Restes de supernova

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Restes de supernova : empreintes d'explosion d'étoile dans le milieu interstellaire, ils sont à plusieurs titres des acteurs majeurs de l'évolution des galaxies.

Objectif de ce cours : fournir un état des lieux de ce que nous comprenons de la physique des restes de supernova, des questions ouvertes et des observations clés pour y répondre.

Résumé du cours

Source principale de production des éléments lourds, les supernovae sont le mécanisme effectif de distribution de ces éléments dans le milieu interstellaire et gouvernent ainsi l'enrichissement chimique galactique. L'observation de restes de supernova permet d'accéder à la quantité d'éléments synthétisés, à leur mélange et dispersion, et apporte des contraintes sur le type de supernovae et le mécanisme d'explosion.

Source principale d'énergie pour le milieu interstellaire, ils sont le lieu où l'énergie cinétique déployée par l'explosion est transmise au milieu interstellaire par son chauffage à des dizaines de millions de degrés, par l'accélération de particules au choc et par la génération de turbulence. Ce sont des sites privilégiés pour rendre compte de l'accélération des rayons cosmiques galactiques et comprendre le mécanisme d'accélération en jeu.

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Plan du cours

I. Introduction
   1. Supernovae et leurs progéniteurs
   2. Hydrodynamique des restes de supernova
   3. Mécanismes d'émission
   4. Moyens d'observation

II. Nucléosynthèse
   1. Synthèse des éléments lourds
   2. Physique de l'explosion
   3. Emission gamma : raies de décroissance radioactive
   4. Emission X : raies d'excitation collisionnelle

III. Accélération de particules
   1. Origine des rayons cosmiques galactiques
   2. Observations de l'accélération de particules dans les restes de supernova : de la radio au TeV
   3. Caractérisation de l'accélération
      1. Amplification du champ magnétique au choc
      2. Energie maximale atteinte dans les restes de supernova
      3. Efficacité de l'accélération : rétroaction des particules accélérées

IV. Modélisation des restes de supernovae

V. Conclusions et perspectives

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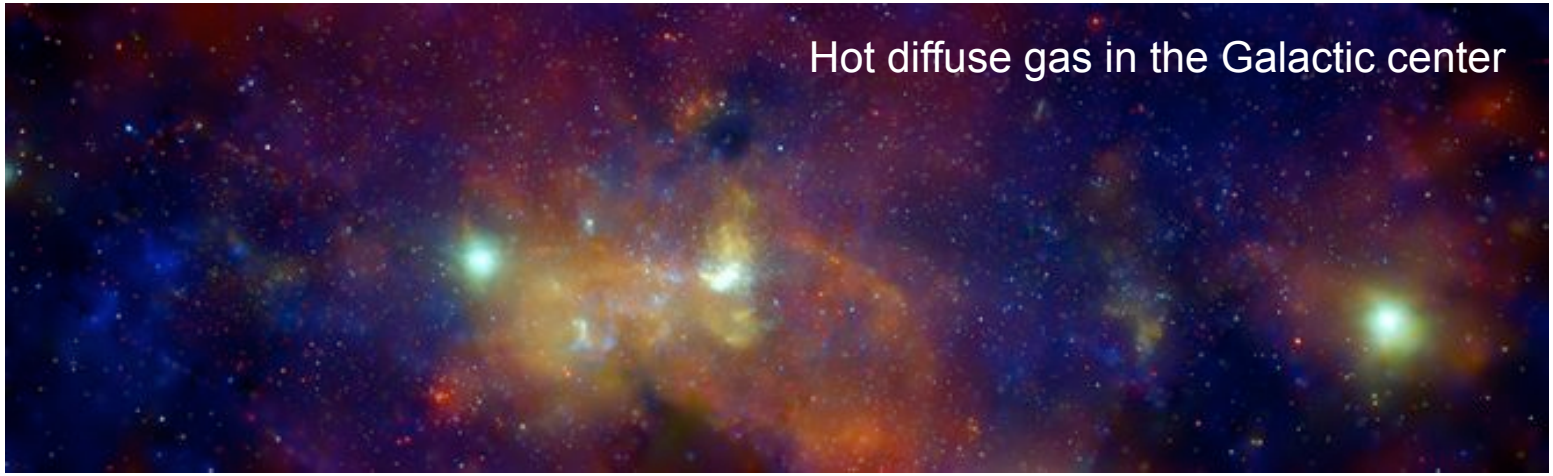
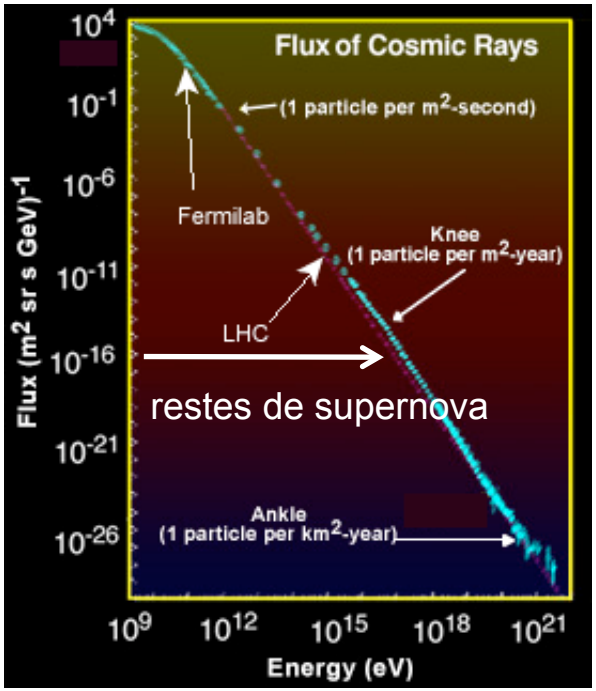
Supernova remnants: key ingredients to understand our Universe



Chemical enrichment, heating and turbulence of the interstellar medium

Physics of supernova explosions

Origin of Galactic Cosmic Rays



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I. Introduction

1. Supernovae et leurs progéniteurs
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I.1 Supernovae et leurs progéniteurs

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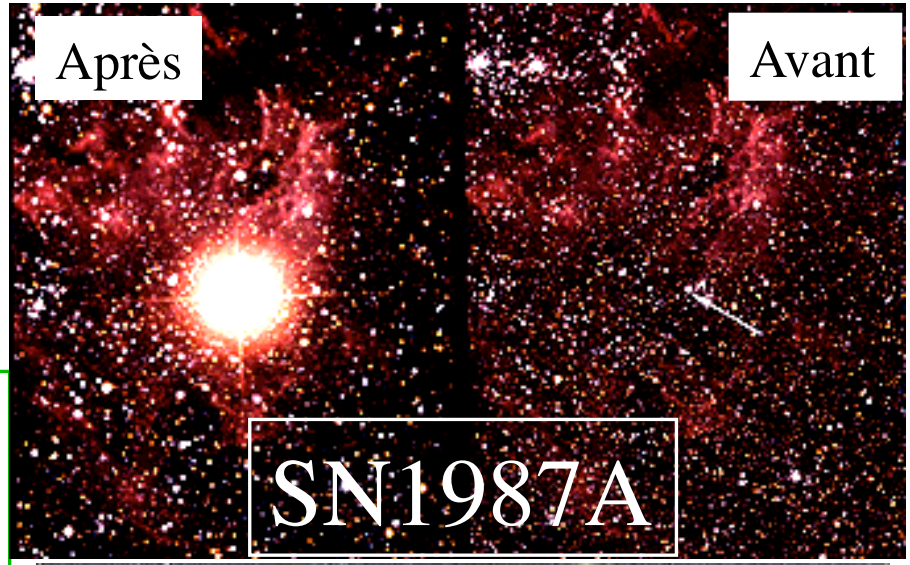
"Novæ" : étoiles qui apparaissent brusquement dans le ciel

"Super" : de brillance gigantesque

⇒ **SNe font partie des événements les plus énergétiques de l'Univers**



Suivant la masse du progéniteur, 2 types d'explosion :

- étoiles massives libère une énergie instantanée de ~ 10^{53} ergs dont 99 % sous forme de neutrinos
- naines blanches libère ~10^{51} ergs

Les 2 mécanismes d'explosion fournissent une énergie cinétique comparable ~ 10^{51} ergs dans la matière éjectée.

⇒ **compression, chauffage et accélération de particules du milieu interstellaire/circumstellaire ambiant.**

Petite fraction sous la forme de lumière visible

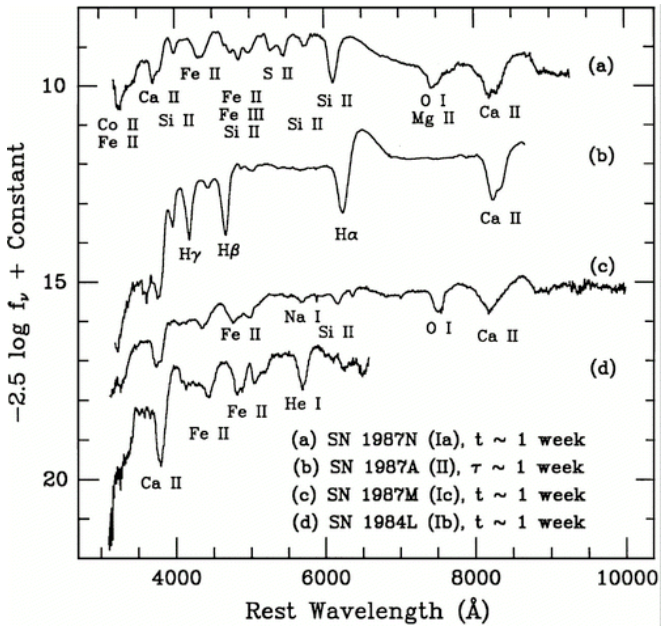
I.1 Types et progéniteurs des supernovae

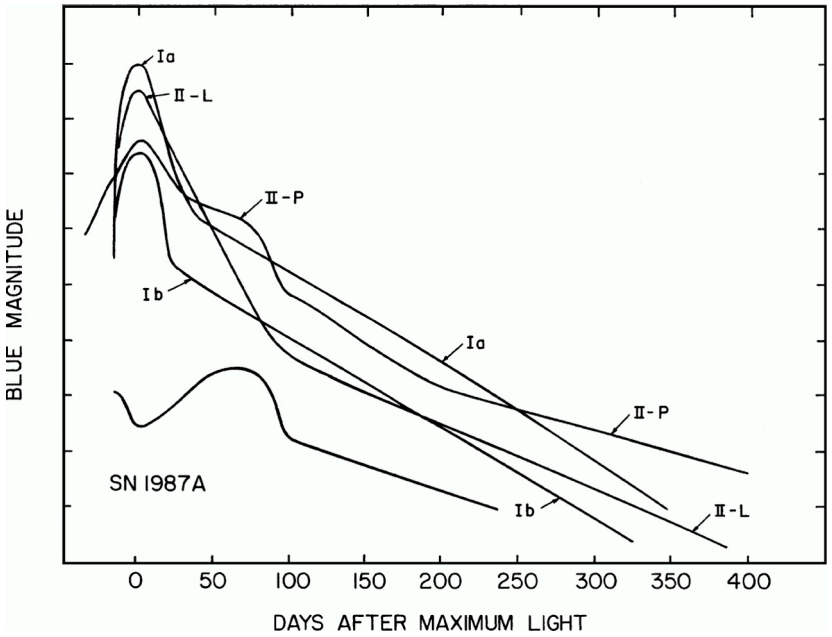
Lumière visible : provient de la décroissance de noyaux radioactive synthétisés lors de l'explosion (^{56}Ni, ^{56}Co). Les photons gamma sont absorbés par le matériel éjecté et réémis dans le domaine optique.

- Forme de la courbe de lumière
- Présence ou non d'éléments identifiés par des raies en absorption dans le spectre

=> Classification en différentes catégories des SNe extragalactiques (Fillipenko 1997)

=> signe le mécanisme d'explosion et la perte de masse, donc la nature du progéniteur





Left: Early-time spectra of supernovae for the four major types. *t* and *t* are the time after the observed maximum in the B band and time after core-collapse, respectively. The ordinate unit is "AB magnitudes".
Right: Schematic light curves for supernovae of Types Ia, averaged Ib and Ic, II-L, II-P, and SN 1987A.

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I.1 Types et progéniteurs des supernovae

Type I : absence d'hydrogène et d'hélium

- Type Ia : présence de fortes raies du silicium, puis des éléments du groupe du fer
  sous-classe homogène => explosion thermonucléaire d'une naine blanche
- Type Ib : forte émission He I
- Type Ic : absence de Si II and He I
  sous-classes inhomogènes => effondrement du cœur de binaire en interaction de masse modérée ayant perdu leur enveloppe d'hydrogène et d'hélium.

Type II : présence d'hydrogène

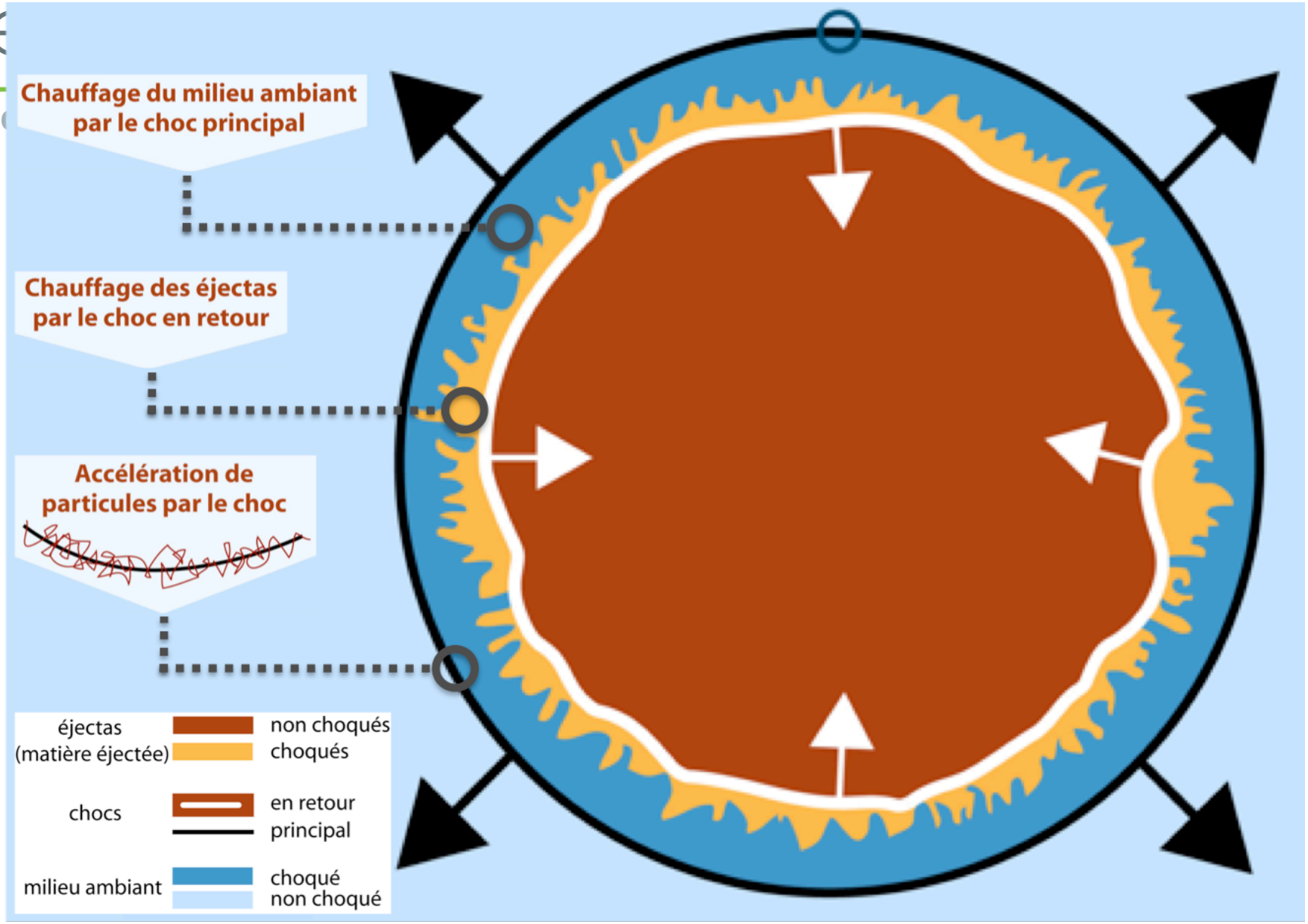
=> effondrement gravitationnel du cœur, plus de dispersion que pour les SNe de type Ia

- Type II-L : « linear » courbe de lumière similaire au Type Ia
- Type II-P « plateau » : période étendue où elle conserve leur brillance maximale
  Progéniteur : supergéante rouge
- Type II-n : raies d'émission étroites courbe de lumière lentement décroissante (Schlegel 1990)
  Progéniteur : avec un vent circumstellaire très dense (Chevalier 1990)
- Type IIb : caractéristiques spectrales évoluant de Type II à Type Ib (Chevalier & Soderberg 2010)
  - cIIb (progéniteur compact avec une enveloppe d'H < 0.1 Msol)
  - eIIb (progéniteur étendu avec une enveloppe d'H > 0.1 Msol)

SN Ia : observée dans les galaxies spirales et elliptiques

SN II, Ib, Ic : observée dans les galaxies spirales, ds ou près des bras spiraux et des régions HII.
Progéniteur : jeunes étoiles massives

I.2 Hydrodynamique des restes de supernova



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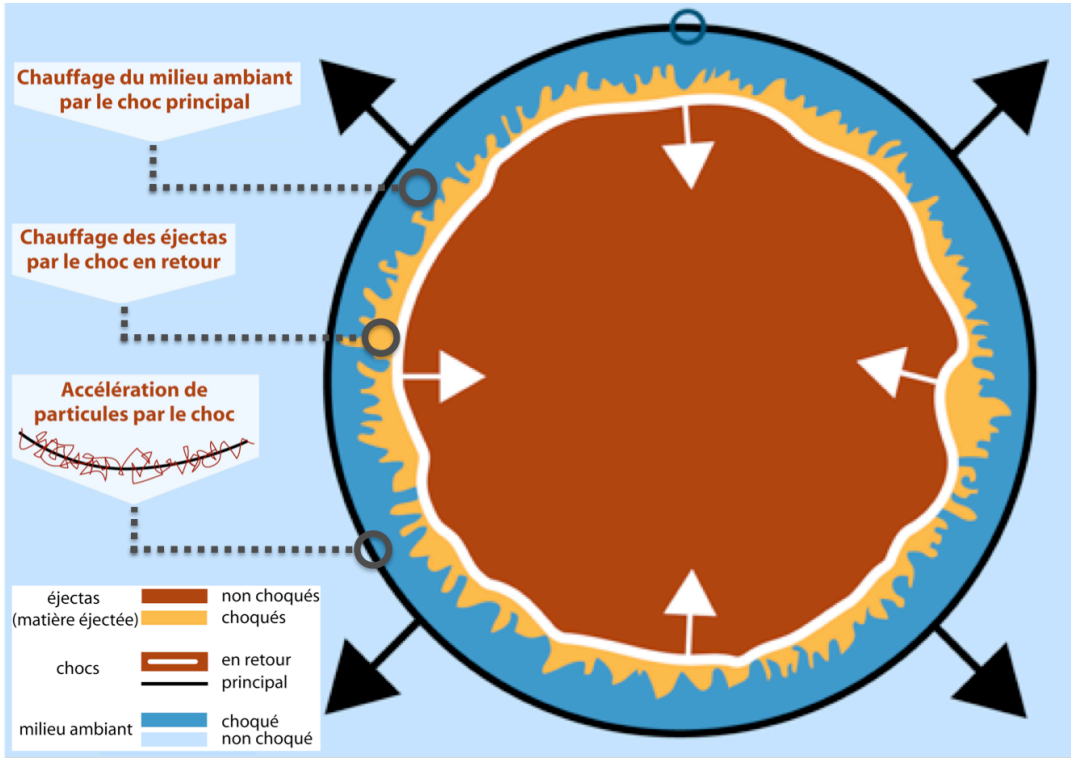
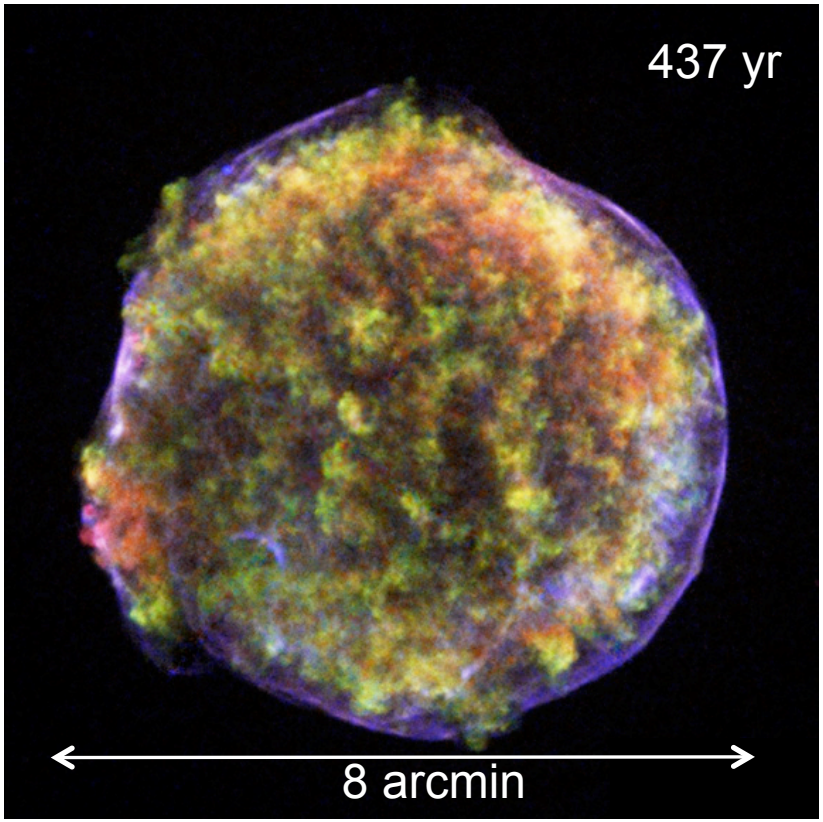
I.2 Hydrodynamique des restes de supernova

Tycho (SN 1572)
Type Ia



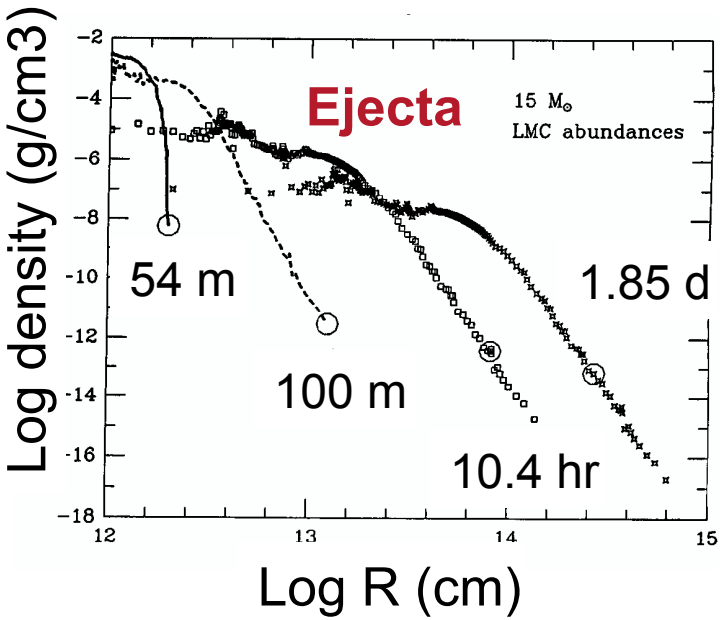


D ~ 2.0 - 4.5 kpc

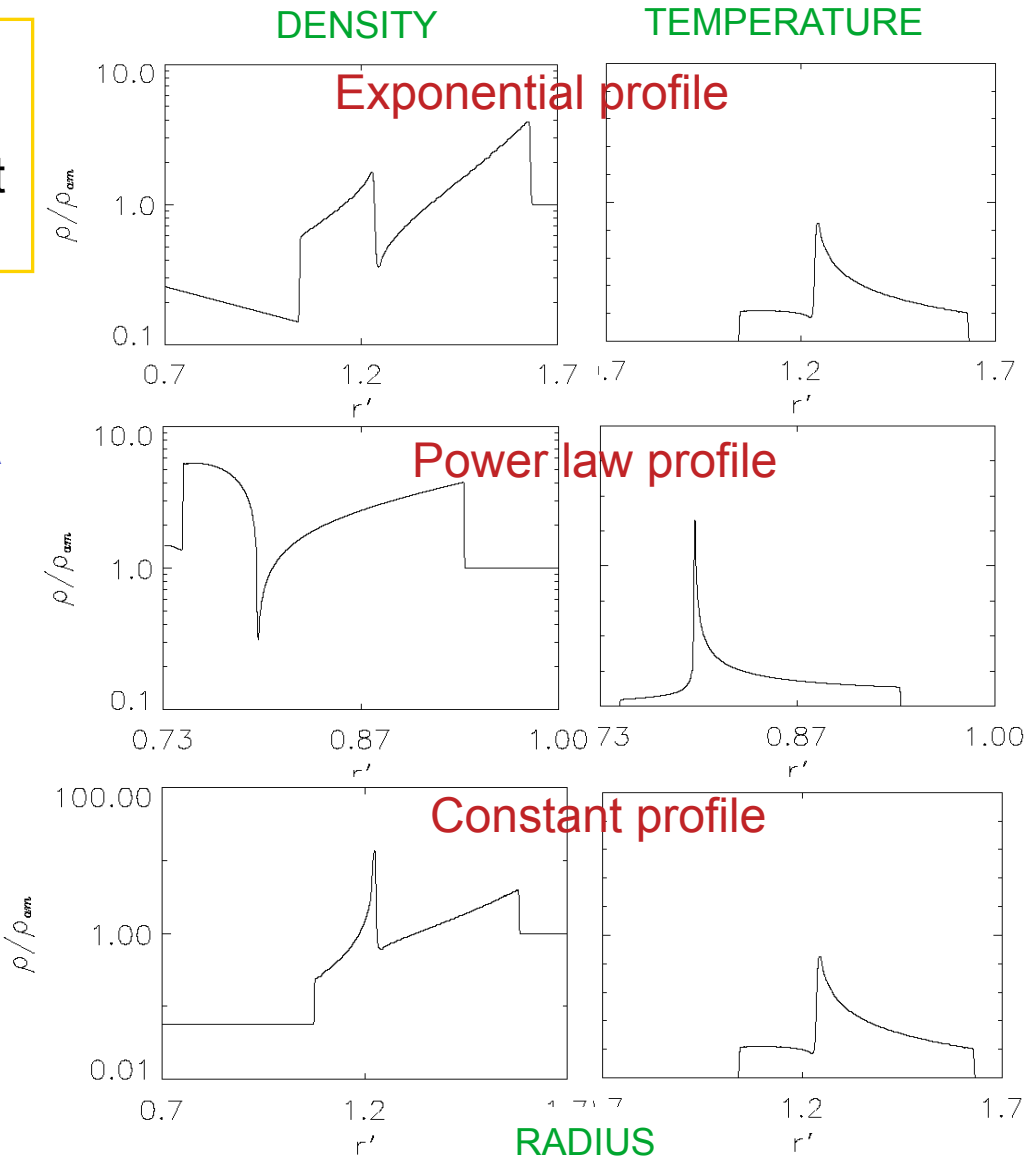
I.2 Hydrodynamique des restes de supernova jeunes

La structure d'interaction dépend des profils de densité initiaux des éjecta et du milieu ambiant

profils de densité pour SN 1987A



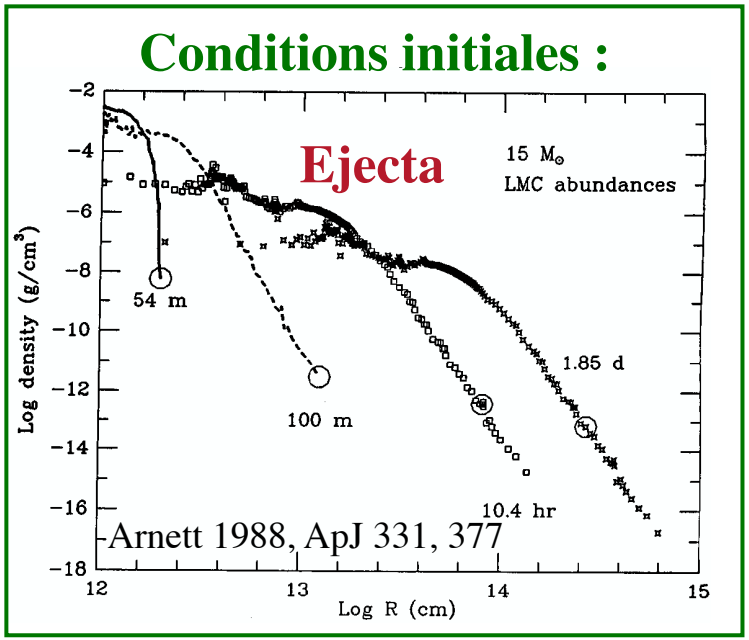
Arnett 1988, ApJ 331, 377

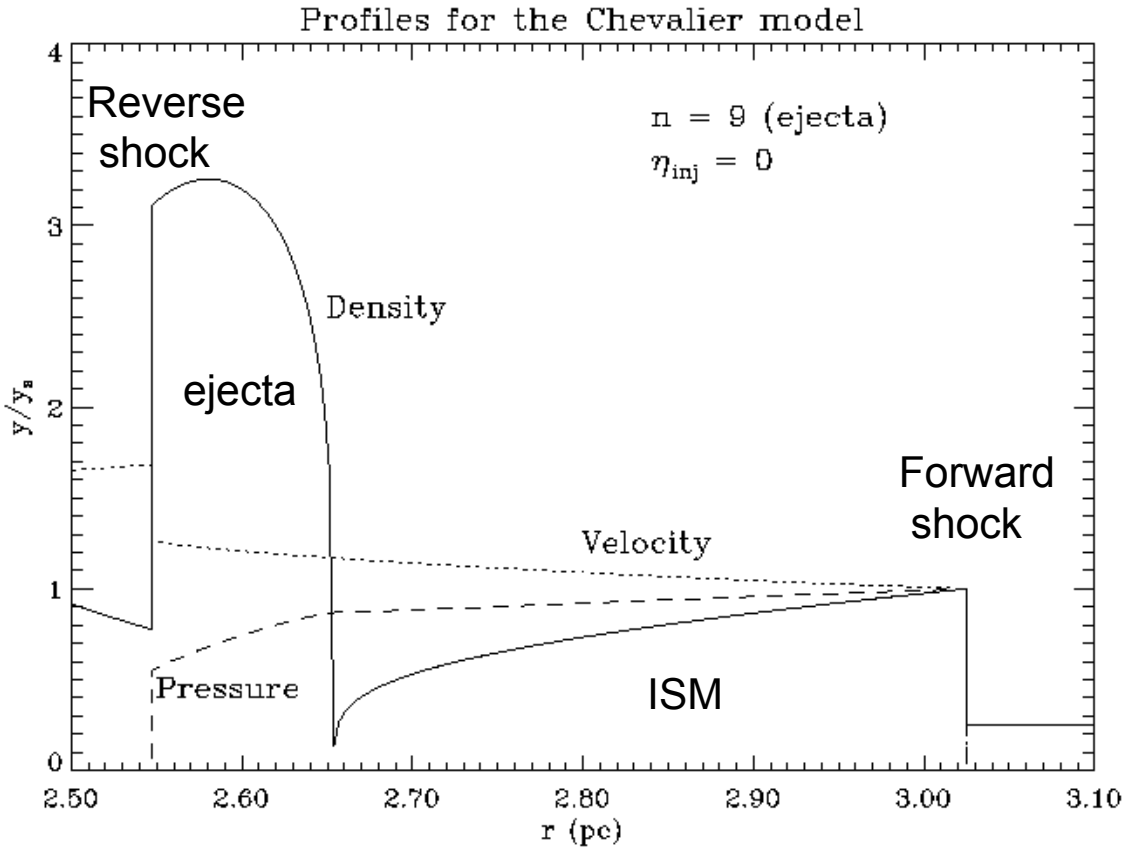


Dwarkadas and Chevalier 1998, ApJ 497, 807

I.2 Solutions hydrodynamiques autosimilaires

Conditions initiales :



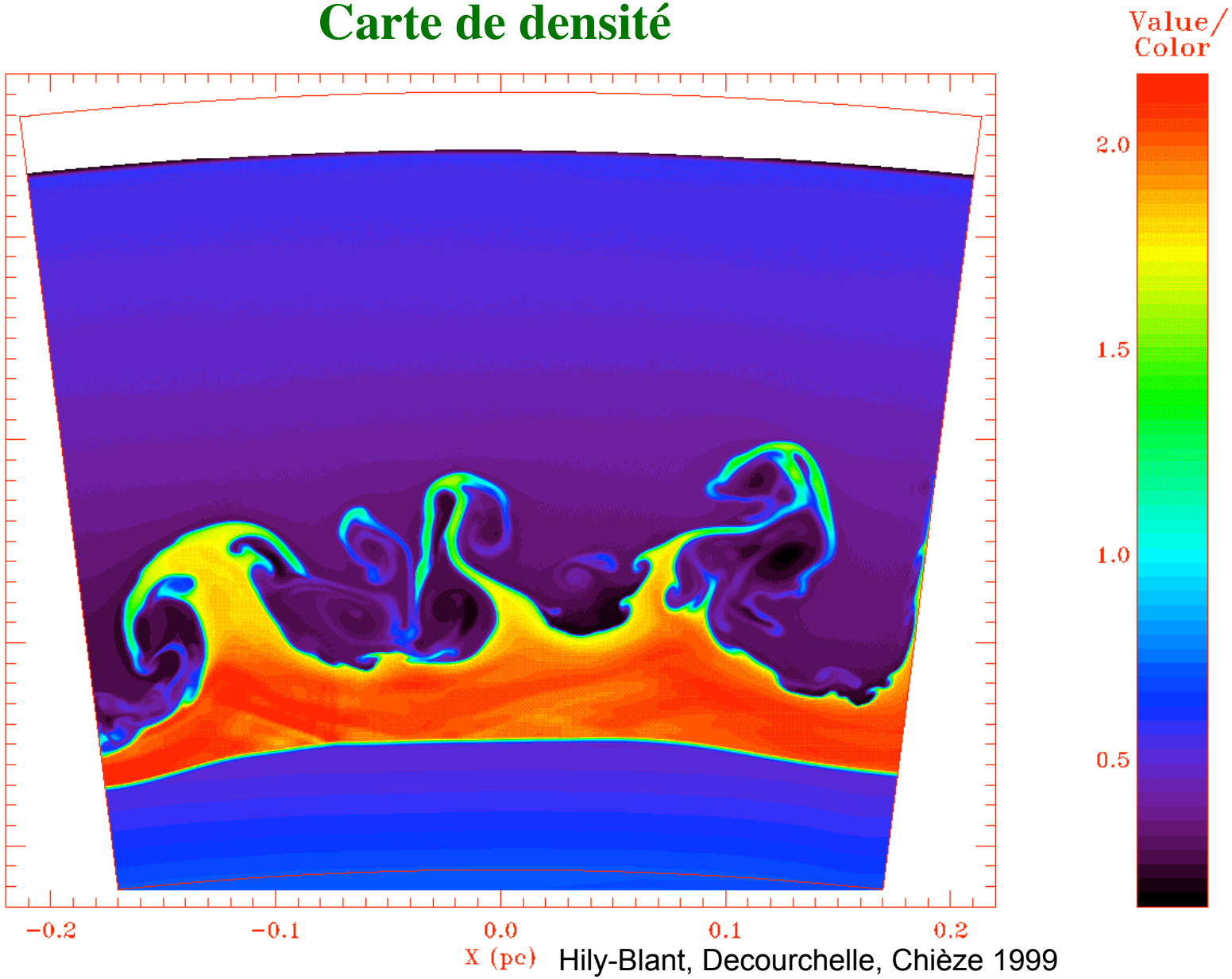


Contact discontinuity

Power law density profiles => self-similar solutions
(Chevalier 1982, ApJ 258, 790)

I.2 Instabilités hydrodynamiques à l'interface

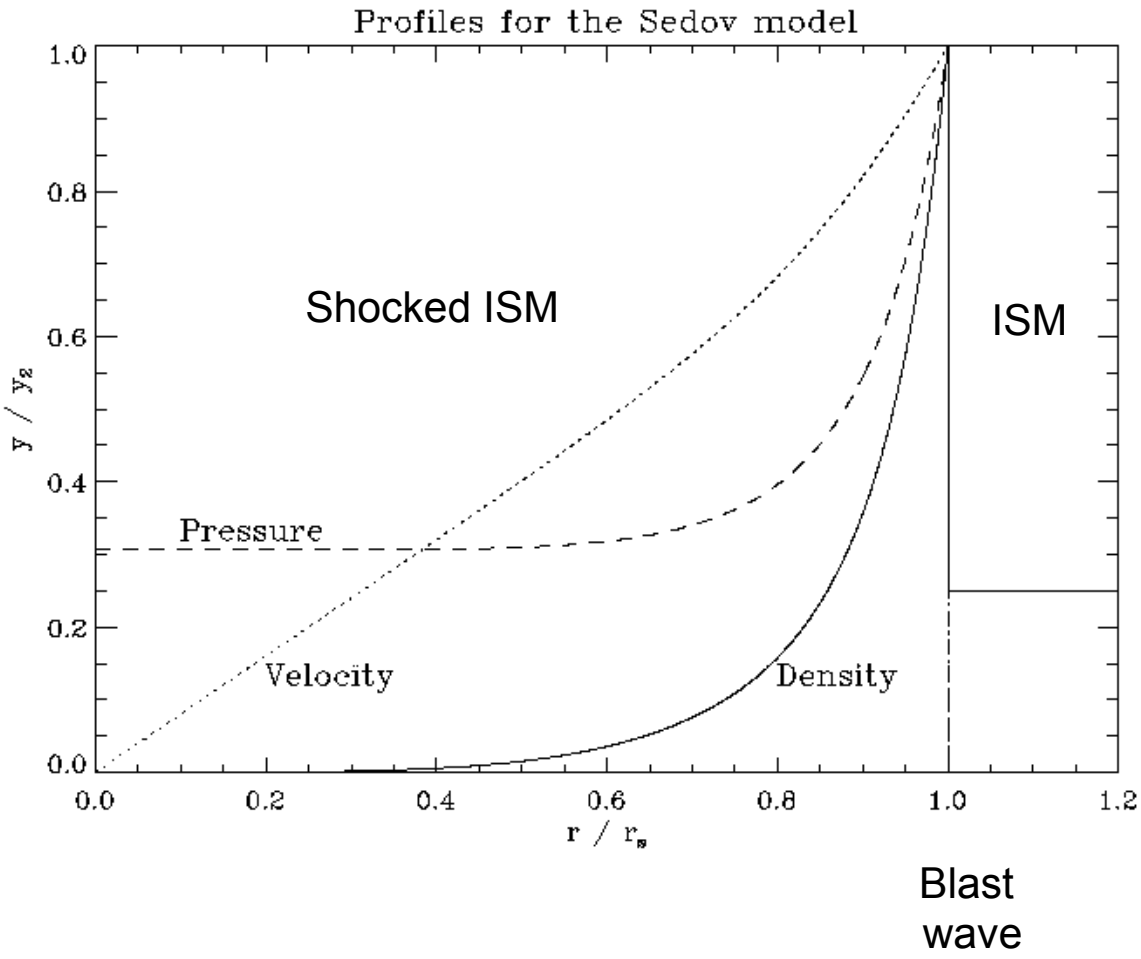
Carte de densité



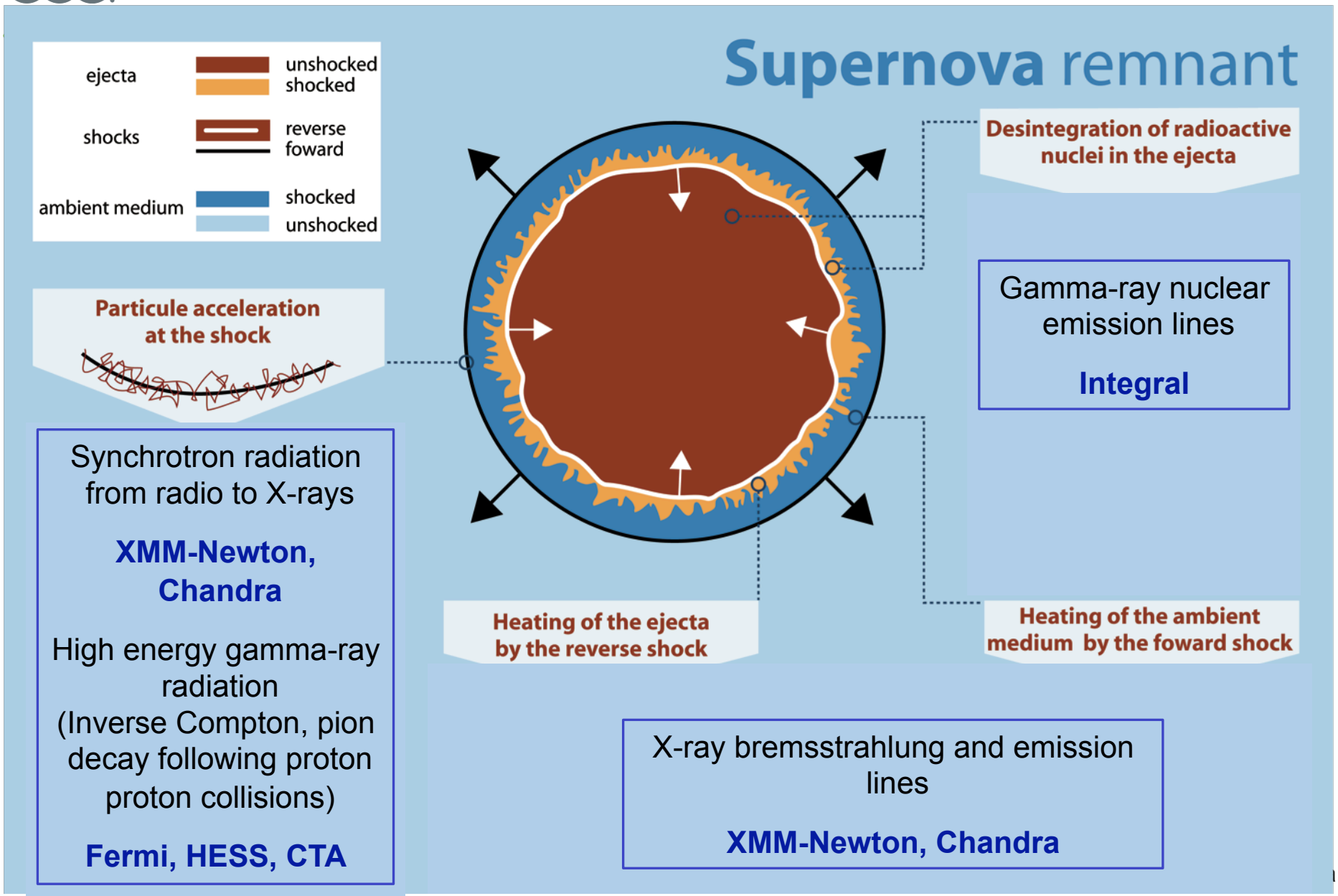
Hily-Blant, Decourchelle, Chièze 1999

I.2 Hydrodynamique des restes de supernova matures

- Energie constante (pas de pertes radiatives)
- Densité constante du milieu ambiant ISM
- Solutions autosimilaires (Sedov 1959)



I.3 Mécanismes d'émission : la haute énergie, un domaine de prédilection pour comprendre les restes de supernova



I.4 Moyens d'observations : Astronomie X et γ de 100 keV au TeV

Astronomie gamma => cours de Bernard Degrange

A very brief history of X-ray astronomy

1946: First rockets (NRL, USA) => UV and X-ray emission from the Sun, but instrumental sensitivity too low by a factor 10^5 to detect the closest stars

Giacconi => instrumental development/improvement of sensitivity

1962: second flight of ASE experiment => powerful extra-solar X-ray source discovered: **Sco X-1**

Beginning of X-ray astronomy: Physics Nobel prize in 2002

Riccardo Giacconi

Prix Nobel de Physique 2002

1970: Uhuru, first X-ray satellite: 300 sources from its sky survey.

1978-1996: numerous US, european and japanese X-ray satellites with improved detectors (Einstein,Exosat, Ginga, Rosat, Asca, RXTE, SAX)

1999: Chandra and XMM-Newton satellites opened a new area of X-ray astronomy combining spectral and spatial resolution with effective area

II. Nucléosynthèse

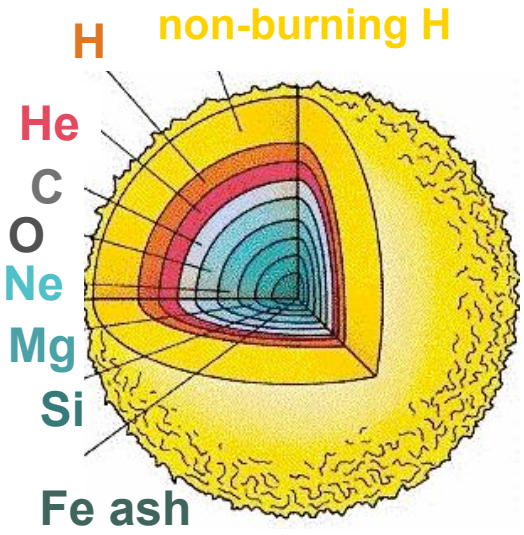
1. Synthèse des éléments lourds
2. Physique de l'explosion
3. Emission gamma : raies de décroissance radioactive
4. Emission X : raies d'excitation collisionnelle

II.1 Synthèse des éléments lourds dans les étoiles et leur dispersion

Hydrostatic nucleosynthesis in stars

- fusion of H to He (main sequence, millions years)
- fusion of He to C and O (giant stars)
- fusion of C, O, Ne to Mg, Si, S up to Fe (supergiant stars)

=> long timescale, classic onion-skin structure



Explosive nucleosynthesis in SNe

- most of heavy elements from Si to Fe peak
- only provider of elements heavier than lead and stable isobars

Very short timescale (s) **and large energy** (kinetic ~ 10^{51} ergs)

⇒ **much more diverse distribution of the elements**

Effective mechanism for dispersing them in the ISM

⇒ **drive heavy-element enrichment of the interstellar medium in galaxies**

II.2 Physics of supernovae: type Ia

Two main types of SN explosions: quantity of synthesized elements depends on the type and on the detailed physics of the explosion

Thermonuclear supernovae: SN Ia

explosion of accreting white dwarf in a binary system when $M_{WD} > 1.4\ M_{\odot}$ via mass transfer

⇒ **total disruption of WD and complete ejection of synthesized elements**

- main provider of Fe (~75 %) and Fe peak nuclei.
- standard candles for cosmology

Open questions

- nature of the companion: normal star (single degenerate) or a white dwarf (double degenerate)?
- Ignition of the burning and burning front propagation ?

Quantity of synthesized elements depends on:

- accretion rate from the companion star
- physics of propagating flame fronts (slow / fast deflagration, transition to detonation)

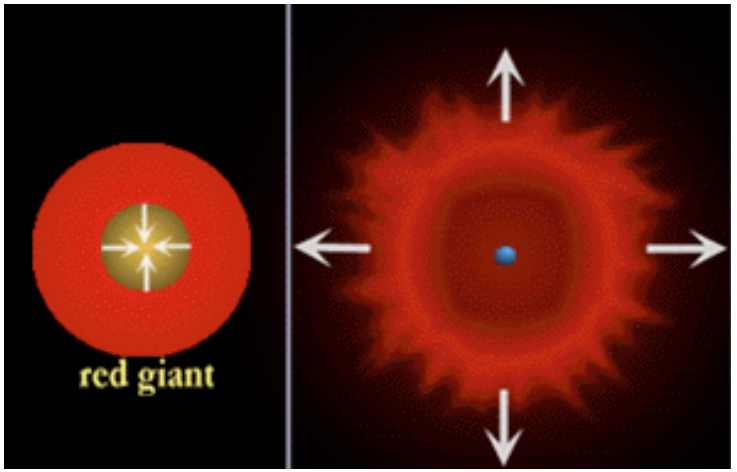
=> constraints from the observed ratio between intermediate elements and iron

II.2 Physics of Supernovae: core collapse

Core collapse supernovae : SN II, Ib, Ic

Gravitational collapse of Fe core of a massive star after successive stages of hydrostatic burning
=> neutron star / black hole and envelope ejection

- main provider of intermediate elements (Si-Ca): 70 %
- responsible for enrichment in very early universe



Open questions depending on the progenitor:

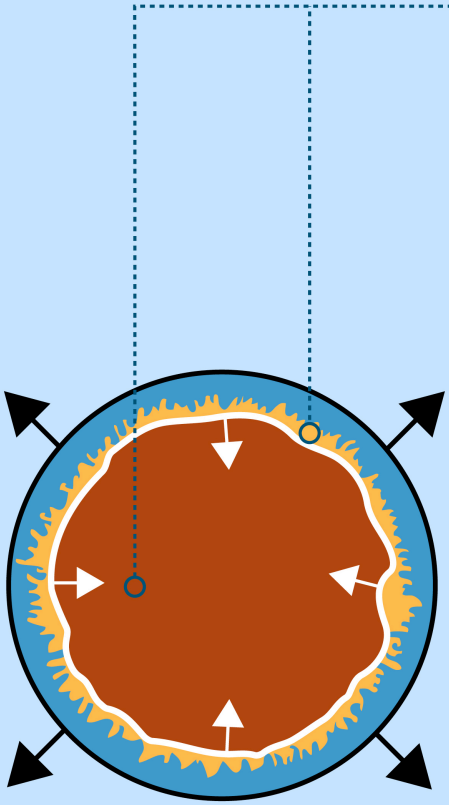
- Value of the mass-cut ? unclear on theoretical grounds
- Explosion mechanism: neutrino-driven, MHD-driven (jets)

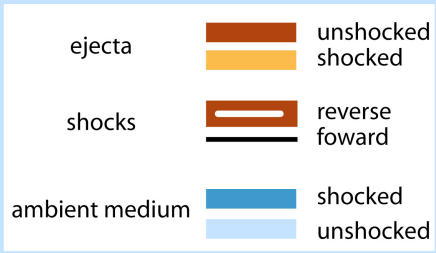
Quantity of synthesized elements depends on:

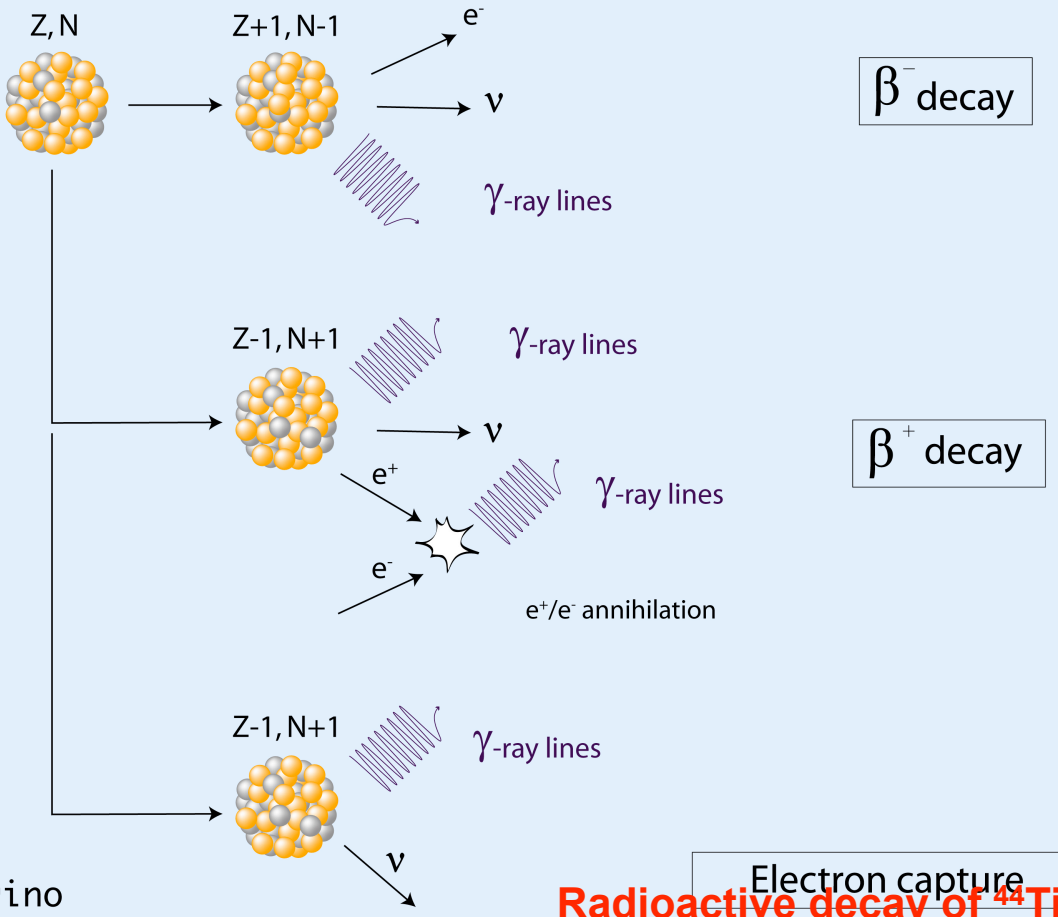
- **progenitor** for element lighter than Si (essentially produced during hydrostatic evolution and spread away in the explosion)
- **explosion energy** and **amount of matter accreting** onto the core before the explosion for intermediate elements enhanced through explosive oxygen burning.
- **details of the explosion and mass-cut** between the residual compact object and the ejected envelope for iron-group nuclei

II.3 Emission gamma : raies de décroissance radioactive

Desintegration of radioactive nuclei in the ejecta







ν : neutrino
e⁺ : positron
e⁻ : electron
Z : proton number
N : neutron number

Radioactive decay of ^{44}Ti

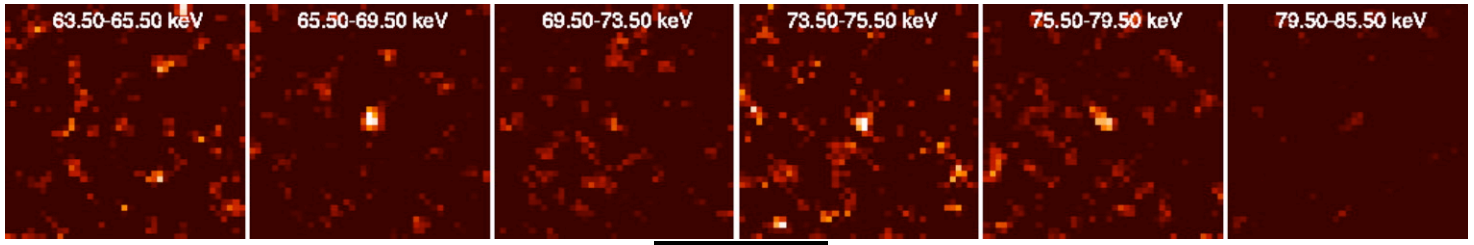
II.3 Emission gamma : raies de décroissance radioactive : ^{44}Ti

Decay-chain by electronic capture: ^{44}Ti (85 yr)→ ^{44}Sc (5.6 h) → ^{44}Ca => 3 γ-ray lines

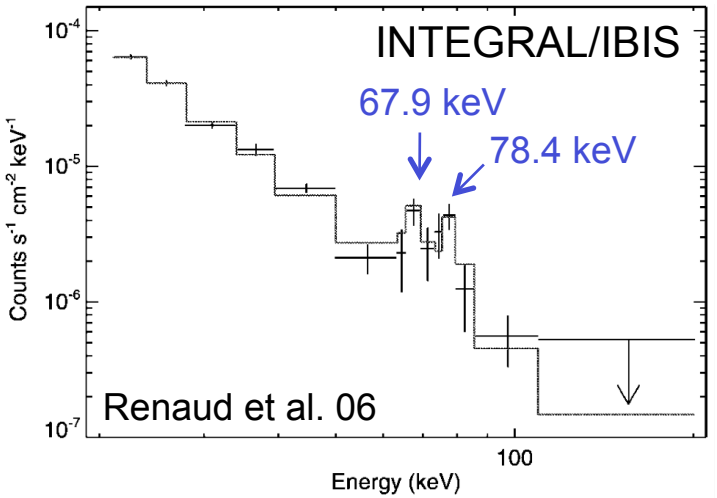
Access to the total mass of ^{44}Ti synthesized by the supernovae

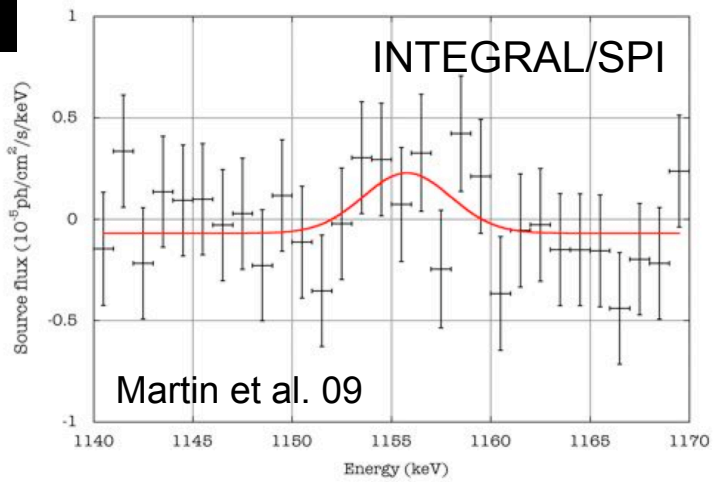
=> keys to the very depths of SNe and to the physical conditions of the explosion

- 67.9 and 78.4 keV (BeppoSAX, Vink et al. 01, INTEGRAL, Renaud et al. 06) => M(^{44}Ti) = 1.6 10^{-4} $M_\odot$
- 1157 keV (Comptel, Iyudin et al. 94) + search with INTEGRAL/SPI (Martin et al. 09)



Cas A

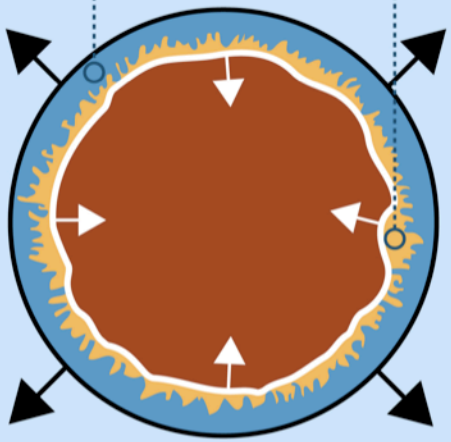


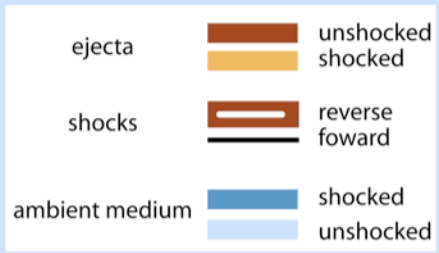


Difficult task with current hard X-ray instruments => **Nustar (2012)**

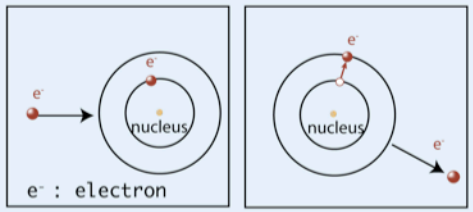
II.4 Emission X : raies d'excitation collisionnelle

Heating of the ambient medium by the foward shock

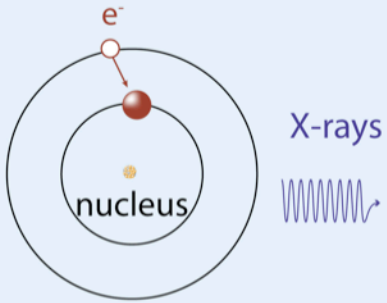




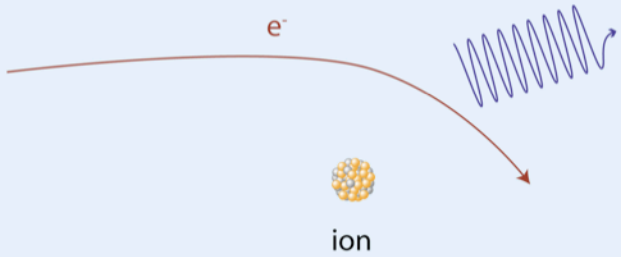
Heating of the ejecta by the reverse shock



Collisionally excited atom



Atomic desexcitation



Braking of the electron in an electric field

Graphic design by Aurélie Bordenave - Cea 2009

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Supernova remnants: key ingredients to understand our Universe

Direct measurements of the composition and spatial distribution of synthesized elements in the ejected material accessible through SNRs

OBJECTIVES

- to understand how heavy elements are produced, mixed and dispersed in the ISM
- to understand the explosion mechanism of stars and their progenitors
- to provide constraints to supernova models

How: by characterizing the emission from shocked and unshocked ejecta in young SNRs

Access to the elements synthesized by the supernovae: determination of the SN type

Access to the emitting conditions in the ejecta (density, temperature): constraints on progenitor and explosion mechanism

Access to the repartition and kinematics of the synthesized elements:

- level of mixing of elemental layers and asymmetry => understanding SN explosion
- level of mixing with the ambient medium => chemical enrichment in galaxies

For either type of explosion

- Intermediate elements (Si to Ca)
- Fe production
- Asymmetries/mixing of layers

are closely related to the explosion mechanism

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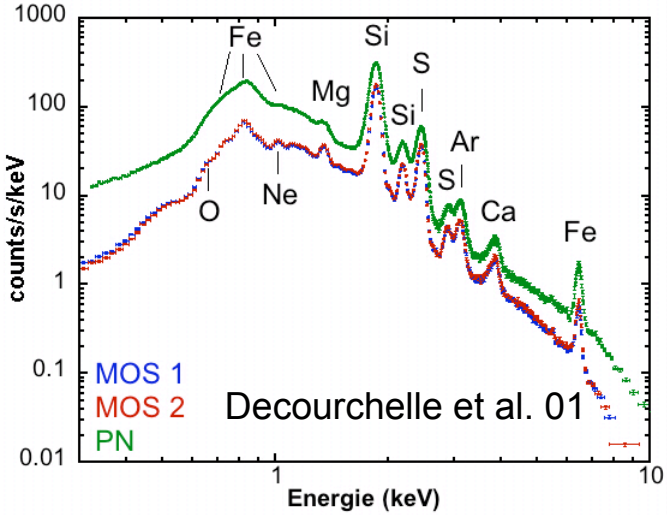
X-ray spatially resolved spectroscopy: a path to shocked ejecta

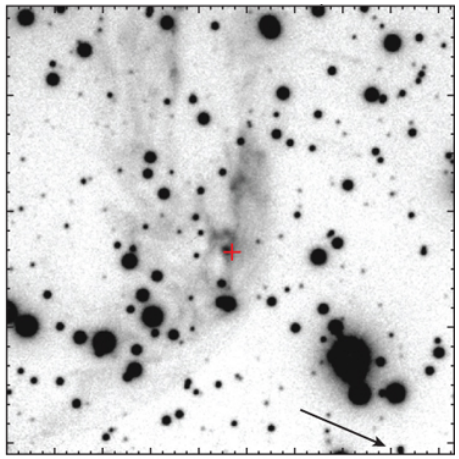
Tycho'SNR : an historical SN Ia supernova remnant (SN 1572)

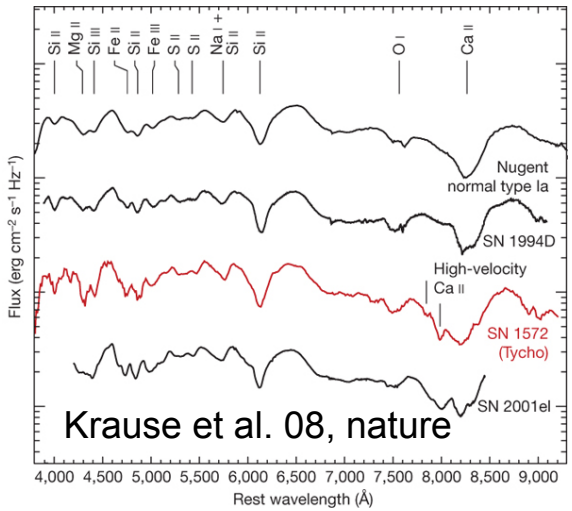
Overall X-ray spectrum constrains SN type and explosion mechanism:

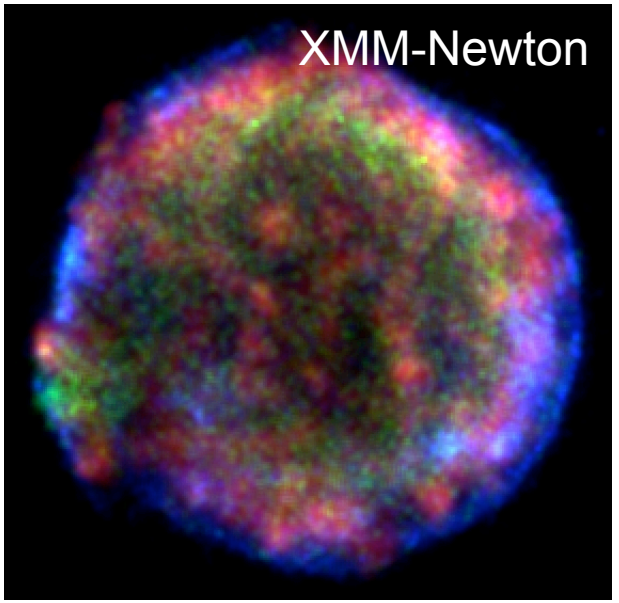
- delayed detonation favored for Tycho (Badenes et al. 06)
- normal type Ia confirmed by optical light echo spectrum (Krause et al. 08)



Optical light echo image and spectrum of SN 1572 compared with spectra of normal extragalactic SNe Ia





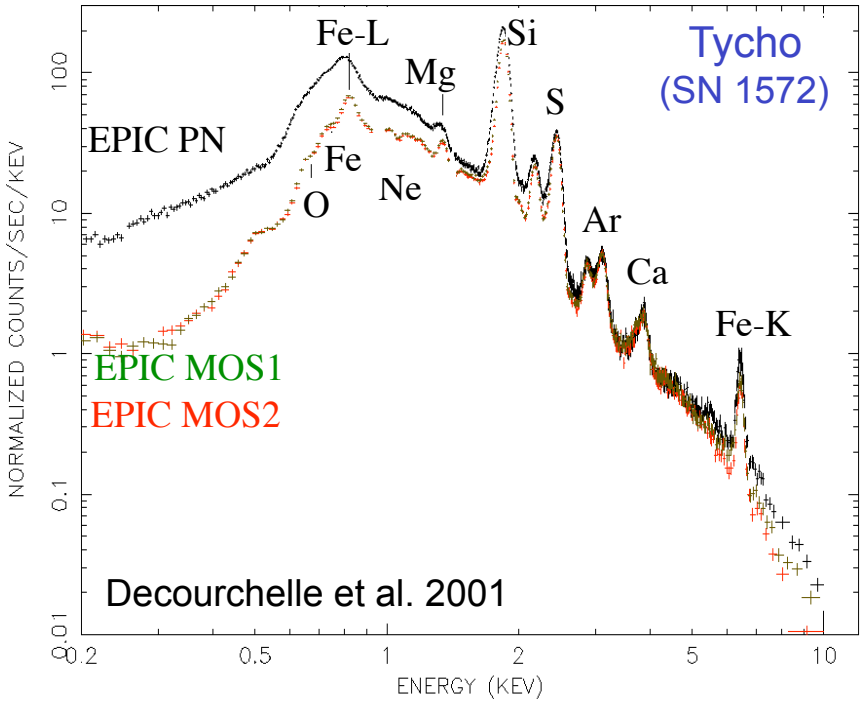


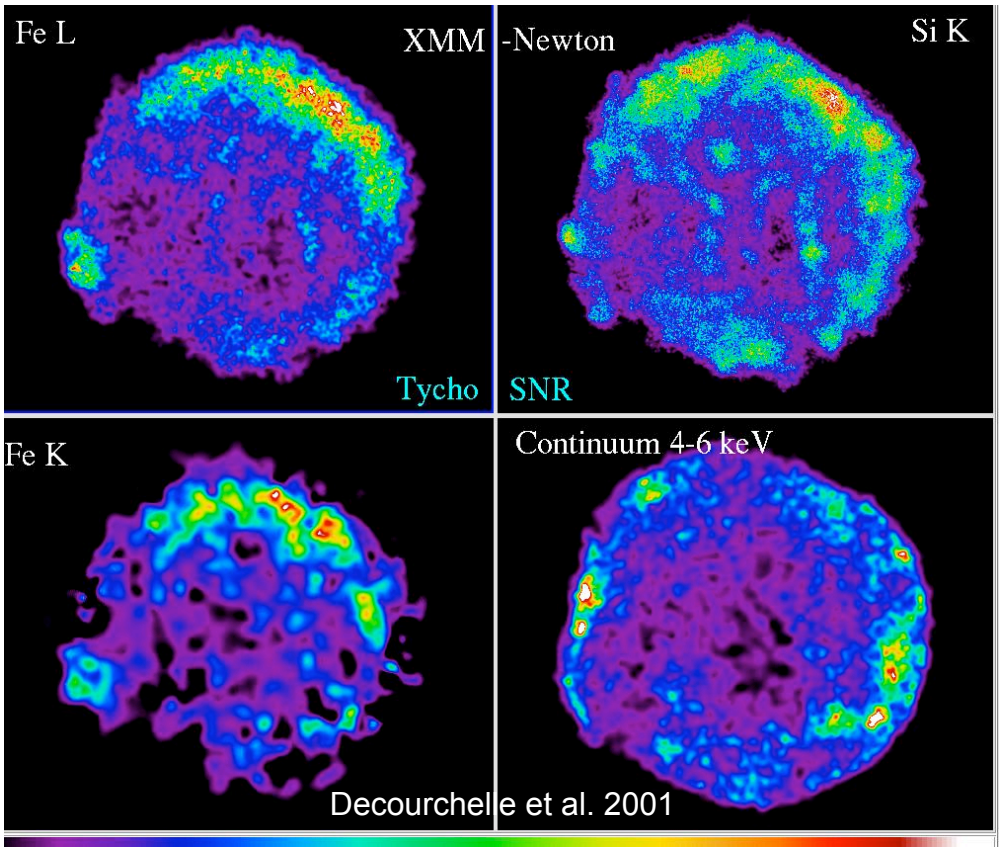
Irfu

Saclay

Characterization of the elements synthesized by type Ia supernovae

Goal: constrain the explosion mechanism and supernova progenitor
Method: characterization of the thermal emission

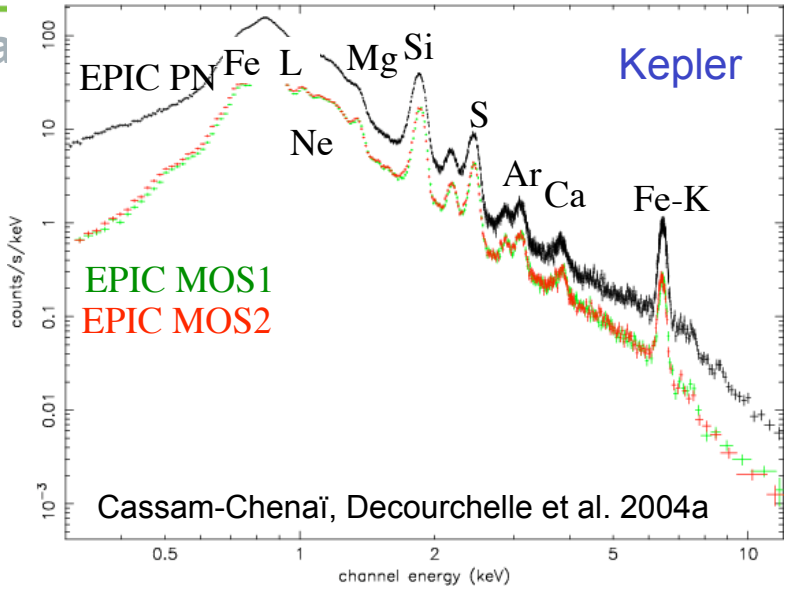


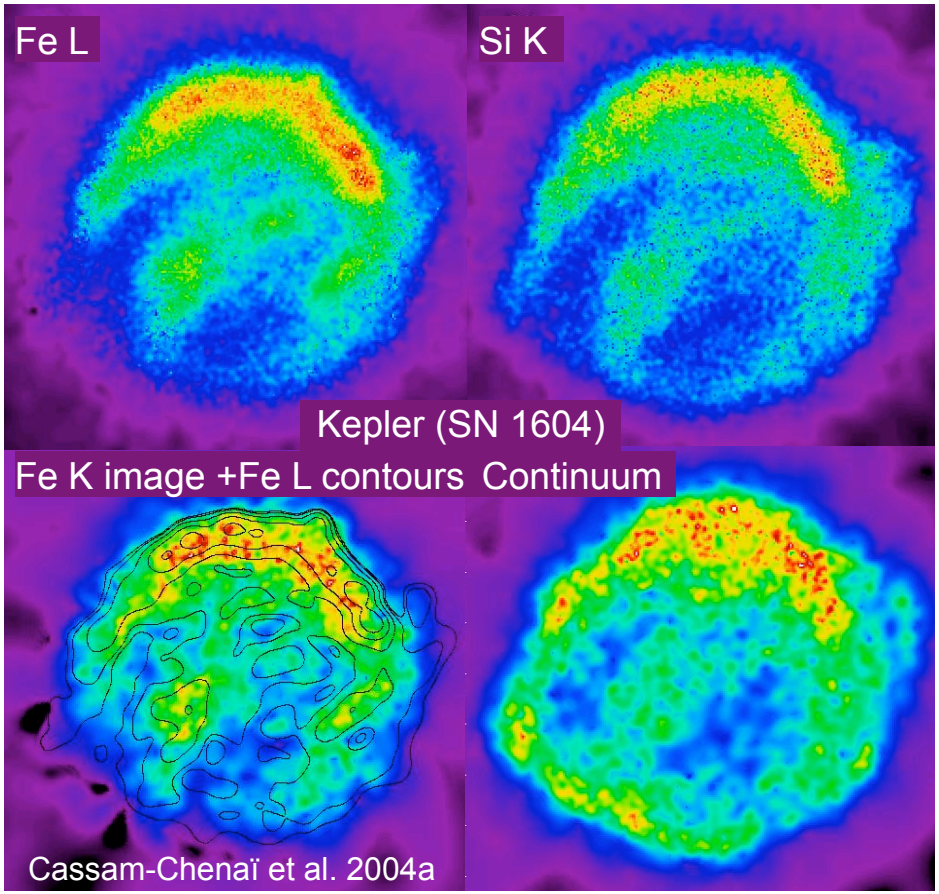


- Efficient overall mixing of the Si and Fe layers, but inhomogeneities at small scale.
- Fe K emission peaks at smaller radius than Fe L: higher temperature towards the interior
- Continuum emission associated with the forward shock (shown by Chandra to be nonthermal)

Characterization of the elements synthesized by supernovae

Kepler's SNR (SN 1604): a long debated historical SN type





Similarity with Tycho SN Ia

- Lines emission from Si, S, Ar, Ca, Fe
- Overall mixing of the Si and Fe layers
- Higher temperature in the interior (Fe K / Fe L)

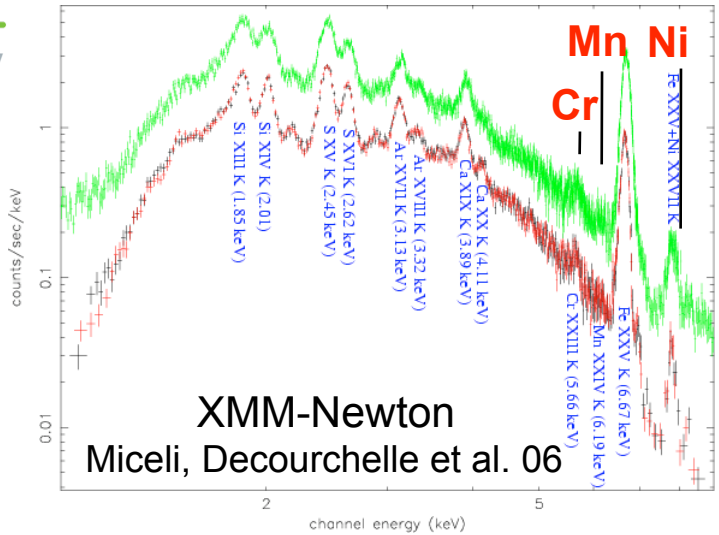
Difference: strong asymmetry of the X-ray morphology

=> circumstellar material (Cassam-Chenaï et al. 2004a)

=> SN Ia in a massive progenitor: **a different path to produce SN Ia?** (Reynolds et al. 2008)

Characterization of the elements synthesized by core collapse SNe

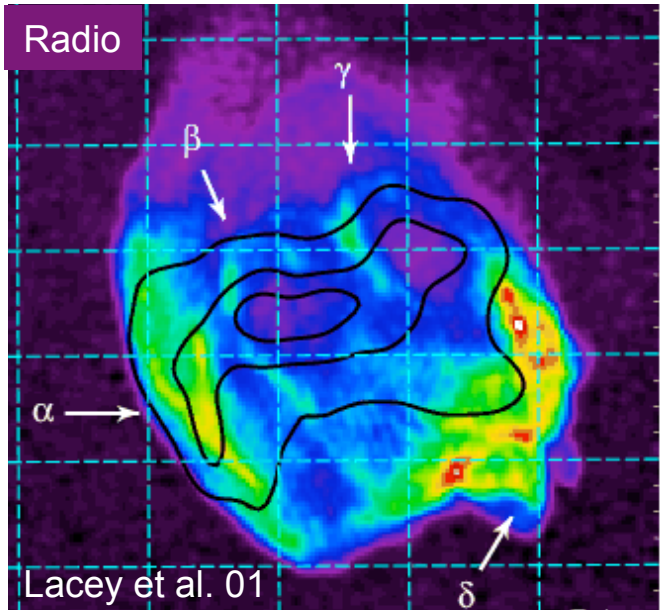
W49B : a pure ejecta-dominated core-collapse supernova remnant

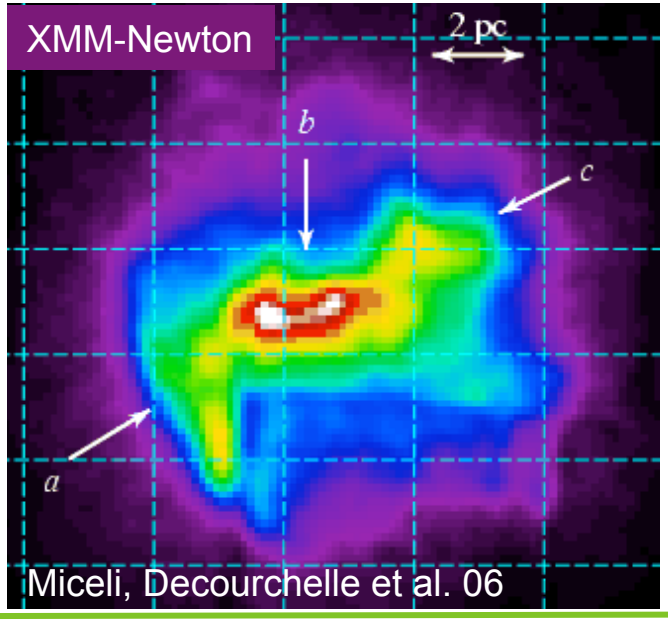


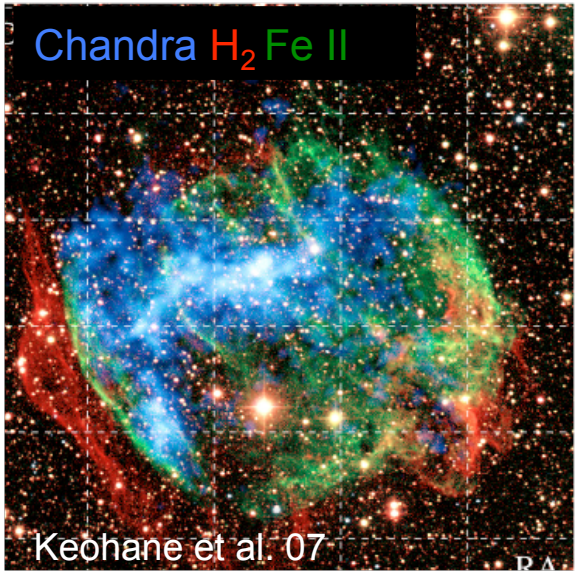
- Presence of rare elements (Cr, Mn, Ni)
- Strong bipolar X-ray ejecta emission :

  asymmetry of the explosion or circumstellar and interstellar environment ?

How are distributed the synthesized elements in the ejecta ?







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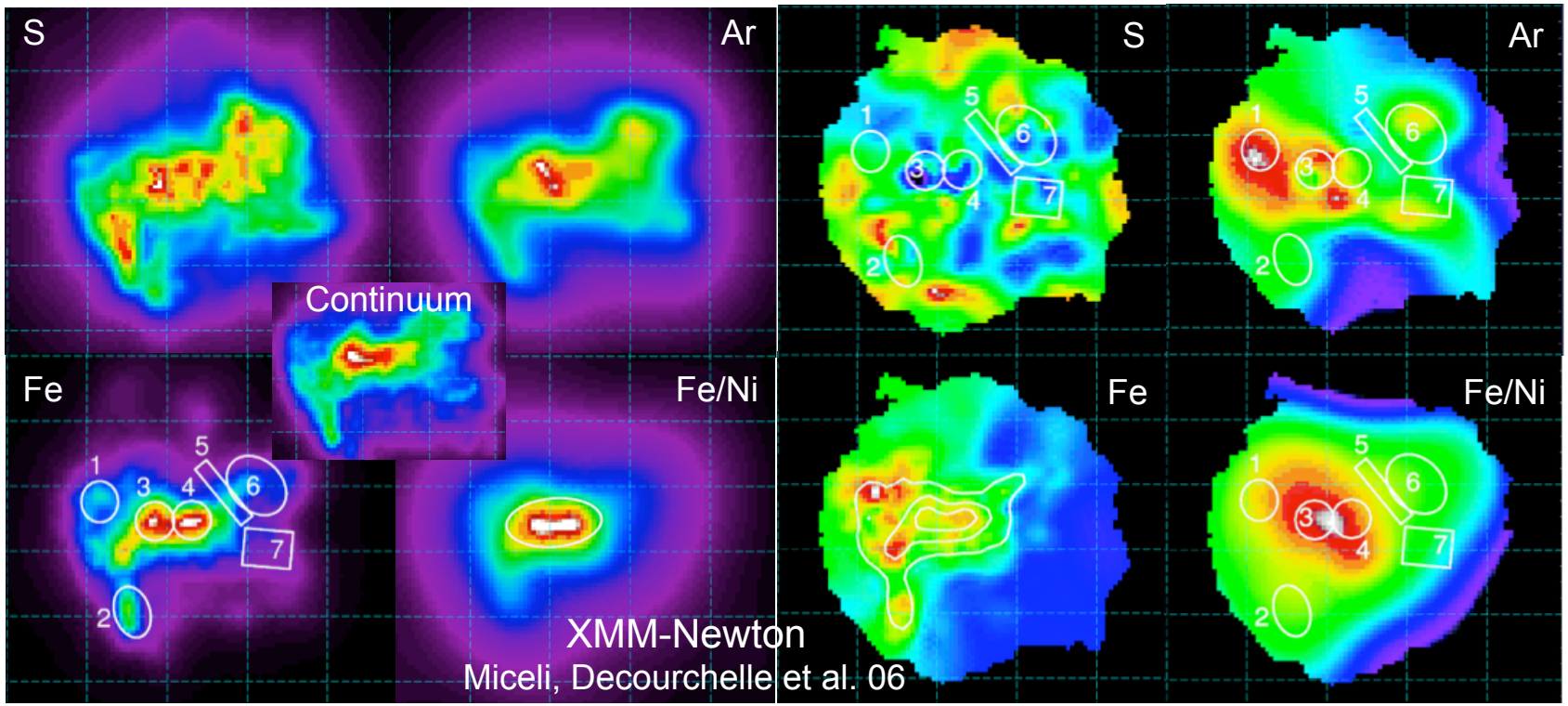
Saclay

Distribution of the synthesized elements in W49B

Line emission maps = f(n_e, Ab_z, T_e)

Equivalent width maps = f(Ab_z, T_e)



Elemental distribution:

=> equivalent width images and spatially resolved spectroscopy

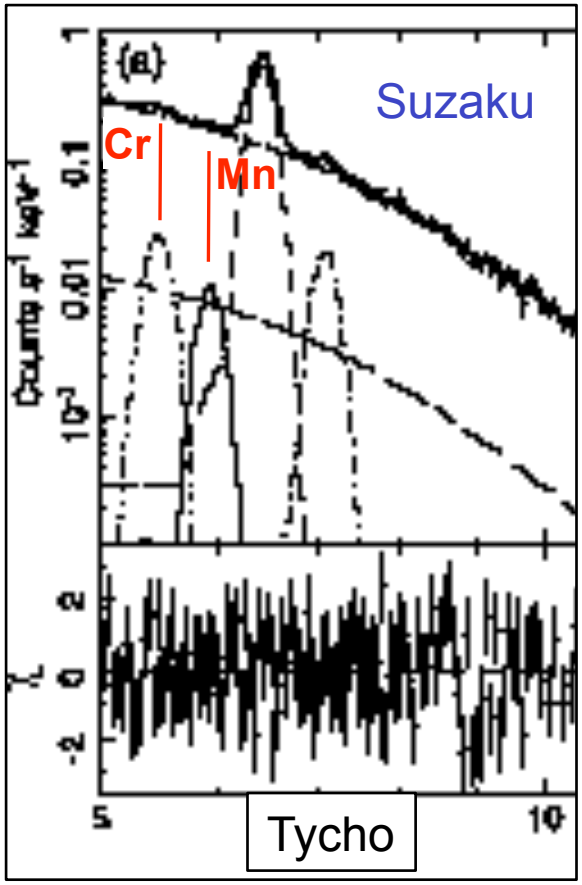
Strong asymmetry in the Fe distribution:

Ab_{Fe} and temperature are the largest in the east side, supported by spatially resolved spectroscopy.

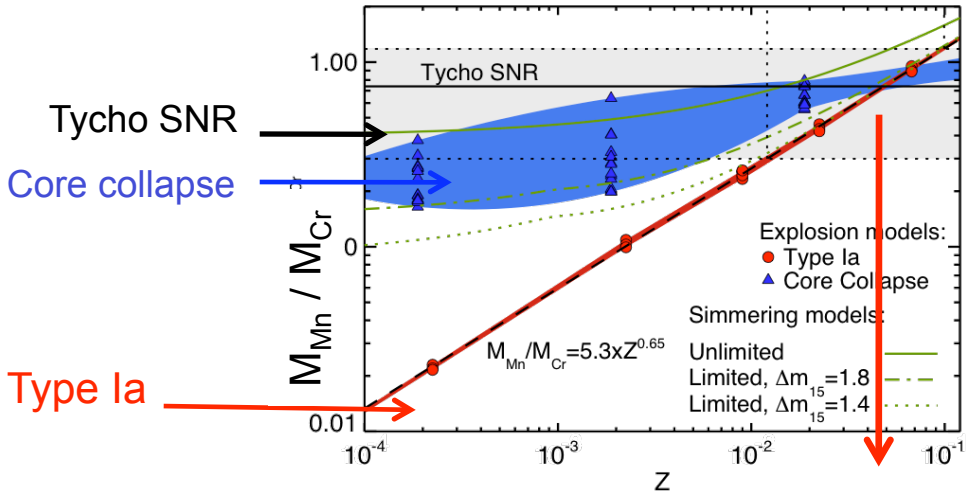
=> Kinematics of the ejecta required to understand the morphology

Presence of Cr and Mn Kα lines in the X-ray spectrum of young SNRs

- W49 B (ASCA, Hwang et al. 00, XMM-Newton Miceli et al. 06)
- Tycho (Suzaku, Tamagawa et al. 09)
- Cas A, Kepler (Cr only, Chandra, Yang et al. 09)



⇒For type Ia, Mn / Cr is a promising tracer of progenitor metallicity (Badenes et al. 08, 09)



Z = 0.048

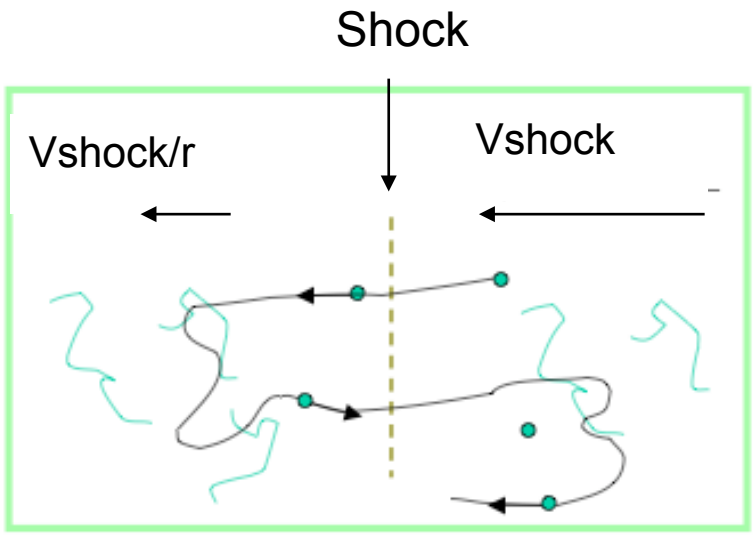
III. Accélération de particules

1. Origine des rayons cosmiques galactiques
2. Observations de l'accélération de particules dans les restes de supernova : de la radio au TeV
3. Caractérisation de l'accélération
   - Amplification du champ magnétique au choc
   - Energie maximale atteinte dans les restes de supernova
   - Efficacité de l'accélération : rétroaction des particules accélérées

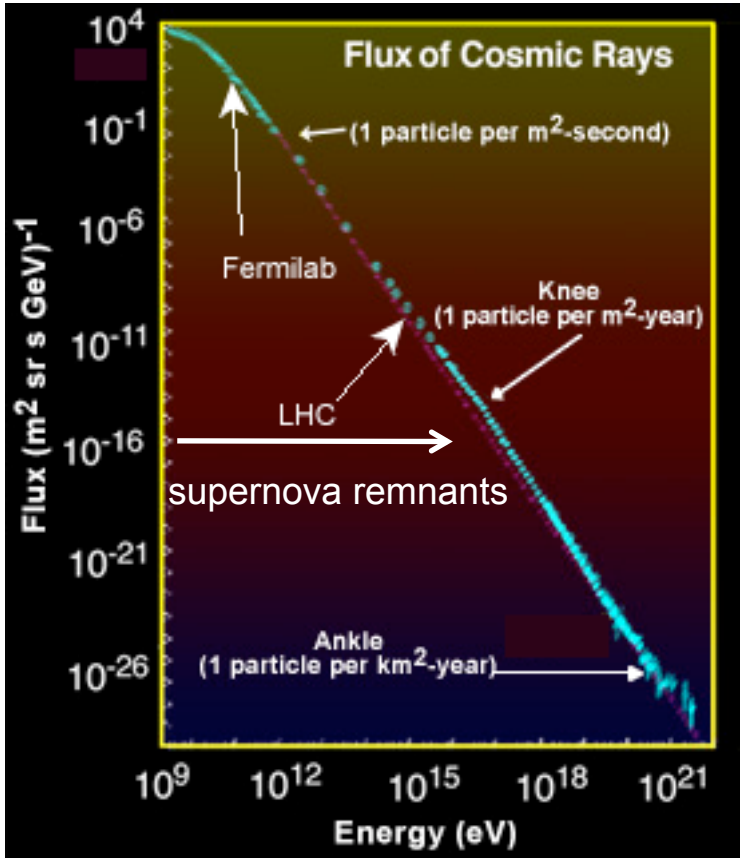
III.1 Origine des rayons cosmiques galactiques et restes de supernova

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

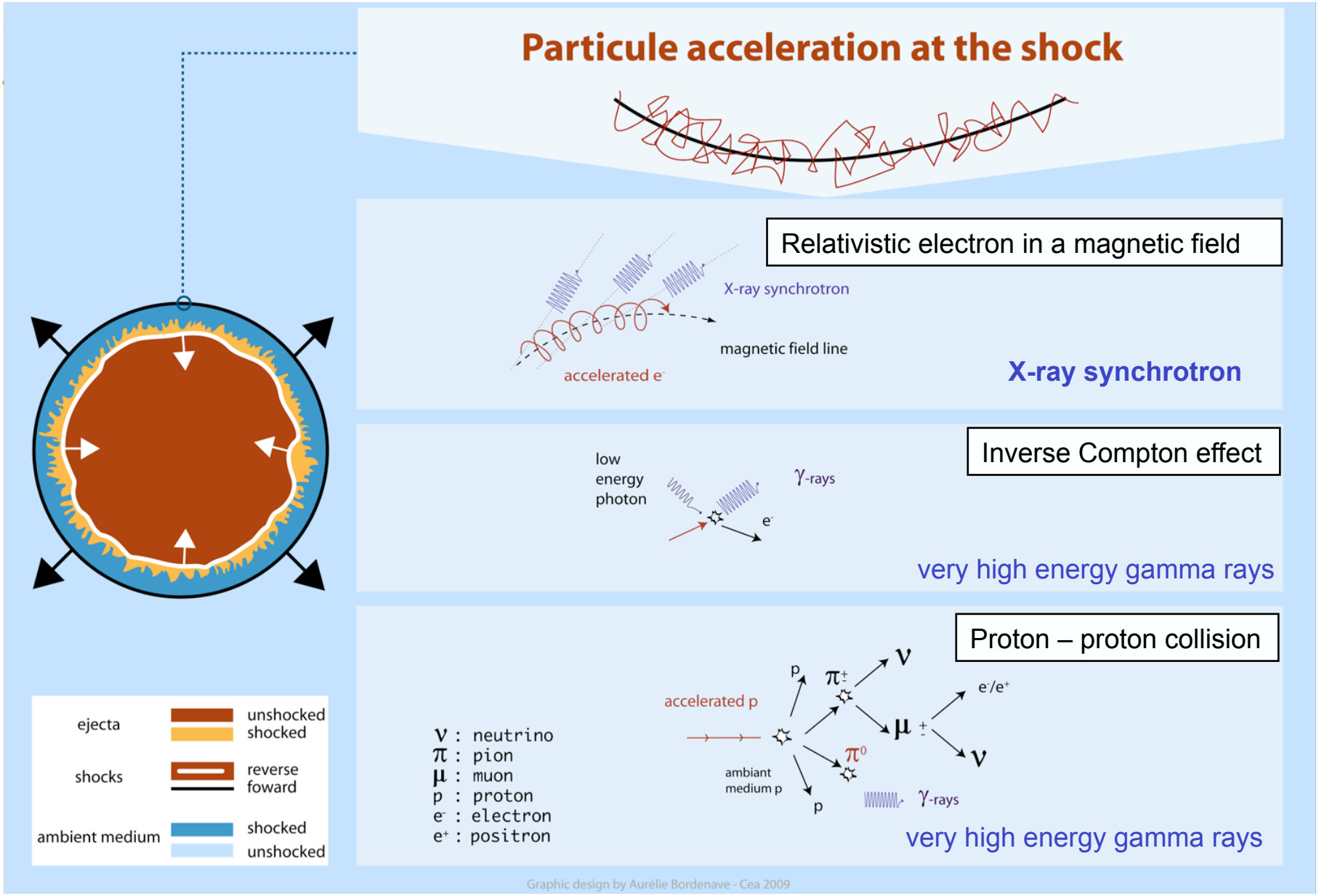
- 10% of their kinetic energy: to maintain the pool of Galactic Cosmic rays
- High mach number shocks: 1st order Fermi mechanism through diffusive shock acceleration (1949)



First order Fermi acceleration



III.2 Observation de l'accélération de particules de la radio au TeV

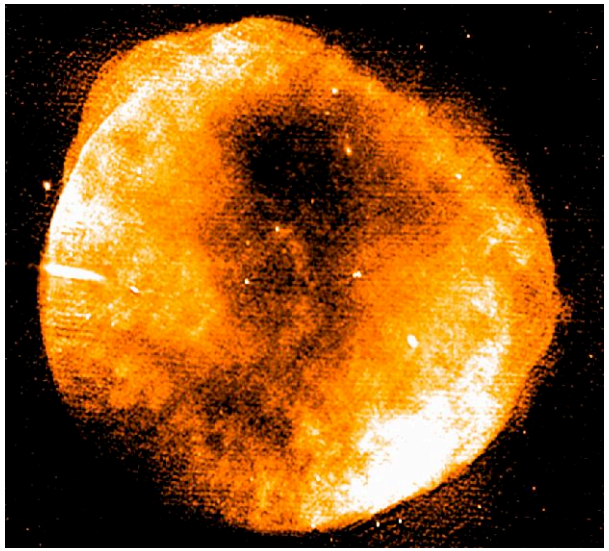


III.3 Emission non thermique de la radio au TeV : SN 1006

Radiative signatures at their shock:

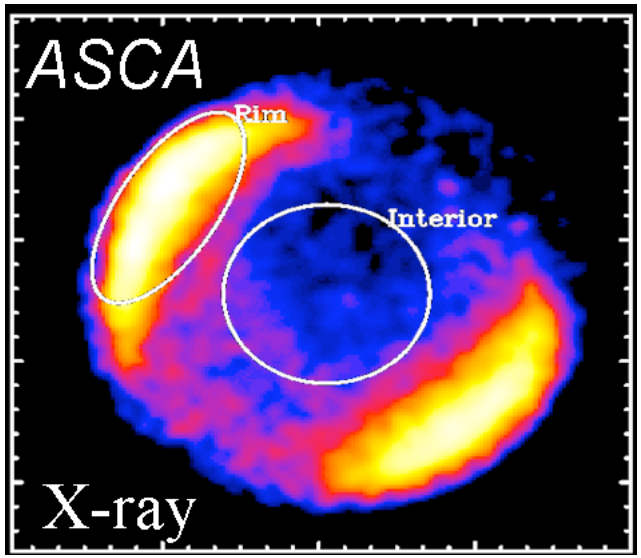
- Radio synchrotron => electrons accelerated to GeV energies (Hanbury Brown 1954)
- X-ray synchrotron => electrons up to TeV energies in SN 1006 (Koyama et al. 1995, Nature)
- TeV gamma-ray emission => particles accelerated to TeV energies (Aharonian et al. 2004, Nature)

Radio



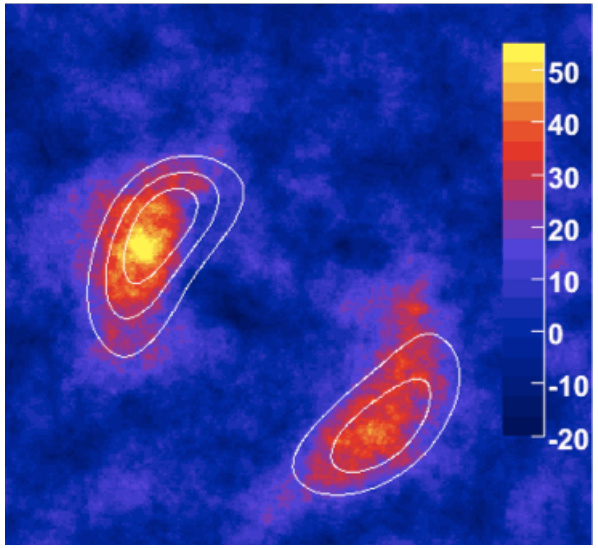
Petruk et al 08

X-ray



Koyama et al. 95

TeV gamma-ray

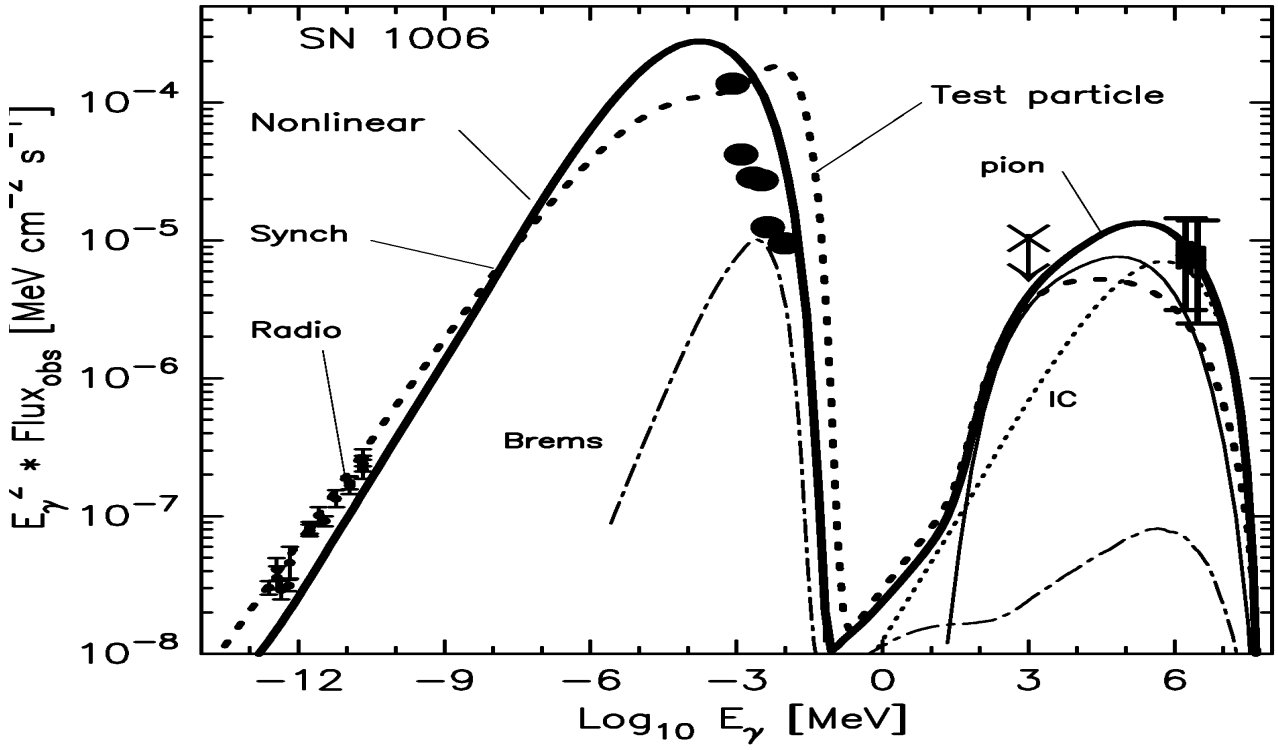


Naumann-Godo et al. 09

III.3 Emission non thermique de la radio au TeV : SN 1006

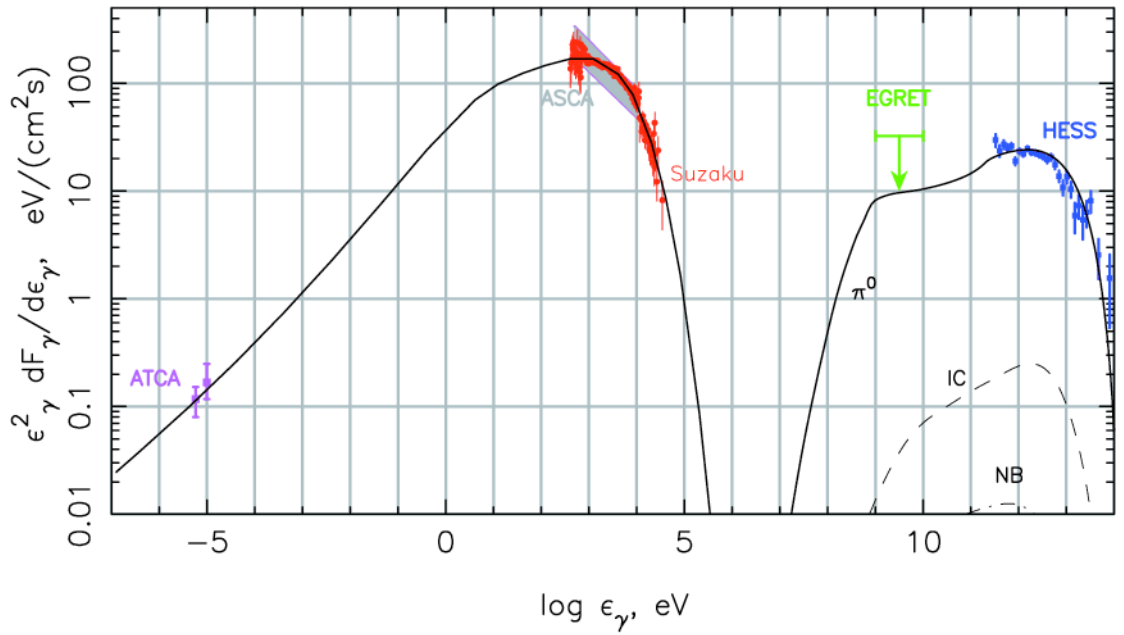
- π^0 following p-p collisions in GeV range
- Inverse Compton on CMB in TeV range

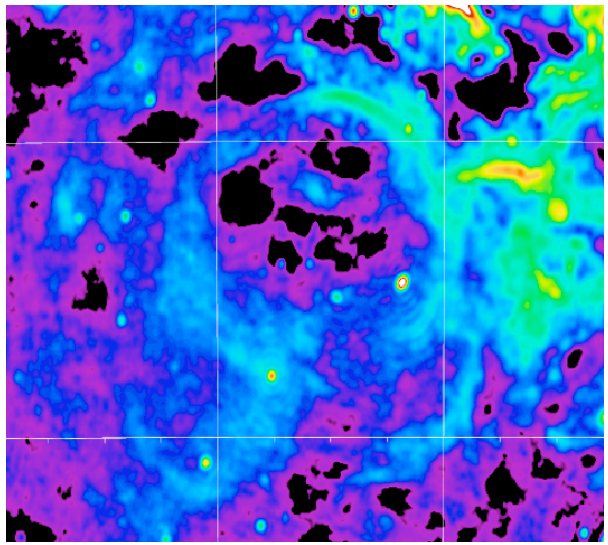
- Synchrotron from radio to X-rays
- Thermal (continuum + lines) in X-rays



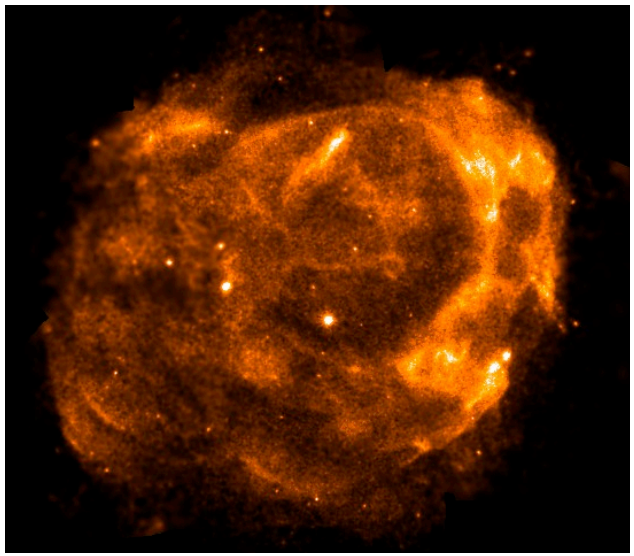
Ellison, Berezhko and Baring 2000, ApJ **540**, 292

III.3 Emission non thermique de la radio au TeV : G347.3-0.5

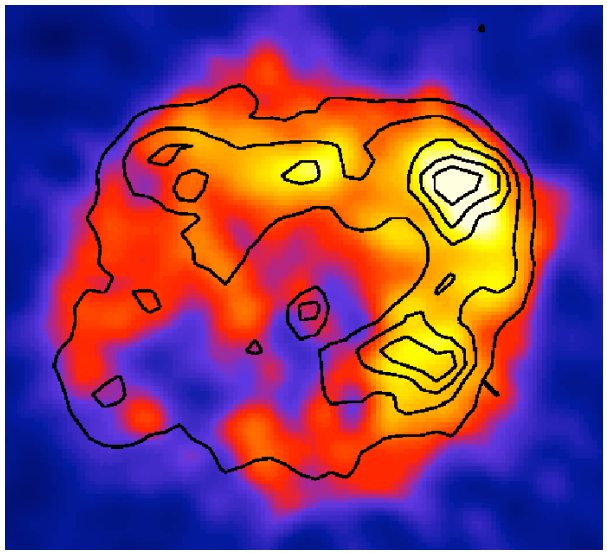




Radio - ATCA



Rayons X - XMM-Newton



Rayons gamma - HESS

III.3 Caractérisation de l'accélération de particules au choc dans les RSN

Objective : to understand the process of particle acceleration and the origin of Galactic cosmic rays

- What is the level of magnetic field amplification at the shock ?
- What is the maximum energy of the accelerated particles ?
- What is the efficiency of particle acceleration ?
- …

Why are X-rays crucial to investigate particle acceleration ?

- Physics of the synchrotron emission of the electrons accelerated at the highest energy
- Physics of the thermal gas
  - Global parameters of the remnant
  - Back-reaction of accelerated protons
- Capability of performing spatially-resolved spectroscopy at small scale

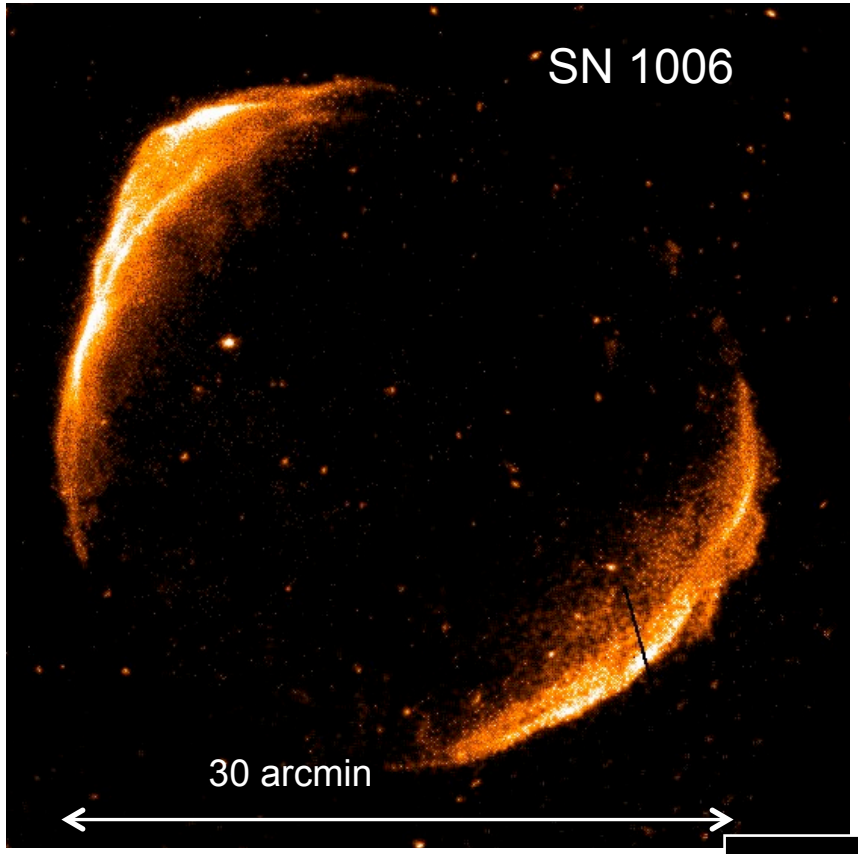
  (< 10 arcsec while VHE gamma-ray instruments ~0.1 deg at best)

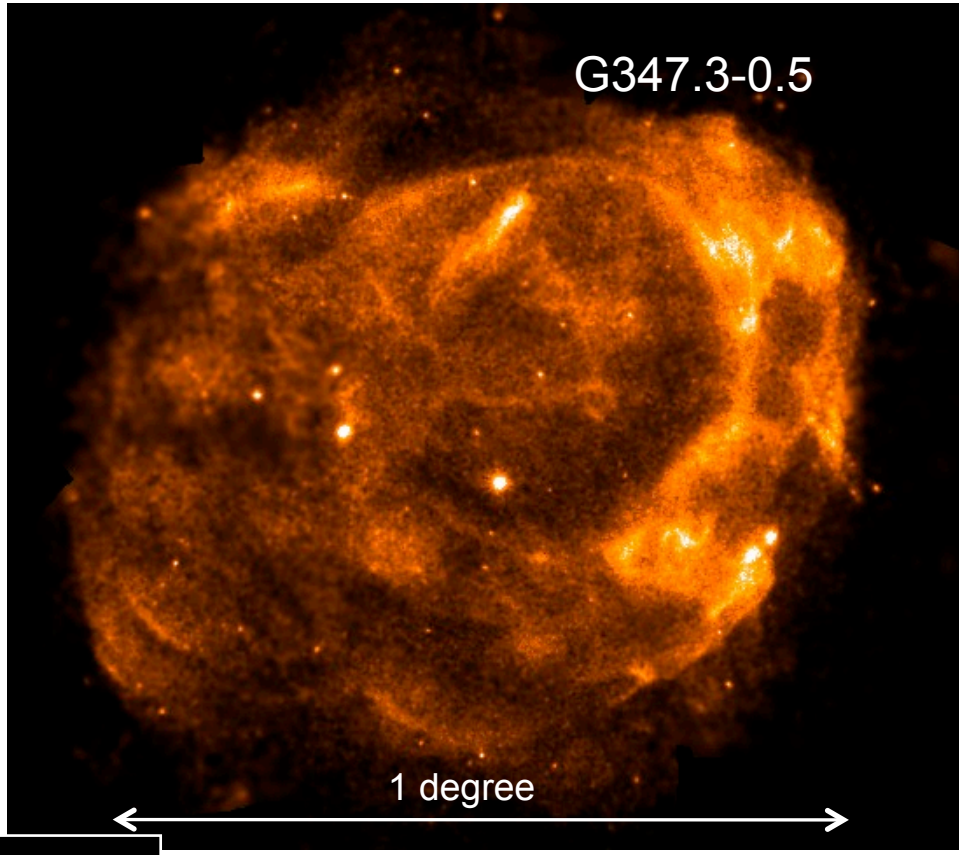
III.3 Observations: characterization of the properties of particle acceleration

Saclay

Method: characterization of the synchrotron and thermal emission

Tool: spatially resolved X-ray spectroscopy using radio and XMM-Newton data





XMM-Newton

Rothenflug et al. 2004
Acero, Ballet, Decourchelle 2007

Cassam-Chenaï, Decourchelle et al. 2004b
Acero, Ballet, Decourchelle et al. 2009

Irfu

Saclay

How large is the magnetic field ? Is it very turbulent ? Is it amplified ?

The magnetic field is a crucial parameter :

- for understanding particle acceleration
- for deriving the maximum energy of accelerated particles
- for interpreting the origin of TeV γ-rays : leptonic versus hadronic

Morphology and variability of the synchrotron emission

- Sharp filaments observed at the forward shock : width determined by synchrotron losses of ultrarelativistic electrons

  (Park et al. 09, Parizot et al. 06, Bamba 05, 04, 03, Vink & Laming 03,…)

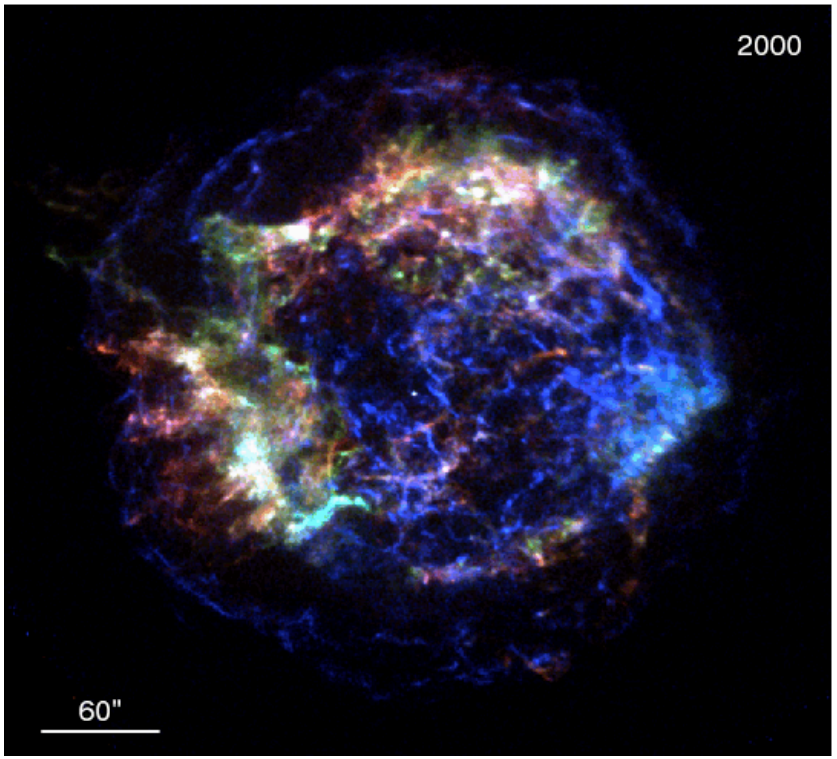
- Fast variability of the brightness of these filaments

  (Patnaude et al. 09, Uchiyama et al. 08, 07)

- Broad band modeling of the nonthermal emission

  (Berezhko et al. 09,Voelk et al. 08,...)

=> high value of $B_{downstream}$(~ 50-500 μG) which implies large magnetic field amplification

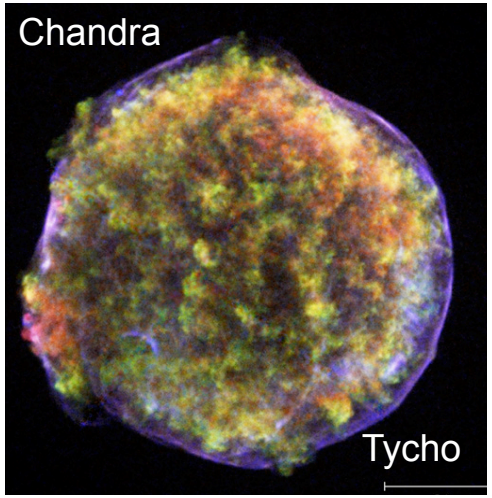


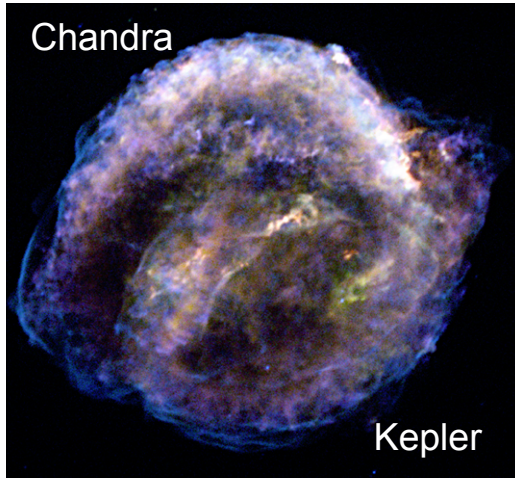
Patnaude et al. 09

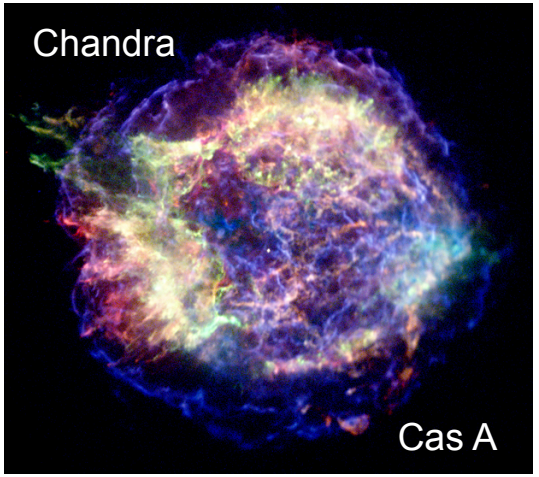
III.3.1 Amplification du champ magnétique au choc : filaments fins

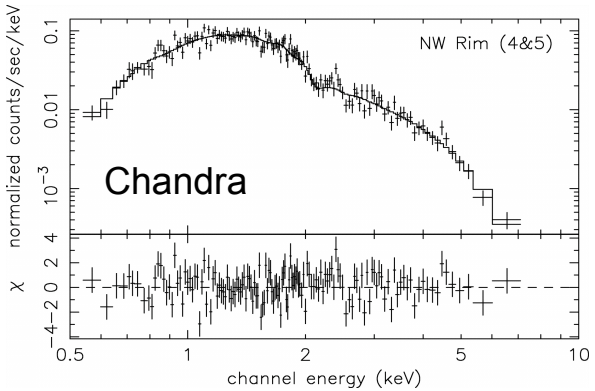
Sharp filaments at the forward shock all along the periphery of young ejecta-dominated SNRs, in bilateral limbs in SN 1006 and irregularly along the periphery of G347.3-0.5

=> synchrotron emission

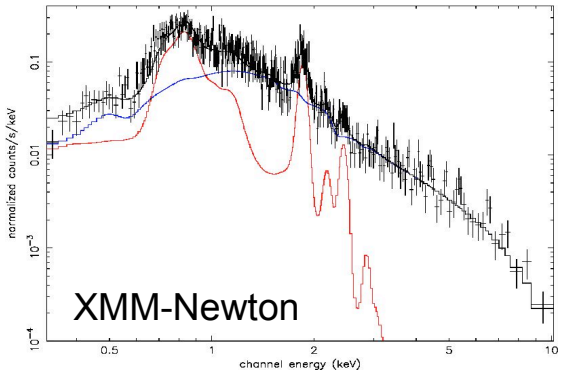




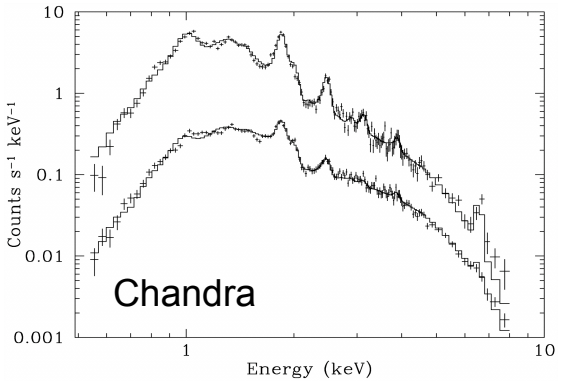




Hwang, Decourchelle et al. 2002



Cassam-Chenaï, Decourchelle et al. 2004a



Vink and Laming 2003

=> width of the filament determined by synchrotron losses of ultrarelativistic electrons

Irfu

Saclay

III.3.2 Energie maximale atteinte dans les restes de supernova

What is the maximum energy 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, except for the radiative losses

Spectrum of the synchrotron emission (radio + X-rays)

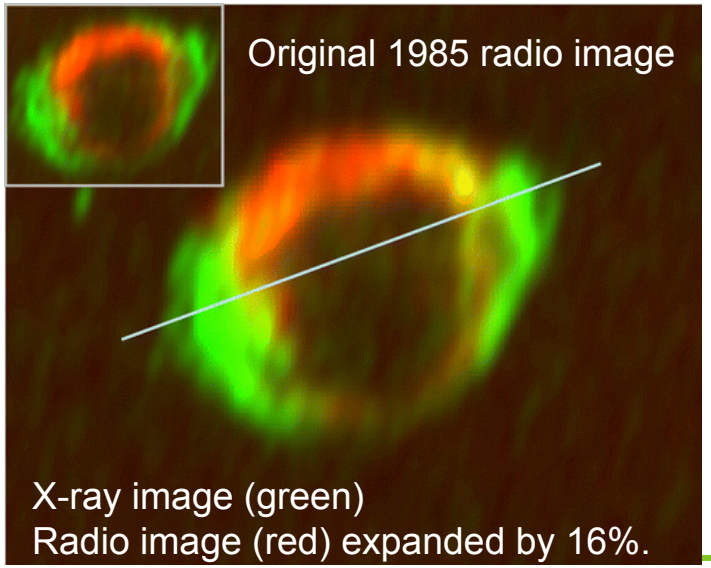
- **Measurement of the roll-off photon energy $h\nu_{roll}$**, observable in X-rays

+

- Estimate of downstream magnetic field

⇒ **Estimate of the maximum energy of accelerated electrons :**

$E_{max} = 39\ (h\nu_{roll} / B_{10})^{1/2}\ \mathrm{TeV}$ **~ few 10 TeV**



G1.9+0.3: the youngest observed galactic SNR

(Reynolds et al. 08, 09, Green et al. 08)

Expansion by 16 % between 1985 and 2007

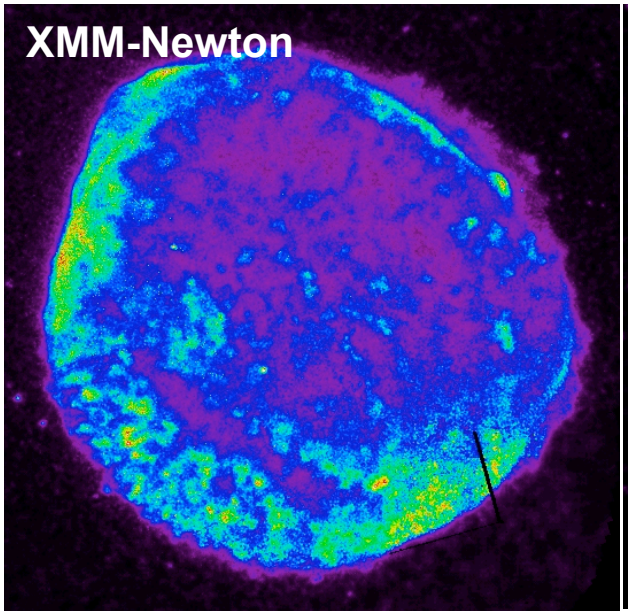
=> Vs ~ 14000 km/s for D ~ 8.5 kpc, age ~100 yr

$h\nu_{roll}$ ~ 2.2 keV, among the highest reported

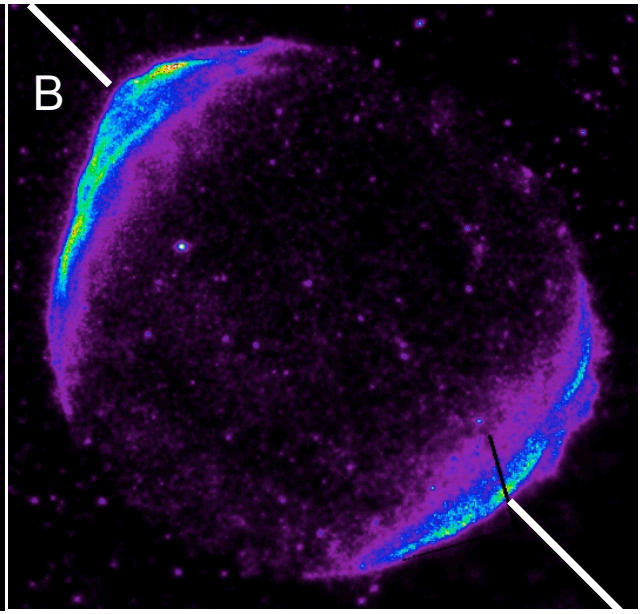
E_{max} ~ 70 TeV assuming B ~10 μG

SN 1006: characterization of the geometry of the acceleration

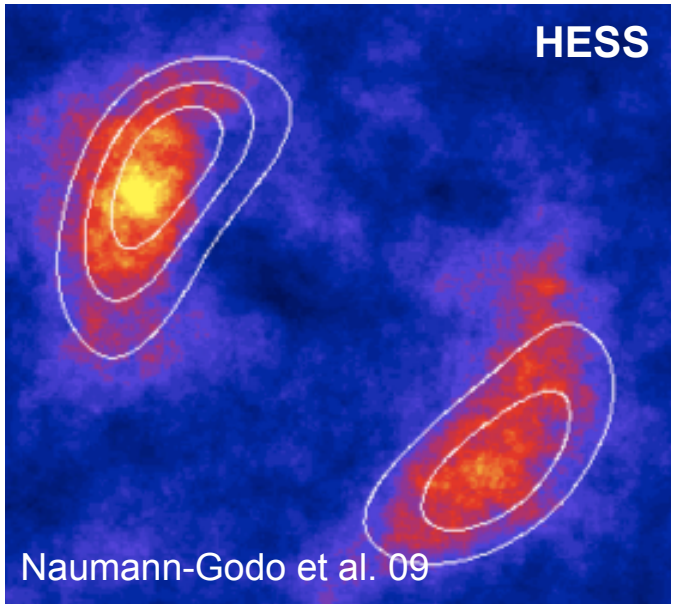
High latitude SNRs evolving in a uniform interstellar magnetic field, like SN 1006, offer the possibility to investigate the dependence of the process of particle acceleration with B orientation



0.5-0.8 keV



2.0 - 4.5 keV



0.4 - 8 TeV

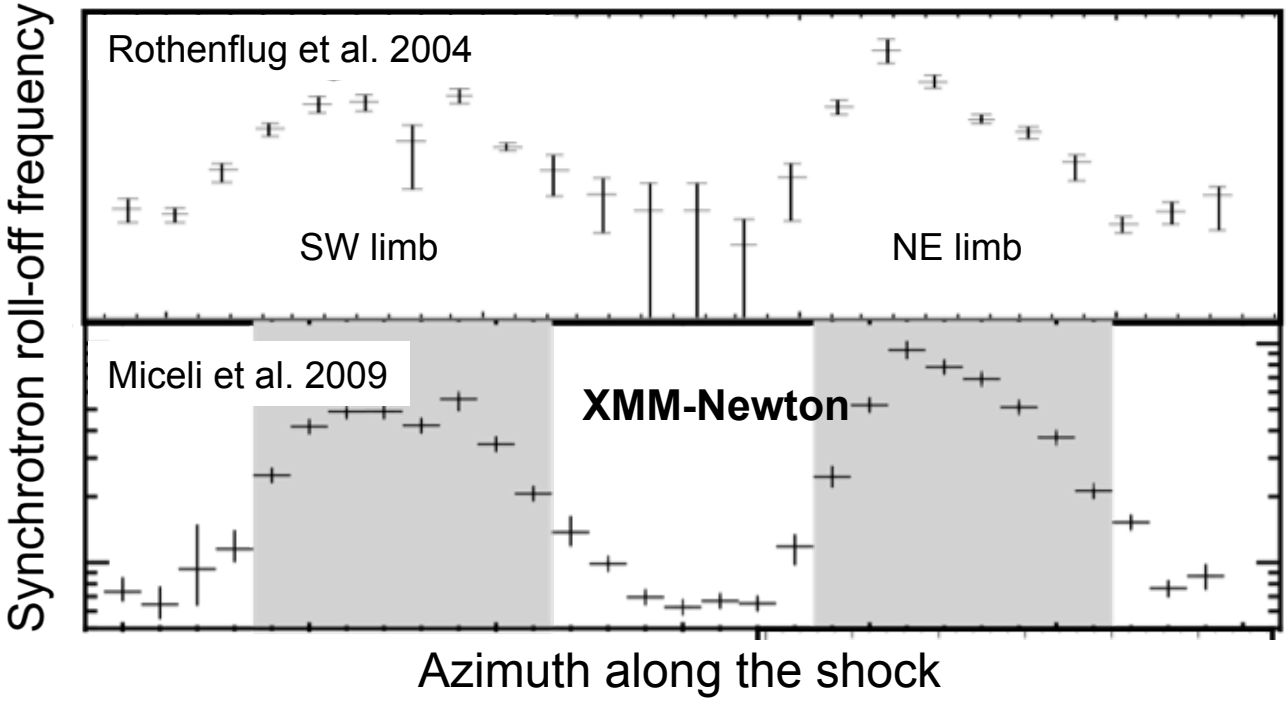
Synchrotron X-ray morphology indicates limbs are polar caps rather than an equatorial belt
(Rothenflug et al. 2004)

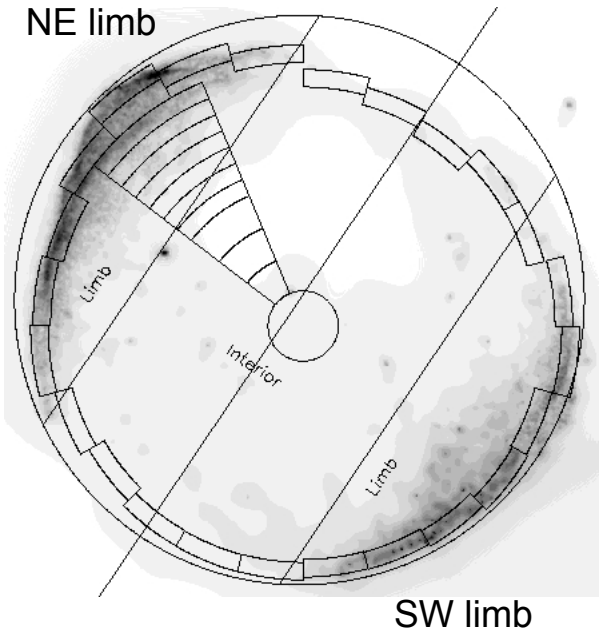
=> particles are accelerated where the magnetic field is parallel to the shock velocity

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





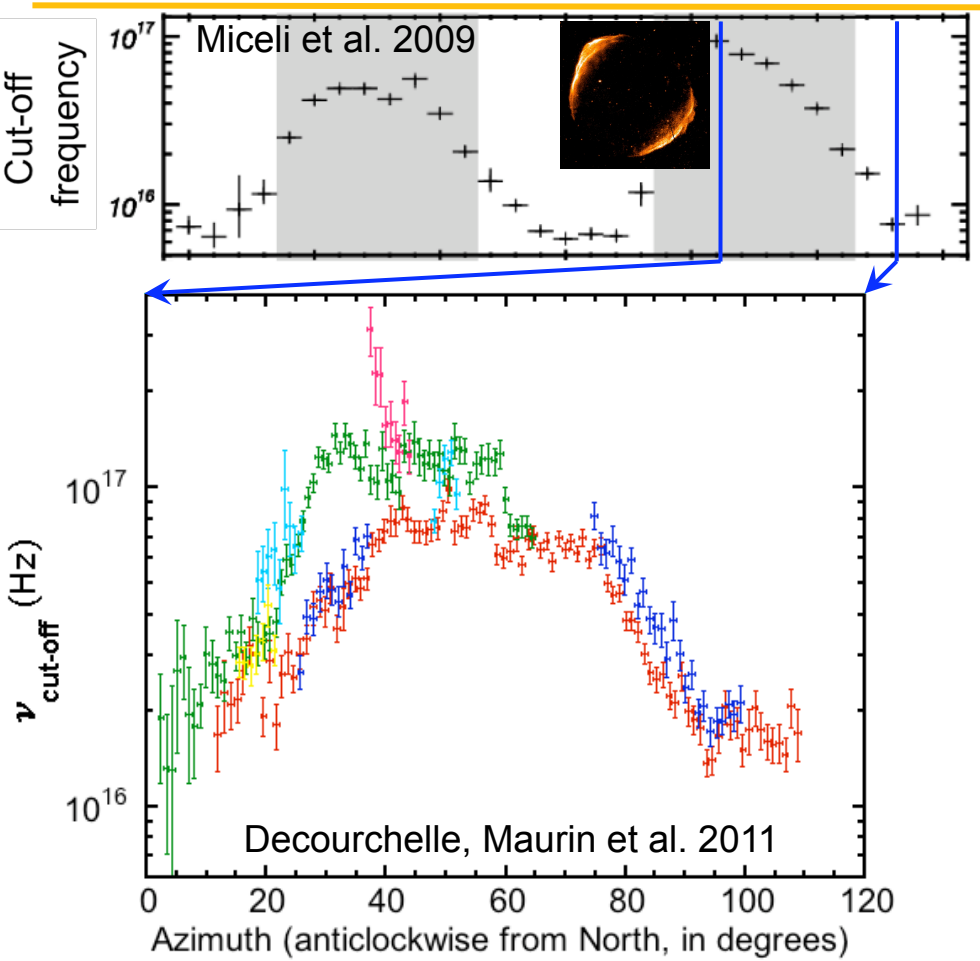
SN 1006: very strong variations of the synchrotron roll-off frequency

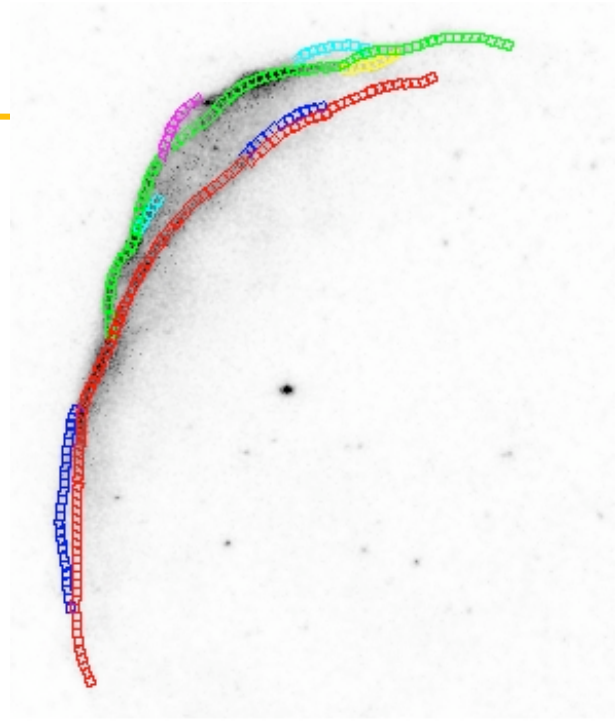
=> Maximum energy of accelerated particles must be higher at the bright limbs than elsewhere

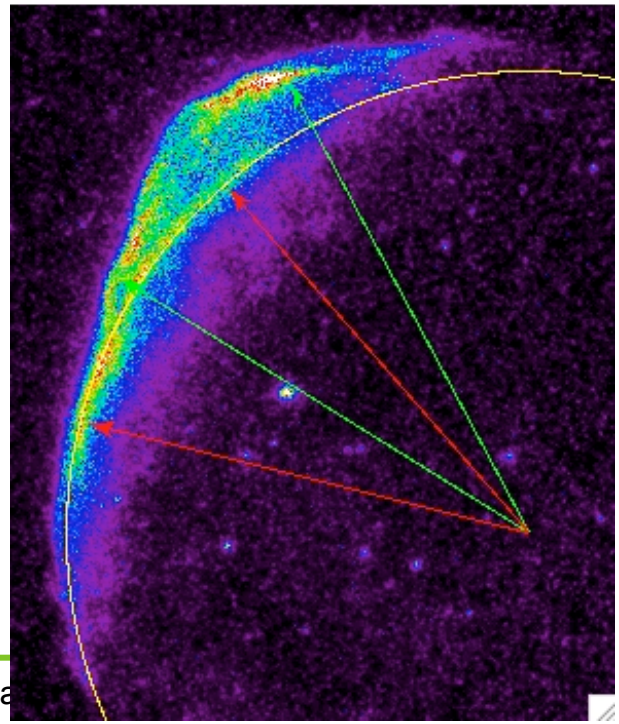
Irfu

Saclay

Cut-off frequency along each filament







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

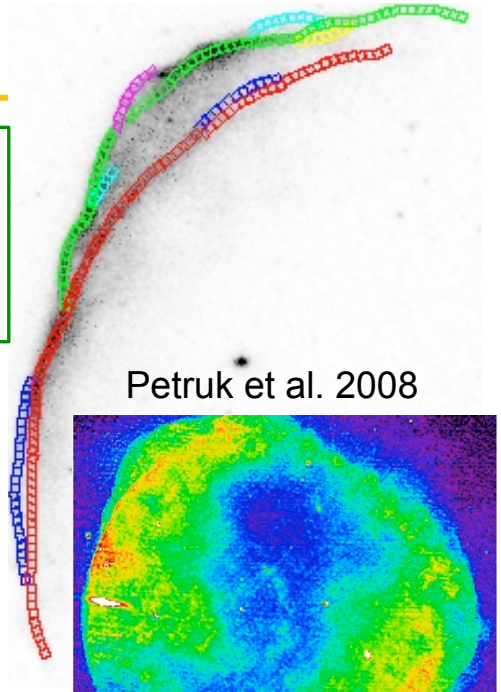
- a rapid increase, followed by a plateau and a rapid decrease
- increase amplitude depends on filaments (from 4 to 10)
- the most outward filaments have larger cut-off frequency

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

Synchrotron spectral index

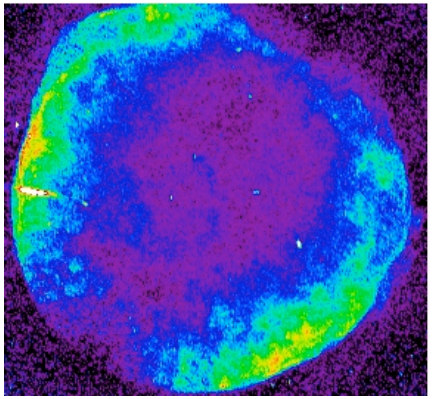
Along all filaments, same behaviour of the spectral index

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

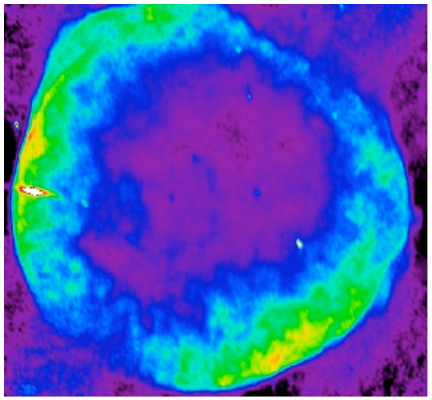


Radio maps

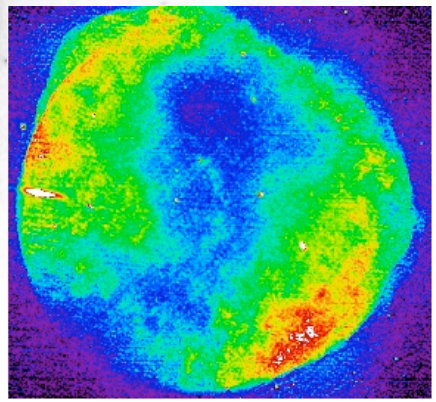
Dyer et al. 2009

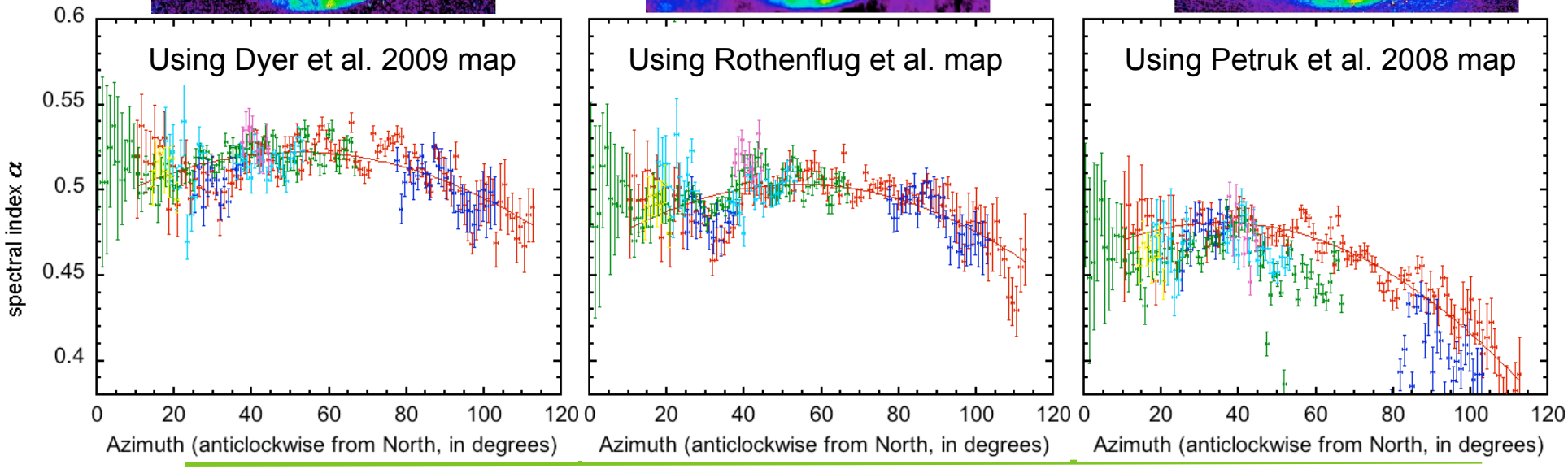


Rothenflug et al. 2004



Petruk et al. 2008





Particle acceleration at the north-east pole in SN 1006

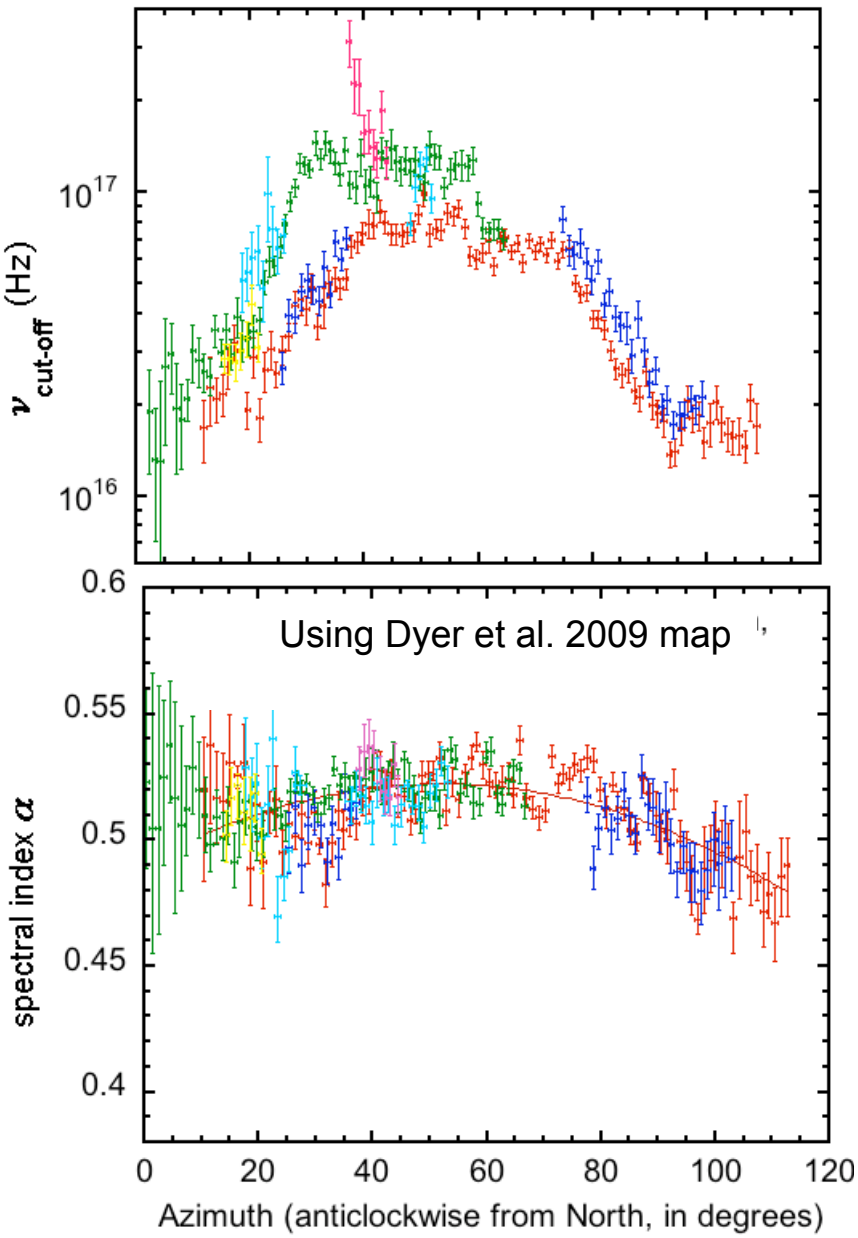
At the north-east pole:

- 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 ?
- Largest spectral index: highest back-reaction on the particle spectrum?
  ⇒highest acceleration efficiency/injection

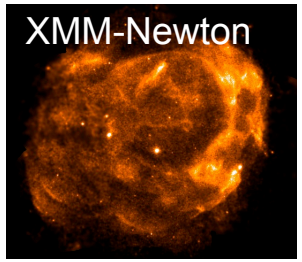
(Decourchelle, Maurin et al., 2010, in prep)

Azimuthal dependence provides very strong constraints to the acceleration mechanism

=> detailed modeling required

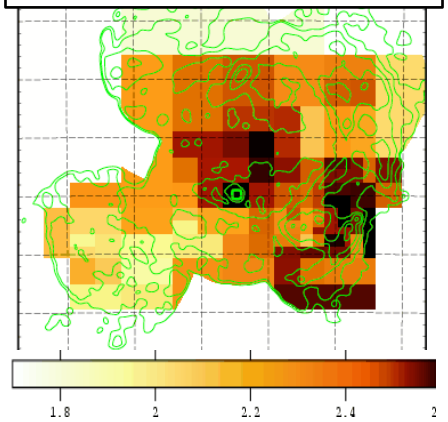


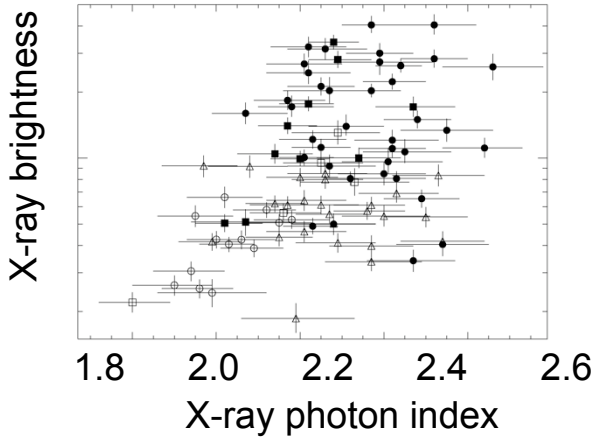
RX J1713.7-3946: X-ray and TeV γ-ray spatially resolved spectroscopy



Acero et al. 2009

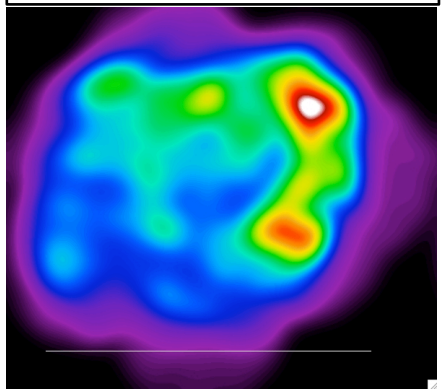
XMM photon index map

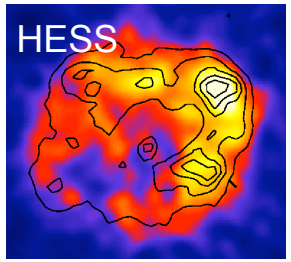




Cassam-Chenai et al. 2004b

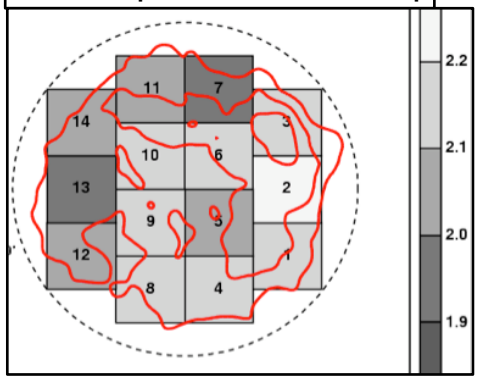
Image XMM avec la PSF de HESS



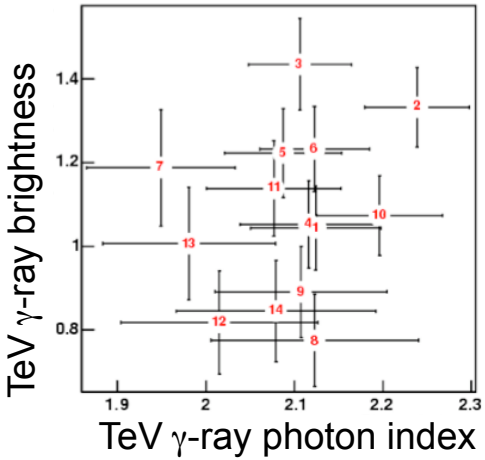


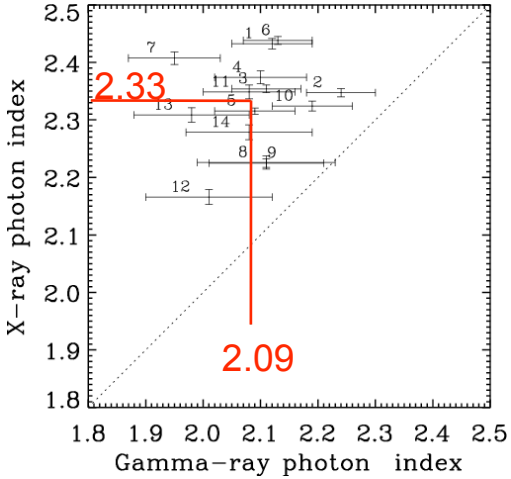
Aharonian et al. 2004

HESS photon index map



Aharonian et al. 2006





- Large variation of X-ray photon index [1.8-2.6], the steepest in the densest regions =>[2.2-2.4]
- Average TeV γ-ray photon index [1.9-2.3], no flux correlation

High and very high energy gamma ray observation

HESS has observed several young supernova remnants with hard spectra below 1 TeV.

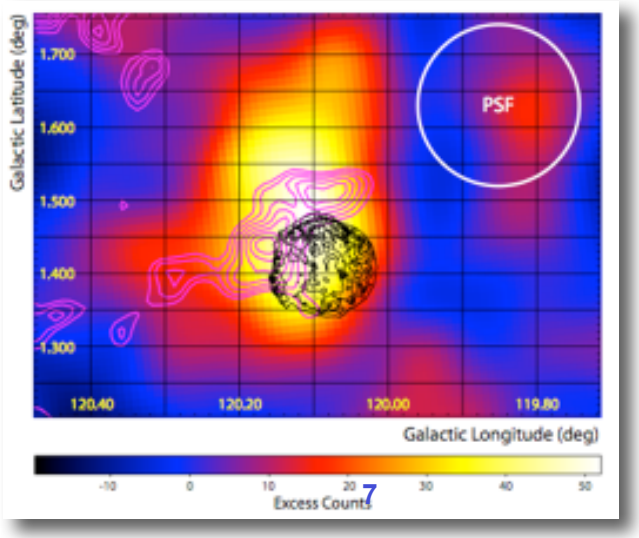
Fermi has observed several middle-aged supernova remnants with broken spectra, steep at 100 GeV

High and very high energy gamma ray observation

Tycho: Recent TeV Detection

Uchiyama Fermi meeting mai 2011

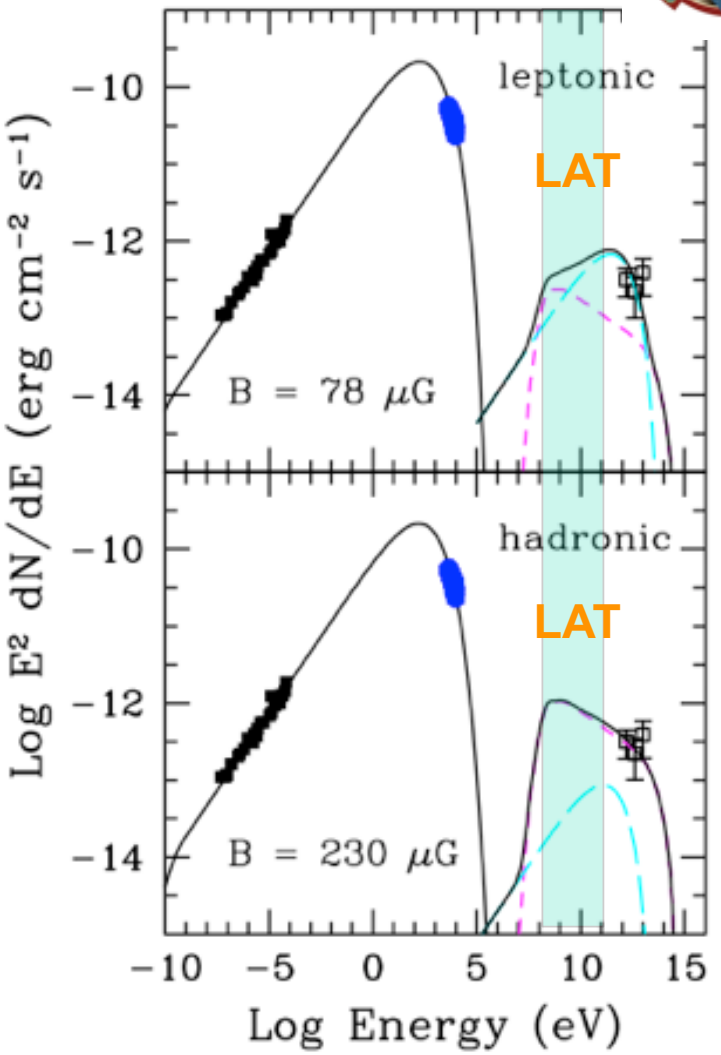
VERITAS Collaboration (2011)



Flux(>1 TeV) ~ 1% Crab
5.0σ detection (post-trial)

B-field constraint put by X-ray does *not* contradict IC origin.

Fermi-LAT can test "leptonic vs hadronic"



High and very high energy gamma ray observation

Tycho: New GeV Detection

See a poster by Fermi-LAT Collaboration (Naumann-Godo+)

Uchiyama Fermi meeting mai 2011

Fermi-LAT Detection (5σ)

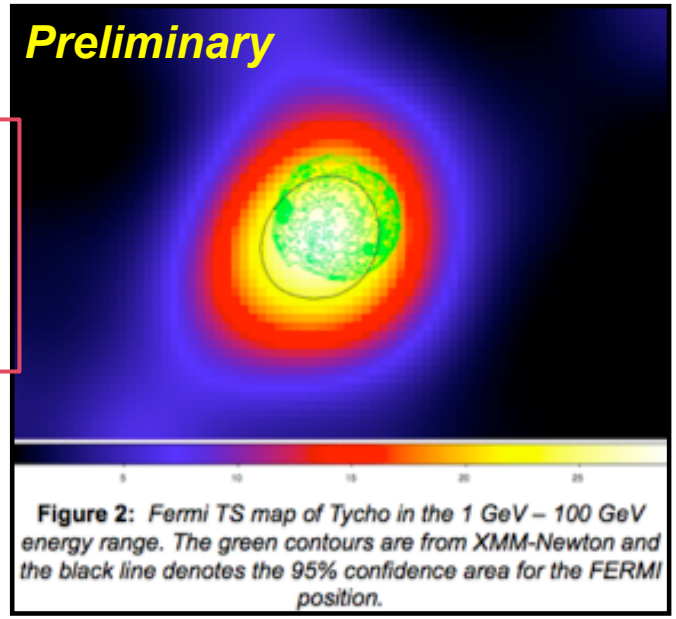
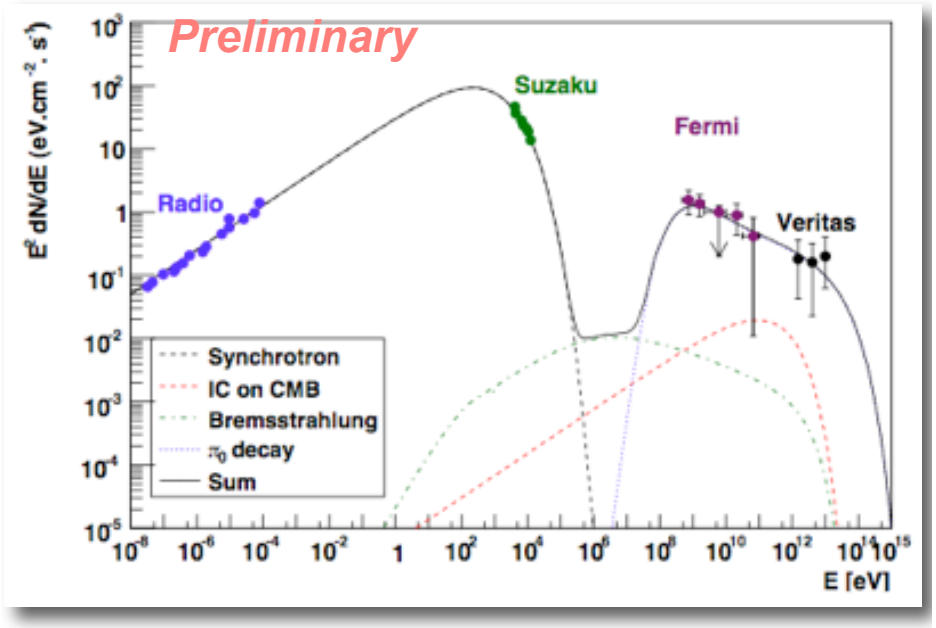


Figure 2: *Fermi TS map of Tycho in the 1 GeV – 100 GeV energy range. The green contours are from XMM-Newton and the black line denotes the 95% confidence area for the FERMI position.*



Case	D_{kpc}	n_H [cm^{-3}]	E_{SN} [10^{51}erg]	$E_{p,tot}$ [10^{51}erg]	K_{ep}
Far	3.50	0.24	2.0	0.150	4.5×10^{-4}
Nearby	2.78	0.30	1.0	0.061	7.0×10^{-4}

Photon index = 2.3 ± 0.1 (favors hadronic origin)

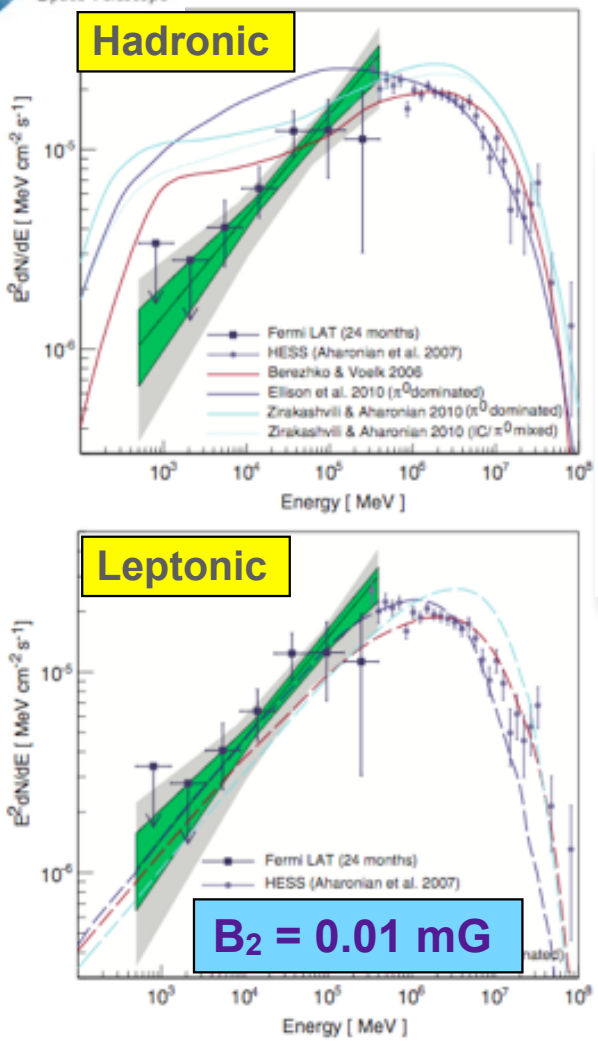
6-8% of E_{SN} transferred to CRs.

High and very high energy gamma ray observation

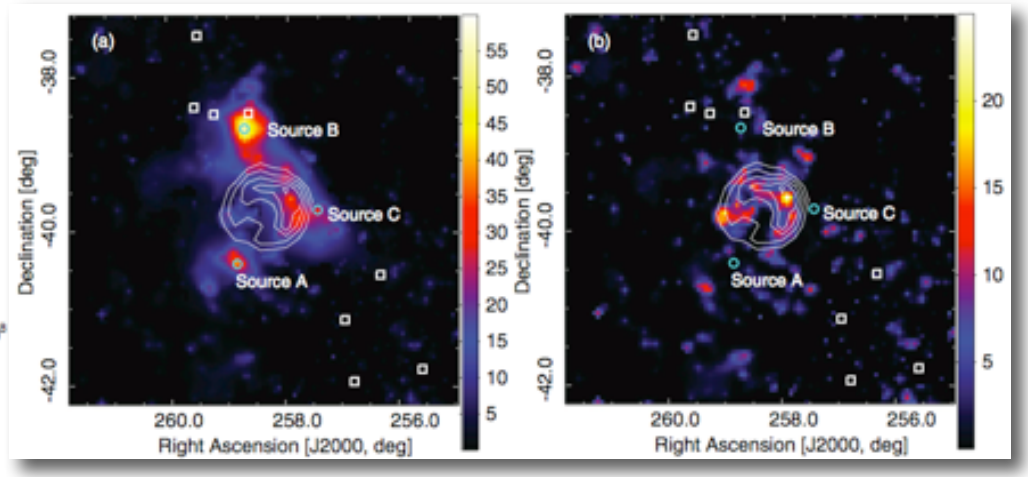
RX J1713.7-3946: LAT Results

Abdo+2011 (in press)

Uchiyama Fermi meeting mai 2011



TS map above 0.5 GeV
(using a point source hypothesis)



1FGL sources in BGD model SrcA,B,C also in BGD model

Photon index: Γ_{LAT} = 1.5 ± 0.1(sta) ± 0.1(sys)

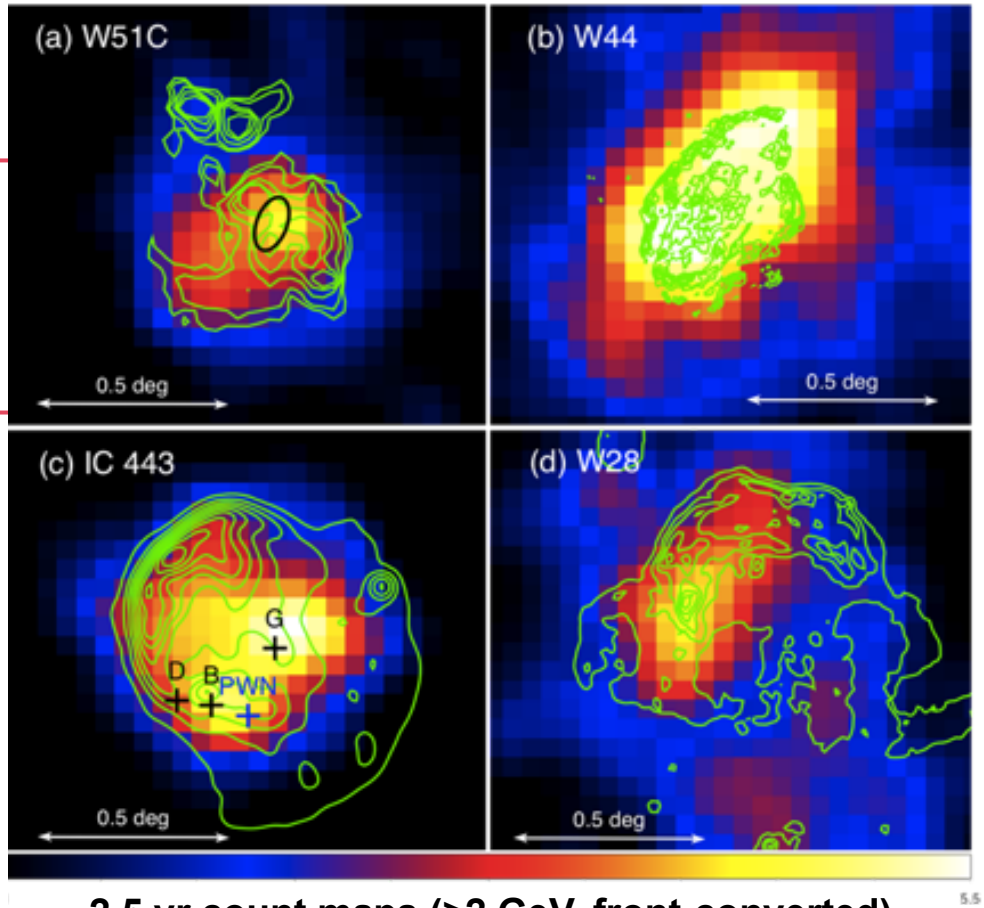
LAT spectral shape is consistent what expected in leptonic scenarios (IC origin), though B_2 = 0.01 mG would be difficult to be reconciled with X-ray measurements. Hadronic origin requires very hard proton spectrum, which challenges current models.

High and very high energy gamma ray observation

LAT Discoveries of MC-SNRs

Fermi-LAT Collaboration (Uchiyama+) 2011

Uchiyama Fermi meeting mai 2011



2.5 yr count maps (>2 GeV, front-converted)

Extended GeV emission has been discovered from several SNRs, with molecular cloud (MC) interactions.

GeV extension is consistent with the size of a radio remnant (except for W28).

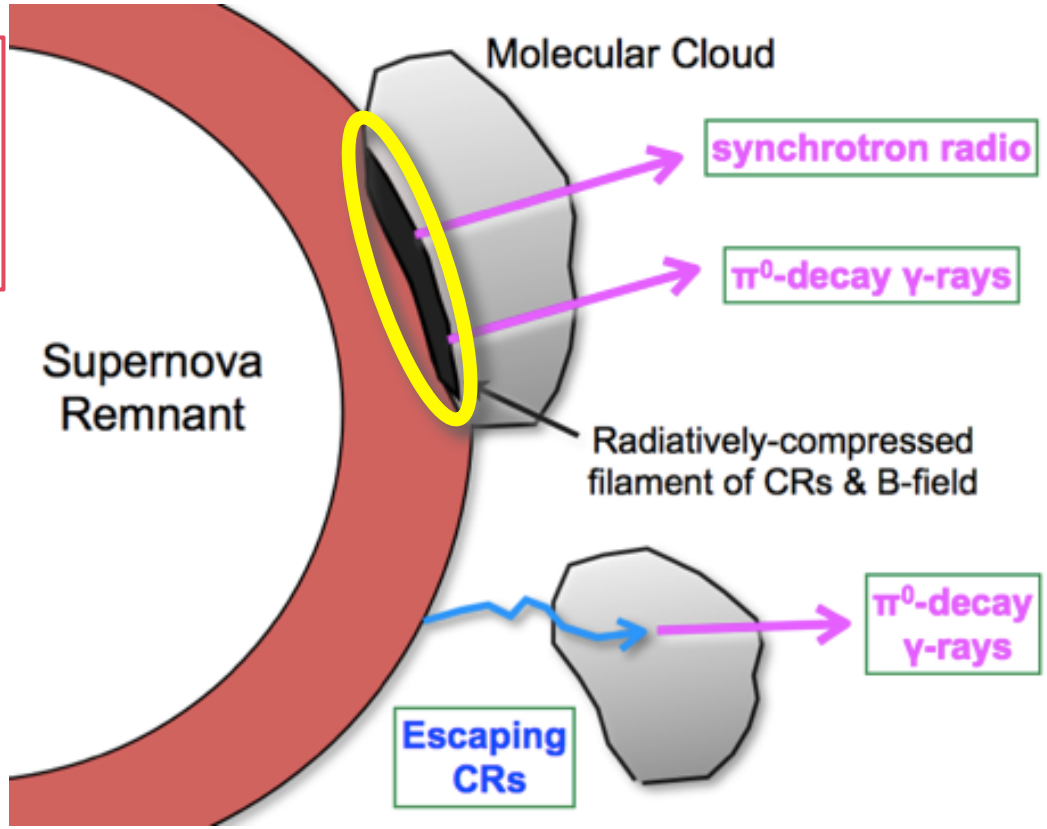
The dominant class of LAT SNRs.

High and very high energy gamma ray observation

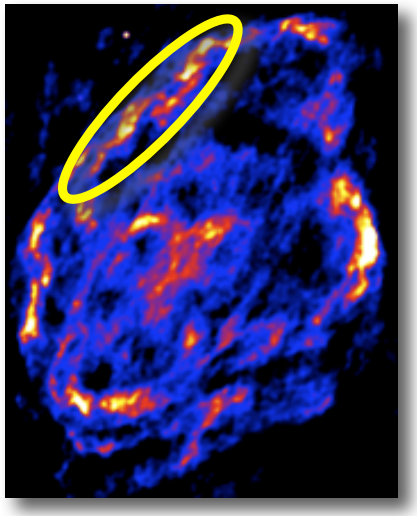
Gamma-ray Emission Sites

Radio & γ-ray emissions from radiatively-compressed filaments
Crushed Cloud Model (Uchiyama+2010)

Uchiyama Fermi meeting mai 2011



SNR W44



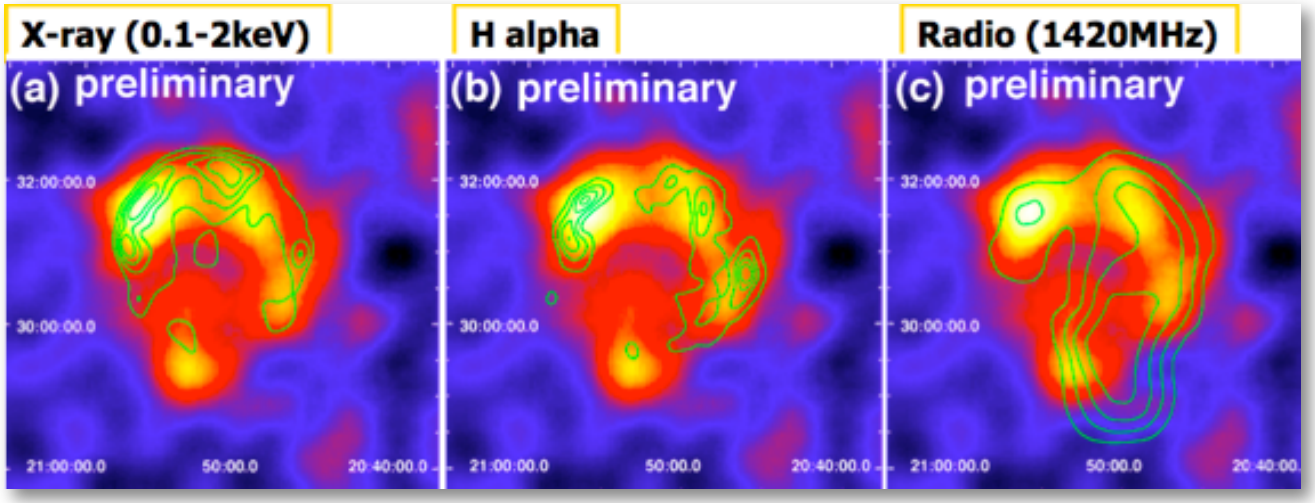
synchrotron radio emission correlated with shocked H_2 gas

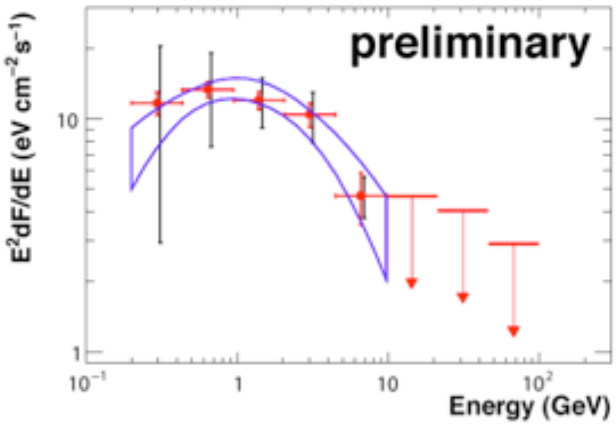
High and very high energy gamma ray observation

Cygnus Loop: LAT Results

Katagiri+ (submitted)

Uchiyama Fermi meeting mai 2011





Correlation with X-ray and Hα emissions
→ Gamma-ray-emitting particles distribute near shock waves
NOTE: southern radio emission would be another SNR.

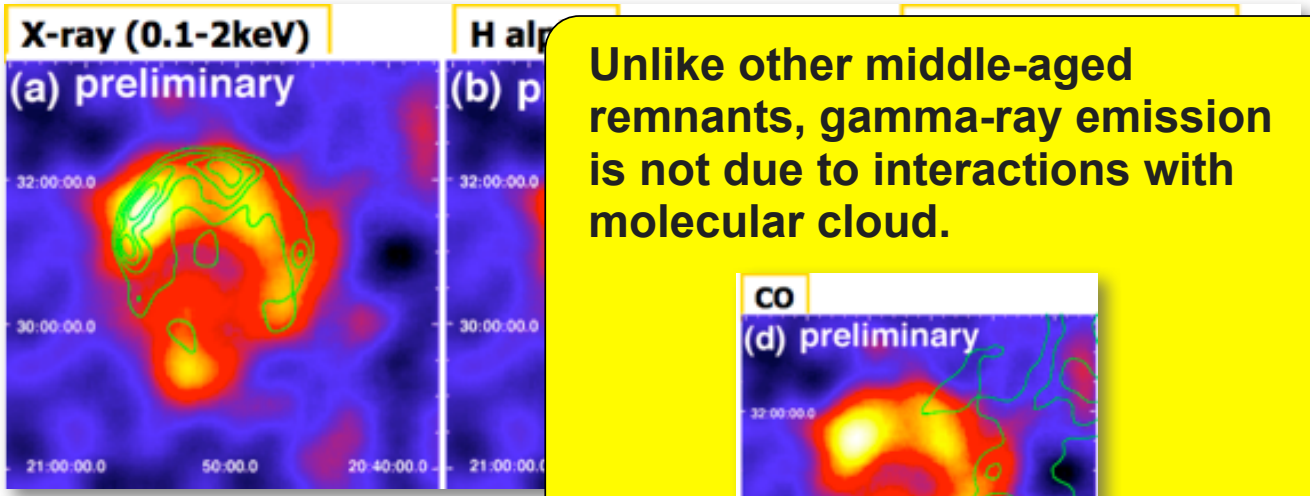
Spectral steepening above ~ 2 GeV.
(simple power-law disfavored at 3.5σ level)
Gamma-ray Luminosity ~ 1×10^{33} erg/s (< other LAT SNRs)

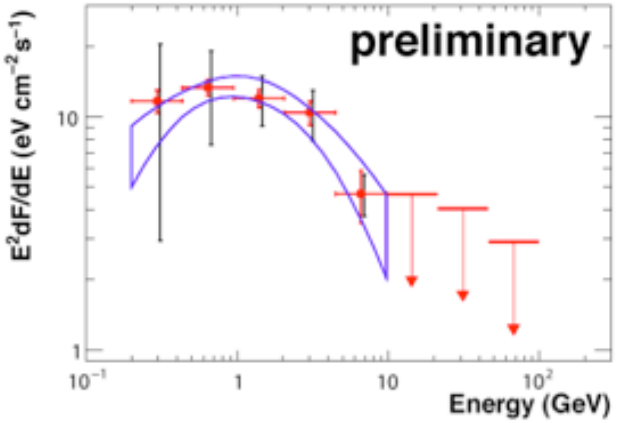
High and very high energy gamma ray observation

Cygnus Loop: LAT Results

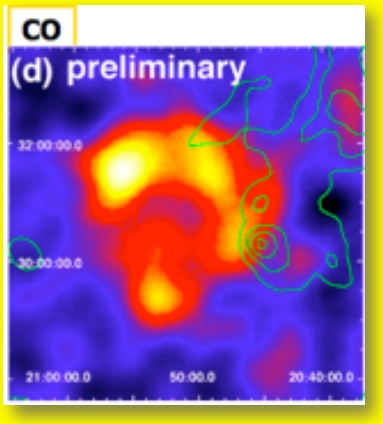
Katagiri+ (submitted)

Uchiyama Fermi meeting mai 2011





Unlike other middle-aged remnants, gamma-ray emission is not due to interactions with molecular cloud.



Gamma-ray emission comes from either (1) main blast wave regions (X-ray) or (2) radiative shock region (Hα).

III.3.3 Efficacité de l'accélération : rétroaction des particules accélérées

=> traité en même temps que la modélisation

Irfu

Saclay

IV. Modélisation des restes de supernovae

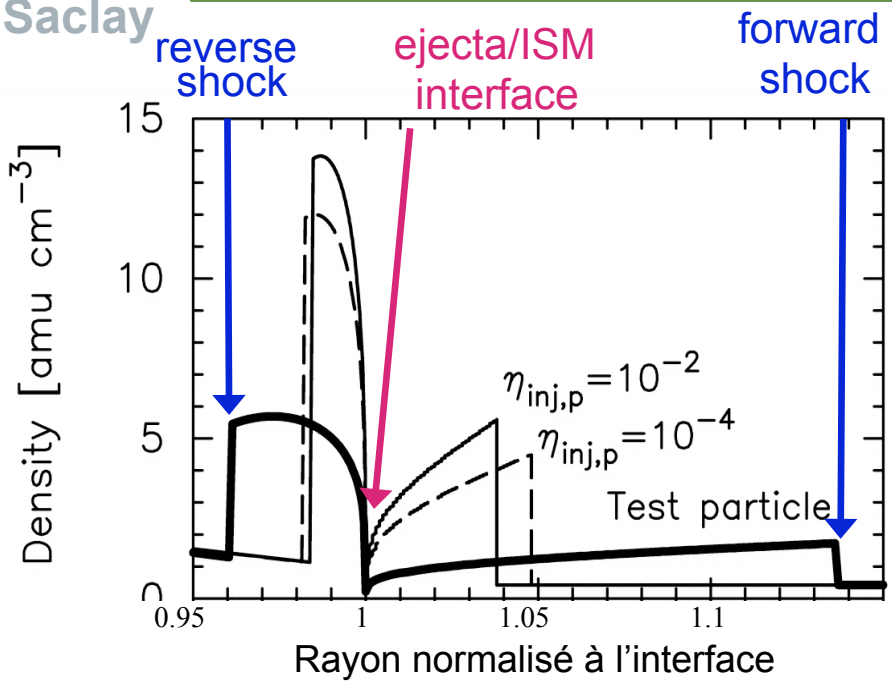
1. Modélisation 1D et contrainte observationnelle sur l'efficacité de l'accélération par rétroaction des particules accélérées

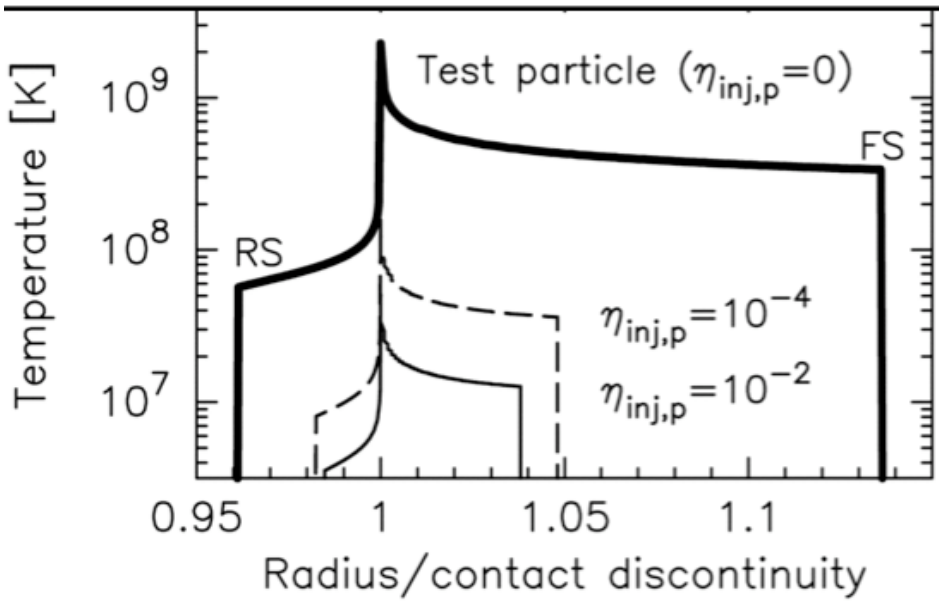
2. Modélisation 3D

IV.1 Modélisation hydrodynamique 1D avec accélération de particules : rétroaction

Saclay

Context: 1D self-similar solutions including a prescribed back-reaction of accelerated particles (Chevalier 1983)





Our work: 1D semi-analytical modelling coupled to a model of particle acceleration (Berezhko & Ellison 1999) => Decourchelle, Ballet, Ellison (2000)

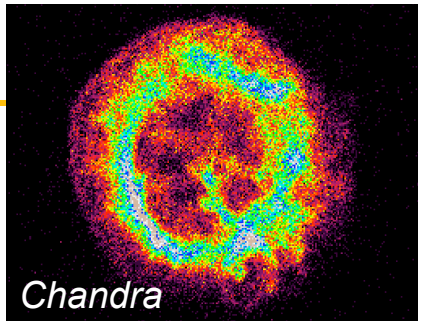
If efficient ion diffusive shock acceleration:

- larger compression ratio (> 4 at the shock)
- lower post-shock temperature than for test-particle case **=> R. X**
- Shrinking of the post-shock region **=> R. X**

Irfu

Saclay

Thermal signature: a lower post-shock temperature



If efficient ion diffusive shock acceleration, lower post-shock temperature than for test-particle case

(Chevalier 1983, Ellison et al. 2000, Decourchelle et al. 2000)

Mean test-particle post-shock temperature in 1E0102 (SMC):

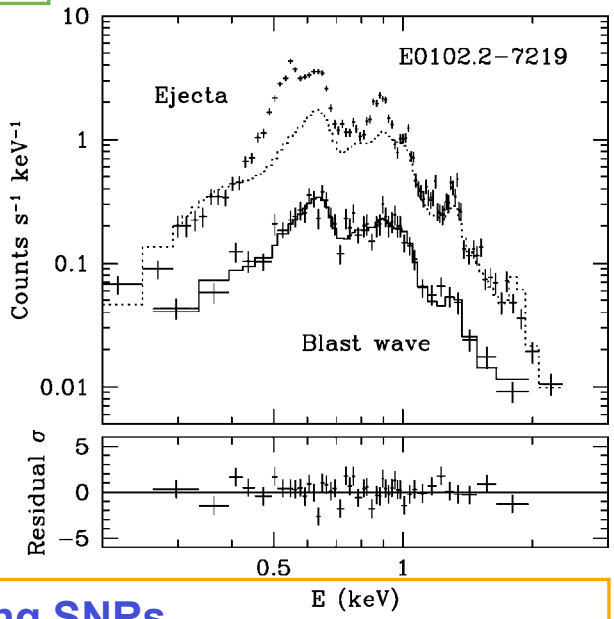
$kT_s = 3/16\ \mu m_p\ V_s^2$ with shock velocity $V_s \sim 6200$ km/s

=> expected kT_s ~ 45 keV

Chandra: kT_e **≤ 1 keV measured**

With coulomb collisions only, one expects: $kT_e > 2.5$ keV

(Hughes, Rakowski, Decourchelle 2000)



Indication of strong back-reaction in young SNRs

- **1E0102**: post-shock kT_e from X-rays and V_s from X-ray proper motion (Hughes, Rakowski, Decourchelle 2000)
- **RCW 86**: post-shock proton temperature from H_α broad line and V_s from X-ray proper motion (Helder et al. 09): 50 % post-shock pressure in relativistic particles

No back-reaction in the older SNR

- **Cygnus Loop**: post-shock kT_e from X-rays and V_s from optical proper motion (Salvesen et al. 09)

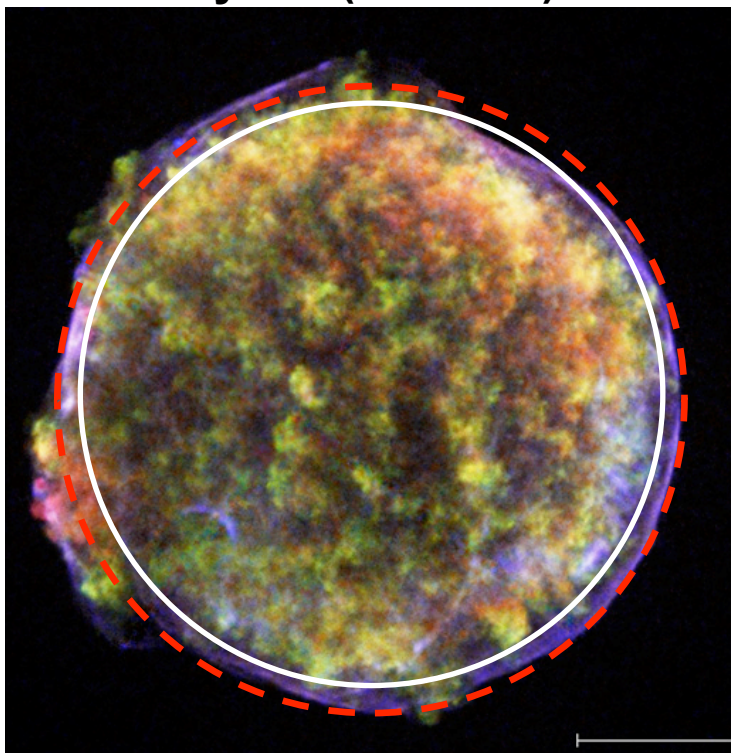
Thermal and non thermal signature: shrinking of the shocked region

If efficient ion diffusive shock acceleration: modified hydrodynamics

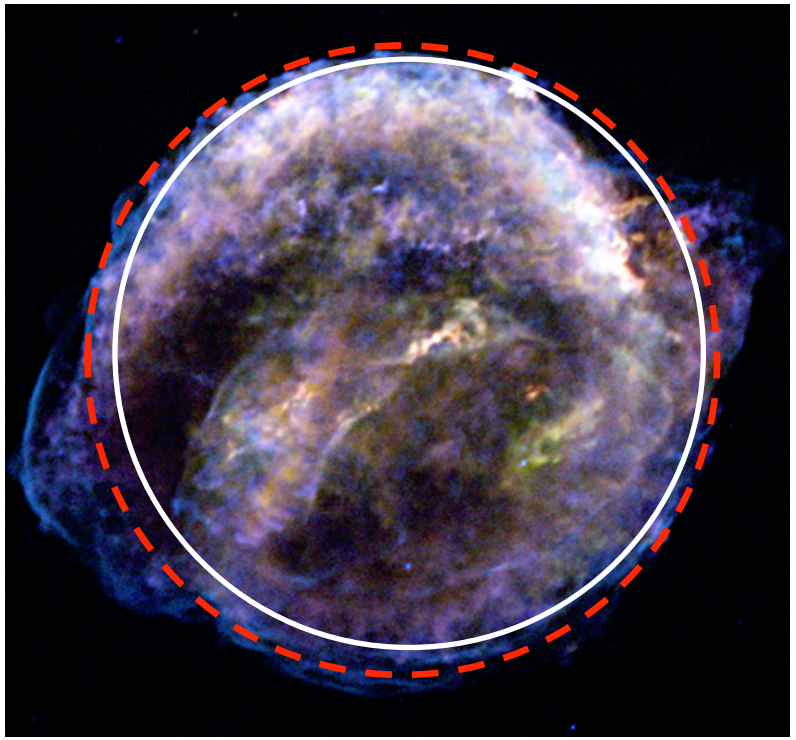
=> narrower shocked region than test-particle case

(Chevalier 83, Decourchelle et al. 00)

Tycho (SN 1572)



Kepler (SN 1604)



Observational diagnostic: shock very close to interface: $R_{shock}/R_{interface} < 1.1$

(Decourchelle 2005, Warren et al. 2005)

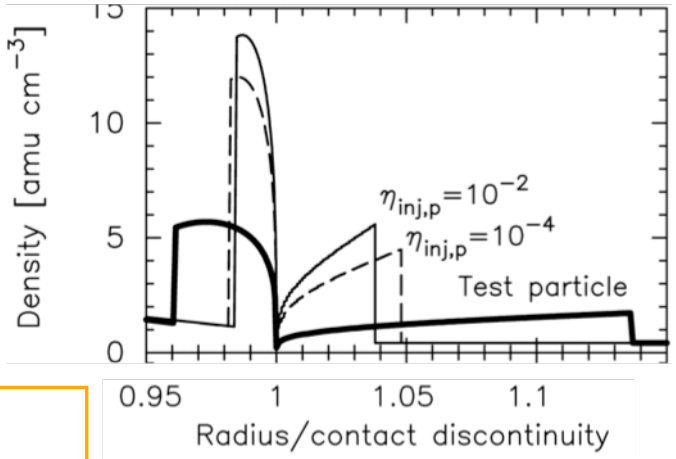
=> Efficient particle acceleration of protons at the shock

Irfu

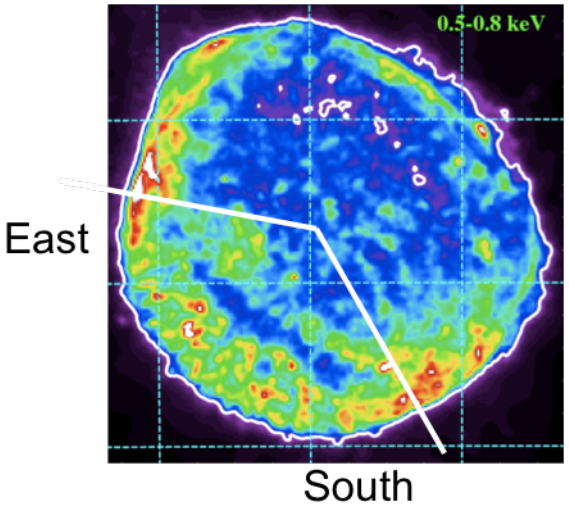
Saclay

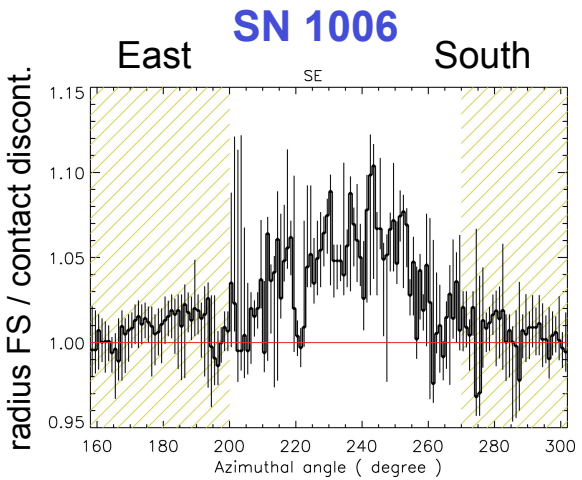
Thermal and non thermal signature: shrinking of the shocked region

Indication of strong back reaction in young SNRs: $R_{fs}/R_{cd} < 1.1$

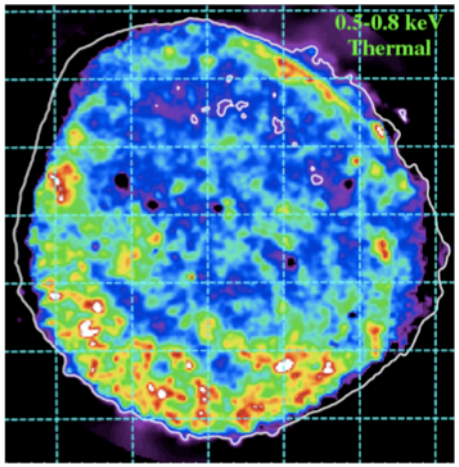


- **Tycho:** morphology (Warren et al. 05, Decourchelle et al. 05)
- **Cas A**: X-ray proper motion and morphology (Patnaude et al. 09)
- **SN 1006:** morphology (Miceli et al. 09, Cassam-Chenaï et al. 08)





Cassam-Chenaï et al. 08



Miceli et al. 09

Efficiency of particle acceleration

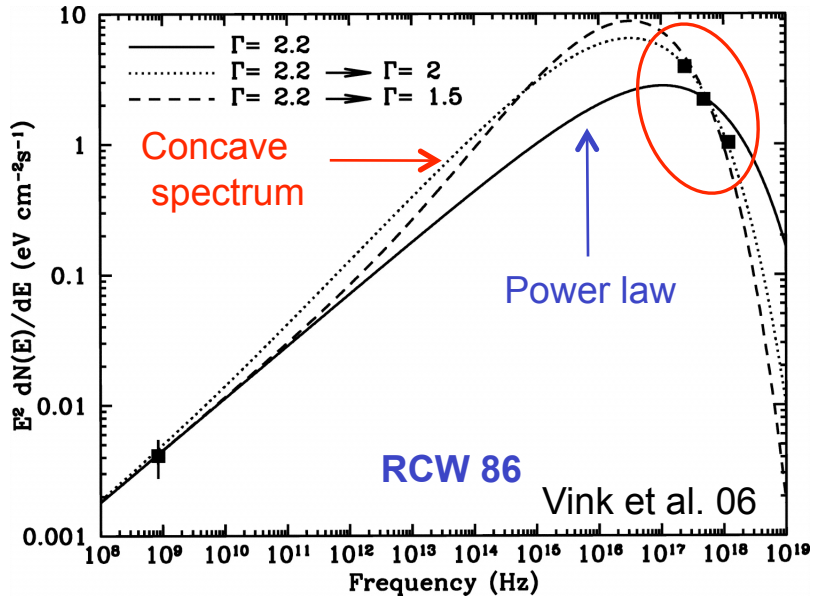
Nonlinear diffusive shock acceleration

=> Curvature of the particle spectra (Berezhko & Ellison 99, Ellison & Reynolds 91,...)

Curvature of the spectrum :

indications in a few SNRs

- **SN 1006**: combining radio and X-ray data (Allen et al. 08)
- **RCW 86:** combining radio and X-ray data (Vink et al. 06)
- **Cas A**: from infrared data (Jones et al. 03)
- **Tycho and Kepler**: from radio data (Reynolds & Ellison 92)



Further developments in the framework of efficient particle and 1D approach

- Coupling of the thermal X-ray emission emission in the framework of the semi-analytical model: non-equilibrium ionization and X-ray spectra (Decourchelle, Ballet, Ellison 2000)
- Impact of a hybrid electron distribution (maxwellian plus power-law tail) on the ionization and recombination rates (Porquet, Arnaud, Decourchelle 2001)
- Coupling of the calculation of the nonthermal synchrotron emission in the framework of the semi-analytical model (Cassam-Chenaï, Decourchelle, Ballet, Ellison 2005)
- Application to the interpretation of Tycho's radio and X-ray synchrotron observations (Cassam -Chenaï, Hughes, Ballet, Decourchelle 2007)
- Development of numerical 1D simulations to extend the domain of applicability of the semi -analytical model (Ellison, Decourchelle, Ballet 2004)
- Ability of the reverse shock to accelerate particles (Ellison, Decourchelle, Ballet 2005)

- Coupling of the calculation of the nonthermal synchrotron emission in the framework of the numerical 1D code (Ellison & Cassam-Chenaï 2005)
- Coupling of the calculation of the thermal X-ray emission in the framework of the numerical 1D code (Patnaude, Ellison, Slane 2009, Patnaude, Slane, Raymond, Ellison 2010)

IV.2 Limitations of the 1D approach

Development of hydrodynamic Rayleigh-Taylor instabilities at the interface between the ejecta and the ambient medium

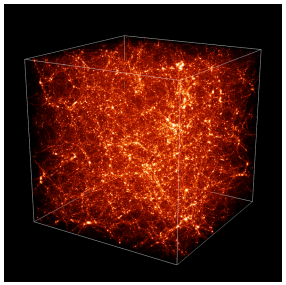
=> 3D simulations required

+ Explosion mechanism can be asymmetric

+ Ambient medium can be not uniform

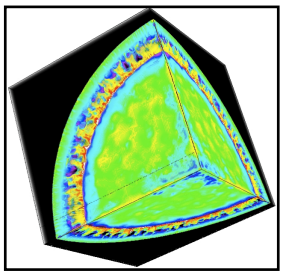
3D simulations coupling a model of efficient particle acceleration required

=> ANR Young researcher obtained "Acceleration of protons in young supernova remnants", 2007-2011



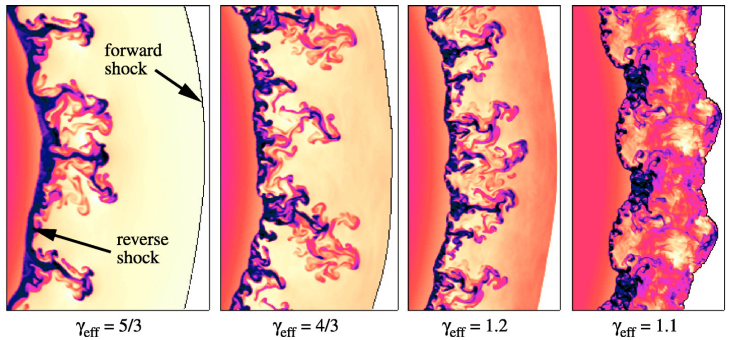
From cosmological simulations to building blocks of galaxies : supernova remnants

RAMSES code (R. Teyssier)



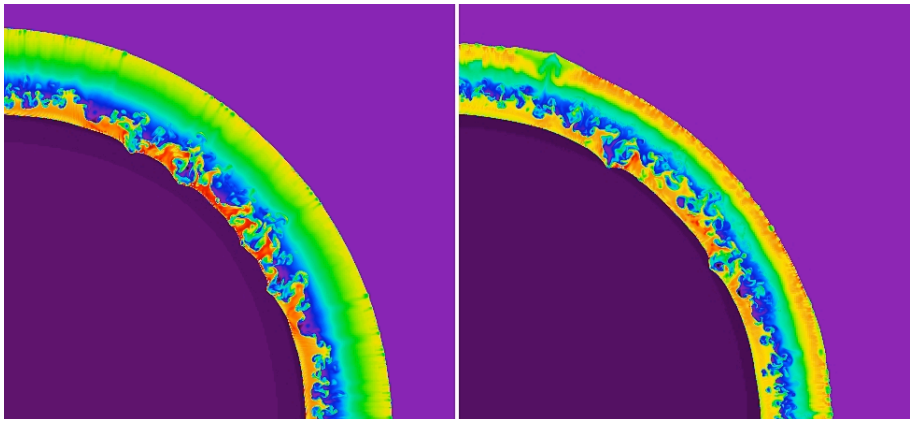
IV.2 3D numerical simulations coupling particle acceleration

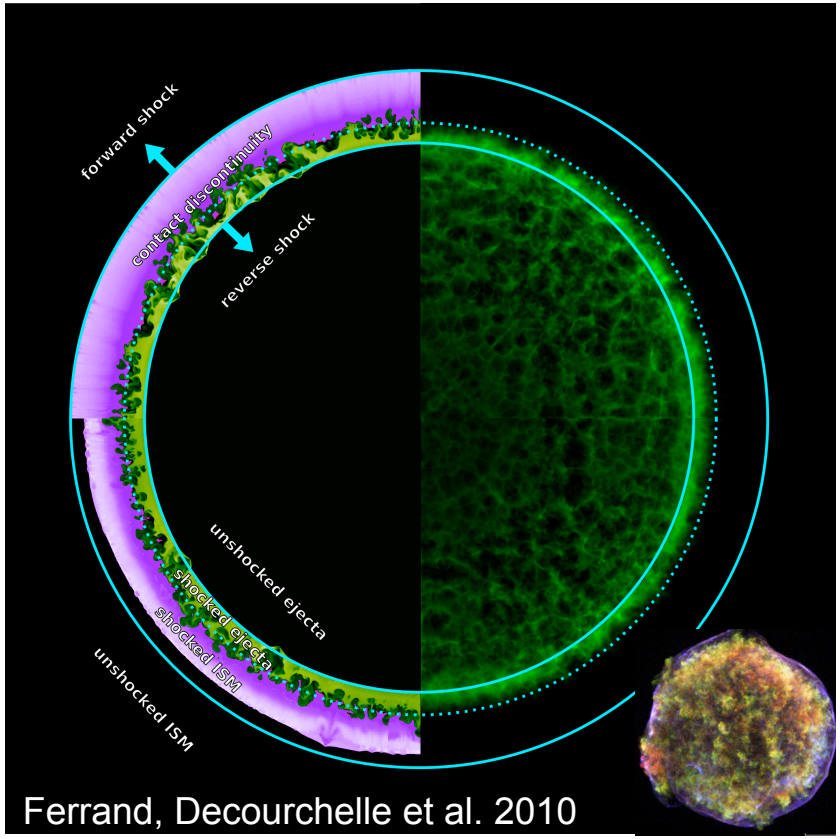
Previous work: 2D/3D simulation including arbitrarily the back-reaction of accelerated particles
(Blondin and Ellison 2001, Wang 2010 submitted)



Blondin and Ellison 2001

Our work (ANR): 3D simulations(1/8 of sphere) time-dependently coupled to a nonlinear acceleration model (Blasi 2002) with a simple coupling method at the shock front





Ferrand, Decourchelle et al. 2010

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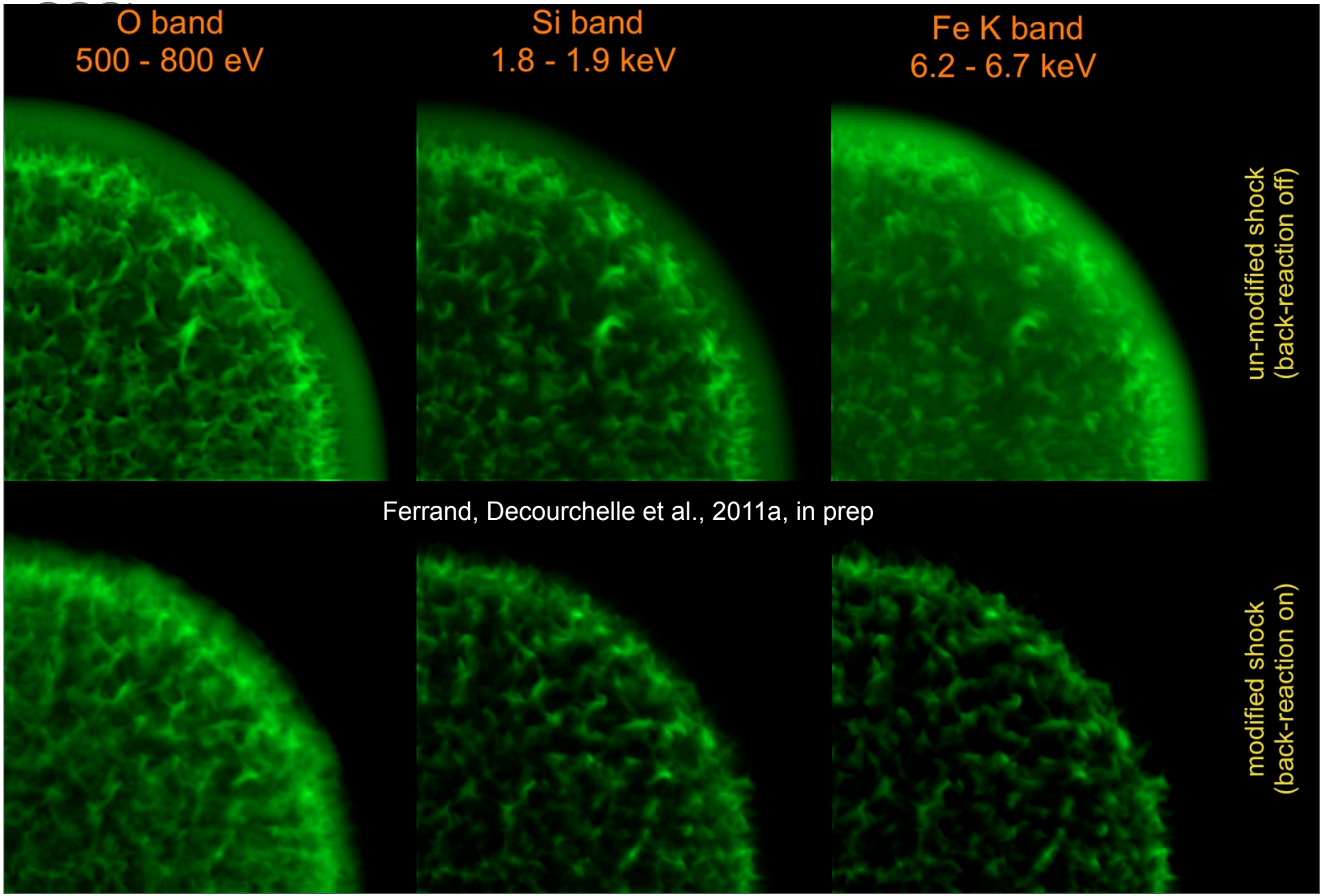
Projected 3D maps of thermal emission in young SNRs



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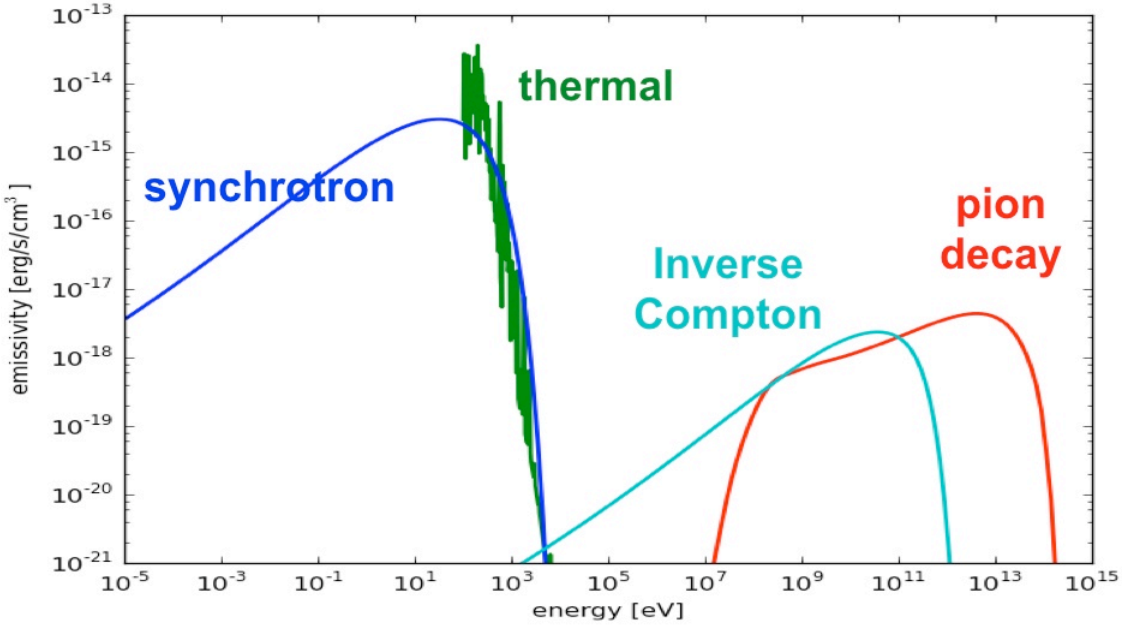
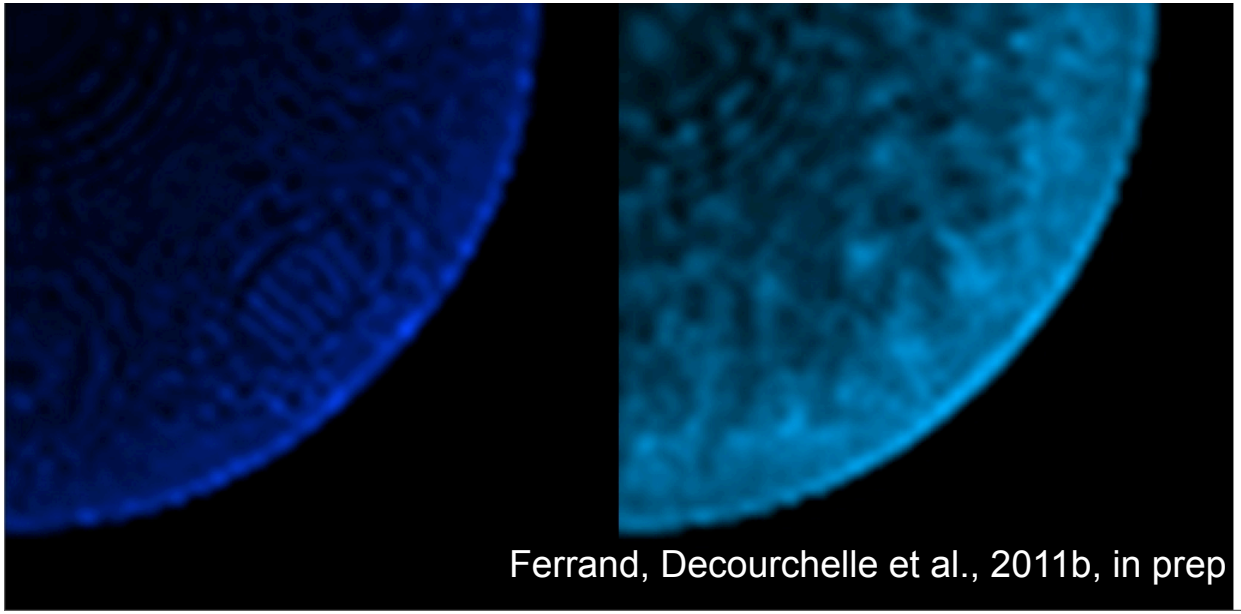
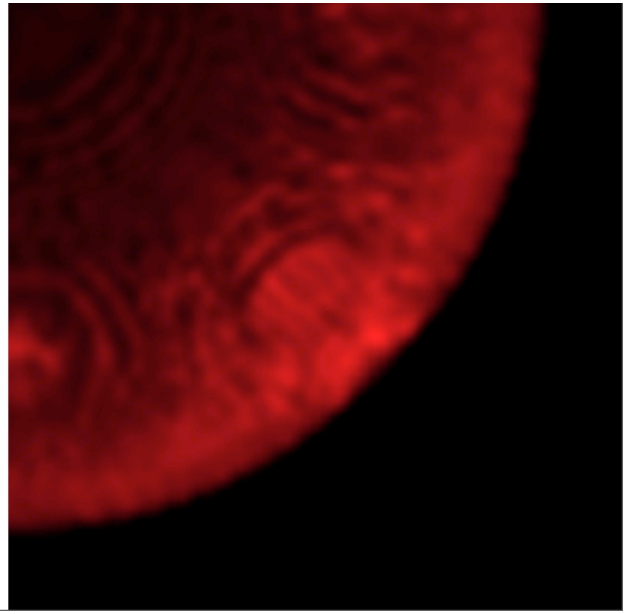
Projected 3D maps of non-thermal emission in young SNRs





Ferrand, Decourchelle et al., 2011b, in prep



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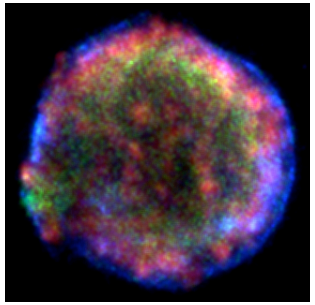
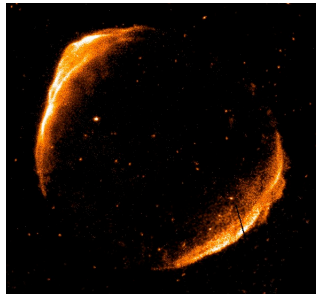
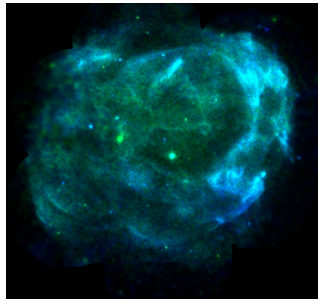
5. Conclusions et perspectives







Observations haute énergie **=> Constraints on the models**

Goal: to characterize the process at play (acceleration, heating, matter ejection and mixing)

Data: XMM-Newton, FERMI, HESS II, CTA

Tools:

- **Spatially resolved-spectroscopy of young supernova remnants at the smallest spatial scale achievable:** nucleosynthesis products, explosion mechanism, particle acceleration
- High-resolution spectroscopy at the shock to probe shock physics (LP SN1006)
- Combined radio and X-ray analysis to probe the accelerated electron spectrum
- Combined radio, X-ray and gamma-ray analysis to probe the accelerated electron and proton spectra

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Perspectives: modelling of high-energy observations

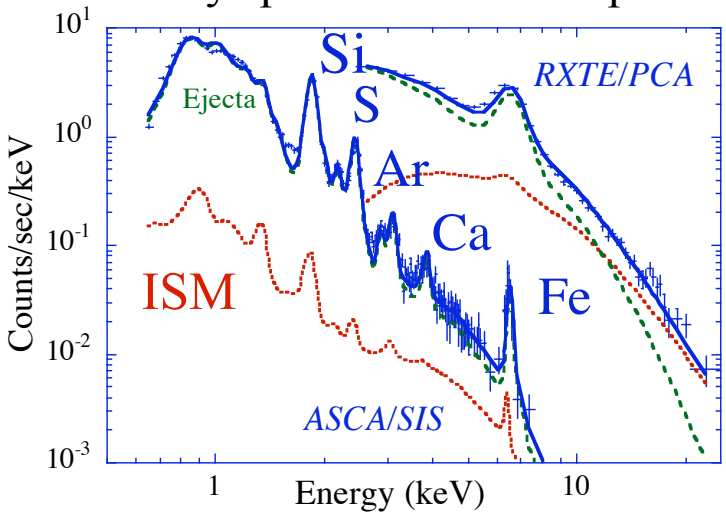
Goal: constrain the prime parameters of the models through a consistent modelling of both the thermal and non-thermal emission of SNRs.

Tools: simple (1D) consistent models including heavy and radioactive elements, back-reaction of accelerated protons, magnetic field, accelerated particles, and emission processes.

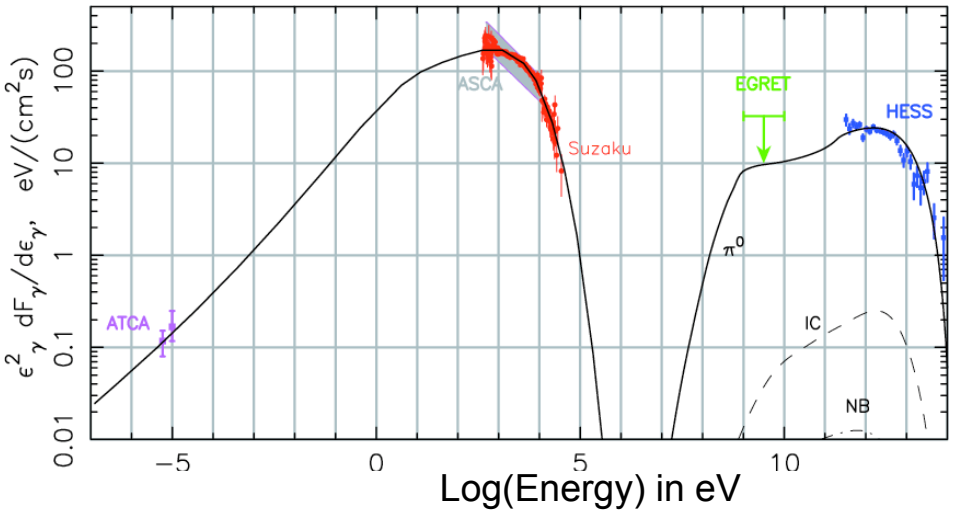
Data: multi-wavelength spectra of supernova remnants

=> Understanding of the physics involved in various supernova remnants

X-ray spectrum of the Kepler SNR



Multi-wavelength spectrum of RXJ 16713-3946



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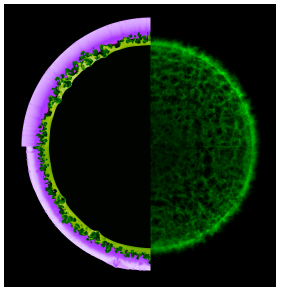
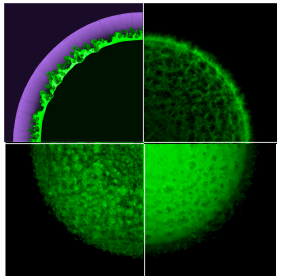
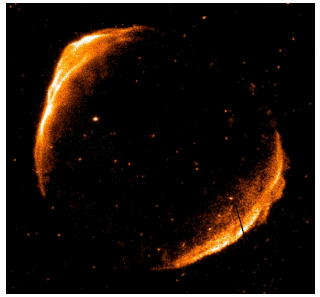
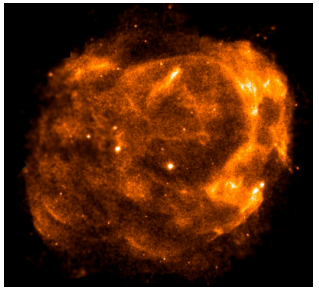
Perspectives: 3D numerical simulations

Goal: modelling

- the geometry of the acceleration (like in SN 1006 or in ejecta-dominated remnants)
- the evolution of a remnant, including in a turbulent interstellar medium (like RXJ1713-3946)
- the impact of the evolution of supernova remnants on the large scale interstellar medium

Requirements: take into account the magnetic field orientation and pressure

Tools: MHD simulations (code RAMSES et HERACLES)

Data:

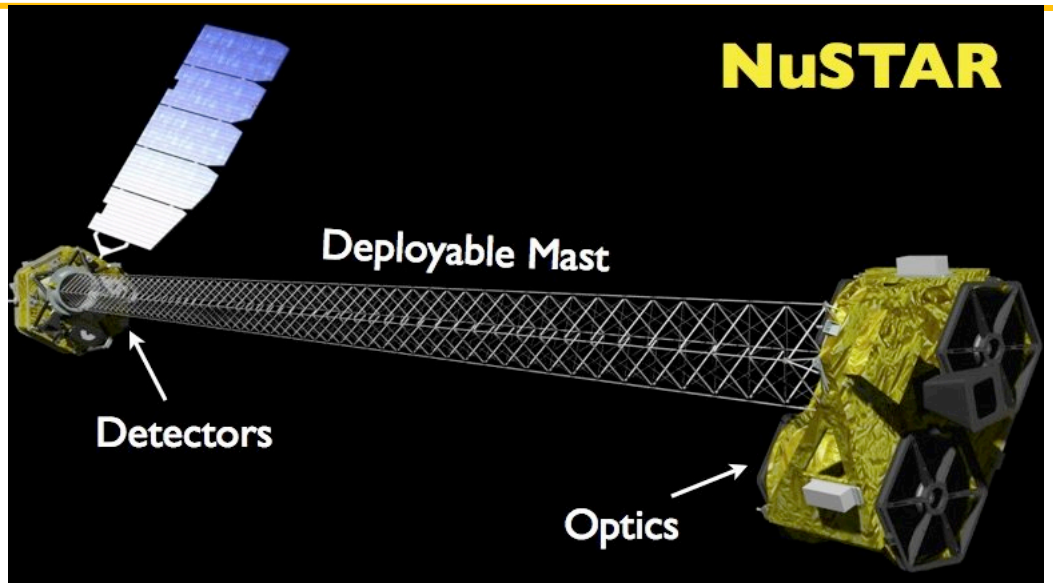
- simulations of the supernova explosion
- simulations of the turbulent interstellar medium

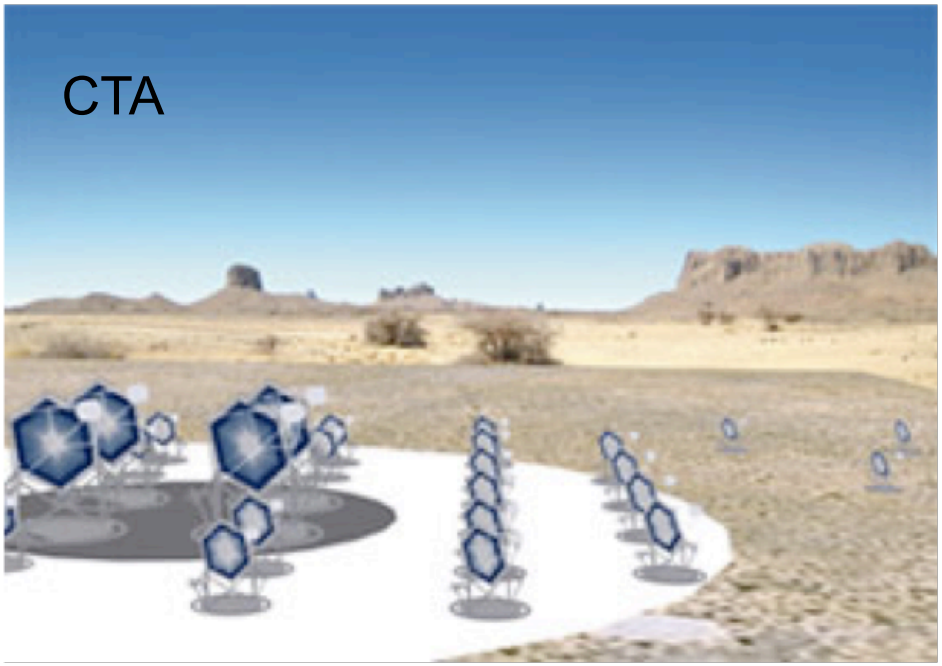
=> Multiwavelength spectra (radio, X et γ-rays, neutrinos)

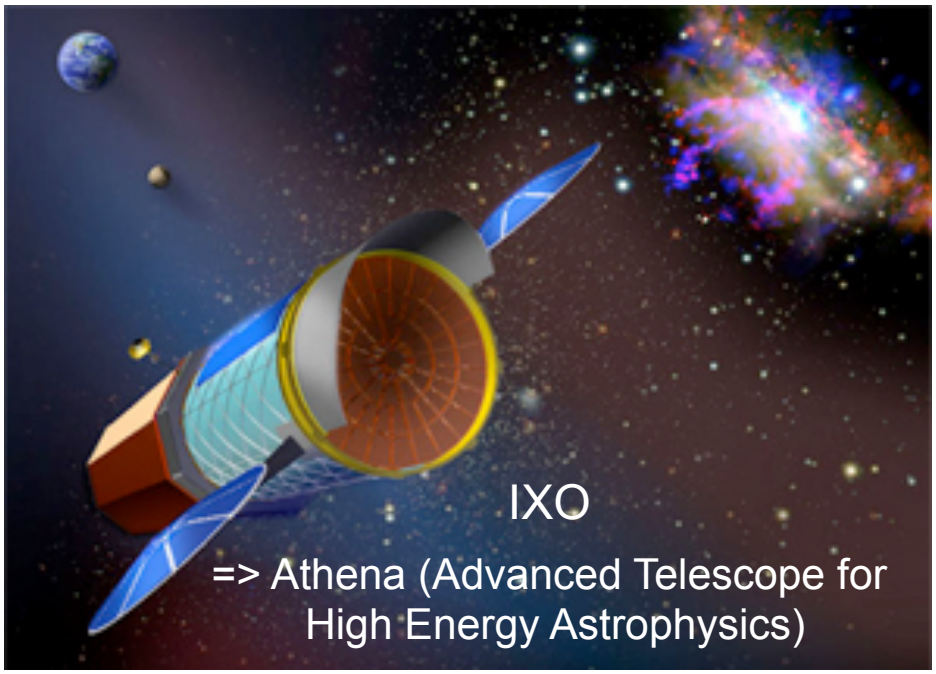
Grant: ANR blanche 2011-2014 *Cosmic rays and compressible MHD turbulence in the ISM*
LERMA / AIM / LPTA

Grant : *The youth of Cosmic Rays and their emergence into interstellar clouds*
LABEX UnivEarthS

Future facilities







Gamma-rays: access to shocked and unshocked radioactive ejecta.

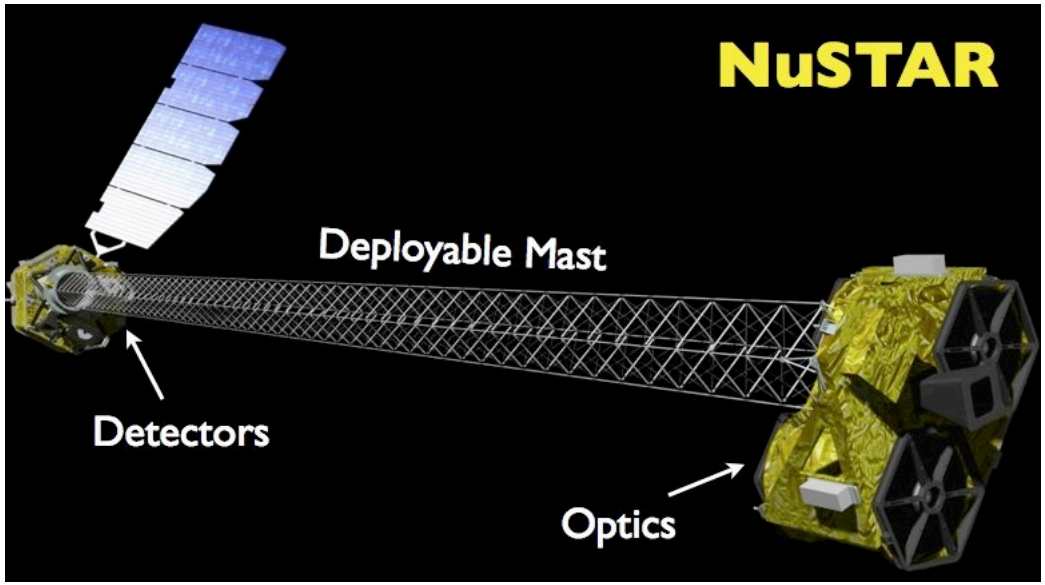
Heavy element production and explosion mechanism of supernovae

Objectives: mass of unstable freshly synthesized products (^{44}Ti) and their spatial distribution (site of alpha-rich freezeout) and contraints on the mass-cut.

Method: spectroscopy of the ejecta.

Needs: higher signal to noise spectra, higher spectral and spatial resolution to determine their mass, locate the site of alpha-rich freezeout and measure their velocity, to detect 44Ti in a sample of SNRs

⇒ **gamma-ray spectro-imager with low background.**



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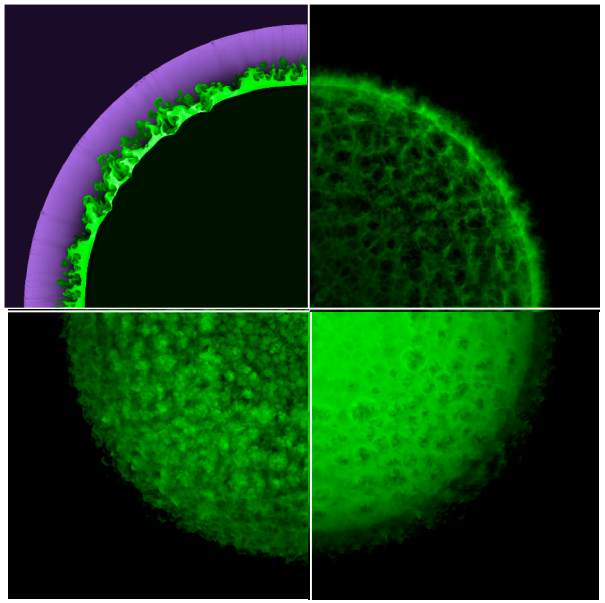
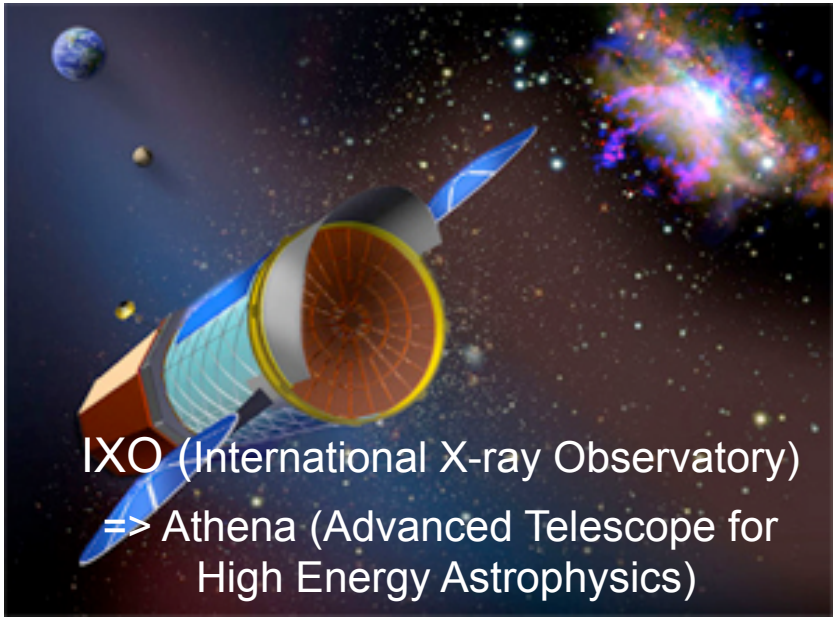
X-rays: access to high ionization states probing the shocked ejecta

Objectives: thermodynamic conditions (electron temperature, density), composition, spatial distribution and kinematics of the synthesized elements

Method: spatially resolved spectroscopy of the shocked ejecta

Needs: 3D maps of the elemental composition and kinematics through Doppler shift measurements of various lines for a sample of SNRs => energy resolution must improve from ~100 eV to ~eV range. Increased effective area to perform spectroscopic studies at a relevant spatial scale, faint lines diagnostics (Cr, Mn, ^{44}Sc) and studies of a larger sample of SNRs including extragalactic SNRs in the local group **=> high throughput, high-resolution spatially resolved spectroscopy: IXO**

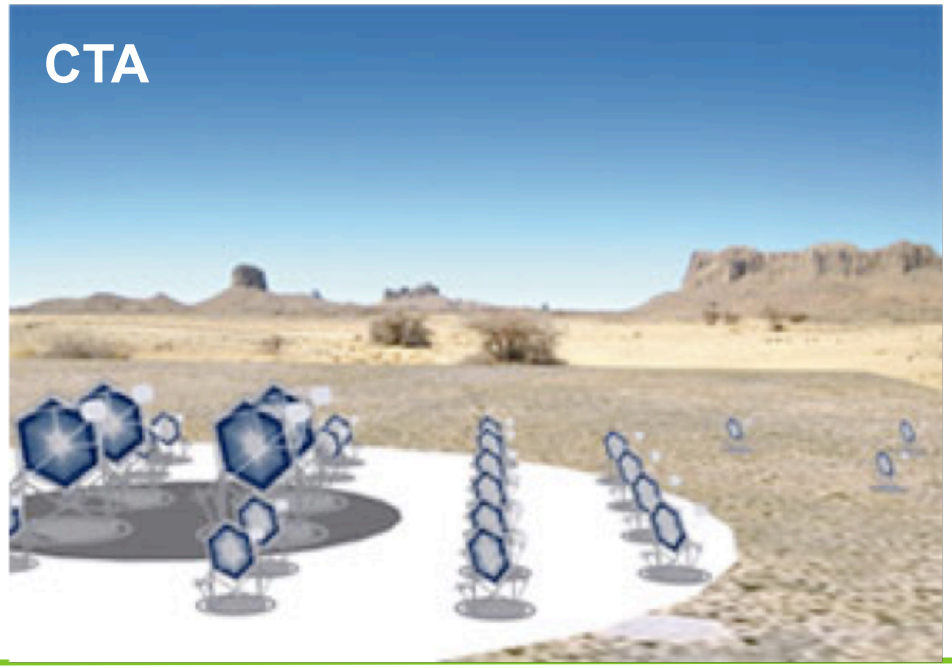




TeV γ-rays: access to particle accelerated to TeV energies

Objectives: caractérisation de l'émission par de la spectro-imagerie à une échelle adaptée à la source

- **Spectro-imagerie des SNRs étendus les plus brillants vus pas HESS :**
- **Caractérisation spatiale et spectrale des restes découverts par FERMI : W51C, W44,...**
- **Découverte de nouveaux restes dans le plan Galactique**

- étude d'une population plus grande de restes émetteurs de gamma
- différentes catégories, âges et processus en jeu (IC versus décroissance de pions)

- **Découverte de spécimens inattendus : RSNe accélérant jusqu'à des énergies du PeV ?**