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Synchrotron Emission from Supernova Remnants

In
"Forging giants: massive stars and their disks"
A celebration of Riccardo Cesaroni's career

When I first met Riccardo ?

Thanks to Franco Pacini

@ European Southern Observatory ?

198?

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Radio synchrotron emission from Crab-like Supernova Remnants "Plerions"

So impressed that…

Radio synchrotron emission from Crab-like Supernova Remnants "Plerions"

So impressed that…

he turned to Masers !

(1)

From synchrotron…
… to cycl…

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… to cycl…

Riccardo's advice helped me in several occasions

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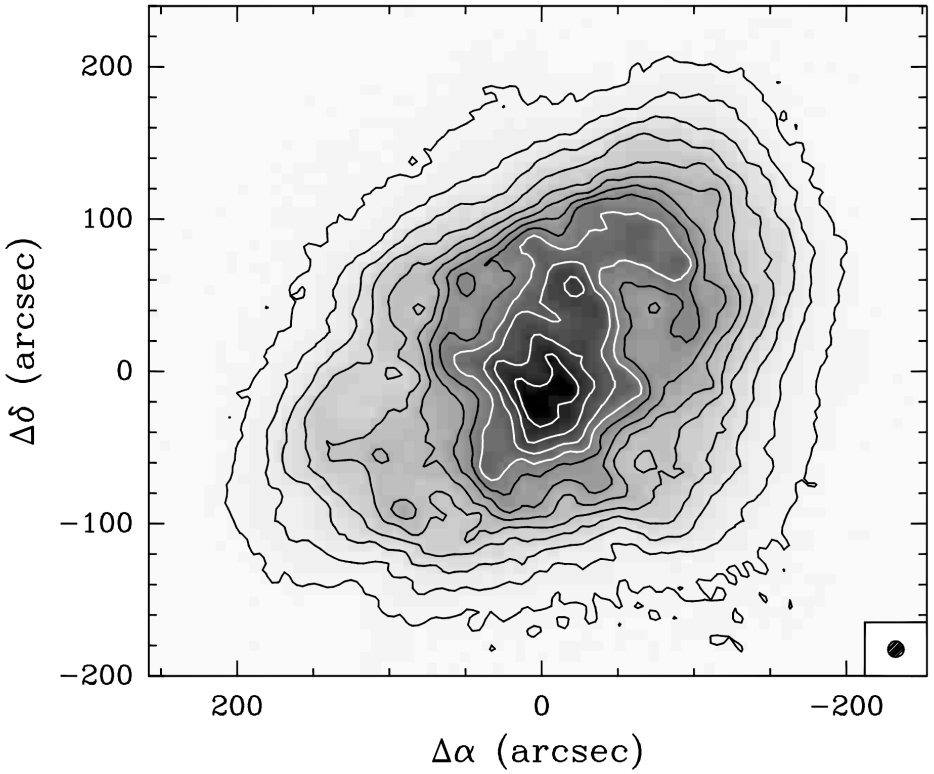
(2)

Millimetric emission from the Crab Nebula and some other Pulsar Wind Nebulae

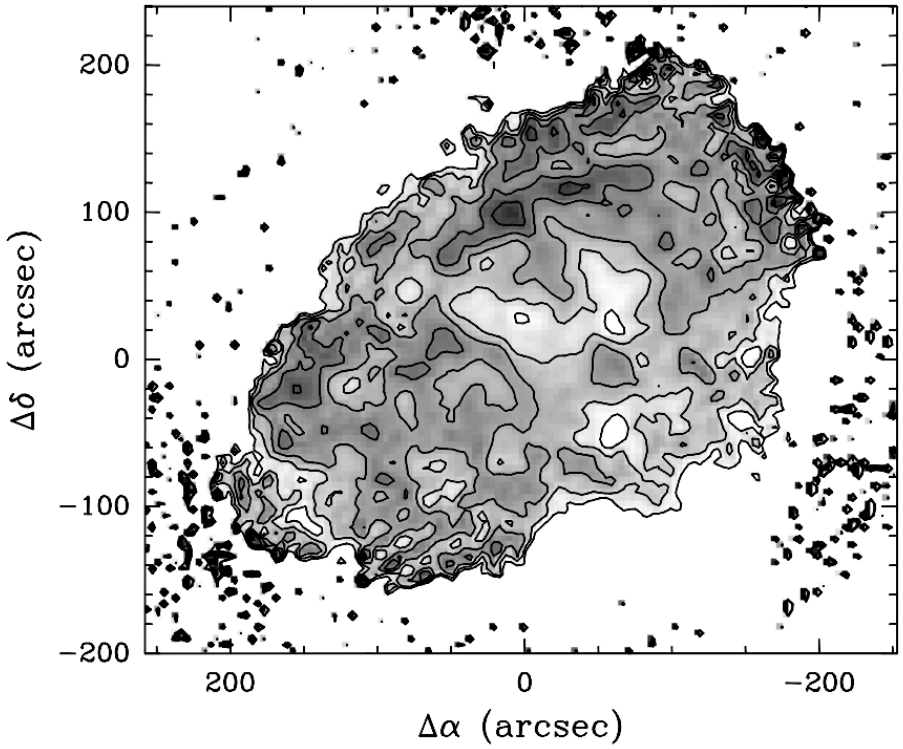
R. Bandiera, R. Neri, R. Cesaroni

Opening a new window on the Crab

- Mapping the Crab at 230 GHz - with MAMBO @ IRAM 30-m
- 10.5” spatial resolution (RB, Neri, Cesaroni 2002)



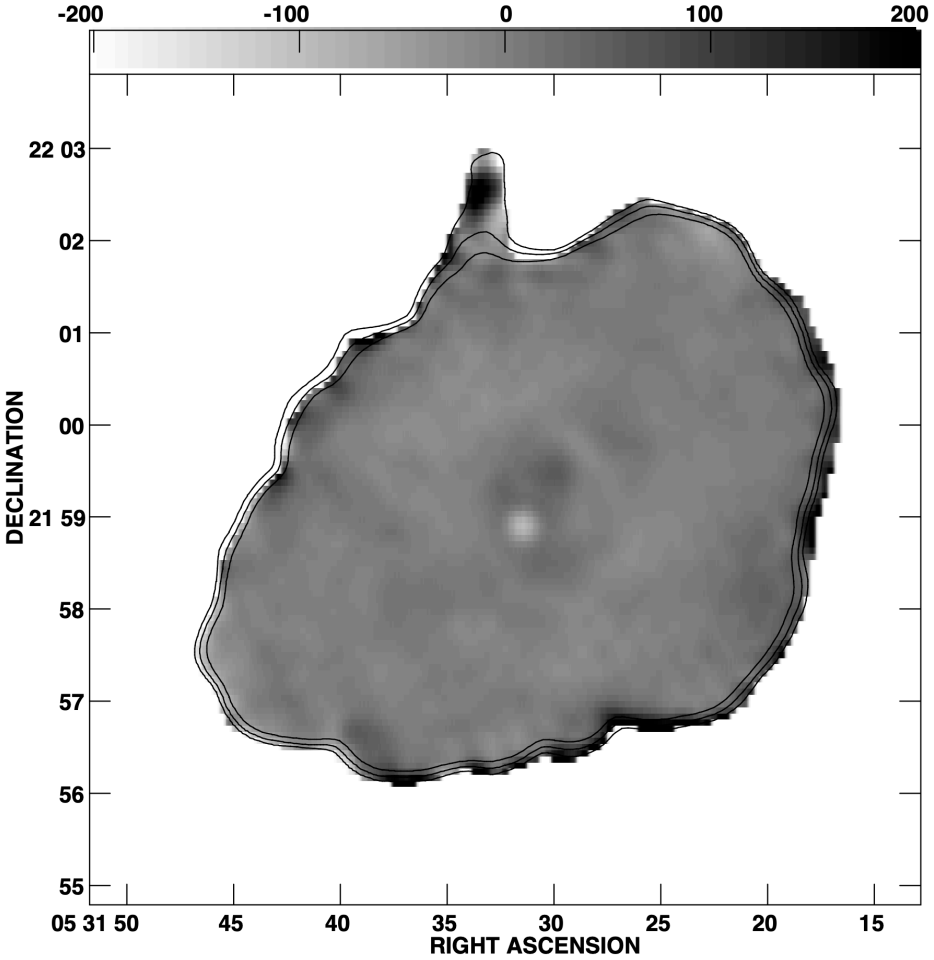
- Comparison with 20 cm VLA map (dated 1985-1986)
  Equalisation of the PSFs
  Correction for secular evolution (+1.9% in size, -2.3% in flux)
- Map of the 20 cm-1.3 mm spectral index;



Flatter in central regions

Contours from -0.28 to -0.20
in steps of 0.02

Why so relevant ?

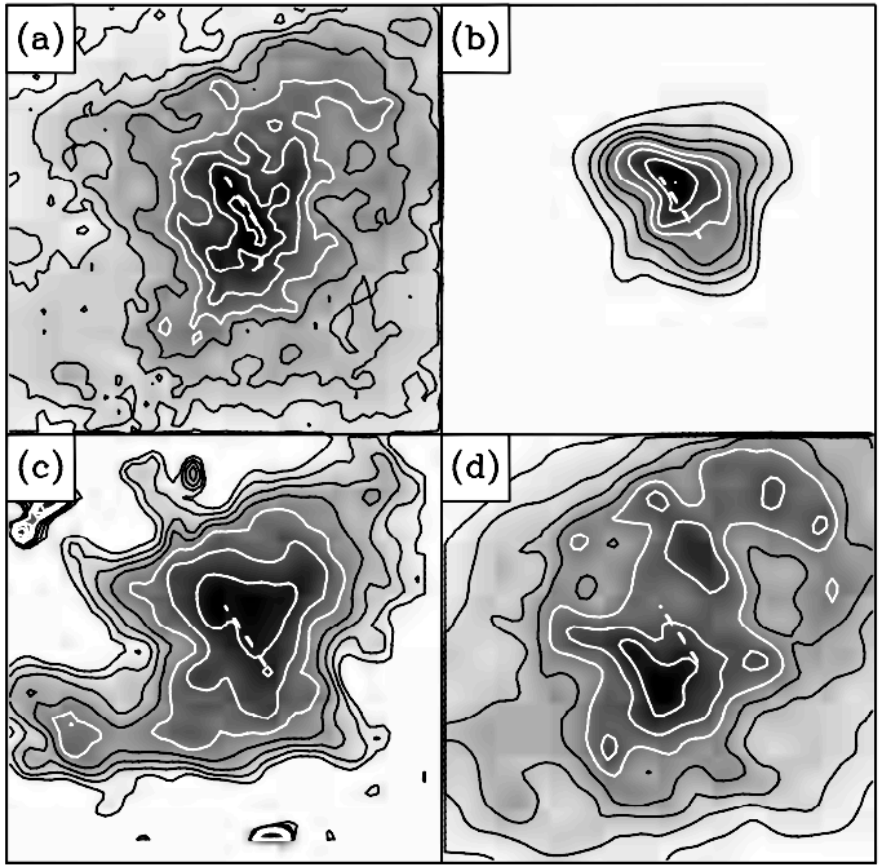


In the radio (327 MHz-1.5 GHz)
the map is boringly flat

(Bietenholz et al. 1997)

- Concave spectrum: no break
but emerging extra component ?

The mm second component

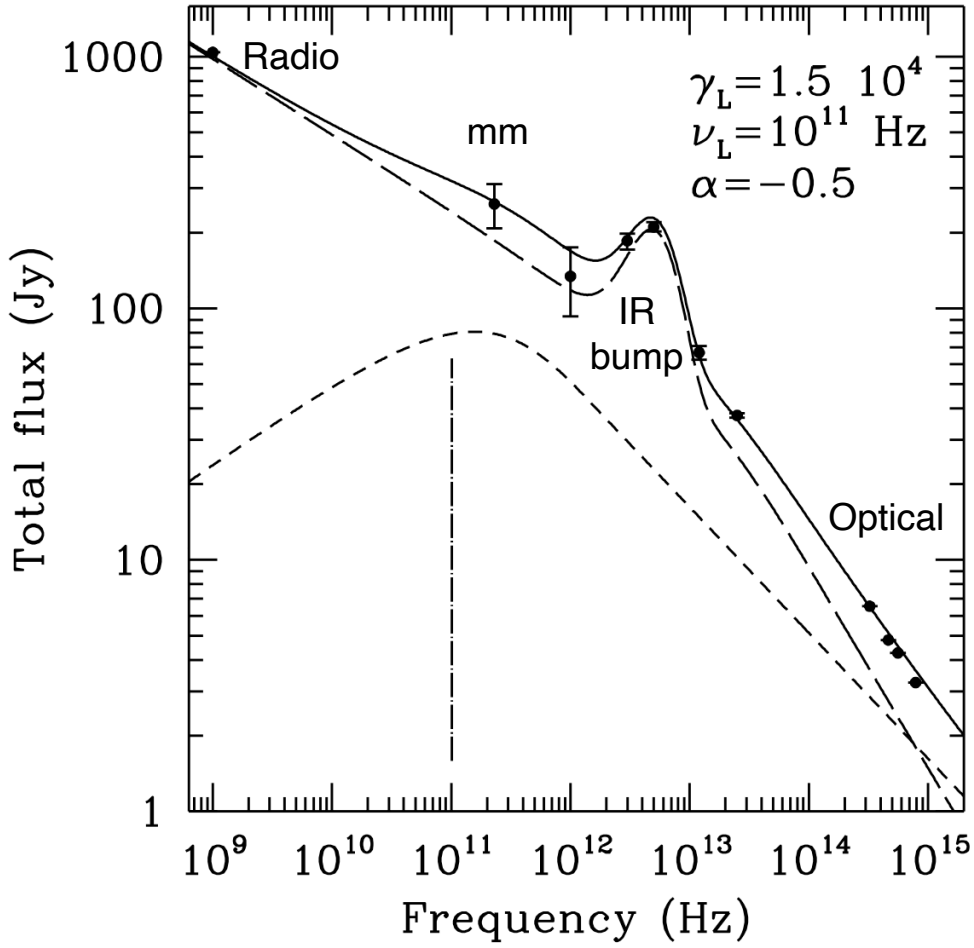


X-rays

Optical

The radio component

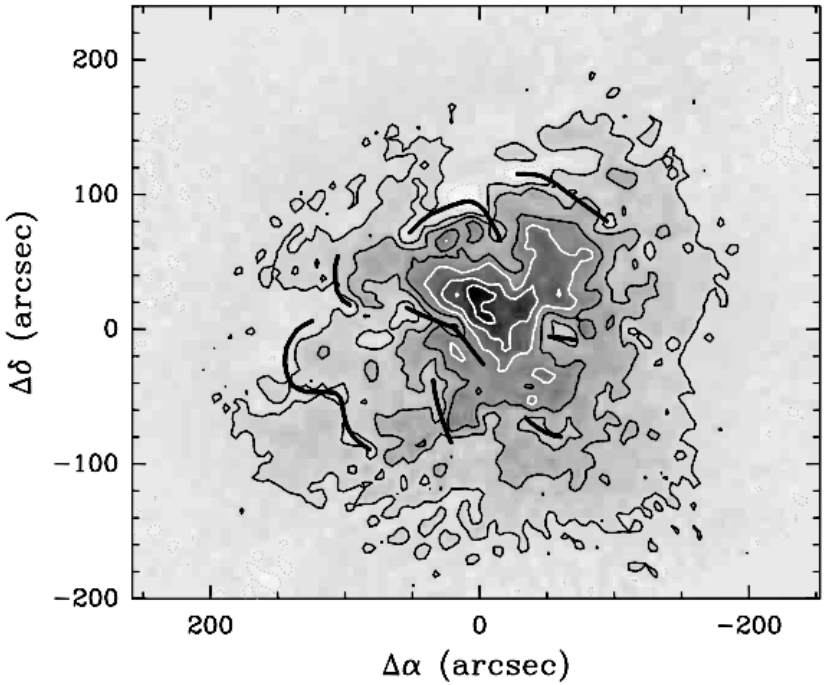
- A possible spectral interpretation



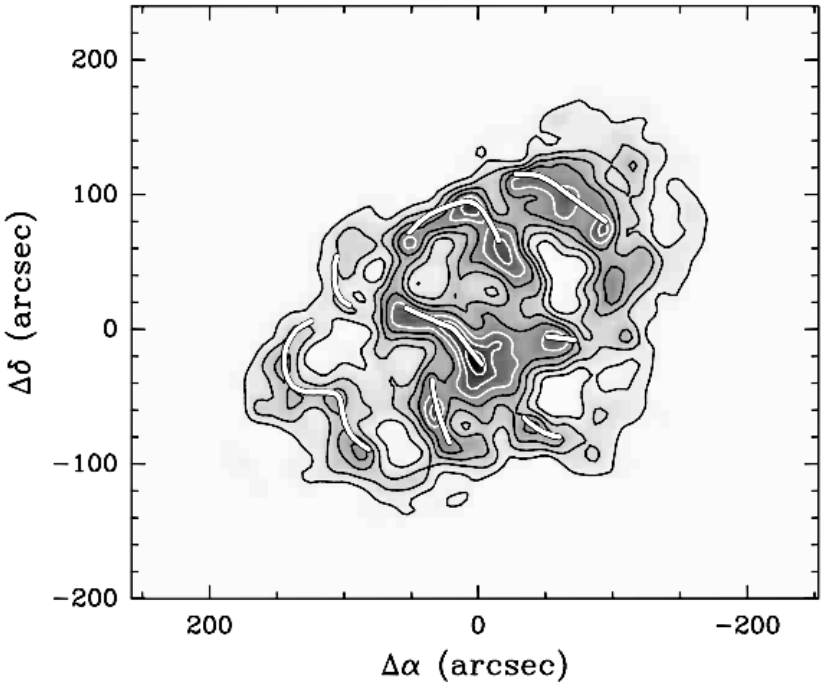
Minor effect on the integrated flux

Imaging is essential

- Opposite trend: sign of breaks corresponding to major filaments



Lower mm flux



Radio filaments

Lower-frequency breaks → Magnetic field & particle trapping

What happened next

- Not many citations, but until present day

Criticisms & Confirmations

- Central flattening confirmed, but attributed to time variability

(Green et al. 1984 - SCUBA at 850 μm - 17” resolution)

- BUT same flattening after years

(Arendt et al. 2011 - IRAM-GISMO at 2 mm - 16.7” resolution)

- Based on global energy distribution, no compelling evidence

(Macias-Perez et al. 2010)

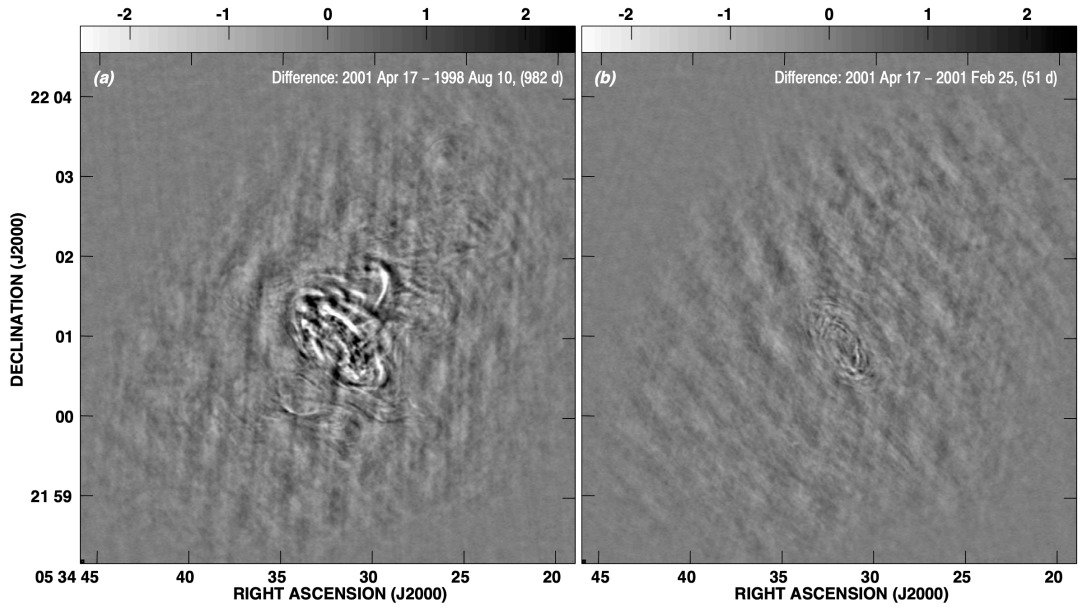
- Deeper study - reality of the mm excess

(various origins discussed: synchrotron vs free-free vs spinning grains vs magnetic grains)

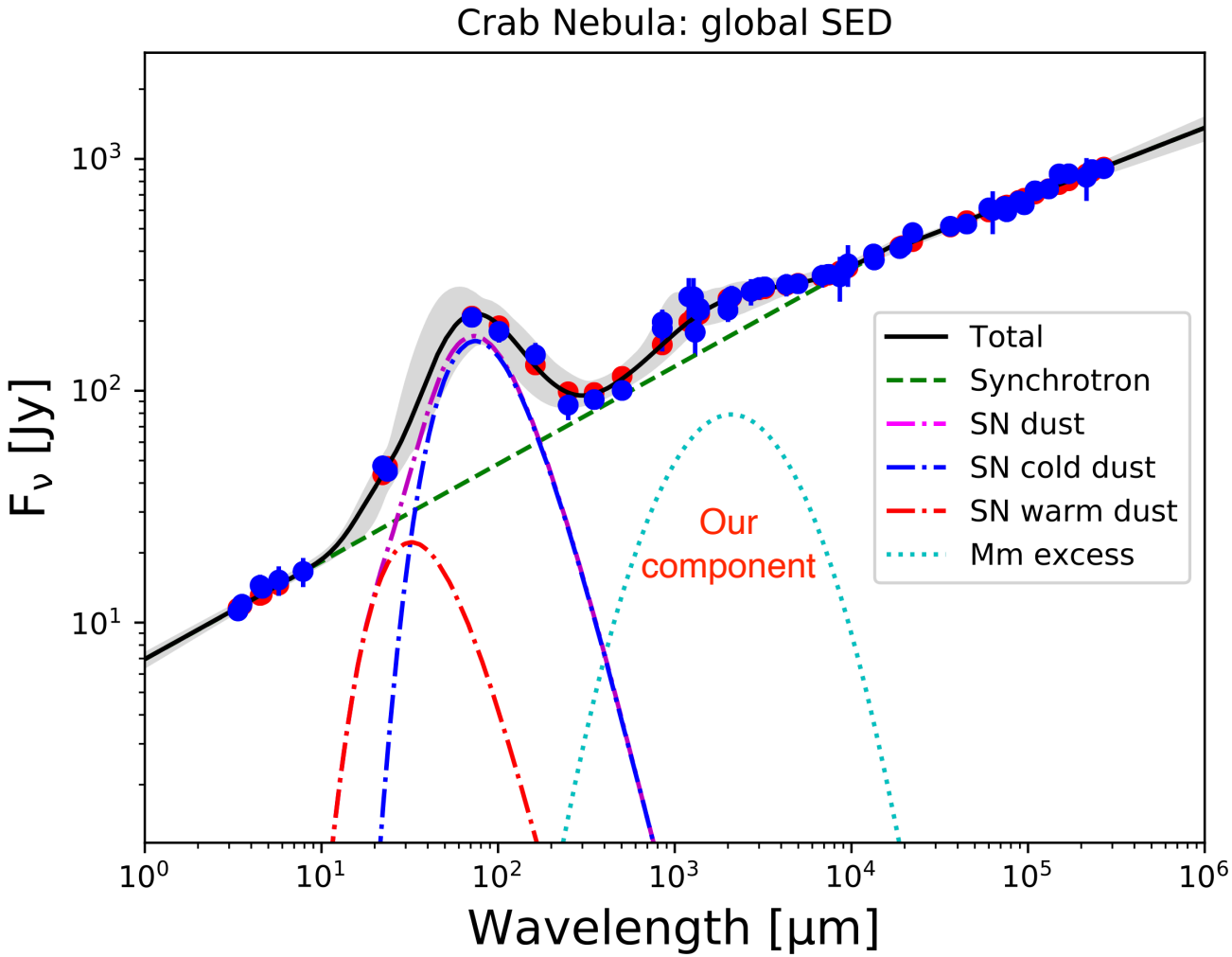
(De Looze et al. 2019)

The Crab nebula wisps

- Rapidly variable features, close to the center (In optical - Scargle 1969)
  moving at transrelativistic velocities
- Seen also in radio (Bietenholz et al. 2004)



- Wavy structure, both in space and in time



(De Looze et al. 2019)

Theoretical explanations

Original model (Kennel & Coroniti 1984)

ultra-relativistic wind - termination shock - emission in the downstream

OK for optical and X-rays BUT it fails to explain radio emission

Still unsolved, after 42 years !!

"multiplicity problem" (e.g. Olmi et al. 2014)

Bottleneck → number of low-energy emitting particles

Pulsar magnetosphere - cascading problem - pair production

but (for Crab) X-rays require $\kappa \sim 10^4$ while radio $\kappa \sim 10^6$

Either:

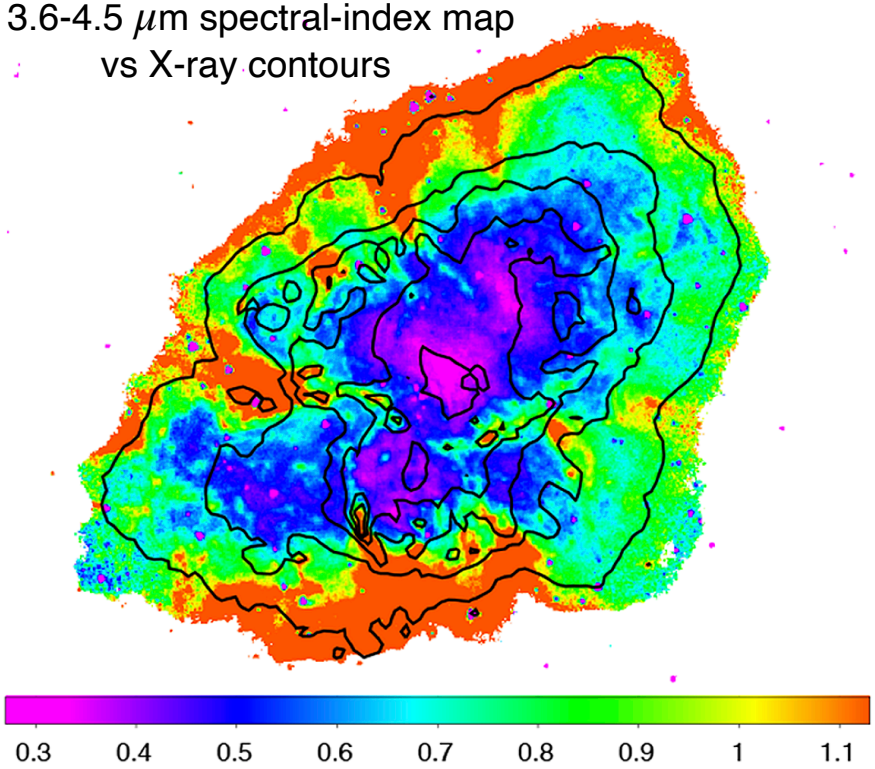
- Huge primordial outburst of particles

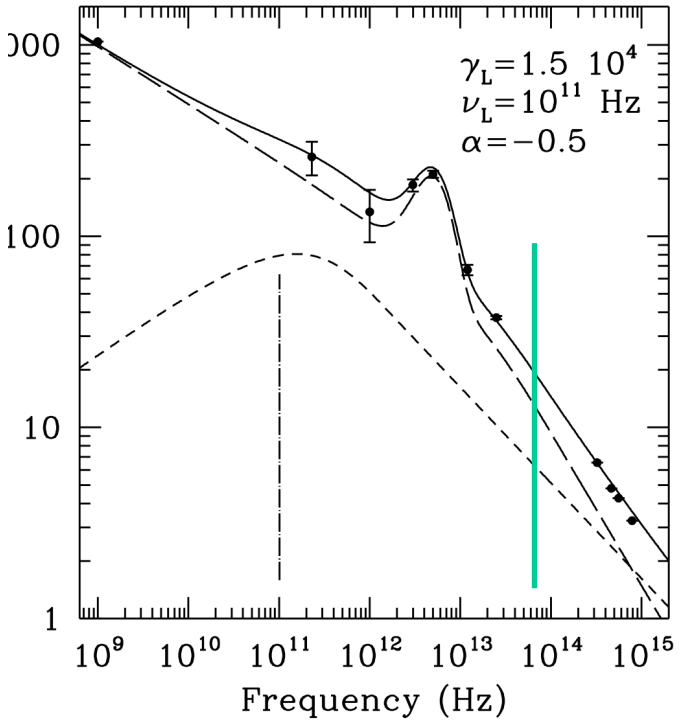
Or:

- Different origin for radio-emitting particles

- Other acceleration mechanism for radio emission (Lyutikov et al. 2019)
magnetic dissipation - reconnection - magnetised turbulence
in the bulk of the nebula

3.6-4.5 μm spectral-index map
vs X-ray contours





What DID NOT happen next

- After 25 yr, our map still the highest resolution map in the millimetric

- Need for map with arcsec resolution (ALMA)

- Failed ALMA observation at 100 GHz (Cycles 1 and 2)

(Dubner et al. 2017)

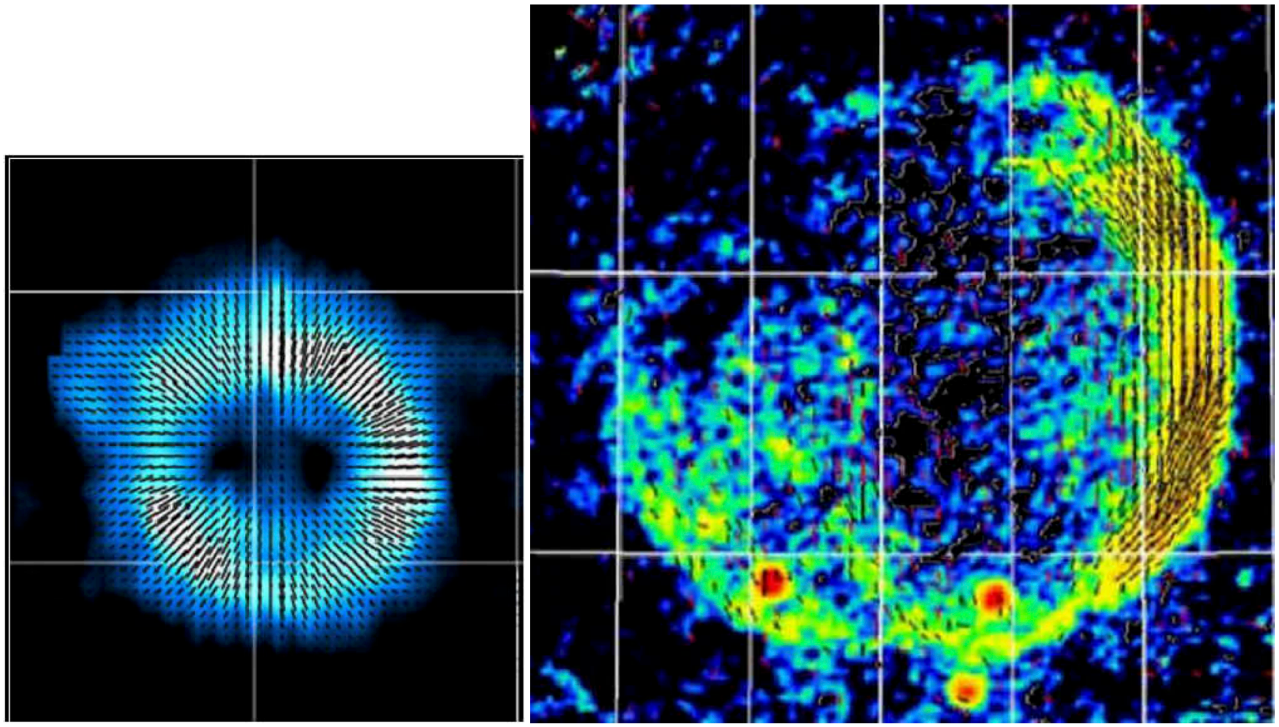
Something to complete, before my (actual) retirement

- New ALMA proposal 🤞 (Castelletti et al.)
  - Arcsec resolution maps & in-band spectral index maps
  - Better morphological comparison with optical & X-ray synchrotron
  - Study of synchrotron break in individual filaments


"UPROARIOUS"
DAILY TELEGRAPH
"LUNATIC"
DAILY MIRROR
"Very funny"
OBSERVER
"ANARCHIC"
SUNDAY TELEGRAPH
MONTY PYTHON'S
AND NOW FOR SOMETHING COMPLETELY DIFFERENT
Stupendous! Spectacular! Incomparable! Unimaginable!
ON THE GIANT CINEMA SCREEN AT THE ALL-ELECTRIC TALKING PICTURE PALACE

Magnetic fields in young Supernova Remnants

(Milne 1976; Atlas of supernova remnant magnetic fields)

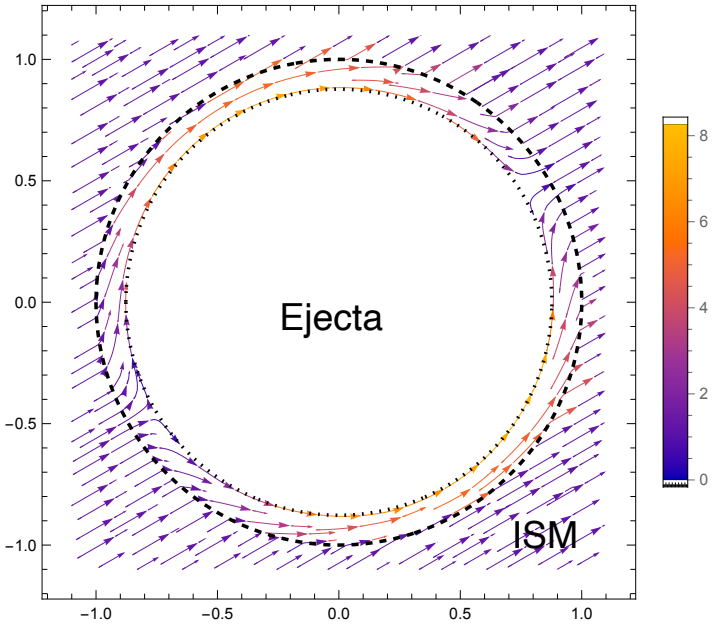


Cas A

CTB1

(from Dubner & Giacani 2015)

The “easy” model for B in Supernova Remnants

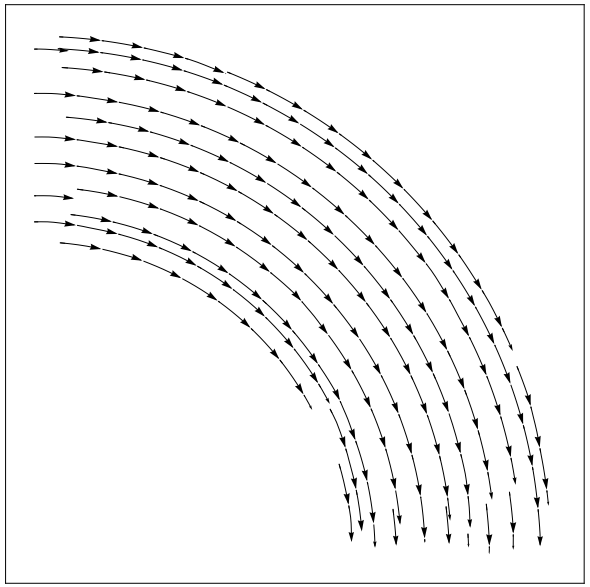


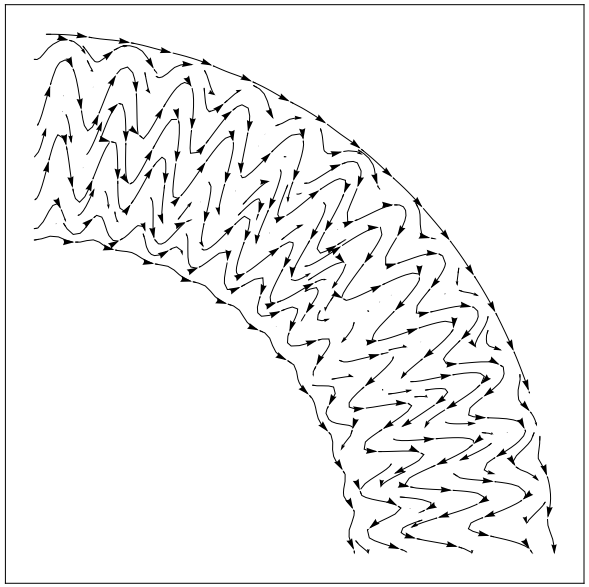
Magnetic field compression // Perpendicular B in higher-B regions.

HOWEVER

Inefficient particle acceleration

The “not-so-easy” model for young Supernova Remnants





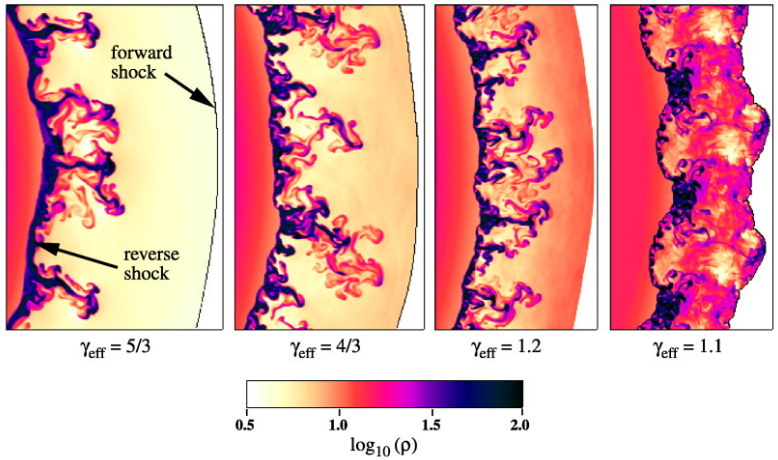
Composition with ”random” radial B.

HOWEVER

Diffusive particle acceleration efficient ONLY if reaches the forward shock

Also, X-ray polarization (IXPE) very close to the forward shock

Rayleigh-Taylor instability at the contact discontinuity?



(Blondin & Ellison 2001)

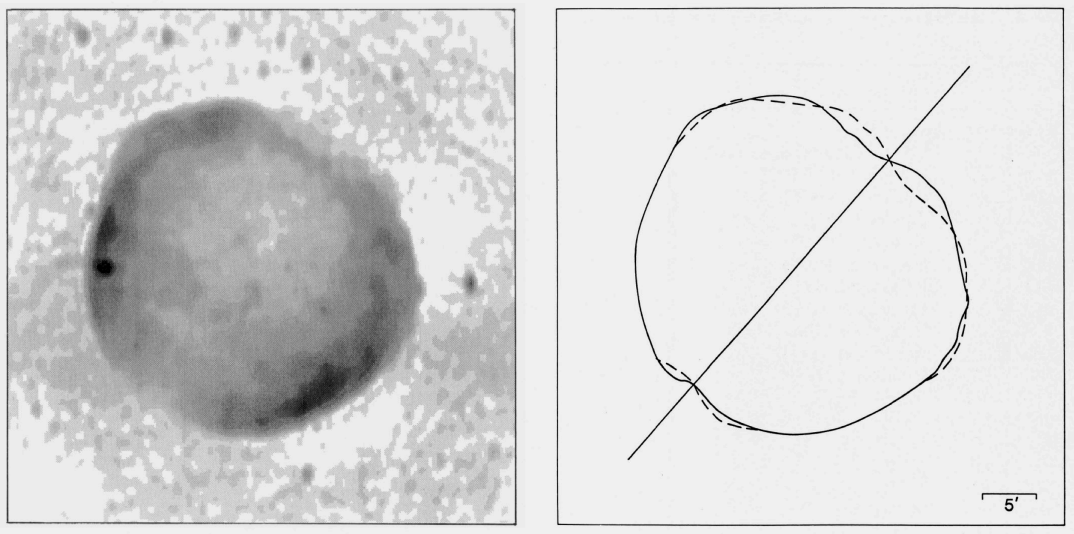
Clumpy ambient medium ?

Shrapnels? Imprint of the Supernova explosion?

The case of SN 1006

A supernova remnant with severe disorientation problems

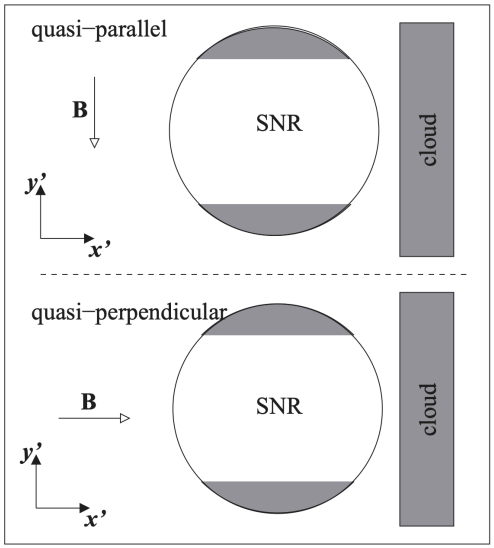
(young SNR → Polarization: mainly radial field)
Originally taken as excellent example of barrel-shaped SNR



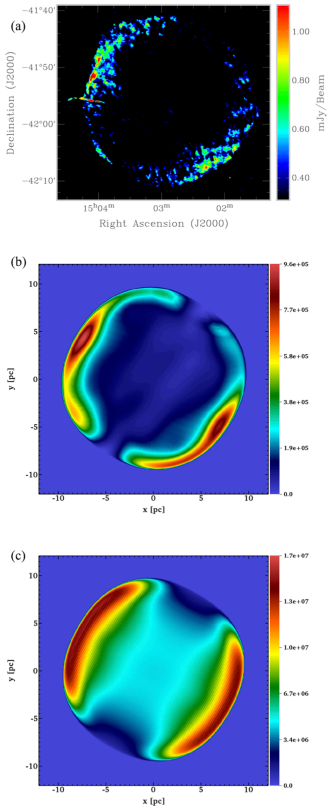
(Kesteven & Caswell 1987)

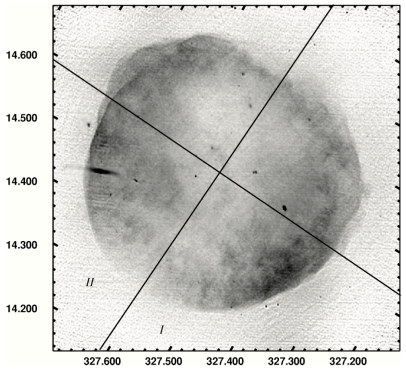
BUT in a 3-D barrel-like structure, the surface brightness of the inner region should be higher than actually measured
THEN the real 3-D structure should be polar-caps !

(Rothenflug et al. 2004)



(Schneiter et al. 2015)





(Petruk et al. 2009)

AFTERWARDS

Bocchino et al. 2011 : tilted polar caps

Petruk et al. 2011: barrel-like + non-uniform ISM magnetic field

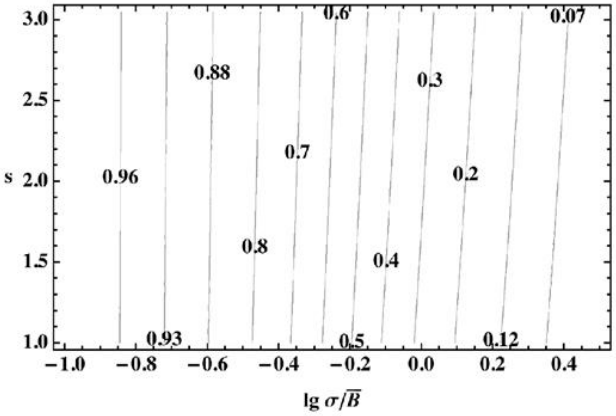
Underlying assumption:
synchrotron emission is here assumed
to be ISOTROPIC

Conclusions correct only if the magnetic field
is ISOTROPIC
(i.e. random - i.e. zero polarization)

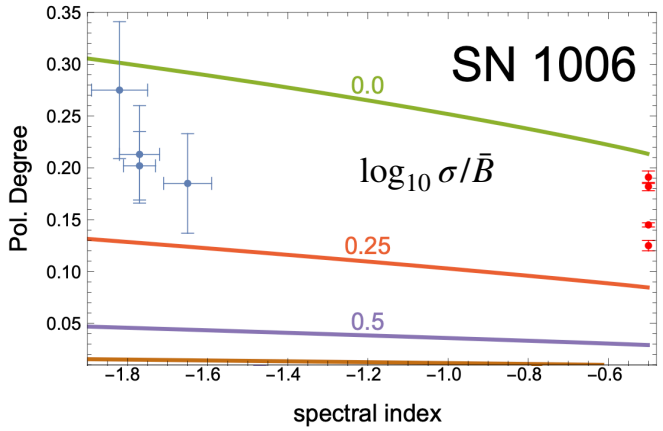
Instead, if mainly radial magnetic fields
in the inner projected regions
lower transverse field

Investigating the magnetic field

- Synchrotron emission $\propto \nu^{-\alpha} B_{\perp}^{1+\alpha}$
- Synchrotron polarization
  direction of the average $B_{\perp}$
- Synchrotron polarization degree
- Polarisation degree in radio & X-rays



(RB & Petruk 2016)
$\alpha = (s-1)/2$; σ = random field



(RB & Petruk 2024)
based on data from
Zhou et al. 2023

- But all times only information about $B_{\perp}$

Rotation Measure as a diagnostic tool

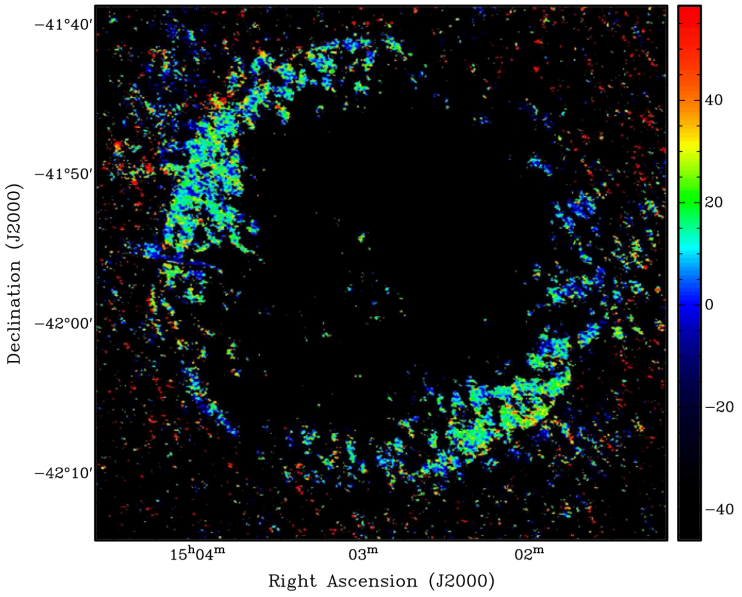
From Faraday Rotation, RM $\propto \int n_e B_{||} dz$

generally used to correct the polarization direction.

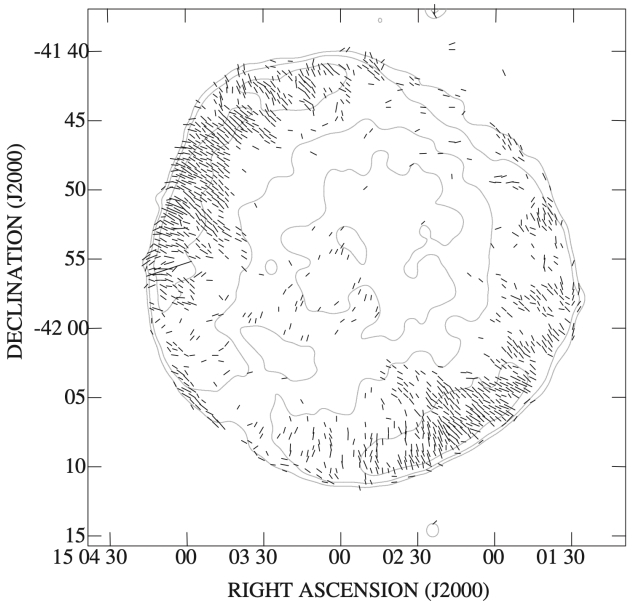
Why not to use it also as a diagnostic tool ?

If ordered B mixed with a turbulent one
RM is sensitive only to the first

VLA measurements of SN 1006



Map of the RM ($\mathrm{rad\ m^{-2}}$)



Map of the B vector

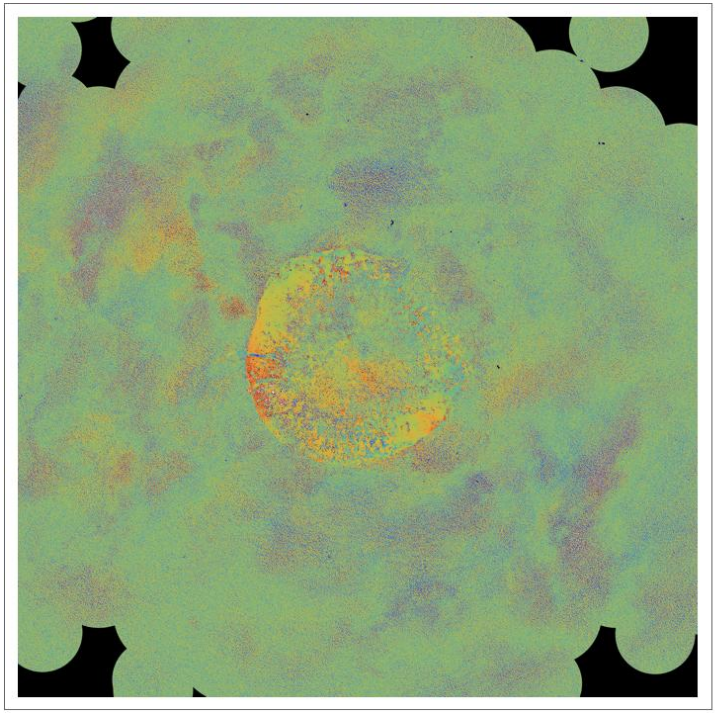
(Reynoso et al. 2013)

More recent, excellent data, from MeerKat (Cotton et al. 2024)

RB + Oleh Petruk

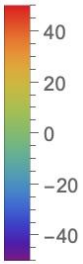
RM map

49 channels used, in the range between 14.3 and 23.4 cm

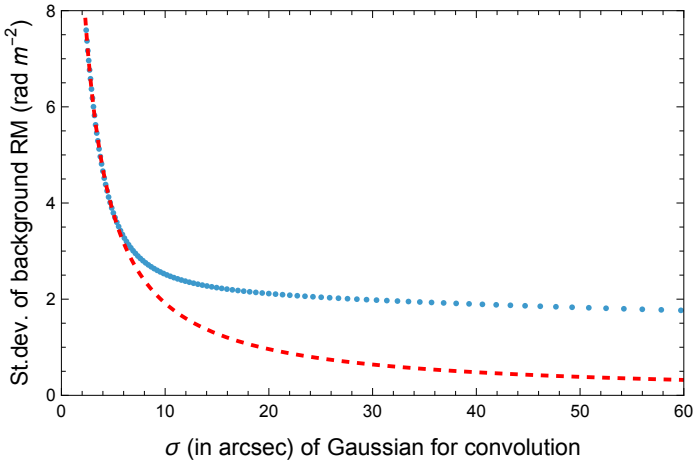


4822 x 4822 pixels = 1.6 x 1.6 degrees

Evidence of intrinsic Faraday Rotation

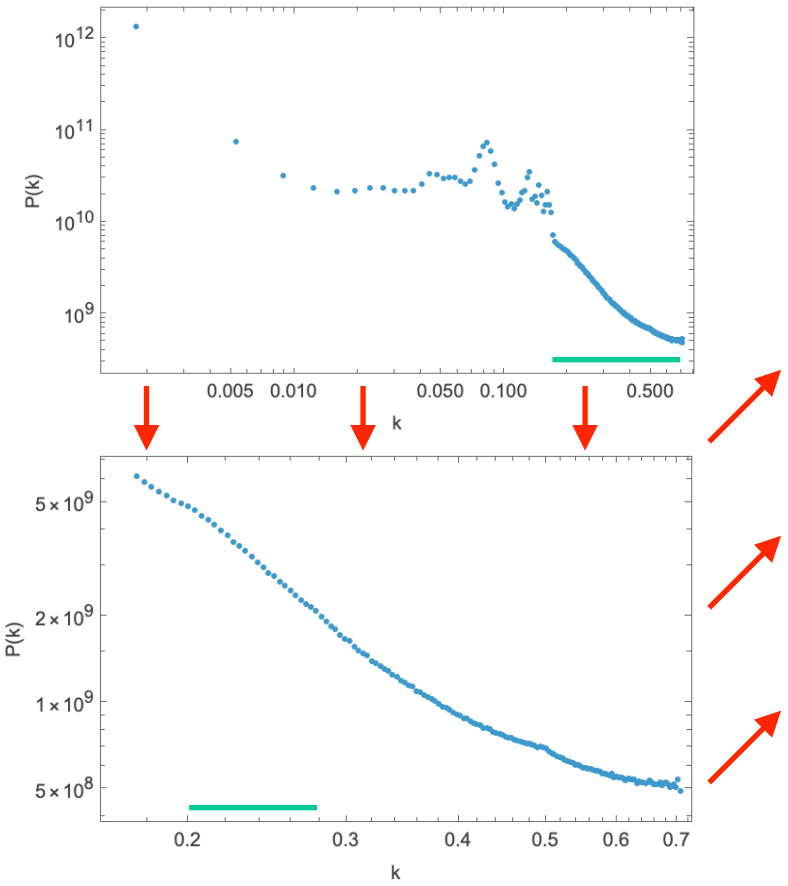


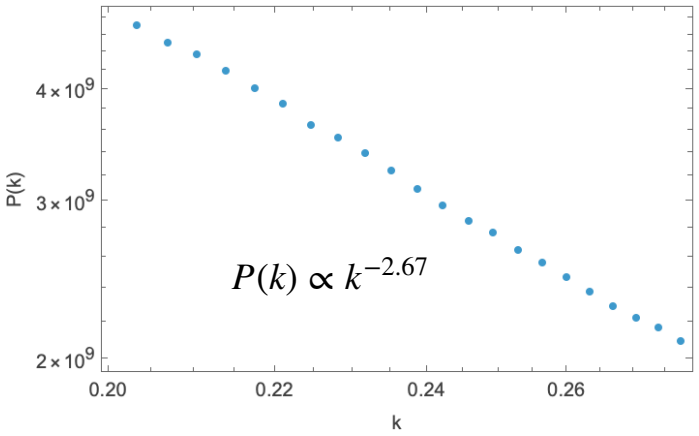
In the background - just noise ?



Background RM map

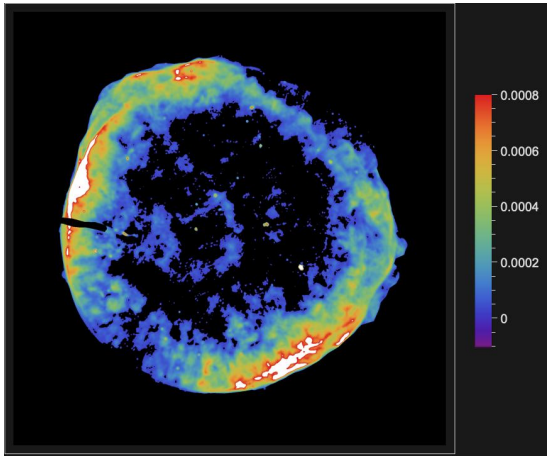
Power Spectrum





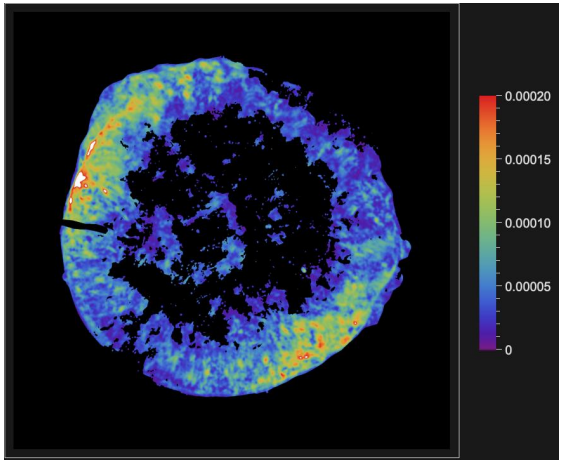
$P(k) \propto k^{-8/3}$ is what expected for Kolmogorov turbulence

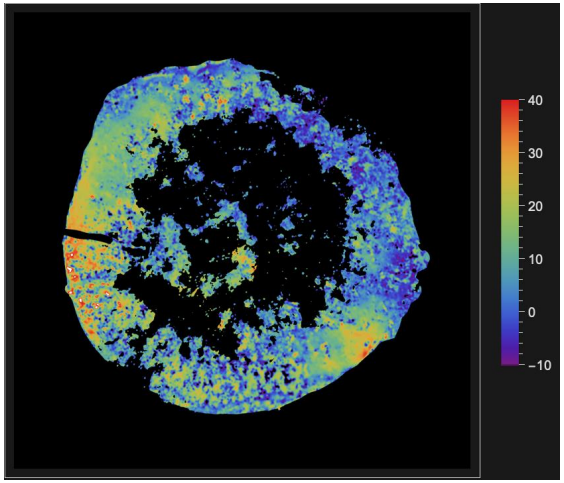
SN 1006 maps



Map I

Map P



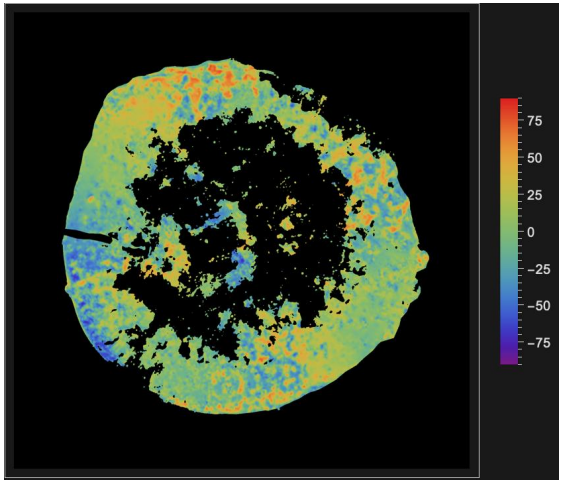


Map RM
(±2)

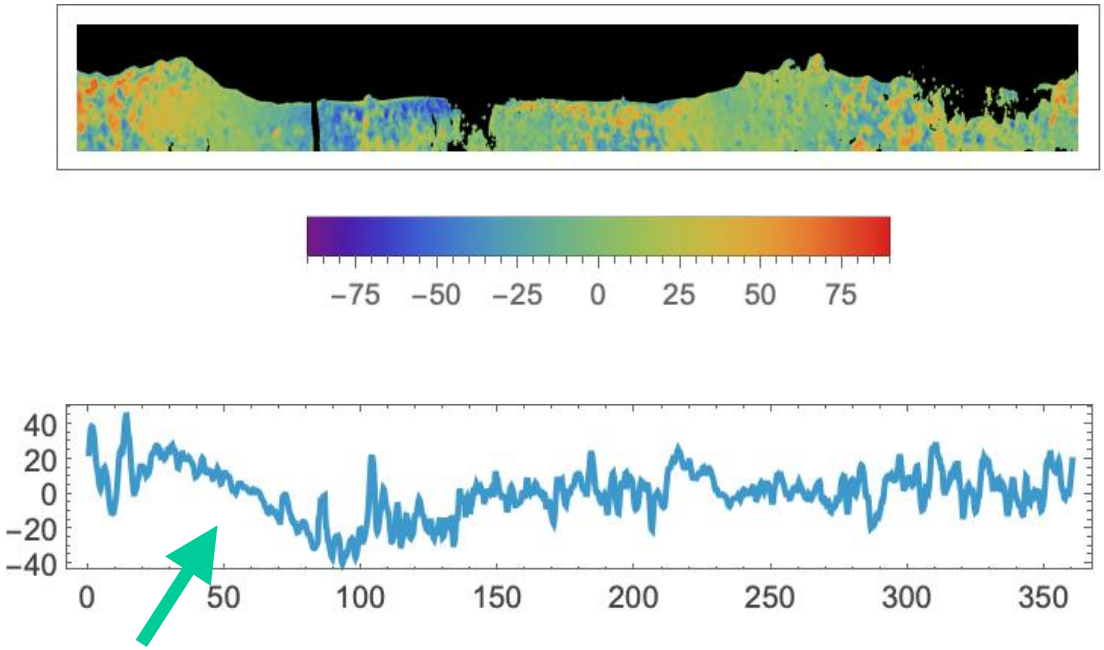
Pattern
on the
S side ?

Map $\chi - \theta$

Trend
on the
N-E side

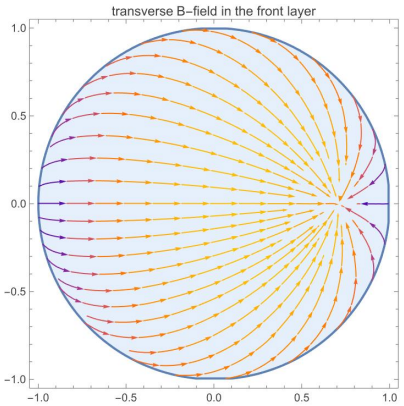


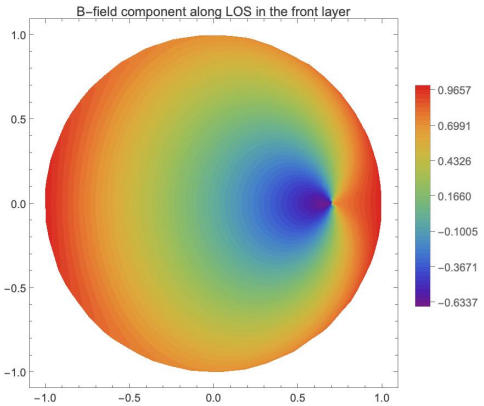
The trend along the N-E side

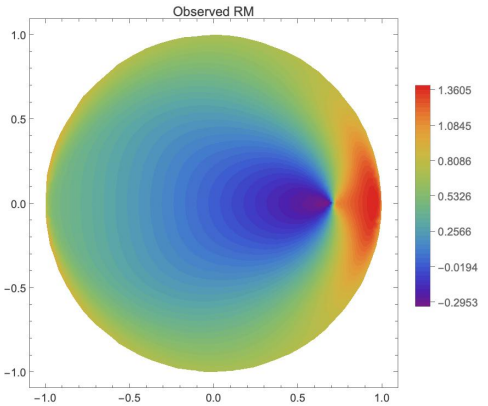


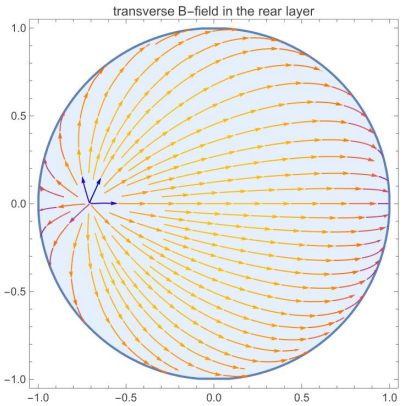
Pattern of the observed (internal) RM

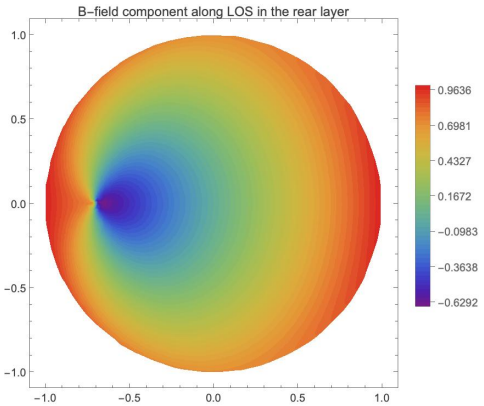
(very simple model)

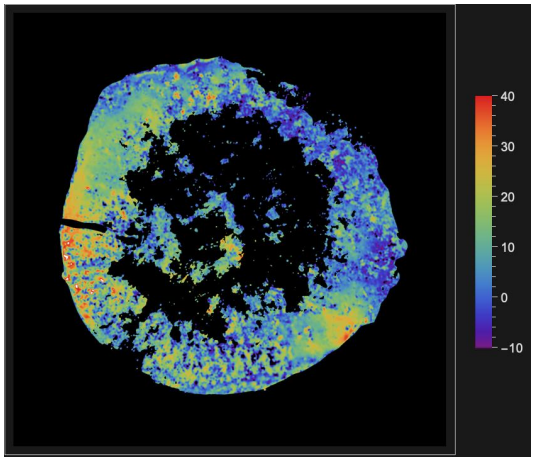












CONCLUSIONS

My approach to the first period after retirement:
trying to fix (with mixed success)
some issues I met over the years

(if you like to join, you are welcome)

OTHERWISE

Why not to share the plans
of a well-known scientist ?

Better that I devote myself to study
the other great mystery of the universe: women!

DOC, in “Back to the Future”