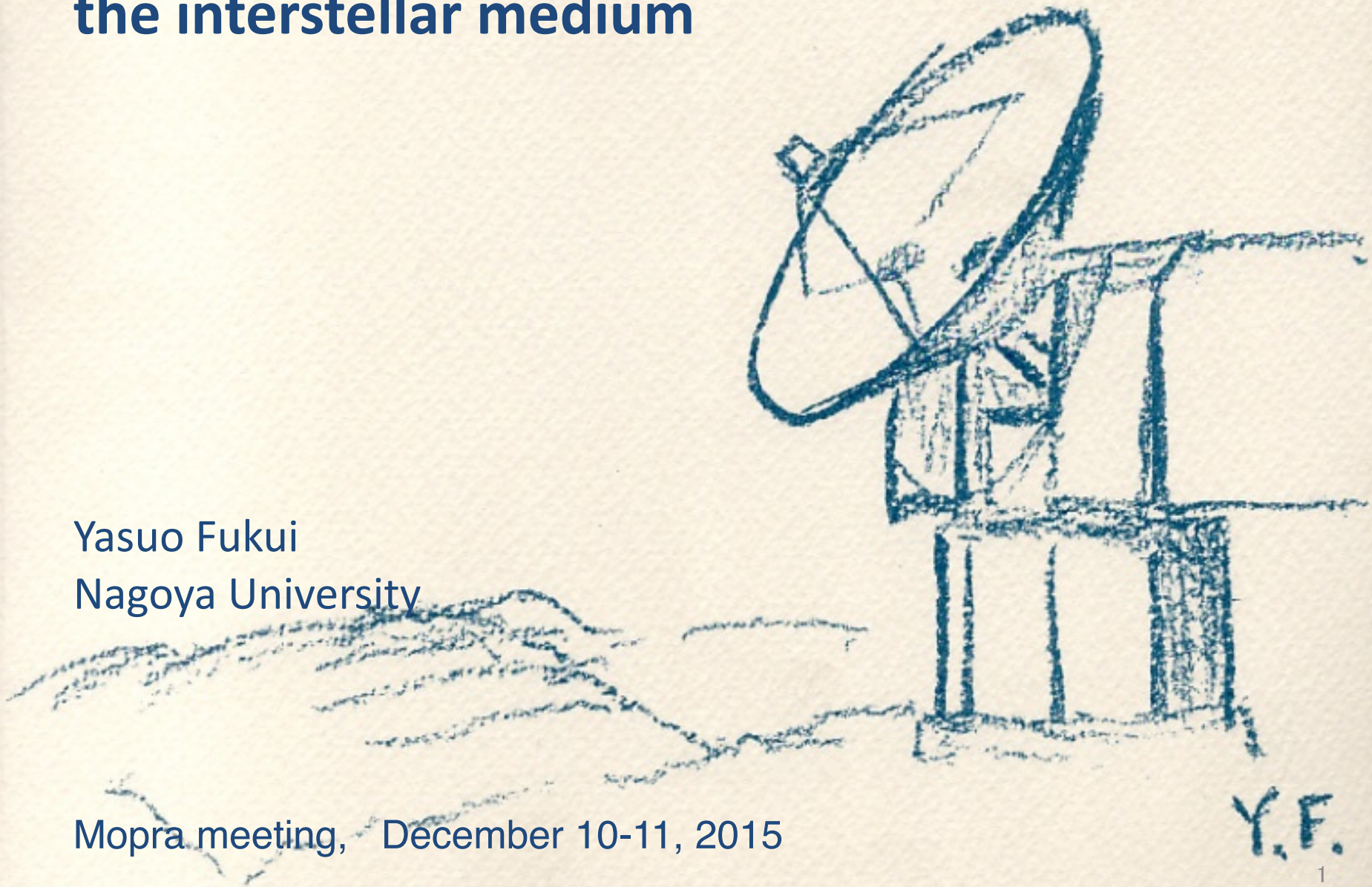
Supernova remnants, cosmic rays and the interstellar medium



Yasuo Fukui
Nagoya University

Mopra meeting, December 10-11, 2015

The origin of gamma rays
⇒The origin of cosmic rays

Origin of gamma rays

Comparison with the ISM is crucial

Reason 1　Interstellar protons are the targets of hadronic gamma rays

—precise measurements of interstellar protons are essential

Reason 2　Interactions between the shock waves and the interstellar medium, lead to magnetic field/ turbulence amplification

—high resolution X ray data are important for identifying the interaction

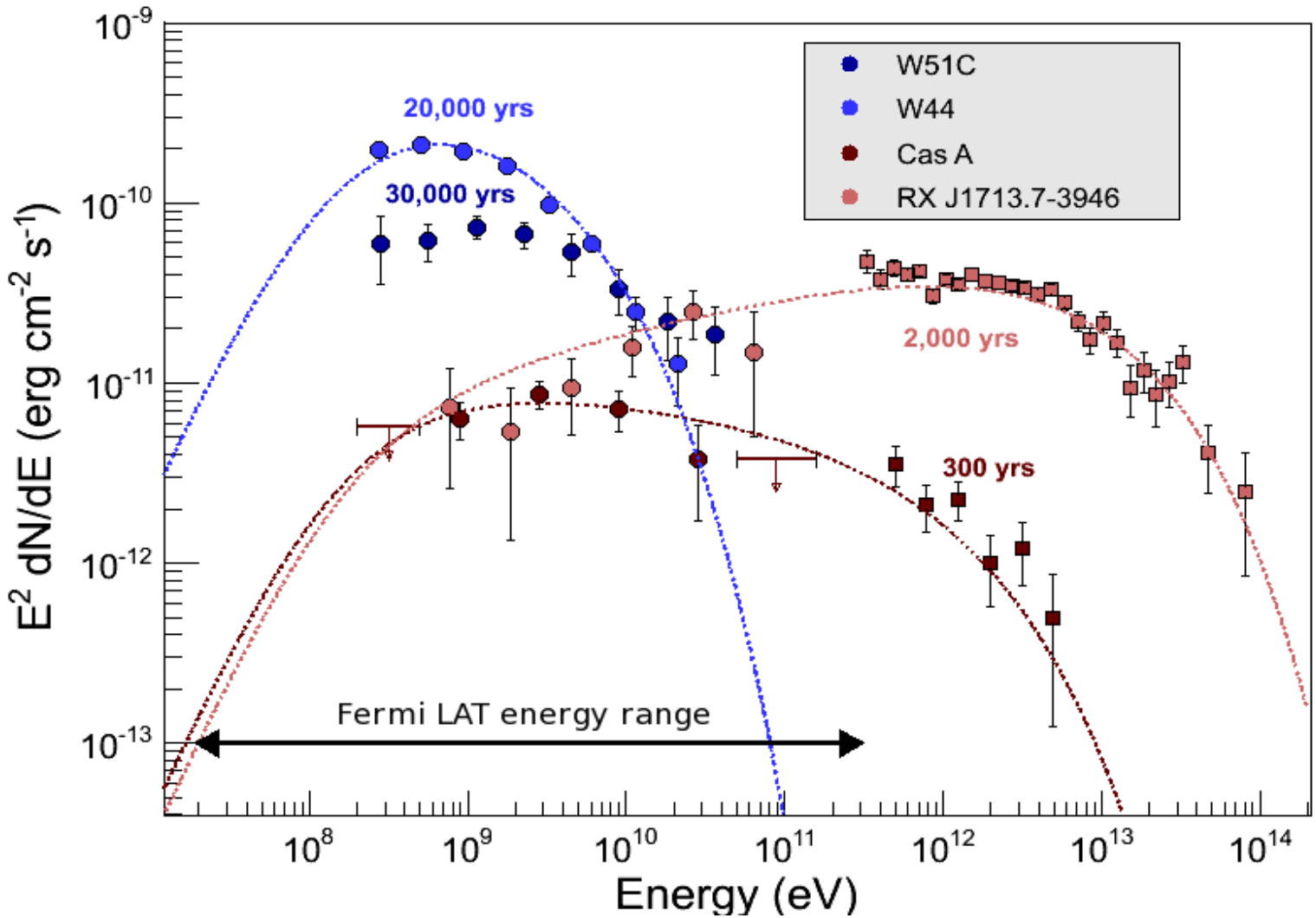
Observations of gamma rays:

HESS, MAGIC, VERITAS, Fermi etc.

CTA: big jump in sensitivity and resolution

Basic processes to be learned in the Local Group galaxies

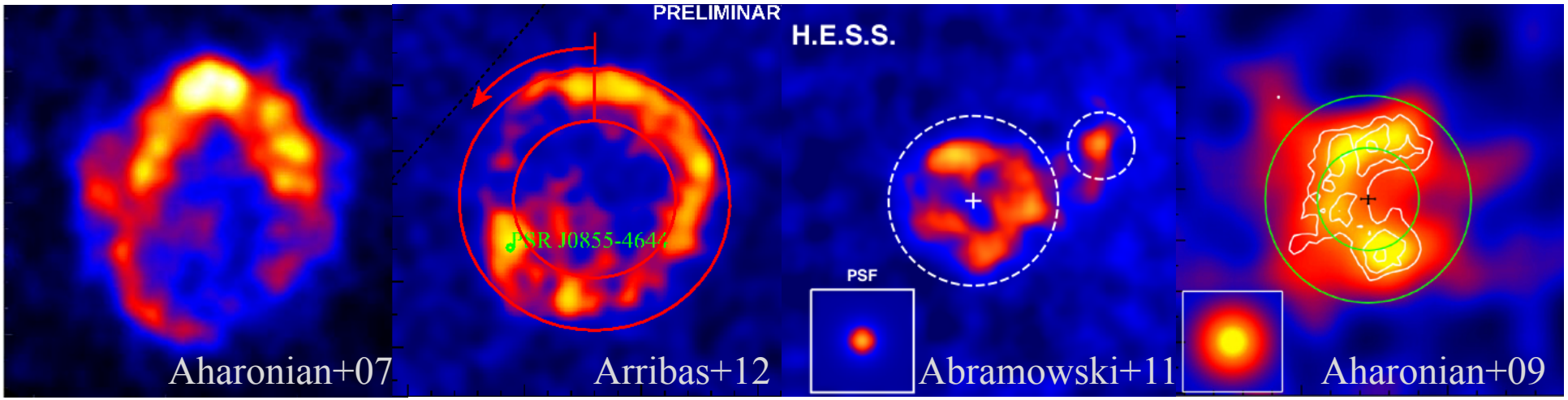
SNRs emitting gamma-rays



Courtesy H. Tajima

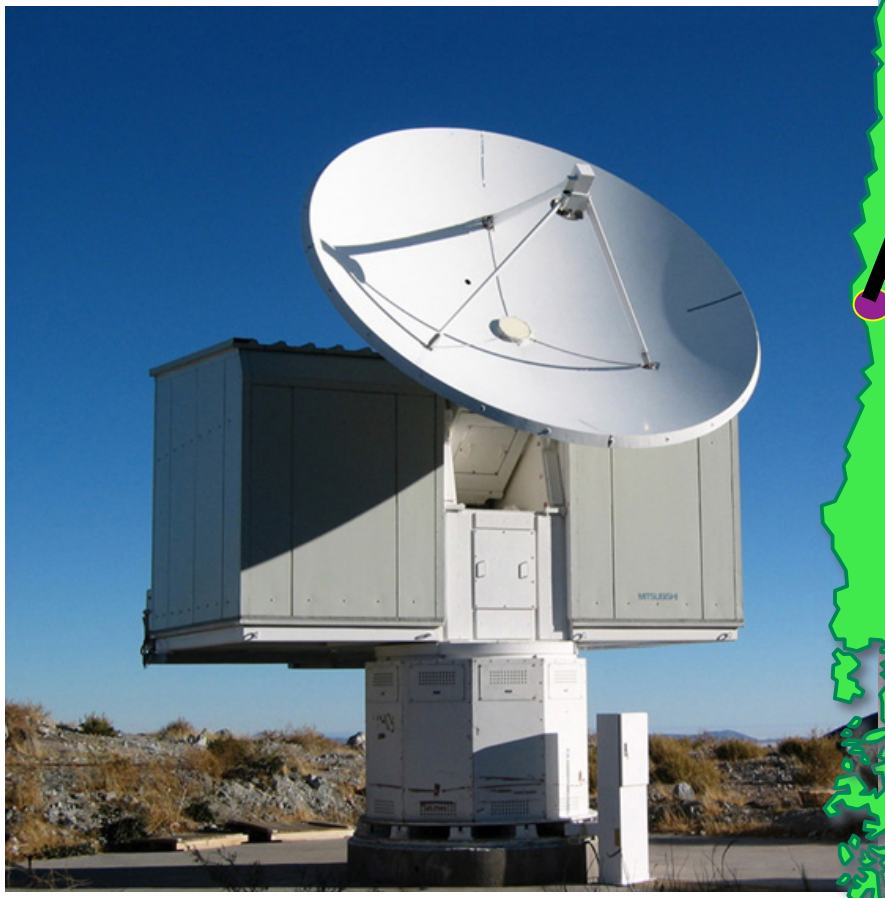
Four TeV Gamma-ray SNRs

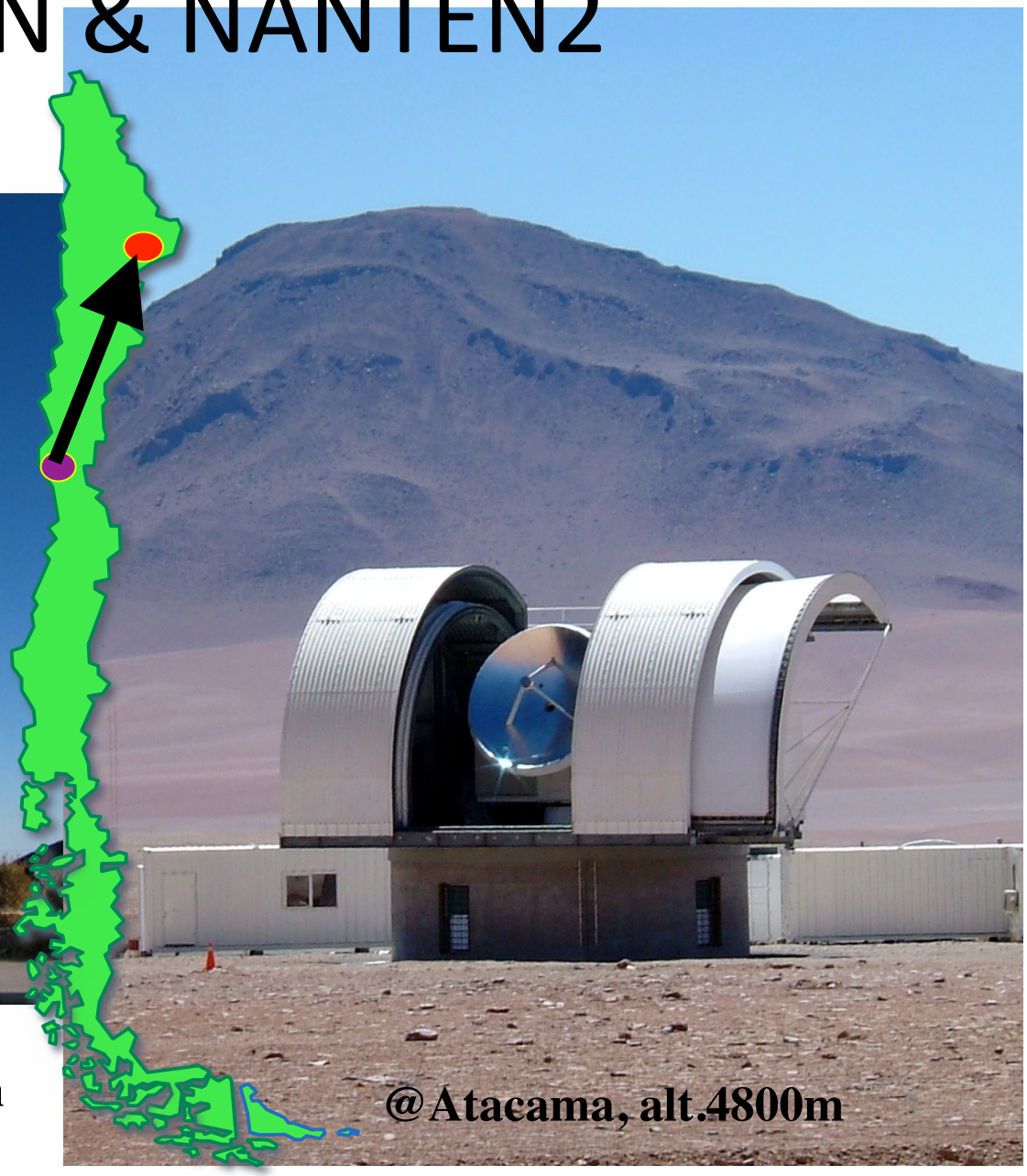
- 4 TeV gamma ray SNRs age 2000yrs
- They are interacting with ISM



	RX J1713.7–3946	RX J0852.0–4622	HESS J1731–347	RCW 86
diameter:	~1 deg.	~2 deg.	~0.5 deg.	~0.5 deg.
age:	~1600 yr	~1700−4300 yr	~3600−7200 yr	~1800 yr
ISM:	rich CO + cold HI	rich HI + little CO	rich CO + HI cavity	rich HI + little CO
X-rays:	pure synchrotron	pure synchrotron ?	pure synchrotron	thermal + non-thermal

NANTEN & NANTEN2



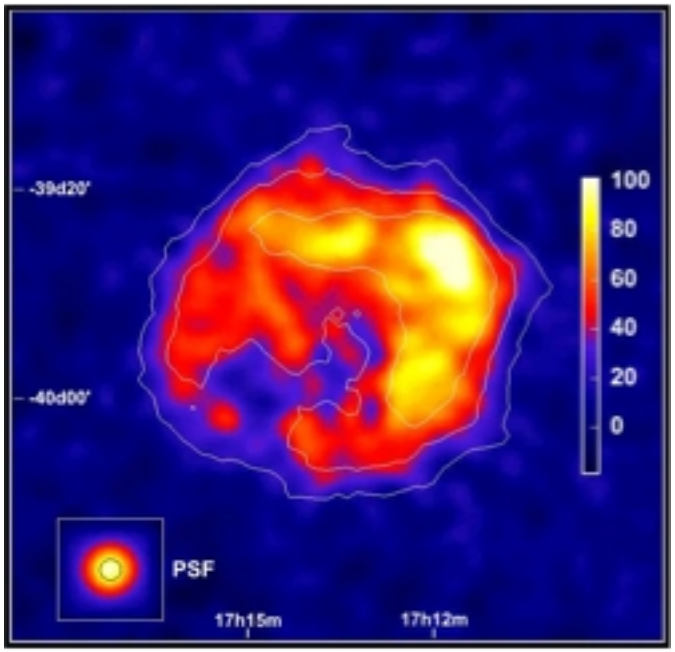


@Las Campanas, alt.2400m

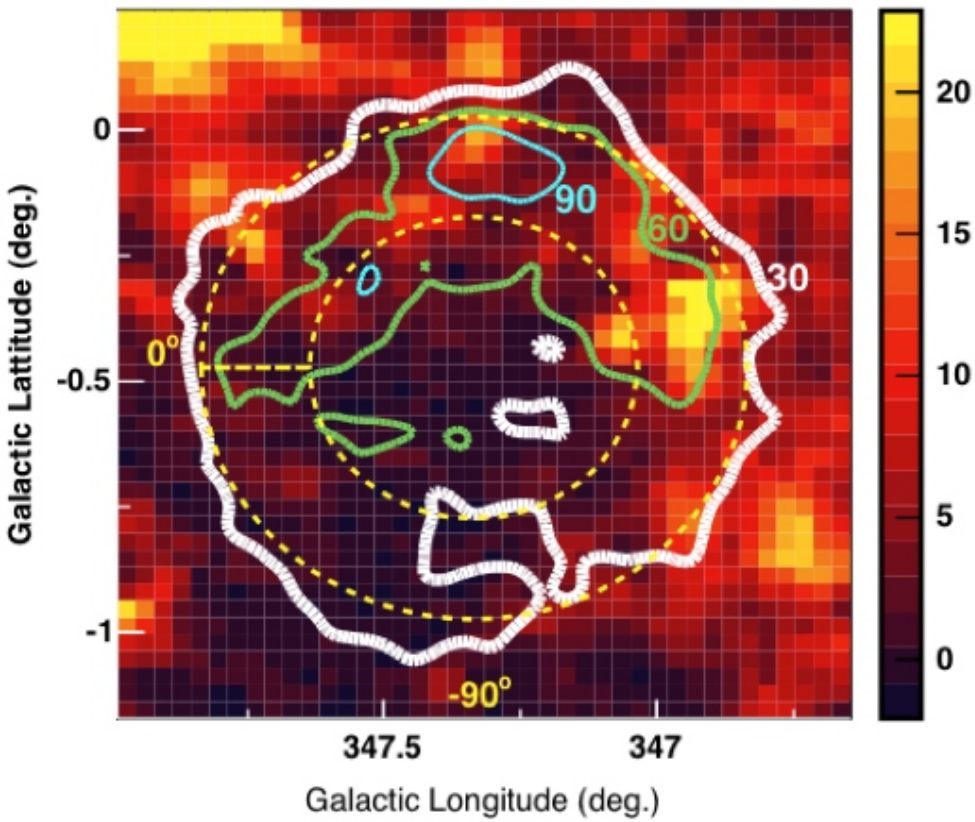
@Atacama, alt.4800m

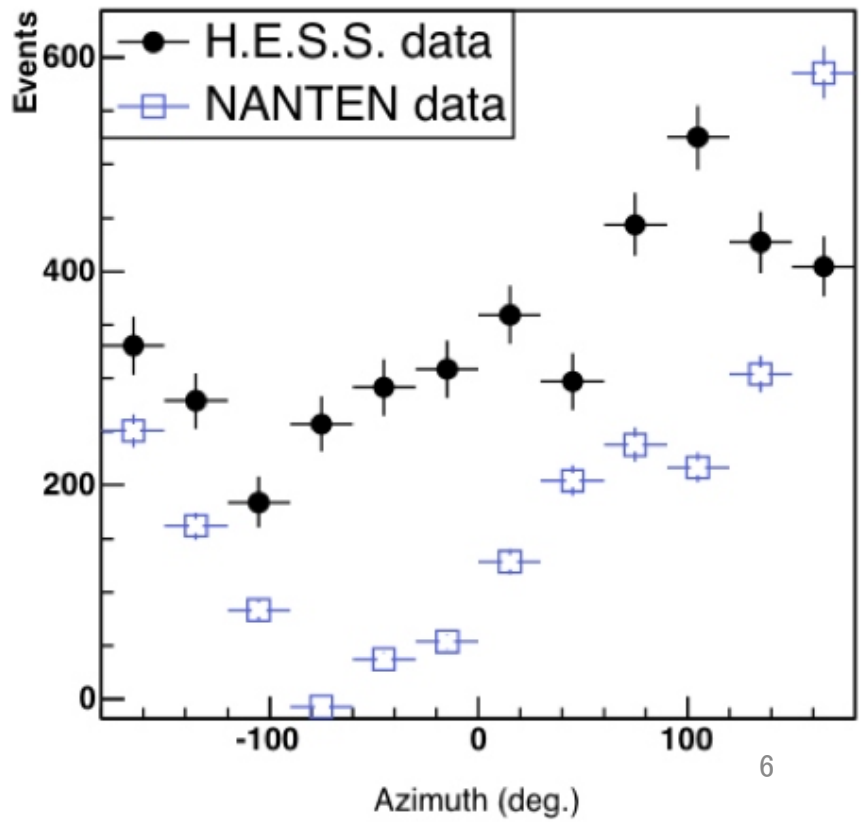
SNR G347.3-0.5 (RXJ1713.7-3946)

- Shell-like structure: similar with X-rays
- No significant variation of spectrum index across the regions
- spatial correlation with surrounding molecular gas

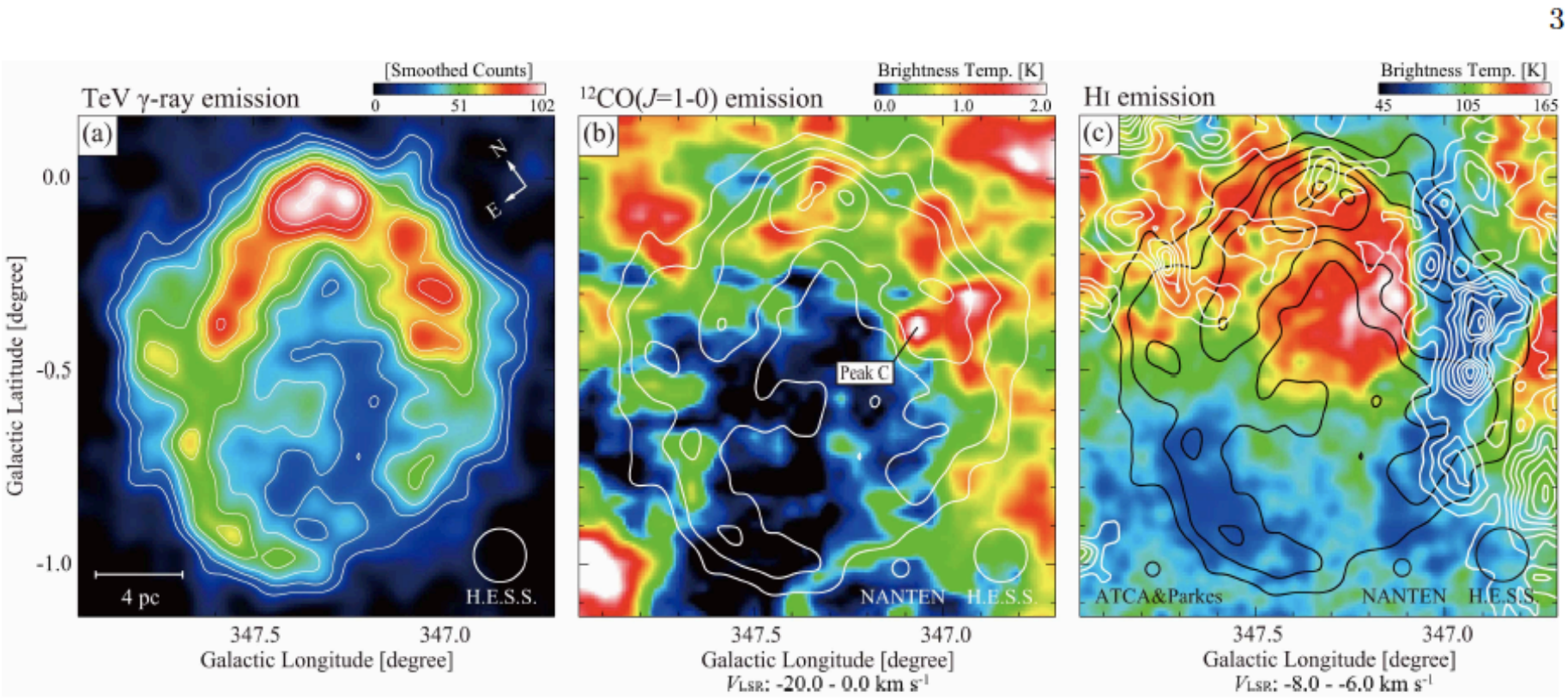


Aharonian et al. 2005



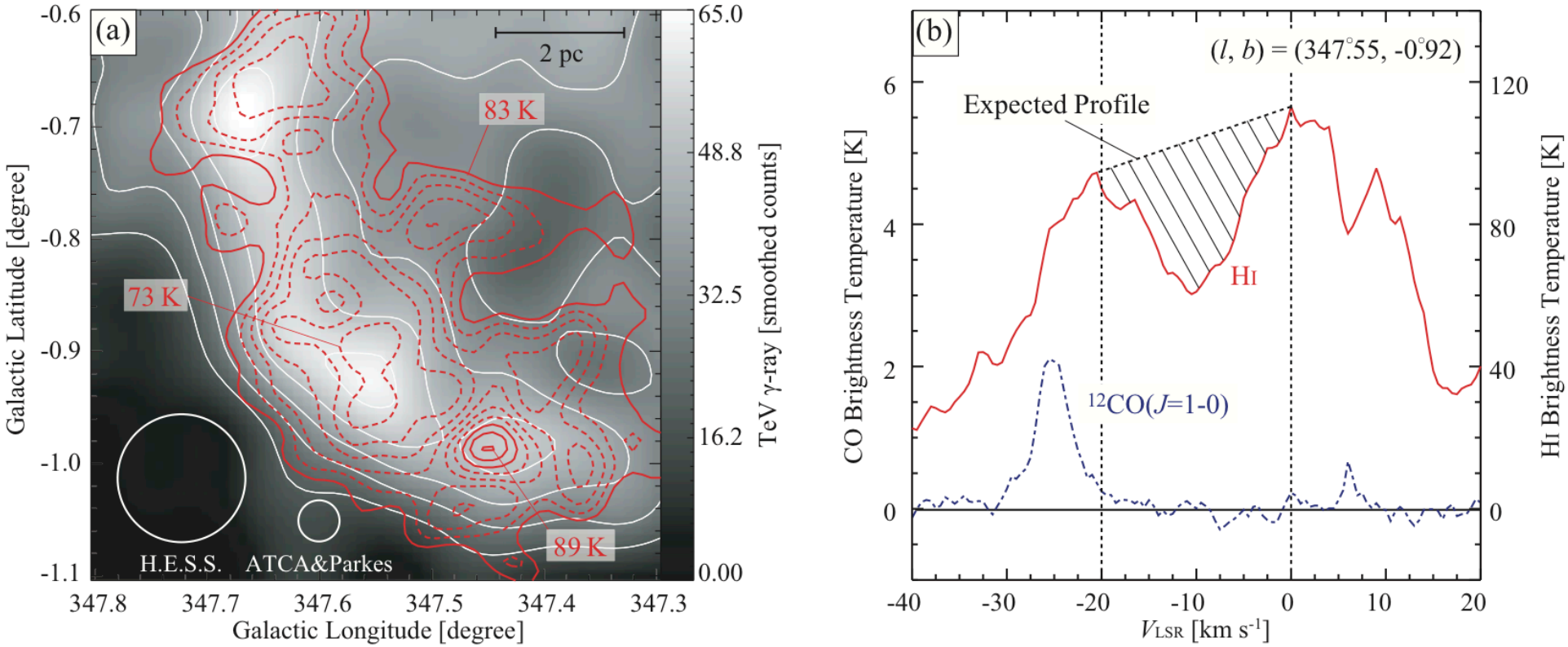


RX J1713.7-3946

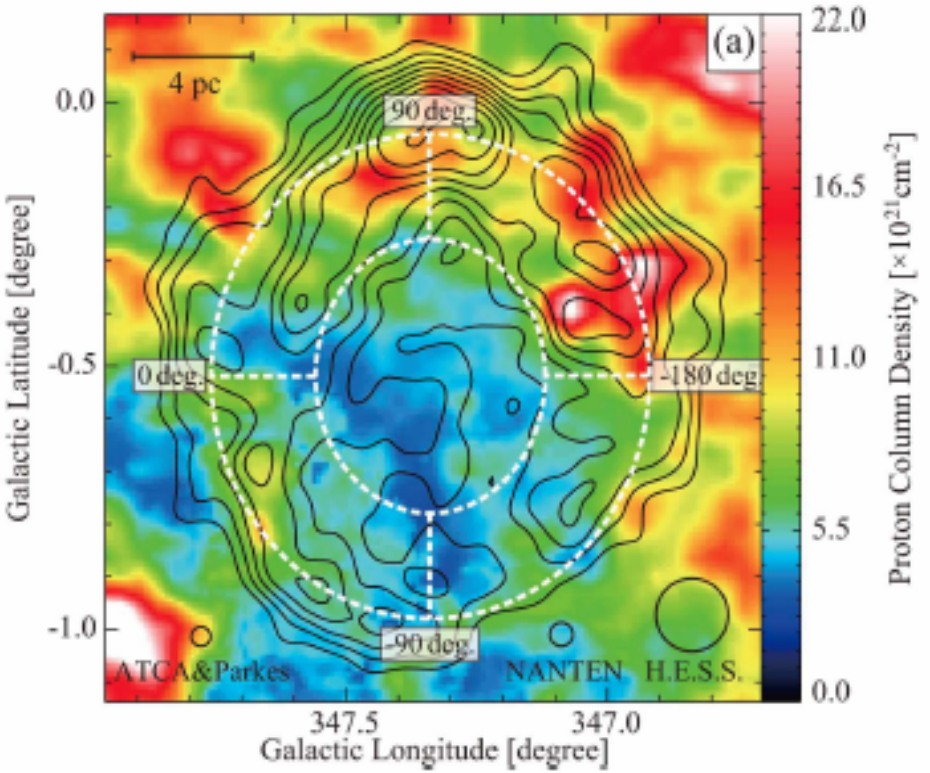


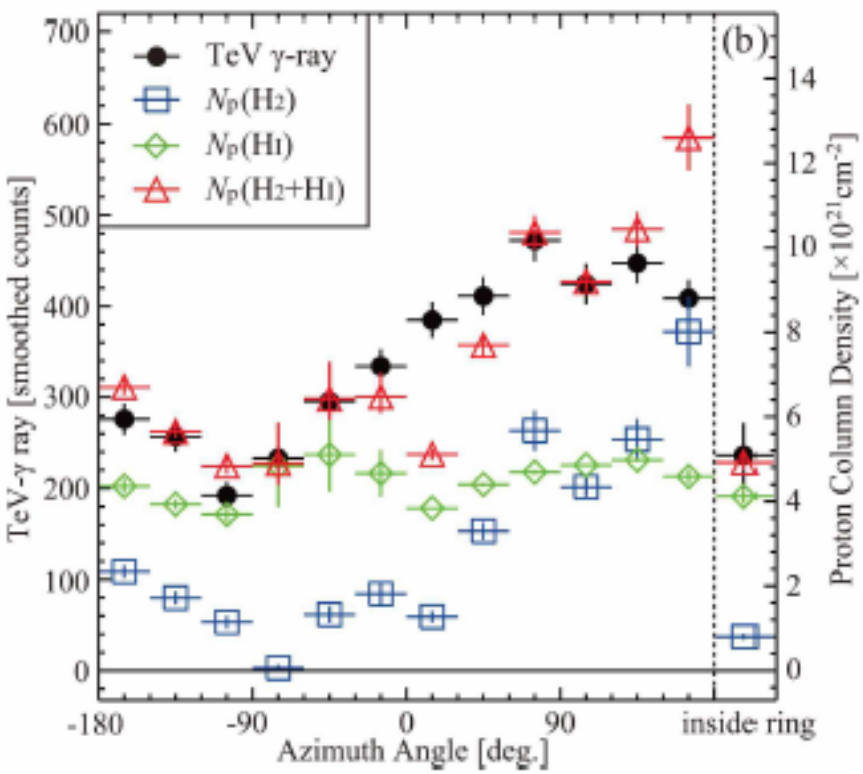
Fukui et al. 2012, ApJ, 746, 82

Dark HI SE Cloud (Self-Absorption)



ISM protons in RX J1713.7-3946
Support hadronic scenario

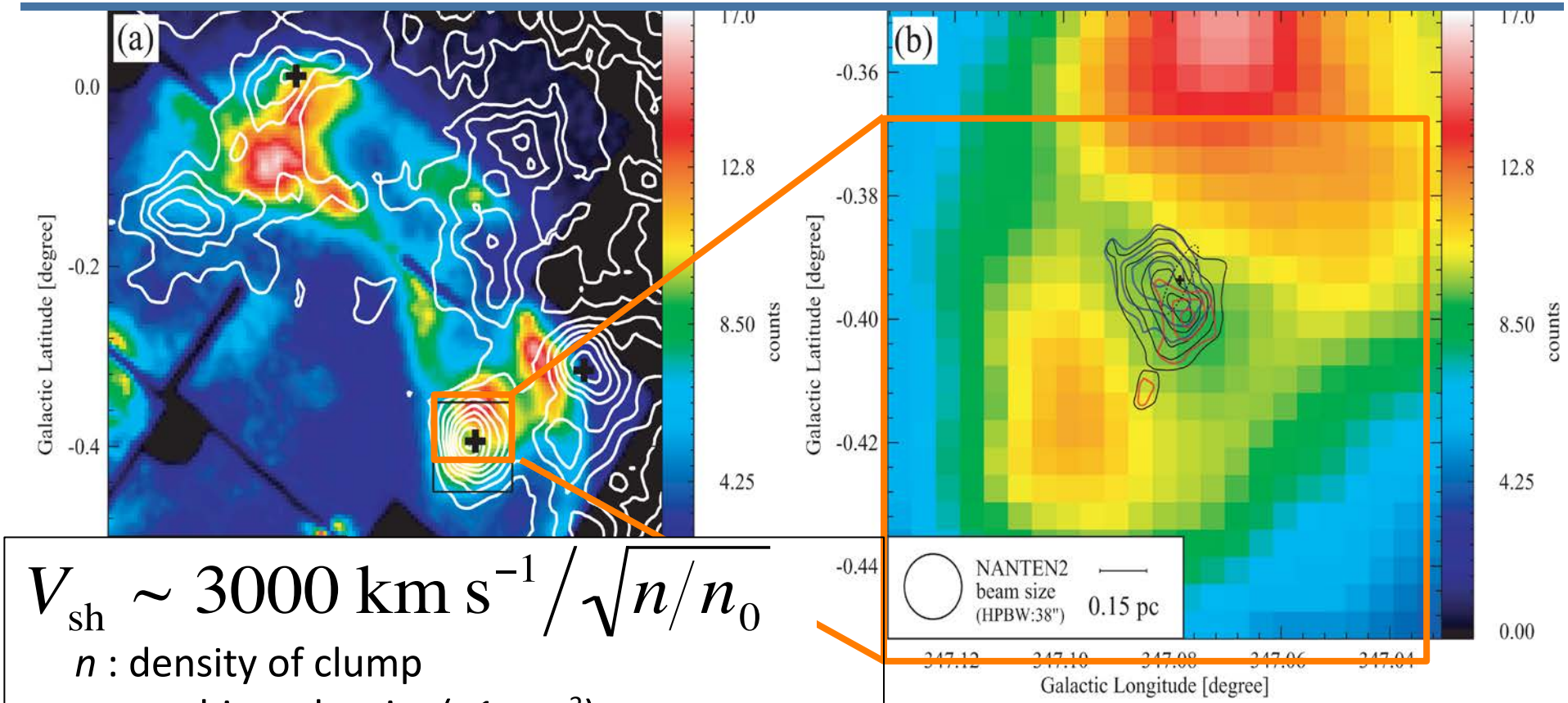




HI + $2H_2$

Fukui et al. 2012

Shock propagation into dense gas



$$V_{\rm sh} \sim 3000\ {\rm km\ s^{-1}} \Big/ \sqrt{n/n_0}$$

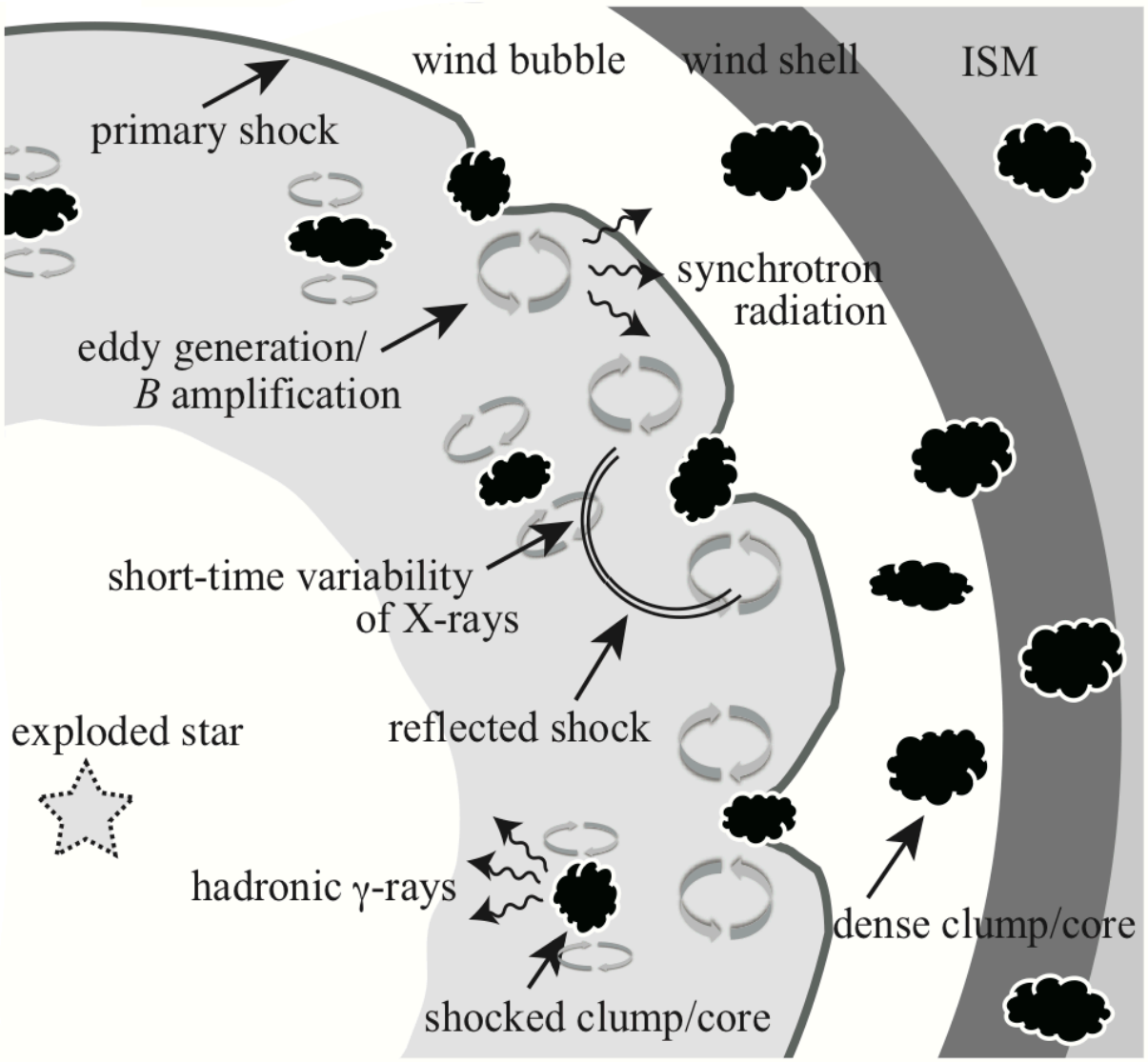
n : density of clump

n_0 : ambient density (=1 cm^{-3})

10^4 cm^{-3}, t~1000yrs

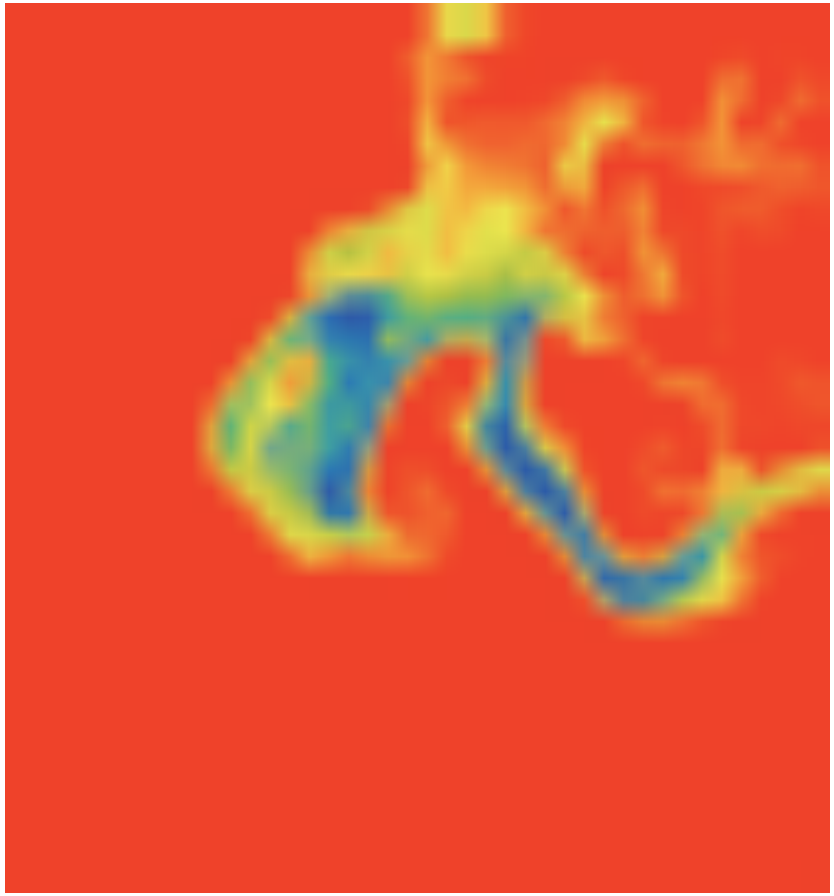
Penetrating Depth = 0.03 pc

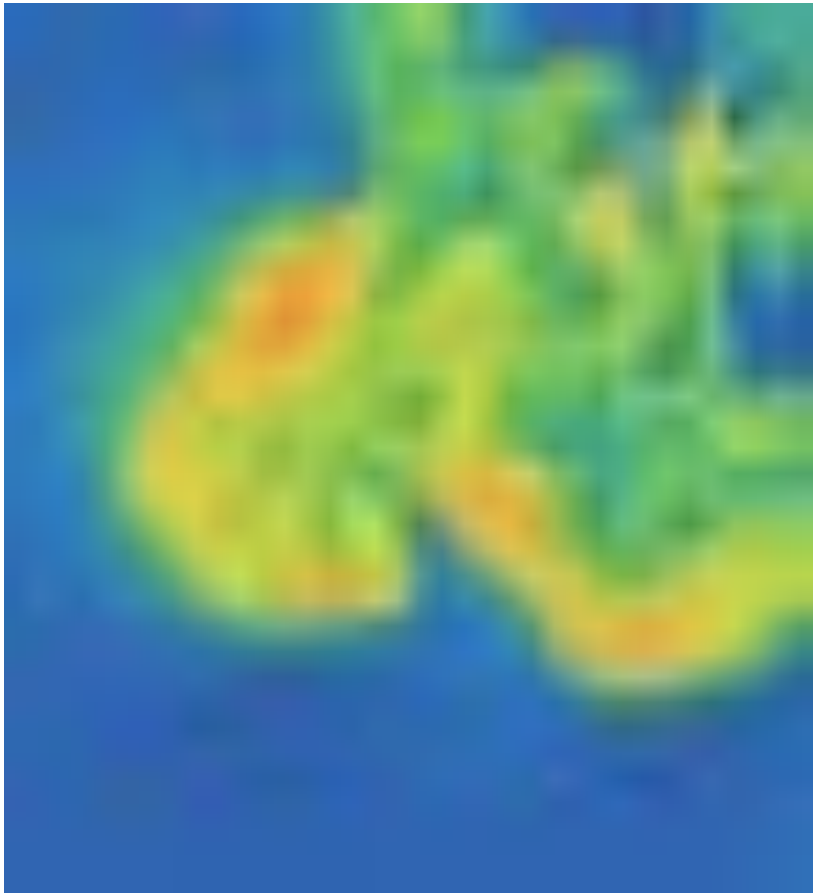
Sano et al. 2010



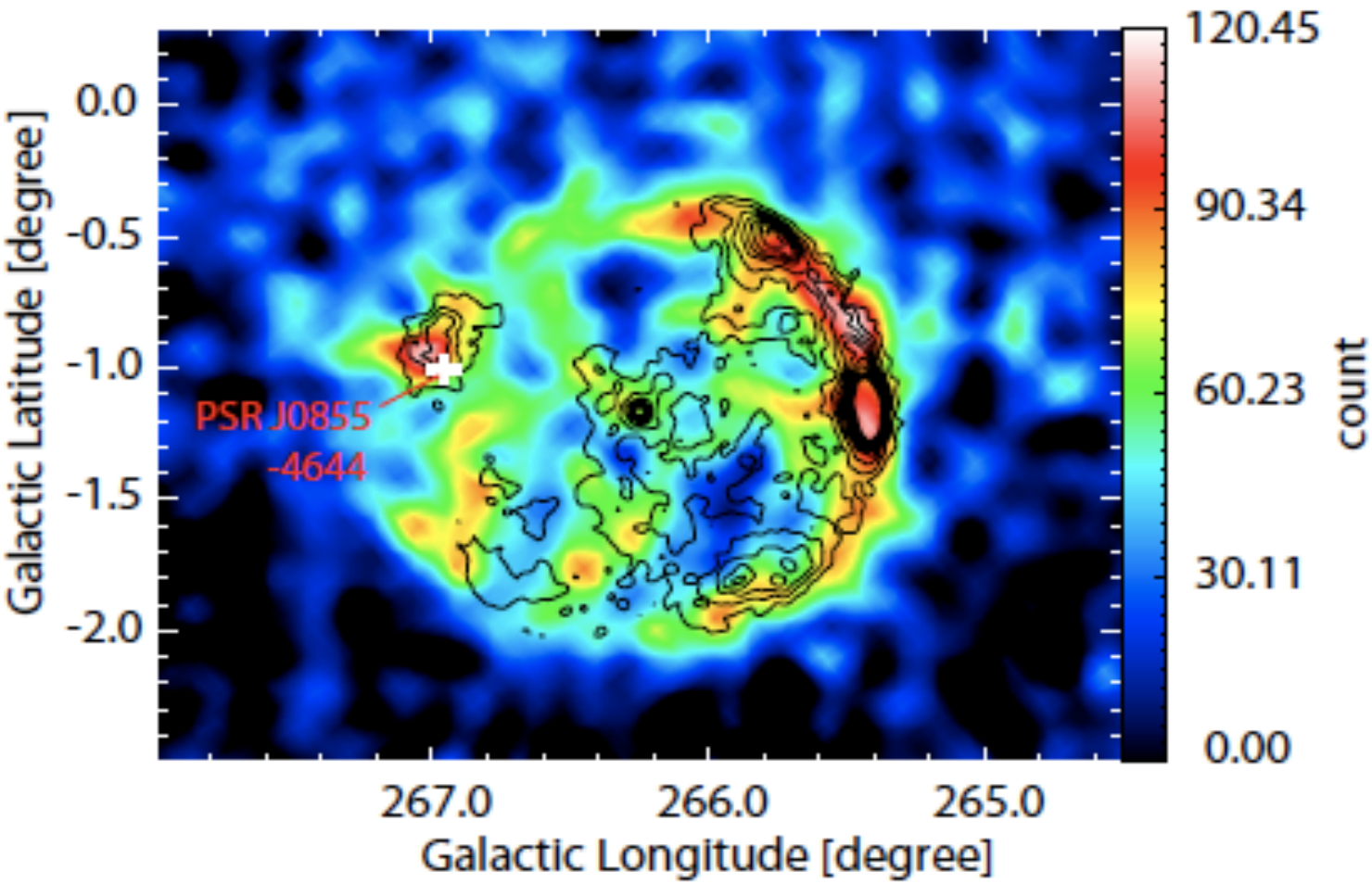
Inoue, Yamazaki, Inutsuka, Fukui 2012, ApJ, 744, 71

density vs. magnetic field
[sub-pc scale]



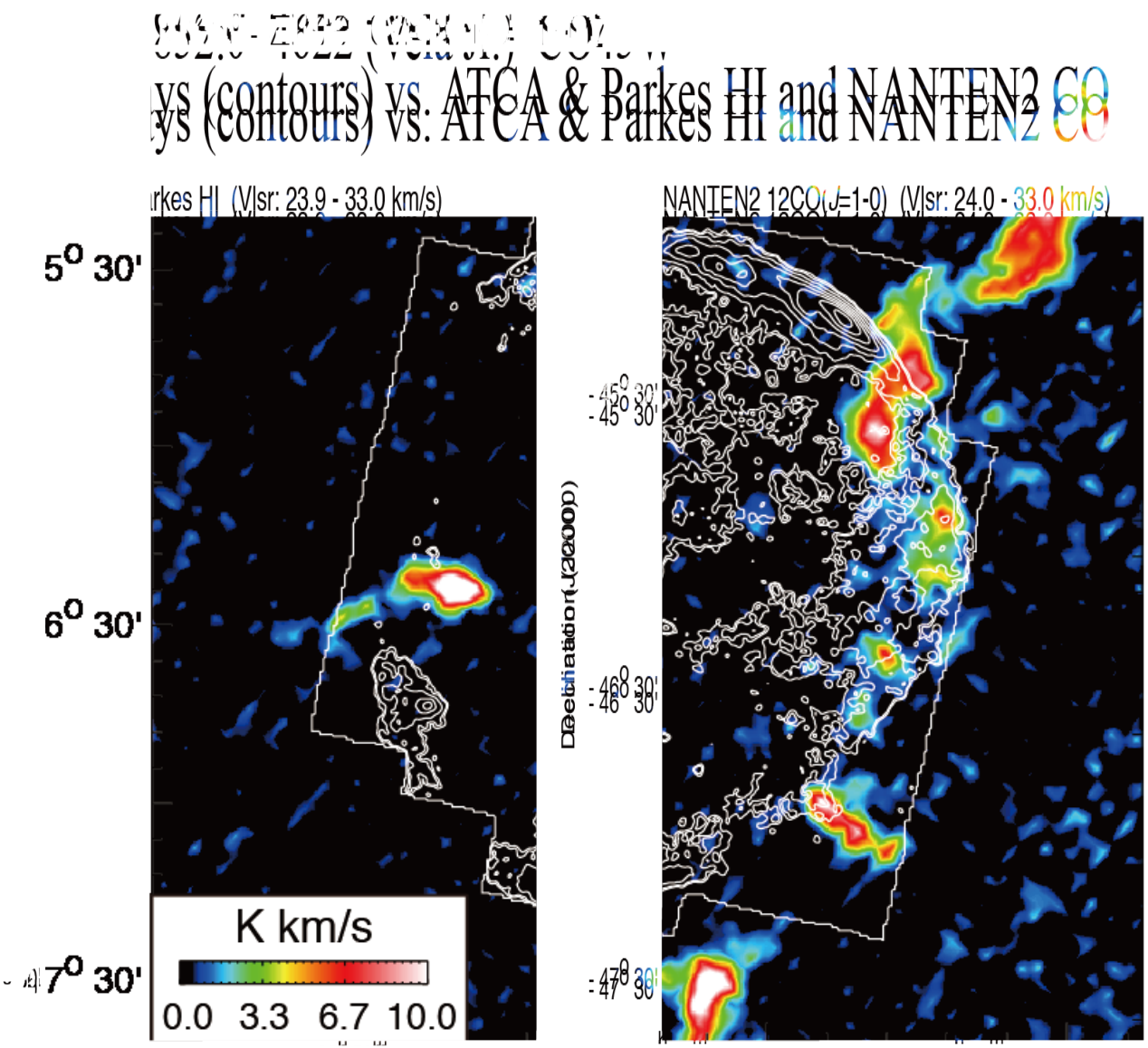


TeV gamma-ray SNR RX J0852.0-4622



Color TeV gamma rays contour X rays

RX J0852: CO distribution (interact with the SNR)



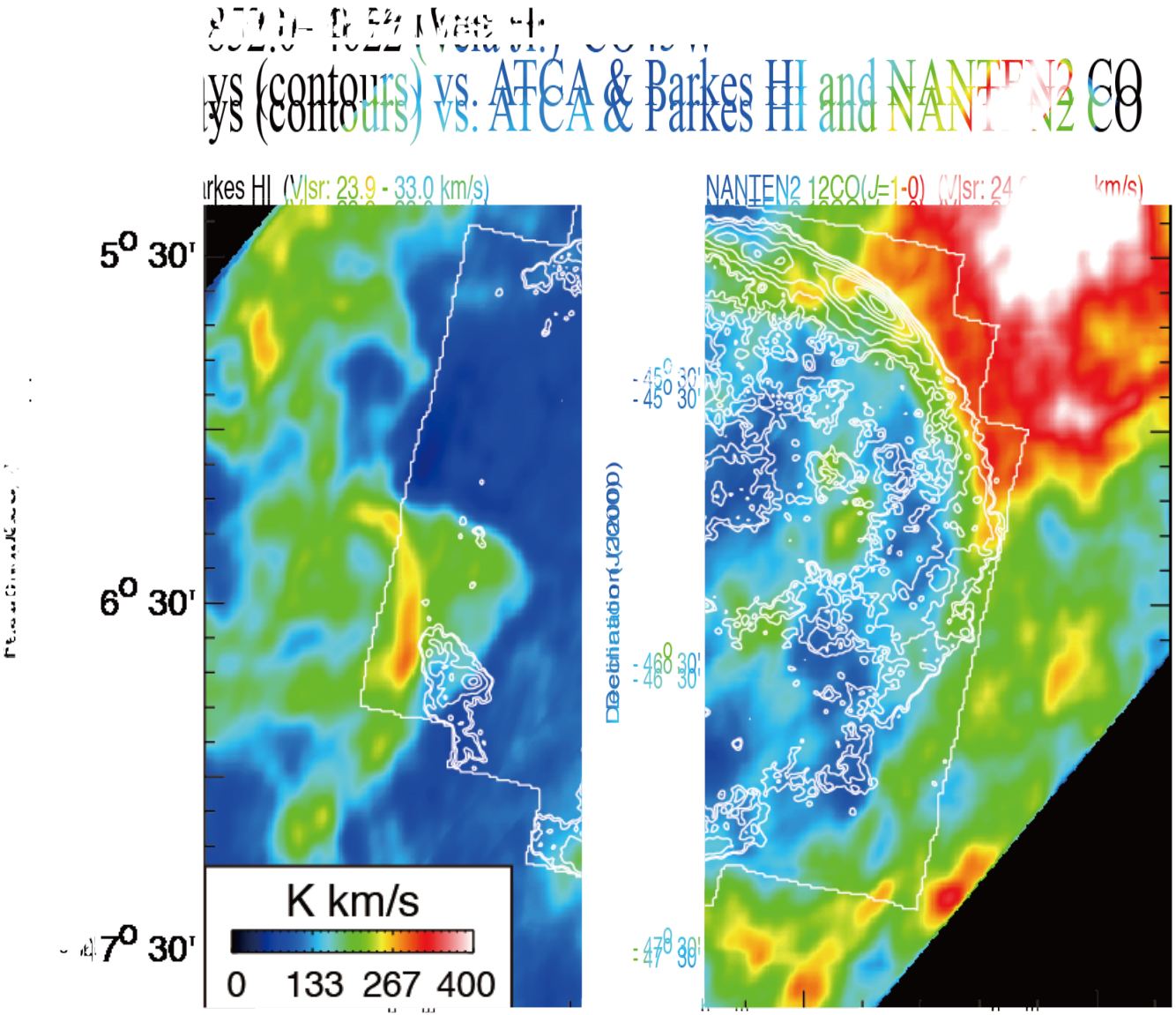
- CO vs. X-rays

good spatial correspondence between the CO and X-rays

Interacting with the SNR

image: CO(1-0) I.I.
(Vlsr: 24-33 km/s)
contours: X-ray (1-5 keV)

RX J0852: HI distribution (interact with the SNR)



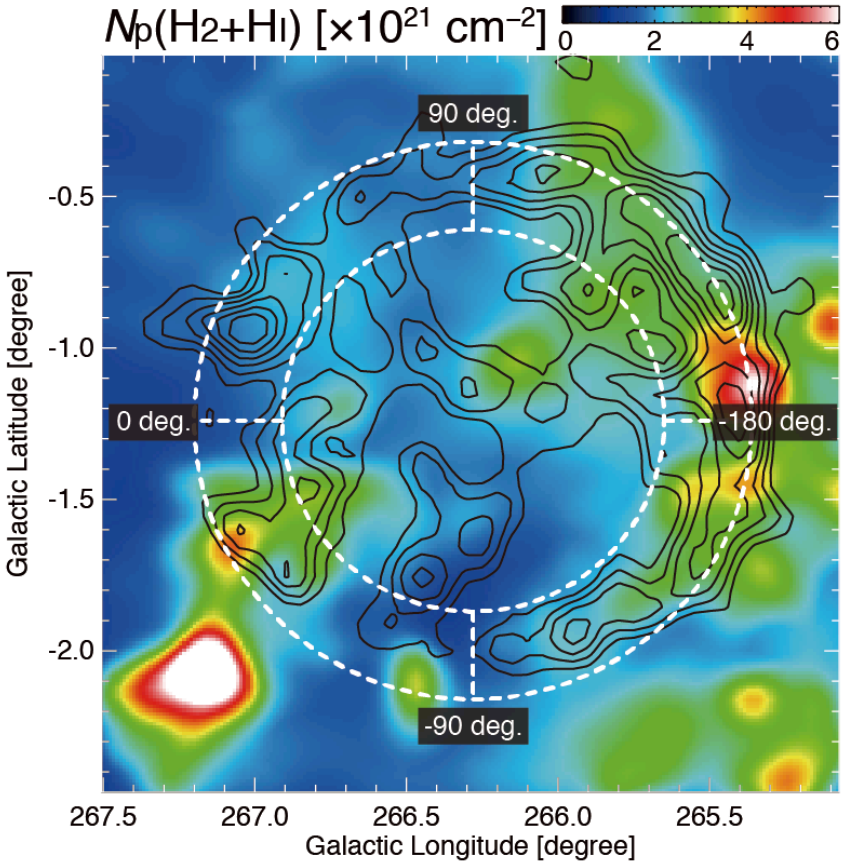
- HI vs. X-rays

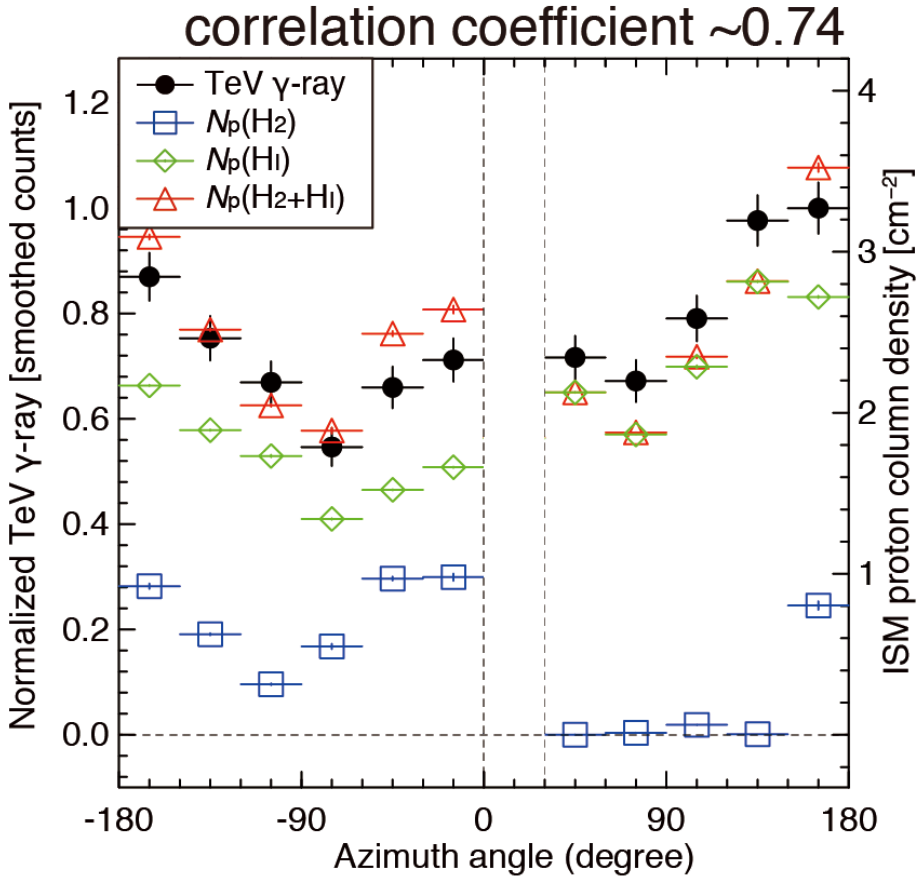
HI wind bubble at same velocity in CO

ISM cavity created by the progenitor

Image: HI I. I.
(Vlsr: 28-34 km/s)
contours: X-ray (1-5 keV)

Vela Jr. total ISM protons & TeV γ-rays

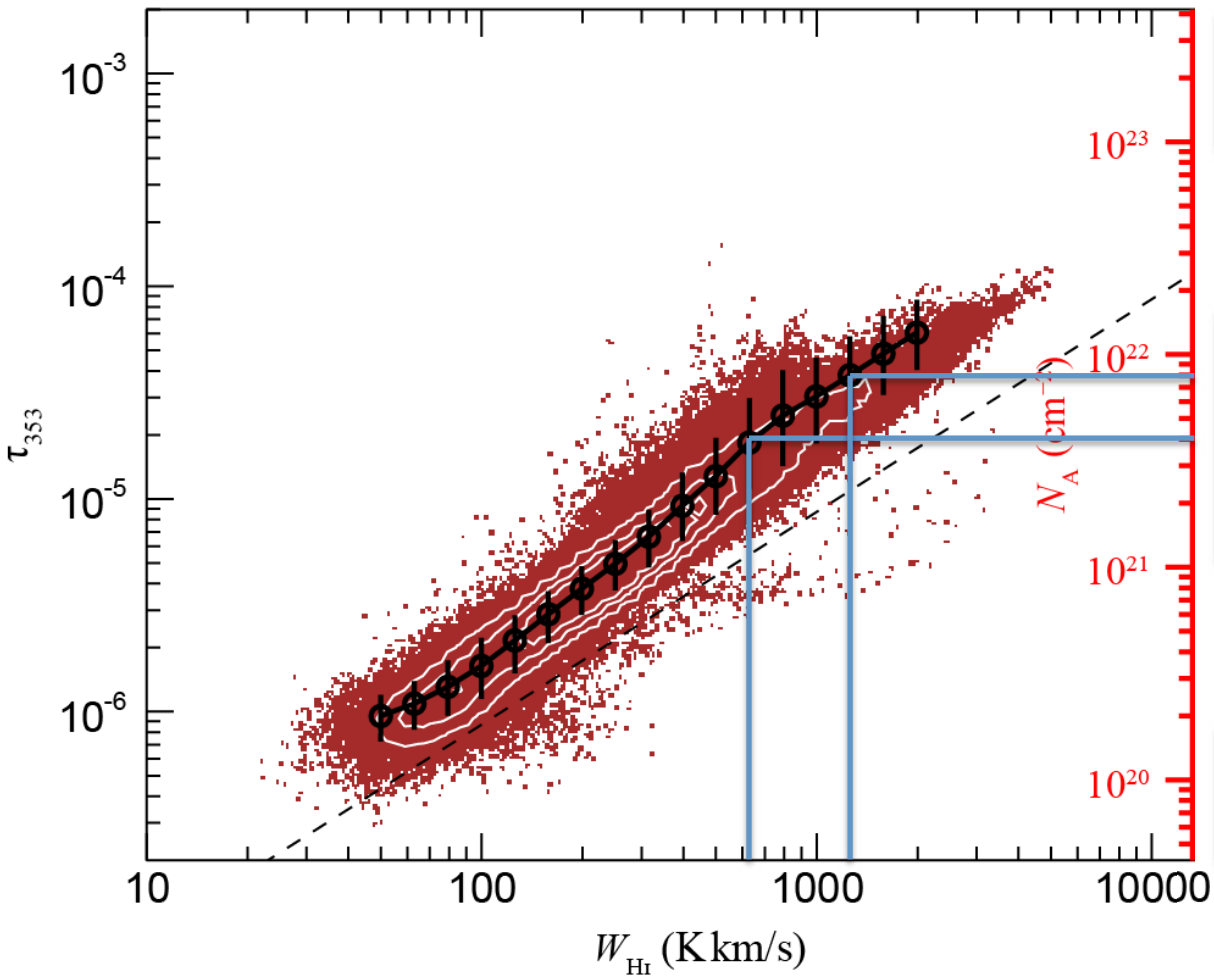




(left) Image: Total interstellar proton column density, contours: TeV γ-rays (Aharonian+07)
(Right) Azimuthal plots

Fukui, Sano+15 in prep.

Tau 353 vs. W(HI) optically thick HI

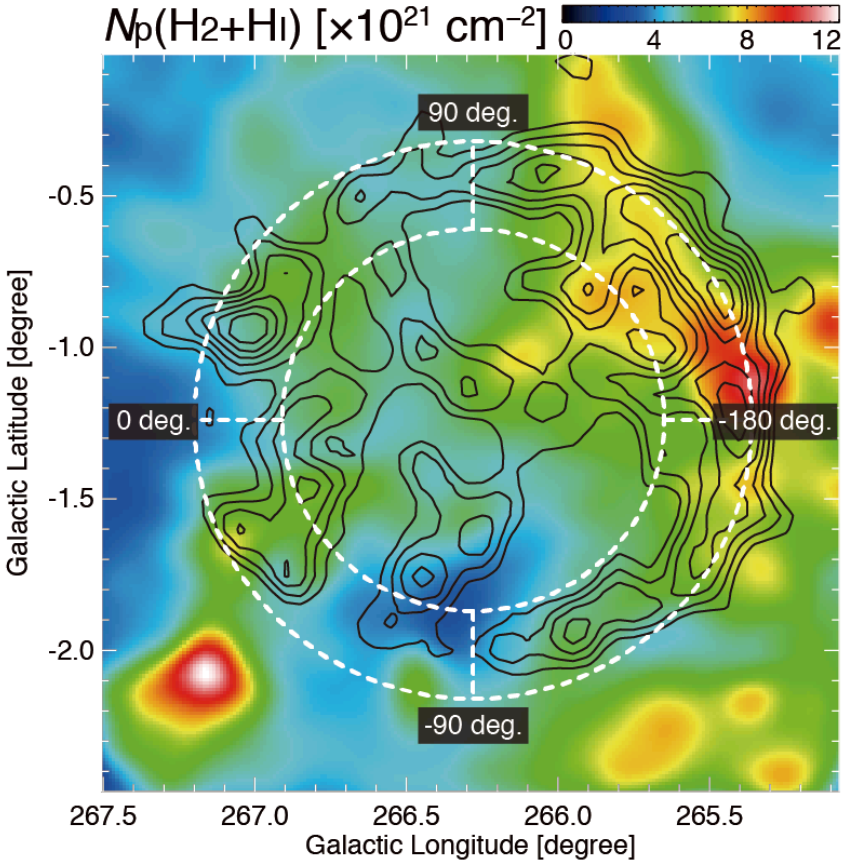


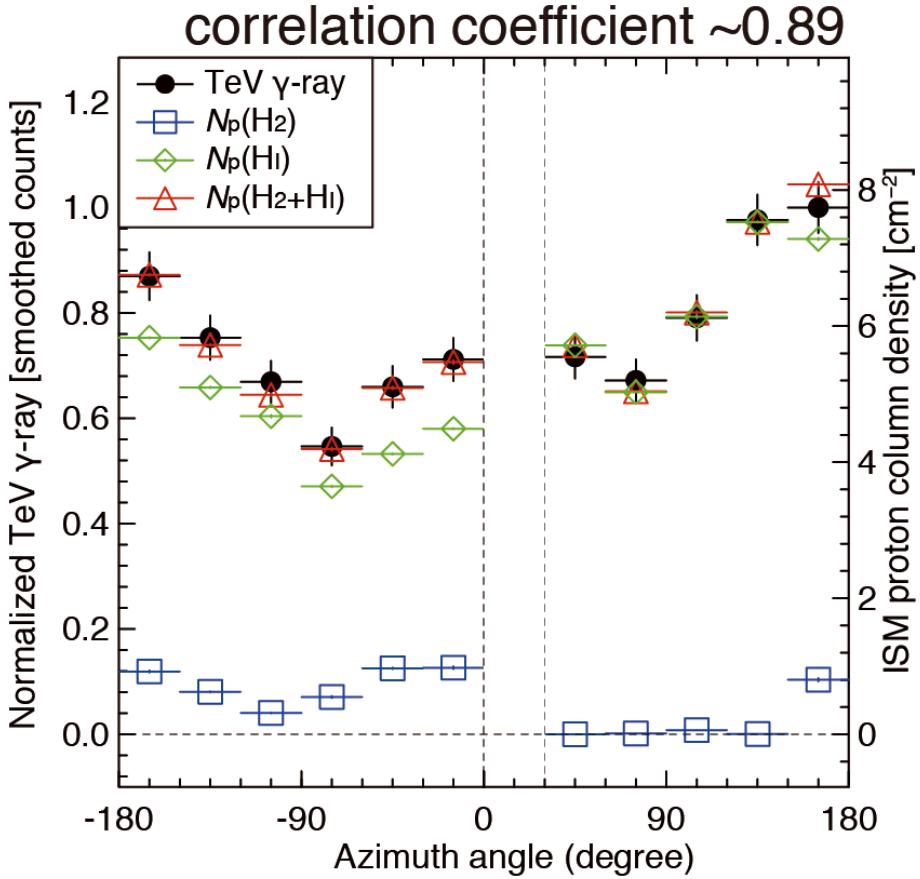
Step 1
We estimate the W(HI) range

Step 2
Estimating a conversion factor form W(HI) to *N*H using linier fitting

Step 3
We apply the correction

Vela Jr. total ISM protons & TeV γ-rays (optically thick HI)





(left) Image: Total interstellar proton column density, contours: TeV γ-rays (Aharonian+07)
(Right) Azimuthal plots

Fukui, Sano+15 in prep.

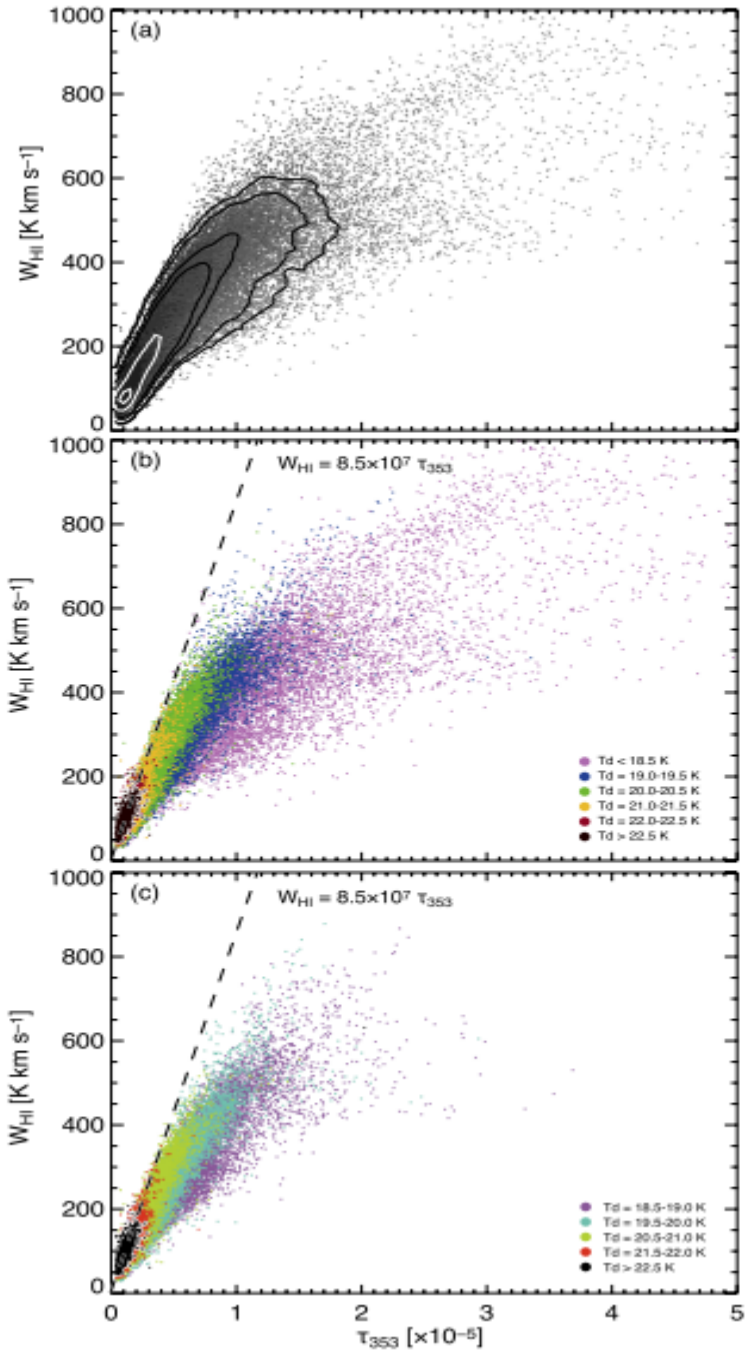
Comparison of young SNRs

Table 1
A Comparison of RX J0852.0-4622, RX J1713.7-3946, and HESS J1731-347

	RXJ0852.0 – 4622[a]	RXJ1713.7 – 3946[b]	HESSJ1731 – 347[c]
Distance (kpc)	0.7	1	5.2[d]
Radius (pc)	13	9	22
Age (years)	1700	1600	4000
Atomic proton mass (10^4 $M_\odot$)	1	1	1.3
Molecular proton mass (10^4 $M_\odot$)	0.1	1	5.1
Total proton mass (10^4 $M_\odot$)	1.1	2	6.4
Average density (cm^{-3})	40	100	60
L_γ (1–10 TeV) (10^{34} erg s^{-1})	0.63	0.81	2.8
Total CR proton energy	$\sim 10^{48}$	$\sim 10^{48}$	$\sim 10^{49}$

If the γ -rays are produced predominantly by the hadronic process,

- Total CR protons energy $10\uparrow 48 - 10\uparrow 49$ erg
- CR acceleration efficiency 0.1% - 1%

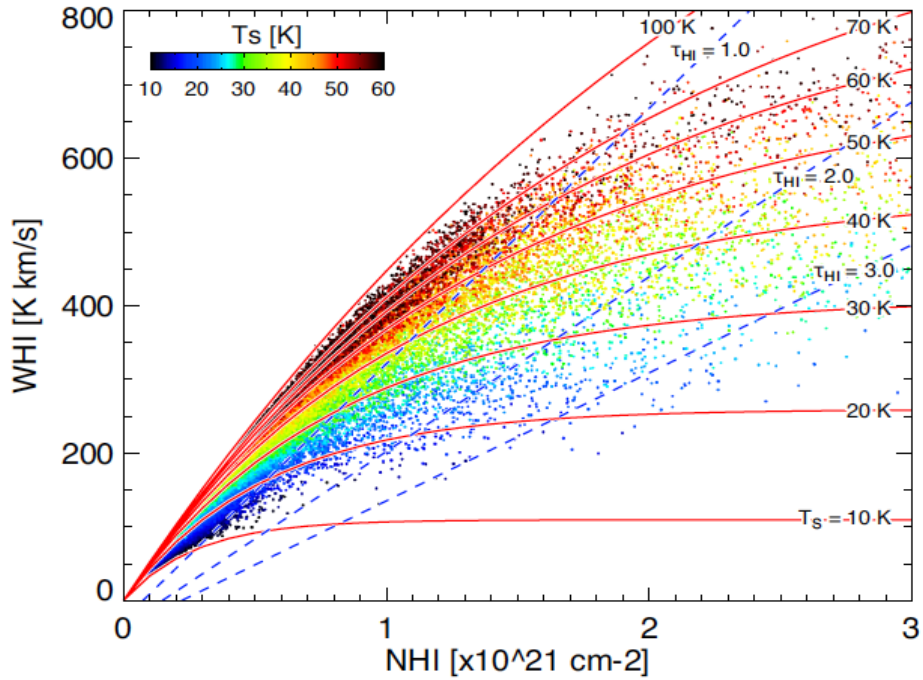


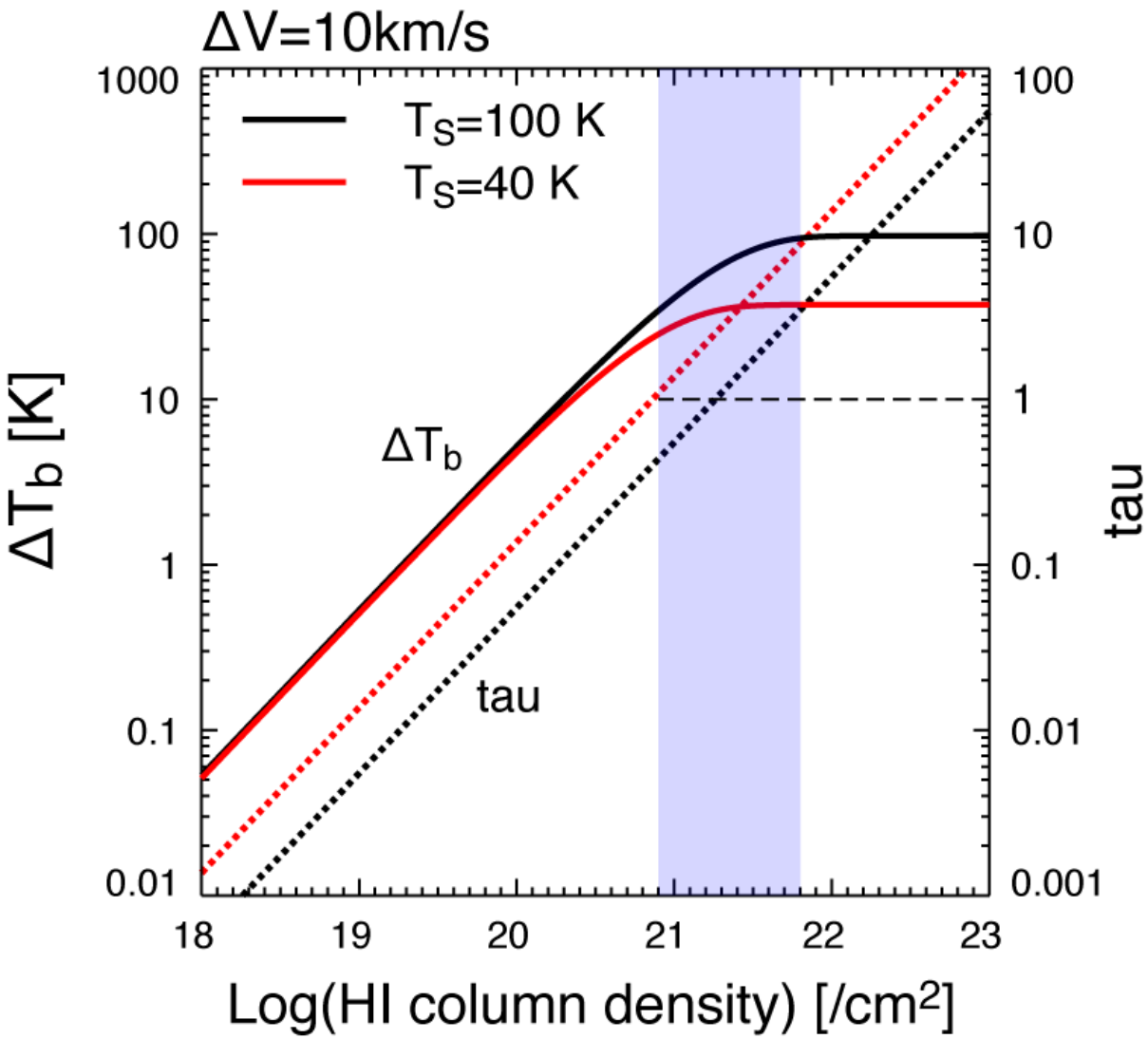
HI observations

Fukui et al. 2015

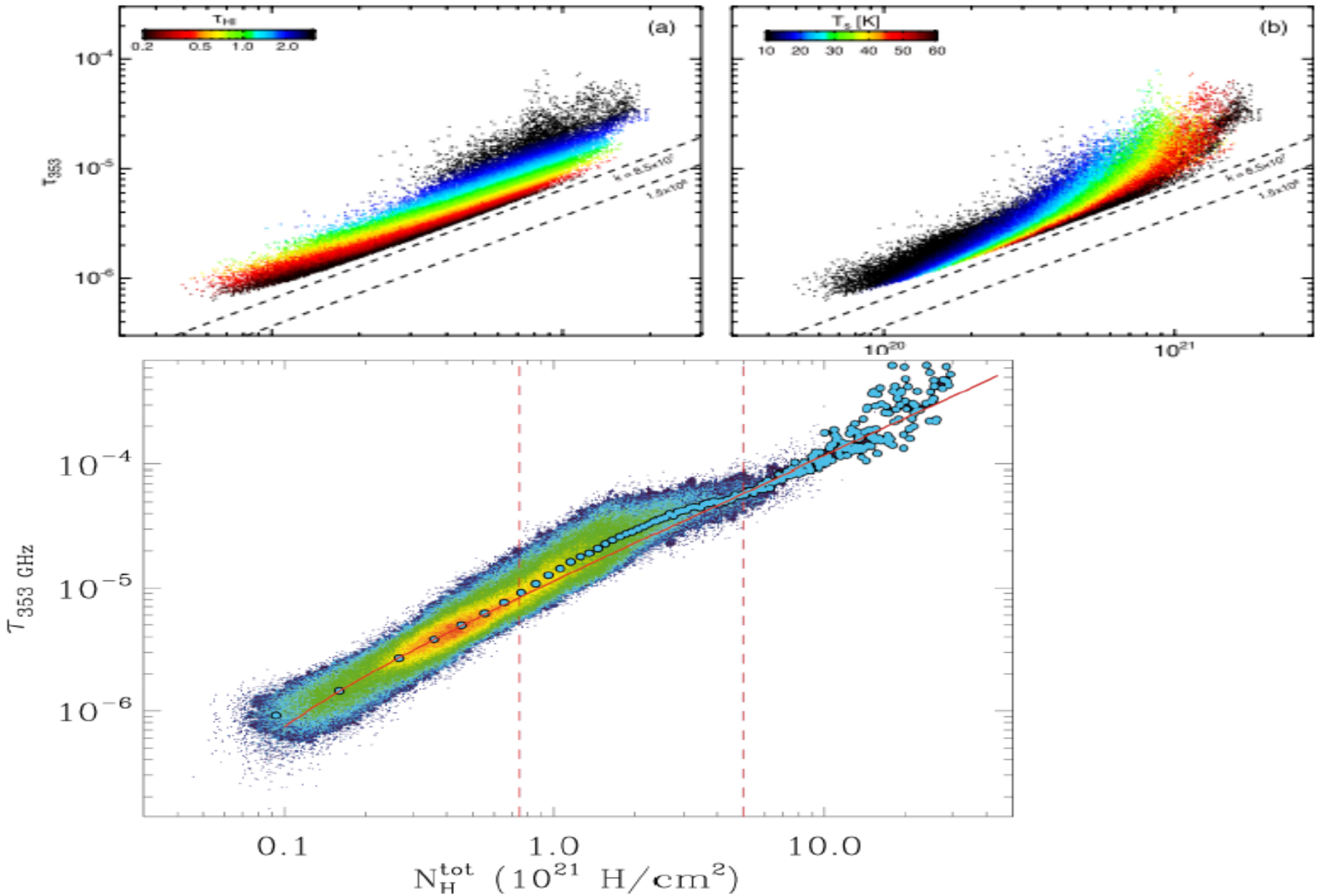
If optically thin, very precise NH

generally HI is thick and need correction for tauHI

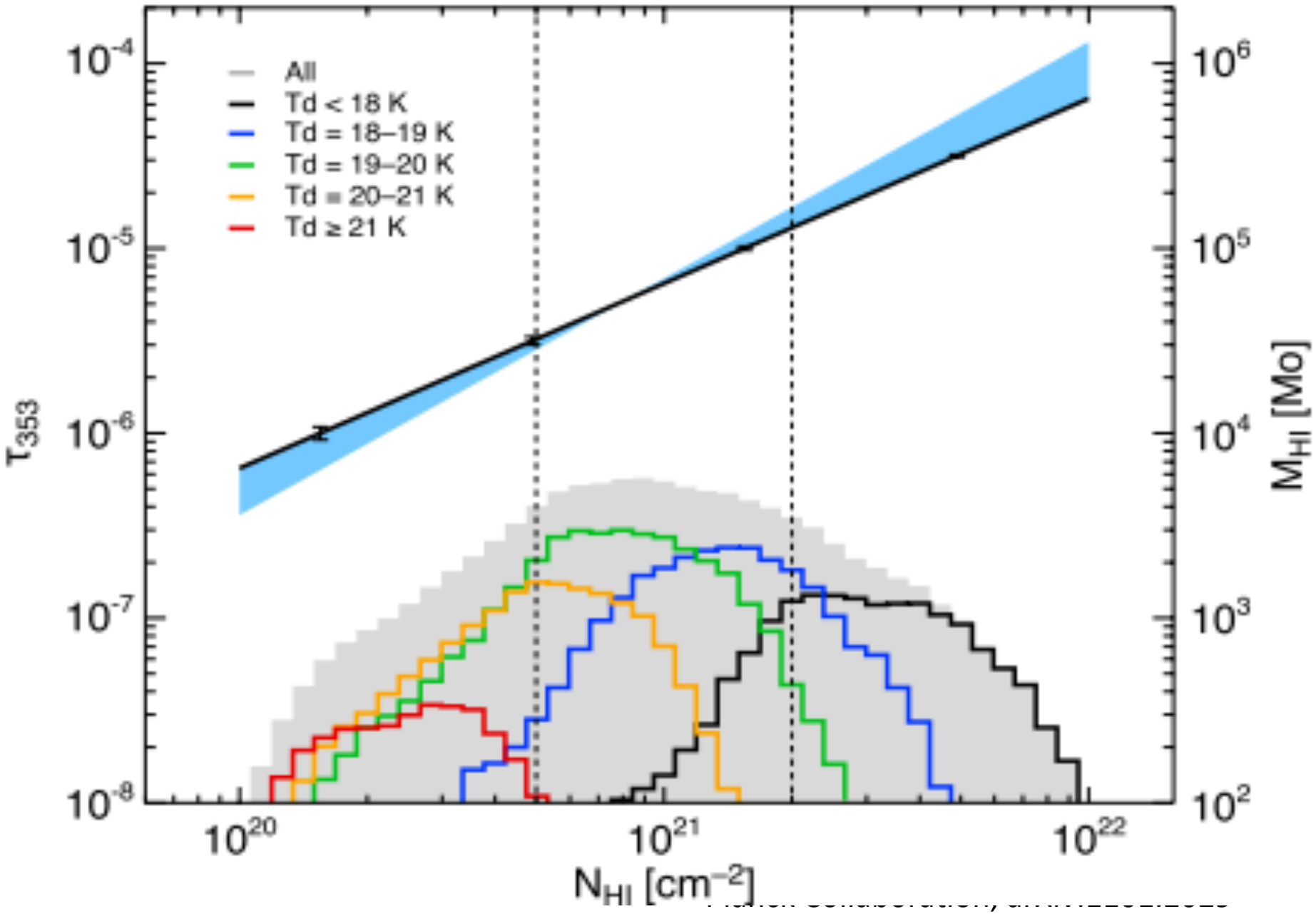


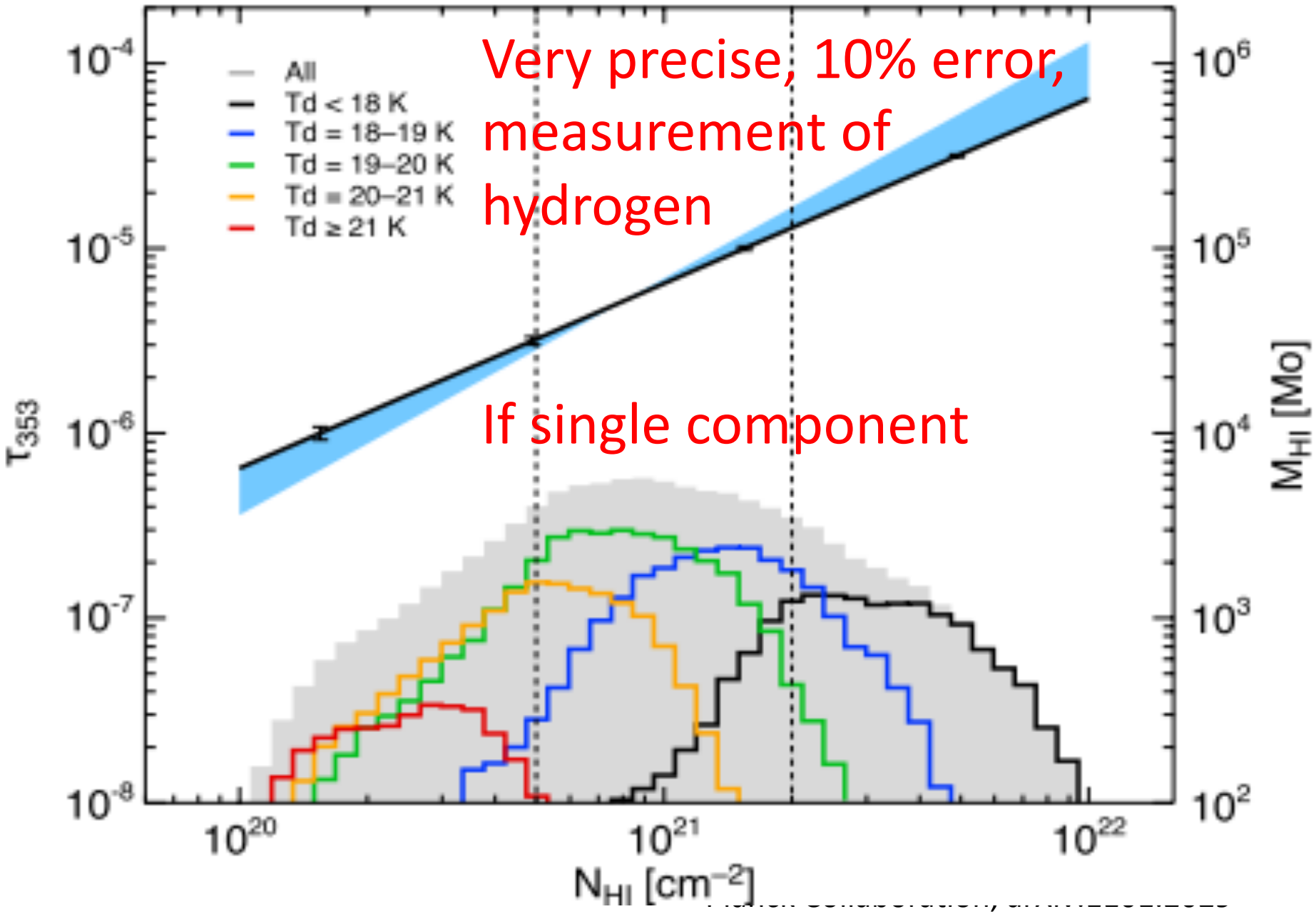


$$\Delta T_{\rm b} = (T_{\rm s} - T_{\rm bg})(1 - \exp(-\tau))$$



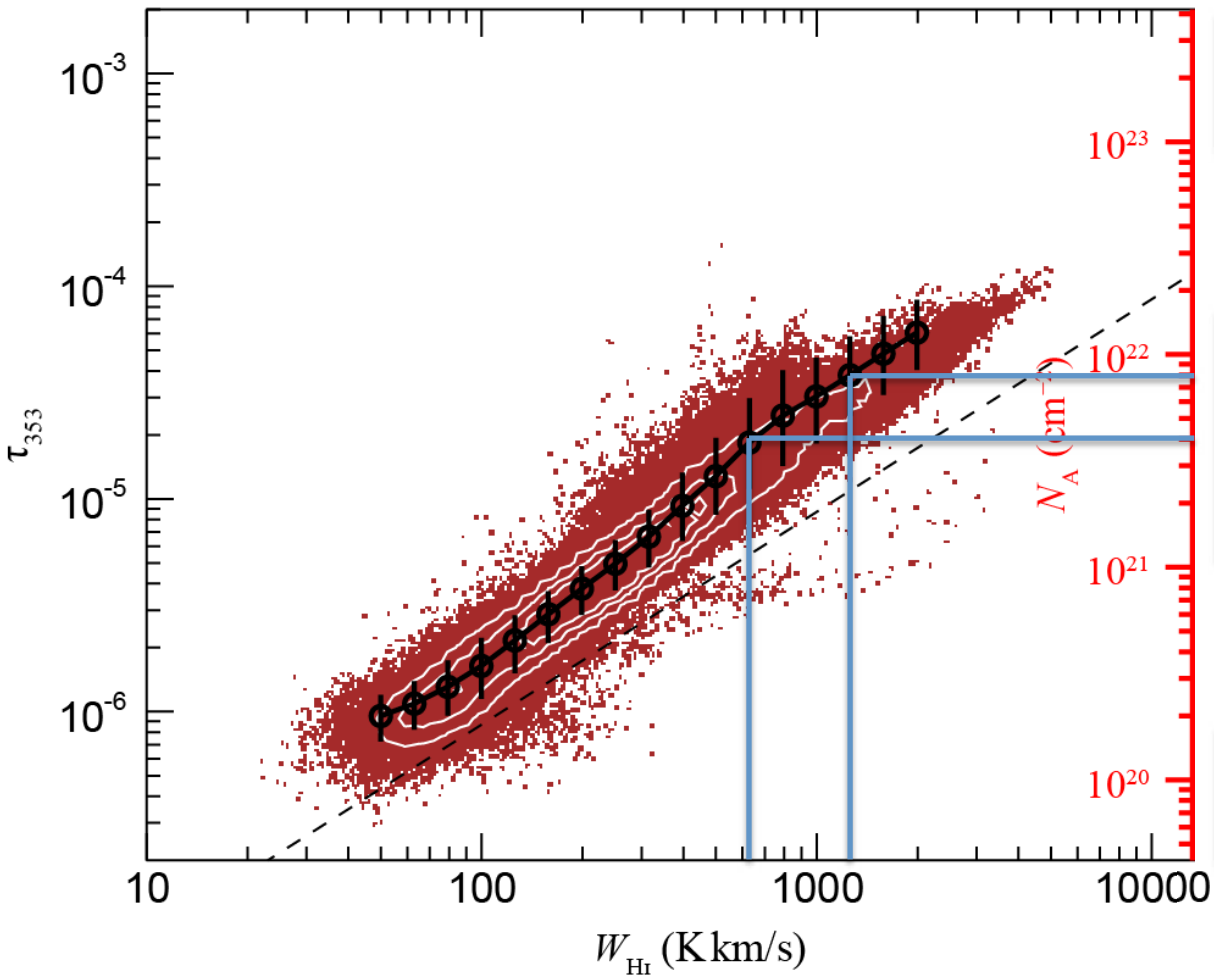
Planck Collaboration, arXiv:1101.2029


All
Td < 18 K
Td = 18–19 K
Td = 19–20 K
Td = 20–21 K
Td ≥ 21 K
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
τ_{353}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
M_{HI} [Mo]
10^{20}
10^{21}
10^{22}
N_{HI} [cm^{-2}]


Very precise, 10% error, measurement of hydrogen
If single component
All
Td < 18 K
Td = 18–19 K
Td = 19–20 K
Td = 20–21 K
Td ≥ 21 K
τ_{353}
M_{HI} [Mo]
N_{HI} [cm^{-2}]
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{20}
10^{21}
10^{22}

W(HI) can be converted into N_H even for multi components

as accurate as 30-50%



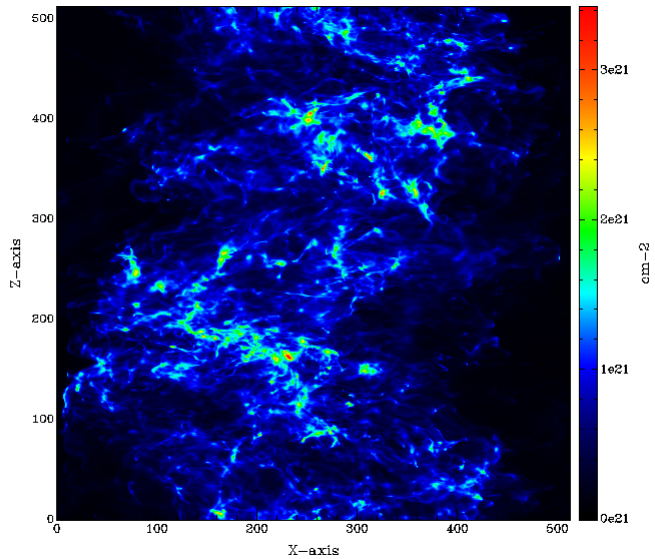
Step 1
We estimate the W(HI) range

Step 2
Estimating a conversion factor form W(HI) to *N*H using linier fitting

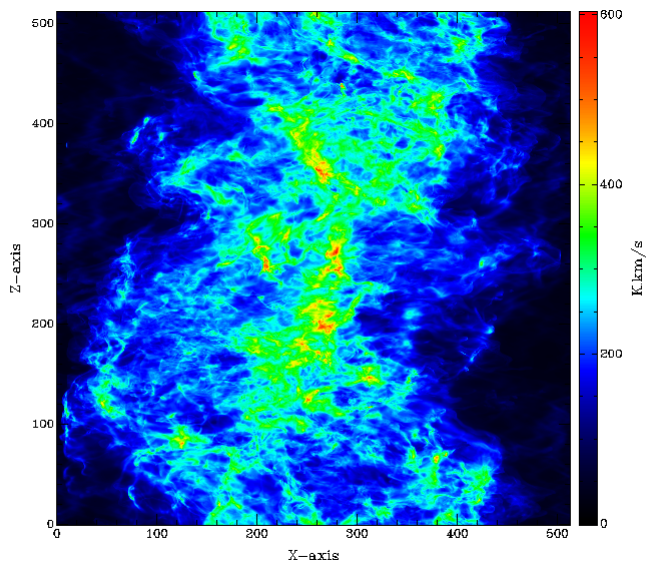
Step 3
We apply the correction

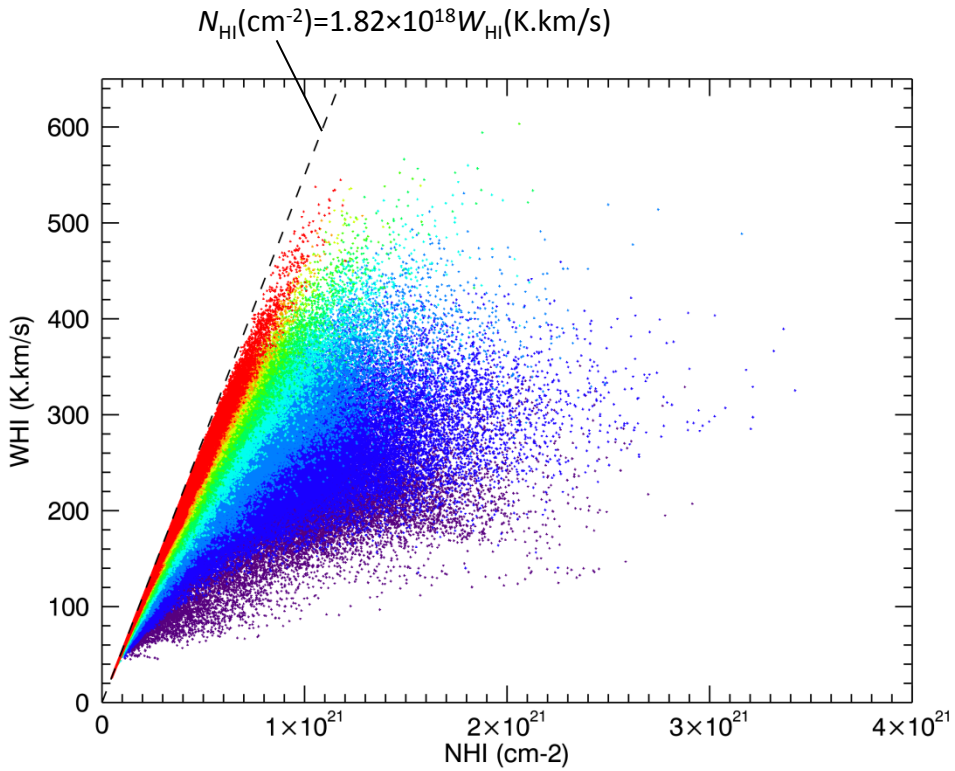
Column density vs. integrated intensity synthetic observations (Inoue and Inutsuka 2012)

N_{HI}

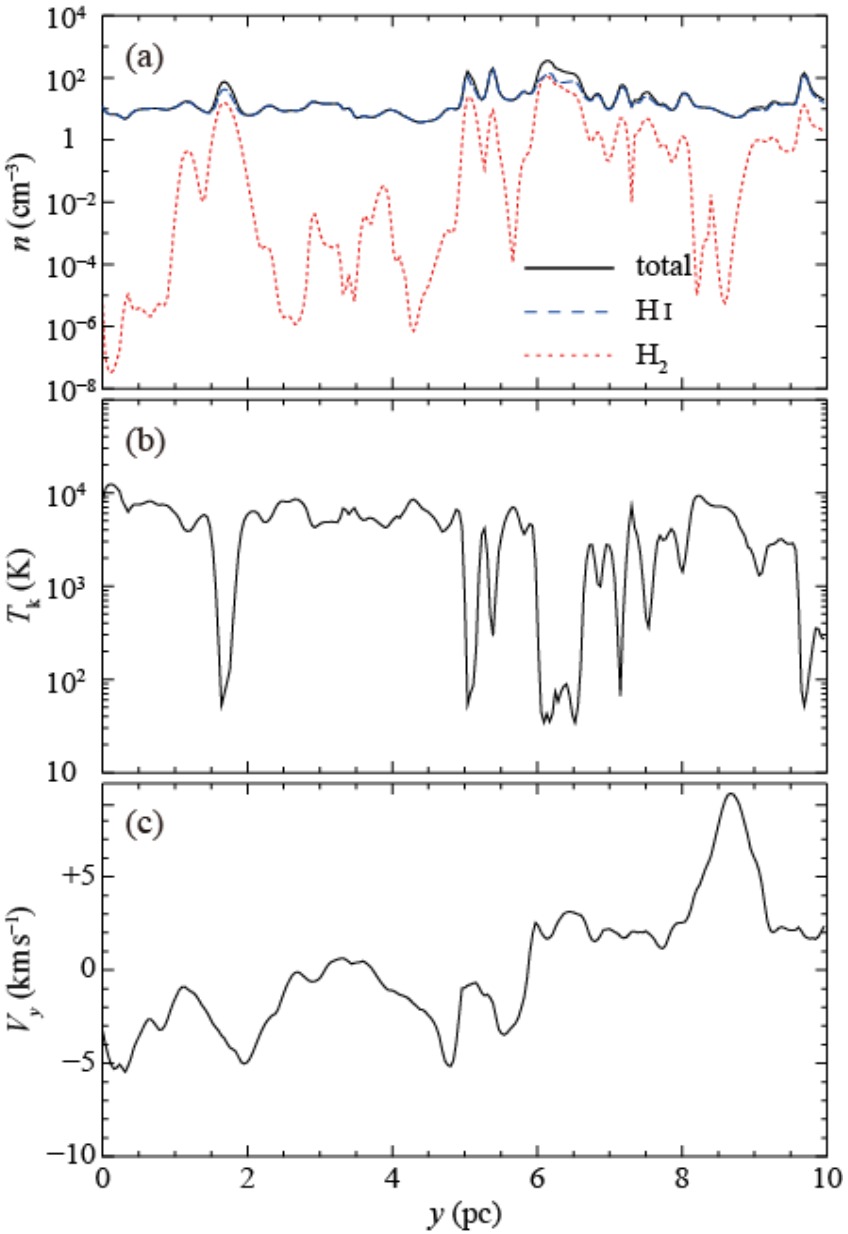


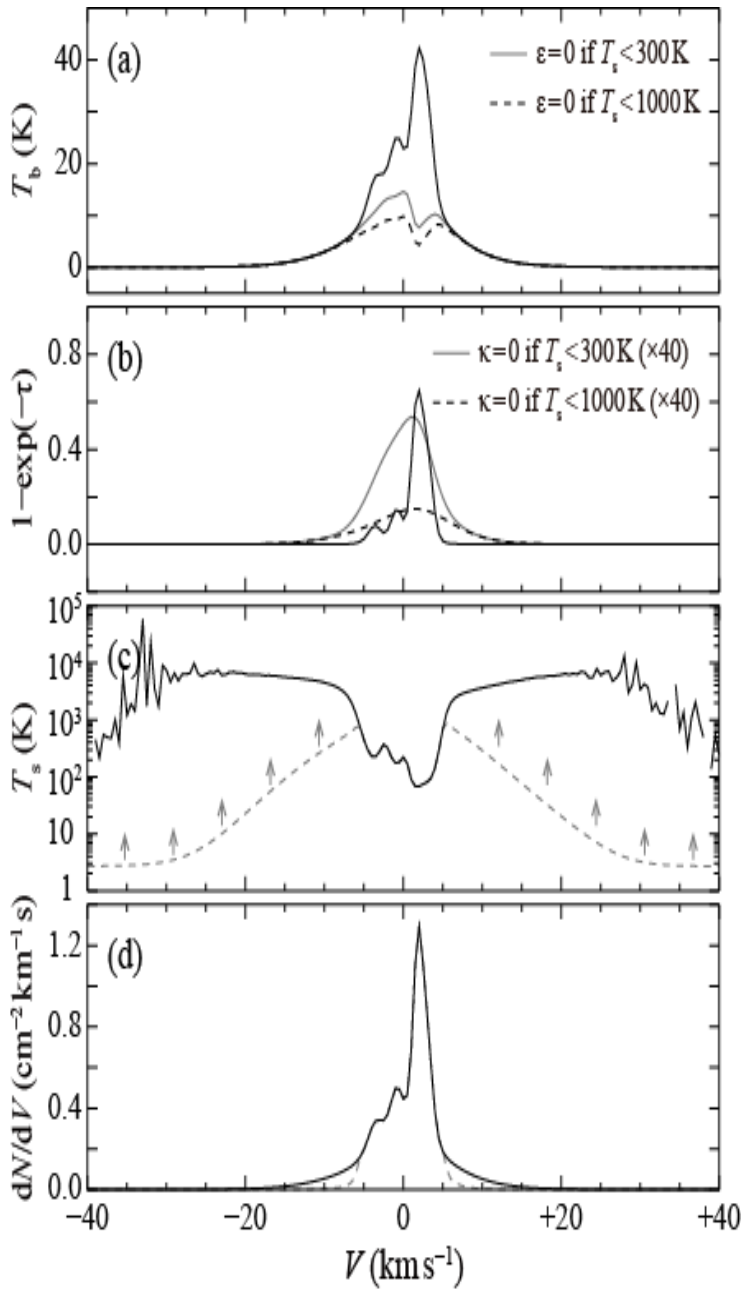
W_{HI}

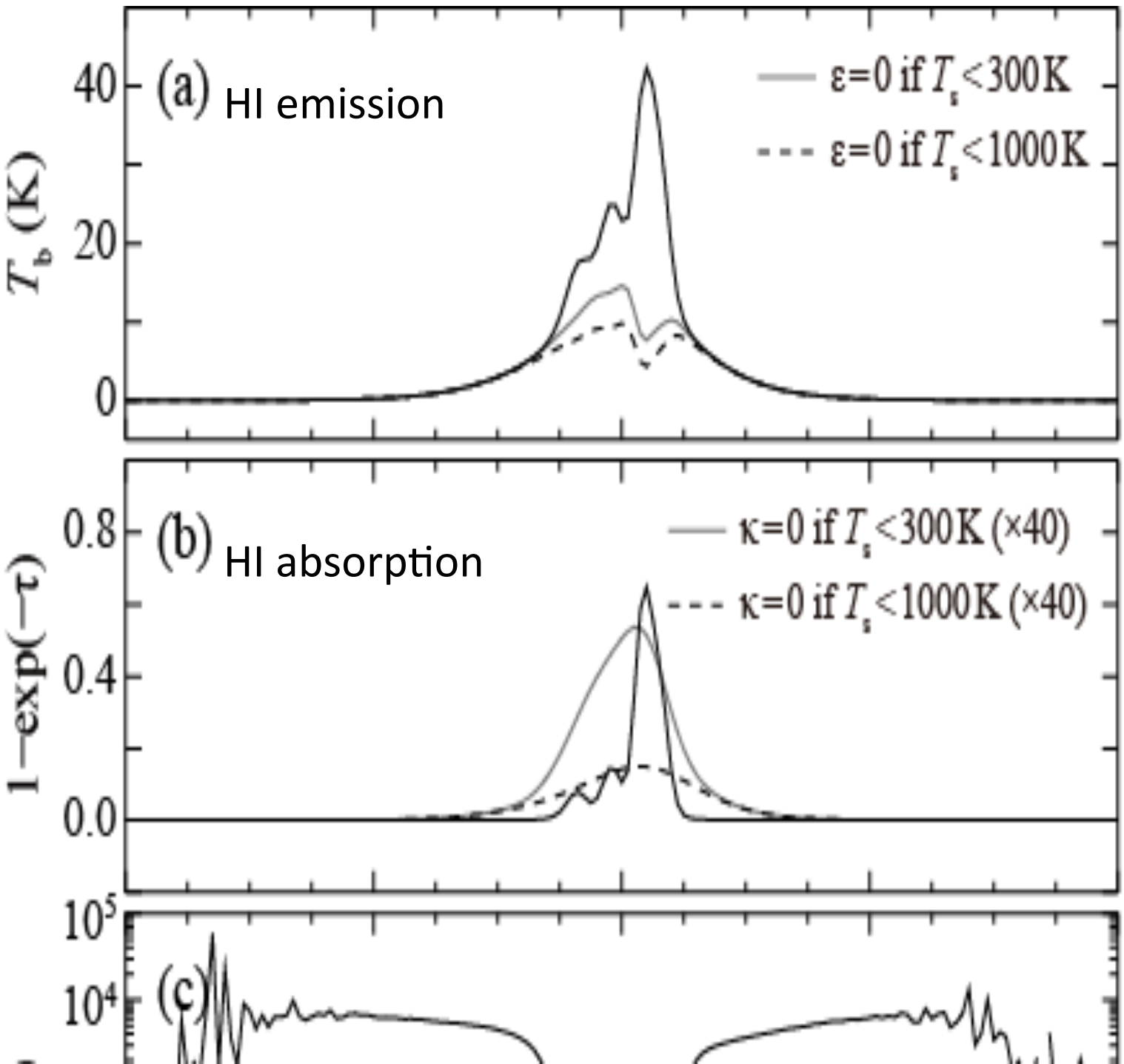


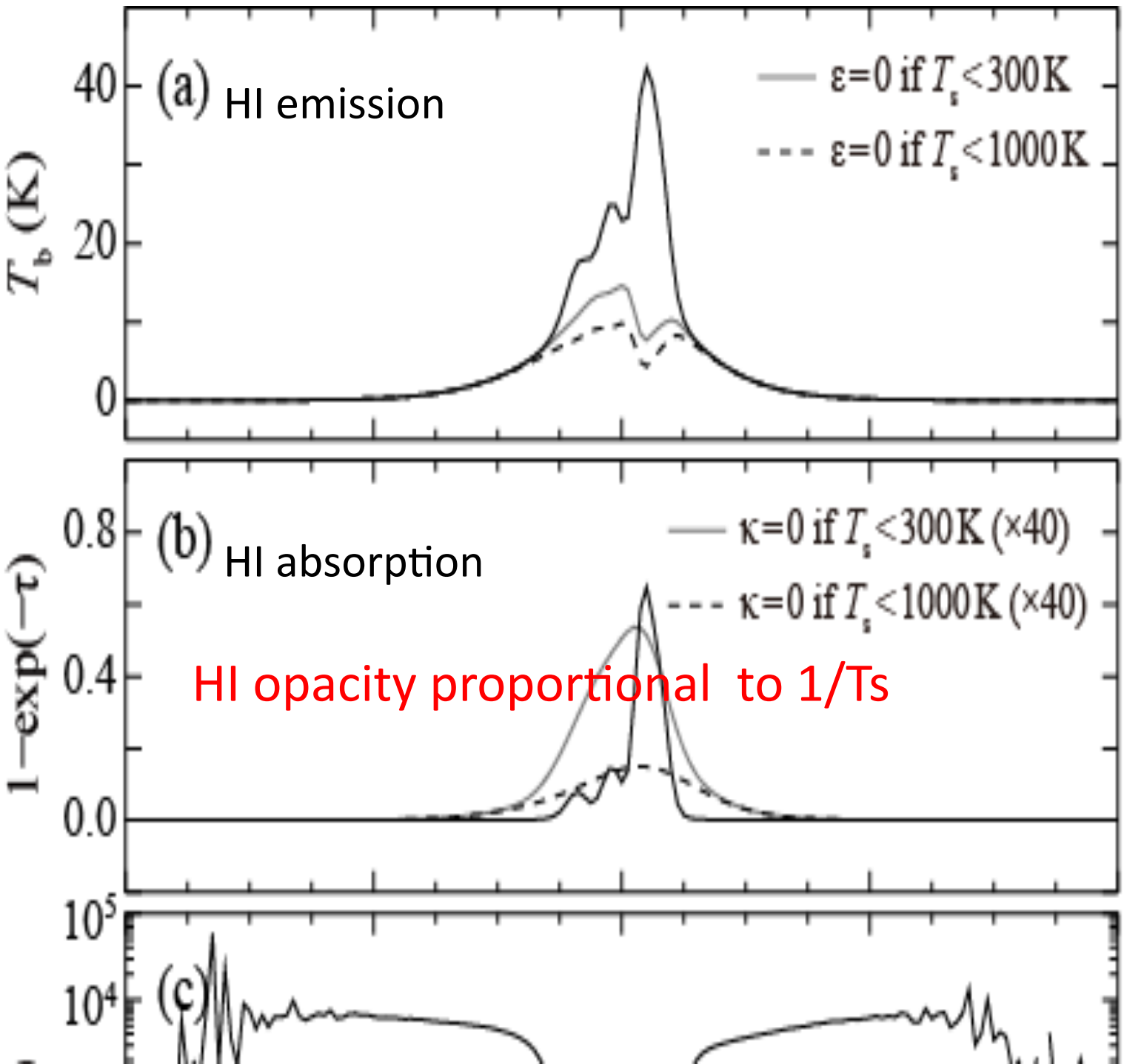


(The color of each point represents T_s.)

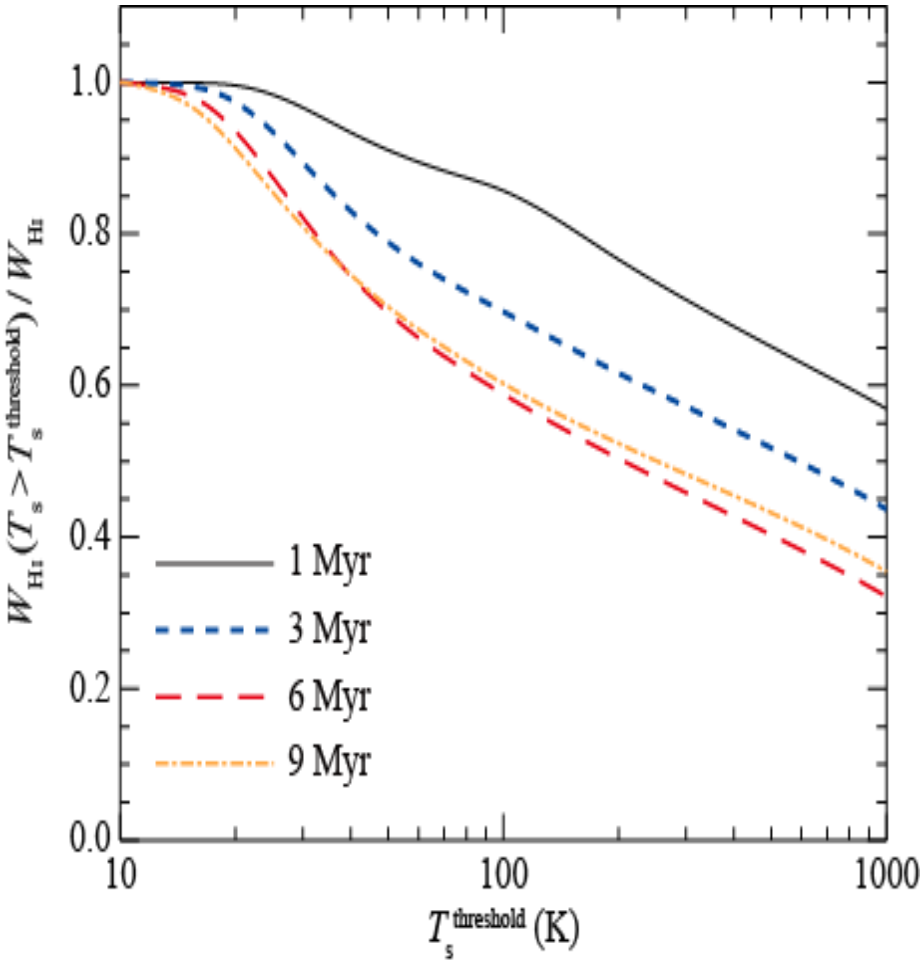

(a)
(b)
(c)
total
H I
H_2
n (cm^{-3})
T_k (K)
V_y (km s^{-1})
y (pc)

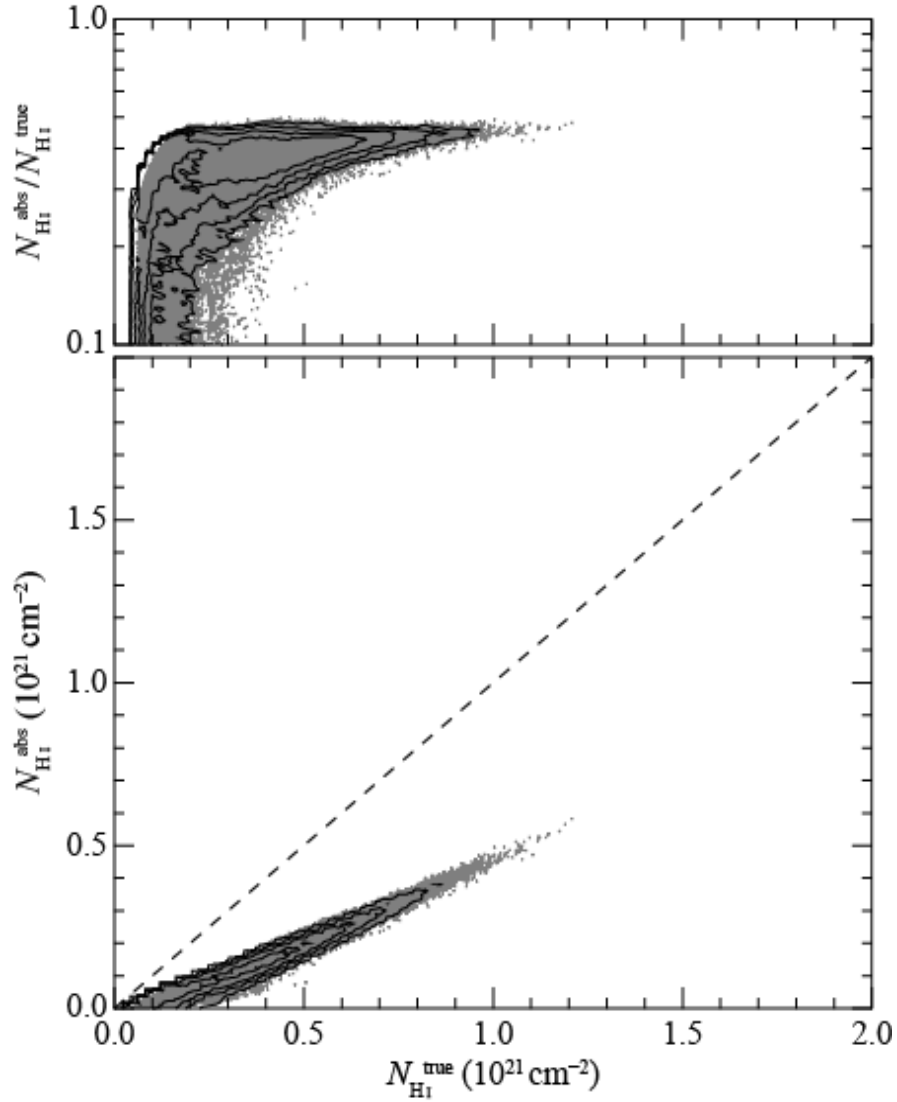

(a)
(b)
(c)
(d)
ε=0 if T_s<300K
ε=0 if T_s<1000K
κ=0 if T_s<300K (×40)
κ=0 if T_s<1000K (×40)
T_b (K)
1−exp(−τ)
T_s (K)
dN/dV (cm^{-2} km^{-1} s)
V (km s^{-1})


(a) HI emission
ε=0 if T_s<300K
ε=0 if T_s<1000K
T_b (K)
40
20
0
(b) HI absorption
κ=0 if T_s<300K (×40)
κ=0 if T_s<1000K (×40)
1−exp(−τ)
0.8
0.4
0.0
(c)
10^5
10^4

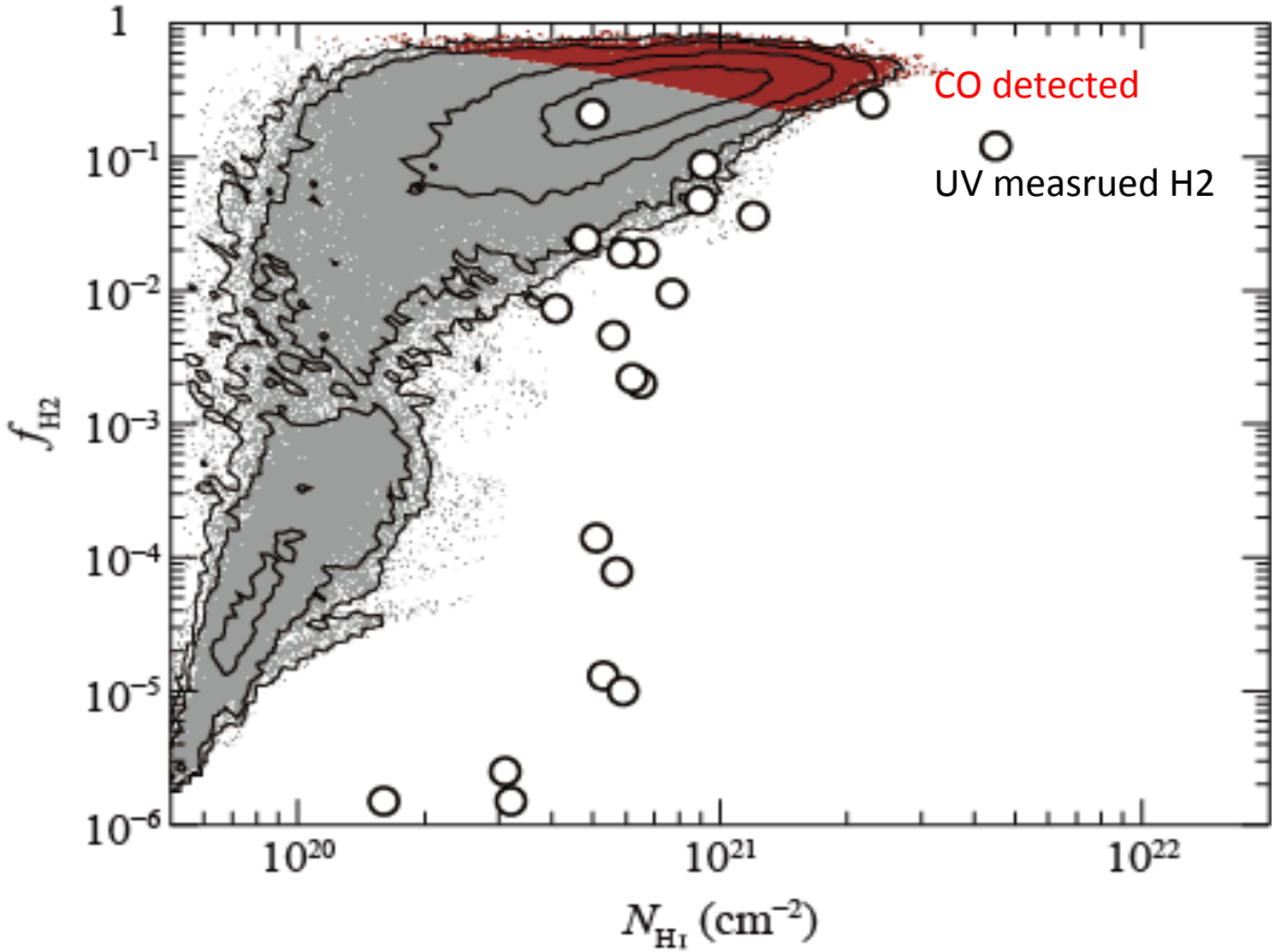

(a) HI emission
ε=0 if T_s<300K
ε=0 if T_s<1000K
T_b (K)
40
20
0
(b) HI absorption
κ=0 if T_s<300K (×40)
κ=0 if T_s<1000K (×40)
HI opacity proportional to 1/Ts
1−exp(−τ)
0.8
0.4
0.0
(c)
10^5
10^4

N_H(absorption) is 25-45 % of N_H(emission)

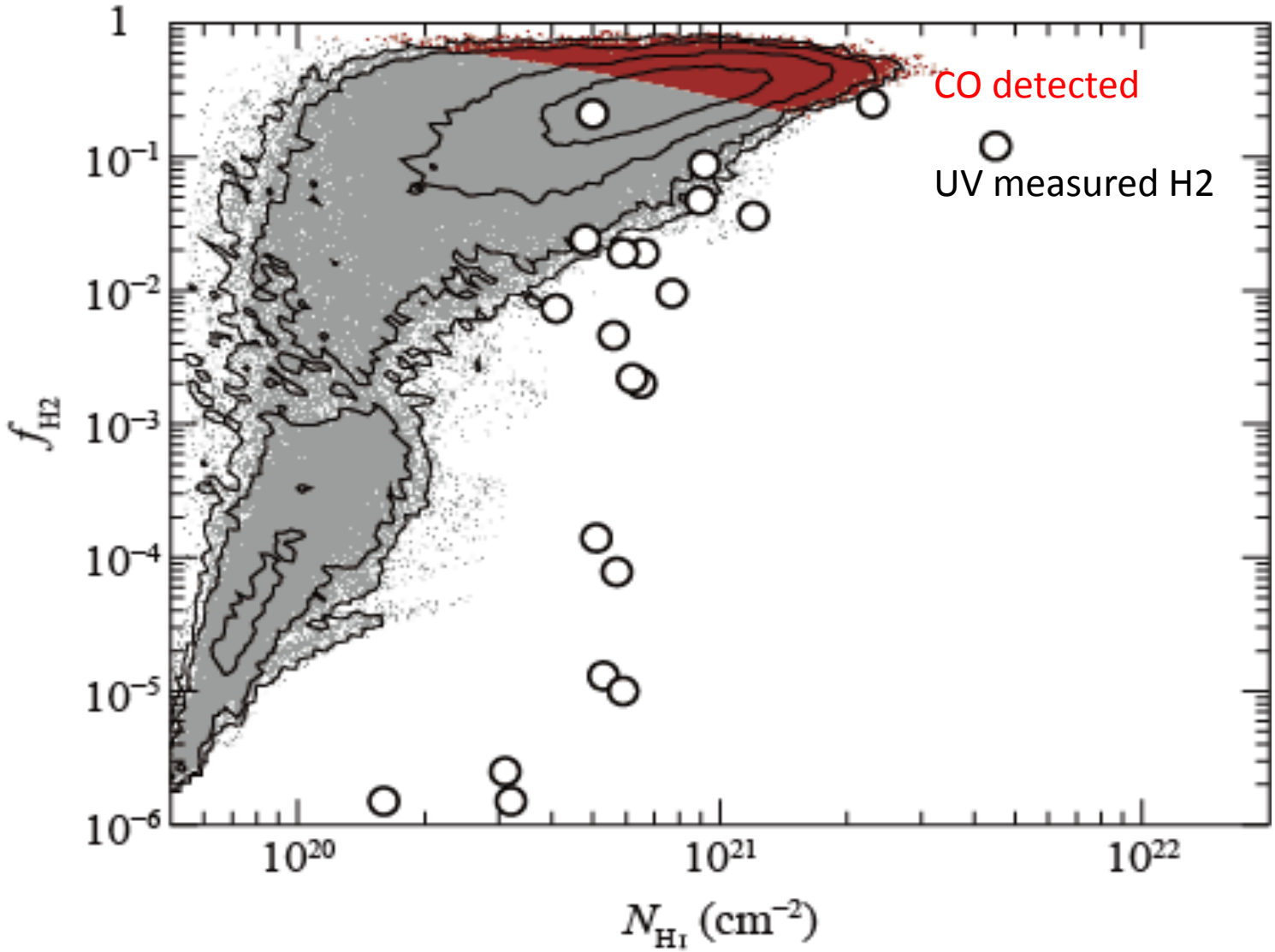




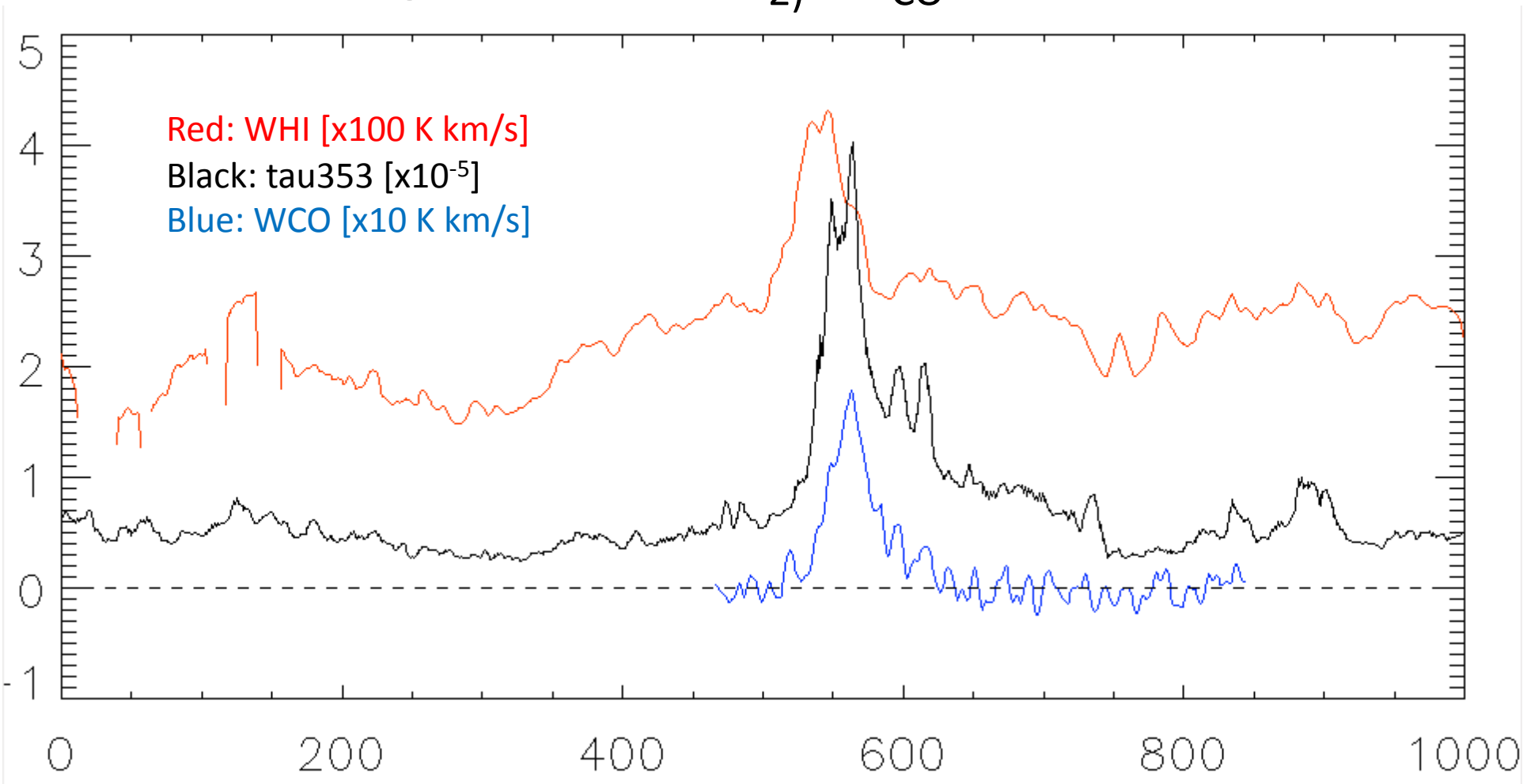
Too much H2 for canonical H2 formation rate Comparison with UV observations

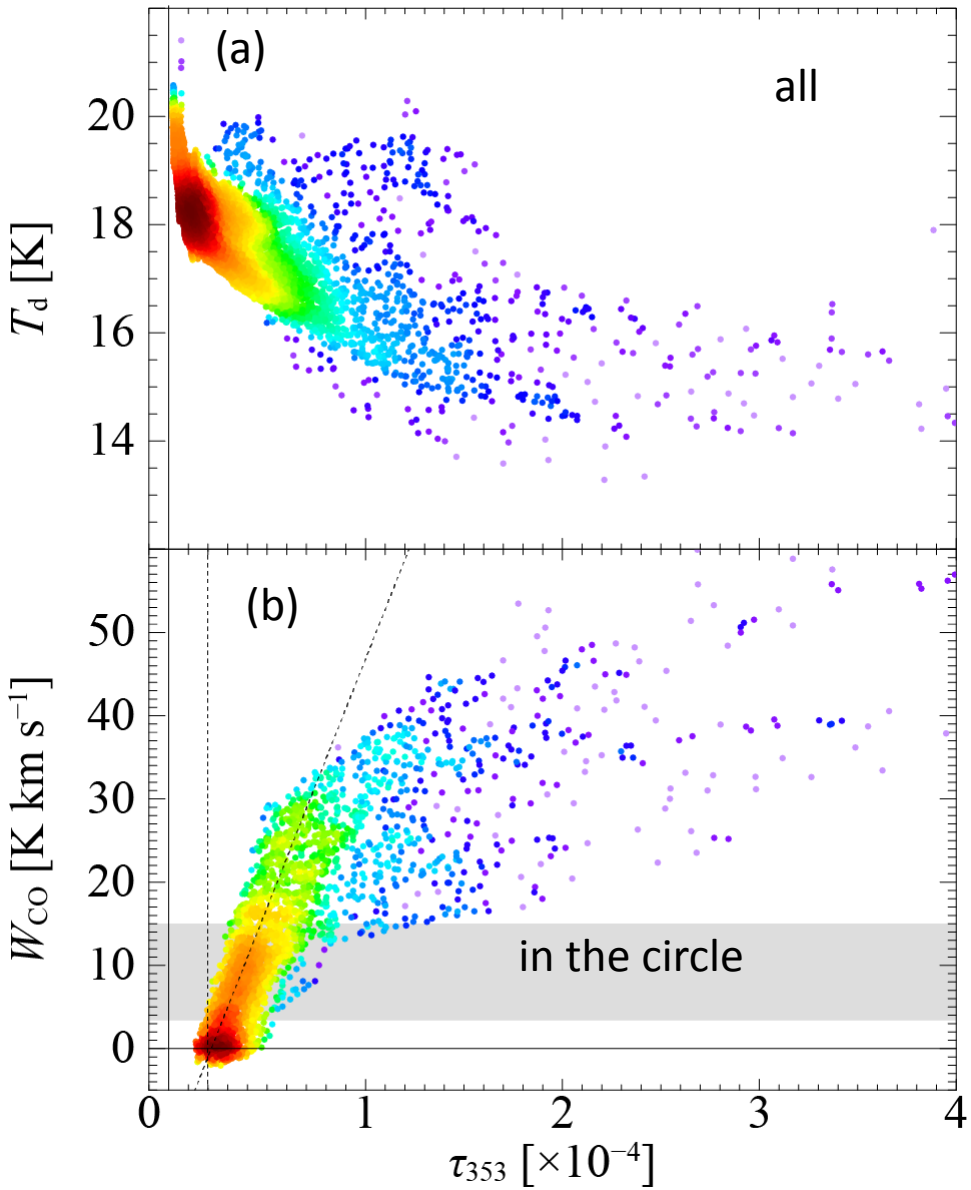


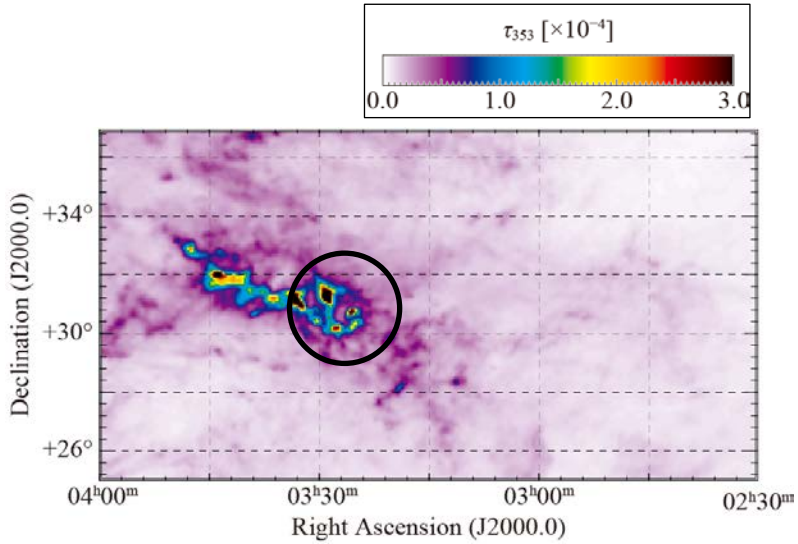
Too much H2 for canonical H2 formation rate (too large)
Comparison with UV observations



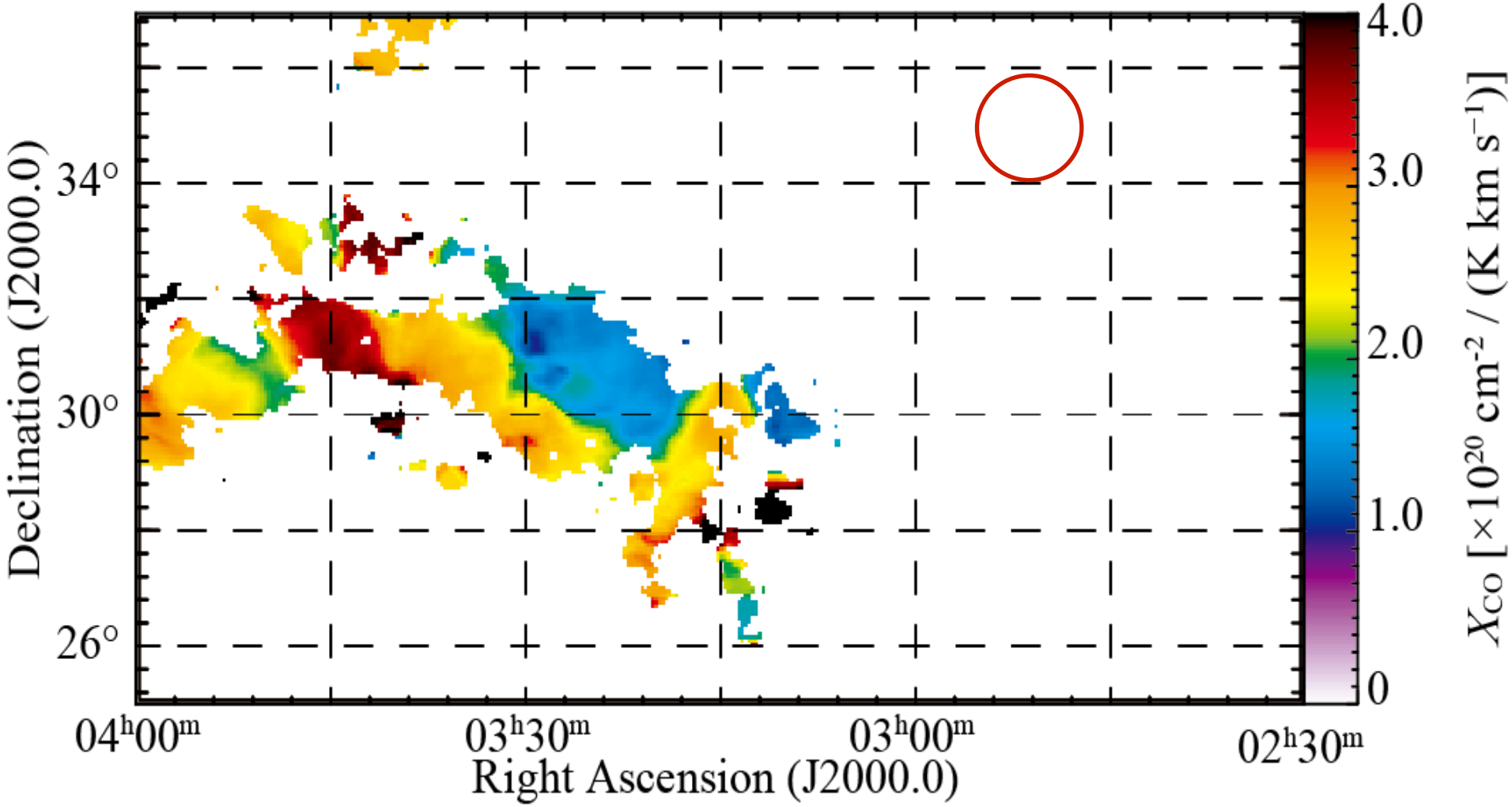
Estimating $X(CO)=N(H_2)/W_{CO}$



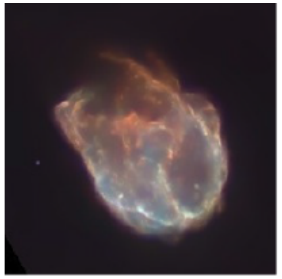

(a)
all
T_d [K]
20
18
16
14
(b)
in the circle
W_{CO} [K km s^{-1}]
50
40
30
20
10
0
0
1
2
3
4
τ_{353} [$\times 10^{-4}$]

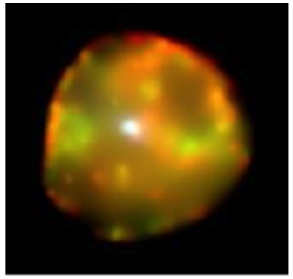

τ_{353} [$\times 10^{-4}$]
0.0
1.0
2.0
3.0
Declination (J2000.0)
+34°
+30°
+26°
04h00m
03h30m
03h00m
02h30m
Right Ascension (J2000.0)

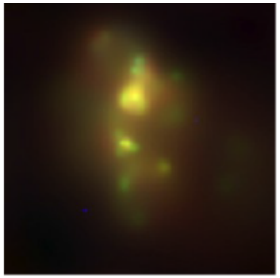
X_{CO} map

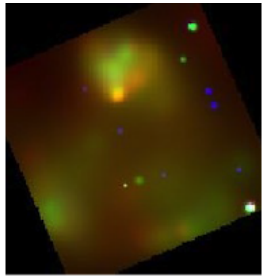

Declination (J2000.0)
34°
30°
26°
04h00m
03h30m
03h00m
02h30m
Right Ascension (J2000.0)
4.0
3.0
2.0
1.0
0
X_{CO} [×10²⁰ cm⁻² / (K km s⁻¹)]

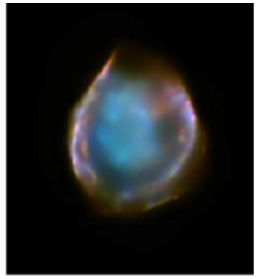
Chandra X-ray
3 color Images

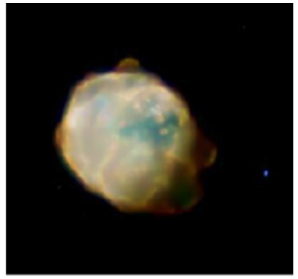

例: SNR J0525.1−6938 (N132D)

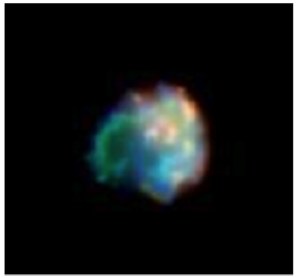

SNR J0453.6−6829 (B0453−685)

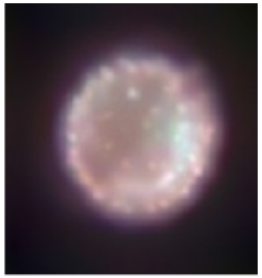

SNR 0454.4−6713 (N9)

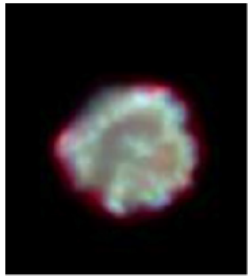

SNR J0459.9−7008 (N186D)

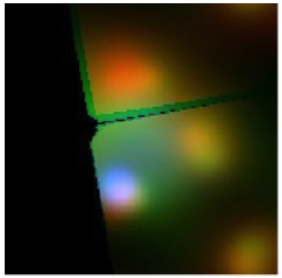

SNR J0505.7−6752 (DEM L71)

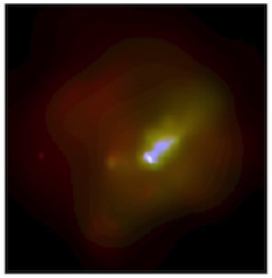

SNR J0535.7−6602 (N63A)

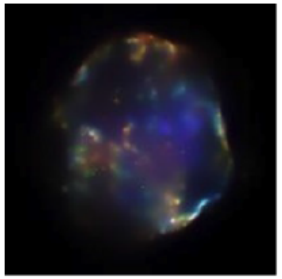

SNR J0509.0−6843 (N103B)

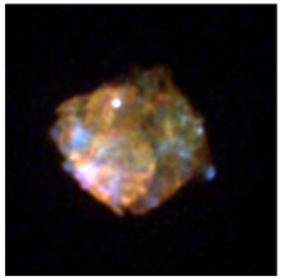

SNR J0509.5−6731 (B0509−67.5)


SNR J0519.5−6902 (B0519−

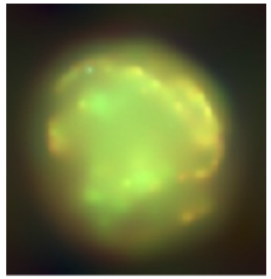

SNR J0523.0−6753 (N44)

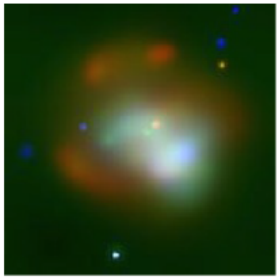

SNR J0537.8−6910 (N157B)

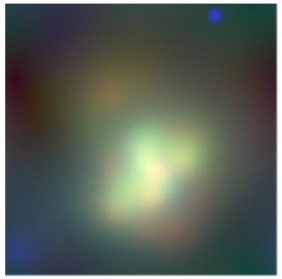

SNR J0525.4−6559 (N49B)

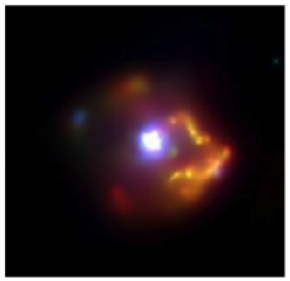

SNR J0526.0−6604 (N49)

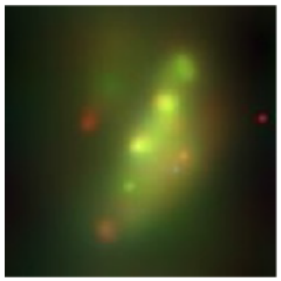

SNR J0531.9−7100 (N206)

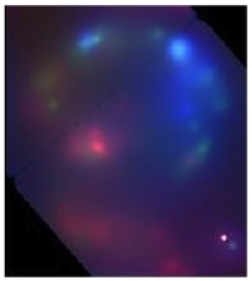

SNR J0534.0−6955 (B0534−69.9)

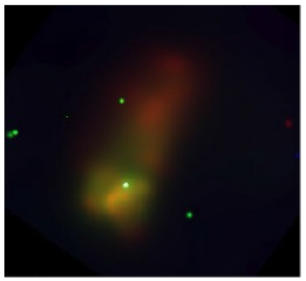

SNR J0534.2−7033 (DEM L238)

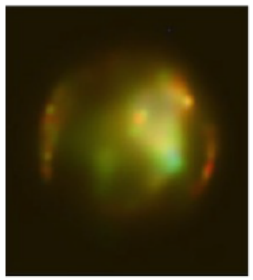

SNR J0536.1−7038 (DEM L249)

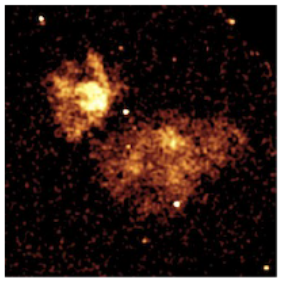

SNR J0540.1−6919


SNR J0535.7−6918 (Honeycomb)


SNR J0536.0−6912 (N157C)

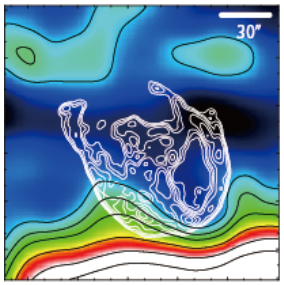

SNR J0535.9−6733 (DEM L241)


SNR J0547.8−7024 (B0548−704)

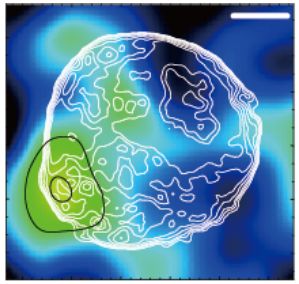

SNR J0547.0−6943 (DEM L316B)

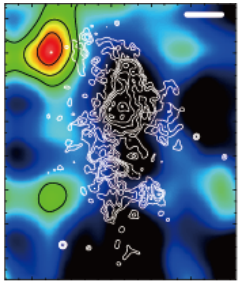
Images:
Mopra CO 1-0

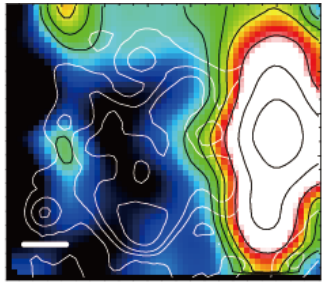
Contours:
Chandra X-ray

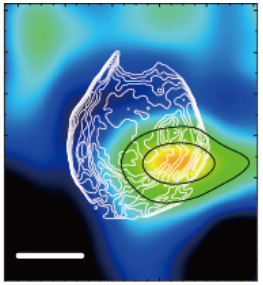


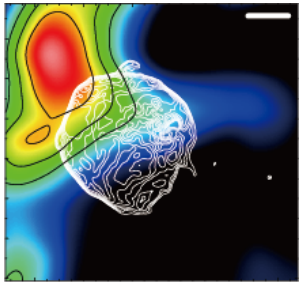
例: SNR J0525.1−6938 (N132D)

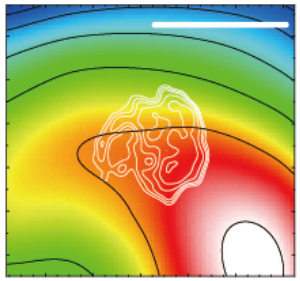

SNR J0453.6−6829 (B0453−685)

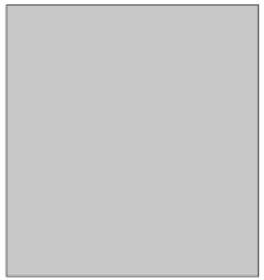

SNR 0454.4−6713 (N9)

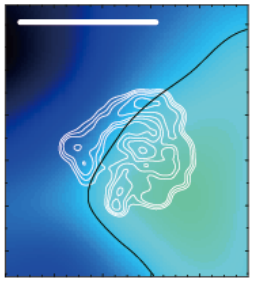

SNR J0459.9−7008 (N186D)

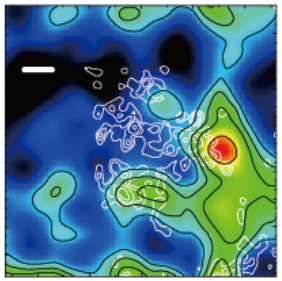

SNR J0505.7−6752 (DEM L71)

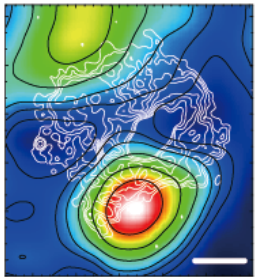

SNR J0535.7−6602 (N63A)

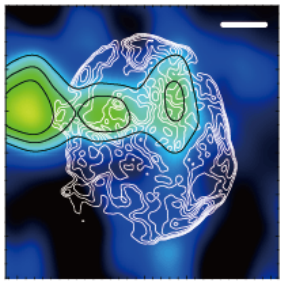

SNR J0509.0−6843 (N103B)

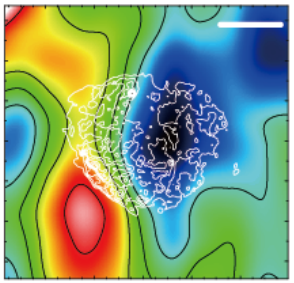

SNR J0509.5−6731
(B0509−67.5)

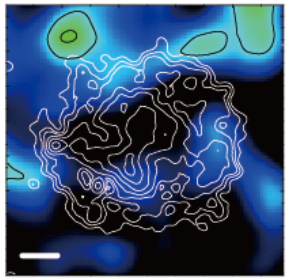

SNR J0519.5−6902 (B0519−

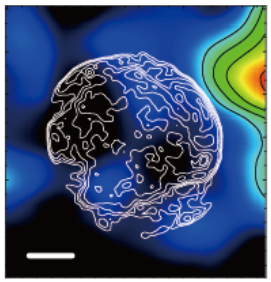

SNR J0523.0−6753 (N44)

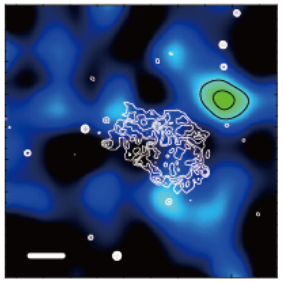

SNR J0537.8−6910 (N157B)

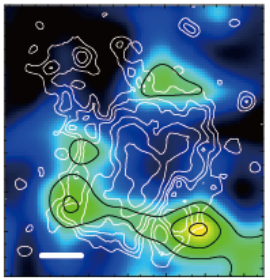

SNR J0525.4−6559 (N49B)

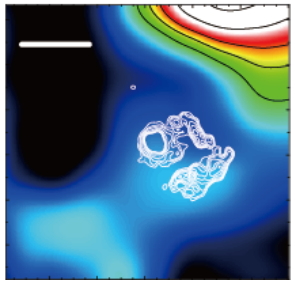

SNR J0526.0−6604 (N49)

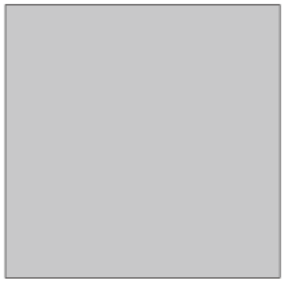

SNR J0531.9−7100 (N206)

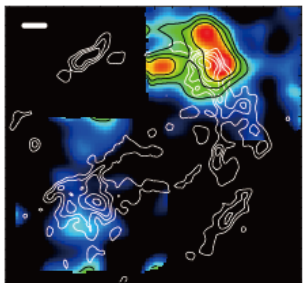

SNR J0534.0−6955 (B0534−69.9)

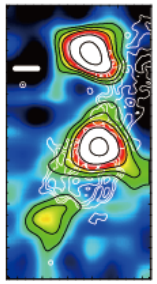

SNR J0534.2−7033 (DEM
L238)

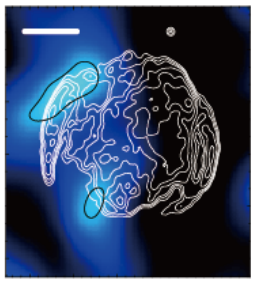

SNR J0536.1−7038 (DEM
L249)

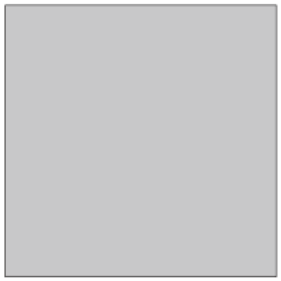

SNR J0540.1−6919


SNR J0535.7−6918 (Honeycomb)


SNR J0536.0−6912 (N157C)


SNR J0535.9−6733 (DEM L241)

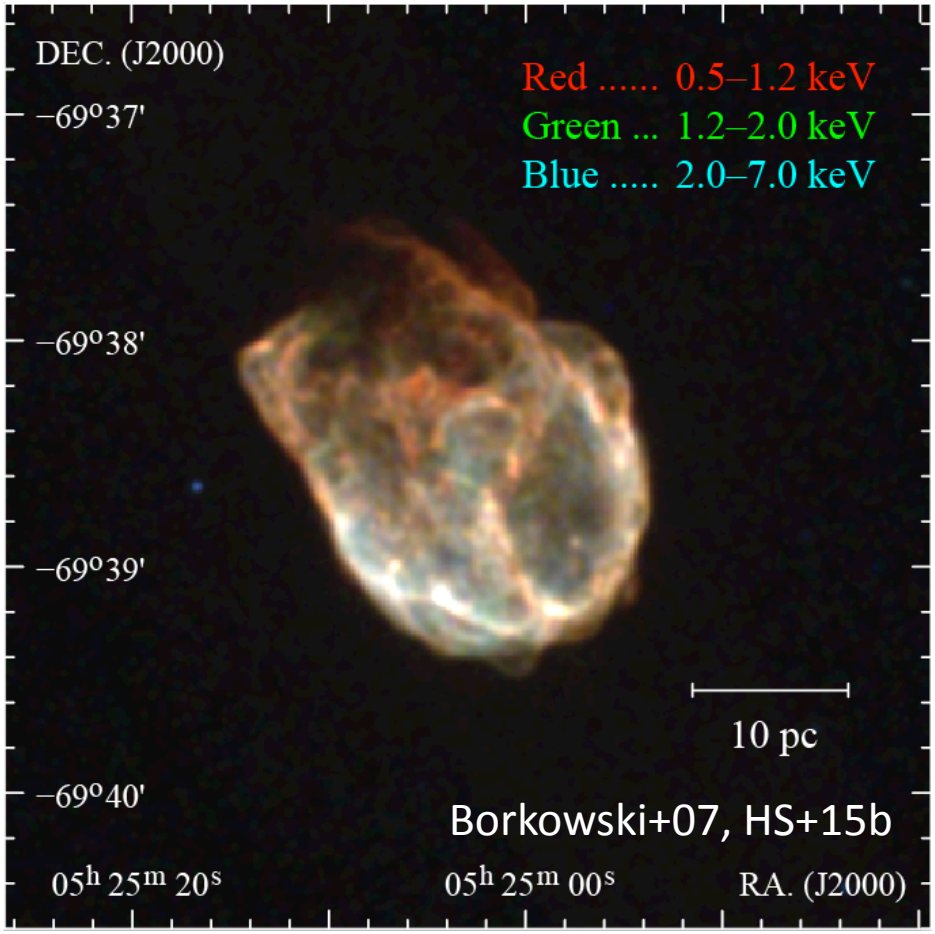

SNR J0547.8−7024
(B0548−704)

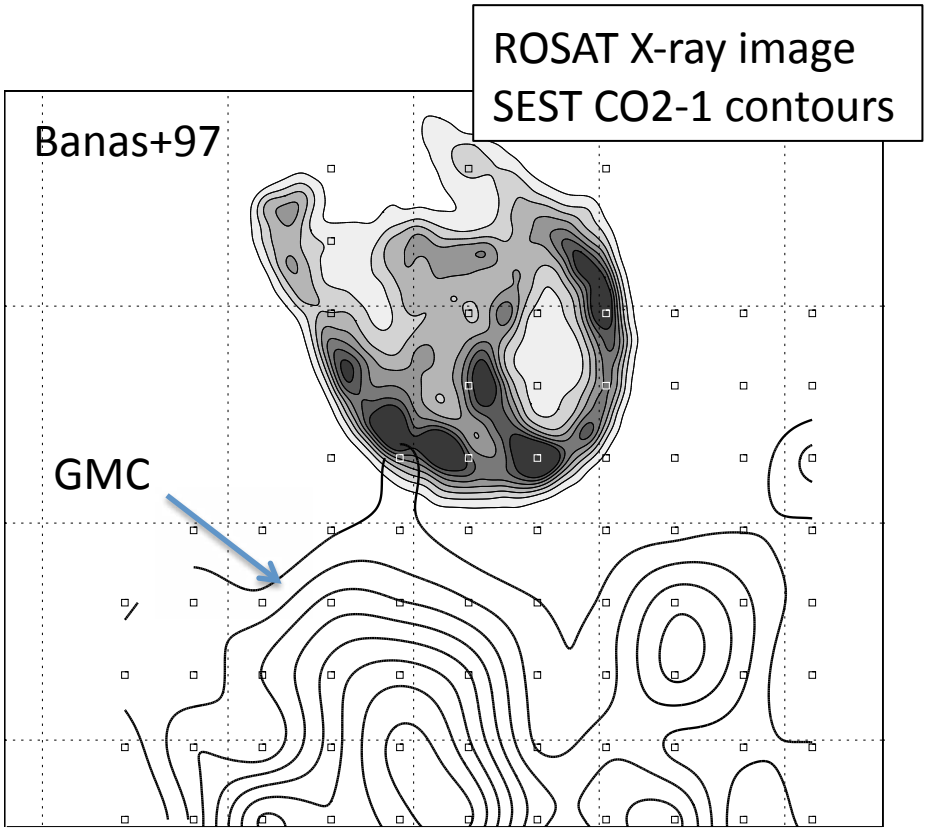

SNR J0547.0−6943 (DEM L316B)

Magellanic SNR N132D

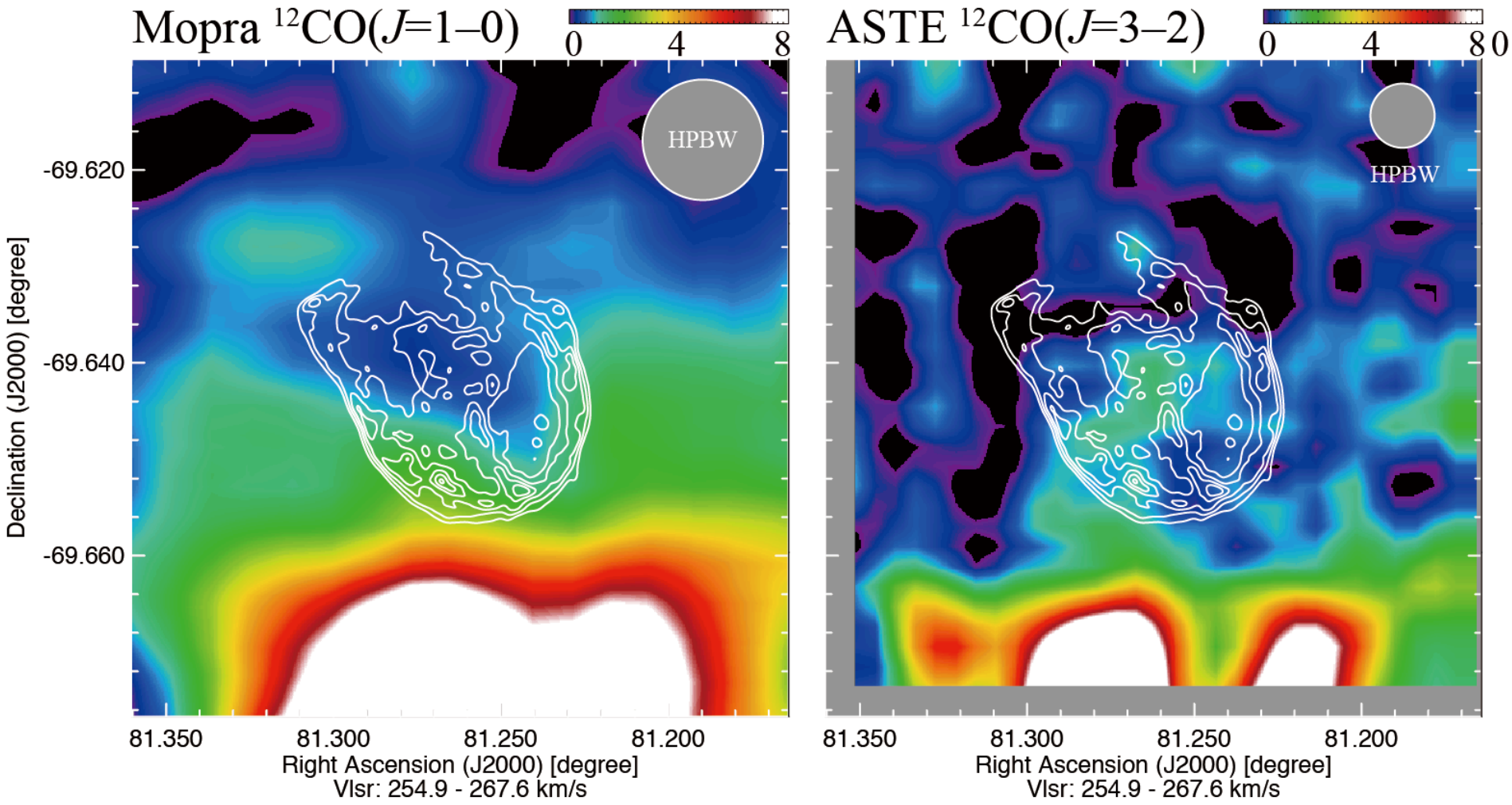
In the LMC（*d*~50 kpc），young core-collapse SNR（age~3150 yr）
X ray bright，TeV gamma ray detected, interaction with GMC?
（e.g., Morse+95, Banas+97, Borkowski+07, H.E.S.S. Col.+15）

(a) *Chandra* X-rays





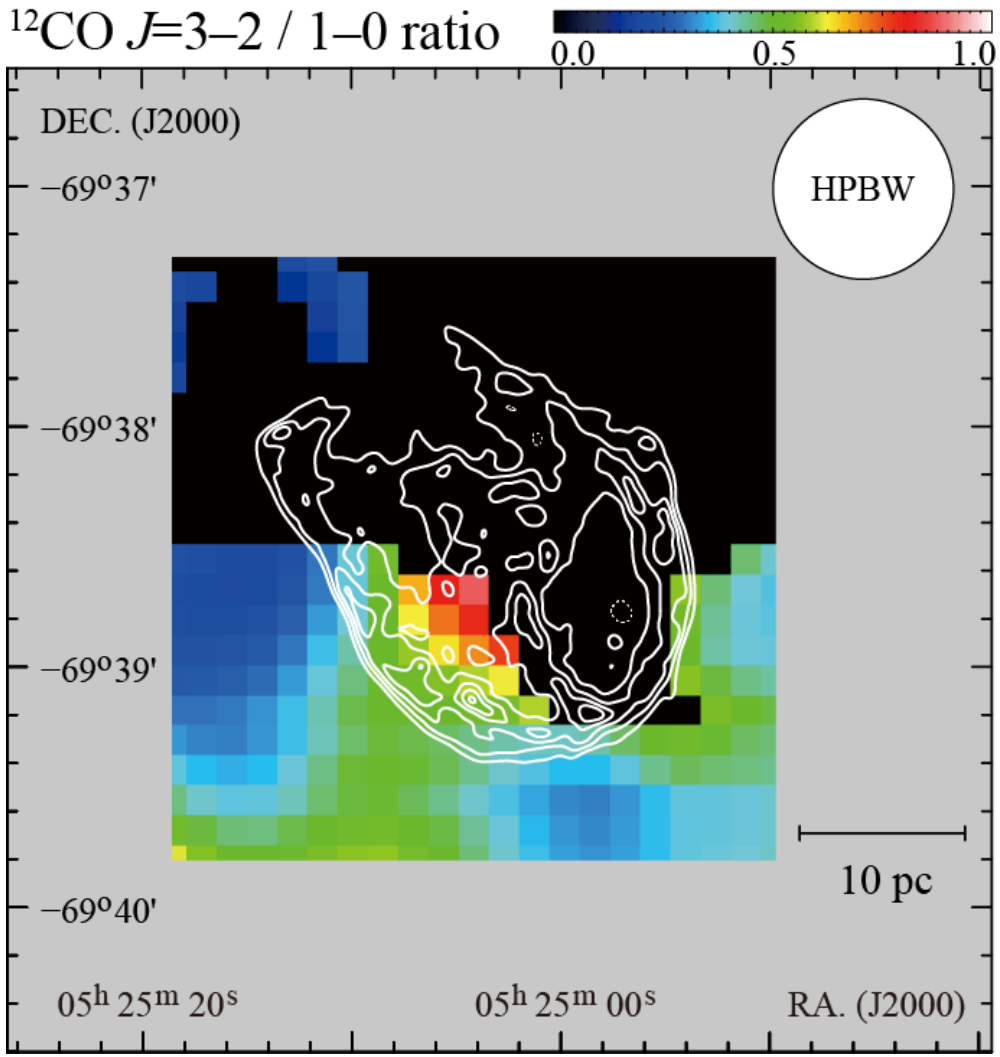
N132D [CO and HI]

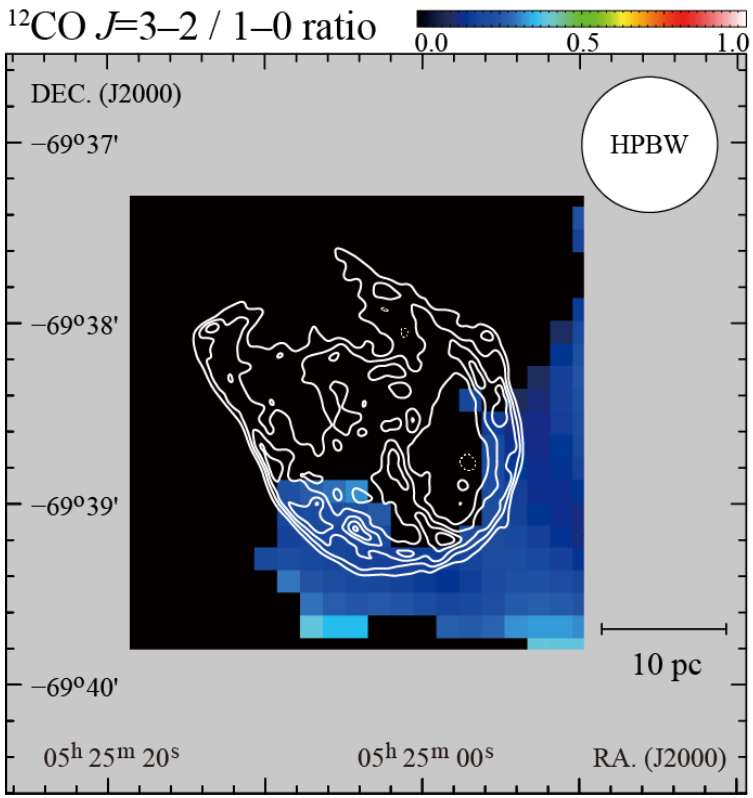


contour: *Chandra* X ray (0.5-7.0 keV)

- In the southeast, X rays and CO+HI show correspondence
- mass of CO ~10,000 $M_{\odot}$, mass of HI > 6,000 $M_{\odot}$

CO 3−2/1−0 line intensity ratio





Non interacting CO

← Interacting CO cloud（256-266 km/s）

contours： *Chandra* X ray (0.5-7.0 keV)

■ The ratio is enhanced (from 0.4 to > 0.8)

Cosmic ray energy

- H.E.S.S. detected TeV gamma rays in N132D（HESS Col.+15）
  ➡ 1-10 TeV cosmic ray protons and/or leptonic origin

–Spatial correspondence of TeV gamma rays with ISM, impossible

–Total energy of cosmic ray protons *Wpp*

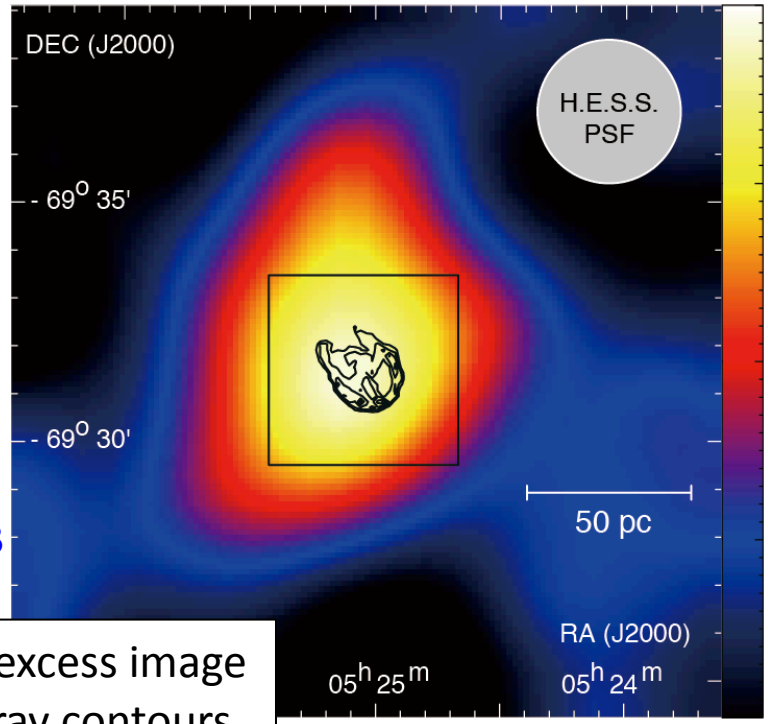
(H.E.S.S. Collaboration+15)

$$W_{\rm pp} = 10^{52}\left(n_{\rm H}/1\ {\rm cm}^{-3}\right)^{-1}\left(d/50\ {\rm kpc}\right)^{-2}$$

gas density　　distance

$d = 50$ kpc, interstellar protons $n_{\rm H} \sim 90{\rm cm}^{-3}$

$$W_{\rm pp} \sim 1\times10^{50}\ {\rm erg}$$

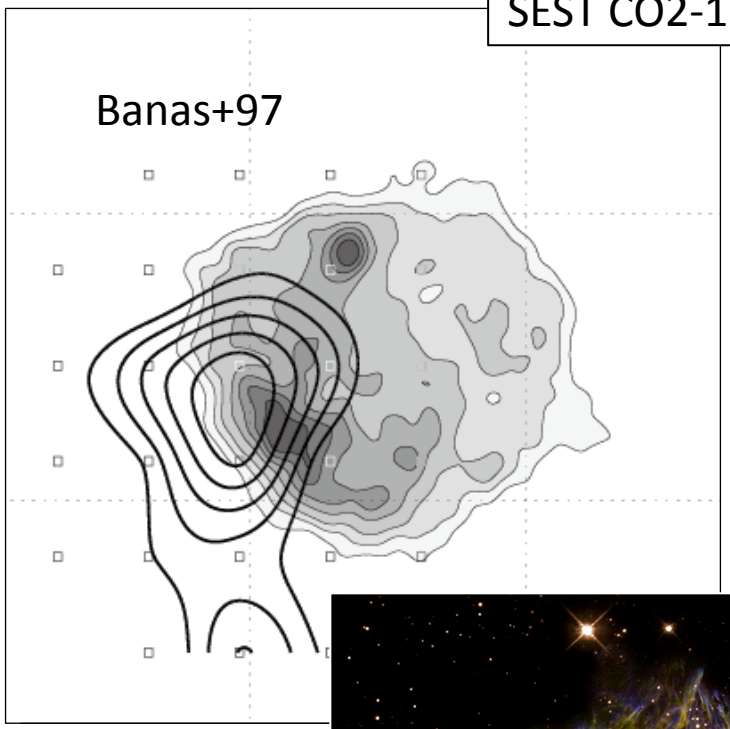


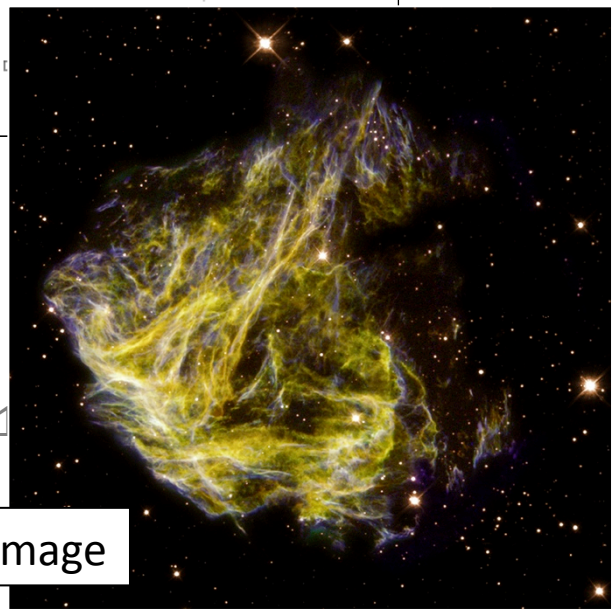
HESS γ-ray excess image
Chandra X-ray contours

Magellanic SNR N49

(a) *Chandra* X-rays

ROSAT X-ray image
SEST CO2-1 contours

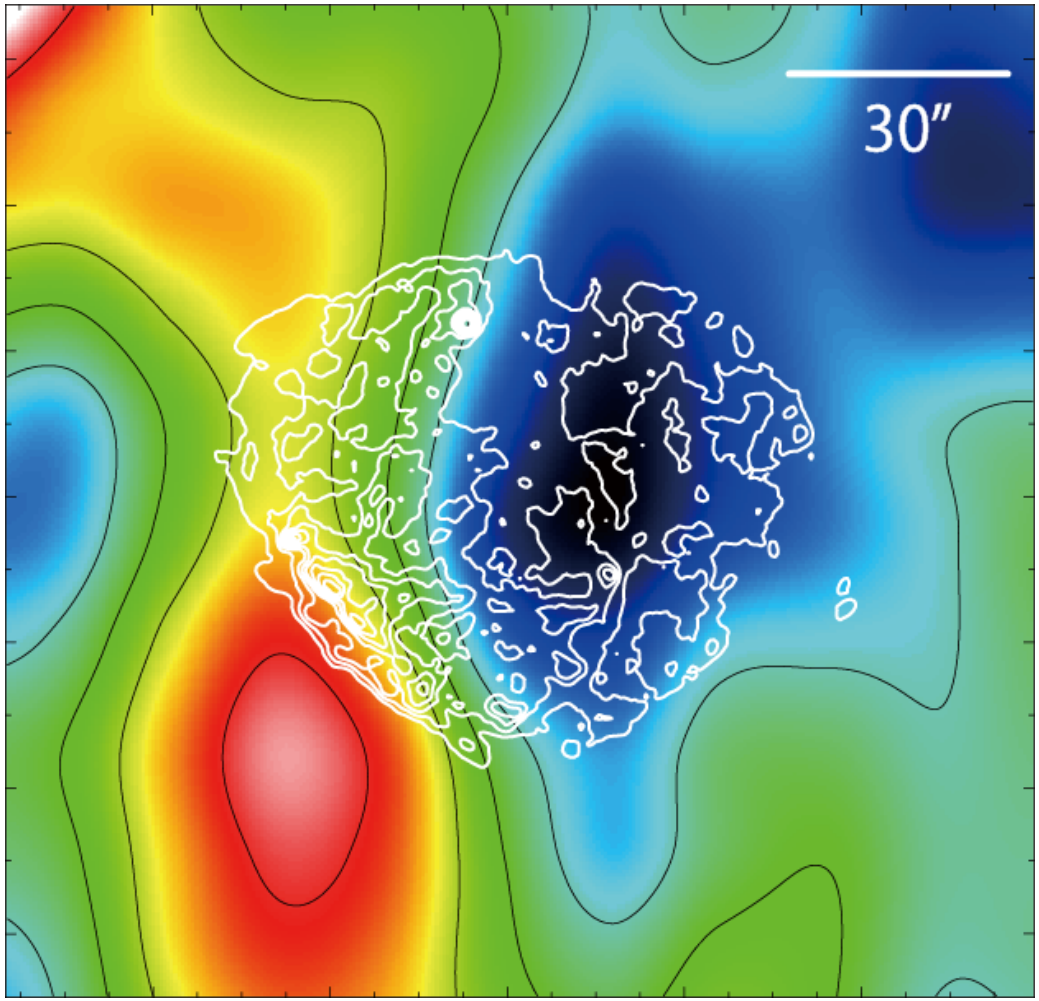




Optical Image

- - Young (~4,800yr) type II SNR located at the LMC (e.g., Park+1
- - Bright in X-rays & Optical (e.g., Bilikova et al. 2007)
- - Associating with GMC（Banas+97)

Magellanic SNR N49



← Image: Mopra CO 1-0
Contours: Chandra X-rays (0.5-7 keV)

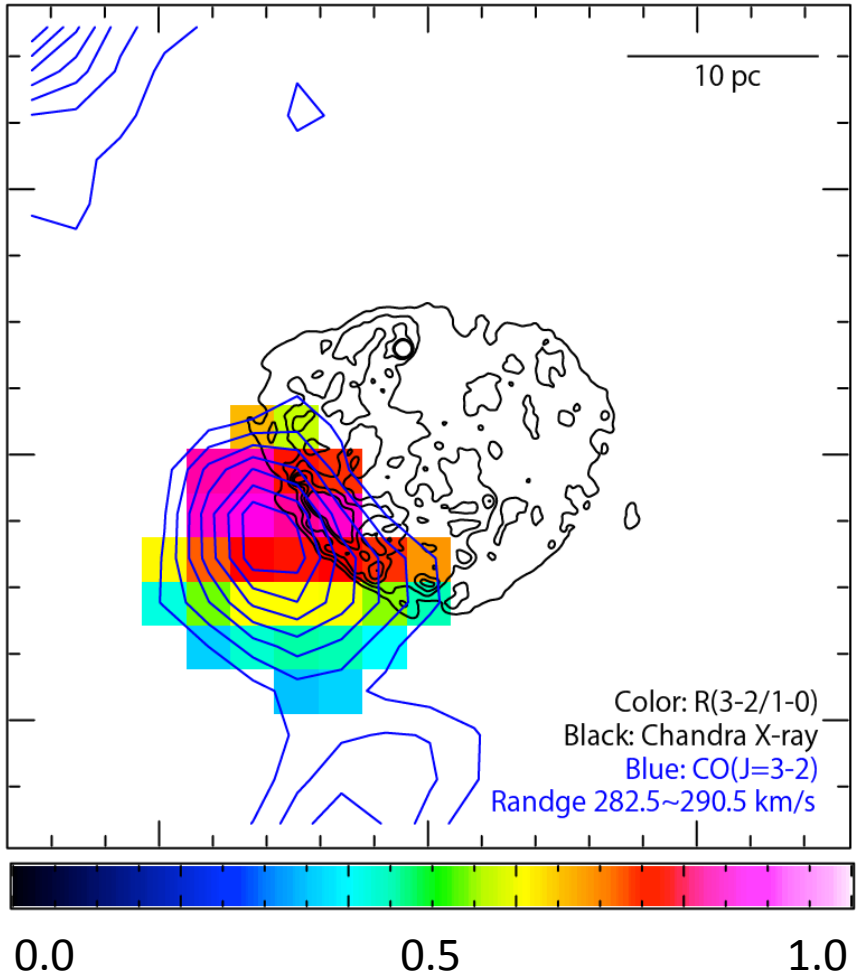
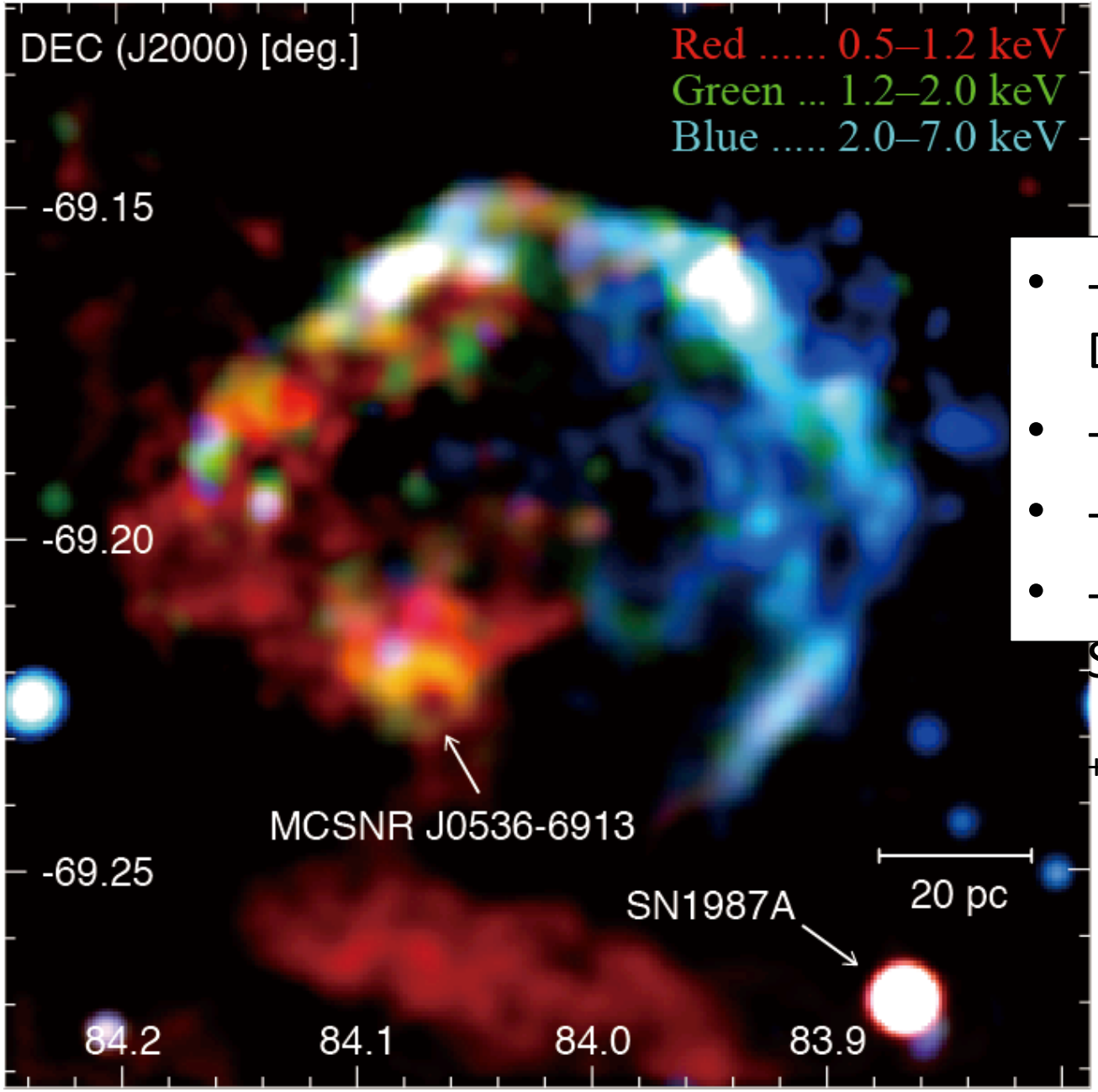


Image: CO 3-2/1-0 Ratio
Contours: Chandra X-rays (0.5-7 keV) →
PI: Fujii

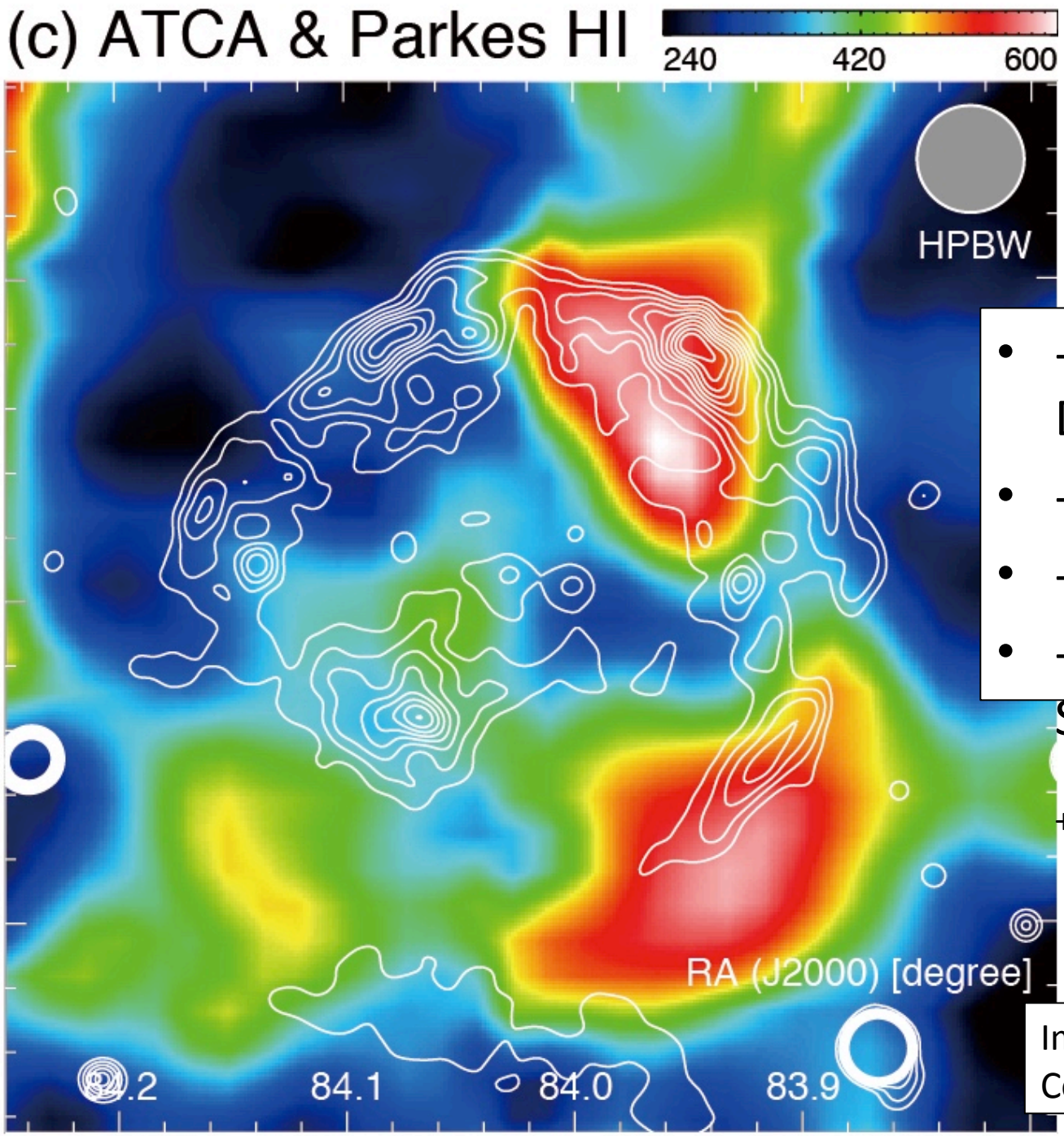
(a) Chandra X-rays



30 Dor C

- - Superbubble in 30 Dor
- - Non-thermal X-rays
- - TeV Gamma-rays
- - Containing young SNR

(Age: 2.2–4.9 kyr, Kavanagh +14)

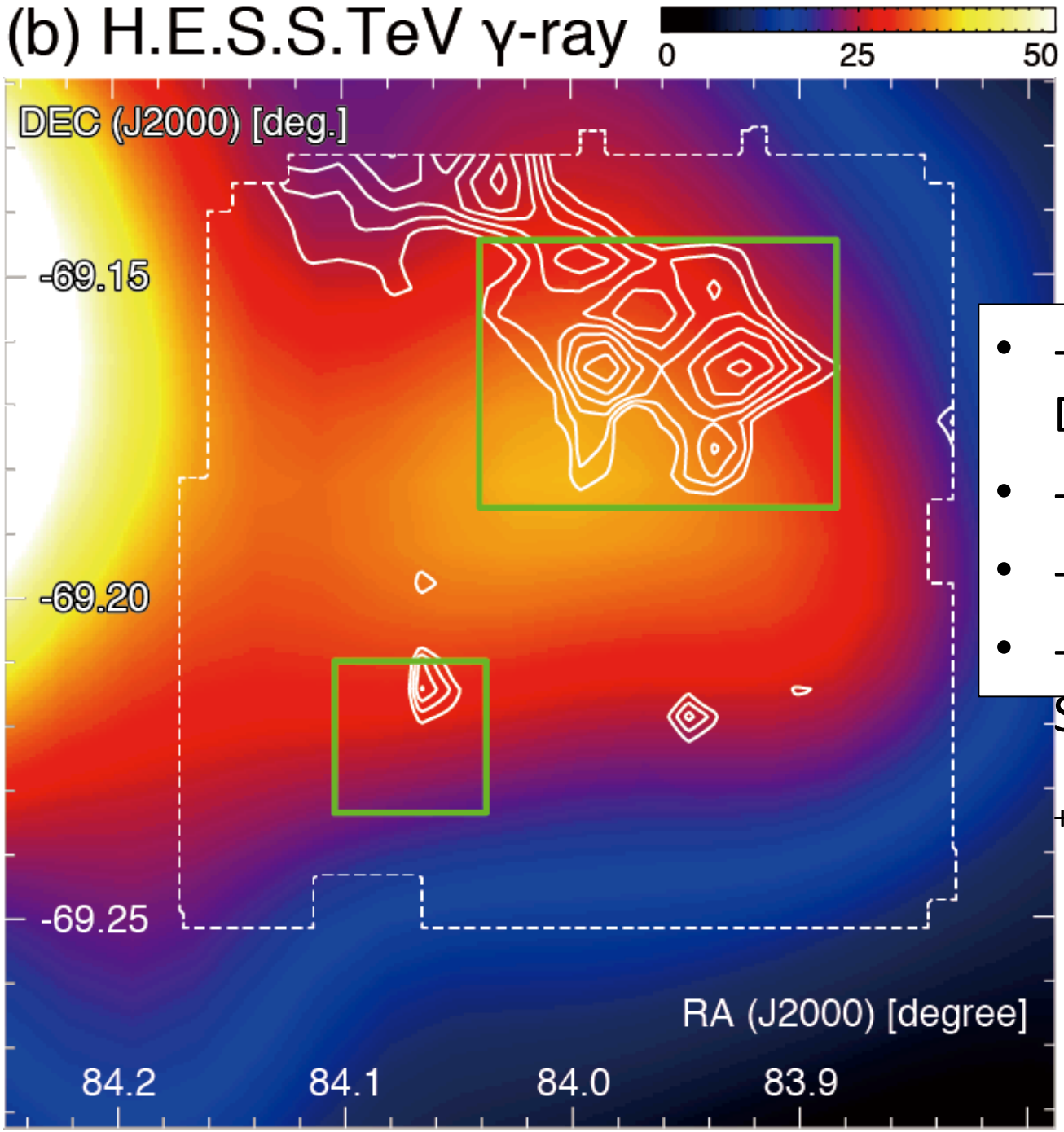


30 Dor C

- - Superbubble in 30 Dor
- - Non-thermal X-rays
- - TeV Gamma-rays
- - Containing young SNR

(Age: 2.2−4.9 kyr, Kavanagh +14)

Image: HI (Kim+03)
Contours : X-rays (0.5-7.0 keV)



30 Dor C

- - Superbubble in 30 Dor
- - Non-thermal X-rays
- - TeV Gamma-rays
- - Containing young SNR

(Age: 2.2–4.9 kyr, Kavanagh +14)

Image: TeV gamma-rays (H.E.S.S. Collaborations+15)
Contours : CO

For better understanding the origin of gamma rays
The origin of cosmic rays In SNRs; summary

１ The Milky Way: In TeV gamma ray SNRs target interstellar protons are identified. Both atomic and molecular hydrogen act as targets.
High resolution CO images with Mopra.
Hadronic dominant in RXJ1713, RXJ0852, HESSJ1731, W28, W44
Leptonic dominant in RCW86

２ SNRs in the MC: Survey for CO with Mopra
Correlation with X rays ―N132D, 30Dor C,N49 etc.

―Comparison with X rays
―CTA: higher sensitivity and resolution, more than 10 times sources
―“Spatial distribution of gamma ray spectrum”
cosmic ray protons and interstellar medium
⇒acceleration theories