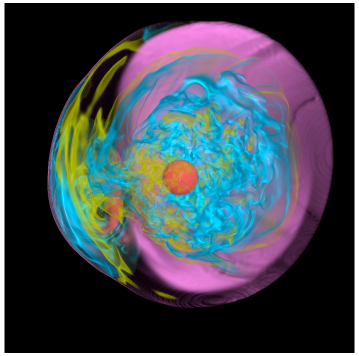
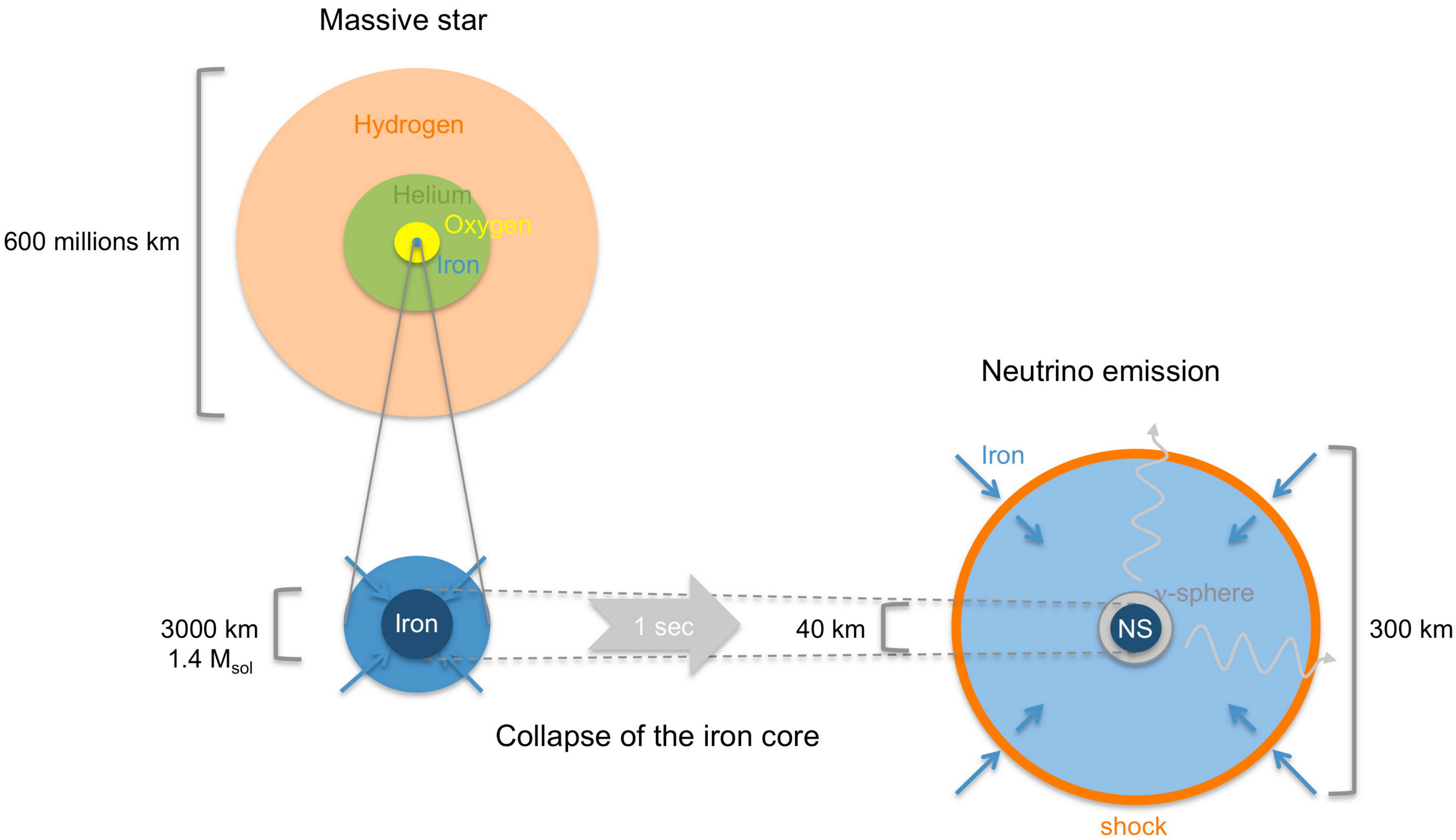
Asymmetric explosion of core-collapse supernovae



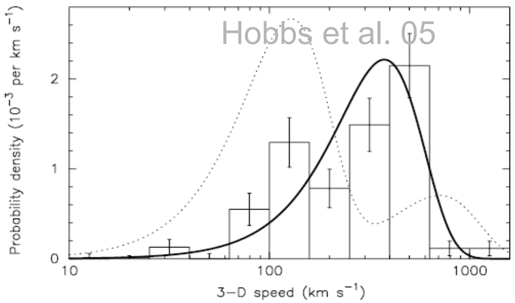
T. Foglizzo, CEA Saclay, France
J. Guilet, J. Sato, S. Fromang

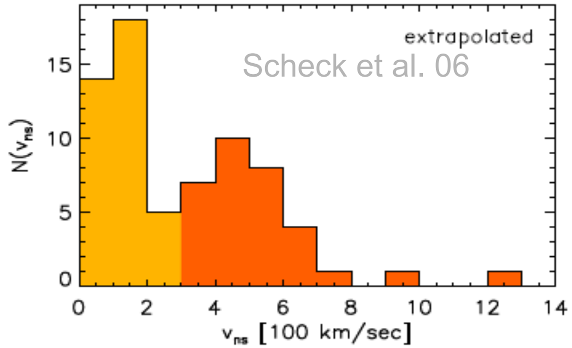
A very narrow window in space and time



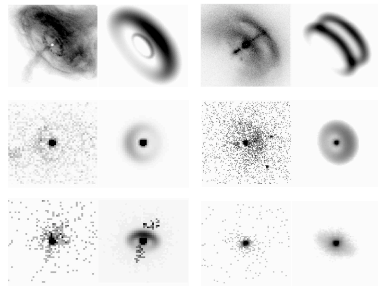
Observational constraints on the asymmetry of the explosion mechanism

Velocity distribution of pulsars





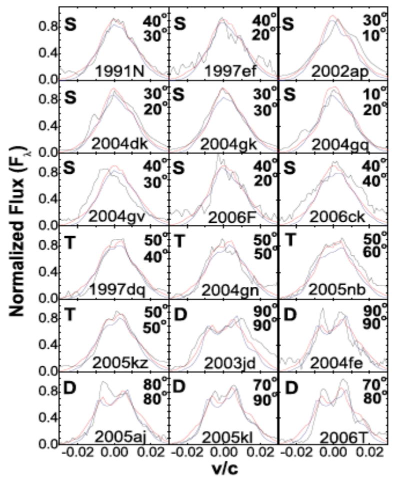
Kick-spin alignement (Wang, Lai & Han 06, Ng & Romani 04)



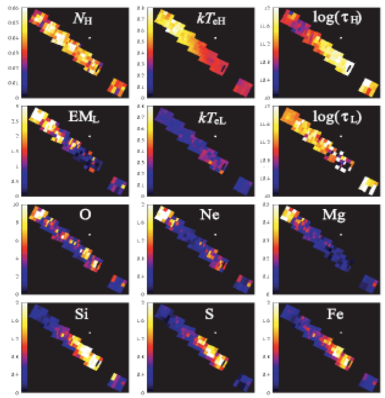
Explosion asymmetry deduced from

-spectropolarimetry (Leonard et al. 06, Wang et al. 03, ...)

-oxygen spectroscopy (Maeda et al. 08)



SNR composition gradients ? (Katsuda et al. 08)

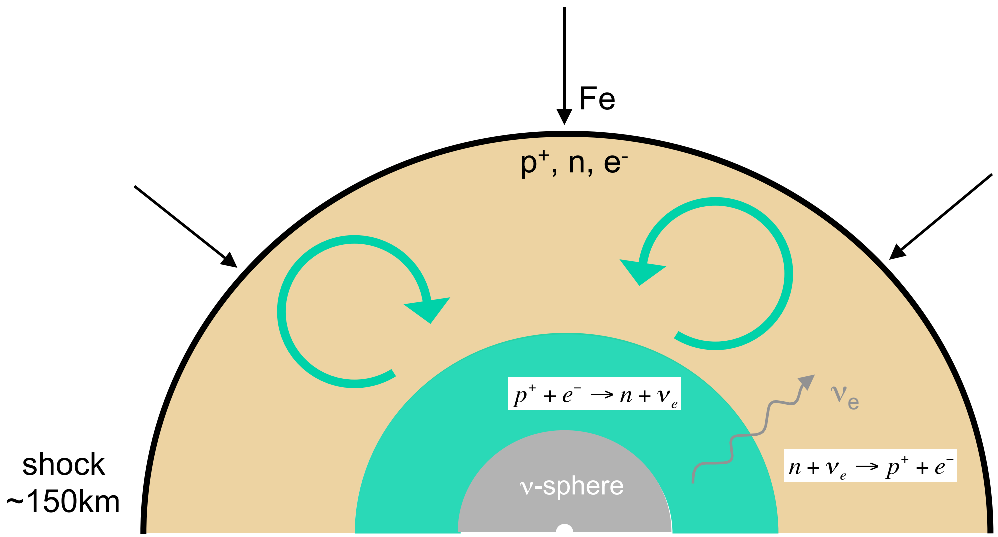


Outline

Core-collapse supernovae since 2003

What do we understand of SASI ?

From the kettle to supernovae

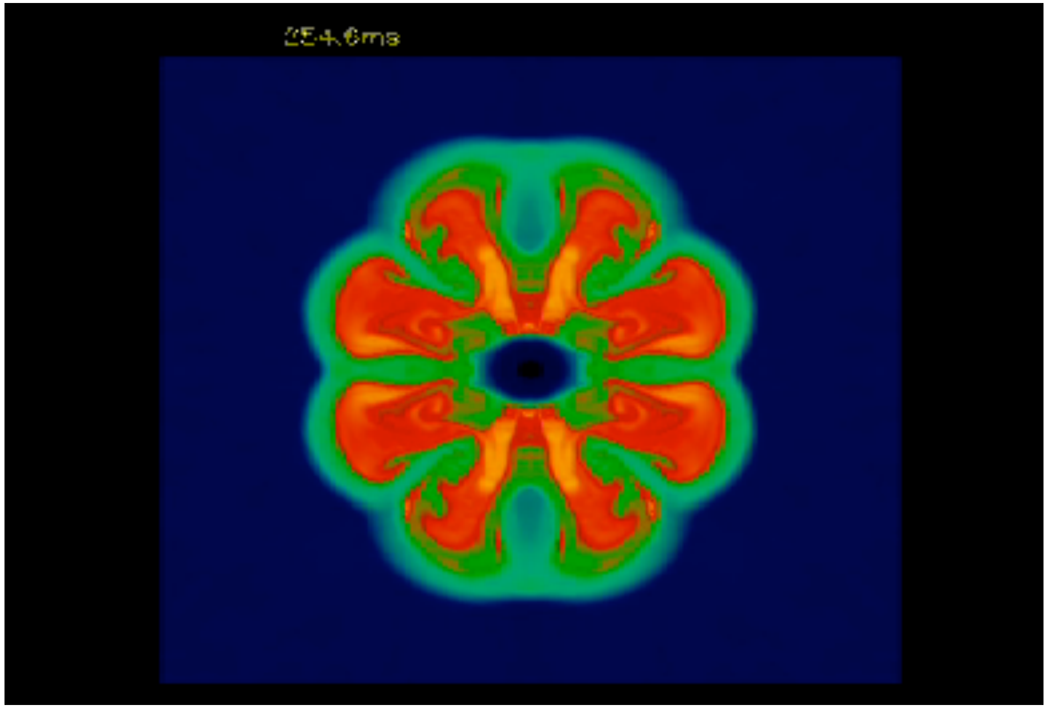


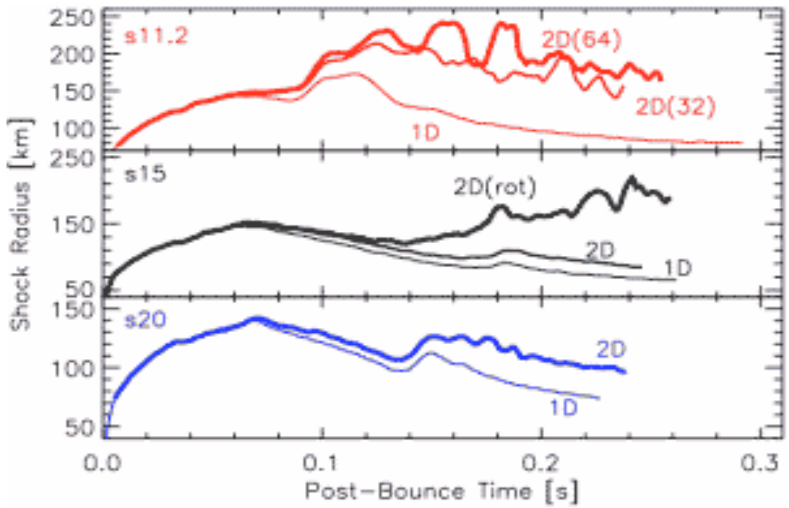
Core collapse in 2003: « What was missing? »

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

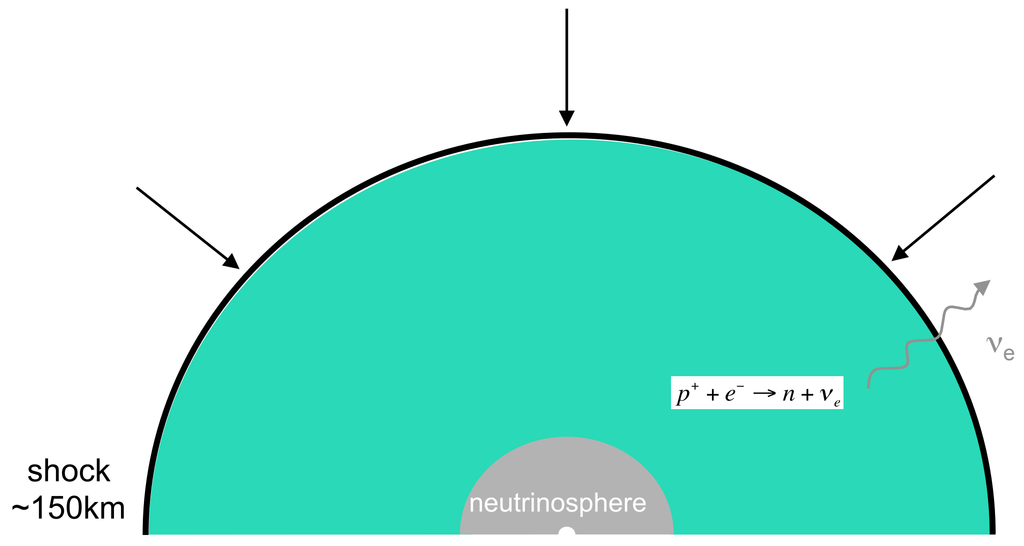


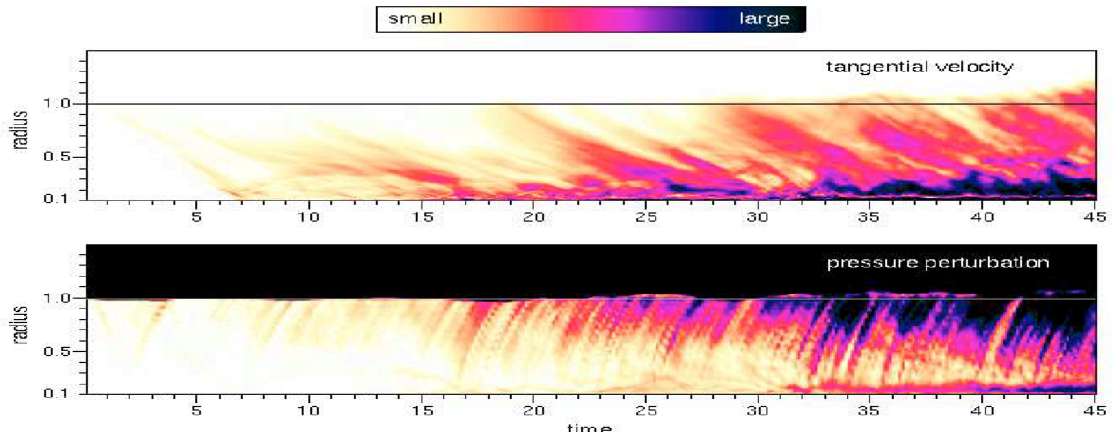


Buras et al. 03

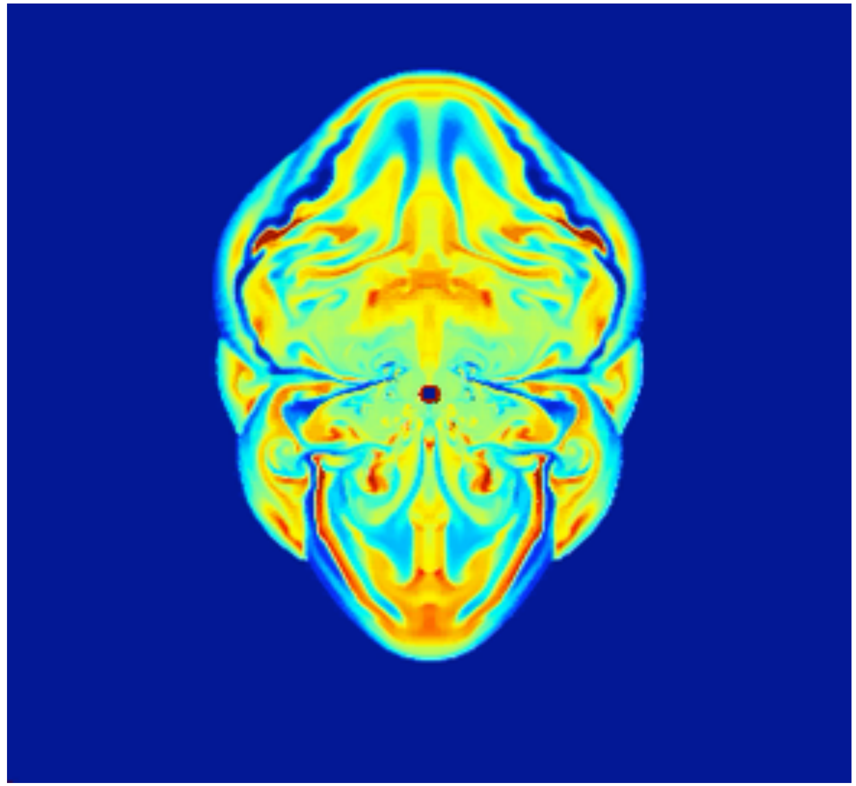
- 90° wedge
- computer time

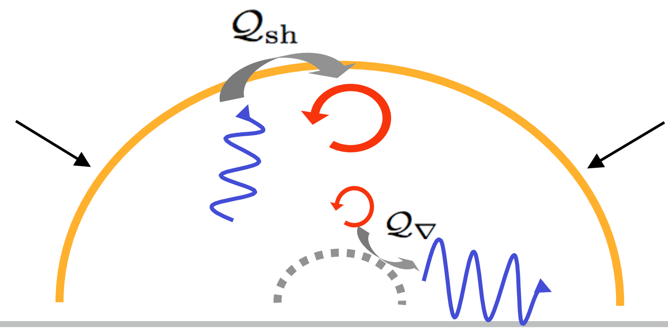
Stationary Accretion Shock Instability : SASI





Blondin et al. 03





Mechanism of SASI: advective-acoustic cycle ?

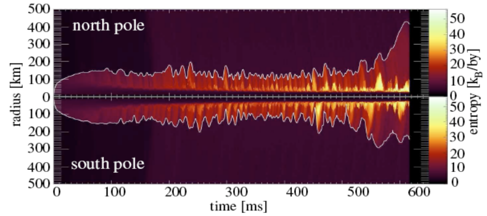
(Foglizzo 2002, Galletti 05, Foglizzo et al. 07)

Numerical simulations: SASI has been ubiquitous since 2003

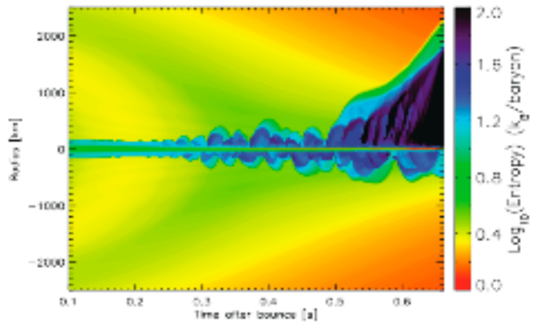
		initial	sym.	SASI	ν-heat
2003	Blondin et al.	stalled	2D axi.	X	-
2004	Scheck et al.	15 M_o	2D axi.	X	X
2006	Scheck et al.	15 M_o	2D axi.	X	X
	Burrows et al.	11 M_o	2D axi.	X	X
	Ohnishi et al.	stalled	2D axi.	X	X
	Blondin & Mezzacappa	stalled	2D axi.	X	-
2007	Blondin & Mezzacappa	stalled	3D	spiral	-
	Kotake et al.	stalled	2D axi.	X	X
	Burrows et al.	11-25 M_o	2D axi.	X	X
	Blondin & Shaw	stalled	2D eq.	spiral	-
	Fryer & Young	23 M_o	3D	X	X
2008	Scheck et al.	15 M_o	2D axi.	X	X
	Iwakami et al.	stalled	3D	X	X
	Murphy & Burrows	11.2 & 15 M_o	2D axi.	X	X
	Ott et al.	20 M_o	2D axi.	X	X
2009	Marek & Janka	11.2 & 15 M_o	2D axi.	X	X
	Iwakami et al.	stalled	3D	spiral ?	X
	Fernandez & Thompson	stalled	2D axi.	X	-
	Fernandez & Thompson	stalled	2D axi.	X	X
	Murphy et al.	12-40 M_o	2D axi.	X	X
2010	Endeve et al.	stalled	2D axi.	MHD	-
	Suwa et al.	13 M_o	2D axi.	X	X
	Fernandez	stalled	3D	spiral	-

The unexpected possible consequences of SASI

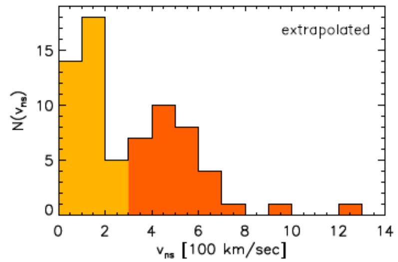
- successful explosion driven by neutrino energy
  15M_{sol} (Marek & Janka 09)



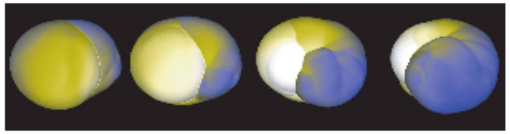
- new explosion mechanism driven by acoustic energy
  11-25M_{sol} (Burrows et al. 06, 07, but Weinberg & Quataert 08)



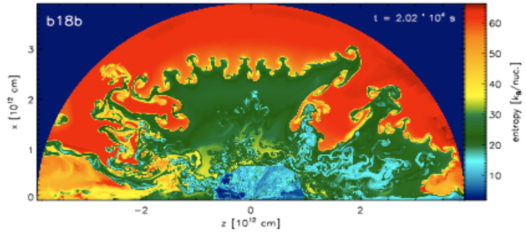
- pulsar kick (Scheck et al. 04, 06)



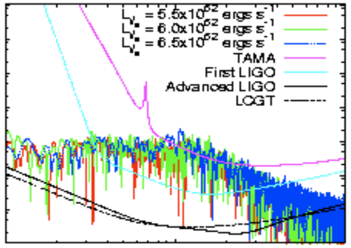
- pulsar spin (Blondin & Mezzacappa 07)



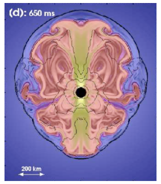
- H/He mixing in SN1987A
  (Kifonidis et al. 06, Hammer et al. 09)



- gravitational waves
  (Ott et al. 06, Kotake et al. 07, Marek et al. 09, Ott 08, Murphy et al. 09)

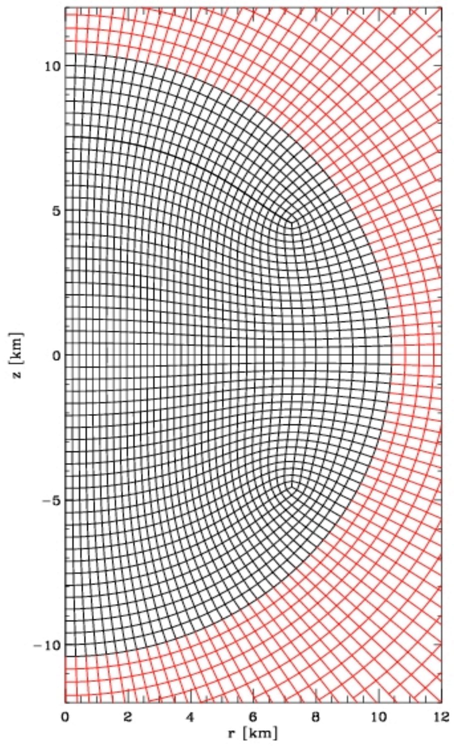


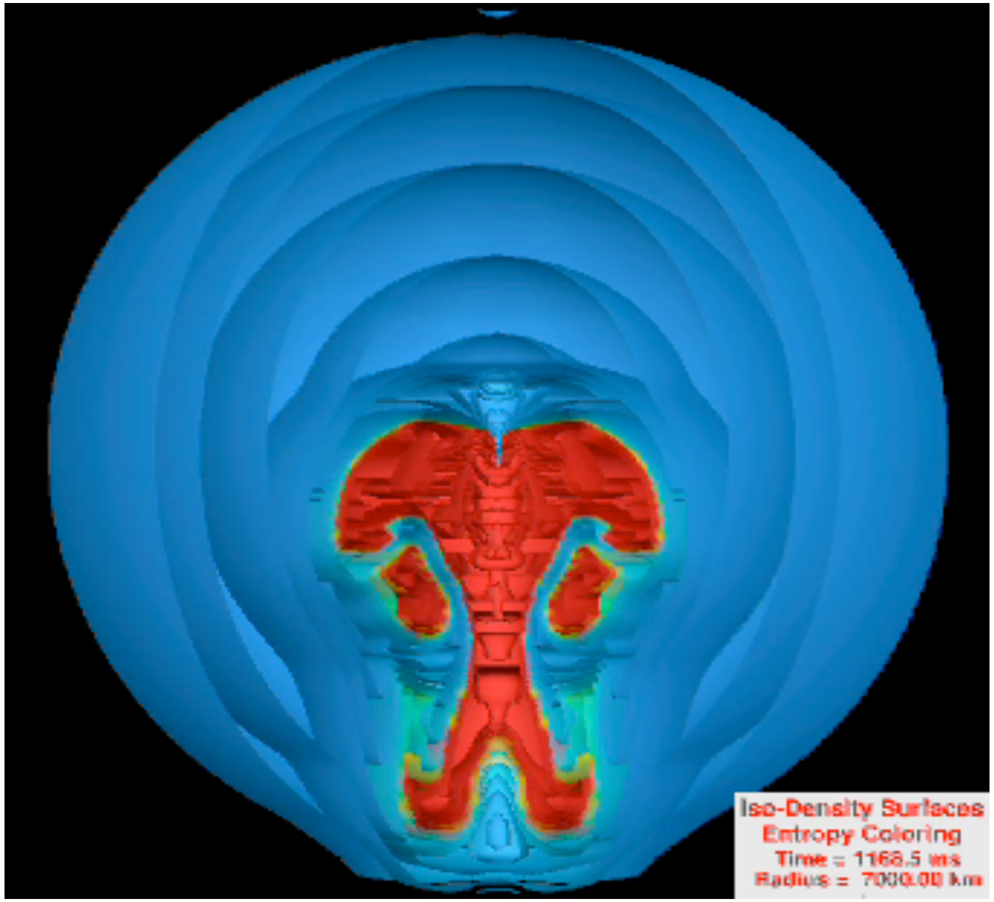
- magnetic field amplification ?
  (Endeve et al. 2008)



A new explosion mechanism based on acoustic energy

Burrows et al. 06, 07





SASI

↓

g modes

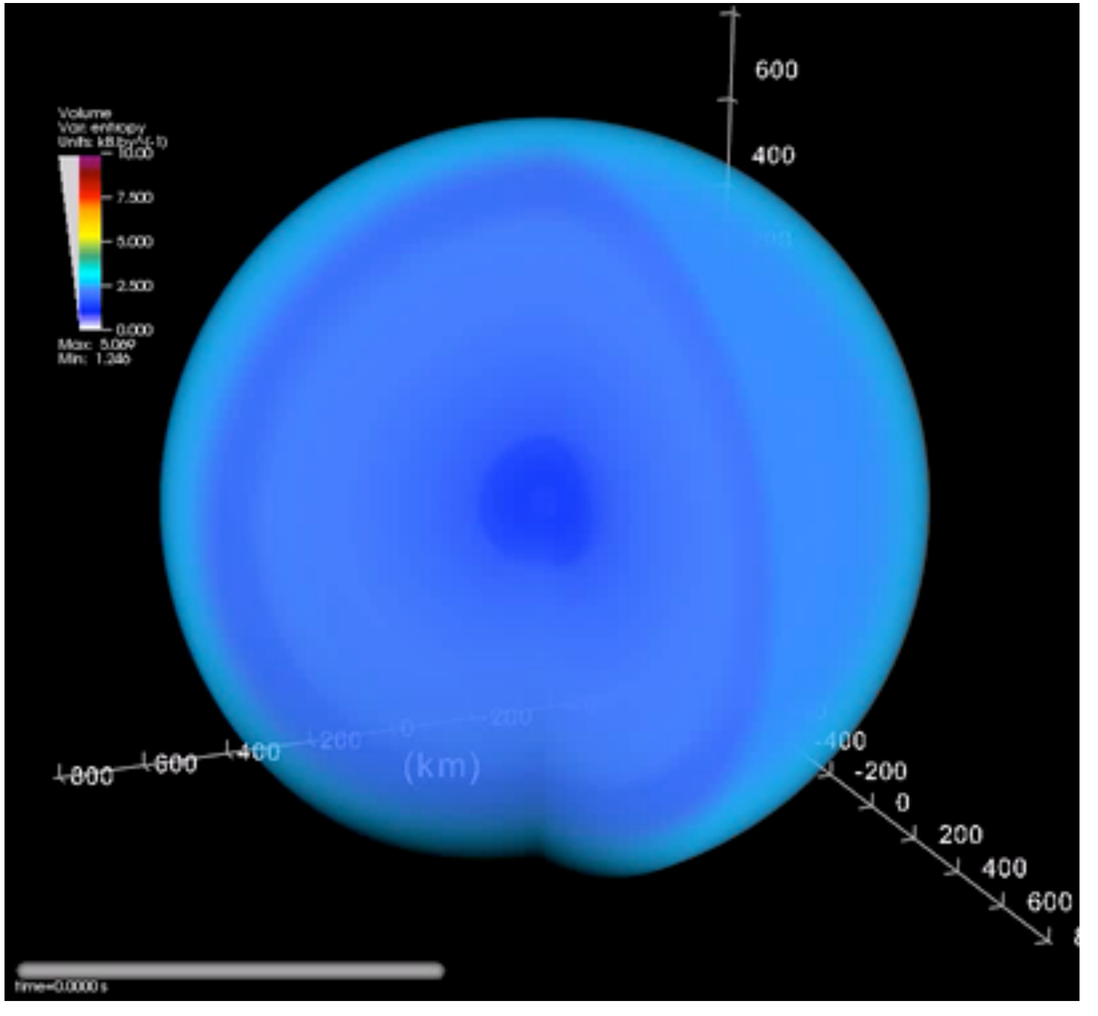
↓

acoustic emission

→ unresolved nonlinear mode coupling (Weinberg & Quataert 08)

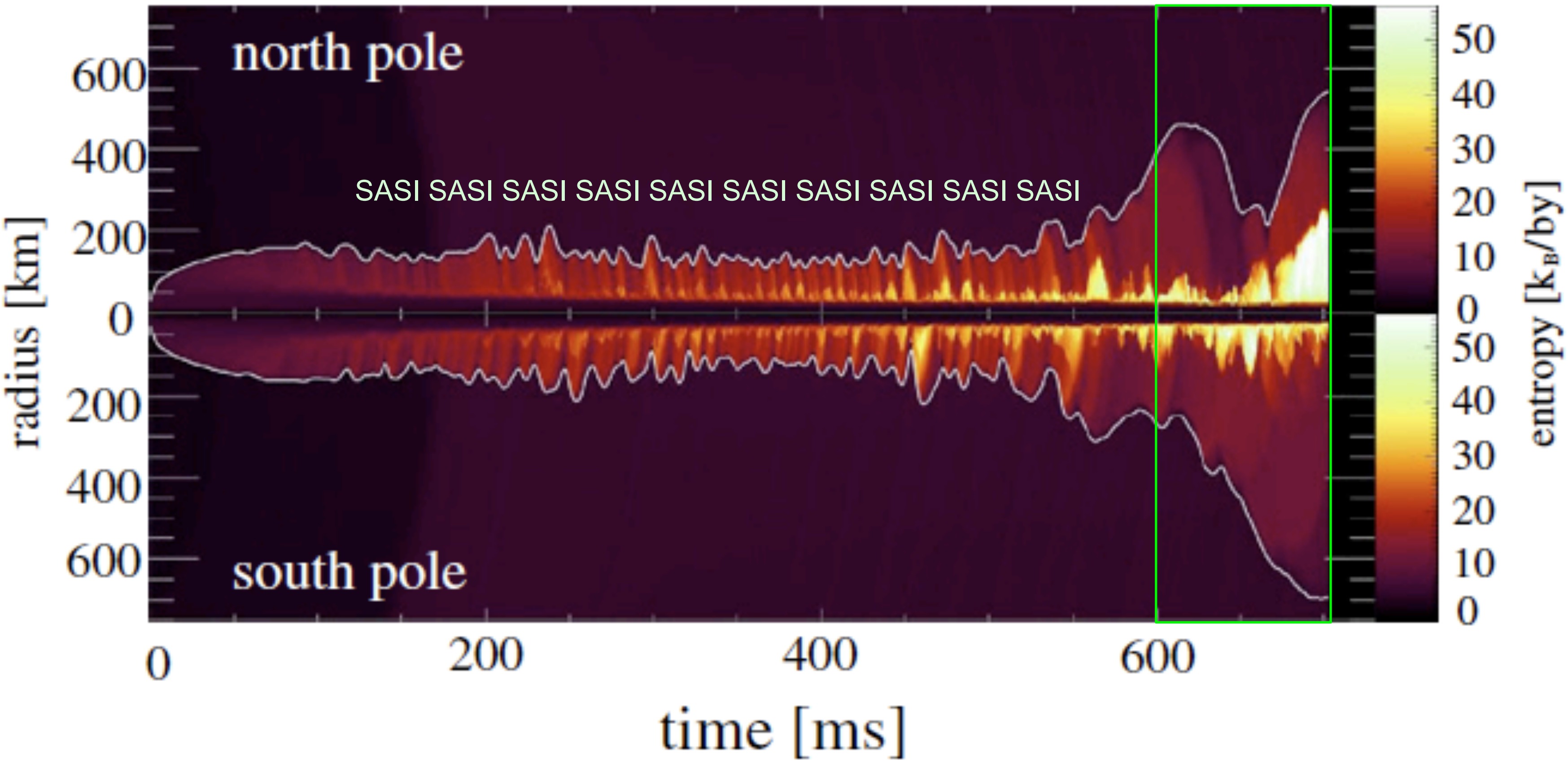
Classical explosion mechanism based on neutrino energy aided by 2D hydrodynamical instabilities

Marek & Janka 09



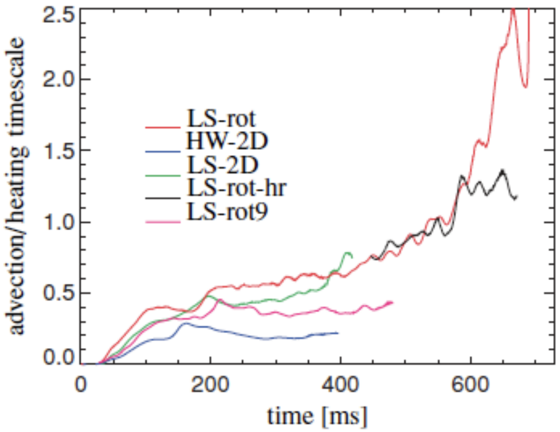
Classical explosion mechanism based on neutrino energy aided by 2D hydrodynamical instabilities

Marek & Janka 09

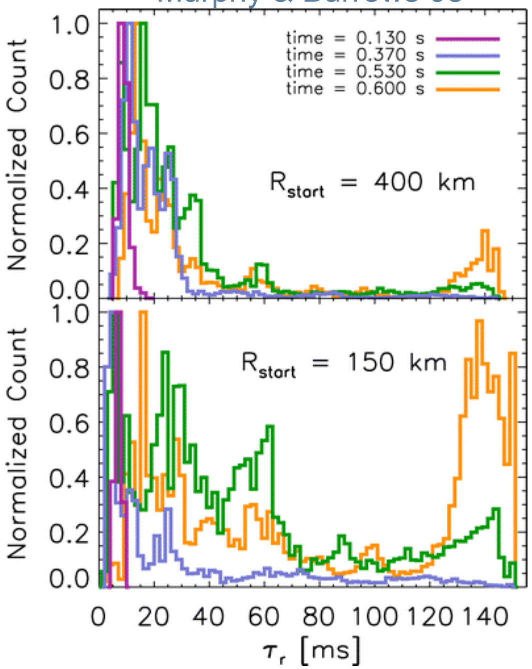


How does SASI help the neutrino-driven explosion ?

Marek & Janka 09



Murphy & Burrows 08



Marek & Janka 09
Murphy & Burrows 08
Fernandez & Thompson 09

non radial motions induced by SASI and convection

→ longer advection time

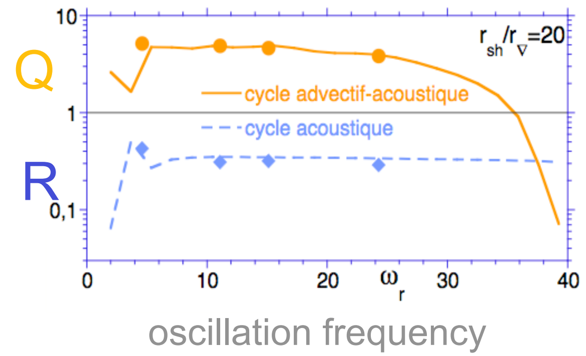
→ longer exposure time to the neutrino flux

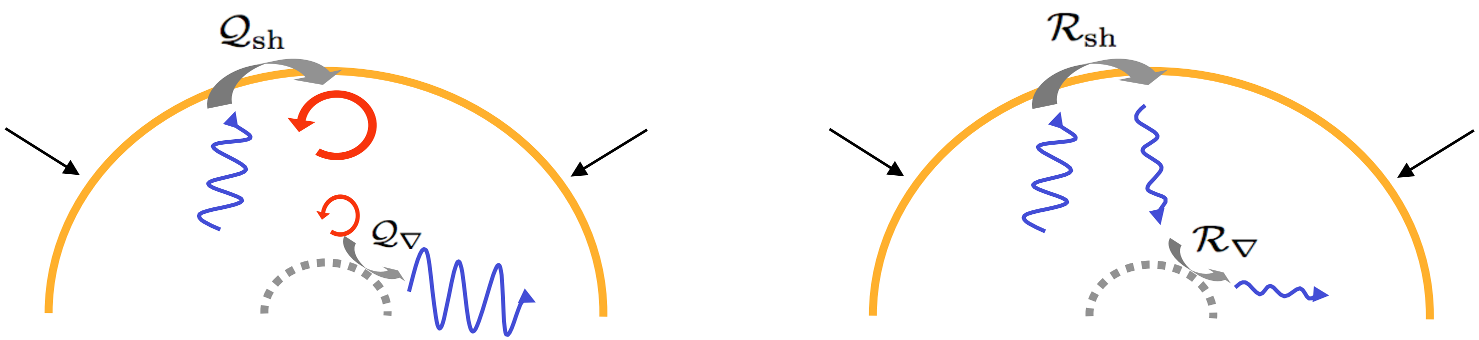
also,
- increased shock radius → larger gain region
- production of entropy gradients → seeds convection

but,
- predictive criterion for a successful explosion ?
(equation of state ? 3D ?)

What is the mechanism at work behind SASI ?

- **Growing evidence for the advective-acoustic mechanism**
  - cycle efficiency of the cycles, wkb (Foglizzo et al. 07)
  - timescales in simulations (Scheck et al. 08)
  - timescale of the dominant mode (Fernandez & Thompson 09)



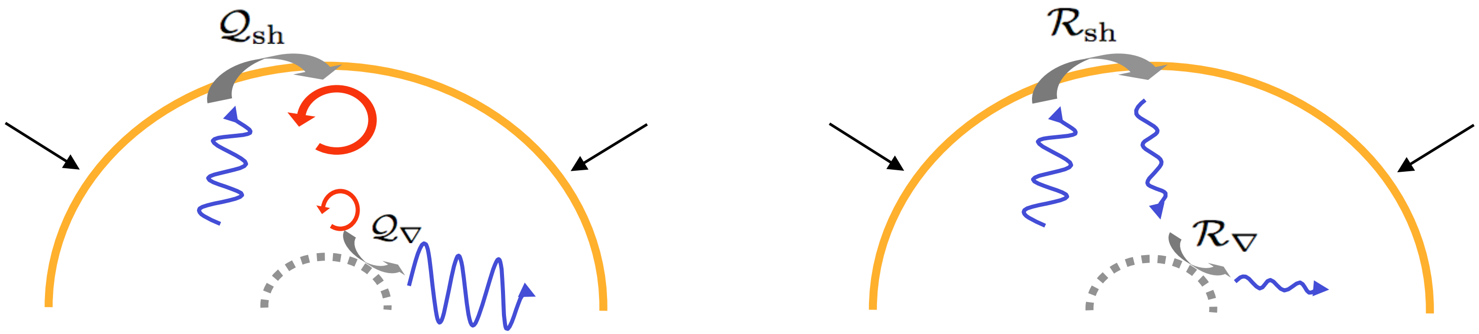


Why bother about the mechanism of SASI ?

- Knowing the mechanism → optimal grid size in simulations ? (Sato et al. 09)

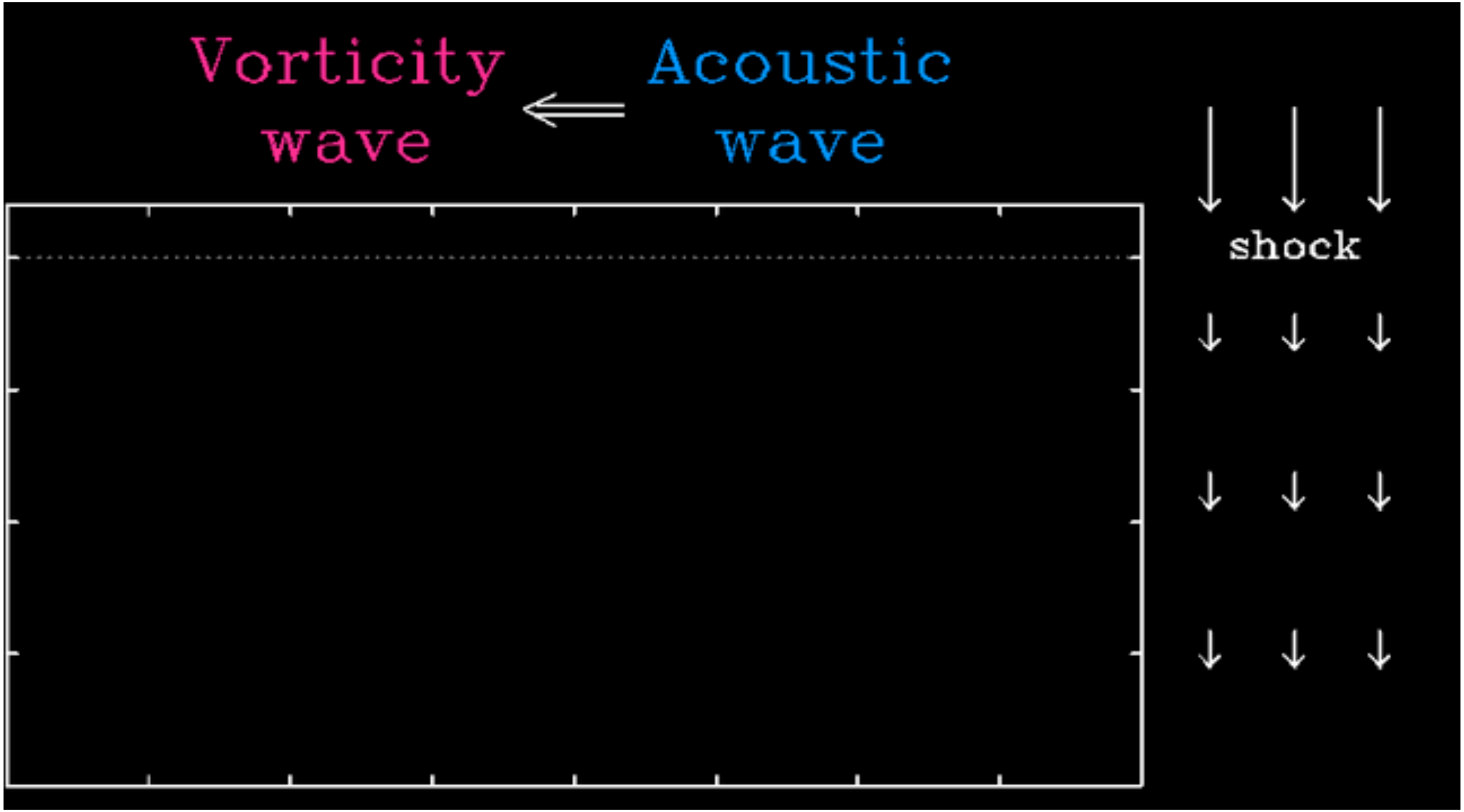
→ why is SASI a low l=1,2, low frequency instability ? (Foglizzo 09)

→ which saturation amplitude ? (Guilet et al. 09)



Linear coupling between the acoustic wave and the entropy/vorticity wave

(Sato, Foglizzo & Fromang 09)

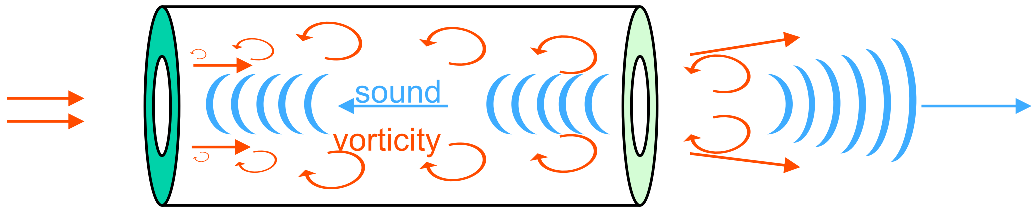


Aero-acoustic instabilities

- advected perturbations
- acoustic feedback

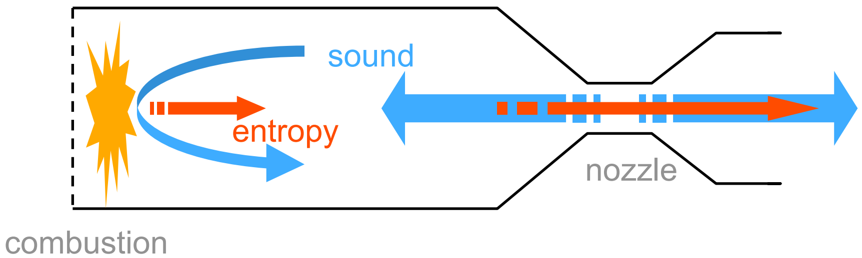
whistling kettle
Chanaud & Powell (1965)

- vortical-acoustic cycle



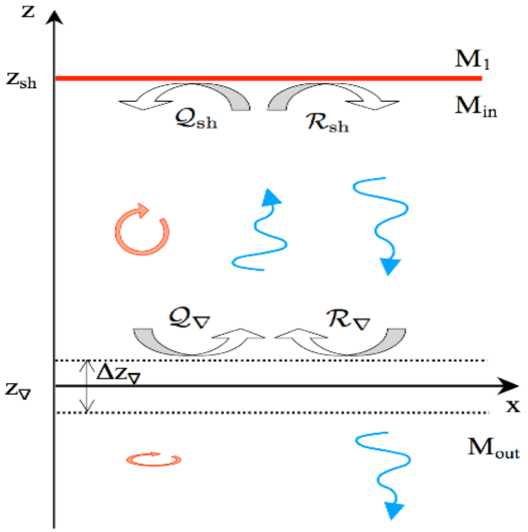
vibrations in Ariane 5
Mettenleiter, Haile & Candel (2000)

- entropic-acoustic cycle

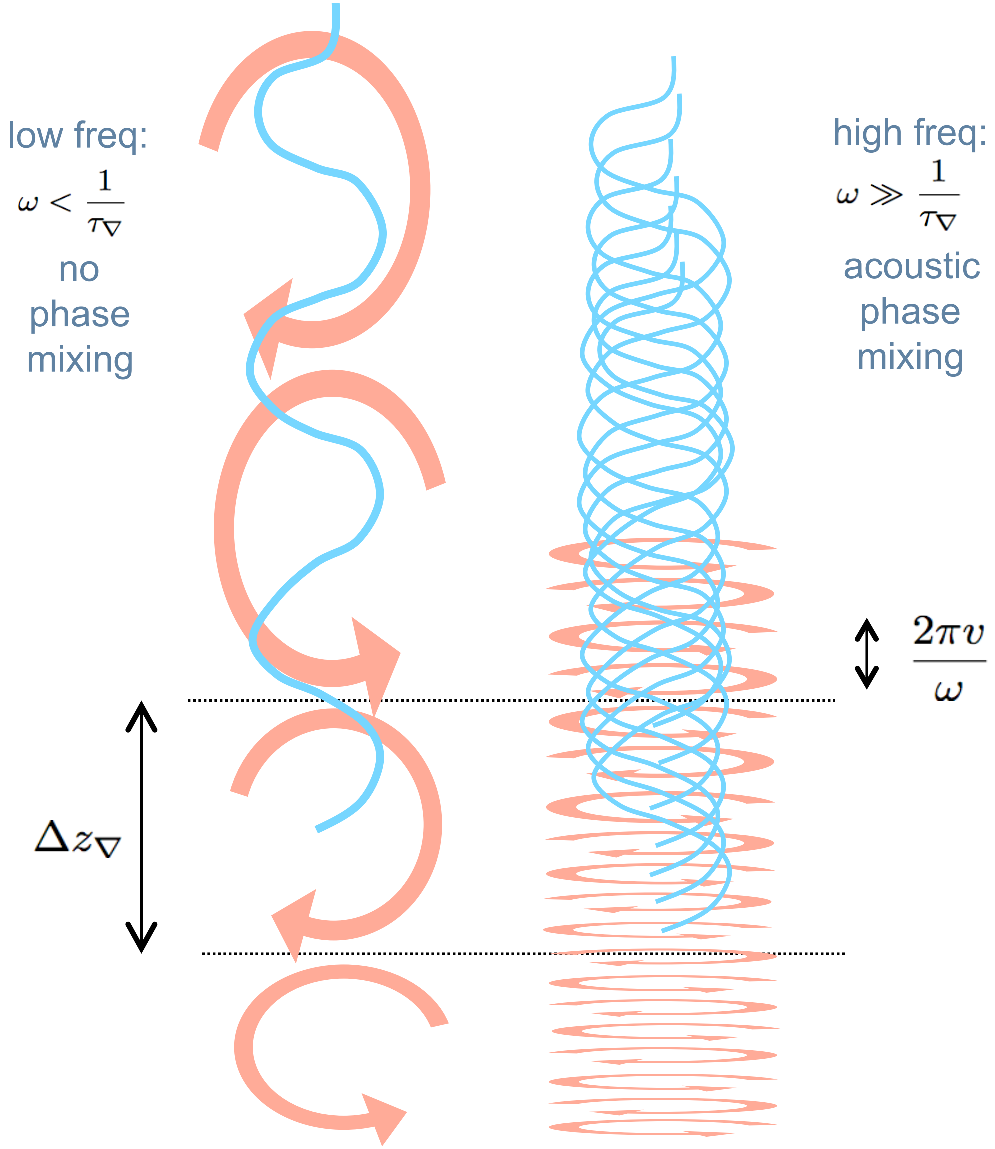


rumble instability of ramjets
Abouseif, Keklak & Toong (1984)

Why is SASI a low frequency instability ? (Foglizzo 09)



$$\tau_\nabla \sim \frac{\Delta z_\nabla}{v}$$

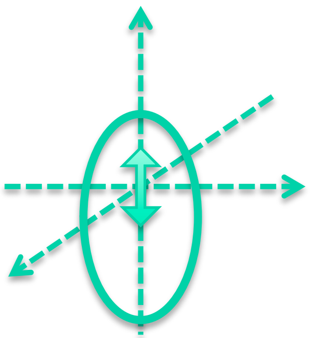


$$\mathcal{Q}_\nabla = \int_{bc}^{sh} b_0 \frac{\delta p_0}{p} e^{\int_{sh} \frac{i\omega}{v} dz} \frac{\partial b_\nabla}{\partial z} dz,$$

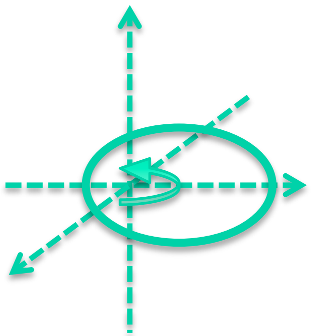
where

$$b_0 \equiv \frac{1}{2}\left(1 + \frac{k_x^2 v_{sh}^2}{\omega^2}\right)\left(1 - \mathcal{R}_\nabla - \frac{1+\mathcal{R}_\nabla}{\mu_{sh}\mathcal{M}_{sh}}\right)$$
$$\frac{1-\mathcal{M}^2}{1-\mathcal{M}_{sh}^2}\frac{\mathcal{M}_{sh}^2}{\mathcal{M}^2}\left(\frac{\delta p_0}{p}\right)_{sh}^{-1} e^{-\int_{sh}\frac{i\omega}{c}\frac{2\mathcal{M}}{1-\mathcal{M}^2}dz},$$
$$b_\nabla \equiv \frac{i\omega}{c_{sh}^2}\frac{i\omega - 2v\frac{\partial \log \mathcal{M}}{\partial z}}{k_x^2\mathcal{M}^2 + \frac{\omega^2}{c^2} - v\mathcal{M}^2\frac{\partial}{\partial z}\frac{i\omega}{v^2}}.$$

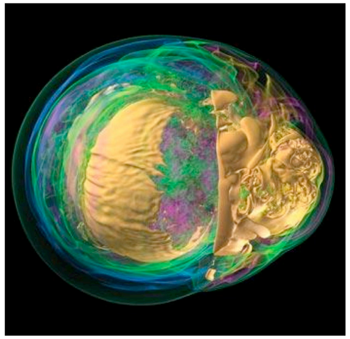
3D effects on SASI evolution



sloshing SASI mode
l=1, m=0

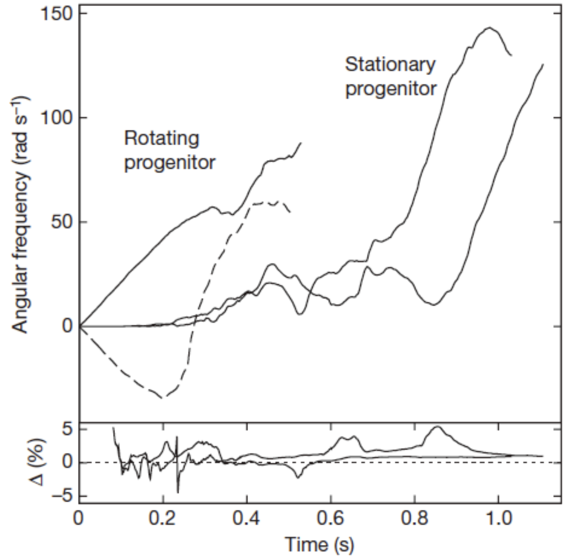


spiral SASI mode
l=1, m=±1

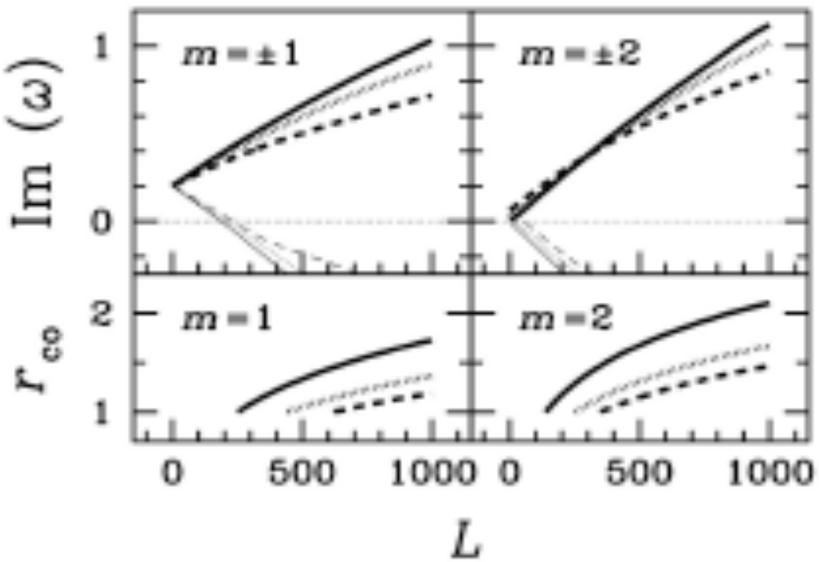


Nature 09

Blondin & Mezzacappa 07



Yamasaki & Foglizzo 08



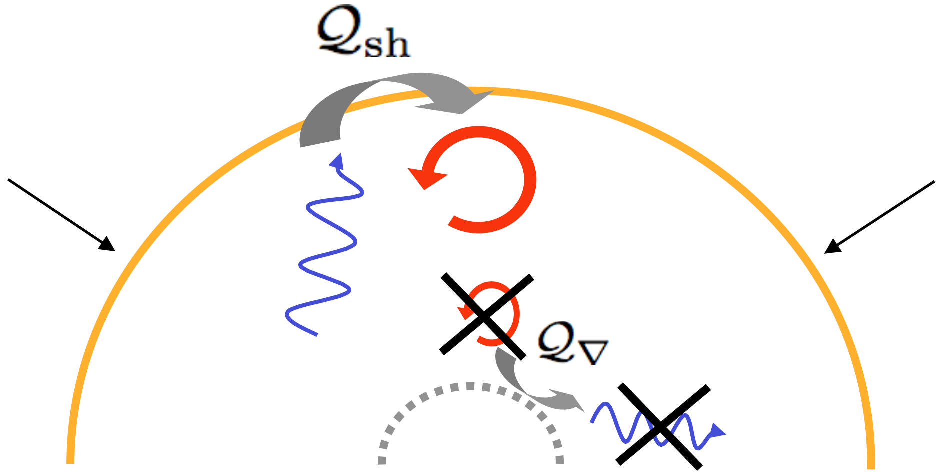
First order effect of rotation:

- negligible centrifugal force $\alpha\ \Omega^2$
- Doppler shifted frequency ω-mΩ

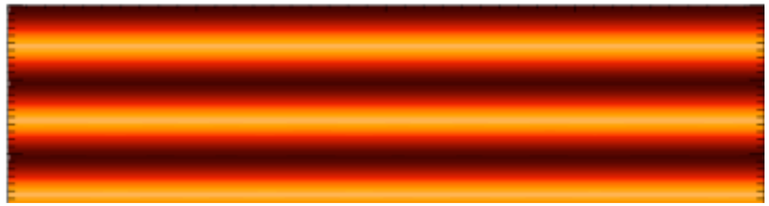
Dominant spiral mode when the core is rotating
(Iwakami et al. 08, 09)

Can the spiral mode dominate even for slow rotators ?

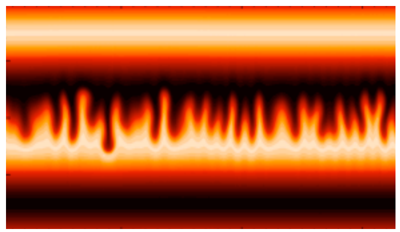
The saturation of SASI by parasitic instabilities



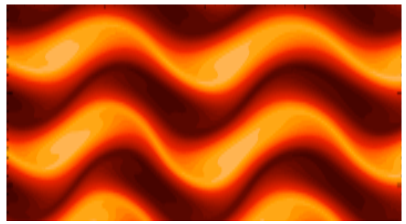
entropy-vorticity wave

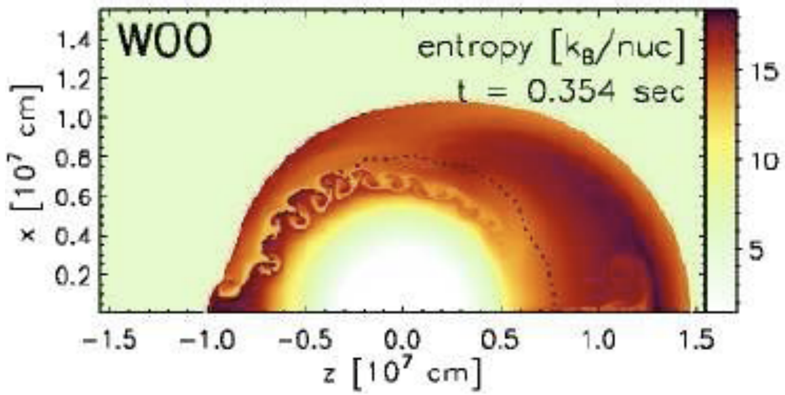


Rayleigh-Taylor



Kelvin-Helmhotz

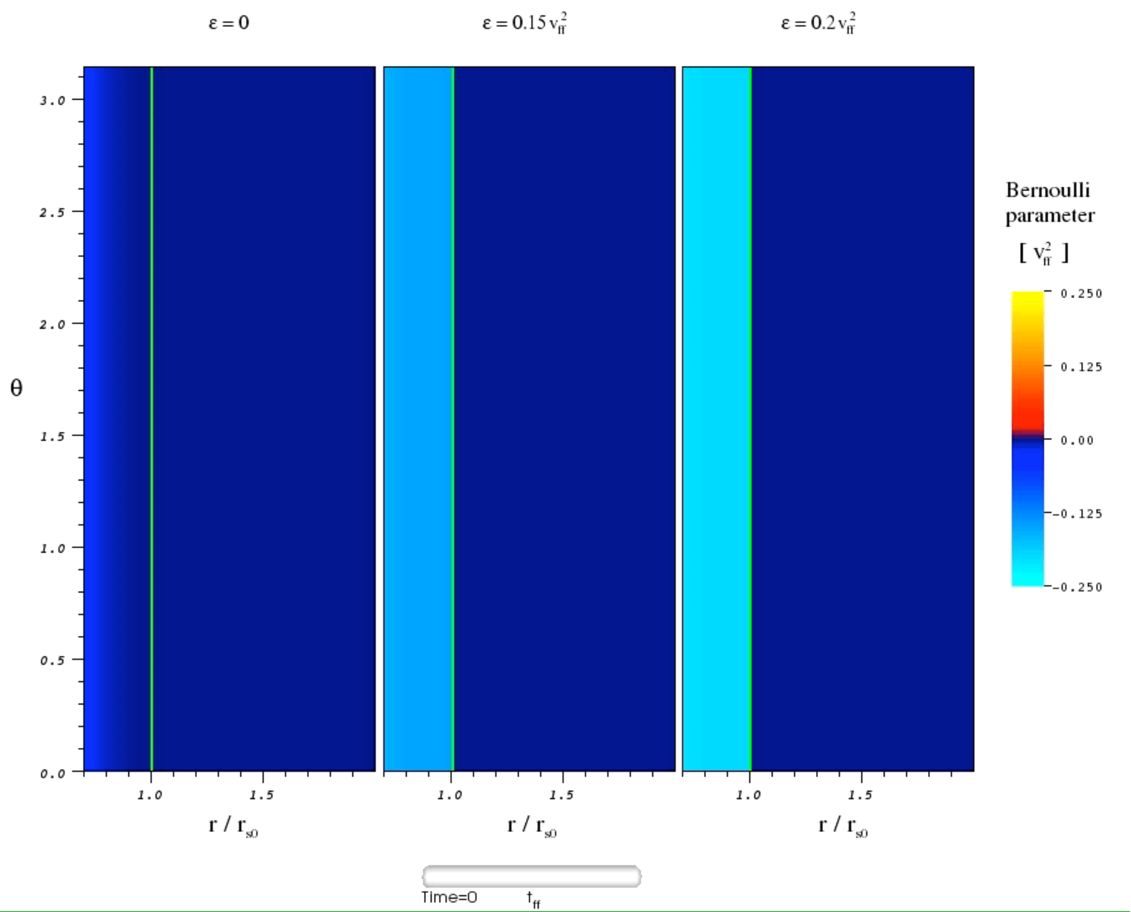


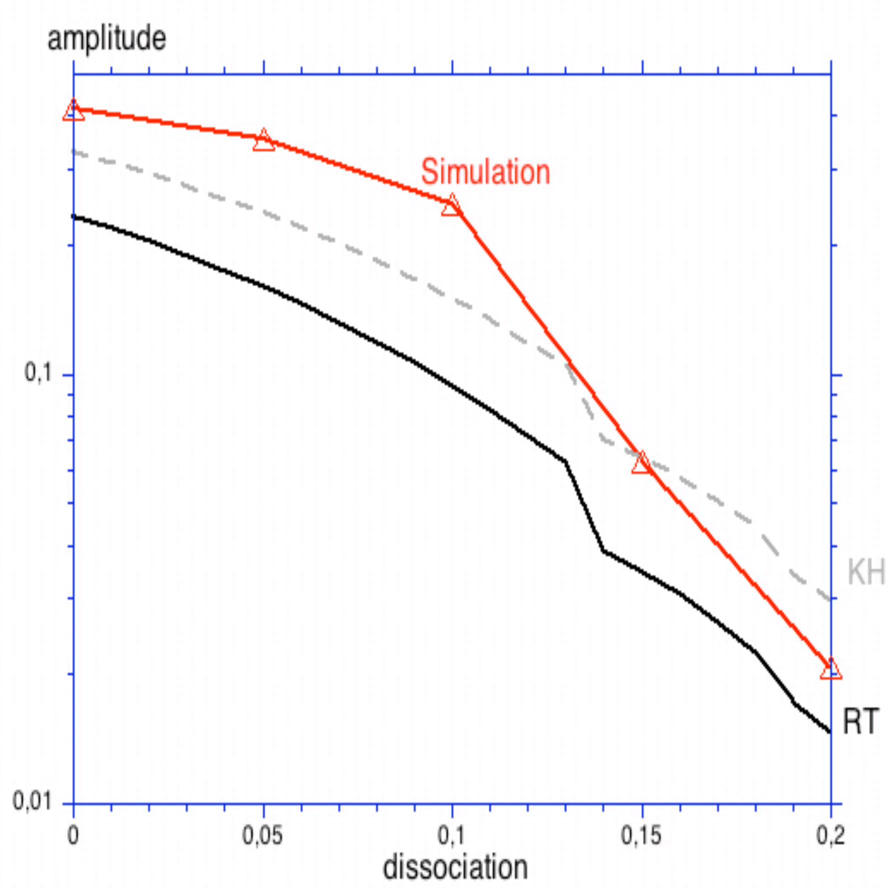


stabilisation if the local parasitic instabilities
- propagate against the flow
- their effective growth rate exceed the SASI growth rate

Comparison with numerical simulations

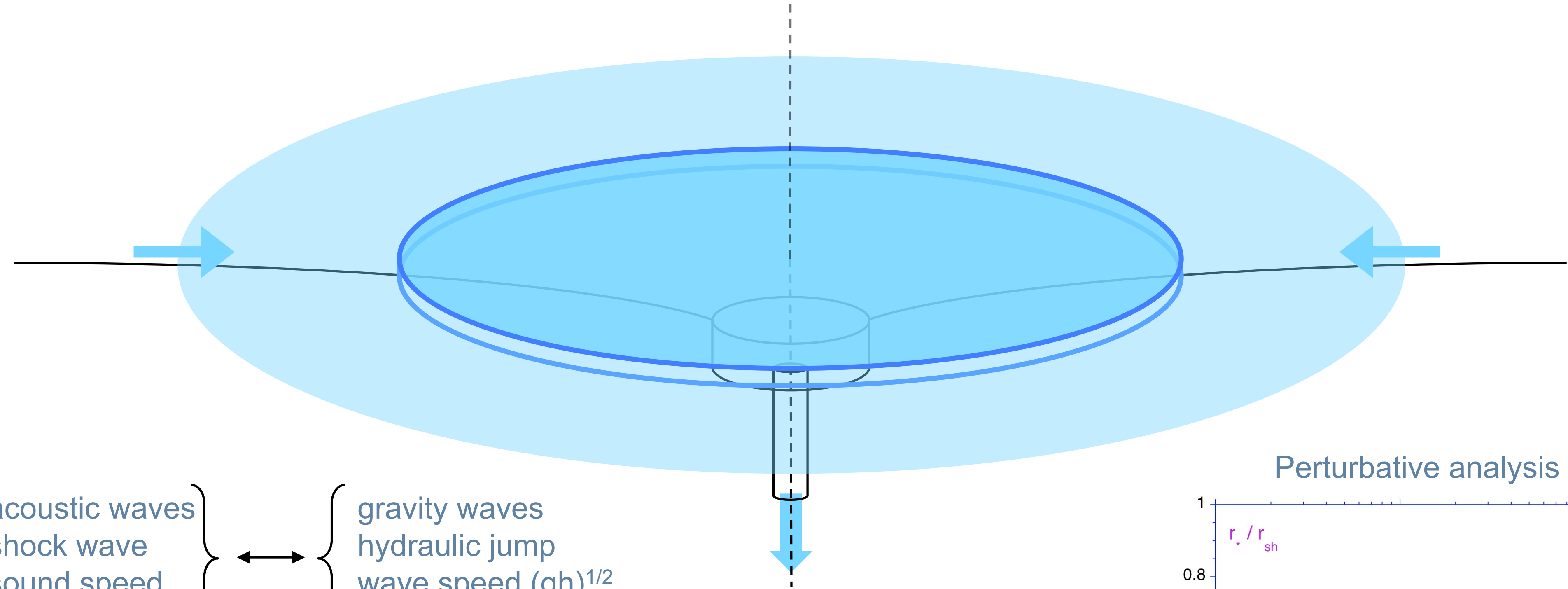
Fernandez & Thompson 09 (no heating)





interaction with ν-driven convection ?

A shallow water SASI experiment: Lab. Astro. at low cost ?



acoustic waves
shock wave
sound speed
Mach number

↔

gravity waves
hydraulic jump
wave speed $(gh)^{1/2}$
Froude number

St Venant approximation

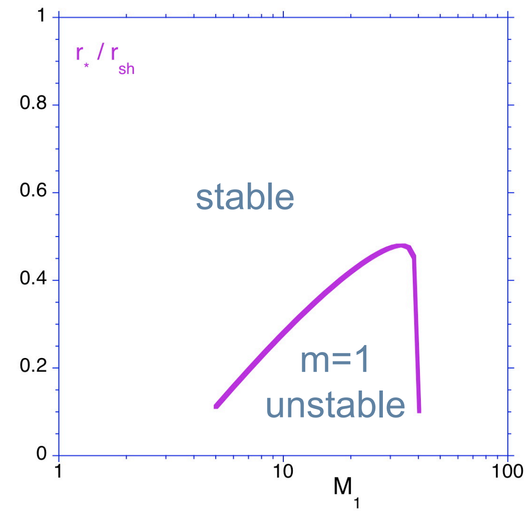
$$\Phi = gz$$
$$c^2 = gh$$

$$\frac{\partial v}{\partial t} + w \times v + \nabla\left(\frac{v^2}{2} + c^2 + \Phi\right) = 0$$
$$\frac{\partial h}{\partial t} + \nabla \cdot (hv) = 0$$

Vorticity-driven advective-acoustic instability

+ energy and angular momentum budgets ?
+ destabilizing effect of rotation ?
+ spiral mode ?
+ non linear saturation ?

Perturbative analysis



Conclusion

Potential consequences of SASI are numerous:

- neutrino driven explosion
- acoustic explosion
- NS kick
- NS spin
- mixing
- grav. waves
- magnetic field

Still large uncertainties concerning 3D & EOS

Understanding SASI can be helpful:

- perturbative analysis: code accuracy, mechanism
- toy model: SASI properties
- first insight into non linear saturation
- SASI experiment in shallow water ?