Recombination X-rays from mixed-morphology SNRs

Hiroya Yamaguchi (CfA/SAO)

not on behalf of Suzaku AO6 key project members
(I'm *not* a member of the project…)

Acknowledgement to…
Randall Smith, Patrick Slane (CfA/SAO)
Li Ji (PMO/CfA)
Katsuji Koyama, Midori Ozawa,
Makoto Sawada, Takao Ohnishi (Kyoto U.)
Kuniaki Masai (TMU), Jelle Kaastra (SRON)

X-ray emission from SNRs

Non-thermal --- acceleration at blast wave or pulsar wind

Thermal --- SN explosion mechanism, nucleosynthesis,
progenitor & their environment, etc…

This session

HY	Recombining (over-ionized) plasma in SNRs
S. Park	Low-abundance elements in Type Ia SNRs
H. Uchida	Spatial abundance distribution in evolved SNRs

Suzaku (XIS) -- high sensitivity for extended sources
good energy response

⇒ unique results on thermal emission from SNRs

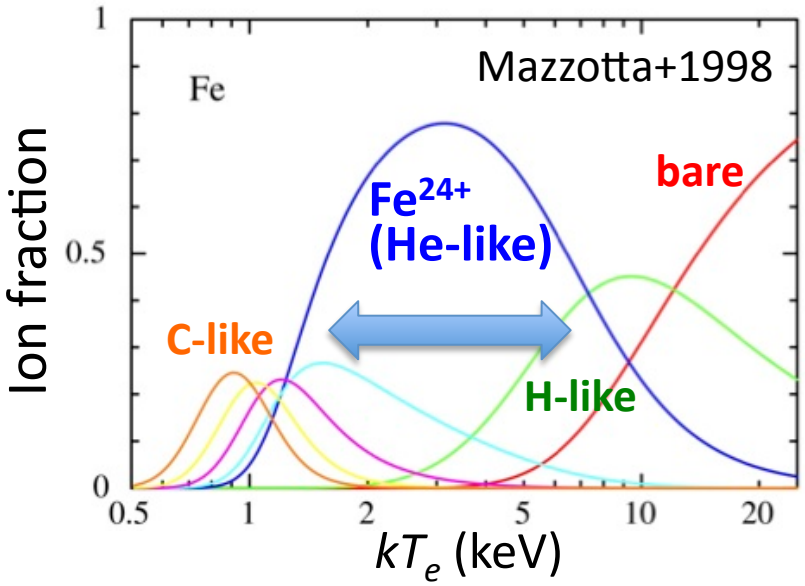
Non-equilibrium in SNRs

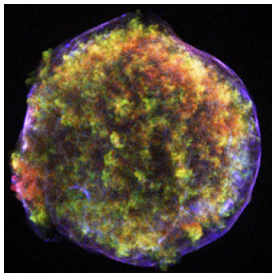
Non-Equilibrium Ionization (NEI)

ionization proceeds slowly compared to shock heating
⇒ ionization balance is not in equilibrium

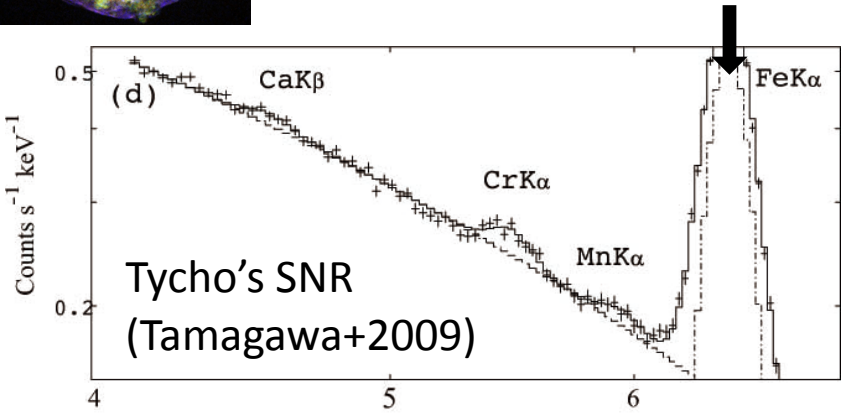
Tycho SNR -- $kT_e > 2$ keV

Ion fraction for equilibrium plasma





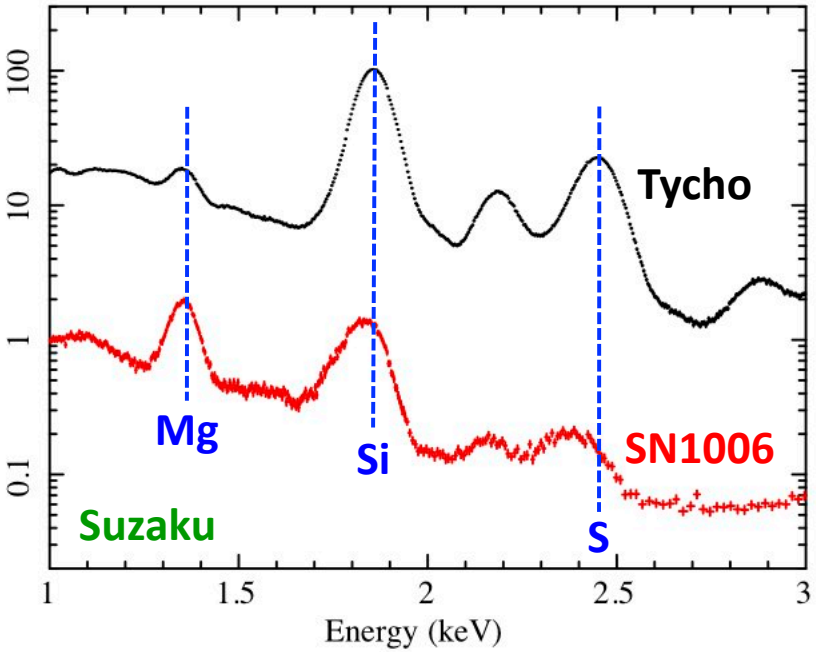
Center energy = 6.45 keV
(~C-like)
cf. He-like : 6.68 keV



kT_z (ionization temperature)
~ 1 keV $< kT_e$

Non-equilibrium in SNRs

Progress of ionization depends on the density of environment



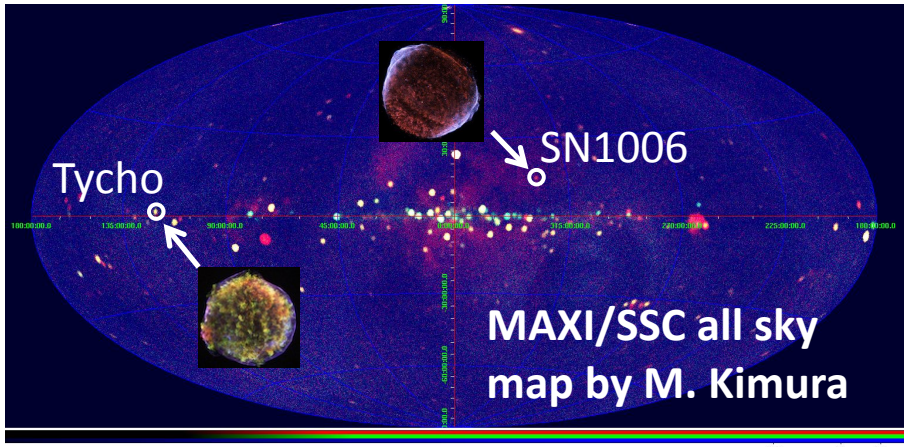
	Tycho	SN1006
Age (yr)	440	1000
Ionization state of Si	He-like	Be/Li-like

(Yamaguchi+2008)

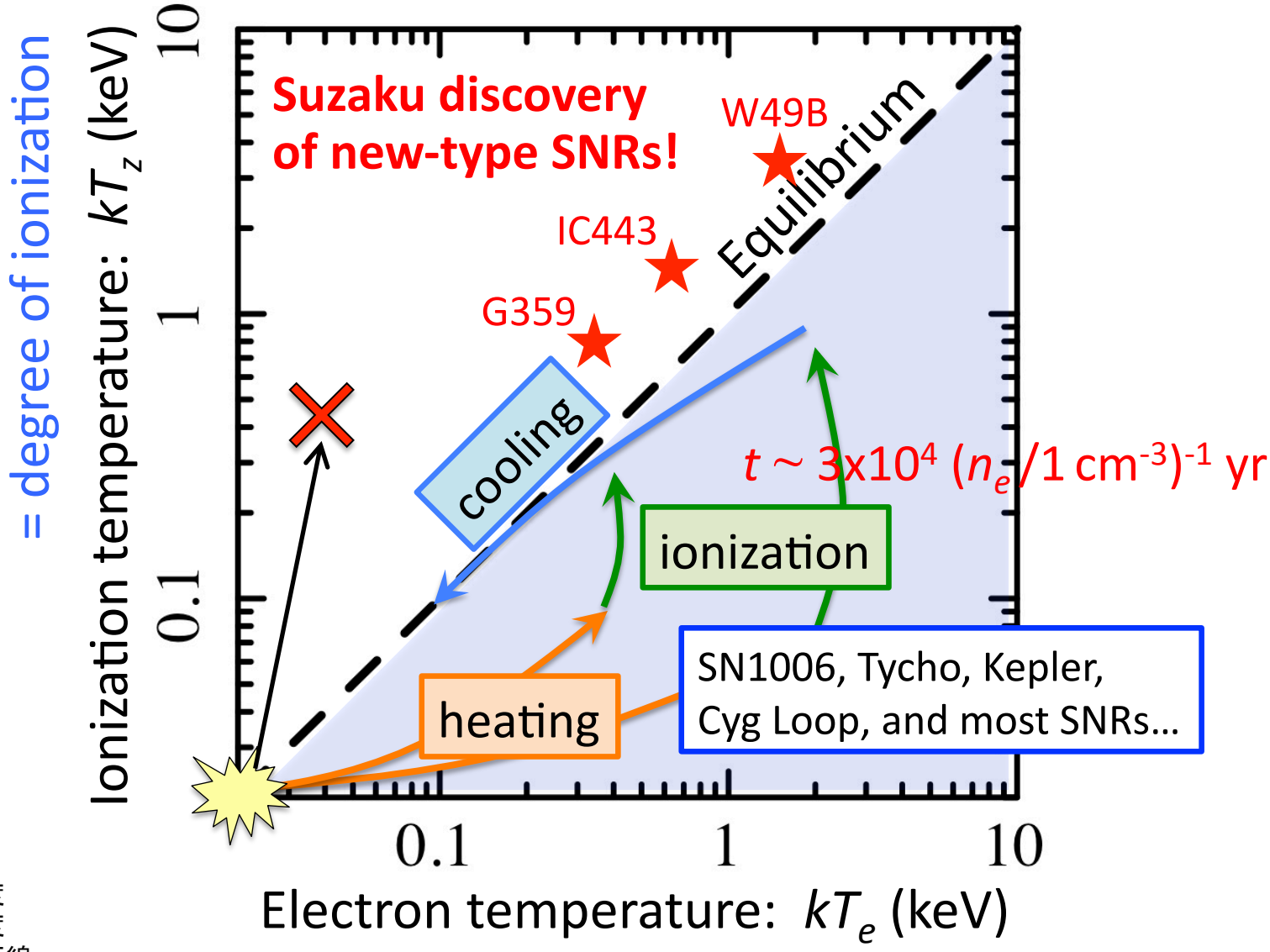
SN1006 is "younger" than Tycho!

Tycho: $Z \sim 100$ pc

SN1006: $Z \sim 550$ pc
(lower density environment)



Plasma evolution in SNRs



横軸：電子温度
縦軸：電離温度
破線：電離平衡線

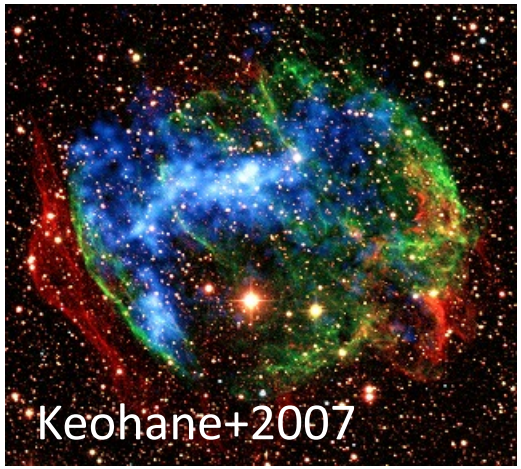
Over-ionized plasma in SNRs

Contents

- W49B (Ozawa+2009, ApJ, 706, L71)
  see also L. Ji's poster
- IC443 (Yamaguchi+2009, ApJ, 705, L6)
- G359.1-0.5 (Ohnishi+, PASJ SP in press)
- W28 (possibly; see M. Sawada's poster)

Changing our understanding of SNR's evolution !!

W49B



D = 8–12 pc, Age ~ 1000 yr (Lopez+2009)

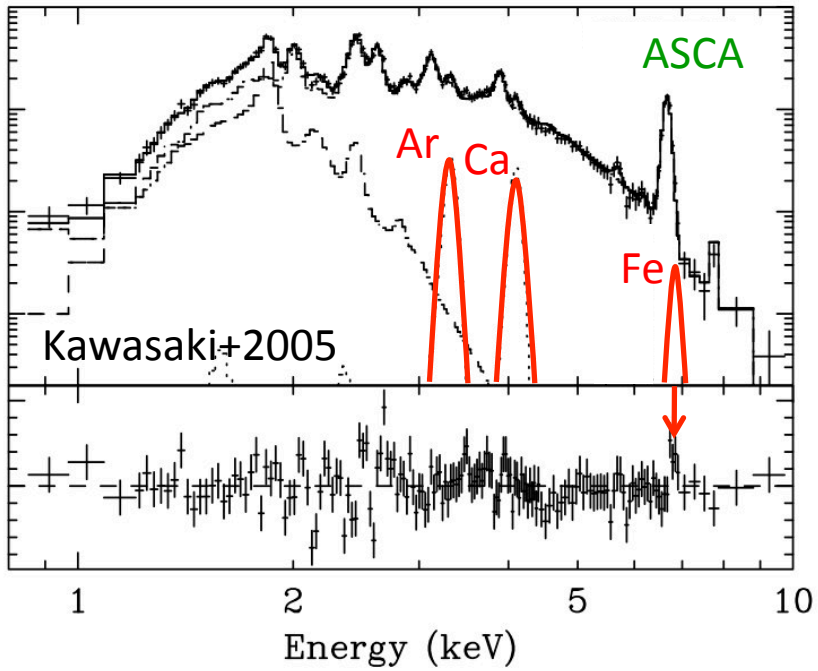
- dense circumstellar cloud?
- jet-like explosion? (Keohane+2007)

First detection of Cr and Mn (Hwang+2000)

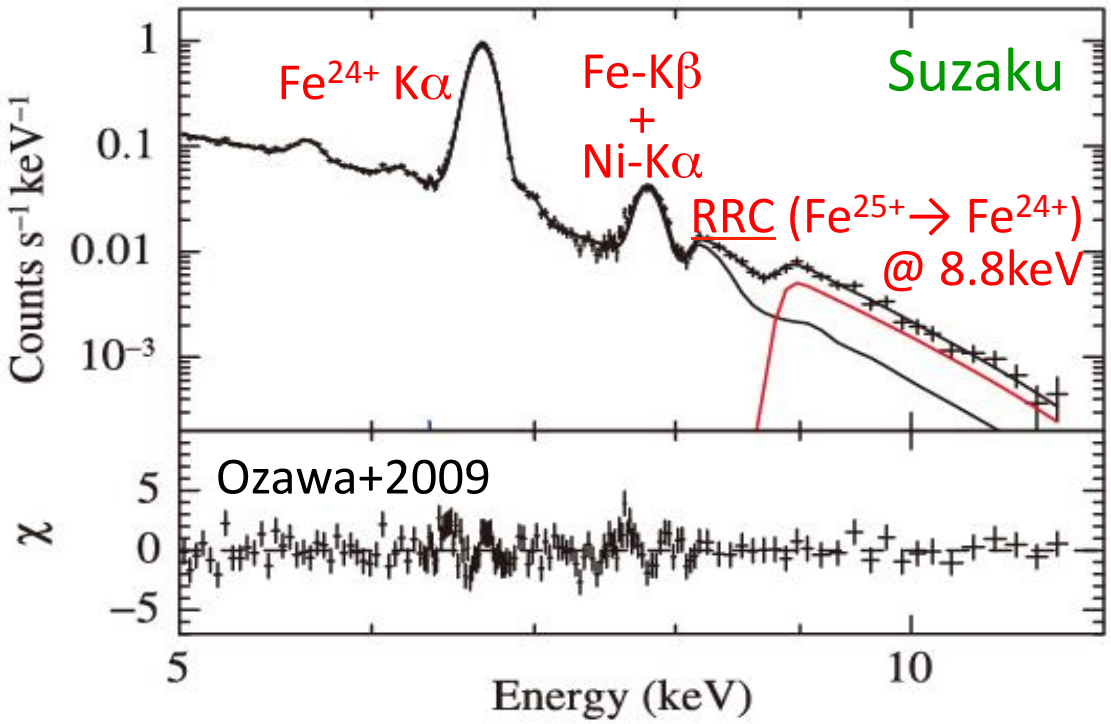
First claim of over-ionization

Excesses of H-like emissions over normal NEI/equilibrium plasma
(ASCA: Kawasaki+2005)

Multi-temperature effect, if any
(XMM: Miceli+2006)



W49B



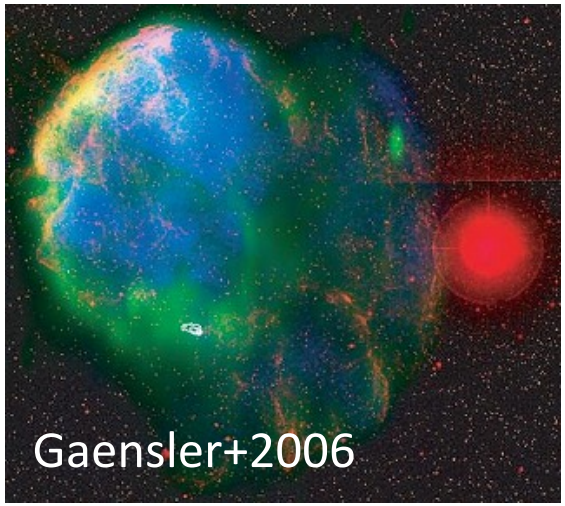
Suzaku discovered strong Radiative recombination continuum (RRC) !

$Fe^{25+} + e^- \rightarrow Fe^{24+} + h\nu$

$$\frac{dP}{dE}(E_\gamma) \propto \exp\left(-\frac{E_\gamma - I_z}{kT_e}\right), \quad \text{for } E_\gamma \geq I_z$$

determined from
the ion fraction (Fe^{24+} : Fe^{25+})
↓
kT_e = 1.5 keV, kT_z = 2.7 keV

IC443



D = 1.5 pc, Age ~ 4000 yr (Troja+2008)

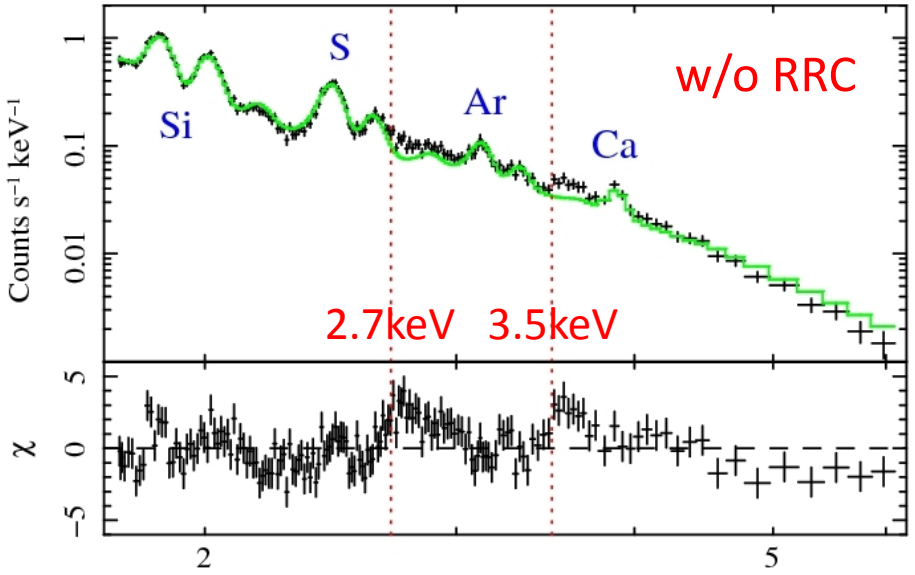
Possible association w/ star forming region
(Cornett+1977)

Over-ionization claim by ASCA
(Kawasaki+2002)

Suzaku: strong RRC of Si/S

bare ions → H-like (HY+2009)

- kT_e ~ 0.6 keV
- kT_z ~ 1.0–1.2 keV



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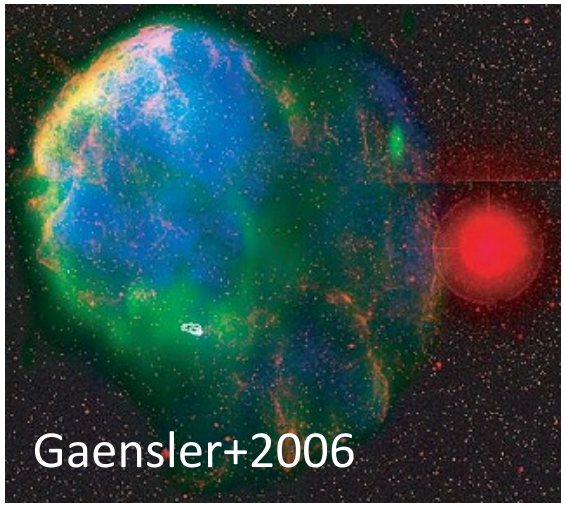

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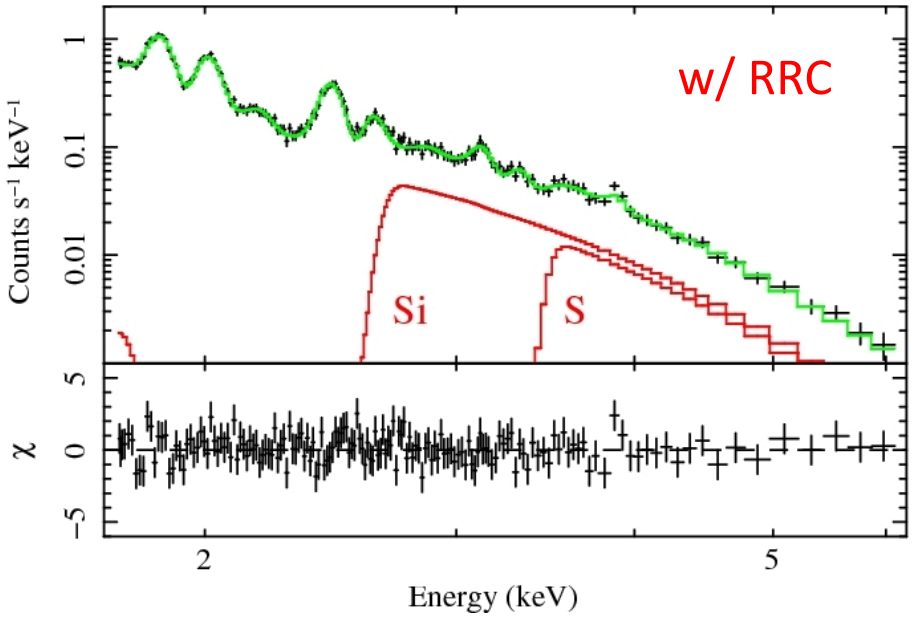
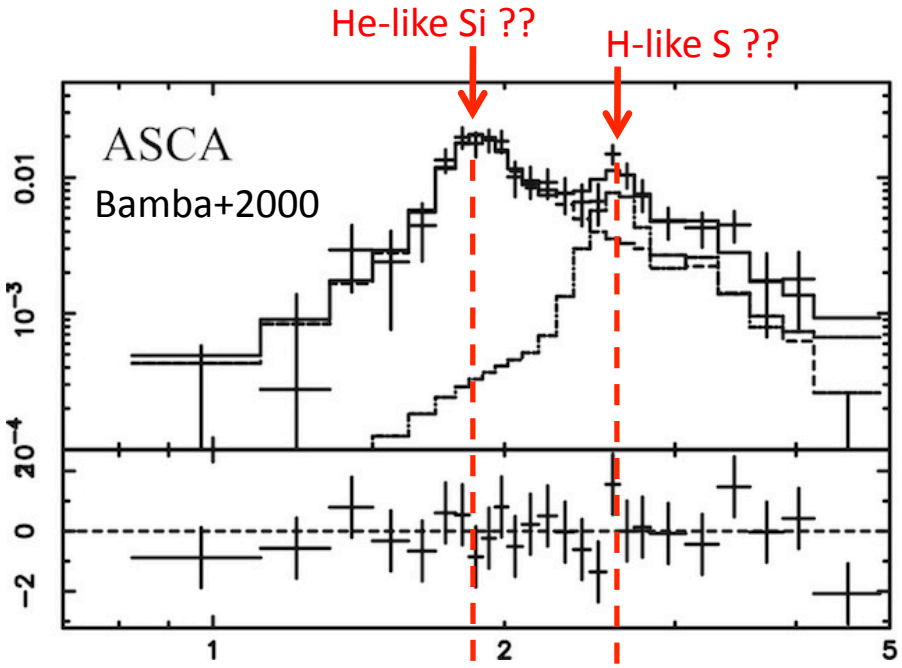


G359.1-0.5

The first X-ray spectroscopy:
ASCA/GIS (Bamba+2000)

two peaks -- emission lines?
@ ~ 1.86 keV & ~ 2.62 keV

	He-like	H-like
Si	1.86	2.01
S	2.45	2.63

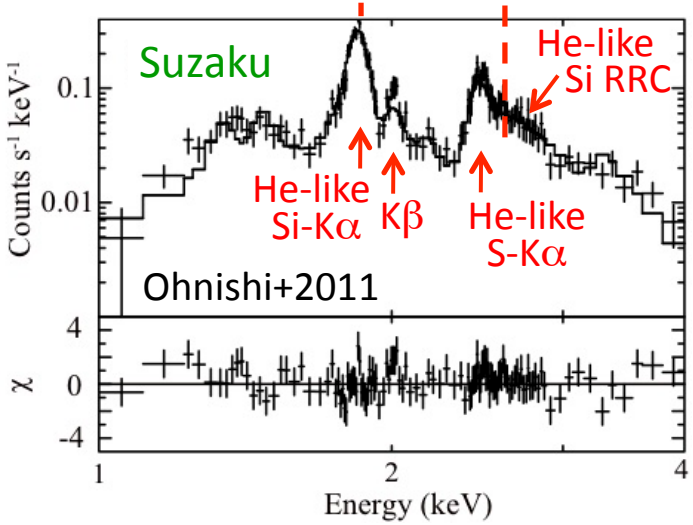


Applied an unnatural 2-kT_e model

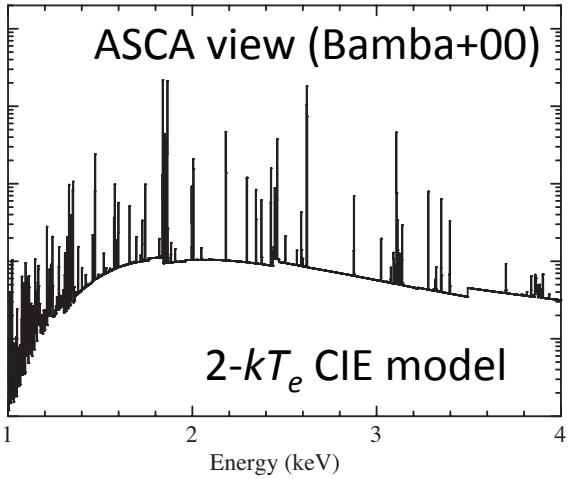
- kT_{e1} ~ 0.4 keV with only Si
- kT_{e2} ~ 1.7 keV with only S

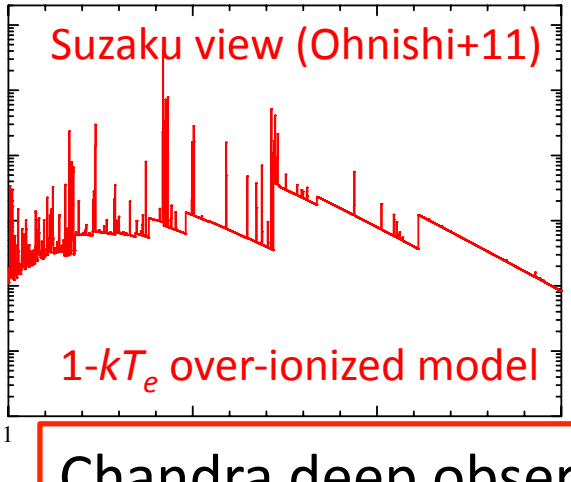
Suzaku unveiled the nature of this peculiar spectrum !!

- kT_e ~ 0.4 keV, kT_z ~ 0.8 keV

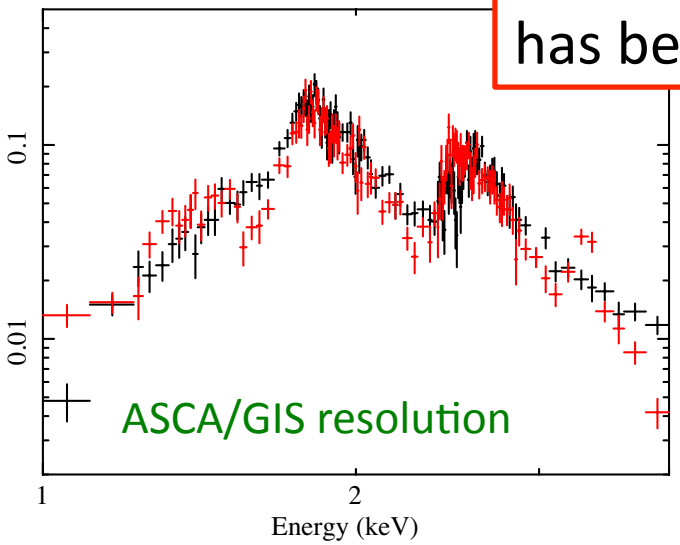


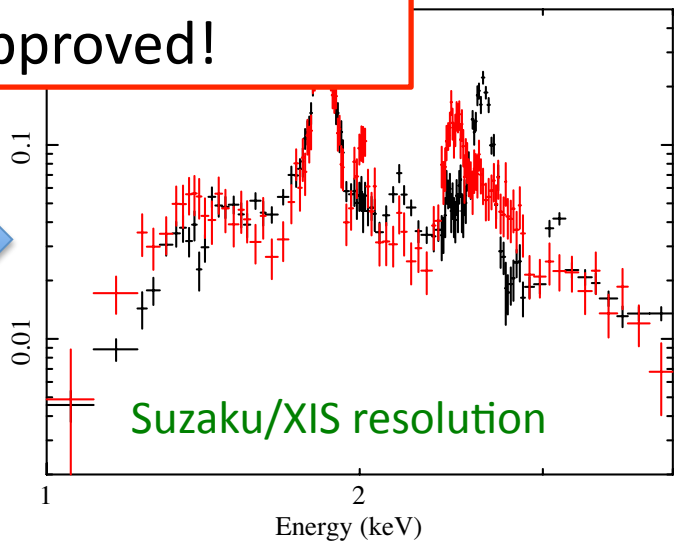
G359.1-0.5





Chandra deep observation proposal for AO13 cycle has been approved!

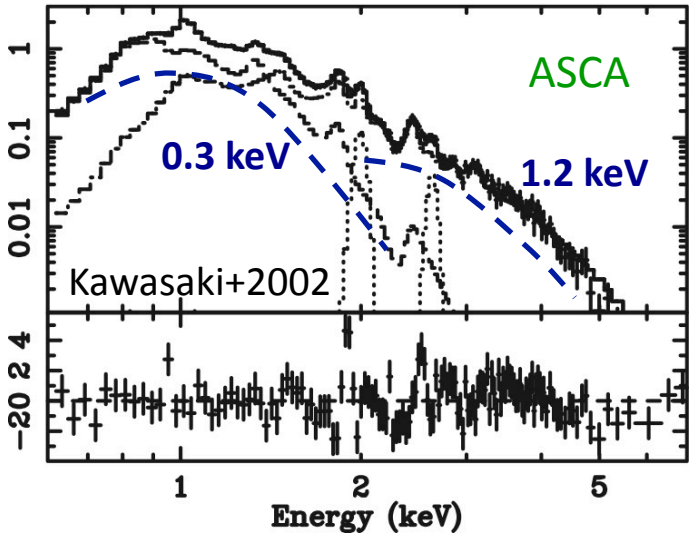




IC443 (fullband)

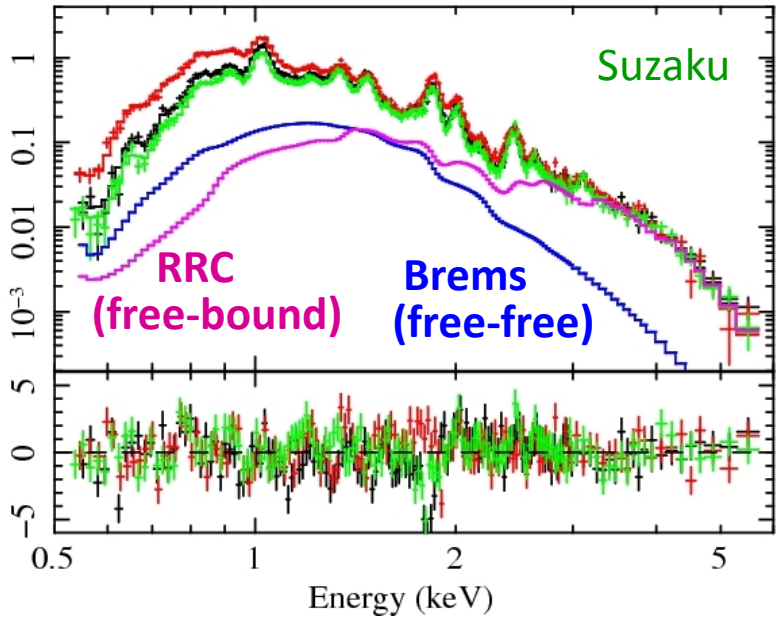
Previous view: 2-kT_e components
($kT_{e1} \sim 0.3$ keV + $kT_{e2} \sim 1.2$ keV)
to reproduce a wide-band continuum

… RRC were not taken into account



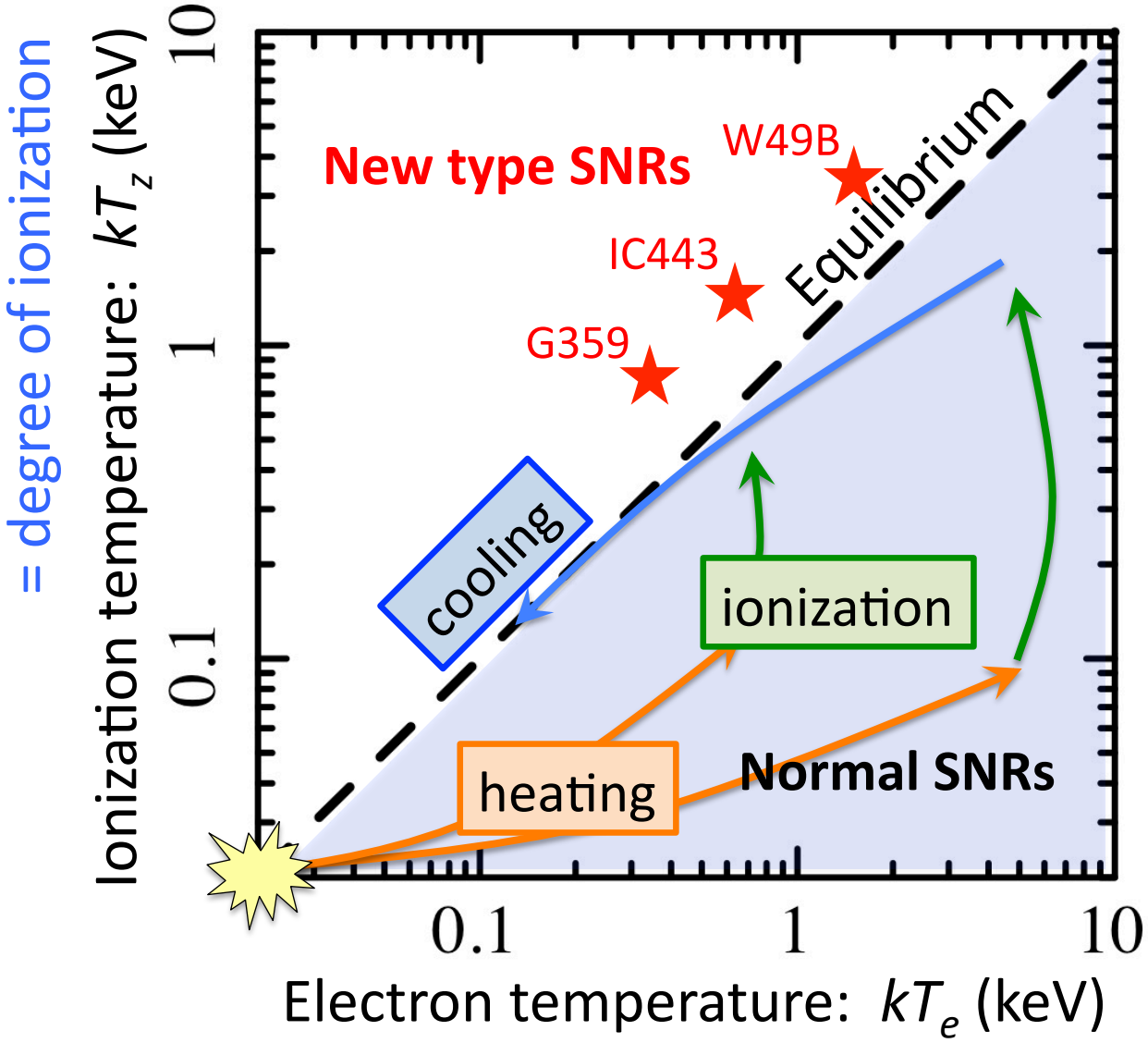
Suzaku view:

- $kT_e \sim 0.6$ keV (1 component)
- RRC dominates in the hard band

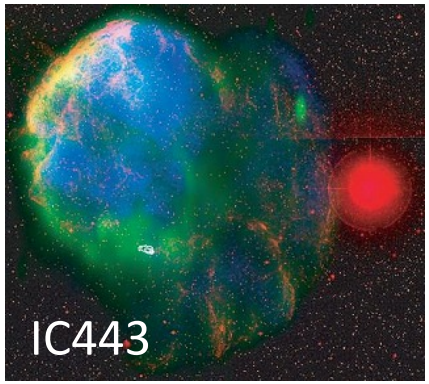


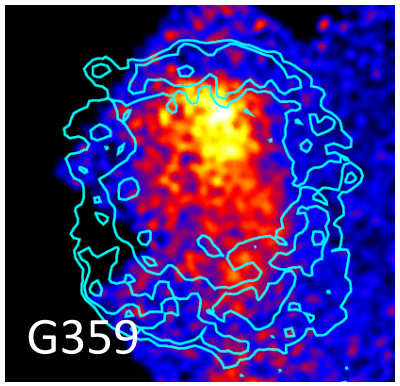
Consider possibility of recombining plasma before applying 2-kT_e model

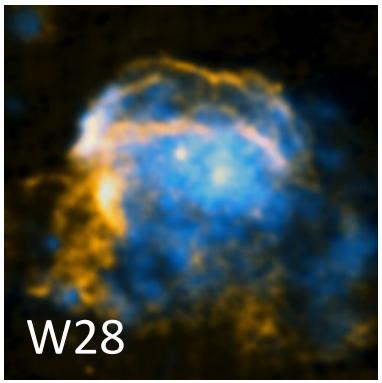
How was over-ionization formed?



Association with MM-SNRs







Mixed-Morphology (MM) SNR (e.g., Rho & Petre 1998)

- Centrally peaked X-rays with radio/optical shells
- Association with Star forming regions and molecular clouds
- GeV γ-ray emission due to *p*-*p* interaction

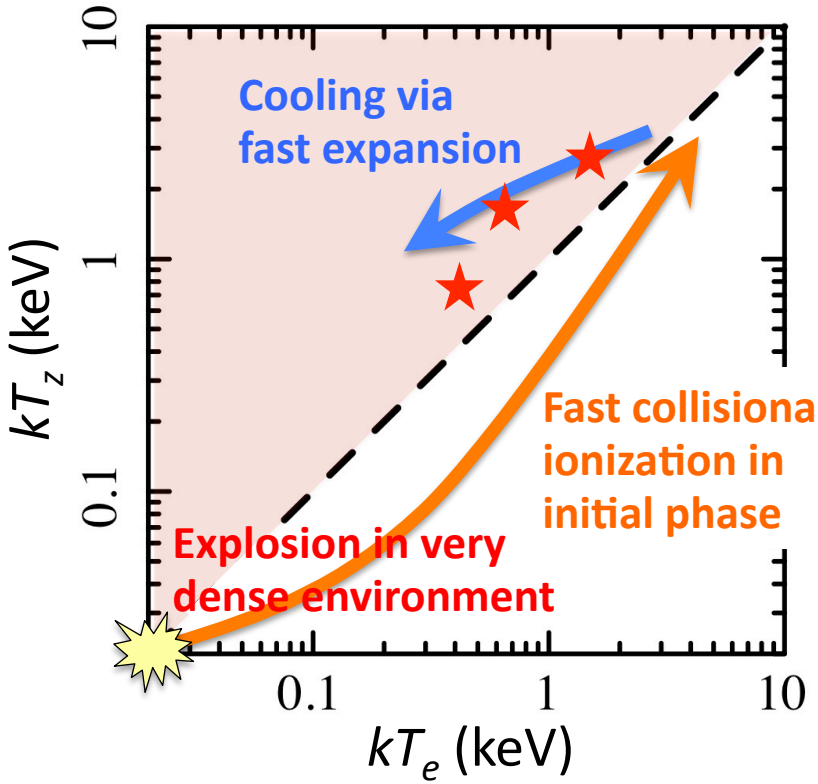
$\Rightarrow$ Massive progenitors in dense environment

Proposed scenarios

(1) Explosion in dense CSM

Like SN1993J (e.g., Uno+2002)
→ ISM/ejecta can be highly ionized

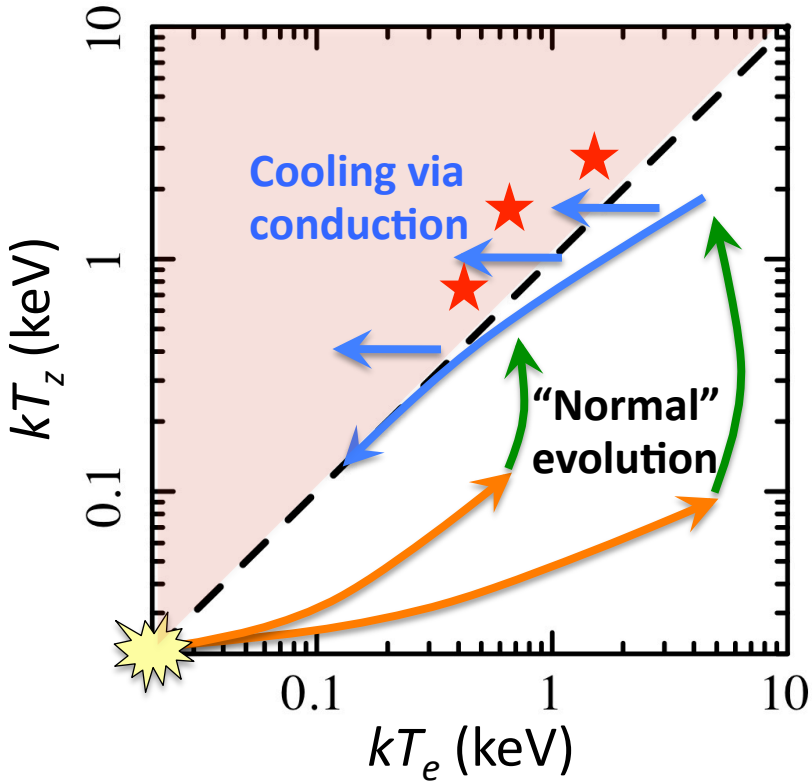
Fast adiabatic cooling (Itoh+1989)



(2) Thermal conduction

Mixing w/ cold circumstellar cloud
-- works for W49B? (Zhou+2011)

See Ji's poster for details



Future prospects

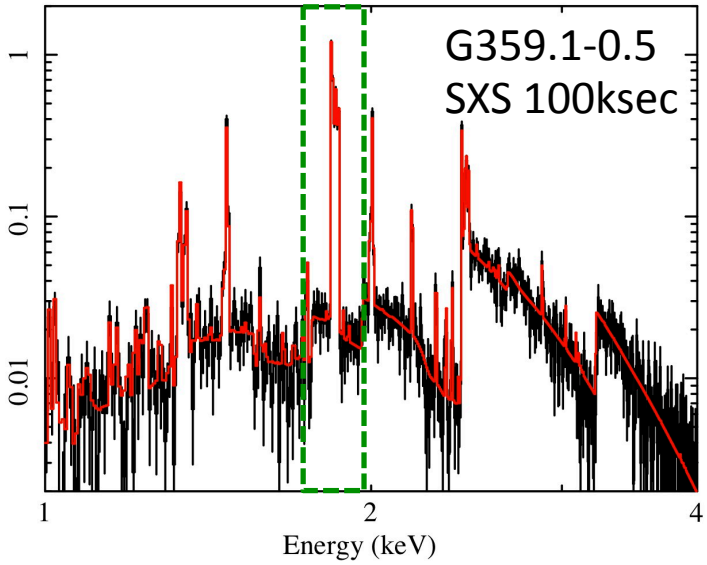
Origin of the over-ionization is not yet understood…

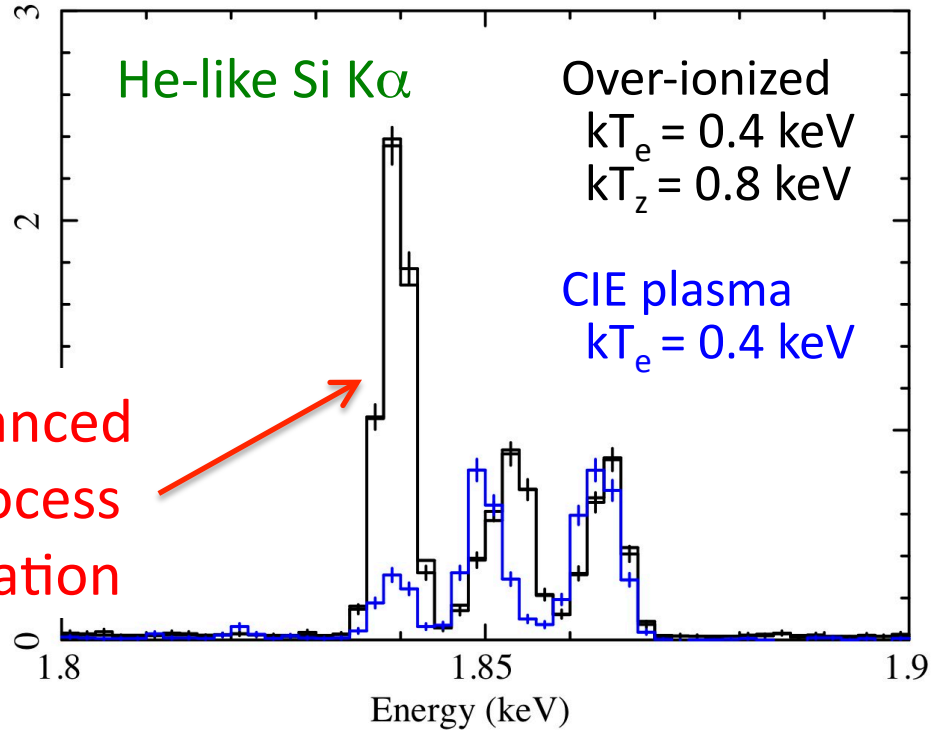
- Spatial distribution of the over-ionized plasma
- Over-ionization in the ejecta

- Numerical work taking into account chemical composition of the ejecta, combined with NEI plasma code
- Survey of other over-ionized SNRs (key proj. by Kyoto group)

Future prospects

- High-resolution spectroscopy with Astro-H





Forbidden line enhanced due to cascaded process following recombination

Measurement of ion temperature

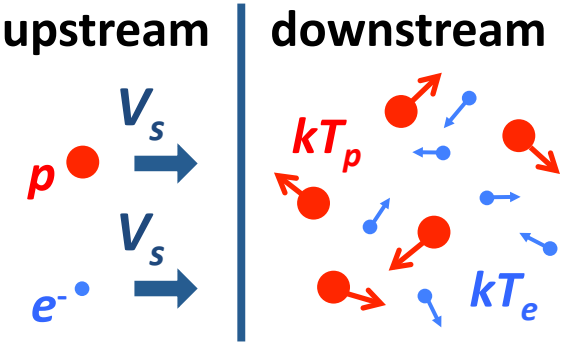
Thermal Non-Equilibrium

$kT_i = (3/16)\, m_i\, V_s^2$ for each species "*i*"

$kT_p / kT_e = m_p / m_e \sim 1800$

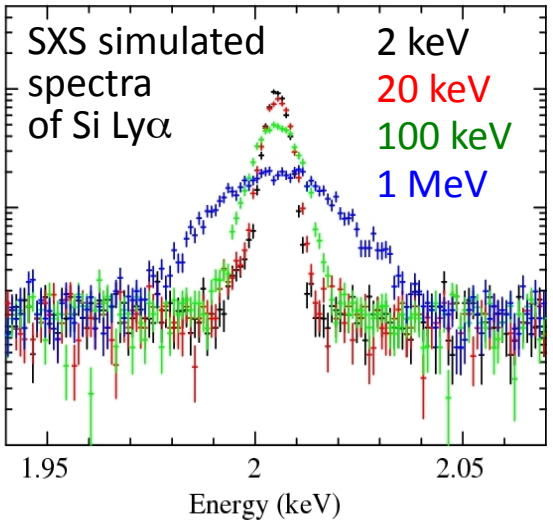
$V_s = 3000$ km s^{-1} $\Rightarrow$ $\langle kT \rangle \sim 20$ keV

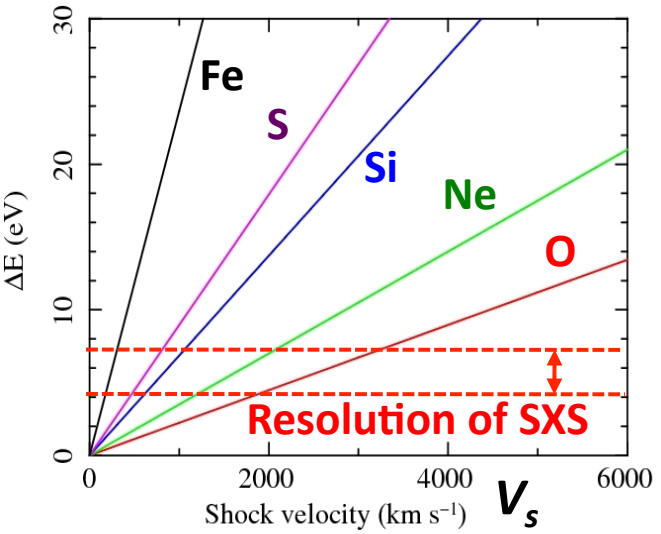
most SNRs --- $kT_e \sim 1$–5 keV still in non-equilibrium?



We need Astro-H!

Direct measurement of ion temperature





Summary

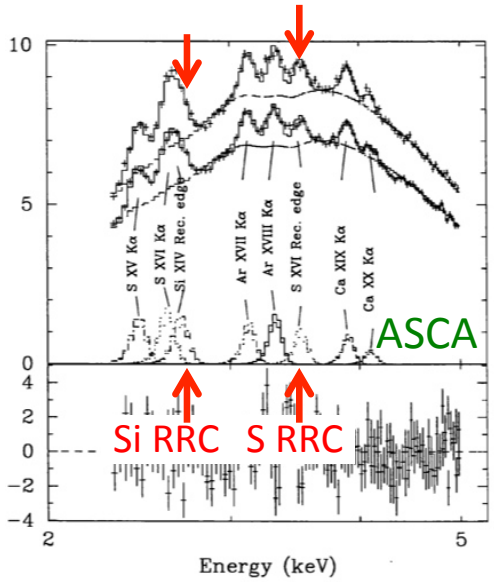
- Presence of over-ionized (recombining) plasma in SNRs is robustly confirmed by the detection of strong radiative recombination continua (RRC) with Suzaku.
  - Appreciate the ASCA results, first claim of over-ionization
- Not expected from standard SNR's evolution.
- Origin of the over-ionization is not yet understood.
  - Ionization in dense CSM & adiabatic cooling?
  - Cooling via thermal conduction into circumstellar cloud?
- Future observations with Astro-H is very important!

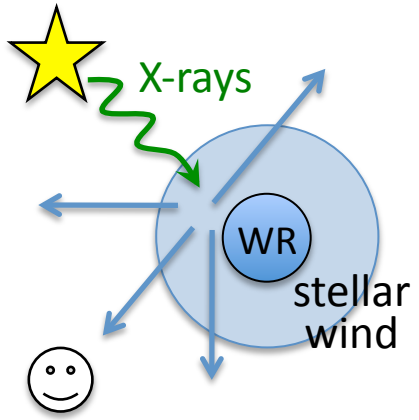
Examples of recombining plasmas

Photo-ionized plasma

e.g., Cyg X-3
(Kawashima & Kitamoto 1996)

Cool stellar wind irradiated by
X-rays from the compact star





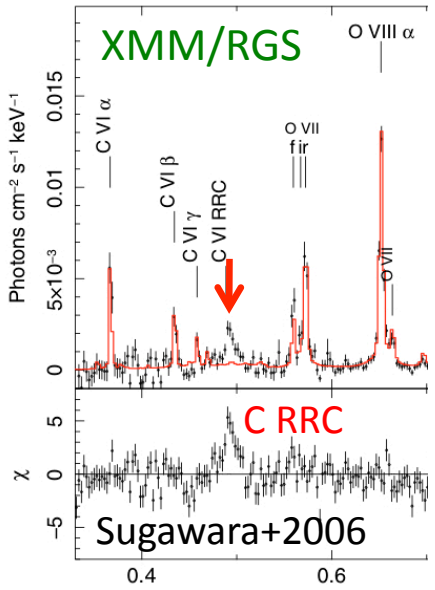
Colliding-wind binary

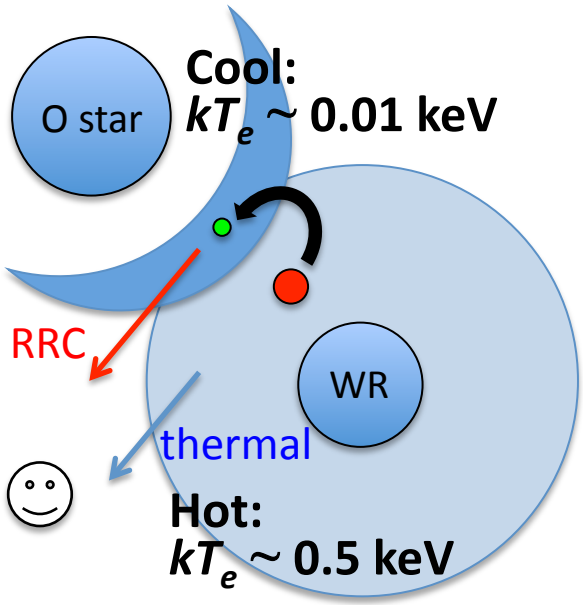
e.g., θ Muscae (Sugawara+2006)

Planetary Nebula

e.g., BD+30◦3639 (Nordon+2009)

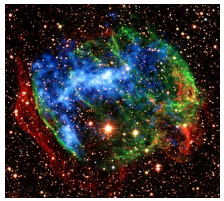
Interaction b/w ions in hotter
bubble (crossing the CD) and
electrons in cooler wind



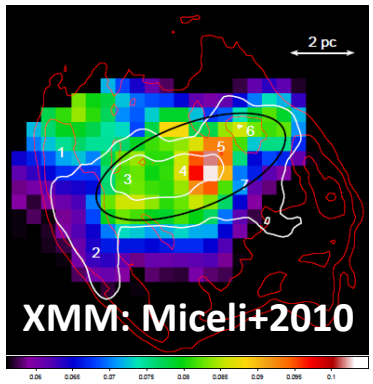


Spatial distribution & abundances

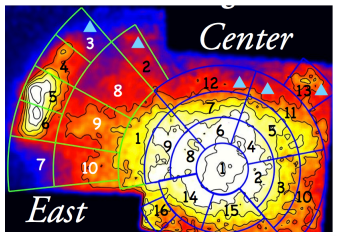
W49B



RRC/Brems ratio
(4.4-6.2keV / 8.3-12keV)

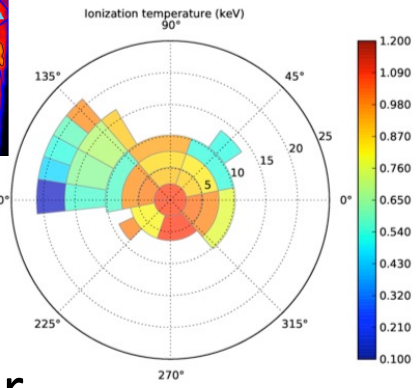


W28



kT_z map

Sawada+, poster



- Over-ionization concentrates at SNRs' center

Abundances

- **W49B**: Fe/O ~ 5.0 solar (Ozawa+2009)
- **G359.1-0.5**: Si/O ~ 12 solar (Ohnishi+2011)

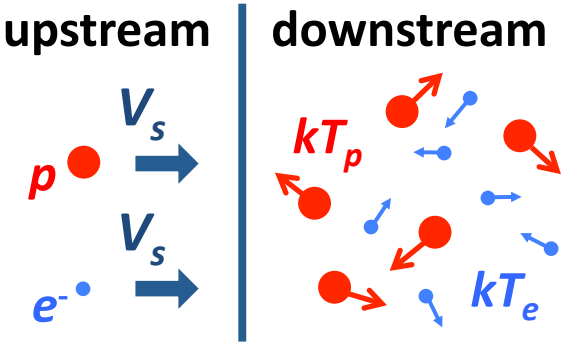
⇒ Central ejecta are highly over-ionized

Scenario 2 (Explosion in CSM and adiabatic cooling) is more preferable?

Measurement of ion temperature

Interaction b/w free expanding ejecta and ambient matters

⇒ forward & reverse shocks



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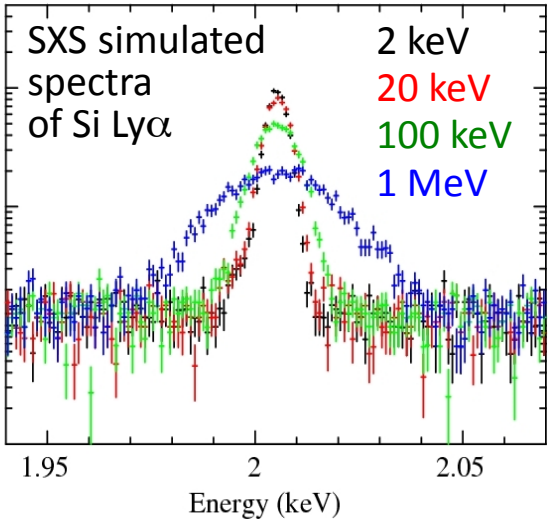
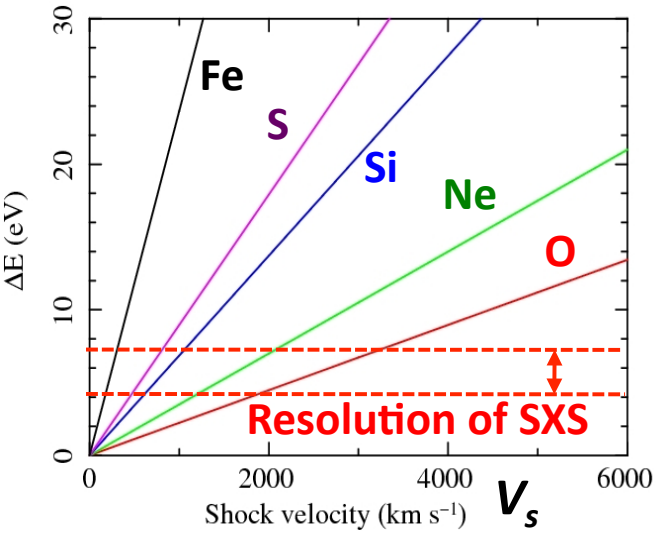
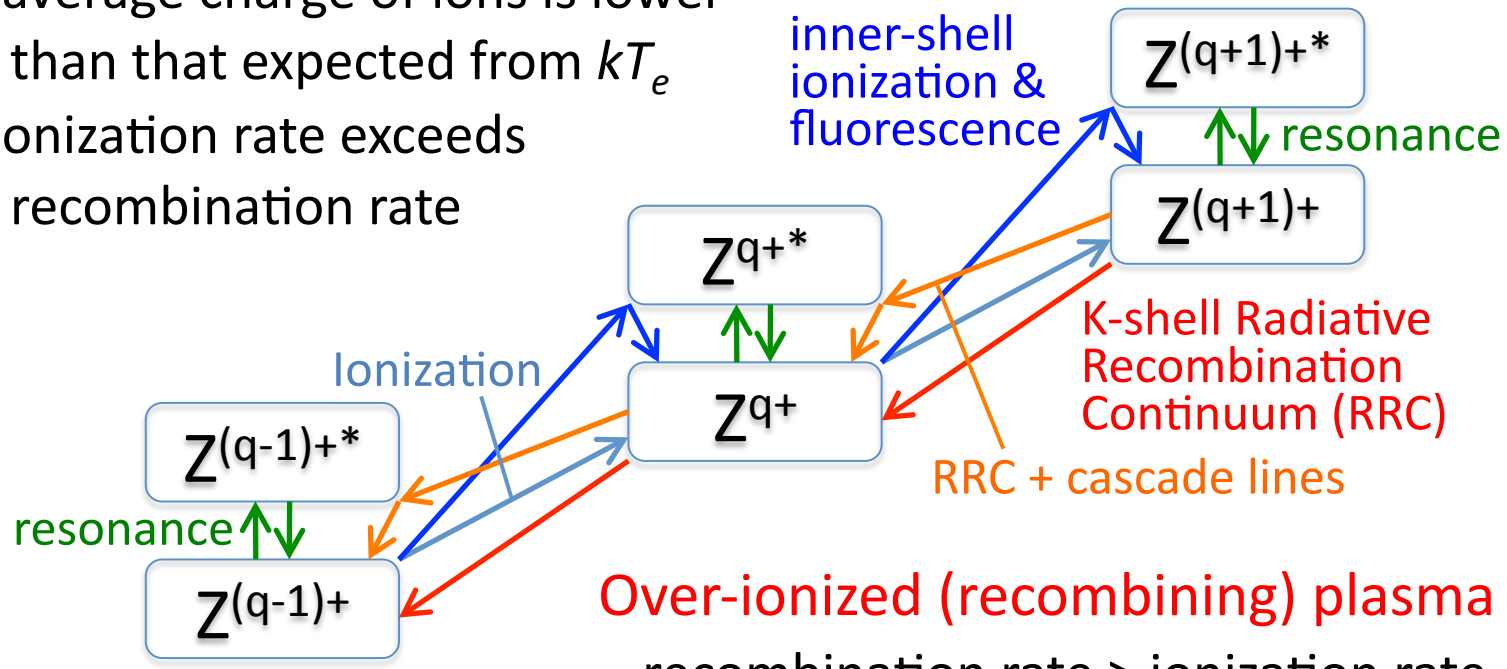




Ionizing and recombining plasmas

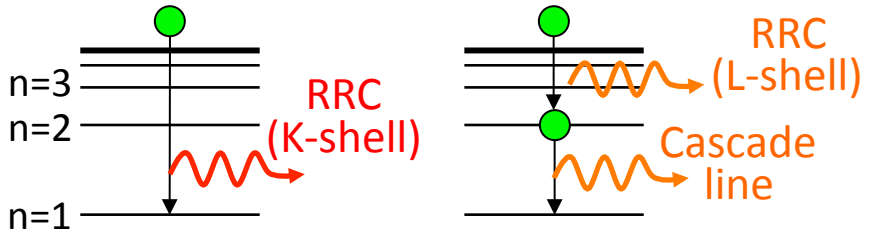
"Normal" NEI (ionizing) plasma

- average charge of ions is lower than that expected from kT_e
- ionization rate exceeds recombination rate



Over-ionized (recombining) plasma

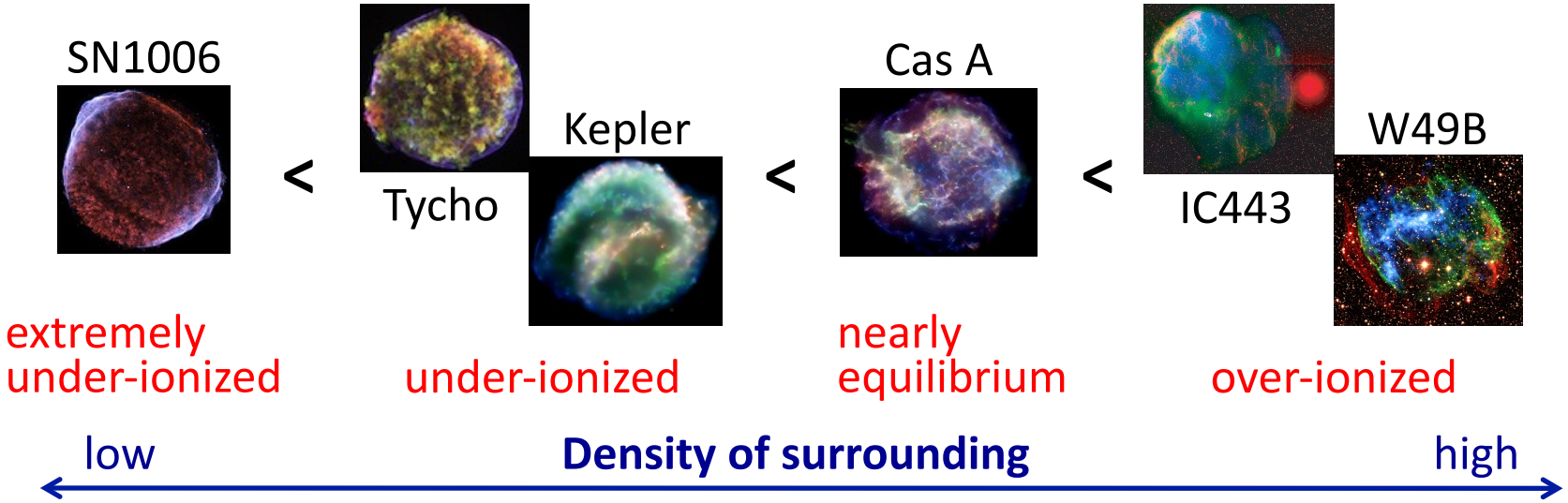
- recombination rate > ionization rate



Review of the proposed scenarios

Initial ionization and cooling via adiabatic expansion

(Itoh & Masai 1989; HY+2009)



- Highly ionized in dense environment, like <u>stellar wind material</u>
- Cooled adiabatically in the outer low-density region

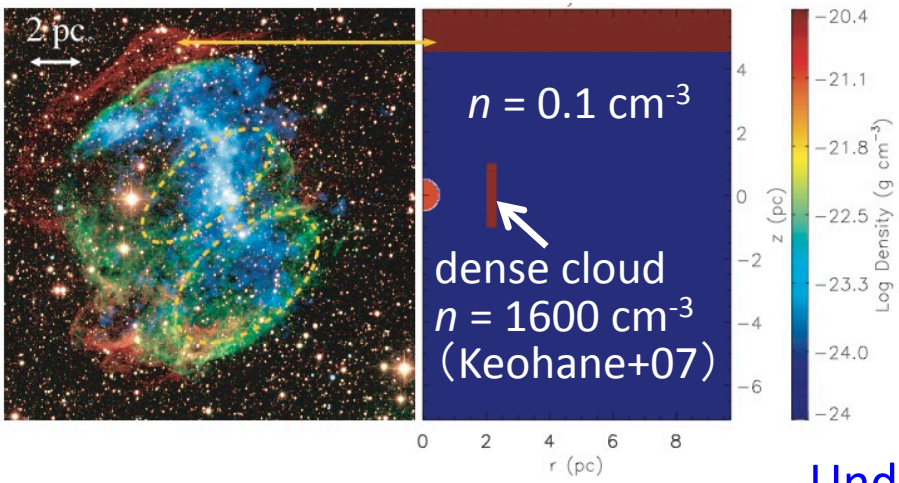
  - Strong stellar wind activities of the progenitors are suggested (e.g., IC443: Meaburn+1990; W49B: Keohane+2007)

Review of the proposed scenarios

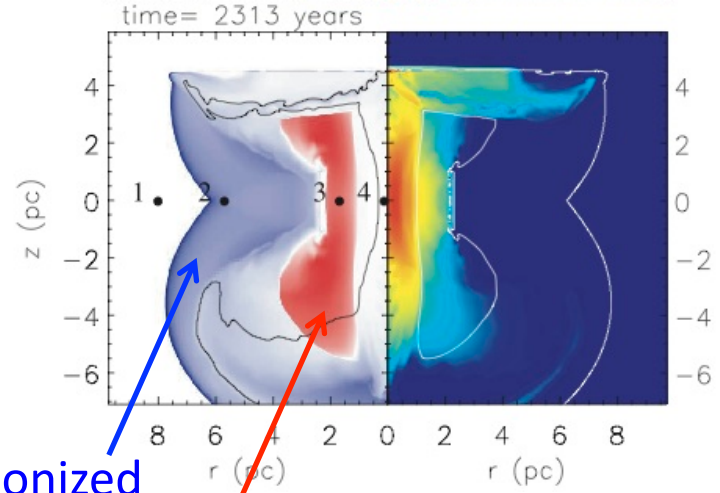
Thermal conduction to dense circumstellar cloud

(Zhou+2011; application to W49B)

Initial condition



Ionization Brightness



Under-ionized

Over-ionized

- Reflected shock from dense cloud enhance the central emission
- Conduction to the cloud make the plasma over-ionized

See Ji's poster for details