Particle acceleration in SN 1006

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First results from an XMM-Newton LP on SN 1006

Co-Is: G. Maurin (post-doc), M. Miceli, F. Bocchino, G. Dubner, E. Giacani, J. Ballet, S. Orlando, J. Vink, E. Helder, D. Kosenko, Acero F., Cassam Chenai G.

see also next talk by F. Bocchino

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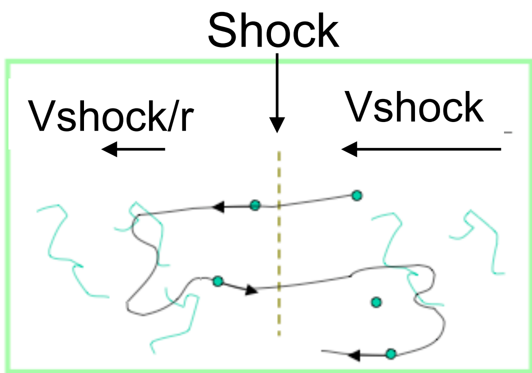
Origin of Galactic Cosmic rays

Supernova remnants: likely the birth places of Galactic CRs up to ~3 10^{15} eV

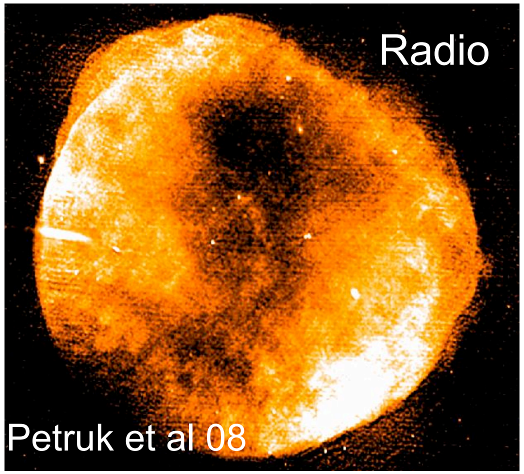
- 10% of their kinetic energy: to maintain the pool of Galactic Cosmic rays
- High mach number shocks: 1st order Fermi mechanism through diffusive shock acceleration (1949)

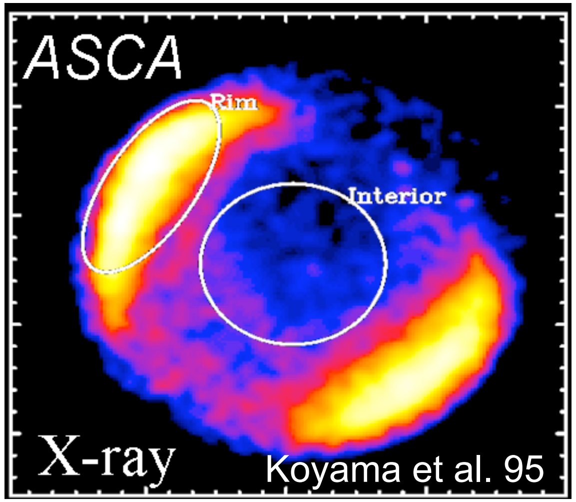
Radiative signatures at their shock:

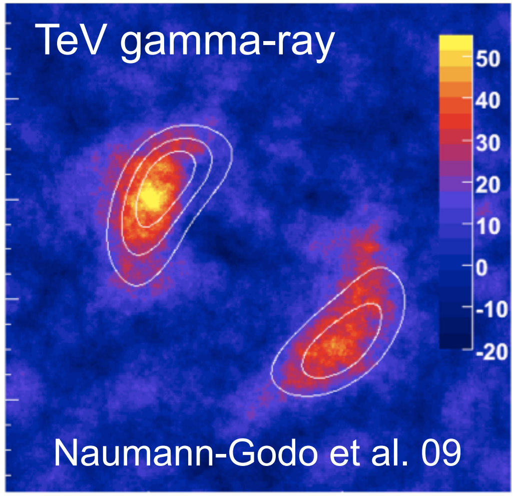
- Radio synchrotron => electrons accelerated to GeV energies (1954)
- X-ray synchrotron => electrons up to TeV energies in SN 1006 (Koyama et al. 1995, Nature)
- TeV gamma-ray emission => particles accelerated to TeV energies (Aharonian et al. 2004, Nature)



First order Fermi acceleration







Particle acceleration under scrutiny: a number of pending questions

- Evidence for ion acceleration? Fraction of shock energy tapped by cosmic rays?
  - Curvature of the particle spectra (Berezhko & Ellison 99, Ellison & Reynolds 91, **Allen et al. 08)**
  - Lower post-shock temperature (Ellison et al. 00, Decourchelle et al. 00)
  - Shrinking of the post-shock region (Decourchelle et al. 00, **Cassam-Chenaï et al. 08, Miceli et al. 09**)
- Where particle acceleration occurs ? Polar caps vs equatorial belt **(**Berezhko et al. 02, **Rothenflug et al. 04)**
- What is the maximum energy E_{max} of accelerated particles ?

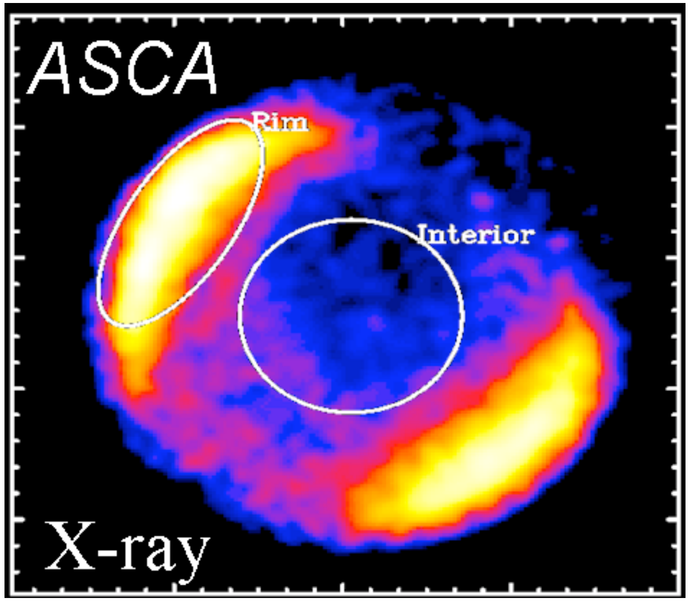
Electrons are a few % of cosmic rays but can reveal a lot on the mechanism of diffusive shock acceleration => accelerated like protons, so their spectrum is expected to be the same.

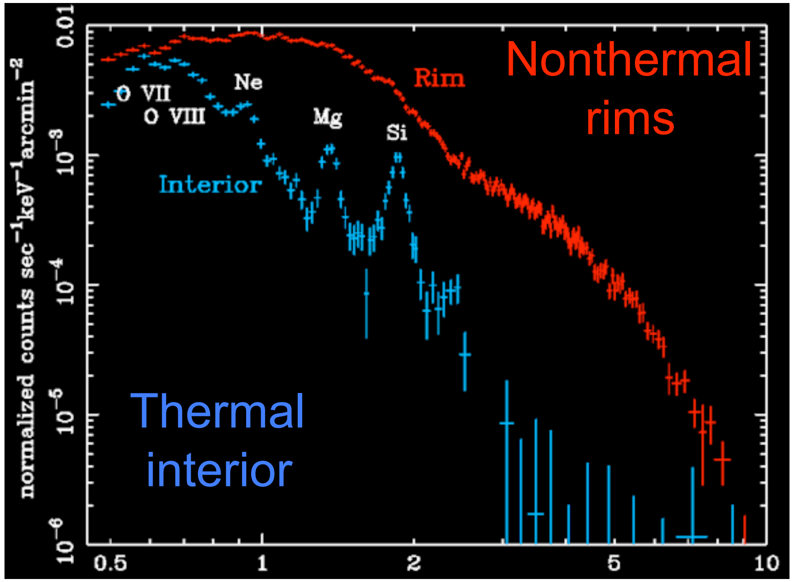
- How does E_{max} and hence particle acceleration vary with ambient B orientation ?

High latitude SNRs evolving in a uniform interstellar magnetic field, like SN 1006, offer the possibility to investigate this dependence (Völk et al. 03)

SN 1006

- Historical type Ia SNR
- Dual nature in X-rays with a bipolar non-thermal morphology like in radio, superposed on a fainter extended thermal emission





First evidence of electrons up to TeV energies in SN 1006 (Koyama et al. 1995, Nature 378, 255)

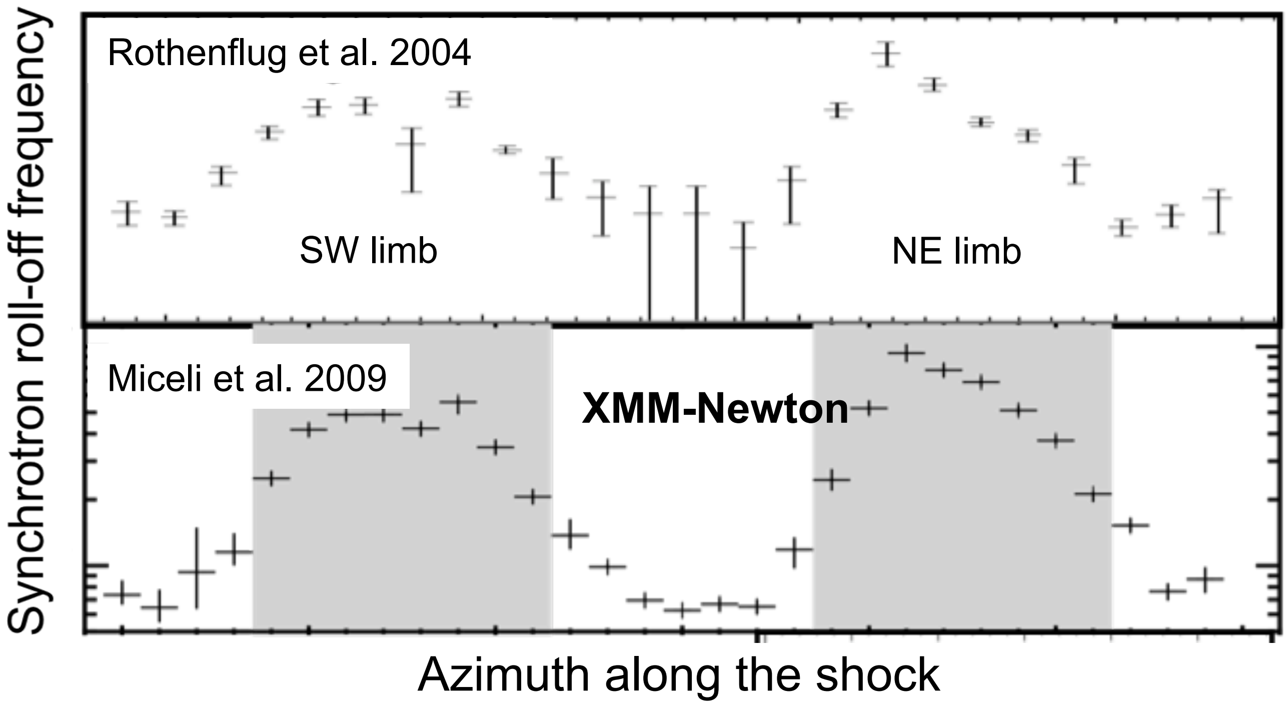
This talk => How does E_{max} and hence particle acceleration vary with ambient B orientation ?

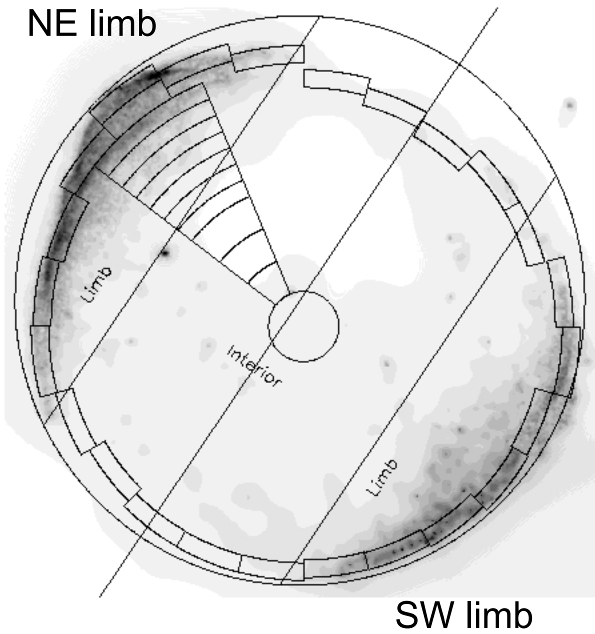
Fabrizio Bocchino => Thermal X-rays from ejecta and shocked ISM

How does E_{max} vary with ambient magnetic field orientation ?

Spatially resolved spectroscopy of the synchrotron emission (+ radio flux)

=> Measurement of the averaged azimuthal variation of the synchrotron roll-off frequency along the shock





SN 1006: very strong variations of the synchrotron roll-off frequency

=> Maximum energy of accelerated particles must be higher at the bright limbs than elsewhere

XMM-Newton Large program on SN 1006

Particle acceleration under scrutiny in SN 1006

Objectives: particle acceleration, magnetic field amplification, heating of the electrons and ions at the shock, abundances and distribution of the chemical elements in the ejecta

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Method: spatially resolved X-ray spectroscopy of the thermal and non-thermal components at a spatial scale close to the point spread function.

Total LP observation time: 650 ks

Status: all observations performed since september 2010

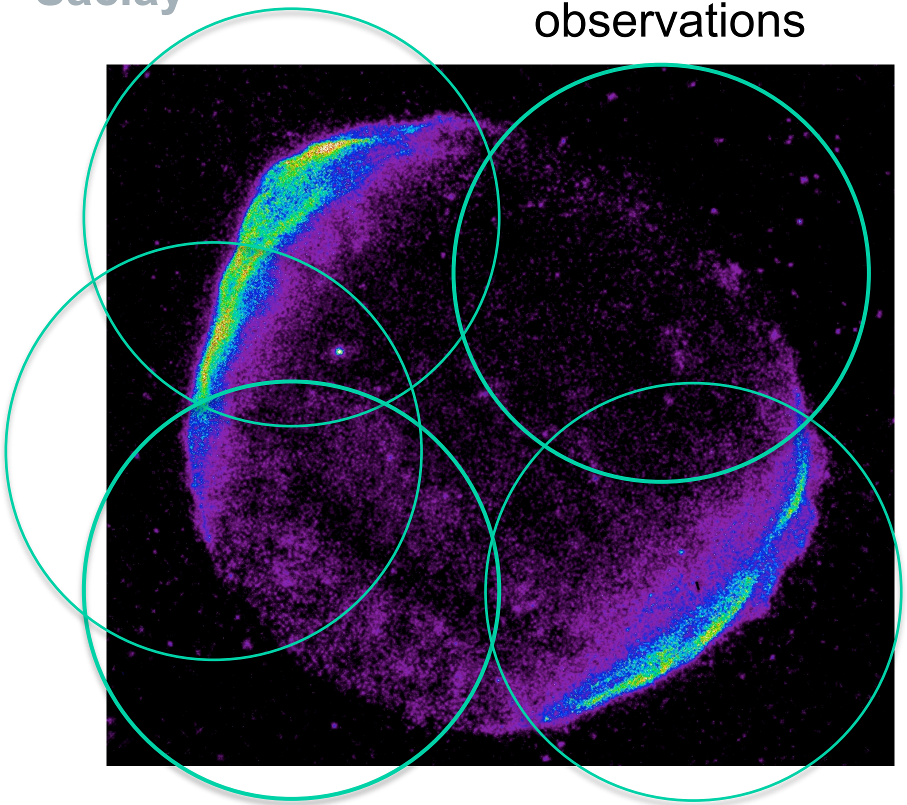
Spatially resolved spectroscopy of the synchrotron emission

⇒ Measurement of the azimuthal variation of $\nu_{cut\text{-}off}$ along the SNR shock

Data: all XMM data available (LP + previous shallow observations)
~950 ks -> ~650 ks after flare rejection

Observing status after the SN 1006 XMM-Newton LP

2 north-western observations



2 south-eastern observations

Observing time (ks)

	OBSID	MOS 1	MOS 2	PN
NW	0077340101	65.5	65.6	63.1
NE	0077340201	57.8	57.8	44.9
NE	0111090101	7.5	7.5	3.4
SE	0111090601	15.9	15.9	11.7
NE	0143980201	30.4	30.4	26.9
SW	0202590101	43.2	43.2	39.9
SE	0306660101	33.8	33.8	29.9
Total		254.1	254.4	219.8
SE	0555630101	45.5	45.5	42.2
E	0555630201	109.4	109.4	103.5
NE	0555630301	121.8	121.5	118.1
NW	0555630401	104.5	104.5	100.7
NW	0555630501	127.2	127.2	123.2
SE	0555631001	65.6	65.6	61.7
SW	0653860101	126.5	126.5	123.2
Total		954.6	954.4	892.4

Factor ≈ 4

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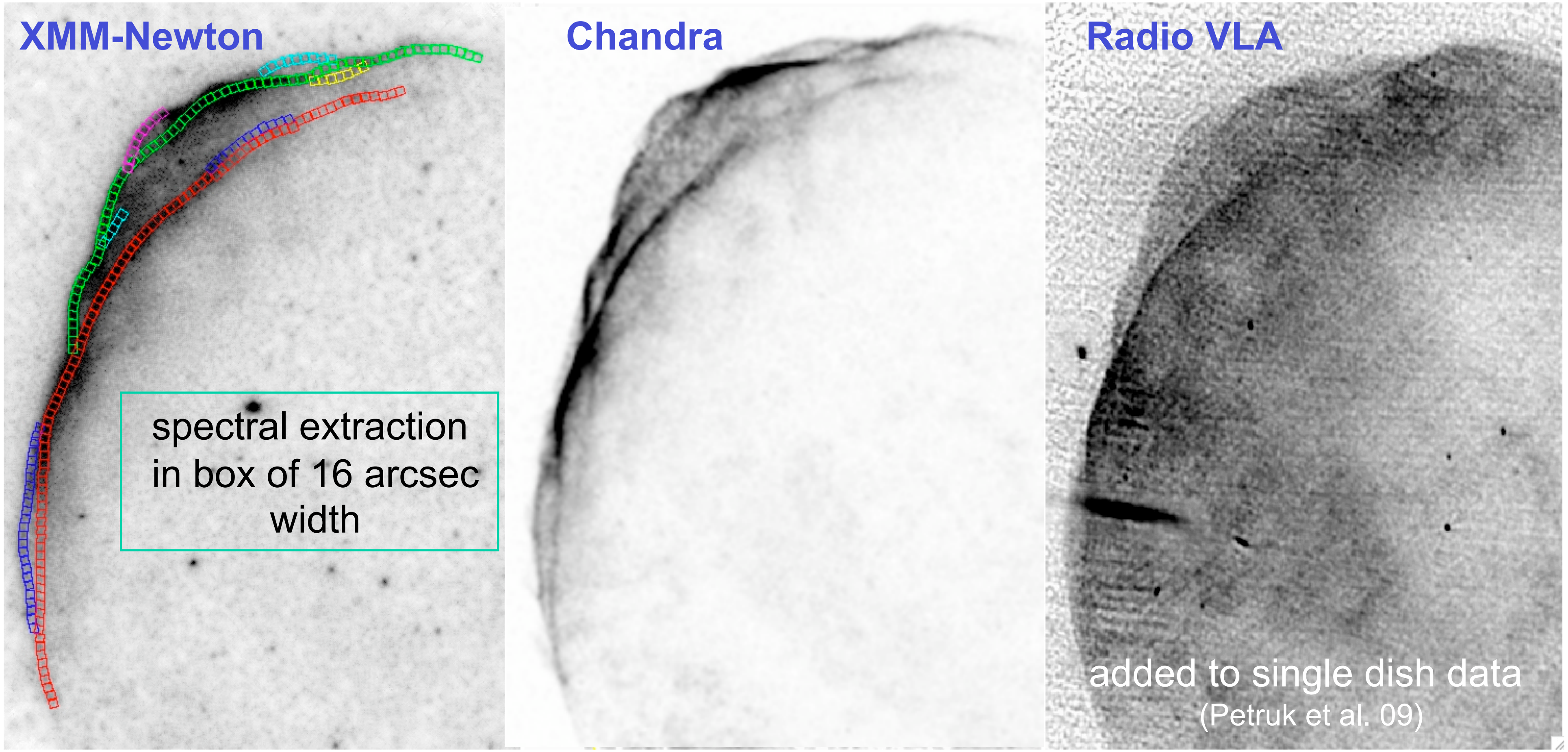
Observations and effective observing time after flare rejection

	OBSID	MOS 1	MOS 2	PN
NW	0077340101	28.9	31.8	23.3
NE	0077340201	22.7	24.1	10.6
NE	0111090101	7.4	7.4	2.9
SE	0111090601	7	7.2	5.9
NE	0143980201	17.0	16.9	12.5
SW	0202590101	27.3	28.8	21
SE	0306660101	7	8.5	1.9
SE	0555630101	44	44.4	28.6
E	0555630201	81.7	91.5	58
NE	0555630301	91.5	93.3	75.0
NW	0555630401	73.2	79.7	50.2
NW	0555630501	84.9	94.9	62
SE	0555631001	60.3	61.3	50.1
SW	0653860101	103.2	104.2	91.4
Total		656.1	694.0	493.4
		69%	**73%**	**55%**

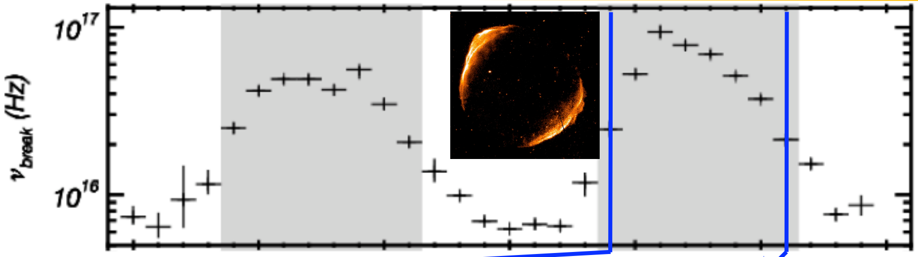
Spectral modelling of the X-ray and radio emission

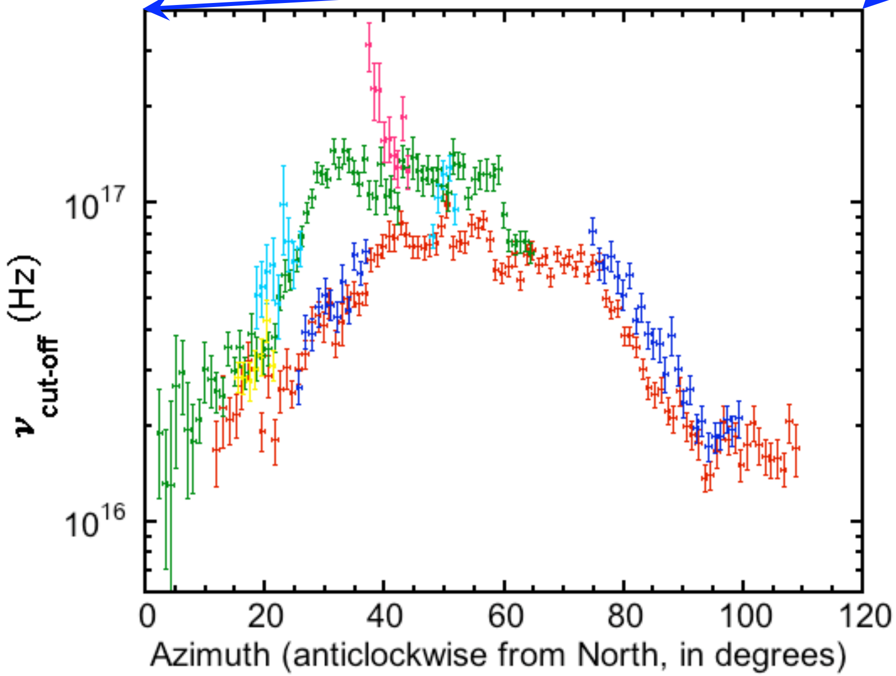
Spectral modelling:
- exponential cut-off power law model (SRCUT, Reynolds & Keohane 99)
- thermal plane-parallel non-equilibrium model (VPSHOCK, Borkowski et al. 01)
- interstellar absorption (WABS): $N_H \sim 7\ 10^{20}\ cm^{-2}$ (Dubner et al. 02)

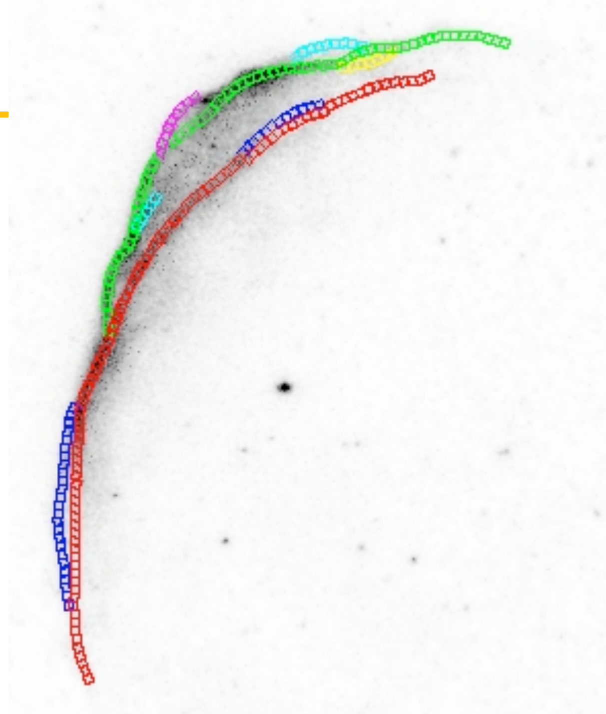


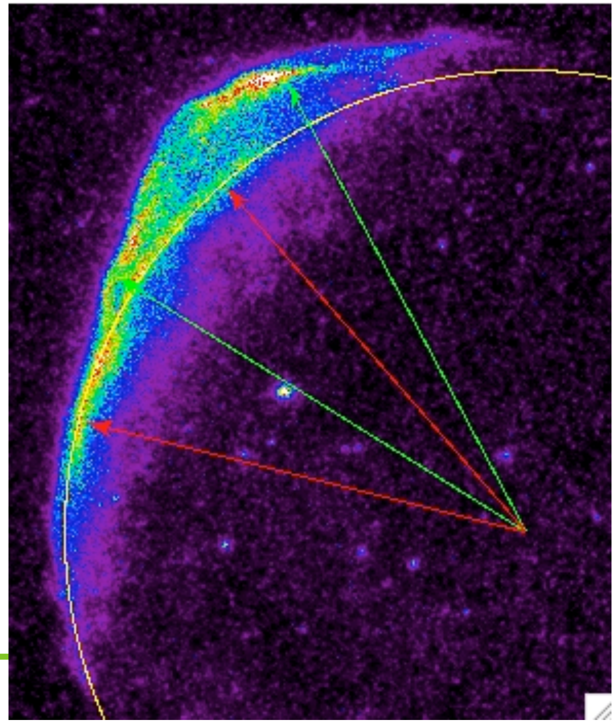
Cut-off frequency along each filament

Cut-off frequency







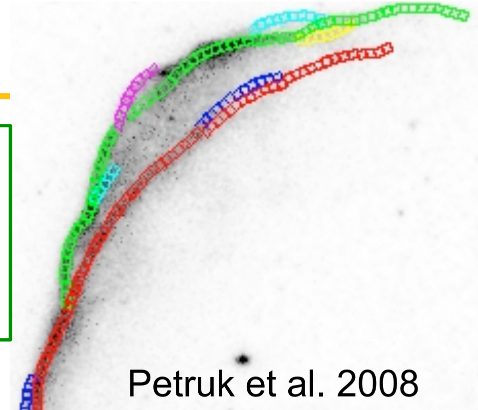


Along the two extended filaments, cut-off frequency shows:

- a rapid increase, followed by a plateau and a rapid decrease
- increase amplitude depends on filaments (from 4 to 10)
- the most outward filaments have larger cut-off frequency

(Vs ~ 5000 km/s, Katsuda et al. 09)

Synchrotron spectral index

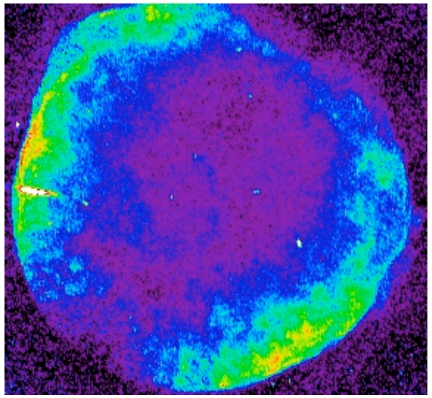


Along all filaments, same behaviour of the spectral index

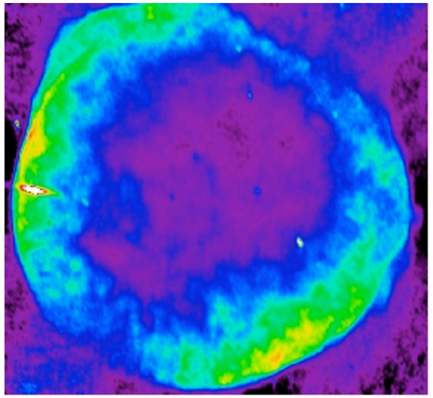
- slight increase towards the pole and decrease outwards
- but exact dependence and values depend on radio maps

Radio maps

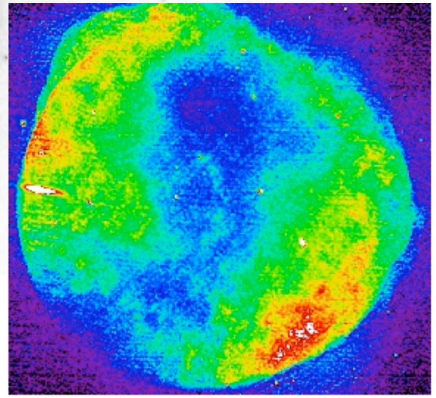
Dyer et al. 2009

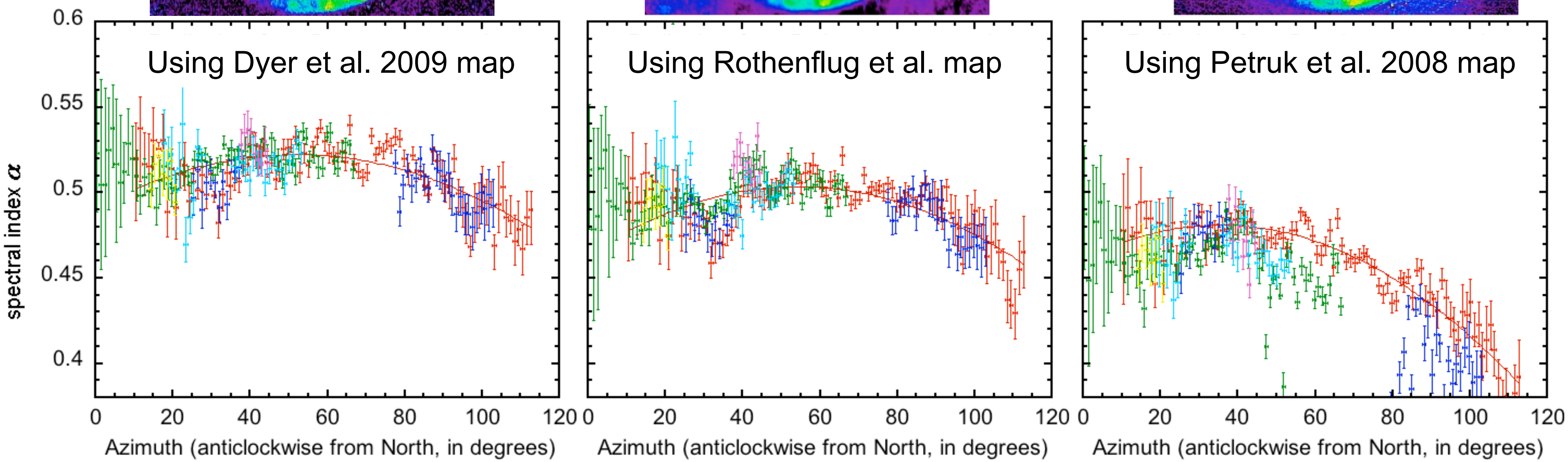


Rothenflug et al. 2004



Petruk et al. 2008



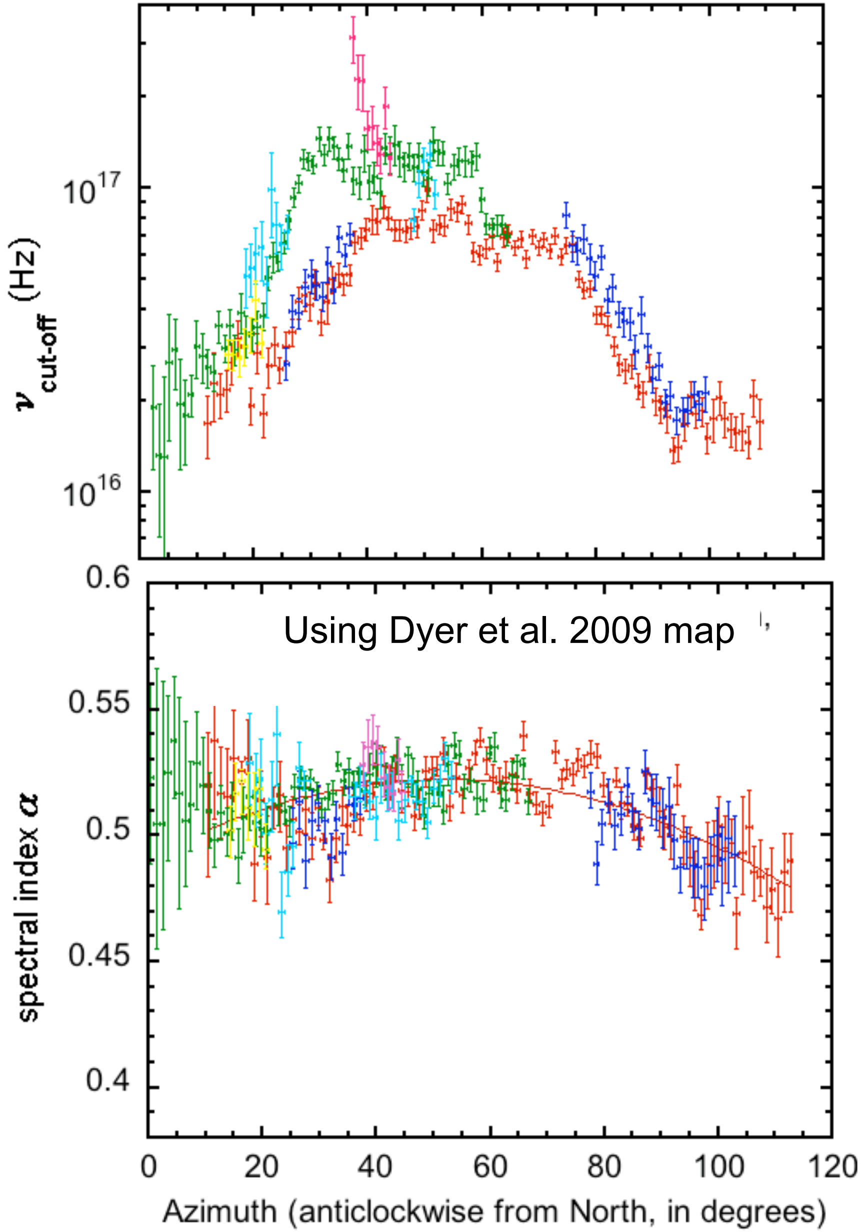


Conclusion on particle acceleration at the north-east pole in SN 1006

At the north-east pole:

- Highest cut-off frequency
  => highest energy reached by particles
- Highest values for the outermost filaments
  => higher energy for higher shock velocity
- Plateau regime: saturation of the cut-off frequency near the pole: loss-limited ?
  ⇒ highest acceleration efficiency/injection

(Decourchelle et al., 2011, in prep)



Azimuthal dependence provides very strong constraints to the acceleration mechanism : dependence with obliquity angle between shock velocity and upstream magnetic field

=> detailed modeling required