The LOFAR view of massive star formation

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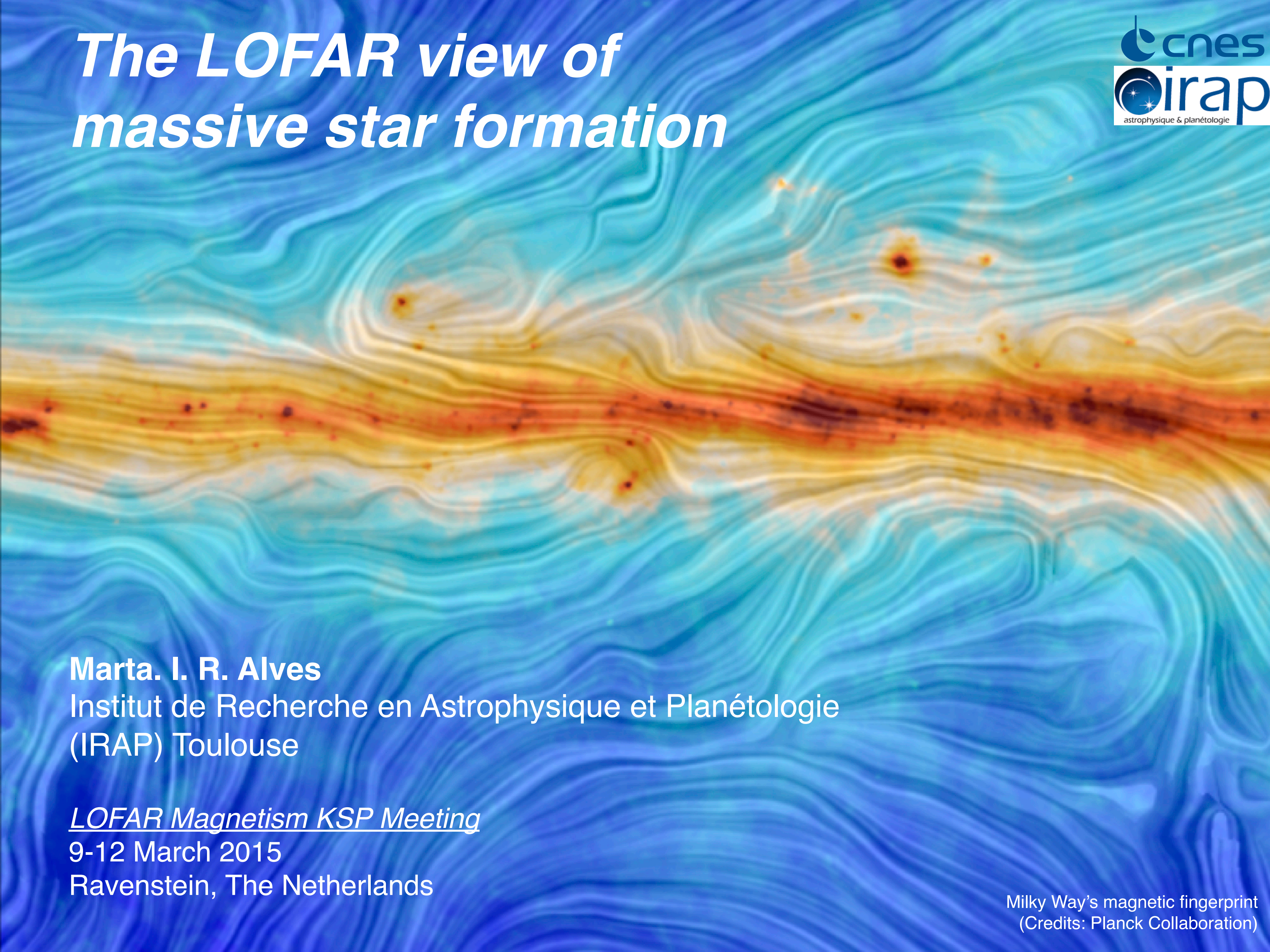


Milky Way's magnetic fingerprint
(Credits: Planck Collaboration)

Outline

- ★ Introduction
  Why are massive star forming regions (SFRs) interesting and why do we want to understand their magnetic field structure?

- ★ Model
  An analytical solution of the magnetic field in a spherical bubble-shell structure

- ★ Observations
  Rosette Nebula: radio rotation measures and sub-millimetre polarization data from *Planck*

- ★ LOFAR
  How can we improve the current picture?

- ★ Summary

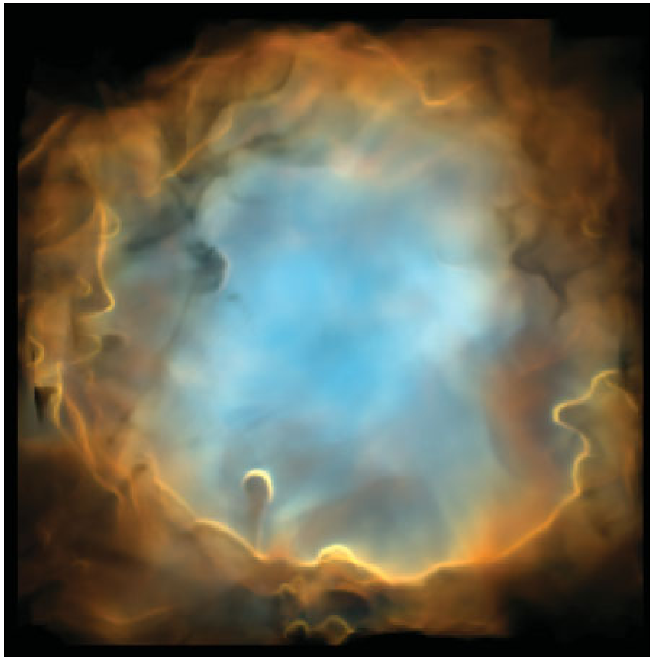
Introduction

Massive stars are the main sources of **turbulent energy** injection in the ISM:

★ Powerful stellar winds
★ HII regions
★ Supernovae

The surrounding ISM is swept up into a dense shell → interstellar bubble

What are the effects of **massive star formation** and **feedback** on $\vec{B}$?



Simulation by Arthur et al. (2011)
Blue [OIII], green [Hα], red [NII]

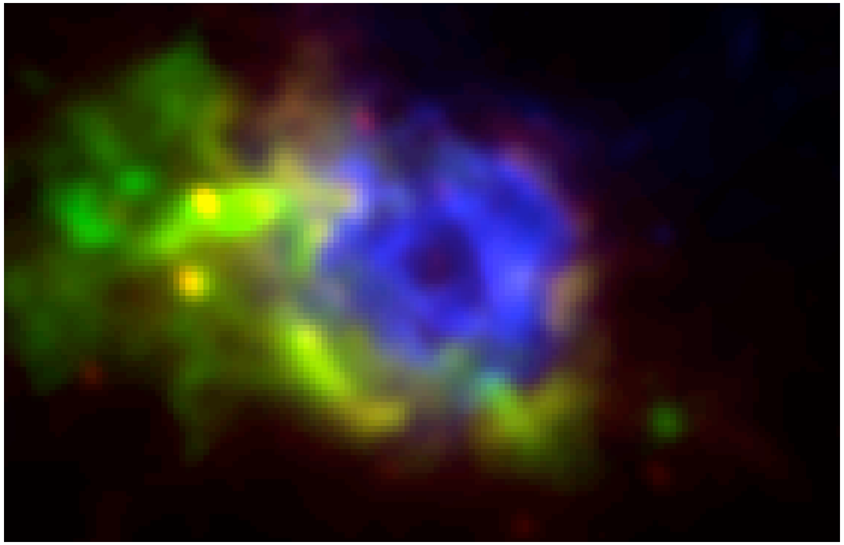
Studies of $\vec{B}$ in massive SFRs:

- high resolution dust polarization in emission and extinction restricted to small regions of the sky (e.g., Zeng 2013, Santos et al. 2014)
- RM observations (e.g. Harvey-Smith et al. 2011, Savage et al. 2013)
- analytical and numerical (e.g., Ferrière et al. 1991, Krumholz et al. 2007, Arthur et al. 2011)

Introduction

RMs → $\vec{B}$ in the ionized nebula

Dust polarized emission → $\vec{B}$ in the dense medium (atomic and molecular)

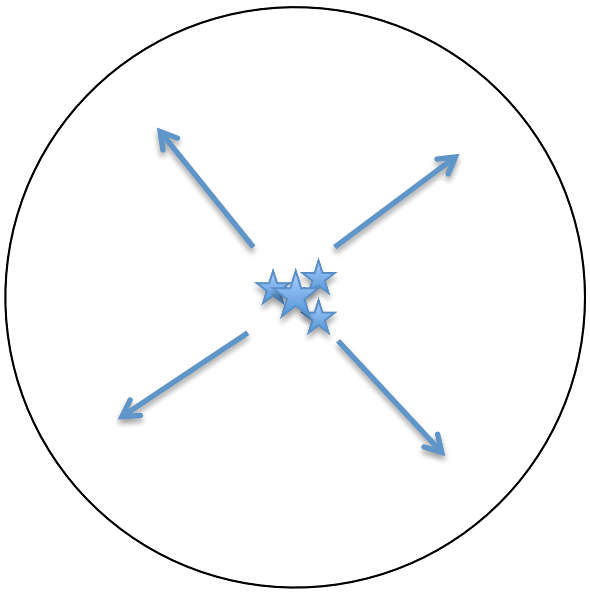


The Rosette nebula and its parent molecular cloud: IRAS 12μm (red), *Planck* 353 GHz (green), SHASSA Hα (blue)

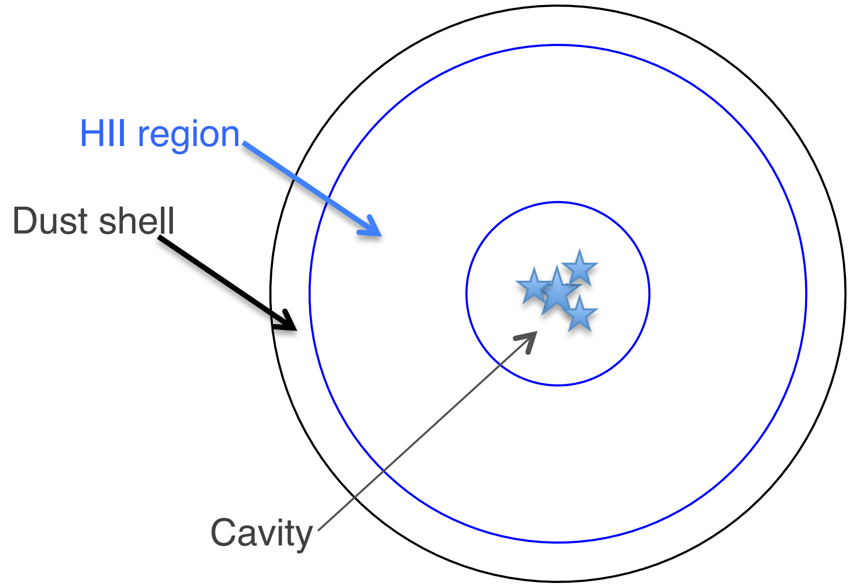
We develop an analytical description of the magnetic field in a spherical bubble-shell structure and use it to reproduce the sub-mm and radio observations consistently

Model: The magnetized Strömgren shell

- Massive stars ionize the surrounding gas up to the Strömgren radius: HII region
- The ionized gas starts expanding in response to an increase in pressure
- This expansion sweeps up the surrounding ISM into a shell, formed around the HII region
- Frozen-in condition: the **magnetic field** lines are **dragged** with the expanding gas



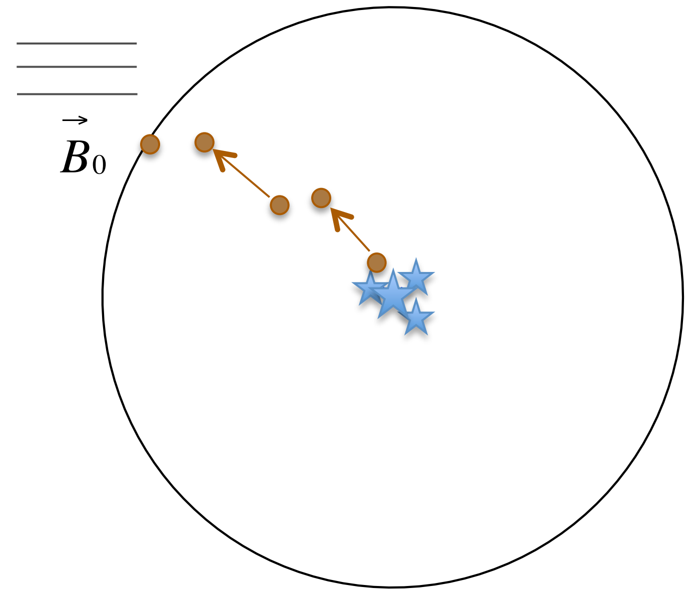
The change in the initial magnetic field structure is due to a change in the distribution of matter



Model: The magnetized Strömgren shell

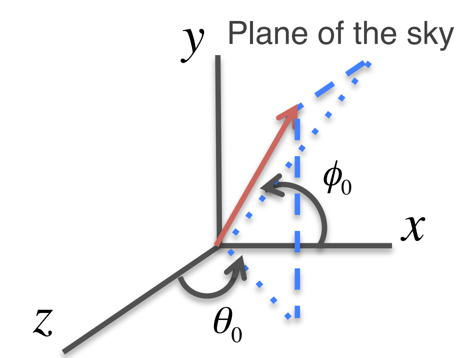
- Radial expansion of the gas:
  - uniform and spherical structure
  - using conservation of mass

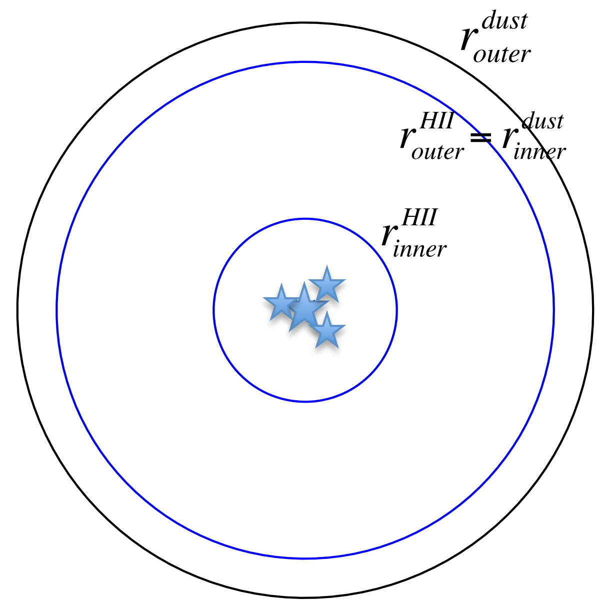
$$r_{final} = f(r_{initial})$$



- Frozen-in condition:
  - start from a uniform $\vec{B}_0$
  - field lines follow the gas (Parker 1970)

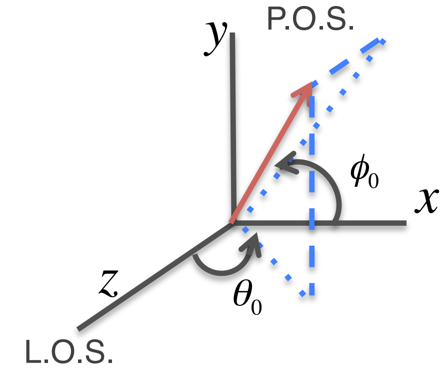
$$\vec{B}(\vec{r}) = \left(\frac{r_0}{r}\right)^2 B_{0r}\,\vec{e}_r + \frac{r_0}{r}\frac{dr_0}{dr}\left(B_{0\theta}\,\vec{e}_\theta + B_{0\phi}\,\vec{e}_\phi\right)$$



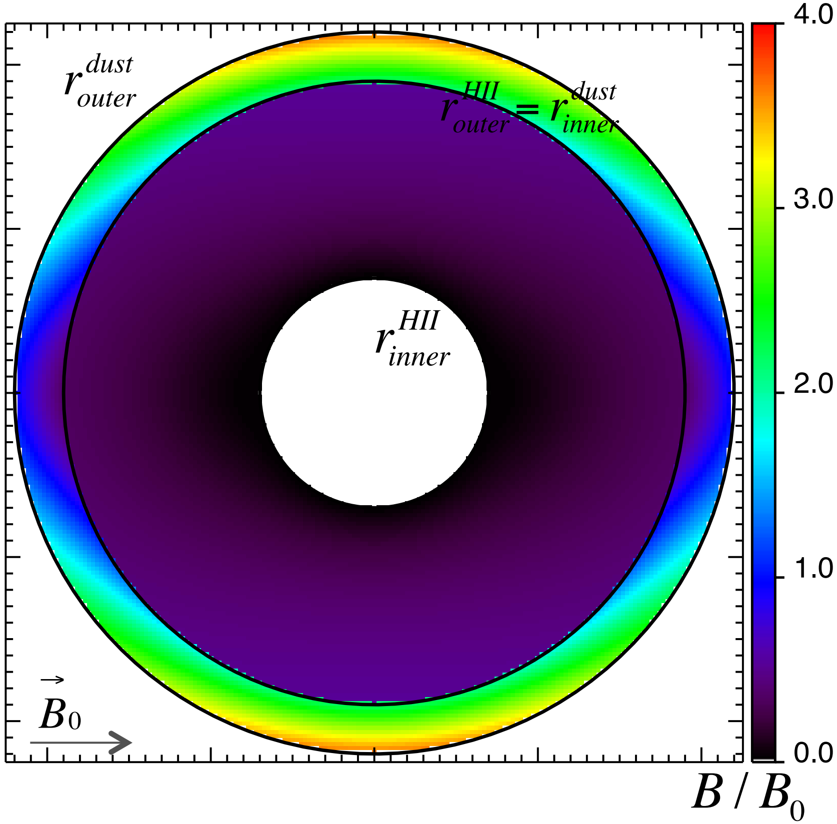


Model: Magnetic field compression?

The expansion law defines where the magnetic field is compressed and where the field lines are pulled apart



Slice through the centre of the shell, in the plane of the sky (xy plane)



- Axial symmetry
- The field is most compressed $\perp$ $\vec{B}_0$
- Along $\vec{B}_0$, $B = B_0$ at the outer surface and B decreases inwards

$\vec{B}_0 = B_0 \vec{e}_x$

$\theta_0 = 90^\circ$

$\phi_0 = 0^\circ$

$\Delta r^{HII} = 0.6 r^{HII}_{outer}$

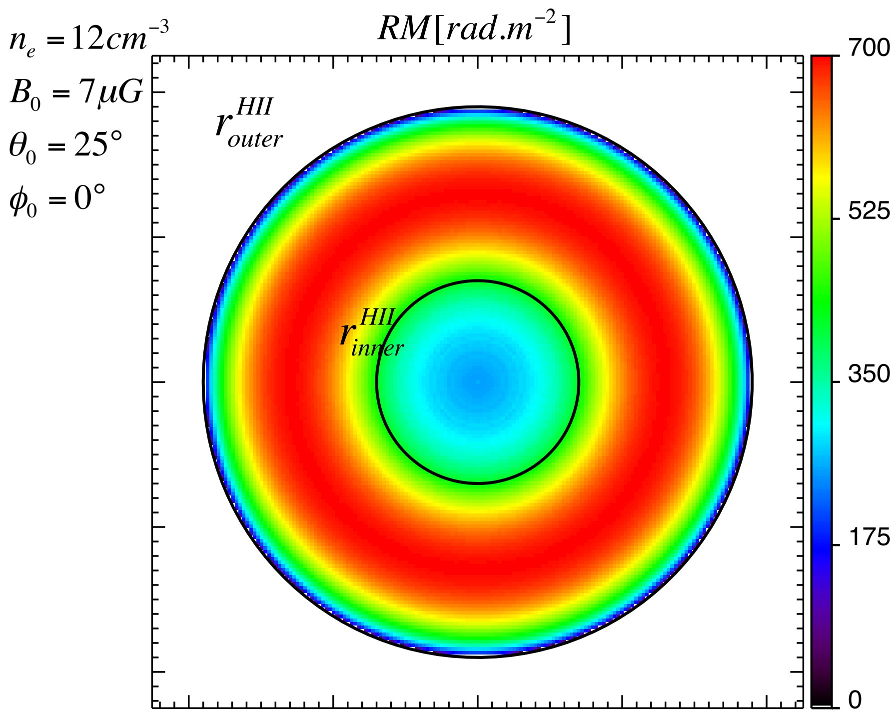
$\Delta r^{dust} = 0.1 r^{dust}_{outer}$

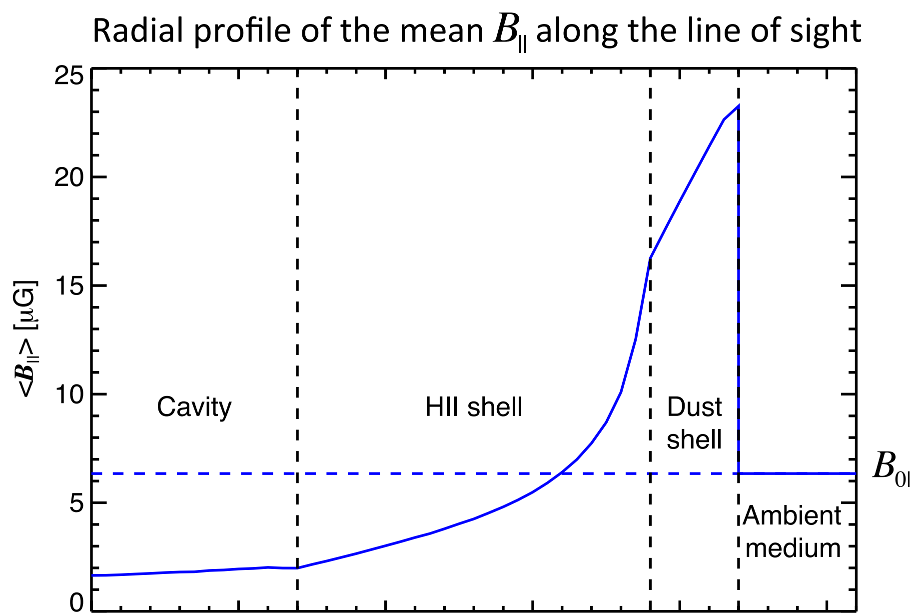
Model: reproducing the observables

Rotation measures:

$$RM = 0.81 \int_0^S \left(\frac{n_e}{cm^{-3}}\right)\left(\frac{B_{II}}{\mu G}\right)\left(\frac{ds}{pc}\right) rad.m^{-2}$$

We use our model for $\vec{B}$ and assume uniform n_e





The exact shape of the curve is determined by the adopted **expansion law**.

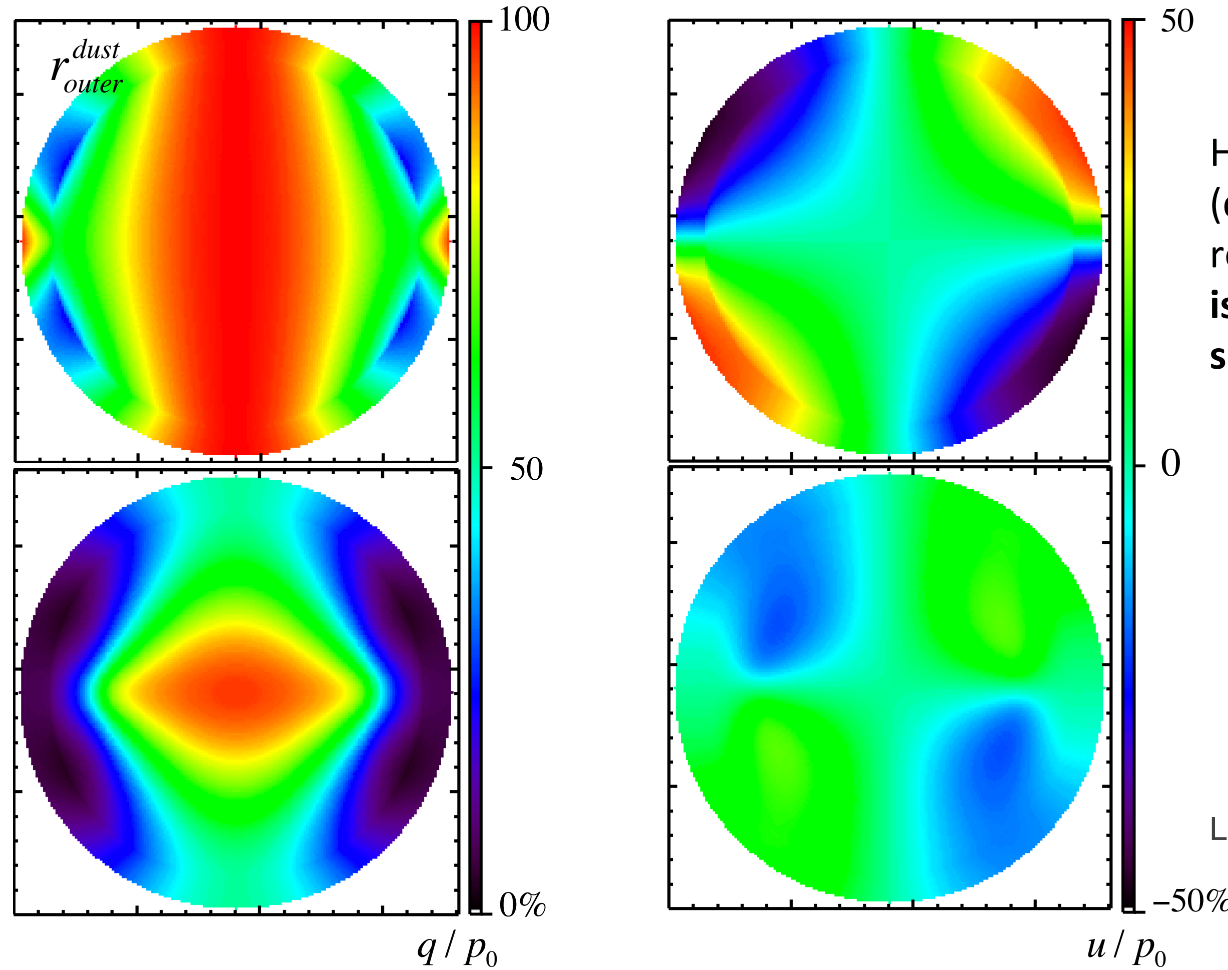
Model: reproducing the observables

Stokes parameters of dust polarized emission (*I*, *Q*, *U*):
We assume a uniform medium (n and T) and constant intrinsic dust polarization fraction p_0

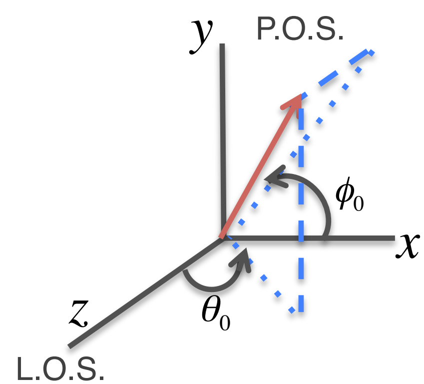
$$q = Q/I = p_0 \sin^2\theta \cos(2\phi) \qquad u = U/I = p_0 \sin^2\theta \sin(2\phi)$$

$\theta_0 = 90^\circ$
$\phi_0 = 0^\circ$

$\theta_0 = 45^\circ$
$\phi_0 = 0^\circ$



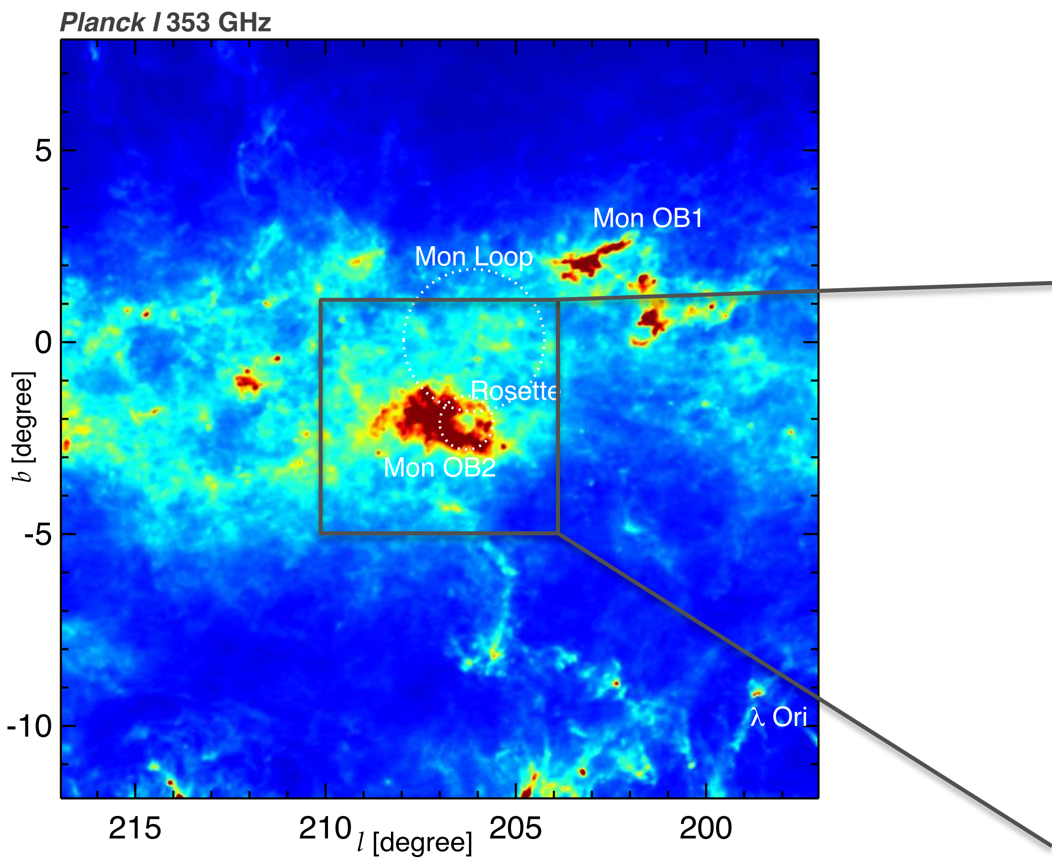
Higher depolarization (decrease of q and u relative to p_0) when $\vec{B}_0$ **is closer to the line of sight** ($\theta_0 \rightarrow 0°$).

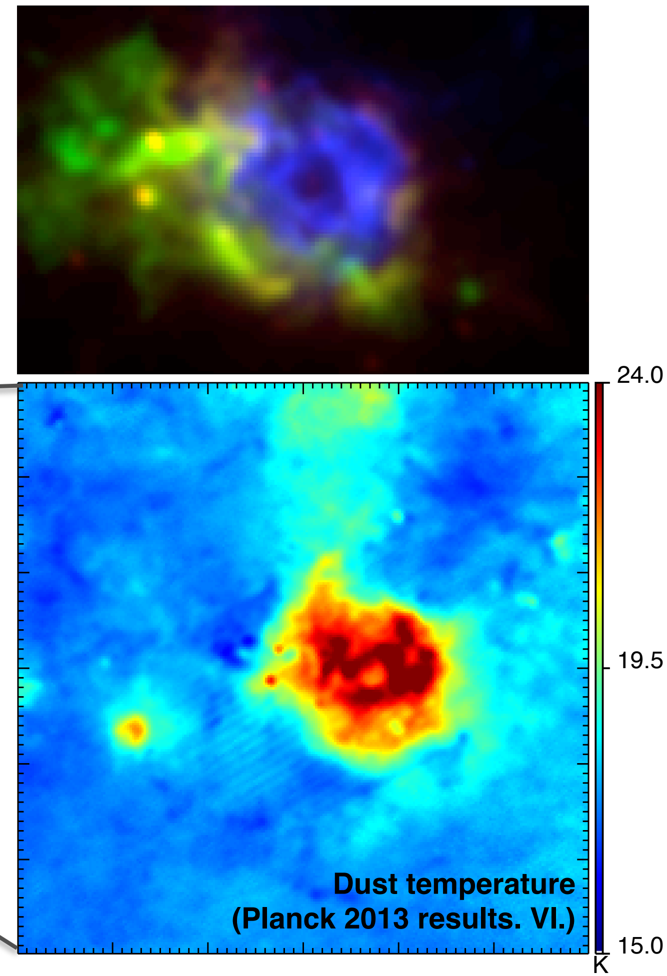


Case study: Rosette Nebula

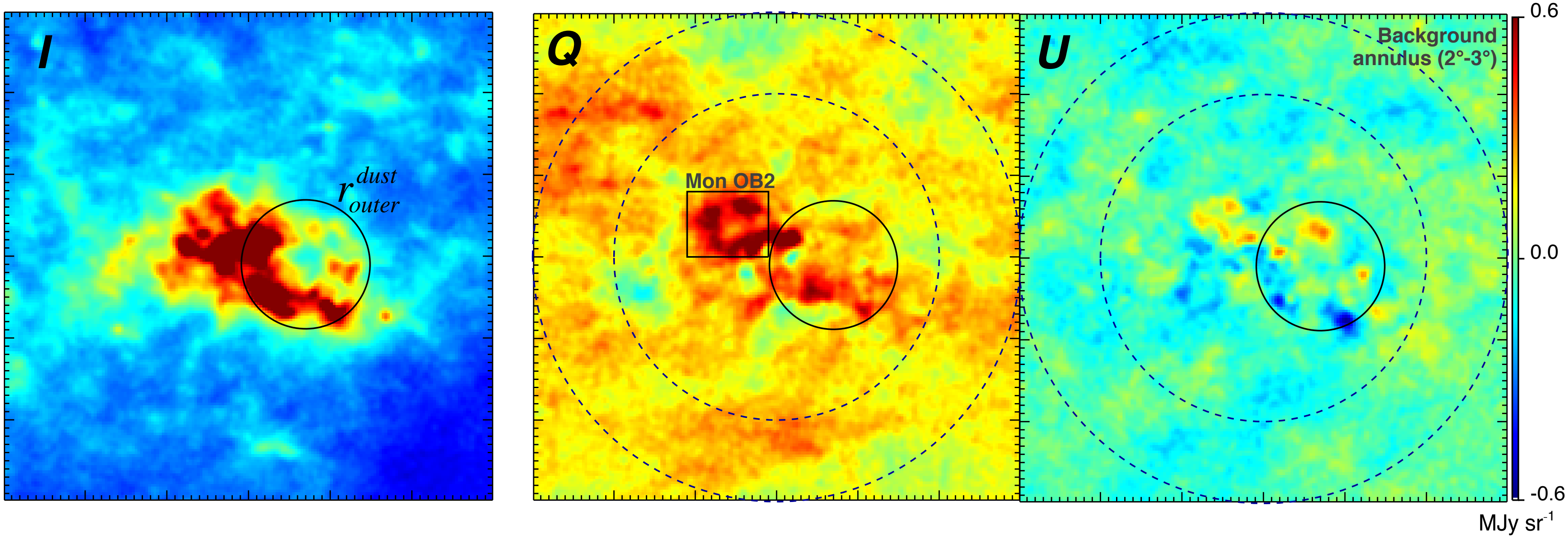
Rosette HII region is powered by the OB cluster NGC2244, formed in the Mon OB2 cloud at $d = 1.6 kpc$

- The HII region is close to a spherical shell with $r_{inner}^{HII} = 7 pc$, $r_{outer}^{HII} = 19 pc$ and $M_{HII} = 1.2 \times 10^4 M_{Sun}$
- The dust shell is seen in the *Planck* map with $r_{outer}^{dust} = 22 pc$ and has $M_{dust} = 8.6 \times 10^4 M_{Sun}$ (Heyer et al. 2006)
- Mass conservation + present radii → initial radii





Observations: *Planck* Stokes parameters at 353 GHz



We use the **average Stokes parameters**, which characterize the mean $\vec{B}$ in the swept-up shell

The average polarization fraction of the parent molecular cloud Mon OB2 is

$$p = \frac{\sqrt{Q^2 + U^2}}{I} = (4 \pm 1)\%$$

Model vs. observations: *Planck* Stokes parameters

Model parameters: $B_0, \theta_0, \phi_0, p_0$

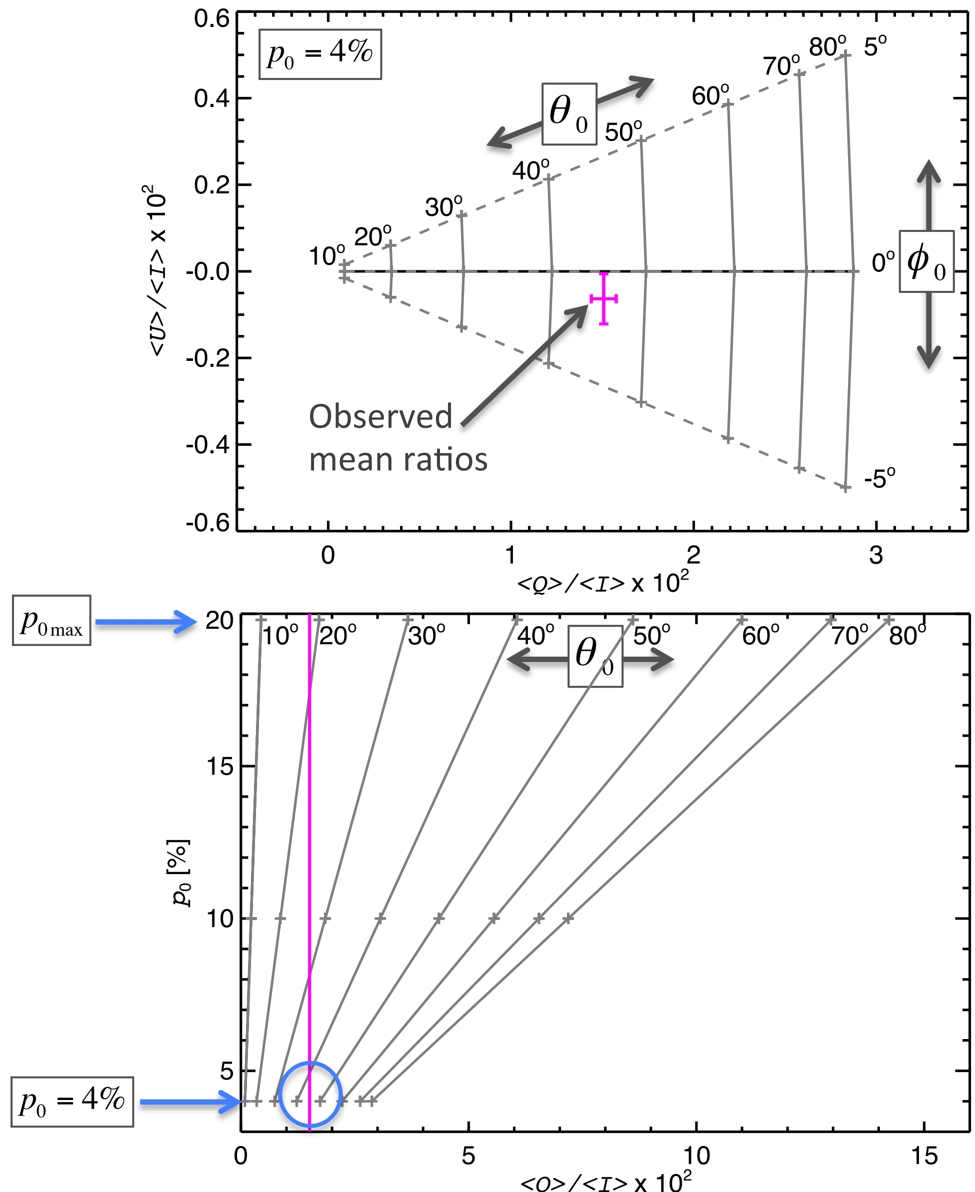
For constant n, T, and p_0

- The Stokes parameters only depend on the geometry of $\vec{B}_0$ (and not on its strength)
- $\frac{\langle U \rangle}{\langle I \rangle} \rightarrow \phi_0 \approx 0^\circ$

$\vec{B}_0$ along the Galactic plane (x axis)

- $\frac{\langle Q \rangle}{\langle I \rangle} \rightarrow \theta_0 \leq 45^\circ$

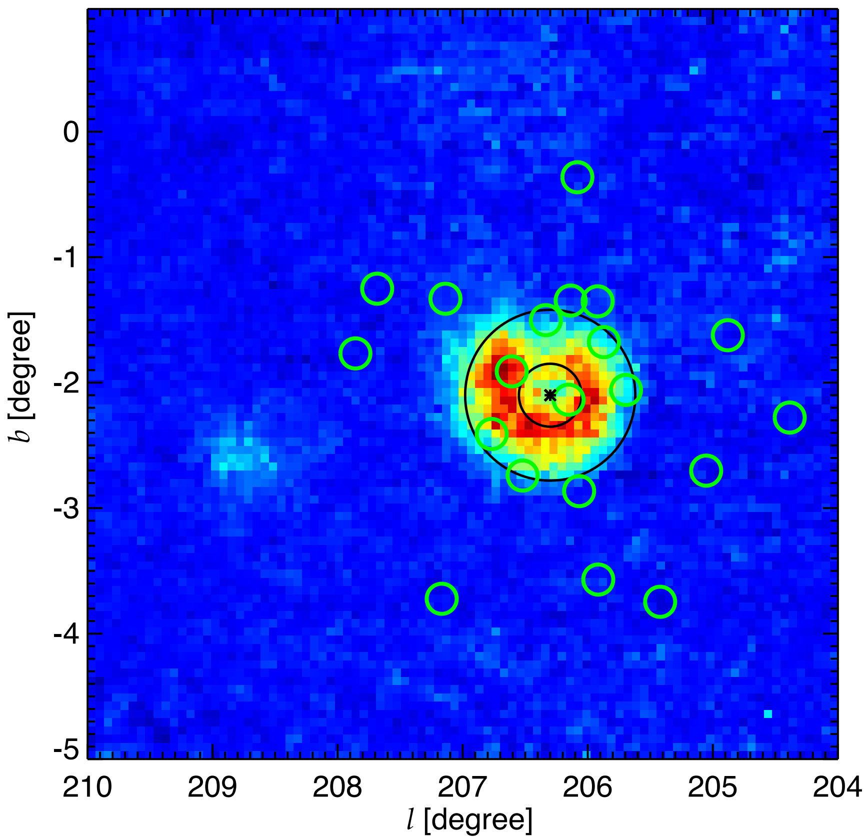
$\vec{B}_0$ at most 45° from the line of sight



Observations: rotation measures

RM data from Savage et al. (2013):
Observed with the VLA, 4.1 – 7.6 GHz
6 measurements towards the Rosette HII region and 14 outside ($r > r_{outer}^{HII} = 19\,pc$)

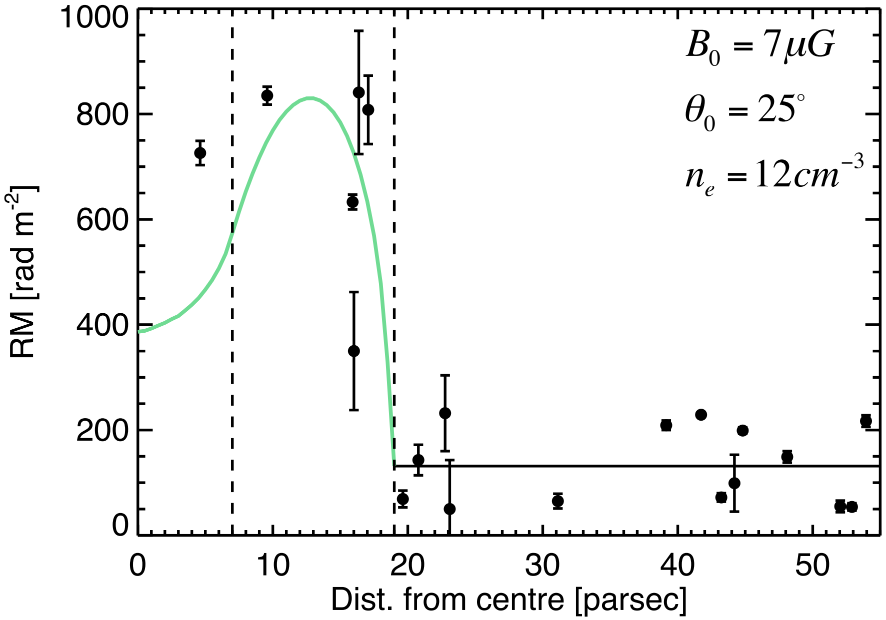
RM positions overlaid on thermal emission at 1.4 GHz (Alves et al. 2014)



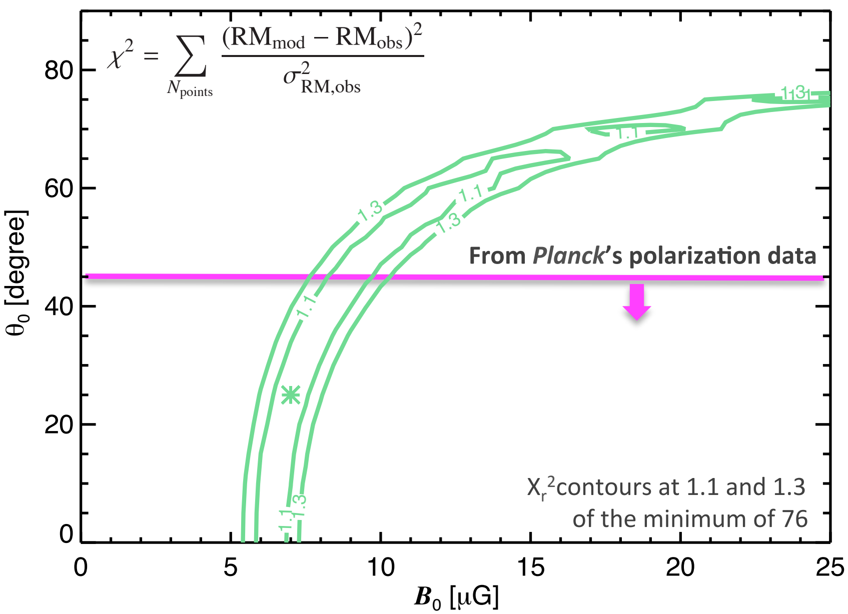
Model vs. observations: rotation measures

Model parameters: $B_0, \theta_0, \phi_0, p_0$

Radial profile of the modelled RM map



χ^2 contours of the RM fit as a function of B_0 and θ_0



RM scatter: non-uniform medium, fluctuations in the magnetic field direction, departures from spherical expansion

$RM \propto B_{\parallel} = B\cos(\theta)$

Degeneracy between B_0 and θ_0

For $\theta_0 = 45°$, $B_0 = 9\mu G$ in the Mon OB2 cloud

LOFAR will…

★ Provide more RMs + statistical study of massive SFRs

Better constraints on the magnetic field strength:

→ understand the role of the field in the evolution of molecular clouds and HII regions/SNRs

→ relate structure and strength of $\vec{B}$ to star formation efficiencies

★ Probe $\vec{B}$ in the low density ionized medium

→ Link between the magnetic field in the massive SFRs – responsible for the turbulent energy injection in the ISM – and the large scale field

★ More ideas are welcome!

Summary

- ★ LOFAR will significantly improve the studies of massive SFRs and our understanding of the role of magnetic fields in their evolution, and the impact on their surroundings
- ★ The analytical model developed in this work (`Planck Collaboration Int. XXXIV 2015`) describes the magnetic field in a spherical bubble-shell structure
- ★ The model reproduces the mean polarization properties and the radio rotation measures observed towards the Rosette massive SFR
- ★ The model can be directly applied to other objects to constrain the structure and strength of the magnetic field in the ionized region, neutral shell and ambient medium

Image credits: ESA/Planck Collaboration. Acknowledgements: M.-A. Miville-Deschênes

This workshop will cover both **observational aspects** (recent advances with LOFAR and *Planck*, status of upcoming instruments) and **theoretical aspects** (numerical simulations, galactic dynamo, X-shape magnetic fields...).

It will stimulate **exchange between the sub-mm and radio communities**.

http://userpages.irap.omp.eu/~malves/PCMI_Workshop/Home.html