Recent Progress on Supernova Remnants
- Progenitors, Evolution, Cosmic-ray Acceleration -

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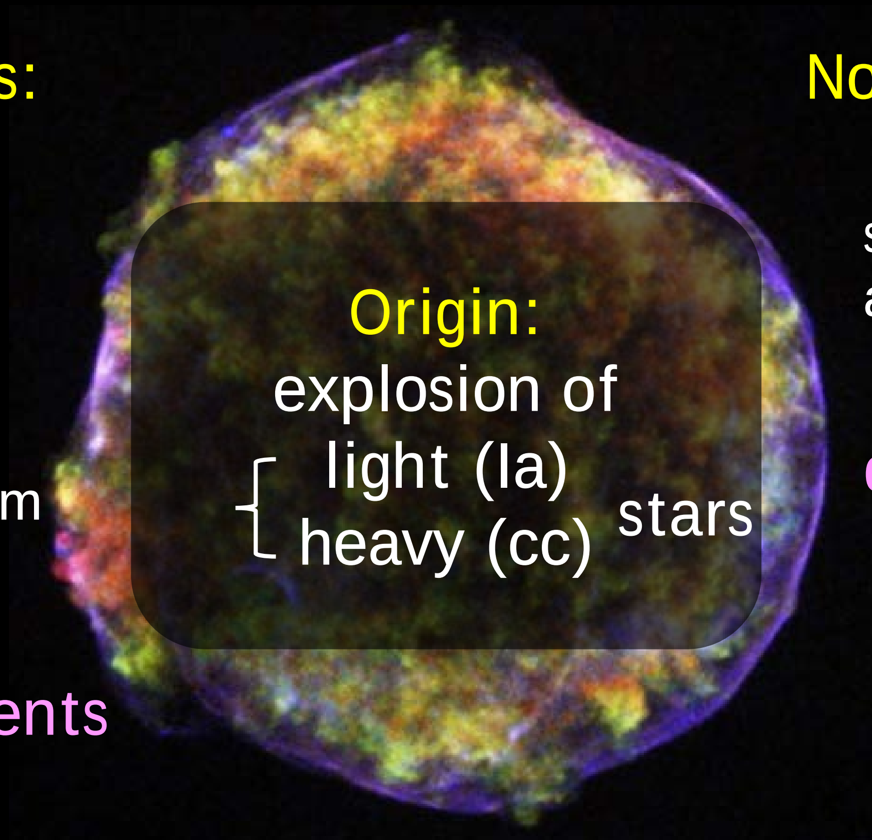
with help of H. Yamaguchi, J. Vink,
S. Katsuda, M. Sawada, …

1.1. Role of supernova remnants in the universe



Thermal aspects:

thin plasma
with kT ~ keV
time scale
<~ 10^4 yrs
in non-equilibrium

distribute
heavy elements

Origin:
explosion of
{ light (Ia) / heavy (cc) } stars

distribute
thermal/kinetic E
compact stars

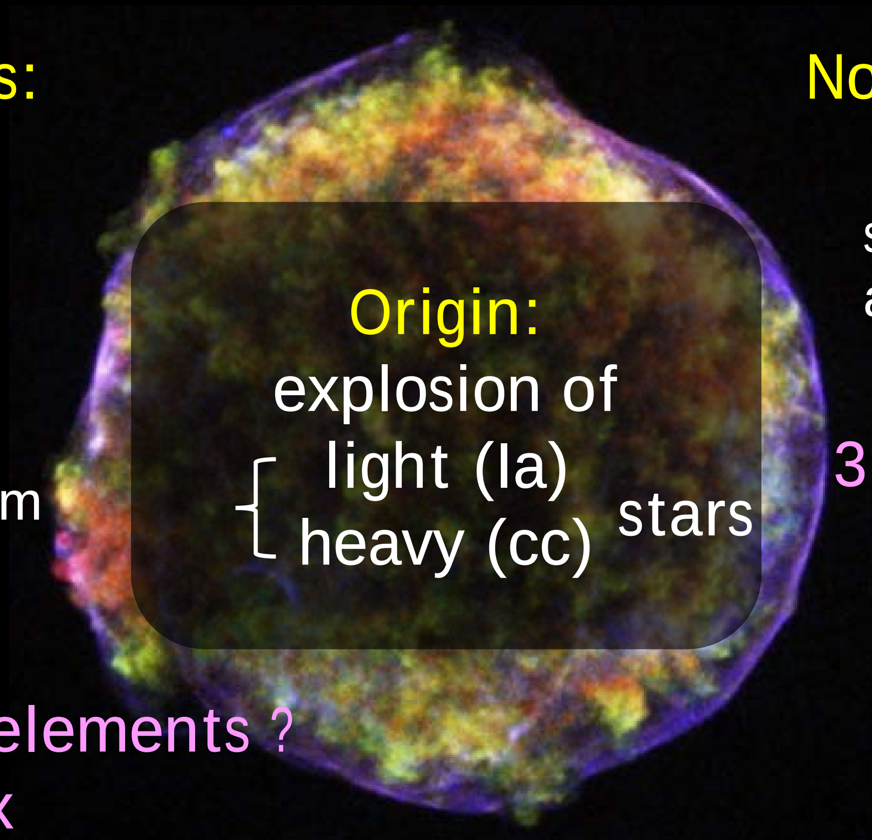
Nonthermal aspects:

shock v ~ 10^{3-4} km/s
accelerate particles
efficiently

distribute
cosmic rays

SNRs makes the diversity of the universe !

1.2. Many unresolved problems



Thermal aspects:

thin plasma
with kT ~ keV
time scale
<~ 10^5 yrs
in non-equilibrium

Origin:
explosion of
{ light (Ia)
{ heavy (cc) stars

Nonthermal aspects:

shock v ~ 10^{3-4} km/s
accelerate particles
efficiently

3. How to escape
to be cosmic rays ?

2. How amount elements ?
How do they mix
into ISM ?
Plasma condition ?

1. Diversity of each class
Are Ia really universal ?
Which cc makes NS/BH ?

We will introduce the recent progress on these topics.

1. Diversity of progenitor explosion

2.1. Types of Supernova remnants

Type Ia	Core-collapsed (CC)
End-point of mass accretion to WD up to M_{ch} (SD) or WD-WD merger (DD)	End-point of heavy stars (>~ 10 M_{O})
A lot of Fe, Ni, Cr, Mn Isotropic explosion ?	A lot of lighter elements O, Ne, Mg, Si, S, …
"Standard candle"	Neutron stars, black holes

Questions:

Can we distinguish Ia/cc for SNRs with X-ray observations ?

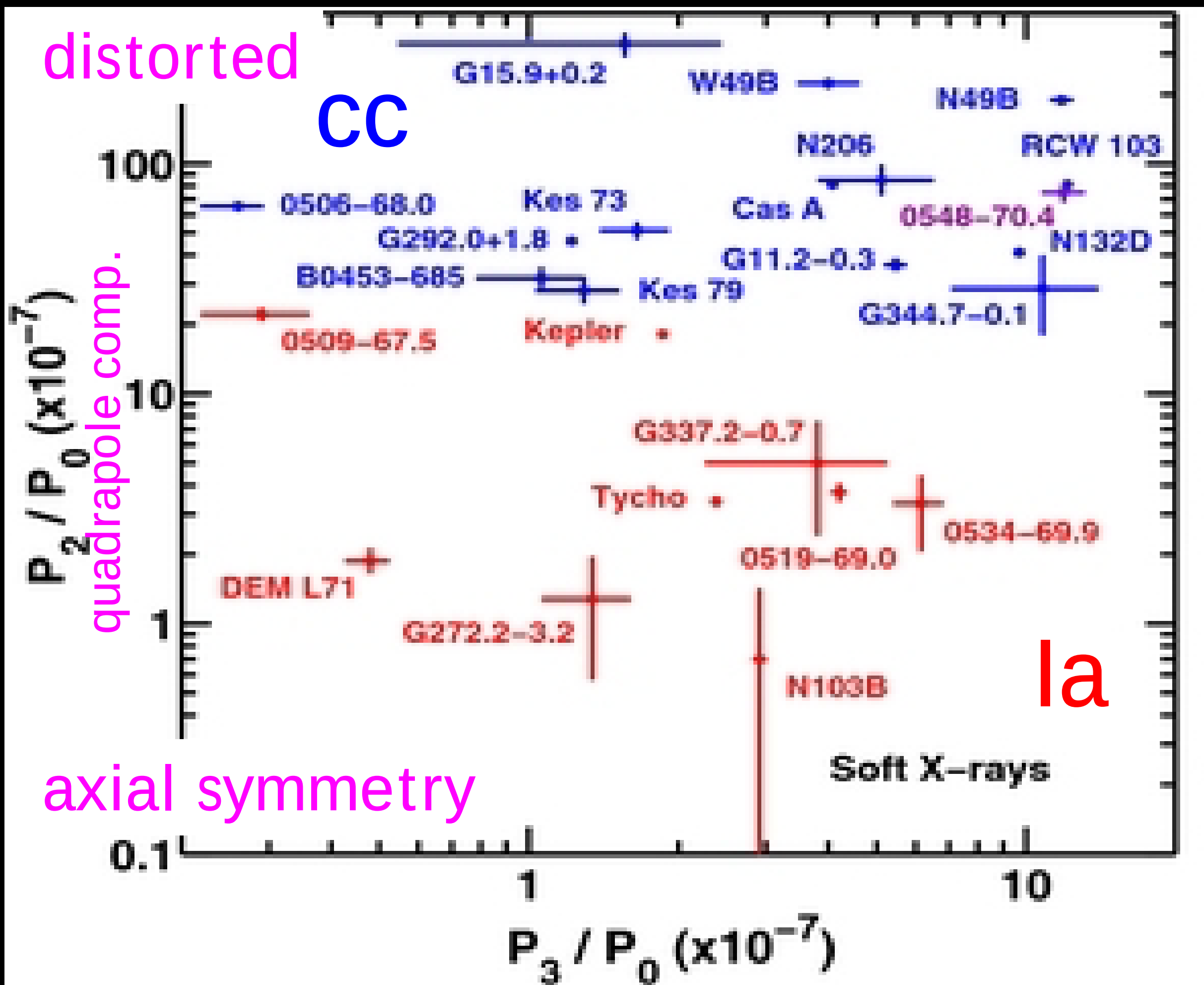
Do they have diversity more than types ?

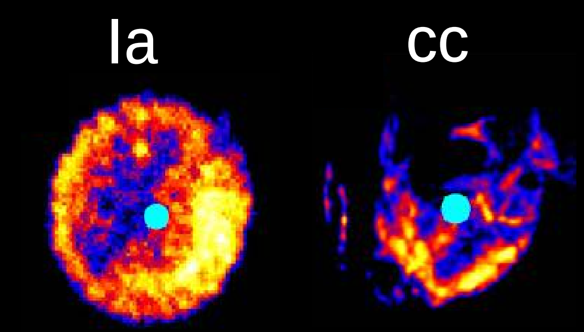
SD/DD progenitor mass of CCs ?

2.2. Type estimation from X-ray morphology (Lopez+11)

Ia: isotropic explosion → circular SNR ?
cc: anisotropic explosion → more complicated SNR ?

Lopez+11: wavelet analysis of Chandra image of many SNRs



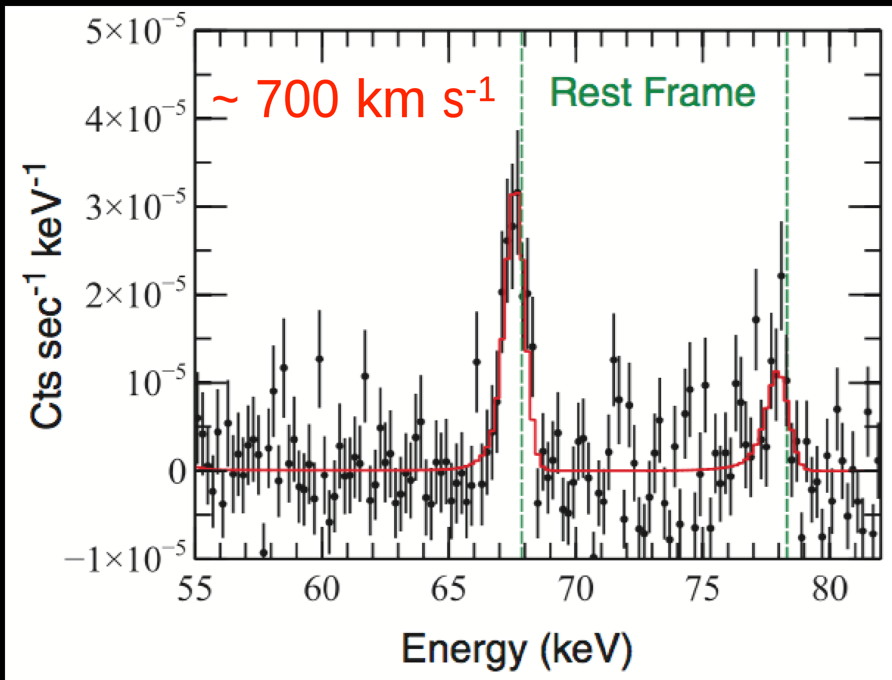


CC SNRs has more distorted morphology !

NuSTAR: ^{44}Ti enables us to access unheated ejecta

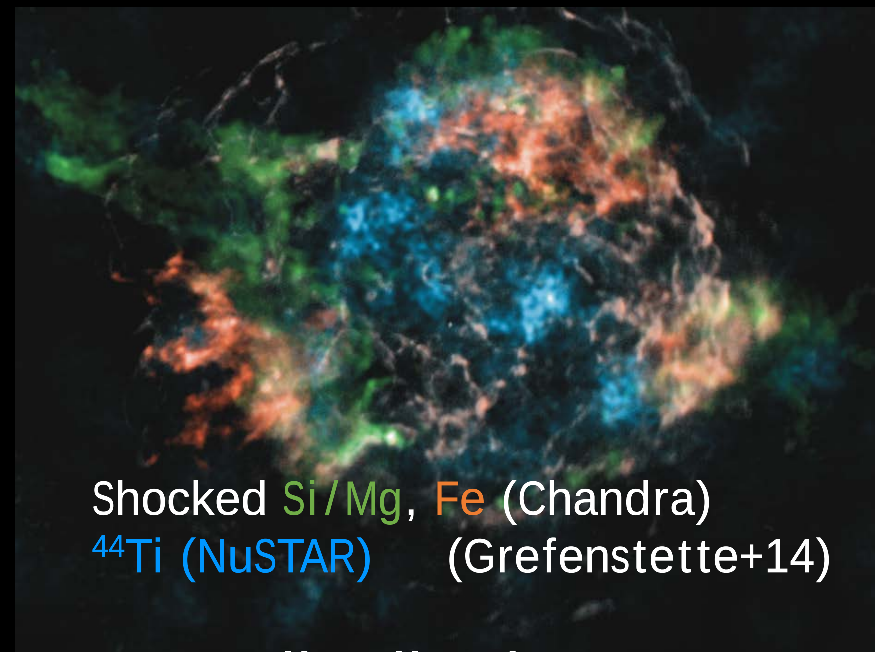
CC SNR expansion with ^{44}Ti

SN 1987A (~30 yrs)



Only red-shift ^{44}Ti line
-> asym. expansion of ejecta

Cas A (~330 yrs)

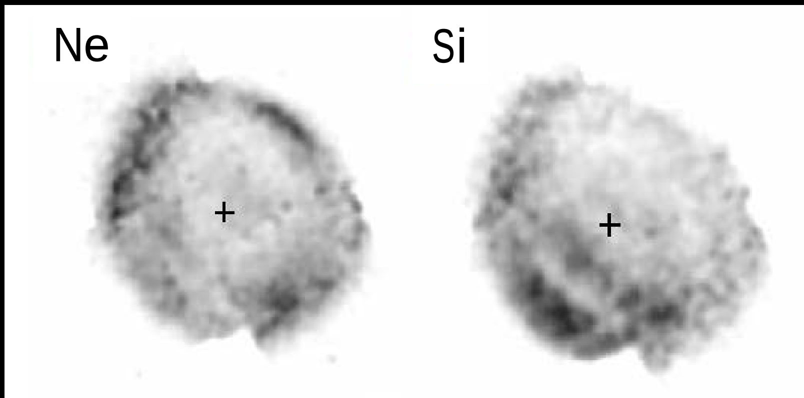


asym. distribution
Neither isotropic
nor axial symmetric
expansion

CC SNRs show highly asymmetric expansion

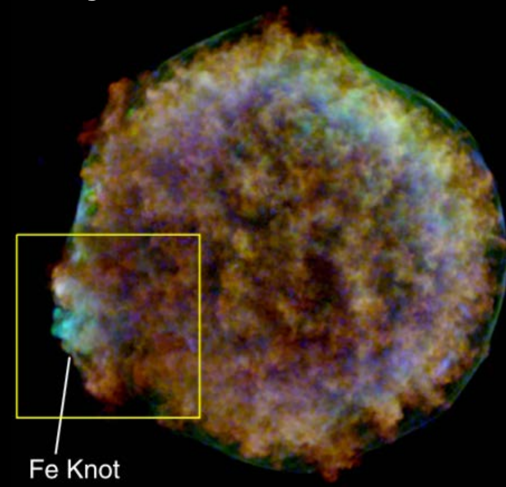
Does Ia expand isotopically ?

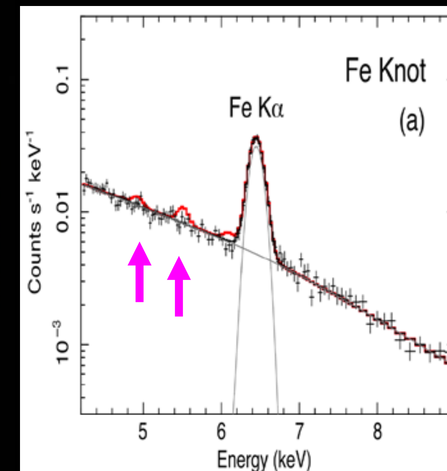
SN1006 (Uchida+13)



Si, S, Fe are abundant
in south eastern region

Tycho (Yamaguchi+17)





pure iron ejecta (no Cr, Mn)

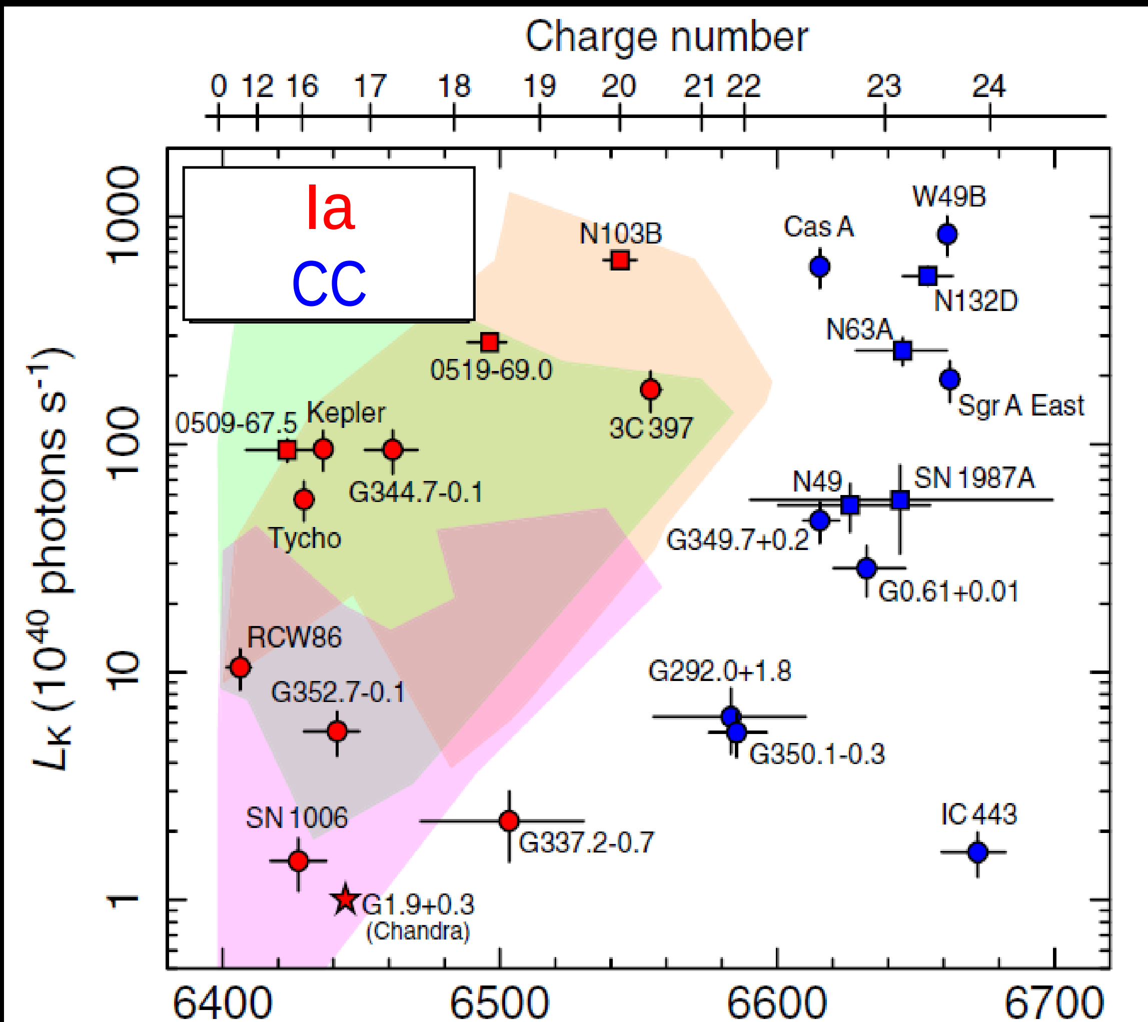
Several “text-book” Ia remnants show anisotropy.

It is still an open issue
how isotropic Ia explosions are.

important on heavy element distribution in the universe,
maximum luminosity of SNe (amount of Ni), etc.

2.3. Type estimation from Iron K line center (Yamaguchi+14)

low density medium for Ia → low ionization state
high density (CSM or ISM) for cc → high ionization state

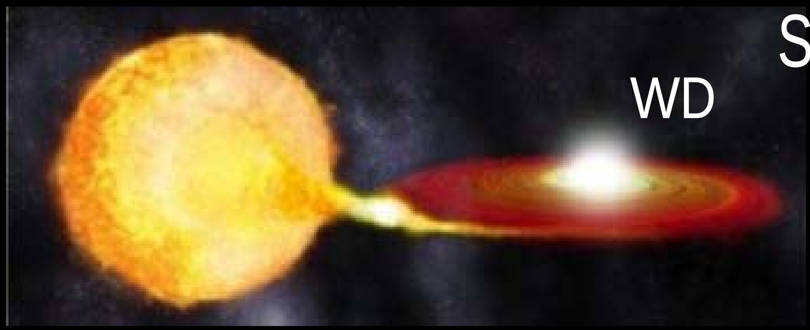


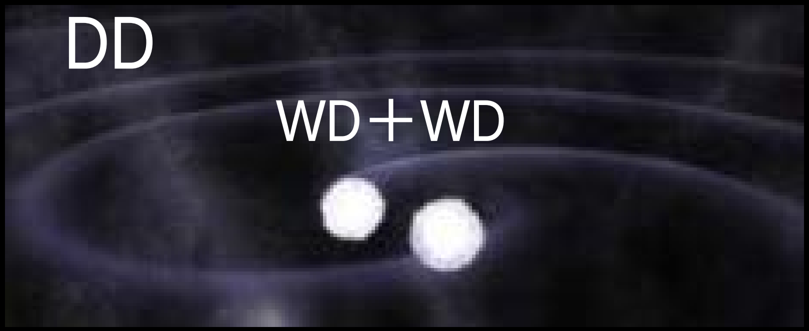
Ia has lower E iron-K

Ia is really in the low density ISM

More classification from spectral info.?

2.4. Origin of Ia ?



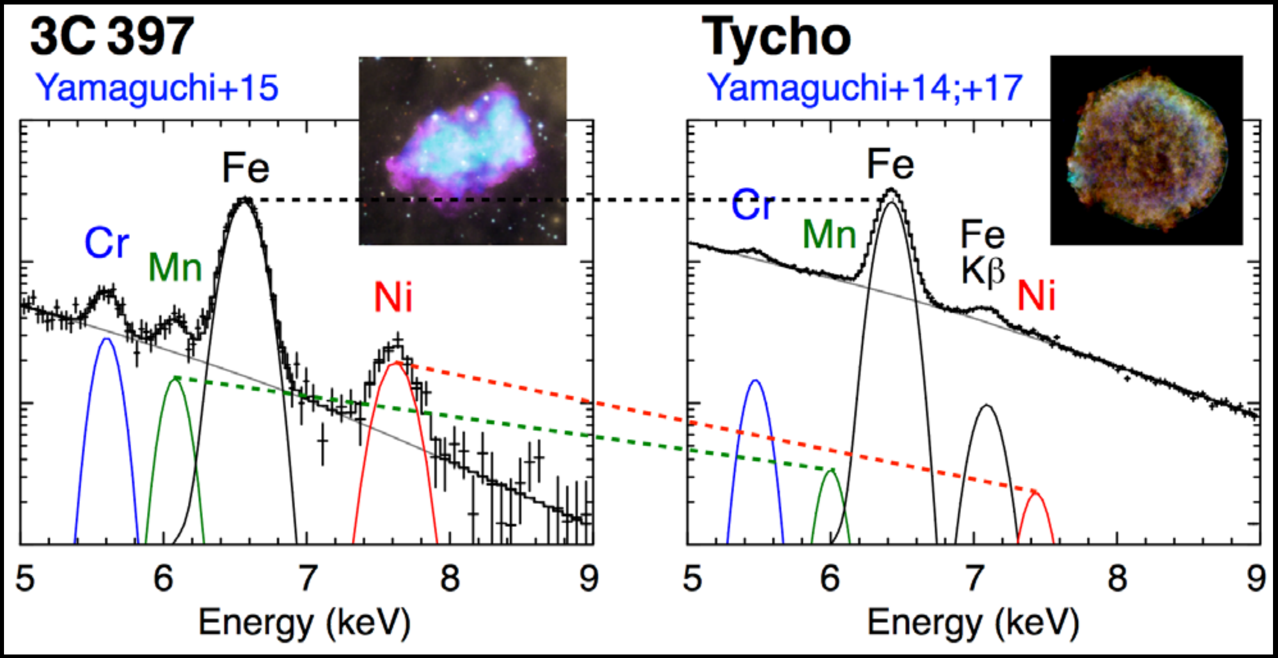


~M_{ch}, dense core ($\rho \geq$ 2e8 g/cm^3)

sub M_{ch}, less dense core

high ρ in SD core makes more Ni, Mn

due to more electron capture

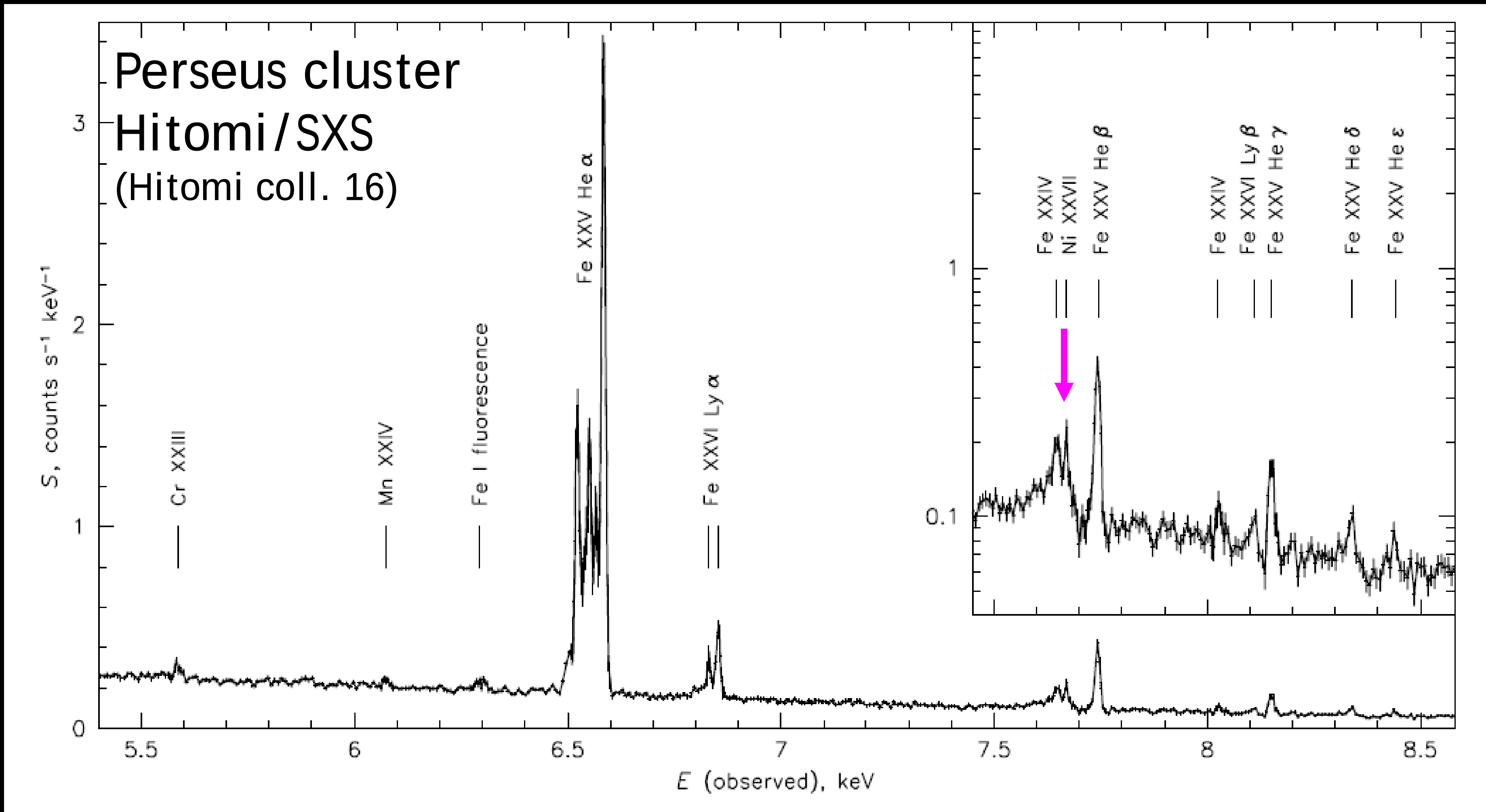


3C397 needs M_{ch}

Strong diagnostics to distinguish SD and DD

Related to abundance of CGs

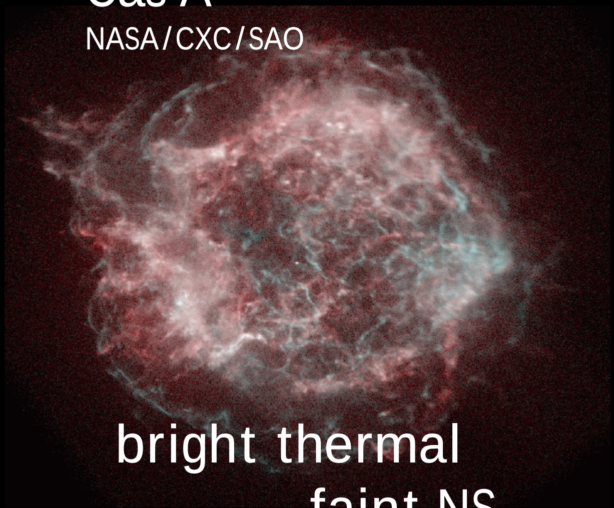
We need calorimeter to resolve Ni from Fe forest



Athena / XARM will identify many Ia SNRs to be SD or DD.

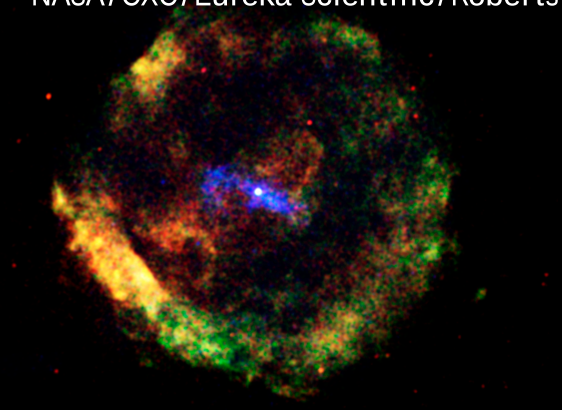
2.5. Variety of CC SNRs

Cas A
NASA/CXC/SAO



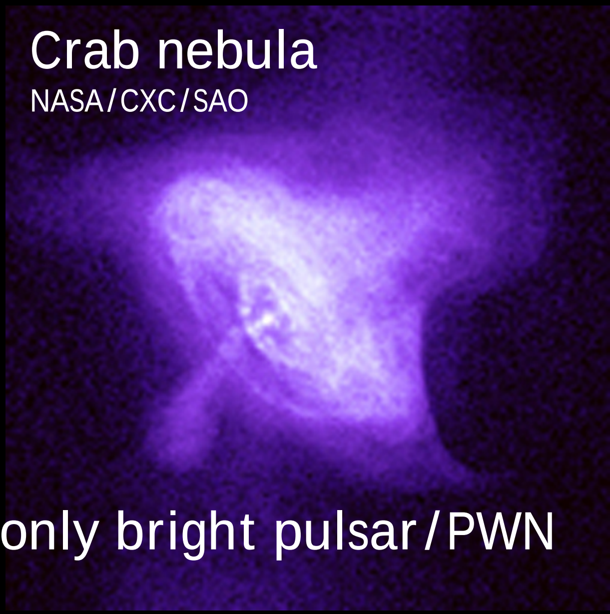
bright thermal
faint NS

G11.2-0.3
NASA/CXC/Eureka Scientific/Roberts+



both thermal/PSR

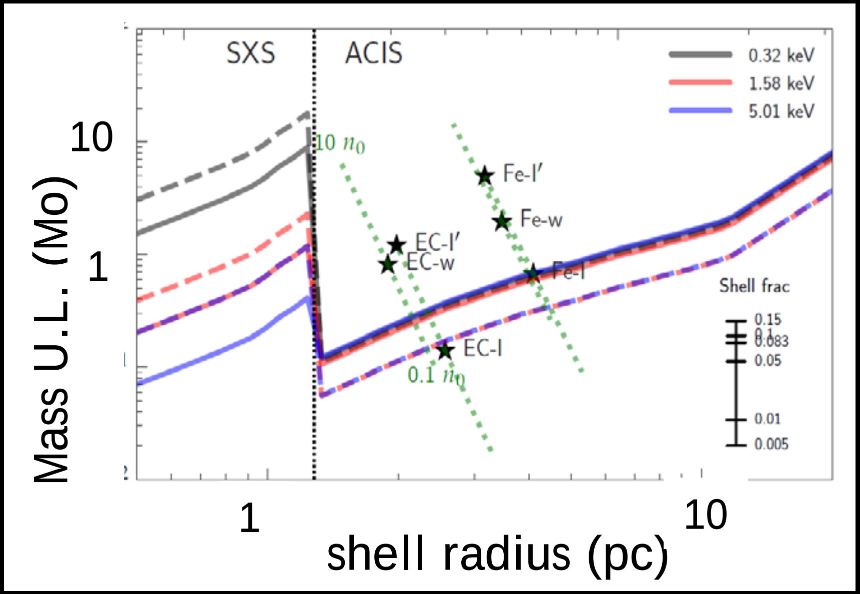
Crab nebula
NASA/CXC/SAO



only bright pulsar/PWN

What makes such difference ?

Crab Thermal line search
with Calorimeter onboard Hitomi
-> very tight upper-limit
plasma mass < 1Mo
-> electron capture SN ?

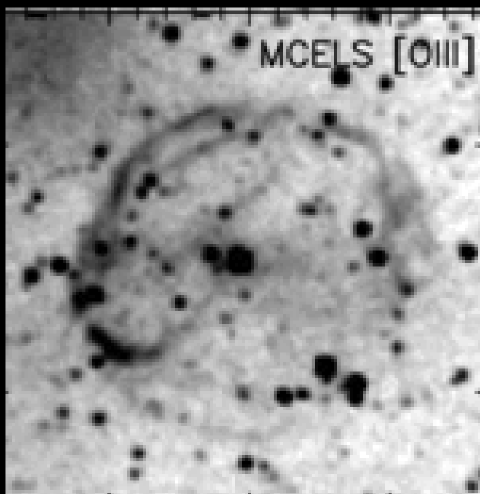


(Tsujimoto+, poster)

2.6. Where are SNRs with BHs ?

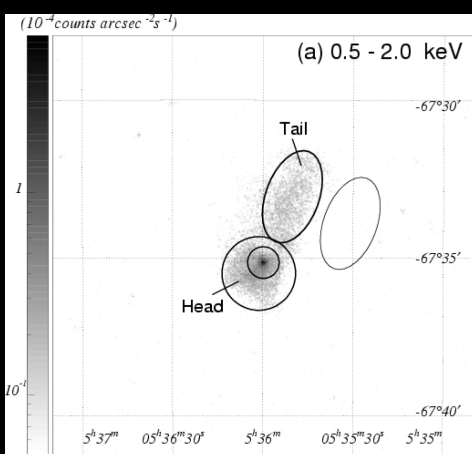
Not yet, but we have several SNRs with a HMXB.

SXP 1062 in the SMC
(Hénault-Brunet+12)



HMXB: P=1062s, maybe neutron star
SNR: too old to see in X-rays (r=20 pc)

CXOUJ053600.0-673507 in DEML241



HMXB with O5III(f) star (Seward+12)
the most luminous gamma-ray binary (Corbet+16)
abundance pattern -> progenitor > 20 Mo
(Bamba+06)

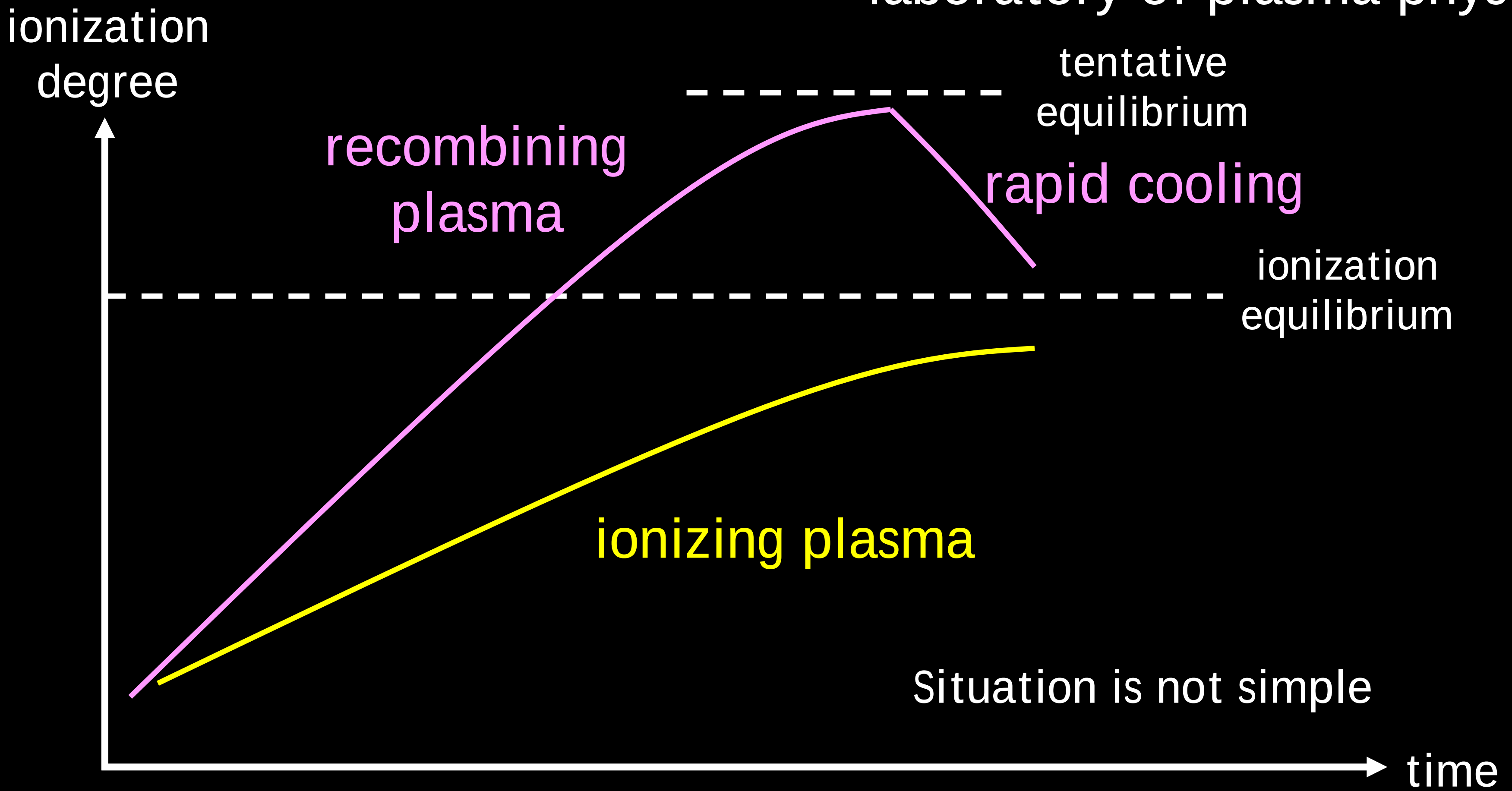
Can we find first SNR w. BH ??

2. Topics on thermal plasma

2.1. Plasma in SNRs are highly non-equilibrium !

density ~ cm^{-3}
time scale ~ 10^{3-4} yrs → $nt < 10^{12}$ s cm^{-3}
non-equilibrium !

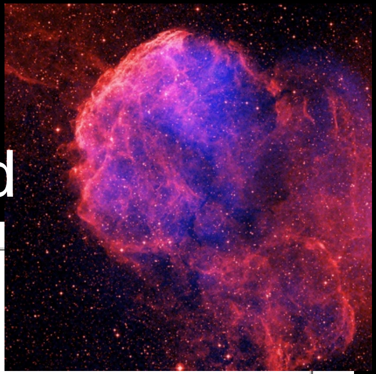
laboratory of plasma physics

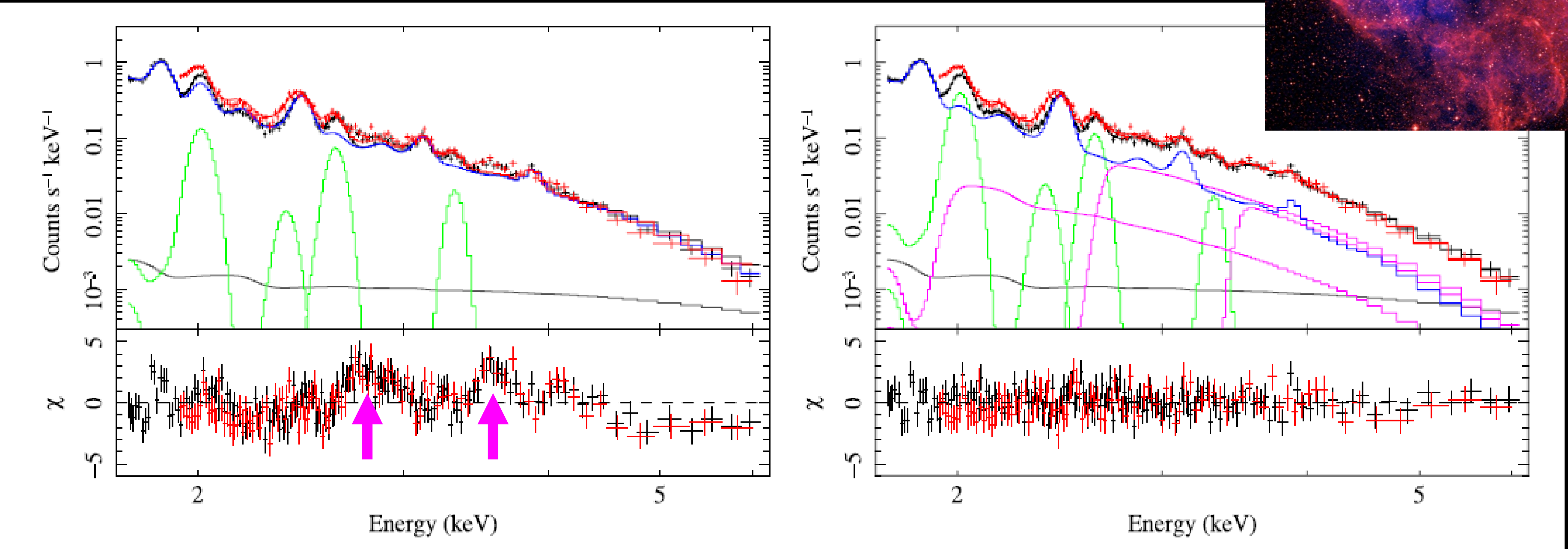


Understandinga the plasma condition is the starting point of thermal aspects of SNRs.

2.2. First firm detection of recombining plasma in SNR

Suzaku spectrum of IC443 (Yamaguchi+09)
middle-aged SNR, interaction with molecular cloud





with apec model

apec + radiative recombination
(free to bound)

Plasma in IC443 underwent rapid cooling.

2.3. What is the origin of recombining plasma ?

Recombining plasma SNR list:

IC443(Yamaguchi+09), W49B(Ozawa+09), G359.1-0.5(Ohnishi+11), W28(Sawada+12), W44(Uchida+12), G346.6-0.2(Yamauchi+13), 3C391(Sato+14) Okon, Matsumura, talks in pararell session

All middle-aged, interaction with dense clouds

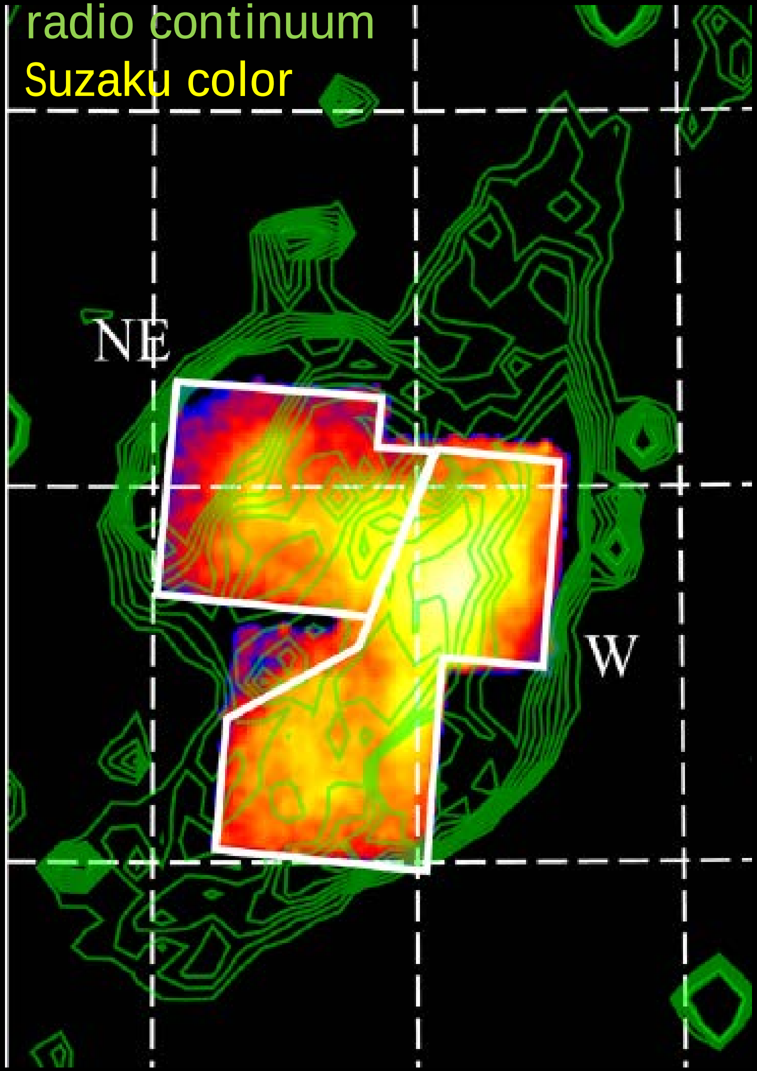
Origin of rapid cooling ?

- rapid expansion in low density medium
- thermal conduction with cold molecular clouds
- energy injection to particle acceleration

Key target: G166.0+4.3 (Matsumura+17)

East:
small radius
interaction ?

Discovery of
RP component



West:
large radius
low density ?

Non-detection of
RP

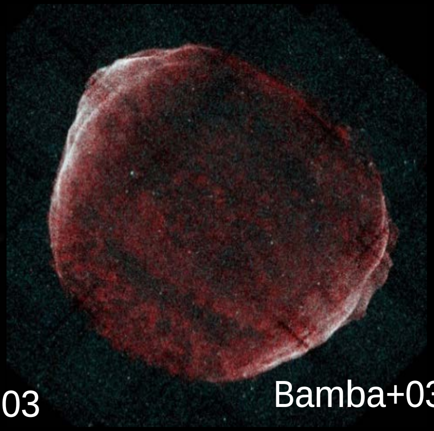
Recombining condition happens due to interaction ?
More samples/studies needed.

3. Topics on particle acceleration

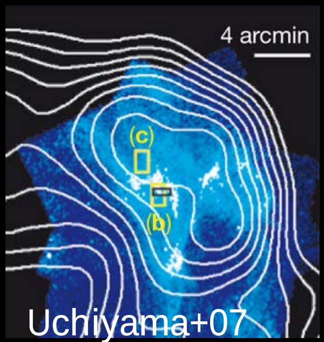
3.1. Are really shocks of SNRs Galactic Cosmic-ray accelerators?

When SNRs are young ....

Vink+03

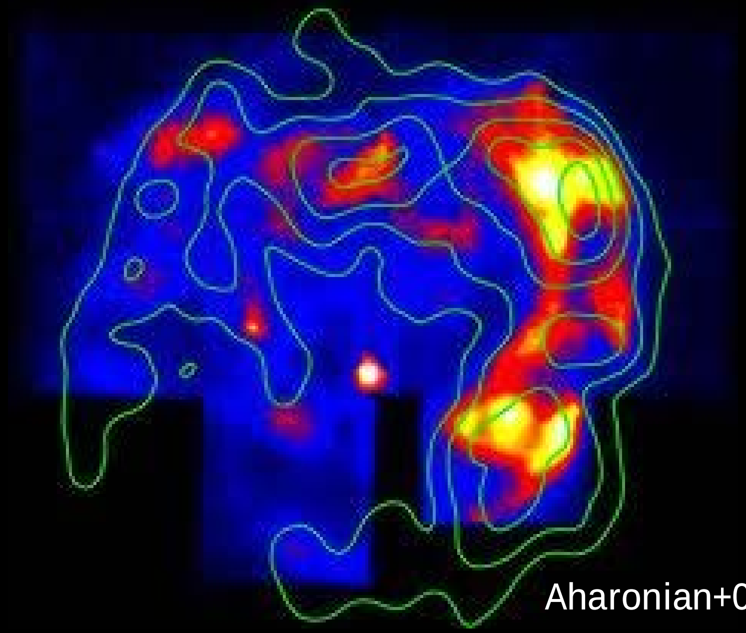


Bamba+03



Uchiyama+07

thin & time variable
synch. X-ray filaments
->
amplified magnetic field



Aharonian+08

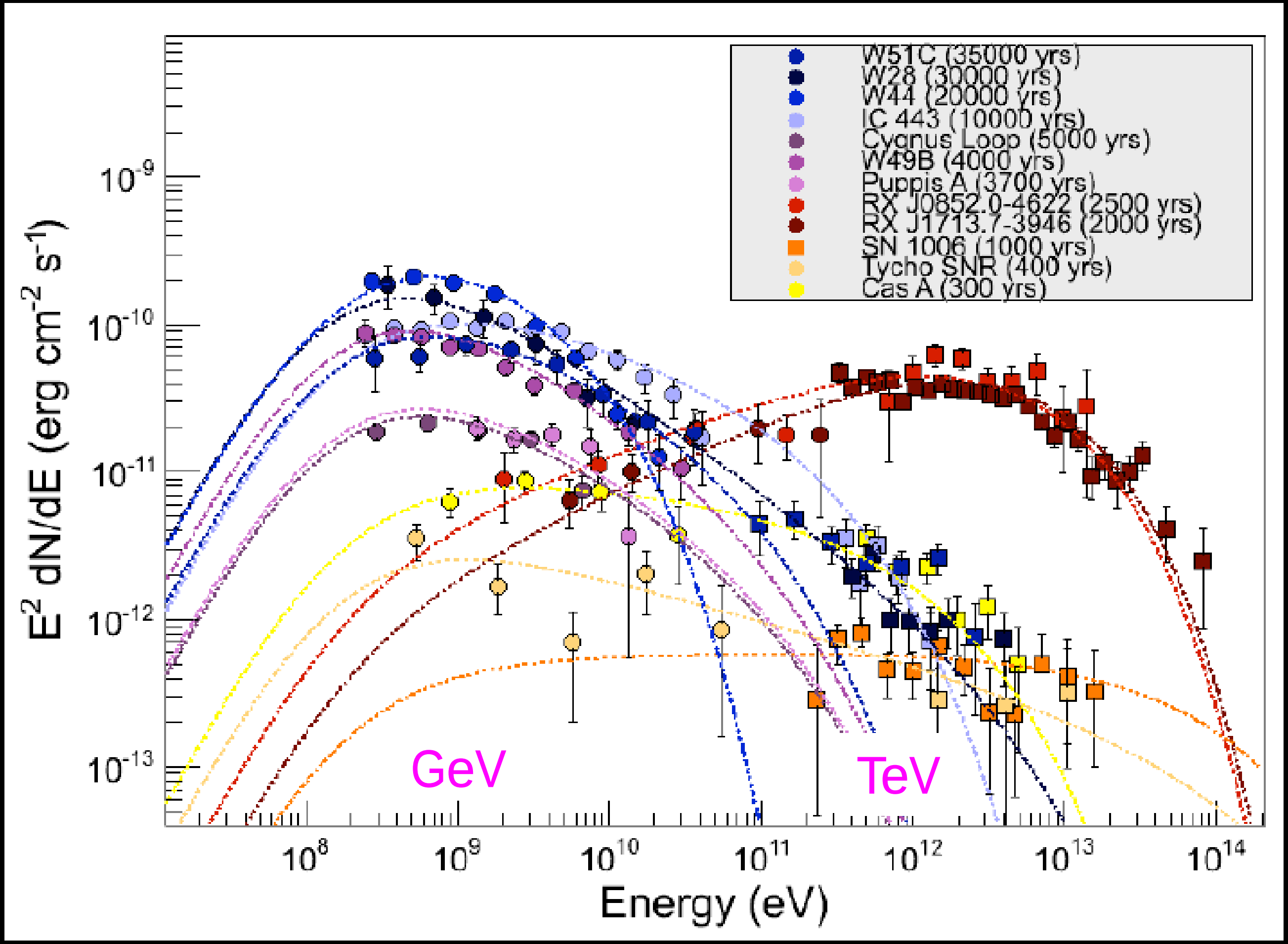
GeV - VHE gamma-rays
-> TeV particles

-> efficient particle accelerators

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 ?

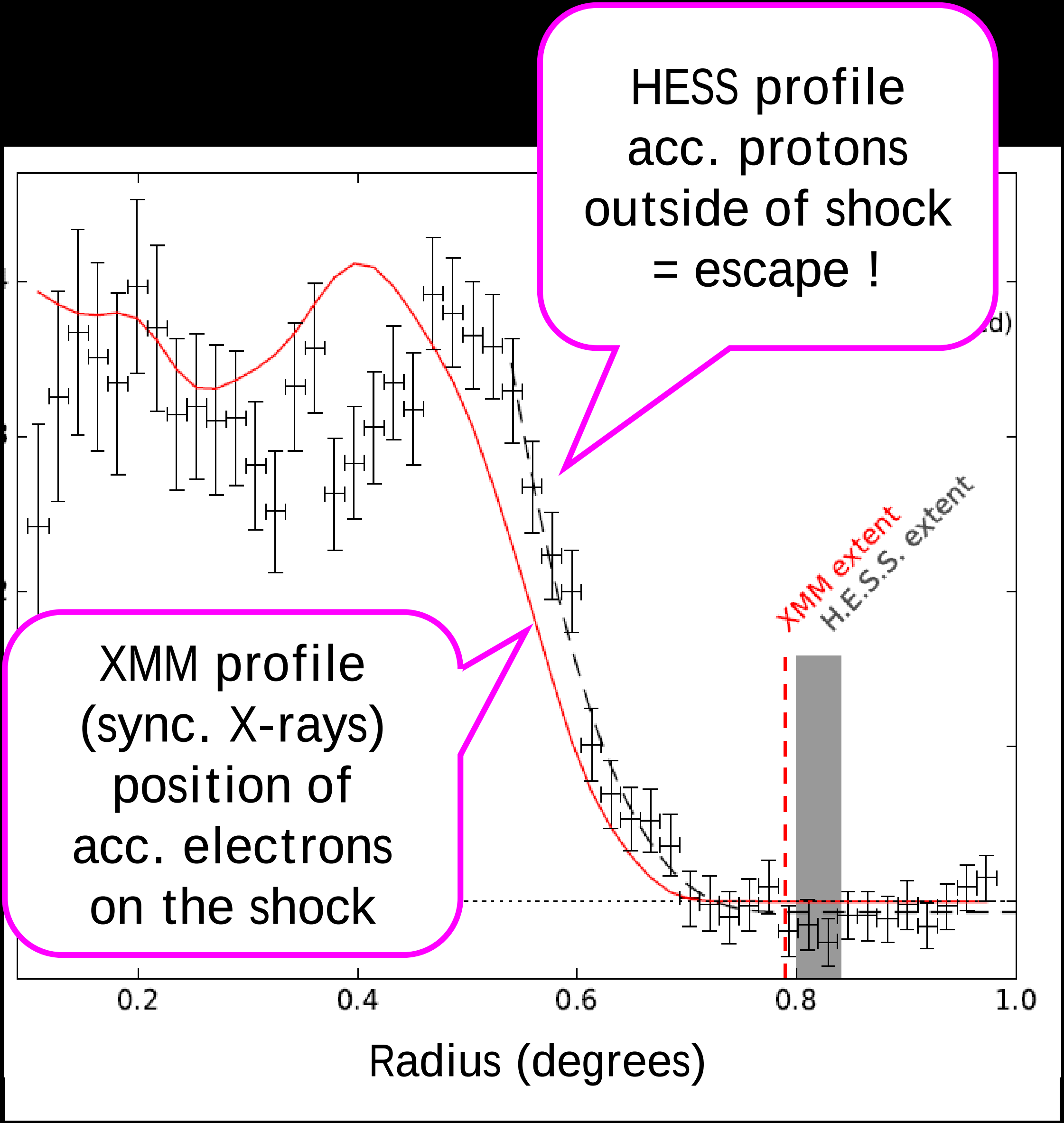


(Funk11)

More clue of particle escape

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

exposure: 163 hour !

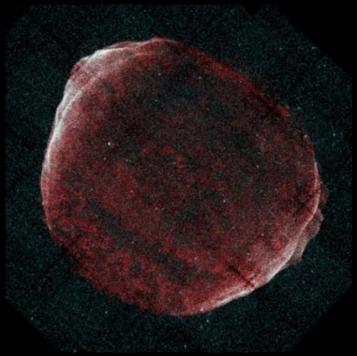


CTA will resolve more.

(Nakamori+17)

3.2. What makes particle escape ?

Amplified magnetic field does not allow particle to escape.



-> Need magnetic field dumping

- interaction with molecular cloud ? (Ohira+12)
  -> similar origin to recombining plasma

RP SNR lists:

IC443(Yamaguchi+09), W49B(Ozawa+09), G359.1-0.5(Ohnishi+11), W28(Sawada+12), W44(Uchida+12), G346.6-0.2(Yamauchi+13), 3C391(Sato+14), G166.0+4.3(Matsumura+17)

GeV source, VHE gamma-ray source

most of RP SNRs are gamma-ray emitters

Interaction with molecular clouds makes both { recombining plasma / particle escape

Thermal info. on escape site environment !

4. Summary

- Supernova remnants make diversity of the universe in thermal and nonthermal aspects.

- We can resolve Type of progenitor SNe.
- Both Ia and CC have variety.

- Plasma condition in SNRs are more complicated than previous understanding.

- We now see the clue of particle escape to be cosmic rays, and we need to understand what makes escape.
- Plasma condition on the escape site may have a key of escape.