Modeling radio emission from bowshocks of high-velocity massive stars

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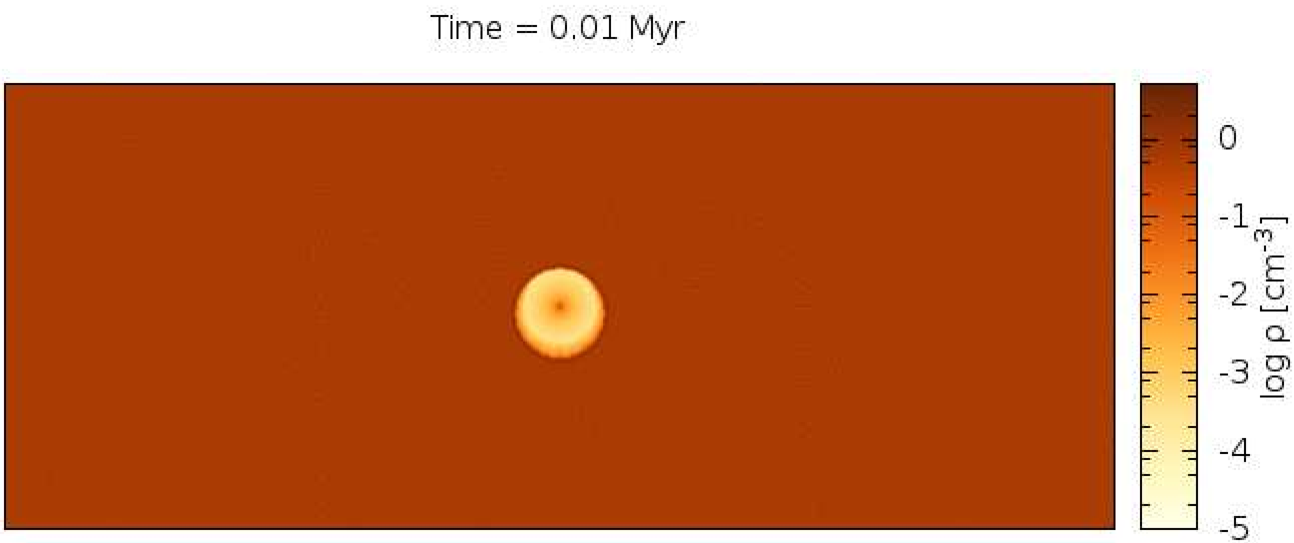
Outline

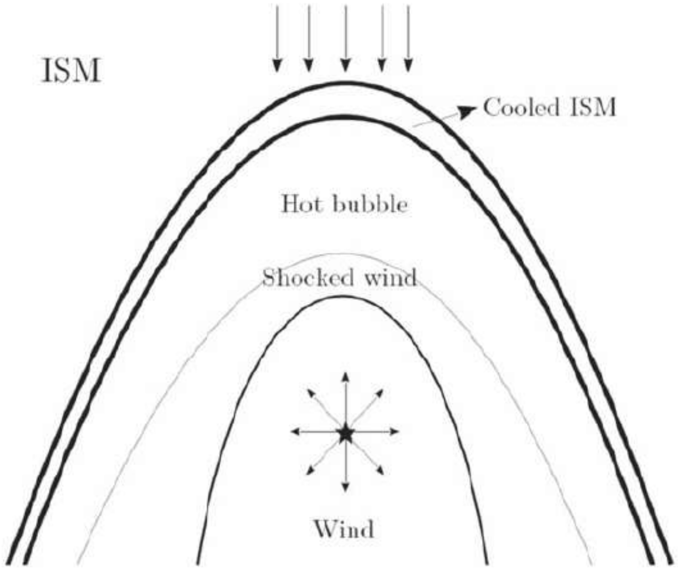
1) Non-thermal emission of high-velocity massive stars
2) Particle acceleration in shocks
3) MHD modeling of stellar wind-ISM interaction
4) Modeling CRe acceleration & transport
5) Synthetic radio emission at ~GHz: synchroton + free-free
6) Depolarizing effects
7) What we learned and future directions

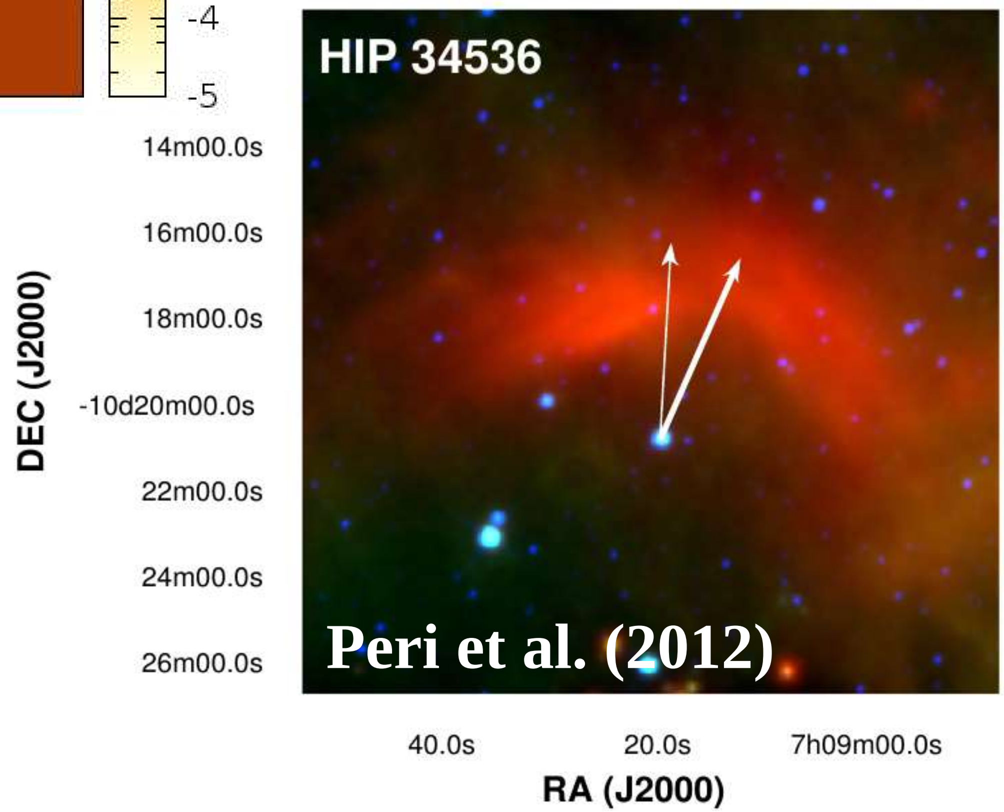
More details:
del Valle, Romero, Santos-Lima (2015)
del Valle & Pohl (2018)
del Valle, Santos-Lima, Pohl (2025)

1. Non-thermal emission of high-velocity massive stars

Runaway massive stars







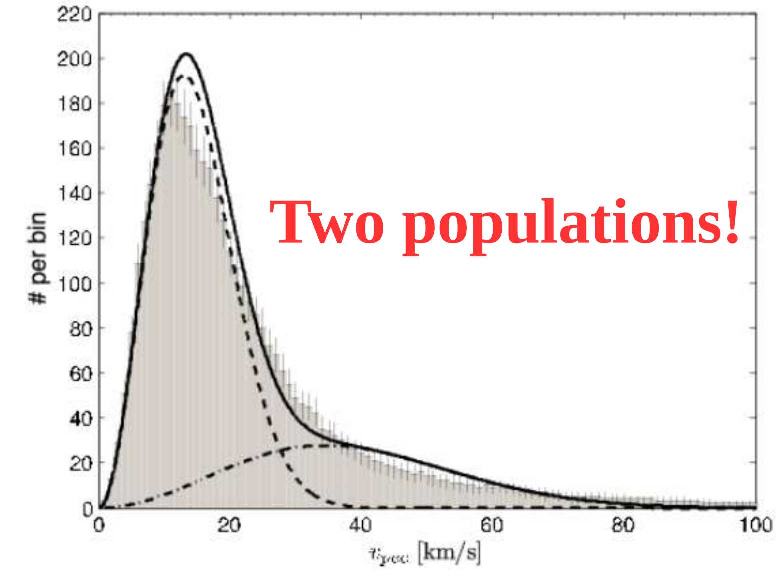
The IR bow shock:

- Gas from the ISM is compressed by the forward shock (bow shock)
- Dust is heated by the stellar UV field
- Dust cools and emits at IR

Stars run away from their birth places

- **Some:** expelled in SN explosion of its binary companion
- **Most:** expelled in close encounters in massive clusters

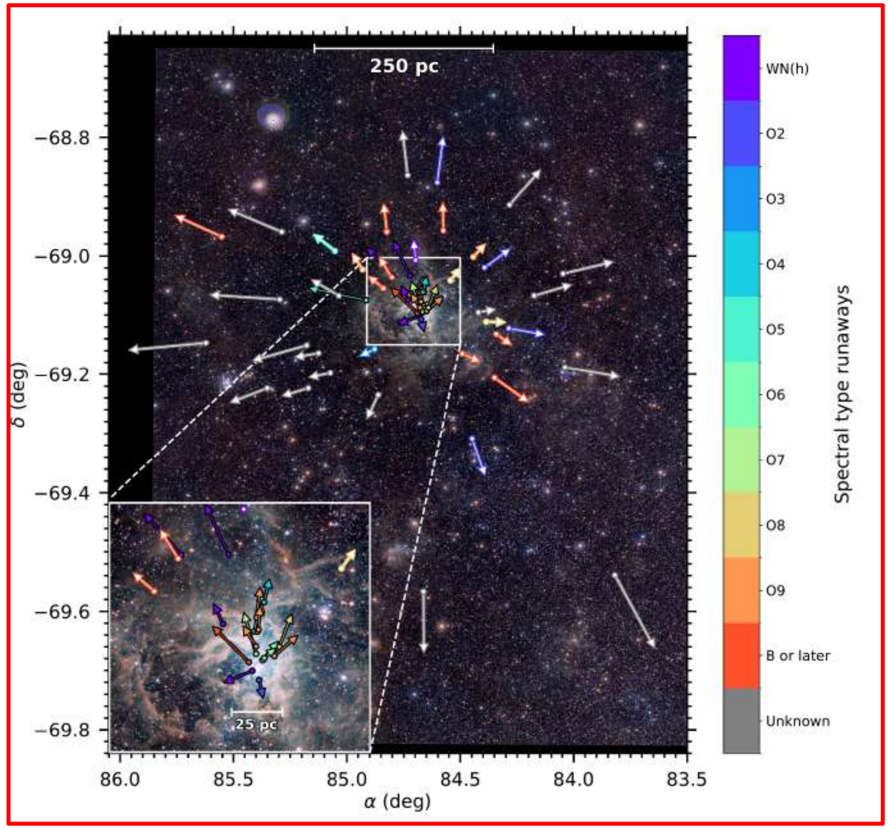
Distribution of
Galactic stars velocities



Runaway stars: V > 30 km/s

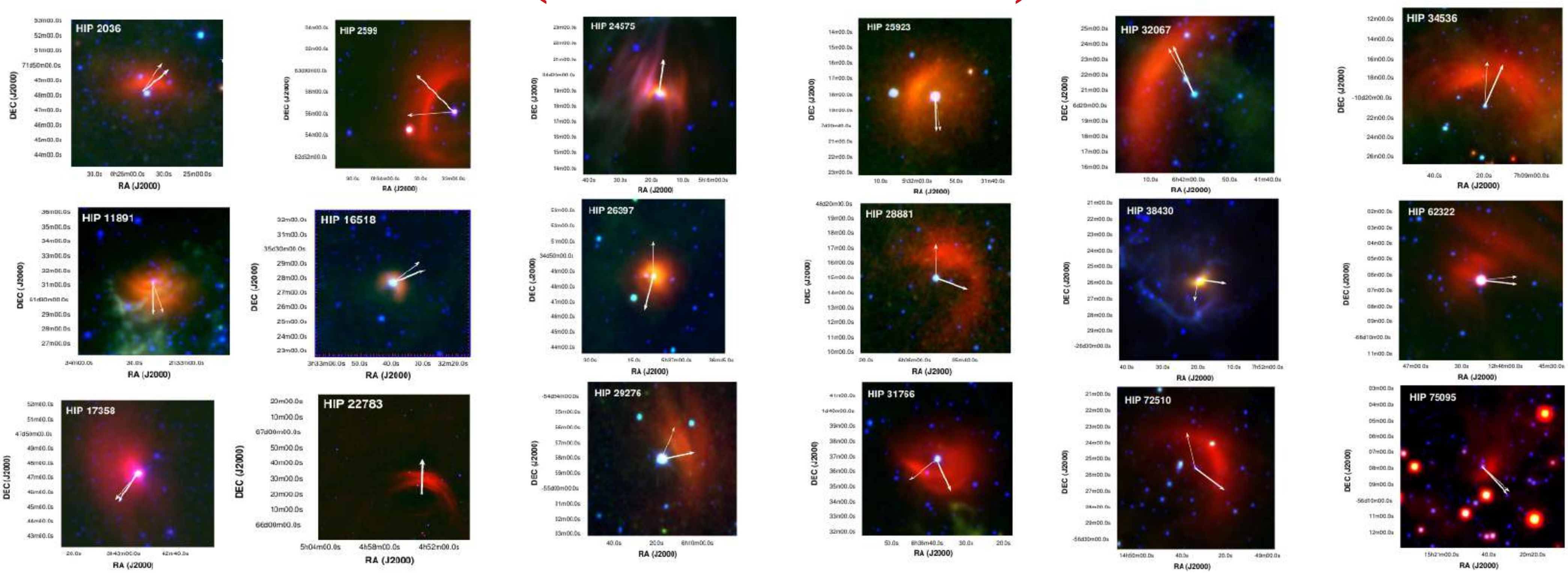
Tetzlaff et al. (2011)

R136 – GMC
55 massive runaway stars

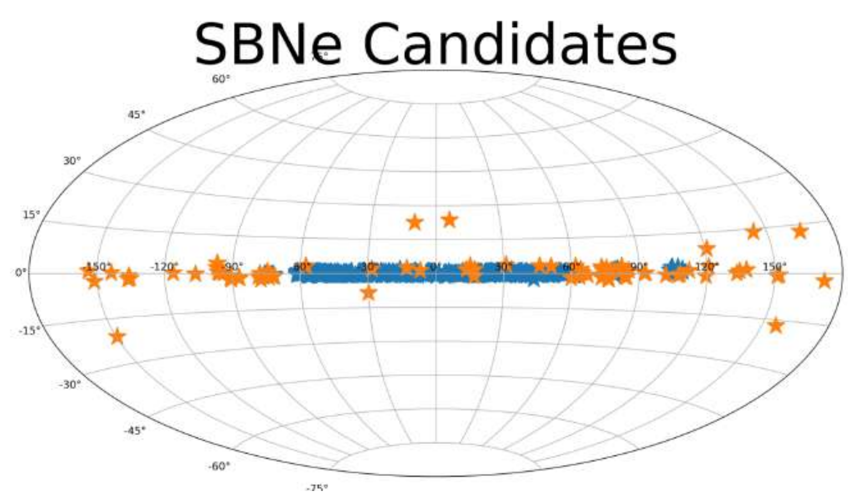


Stoop et al. (2024)

EBOSS & EBOSS II
(Peri+2012/2015)

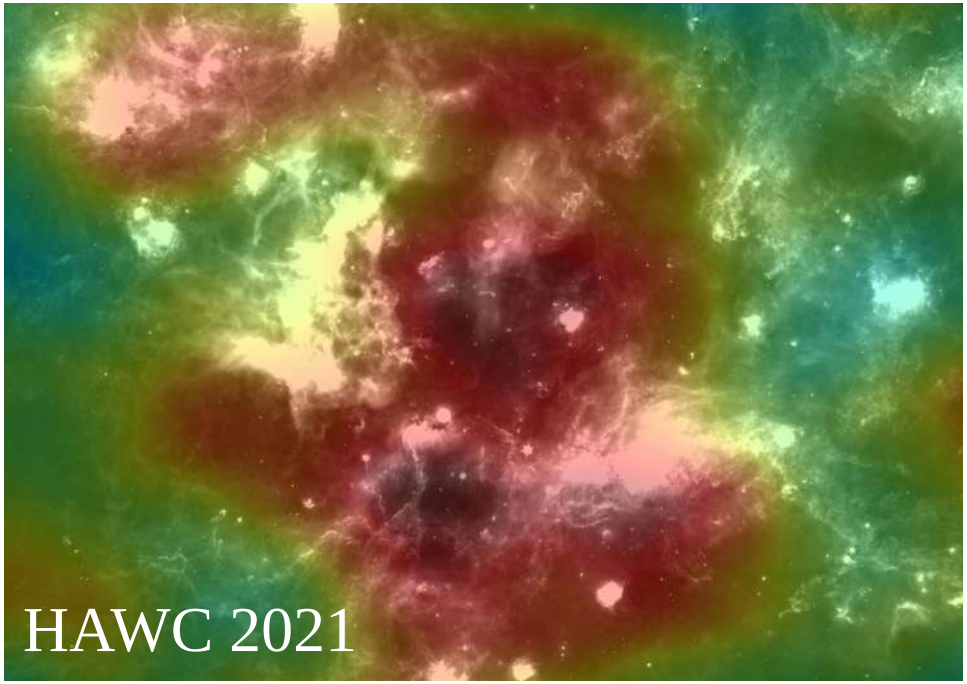


Stellar bow shock:
709 candidates
(Kobulnicky+2017)



New sources of Galactic cosmic rays

Cygnus Cocoon



Winds

↓ ISM

Mechanical Power

↓ DSA

Particles acceleration

↓ Target fields

Non-thermal radiation

Synchrotron, IC, pp

See Poster by
Luna Espinosa

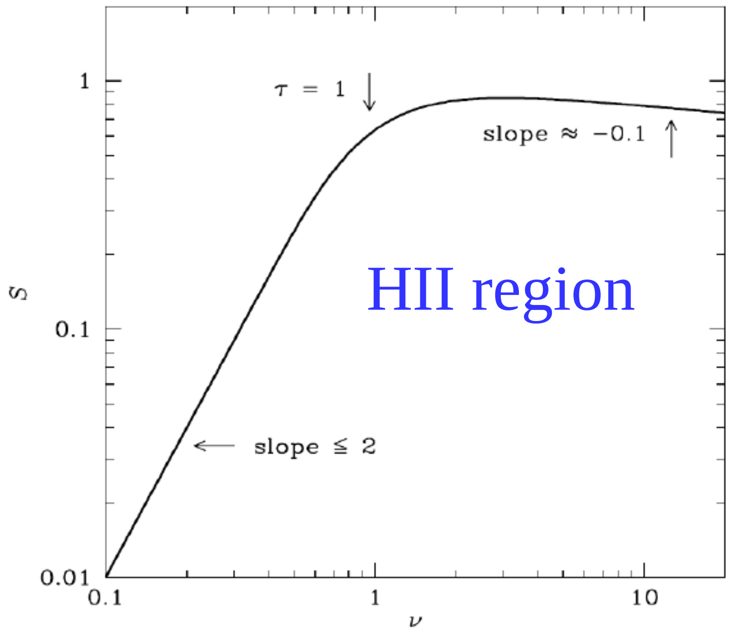
Radio emission

- Blackbody radiation
- Synchrotron
- Bremsstrahlung
- Molecular and atomic lines
- HI (recombination)

} Continuum

Blackbody

$$B_\nu(T) = \frac{2\nu^2 kT}{c^2}$$



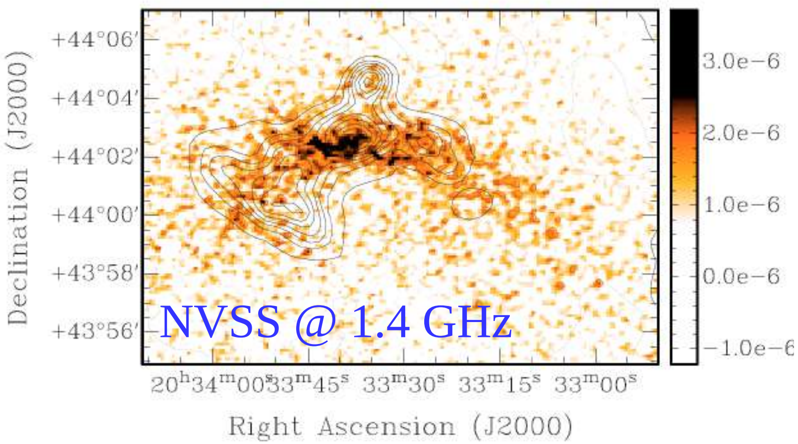
Synchrotron

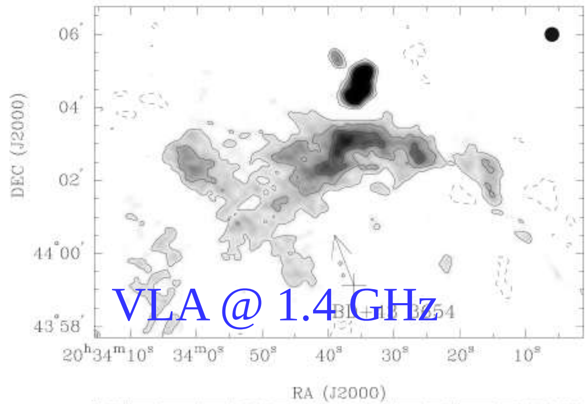
$$S(\nu) \propto \nu^{-(p-1)/2}$$

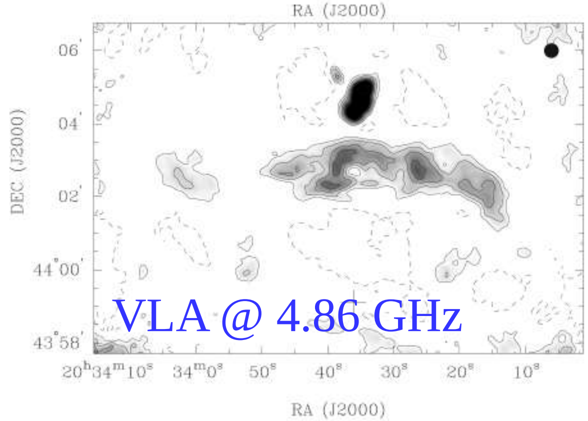
Index < -0.1 ⇒ Nonthermal

Non-thermal radio detection

Massive runaway star
BD+43°3654
d ~1.5 kpc



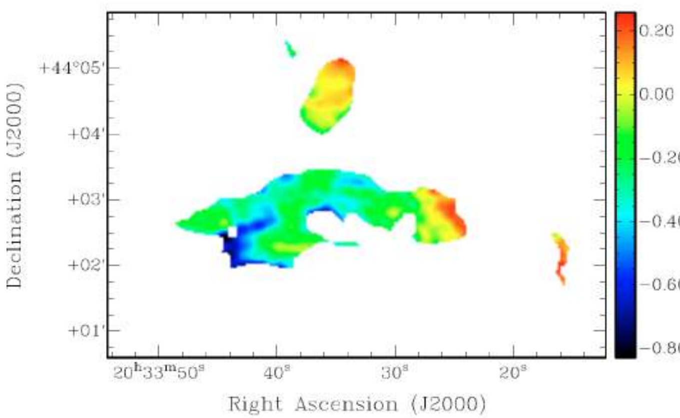




Spectral index

$$S(\nu) \quad = \quad K\,\nu^{-\alpha}$$

$$\alpha = \left(\frac{\log_{10}(F_2) - \log_{10}(F_1)}{\log_{10}(\nu_2) - \log_{10}(\nu_1)}\right)$$



- Extended radio emission, coma shape
- Spectral index consistent with synchrotron emission

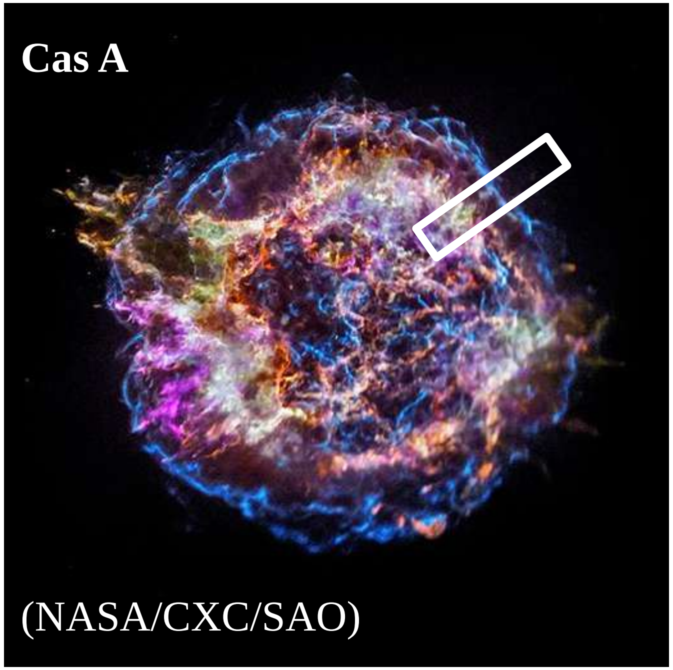
Benaglia+2010

Non-thermal radio emission: consequences

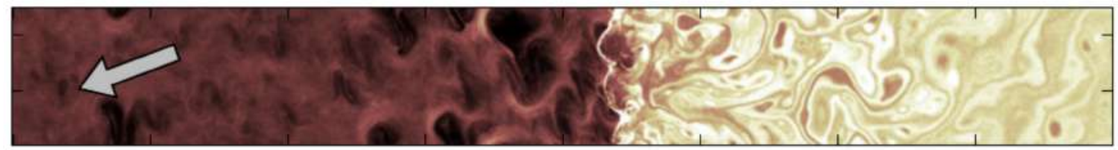
- Non-thermal emission is produced by a non-thermal population of particles
- Synchrotron emission is produced by relativistic electrons interacting with the local magnetic fields
- New systems component: high-energy particles
- New information from the source (e.g. magnetic field)
- New predictions from the effects of this population of particles → high energy sources
- Requires acceleration of particles in the source (or not?) → **laboratories for shock acceleration models**

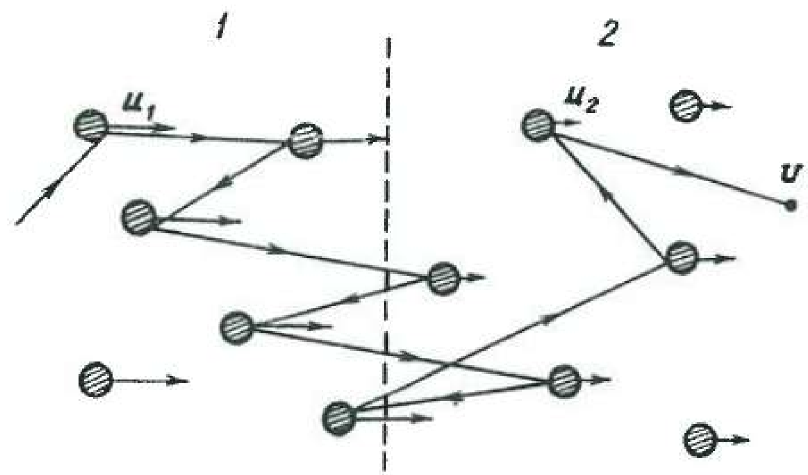
2. Particle acceleration in shocks

Shock Acceleration

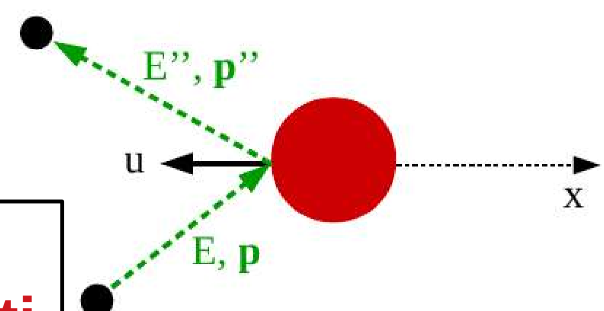


(Caprioli & Spitkovsky 2014)





(Uzdenskii+ 1990)

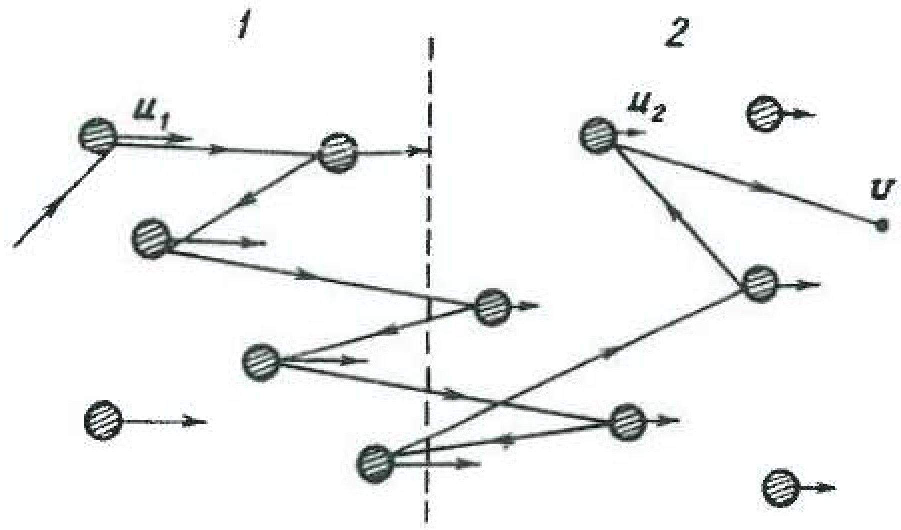


SN shocks are the favored mechanism for acceleration CRs up to energies ~PeV

Converging flow at the shock ⇔ Fermi reflection across the shock front

See Poster by
Jaqueline F. Masotti

Particle scattering:



After a round trip (1 ⟶ 2 ⟶ 1), relative energy gain:

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{4}{3}\beta = \frac{4}{3}\frac{(u_1 - u_2)}{c}$$

Change in energy proportional to the first order in the small parameter β

⇒ Fermi first order acceleration

Back to energy, in the ultra-relativistic case ($E_0 >> mc^2$):

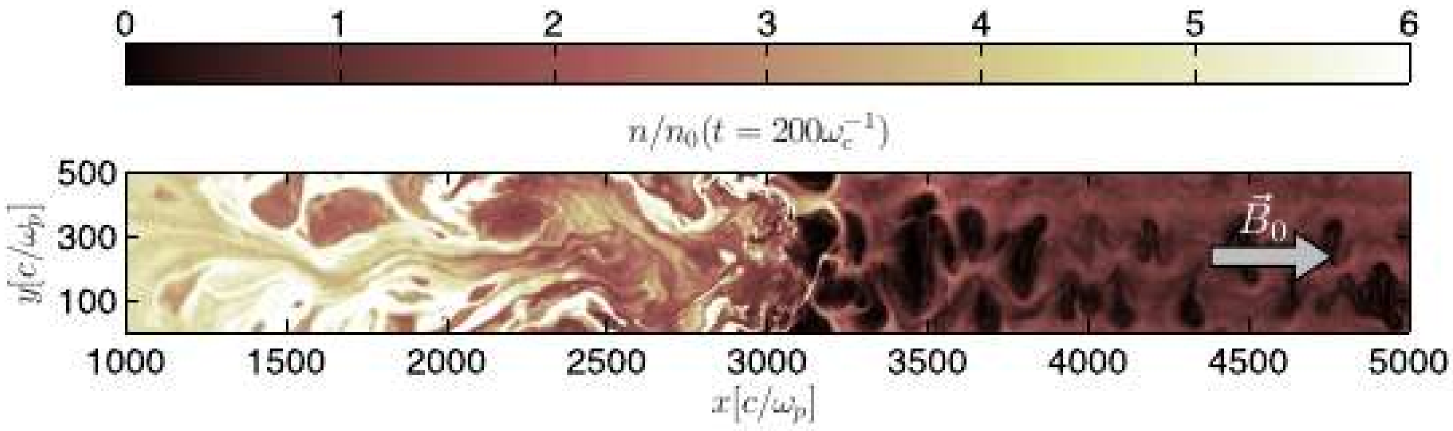
$$N(E) = C_0(\Gamma + 2)E_0^{-1}\left(\frac{E}{E_0}\right)^{-\Gamma} \rightarrow \boxed{N(E) \propto E^{-2}}$$

Non-relativistic case (in kinetic energy):

$$N(E_k) = C_0(\Gamma/2 + 1)E_{k0}^{-1}\left(\frac{E_k}{E_{k0}}\right)^{-(\Gamma+1)/2} \rightarrow \boxed{N(E_k) \propto E_k^{-1.5}}$$

- No dependence on the details of the scattering process
- E_{max}?

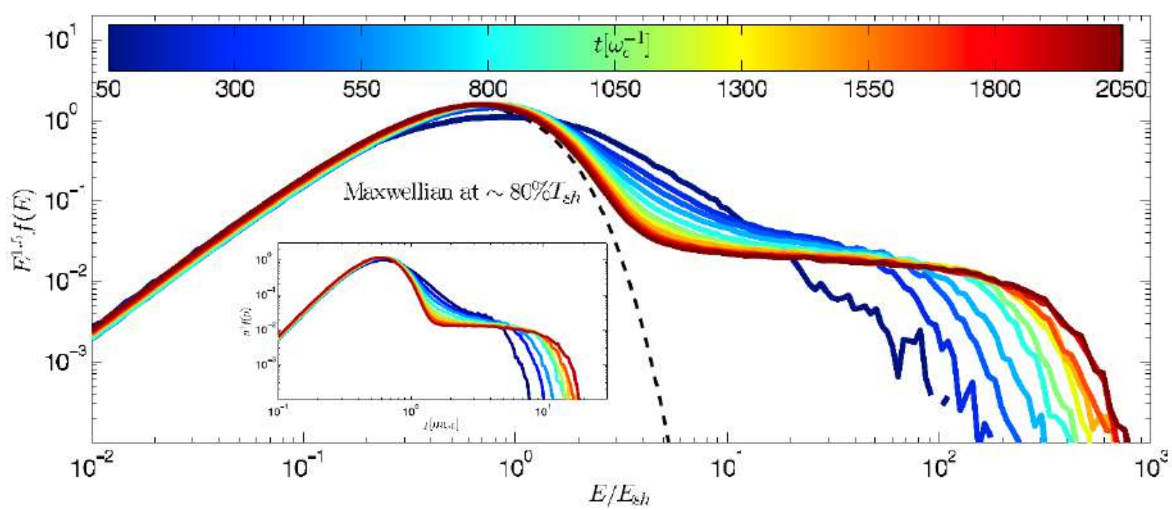
PIC simulation - non-relativistic shock, non-relativistic energies (Caprioli & Spitkovsky 2014)



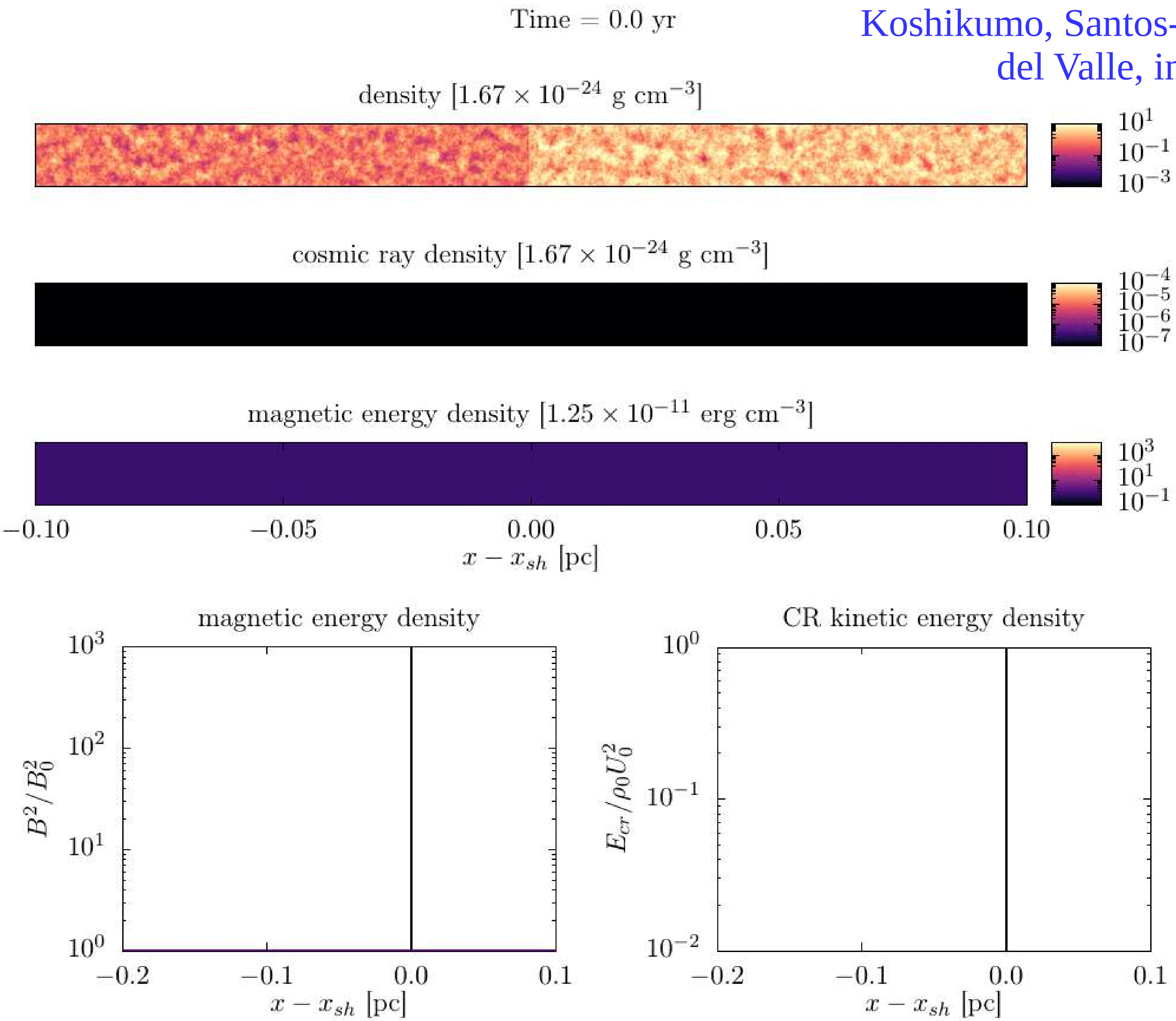
Still several open questions!

See Posters by

- **Camila N. Koshikumo**
- **Larissa R. Magalhães**

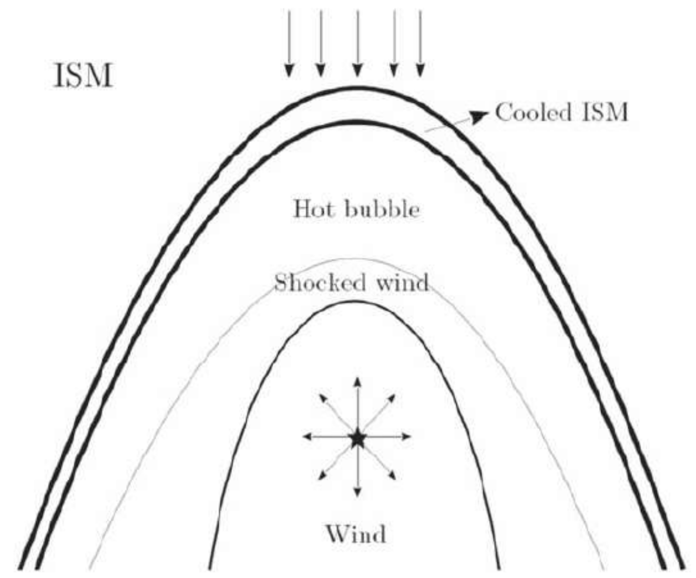


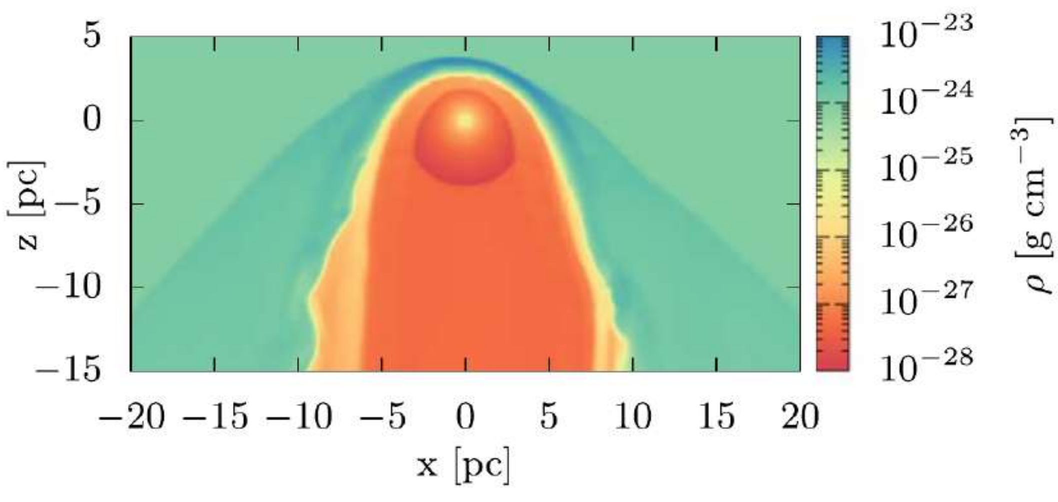
Koshikumo, Santos-Lima, del Valle, in prep.



Stellar Bowshock Nebulae (SBNe): two-shock systems

- **Forward shock:**
  - $V \sim V_{\star} \sim 40$ km/s
  - Radiative
  - Propagates through the ISM
  - Not enough power for explaining the non-thermal detection at ~GHz
- **Reverse shock:**
  - $V \sim V_W \sim 10^3$ km/s
  - Adiabatic
  - Propagates through the wind





3. MHD modeling of stellar wind-ISM interaction

Stellar wind model + radiative cooling

MHD: PLUTO code

$$\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) = 0$$

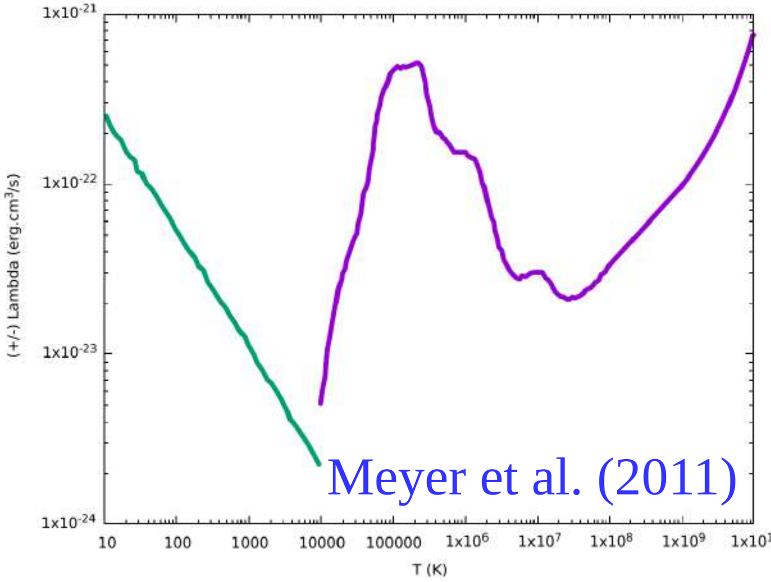
$$\frac{\partial (\rho \boldsymbol{v})}{\partial t} + \nabla \cdot \left[\rho \boldsymbol{v}\boldsymbol{v} + \left(p + \frac{B^2}{8\pi} \right) \boldsymbol{I} - \frac{\boldsymbol{B}\boldsymbol{B}}{4\pi} \right] = 0,$$

$$\frac{\partial e}{\partial t} + \boldsymbol{\nabla} \cdot \left[\left(e + p + \frac{B^2}{8\pi} \right) \boldsymbol{v} - \frac{\boldsymbol{B}(\boldsymbol{v} \cdot \boldsymbol{B})}{4\pi} \right] = \Phi(T, \rho)$$

$$\frac{\partial \boldsymbol{B}}{\partial t} - \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) = 0,$$

$$\nabla \cdot \boldsymbol{B} = 0,$$

ISM Cooling



Meyer et al. (2011)

Stellar wind: Parker's Solar wind like

$$B_\phi = -B_\star \sin\theta \frac{R_\star V_{\rm rot}}{r\ V_{\rm w}},$$

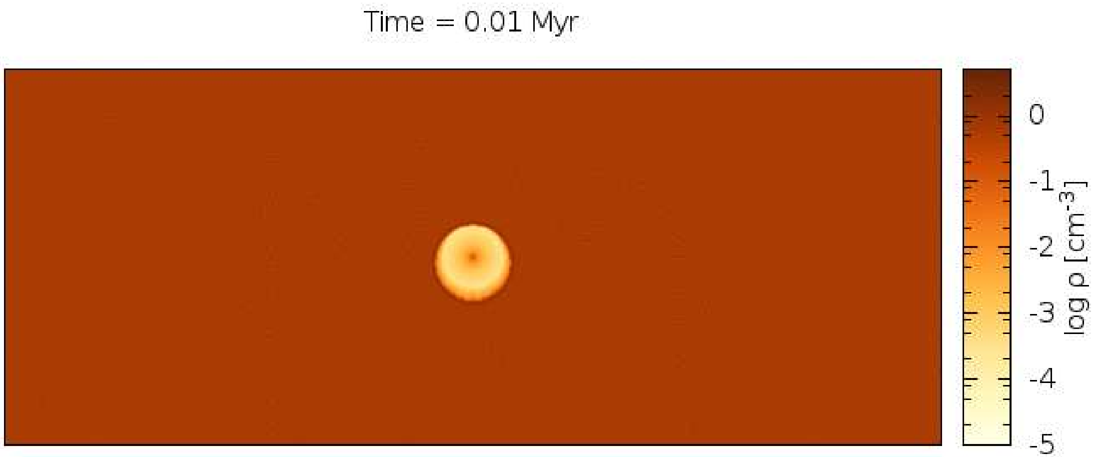
$$B_r = B_\star \left(\frac{R_\star}{r} \right)^2,$$

A general case:

fiducial parameters

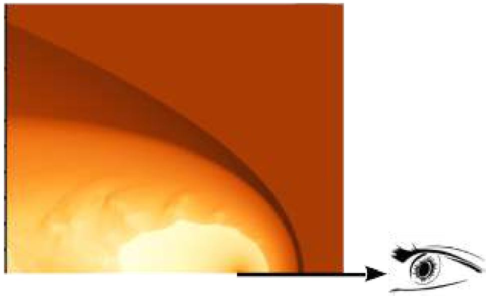
Parameter	Value
$M_\star$	$40\ M_\odot$
$R_\star$	10^{12} cm
$T_\star$	4.25×10^4 K
$B_\star$	200 G
$V_\star$	40 km s^{-1}
$\dot{M}_{\rm w}$	$7 \times 10^{-7}\ M_\odot\ yr^{-1}$
$V_{\rm w}$	2000 km s^{-1}
$L_{\rm w}$	10^{36} erg s^{-1}
$V_{\rm rot}$	100 km s^{-1}
$n_{\rm ISM}$	0.57 cm^{-3}
$T_{\rm ISM}$	8000 K
$B_{\rm ISM}$	5 μG

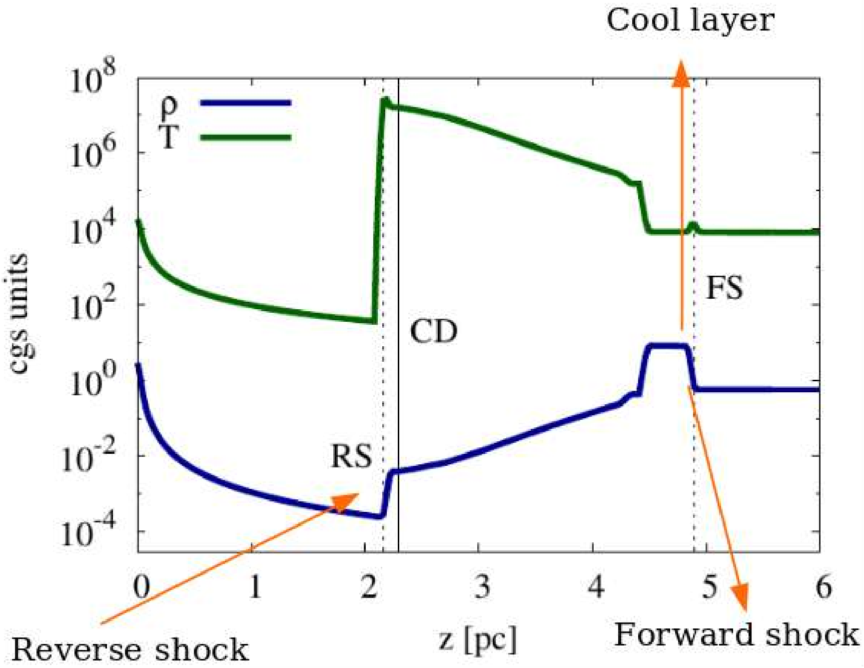
3D MHD fields & shock structure



See Posters by

- **Augusto Carvalho**
- **Yasmmin Tamburus**





4. Modeling CRe acceleration & transport

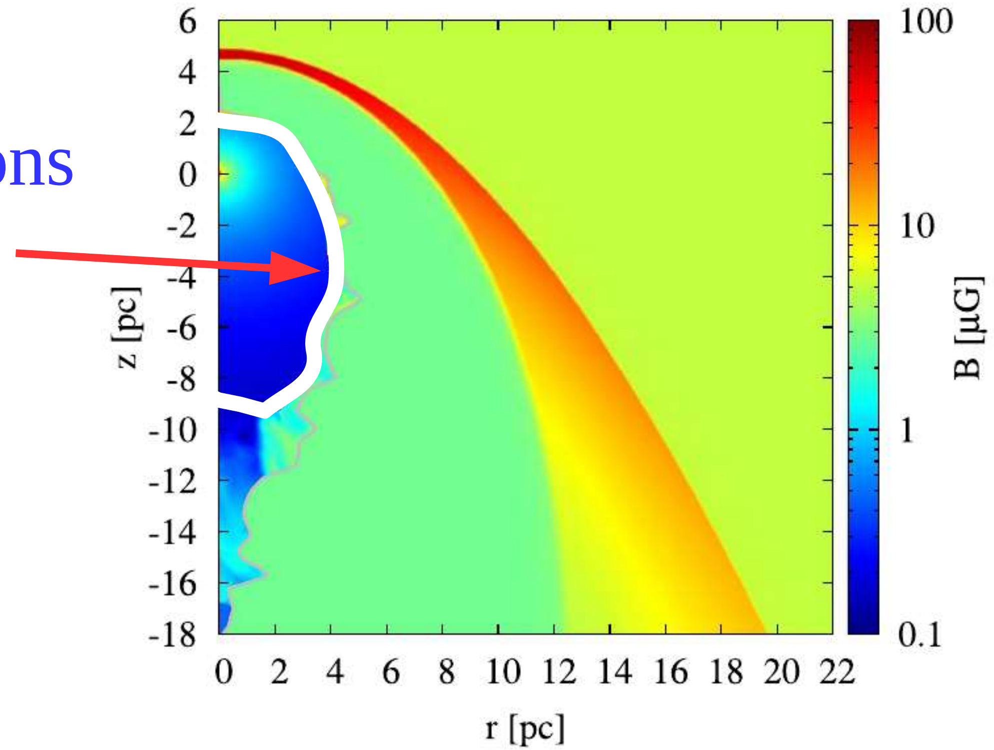
Accelerated CRe

- Continuous injection of accelerated relativistic electrons at the reverse shock position

$$Q \propto E^{-\alpha}$$

$$\alpha = 2$$

$$E_{max} = 10\ \mathrm{GeV}$$



- Efficiency: 1% of the wind power ⇒ $L_e \sim 10^{34}$ erg/s
- Population of Galactic CRe: $N(E) \equiv \frac{4\pi}{c} J_{CR}(E)$

CRe transport

- Transport calculated in 2D axisymmetric geometry
- Synchrotron losses
- Simplistic diffusion model: homogeneous & isotropic (Alfvenic turbulence / Galactic representative values)

$$\frac{\partial N(E,\vec{x},t)}{\partial t} = \nabla(D(E,\vec{x},t)\nabla N(E,\vec{x},t)) - \nabla(\mathbf{V}(\vec{x},t)N(E,\vec{x},t)) - \frac{\partial}{\partial E}(P(E,\vec{x},t)\,N(E,\vec{x},t)) + Q(E,\vec{x},t).$$

D power-law in E

$$D(E) = \chi D_{10}\left(\frac{E}{10\,\mathrm{GeV}}\right)^{\delta}$$

From simulation:
Magnetic field

From simulation:
Velocity field

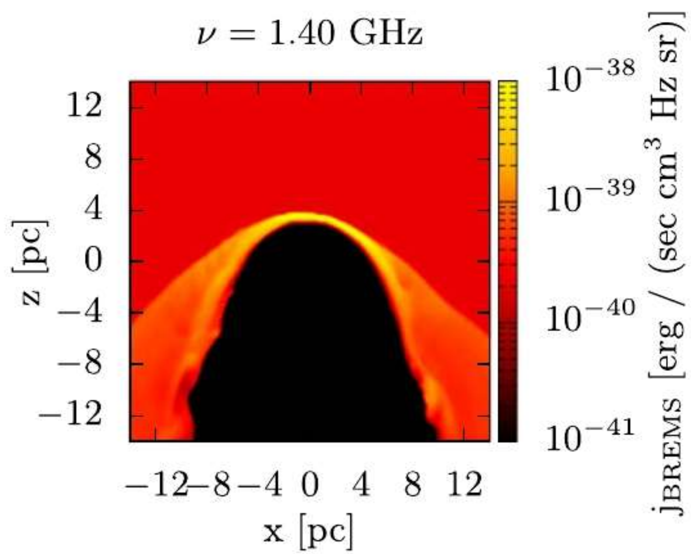
Analytical
But depends
on ρ(r,z)

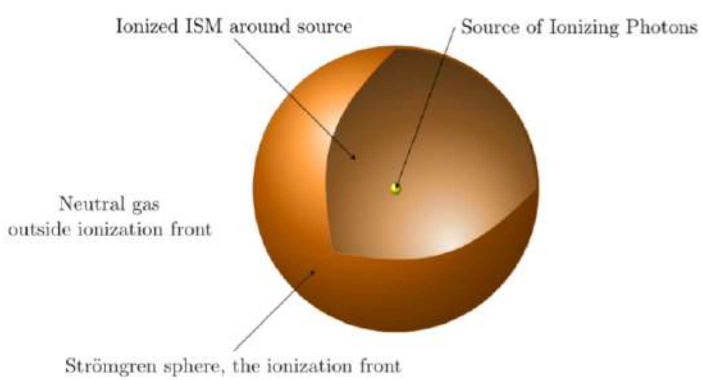
See Poster by **Augusto Carvalho**

4. Synthetic radio emission at ~GHz: synchroton + free-free

From 3D MHD fields and axissymetric CRe distribution: 3D emissivity maps

Free-free

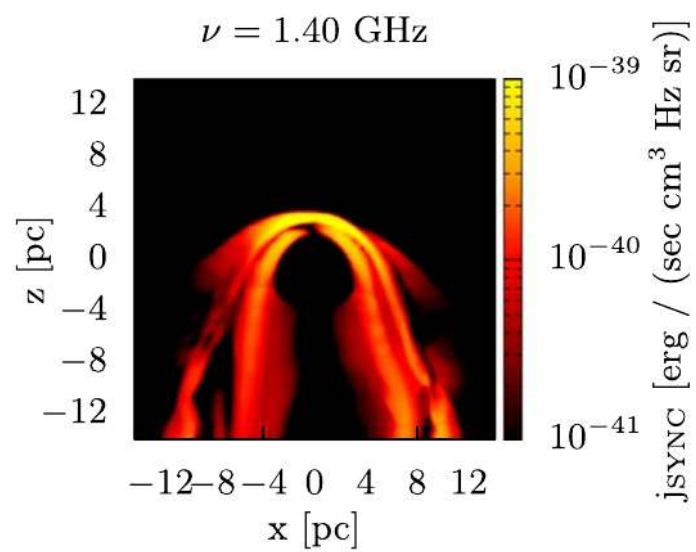




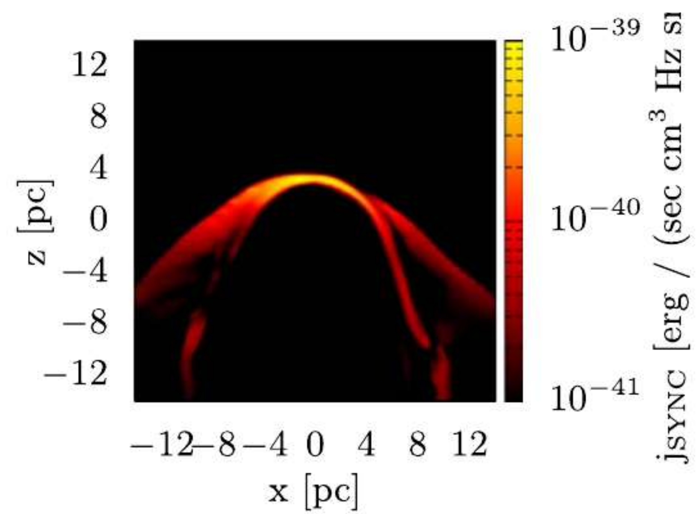
R ~ 75 pc

Synchrotron

On-site accelerated electrons



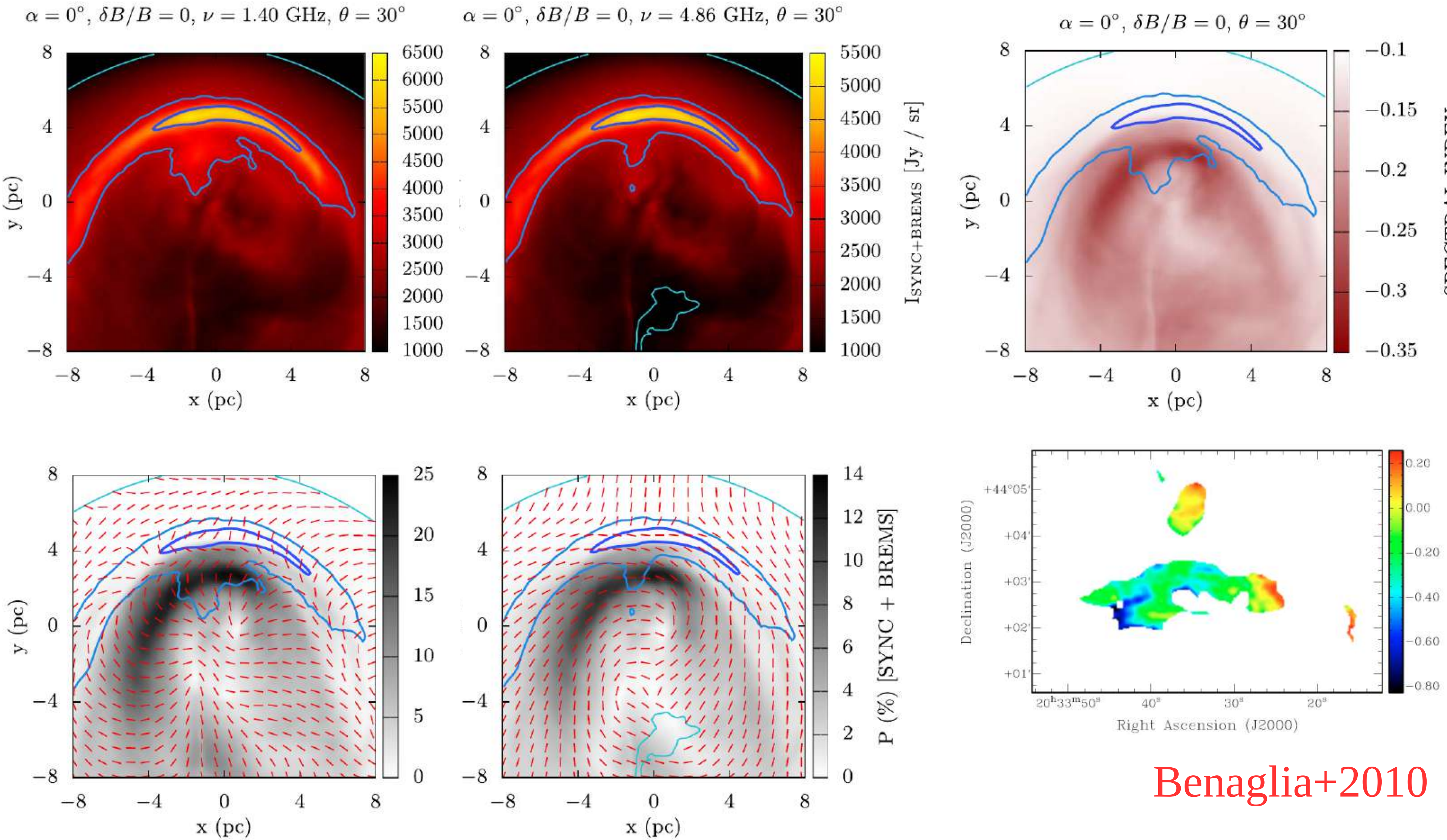
Galactic background of CRe



Optically thin radiation transfer

$$S(\nu) = K\,\nu^{-\alpha}$$

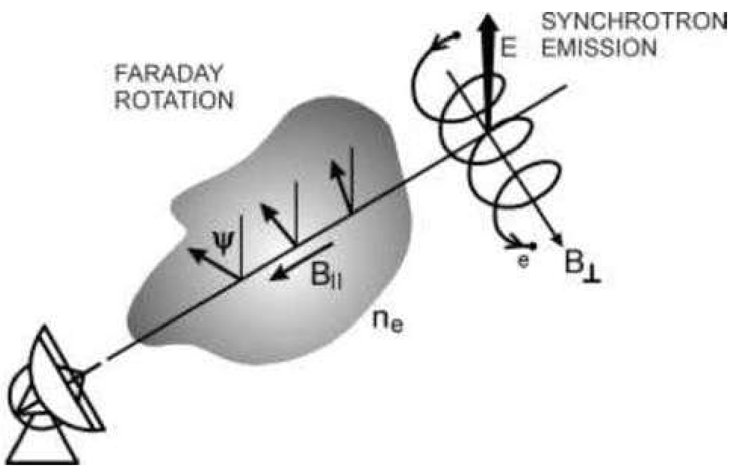
$$\alpha = \left(\frac{\log_{10}(F_2) - \log_{10}(F_1)}{\log_{10}(\nu_2) - \log_{10}(\nu_1)}\right)$$



Benaglia+2010

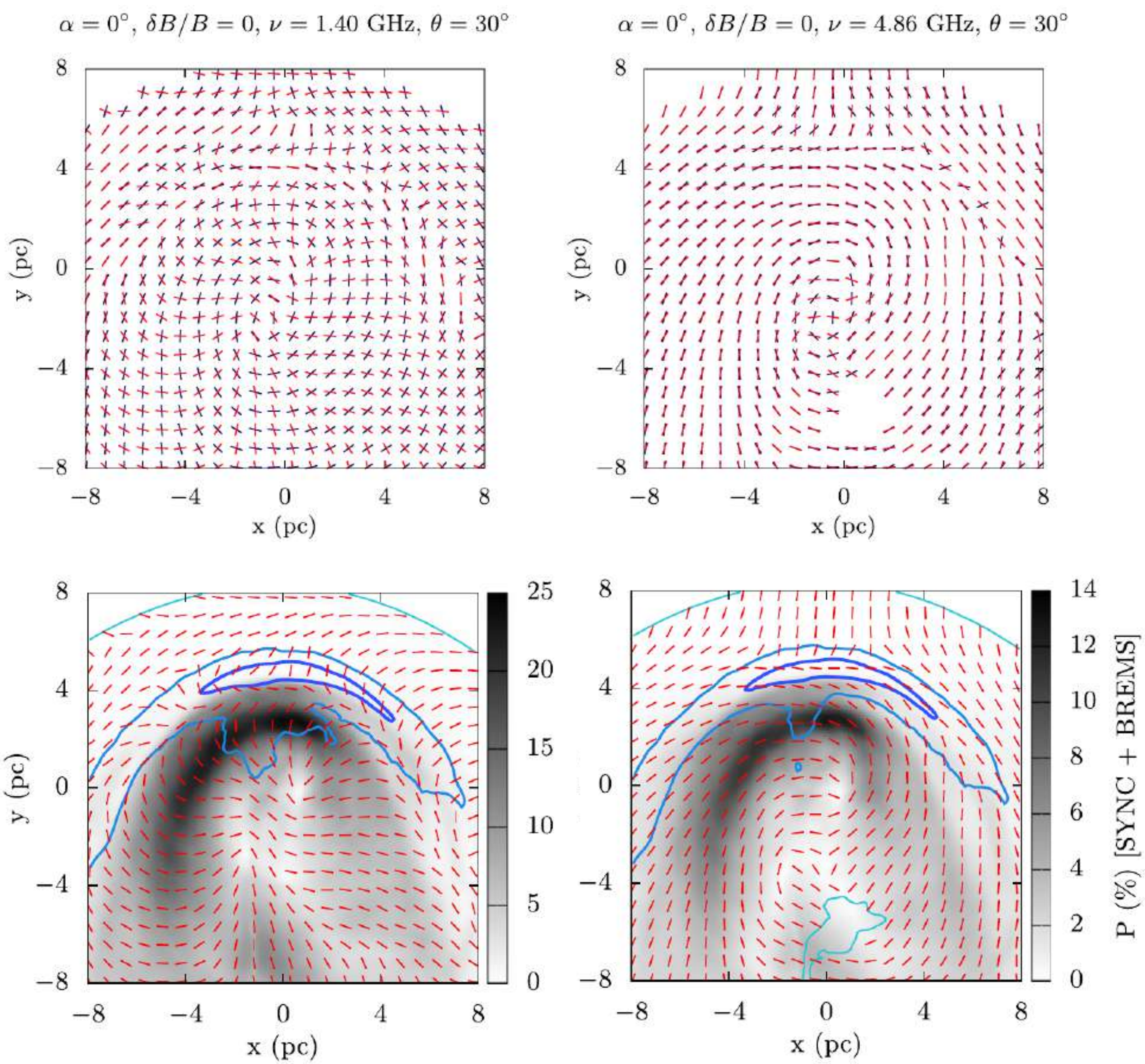
6. Depolarizing effects: FR & turbulence

Faraday Rotation

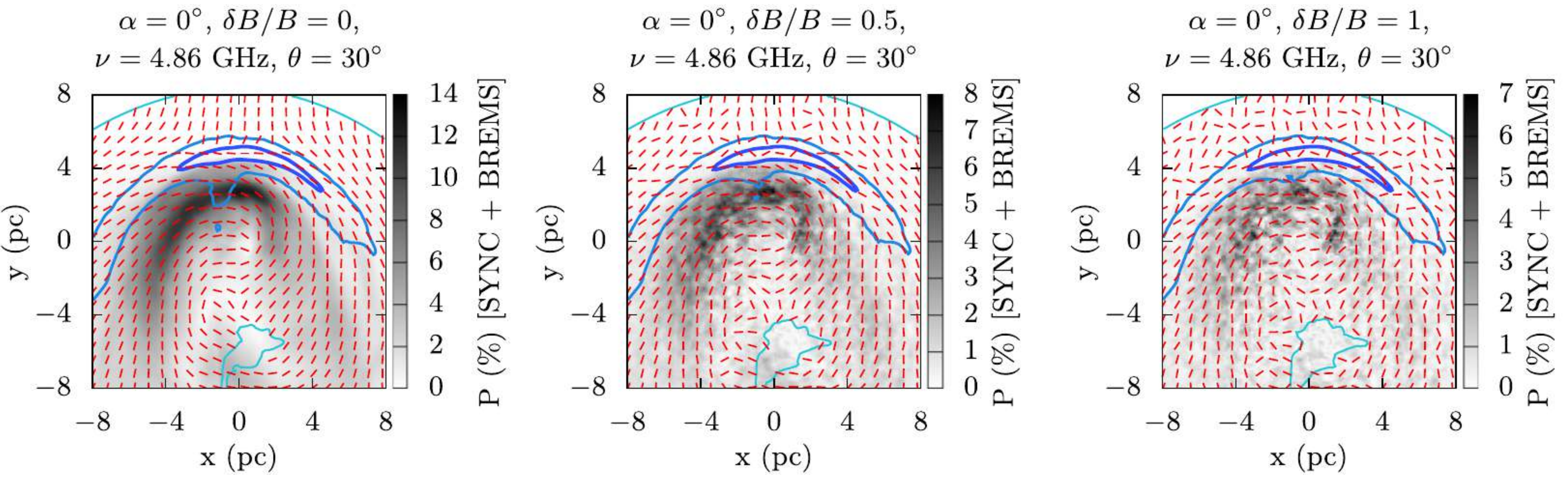


$$\Delta\chi = \frac{e^3\,\lambda^2}{2\pi\,(mc^2)^2}\int_{LOS} n_e(z)\,B_{\parallel}(z)\,dz$$

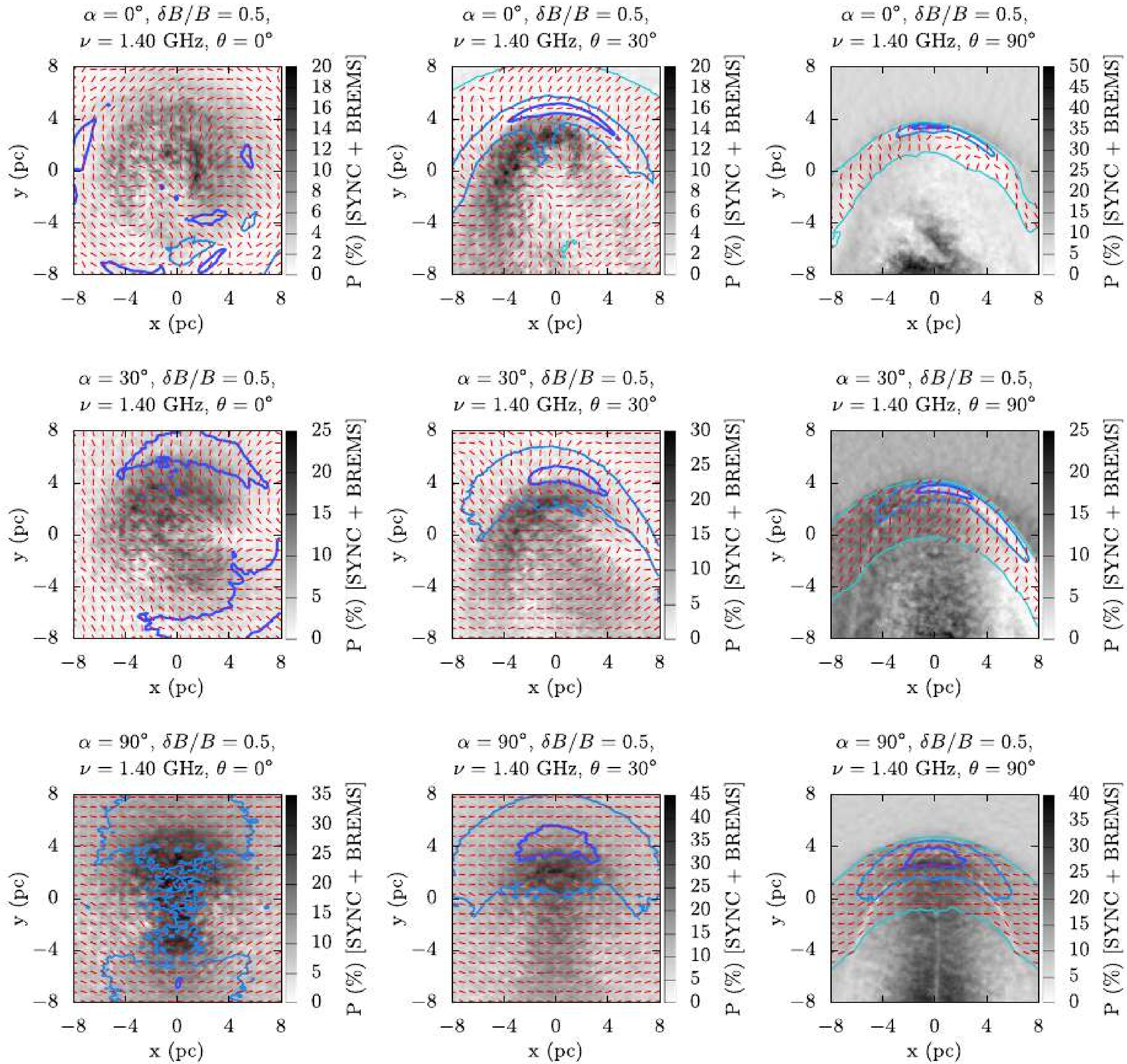
$$\frac{d}{ds}\begin{bmatrix} Q \\ U \end{bmatrix} = (j_{\nu\perp} - j_{\nu\parallel})\begin{bmatrix} \cos\{2(\psi + \pi/2)\} \\ \sin\{2(\psi + \pi/2)\} \end{bmatrix} + 2\begin{bmatrix} -U \\ Q \end{bmatrix}\frac{d\chi}{ds}$$



Turbulence (~1pc, Kolmogorov)



See Poster by
Luiz Henrique de Paula Santos



$\alpha = 0°$, $\delta B/B = 0.5$,
$\nu = 1.40$ GHz, $\theta = 0°$
$\alpha = 0°$, $\delta B/B = 0.5$,
$\nu = 1.40$ GHz, $\theta = 30°$
$\alpha = 0°$, $\delta B/B = 0.5$,
$\nu = 1.40$ GHz, $\theta = 90°$
$\alpha = 30°$, $\delta B/B = 0.5$,
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$\nu = 1.40$ GHz, $\theta = 30°$
$\alpha = 90°$, $\delta B/B = 0.5$,
$\nu = 1.40$ GHz, $\theta = 90°$
x (pc)
y (pc)
P (%) [SYNC + BREMS]

7. What we learned and future directions

Lessons from models

- Faraday rotation effects are intense, specially at the lowest frequencies (~1 GHz): radio polarization can tell little about the direction of **B**
- Polarization can shed light on where particles are accelerating
- Contamination by free-free emission is important, and can masquerade the nonthermal synchrotron emission and polarization
- Emission from background CRe contributes, at different spatial regions ⇒ brighter IR sources are not good candidates!
- More radio observations with polarization are needed
- Currently, acceleration process better investigated at radio than in gamma at these sources

Model improvements and other accelerating systems related to high-mass stars

- Full 3D transport of CR and diffusion physically motivated (inomogeneous & anisotropic)
- Study of colliding wind binary systems
  - See poster by **Augusto Carvalho**
- Study of stellar bubble of massive stars (see posters by **Luna Espinosa**, **Yasmmin Tamburus**)