Observational study of Nonthermal phenomena on SNR shocks

Aya Bamba (U. Tokyo, Japan)

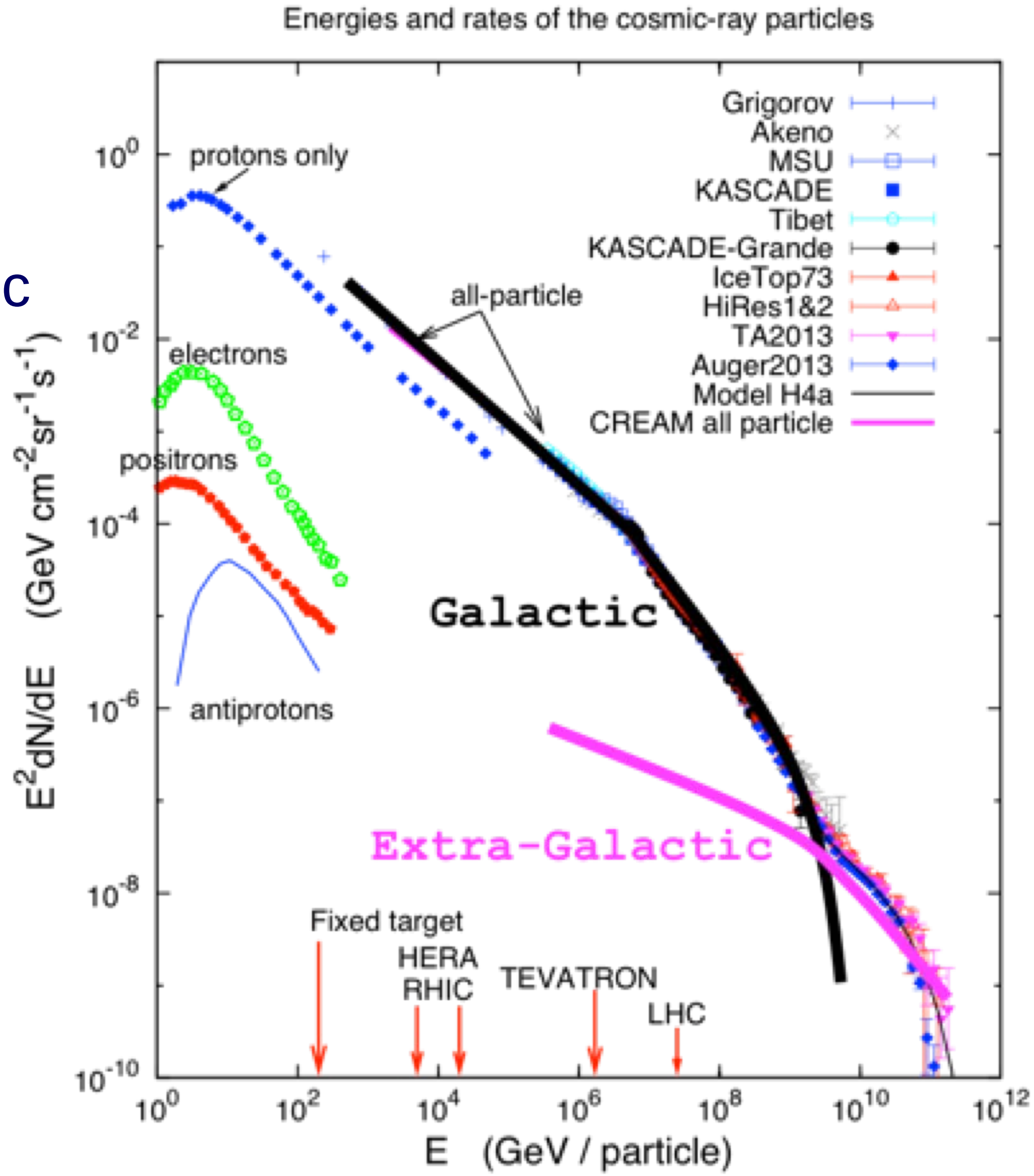
with helps by
H. Yamaguchi, T. Tanaka, M. Sawada, T. Sato,
H. Suzuki, K. Nobukawa, …

0.1. Cosmic rays

high E particles
up to 10^{20} eV
energy density ~ 1eV/cc
(similar to CMB)

power-law spectrum
origin:
$<10^{15.5}$ eV Galactic

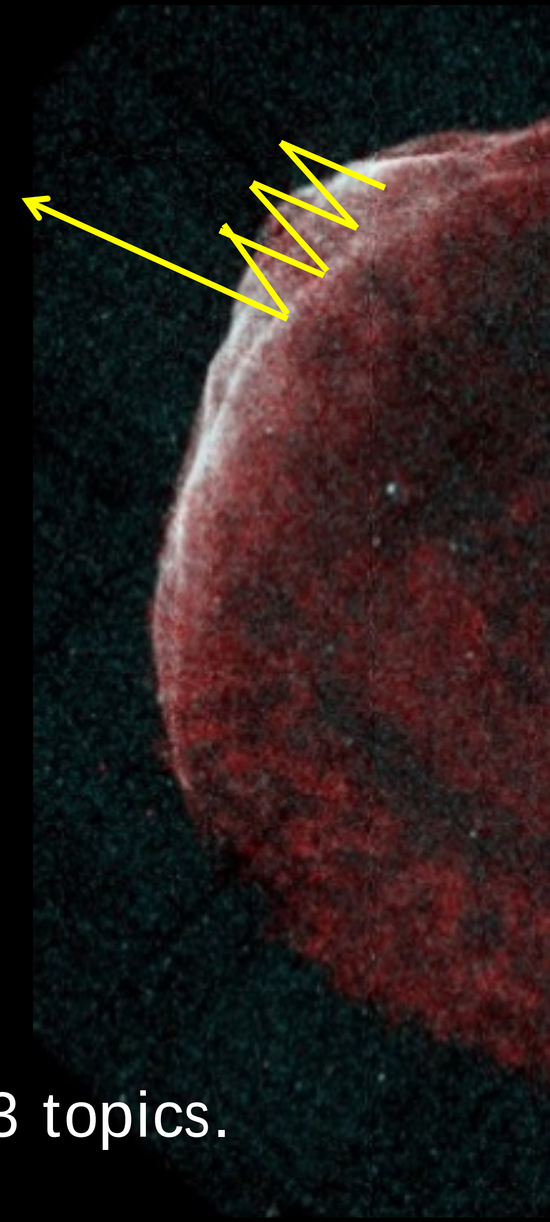
diffusive shock acc.
on shocks of SNRs.



(c) IceCube team

0.2. SNRs as Main Galactic cosmic ray accelerators

Still many unresolved problems



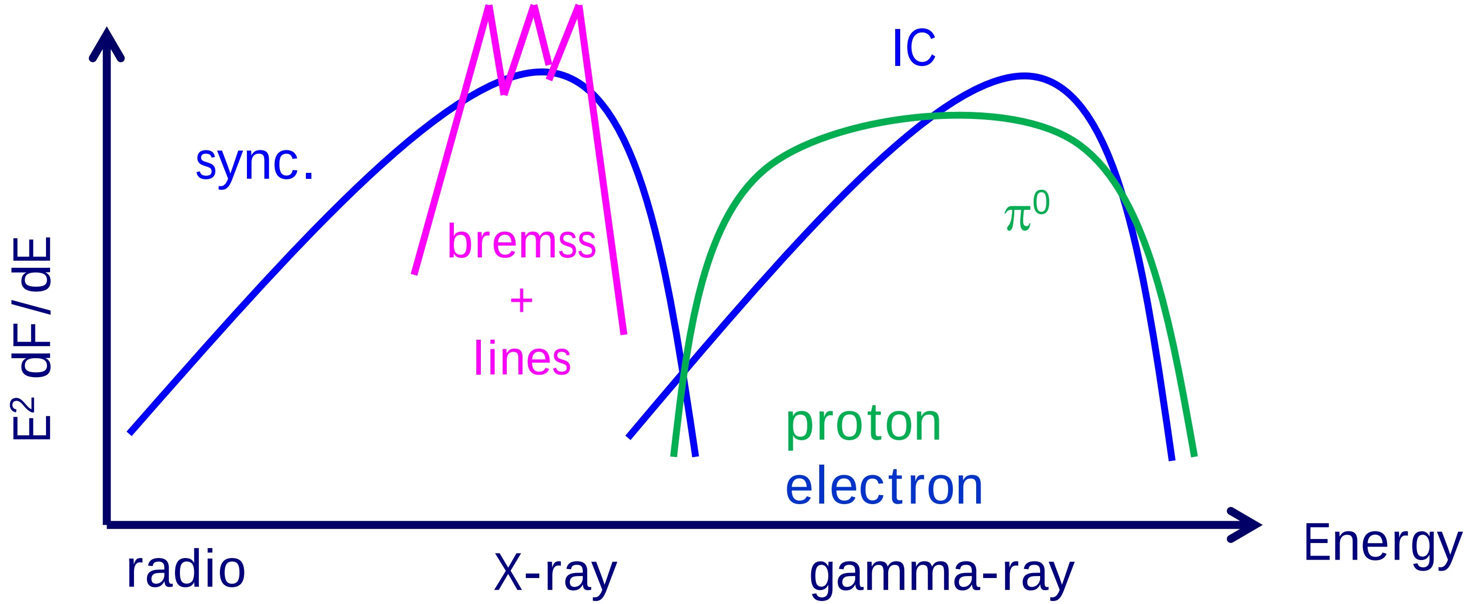
1. wide-band info. of accelerated particles
   - injecting, MeV, GeV, TeV (E_{max}) particles
   - protons and electrons

2. acceleration efficiency
   - How efficient are particles accelerated ?
   - Where is the most efficient acc. site ?

3. escape history to be cosmic rays
   - When/how particles escape
     from the acceleration sites ?

I will talk on the recent progresses on these 3 topics.

0.3. Acceleration sites and observations



electrons: radio — X-rays (sync.), VHE gamma-rays (IC)

protons: GeV-VHE gamma-rays (via pi-on decay)

Plasma: 10^{6-7} K -> bremss + lines in X-ray band
info. on environment
density, kT, time scale ...

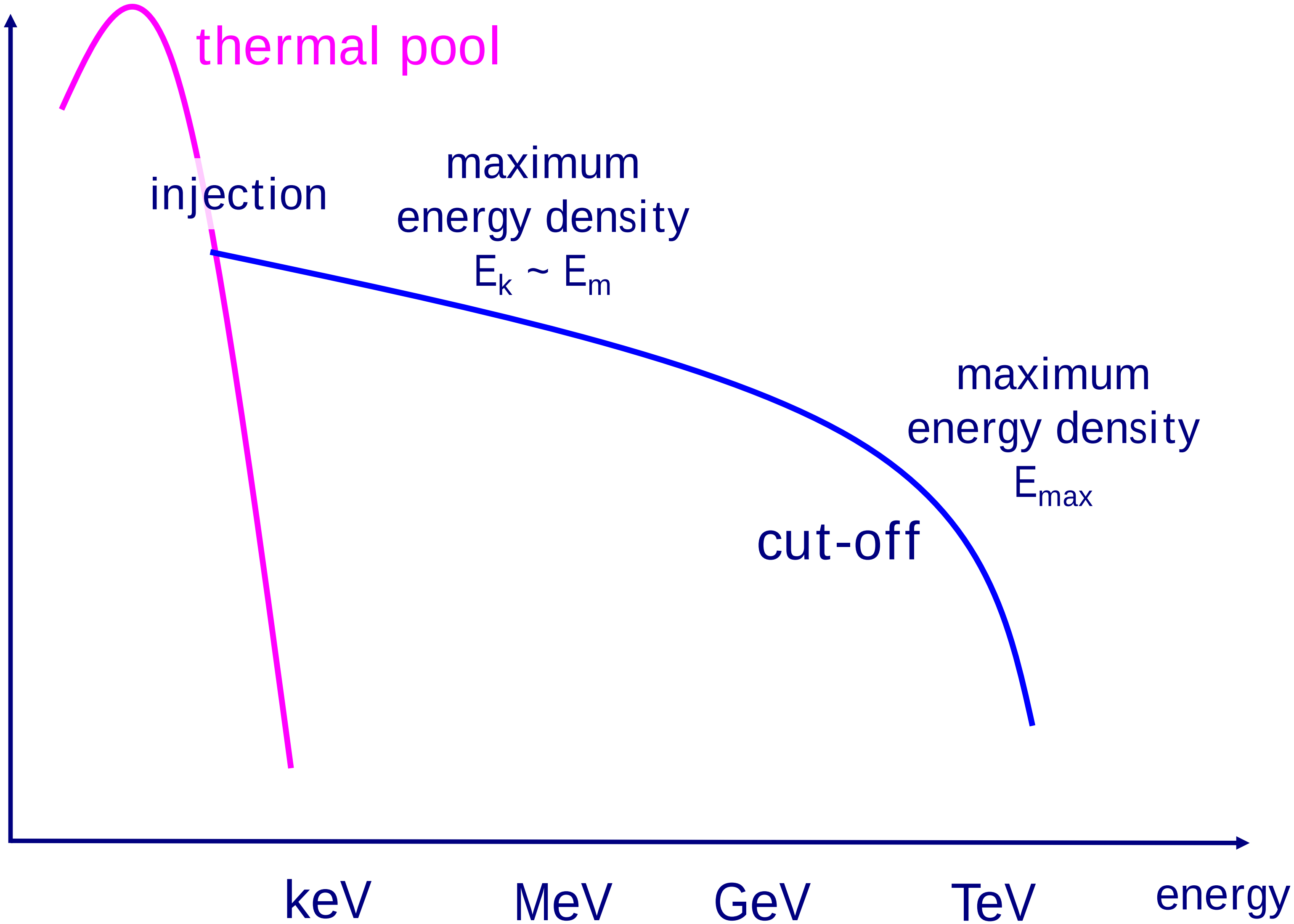
Wide-band observations are important to understand accelerated particles and acc. environment

topic 1:

Observations of accelerated particles

from highest energy to the injection points

Schematic spectrum of accelerated particles

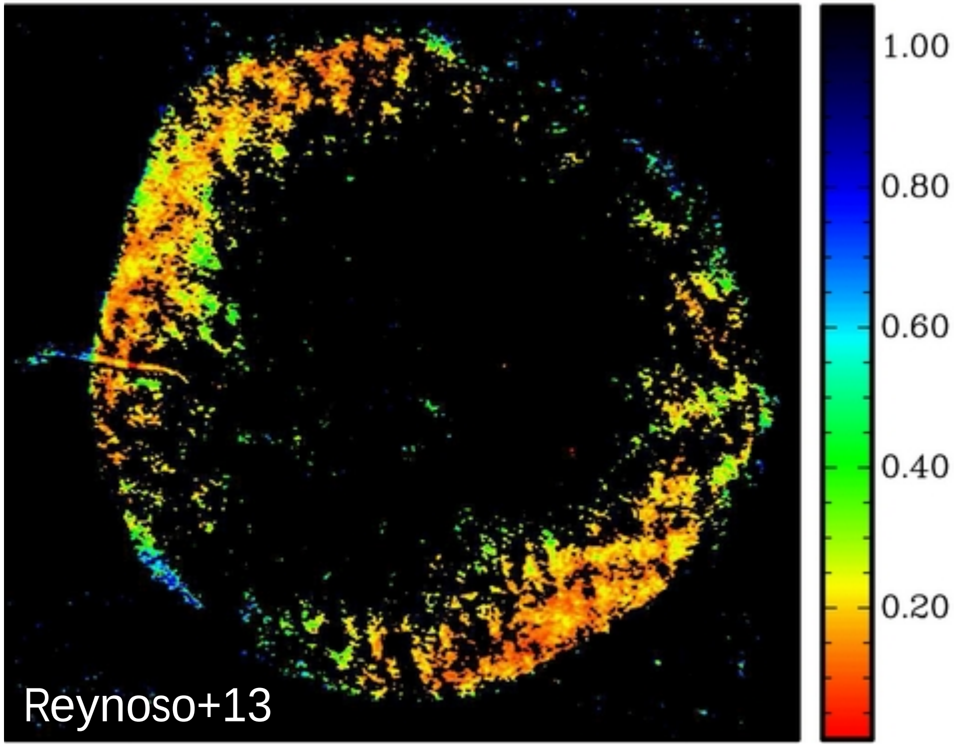


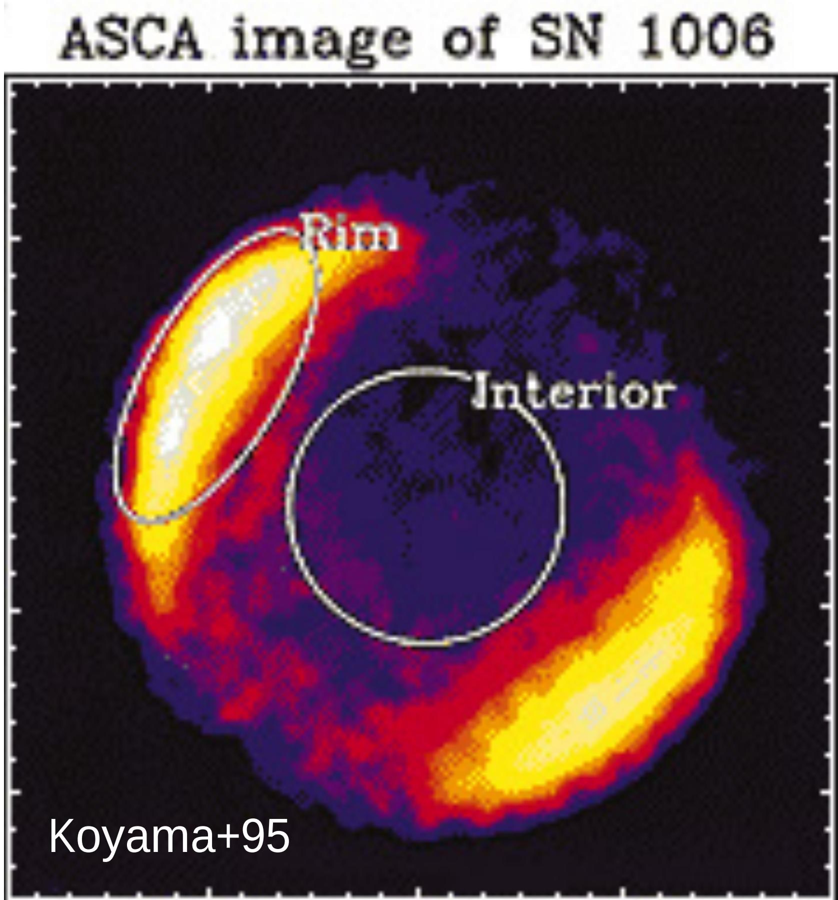
1.1. TeV electrons from SNR shocks

shocks of supernova remnants: bright sync. radio from GeV e

Koyama+95: Synchrotron X-rays from shells of the SNR SN1006
if B ~ uG -> electron energy should be ~ multi TeV
-> first discovery of TeV electrons from shocks of SNRs

fraction of polarization in radio





X-rays: sync. from TeV e -> info. of maximum E electrons

What determine the E_{max} ?

age ?   sync. cooling ?   or escape ?

From spectral cut-off shape:

-> origin of E_{max}

RXJ1713-3946:

sync. cooling limits E_{max}

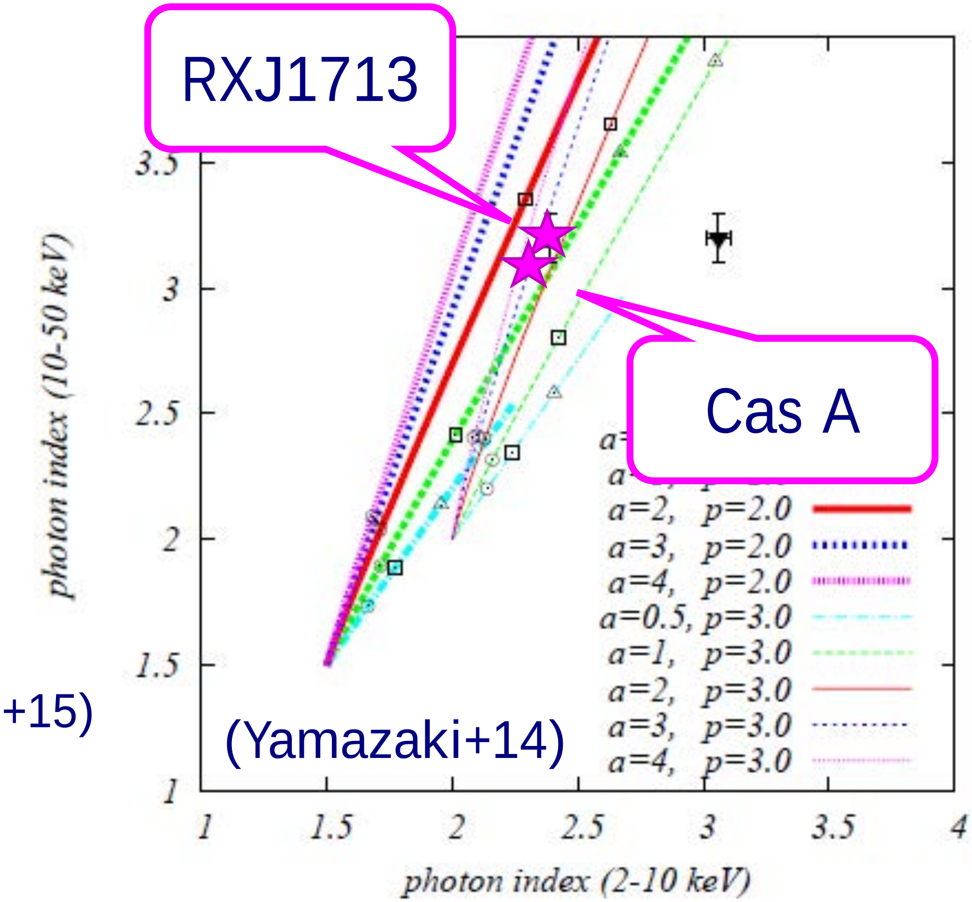
w. Bohm limit B

(Tanaka+08)

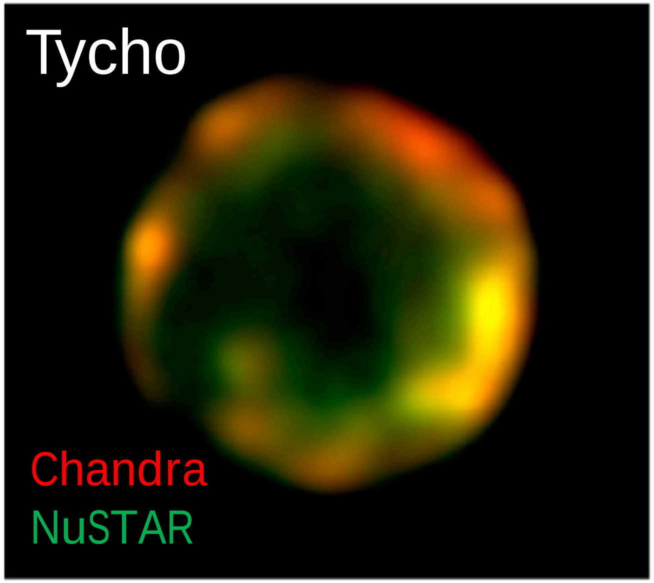
Cas A:

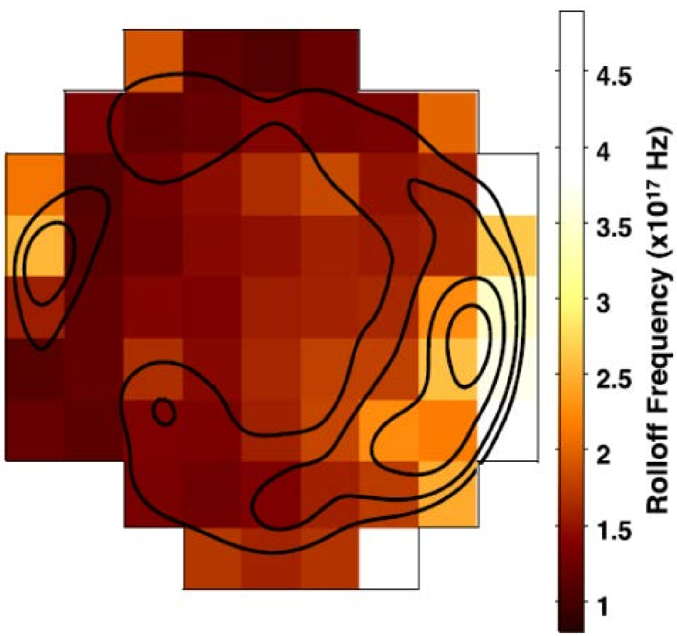
Also sync. cooling limit

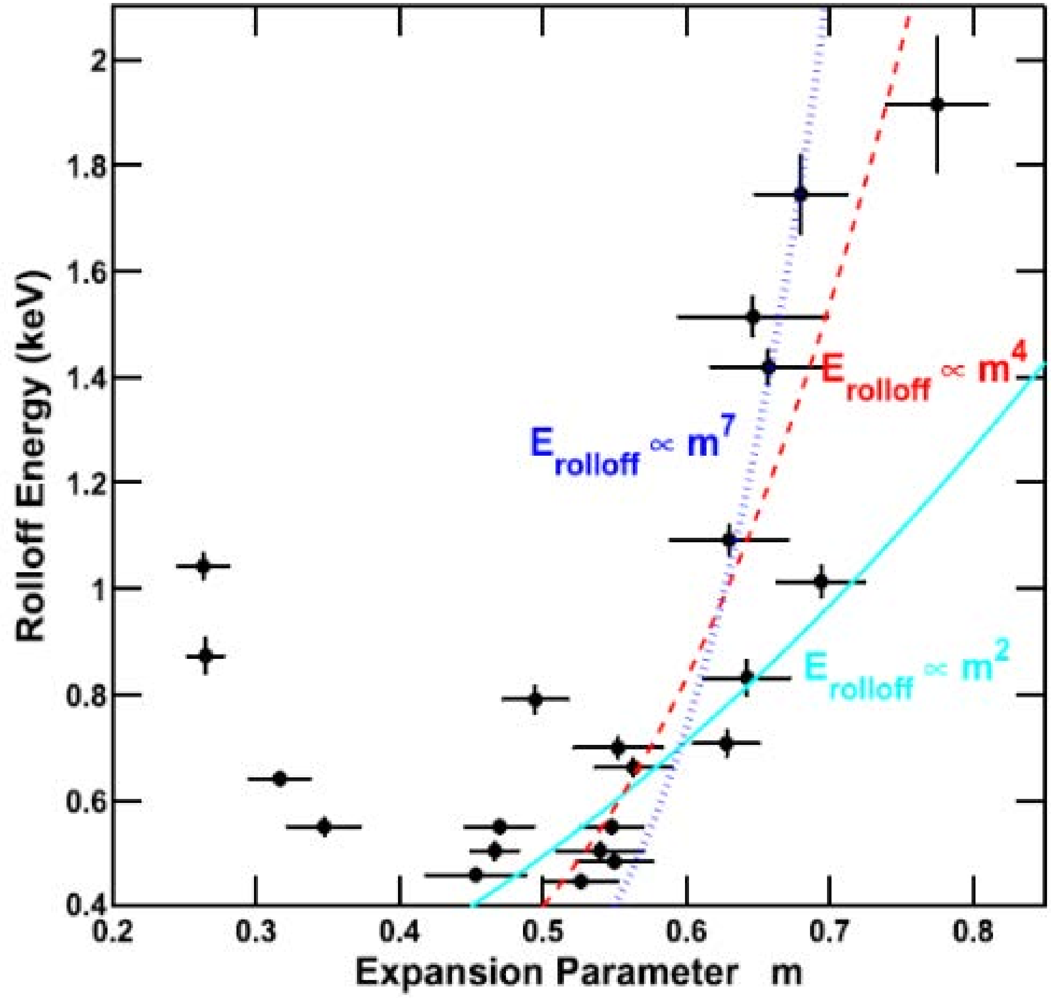
(Helder&Vink+08, Maeda+09, Grefenstette+15)



velocity dependence of roll-off E with NuSTAR (Lopez+15)

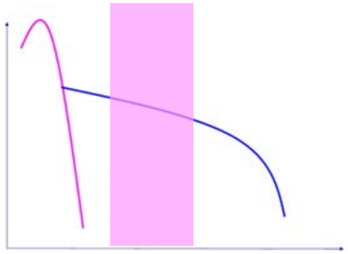




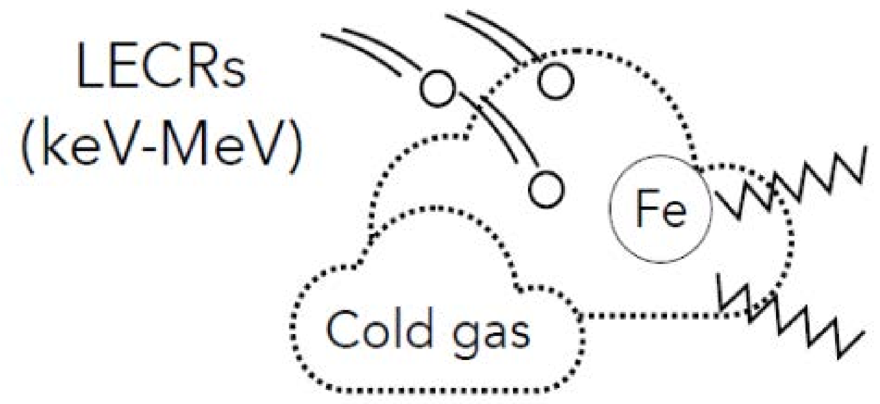


high roll-off on high shock speed region
age-limited ?

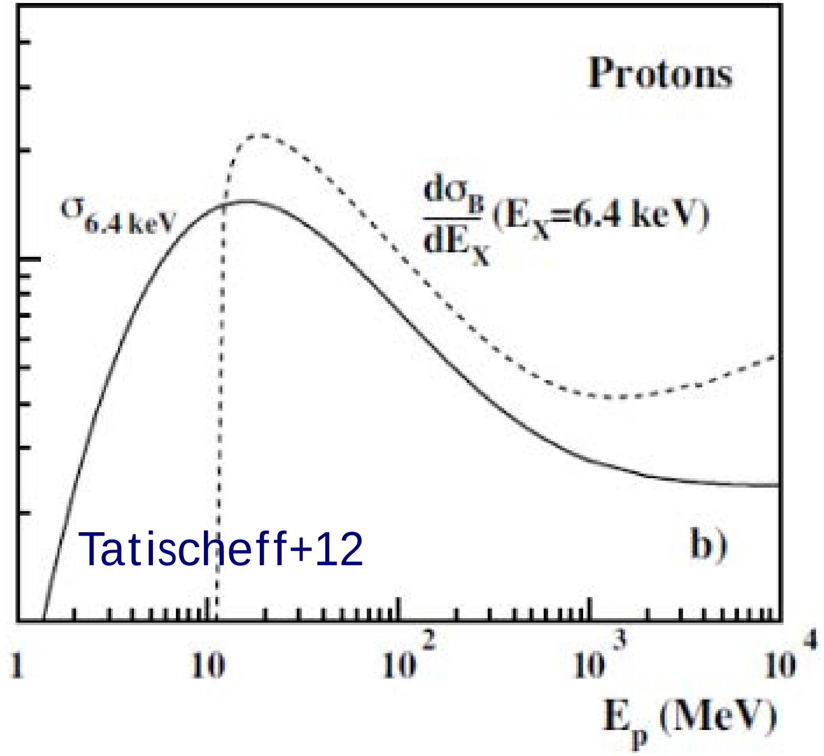
1.2. Clue of MeV protons ?



MeV – GeV protons:
highest contribution of
energy density of CRs
How they make emission ?



proton – cold iron cross section

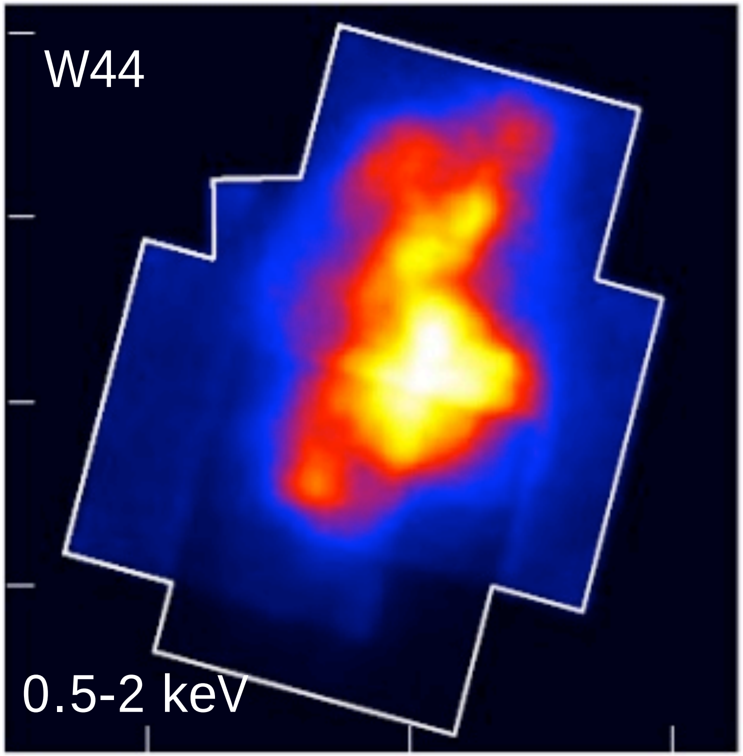


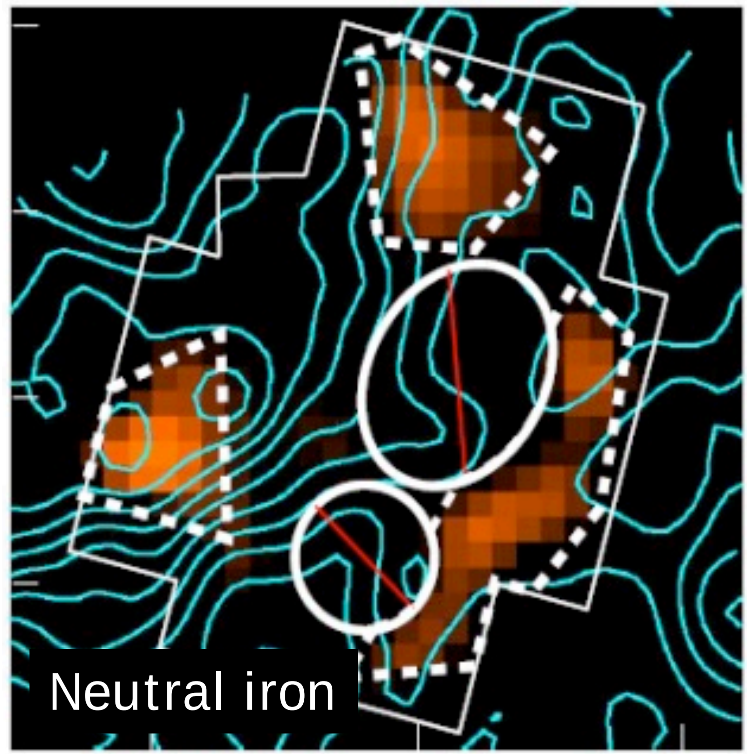
When low energy (~10 MeV) CRs collide with cold gas,
neutral Iron line is produced (6.4 keV)

-> good indicator of ~MeV protons

Deep observations show several SNRs have neutral iron line

(Nobukawa+18)



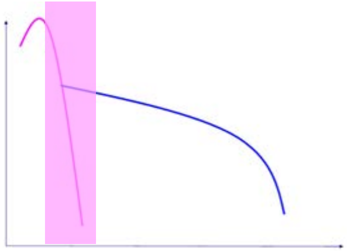


Several SNRs have neutral iron line on the interacting points with molecular clouds.

Energy density ~ 10-100 eV/cc.

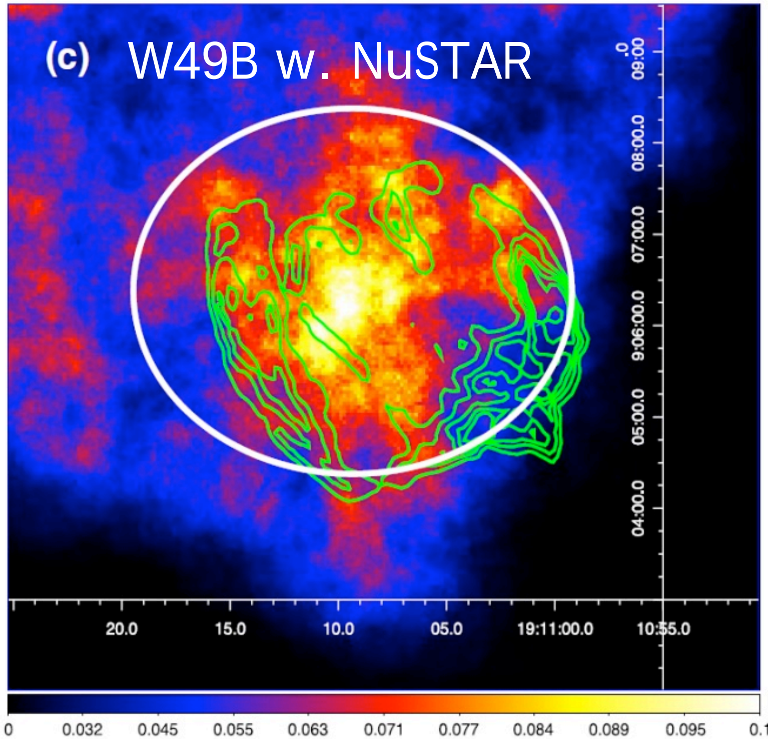
First measurement of CR energy density.

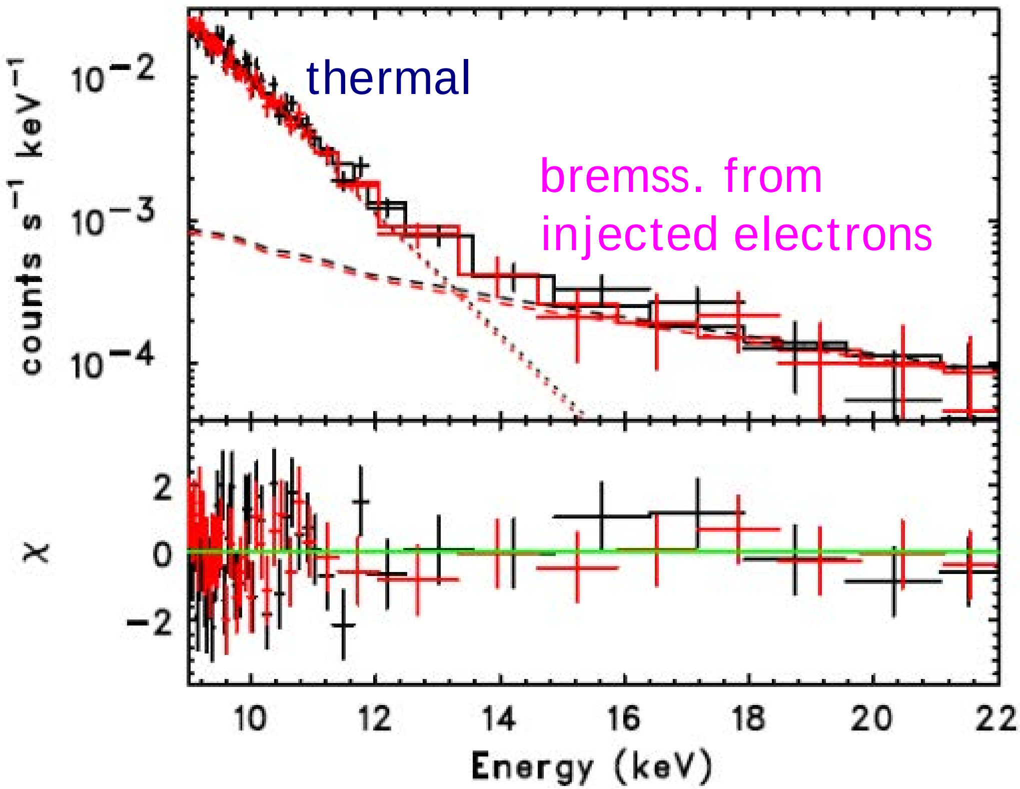
1.3. Particle information on the injection points



SNR thermal plasma: kT ~ keV

How they are injected into the acc. system ?





Tanaka+18

Detection of hard tail: Gamma = 1.4+-1.0 too hard for sync.

The first detection of nonthermal bremss.

from sub-relativistic electrons.

1.4. Summary of information on accelerated particles in SNRs

	Protons	Electrons
keV (injected)	-	nonthermal bremss.
MeV	neutral iron	-
GeV	pi-on decay	radio sync.
TeV	TeV gamma-rays	X-ray sync.

Recent X-ray obs. showed us on the low energy part of acceleration particles.

Now we have pieces of the accelerated particle info. with several ways.

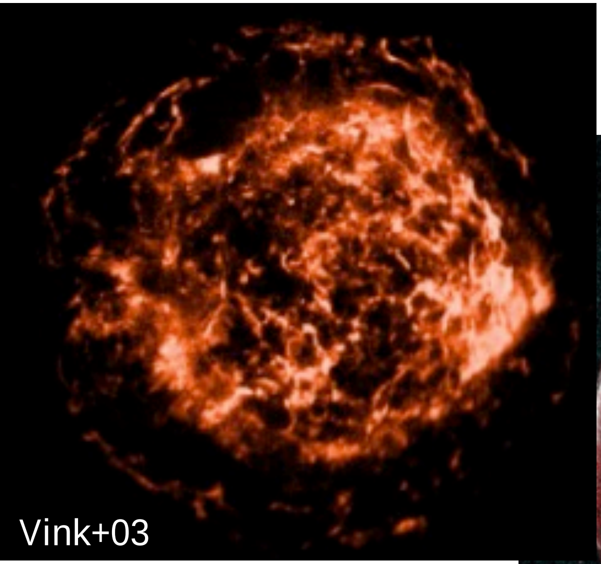
X-ray/gamma-ray observations are the strong tool for various energy range of accelerated particles.

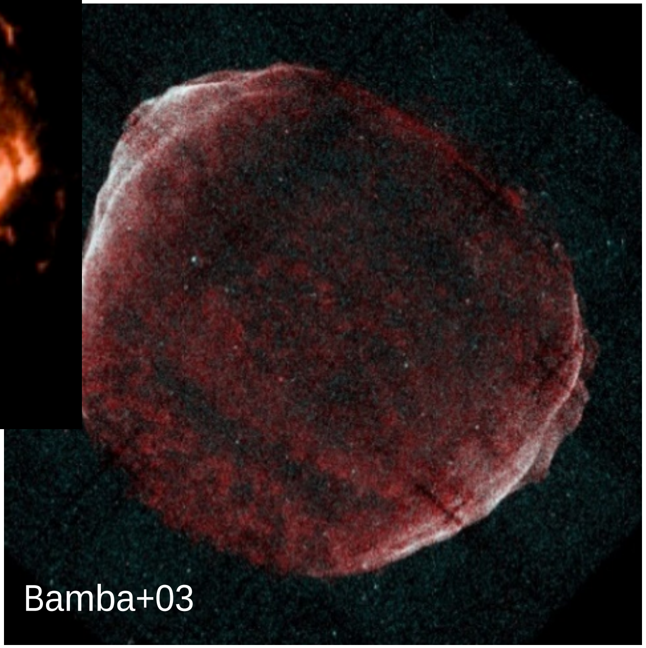
topic 2:

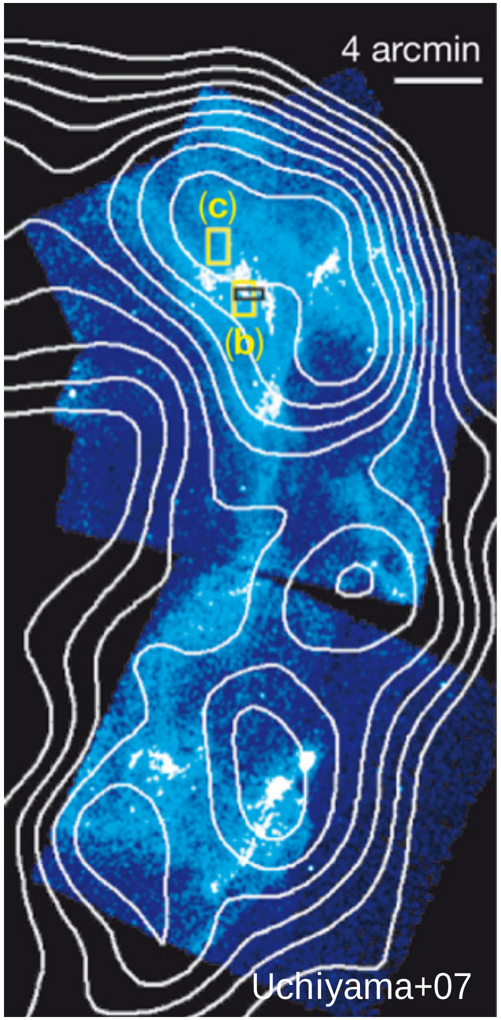
Acceleration efficiency

at the shocks of supernova remnants

2.1. Young SNRs are efficient accelerators







Chandra discovered thin & time variable synch. X-ray filaments

-> small gyro radius and diffusion, short sync. cooling

-> amplified and turbulent magnetic field

-> efficient particle accelerators

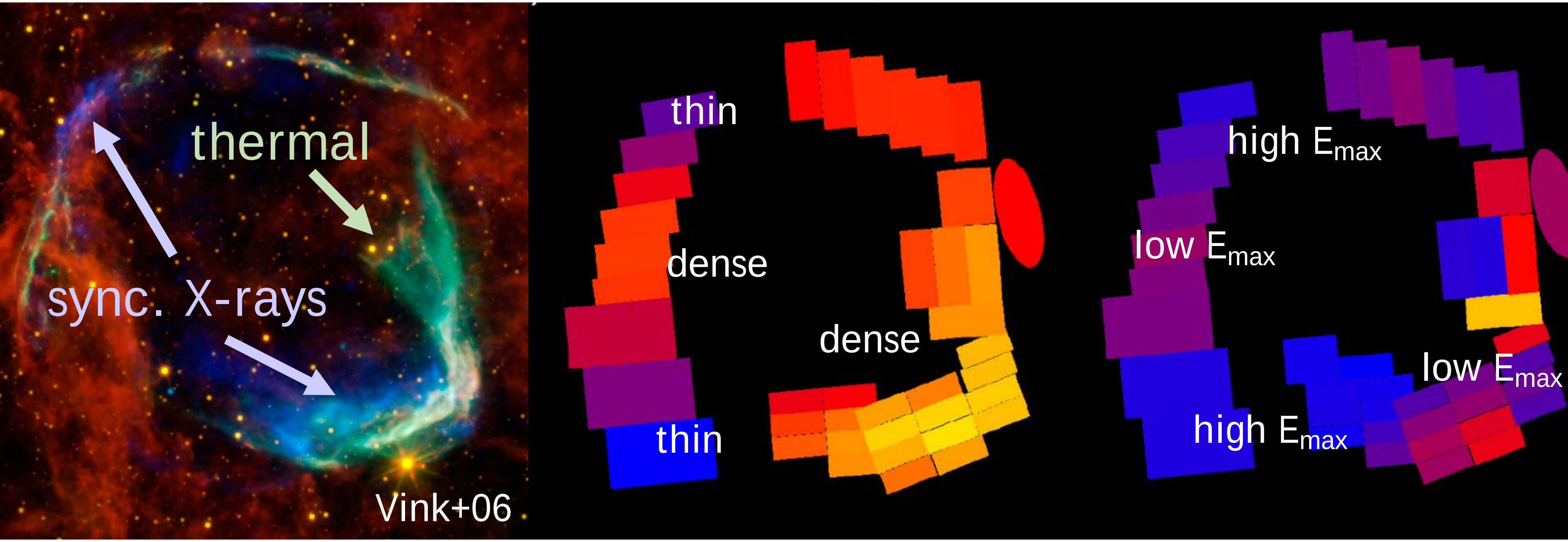
2.2. Which part of SNR make E_{max} particles ?

Thermal X-rays tells us the environment of acc. sites.

RCW86 case:

emission measure$^{1/2}$
$\propto$ ISM density

photon index



low ISM density region has (Tsubone+17)

harder sync. X-rays = large E_{max} for acc. electrons

When E_{max} is determined by sync. loss limit:

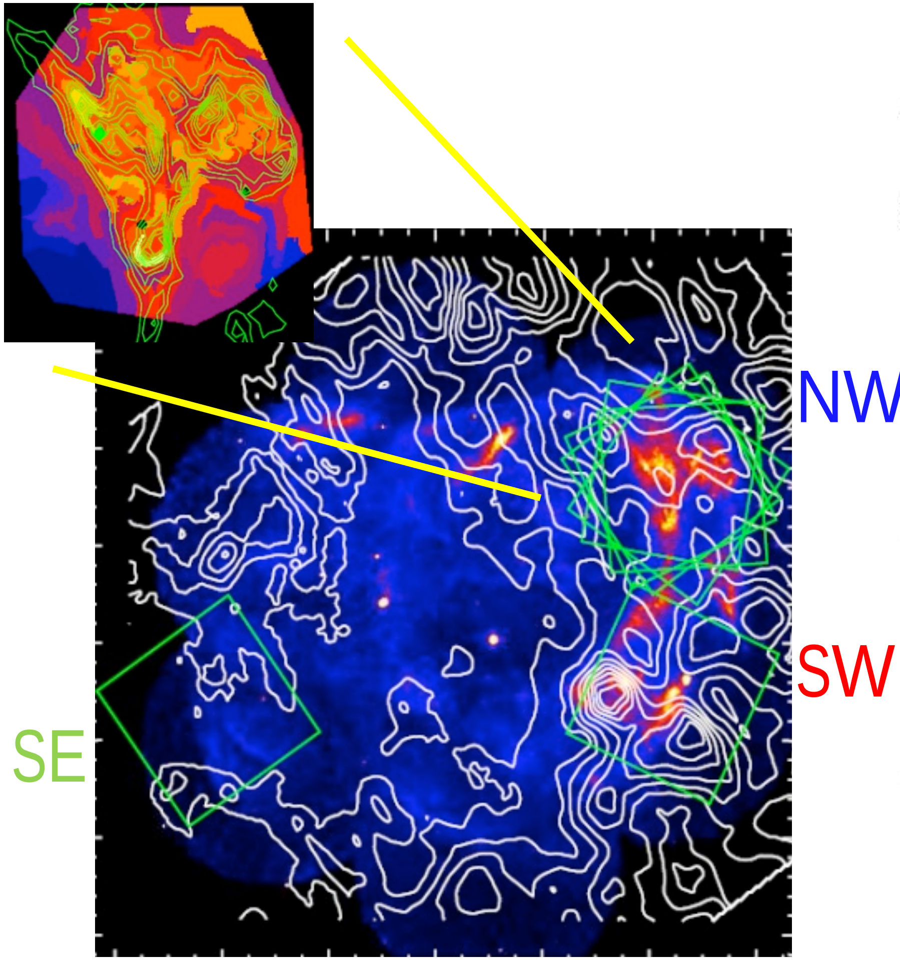
cut-off E of sync. X-rays $\propto$ shock velosity^2

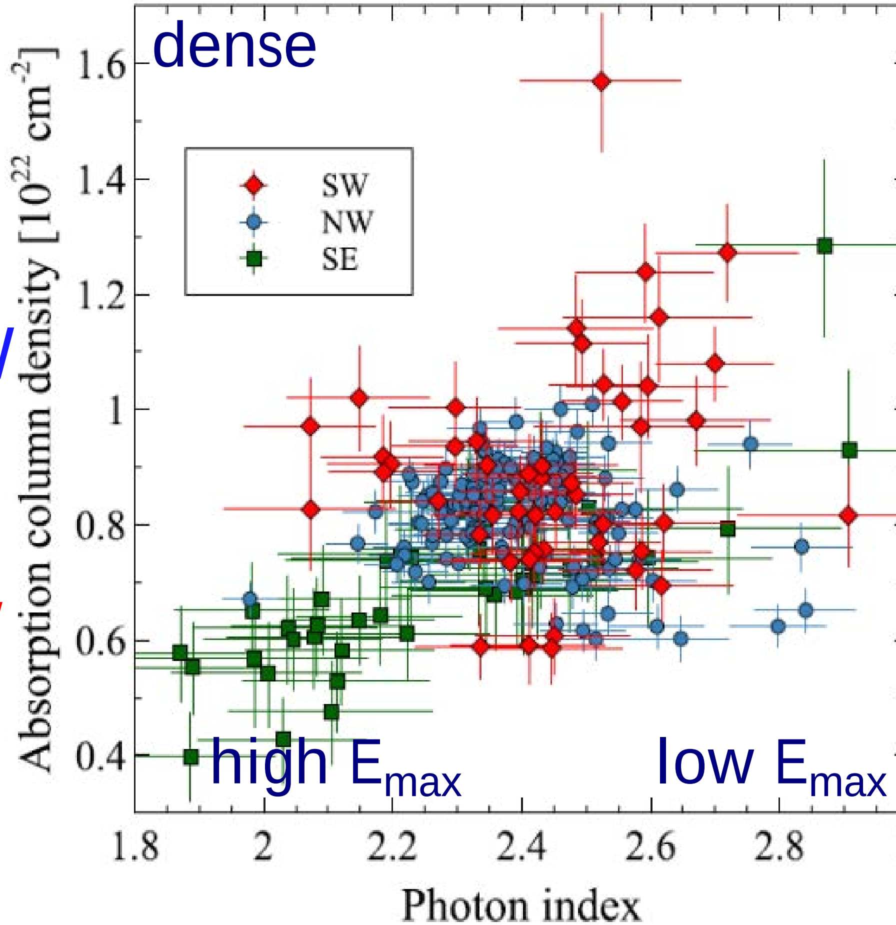
(Yamazaki+06, Aharonian & Atoyan 1999)

low ISM density <-> shock keeps large velocity <-> large E_{max}

Situation is not so clear in RXJ1713 case …

(Okuno+18)





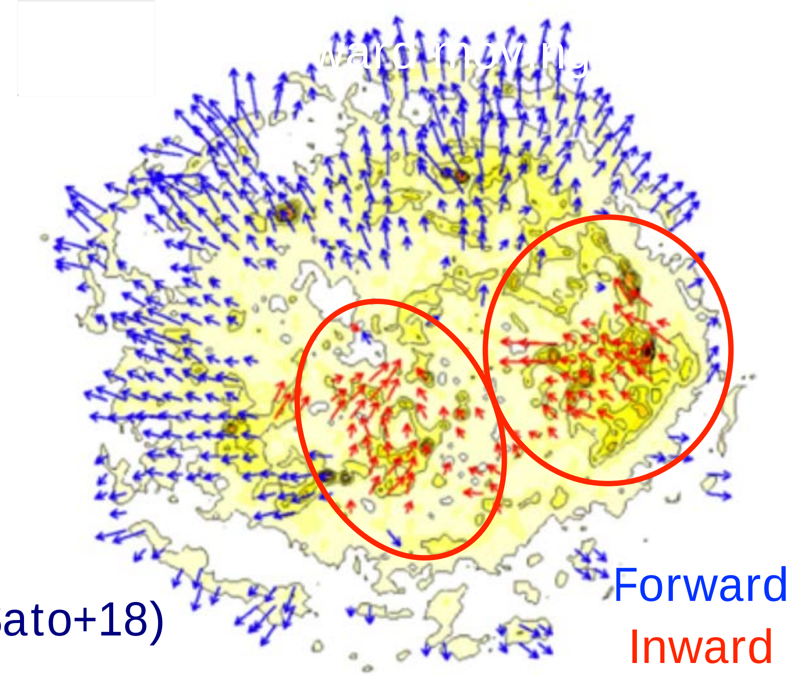
SE part: large abs. (dense) region has lower E_{max}
consistent with our scenario

NW/SW parts: it is not the case
due to shock-cloud interaction ?

2.3. efficient acceleration on inward shocks

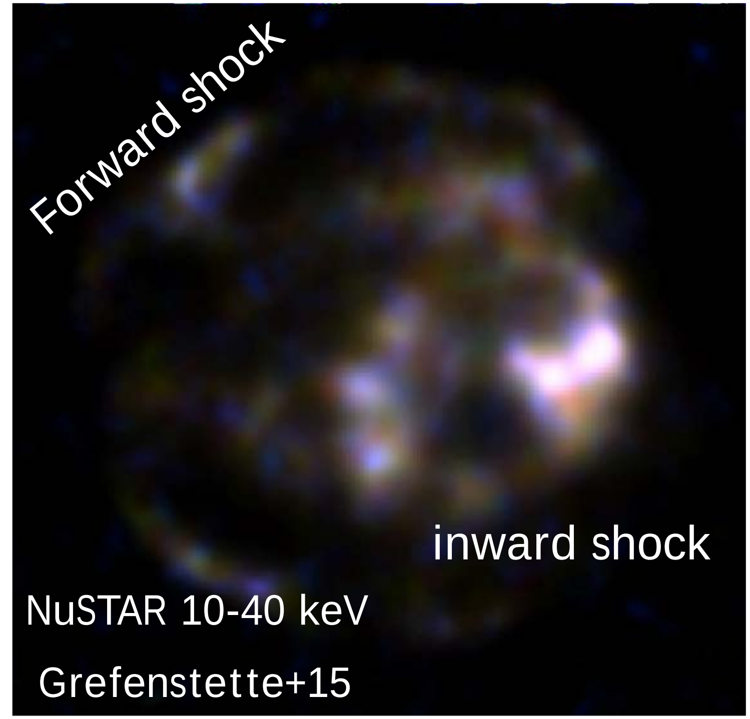
Cas A:

Proper motion
w. optical flow method



(Sato+18)

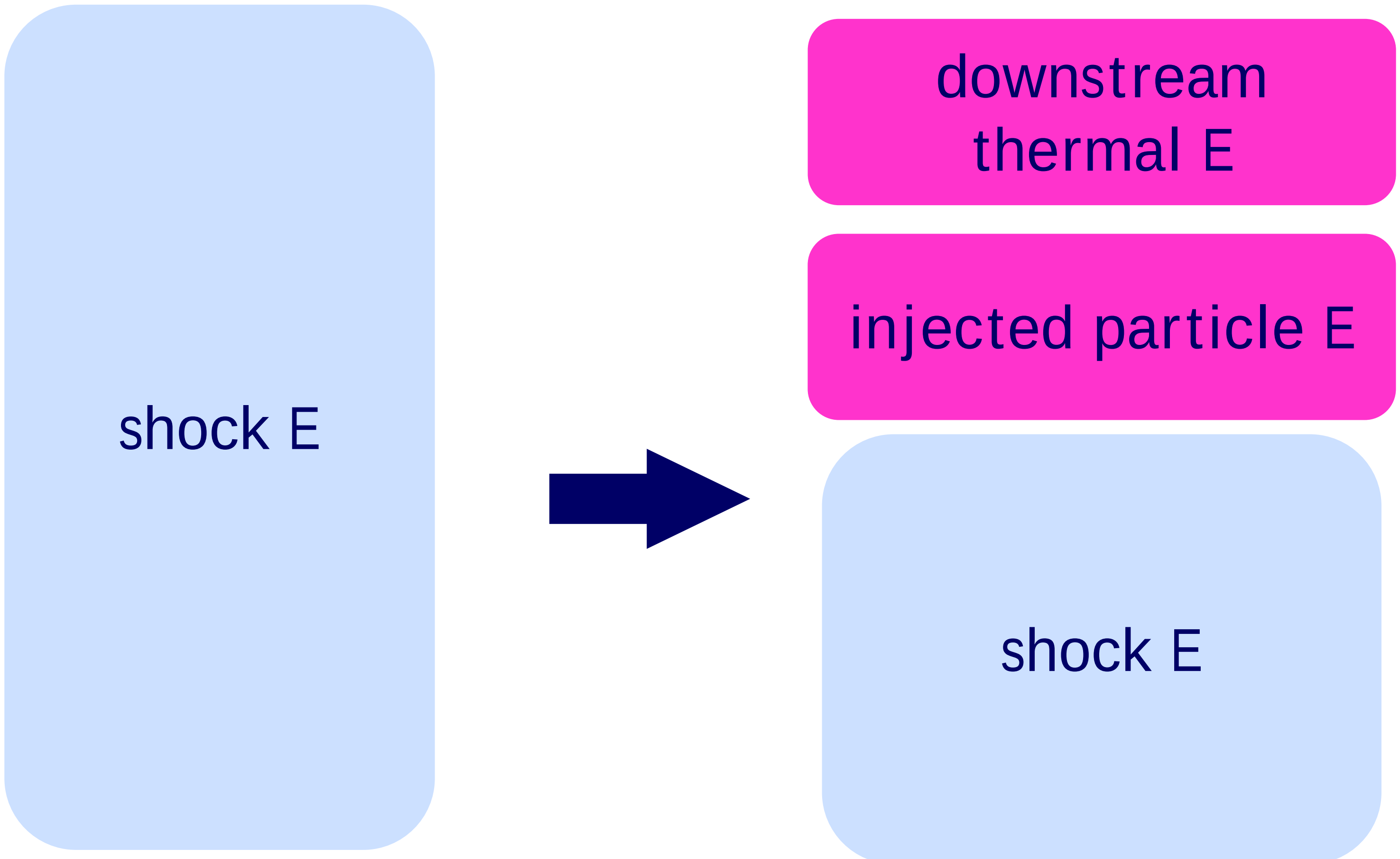
Hard X-ray hot spots



Inward shocks could be produced
by the shock cloud interaction (Kilpatrick+14)
but Zhou+18 found no clue of interaction
Interaction makes B-amplification and fast shock ? (Sato+18)

2.4. Main energy contributor is lower energy particles -> how to measure the input energy ?

From Rankine Hugoniot relation

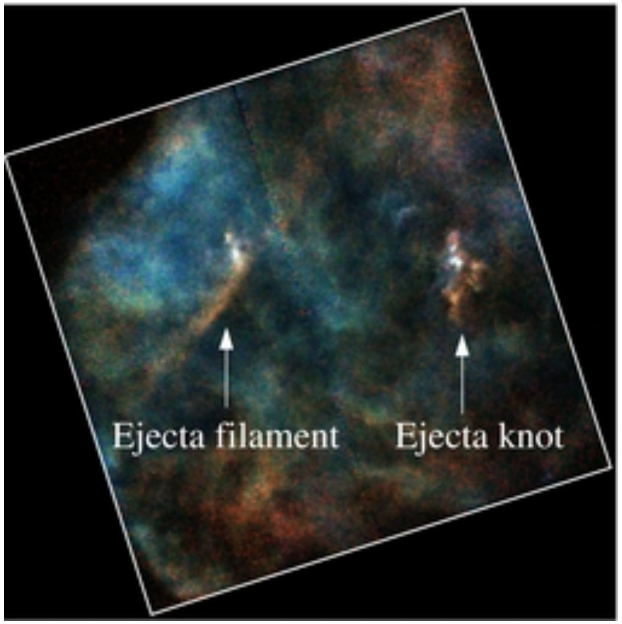


efficient particle acceleration steal energy from the thermal energy of downstream plasma

We need to know both shock velocity and thermal condition

Injection efficiency
measured from ion kT

obs. of ejecta knots in SNRs
-> Dopp. shift + thermal broard



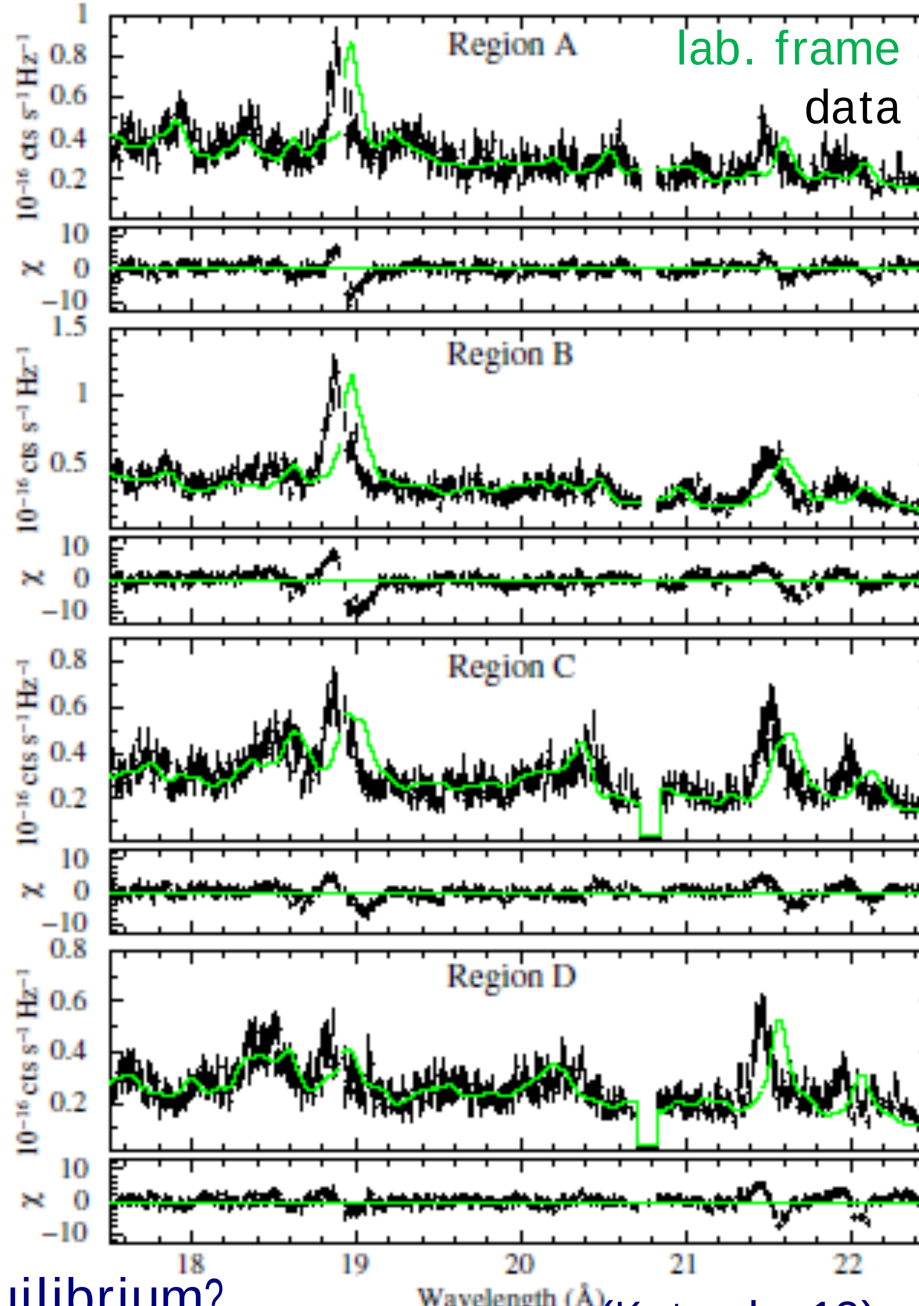
In the case of Puppus A Oxygen

Doppler v ~ 1500km/s
expected O kT ~ 130 keV
<-> observed O kT < 30 keV

(Katsuda+13)

due to energy injection ? just non-equilibrium?

We need more energy resolusion



(Katsuda+13)

2.5. We need better energy resolution

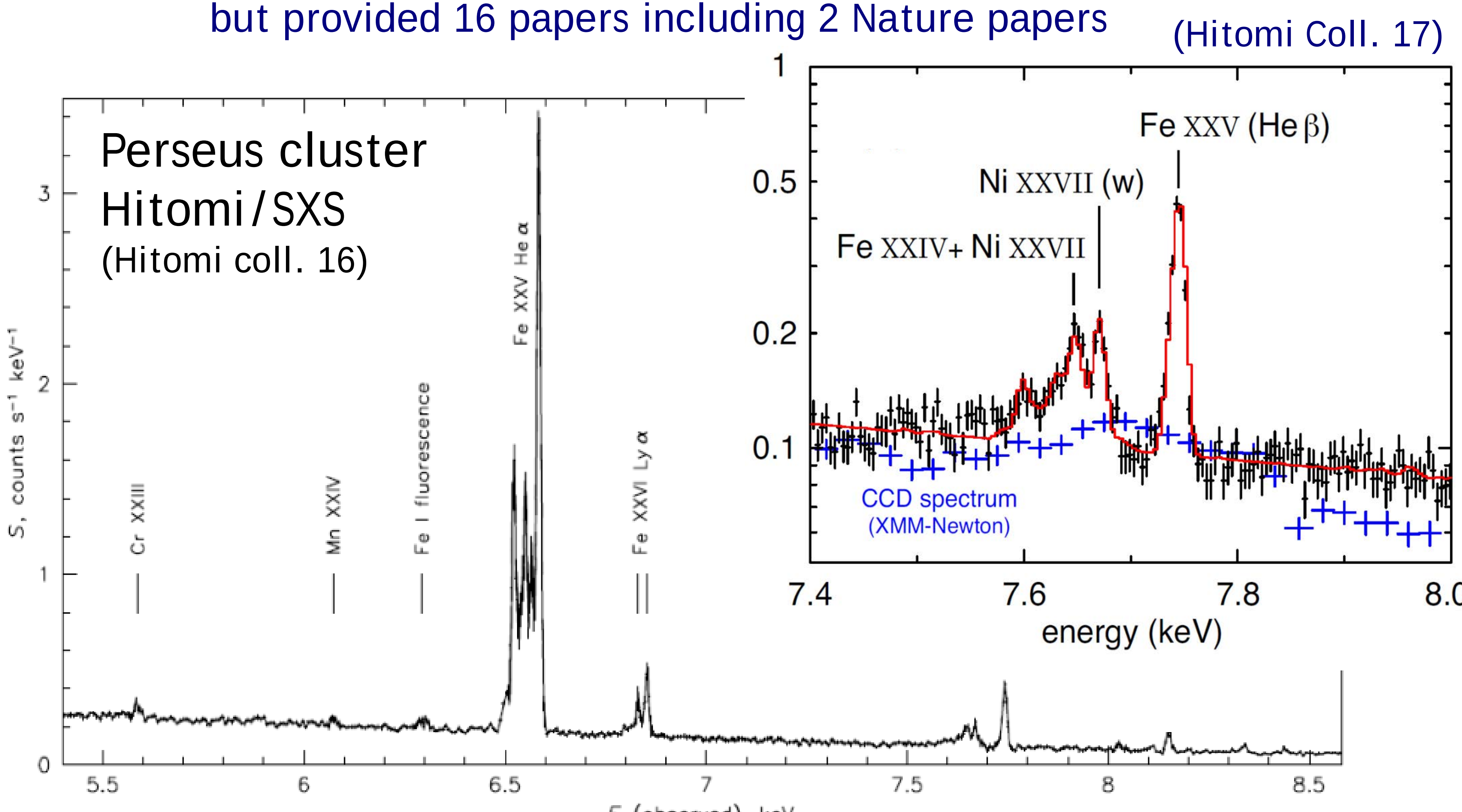
Hitomi: the first successful observations with an X-ray calorimeter

30 times better energy resolution for diffuse sources

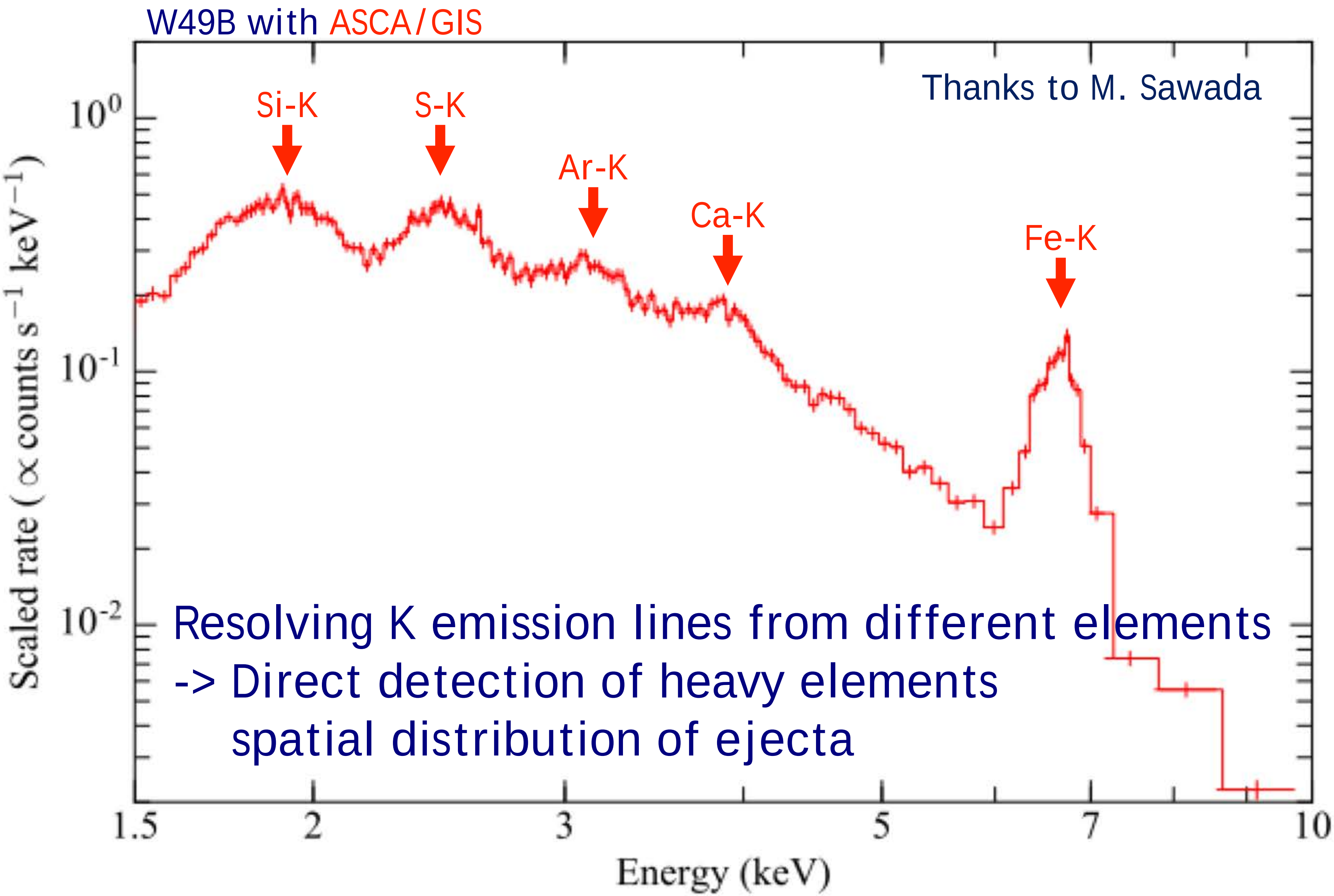
-> ideal for studying the plasma diagnostics

Only 1 month operation due to the accident,

but provided 16 papers including 2 Nature papers

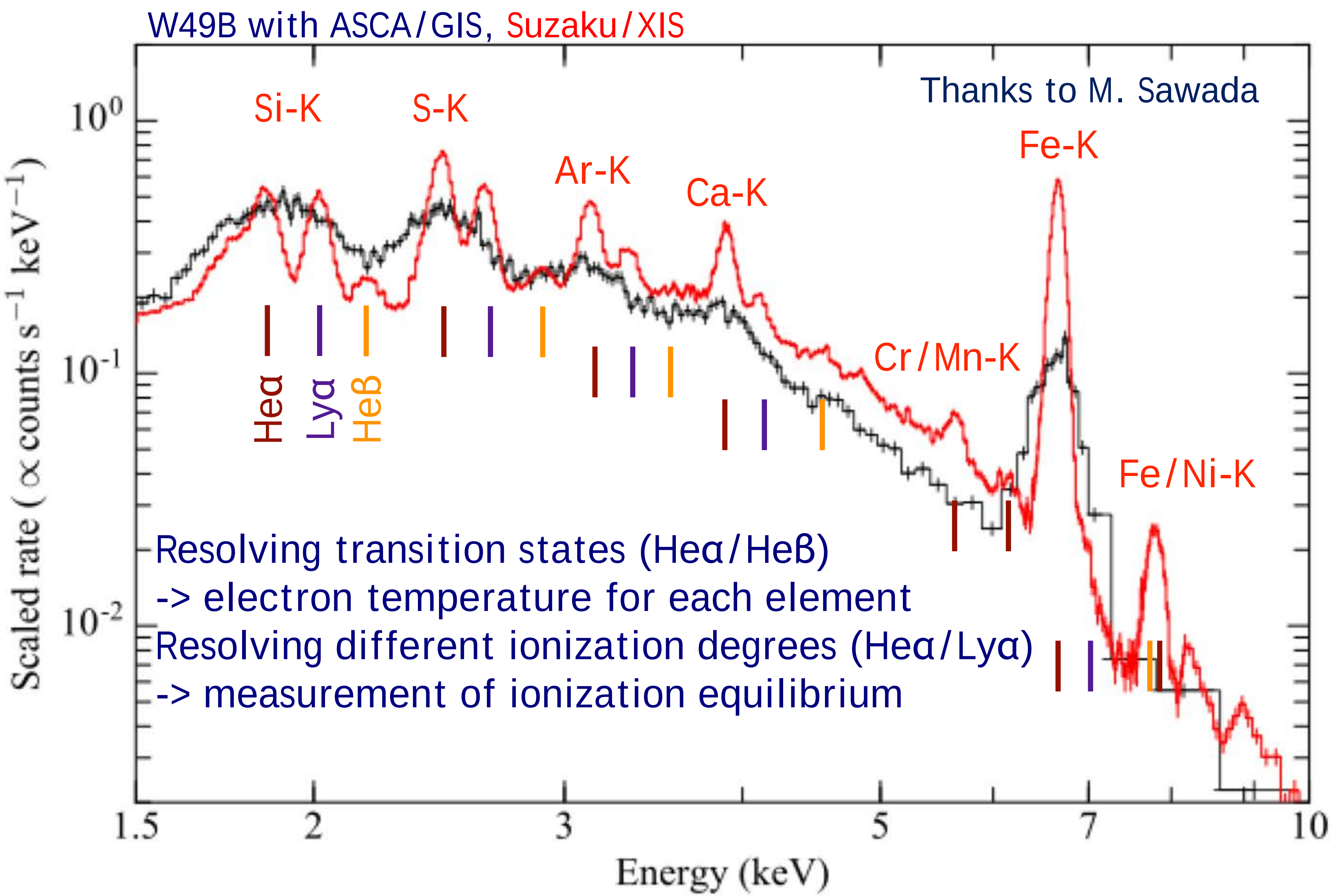


2.6. What we will see in SNR spectra with calorimeter

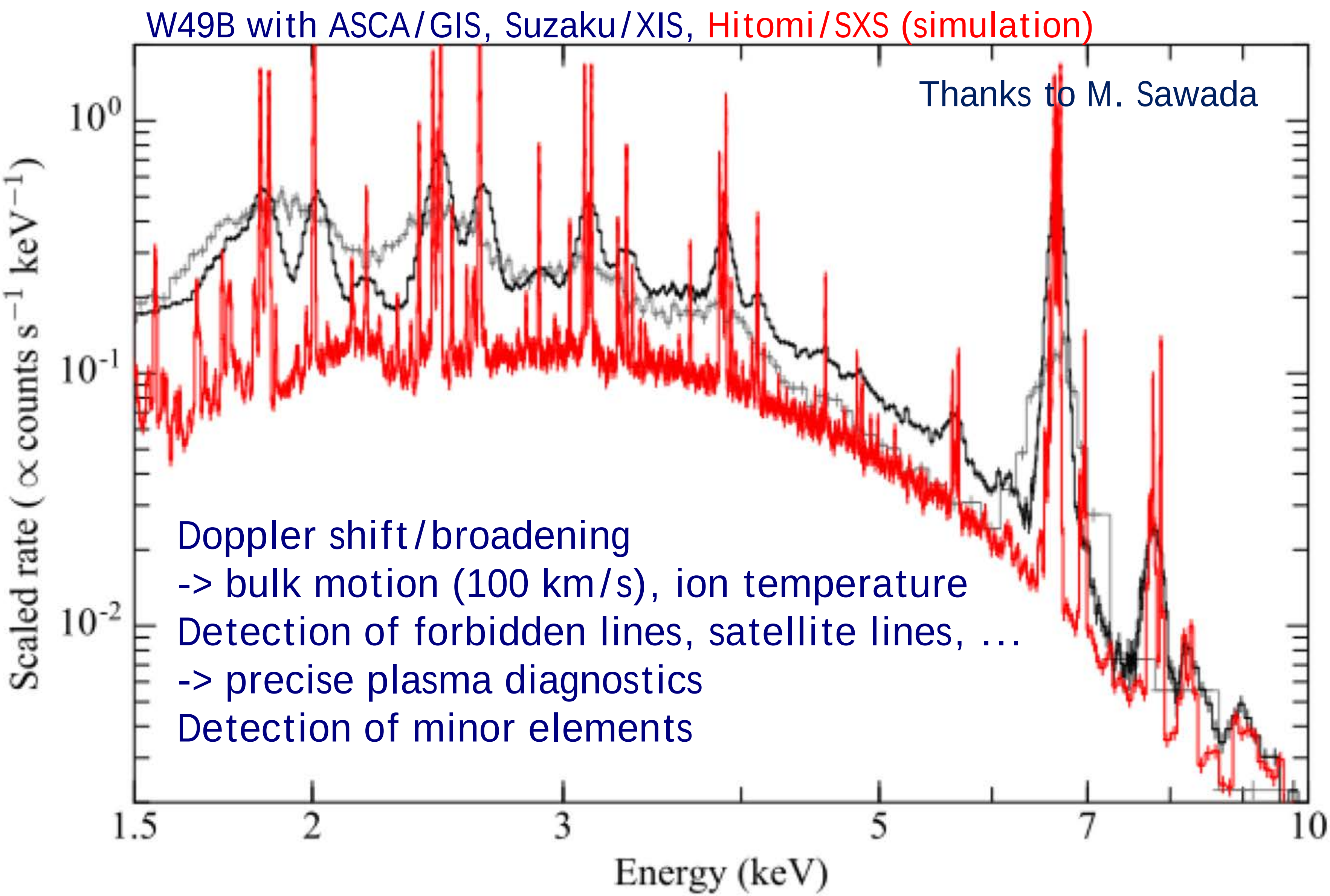


Resolving K emission lines from different elements
-> Direct detection of heavy elements
spatial distribution of ejecta

2.6. What we will see in SNR spectra with calorimeter



2.6. What we will see in SNR spectra with calorimeter

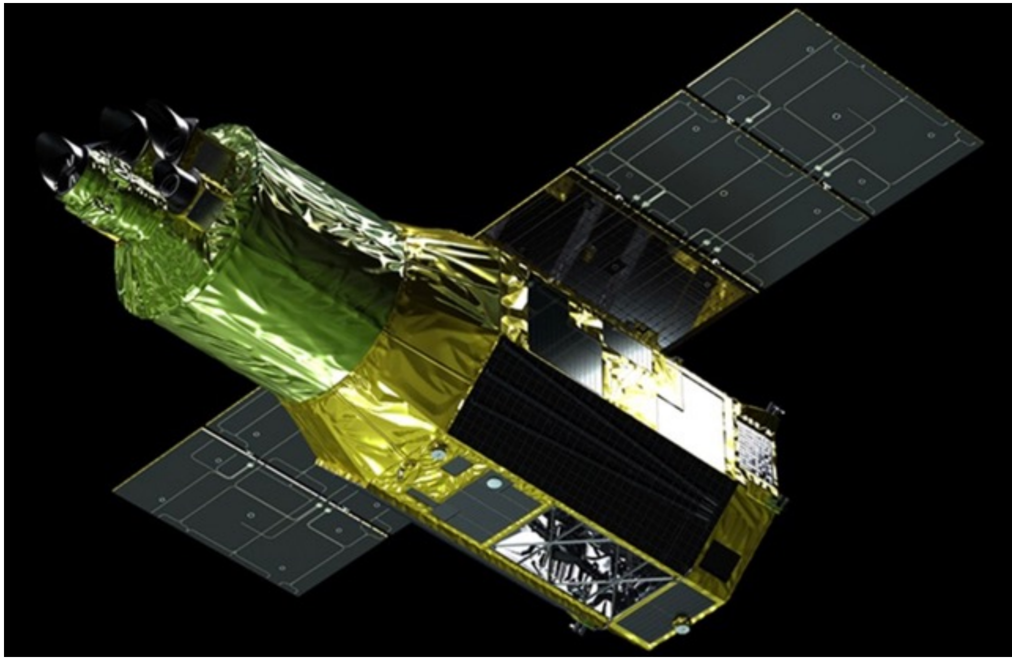


2.7. We will have the calorimeter mission again

XRISM: X-ray imaging spectroscopy mission
X-ray calorimeter + X-ray imaging CCD
Planed to launch 2021 Japanese fiscal year

XRISM will measure the stolen energy of SNR shock
by cosmic rays within ~10 % accuracy.

XRISM web site just opened !!
http://xrism.isas.jaxa.jp/en/

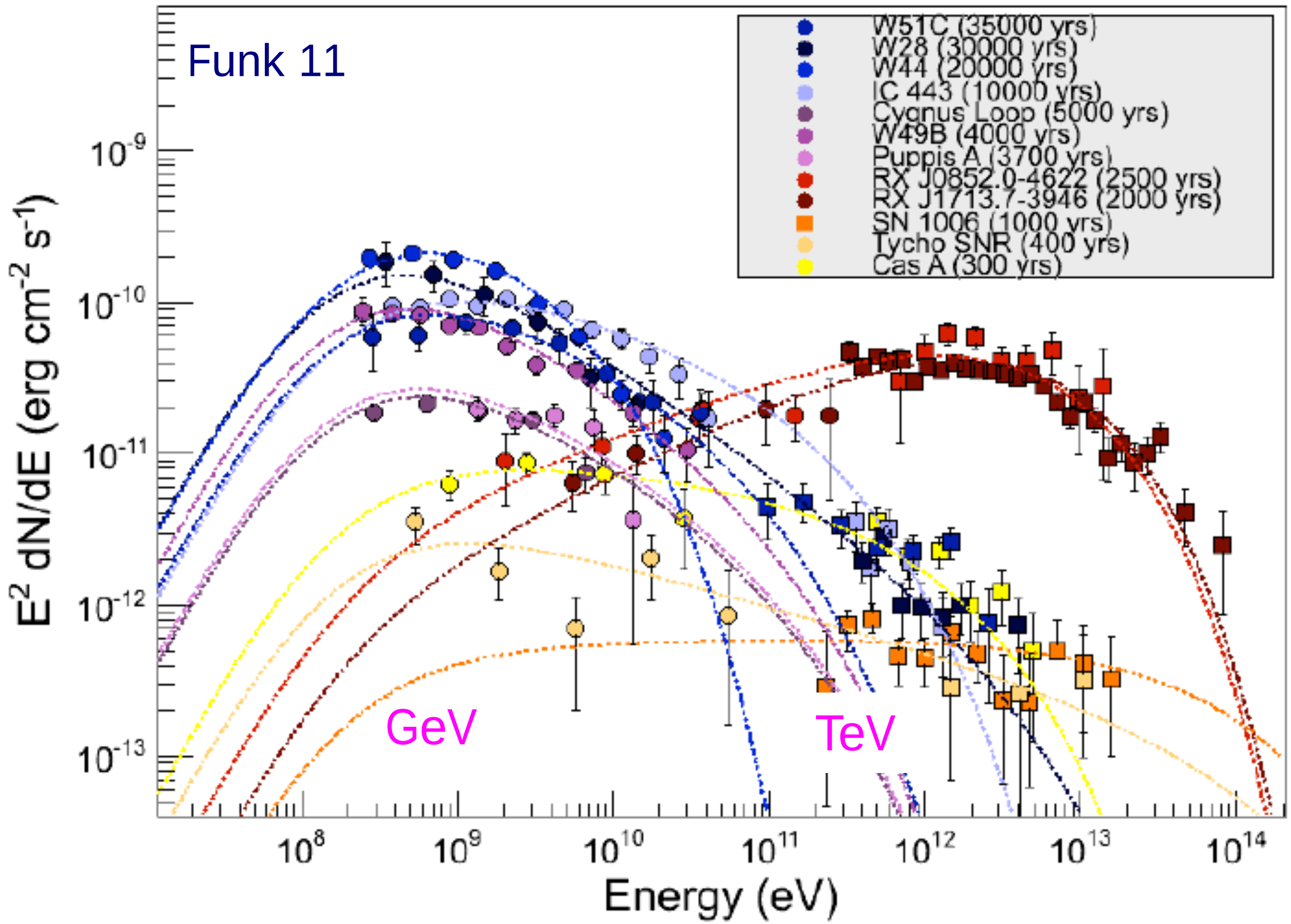


topic 3:
Particle escape from supernova remnants
to be cosmic rays

3.1. When SNRs become older (~2000 yrs old) …

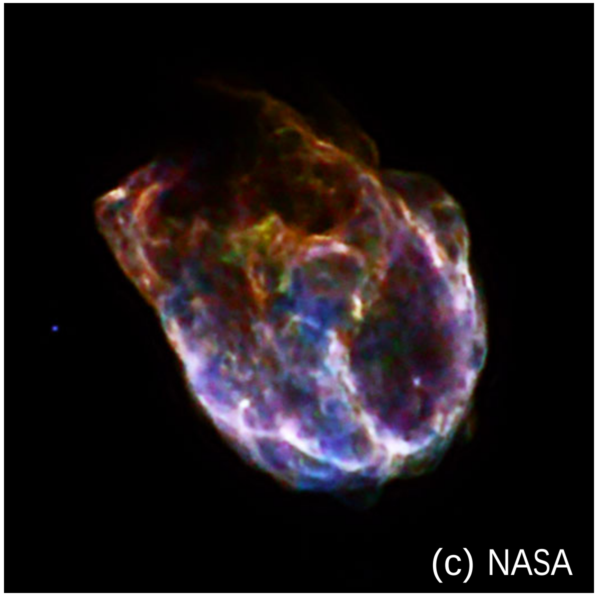
no sync. X-rays
only GeV gamma-rays
with cut-off ~ 10 GeV
(Acero+16)

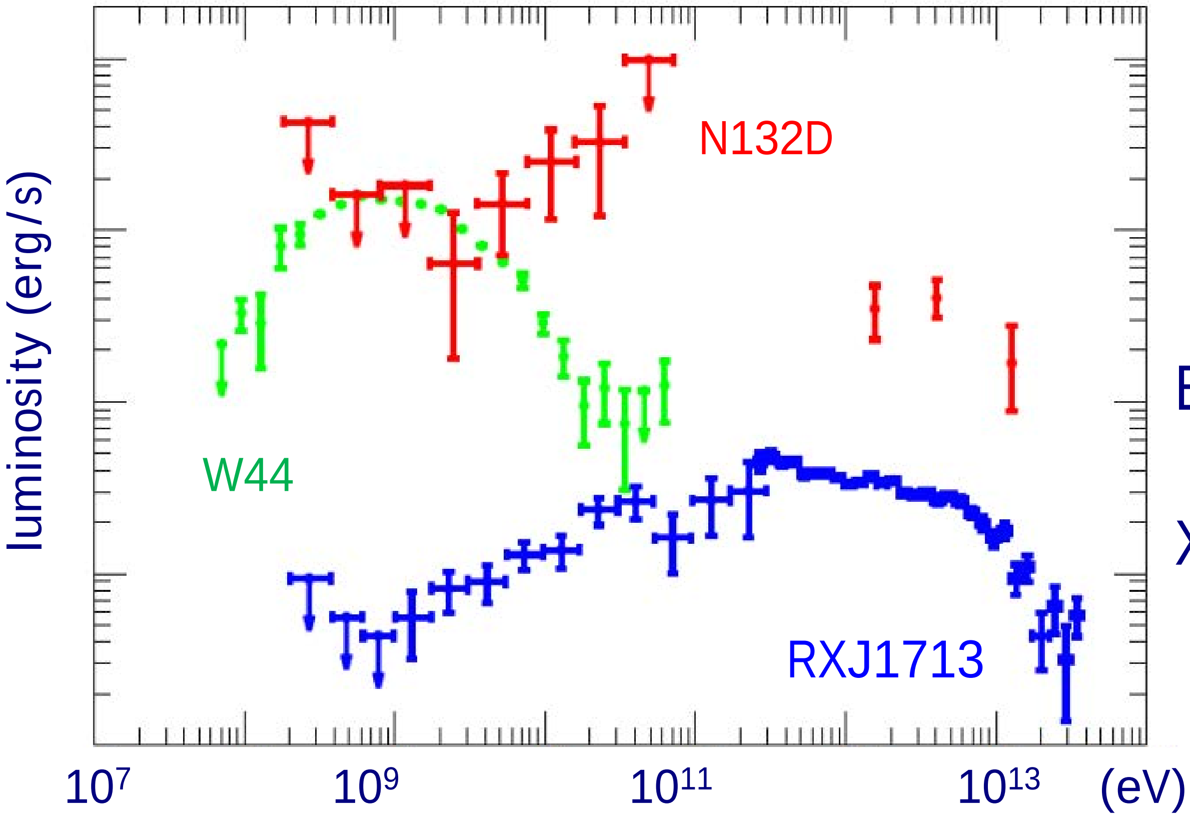
Acc. particles escape
from the acc. sites ?



Transiton from young to middle-aged: N132D

N132D:
O-rich CC SNR, age ~ 2500 years
the brightest in gamma-rays
also bright in X-rays



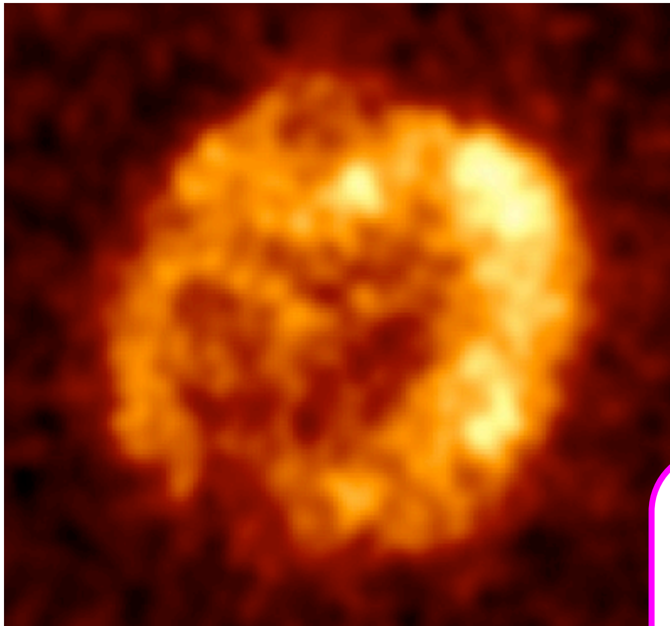


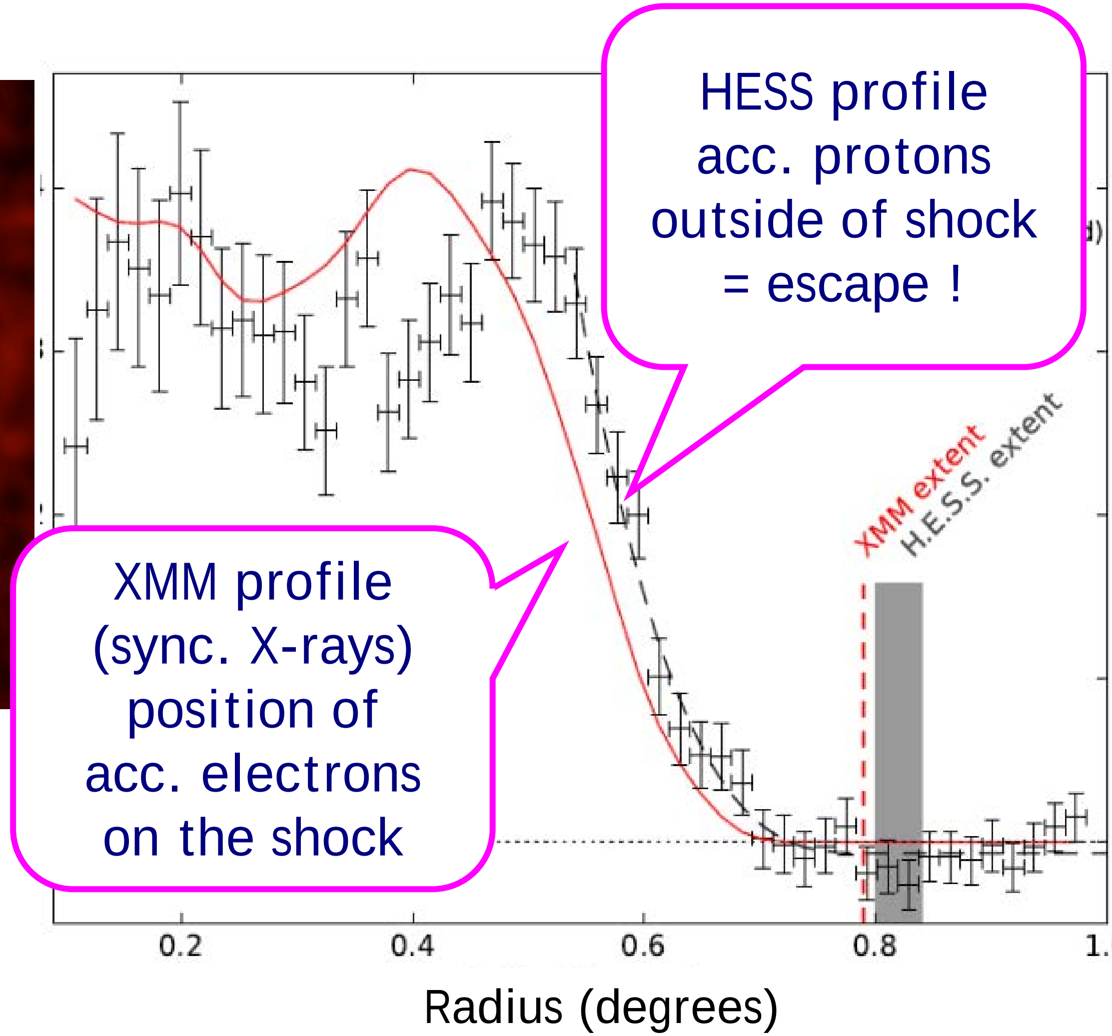
Between young and old in gamma-rays
X-ray properties are also between (Bamba+18)

More clue of particle escape

VHE gamma-ray image of RX J1713-3946 (H.E.S.S.+16)

exposure: 163 hours !



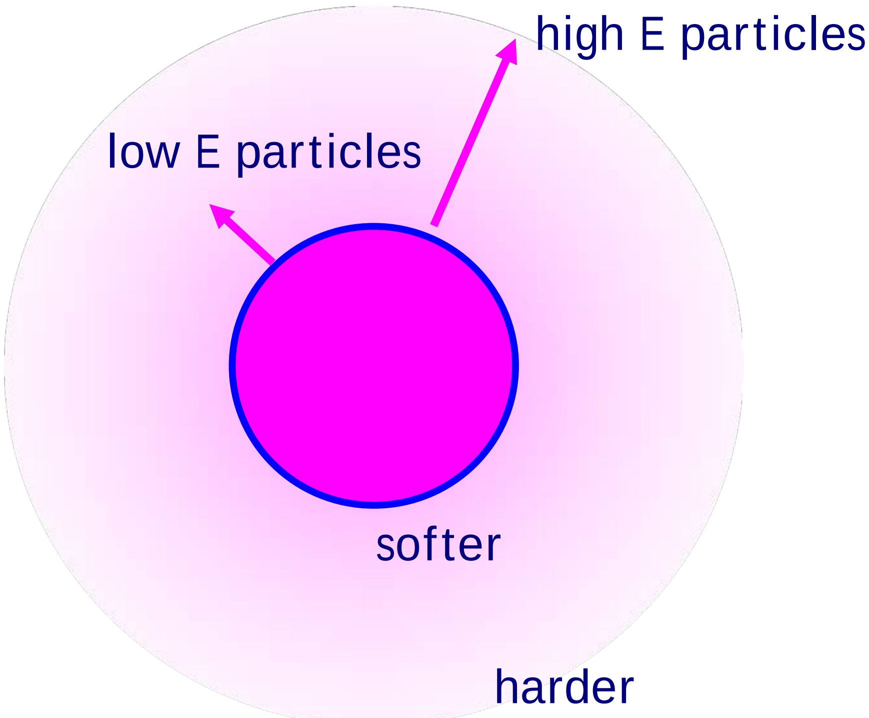


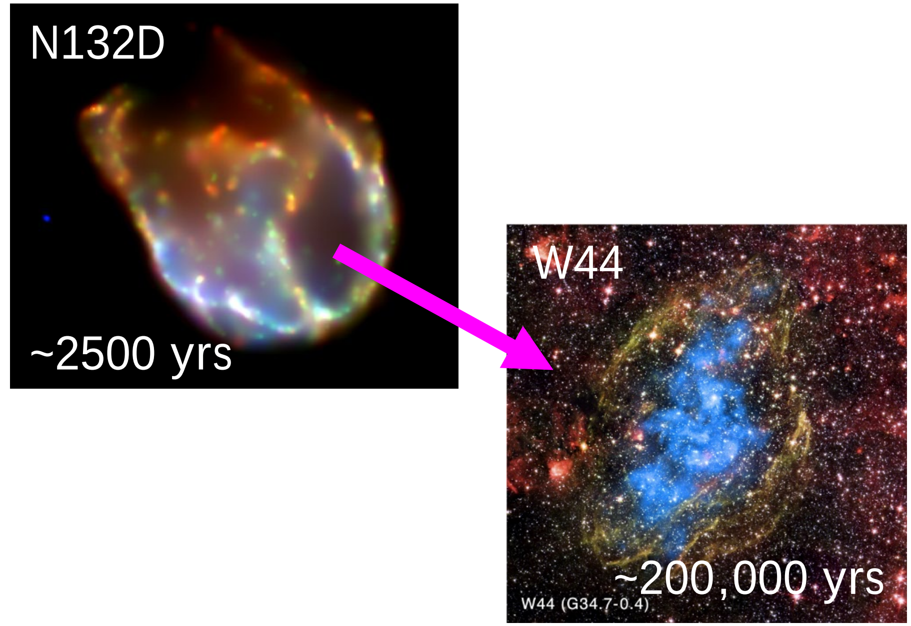
TeV emission comes from ~TeV particles
Sync. X-rays comes from ~10 TeV electrons

-> first detection on the proton escape

3.2. How to measure the time scale of escape ?

higher energy protons have
larger gyro radius/diffusion coefficient
-> higher energy protons escape faster



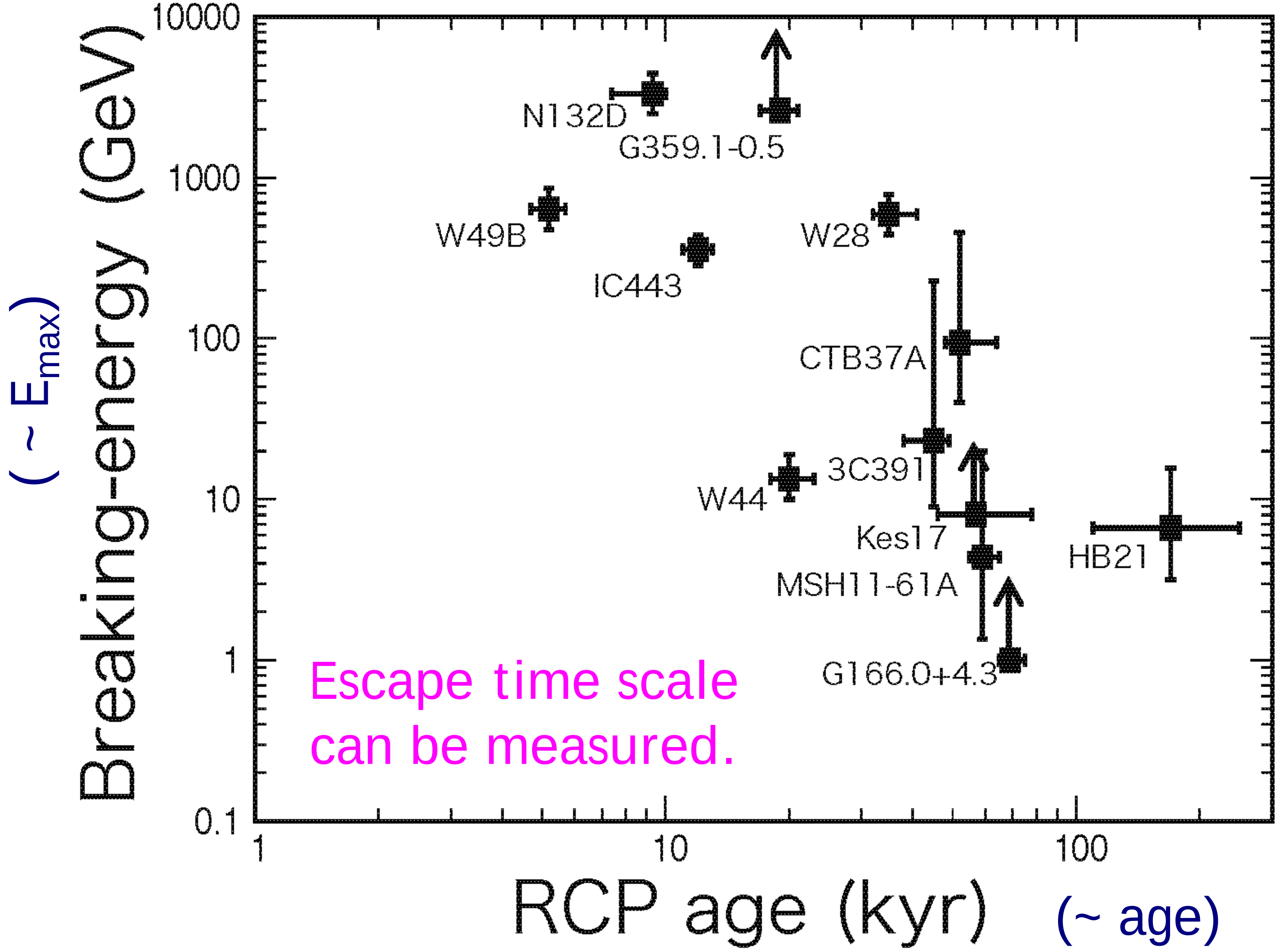


harder gamma-rays
from distant place
-> CTA will resolve it
(Nakamori+17)

time evolution of gamma-ray spectra
with several SNR samples
We can use thermal X-ray emission
as a clock to measure the timescale

3.3. E_{max} and plasma age comparison in old SNRs

Suzuki+, poster session
Zeng+, poster session



Escape time scale can be measured.

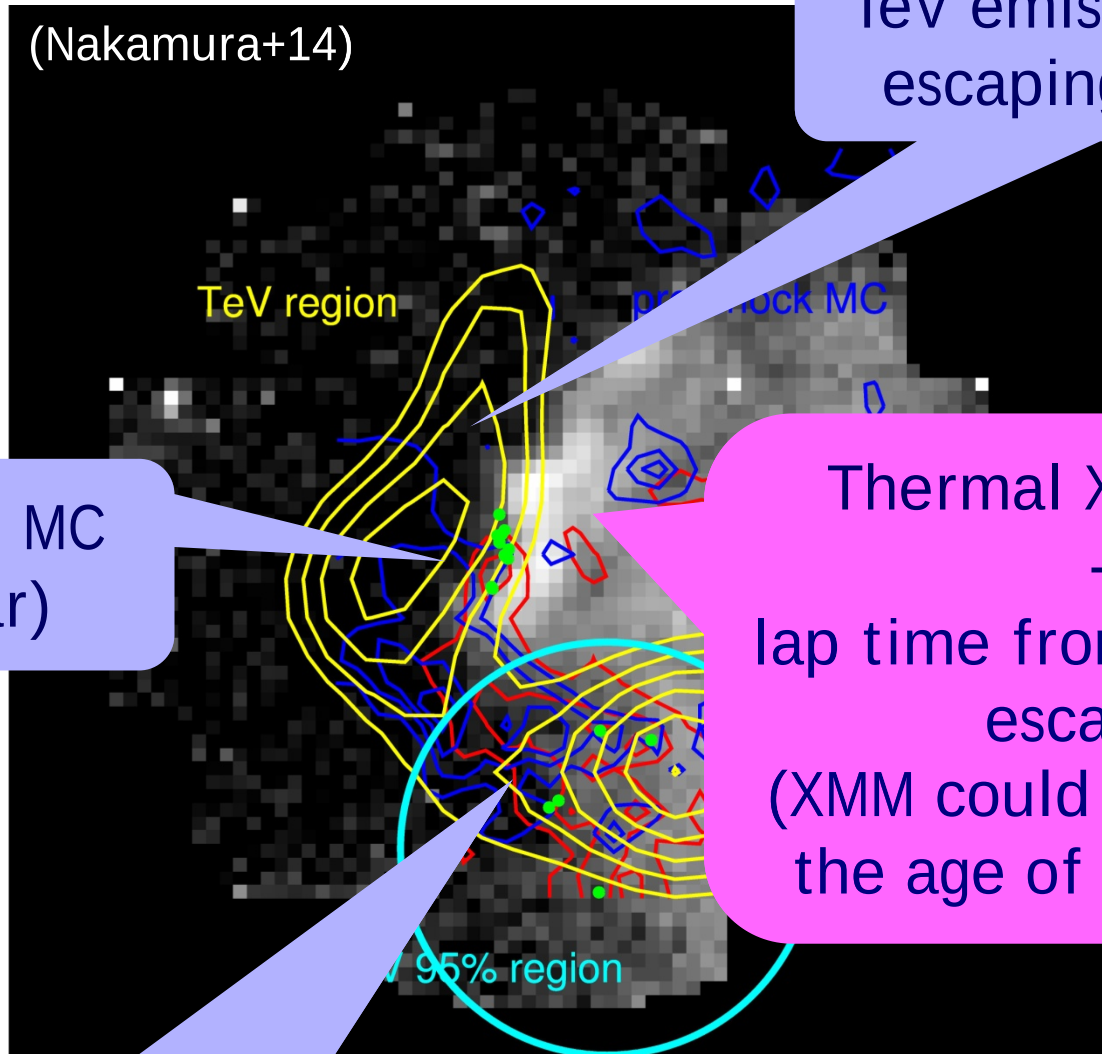
3. Summary

- Supernova remnants are the prime Galactic comic-ray accelerator.

- Recent observations show us
  - information on particles
    w. maximum energy to injection energy
  - where are efficient sites
  - Sites and time scale of particle escape

- More quantitative studies are still ongoing.

Excellent example: NE shell of W28



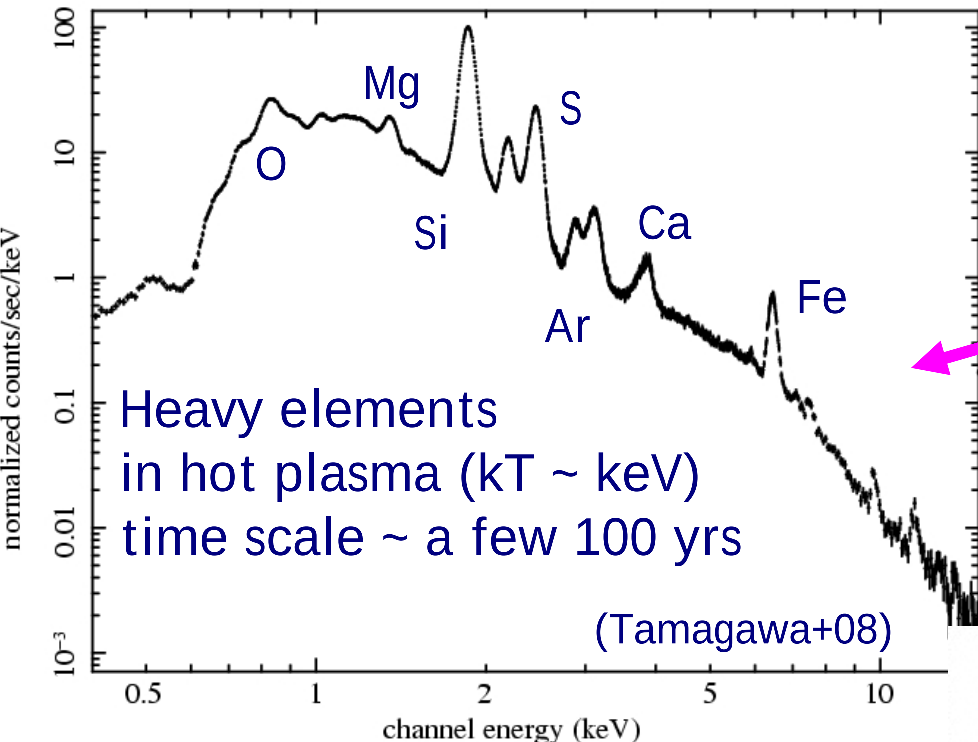
TeV emission from MC escaping particles ?

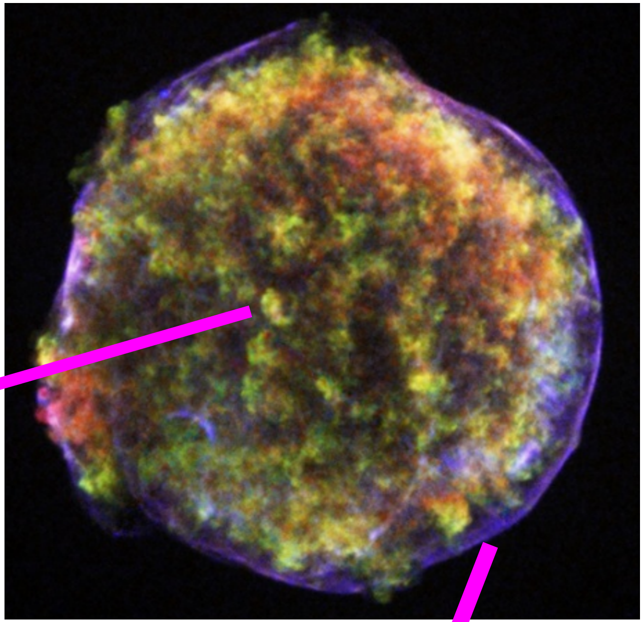
colliding w. MC (OH masar)

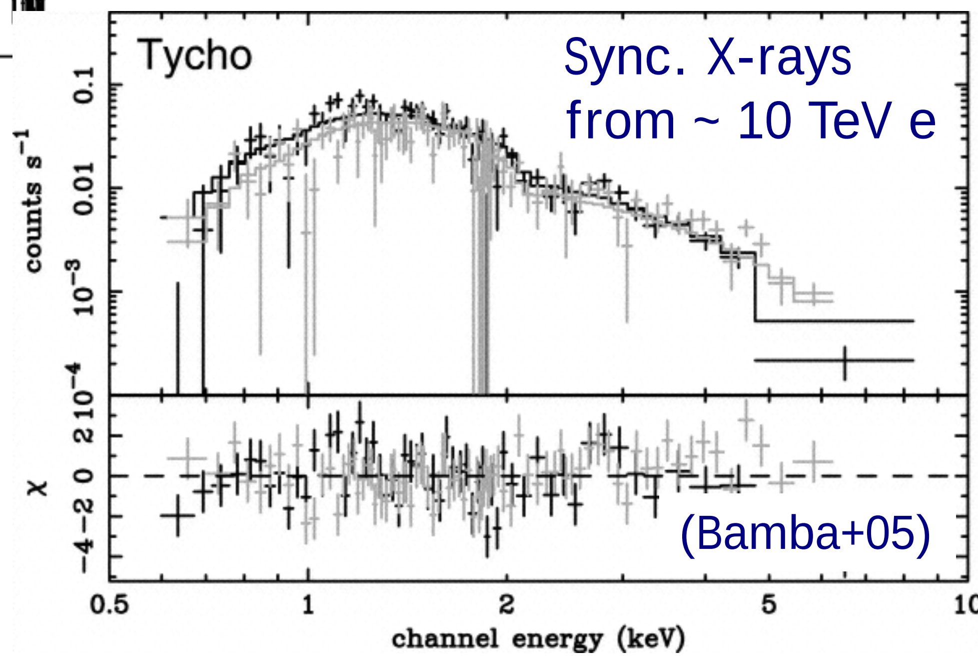
Thermal X-ray knots
->
lap time from collision to escape ??
(XMM could not measure the age of the plasma)

GeV+TeV from shocked MC softer particle escaping ?

Example: Tycho's remnant (SN1572)







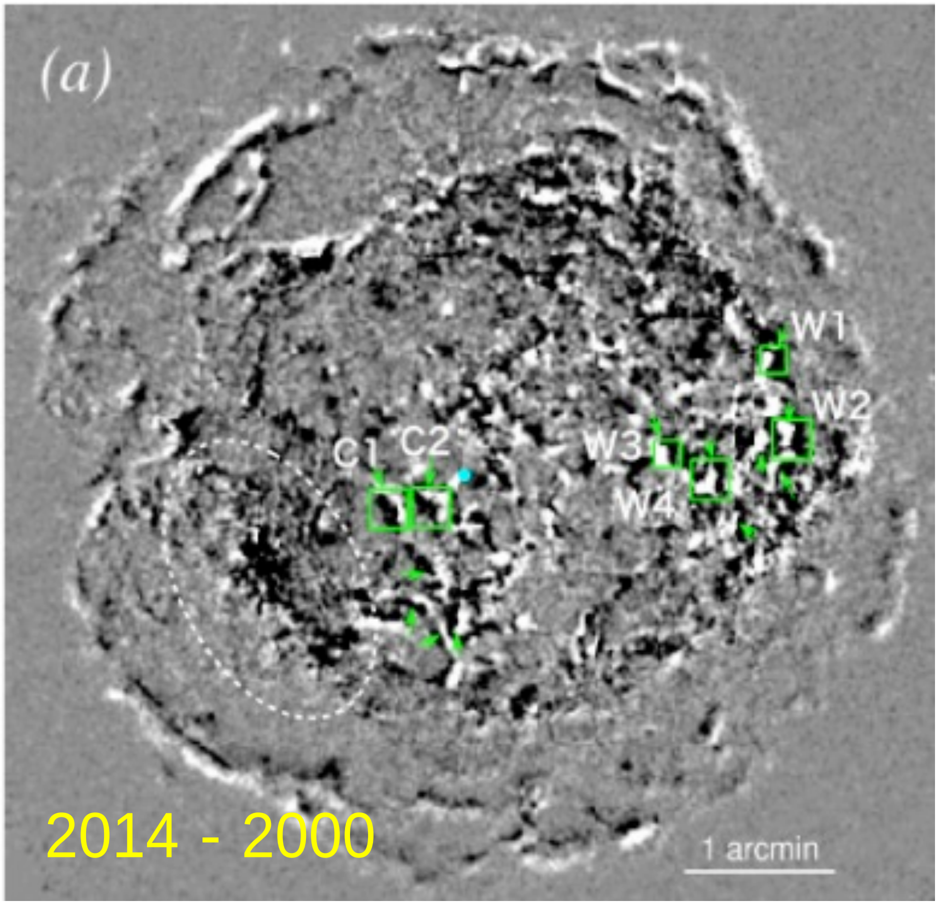
Many young SNRs are known to be sync. X-ray emitters
-> ~10 TeV e is common in young SNRs.

2.3. Shock speed measurements in X-rays

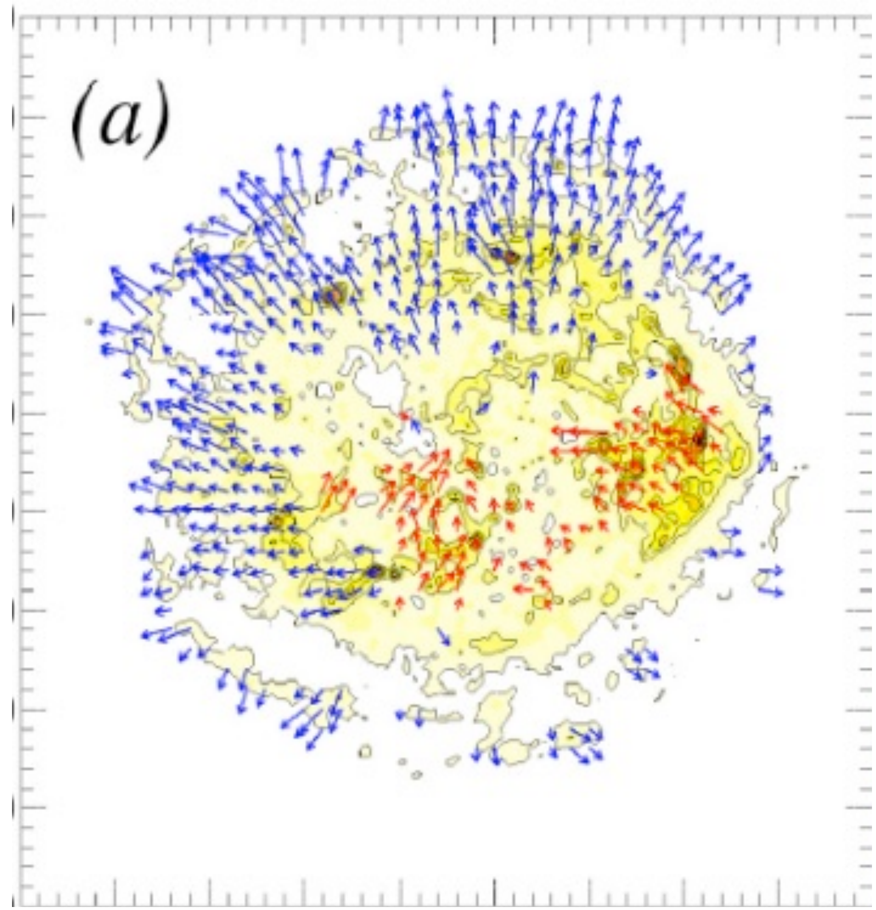
Measurements with proper motion

Cas A (SN1682)

Sato+18



differential image



optical flow method

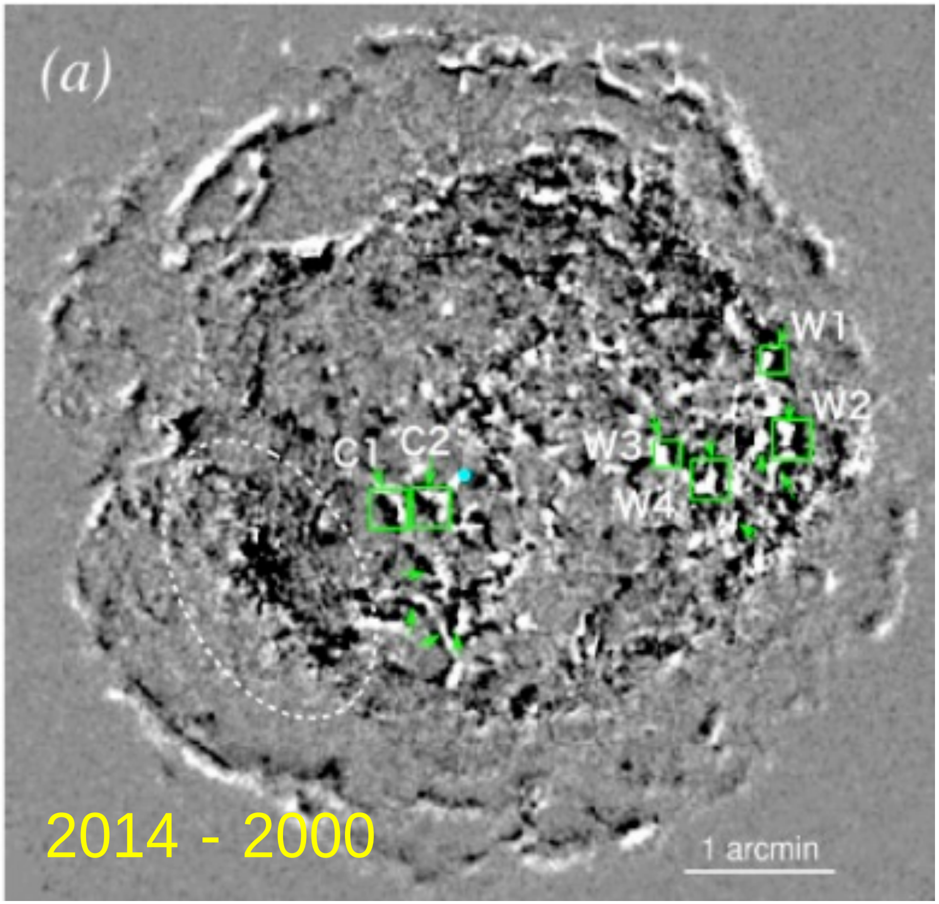
velocity ~ 2000-3000 km/s

2.3. Shock speed measurements in X-rays

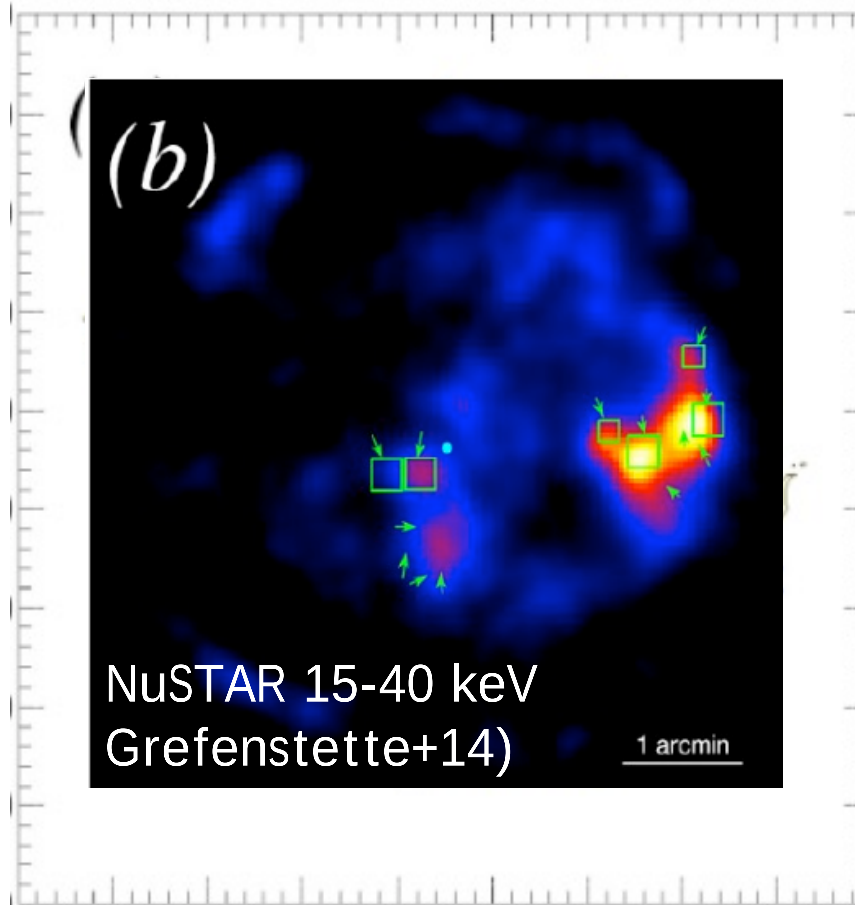
Measurements with proper motion

Cas A (SN1682)

Sato+18



differential image



optical flow method

efficient acceleration on the reverse shock