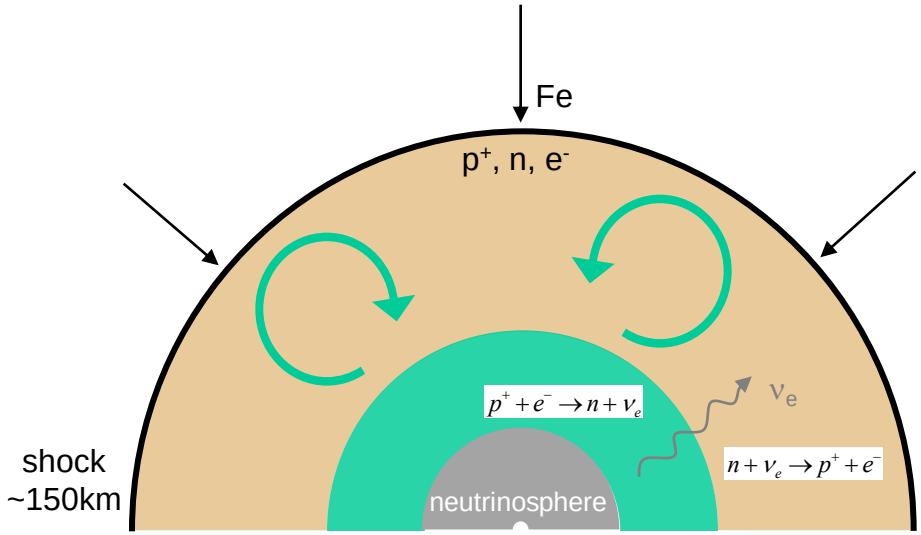
From the whistle of a kettle to the asymmetric explosion of supernovae



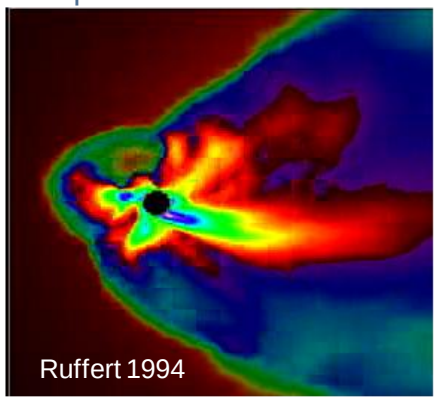
T. Foglizzo, CEA Saclay
T. Yamasaki, J. Sato, J. Guilet

The family of advective-acoustic instabilities

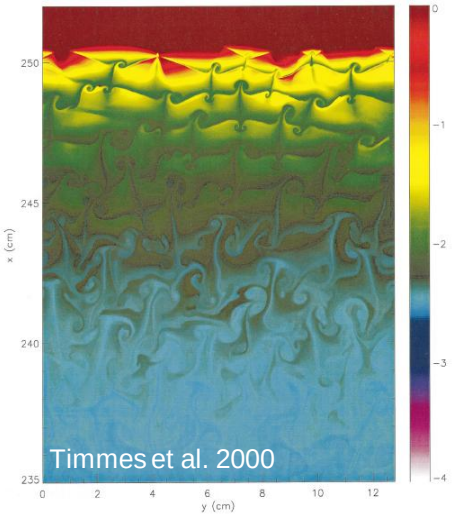
Ariane 5

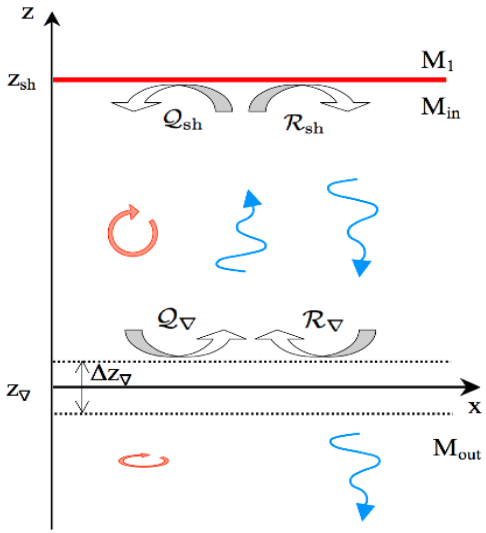
whistling kettle

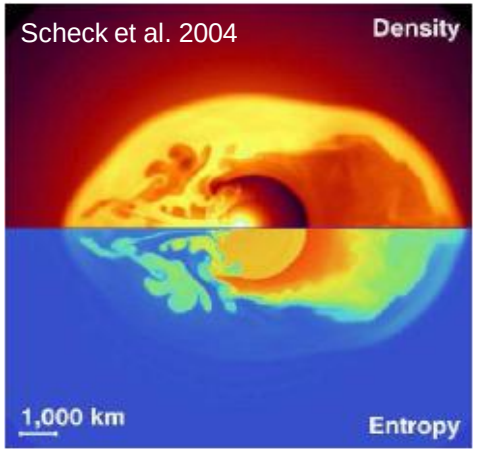
supersonic black hole



cellular detonation







asymmetric supernova

Outline

Core-collapse supernovae, before and after SASI (2003)

How far do we understand SASI ?

->the link with whistling kettles

Observational constraints

Perspectives

The difficult energy budgets of supernovae

(orders of magnitude)

$$E_{\rm K} \sim 1 - 2 \times 10^{51} {\rm erg}$$

Collapse of the core of a massive star to a neutron star (SNII, Ib/c): $E_{grav} >> E_K$

$$\frac{3GM^2}{5R} = 3.1 \times 10^{53} \left(\frac{M}{1.4 M_{\rm sol}} \right)^2 \frac{10{\rm km}}{R} \ {\rm erg}$$

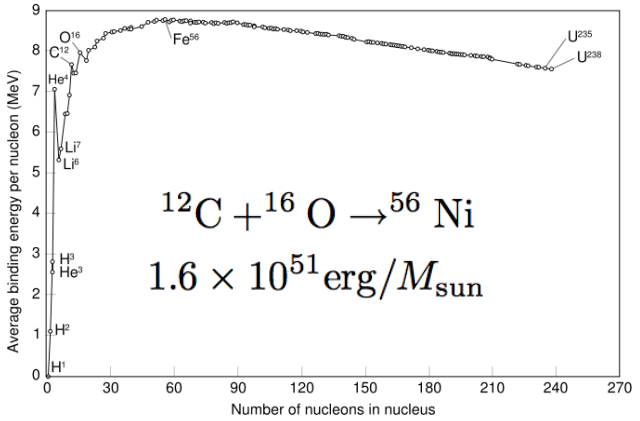
but ... $p^+ + e^- \rightarrow n + \nu$

essentially carried away by neutrinos

White Dwarf thermonuclear disruption (SNIa) : tight budget

$$\frac{3GM^2}{5R} = 1.6 \times 10^{51} \left(\frac{M}{1.4 M_{\rm sol}} \right)^2 \frac{2000{\rm km}}{R} \ {\rm erg}$$

$$1 \ {\rm MeV/nucleon} \sim 2 \times 10^{51} \ {\rm erg}/M_{\rm sun}$$

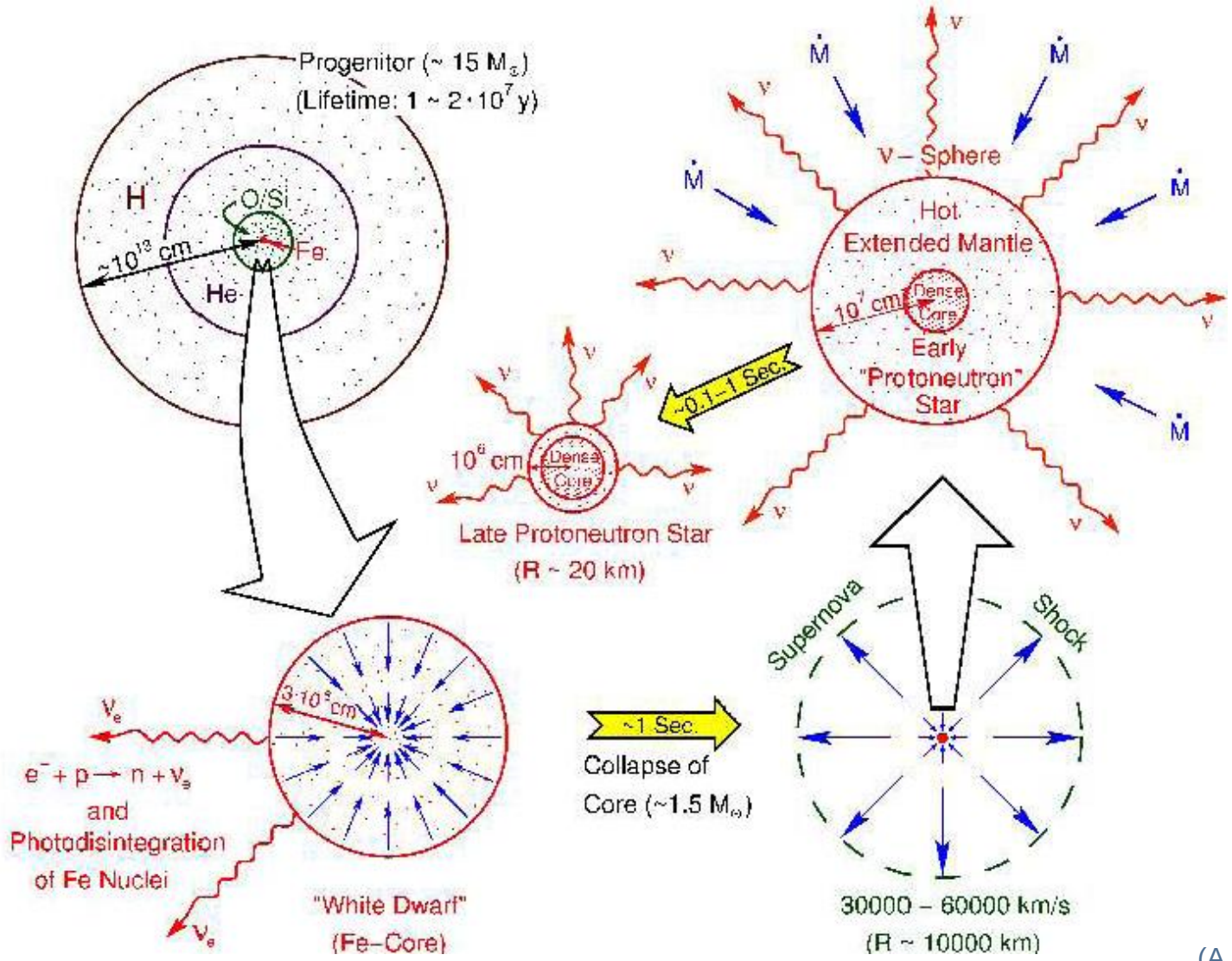


$^{12}{\rm C} + ^{16}{\rm O} \rightarrow ^{56}{\rm Ni}$

$1.6 \times 10^{51} {\rm erg}/M_{\rm sun}$

Core-collapse supernovae: delayed explosion mechanism

(Bethe & Wilson 1985)



(A. Burrows)

but ... inefficient in 1D (Liebendörfer et al. 2001)

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

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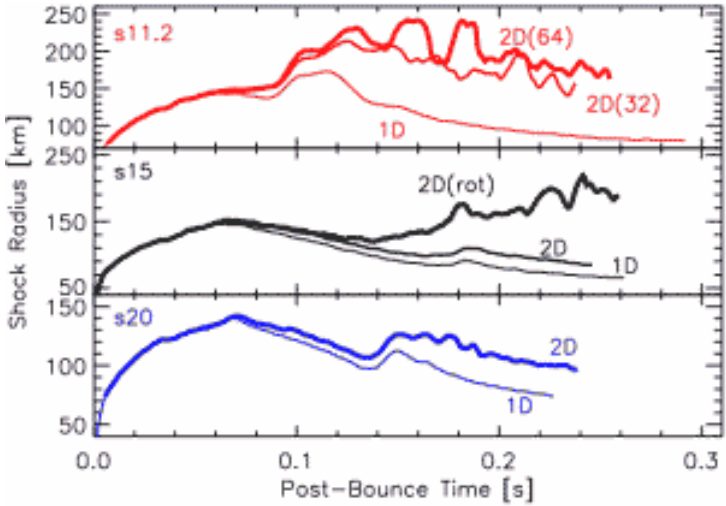
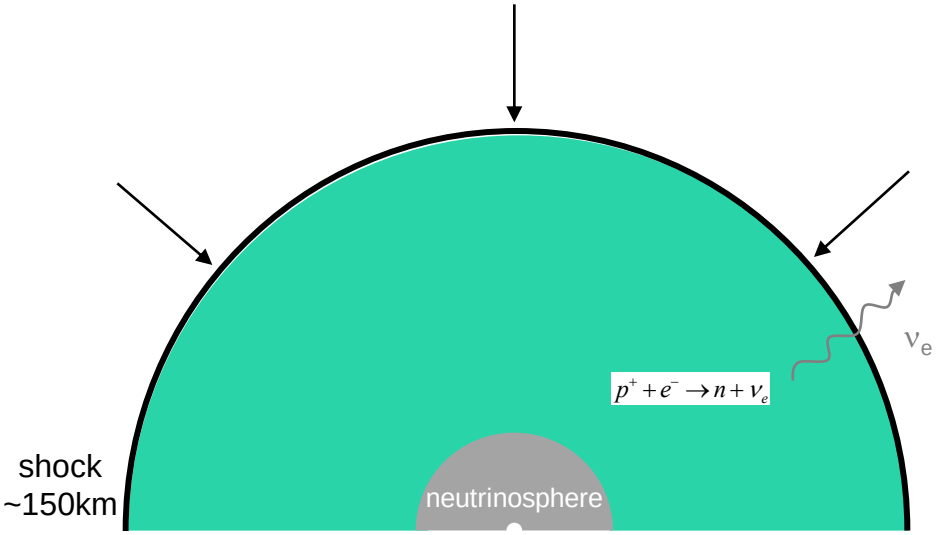
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ et un
décompresseur codec YUV420
sont requis pour visionner cette image.



Buras et al. 03

Stationary Accretion Shock Instability : SASI



Blondin et al. 03

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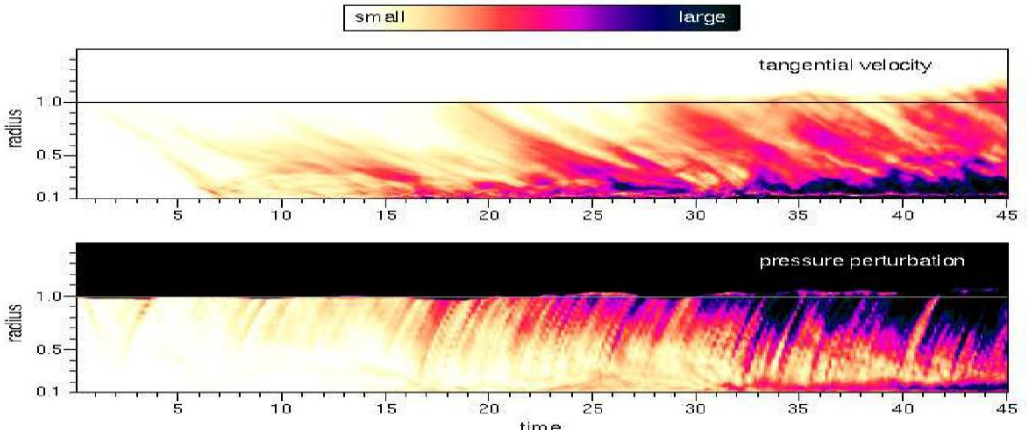


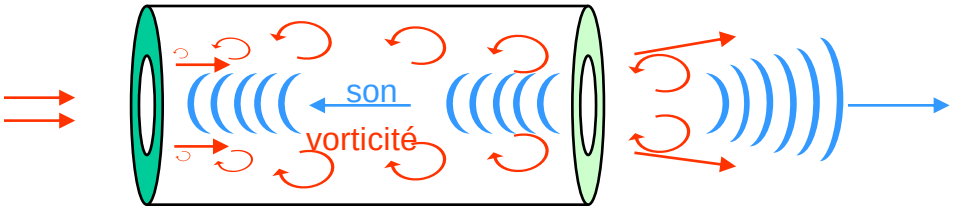
the mechanism of SASI must be fundamentally different from neutrino-driven convection
(Foglizzo et al. 06, Yamasaki & Yamada 07)

-> an advective-acoustic cycle ? (Blondin et al. 03, Galletti 05, Ohnishi et al. 2006, Foglizzo et al. 07, ...)

Aero-acoustic instabilities

- advected perturbations
- acoustic feedback

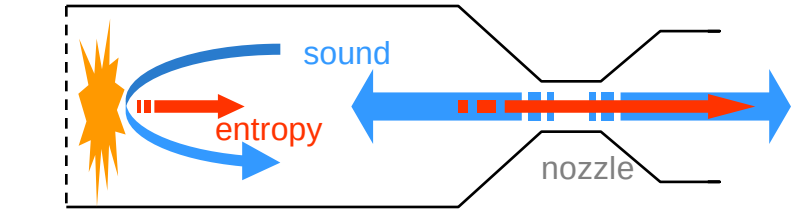
• vortical-acoustic cycle



whistling kettle
Chanaud & Powell (1965)

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

• entropic-acoustic cycle



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

SASI in numerical simulations: ubiquitous since 2003

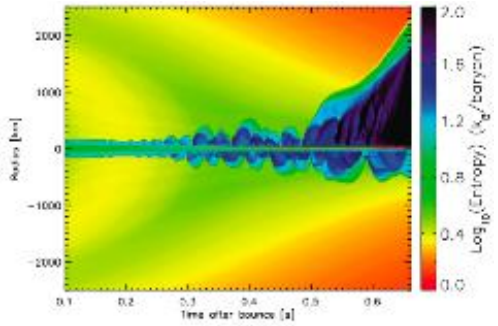
		initial setting	symmetry	SASI	ν-driven convection	NS g-modes
2003	Blondin et al.	stalled	2D axi.	X	-	-
2004	Scheck et al.	collapse	2D axi.	X	X	-
2006	Scheck et al.	collapse	2D axi.	X	X	-
	Burrows et al.	collapse	2D axi.	X	X	X
	Ohnishi et al.	stalled	2D axi.	X	X	-
	Blondin & Mezzacappa	stalled	2D axi.	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	?

Unexpected consequences of SASI

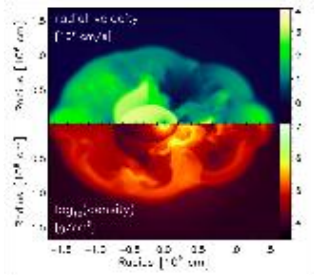
-successful explosion mechanism based on neutrino energy deposition, $15M_{sol}$ (Marek & Janka 08)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

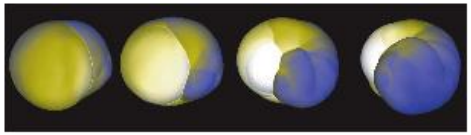
- new explosion mechanism based on acoustic energy, $11\text{-}25M_{sol}$
  (Burrows et al. 06, 07, Yoshida et al. 2007, Weinberg & Quataert 08)



- pulsar kicks (Scheck et al. 04, 06, Iwakami et al. 09)



- pulsar spin
  (Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08, Iwakami et al. 09)



QuickTime™ et un
décompresseur TIFF (LZW)
sont requis pour visionner cette image.

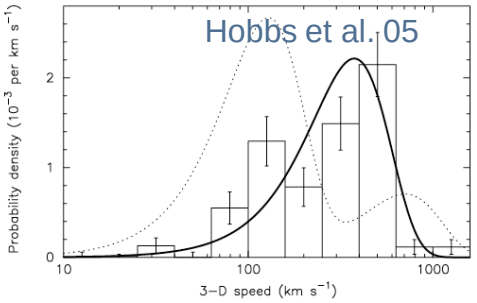
- H/He mixing in SN1987A (Kifonidis et al. 06)

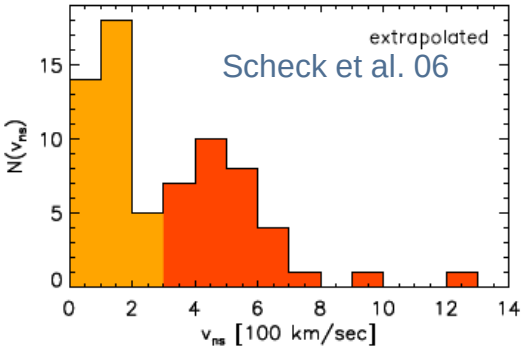
- additional source of gravitational waves
  (Ott et al. 06, Kotake et al. 07, Marek et al. 08, Ott 08)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Observational constraints on the explosion mechanism

Velocity distribution of pulsars





Kick-spin alignement (Wang, Lai & Han 06, Ng & Romani 04)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Explosion asymmetry deduced from
-spectropolarimetry (Leonard et al. 06, Wang et al. 03, ...)
-oxygen spectroscopy (Maeda et al. 08)

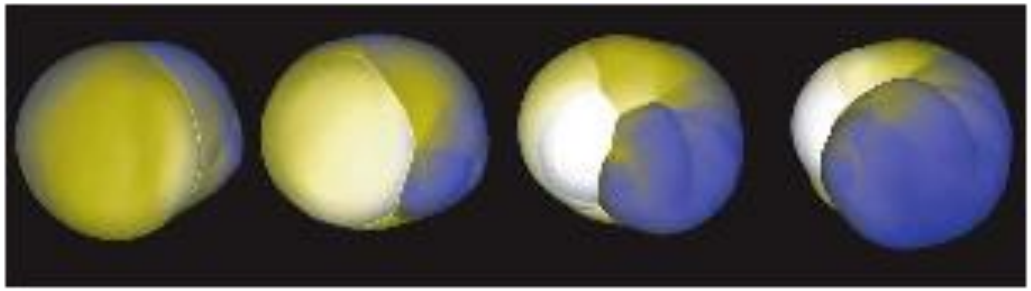
QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

SNR composition gradients ? (Katsuda et al. 08)

SASI in 3D: dominated by a spiral mode ?

even if the progenitor is not rotating ?



QuickTime™ et un
décompresseur Animation
sont requis pour visionner cette image.

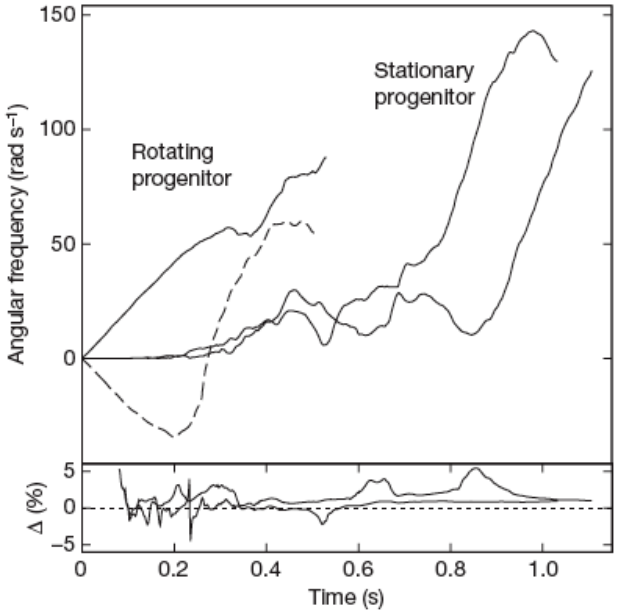
Blondin & Mezzacappa 07, Iwakami et al. 08, 09

If the spiral mode of SASI always dominates the sloshing mode, what is the relevance of all previous 2D axisymmetric simulations ?

-> successful 2D explosion mechanism(s) ?

-> successful 2D pulsar kicks ?

-> prediction of kick-spin misalignement ?



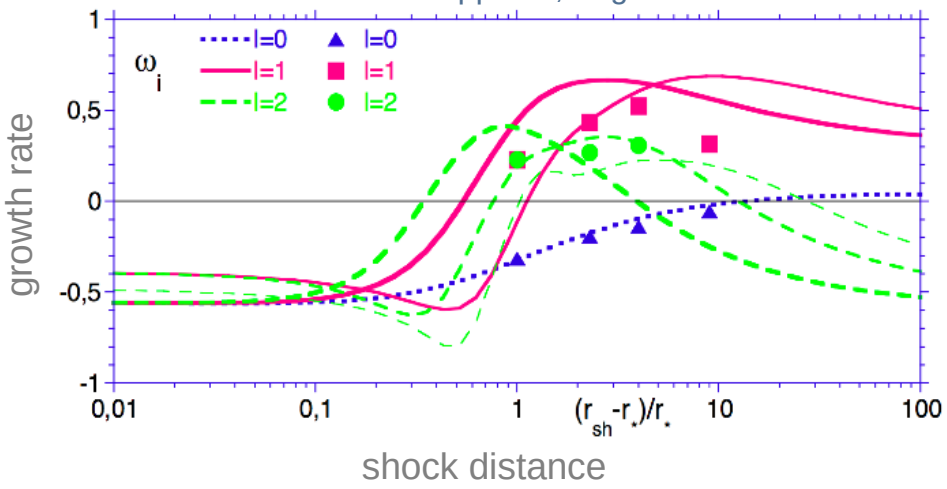
Should we trust the simulations of SASI ?

Existing debates about

- the explosion threshold
- the growth of the neutron star g-mode
- the kick amplitude
- the spiral mode of SASI in a non-rotating progenitor

-> Validation of the simulations of SASI in the linear regime

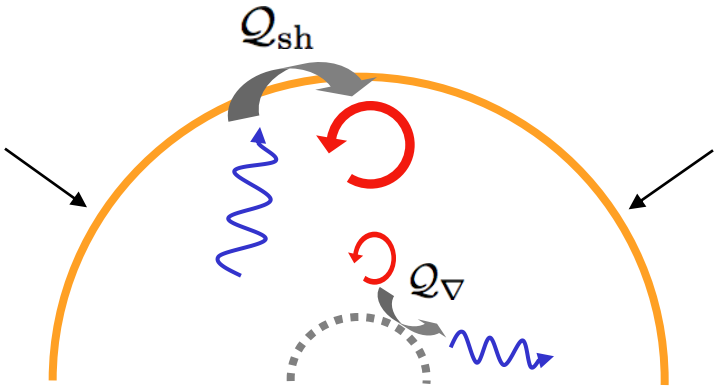
Blondin & Mezzacappa 06, Foglizzo et al. 07

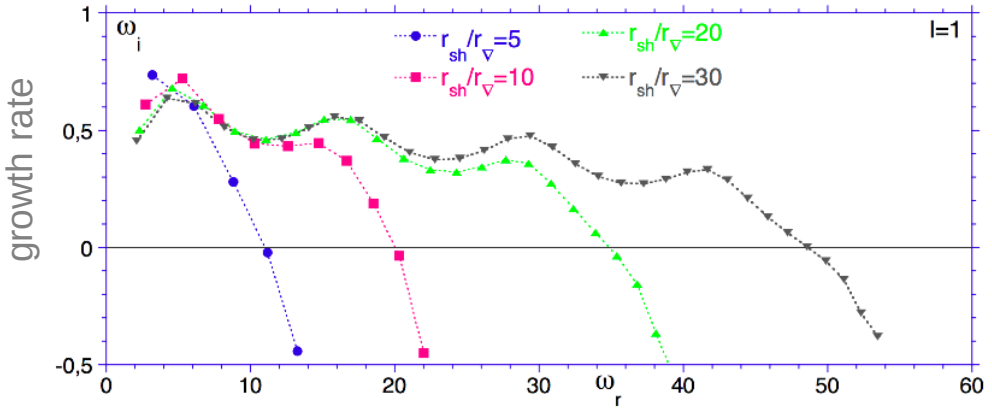


Do we really understand the mechanism of SASI ?

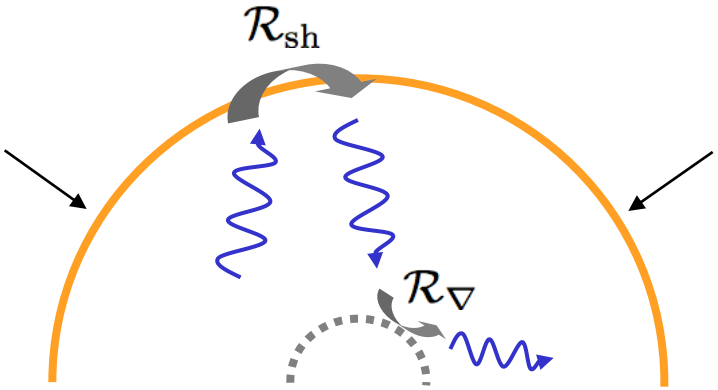
Advective-acoustic cycle in a decelerated, cooled flow

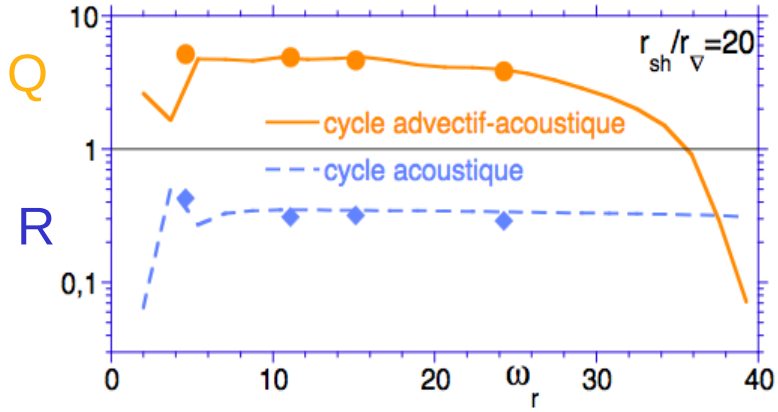
Foglizzo et al. 07





Unstable advective-acoustic cycle,
Stable acoustic cycle





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

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TIFF (Uncompressed) decompressor
are needed to see this picture.

$R_c \sim R_\nabla$

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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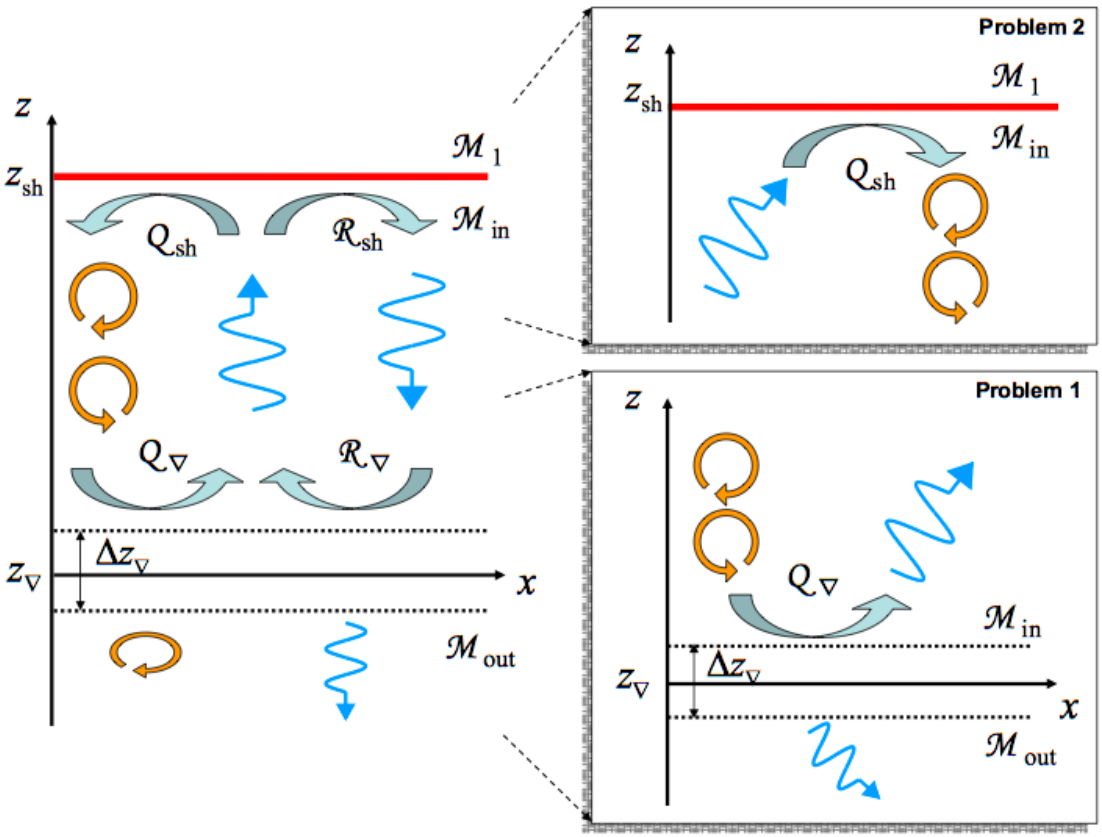
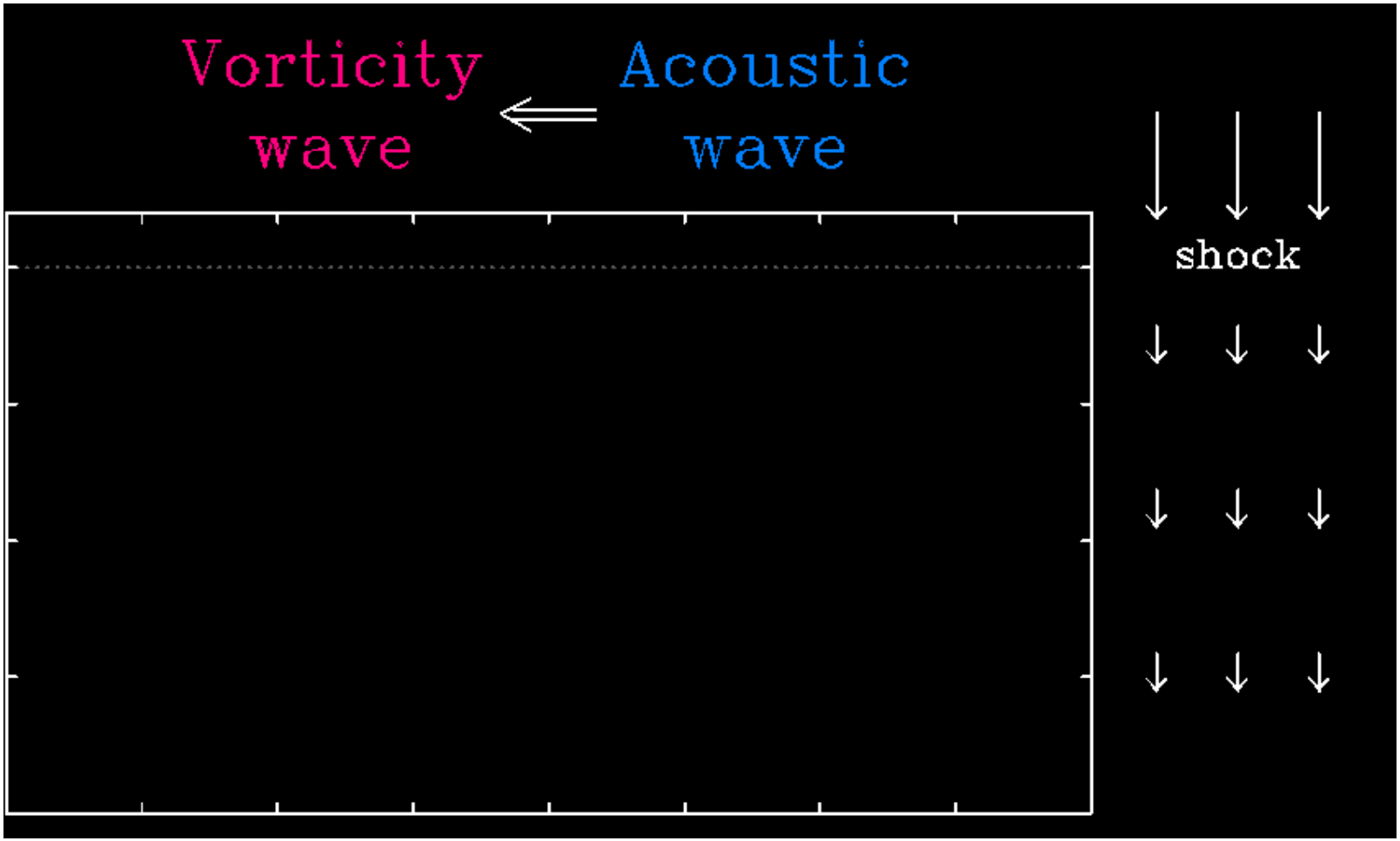
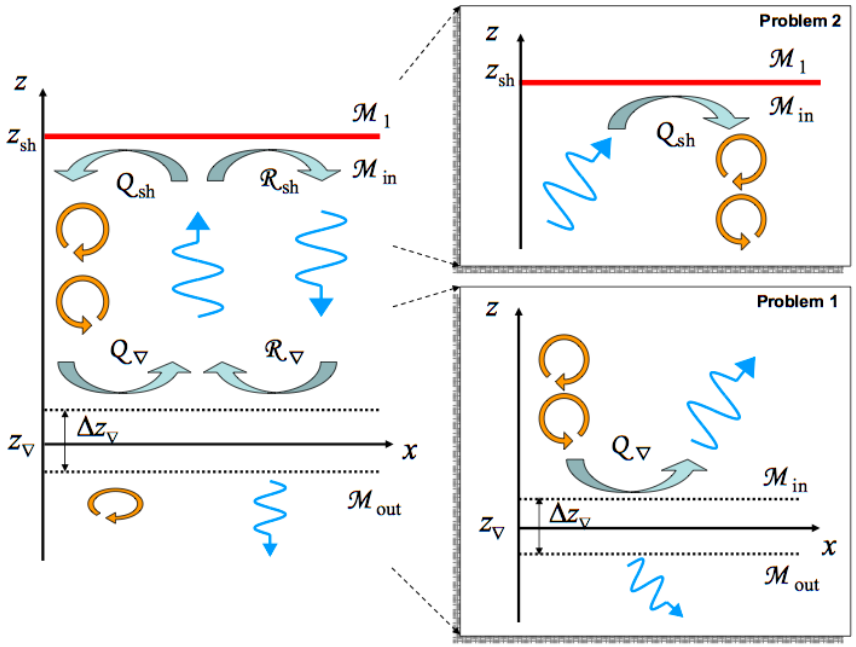
The simplest example of a 2D advective-acoustic cycle



Acoustic feedback generated by the deceleration of a vorticity wave (Sato, Foglizzo & Fromang 08)



Explicit analytical expressions for the coupling efficiencies (Foglizzo 08)



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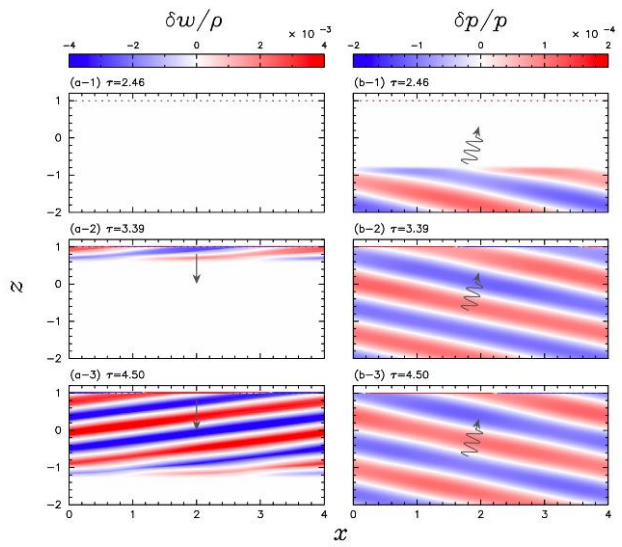
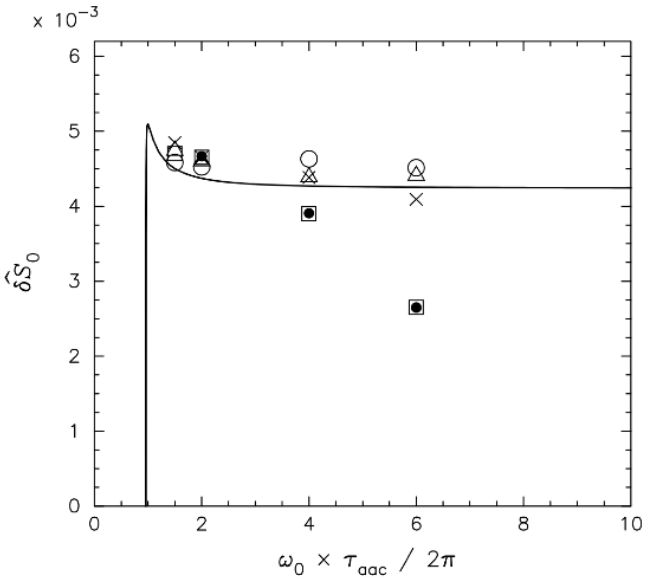
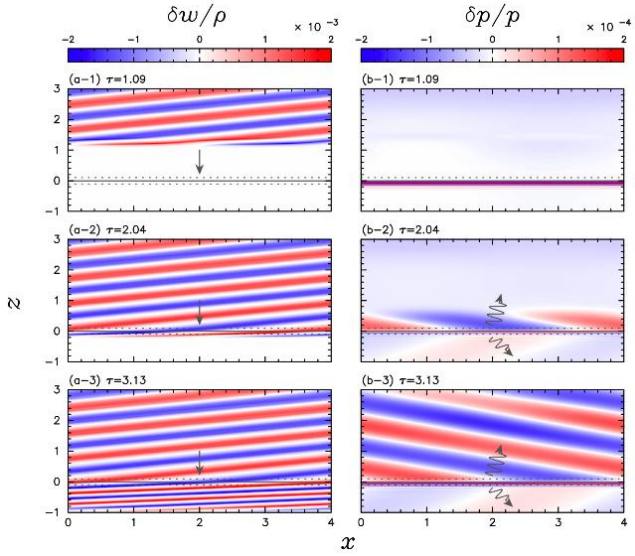
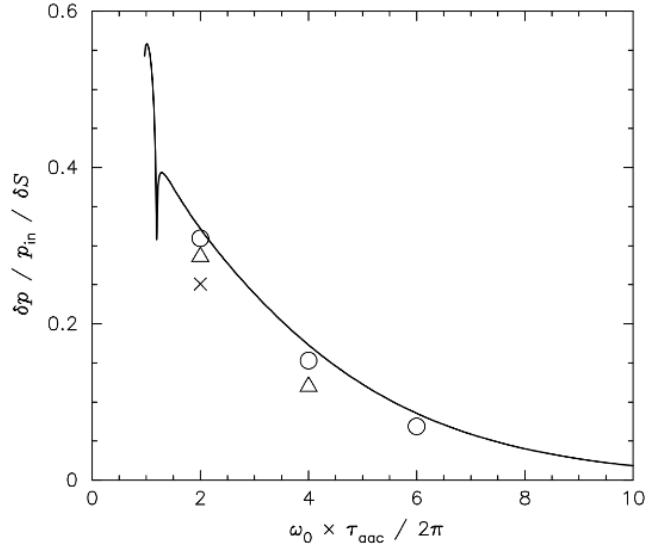
Numerical check of analytical formulae (Sato, Foglizzo & Fromang 08)

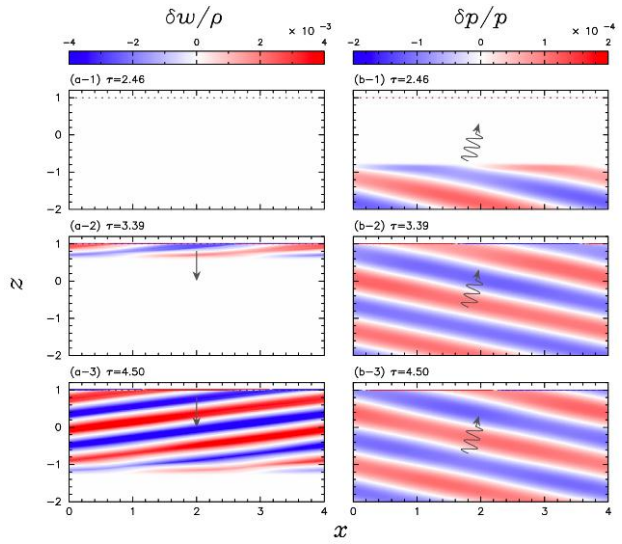


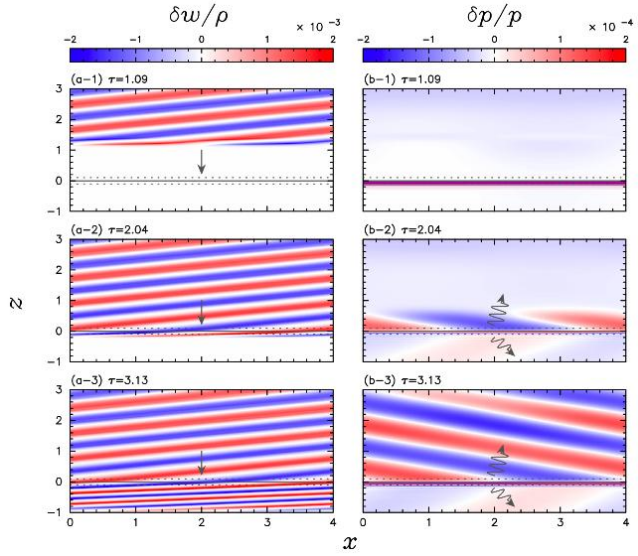


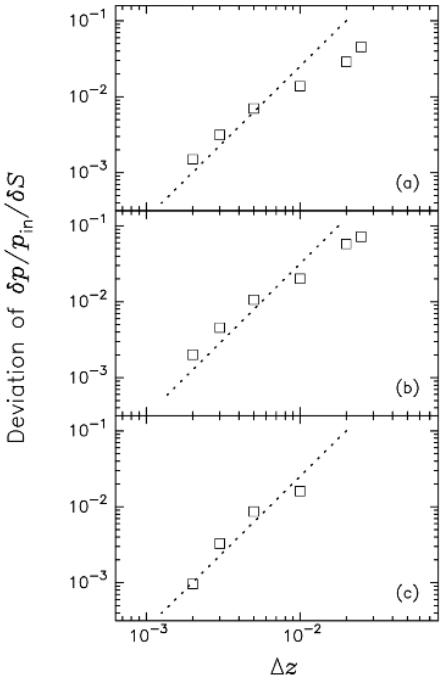


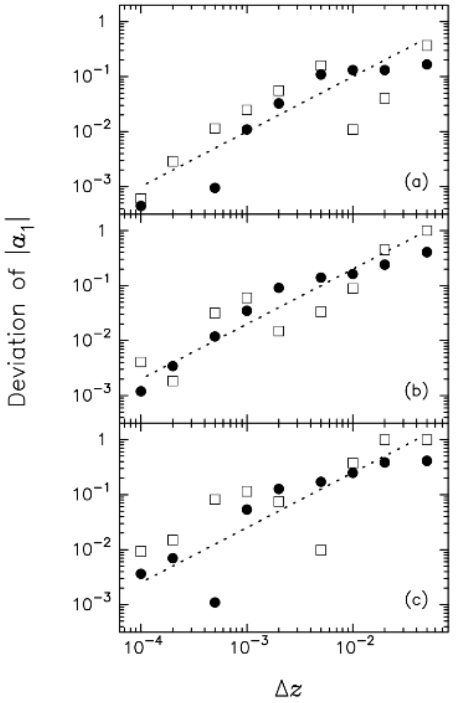


Numerical convergence: only linear at the shock (Sato, Foglizzo & Fromang 08)

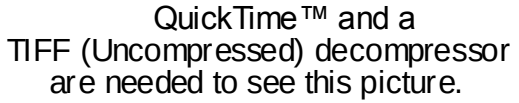


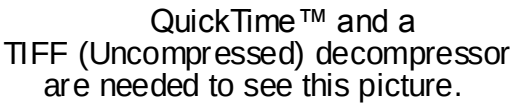


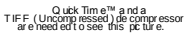




Understanding the efficiency of the acoustic feedback (Foglizzo 08)







-high frequency: stabilized above the cut off
-high l: evanescent pressure feedback

->SASI is a low frequency, low l instability

Effect of core rotation on SASI in a cylindrical flow (Yamasaki & Foglizzo 08)

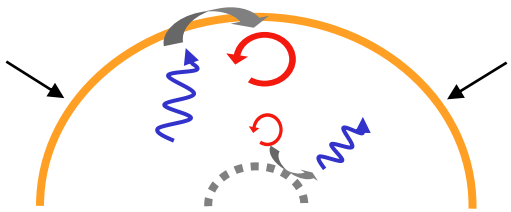
- Growth rate of the spiral mode

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

First order effect of rotation:
- negligible centrifugal force $\alpha\ \Omega^2$
-Doppler shifted frequency ω-mΩ

Domination of the spiral mode without rotation ???

- WKB interpretation



QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

Conclusions

SASI in 2D is able to produce
- a successful neutrino driven delayed explosion
- a powerful pulsar kick

The mechanism responsible for SASI is the advective-acoustic cycle
(the same family as the whistling kettle)

A toy model can explain why SASI is a low frequency, low l instability

A « moderate » progenitor rotation favours the spiral mode of SASI in 3D

Numerical difficulties associated to the
- lower boundary condition
- shock treatment/grid size

Some open questions

Numerical confirmation of 2D results: explosion, kick ?

How marginal is the spiral mode of SASI ? 3D

- -spiral mode even without core rotation ?
- -successful neutrino driven explosion in 3D ?
- -powerful kick in 3D ?
- -kick-spin misalignment ?

Towards a MHD SASI ?

Energy and momentum budget of SASI ?

More observational constraints ?