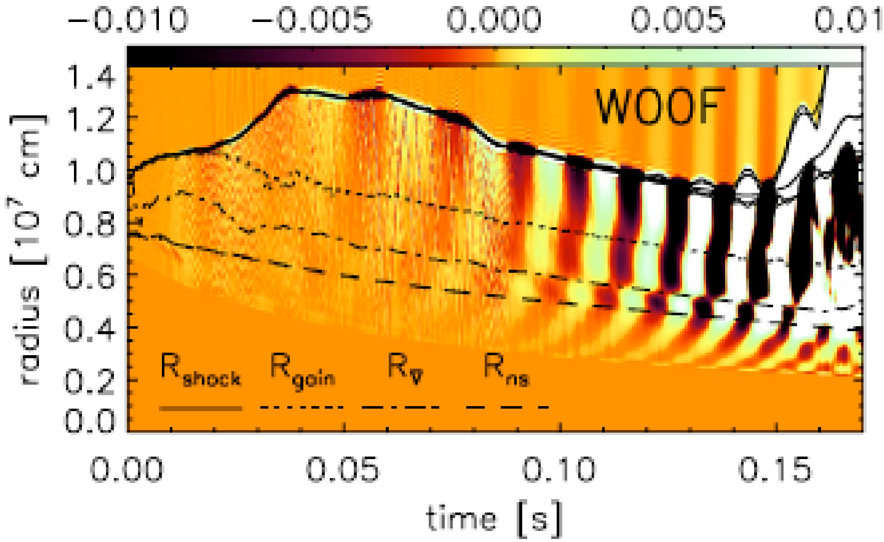


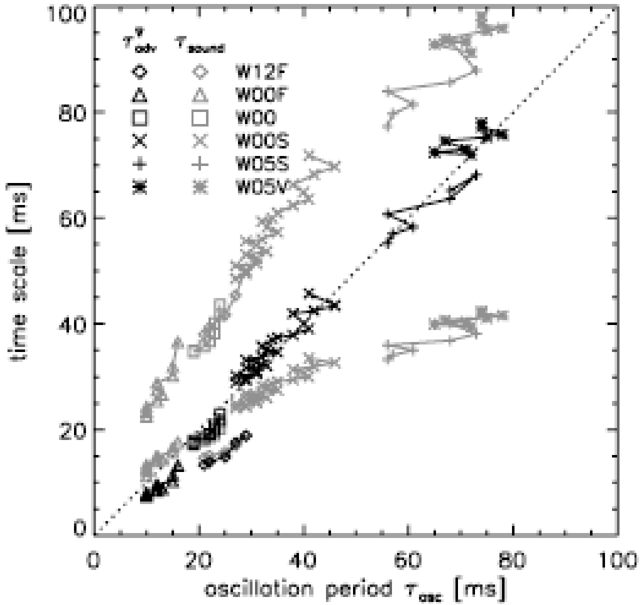


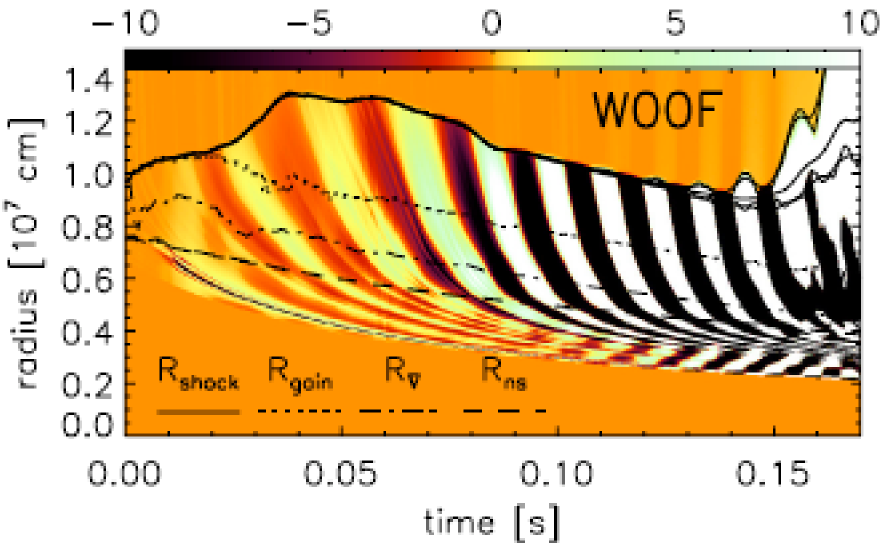
Advective-acoustic cycle in a simplified core-collapse simulation Scheck et al. 08



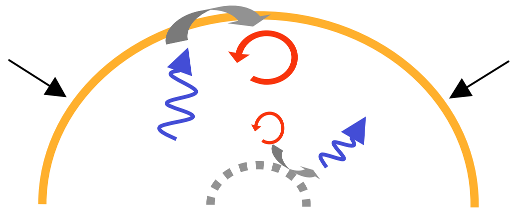
$R_c \sim R_\nabla$



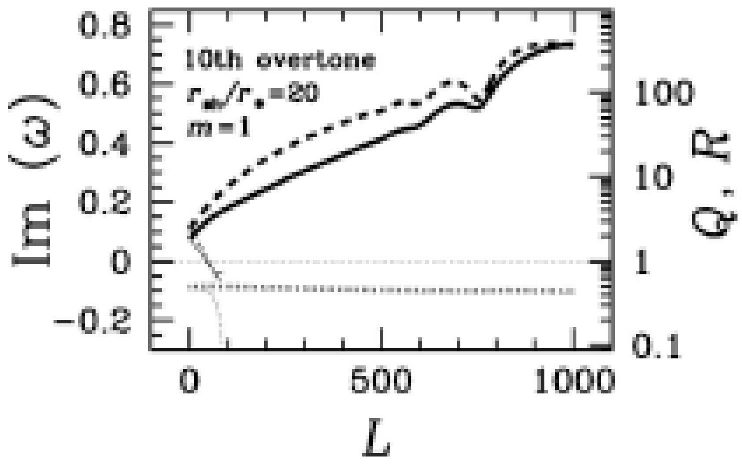




Evidence for the advective-acoustic cycle in a cylindrical flow



Yamasaki & Foglizzo 08



Core collapse supernovae, before and after SASI

How far do we understand SASI, why bother ?

What is an advective-acoustic cycle ?

Are there alternative explanations for SASI ?

Some evidence for the AAC

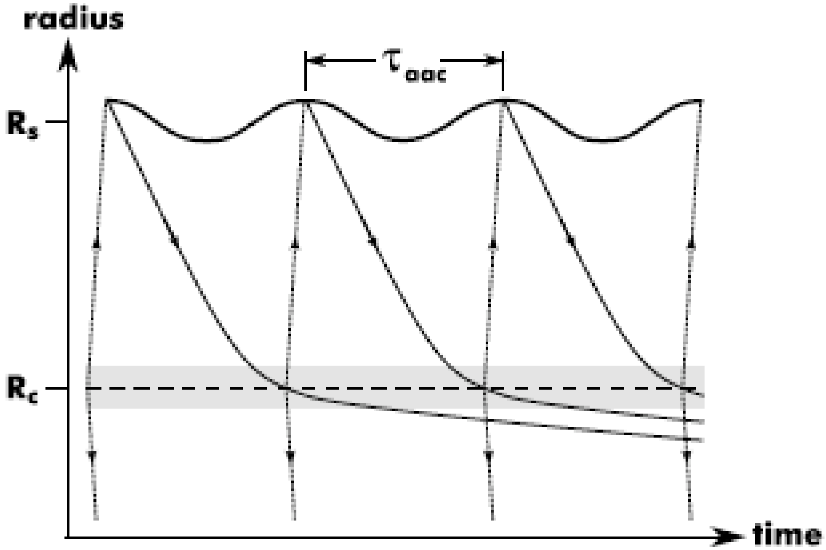
Some misleading properties of advective-acoustic cycles
(that should not be considered as evidence against AAC)

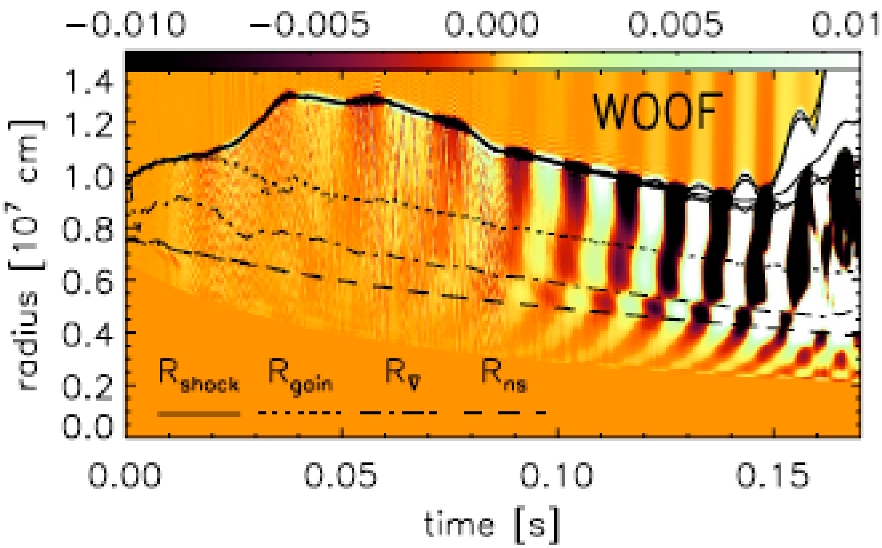
Perspectives

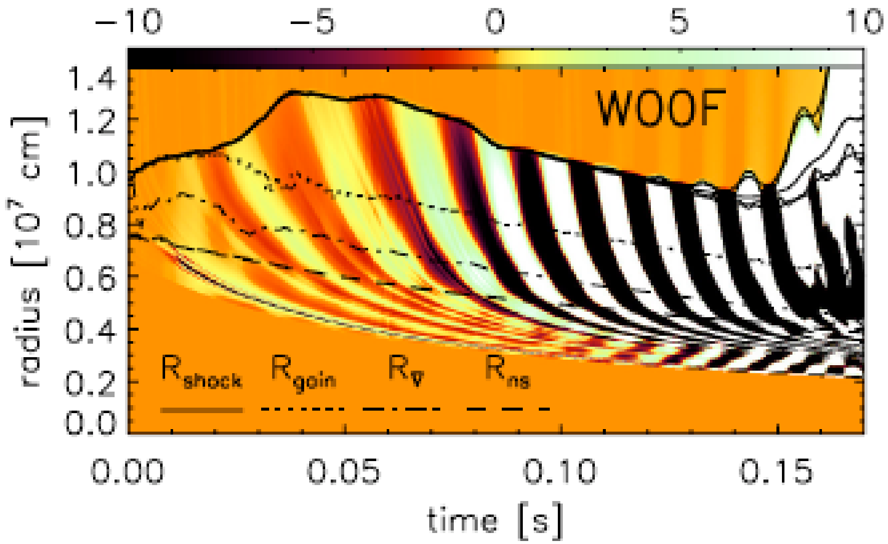
Some misleading properties of the AAC

Scheck et al. 08

« effective coupling radius »: the acoustic feedback is not necessarily localized radially

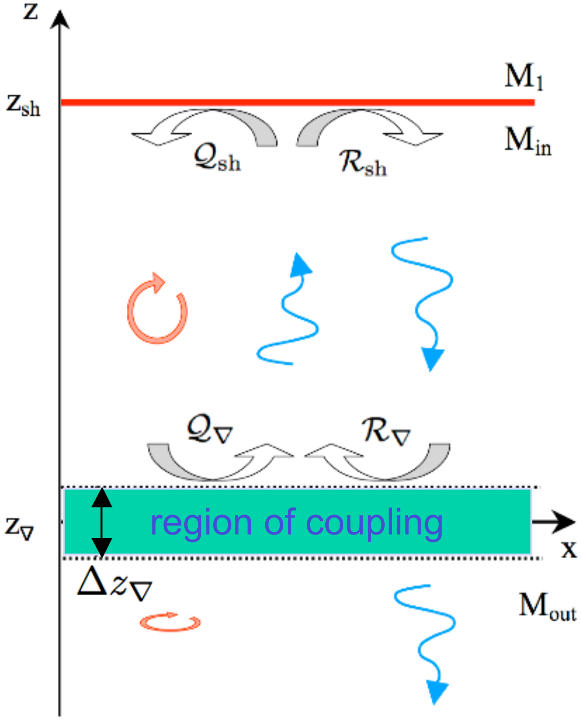


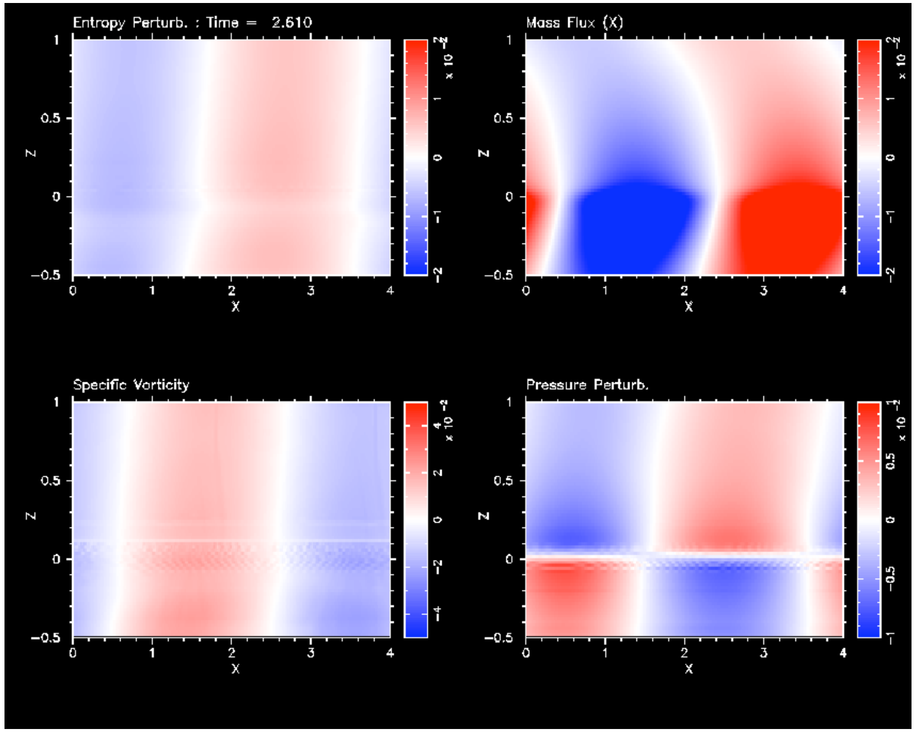




Some misleading properties of the AAC

The acoustic feedback does not necessarily propagate radially: it can be evanescent and propagate horizontallv





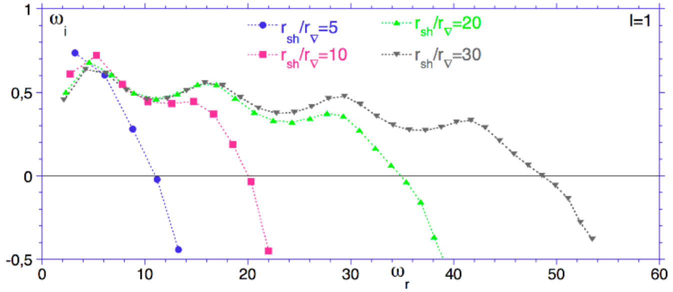
The acoustic cycle alone is always stable (R<1), but can help destabilize the advective-acoustic cycle (Q + R > 1)

Conclusions

The mechanism responsible for SASI is the advective-acoustic cycle

(neither purely acoustic, nor purely convective)

The strict proof is limited to higher harmonics



Why bother ?

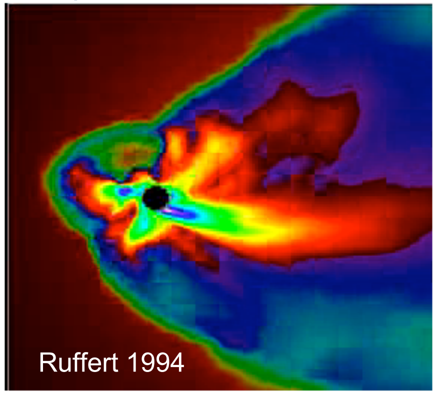
- interpret the outcome of numerical simulations
- importance of the lower boundary condition: spurious vs physical feedback ?
- first step towards understanding the effect of rotation and magnetic fields on SASI
- challenge our understanding by comparing SASI with other advective-acoustic instabilities

Diversity of advective-acoustic cycles

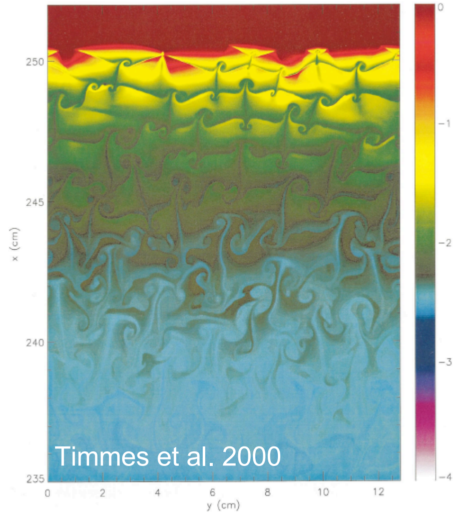
Ariane 5

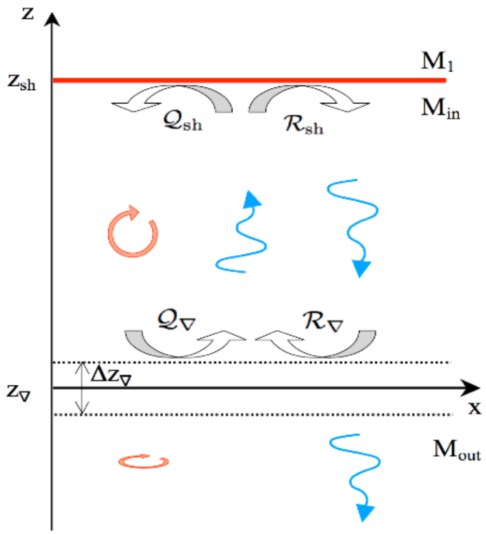
kettle

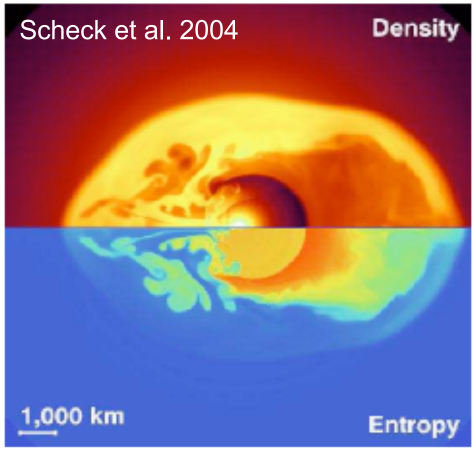
supersonic black hole



cellular detonation

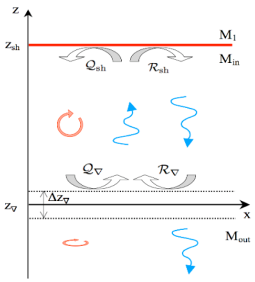


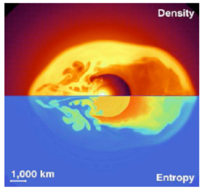
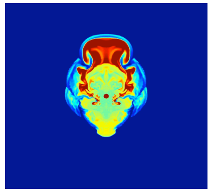
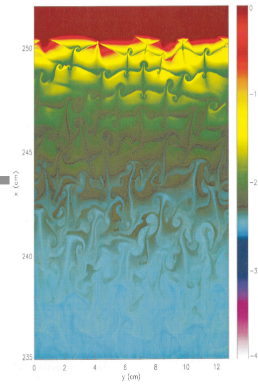
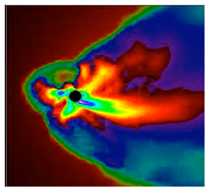




asymmetric supernova

Classification of advective-acoustic cycles



	cooling	adiabatic	heating
decelerated subsonic			
accelerated subsonic			
accelerated transonic			

Scheck et al. '04, Blondin et al. '03, Ruffert '95, Timmes et al. '00