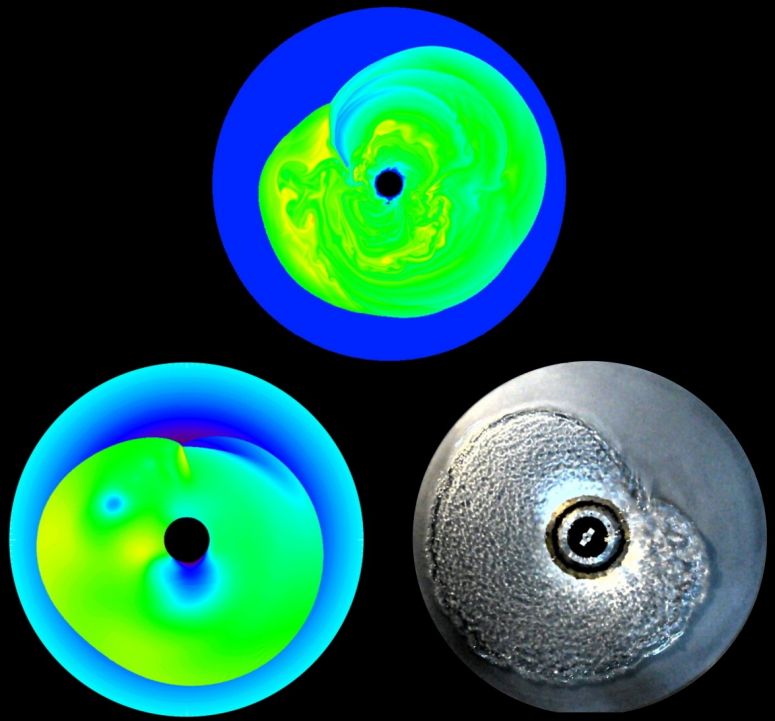
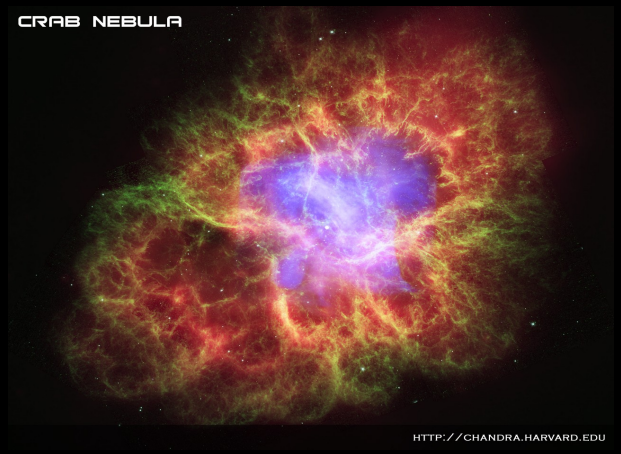
# *Asymmetric explosion of core-collapse supernovae*






Rémi Kazeroni (CEA)

Thierry Foglizzo (CEA), Jérôme Guilet (MPA Garching)

# About me

- Rémi Kazeroni (IRFU/SAp)
- Advisor: Thierry Foglizzo. Collaborator: Jérôme Guilet (MPA).
- Curriculum: ENSTA ParisTech + Master M2S (Modélisation et Simulation)
- Master thesis: @Sap, numerical simulations of the Standing Accretion Shock Instability (SASI).

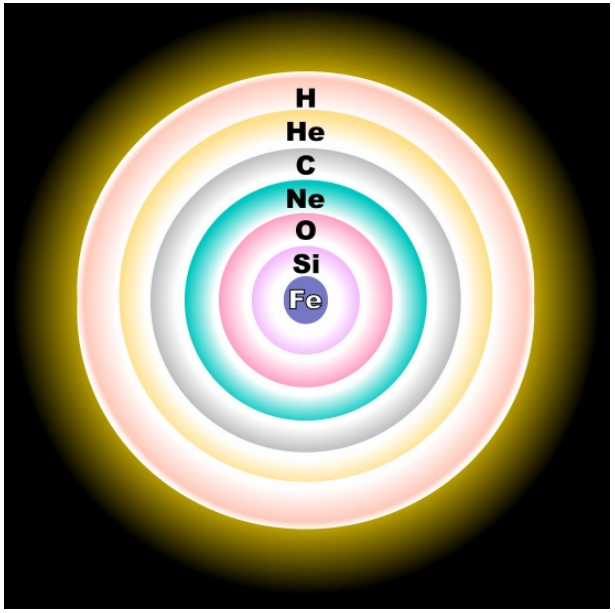
# PhD thesis

## *Asymmetric explosion of core-collapse supernova*

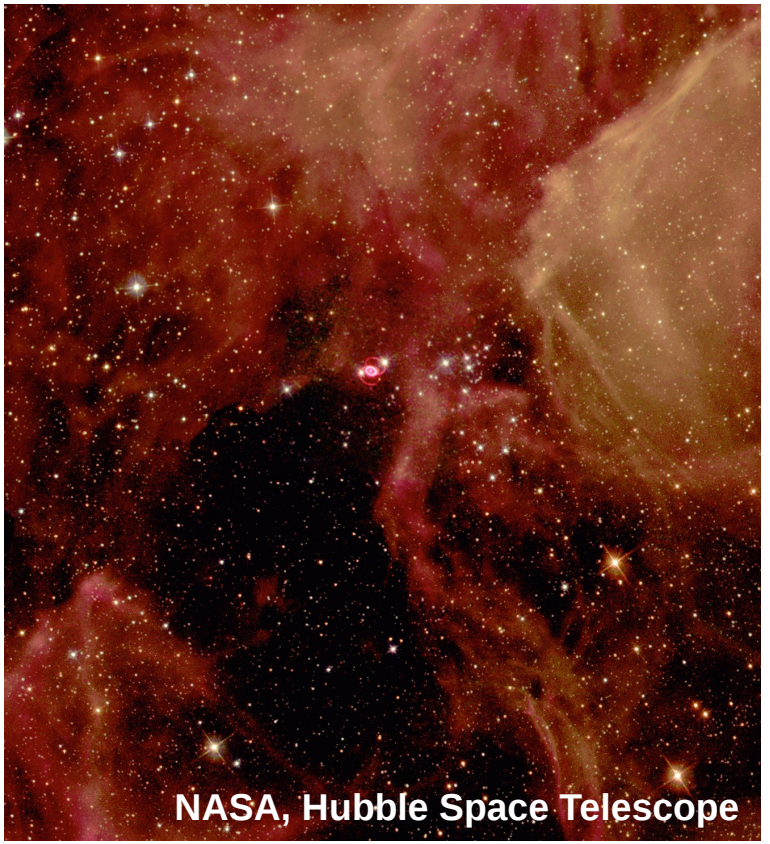
Massive stars at the end of their lives explode in supernova.

A supernova starts with the collapse of the iron core of the star.

The supernova remnant is a neutron star or a black hole.




*massive star ($M > 8$-$10\ M_{sun}$)*

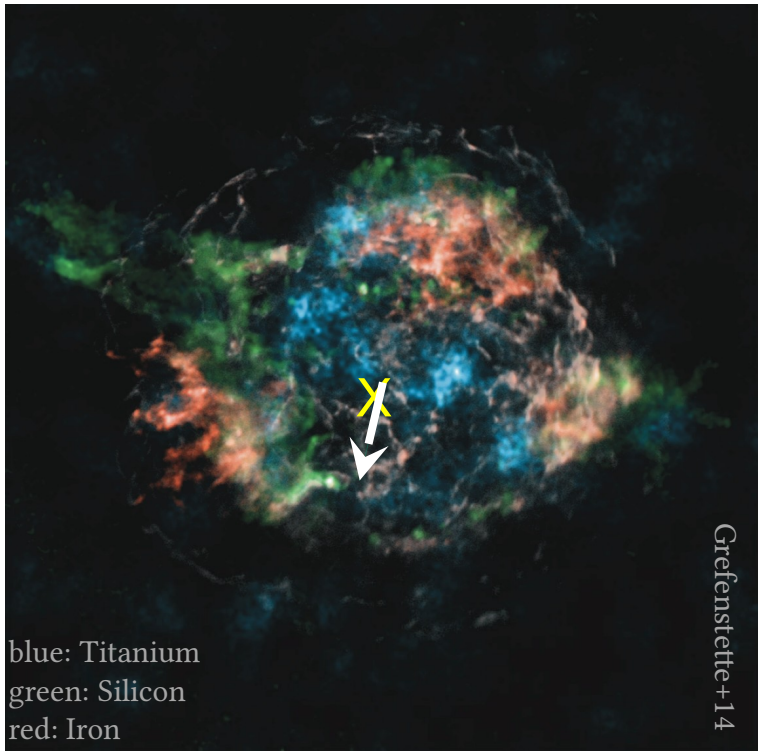



*SN 1987A*

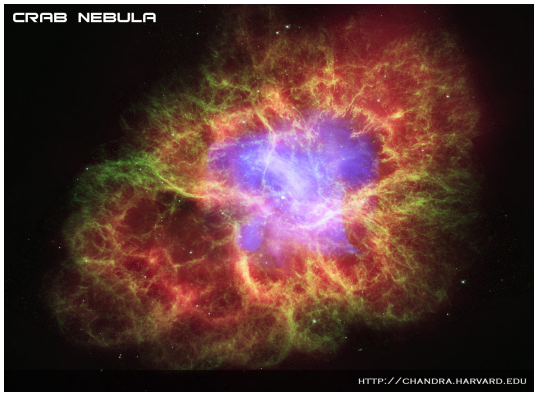
# PhD thesis

## *Asymmetric explosion of core-collapse supernova*

Hydrodynamic instabilities in the inner region generate large scale asymmetries and impact both the explosion and the properties of the remnant.

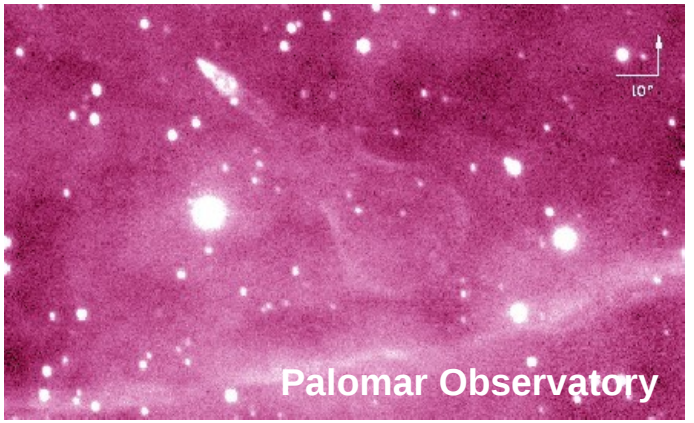



***nucleosynthesis***



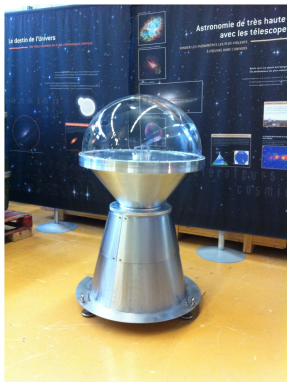

***spin***

**Guitar nebula @ 1600km/s**

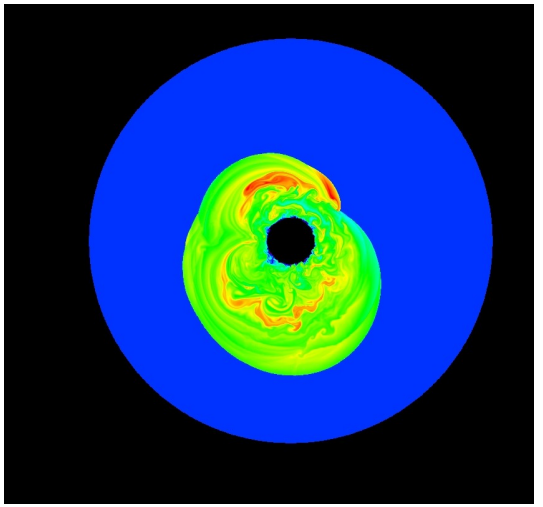



***kick***

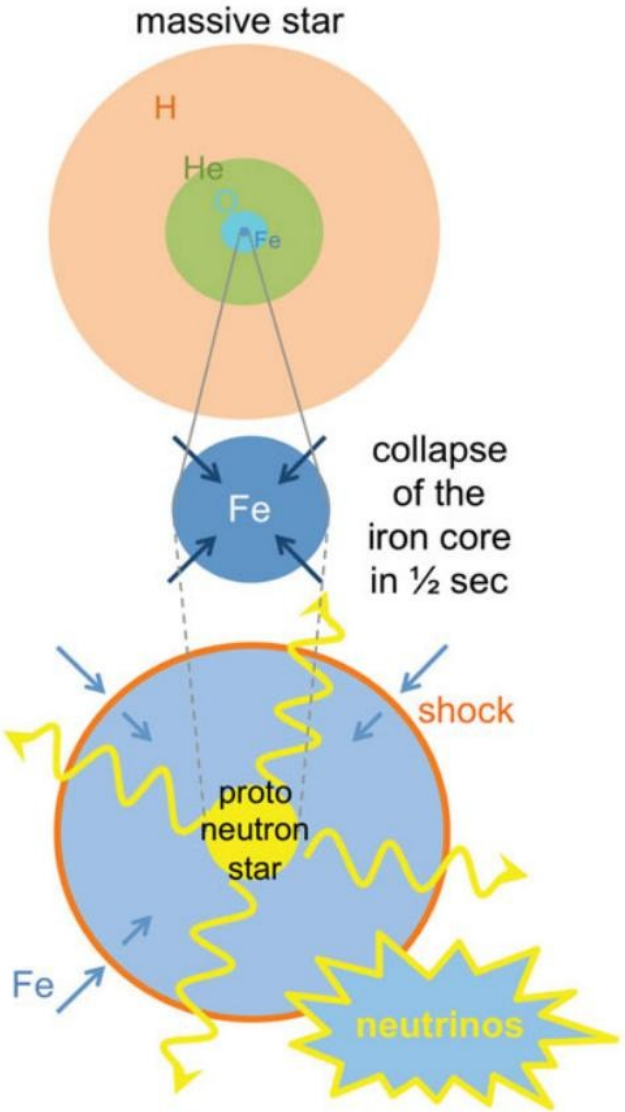
# Outline



- Standing Accretion Shock Instability & neutron star spin
- Modeling & numerical simulations
- Our results
- Towards more realistic models



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

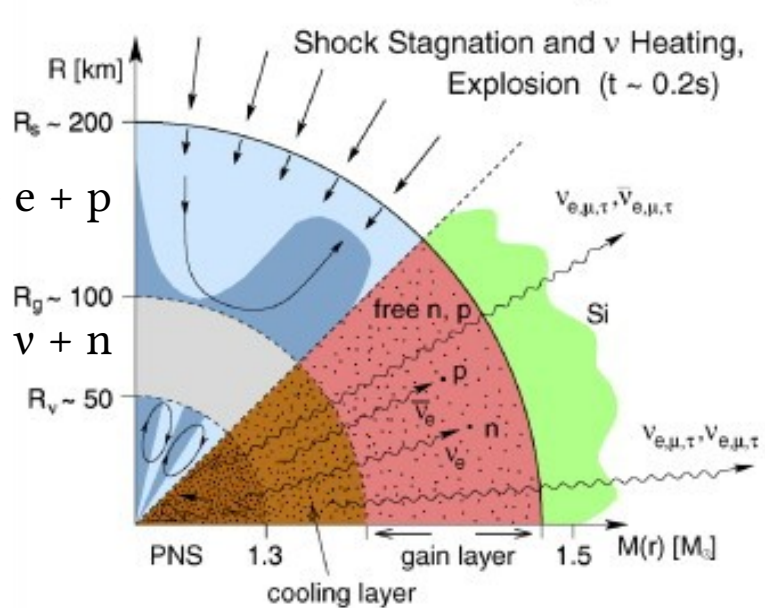



*Foglizzo, RK+ 15*

- 1D fails (Liebendörfer+ 01)
- Multi-D hydro instabilities:
  - Neutrino-driven convection
  - SASI

$\nu + n \longrightarrow e + p$

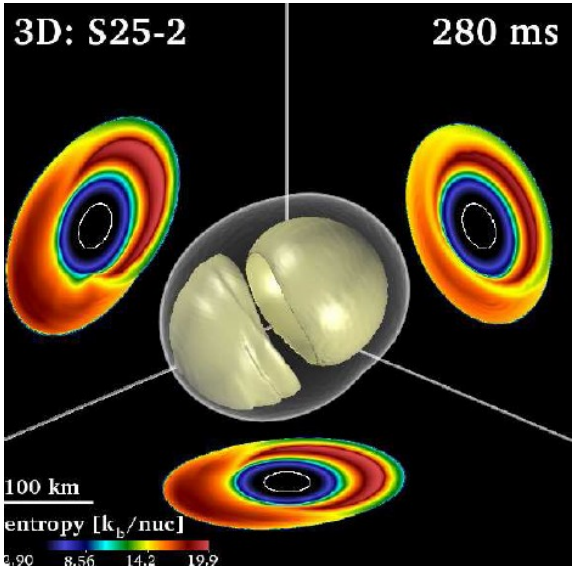
$e + p \longrightarrow \nu + n$



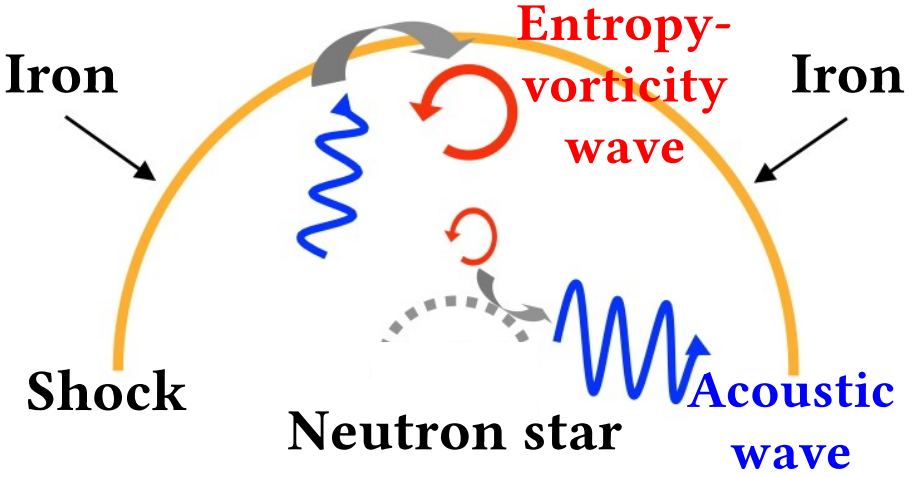

*Janka+ 07*

# Standing Accretion Shock Instability

**SASI** (Blondin+ 03)




*Hanke+ 13*




*Foglizzo+ 07*

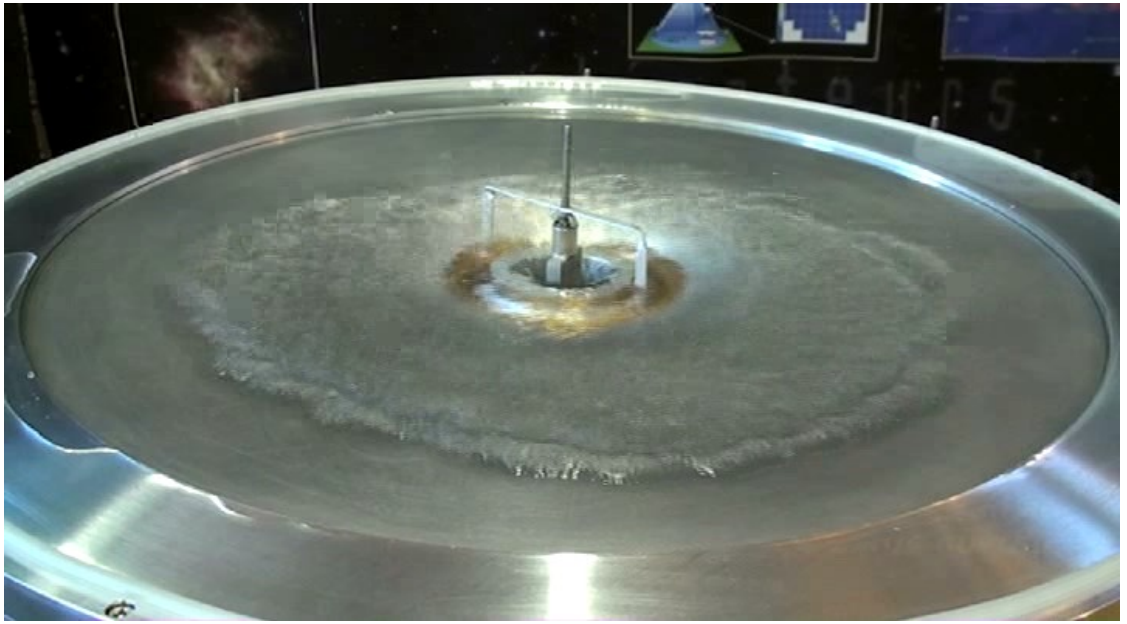
- Large scale shock oscillations
- Advective-acoustic cycle
- Induces a global asymmetry
- Unstable modes: l ~ 1-2
- Sloshing modes and **spiral modes**

**Some consequences of SASI**

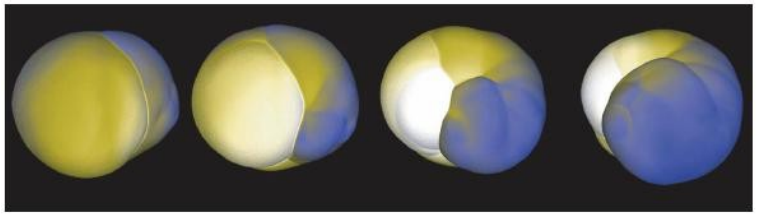
- Help successful explosions
- Pulsar kick
- **Pulsar spin**

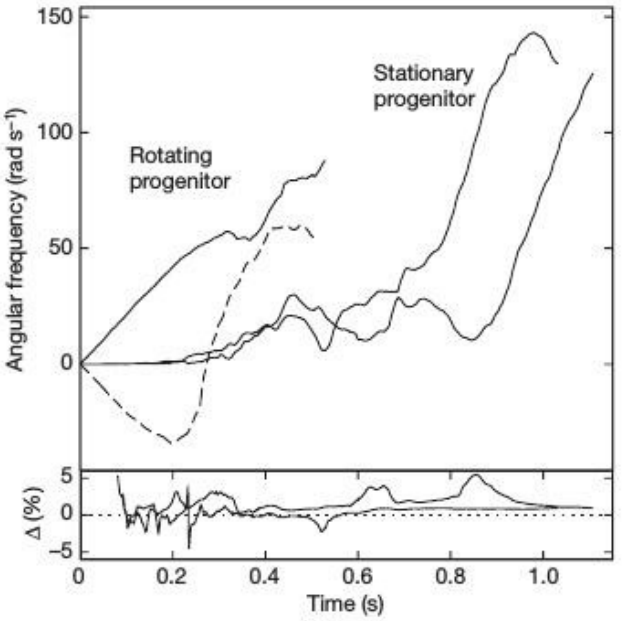
# SASI spiral modes and neutron star (NS) spins

Gas dynamics in the supernova core:
1 000 000 x bigger and 100 x faster



*see Foglizzo+ 12*





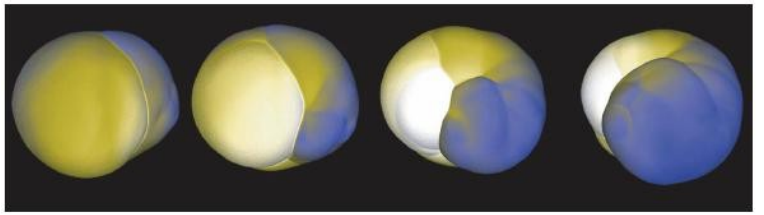

*Blondin & Mezzacappa 07*

- **Spin-up** of a NS born from a non-rotating progenitor
- **Spin-down** a NS born from a rotating progenitor?

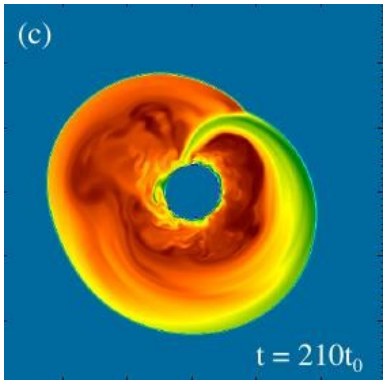
  **Counter-rotating NS**?

# SASI spiral modes and neutron star (NS) spins key issues:

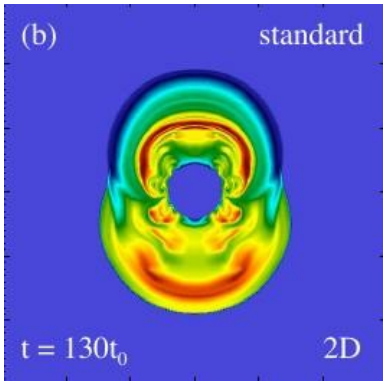
- **Flow pattern**: spiral mode or sloshing mode?
  Only spiral modes can redistribute angular momentum efficiently.



**spiral mode**

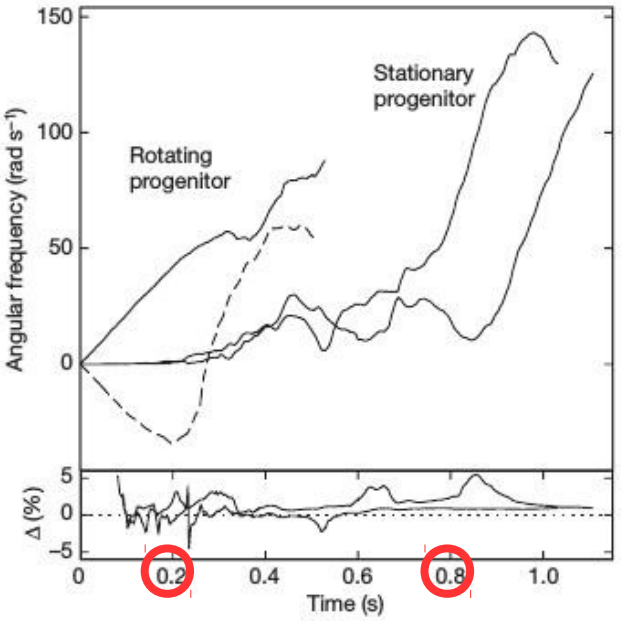



**sloshing mode**




*Fernández 15*

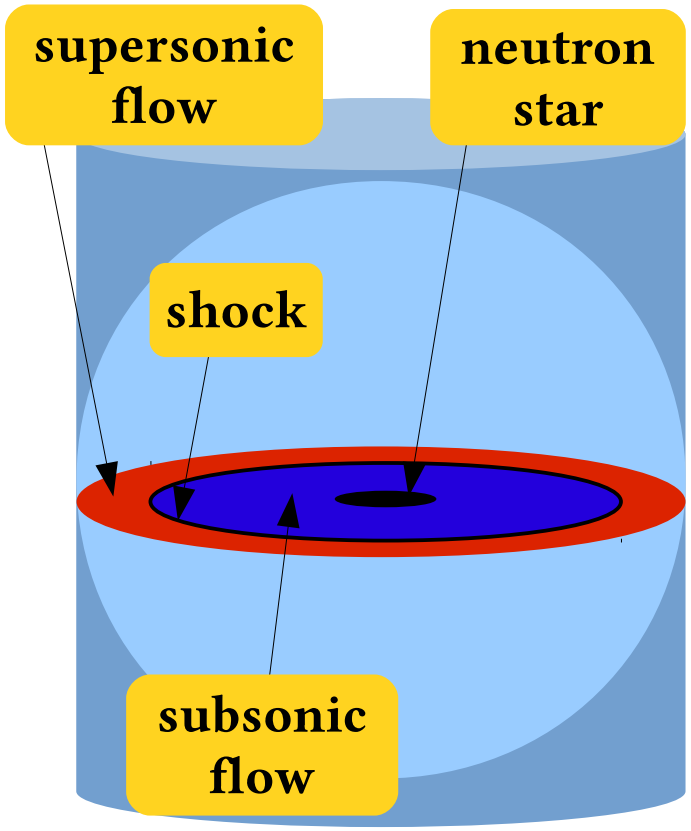
- What is the **timescale** to obtain a robust spiral mode?
  In order to affect the NS spin, a spiral wave must form before the explosion sets in.




*Blondin & Mezzacappa 07*

# Modeling: 2D framework

Aim: simplified setup to characterize the hydrodynamics

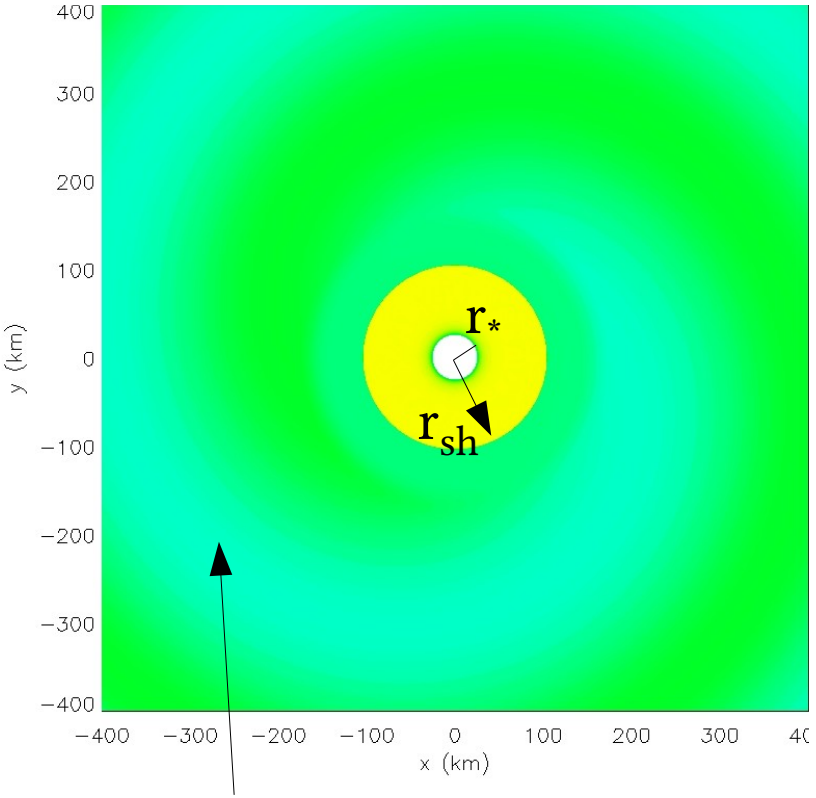



**2D cylindrical domain**

**Physics**

- Perfect gas equation of state ($\gamma$=4/3)
- Approximation of the cooling (Blondin & Mezzacappa 06, Fernandez & Thompson 09)
- No neutrino heating
- Newtonian potential of a point mass
- Constant accretion rate

# Numerical simulations




entropy perturbation

## Numerics

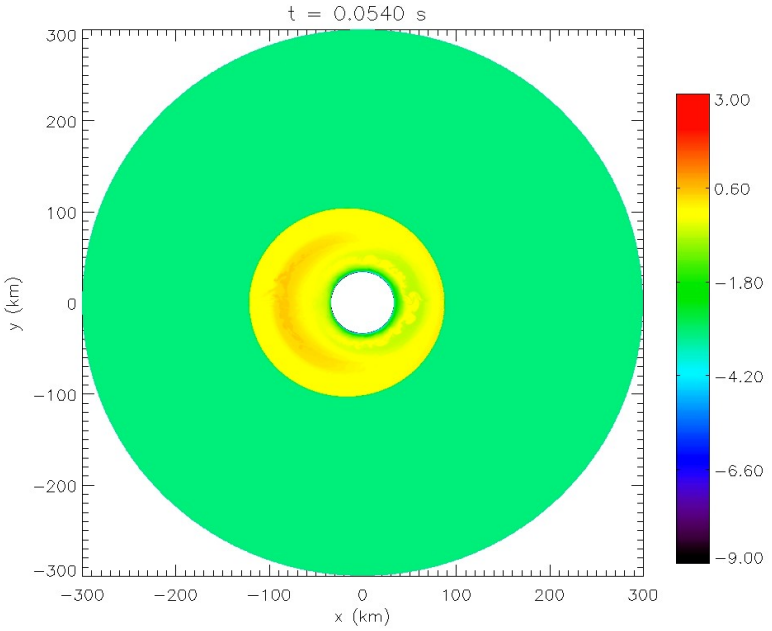
- Simulations with RAMSES: MHD code using Godunov type method.

  New version: DUMSES-Hybrid running on GPUs

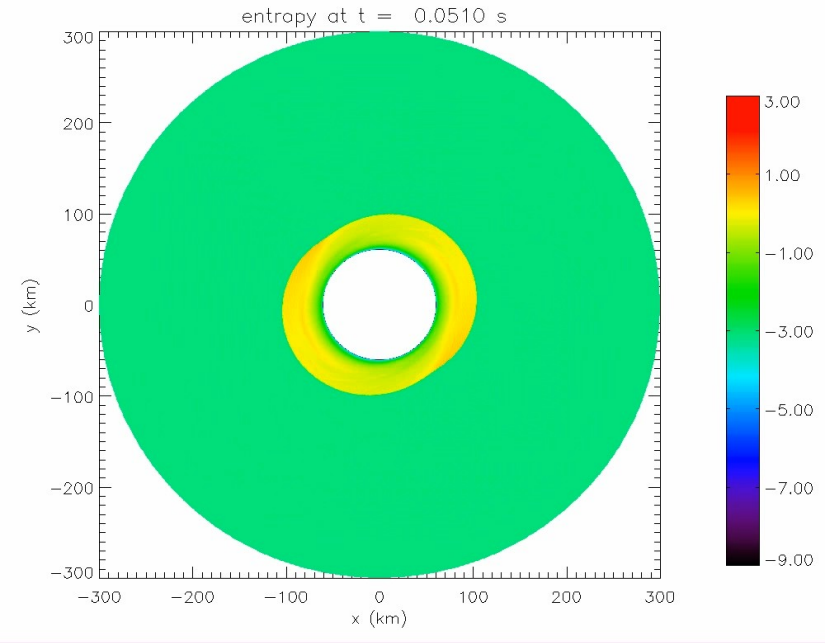
- Parametric study:
  - $R = r_{sh} / r_*$
  - $\varepsilon = (A^2_p - A^2_{-p})/(A^2_p + A^2_{-p})$

    $A_p$: mode amplitude

# Spiral domination threshold



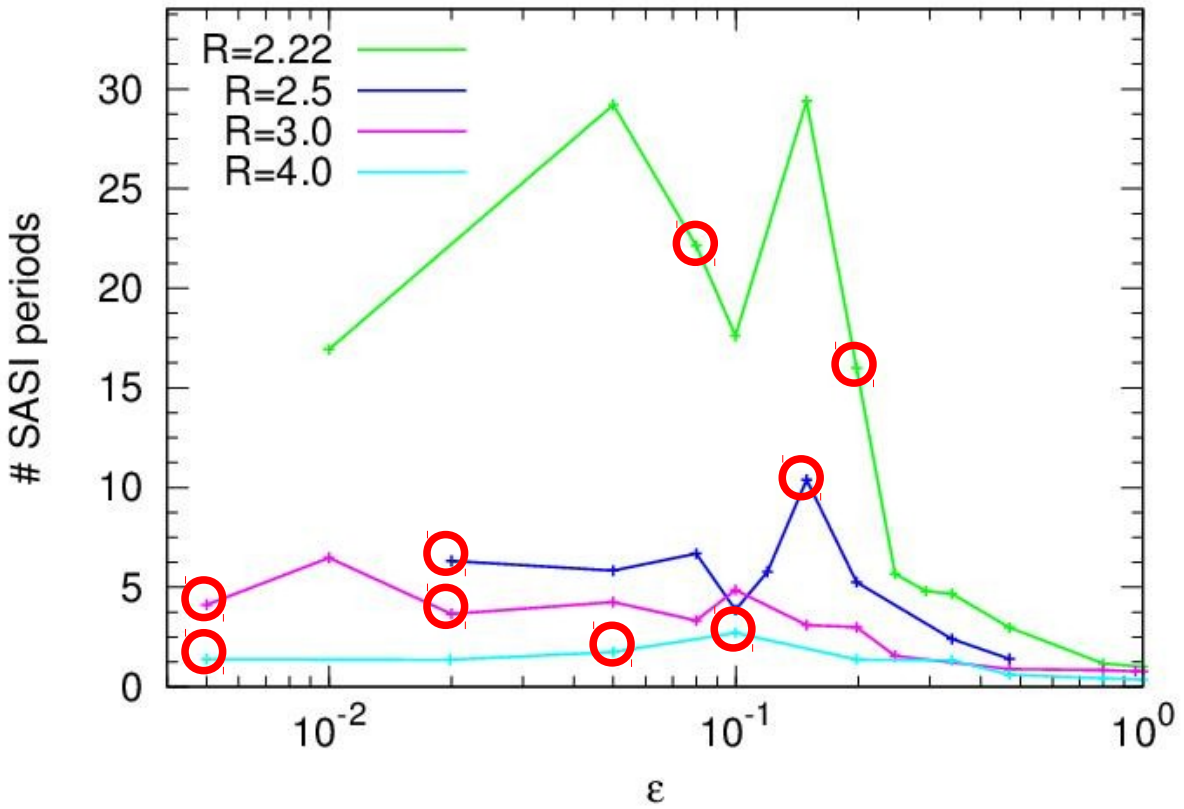

R=3
early spiral mode




R=1.67
a sloshing mode dominates:
no NS spin-up!

**Spiral modes dominate only if $R=r_{sh} / r_{*} > 2$**

# Timescale to obtain a spiral mode ($T_{sp}$)

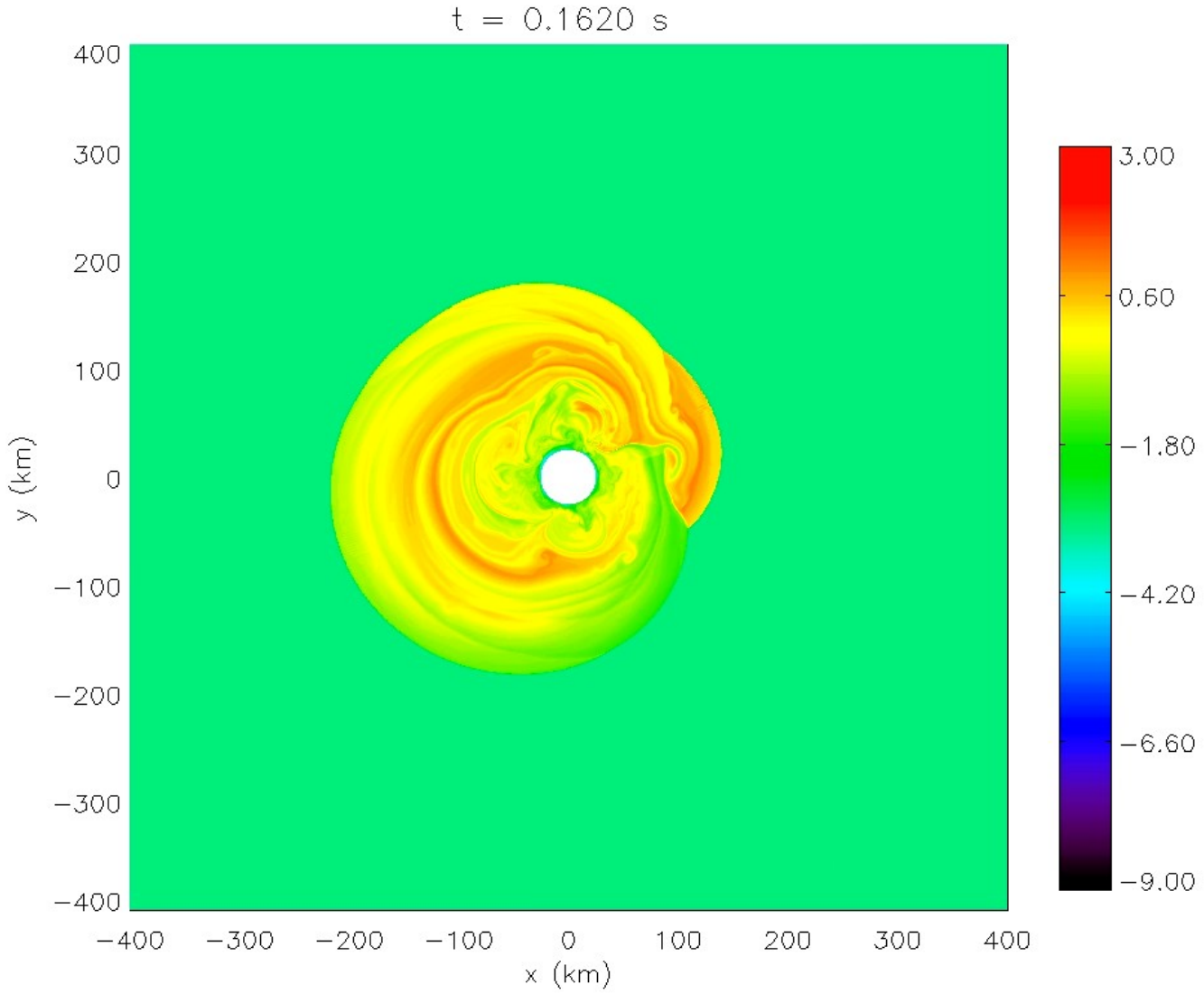



Unexpected direction of rotation

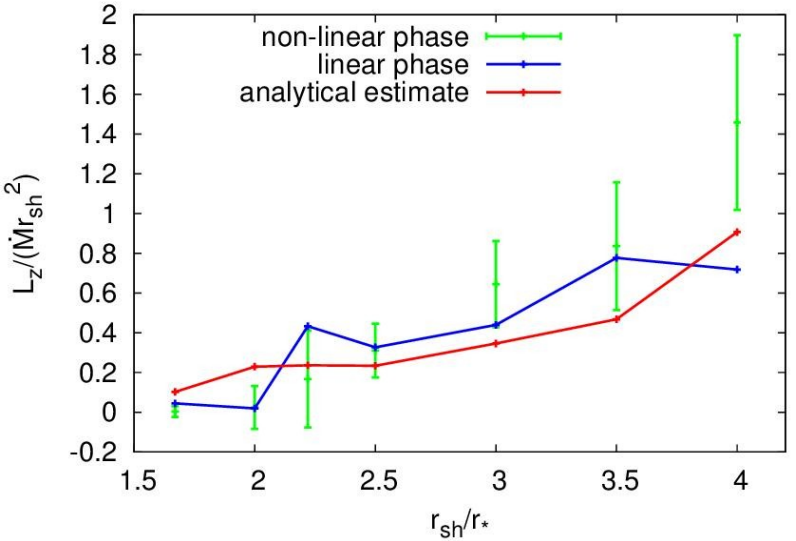
- $T_{sp}$ decreases with R
- For R=2.22, $T_{sp} \approx$ 1s
- Direction of rotation unpredictable if ε<<1

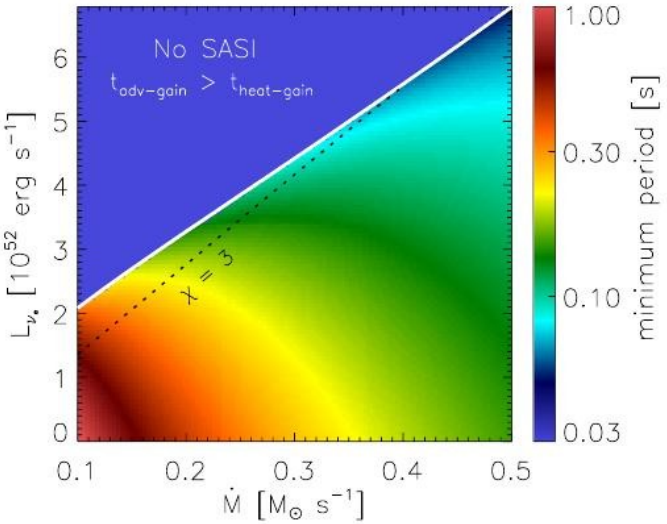
  ⟹ stochasticity

# Non-linear dynamics: reversal of the direction of rotation



# Pulsar spin estimates from analytical calculations and numerical simulations



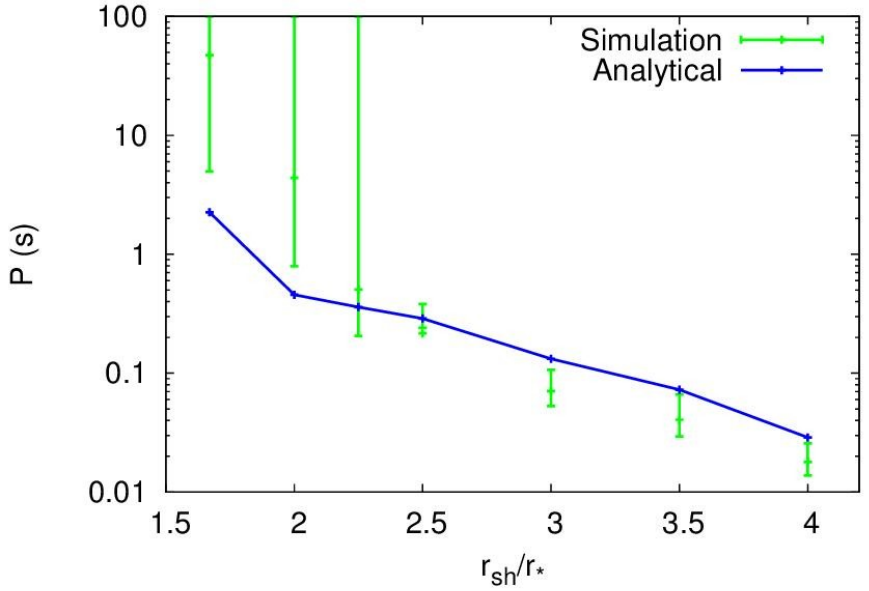




results similar to Fernández 10, Guilet & Fernández 14

*paper to be submitted soon: RK, J. Guilet & T. Foglizzo 15*

*Minimal period: 50ms ≤ P ≤ 1s*

*Guilet & Fernández 14*




- SASI may spin-up the NS if R ≥ 2.5
- SASI may not impact the spin if R < 2.5

# Ongoing work: role of the initial rotation

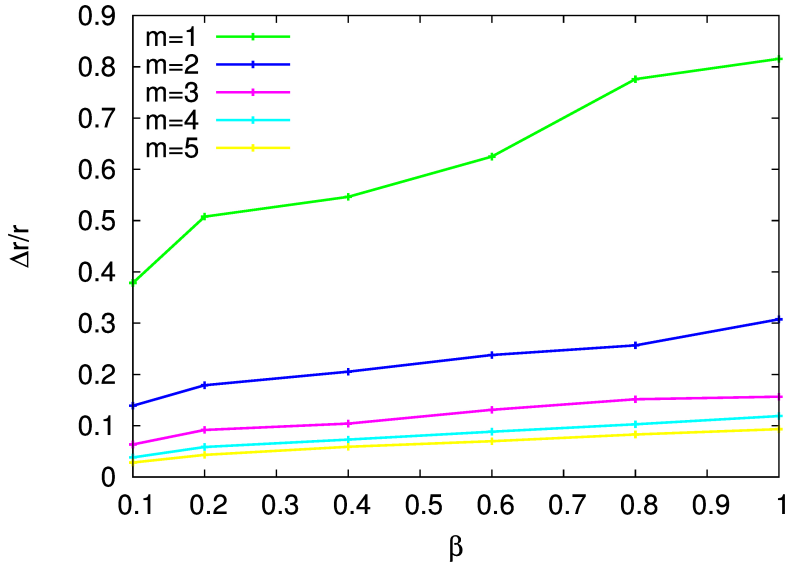
## Importance of the rotation

- Reduces the critical neutrino luminosity required for explosion (Nakamura+14, Iwakami+ 14)
- A spiral mode may spin-down a NS up to the point of reversing its direction of rotation (Blondin & Mezzacappa 07)

## Our study

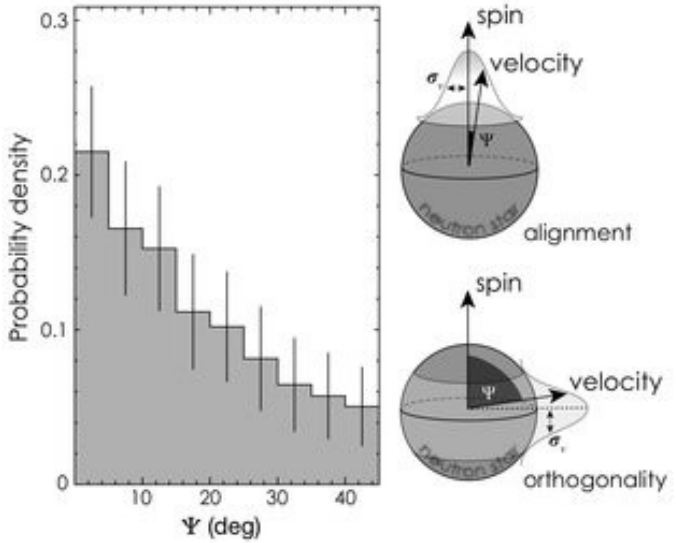
- Effect on the saturation amplitude?
- Angular momentum accreted by the PNS?
- Maximal rotational energy available to match with pulsar spin observations?
- *in prep: RK, T. Foglizzo, J. Guilet et al*

$L = \beta x 10^{16}$ (cm$^2$/s)
$\beta = 0.1 \Longleftrightarrow P \approx 6$ms

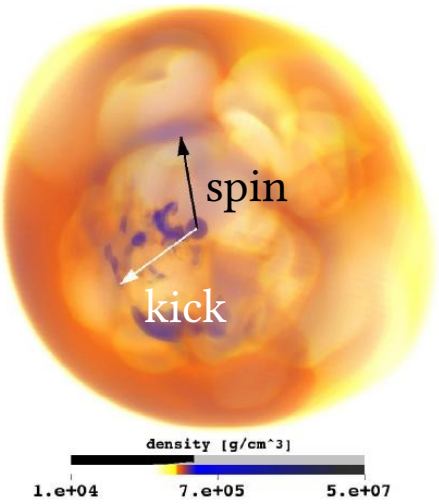


# Future work: neutrino heating

- Including neutrino heating (convection)
- Characterizing convection with rotation in 3D, 300.000 CPU hours on Occigen (CINES)
- Imprint on the kick-spin angle? (Mis)alignment related to the hydrodynamics?




*Noutsos+ 13*




*Wongwathanarat+ 13*

# Conclusion

- Spiral vs sloshing mode
- Reversal of the direction of rotation
- SASI has the potential to spin-up the NS for an identified set of parameters
- Impact of the rotation on:
  - the saturation amplitude of SASI
  - the NS spin at birth
- Next step: - convection & rotation in 3D: kick-spin alignment issue.

**Thanks for your attention!**