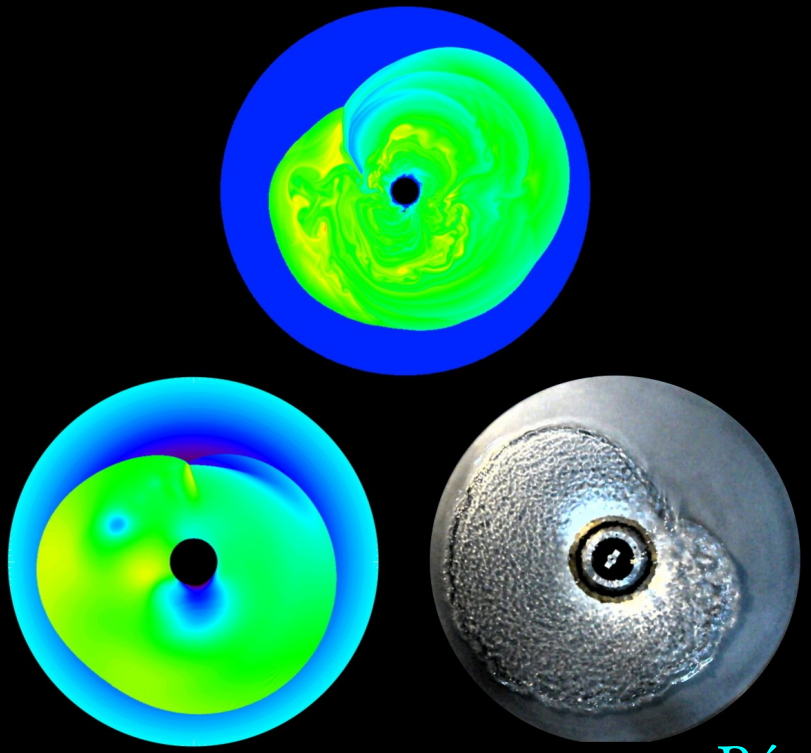
Incidence of stellar rotation on the explosion mechanism of massive stars



Rémi Kazeroni (MPA)

with Thierry Foglizzo, Jérôme Guilet (CEA)

CoCoNuT Meeting 2018

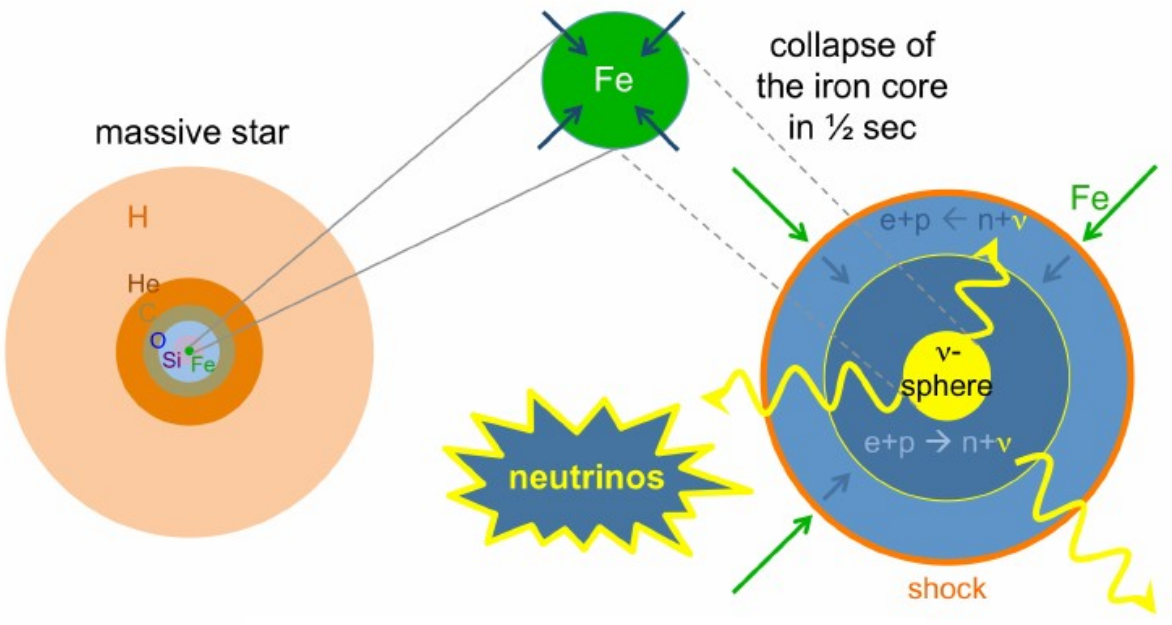
Max-Planck-Institut für Astrophysik

CEA Saclay
15/11/2018

Outline

- Hydrodynamical instabilities in collapsing stellar cores
- Dynamical influence of rotation on one-armed instabilities
- Angular momentum budget: from progenitor rotation to pulsar spin

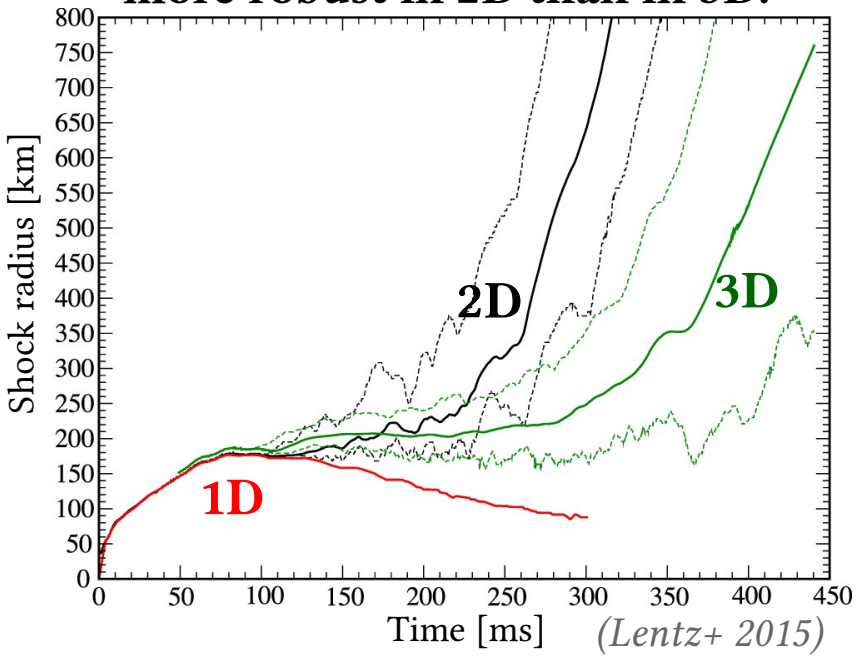
Neutrino-driven explosion *(Bethe & Wilson 1985)*



$$E_{\rm grav} \equiv \frac{GM_{\rm NS}^2}{R_{\rm NS}} \sim 1.7 \times 10^{53} \left(\frac{30{\rm km}}{R_{\rm NS}}\right) \left(\frac{M_{\rm NS}}{1.4M_\odot}\right)^2 {\rm erg}$$

Does not work in 1D,

more robust in 2D than in 3D!

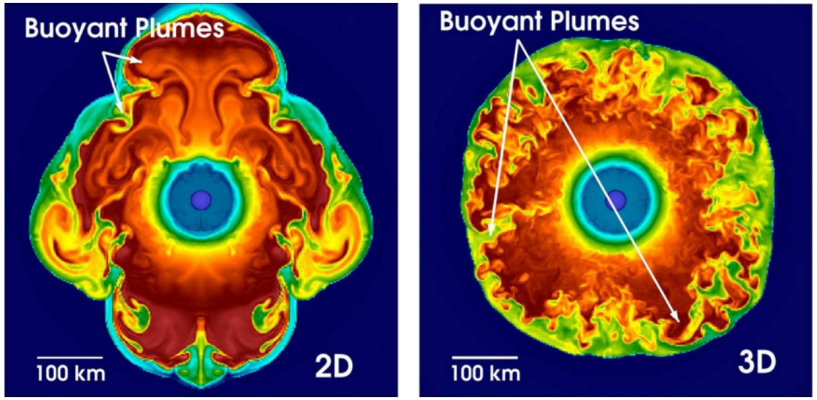


(Lentz+ 2015)

Simulation ingredients

- Initial conditions
- MHD
- Neutrino transport
- Equation of state
- General relativity

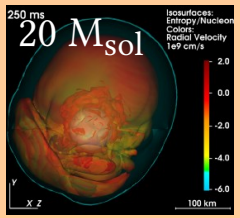
Multi-D hydro

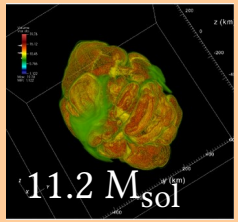


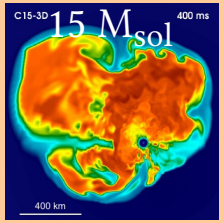
(Murphy+ 2013)

Which ingredients could make explosions more robust?

Complex models





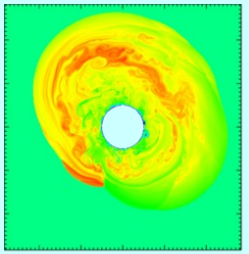


(Lentz+ 2015, Melson+ 2015b, Müller 2015)

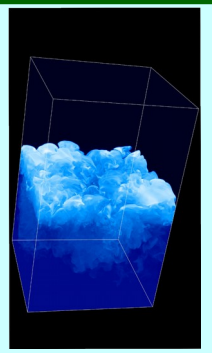
simplicity

realism

Simplified models



SASI



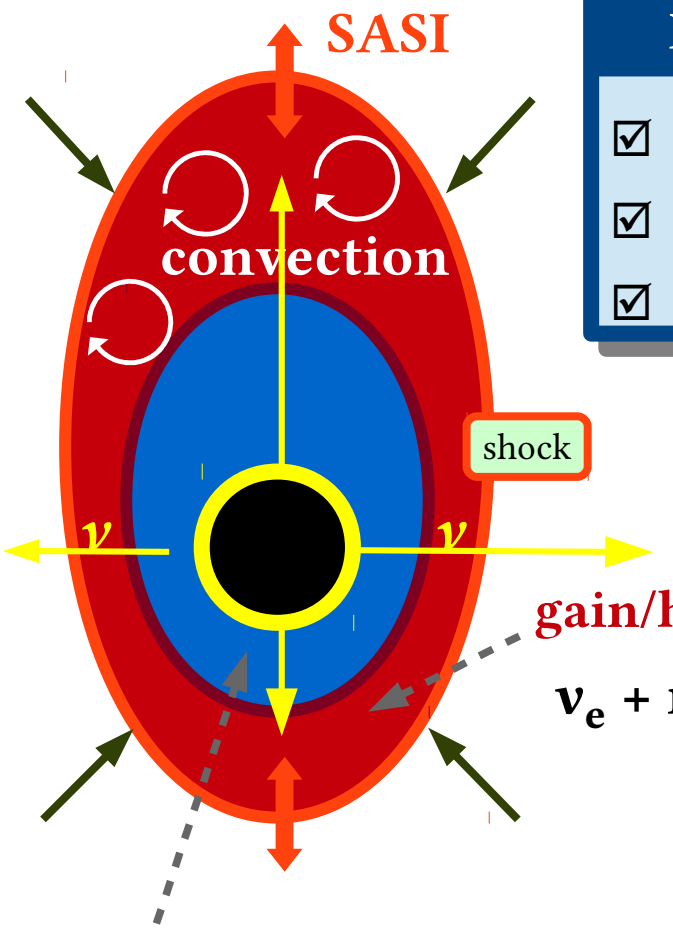
convection

(RK+ 2016, 2017, 2018)

Ingredients

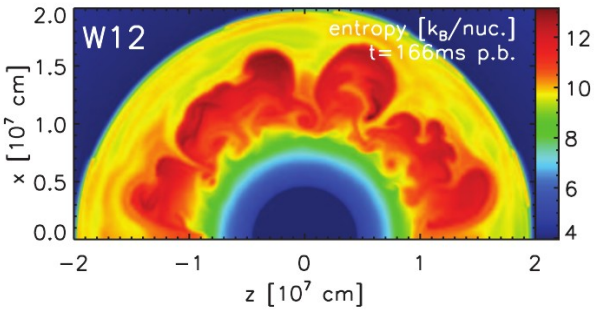
- rotation
- magnetic fields
- perturbations
- numerical resolution

See talks by M. Bugli, B. Pagani, N. Yadav, …



Neutrino-driven convection

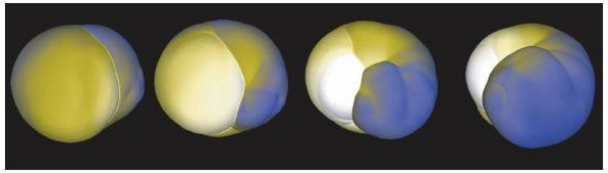
- ☑ neutrino heating in the gain region
- ☑ spatial scale: l ~ 5-6
- ☑ may be stabilized by advection



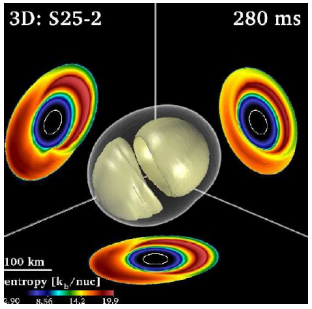
(Foglizzo+ 2006)

Standing Accretion Shock Instability (SASI, Blondin+ 2003)

- ☑ advective-acoustic cycle
- ☑ spatial scale: l ~ 1-2
- ☑ spiral and sloshing motions



(Blondin & Mezzacappa 2007)



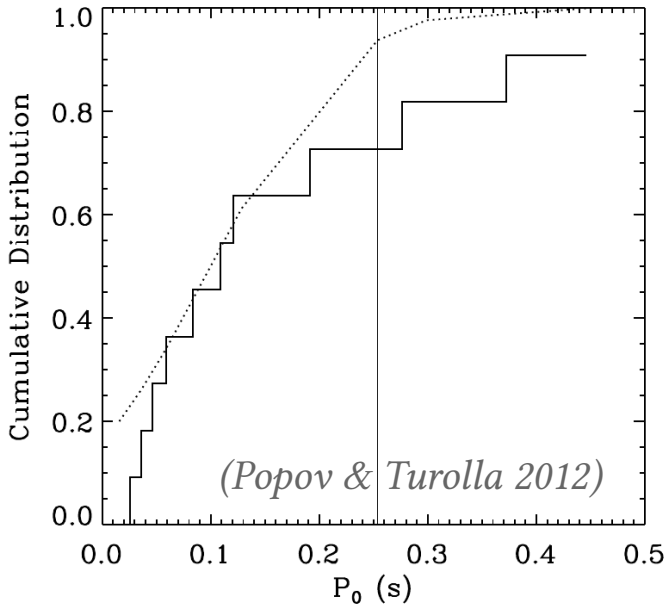
(Hanke+ 2013)

☑ Hydrodynamic instabilities can induce a **large scale asymmetric explosion**.

Non-rotating picture!

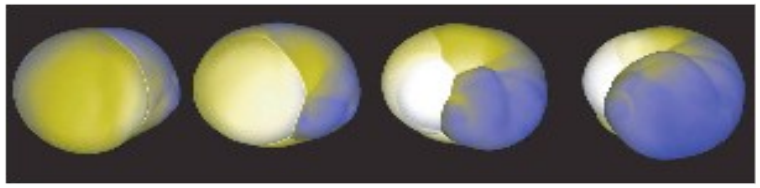
Which rotation rates should be considered?

Pulsar spin at birth



- Natal pulsar spin distribution: from ~10ms to several 100ms.
- Stellar evolution: j ~ 10^{15} cm^2/s (P_0 ≈ 6 ms) *(e.g. Heger+ 2005).*
- Large uncertainties on angular momentum transport processes.
- Binarity may alter the picture and widen the parameter space.

SASI

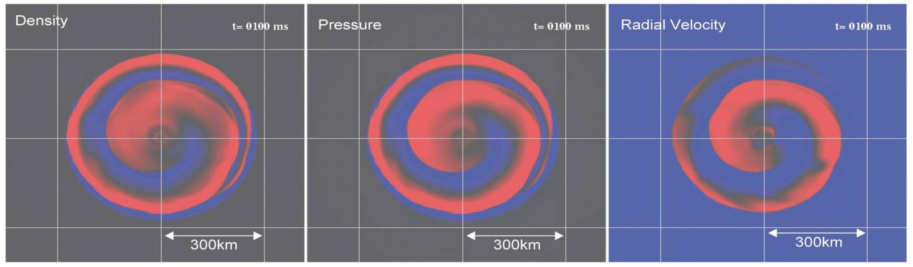


(Blondin & Mezzacappa 2007)

j = 10^{15} cm^2/s or P_0 ≈ 6 ms

"Slow" rotating progenitor

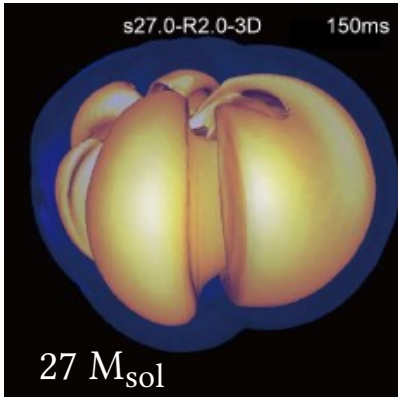
Low-T/|W| (corotation)

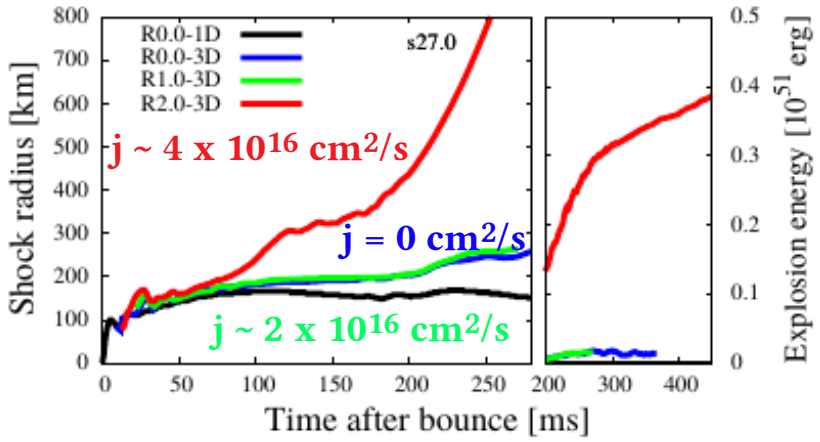


(Takiwaki+ 2016)

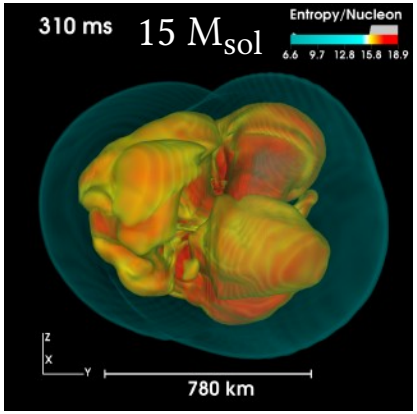
j = 4.10^{16} cm^2/s or P_0 ≈ 0.15 ms

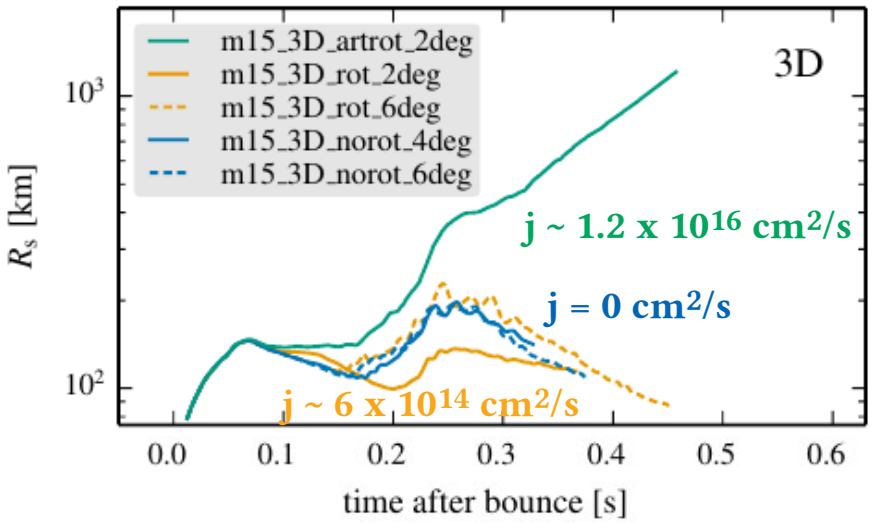
"Fast" rotating progenitor





(Takiwaki+ 2016)





(Summa+ 2018)

- Explosion enhanced only for very fast rotation due to a strong spiral mode associated to low-T/|W|
- Would result in a sub-ms NS

- Explosion obtained only for the fast rotation case due to a strong spiral mode associated to SASI
- Would result in a 5 ms NS

Outline of the talk

- Hydrodynamical instabilities in collapsing cores
- Dynamical influence of rotation on one-armed instabilities
- Angular momentum budget: from progenitor rotation to pulsar spin

Physics – stationary flow

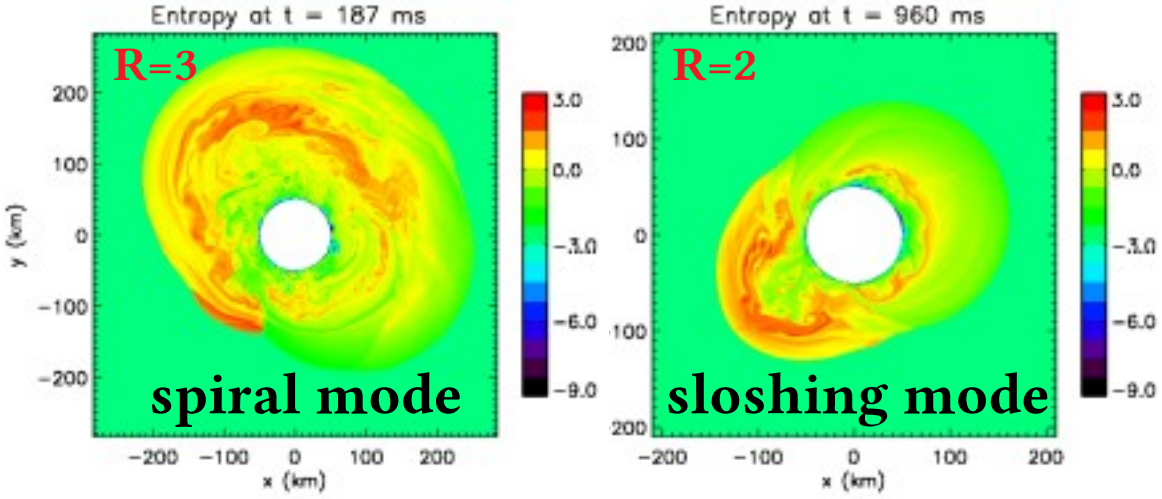
- ☑ Perfect gas equation of state (γ=4/3)
- ☑ Approximation of the cooling

(Blondin & Mezzacappa 2006)

- ☑ No neutrino heating

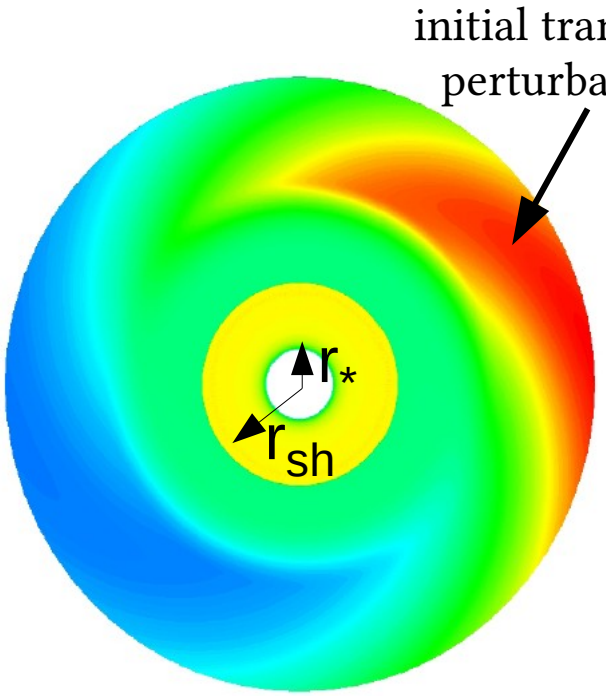
Numerics – parametric study with RAMSES

- Radii ratio: $R=r_{sh} / r_*$ (e.g. r_{sh} =150 km, r_*= 50 km)

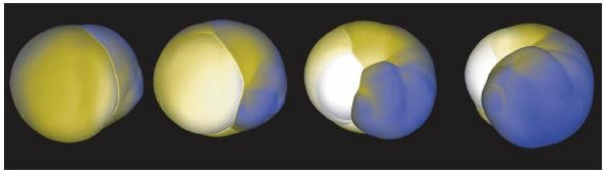


(RK, Guilet & Foglizzo 2016)

An idealized model to study SASI



2D cylindrical domain equatorial plane

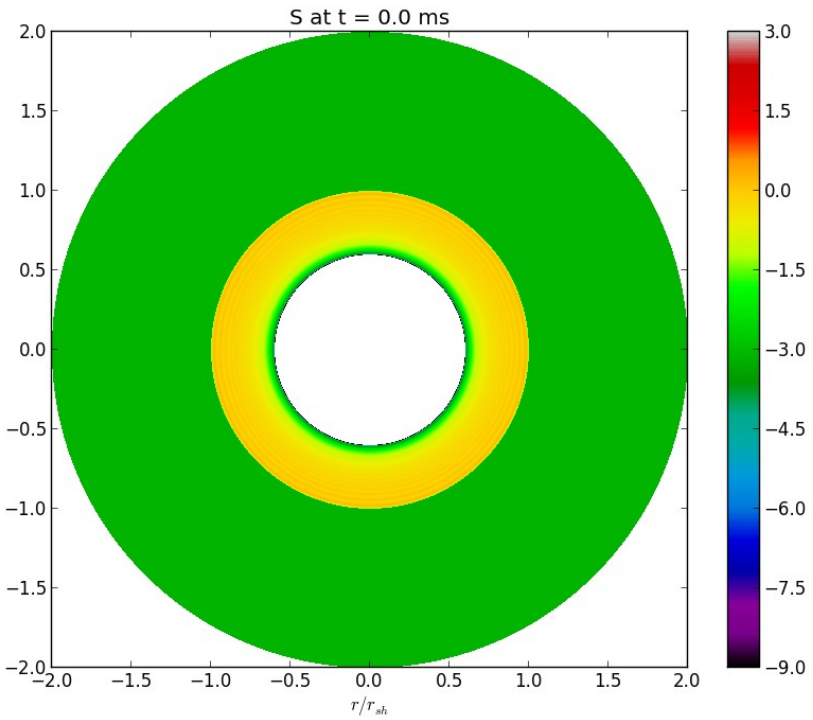


A parametric study (R)

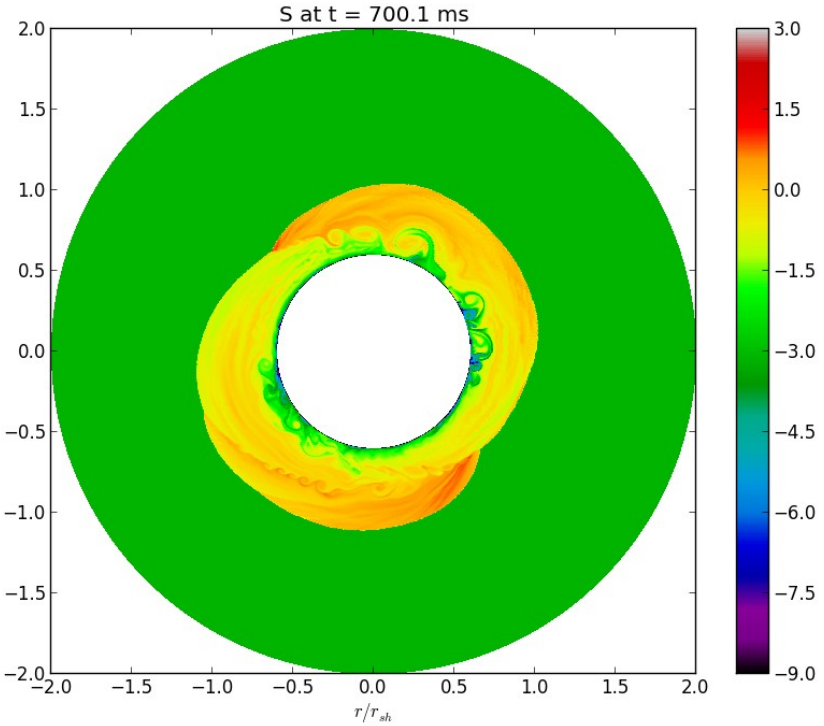
R = 1.67

$j = 4.10^{15}$ cm^2/s

$P_0 \approx 1.5$ ms



SASI, spiral m=2



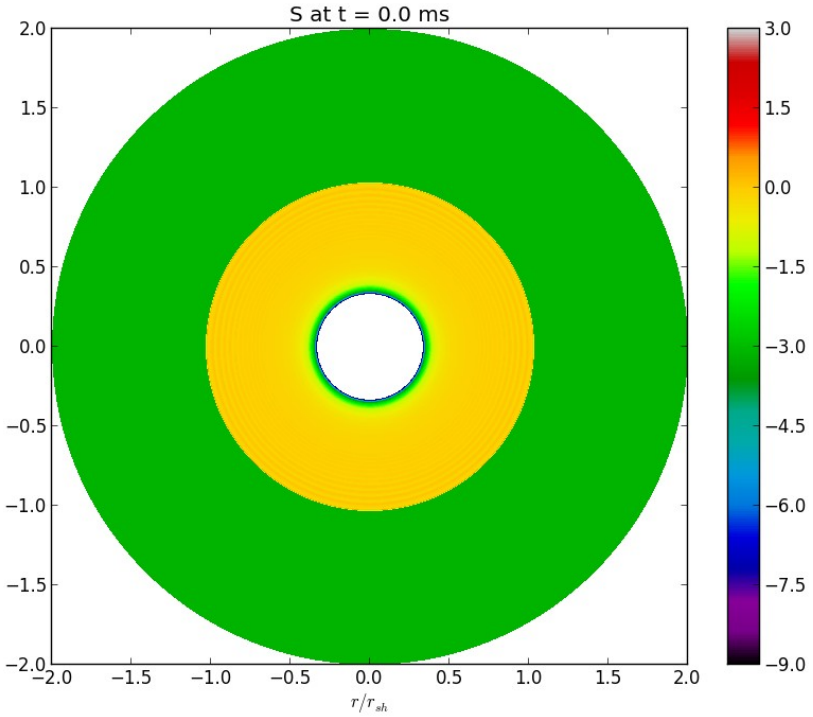
A parametric study (R)

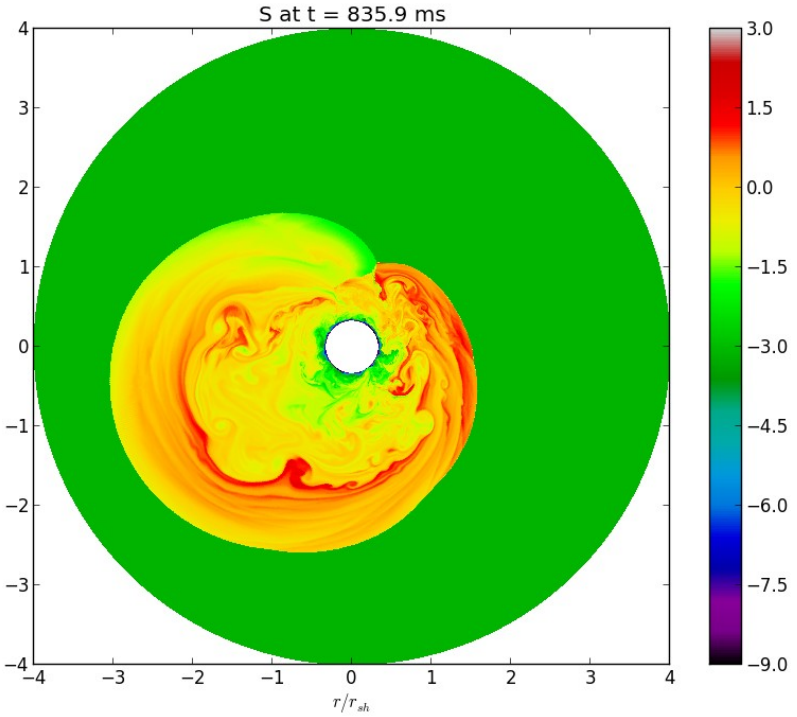
R = 3

$j = 4.10^{15}$ cm²/s

$P_0 \approx 1.5$ ms

SASI, spiral m=1





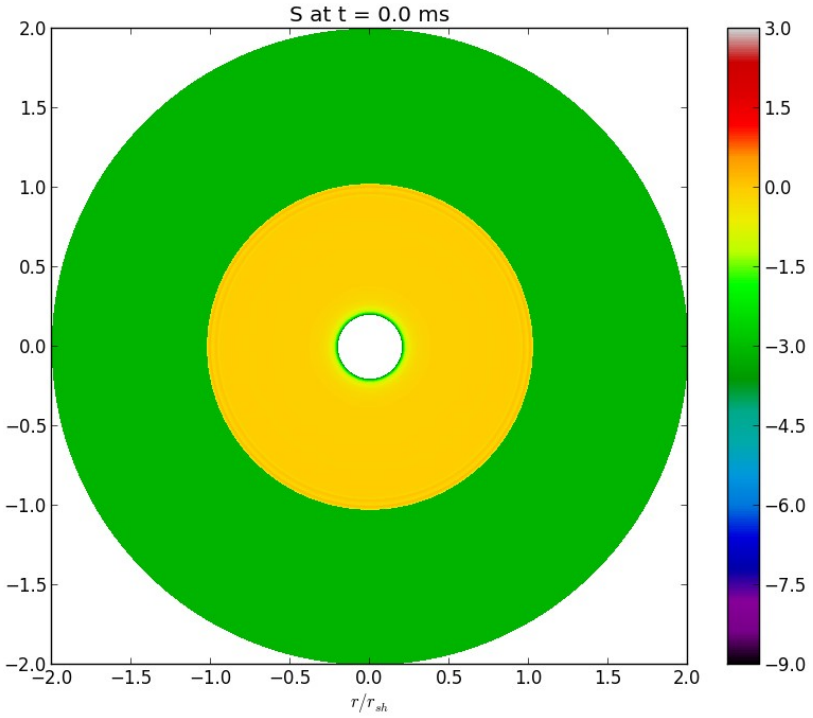
A parametric study (R)

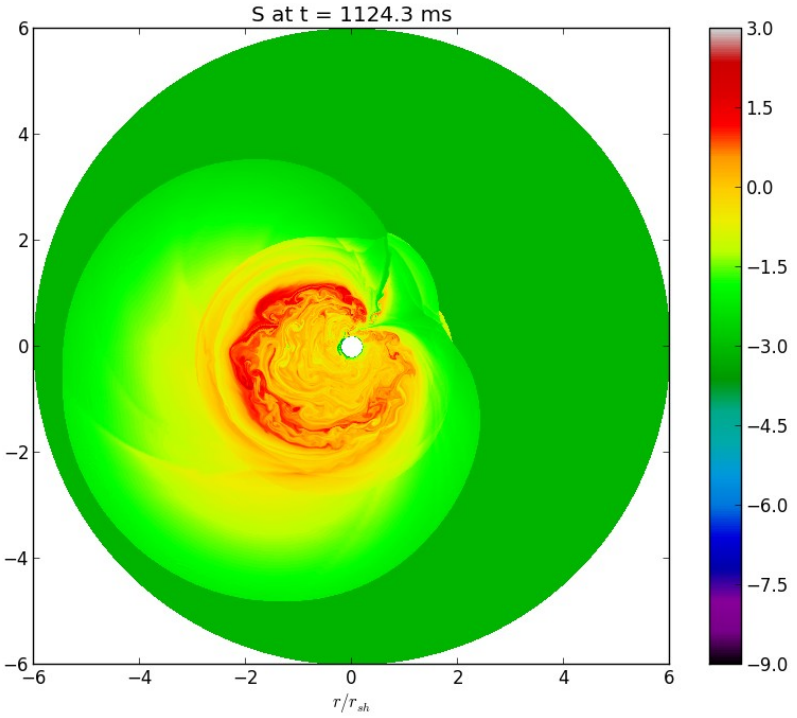
R = 5

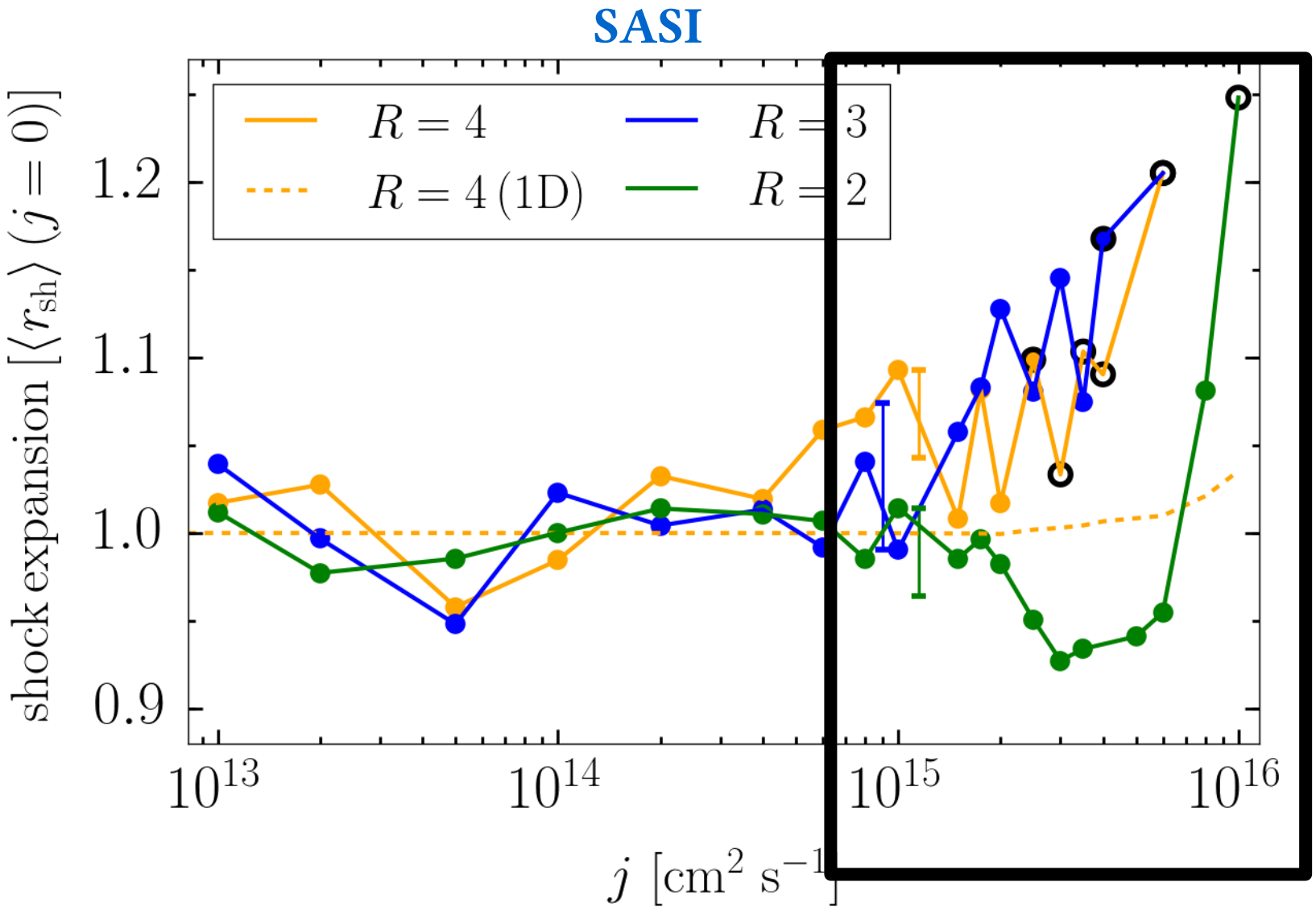
$j = 4.10^{15}$ cm²/s

$P_0 \approx 1.5$ ms

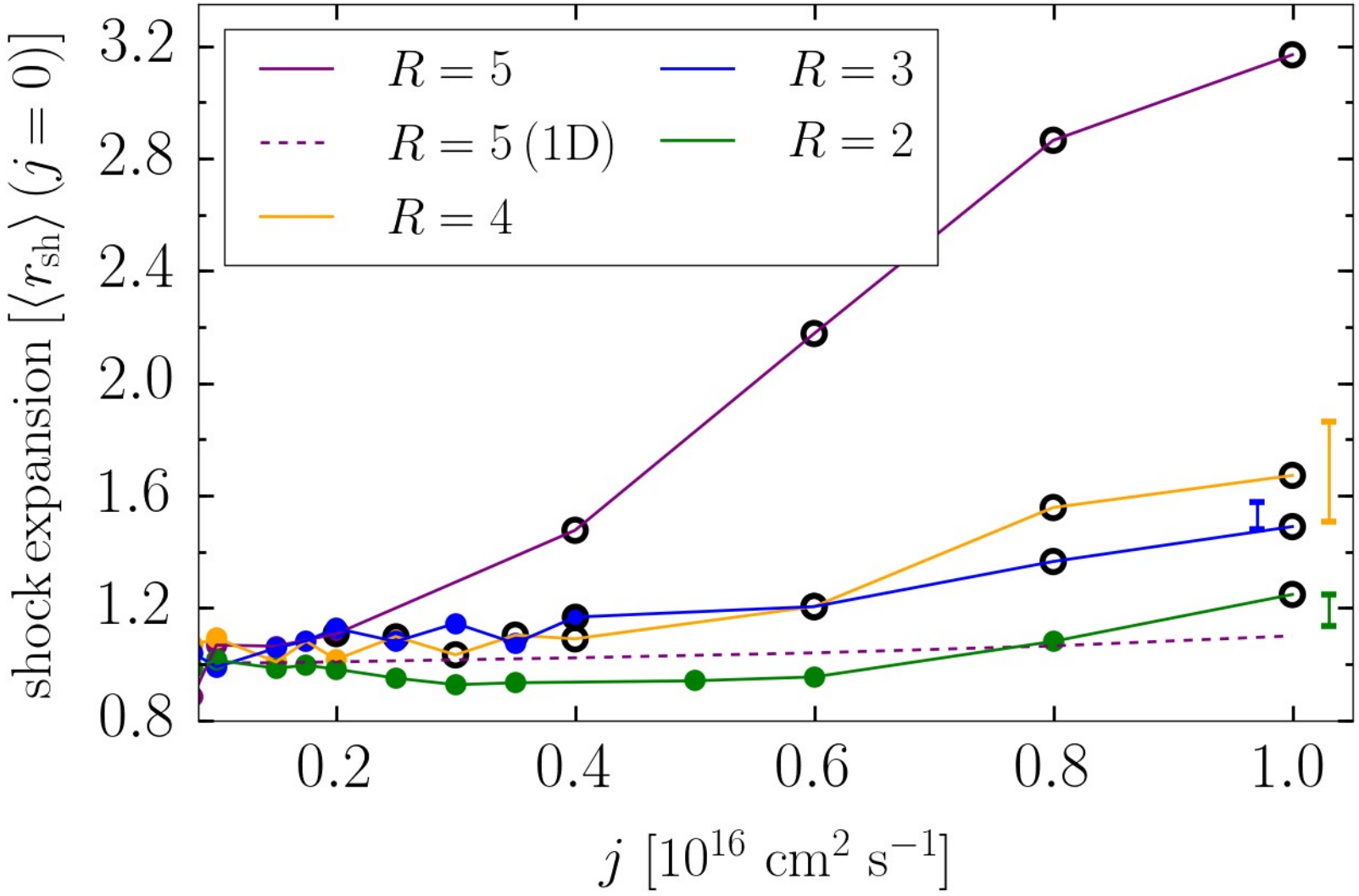
SASI, spiral m=1
+ corotation






SASI
$R = 4$
$R = 4\,(1\mathrm{D})$
$R = 3$
$R = 2$
shock expansion $[\langle r_{\mathrm{sh}} \rangle\,(j=0)]$
1.2
1.1
1.0
0.9
10^{13}
10^{14}
10^{15}
10^{16}
j [cm^2 s^{-1}]

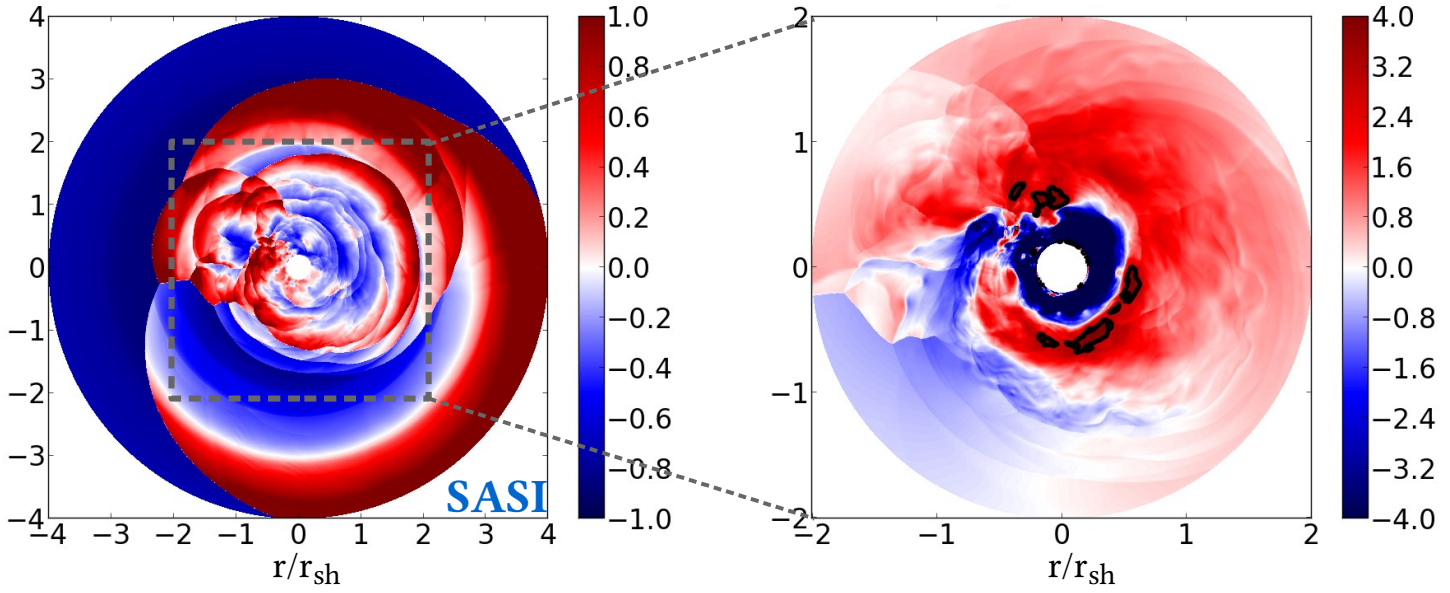
SASI + corotation



Corotation radius and low-T/|W|

R = 5

$j = 10^{15}$ cm²/s

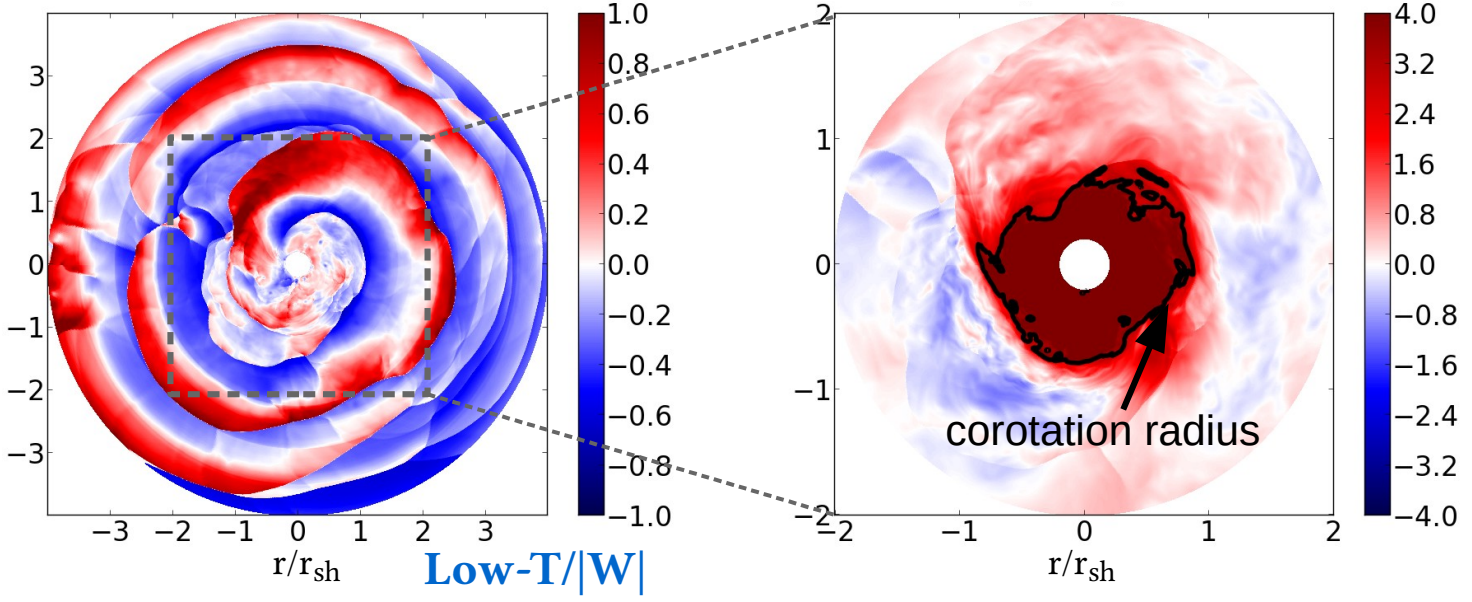


pressure variation

rotation frequency

R = 5

$j = 6.10^{15}$ cm²/s



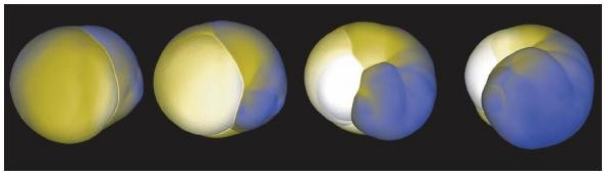
Outline of the talk

- Hydrodynamical instabilities in collapsing cores
- Dynamical influence of rotation on one-armed instabilities
- Angular momentum budget: from progenitor rotation to pulsar spin

SASI spiral modes may spin up a NS born from a non-rotating progenitor

This was demonstrated with several approaches :

Numerical simulations

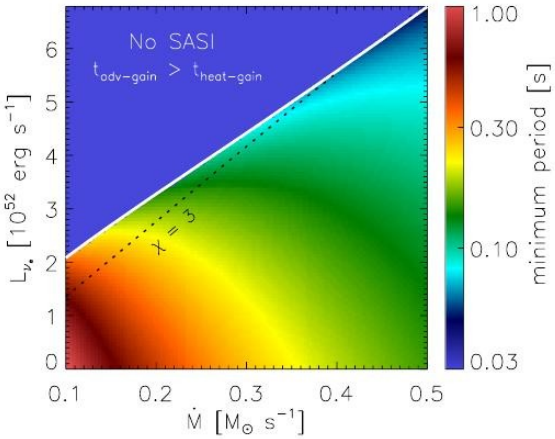


P_{NS} ~ 50 ms

(Blondin & Mezzacappa 2007)

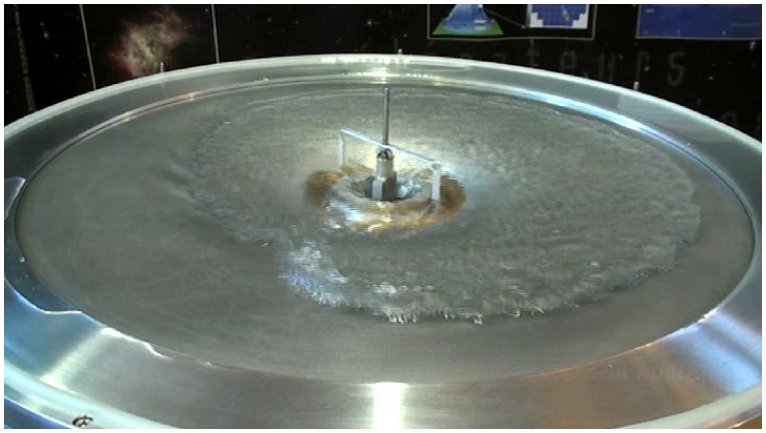
Analytical estimate

P_{NS} ~ 0.05 - 1s



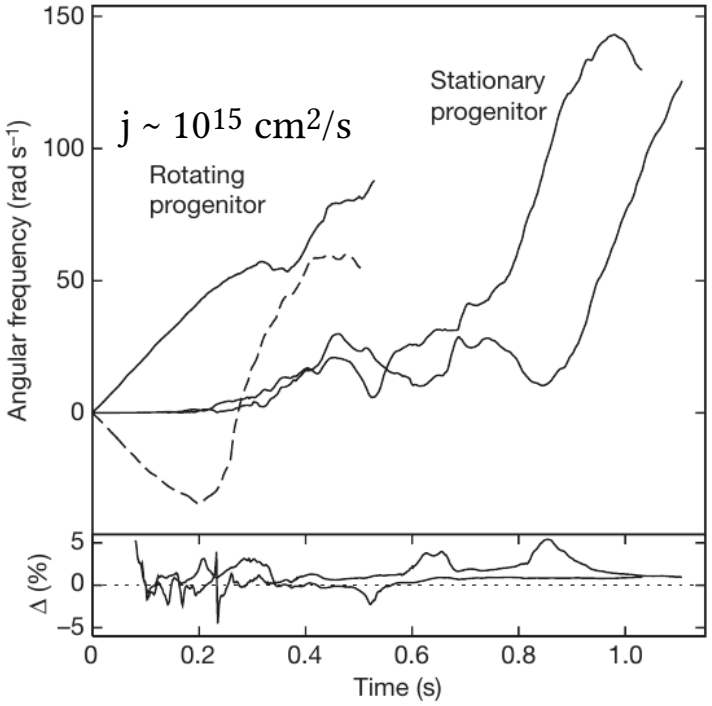
(Guilet & Fernández 2014, confirmed in the simulations of RK+ 2016)

Shallow water experiment



(Foglizzo+ 2012, 2015)

How does the picture evolve with stellar rotation?



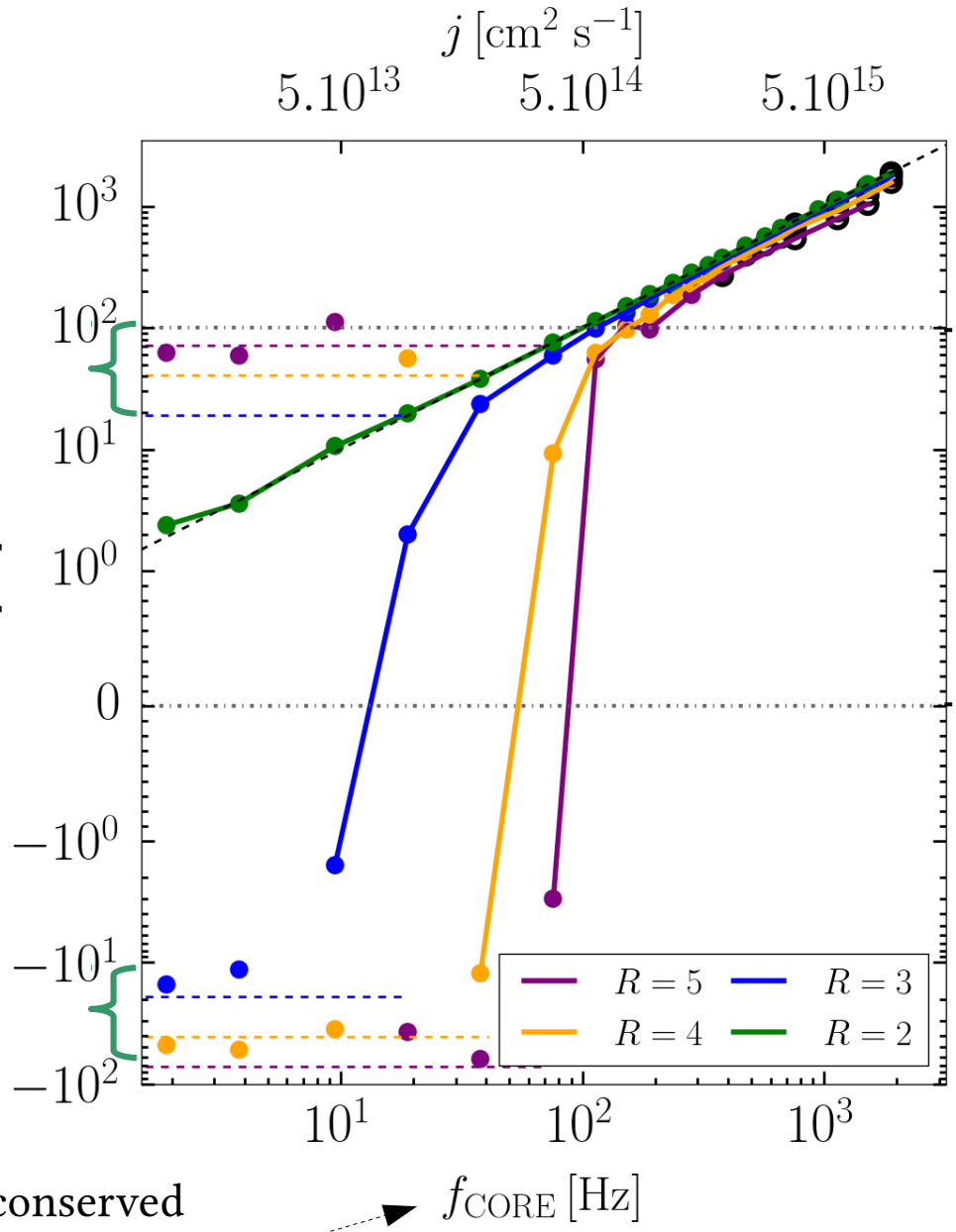
(Blondin & Mezzacappa 2007)

Possible outcomes of SASI

- SASI may spin-down a PNS
- Formation of a counter-rotating NS ?

Is the NS spin-down a systematic outcome of SASI in rotating progenitors?

Angular momentum redistribution Pulsar spin-up and down by SASI



SASI alone (F_{CORE}=0)

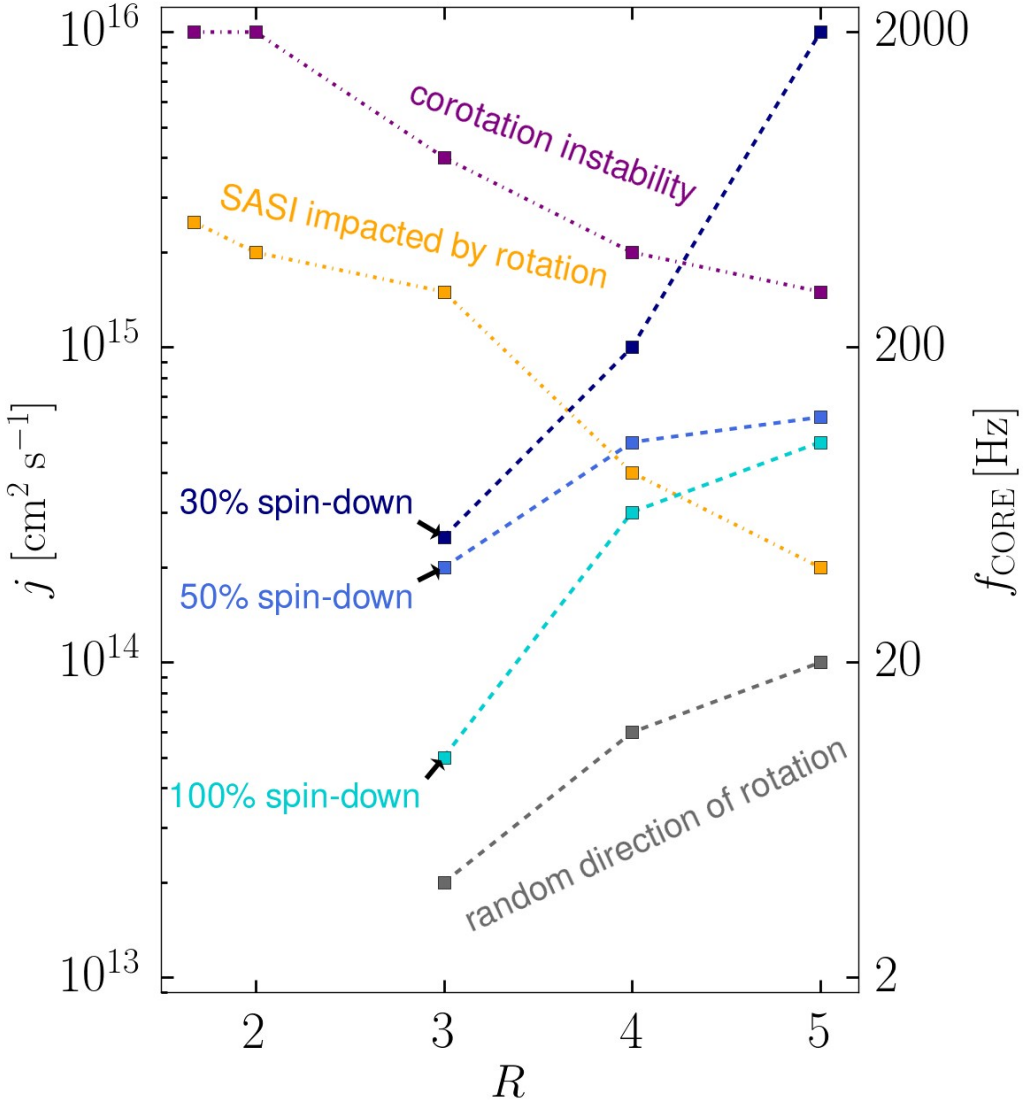
SASI alone (F_{CORE}=0)

observational constraints

counter-rotating NS

Neutron Star rotation frequency *(hydro instabilities)*

Core angular momentum conserved *(no hydro instabilities)*



RK, Guilet & Foglizzo 2017

- Rotation does not always increase the amplitude of the SASI spiral mode.
- Strong spiral mode associated to a corotation radius.
- NS spin-up and spin-down are possible if $f_{\rm core} \lesssim 100$ Hz.
- The spin-down is much less efficient when a corotation instability develops.

Summary

☑ Idealized setup used to investigate the diversity of post-shock dynamics seen in CCSN simulations that include stellar rotation.

☑ Quantitative study of the NS spin-up and spin-down by spiral modes:
⟹spiral modes cannot reconcile fast rotating progenitors with observational constraints.

Open issues

- Inclusion of more realistic physical ingredients:
  - Neutrino heating *(see talk by B. Pagani)*
  - Magnetic fields
  - 3D geometry.
- Overlap of SASI and a corotation?
- Role of "rapid" rotation in the CCSN mechanism?

Thanks!