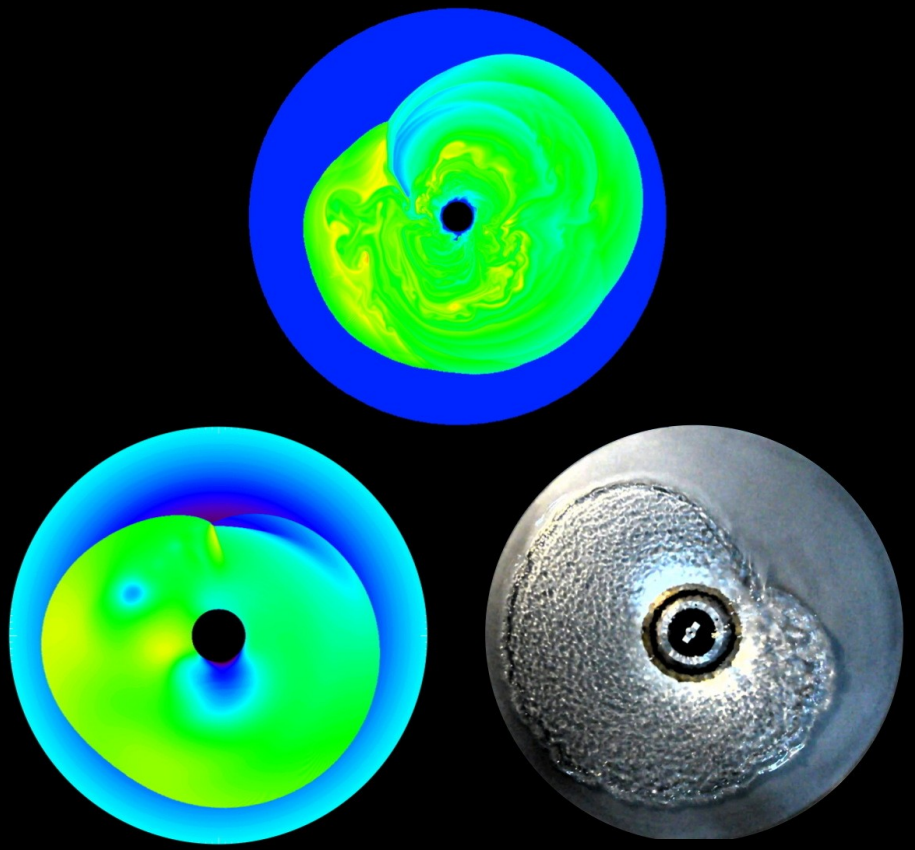
Incidence of stellar rotation on the explosion mechanism of massive stars



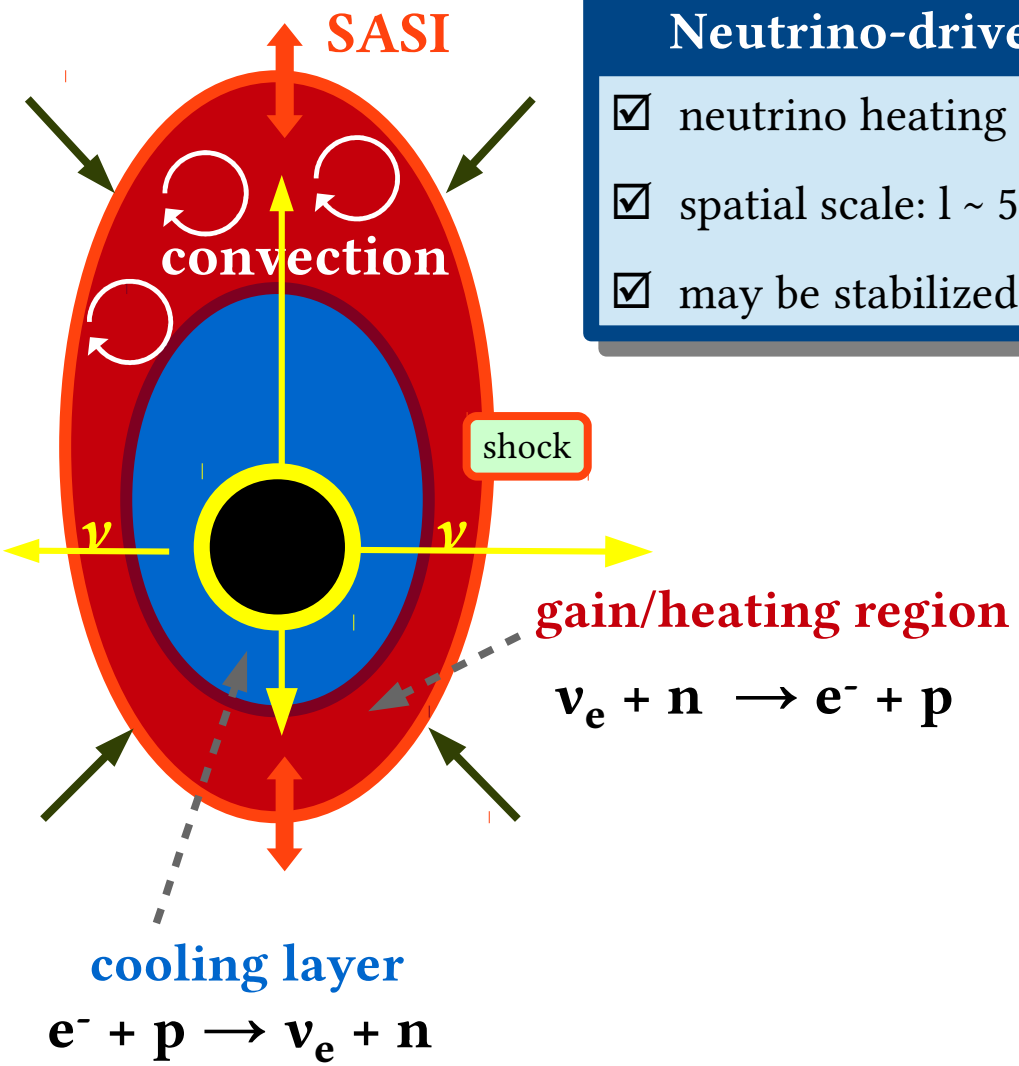
Rémi Kazeroni (CEA/MPA)
Thierry Foglizzo (CEA), Jérôme Guilet (MPA)

IAUS 331
SN 1987A, 30 years later

La Réunion
20/02/2017

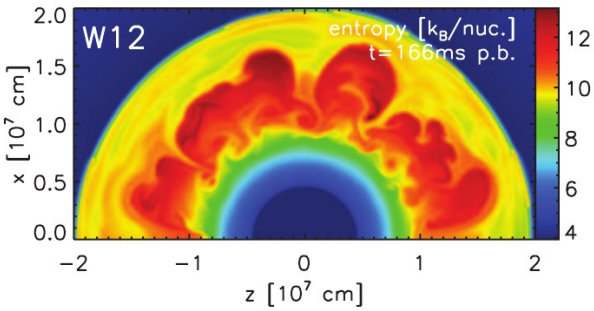
Outline

- 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 convection

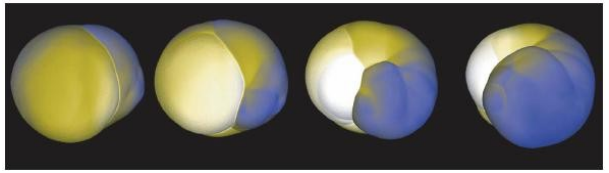
- ☑ neutrino heating in the gain region
- ☑ spatial scale: l ~ 5-6
- ☑ may be stabilized by advection



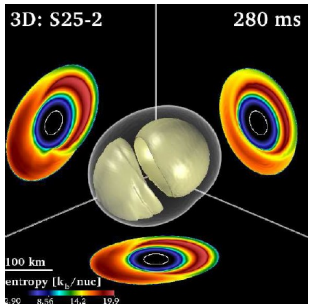
(Foglizzo+ 2006)

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**.

Physics – stationary flow

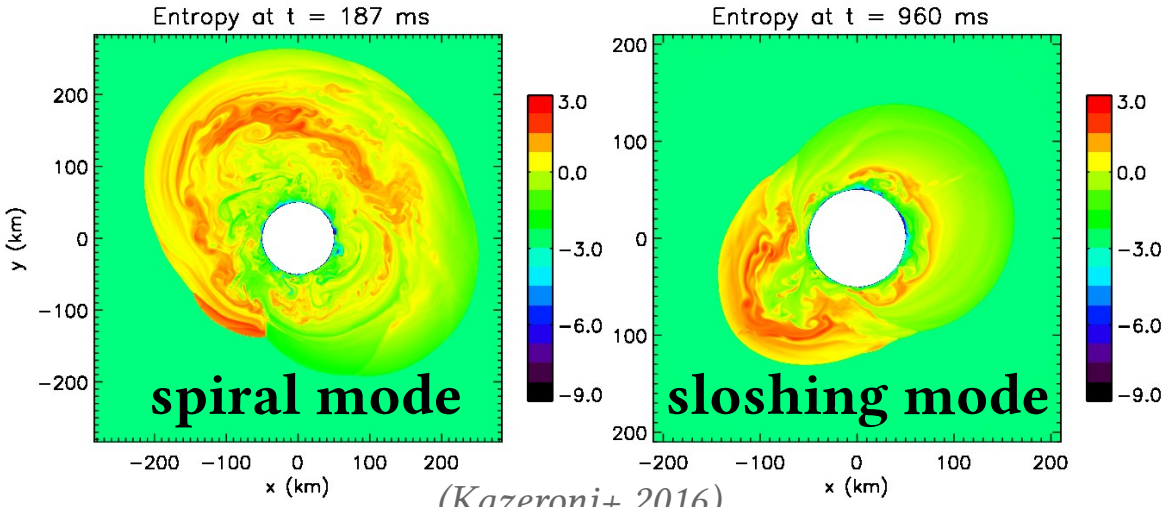
- ☑ Perfect gas equation of state (γ=4/3)
- ☑ Approximation of the cooling

(Blondin & Mezzacappa 2006)

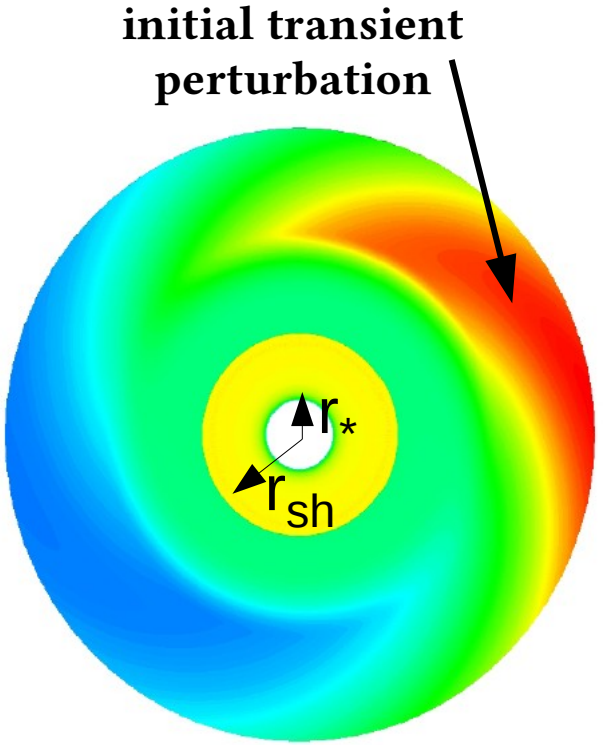
- ☑ No neutrino heating

Numerics – parametric study with RAMSES

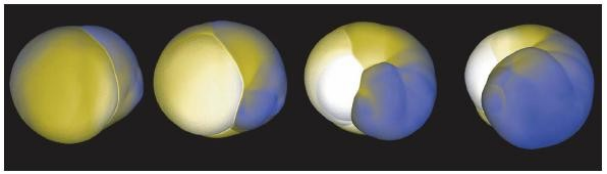
- Radii ratio: $R=r_{sh} / r_*$ (e.g. r_{sh} =150 km, r_*= 50 km)



(Kazeroni+ 2016)



2D cylindrical domain equatorial plane



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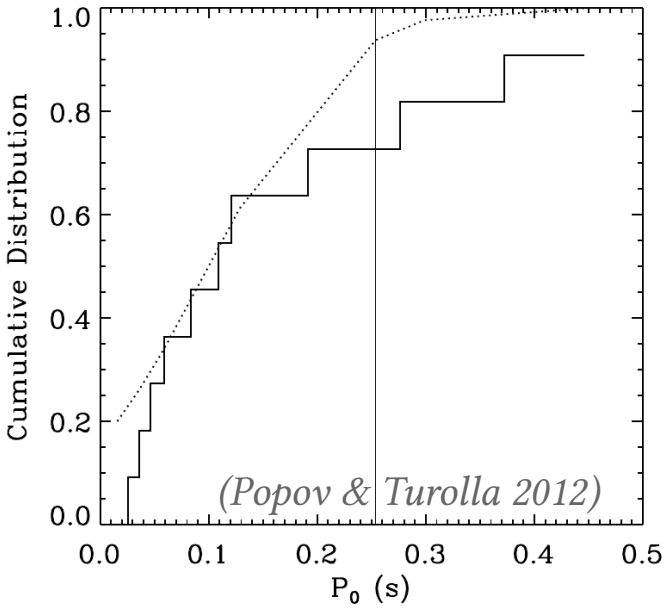
Pulsar spin at birth



⟶ Natal pulsar spin distribution: from ~10 ms

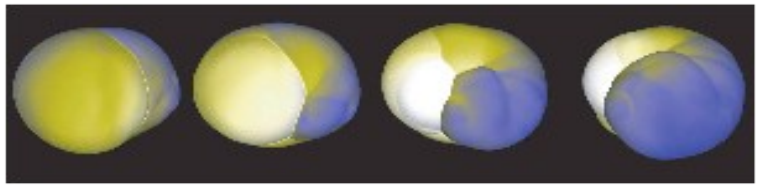
to several 100 ms at birth.

⟶ stellar evolution favours: j ~ 10^{15} cm^2/s (P_0 ≈ 6 ms)

(e.g. Heger+ 2005).

- ***What about intermediate rotation rates?***

SASI

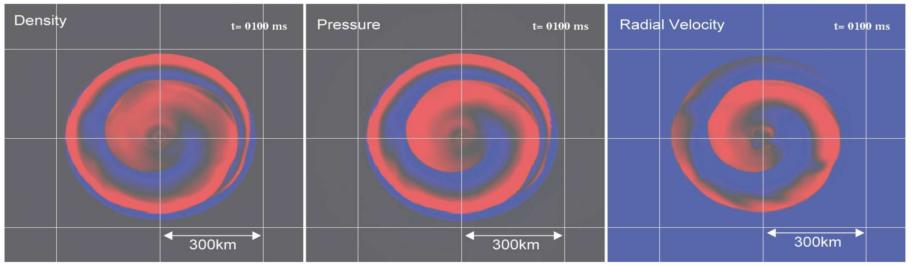


(Blondin & Mezzacappa 2007)

j = 10^{15} cm^2/s or P_0 ≈ 6 ms

"Slow" rotating progenitor

Low-T/|W| (corotation instability)



(Takiwaki+ 2016)

j = 4.10^{16} cm^2/s or P_0 ≈ 0.15 ms

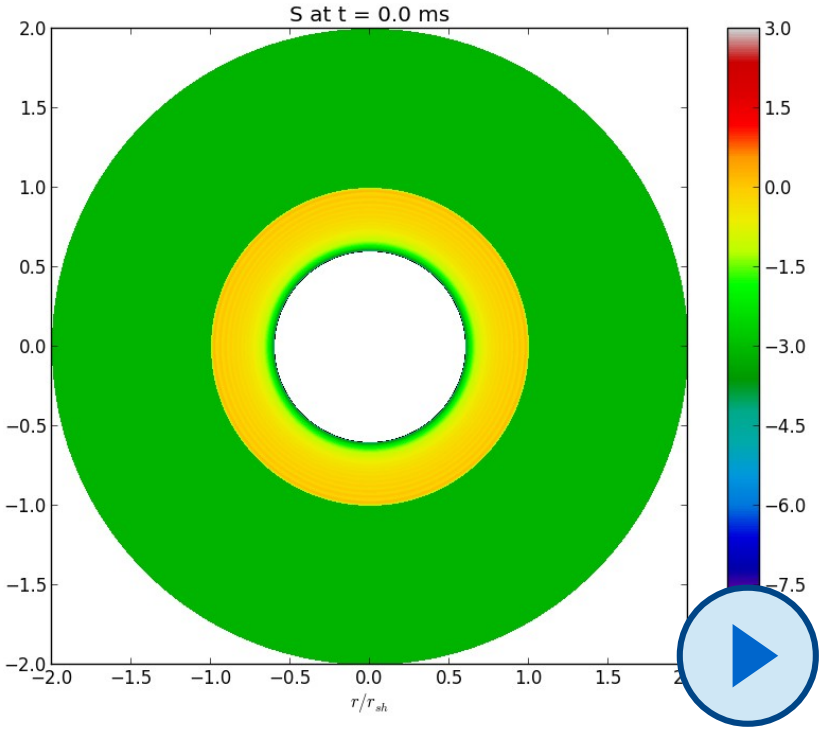
"Fast" rotating progenitor

R = 1.67

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

$P_0 \approx 1.5$ ms

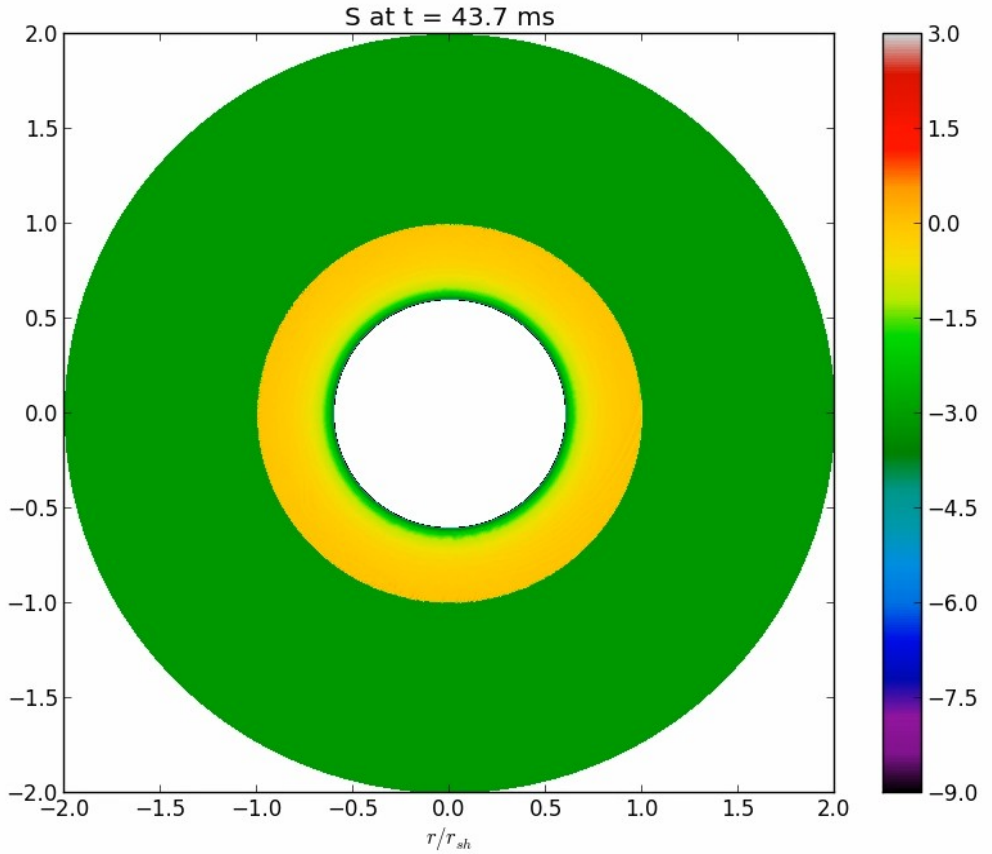
A parametric study (R)



R = 1.67

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

$P_0 \approx 1.5$ ms



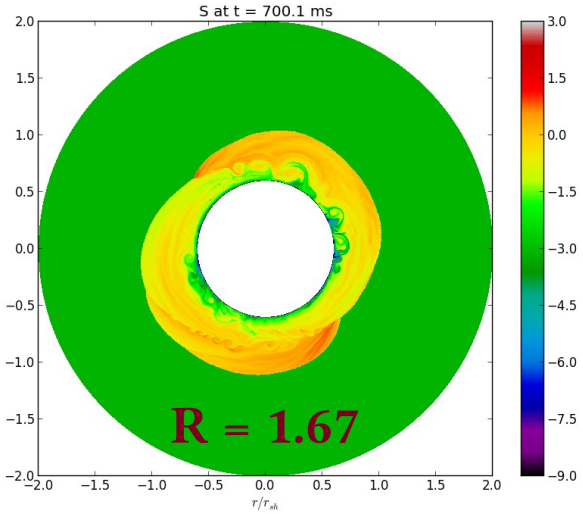
SASI, m=2

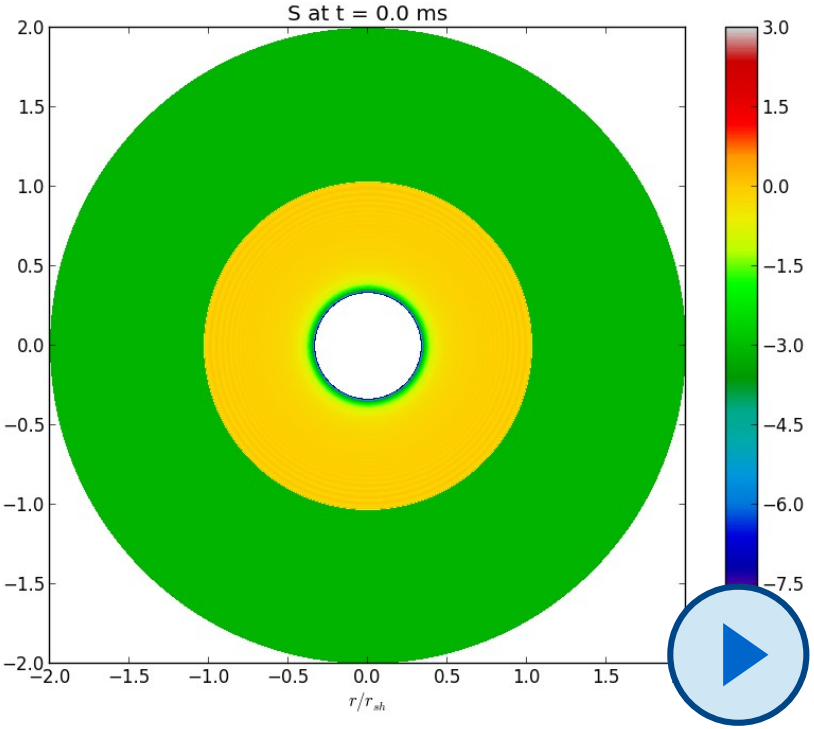
A parametric study (R)

R = 3

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

$P_0 \approx 1.5$ ms

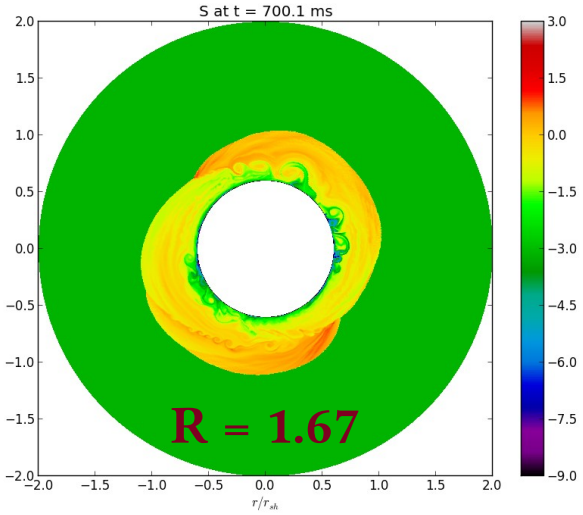


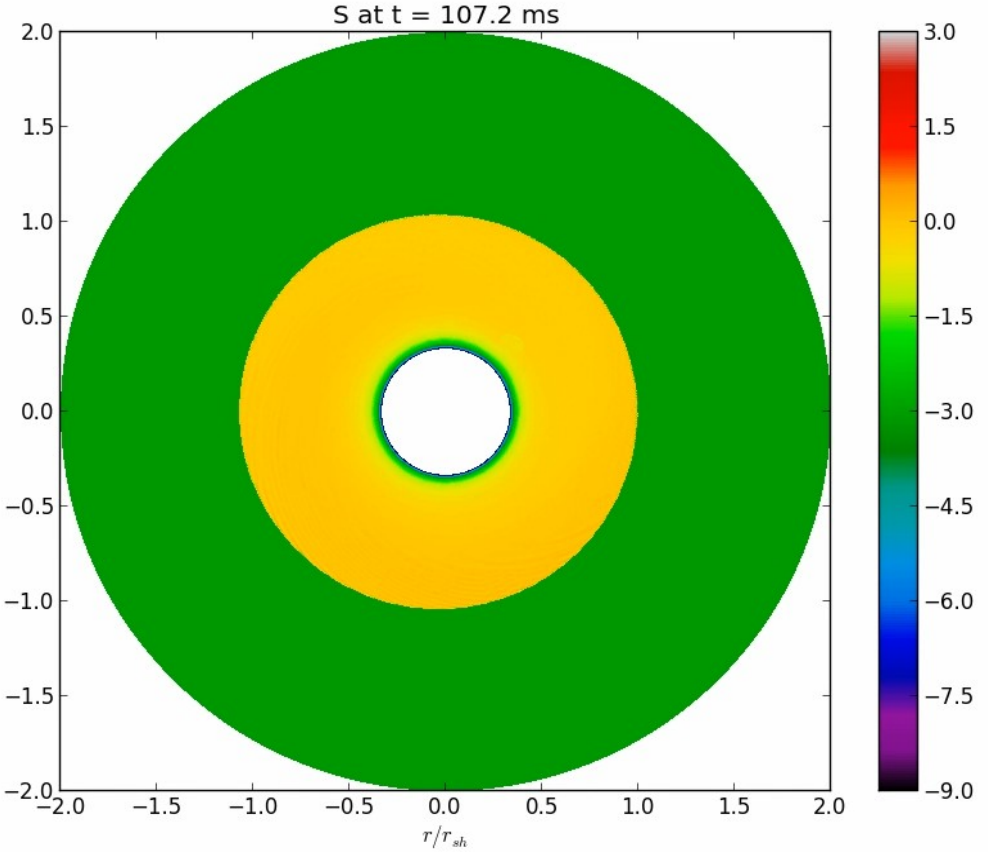


R = 3

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

$P_0 \approx 1.5$ ms





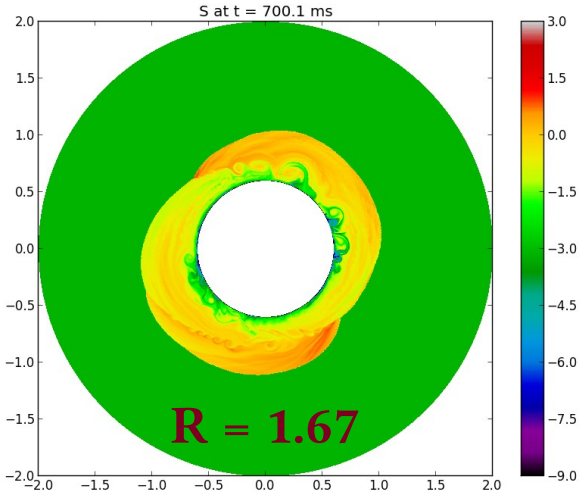
SASI, m=1

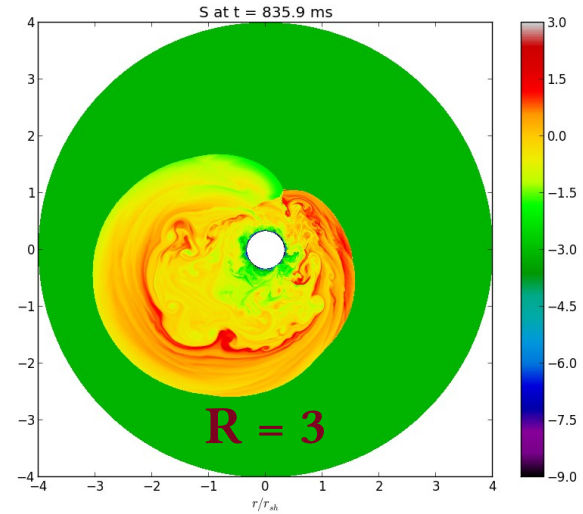
R = 5

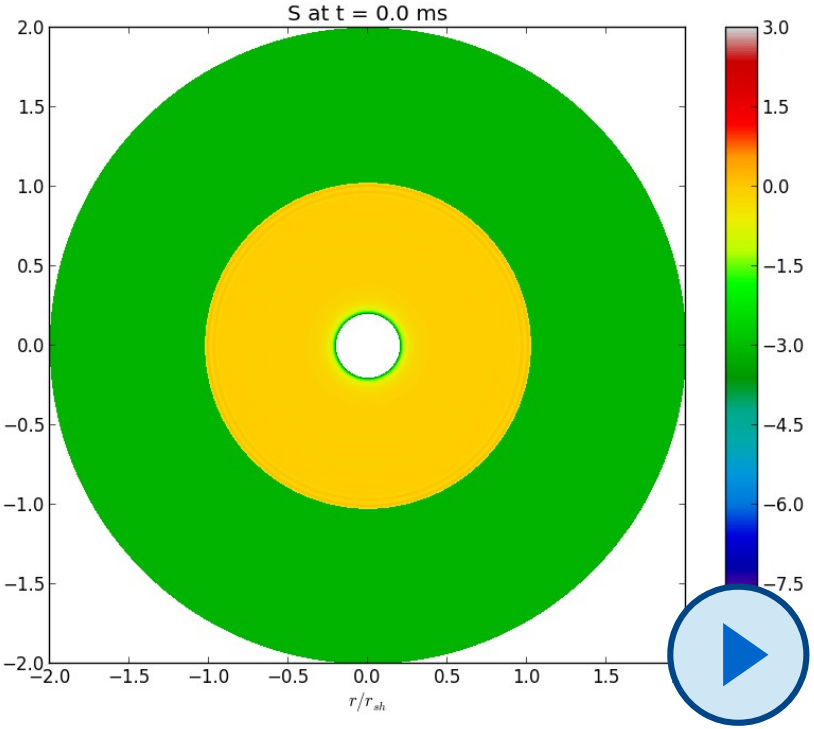
$j = 4.10^{15}$ cm^2/s

$P_0 \approx 1.5$ ms

A parametric study (R)



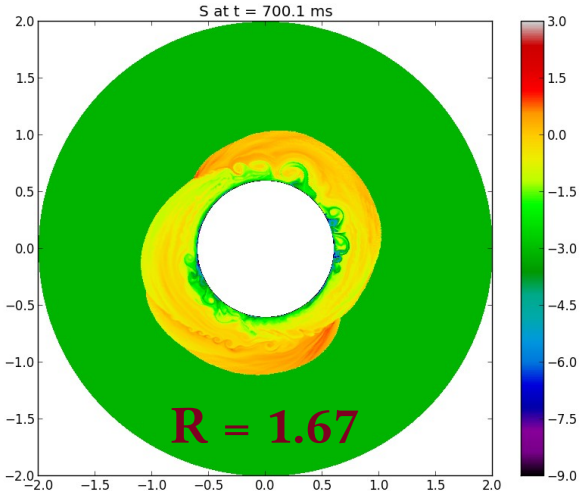


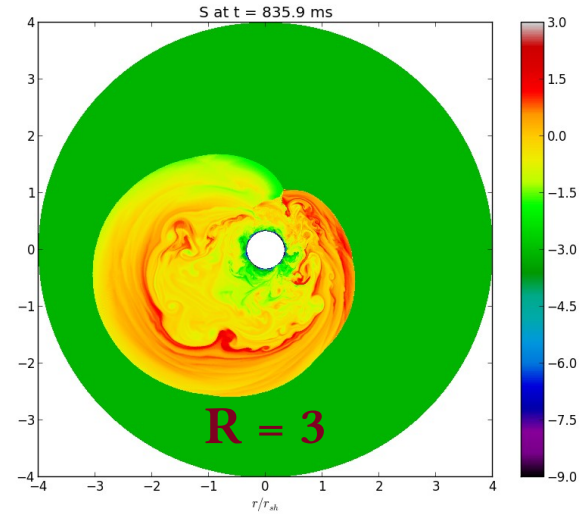


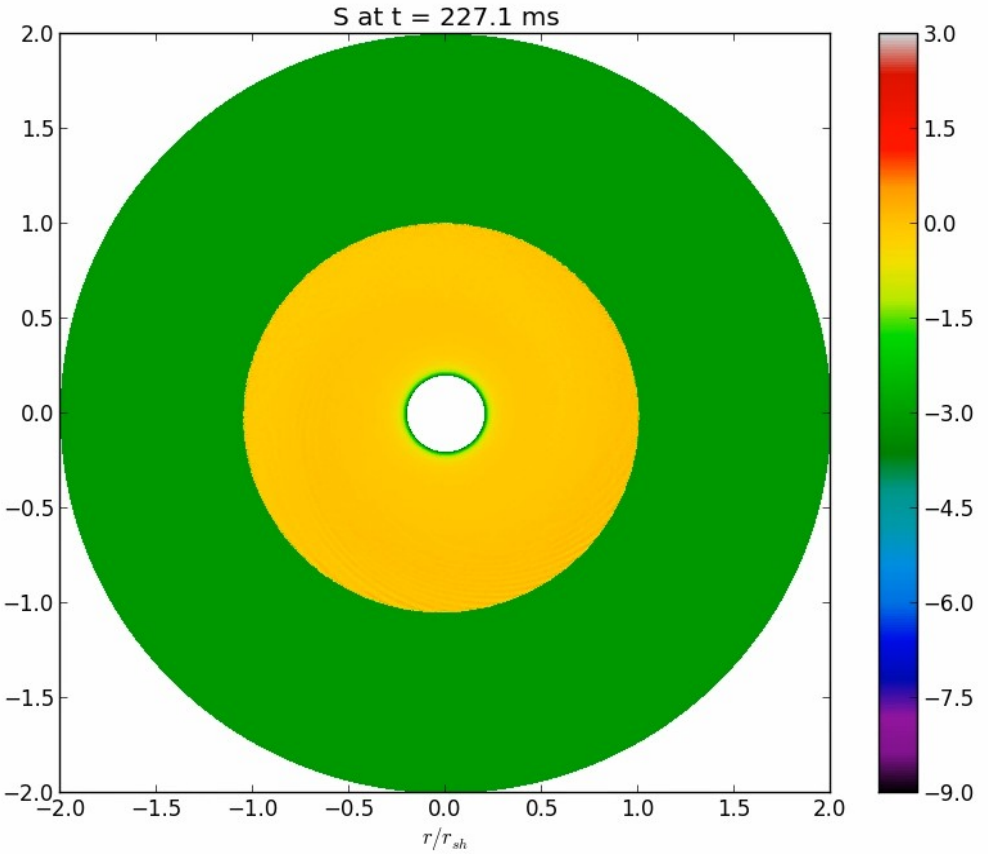
R = 5

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

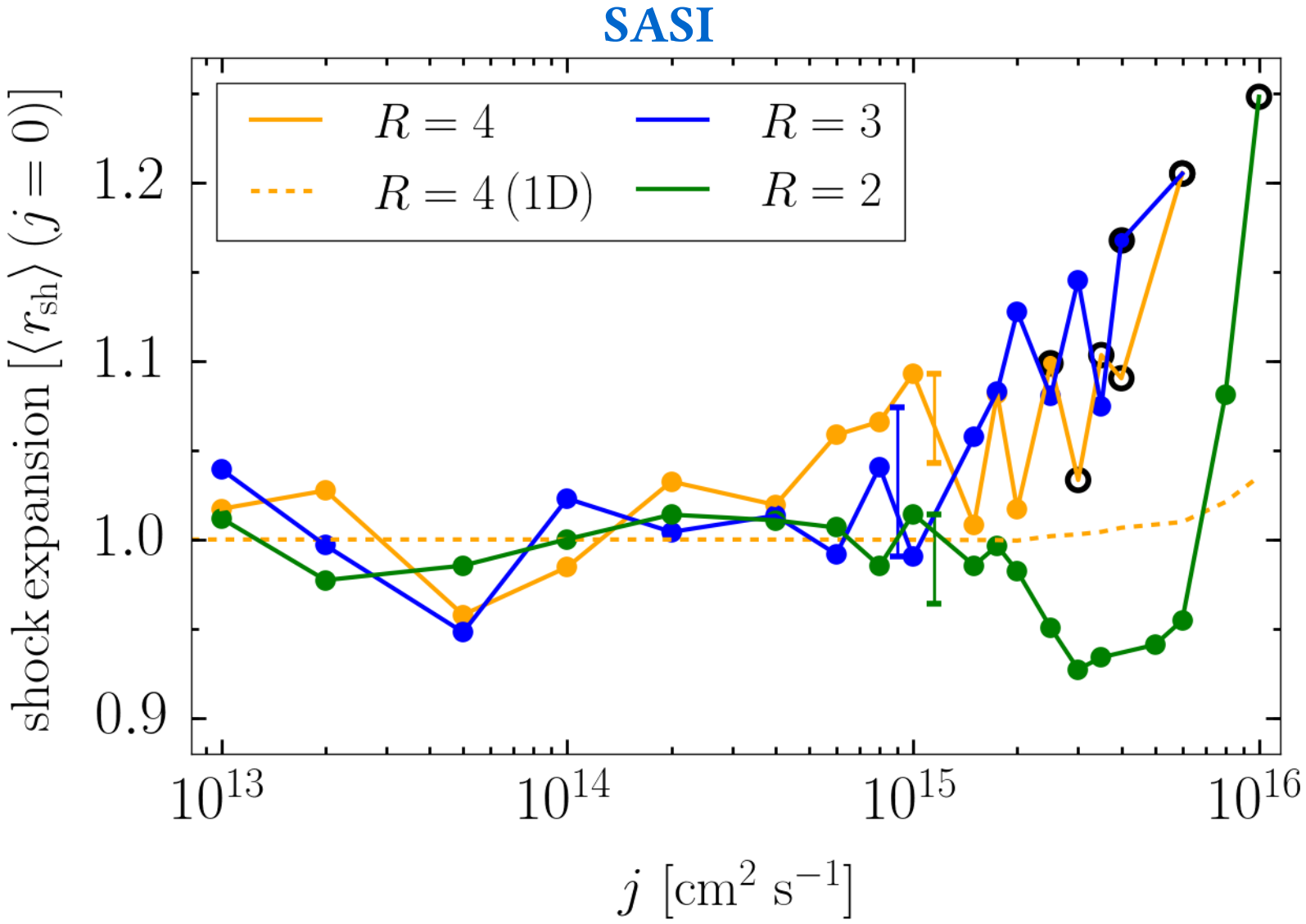
$P_0 \approx 1.5$ ms



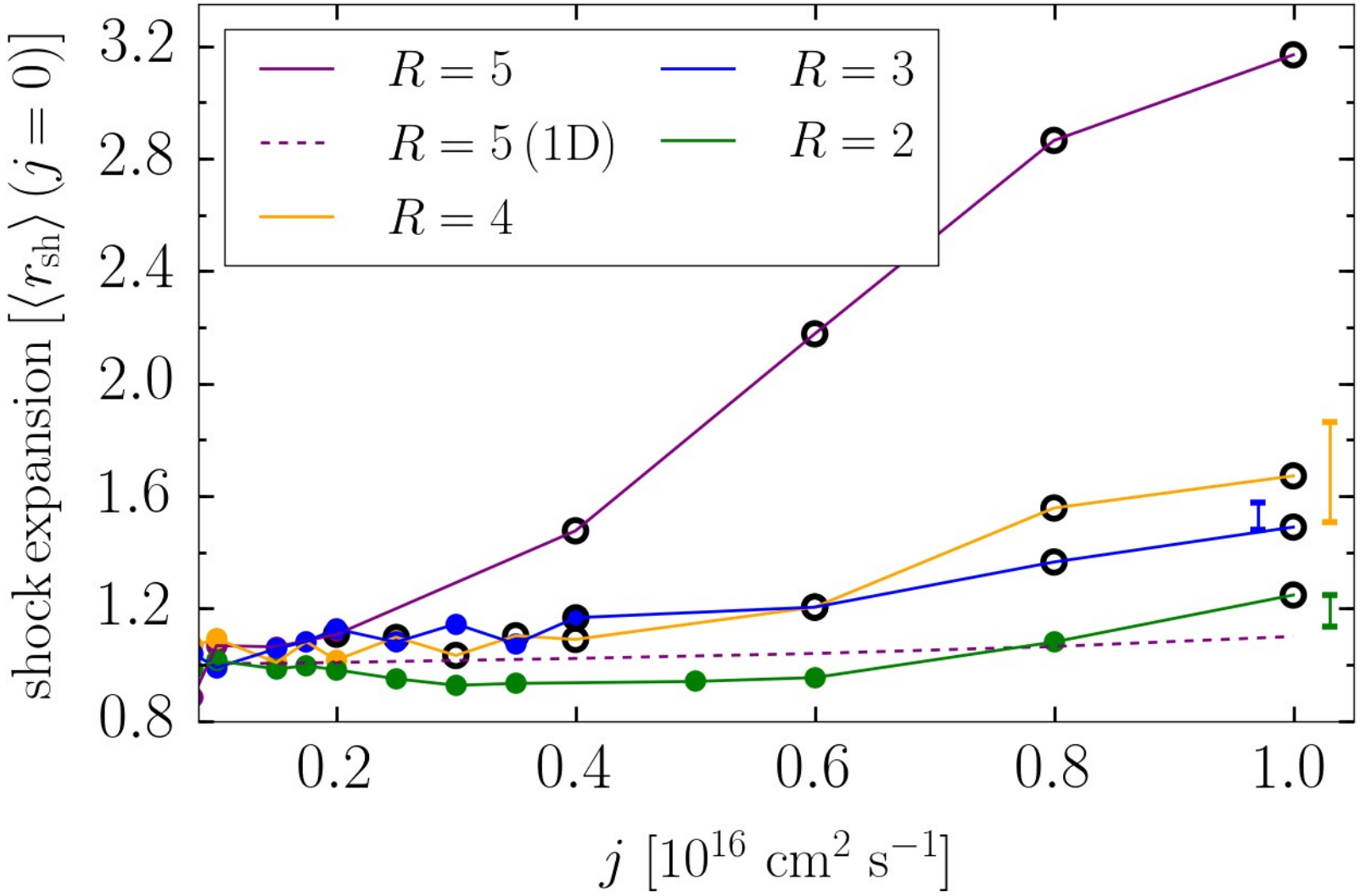




Low-T/|W|, m=1


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 $[\mathrm{cm}^2\ \mathrm{s}^{-1}]$

Corotation instability



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A Neutron Star (NS) may be spun up without stellar rotation!

Shallow water experiment

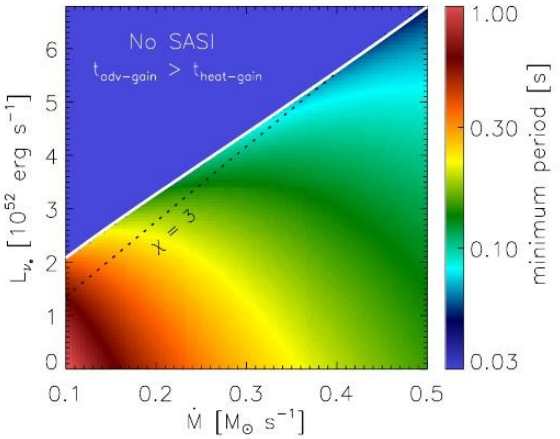
(Foglizzo+ 2012, 2015)

What about rotating progenitors?

- NS spin-down? Counter-rotating NS?
  (Blondin & Mezzacappa 2007)

Analytical estimate

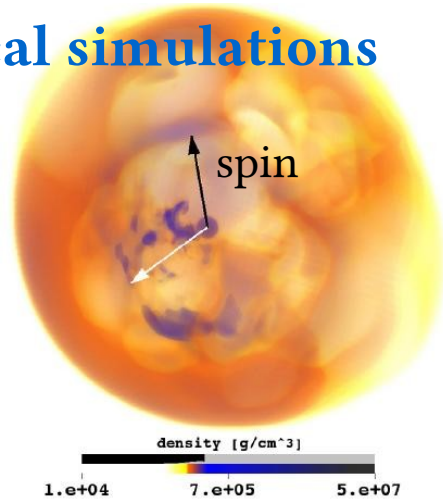
P_{NS} ~ 0.05 - 1s



(Guilet & Fernández 2014)

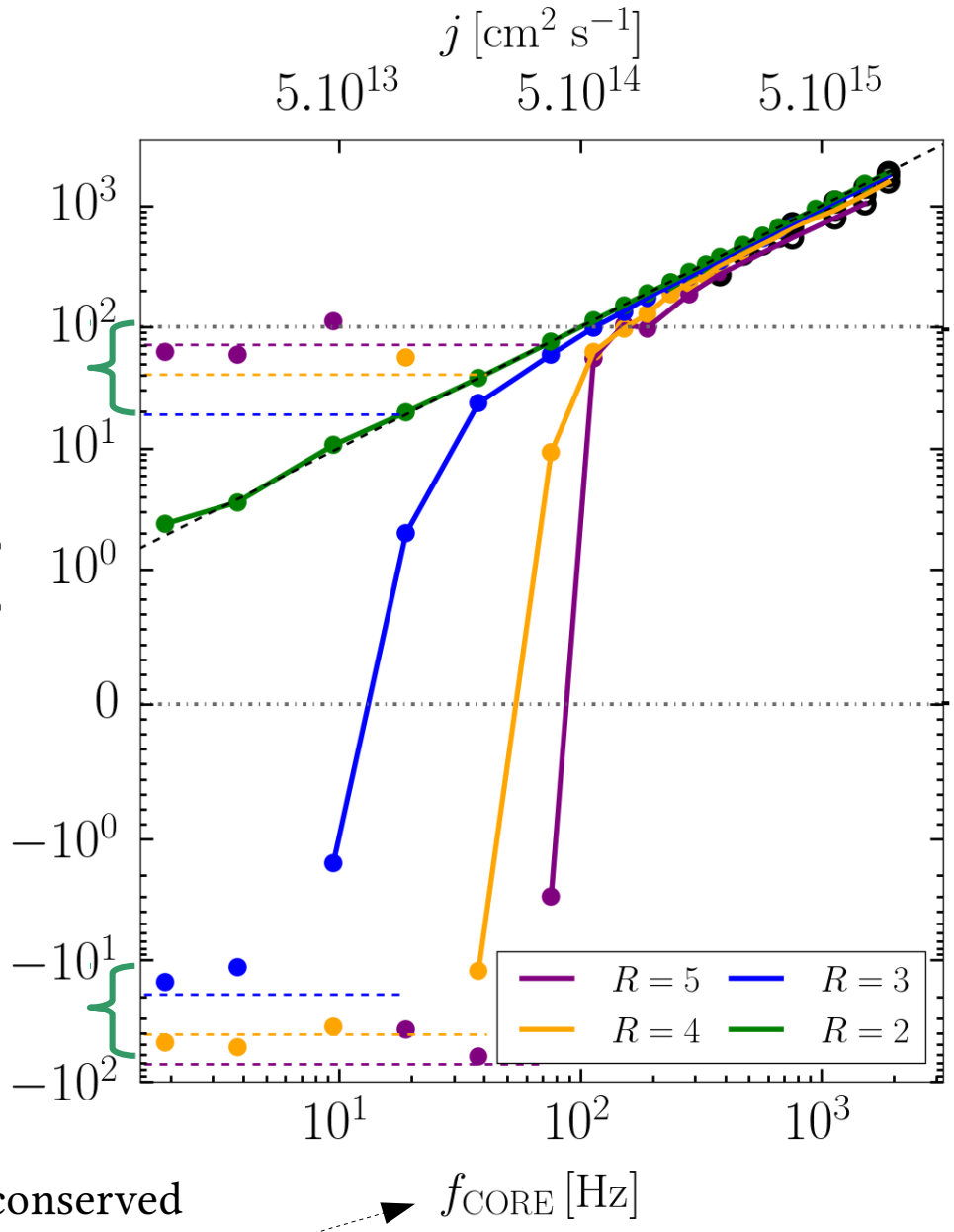
Numerical simulations

P_{NS} ~ 0.1 - 8s



(Wongwathanarat+ 2013)

Angular momentum redistribution Pulsar spin-up and down by SASI



SASI alone (F_{CORE}=0)

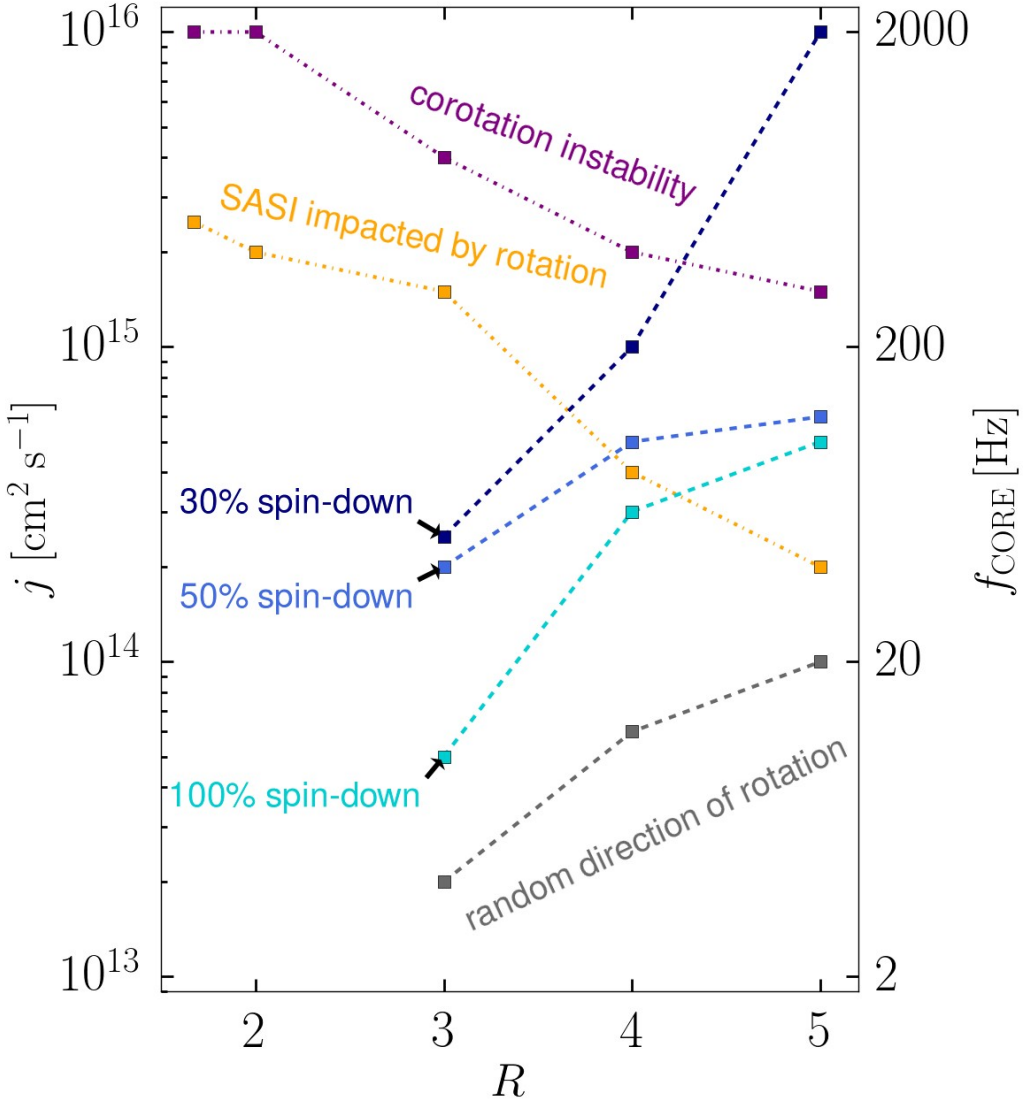
SASI alone (F_{CORE}=0)

observational constraints

counter-rotating NS

Neutron Star rotation frequency *(hydro instabilities)*

Core angular momentum conserved *(no hydro instabilities)*



Kazeroni, Guilet & Foglizzo 2017, arXiv:1701.07029

- Rotation does not always increase the amplitude of the SASI spiral mode.
- Strong spiral mode associated to a corotation instability.
- 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.

Thanks!