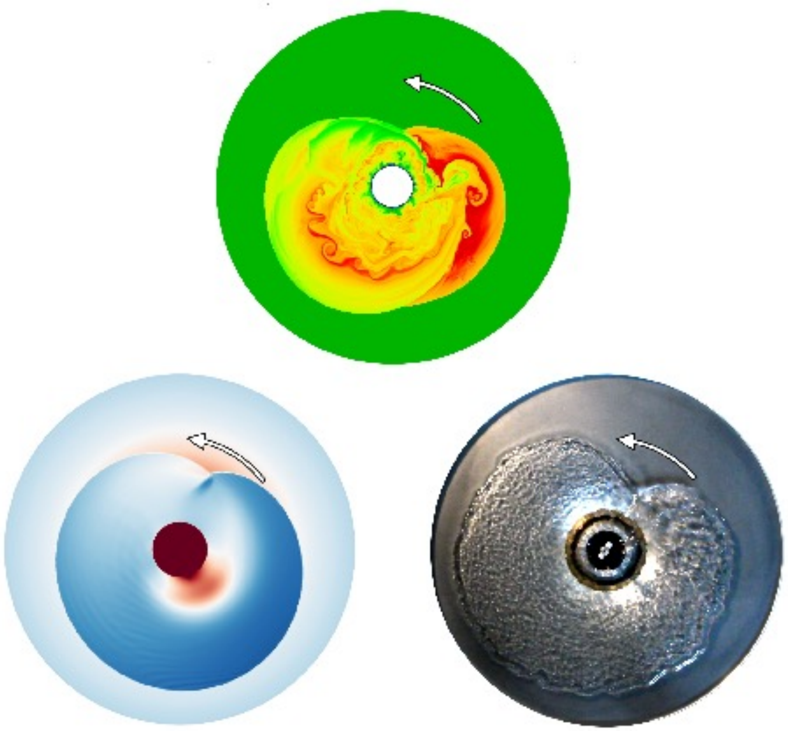


Supernova explosions from multi-messenger observations, theory and experiments

Thierry Foglizzo
CEA Saclay

G. Durand, J. Guilet, M. Gonzalez, B. Pagani, A.C. Buellet, S. Orbach, M. Bugli
K. Kotake (U. Fukuoka), T. Takiwaki (NAOJ)
L. Walk, I. Tamborra (U. Copenhagen)
E. Abdikamalov (U. Nazarbayev)

Outline

current questions
evidence for asymmetric explosions
SASI, convection & rotation
multi-messenger expectations
SASI vs low T/W: experimental & analytical insight

Long standing questions

extreme physics laboratory
nuclear EOS
GR
3D HD & MHD
neutrino interactions

why should most of the massive stars explode?

how do NS get their kick and spin?

stellar evolution
binary disruption
population synthesis

stellar structure
mass,
rotation,
magnetic field,
metallicity,
binarity

what is the fraction of NS/BH?
common vs extreme explosions?

fallback
magnetars,
hypernovae,
GRBs
cosmological probes

what is the origin of heavy nuclei?

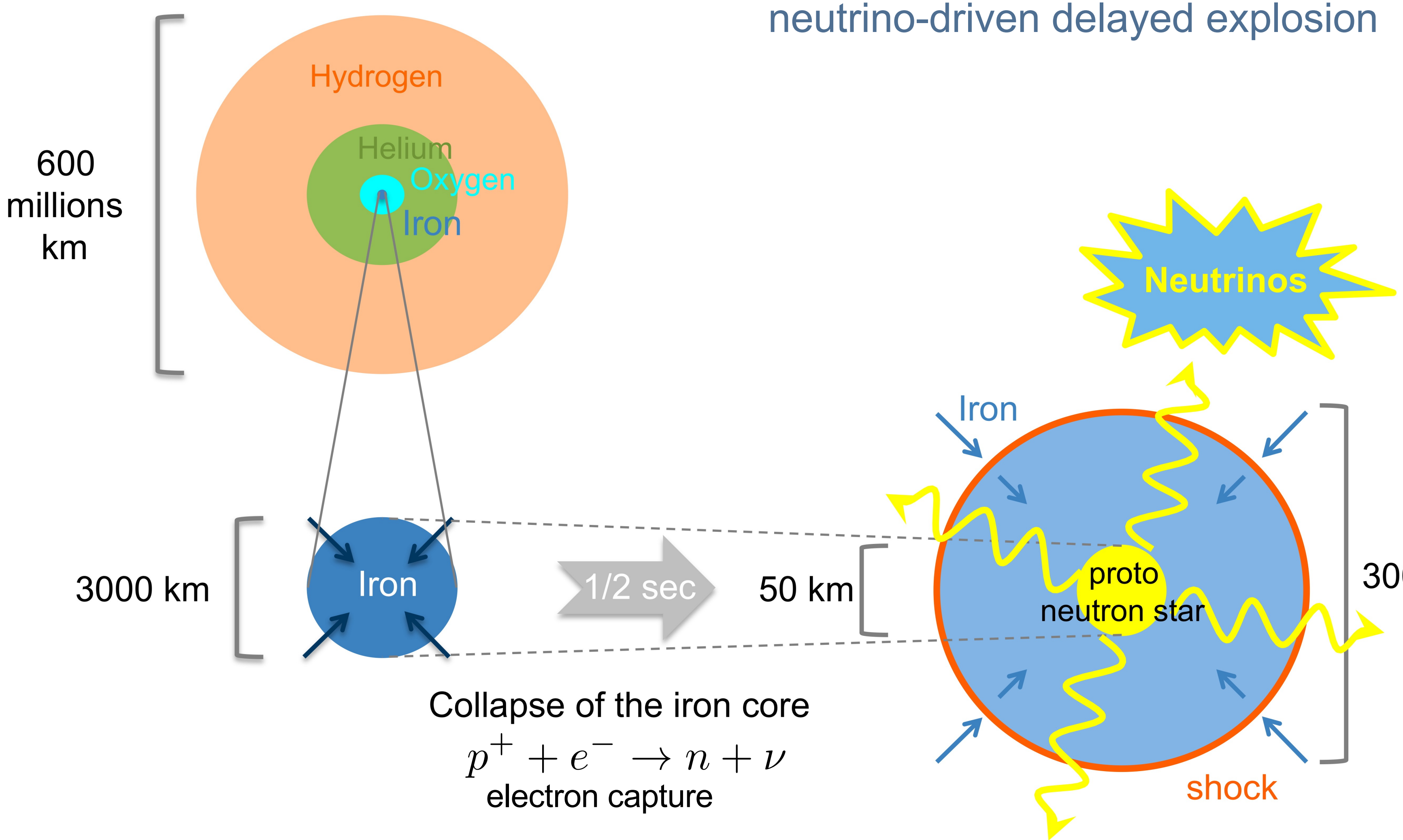
SN, NS mergers, other?
galactic chemical evolution

what can be learnt from future GW and neutrino detections?

reverse engineering
degeneracy?

Theoretical framework (Bethe & Wilson 85)
neutrino-driven delayed explosion

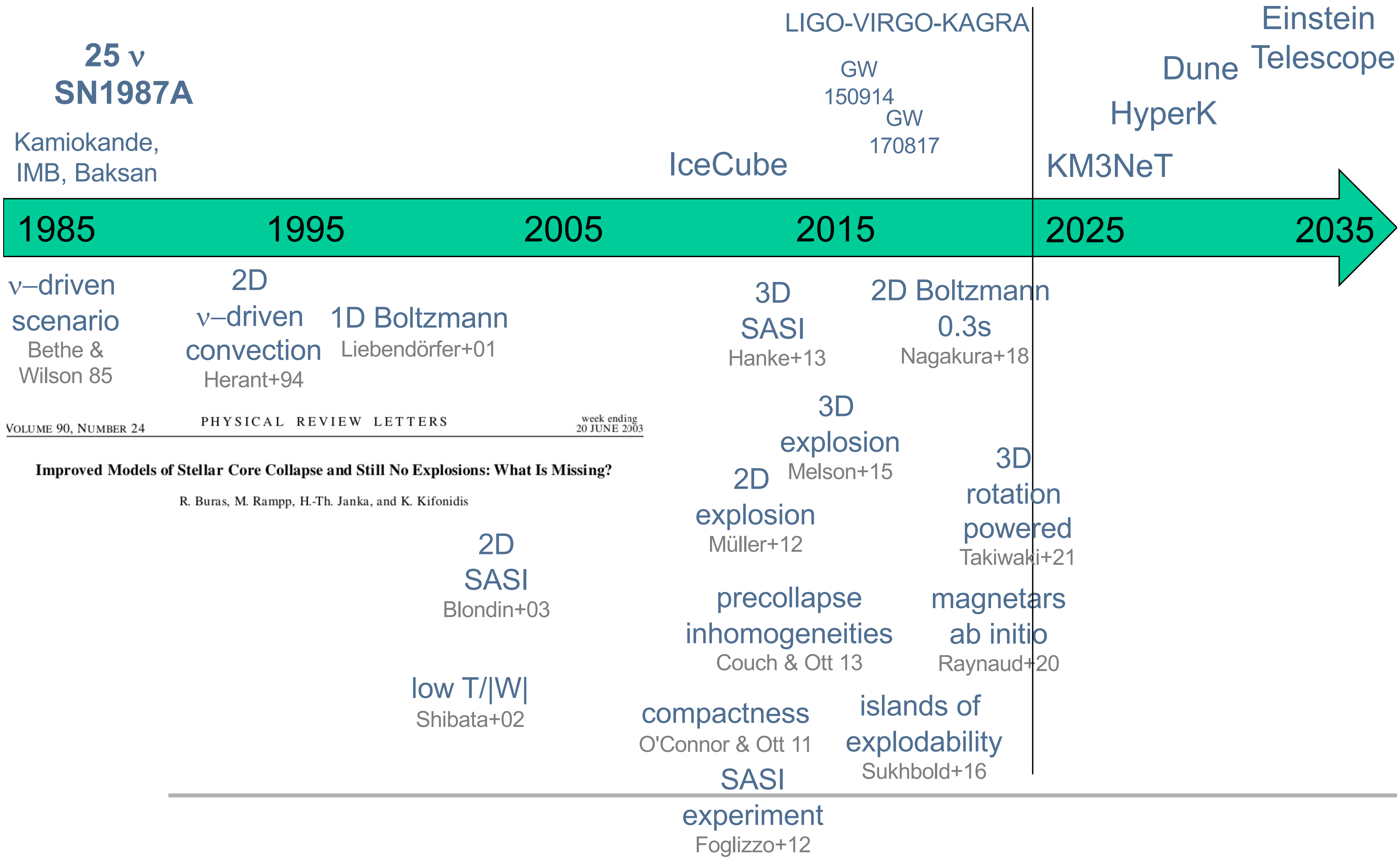
Massive star $15M_{sol}$



$$\frac{GM_{\rm ns}^2}{R_{\rm ns}} \sim 2\times 10^{53}{\rm erg}\left(\frac{30{\rm km}}{R_{\rm ns}}\right)\left(\frac{M_{\rm ns}}{1.5M_{\rm sol}}\right)^2$$

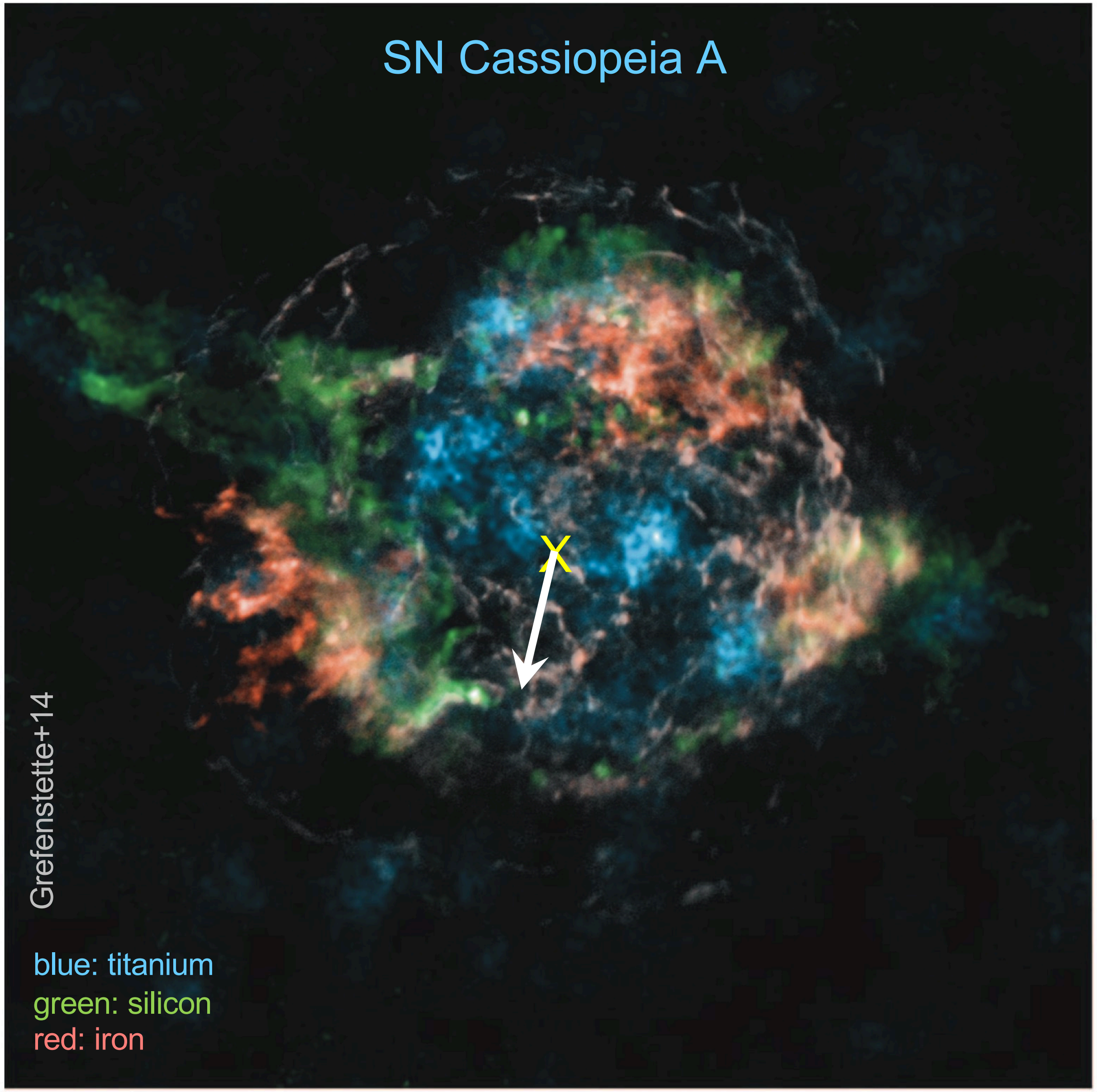
modest energy in differential rotation: $E_{\rm diff} < E_{\rm rot} \sim 2.4\times 10^{50}{\rm erg}\left(\frac{M_{\rm ns}}{1.5M_{\rm sol}}\right)\left(\frac{R_{\rm ns}}{10{\rm km}}\right)^2\left(\frac{10{\rm ms}}{P_{\rm ns}}\right)^2$

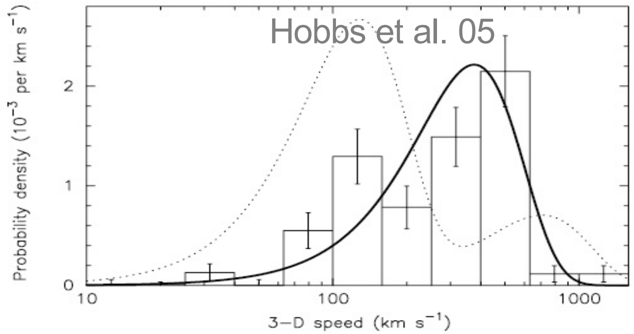
A short perspective on the evolution of SN numerical models

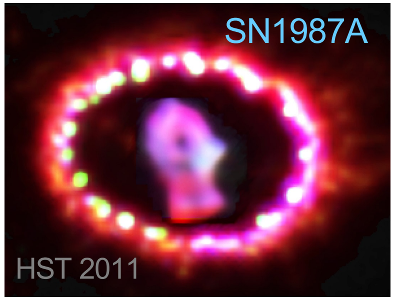


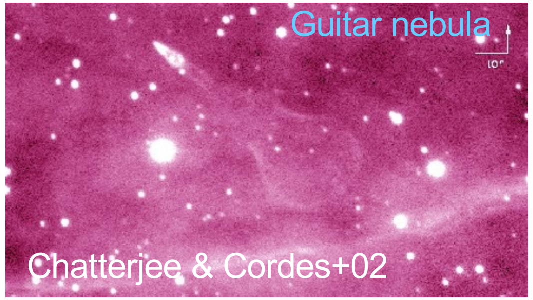
The asymmetric character of stellar core collapse

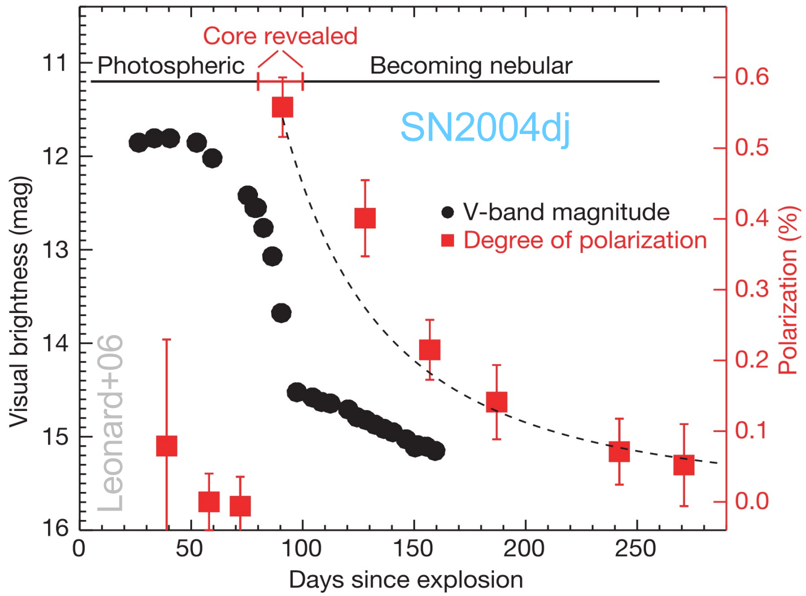
- -pulsar kicks
- -polarization
- -morphology



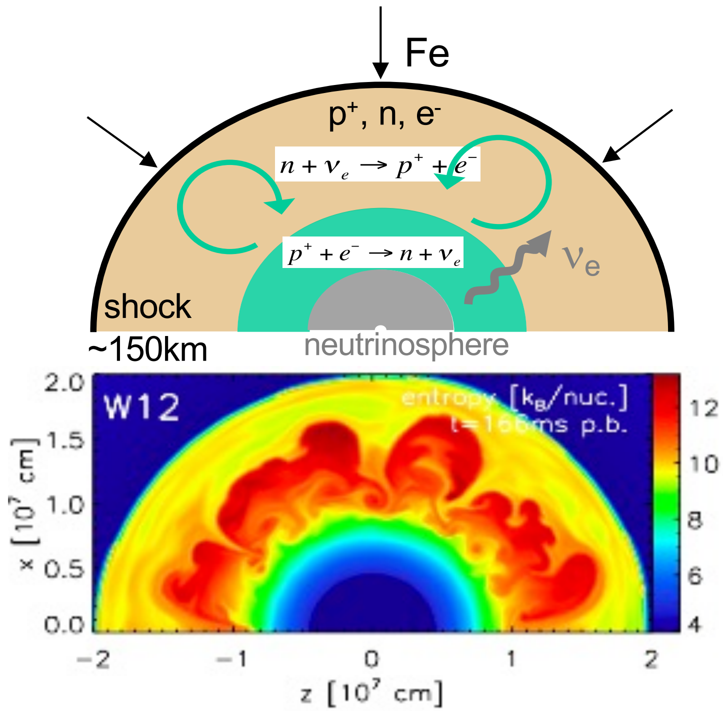








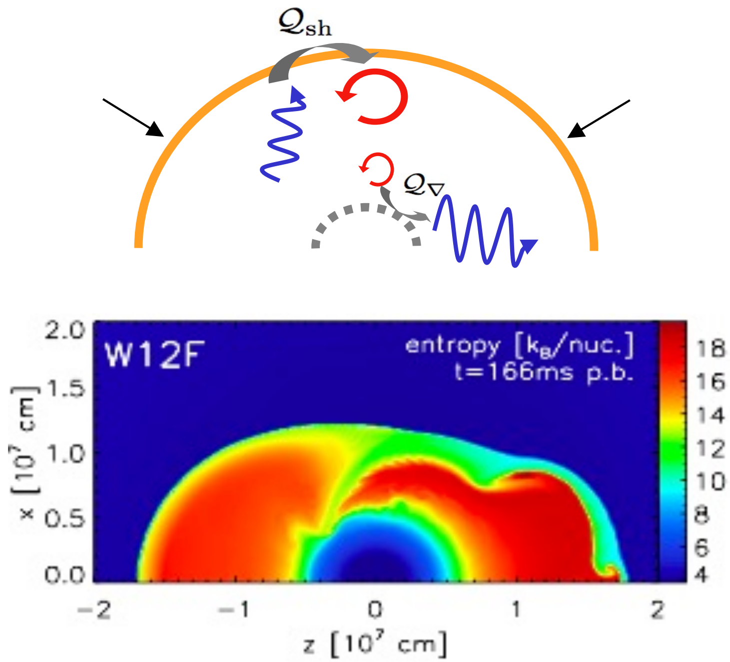
Instabilities during the phase of stalled accretion shock



Neutrino-driven convection (Herant+92, ...)

- entropy gradient, fed by neutrino absorption
- inhibited if the advection time is too short (Foglizzo+06)

$$\chi \equiv \int_{\rm sh}^{\rm gain} \omega_{\rm BV} \frac{{\rm d}r}{v_r} < 3$$



SASI: Standing Accretion Shock Instability (Blondin+03 ...)

- advective-acoustic cycle
- oscillatory, large angular scale l=1,2: pulsar kick, nucleosynthesis, gravitational waves & neutrino signatures

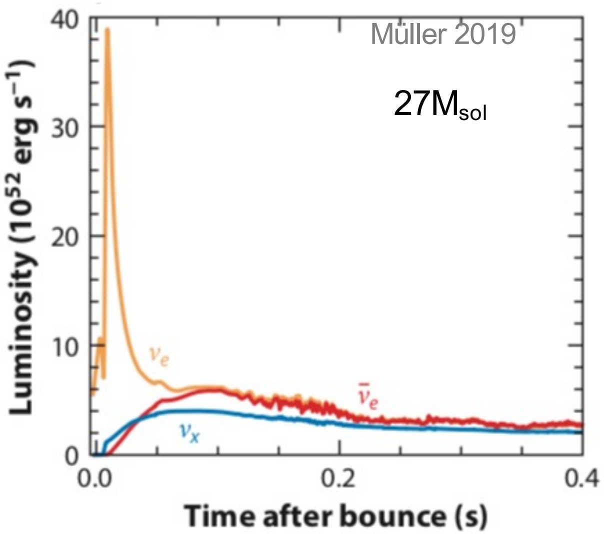
Multimessenger direct information from the collapsing core dynamics

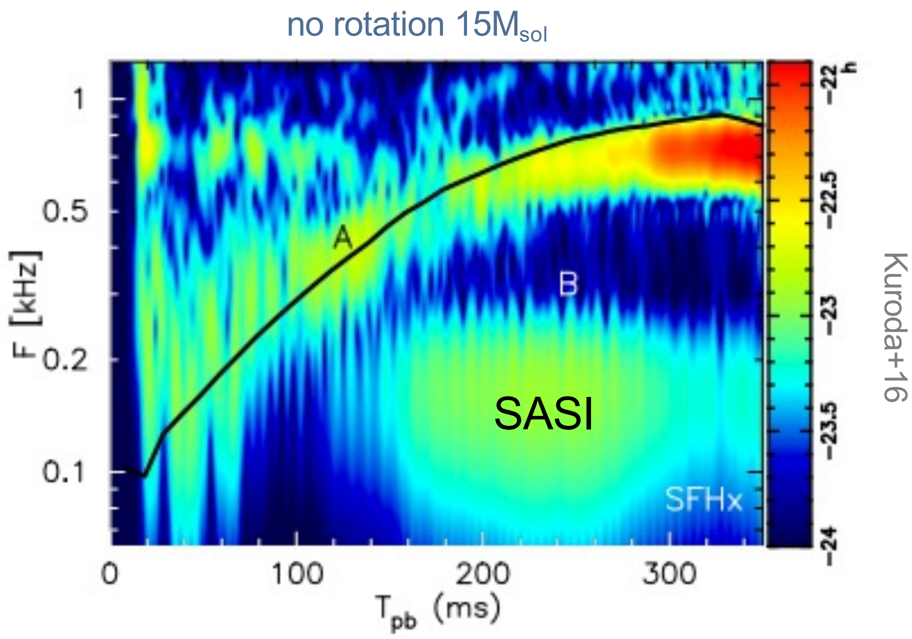
-gravitational waves

(e.g. Kuroda+16, Torres-Forne+18,19, Andresen+17,19, Takiwaki+21, Powell & Müller+22)

LIGO – VIRGO - KAGRA

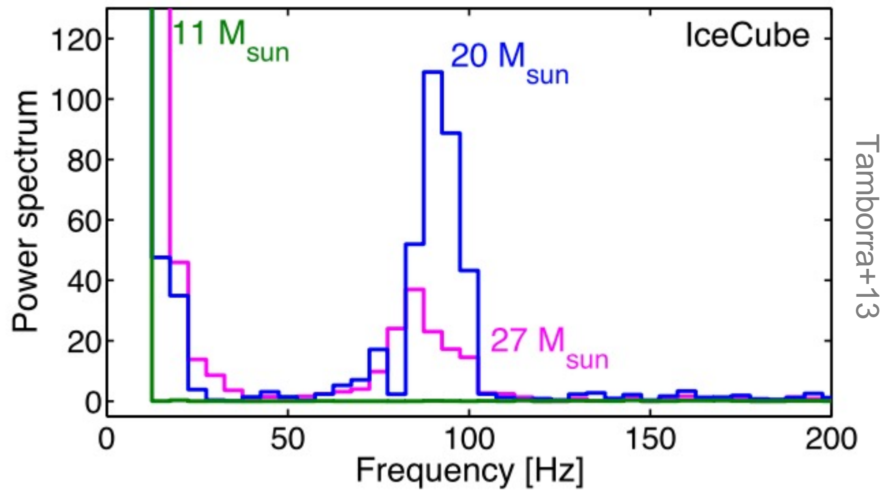
Einstein Telescope





- neutrino signature

(e.g. Tamborra+13, Walk+18,19, Müller 19, Takiwaki+21)

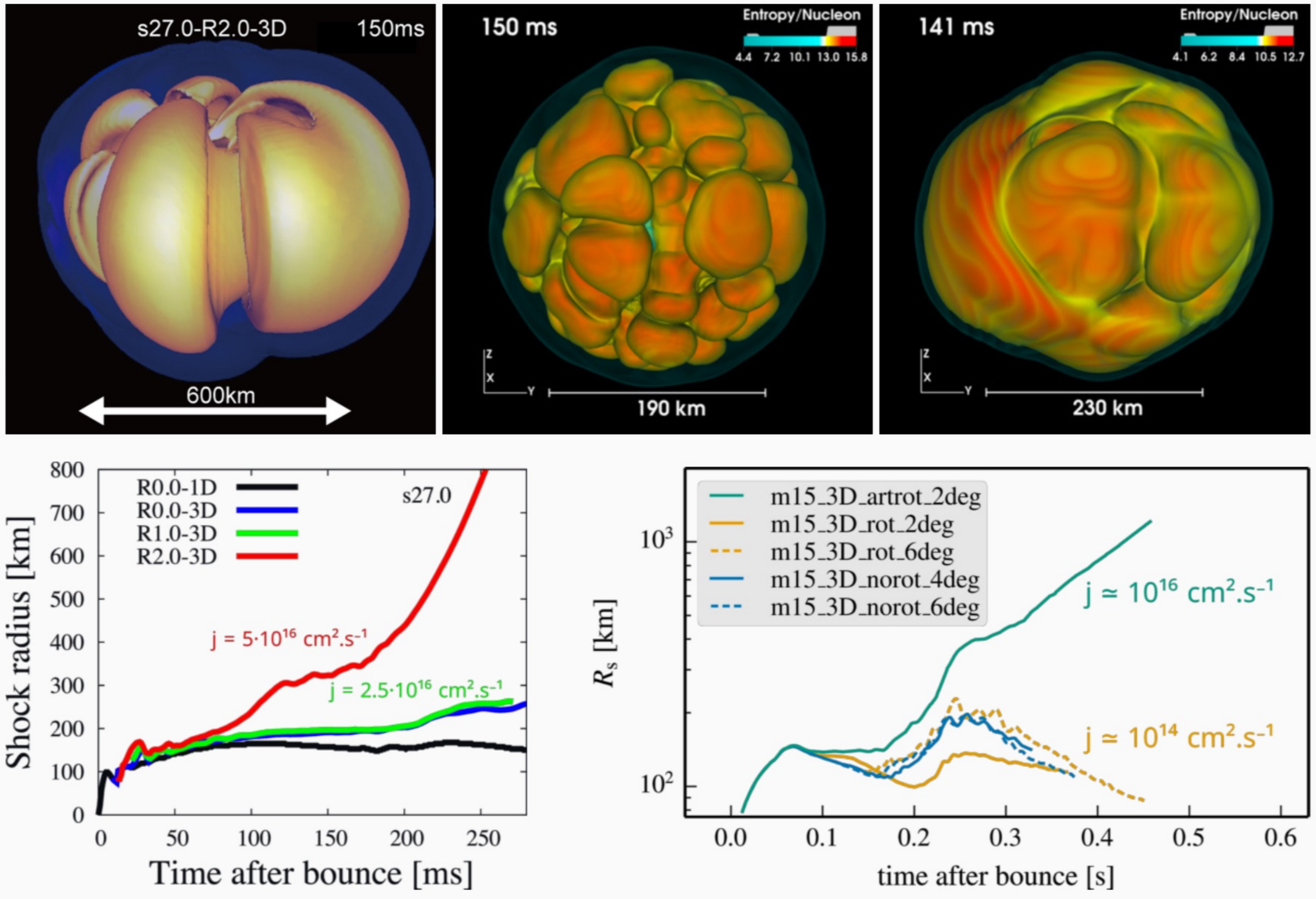


Experiment	Detected neutrino flavour	Effective masse (kT)	Estimated number of events	
			11.2 M$_\odot$	27 M$_\odot$
KM3NeT	$\bar{\nu}_e$	150	$17\times10^3/18\times10^3$	$37\times10^3/38\times10^3$
DUNE	ν_e	40	2700/2500	5500/5200
DarkSide-20K	any ν	0.0386	-	250
IceCube	$\bar{\nu}_e$	2500	$320\times10^3/330\times10^3$	$660\times10^3/660\times10^3$
Super-Kamiokande	$\bar{\nu}_e$	32	4000/4100	7800/7600

Kharusi+21 in Bendahman+21

Impact of rotation on the 3D dynamics of SASI + convection:

difficult interpretation from linear Coriolis effects to quadratic centrifugal effects



Takiwaki et al., 2016

Summa et al., 2018

Uncertain instabilities induced by moderate rotation

-low T/|W| instability?

(Shibata+02, Watts+05, Passamonti & Andersson 15, Takiwaki+21)

- corotation radius
- vorticity gradient?

-Papaloizou-Pringle instability?

(Papaloizou & Pringle 84, Goldreich & Narayan 85)

- corotation radius
- reflecting boundaries

-spiral mode of SASI?

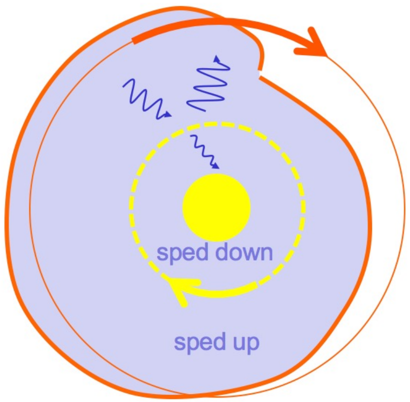
(Blondin & Mezzacappa 07, Yamasaki & Foglizzo 08)

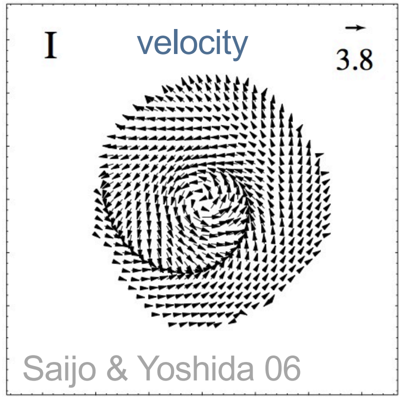
- stationary shock
- rotation-enhanced advective-acoustic cycle?

-fast dynamo in the PNS?

(Raynaud+20, Reboul-Salze+21, Guilet+22)

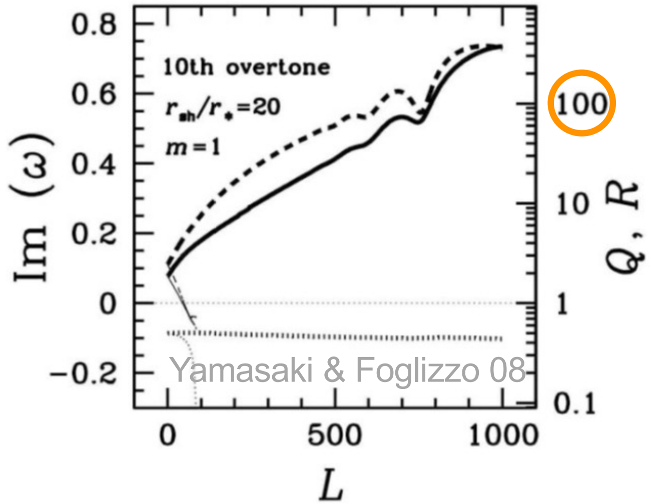
- convection & MRI + rotation





Saijo & Yoshida 06

?



Yamasaki & Foglizzo 08

stellar parameters: progenitor mass, compactness, angular momentum, inhomogeneities

+

puzzling dynamics: SASI, ν-driven convection, low T/|W|, PNS dynamo

+

uncertain physics: reaction rates, EOS, neutrino interactions, magnetic fields

+

numerical approximations: neutrino transport, 2D vs 3D, turbulence

Can gravitational waves and neutrino signatures disentangle so many processes ?

Additional instabilities induced by moderate rotation

-low T/|W| instability?

(Shibata+02, Watts+05, Passamonti & Andersson 15, Takiwaki+21)

- corotation radius
- vorticity gradient?

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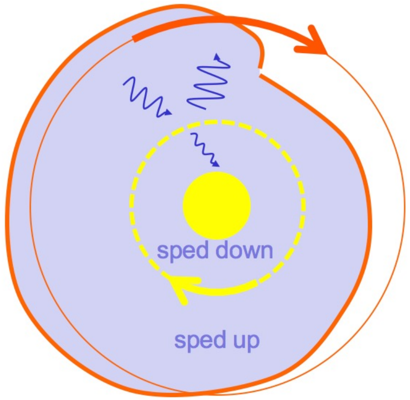

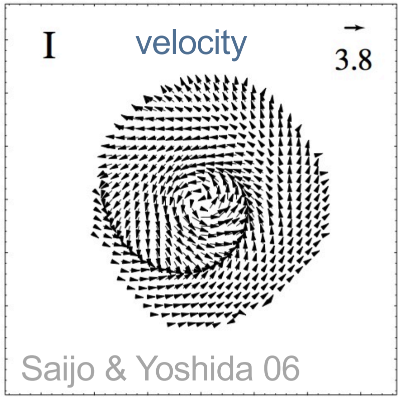

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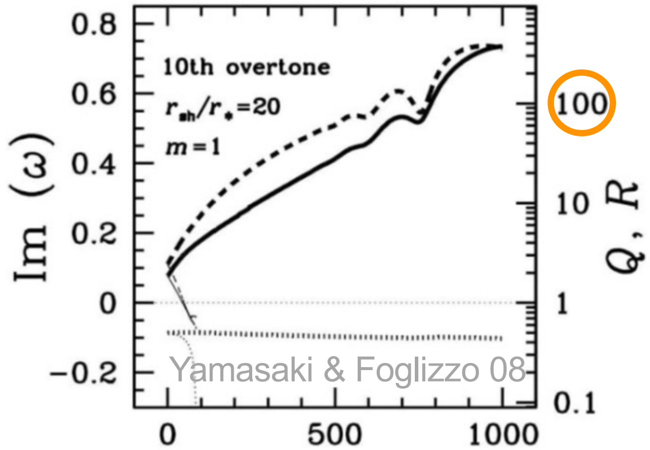


$L = r\,\Omega$

stellar parameters: progenitor mass, compactness, angular momentum, inhomogeneities

\+

puzzling dynamics: SASI, ν-driven convection, low T/|W|, PNS dynamo

\+

uncertain physics: reaction rates, EOS, neutrino interactions, magnetic fields

\+

numerical approximations: neutrino transport, 2D vs 3D, turbulence

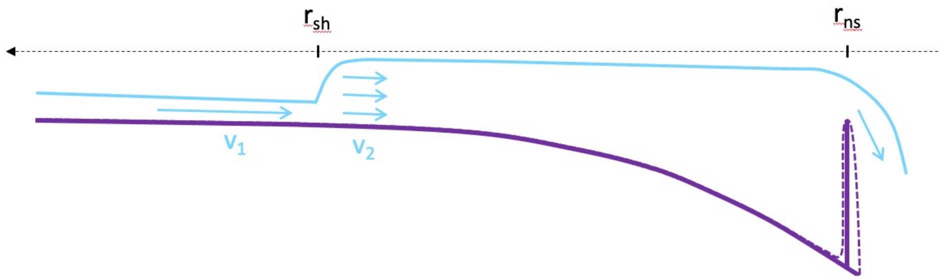
Can gravitational waves and neutrino signatures disentangle these processes ?

Work in progress at Saclay

-analytical insight on SASI with rotation

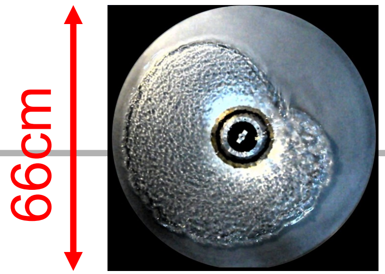
-why is rotation so efficient at destabilizing the prograde mode of SASI ?
-what is the mechanism of spiral SASI with a corotation radius?

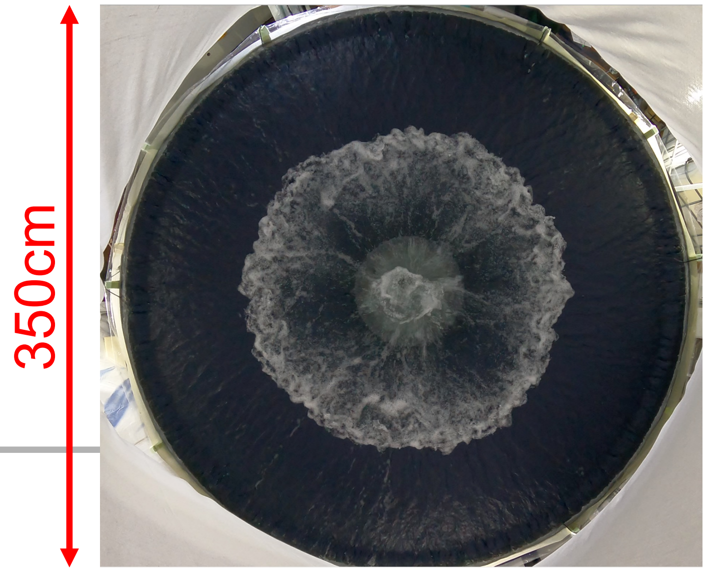
METHOD
spherical/cylindrical comparison
+
adiabatic model of gas accretion
inspired by experimental and
perturbative results in shallow water



-impact of turbulence on SASI dynamics

- without rotation, why turbulent SASI @ 100L/s
seems less unstable than viscous SASI @1L/s?



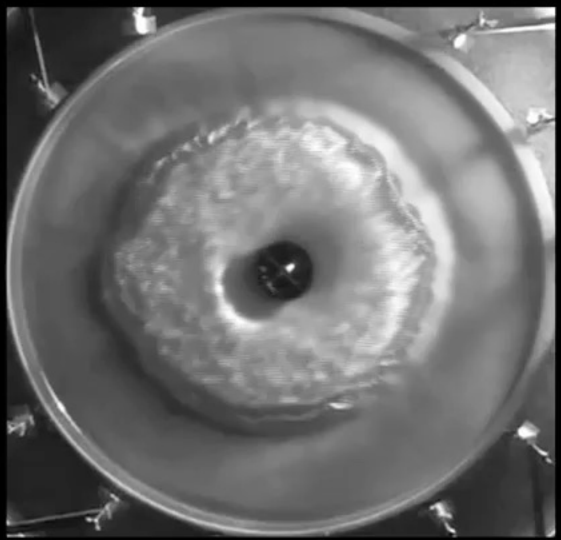


Dynamics of water in the fountain

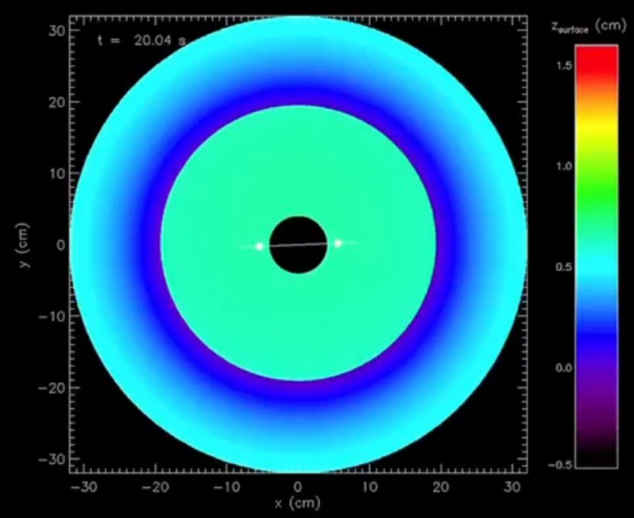
Dynamics of the gas in the supernova core

diameter 40cm ← 1 000 000 x bigger → diameter 400km

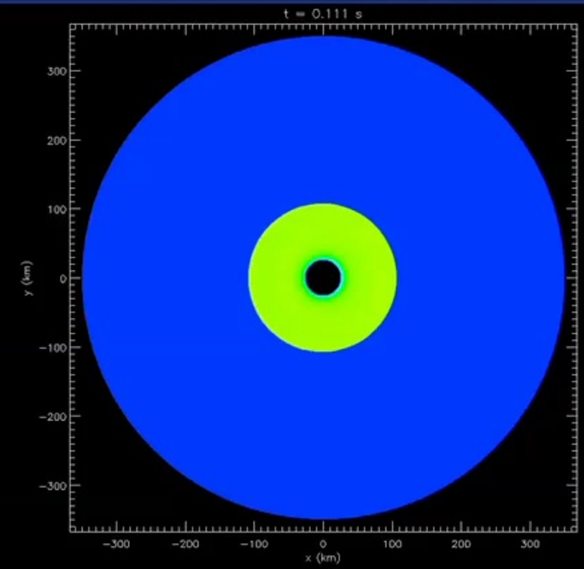
3s/oscillation ← 100 x faster → 0.03s/oscillation



Expérience hydraulique



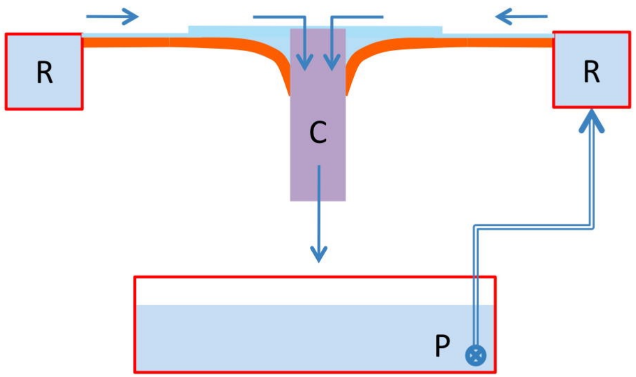
Simulation numérique de l'expérience hydraulique

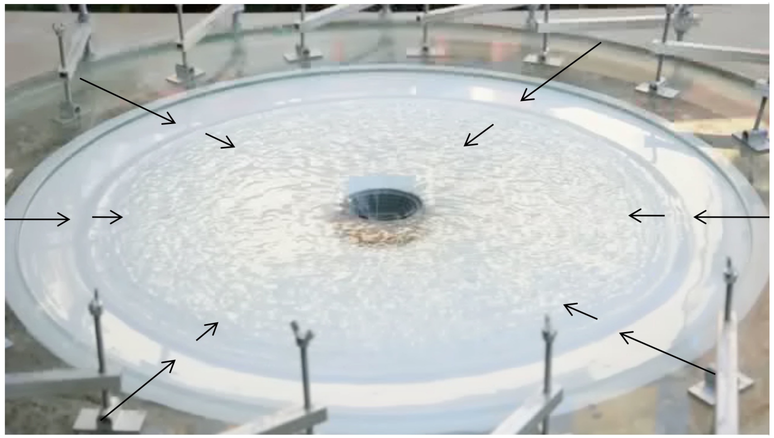


Simulation numérique de l'onde de choc dans le coeur de la supernova

SASI dynamics seems to be adiabatic

Shallow water analogy





adiabatic gas

$$c_s^2 \equiv \frac{\gamma P}{\rho}$$

$$\Phi \equiv -\frac{GM_{\rm ns}}{r}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

$$\frac{\partial v}{\partial t} + (\nabla \times v) \times v + \nabla \left(\frac{v^2}{2} + \frac{c_s^2}{\gamma - 1} + \Phi \right) = \frac{c_s^2}{\gamma} \nabla S$$

Inviscid shallow water is analogue to an isentropic gas γ=2

St Venant

$$c_{\rm sw}^2 \equiv gH$$

$$\Phi \equiv gH_\Phi$$

$$\frac{\partial H}{\partial t} + \nabla \cdot (Hv) = 0$$

$$\frac{\partial v}{\partial t} + (\nabla \times v) \times v + \nabla \left(\frac{v^2}{2} + c_{\rm sw}^2 + \Phi \right) = 0$$

acoustic waves shock wave density ρ	⟷	surface waves hydraulic jump depth H

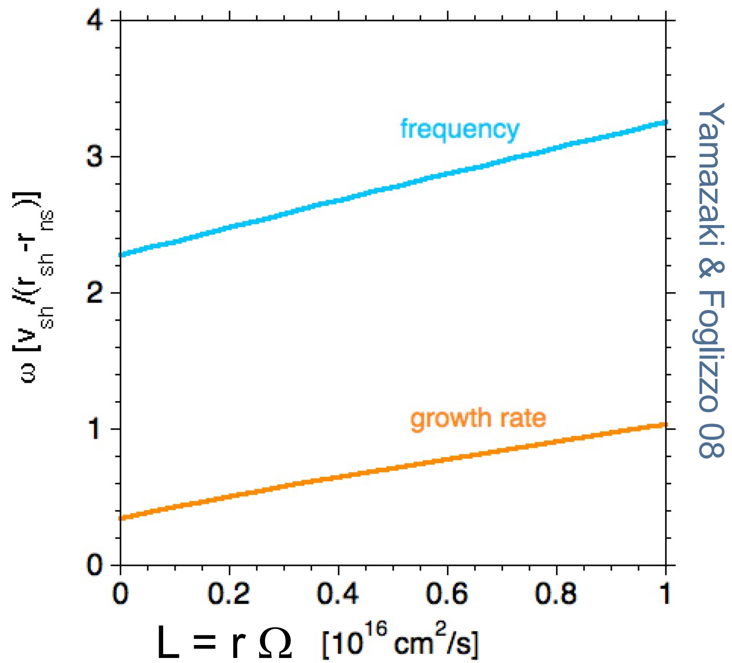
expected scaling

$$\frac{t_{\rm ff}^{\rm sh}}{t_{\rm ff}^{\rm jp}} \equiv \left(\frac{r_{\rm sh}}{r_{\rm jp}} \right) \left(\frac{r_{\rm sh} g H_\Phi^{\rm jp}}{GM_{\rm ns}} \right)^{\frac{1}{2}} \sim 10^{-2}$$

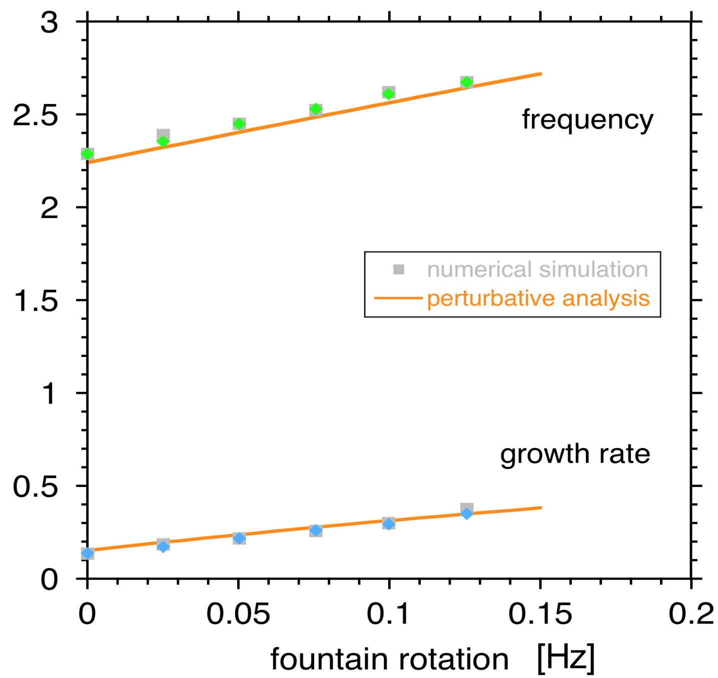
shock radius $\times 10^{-6}$ 200 km $\rightarrow$ 20 cm

oscillation period $\times 10^{2}$ 30 ms $\rightarrow$ 3 s

Perturbative analysis: same destabilizing effect of rotation in adiabatic shallow water and in non-adiabatic gas dynamics



shocked gas dynamics



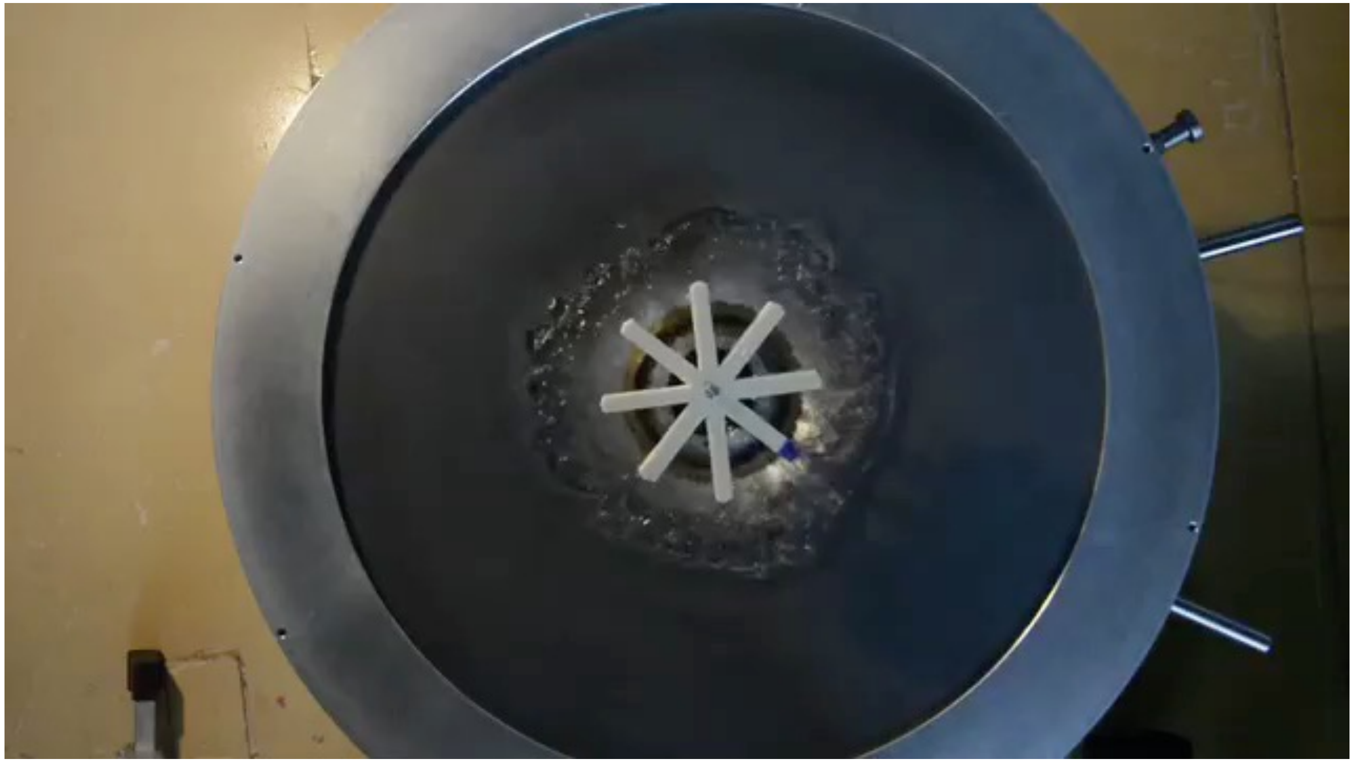
shallow water dynamics

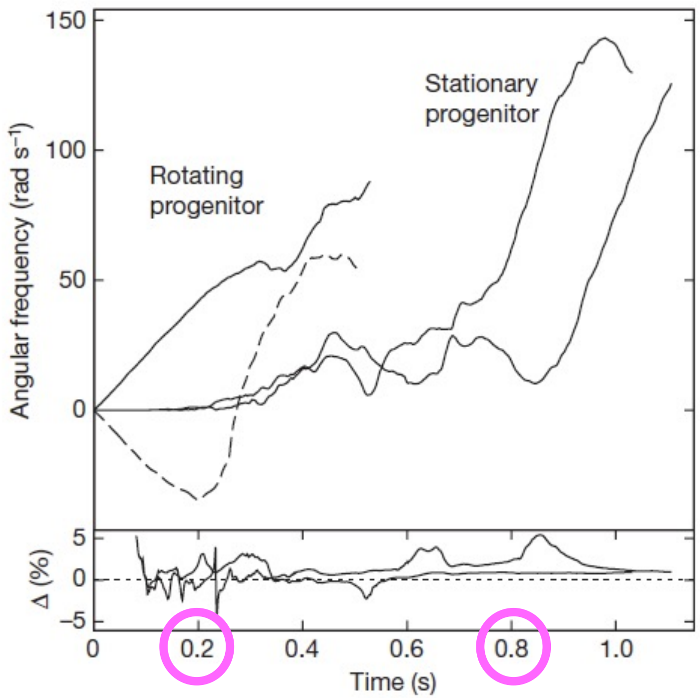
$$\omega' \equiv \omega - \frac{mL}{r^2}$$

Why is the prograde mode of SASI linearly destabilized by rotation?

Impact of spiral SASI on the NS spin:
accreted angular momentum changes its sign as SASI grows

same as in shocked gas dynamics





Blondin & Mezzacappa 07
Kazeroni +16,17

fountain rotation period: 246s
injection slit: 0.55mm
flow rate: 1.17L/s

increased angular momentum in the post shock flow
+
decreased angular momentum in the neutron star
= 0

Comparing stationary shocked accretion in spherical and cylindrical geometries

Postshock subsonic accretion flow ~ quasi-hydrostatic

Same density, pressure, acoustic structures

Different radial velocity = different advection times

$$\left(\frac{r}{r_{\rm sh}}\right)^2 \frac{\rho}{\rho_{\rm sh}}\frac{v}{v_{\rm sh}} = 1 \text{ spherical}, \qquad \frac{v}{v_{\rm sh}} = \left(\frac{r}{r_{\rm sh}}\right) \text{ spherical},$$

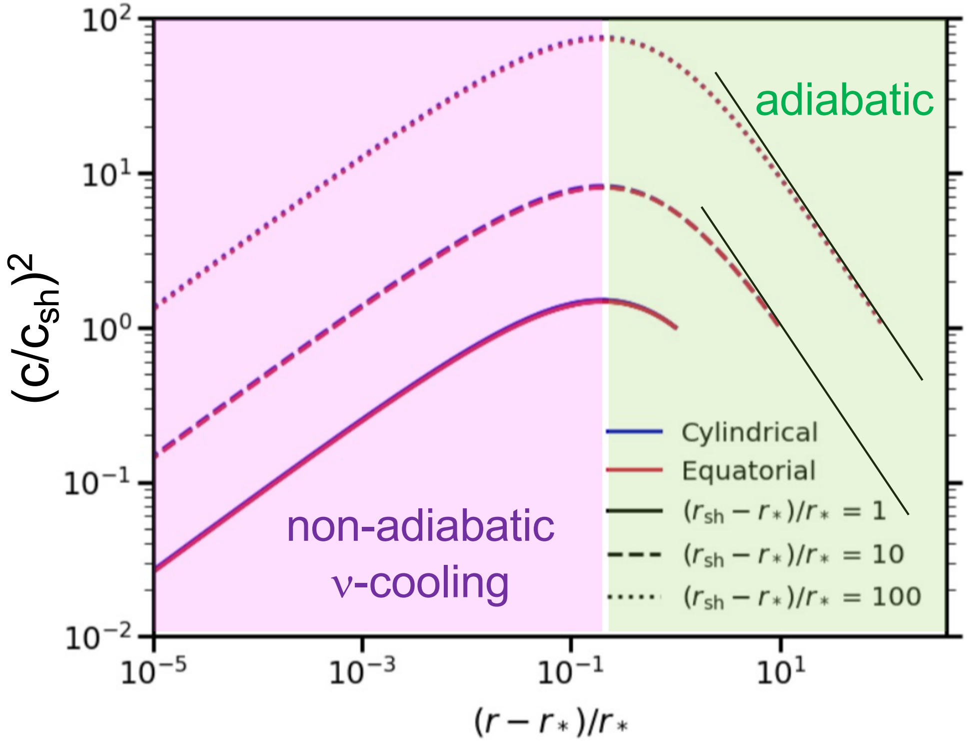
$$\left(\frac{r}{r_{\rm sh}}\right) \frac{\rho}{\rho_{\rm sh}}\frac{v}{v_{\rm sh}} = 1 \text{ cylindrical}. \qquad \frac{v}{v_{\rm sh}} = \left(\frac{r}{r_{\rm sh}}\right)^2 \text{ cylindrical}.$$

γ=4/3

$$\frac{\rho}{\rho_{\rm sh}} = \left(\frac{c}{c_{\rm sh}}\right)^{\frac{2}{\gamma-1}} \sim \left(\frac{r_{\rm sh}}{r}\right)^{\frac{1}{\gamma-1}}$$

adiabatic — Bernoulli $c^2 \sim (\gamma-1)GM/r$

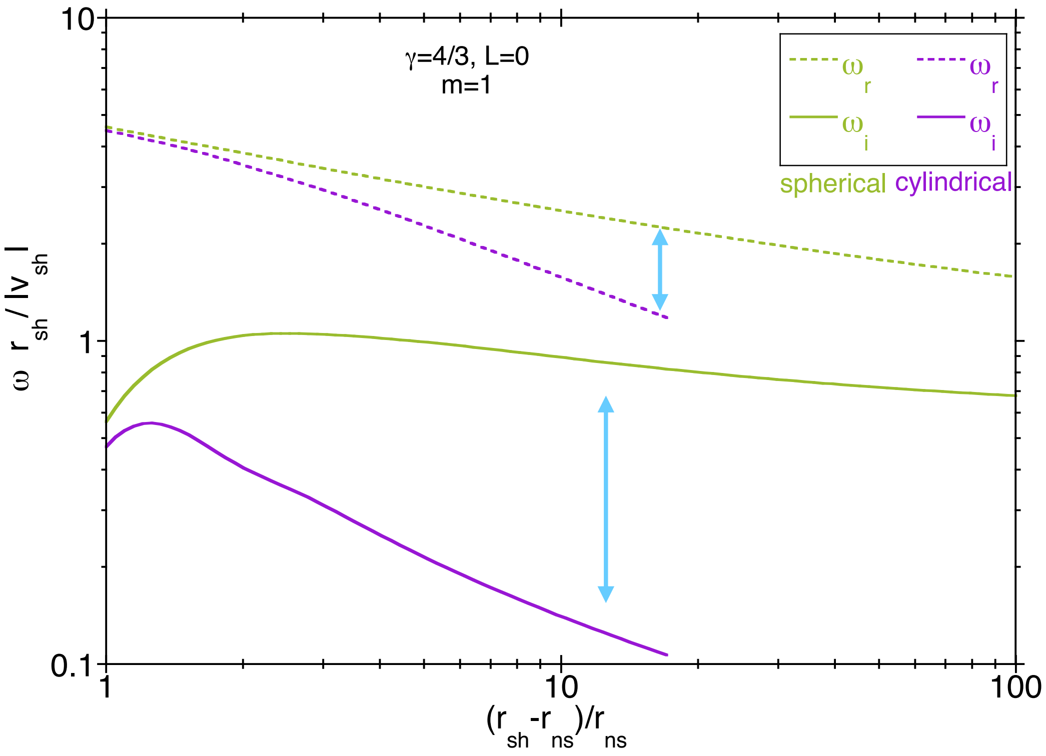
$$\tau_{\rm adv} \equiv \int_{\rm sh}^{r} \frac{{\rm d}r}{v},$$
$$\sim \frac{r_{\rm sh}}{|v_{\rm sh}|} \log \frac{r_{\rm sh}}{r} \text{ spherical},$$
$$\sim \frac{r_{\rm sh}}{|v_{\rm sh}|}\left(\frac{r_{\rm sh}}{r} - 1\right) \text{ cylindrical}.$$

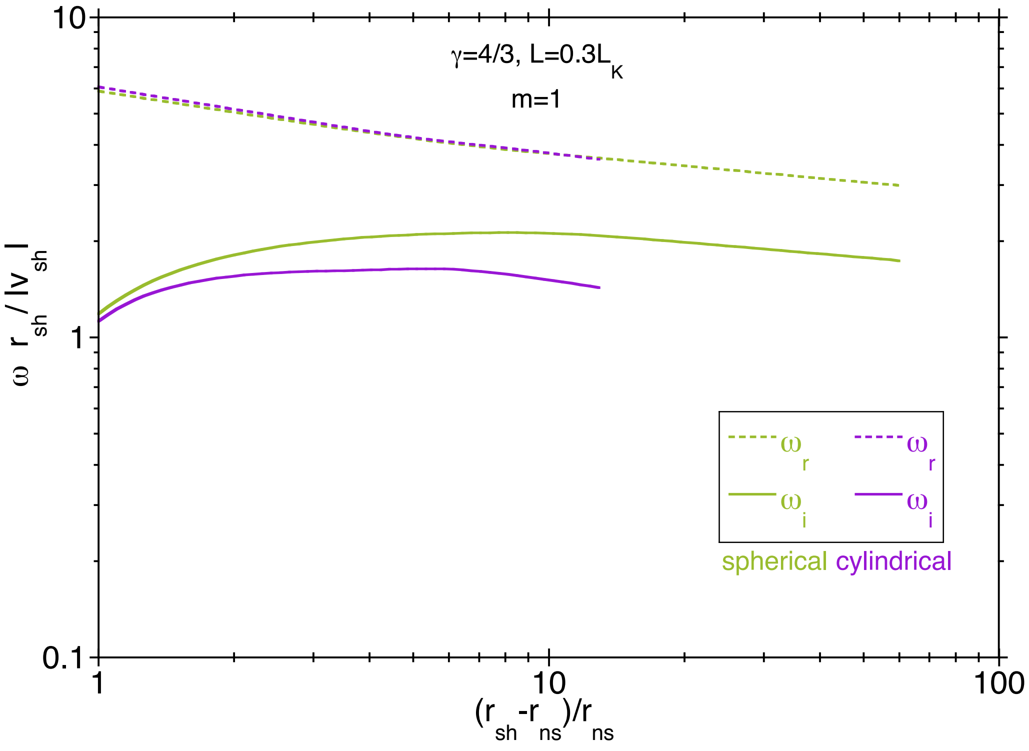


The layer of non-adiabatic cooling dominated by ν-emission is localized near the NS surface
Most of the flow is adiabatic if $r_{sh} >> r_{ns}$

Walk, Foglizzo, Tamborra, in prep

Growth rate and oscillation frequency of SASI for a large shock radius: cylindrical vs spherical geometry





without rotation,
the spherical and cylindrical eigenfrequencies
diverge as the shock distance increases

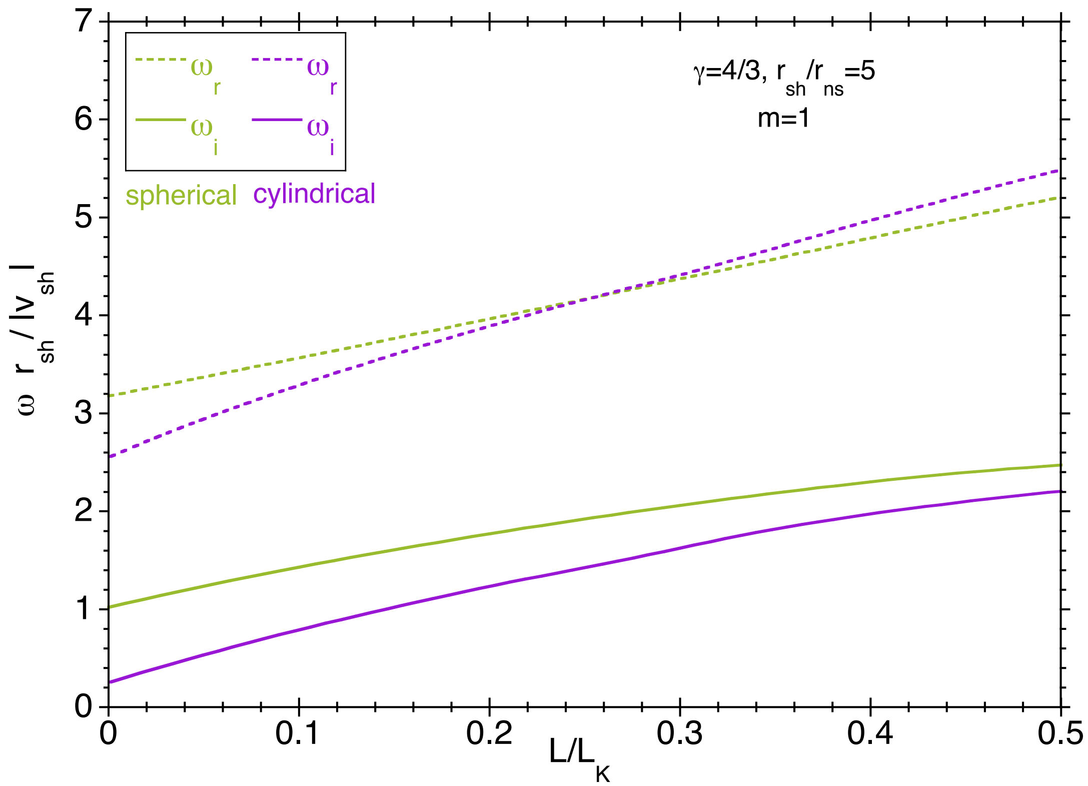
as expected from an advective-acoustic mechanism

with 30% Keplerian rotation,
the spherical and cylindrical eigenfrequencies
remain similar

unexpected for an advective-acoustic mechanism??

Walk, Foglizzo, Tamborra, in prep

Growth rate and oscillation frequency of SASI for a large shock radius: cylindrical vs spherical geometry



the spherical and cylindrical eigenfrequencies are surprisingly similar
despite very different advection times (x2.5)

unexpected for an advective-acoustic mechanism??

$$
\begin{aligned}
\tau_{\rm adv} &\equiv \int_{\rm sh}^{r} \frac{{\rm d}r}{v}, \\
&\sim \frac{r_{\rm sh}}{|v_{\rm sh}|} \log \frac{r_{\rm sh}}{r} \quad \text{spherical}, \\
&\sim \frac{r_{\rm sh}}{|v_{\rm sh}|} \left(\frac{r_{\rm sh}}{r} - 1 \right) \quad \text{cylindrical}.
\end{aligned}
$$

Walk, Foglizzo, Tamborra, in prep

adiabatic inner boundary condition
inspired by the shallow water experiment

Stellar SASI:

- spherical geometry
- γ=4/3
- buoyancy effects
- neutronization at the NS surface

non adiabatic ν-processes

➢ 4th order differential system

$$\omega' \equiv \omega - \frac{mL}{r^2}$$

Yamasaki & Foglizzo 08

🤢

$$\begin{cases} \frac{\partial}{\partial r}(r\delta v_\phi) = \frac{im}{v_r}\left(v_r\delta v_r - \frac{\delta K}{m^2} + \frac{c^2}{\gamma}\delta S\right) \\ \frac{\partial \delta h}{\partial r} = \frac{i\omega'}{v_r}\frac{\delta\rho}{\rho} - \frac{im}{rv_r}\delta v_\phi \,, \\ \left(\frac{\partial}{\partial r} - \frac{i\omega'}{v_r}\right)\delta S = \delta\left(\frac{\mathcal{L}}{pv_r}\right) \,, \\ \left(\frac{\partial}{\partial r} - \frac{i\omega'}{v_r}\right)\frac{\delta K}{m^2} = \delta\left(\frac{\mathcal{L}}{\rho v_r}\right) \,. \end{cases}$$

Shallow water analogue:

- cylindrical geometry
- γ=2
- isentropic fluid
- adiabatic inner boundary

adiabatic evolution

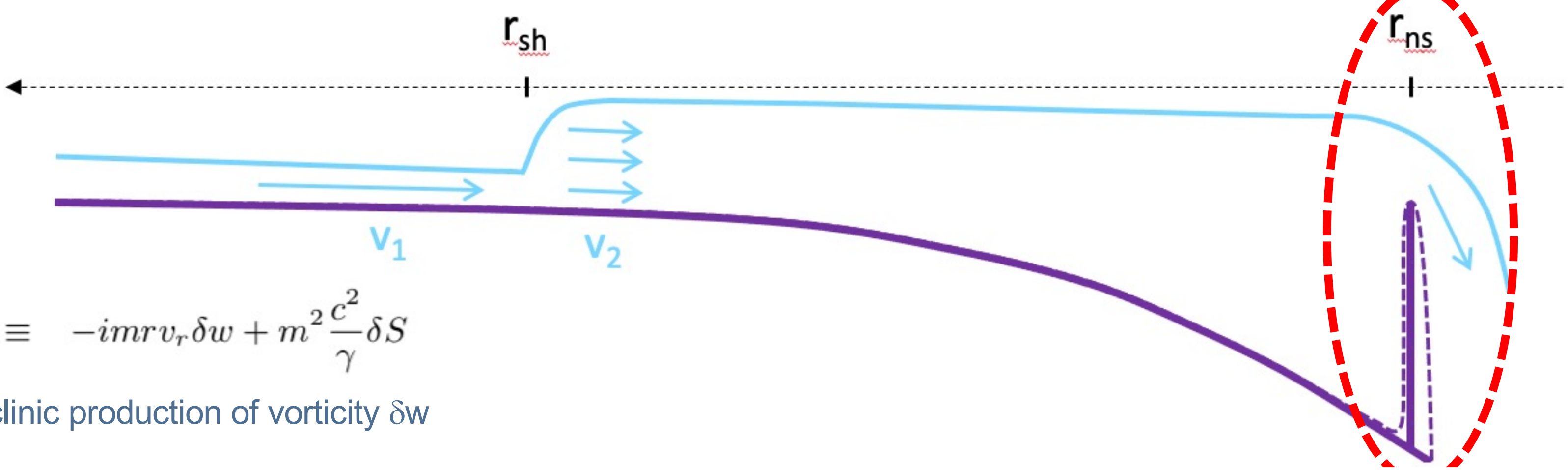
➢ conservation of "vorticity" δK + entropy δS

➢ 2nd order differential system

➢ analytic approximation

🙂

$$\begin{cases} \frac{\partial^2 Y}{\partial X^2} + \left[\frac{\omega'^2}{c^2} - \frac{m^2}{r^2}(1-\mathcal{M}^2)\right]\frac{Y}{v_r^2} = \mathcal{S}, \\ \mathcal{S} \equiv -\frac{r_{\rm sh}}{v_{\rm sh}}\delta w_{\rm sh} e^{\int_{\rm sh}\frac{i\omega'}{c^2}{\rm d}X}\frac{\partial}{\partial X}\left(\frac{\mathcal{M}_{\rm sh}^2}{\mathcal{M}^2}e^{\int_{\rm sh}\frac{i\omega'}{v_r}{\rm d}r}\right) \end{cases}$$



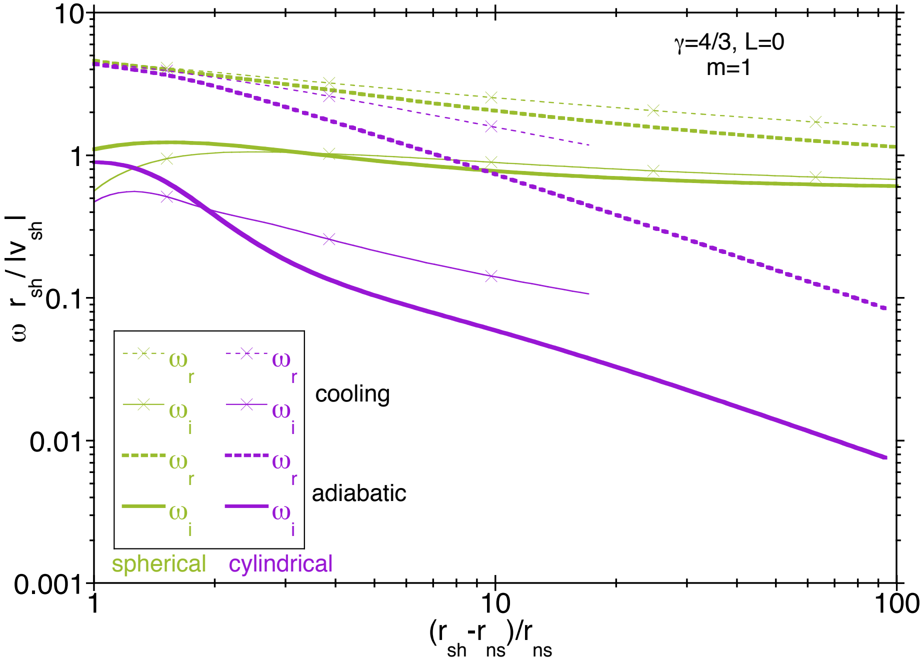
$$\delta K \equiv -imrv_r\delta w + m^2\frac{c^2}{\gamma}\delta S$$

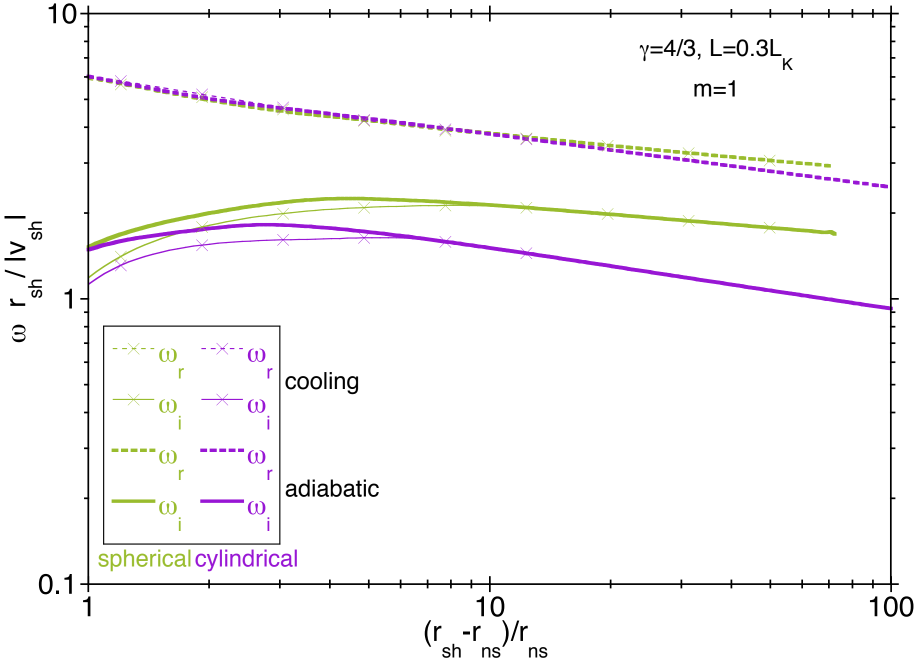
baroclinic production of vorticity δw

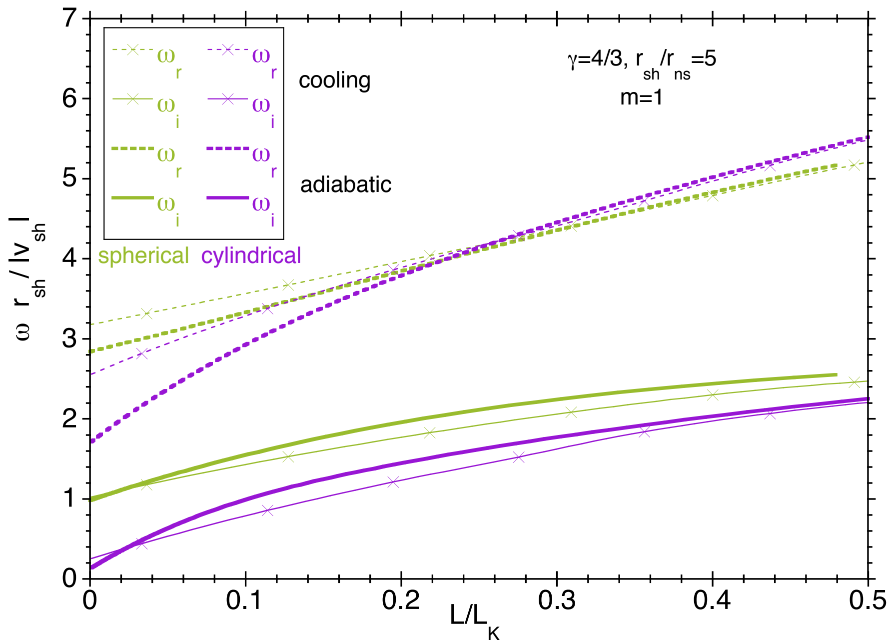
$${\rm d}X \equiv \frac{v_r}{1-\mathcal{M}^2}{\rm d}r,$$

$$Y \equiv r\delta v_\phi e^{\int_{\rm sh}\frac{i\omega'\mathcal{M}^2}{1-\mathcal{M}^2}\frac{{\rm d}r}{v_r}},$$

Comparison of the non-adiabatic and adiabatic models







The adiabatic model
captures the main properties
of SASI eigenfrequencies with rotation

The adiabatic model can be interpreted physically

$$\mathrm{dX} \equiv \frac{v_r}{1-\mathcal{M}^2}\mathrm{dr},$$

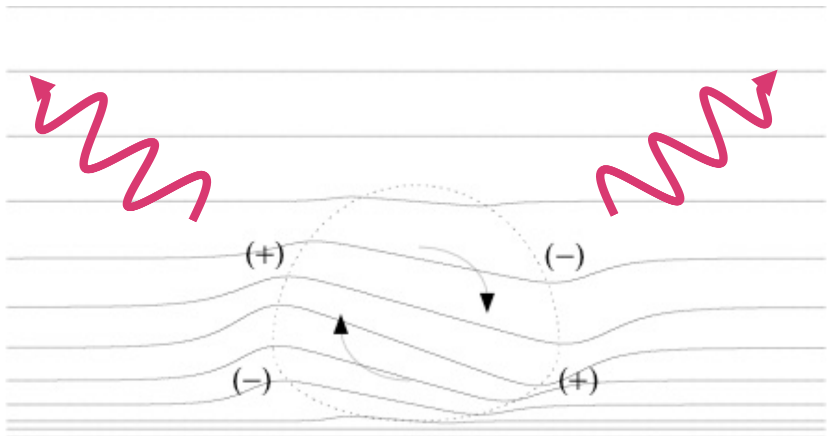
$$\omega' \equiv \omega - \frac{mL}{r^2}$$

$$Y \equiv r\delta v_\phi \mathrm{e}^{\int_{\mathrm{sh}} \frac{i\omega' \mathcal{M}^2}{1-\mathcal{M}^2}\frac{\mathrm{dr}}{v_r}},$$

Forced oscillator 🙂

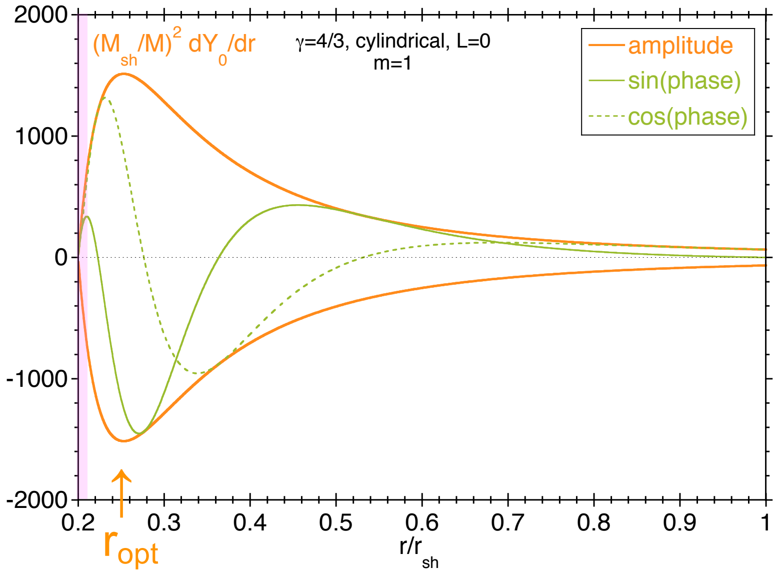
$$\left\{\begin{aligned} &\frac{\partial^2 Y}{\partial X^2} + \left[\frac{\omega'^2}{c^2} - \frac{m^2}{r^2}(1-\mathcal{M}^2)\right]\frac{Y}{v_r^2} = \mathcal{S}, \\ &\mathcal{S} \equiv -\frac{r_{\mathrm{sh}}}{v_{\mathrm{sh}}}\delta w_{\mathrm{sh}} \mathrm{e}^{\int_{\mathrm{sh}} \frac{i\omega'}{c^2}\mathrm{dX}} \frac{\partial}{\partial X}\left(\frac{\mathcal{M}^2_{\mathrm{sh}}}{\mathcal{M}^2}\mathrm{e}^{\int_{\mathrm{sh}} \frac{i\omega'}{v_r}\mathrm{dr}}\right)\end{aligned}\right.$$

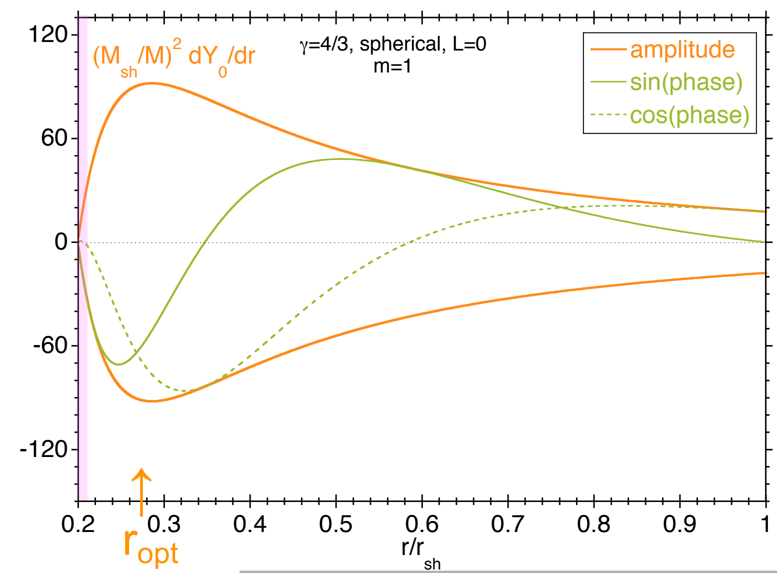
The acoustic cavity is forced by the radial advection of vorticity perturbations δw



vortical-acoustic coupling

The effect of moderate rotation is clarified





$r_{opt} > r_{ns}$ → insensitive to the cooling layer

The forcing efficiency depends on

- the forcing amplitude $\frac{\partial Y_0}{\partial r}\frac{\mathcal{M}_{\rm sh}^2}{\mathcal{M}^2}$ increases inward maximal at r_{opt}
- the phase match $e^{\int_{\rm sh}\frac{i\omega'}{v_r}{\rm d}r}$ phase mixing as $v_r \to 0$

$$\left\{\begin{array}{l}\frac{\partial^2 Y}{\partial X^2}+\left[\frac{\omega'^2}{c^2}-\frac{m^2}{r^2}(1-\mathcal{M}^2)\right]\frac{Y}{v_r^2}=\mathcal{S},\\ \mathcal{S}\equiv-\frac{r_{\rm sh}}{v_{\rm sh}}\delta w_{\rm sh}e^{\int_{\rm sh}\frac{i\omega'}{c^2}{\rm d}X}\frac{\partial}{\partial X}\left(\frac{\mathcal{M}_{\rm sh}^2}{\mathcal{M}^2}e^{\int_{\rm sh}\frac{i\omega'}{v_r}{\rm d}r}\right)\end{array}\right.$$

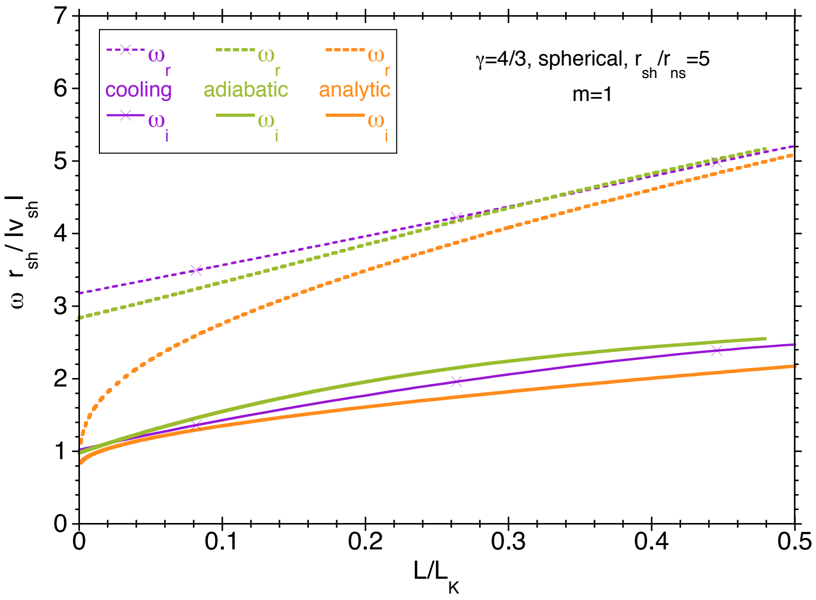
$Y_0(r)$ = (acoustic) solution to the homogeneous equation

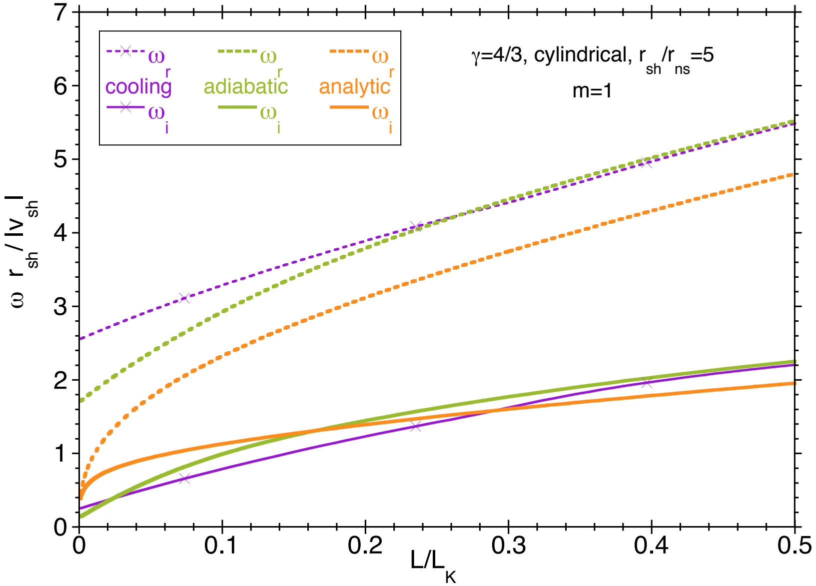
$$a_1'Y_0^{\rm sh}+a_2'\left(\frac{\partial Y_0}{\partial X}\right)_{\rm sh}+a_3'Y_0^{\rm ns}=-\int_{\rm ns}^{\rm sh}\frac{\partial}{\partial r}\left(Y_0e^{\int_{\rm sh}\frac{i\omega'\mathcal{M}^2}{1-\mathcal{M}^2}\frac{{\rm d}r}{v_r}}\right)\frac{\mathcal{M}_{\rm sh}^2}{\mathcal{M}^2}e^{\int_{\rm sh}\frac{i\omega'}{v_r}{\rm d}r}{\rm d}r,$$

$$\omega'\equiv\omega-\frac{mL}{r^2}$$

Reduced phase mixing near the PNS explains the efficient destabilizing effect of moderate rotation on the prograde mode of SASI

The mechanism of spiral SASI is clarified





$$a_1' Y_0^{\rm sh} + a_2' \left(\frac{\partial Y_0}{\partial X}\right)_{\rm sh} + a_3' Y_0^{\rm ns} =$$

$$-\int_{\rm ns}^{\rm sh} \frac{\partial}{\partial r}\left(Y_0 {\rm e}^{\int_{\rm sh} \frac{i\omega' \mathcal{M}^2}{1-\mathcal{M}^2}\frac{{\rm d}r}{v_r}}\right) \frac{\mathcal{M}_{\rm sh}^2}{\mathcal{M}^2} {\rm e}^{\int_{\rm sh} \frac{i\omega'}{v_r}{\rm d}r} {\rm d}r,$$

$$\Psi \equiv \int_{\rm sh}^{r} \omega' \frac{{\rm d}r}{v}$$

$$\omega' \equiv \omega - \frac{mL}{r^2}$$

$$\omega_r \equiv \frac{mL}{r_{\rm co}^2},$$

Taylor expansion

$$\Psi \sim \Psi_{\rm co} - \left(\frac{r - r_{\rm co}}{\Delta r}\right)^2$$

The stationary phase approximation captures the dominant coupling at the corotation radius $\omega'=0$

$$a_1' Y_0^{\rm sh} + a_2' \left(\frac{\partial Y_0}{\partial X}\right)_{\rm sh} + a_3' Y_0^{\rm ns} =$$

$$-{\rm e}^{i\Psi_{\rm co}} \pi^{\frac{1}{2}} {\rm e}^{-i\frac{\pi}{4}} \frac{\mathcal{M}_{\rm sh}^2}{\mathcal{M}_{\rm co}^2} \left(\frac{\partial Y_0}{\partial r}\right)_{\rm co} \Delta r.$$

$r_{co} >> r_{ns}$ explains:

- cylindrical/spherical similarity
- adiabatic/non-adiabatic similarity

Conclusions

Most massive stars explode in a non-spherical manner

A diversity of dynamical evolutions is expected based on the interplay of SASI, ν-driven convection and rotation.

Neutrinos and GW carry direct information on the explosion engine -> LEAK collaboration

Improved understanding of spiral SASI inspired by the shallow water analogy

- SASI mechanism is mostly adiabatic
- SASI is best understood as a forced oscillator

- prograde SASI mode destabilized by rotation = reduced phase mixing near the PNS
- corotating SASI spiral = stationary phase approximation at the corotation radius
- warning on using the cylindrical approximation

In progress:

Interpreting turbulent experimental results using this new framework

Effective extraction of the stellar parameters, including rotation, from ν and GW frequencies?