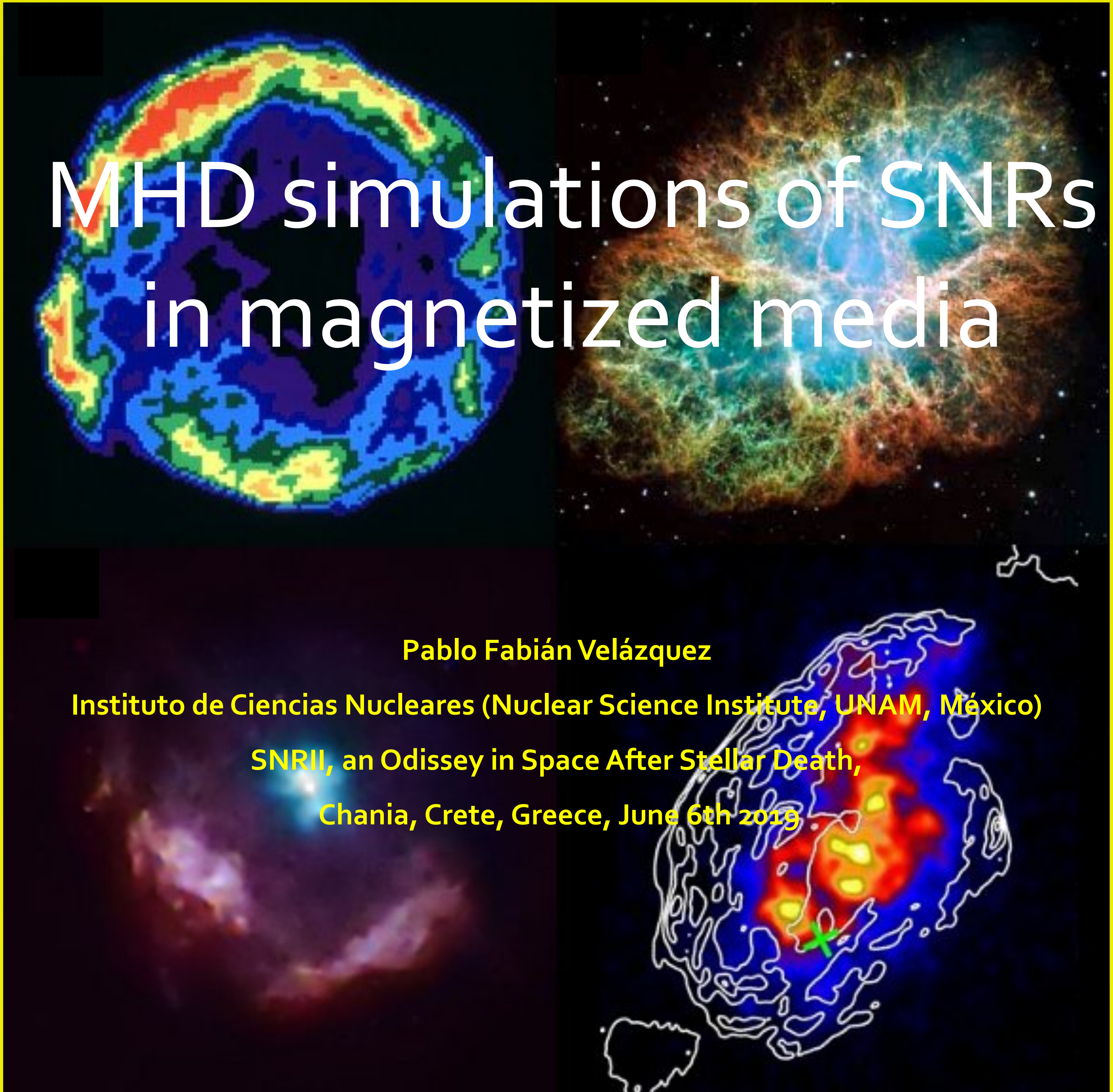

MHD simulations of SNRs in magnetized media

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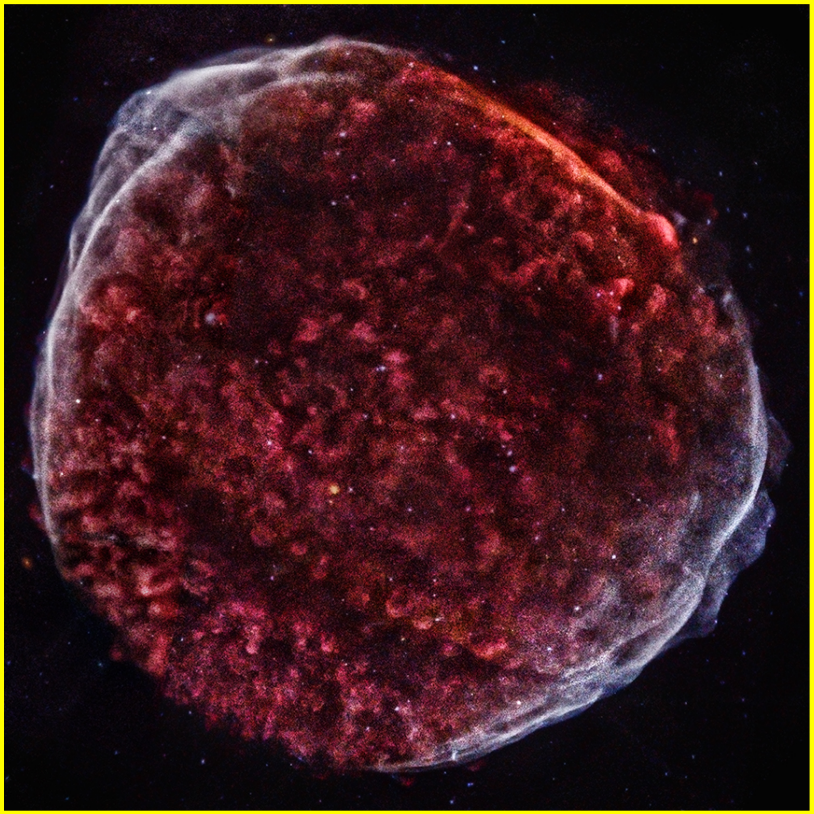
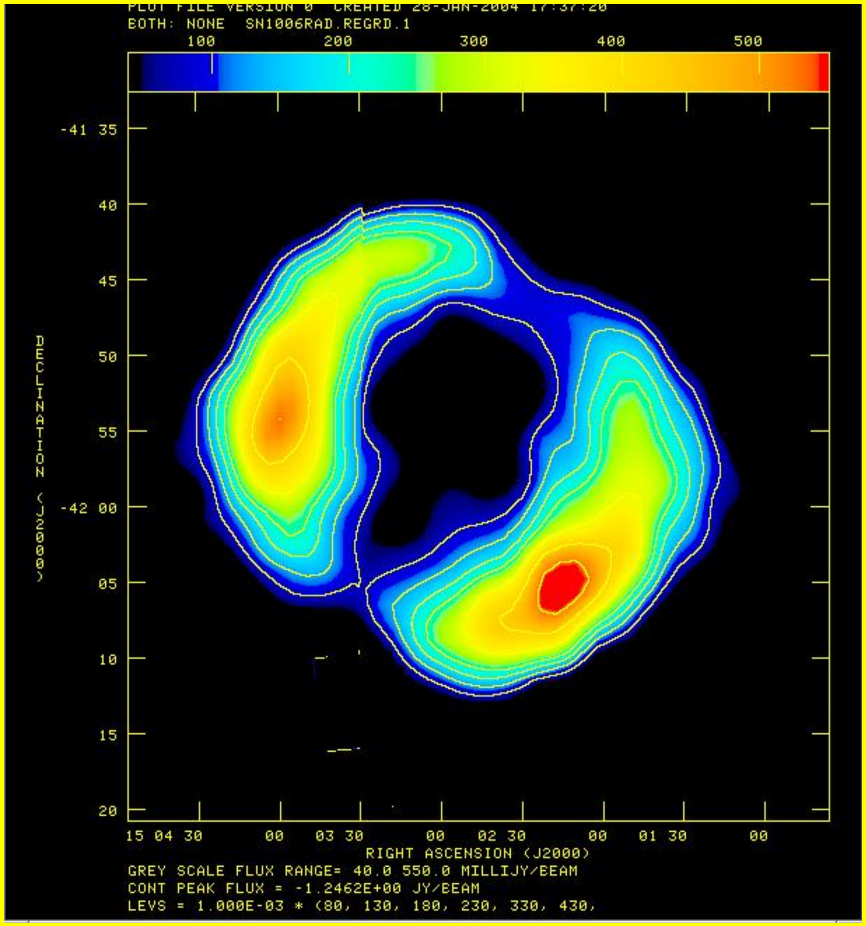
SNRII, an Odissey in Space After Stellar Death,

Chania, Crete, Greece, June 6th 2019

BSNR: SN1006





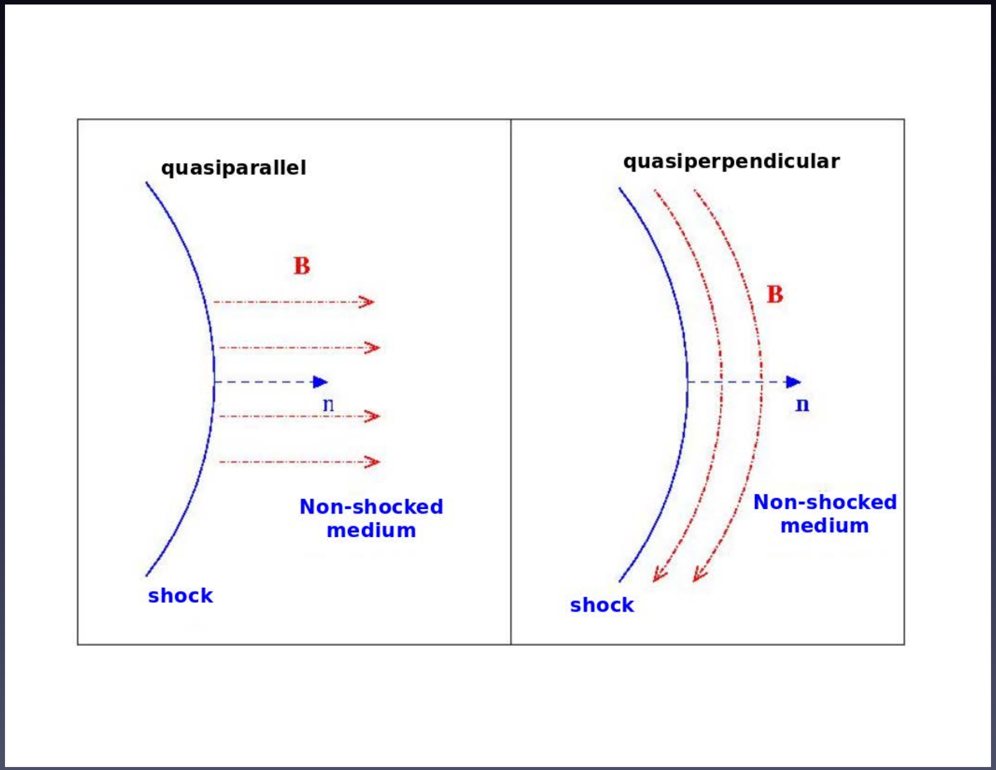
Left.: X-ray image of SN 1006 remnant (Chandra, Winkler et al. 2014), white: non-thermal emission, red: thermal emission. A bright filament is observed to the NW(Acero et al. 2007). Right: 20cm radio-continuum image (VLA).

Origin of BSNRs

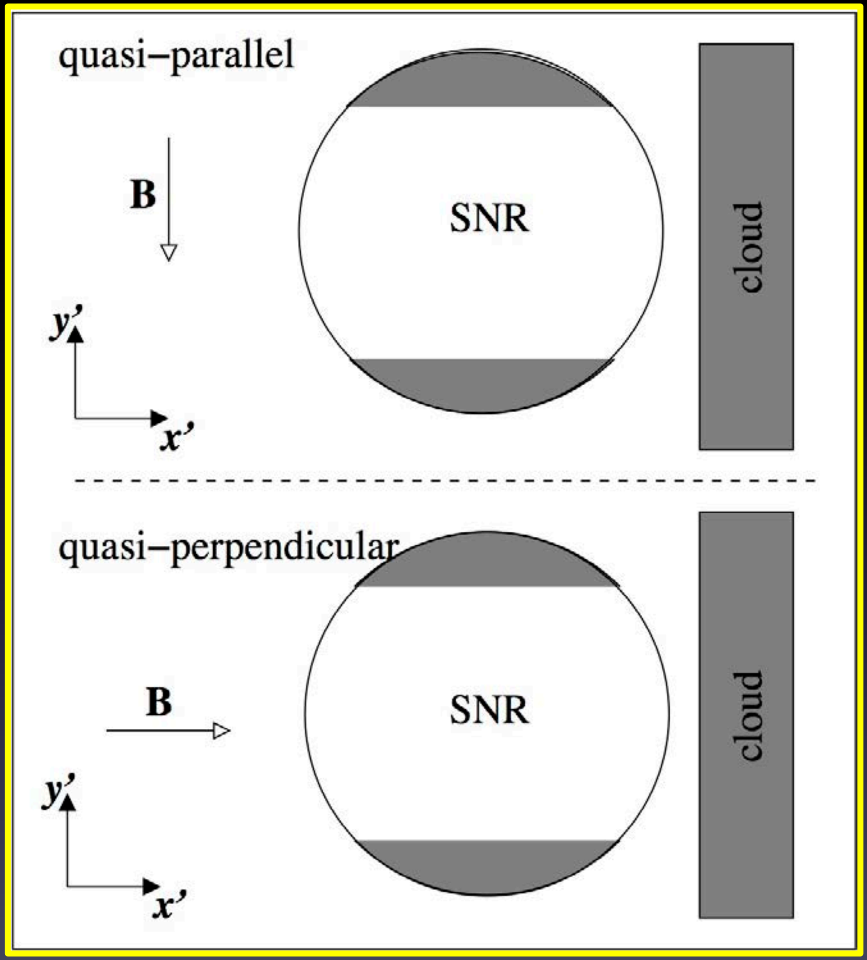
- Reynolds (1998), acceleration mechanisms
- Orlando et al (2007), MHD simulations with Flash. BSNRs are obtained considering B and/or densities gradients. Quasi-perpendicular mechanism fits better with observations.
- Petruk et al (2009), quasi-perpendicular case for SN1006
- Schneiter et al (2010), for SN 1006 the quasi-perpendicular case. 2D MHD simulations were carried out, which set limits to the B-field configuration .
- Bocchino et al (2011), for SN 1006, the quasiparallel case
- Reynoso et al (2013), observations confirm the quasi-parallel case for SN 1006
- West et al (2016, 2017), survey of Galactic BSNR.

Synchrotron emission

- $i(\nu)=K\,\rho\, v^{4\alpha}\,(B_{per})^{\alpha+1}\nu^{-\alpha}$ (Cécere et al. 2016), where B_{per} is the magnetic field on the plane of the sky, α is the spectral index, ν is the observed frequency.
- K is proportional to $\sin^2(\theta_{Bs})$, quasi-perpendicular case, or $\cos^2(\theta_{Bs})$, quasi-parallel case.



The 3D model for SN 1006



Schneiter et al. (2015) and Velázquez et al. (2017). MHD simulations were performed employing with the Mezcal code (developed by Fabio De Colle).

Polarized emission

$$Q(\nu) = \int_{los} f_0 i(\nu) \cos\left[2\phi(s)\right] ds$$

$$U(\nu) = \int_{los} f_0 i(\nu) \sin\left[2\phi(s)\right] ds$$

$$f_0 = \frac{\alpha + 1}{\alpha + 5/3}$$

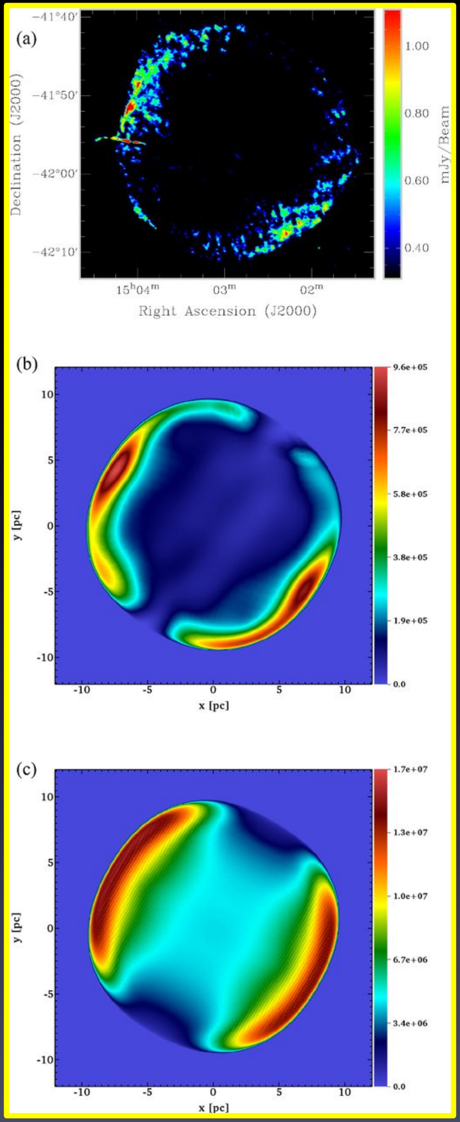
$$I_P(\nu) = \sqrt{Q(\nu)^2 + U(\nu)^2}$$

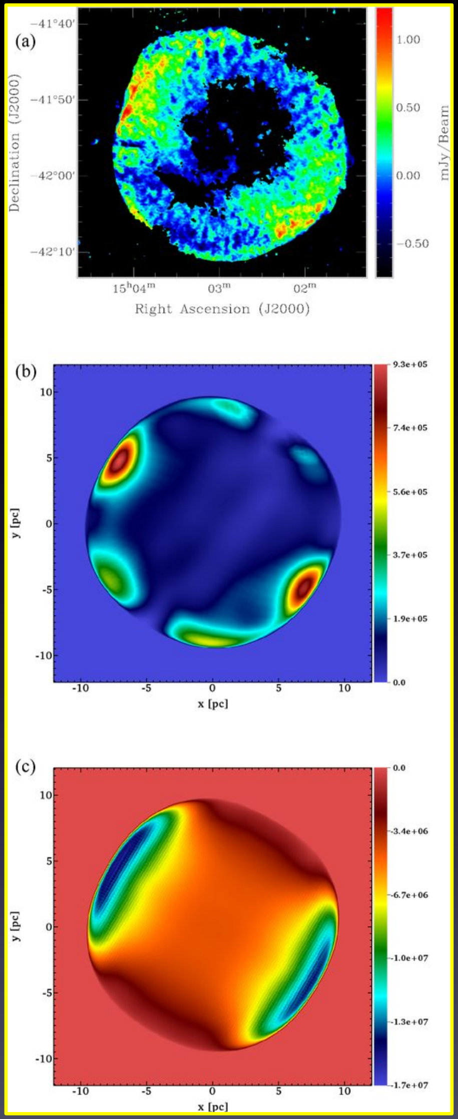
$$\phi(s) - \pi/2 + \Delta\chi_{\mathrm{F}}$$

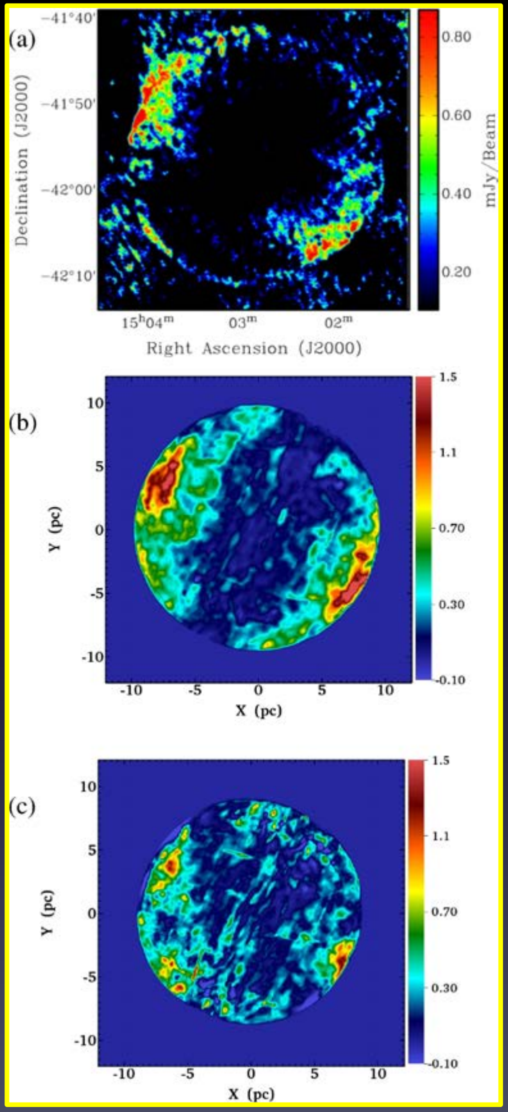
$$\chi = \frac{1}{2}\tan^{-1}(U/Q)$$

$$\Delta\chi_{\mathrm{F}} = \frac{\mathrm{RM}}{[\mathrm{rad\ m^{-2}}]}\left(\frac{\lambda}{[\mathrm{m}]}\right)^2$$

I_p & parameter Q maps







Comparing I_p and Q maps (Schneiter et al 2015 and Velázquez et al. 2017). Q maps indicate the quasi-parallel mechanism.

Turbulent B and ρ

$$\mathbf{B(x,y,z)} = \mathbf{B_0} + \delta\mathbf{B}$$

$$\delta\mathbf{B} = \sum_{\mathbf{n=1}}^{\mathbf{N_m}} \mathbf{A(k)} \left[\cos\alpha_{\mathbf{n}}\hat{\mathbf{x}}' + \mathbf{i}\sin\alpha_{\mathbf{n}}\hat{\mathbf{y}}'\right] \exp(\mathbf{i}\mathbf{k_n}\mathbf{z'_n})$$

$$P \propto \frac{1}{(kL_c)^{11/3}}$$

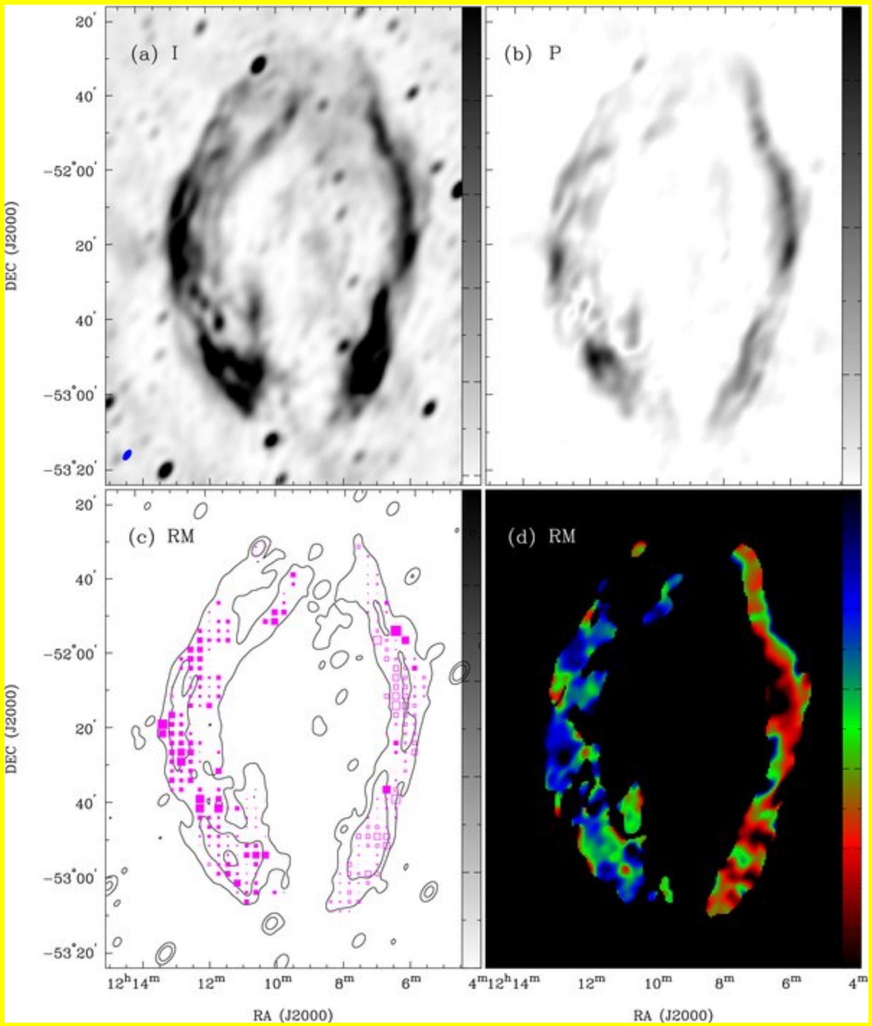
$$A(k_n)^2 = \sigma_B^2 \frac{\Delta V_n}{1+(k_n L_c)^{11/3}} \left[\sum_{n=1}^{N_m} \frac{\Delta V_n}{1+(k_n L_c)^{11/3}}\right]^{-1}$$

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \cos\theta_n\cos\phi_n & \cos\theta_n\sin\phi_n & \sin\theta_n \\ -\sin\phi_n & \cos\phi_n & \\ -\sin\theta_n\cos\phi_n & \sin\theta_n\sin\phi_n & \cos\theta_n \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}$$

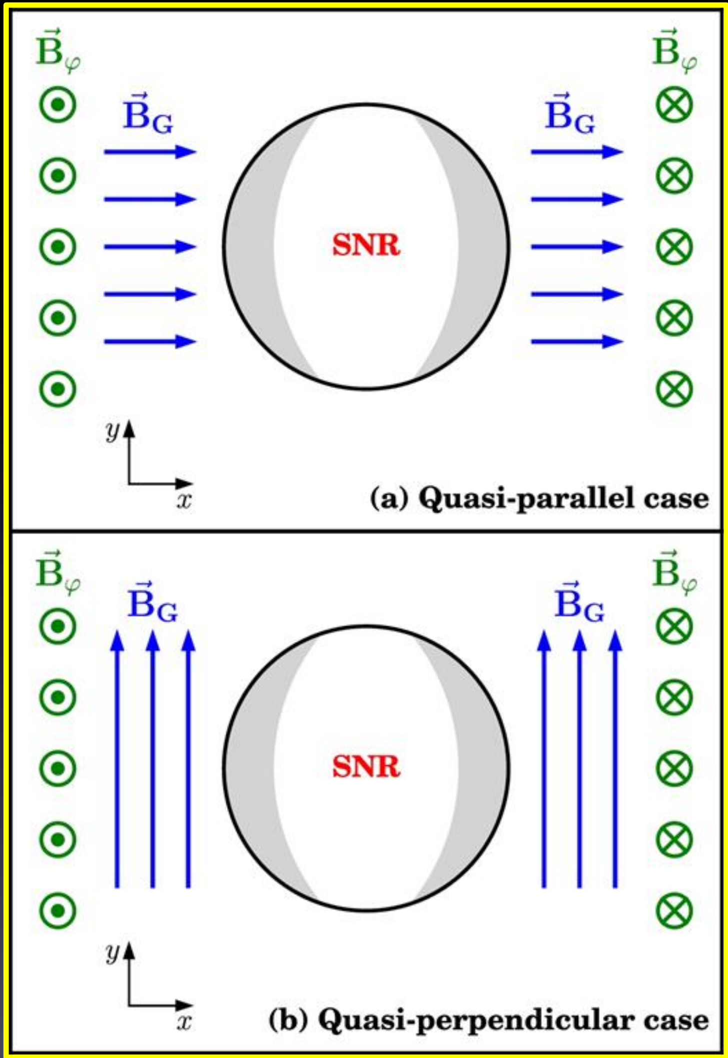
For the density fluctuation we employed the same log-normal distribution as in Giacalone & Jokipii (2007)

$$n(x,y,z) = n_0 \exp(f_0 + \delta f) \tag{6}$$

SNR G296.5+10

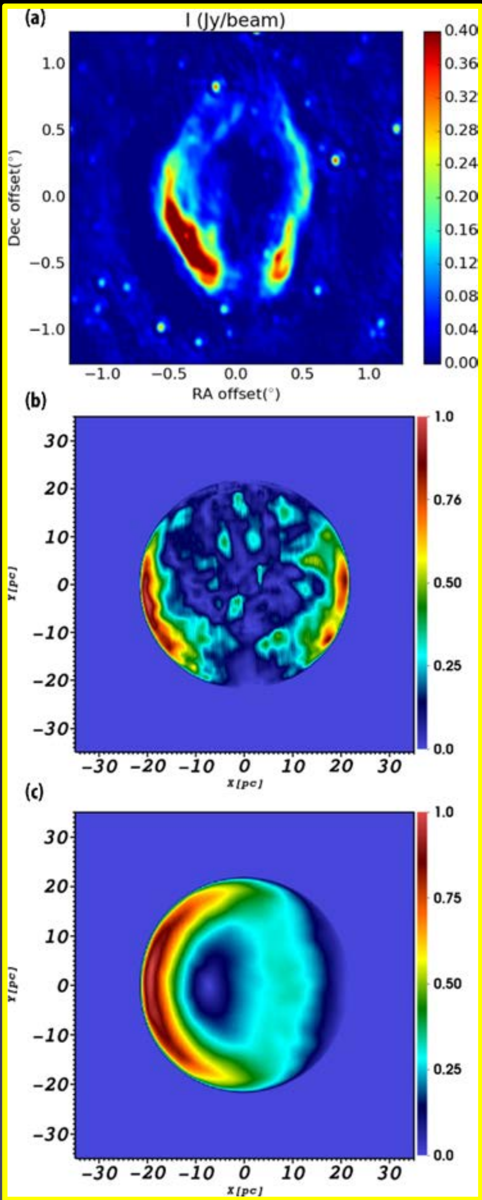


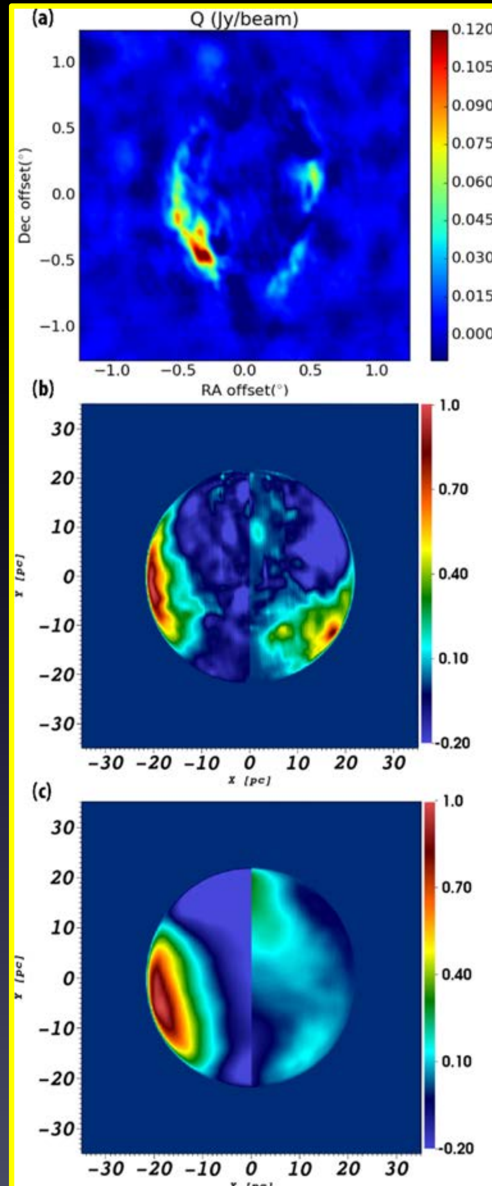
This bilateral SNR has an unusual RM distribution (Harvey-Smith et al 2010)

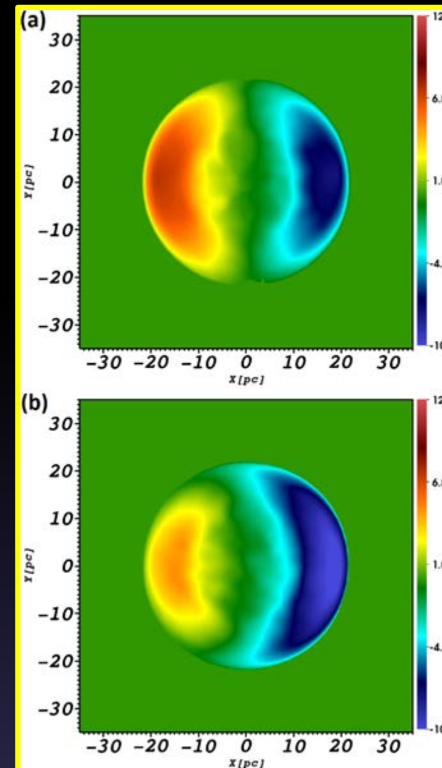


Initial setup for MHD simulations of this object (Moranchel-Basurto et al 2017)

Comparing with observations





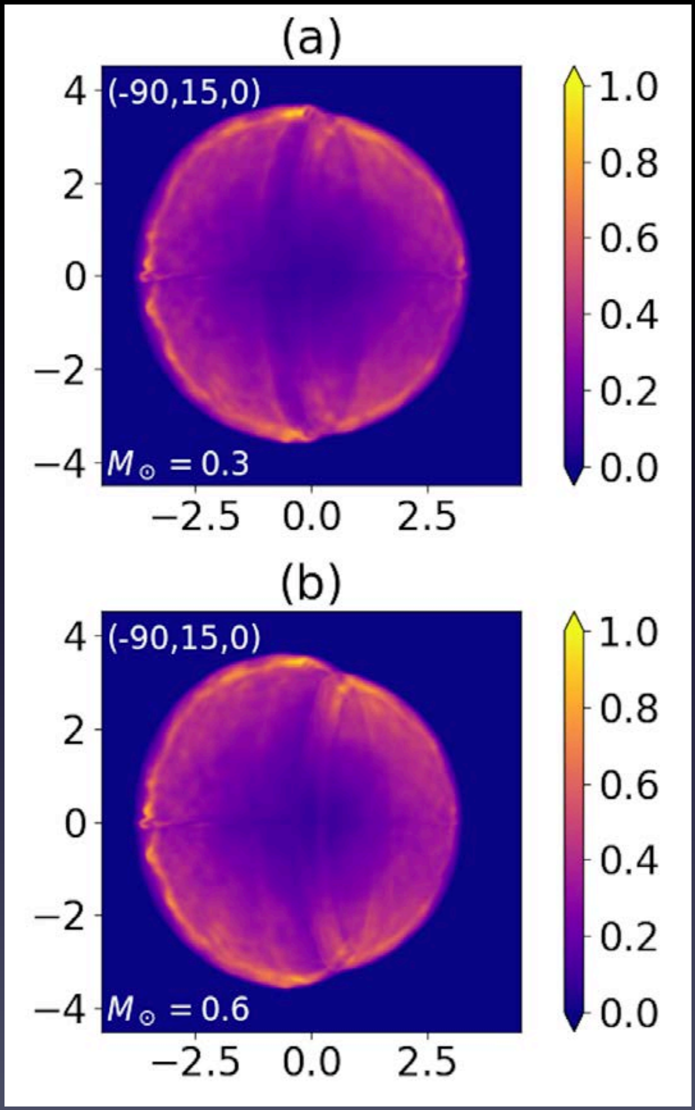


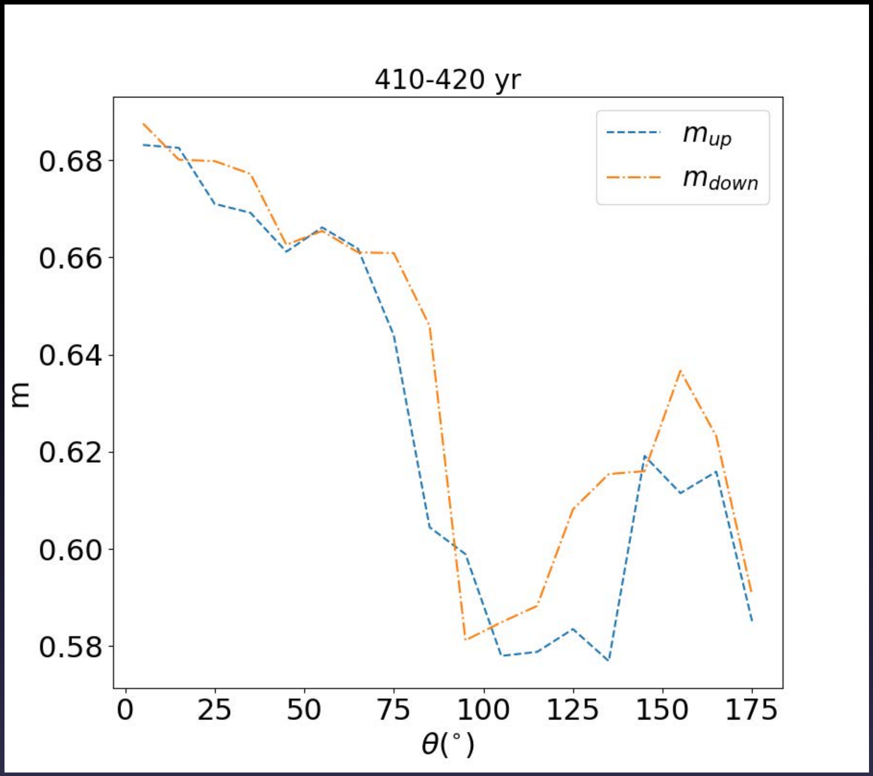
Synthetic maps of I_p and Q-Stokes parameter, and RM (Moranchel-Basurto et al. 2017). In order to know which mechanism is actually taking place at the shock front, it is necessary to analyze (together) maps of I_p, of the Stokes parameter Q, and RM

Quasi-parallel, perpendicular, or both?

- In studies of the interplanetary B, both processes are actually present.
- $K = K_{par} [\cos^2\theta_{Bn} + \sin^2\theta_{Bn} /(1+ \eta^2)]$, where $\eta=(B/\delta B)^2$ (Reynolds 1998)
- How to estimate η?

A first approach



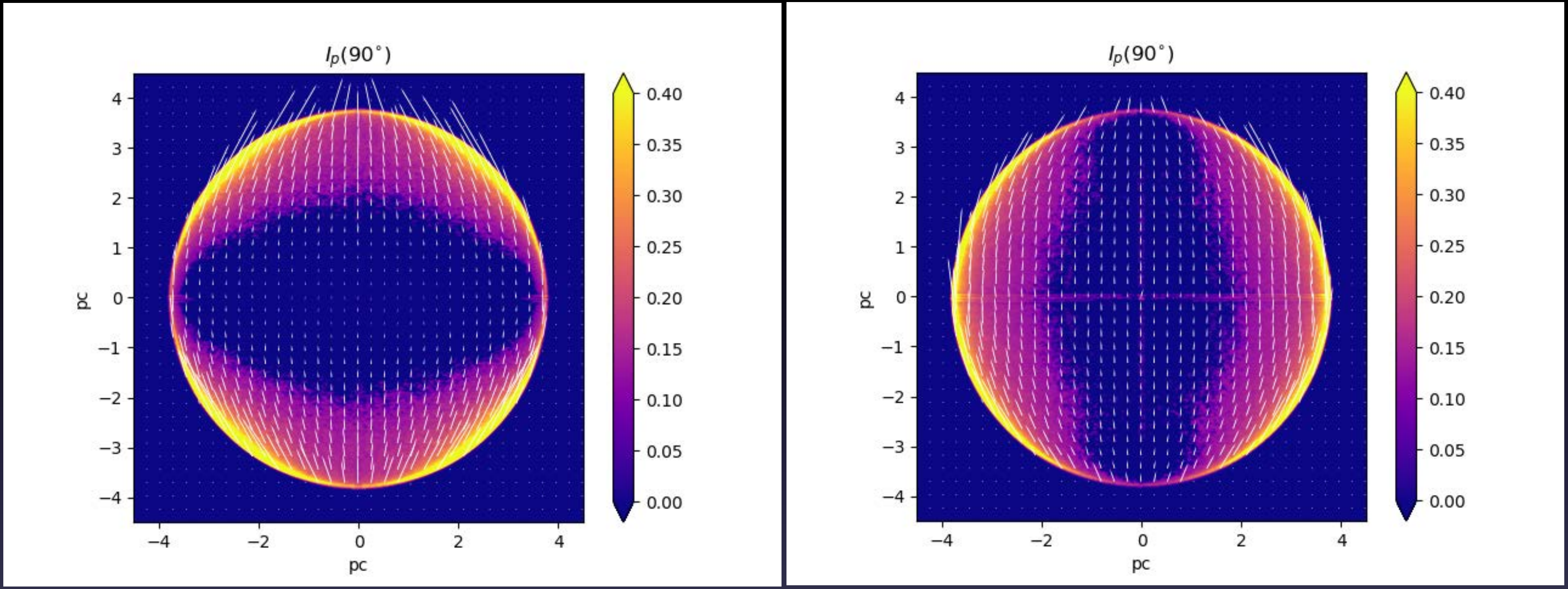


We model an asymmetrical distribution of the SN mass following the model proposed by Vigh et al. (2011). The SNR expands into a turbulent ISM (in density). Left figure show the synchrotron emission. Right figure displays a plot m vs θ. The parameter η is a function of Alfven number M_A. See poster of Alicia Moranchel (S8.1).

Estimating η

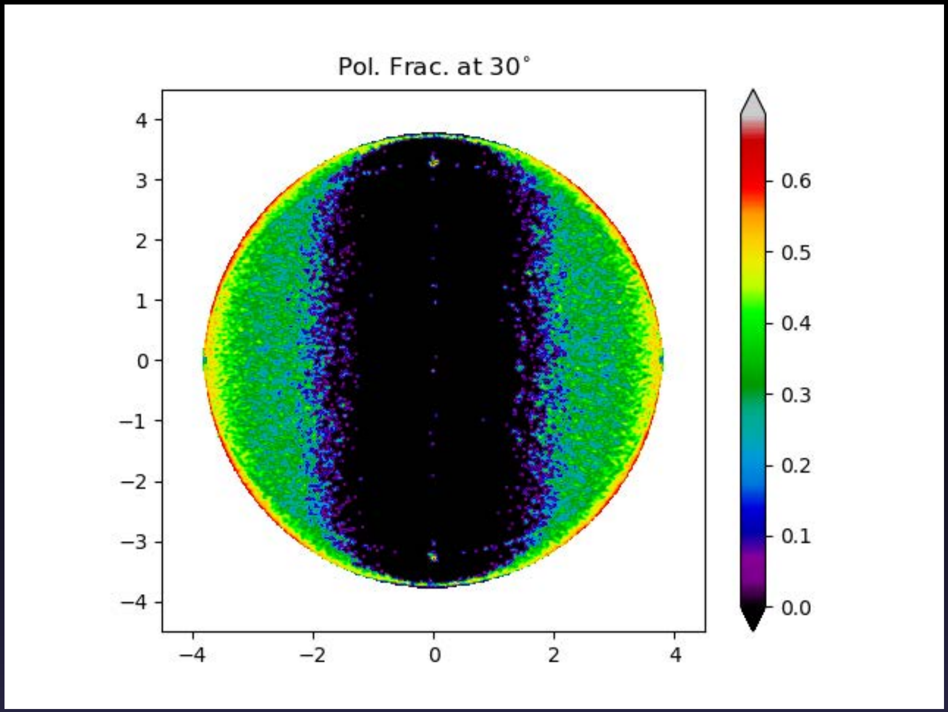
- 3D MHD simulations were carried (Guacho code, developed by Alex Esquivel) considering the expansion of a young (close to the Sedov phase) SNR into a ISM with a turbulent magnetic field.
- Different σ_B were taken into account, being $\sigma_B = p\ B_0$, with p=0, 30, 50, 70, and 90 % of B_0(1 μG)
- Synthetic maps of the polarized emission were performed from MHD simulations

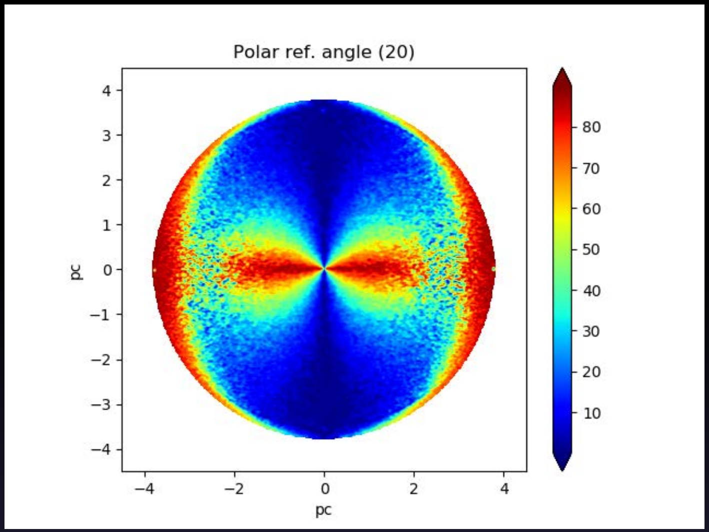
I_p for different B perturbations

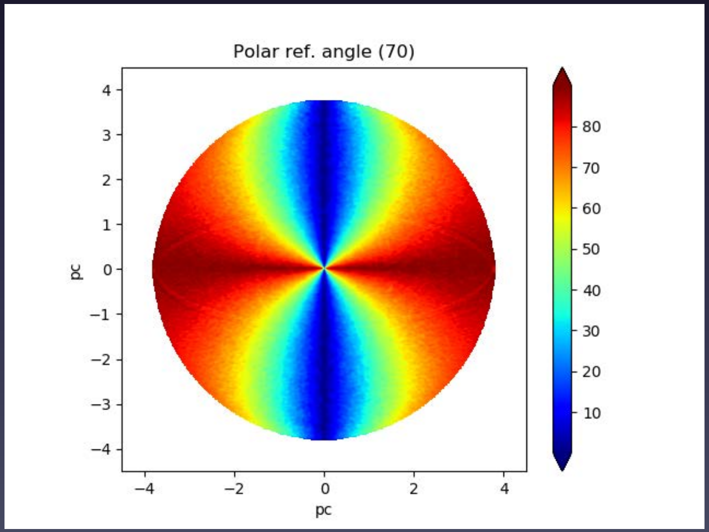


Synthetic I_p maps obtained for B perturbations of 50% (left image) and 90% (right). Both maps were generated considering an angle between B_o (the ordered component of the magnetic field) and the line of sight of 90° (Ávila-Aroche et al. in preparation)

Polarization fraction and polar ref. angle distributions

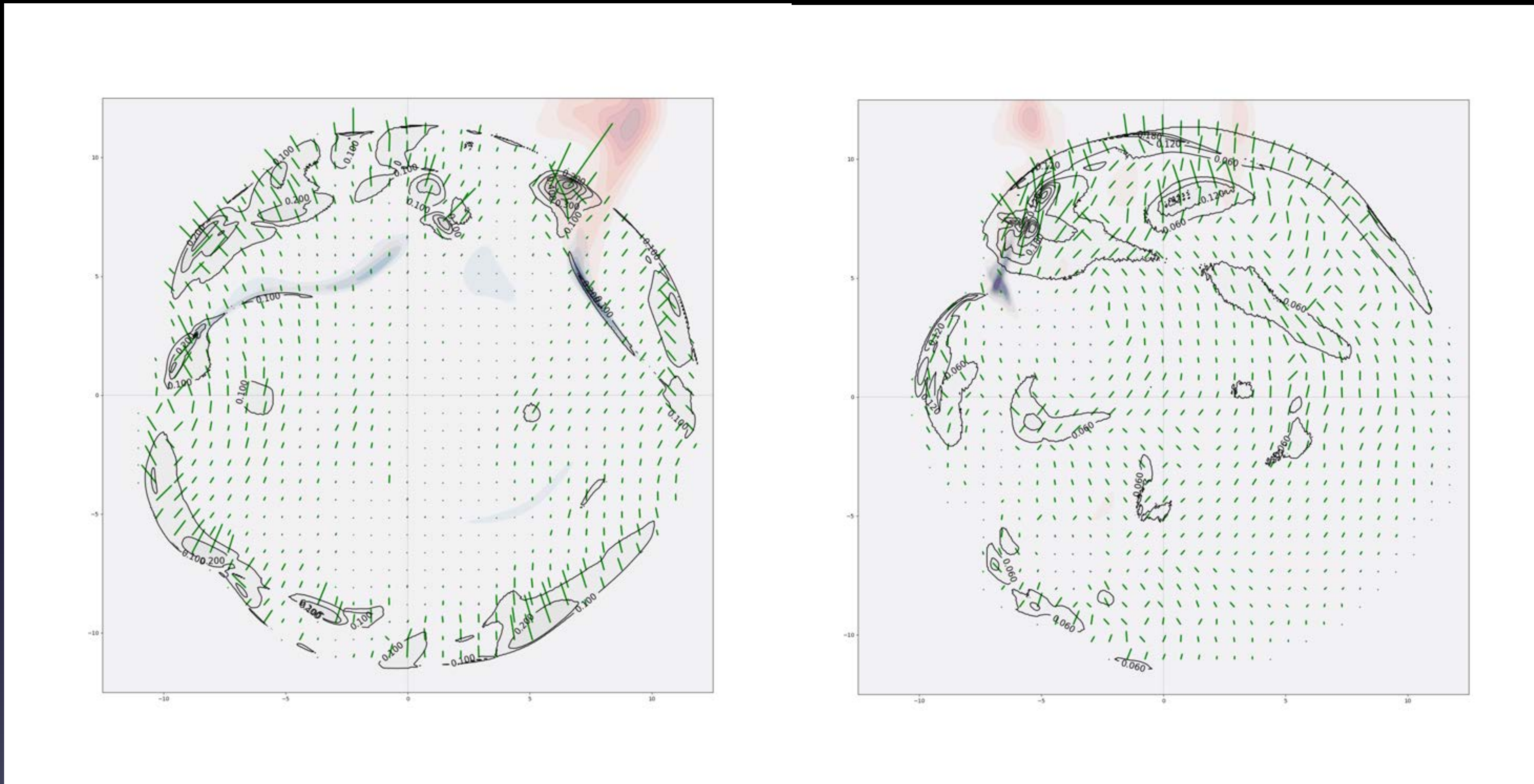






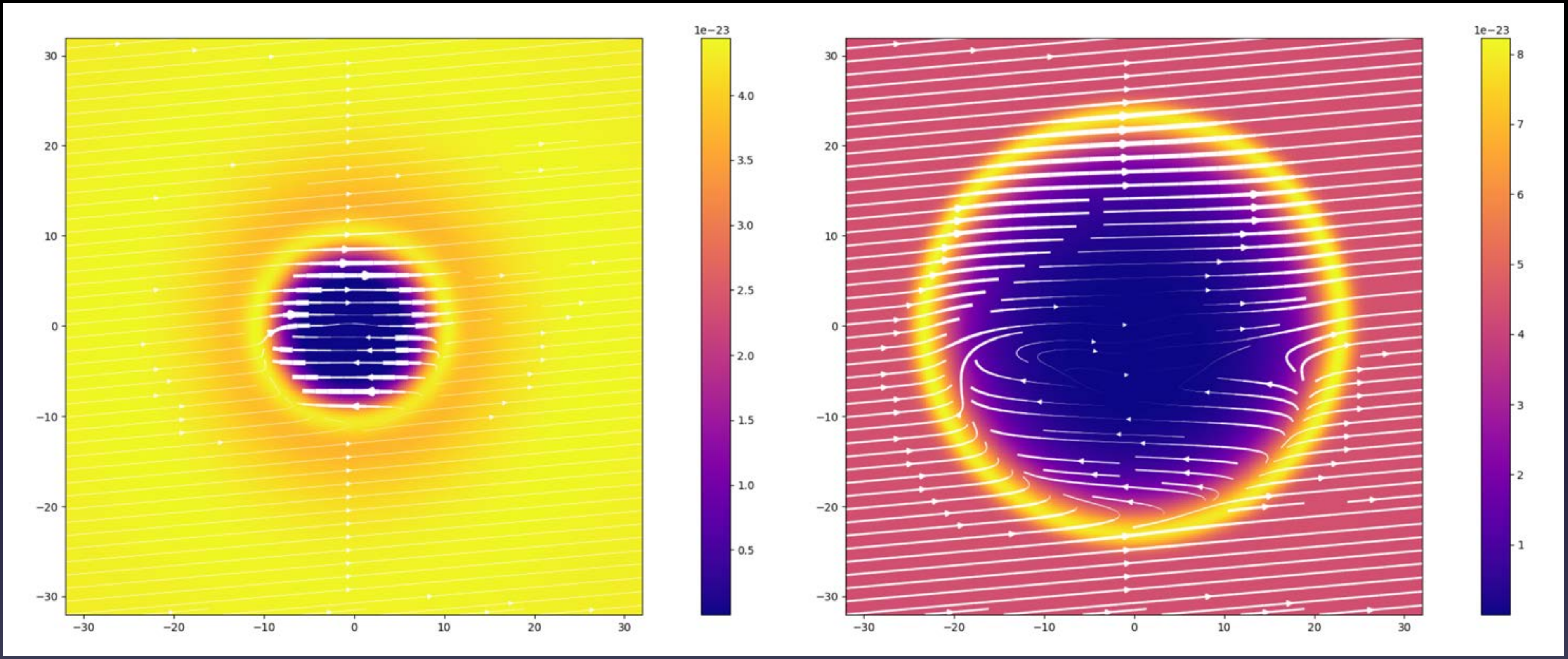
Polarization fraction at an aspect angle of 30° (upper figure). The distribution of the polar referenced angle are shown in both figures on the right (for two different aspect angles).

SNR into a turbulent ISM



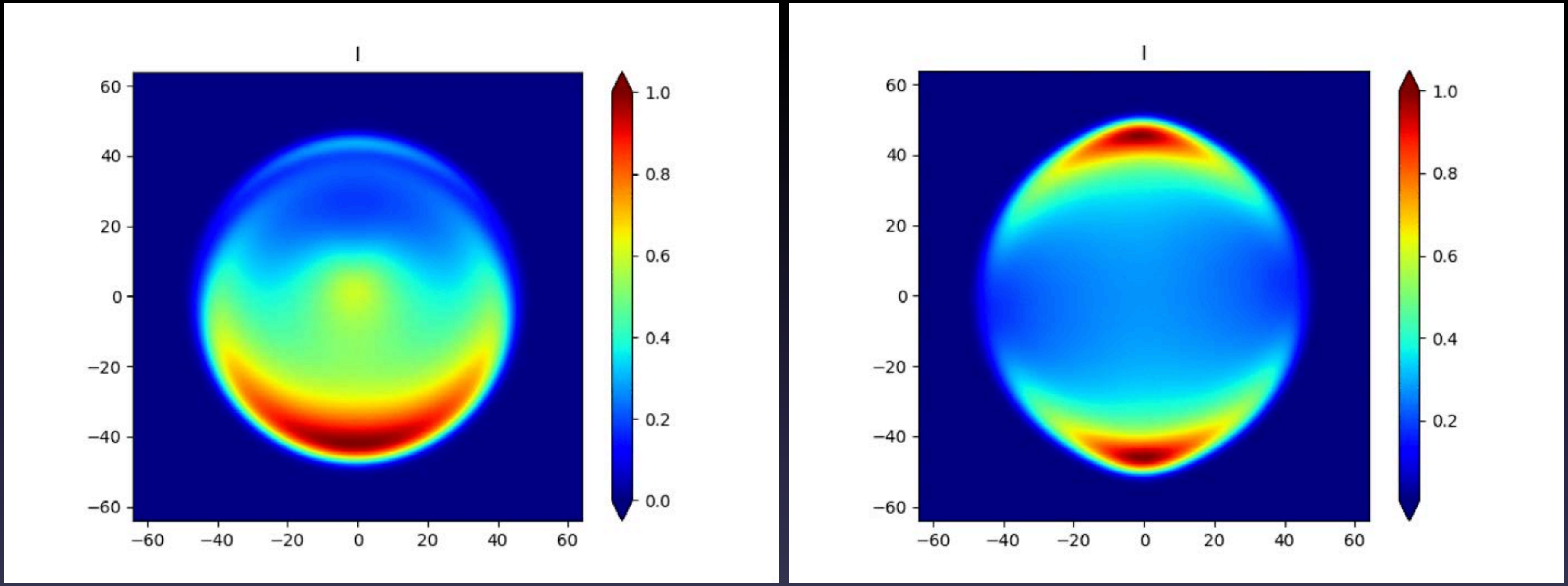
Villagrán, Velázquez, Gómez & Giacani (in preparation). The SNR evolves into a ISM, with a completely developed turbulence. The physical size is 25 x 25 pc. The right map corresponds to a rotation of 60 degrees around the vertical axis

SNR evolving into the progenitor's stellar bubble



Camps-Fariña, Velázquez , Castellanos, Esquivel (in preparation)

Evolution of the synchrotron emission



Comparison of the synchrotron emission, considering different line of sight.
The left /right map corresponds to a rotation of (90,0,0) / (0,0,0,).
[Camps-Fariña, Velázquez , Castellanos, Esquivel (in preparation)]

$\mathrm{E}\upsilon\chi\alpha\rho\iota\sigma\tau\acute{\omega}$!

Thank you!

Gracias!