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VNIVERSITAT DE VALÈNCIA
amap
Are relativistic jets the birth cryings of supernova remnants?
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on behalf of the Valencia Collaboration
J.M. Ibáñez, J.M. Martí, J.A. Font, P. Cerdá-Durán, P. Mimica,
M. Obergaulinger, I. Cordero-Carrión, T. Rembiasz
Ringberg, 27 – 07 - 2017

According to ADS, we have published together 73 papers since 1994!

# A lot of things done together!

## Relativistic jets

**AGN jets:**
- kpc-scale
- pc-scale
- blazars

**GRB jets:**
- collapsars
- mergers

- **EM - Martí - Ibáñez (1994-98):** Exact solution of the RRP and first relativistic jets in planar and cylindrical symmetry.
- **EM - Aloy - Martí - Ibáñez (1998-03):** Relativistic jets in 3D planar symmetry.
- **EM - Mimica - Aloy (2004-08):** advanced radiation transfer coupled to RMHD for blazars.
- **EM - Scheck - Aloy - Martí (2001-02):** Long term evolution with realistic EoS.
- **EM - Leismann - Aloy - Martí - Ibáñez (2001-02):** RMHD jets.

## Supernova connection

**Modeling the central engine**
- GR-CC-CoCoNuT
- CFC GW-forms
- MHD core collapse
- Growth of seed B-fields

**SN bound remnants**
- Magneto-elastic oscillations of NS
- GRHD CC to BH

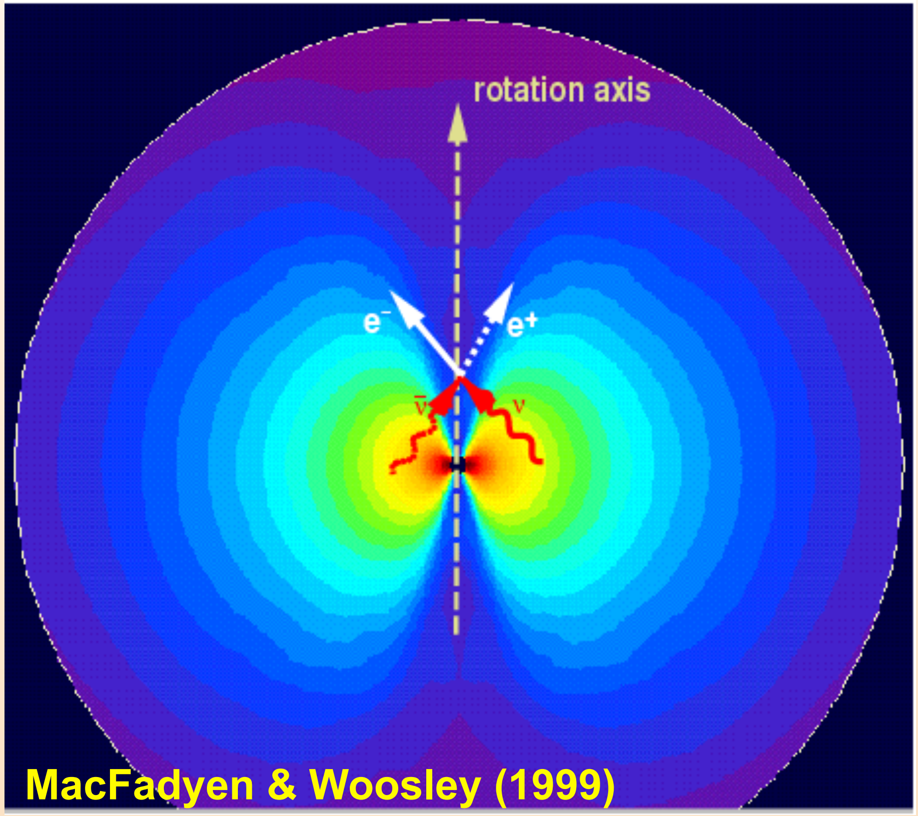
**SNR**
- 3D simulations of SN remnants

- **EM - Dimmelmeier - Font -Cerdá-Durán - Ibáñez, 2000-08:** 1st relativistic waveforms in CFC. Birth of the `CoCo+ codes` (`CoCoA, CoCoNuT, M-CoCoA,…`) *Ibáñez talk!*
- **EM - Obergaulinger - Cerdá-Durán - Rembiasz - Dimmelmeier - Aloy, 2004-17:** Dynamical effects of the B-field on CC, GW-signals, explosion mechanism
- **EM - Gabler - Font -Cerdá-Durán - Ibáñez, 2011-17:** Relation between torsional oscillations of magnetars and observed QPOs.
- **EM - Cordero-Carrión- Montero - Cerdá-Durán - Font, 2006-17:** “hydro-without-hydro” evolutions of spherical and rotating relativistic stars in equilibrium, and single BHs
- **EM - Obergaulinger 2013-14:** interaction of supernova shock waves with a clumpy environment.

# Progenitors lGRB: Collapsars

Woosley (1993)

- Collapse of a massive ($M_* \sim 30M_\odot$) rotating star that *does not* form a successful SN but collapses to a BH ($M_{BH} \sim 3M_\odot$) surrounded by a thick accretion disk. The hydrogen envelope is lost by, e.g., stellar winds, interaction with a companion (WR).
- Key: Formation of a funnel around the rotation axis ($\rho_{funnel}/\rho_{disk} \sim 10^{-3}$- $10^{-4}$) if $3 \leq j_{16} \leq 20$ cm$^2$ s$^{-1}$
- The viscous accretion onto the BH ⇒ strong heating ⇒ thermal $\nu\nu$-annihilating preferentially around the axis ⇒ formation of a relativistic jet ($\Gamma$>10)?.
- Alternative generation: hydromagnetic (Blandford-Payne mechanism) or electromagnetic (Blandford Znajek mechanism).



# Things I learned with Ewald from simulations of collapsar jets

– Outflows highly variable due to KH or SD instabilities ⇒ extrinsic variability which can be the source of internal shocks. Extrinsic/intrinsic$^{(=\text{source})}$ variability might be indistinguishable.

– Jets show transverse structure: ultrarelativistic spine ($\Gamma$~50) + moderately relativistic, hot shear layer ($\Gamma$~5-10).

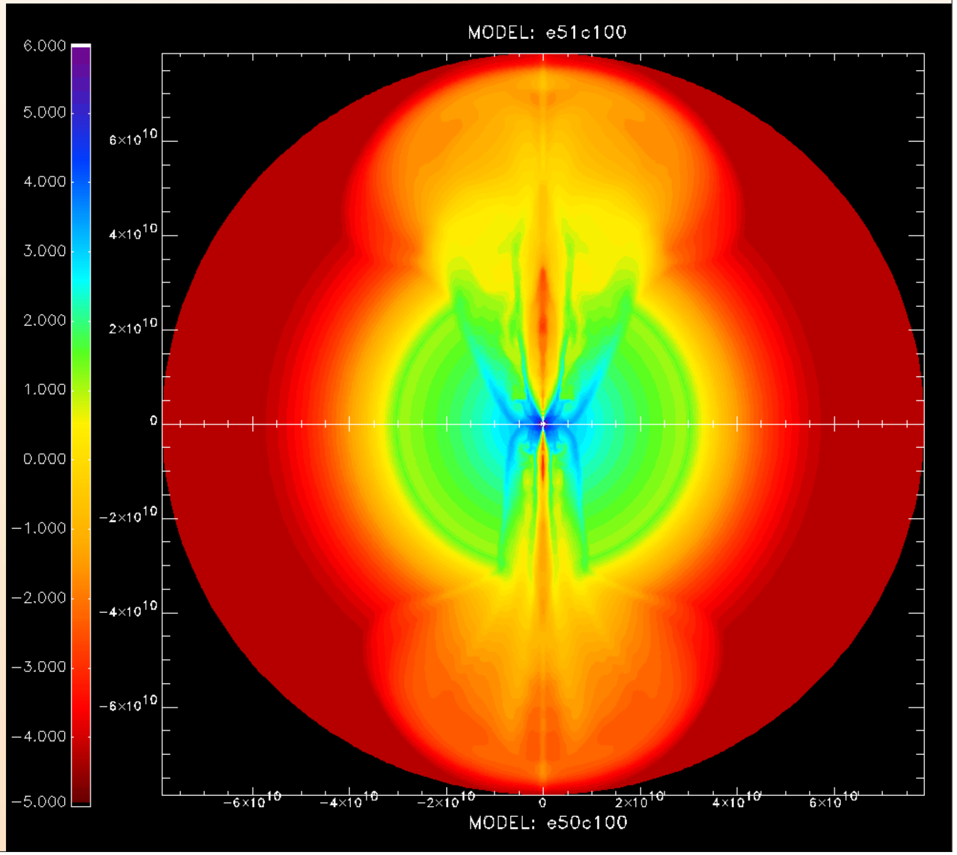
– The jet breakout through the stellar surface and its interaction with the stellar wind could lead to some *precursor* activity.

– The cocoon transports a sizeable fraction of the energy and could yield $\gamma$-ray/hard X-ray transients

⇒ unification GRBs/XRR-GRBs/XRF

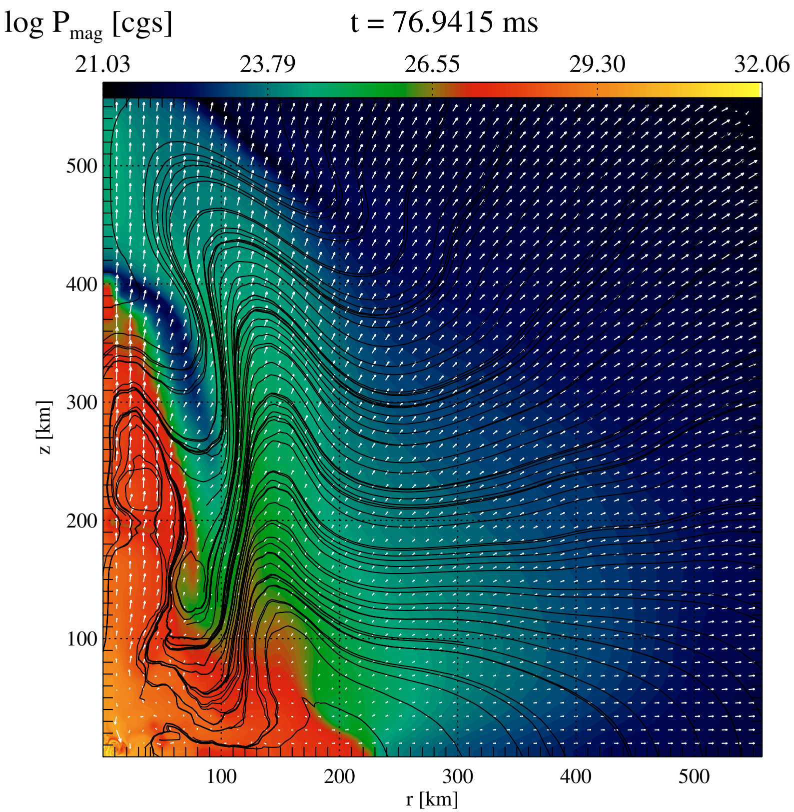
– Jets are inertially confined by the star with $\theta_{\text{break}}$<5º.

Aloy, Müller, Ibáñez, Martí & MacFadyen (2000)



Obergaulinger, Aloy, **Müller** (2006) Obergaulinger, Aloy, Dimmelmeier, **Müller** (2006)

# Core collapse with B-fields and rotation




- Axisymmetric collapse with simplified physics: influence of ***B*** and Ω on dynamics and GW signal
- First with simple MHD methods
- The byproduct of these models are realistic configurations for collapsars.

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# The *Aenus* MHD code

Obergaulinger et al. (2006a, 2006b, 2009, 2010,…)

1. Flux-conservative, FV, Eulerian formulation of the ideal MHD equations
2. High-resolution shock capturing methods:
   - various optional high-order reconstruction algorithms:
     - 2nd-order total-variation diminishing piecewise-linear (TVD-PL) scheme (Minmod, van Leer or MC).
     - 4th-order weighted essentially non-oscillatory (WENO4) scheme (Levy et al. 2002).
     - 5th-, 7th- and 9th-order monotonicity-preserving (MP5, MP7, MP9) schemes (Suresh & Huynh 1997)
   - Approximate Riemann solvers based on the MUSTA method (Toro & Titarev 2006).
3. Self-gravity: Poisson solver.
4. Constraint-transport scheme to maintain a $\nabla\mathbf{B} = 0$ (Evans & Hawley 1988):
   - Due to the staggering of different variables, careful (high-order) interpolation between different numerical grids.
   - We compute **E** from the velocity and the B-field at cell interface which we get as the result of the Riemann solver: E-field consistent with the solution of the Riemann problem!.
5. Parallel (MPI/OpenMP)-Fortran90 code.

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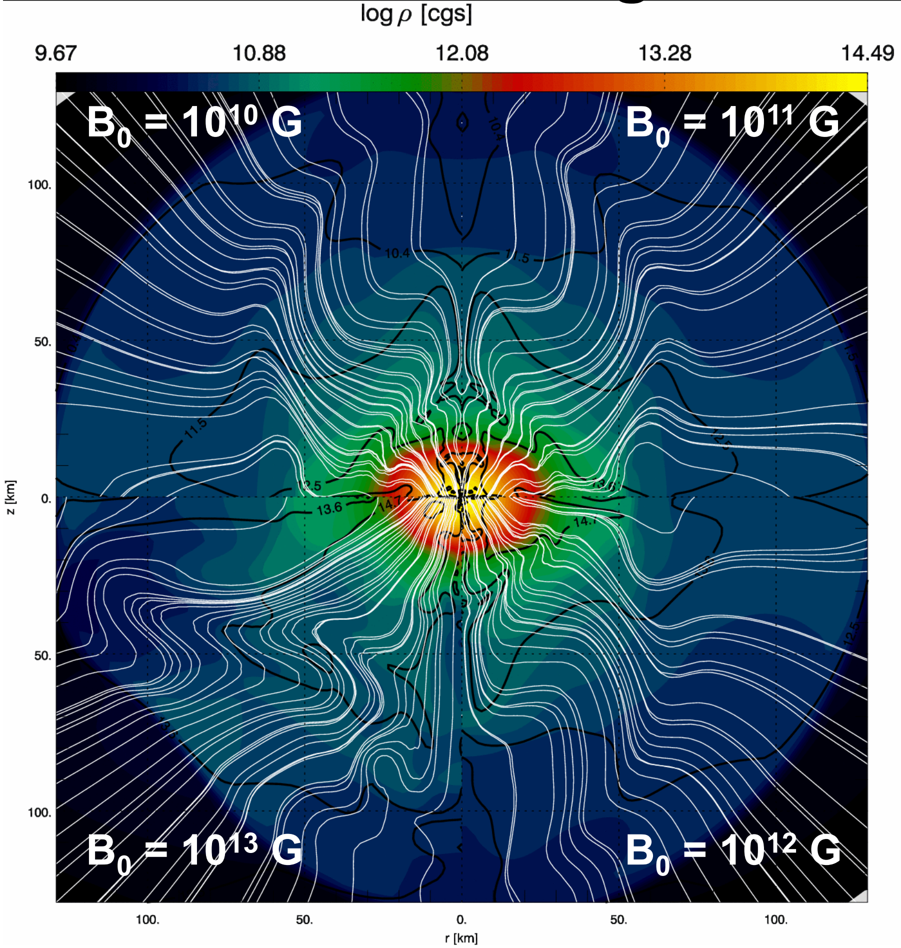
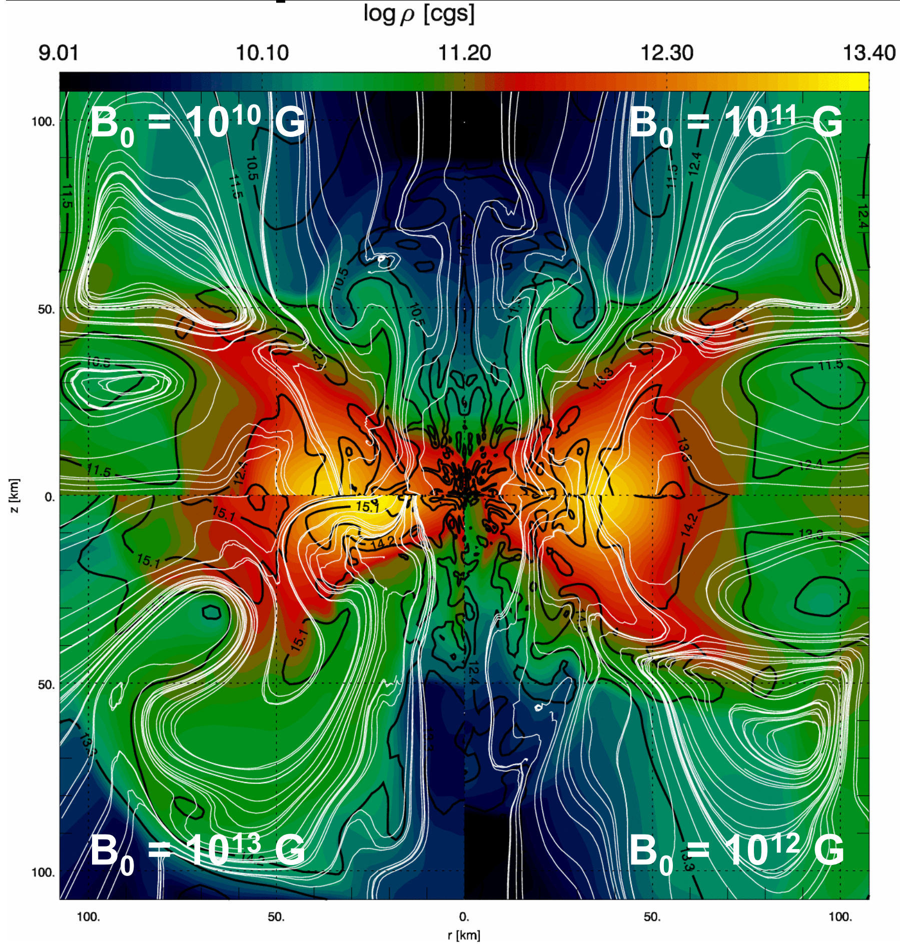
Obergaulinger, Aloy, **Müller** (2006) Obergaulinger, Aloy, Dimmelmeier, **Müller** (2006)

# Byproduct of magneto-rotational CC: realistic configurations for collapsars.




Initial models: Rigid rotator + $E_{rot}/E_{grav}$ = 0.009

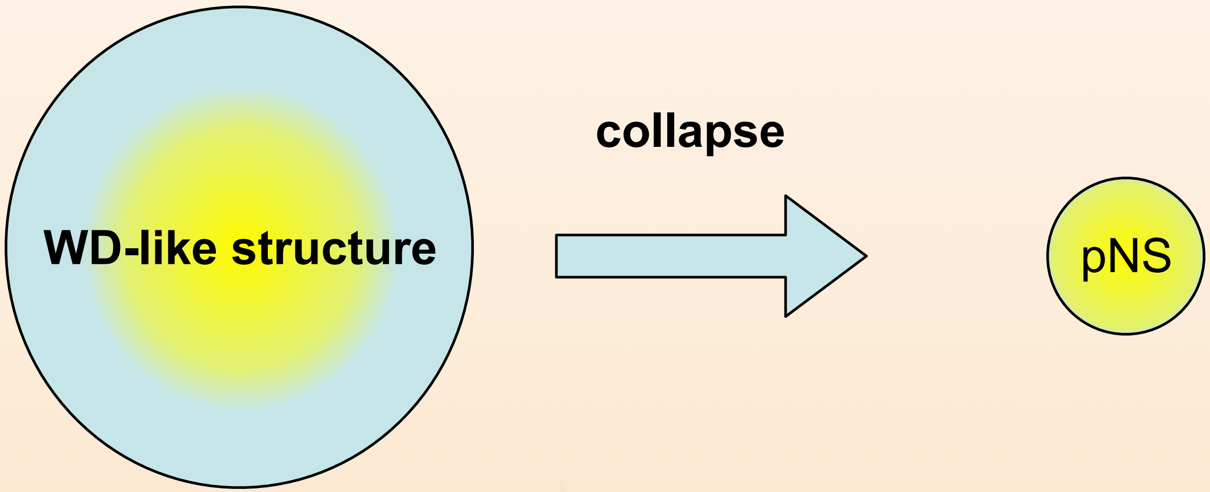
- Do not form tori+funnel systems
- Do not produce polar outflows
- Yield $B_{max}$ ~ $5\times10^{14}$ G, with $B_{tor}/B_{pol}$ ~1-10
- $M_c$~ 0.75 $M_\odot$, $J_c$~ $2\times10^{15}$ cm²/s $\Rightarrow j_{BH}$ ~ 0.6

Initial models: differential rotator + $E_{rot}/E_{grav}$ = 0.04

- Form tori+funnel systems
- For $B_0$>~$10^{12}$ G produce polar outflows
- Yield $B_{max}$ ~ $10^{15}$ G, with $B_{tor}/B_{pol}$ ~1-10
- $M_c$~ 1 $M_\odot$, $J_c$~ $10^{16}$ cm²/s $\Rightarrow j_{BH}$ ~ 1

# B-field growth during collapse

**Since we begin from massive stars with cores having WD-like configurations ($B_0 \sim 10^8 - 10^9$ G) and by compression the (*seed*) *B-field is be amplified to* $B_c \sim 10^{12} - 10^{13}$ G.**




**R~1000 km**
**$B_0 \sim 10^9$ G**

B-flux conservation

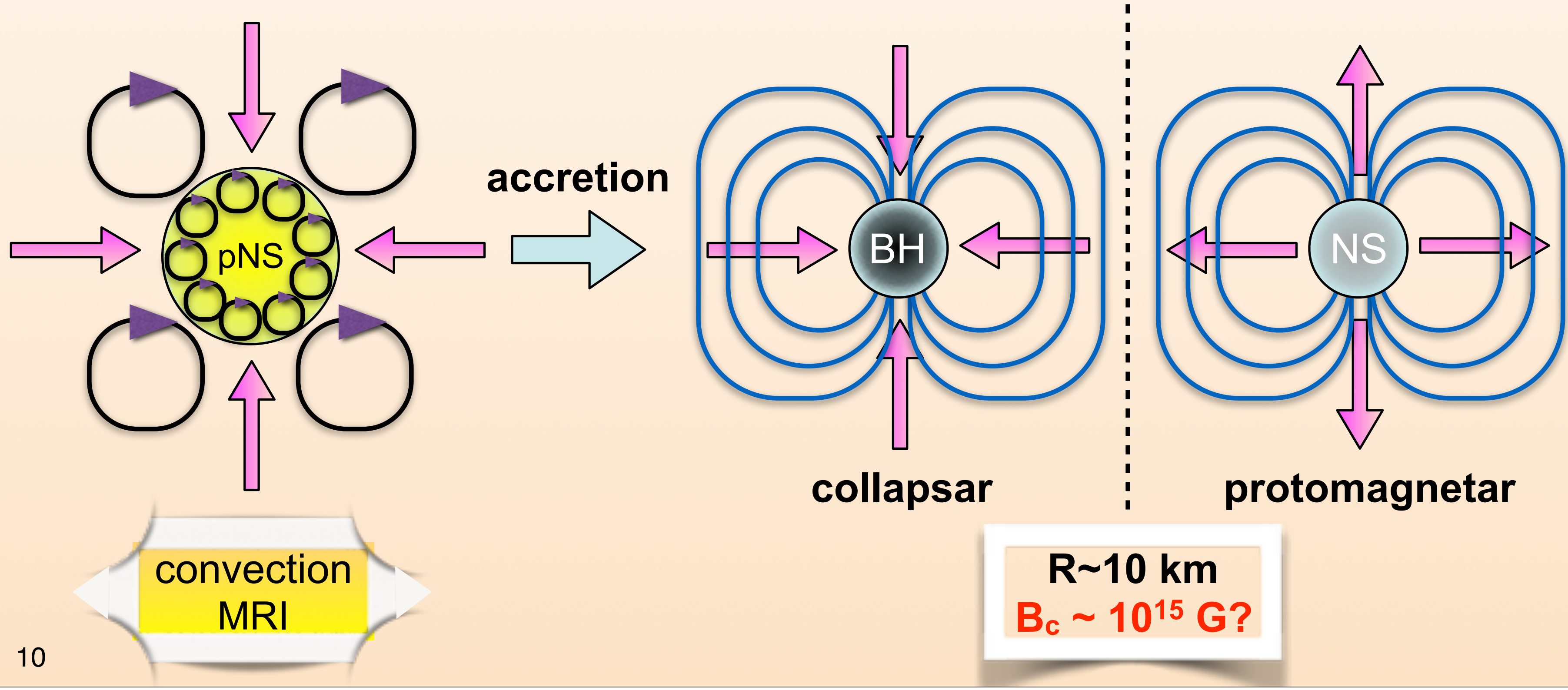
**R~10 km**
**$B_c \sim 10^{13}$ G**

**but $B_c \ll 10^{15}$ G ⇒ collapse insufficient**

# Mechanisms for extra B-field growth

(*differential*) rotation
+
convection
+
seed B-fields

→ magnetic field amplification




R~10 km
$B_c \sim 10^{15}$ G?

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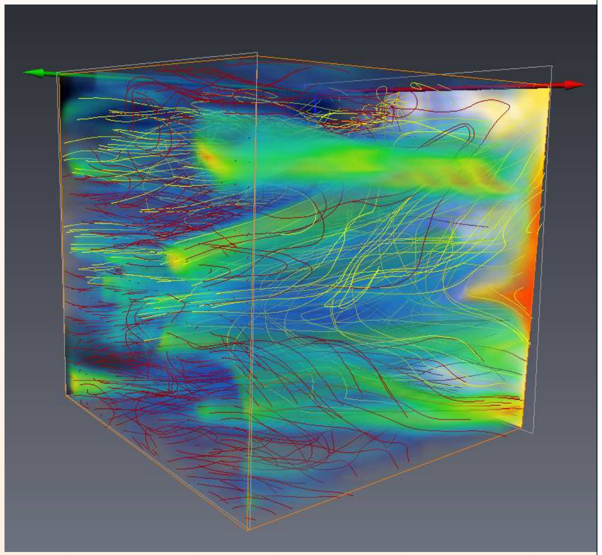
# B-field growth in PNS and CC-SNe

**mode analysis and local modelling**
(Obergaulinger, Cerdá-Durán, **Müller**, Aloy 2009)

- but small-scale effects (MRI) crucial
- new high-resolution code
- more detailed local investigations of MHD instabilities: MRI, KH instabilities

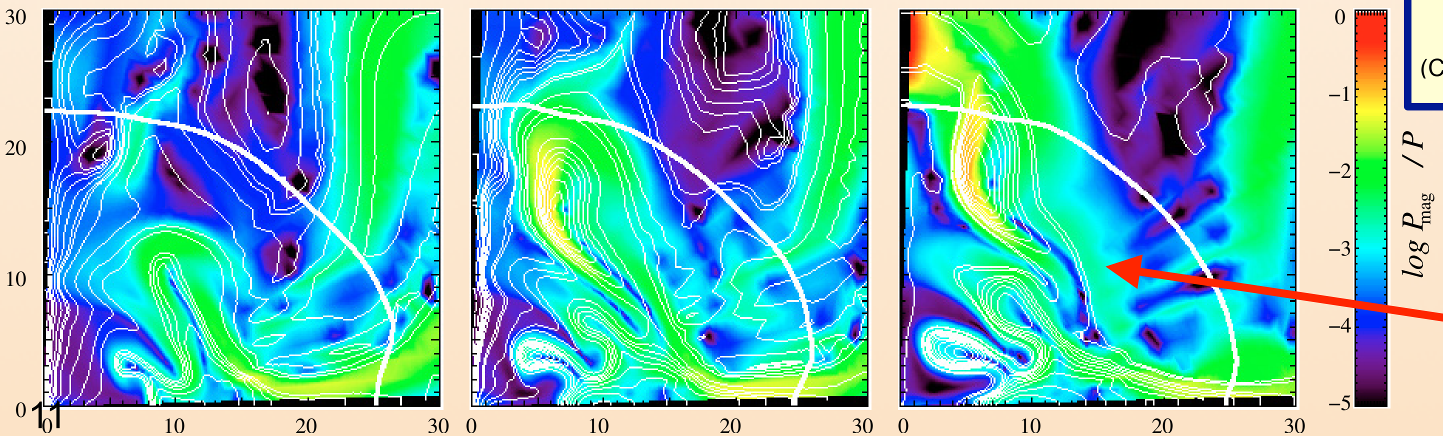


- field amplification by
  - Convection
  - Magneto-rotational instability (MRI)
    - approach: combine local and global modeling, using numerical techniques of a very high order of accuracy
    - goal: a simple description of the saturation of the MRI as a sub-grid model in global simulation

**closure relations**

$$\partial_t e_{MRI} + \vec{\nabla} e_{MRI} \vec{v} = \Gamma_{MRI} e_{MRI} - \Gamma_{par} e_{par}$$
$$\partial_t e_{par} + \vec{\nabla} e_{par} \vec{v} = \Gamma_{par} e_{par} - \varepsilon_{dis}$$

**global modeling**
(Cerdá-Durán, Font, Antón, **Müller** 2008)




MRI channel modes in the post bounce phase.

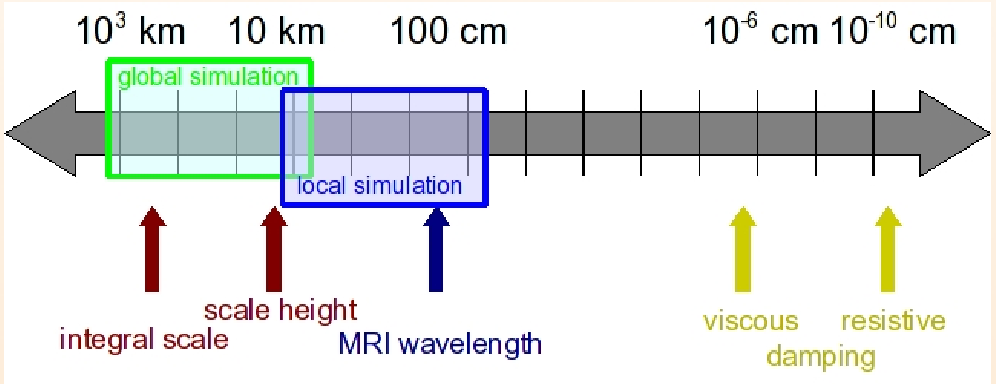
# Amplification by MRI: a challenge for numerical models

- The amplification of seed B-fields is a very computationally demanding task because we have to ***resolve extremely small scales*** (Obergaulinger et al. 2009):

$$\lambda_{\rm MRI}^{\rm FGM} \simeq 6.9\,{\rm m} \left(\frac{\rm B}{10^{13}\,{\rm G}}\right) \left(\frac{\rho}{2.5\times10^{13}\,{\rm gr\,cm^{-3}}}\right)^{-1/2} \left(\frac{\Omega}{1900\,{\rm Hz}}\right)^{-1}$$

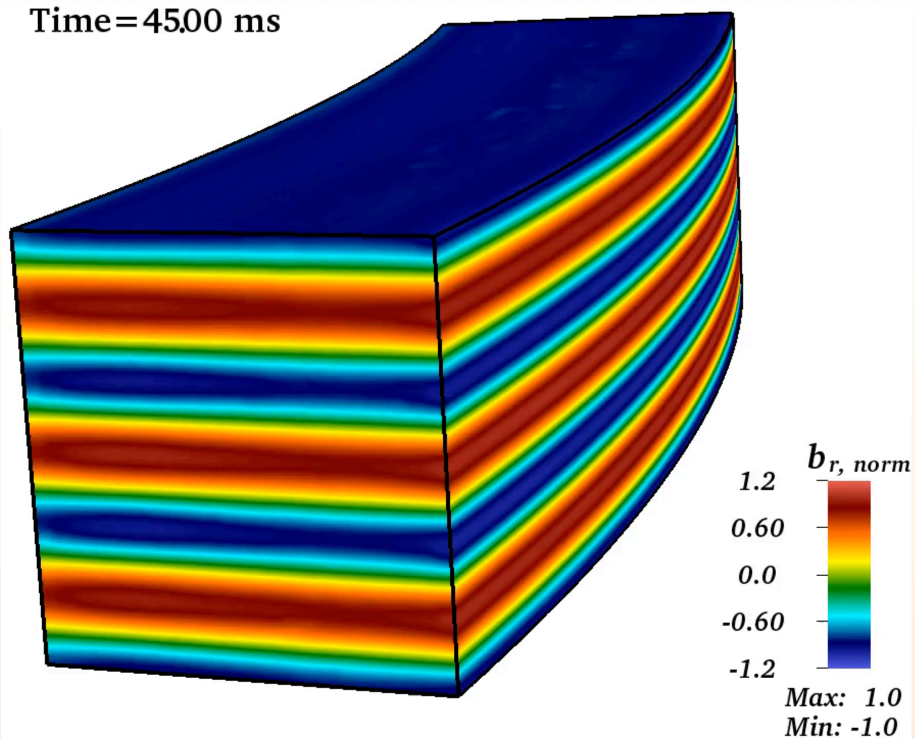
*[see J. Guillet's talk]*

➡ ***Resolution is important to properly set the saturation level*:** **depends on the development of parasitic instabilities (e.g., KH, tearing modes), which feed off the MRI channel flows.**




➡ ***Though problem!***

# B-field saturation in PNS




Rembiasz, Obergaulinger, Cerdá-Durán, Müller, Aloy (2016a):

$(r,z,\varphi)$ = (100, 400, 100) or (200, 800, 200)

$r \times z \times \varphi$ = 1 km x 4 km x 1 km

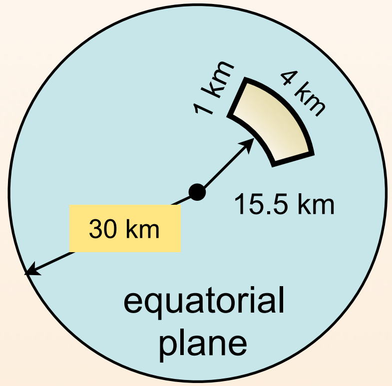
$r_0$ = 15.5 km

$B_{z0} = 4.6 \times 10^{13}$ G

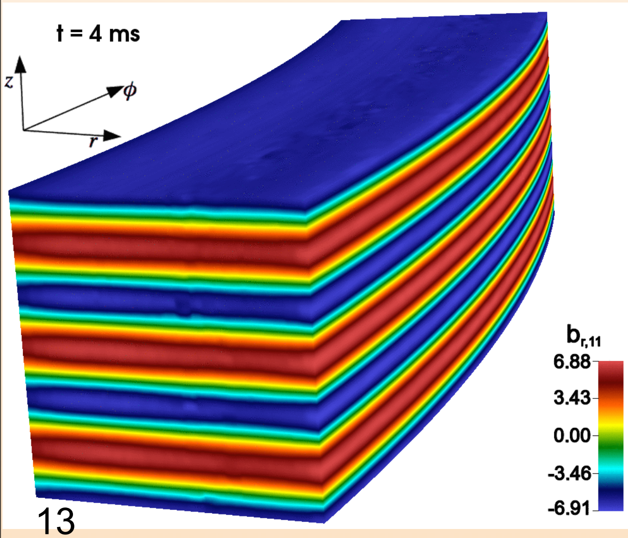
$\lambda_{MRI}$ = 0.33 km

$\nu = \eta = 4.45 \times 10^8$ cm²/s

$$\Omega = \Omega_0 \left(\frac{r_0}{r}\right)^q$$




**MRI exponential growth**

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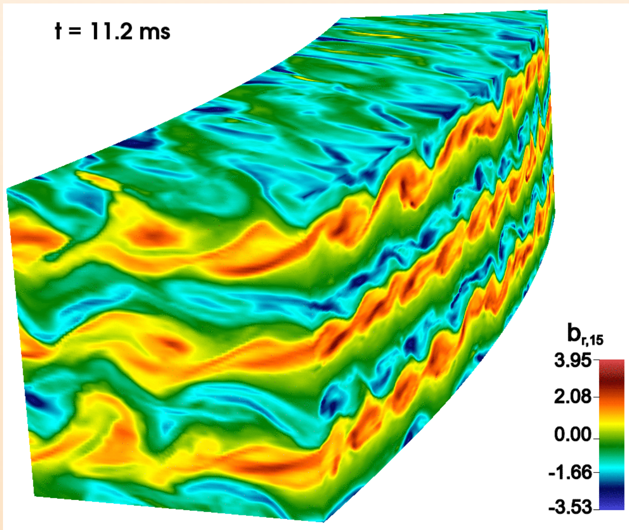
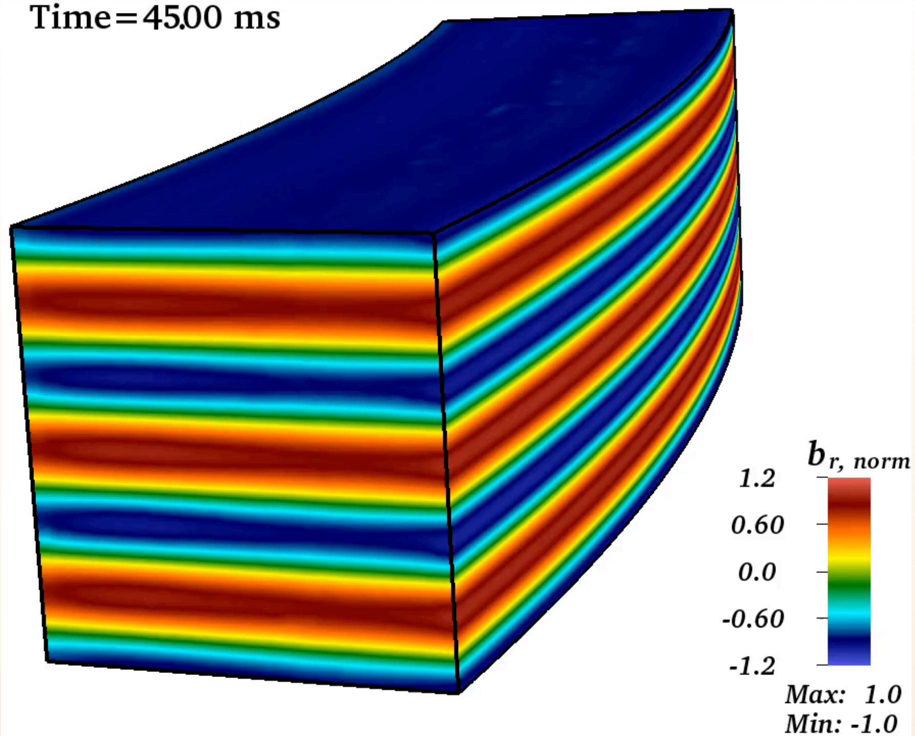
**Parasites saturate the growth**




development of parasites:
Goodman & Xu 1994
Pessah & Goodman 2009
Latter et al. 2009
Obergaulinger et al. 2009
Pessah 2010.




# B-field saturation in PNS

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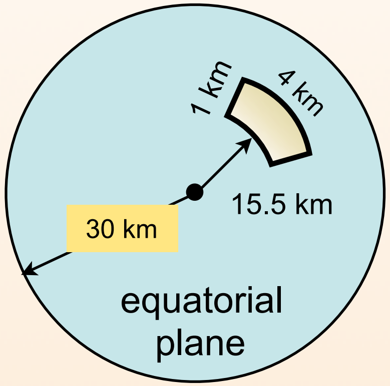
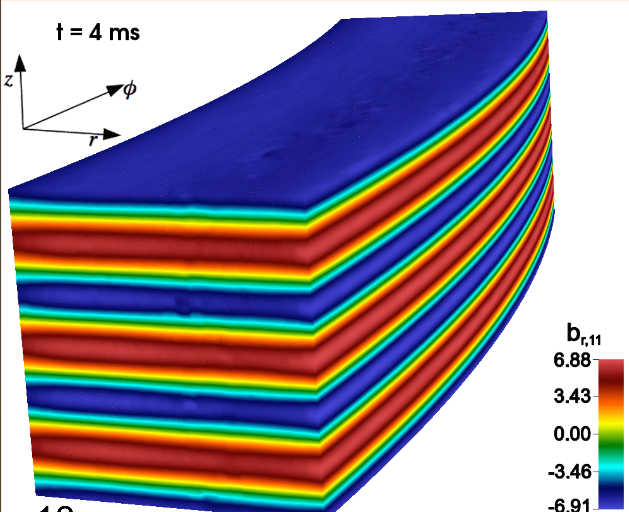
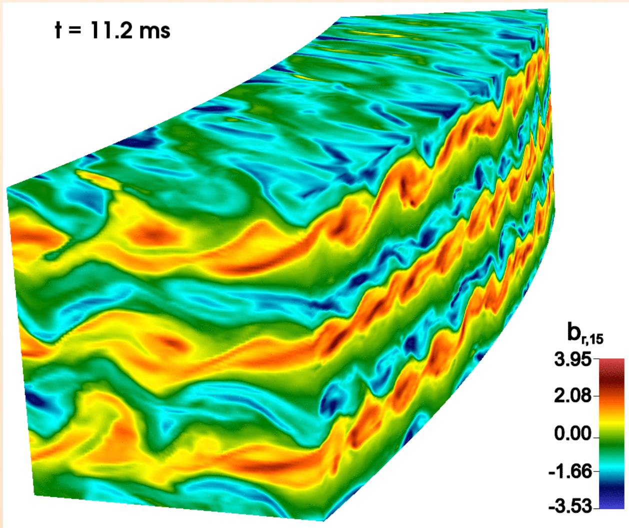


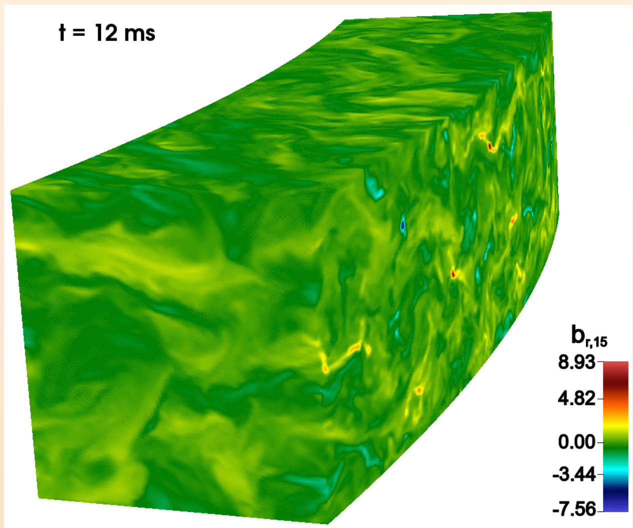

## MRI exponential growth



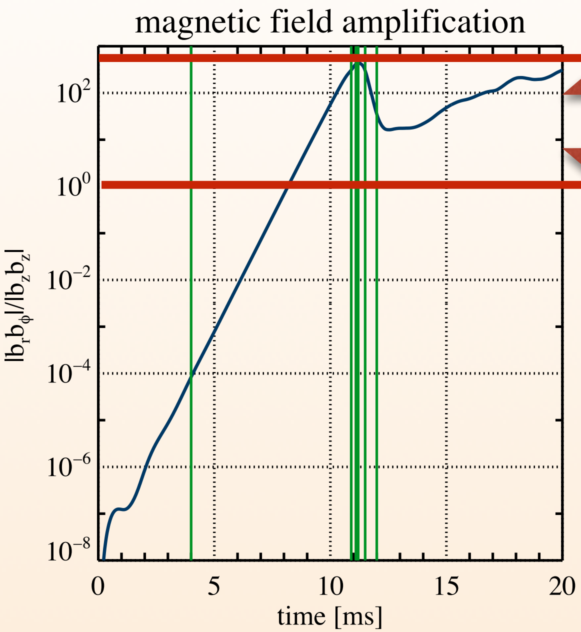

## Parasites saturate the growth




## Final turbulent stage



# B-field saturation in PNS

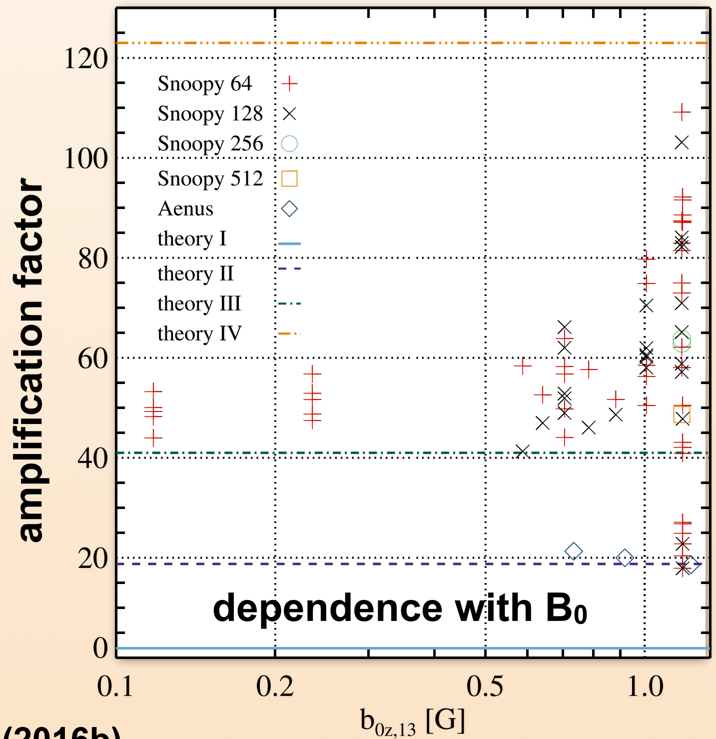



$B_{p,max}$ ~ $10^{15}$ G

AMPLIFICATION FACTOR ~ 10-20

$B_{z0}$ = 4.6 x $10^{13}$ G

**Under the conditions found in PNSs:**
***independently of the initial magnetic field strength*,**
**an amplification by a factor ~10 can be produced by MRI channel modes.**




**Initially, we did not observed the sage remarks Ewald does to his pupils:**

***If boundary conditions are a problem, put them away!!***

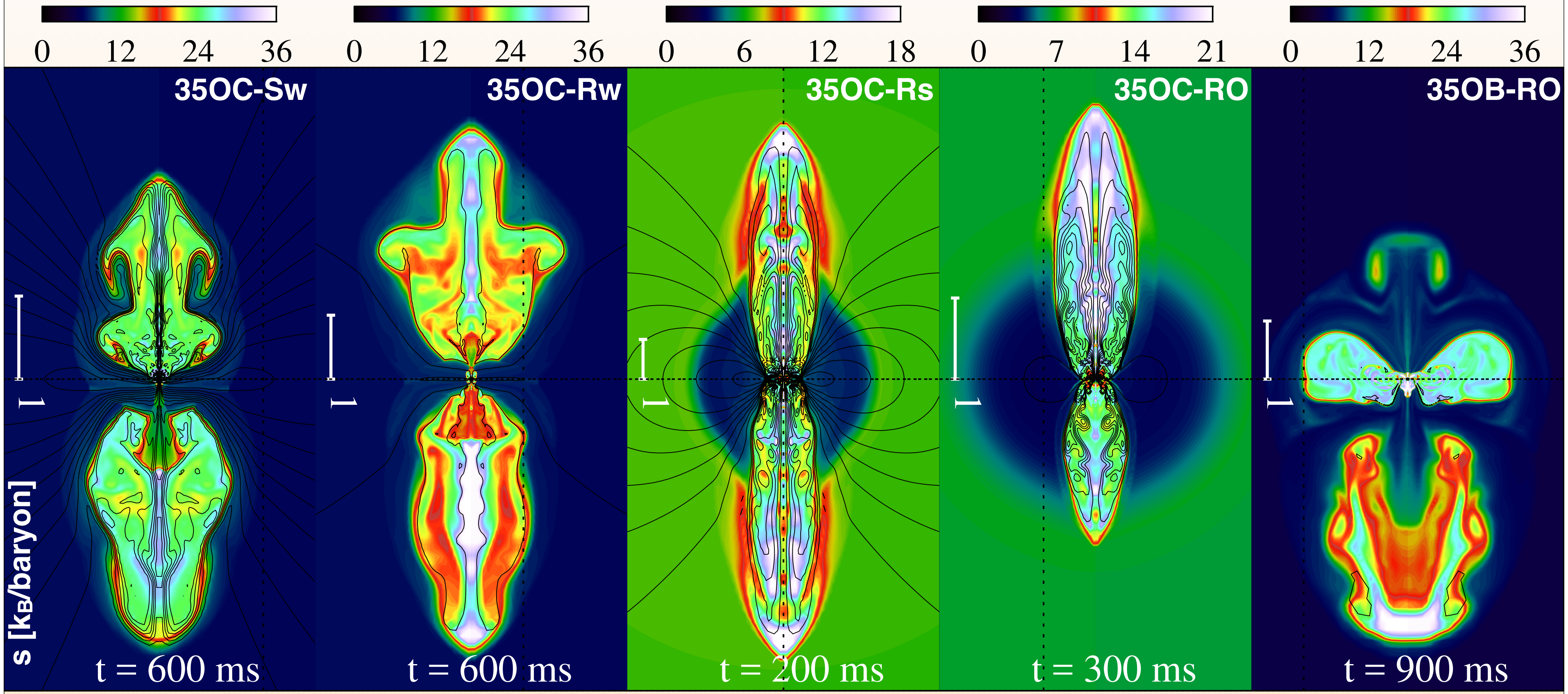
**Thus, we had to use 2 different codes to validate our results.**



**Rembiasz, Guilet, Obergaulinger, Cerdá-Durán, Aloy, Müller (2016b)**

# Relativistic jets? SNe?

Obergaulinger & Aloy (2017)




- In unusual progenitors with low metallicity, fast rotation or *strong enough* B-fields jet-like asymmetric SN explosions result.

*[see Obergaulinger's talk]*

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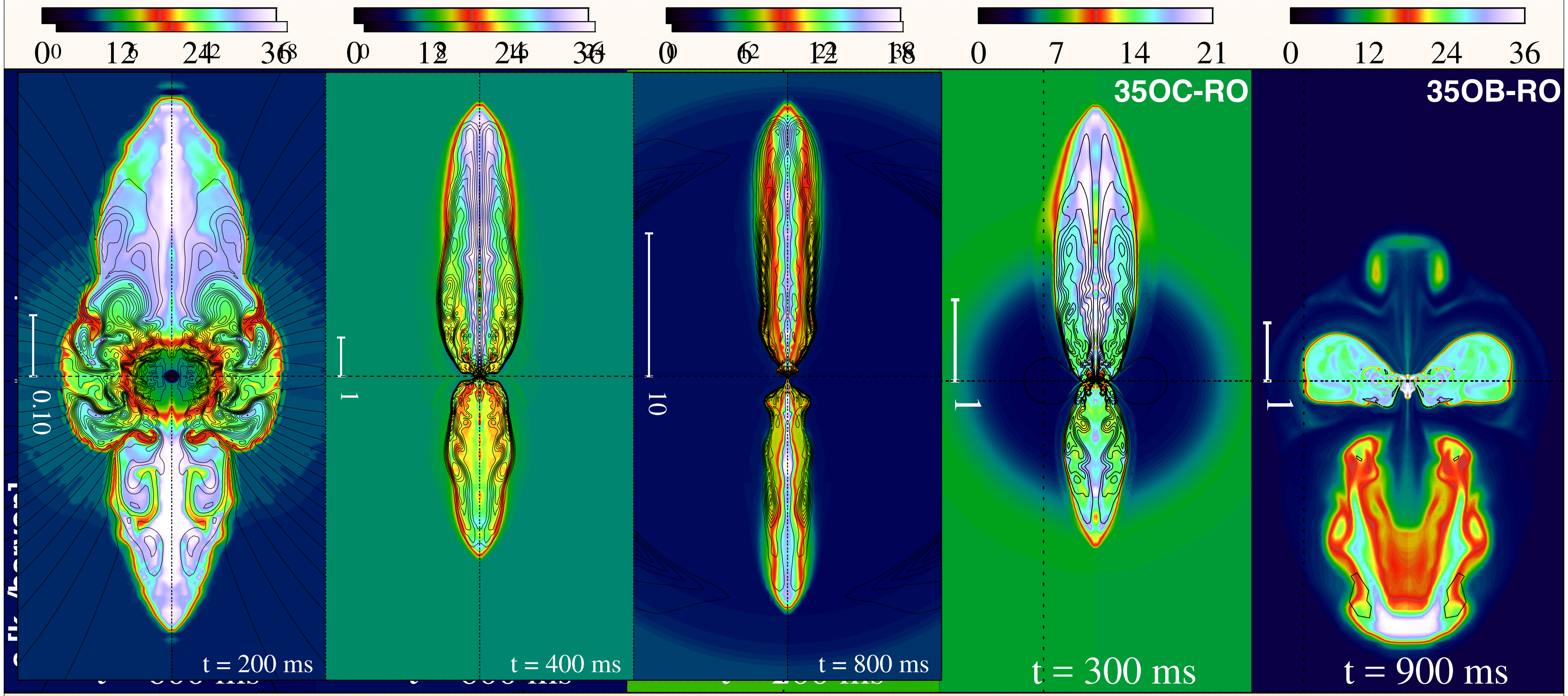


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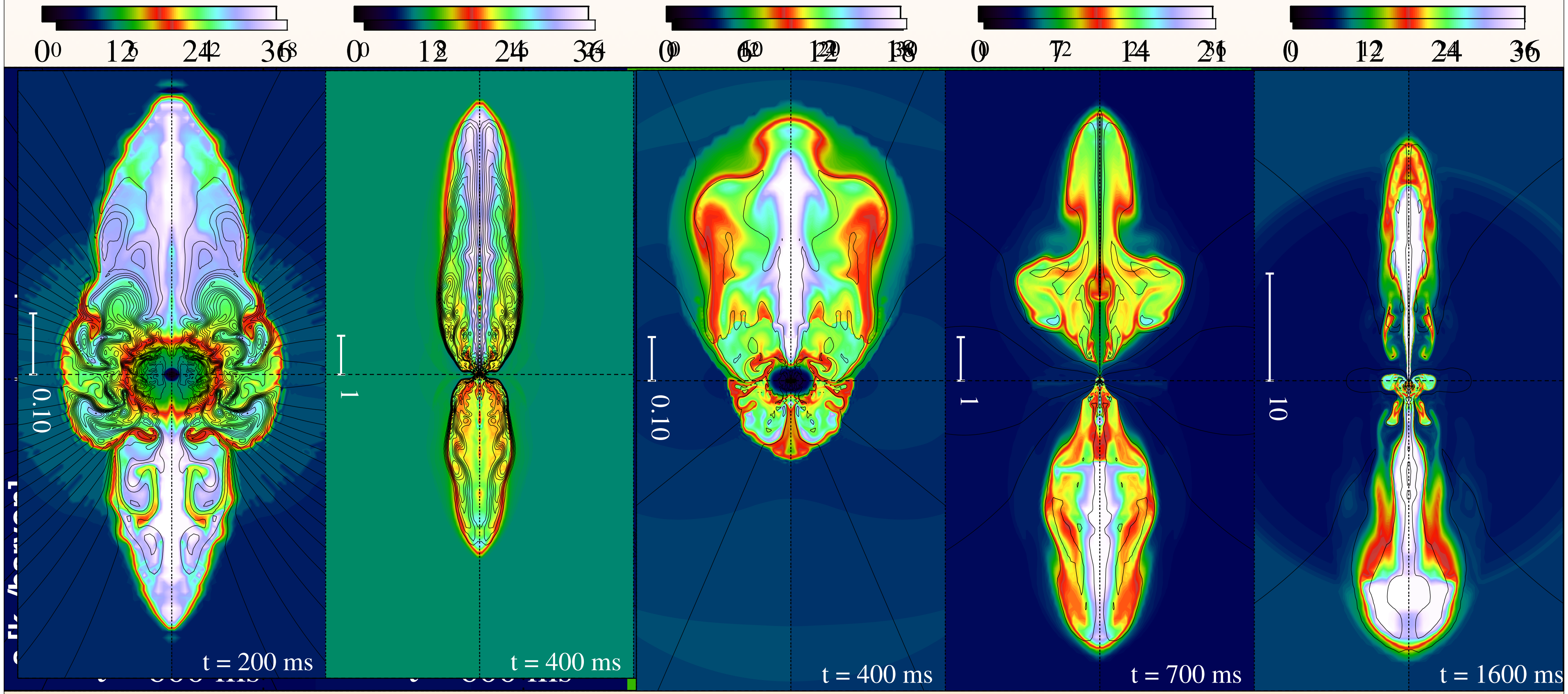


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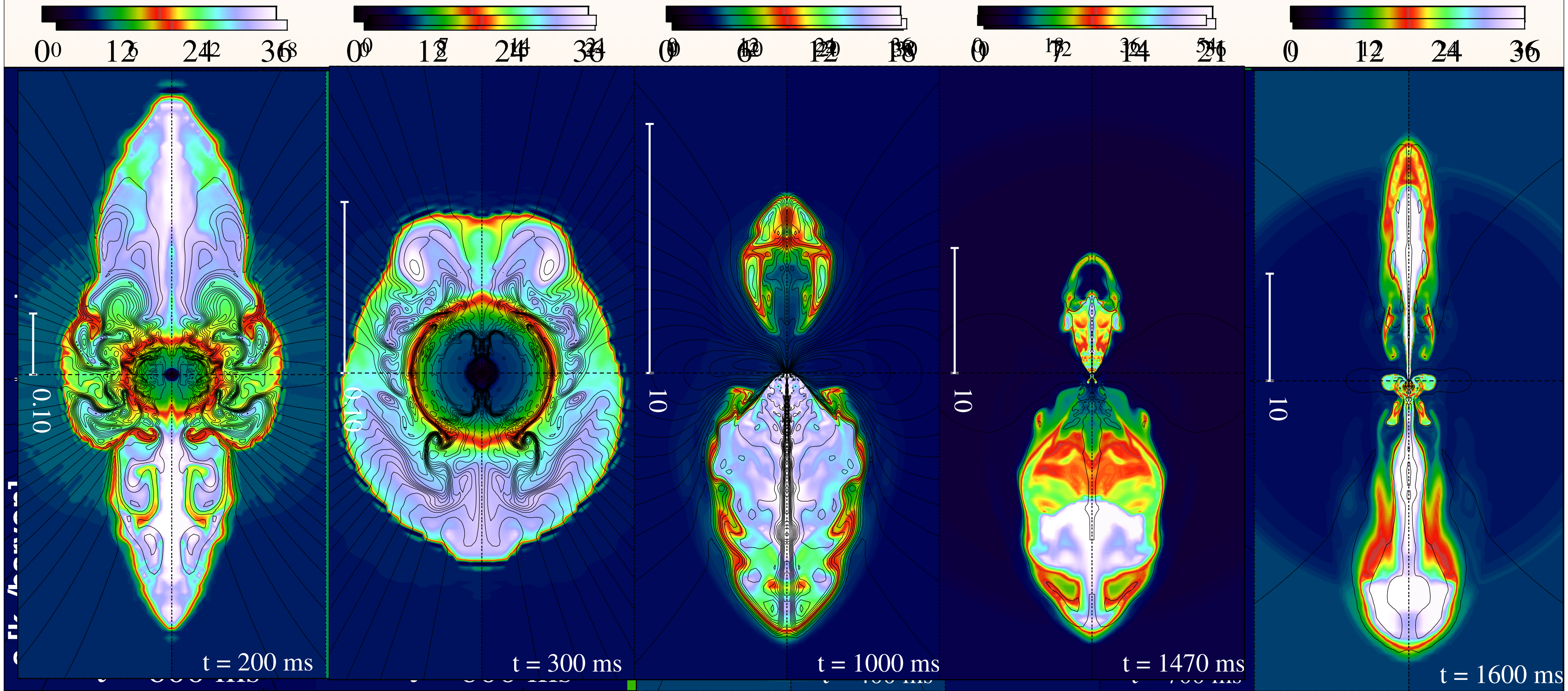



- In unusual progenitors with low metallicity, fast rotation or *strong enough* B-fields jet-like asymmetric SN explosions result.
- However, even smaller rotational rates and initial B-fields than assumed in the stellar evolution models yield very prolate SNe.

*[see Obergaulinger's talk]*

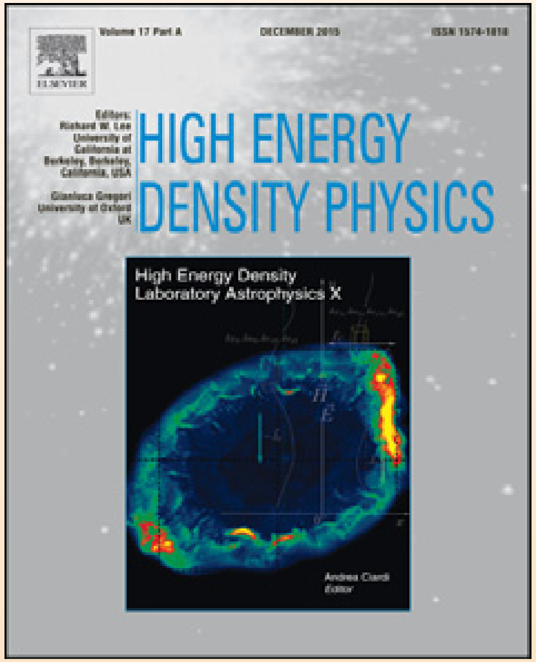
# Spin-off project: Vela-Jr SNR

**Obergaulinger, Iyudin, Müller, Smoot (2014)**

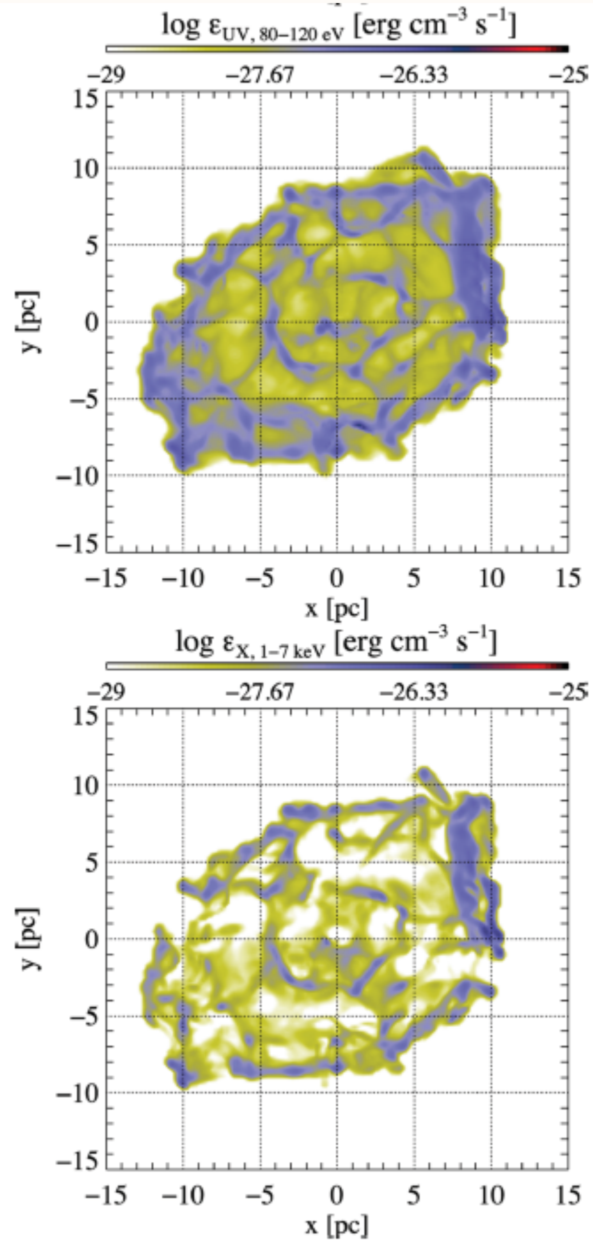
- Asymmetries in the SN or a clumpy circumstellar medium may produce aspheric shapes in SNRs.
- Obergaulinger et al. (2004) study the generation of inhomogeneities and the mixing of elements arising from these two sources in 3D HD simulations of the propagation of a SN blast wave into a cloudy environment.
- Modeling Vela Jr (RX J0852.0-4622) and comparing with observations, they constrain the properties of the explosion:

1. Very energetic SN of few x $10^{51}$ erg @ $t_{exp}$ ~ 800 yr
2. Canonical SN of ~ $10^{51}$ erg @ a few x 1000 yr

**Obergaulinger, Chimeno, Mimica, Aloy, Iyudin (2015)**

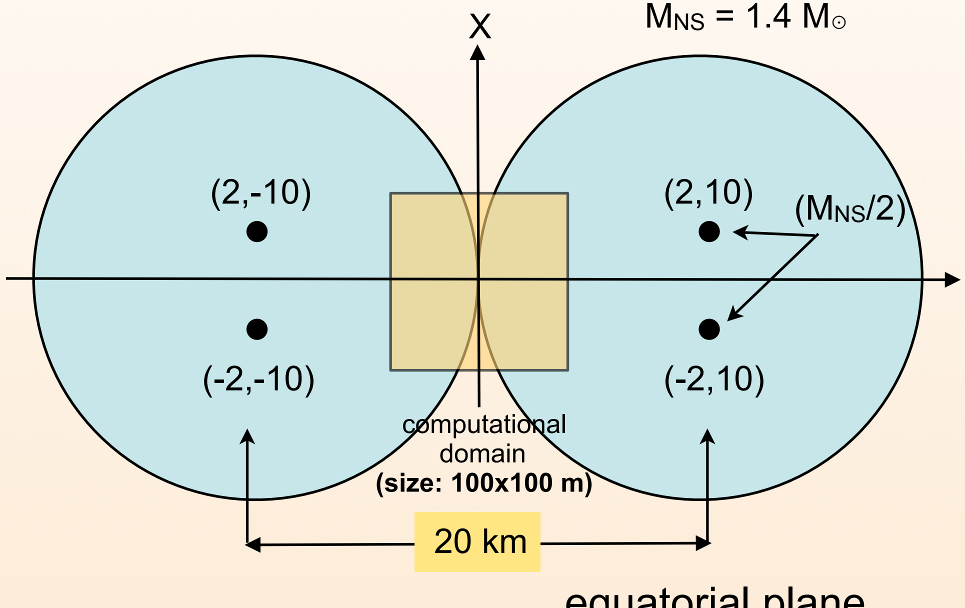



- We obtain the the broad-band emission of SNRs from 3D HD simulations.
- Test case: simulation of a bipolar SN expanding into a cloudy medium.
- We qualitatively reproduce the main observational features of typical SNRs and produce fluxes that agree with observations to within a factor of a few allowing for further use in more extended sets of models.



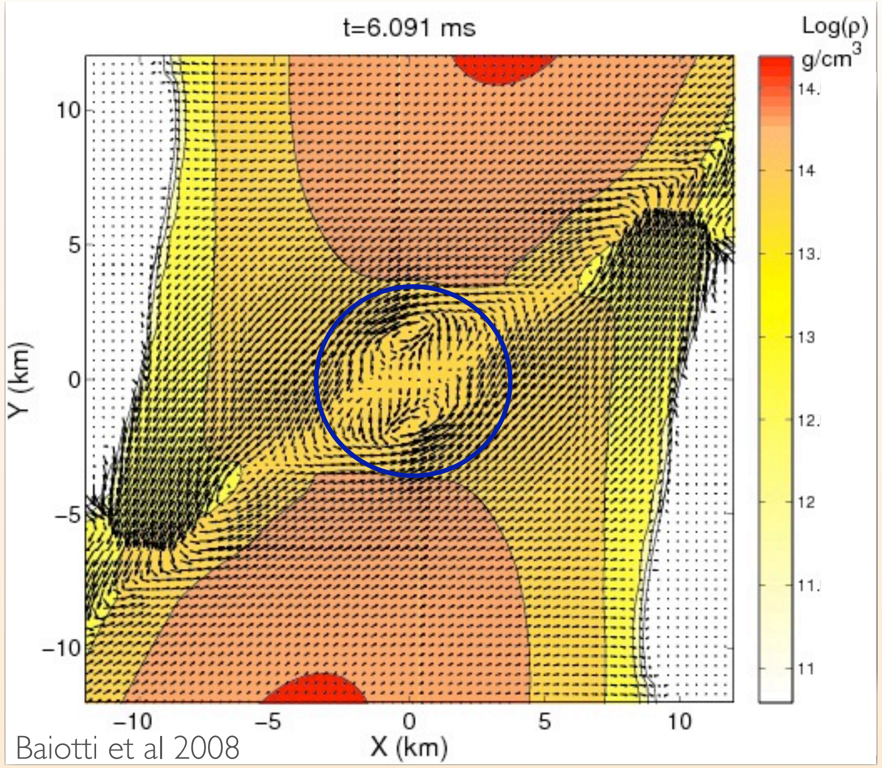
# KH-instabilities in NS mergers

**Initial conditions:**




$\rho$ = $10^{13}$ gr/cm$^3$

$e_{th}$= 0




## LNS

Assume hydrostatic equilibrium
Shearing velocity = rotational velocity of the NSs
BCs: x(z)-direction: periodic, y-direction: reflection

— Growth of seed magnetic fields is possible at the expense of the kinetic energy of the system (orbital motion + NSs rotation).

— KH instability: leads to the growth (few ms) of KH vortices between the NSs, which can modify the merger dynamics via kinetic-to-magnetic energy conversion (e.g., Price & Roswog 2006; Giacomazzo et al. 2009, Obergaulinger et al. 2010).

*Obergaulinger, Aloy, Müller (2010)*

# How large can the magnetic field be?

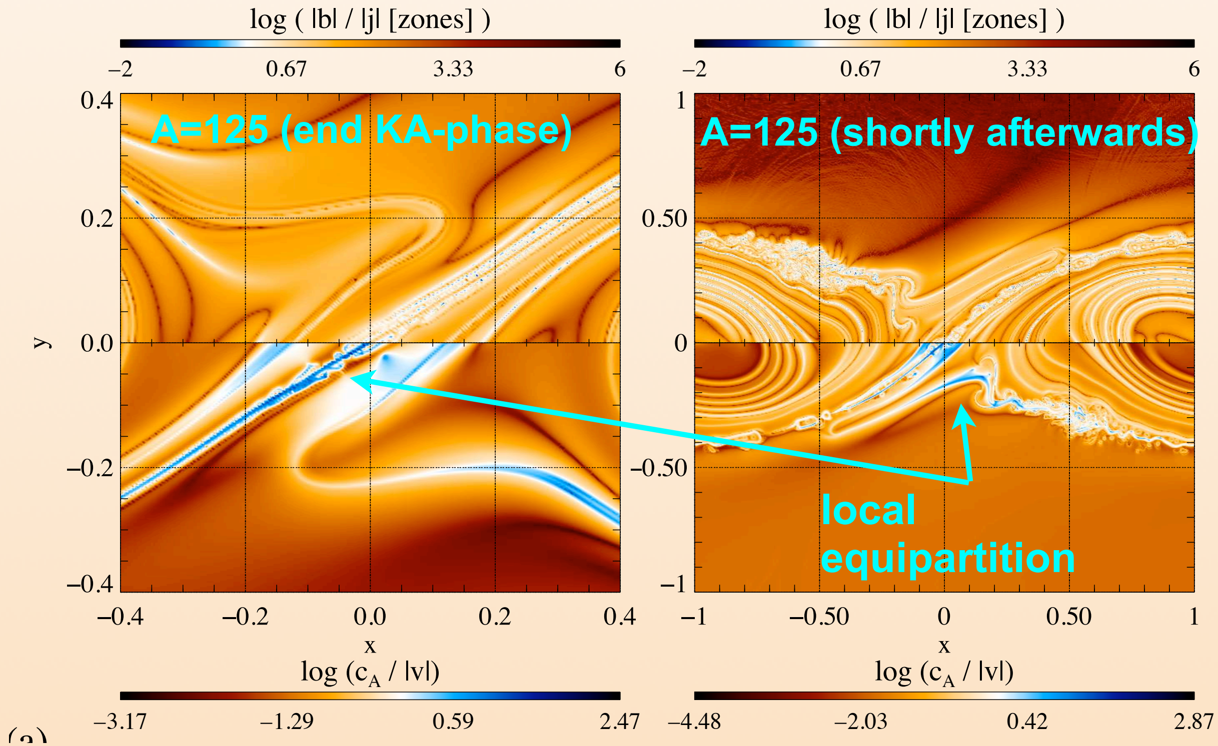
➡ $|B|^{max}$: limited by the non-linear dynamics (stresses on the flow or work against fluid forces make $e_{mag}$ to decrease).

➡ Global numerical simulations (so far) do not reach sufficient numerical resolution to study instabilities and turbulence in its full glory (particularly to address KH-growth).

➡ Local numerical simulations (LNS) of KH-growth in NS mergers:

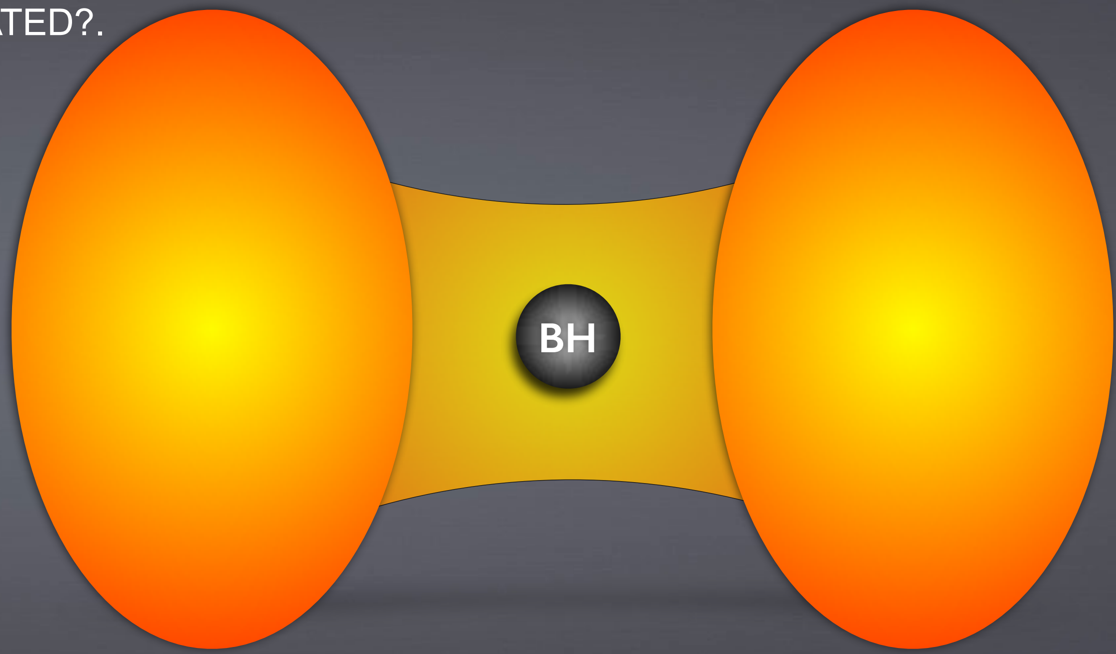
- $|B|^{max} \sim 10^{16}$ G **(0.1ms)** , $|B|^{max}_{rms} \sim 10^{15}$ G, when LOCALLY $e_{mag} \sim 0.1 \times e_{kin}^{z}$
- h ~ 0.1-0.8 m needed for converged results in LNS of the KH growth

Numerical resistivity becomes important, but convergence is possible **because thin B-field sheets are pushed together to distances ~ h**, not because the thickness of 1 sheet ~ $l_b$ ~ h -similar dynamics to Keppens et al 1999-.



# Making up an sGRB:
# The cosmic neutrino heater

- The disk matter is heated up an compressed until it begins to release ***neutrinos and antineutrinos***.
- Neutrinos annihilate producing pairs, which annihilate too producing photons.
- Key question: will the fireball be COLLIMATED?.



# Tl

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begins to release ***neutri***
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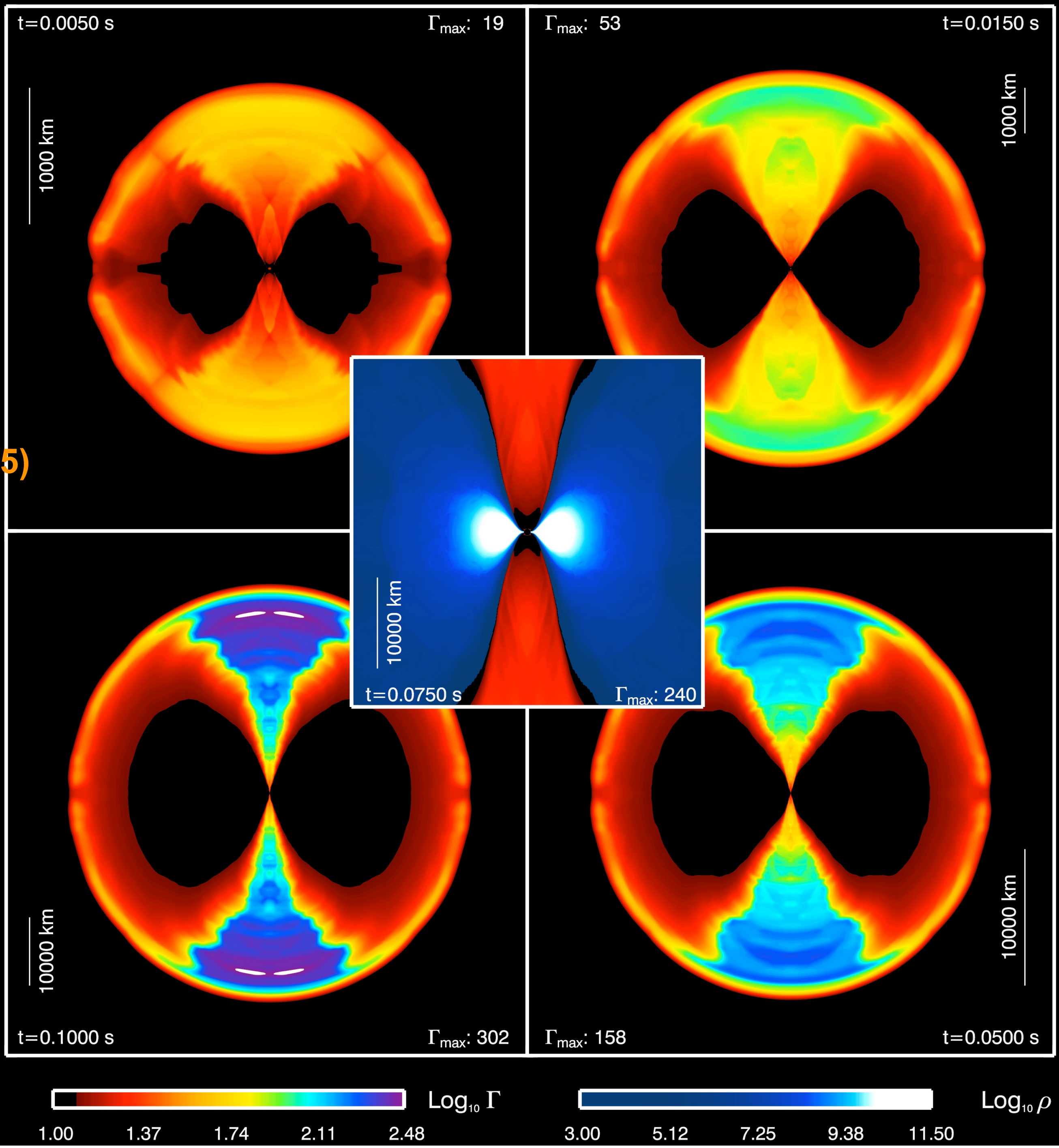
**Reply: YES!**
**Aloy, Janka, Müller (2005)**

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