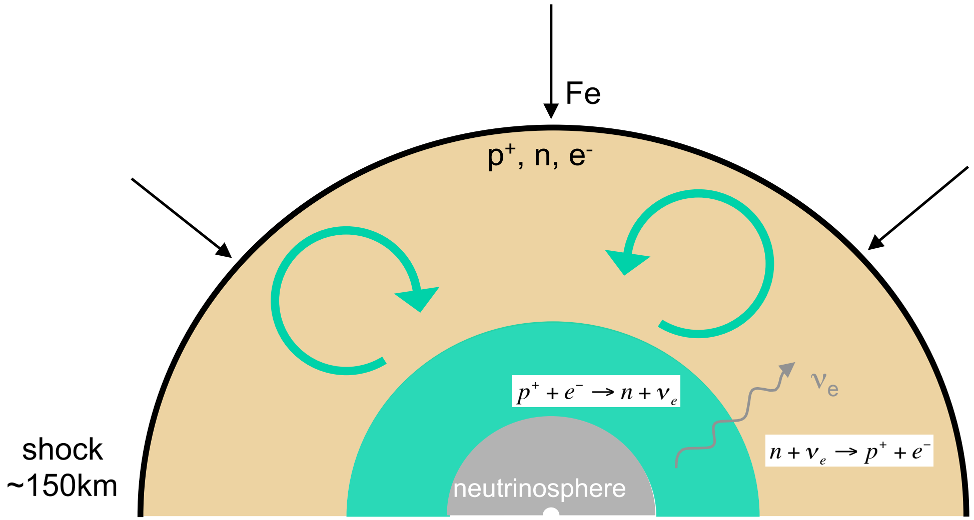
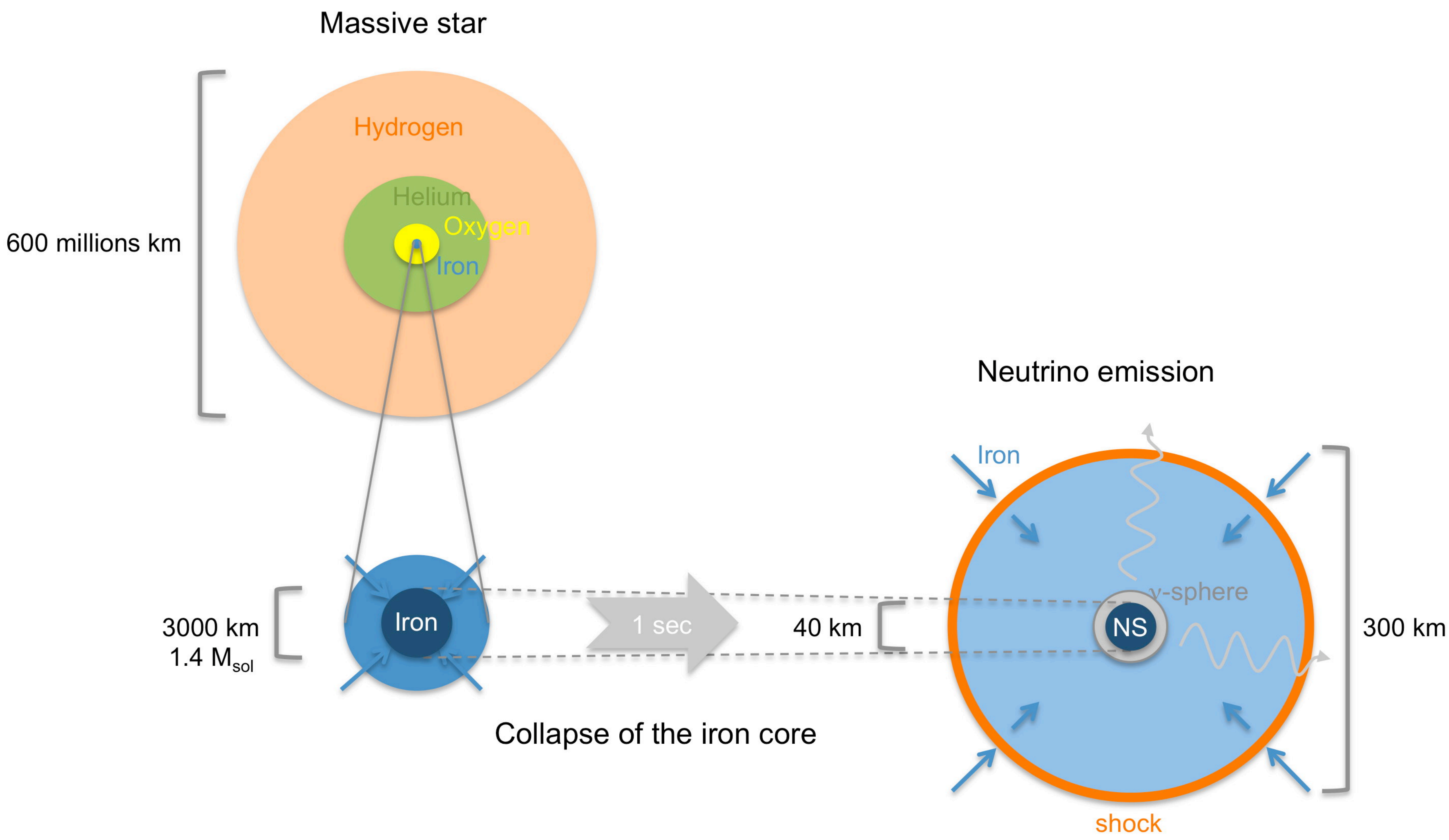
Role and impact of SASI on core collapse supernovae

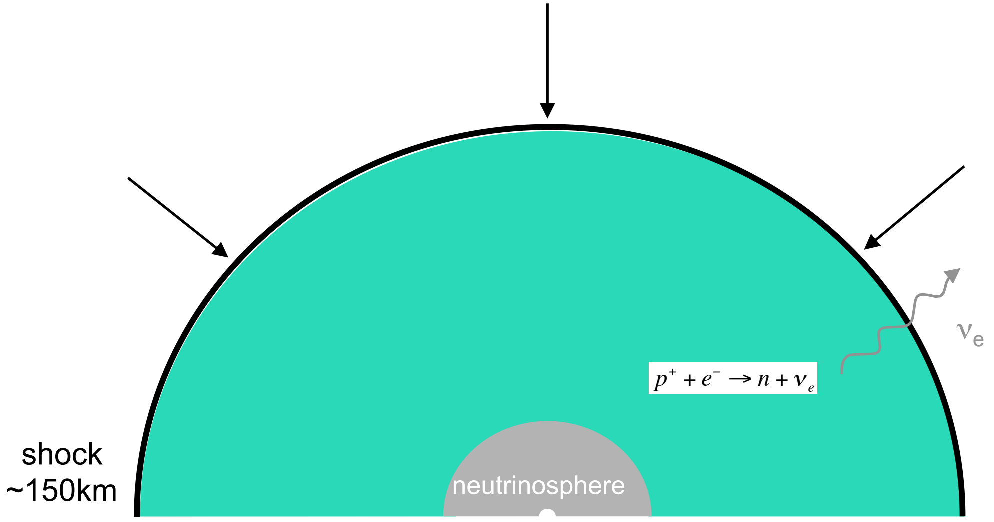


T. Foglizzo, CEA Saclay
J. Guilet, J. Sato, T. Yamasaki, S. Fromang

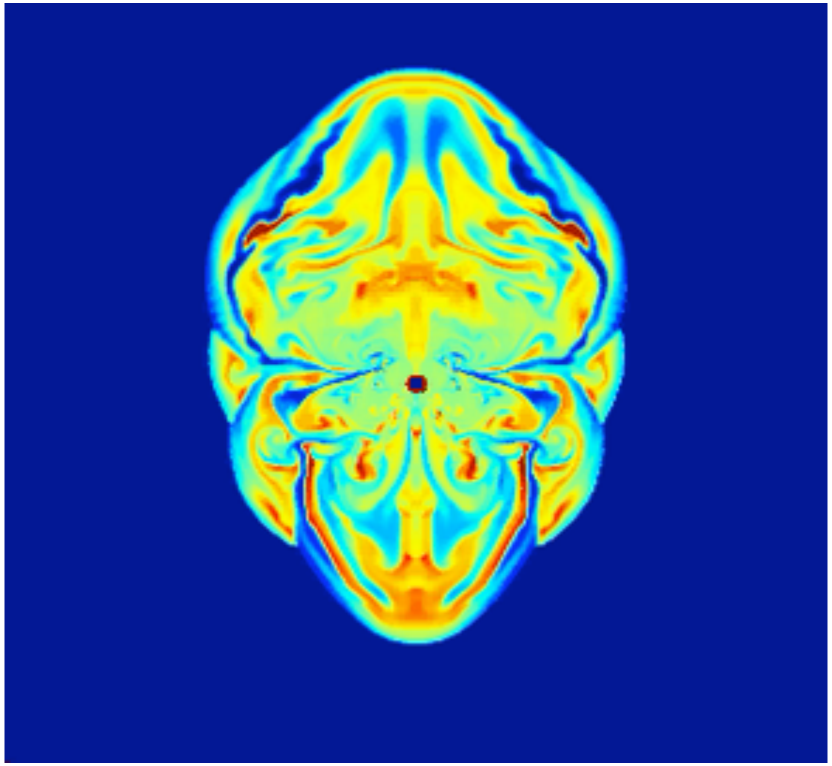
A very narrow window in space and time

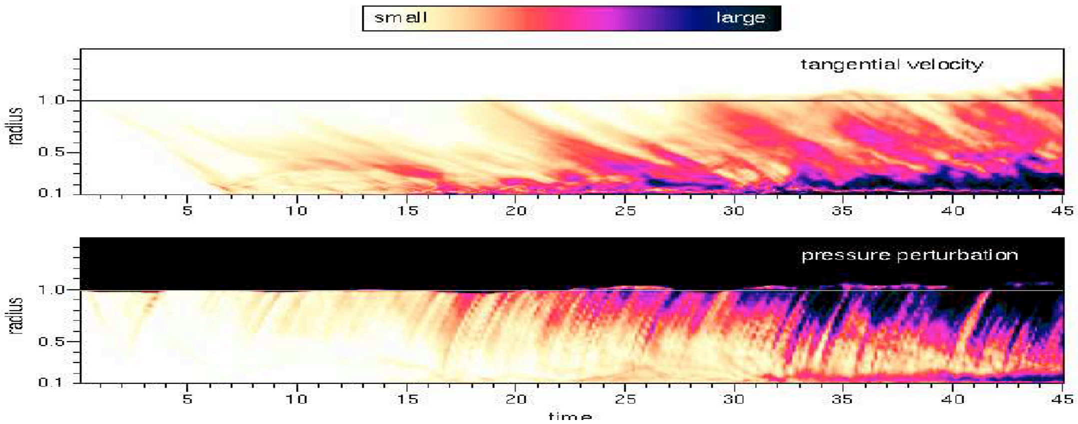


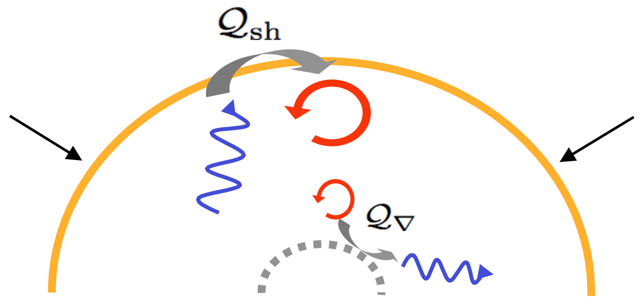
Stationary Accretion Shock Instability : SASI



Blondin et al. 03







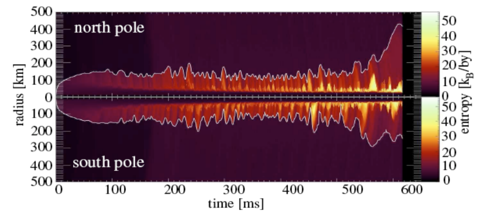
Mechanism of SASI: advective-acoustic cycle ?
(Foglizzo 2002, Galletti 05, Foglizzo et al. 07)

Numerical simulations: SASI is ubiquitous since 2003

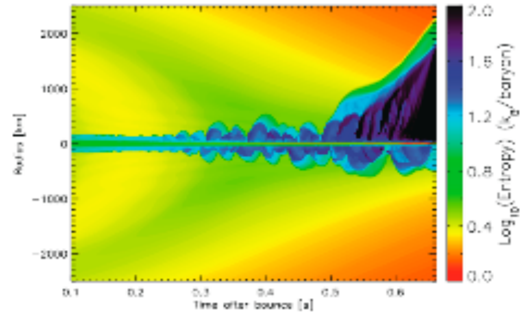
		initial	sym.	SASI	ν-heat
2003	Blondin et al.	stalled	2D axi.	X	-
2004	Scheck et al.	collapse	2D axi.	X	X
2006	Scheck et al.	collapse	2D axi.	X	X
	Burrows et al.	collapse	2D axi.	X	X
	Ohnishi et al.	stalled	2D axi.	X	X
	Blondin & Mezzacappa	stalled	2D axi.	X	-
2007	Blondin & Mezzacappa	stalled	3D	spiral	-
	Kotake et al.	stalled	2D axi.	X	X
	Burrows et al.	collapse	2D axi.	X	X
	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
	Murphy & Burrows	collapse	2D axi.	X	X
	Ott et al.	collapse	2D axi.	X	X
2009	Marek & Janka	collapse	2D axi.	X	X
	Iwakami et al.	stalled	3D	spiral ?	X
	Fernandez & Thompson	stalled	2D axi.	X	-
	Fernandez & Thompson	stalled	2D axi.	X	X
	Endeve et al.	stalled	2D axi.	MHD	-
	Murphy et al.	collapse	2D axi.	X	X

The unexpected possible consequences of SASI

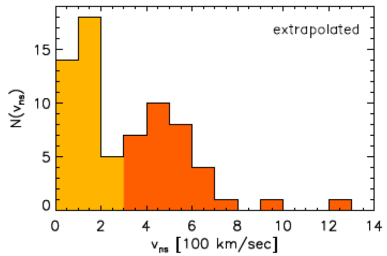
- successful explosion based on neutrino energy
  $15M_{sol}$ (Marek & Janka 09)



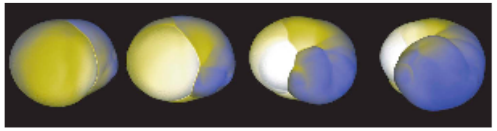
- new explosion mechanism based on acoustic energy
  $11\text{-}25M_{sol}$ (Burrows et al. 06, 07, but Weinberg & Quataert 08)



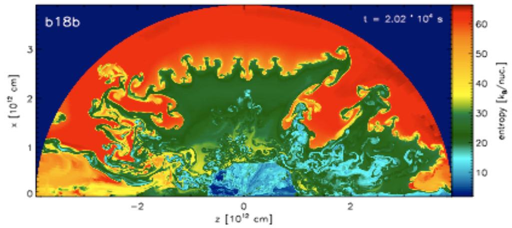
- pulsar kick (Scheck et al. 04, 06)



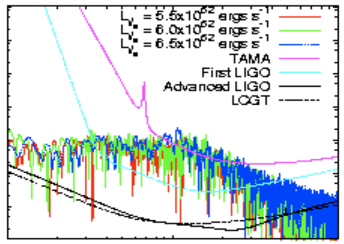
- pulsar spin (Blondin & Mezzacappa 07)



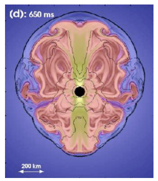
- H/He mixing in SN1987A (Kifonidis et al. 06)



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

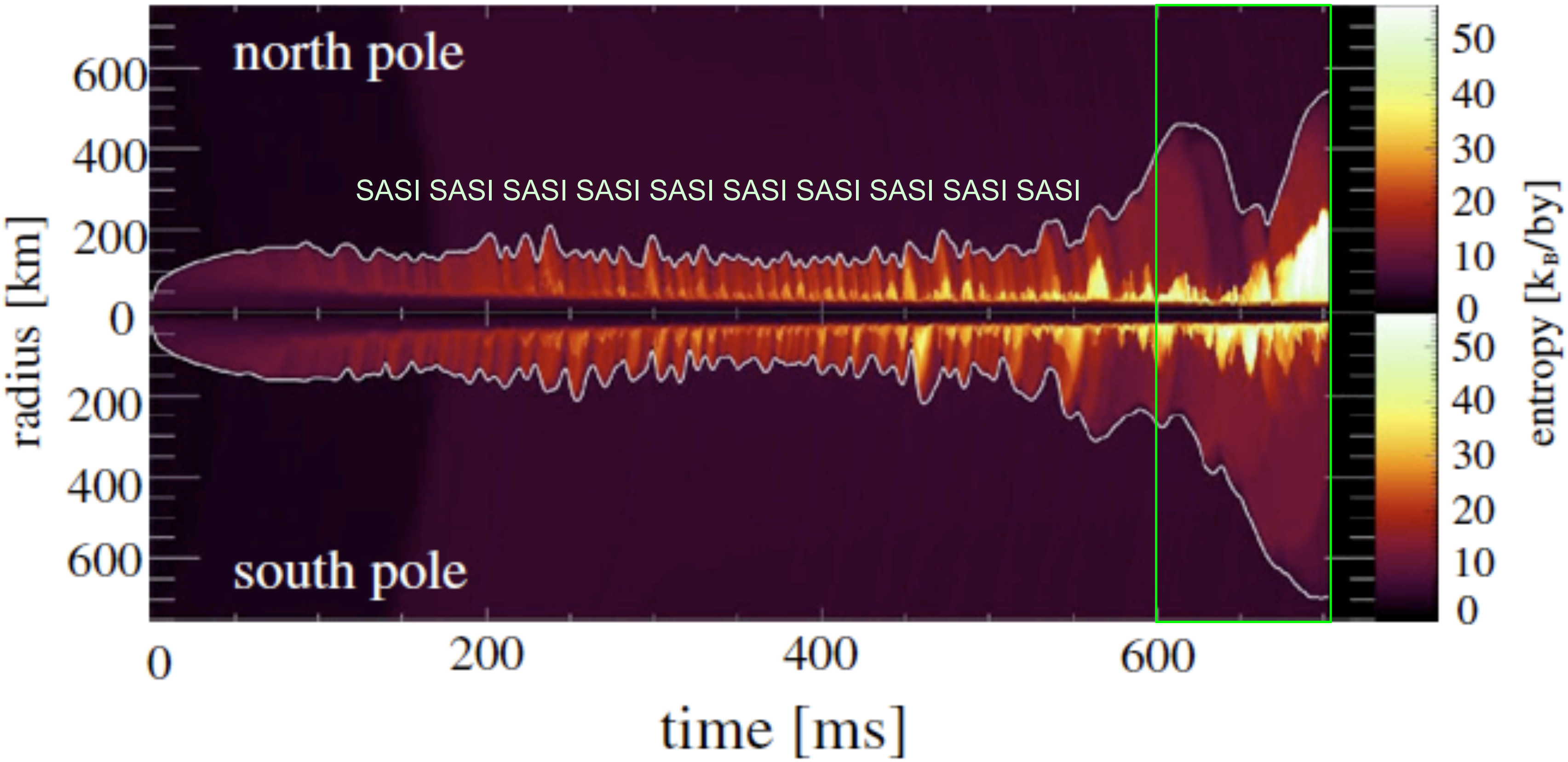


- magnetic field amplification ?
  (Endeve et al. 2008)



How does SASI help the neutrino-driven explosion ?

Marek & Janka 09



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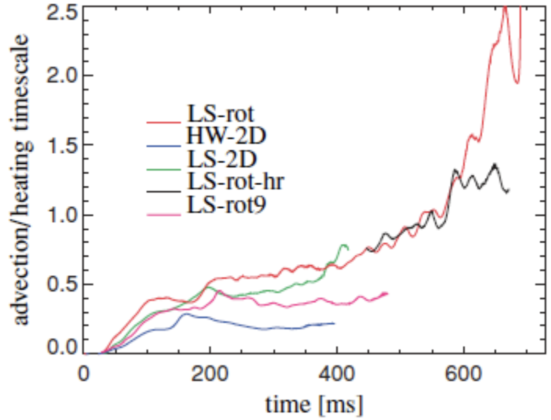
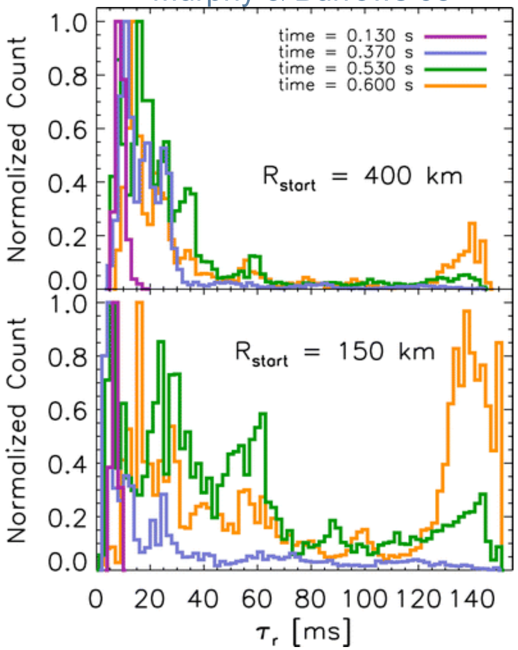


Murphy & Burrows 08



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

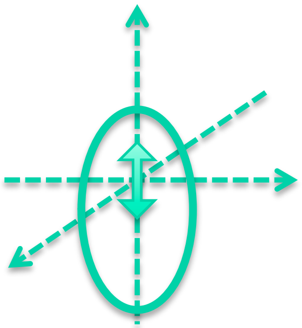
also,

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

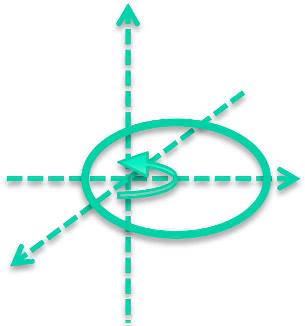
but,

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

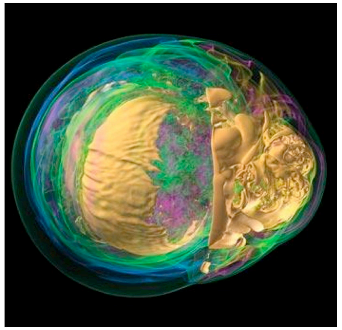
3D effects on SASI evolution



sloshing SASI mode
l=1, m=0

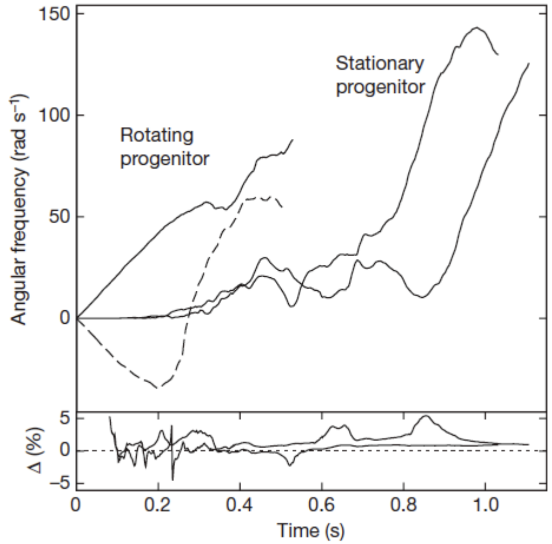


spiral SASI mode
l=1, m=±1

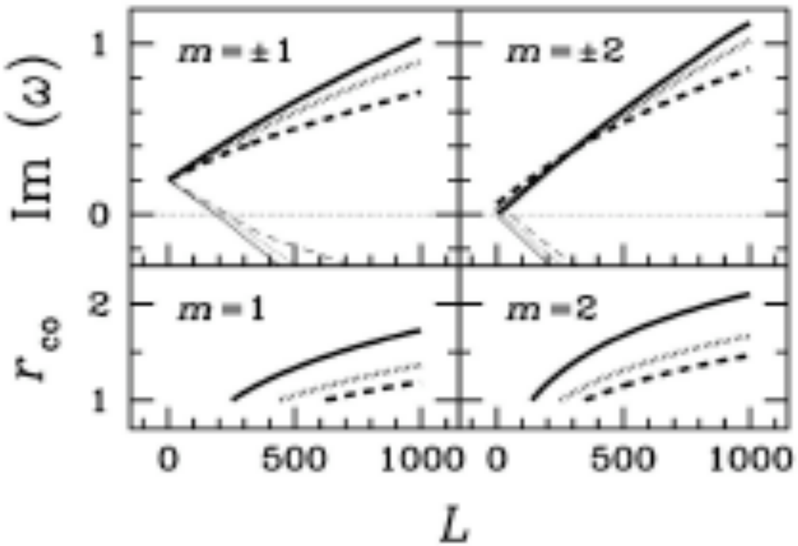


Nature 09

Blondin & Mezzacappa 07



Yamasaki & Foglizzo 08



First order effect of rotation:

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

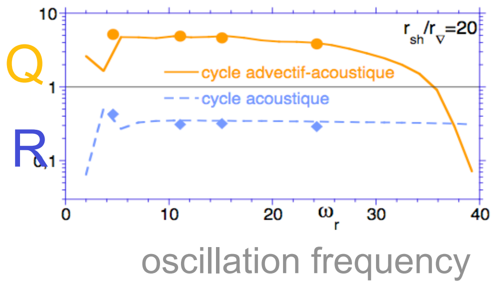
Dominant spiral mode when the core is rotating
(Iwakami et al. 08, 09)

Can the spiral mode dominate even for slow rotators ?

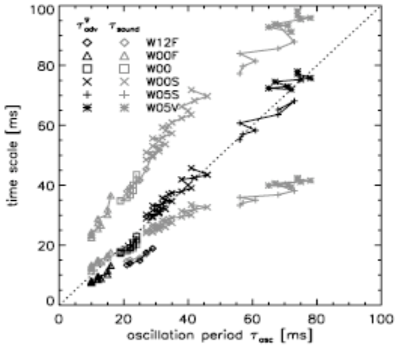
What is the mechanism at work behind SASI ?

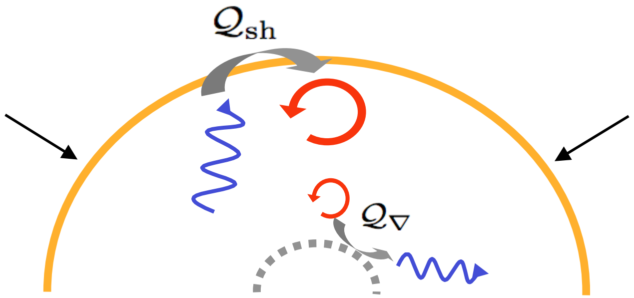
- Growing evidence for the advective-acoustic mechanism

- cycle efficiency of overtones, wkb (Foglizzo et al. 07)
- timescales in simulations (Scheck et al. 08)
- timescale of the dominant mode (Fernandez & Thompson 09)



$$t_{\rm advect} \sim t_{\rm acoust}$$





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

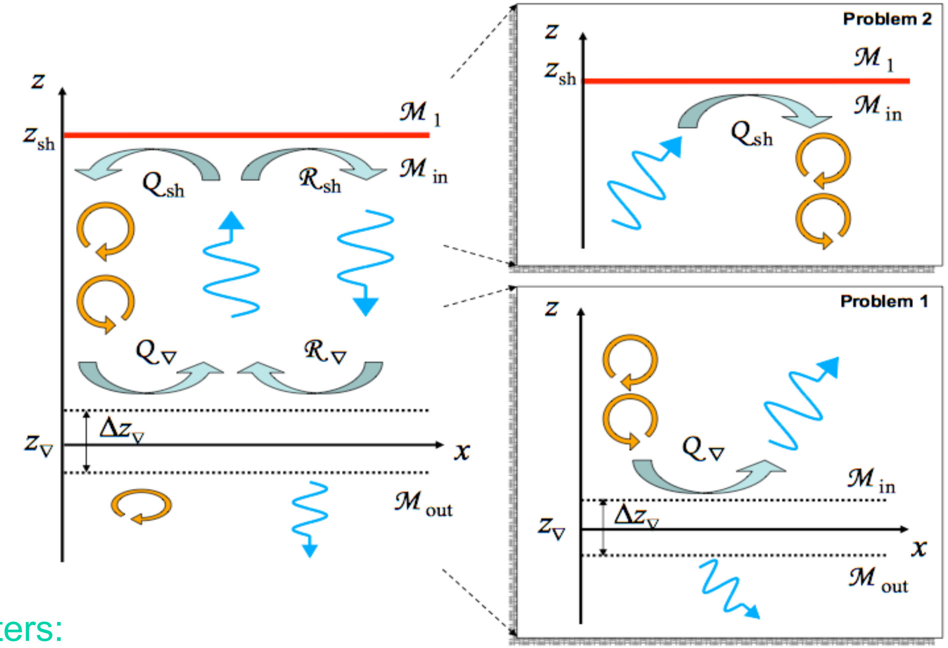
→ why is SASI a low l=1,2, low frequency instability ? (Foglizzo 09)

→ what saturation mechanism ? (poster by J. Guilet)

The simplest example of a 2D advective-acoustic cycle (Foglizzo 09)

Main hypothesis:

- plane parallel flow
- localized region of deceleration
- adiabatic deceleration through an external potential



Parameters:

- adiabatic index
- Mach number
- size of the deceleration region
- strength of deceleration
- aspect ratio Lx/H

Explicit analytical coupling efficiencies

$$\mathcal{R}_{sh} \equiv \frac{\delta f_{sh}^+}{\delta f_{sh}^-} = \frac{1+\mu_{sh}\mathcal{M}_{sh}}{1-\mu_{sh}\mathcal{M}_{sh}}\frac{\delta p_{sh}^+}{\delta p_{sh}^-},$$

$$= -\frac{\mu_{sh}^2 - 2\mathcal{M}_{sh}\mu_{sh} + \mathcal{M}_1^{-2}}{\mu_{sh}^2 + 2\mathcal{M}_{sh}\mu_{sh} + \mathcal{M}_1^{-2}}\frac{1+\mu_{sh}\mathcal{M}_{sh}}{1-\mu_{sh}\mathcal{M}_{sh}}.$$

$$\mathcal{Q}_{sh} \equiv \frac{\delta f_{sh}^S}{\delta f_{sh}^-} = \frac{1}{1-\mu_{sh}\mathcal{M}_{sh}}\frac{p_{sh}\delta S_{sh}}{\delta p_{sh}^-},$$

$$= \frac{2}{\mathcal{M}_{sh}}\frac{1-\mathcal{M}_{sh}^2}{1+\gamma\mathcal{M}_{sh}^2}\left(1-\frac{\mathcal{M}_{sh}^2}{\mathcal{M}_1^2}\right)$$

$$\times\frac{\mu_{sh}}{(1-\mu_{sh}\mathcal{M}_{sh})(\mu_{sh}^2+2\mu_{sh}\mathcal{M}_{sh}+\mathcal{M}_1^{-2})},$$

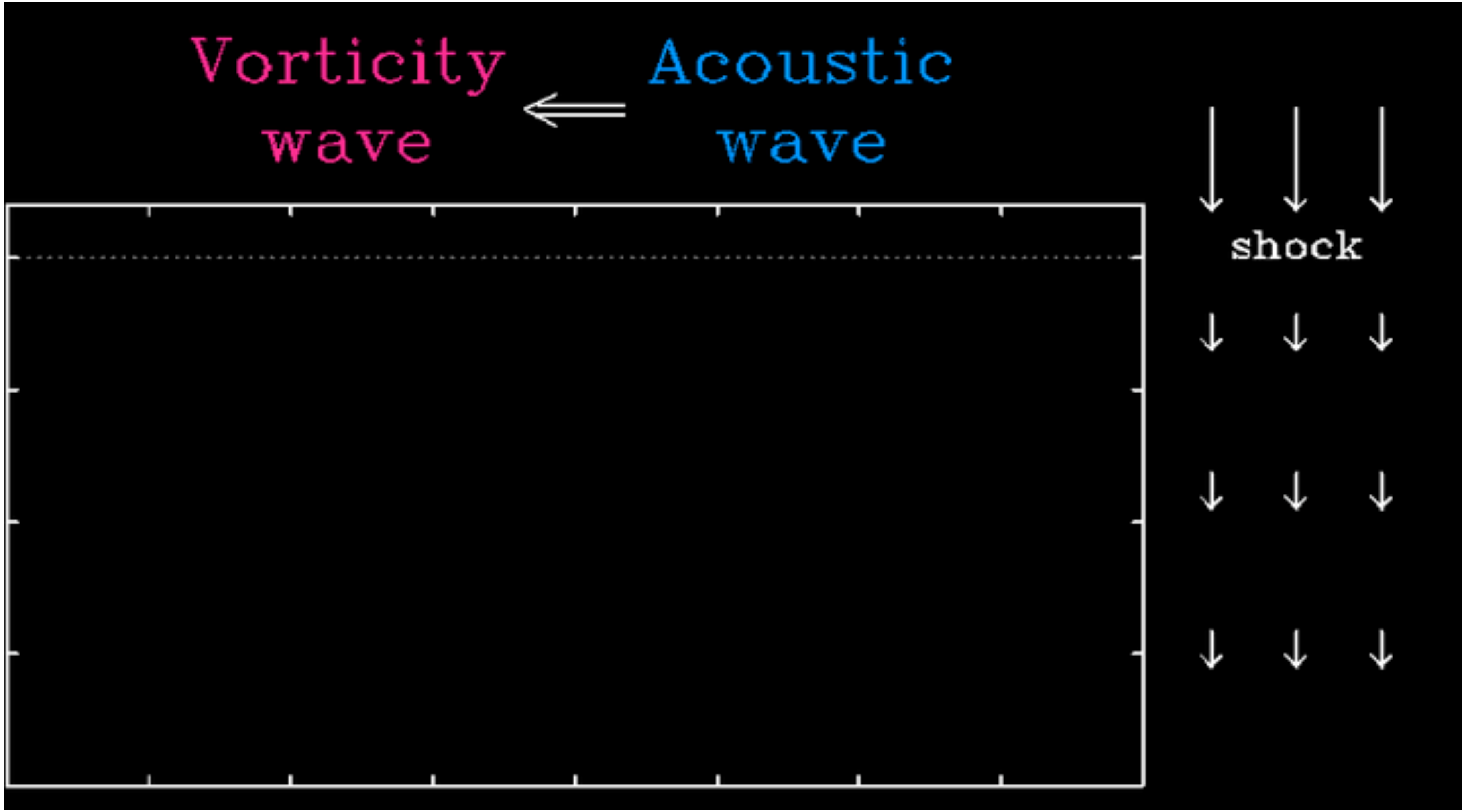
$$\mathcal{R}_\nabla = \frac{\mu_{in}\mathcal{M}_{out}c_{out}^2 - \mu_{out}\mathcal{M}_{in}c_{in}^2}{\mu_{in}\mathcal{M}_{out}c_{out}^2 + \mu_{out}\mathcal{M}_{in}c_{in}^2}\mathrm{e}^{i\omega\tau_\mathcal{R}},$$

$$\mathcal{Q}_\nabla = \frac{\mathcal{M}_{out}+\mu_{out}}{1+\mu_{out}\mathcal{M}_{out}}\frac{\mathrm{e}^{i\omega\tau_\mathcal{Q}}}{\mu_{out}\frac{c_{in}^2}{c_{out}^2}+\mu_{in}\frac{\mathcal{M}_{out}}{\mathcal{M}_{in}}}$$

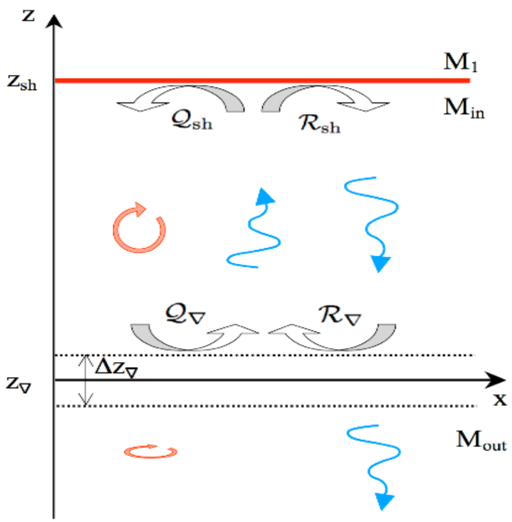
$$\times\left[1-\frac{c_{in}^2}{c_{out}^2}+\frac{k_x^2c_{in}^2}{\omega^2}(\mathcal{M}_{in}^2-\mathcal{M}_{out}^2)\right],$$

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

(Sato, Foglizzo & Fromang 09)



Why is SASI a low frequency instability ? (Foglizzo 08)



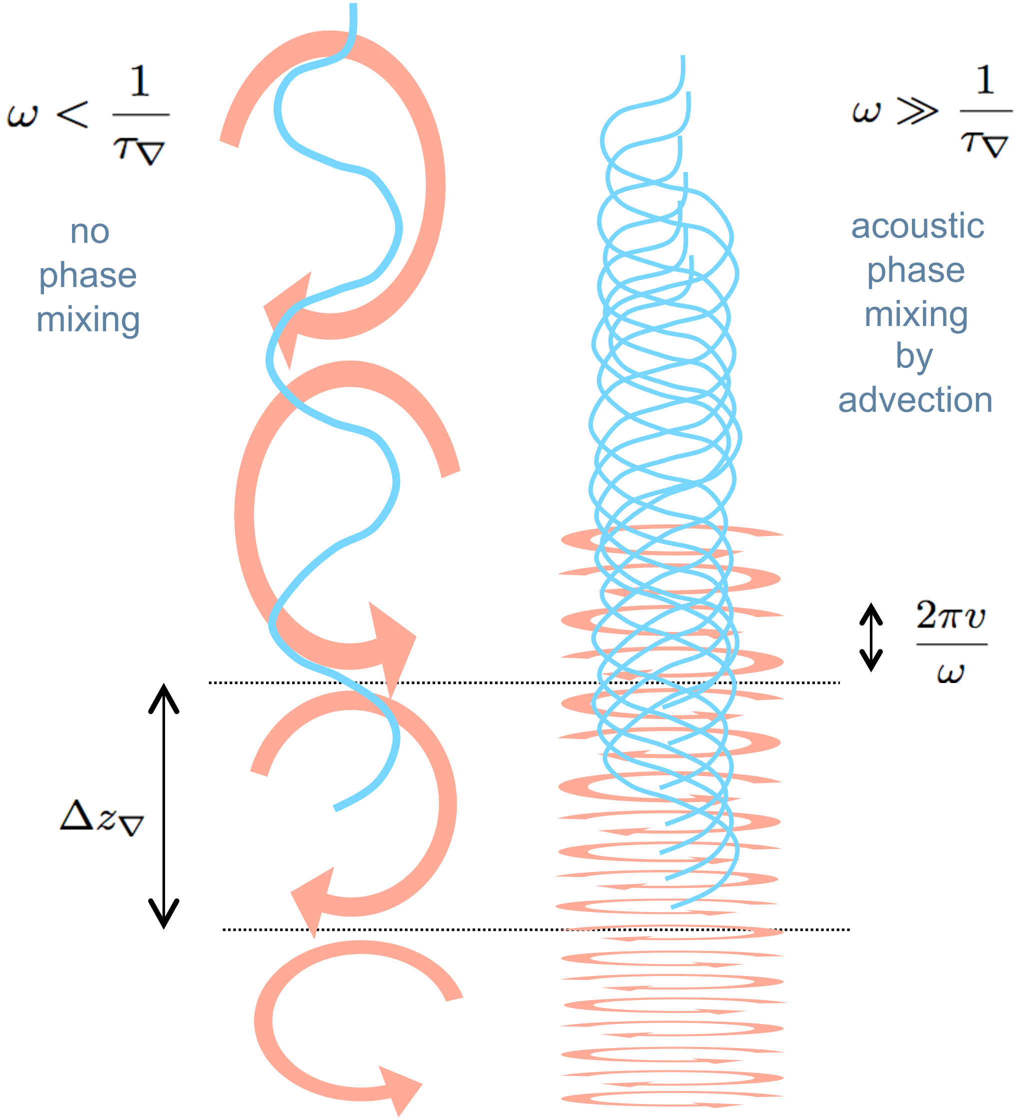
$$\tau_\nabla \sim \frac{\Delta z_\nabla}{v}$$

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

where

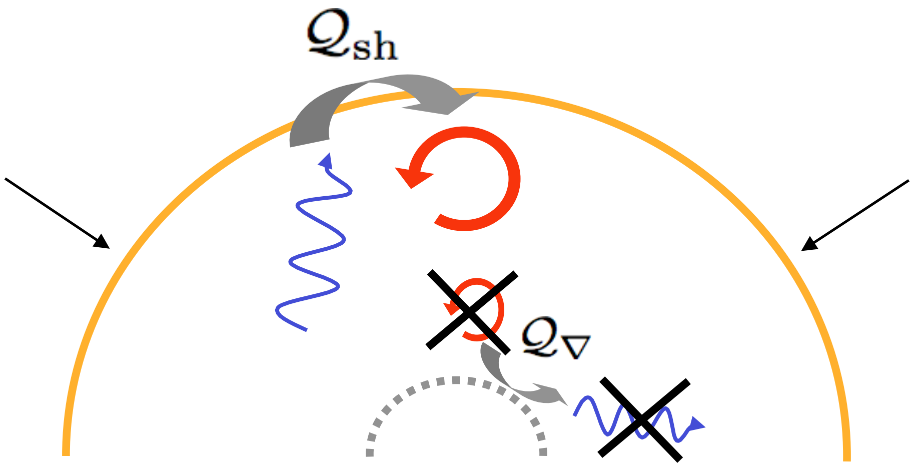
$$b_0 \equiv \frac{1}{2} \left(1+\frac{k_x^2 v_{sh}^2}{\omega^2}\right)\left(1-\mathcal{R}_\nabla - \frac{1+\mathcal{R}_\nabla}{\mu_{sh}\mathcal{M}_{sh}}\right) \frac{1-\mathcal{M}^2}{1-\mathcal{M}_{sh}^2}\frac{\mathcal{M}_{sh}^2}{\mathcal{M}^2}\left(\frac{\delta p_0}{p}\right)_{sh}^{-1} e^{-\int_{sh}\frac{i\omega}{c}\frac{2\mathcal{M}}{1-\mathcal{M}^2}dz},$$

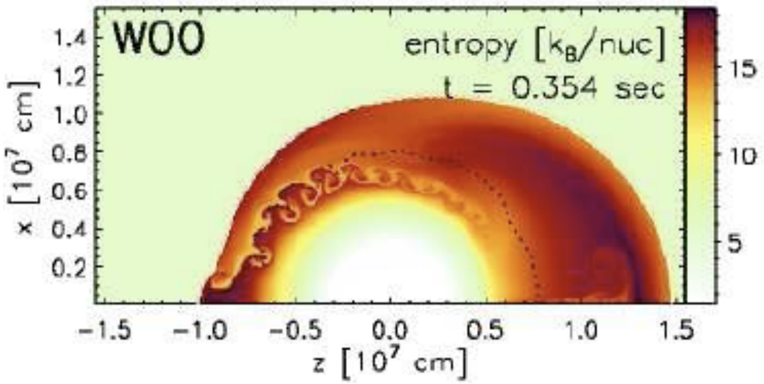
$$b_\nabla \equiv \frac{i\omega}{c_{sh}^2}\frac{i\omega - 2v\frac{\partial \log\mathcal{M}}{\partial z}}{k_x^2\mathcal{M}^2+\frac{\omega^2}{c^2} - v\mathcal{M}^2\frac{\partial}{\partial z}\frac{i\omega}{v^2}}.$$



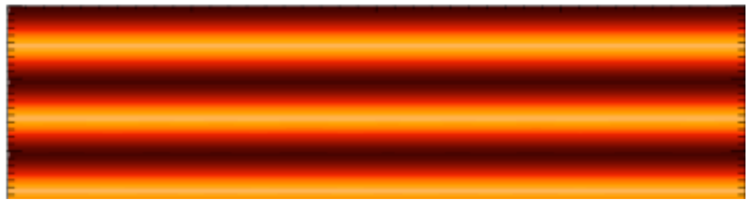
The saturation of SASI by parasitic instabilities

poster
J. Guilet

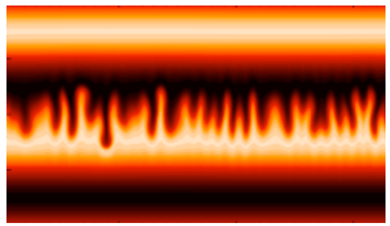




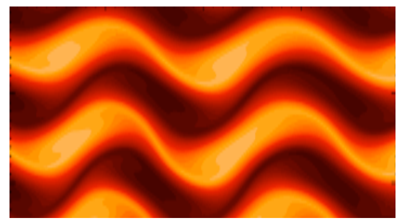
entropy-vorticity wave



Rayleigh-Taylor



Kelvin-Helmhotz

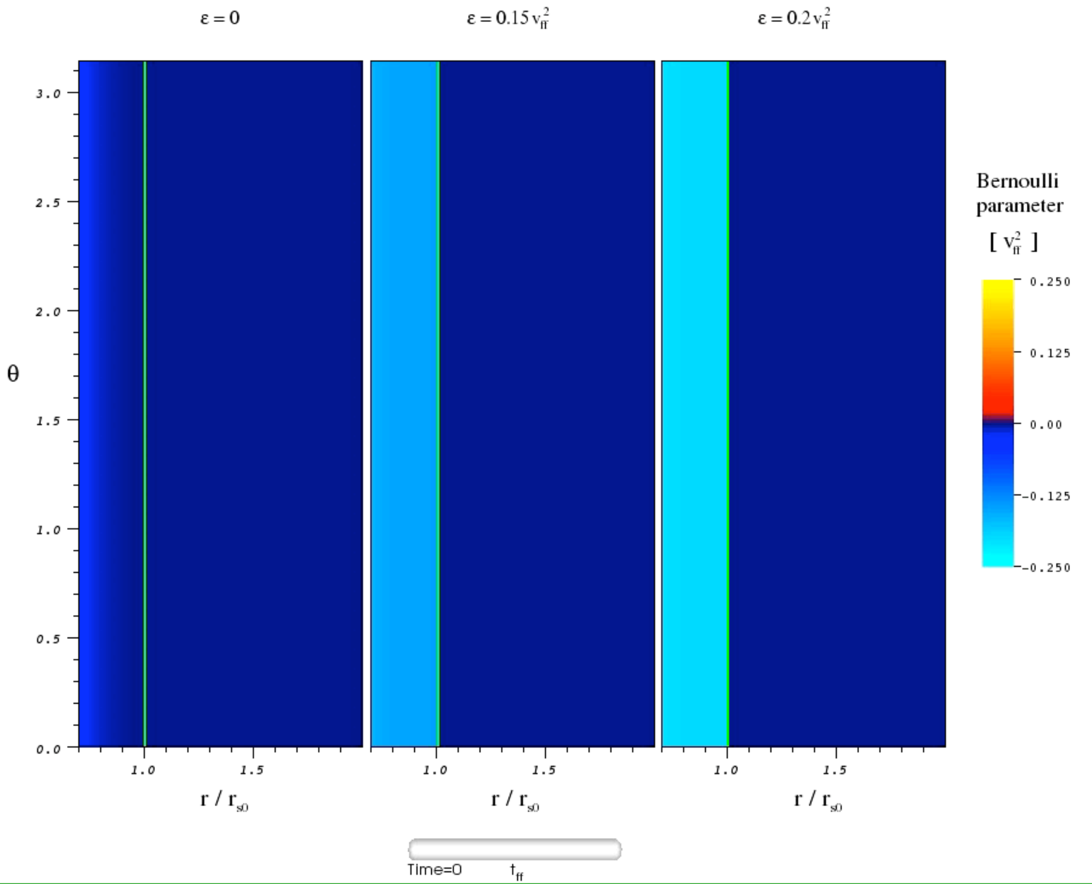


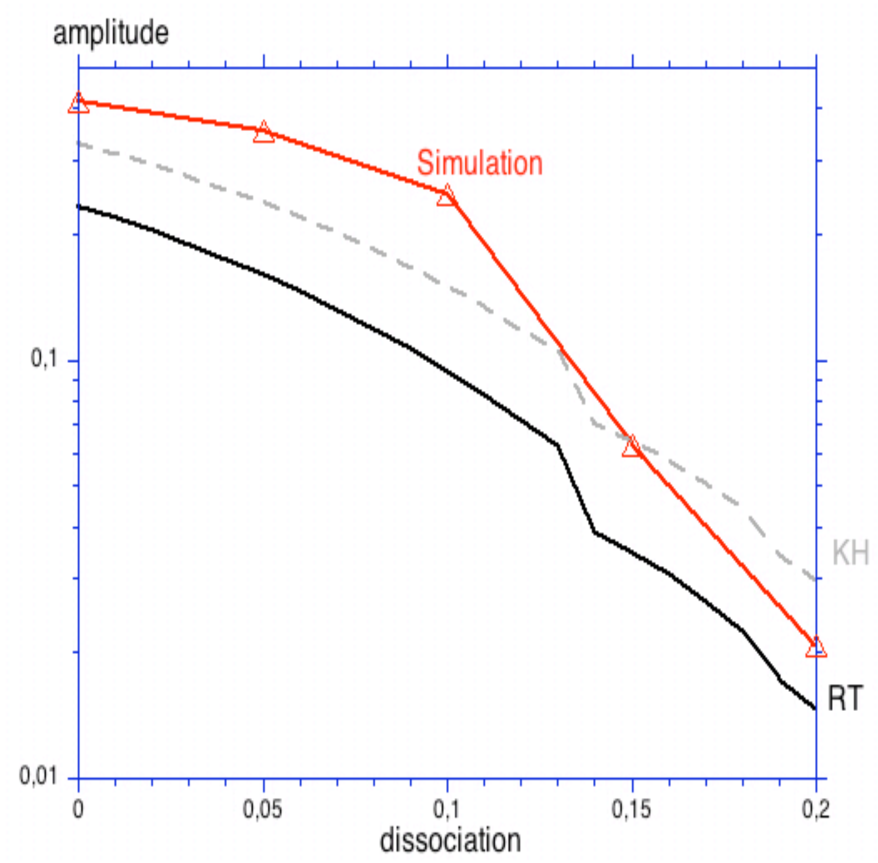
stabilisation if the local parasitic instabilities
- propagate against the flow
- their effective growth rate exceed the SASI growth rate

Comparison with numerical simulations

poster
J. Guilet

Fernandez & Thompson 09 (no heating)





interaction with ν-driven convection ?

Conclusion

Potential consequences of SASI are numerous:

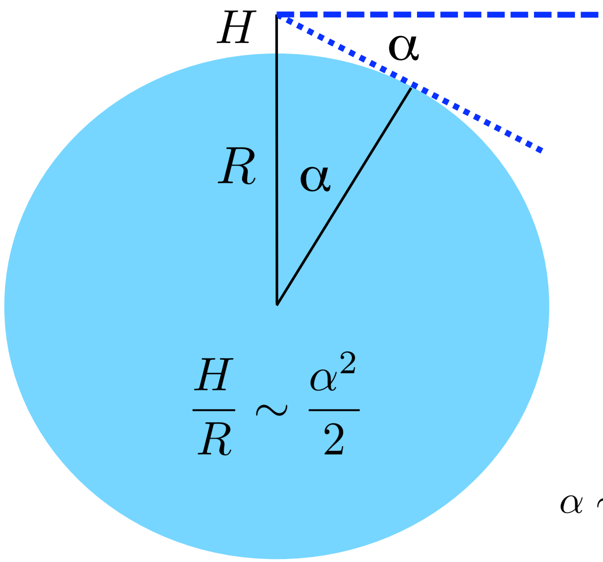
- neutrino driven explosion
- acoustic explosion
- NS kick
- NS spin
- mixing
- grav. waves
- magnetic field

Still large uncertainties concerning 3D

Understanding SASI can be helpful:

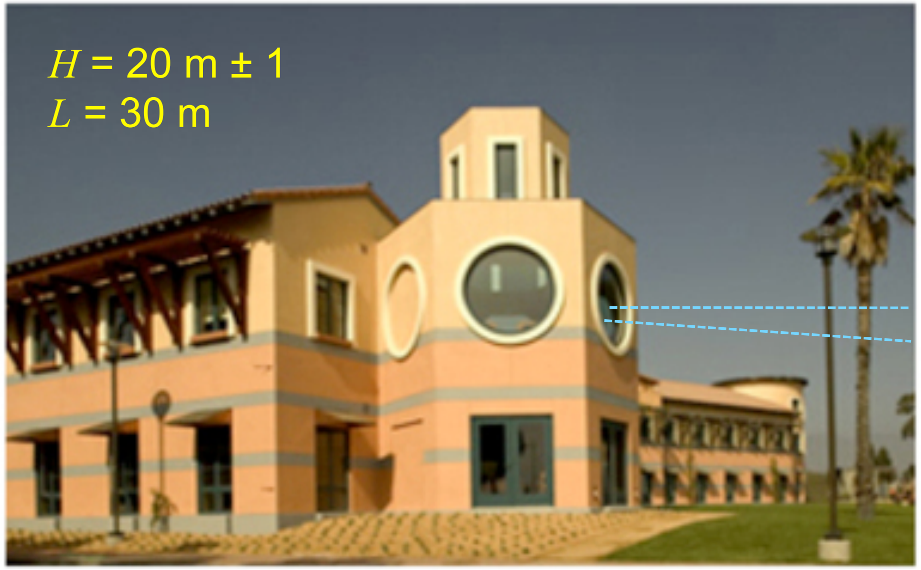
- perturbative analysis: code accuracy, mechanism
- toy model: SASI properties
- first insight into non linear saturation: SASI vs convection ?

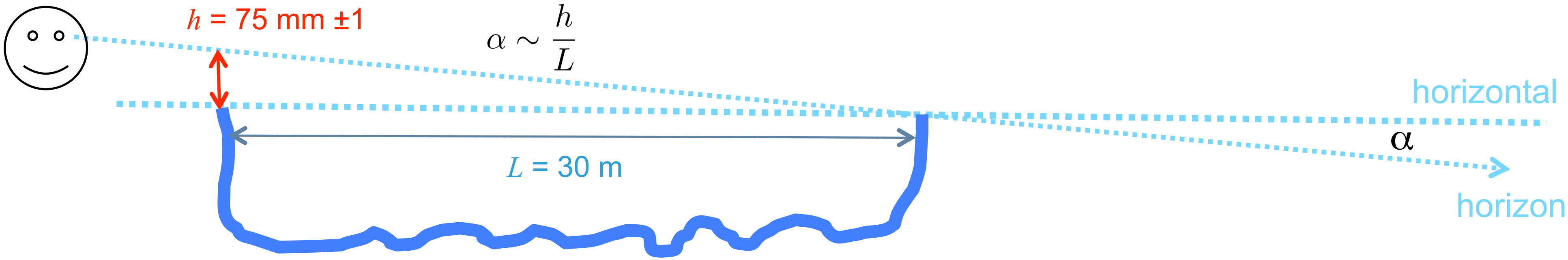
Measuring the earth from KITP with a hose



$$\frac{H}{R} \sim \frac{\alpha^2}{2}$$

$$\alpha \sim 8.6 \left(\frac{H}{20\mathrm{m}}\right)^{\frac{1}{2}} \mathrm{arcmin}$$





$$\alpha \sim \frac{h}{L}$$

$R \sim 6780$ km $\pm 180 \pm 340$ (yesterday)