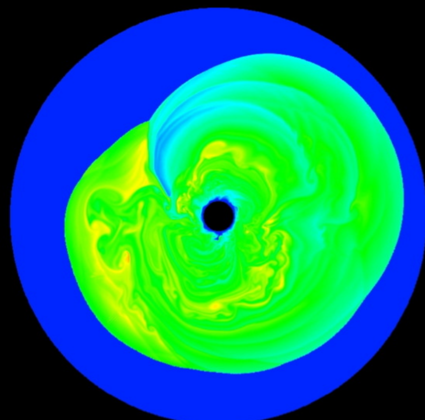
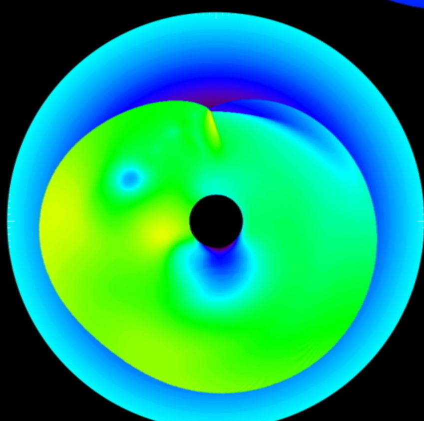
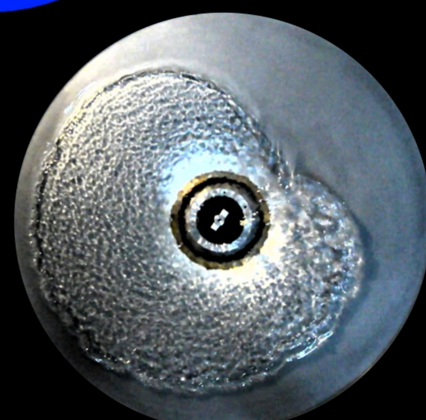
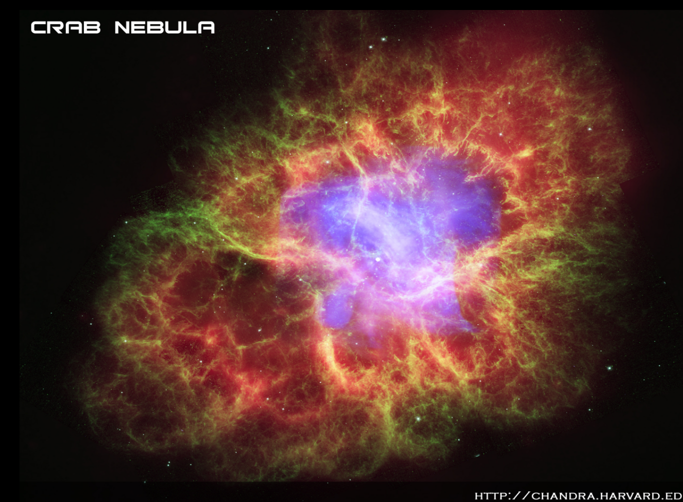
Impact of stellar rotation on the explosion mechanism of core-collapse supernovae









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SF2A 2016, Lyon

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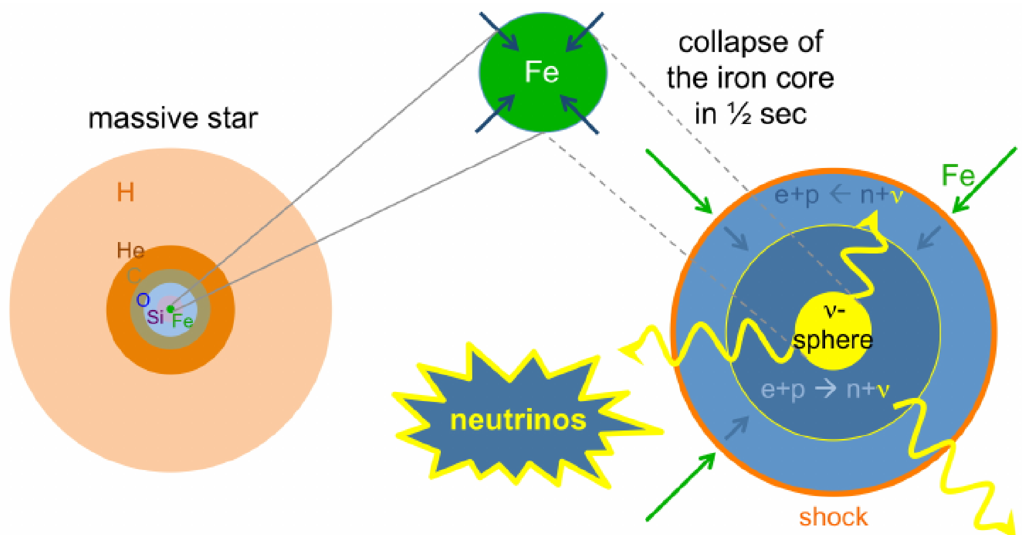
Outline of the talk

- Explosion mechanism of massive stars:
  - a challenging numerical problem
  - multi-D dynamics & hydrodynamical instabilities

- Influence of stellar rotation
  - on the shock wave dynamics
  - on the neutron star spin at birth

Core-collapse supernovae: framework

Neutrino-driven explosion (Bethe & Wilson 1985)

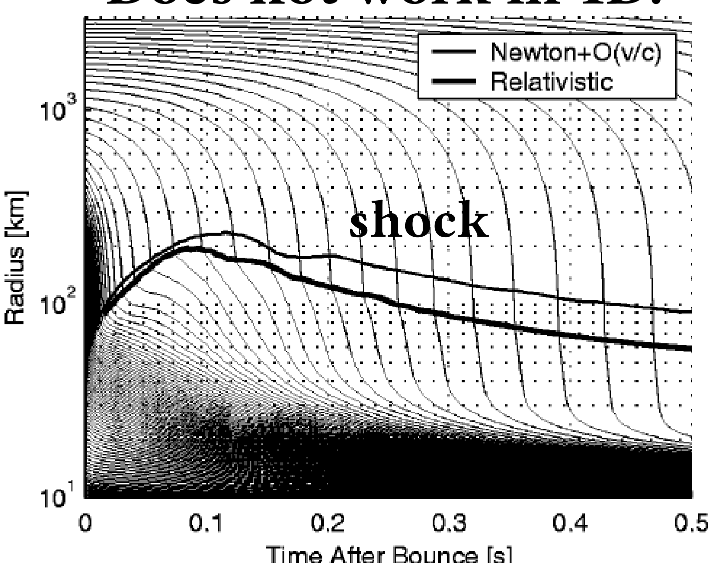


$$E_{\rm grav} \equiv \frac{GM_{\rm NS}^2}{R_{\rm NS}} \sim 1.7 \times 10^{53} \left(\frac{30{\rm km}}{R_{\rm NS}}\right)\left(\frac{M_{\rm NS}}{1.4M_\odot}\right)^2 {\rm erg}$$

Simulation ingredients

- Neutrino transport
- General Relativity
- Equation of State
- Microphysics
- Rotation & Magnetic fields?

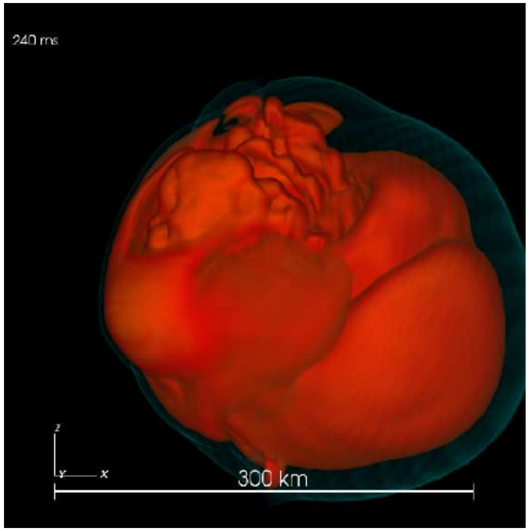
Does not work in 1D!



Liebendoerfer+ 2001

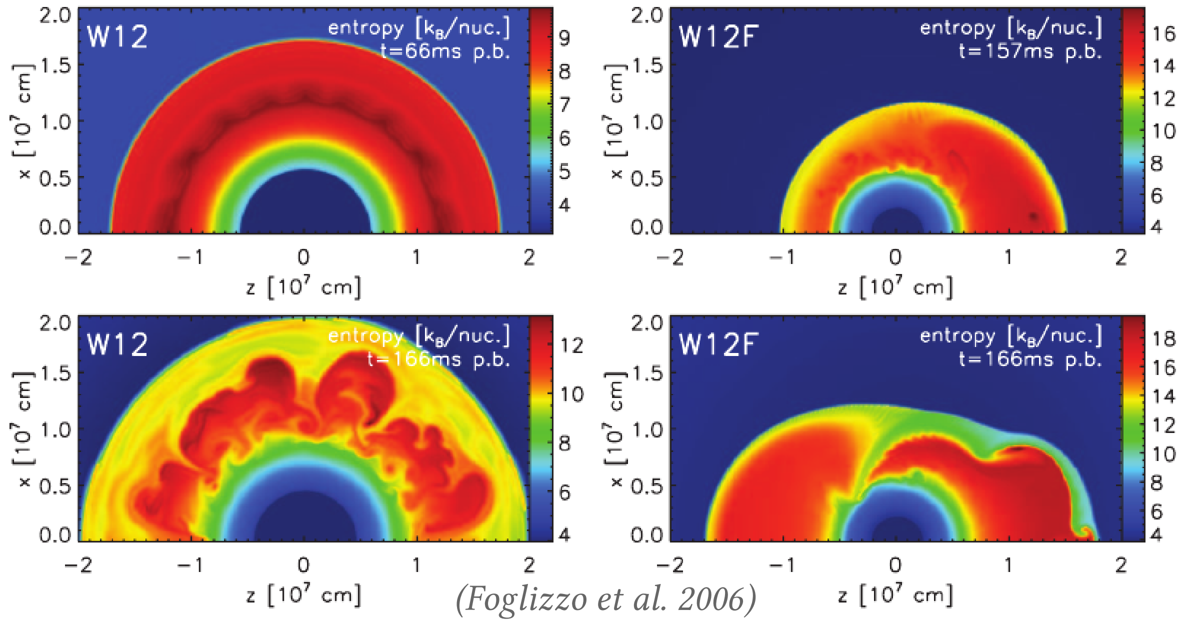
- ~50M CPU hours per model
- 3D close to explode
- under-energetic explosions

Requires multi-D hydro!



Hanke+ 2013

Hydrodynamical instabilities: a key process



(Foglizzo et al. 2006)

Neutrino-driven convection

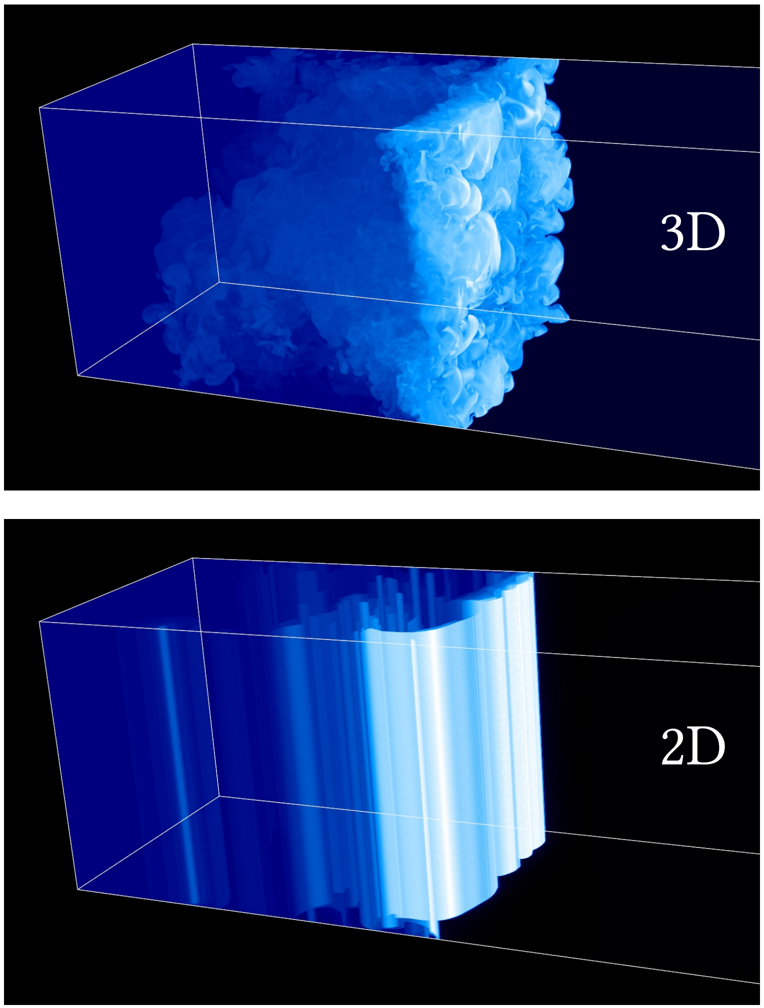
- neutrino heating below the shock
- angular scales l ~ 5-6
- may be stabilized by advection

Standing Accretion Shock Instability (SASI)

- advective-acoustic cycle
- global asymmetry l ~ 1-2
- sloshing and **spiral motions**
- impact on the kick and the **spin of pulsars**

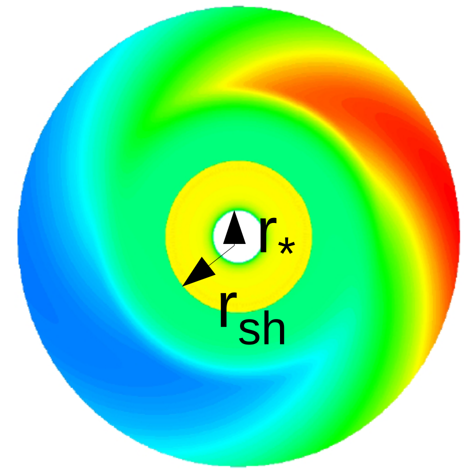
Simplified models dedicated to hydro instabilities

Convection



Entropy variations in the gain region
(credit: SDvision)

SASI



2D cylindrical domain

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

- Minimal set of ingredients for each instability
- Address the dimensionality issue
- Parametric studies
- Physical effect: impact of rotation
- Simulations with the RAMSES code.

Outline of the talk

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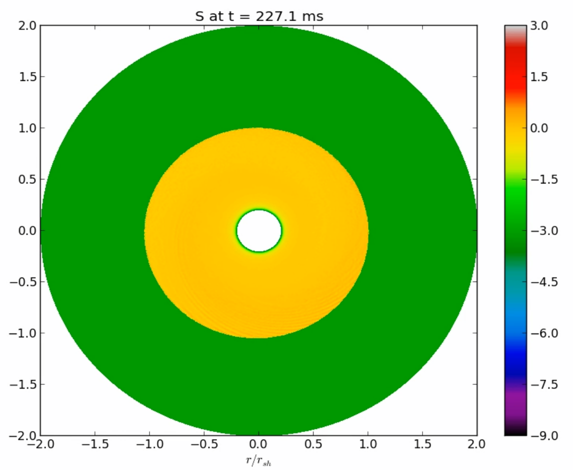
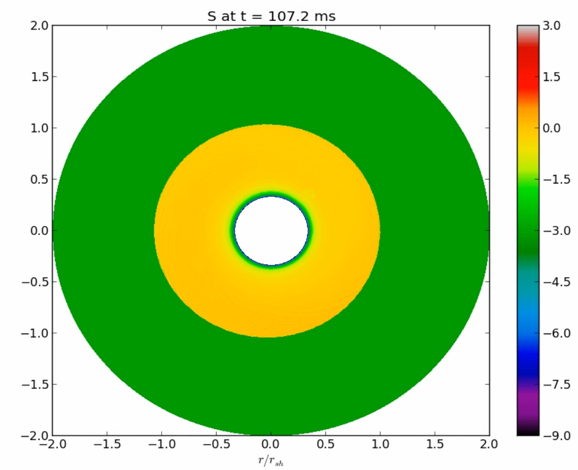
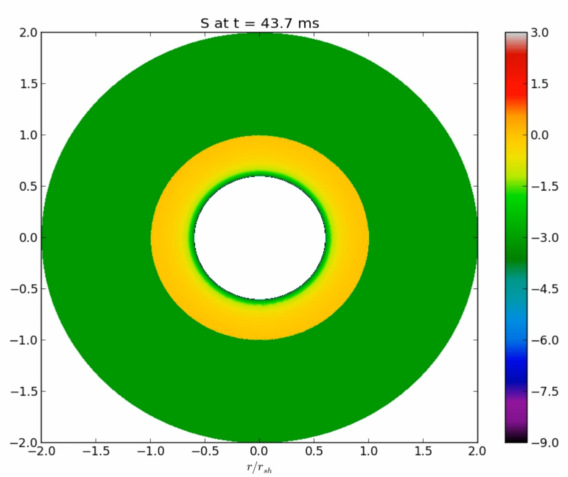
Effect of rotation on the post-shock dynamics





R=5

R=3



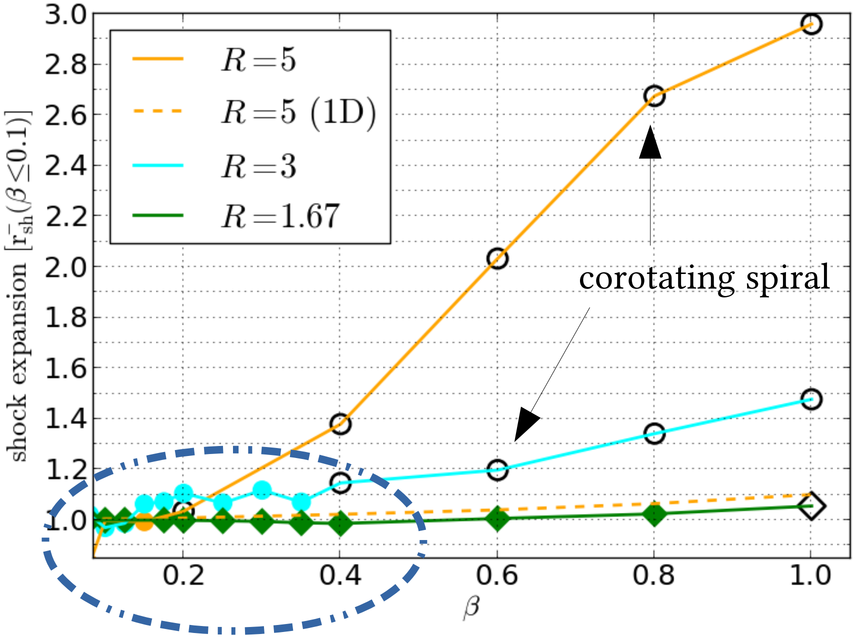
R=1.67

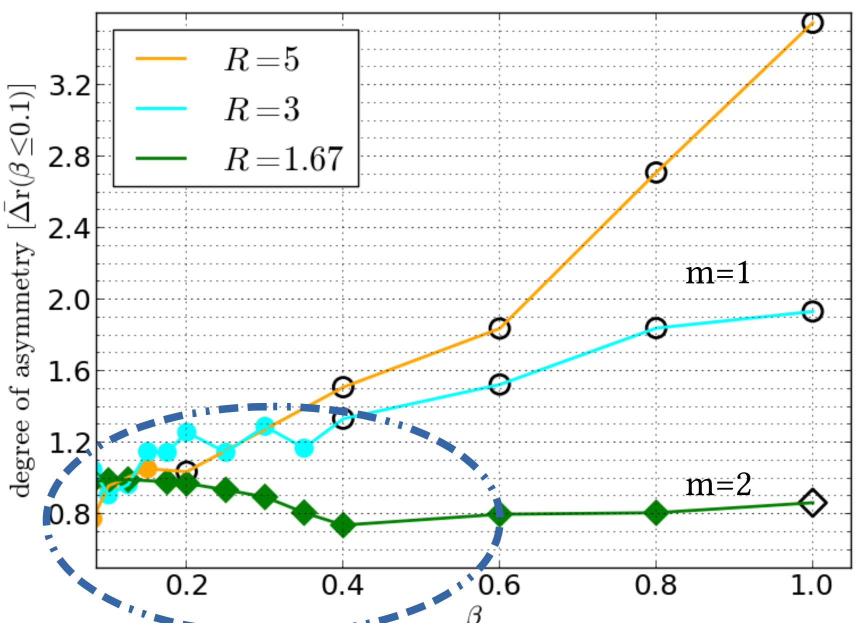
β=0.4

T_{10km}=1.5ms

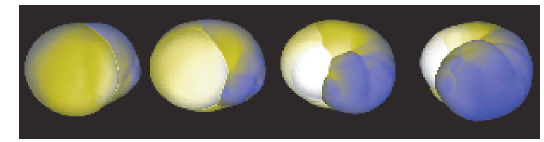
Effect of rotation on the shock dynamics: several regimes

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





SASI



β=0.1

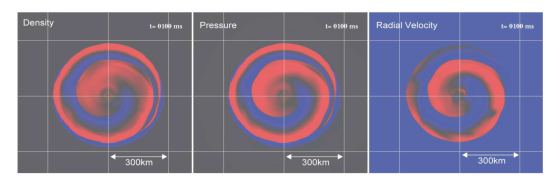
(Blondin & Mezzacappa 2007)

Significant shear even when the centrifugal force $\Omega^2 R$ is weak.

$$\frac{\Omega}{\Omega_{NS}} \propto \left(\frac{r_{NS}}{r}\right)^2$$

$$\beta \equiv \frac{L}{10^{16}\mathrm{cm}^2\mathrm{s}^{-1}} = \frac{0.63\,\mathrm{ms}}{P_{10\mathrm{km}}}$$

Low T/W



β=3.9

(Takiwaki+ 2016)

A corotation radius appears (low T/W) for fast rotation rates.

$$r_{co} \equiv \sqrt{\frac{mj}{\omega_r}} > r_*$$

	mean shock radius	shock asymmetry
centrifugal force	x1.05	-
SASI without rotation	x1.3-2.3	30-60 %
SASI + rotation	x1.4-2.7	40-80 %

Angular momentum budget: from stellar rotation to pulsar spins

Rotation profile of massive stars

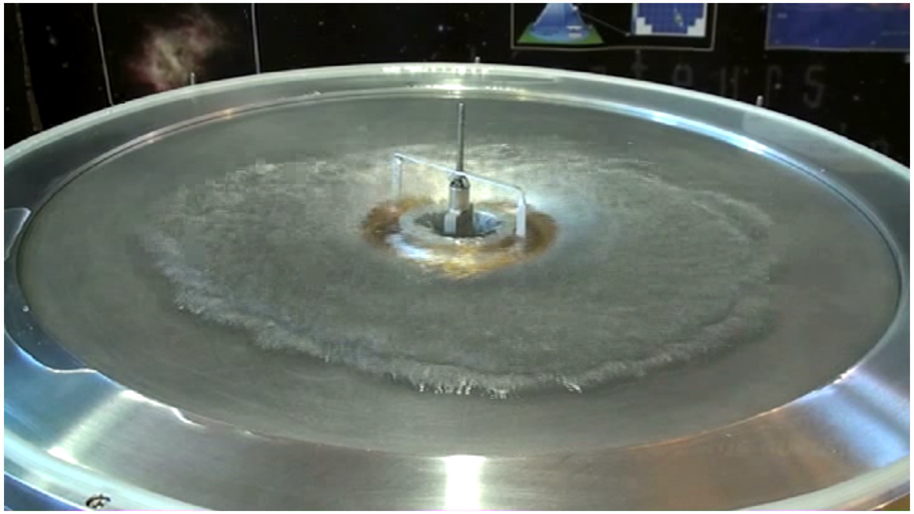
??

- Slow rotations favoured: β~0.1 (e.g. Heger+ 2005)
- Large uncertainties in the inner region.

Natal pulsar spin distribution

- Slow periods from ~10ms to ~100ms at birth (e.g. Faucher-Giguère & Kaspi 2006, Popov & Turolla 2012, Noutsos+ 2013)
- **Constraint for the explosion mechanism.**

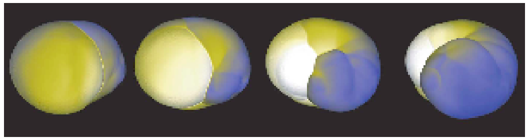
Non-axisymmetric collapse: angular momentum is redistributed!



(Foglizzo+ 2012, 1015)

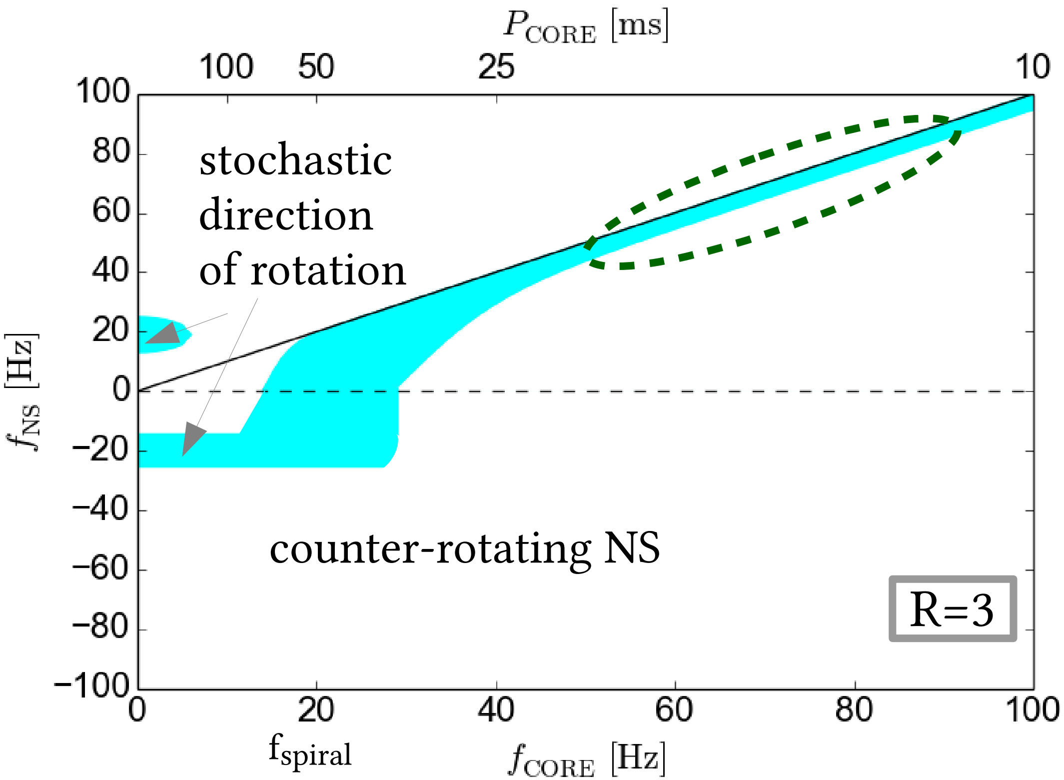
Effect of the SASI spiral mode on the NS spin

- NS spin up without stellar rotation: (Blondin & Mezzacappa 2007, Guilet & Fernández 2014)
- Counter rotating NS with stellar rotation: P~50ms (Blondin & Mezzacappa 2007)



(Blondin & Mezzacappa 2007)

Angular momentum budget: from stellar rotation to pulsar spins

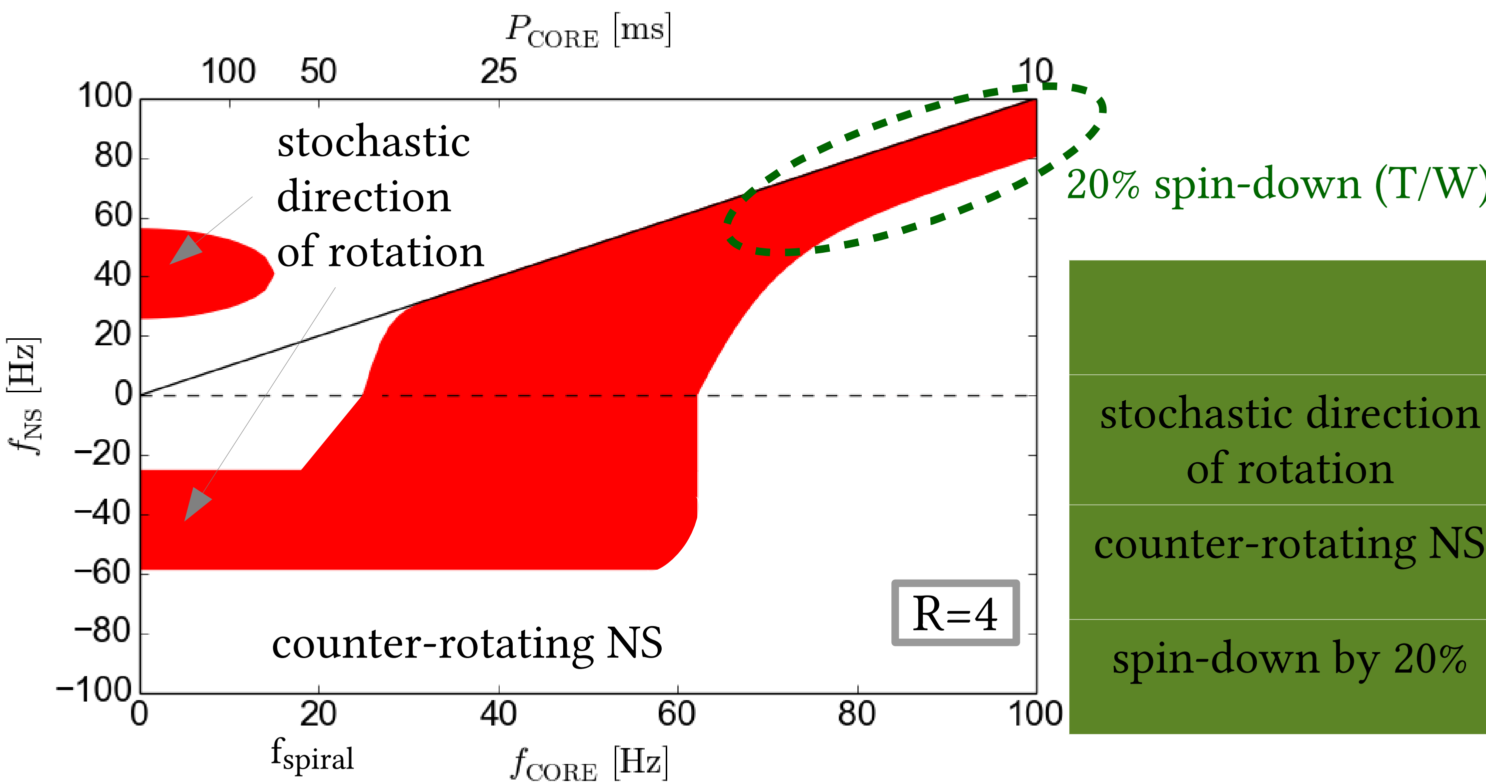


5% spin-down (T/W)

$$\beta \equiv \frac{L}{10^{16}{\rm cm}^2{\rm s}^{-1}} = \frac{0.63}{P_{\rm 10km}}$$

	f_{core}	P_{core}	β
stochastic direction of rotation	<5Hz	>200ms	0.005
counter-rotating NS	<25Hz	>40ms	0.1
spin-down by 20%	<80Hz	>12ms	0.4

Angular momentum budget: from stellar rotation to pulsar spins



$$\beta \equiv \frac{L}{10^{16}\mathrm{cm}^2\mathrm{s}^{-1}} = \frac{0.63}{P_{10\mathrm{km}}}$$

	f_{core}	P_{core}	β
stochastic direction of rotation	<10Hz	>100ms	0.01
counter-rotating NS	<60Hz	>16ms	0.1
spin-down by 20%	~1000Hz	~1ms	~1.0

Summary

- Simplified models to study hydro instabilities in core-collapse supernovae.

- The dynamical influence of rotation on SASI depends on $R=r_{sh}/r_*$. Calls for a parametric study of realistic models with rotation.

- For fast enough rotation rates, a corotation instability overlaps with SASI and greatly influences the dynamics.

- One-armed instabilities significantly affect the pulsar spin for R=rsh/r≥3.

- Additional effect of neutrino-driven convection should be considered.