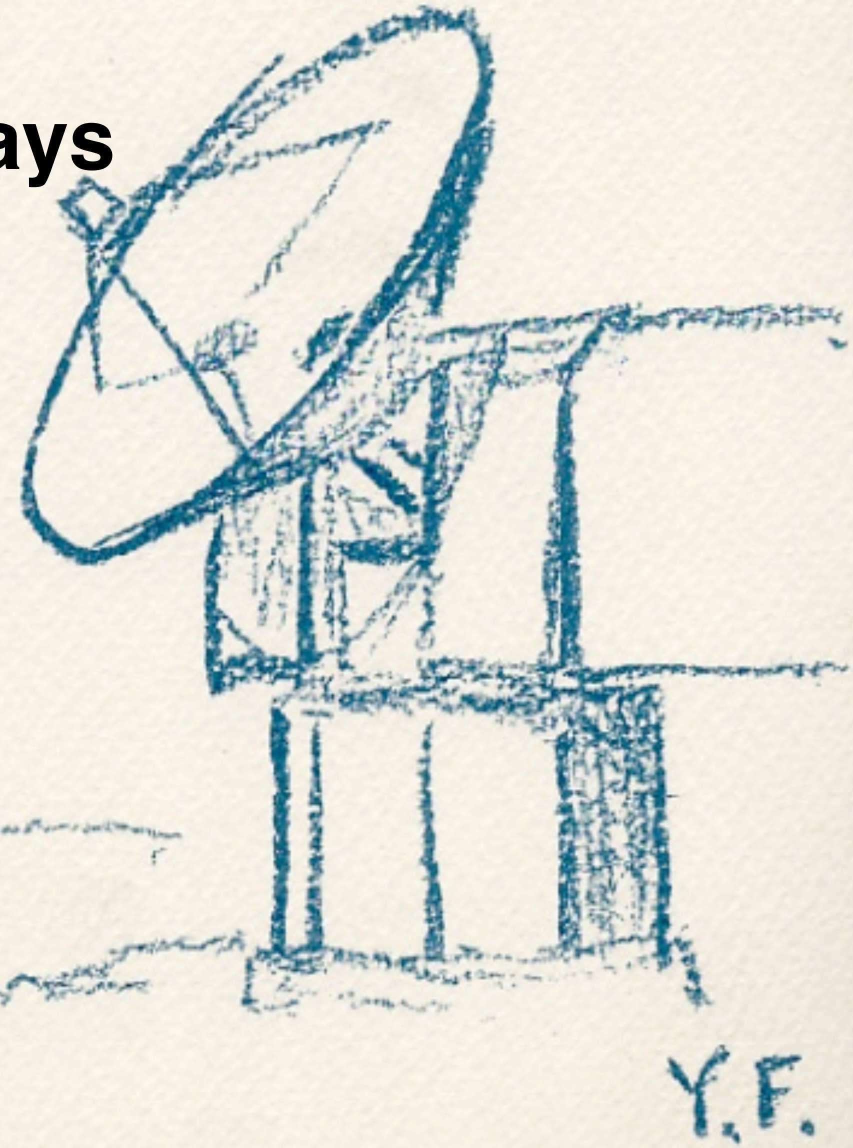
Gas distribution in our Galaxy: Molecular clouds and high energy gamma-rays



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Southern Observatories

July 4-15, 2011 Dublin Summer School
High Energy Astrophysics

Lecture plan

- Part 1 ISM properties: CO, HI and "dark gas"
  - Molecular clouds, atomic gas,
  dust extinction/emission, excitation
  of quantum levels, column density, distance

- Part 2 ISM vs. Gamma rays
  - SNR RXJ1713, hadronic vs. leptonic
  scenario for gamma-ray production, ISM
  protons in hadronic scenario, MHD model

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ISM between stars

- We have interstellar medium ISM among stars
- ISM consists of gas and dust

  Mgas/Mdust is 100, Dust grains include most of the heavy elements, abundance ratio; H:He:CNO = 1:10^{-1}:10^{-4}
- Gas consists of neutral and ionized components

  Here with an emphasis on neutral gas because neutral is dominant, related to star formation and ultimately galactic evolution, Ionized gas is minor in mass and probes UV radiation field, PDR
- Neutral consists of molecular and atomic gas
  - 1951 discovery of 21cm HI
  - 1970 discovery of 2.6mm CO

Molecular vs. atomic

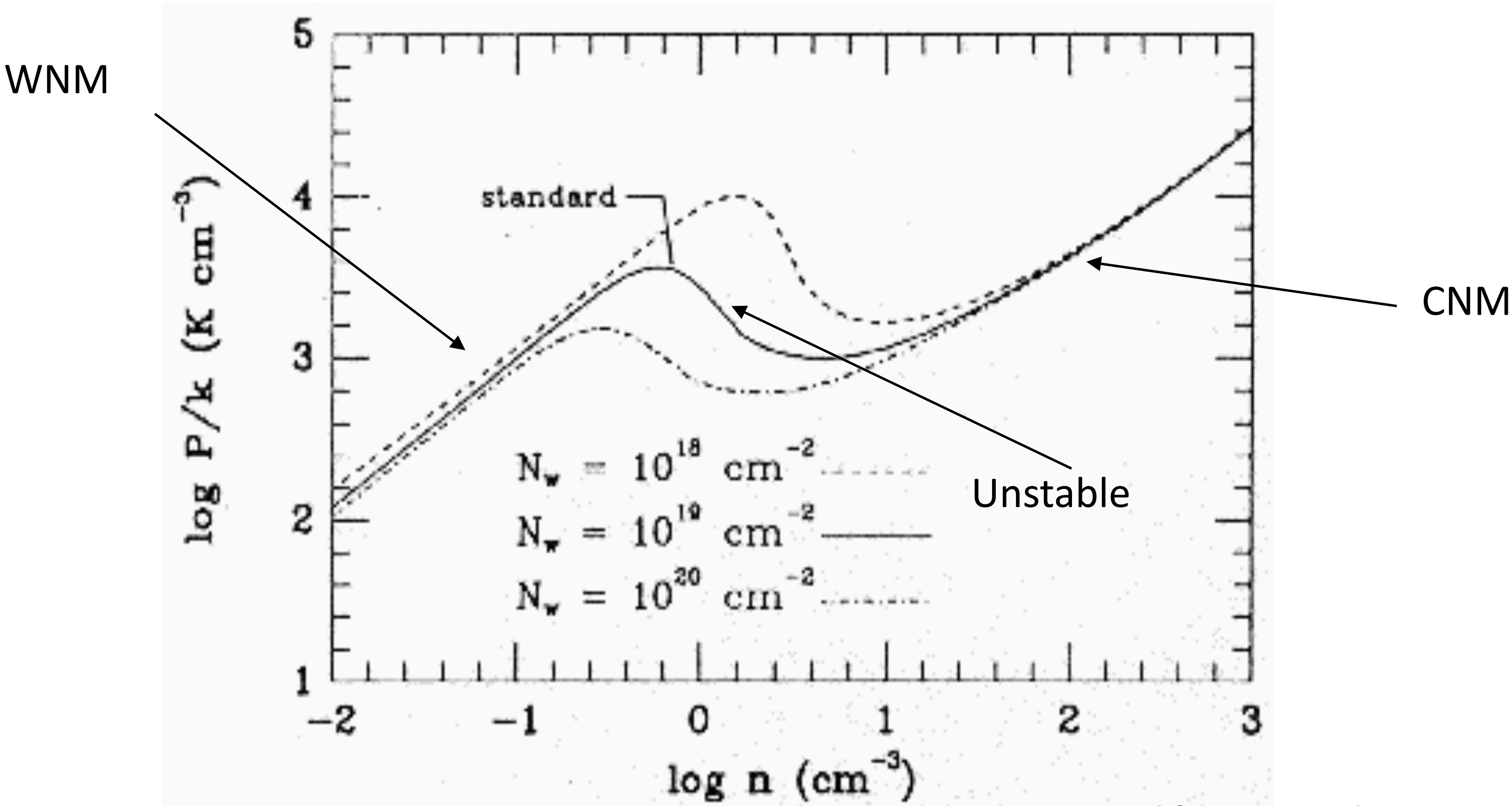
- HI gas is less dense, average is 1 cm^{-3} with a range of 0.01cm^{-3} to 100 cm^{-3}, temperature average is 100K with a range of 10–10000 K
- Molecular gas is dense, average is 1000 cm^{-3}, up to 10^7 cm^{-3} or higher
- Temperature is low, 10–20 K in the disk, can be higher in high-mass star forming regions
- but is higher in the Galactic center, 30–300 K, due to not-well known heating

Molecular clouds

		GMC	Dark cloud
molecular cloud complex	size (pc)	20–80	6–20
	density (cm^{-3})	100–100	100–1000
	mass ($M_\odot$)	8×10^4–2×10^6	10^3–10^4
	Temperature (K)	7–15	$\sim$10
individual molecular cloud	size (pc)	3–20	0.2–4
	density (cm^{-3})	10^3–10^4	10^2–10^4
	mass ($M_\odot$)	10^3–10^5	5–500
	Temperature (K)	15–40	8–15
molecular cloud core	size (pc)	0.5–3	0.1–0.4
	density (cm^{-3})	10^4–10^6	10^4–10^5
	mass ($M_\odot$)	10–10^3	0.3–10
	Temperature (K)	30–100	$\sim$10

Goldsmith 1987

Thermal equilibrium curve



Wolfire et al. 95

criterion for instability: $$\left.\frac{\partial P}{\partial \rho}\right)_{L=0} \leq 0$$

(Field et al. 69, Wolfire et al. 95)

Interstellar molecular clouds and gamma-rays

Interstellar Medium ISM

- Molecular clouds: dense neutral gas H2
  - density 10^3 cm-3 or higher, Tk=10-20K
- Atomic clouds: dense atomic gas HI
  - density 1-100 cm-3, Ts=30-100K

Gamma-rays produced by

1) Hadronic scenario

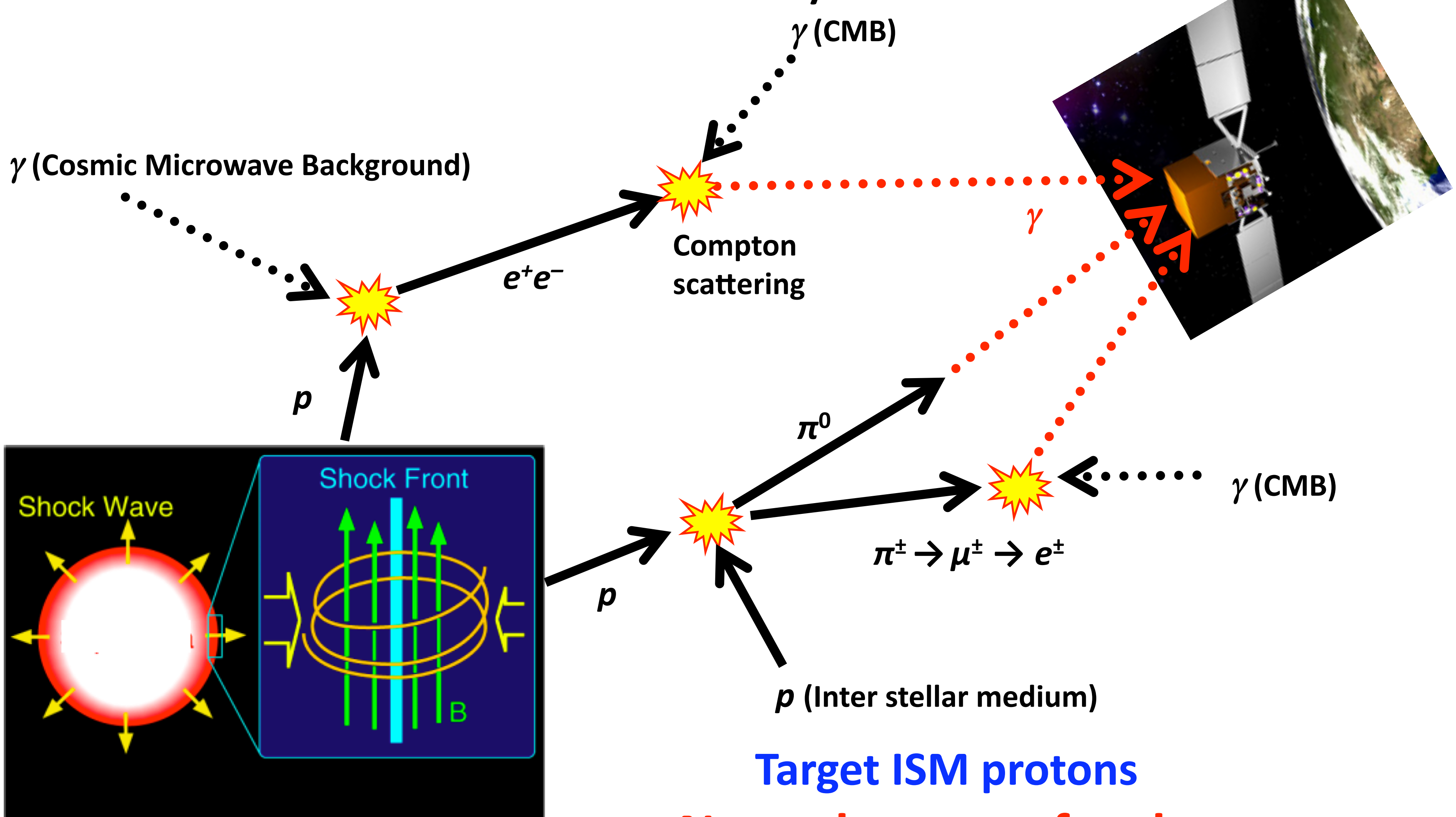
   - cosmic ray CR proton - ISM proton reaction,
   neutral pions decay into gamma rays

2) Leptonic scenario

   - CR electrons, Inverse Compton (IC) effect, CMB etc.

   Gamma-rays (0.1GeV-100TeV) observed by HESS, MAGIC, VERITAS, Fermi, AGILE[2005-] and CTA[2013-]

Hadronic Cosmic-ray Interactions

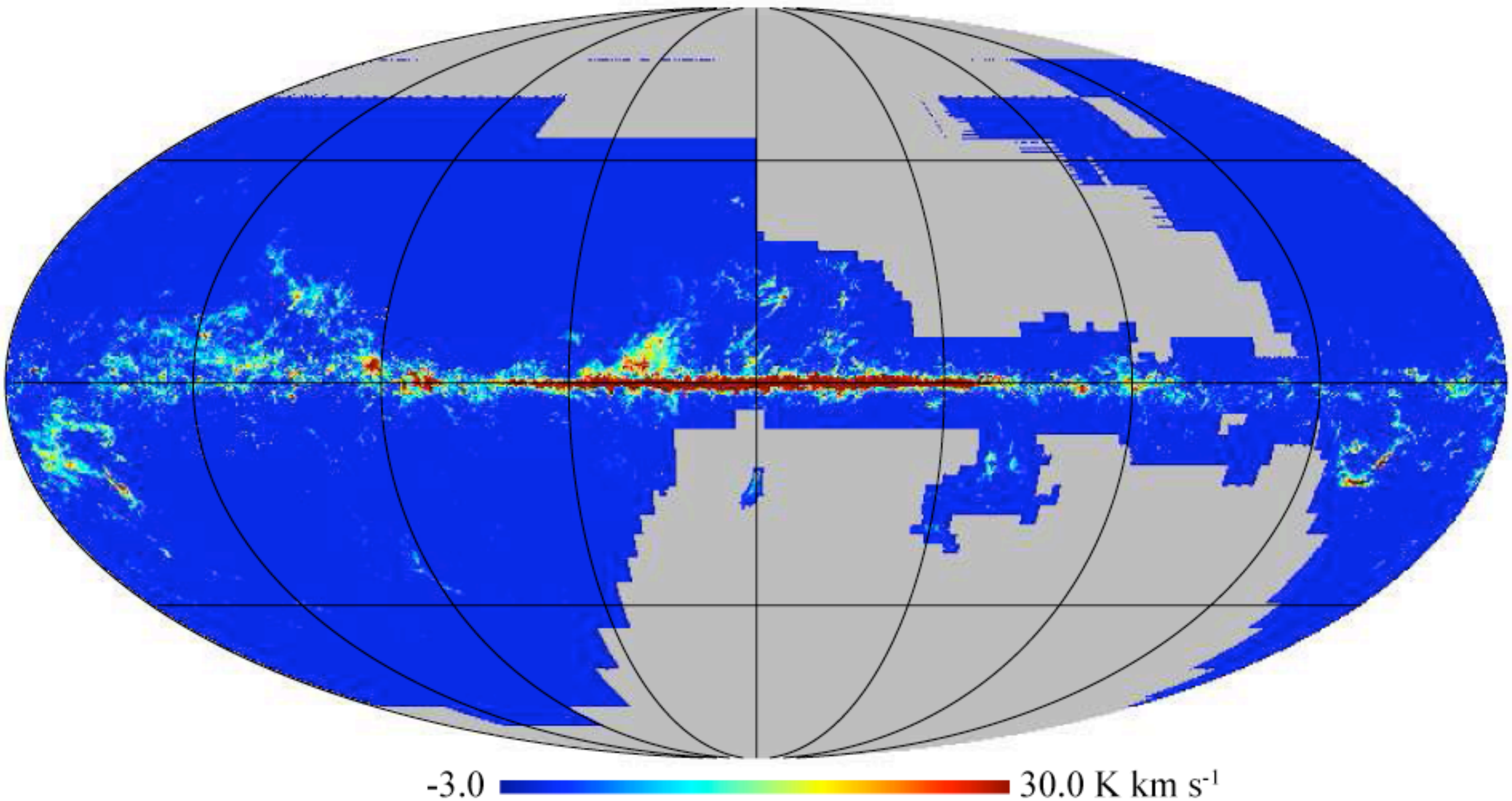


By H. Tajima 2006

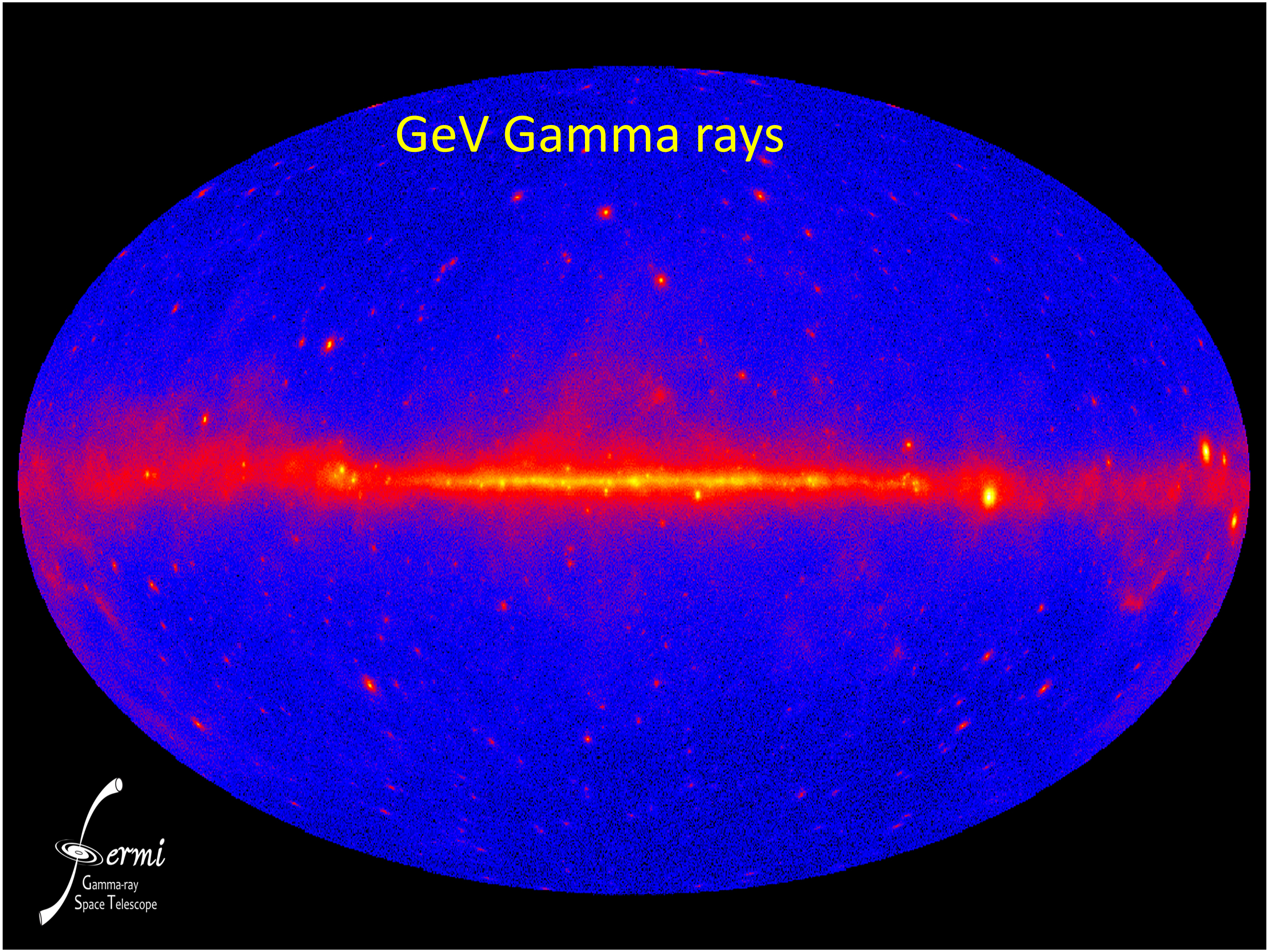
Target ISM protons

No real test yet for the targets

CO surveys : CfA + NANTEN



Planck Collaboration, arXiv:1101.2029


GeV Gamma rays
Fermi
Gamma-ray
Space Telescope

ISM Heating processes

- Based on the ionization of ISM components by an energetic radiations. Then, CR protons interact with the ISM and thermalize.
  - Cosmic rays; heat gas to 10 K (Black 1987; Lequex 2002)
  - Photoelectric effect on small dust grains and PAH (Watson 1972; de Jong 1977; Draine 1978; Bakes & Tielens 1994)
  - Ionization of atoms and molecules (e.g., HCO^+) frozen-in condition is good approx. MHD
  - X-ray
  - Chemistry
  - Mechanical heating

CR reactions in molecular clouds

Reaction	Cross section
$p_{CR} + H_2 \rightarrow p_{CR} + H_2^+ + e$	σ_p^{ion}
$p_{CR} + H_2 \rightarrow H + H_2^+$	$\sigma_p^{e.c.}$
$p_{CR} + H_2 \rightarrow p_{CR} + H + H^+ + e$	$\sigma_p^{diss\ ion}$
$p_{CR} + H_2 \rightarrow p_{CR} + 2H^+ + 2e$	$\sigma_p^{doub\ ion}$
$e_{CR} + H_2 \rightarrow e_{CR} + H_2^+ + e$	σ_e^{ion}
$e_{CR} + H_2 \rightarrow e_{CR} + H + H^+ +e$	$\sigma_e^{diss\ ion}$
$e_{CR} + H_2 \rightarrow e_{CR} + 2H^+ + 2e$	$\sigma_e^{doub\ ion}$
$p_{CR} + He \rightarrow p_{CR} + He^+ + e$	σ_p^{ion}
$p_{CR} + He \rightarrow H + He^+$	$\sigma_p^{e.c.}$
$e_{CR} + He \rightarrow e_{CR} + He^+ + e$	σ_e^{ion}

Padovani+ 2009

ISM Cooling processes

Cooling by line radiation processes is dominant.

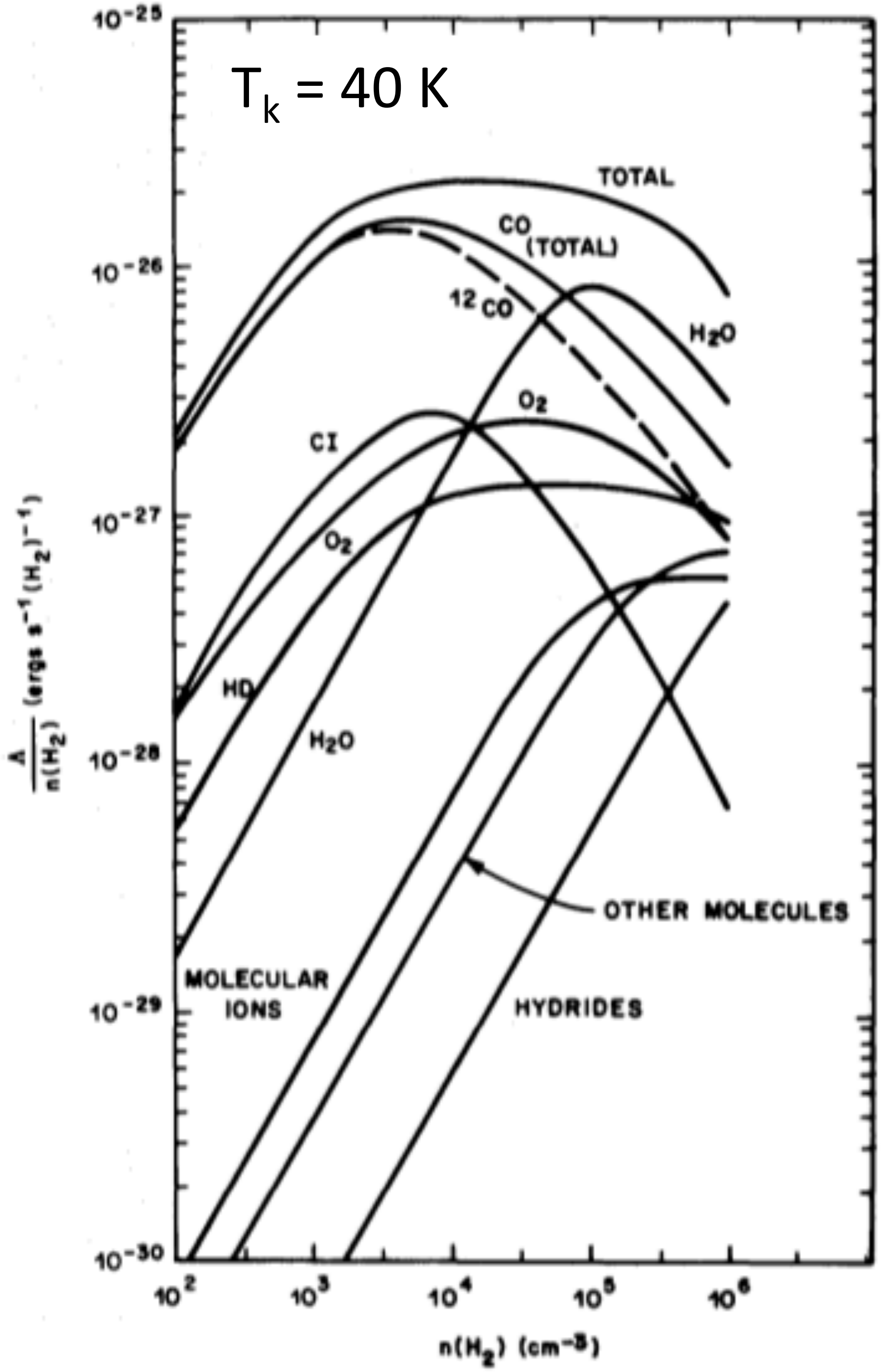
Proportional to n^2.

- Atomic gas
  - Forbidden lines. (< few 1000 K, e.g., CII)
  - Lyman α (> few 1000 K)

- Molecular gas

Cooling by the line radiation from molecules

  - CO, H_2O and other molecules



Molecular cooling

- CO is the dominant cooling line for low *n* and *T*
- H_2O and other molecules are dominant for $n > 10^6$ cm^{-3} and T > 200 K

Goldsmith & Langer 1978

Some chemistry

- HI is converted into H_2 on grain surface because gas phase reaction is very slow, exception the first stars form without dust grains
- H_2 is readily dissociated if Av is small,
  less than ~ 0.2 mag
- but can survive if Av is more than 1 mag
- Other molecules are often formed via ion neutral reactions
- At very high densities more than $10^7 cm^{-3}$ molecules freeze onto dust grain surface

Formation time scale of H_2

$$\frac{dn_2}{dt} = \frac{1}{2}\gamma < v_1 > n_{\rm g} n_1 < \sigma_{\rm g} >$$

(Hollenbach & Salpeter 1970; Jura 1974)

γ : sticking probability for incident H atoms.

$<v_2>$: mean thermal velocity of H atoms.

$<\sigma_g>$: average grain cross section.

n_1, n_2 & n_g: number density of HI, H_2 and grains, respectively

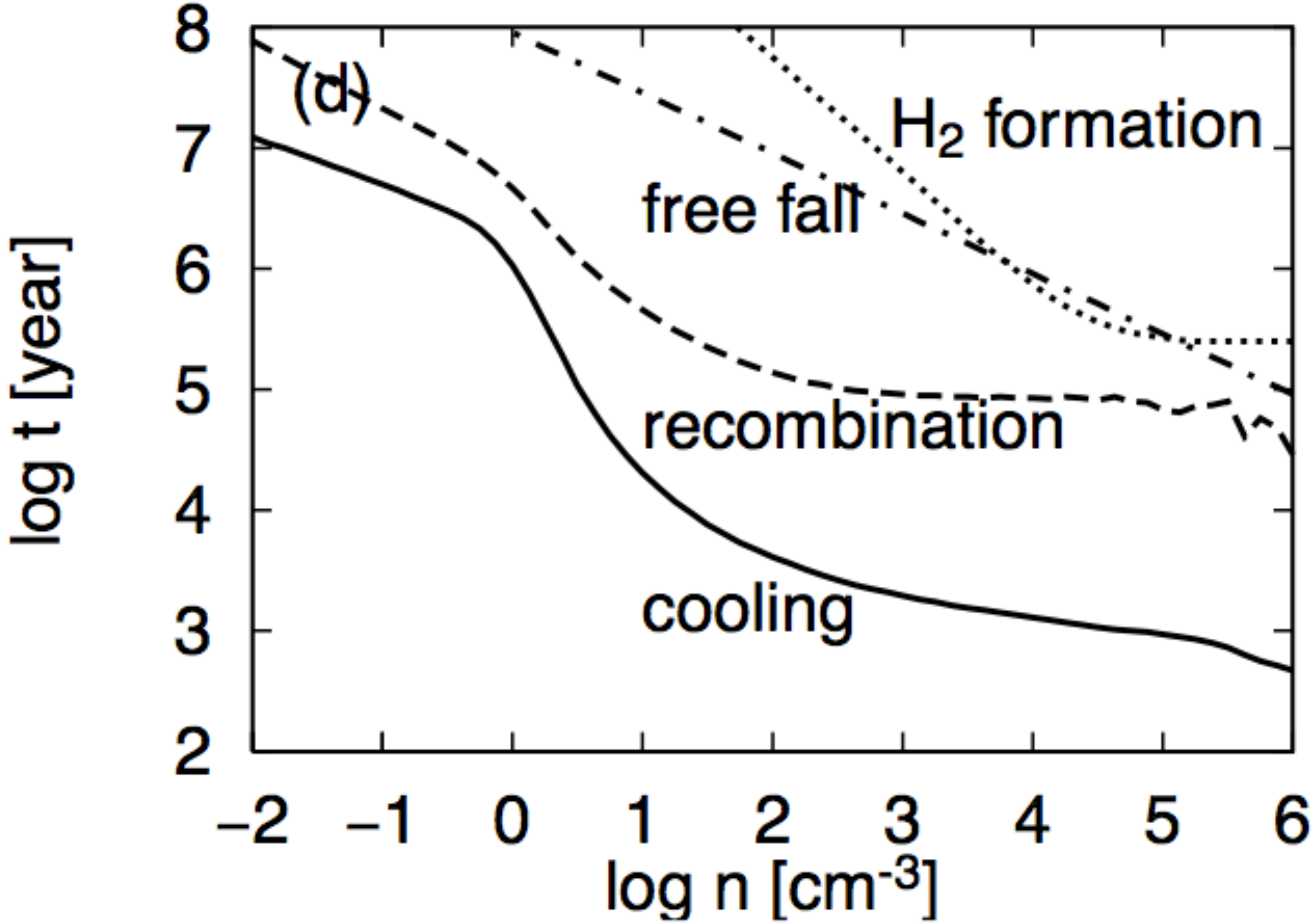
$$t_{\rm form} = 1/\left(\frac{dn_2}{dt} n_1\right) \sim 10^7 \left(\frac{10^2 {\rm cm}^{-3}}{n_1}\right) \quad \text{[yr]}$$

Timescales of molecular clouds*

- Crossing timescale: 10^5-10^7 yrs
- Free fall timescale: 10^6 yrs
- Cooling timescale: less than 10^4 yrs
- H_2 formation timescale: 10^7 yrs

* density $10^3 cm^{-3}$

Time scale summary

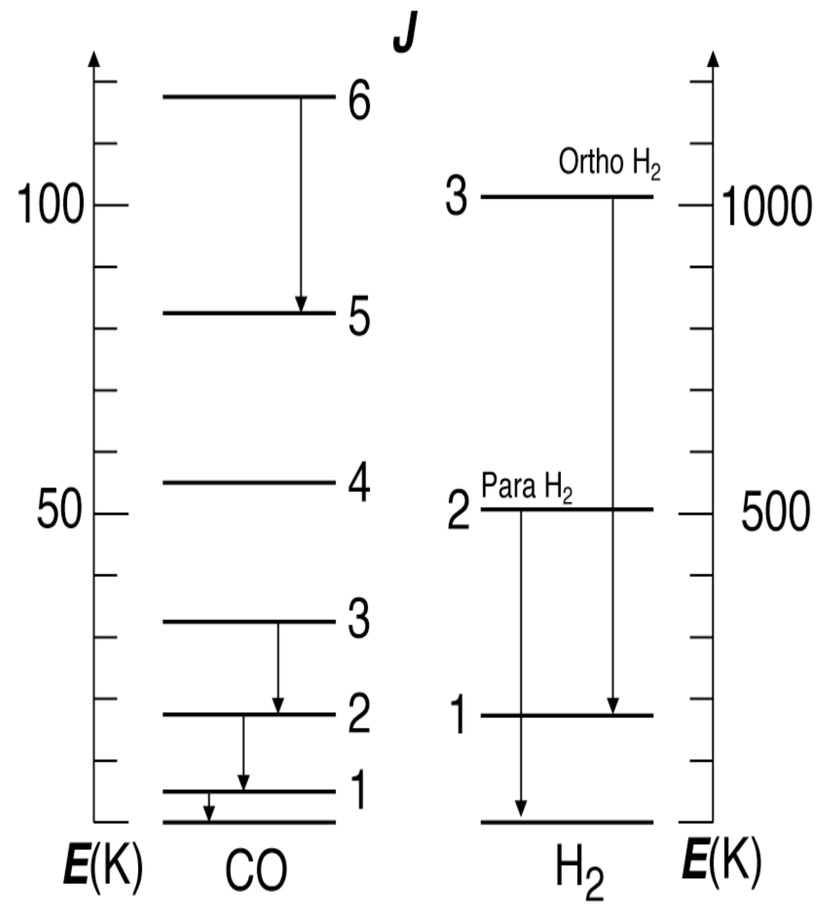


Koyama & Inutsuka 2000

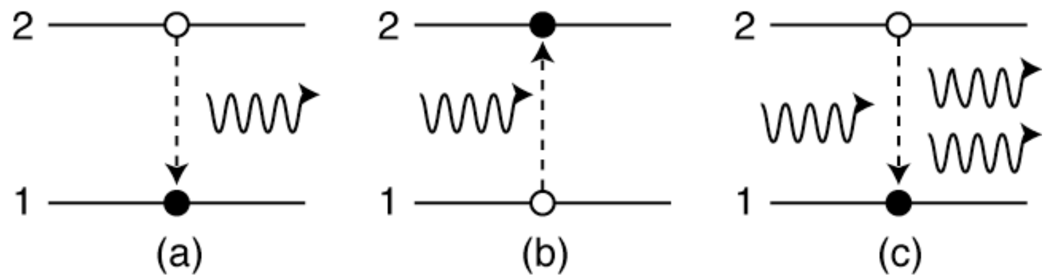
Excitation

- Hydrogen molecules are not observable in radio. Too high energy levels. Only in absorption.
- Carbon monoxide CO and others can be observed rotational energy levels, high excitation vibration. cf. electronic, spin-spin interaction

- Sub-mm transitions
generally higher excited states
ratio between J and J' gives density/tempearture.



Radiative transitions



The Einstein coefficients

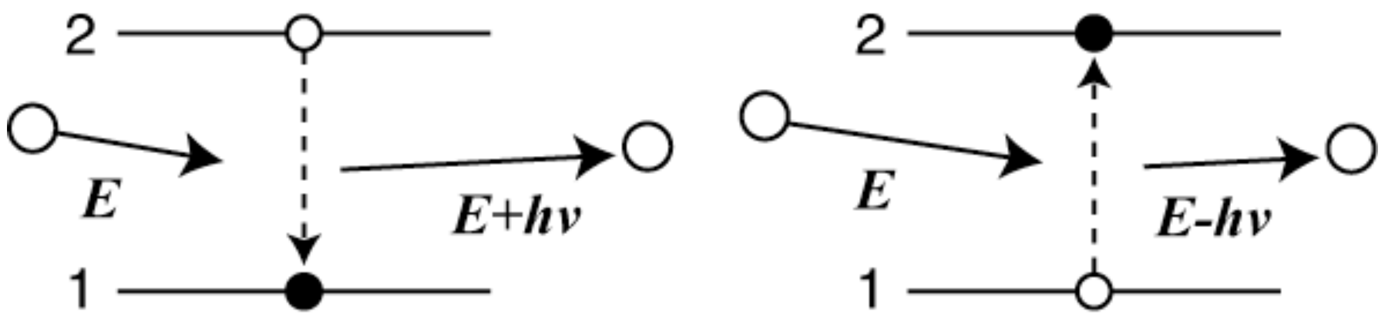
- (a) Spontaneous emission: $A_{21}n_2$
- (b) Photo absorption: $B_{12}I_\nu n_1$
- (c) Stimulated emission: $B_{21}I_\nu n_2$

$$A_{21} = \frac{2h\nu^3}{c^2}B_{21} = \frac{64\pi^4\nu^3}{3hc^3}\mu^2$$

(Electric dipole transition)

$$g_1 B_{12} = g_2 B_{21}$$

Collisional Excitation



De-excitation Excitation

- C coefficient : $C \approx N < \sigma v >$

(N: density, σ: cross section, v: velocity)

$$C_{21} = C_{12} \frac{g_1}{g_2} \exp\left(-\frac{\Delta E}{kT_{\rm k}}\right)$$

Detailed balancing

- Ex. Simple two level system rate equation

$$n_2[A_{21} + B_{21}I_\nu + C_{21}] \;=\; n_1[B_{12}I_\nu + C_{12}]$$

- Collision dominated $\quad C_{21} \;\gg\; A_{21} + B_{21}I_\nu$

$$\frac{n_2}{n_1} \;=\; \frac{C_{12}}{C_{21}} \;=\; \frac{g_2}{g_1}\exp\left(-\frac{E_{21}}{kT_{\rm k}}\right)$$

- Radiation dominated $\quad C_{21} \;\ll\; A_{21} + B_{21}I_\nu$

$$\frac{n_2}{n_1} \;=\; \frac{B_{12}I_\nu}{A_{21} + B_{21}I_\nu} \;=\; \frac{g_2}{g_1}\exp\left(-\frac{E_{21}}{kT_{\rm rad}}\right)$$

$$T_{\rm rad} \;\leq\; T_{\rm ex} \;\leq\; T_{\rm k}$$

Critical density

- When $I_\nu \rightarrow 0$ $$\frac{n_2}{n_1} = \frac{g_2}{g_1} \exp\left(-\frac{h\nu}{kT_{\rm ex}}\right) = \frac{C_{12}}{A_{21}+C_{21}}$$

$$\Rightarrow \quad \exp\left(-\frac{h\nu}{kT_{\rm ex}}\right) = \exp\left(-\frac{h\nu}{kT_{\rm k}}\right)\left[\frac{A_{21}}{C_{21}}+1\right]^{-1}$$

- Critical Density: $$n_{\rm crit} = \frac{A_{21}}{<\sigma v>}$$

- $n_{\rm crit} << n(H_2)$: LTE
- $n_{\rm crit} \sim n(H_2)$: excited but subthermal
- $n_{\rm crit} >> n(H_2)$: unexcited

Critical density

molecule	transition	freq. [GHz]	A [s^{-1}]	$n_{\rm crit}$ [cm^{-3}]
CO	$1 \to 0$	115.27	7.2×10^{-8}	2×10^{3}
CO	$3 \to 2$	345.80	2.5×10^{-6}	3×10^{4}
CO	$7 \to 6$	806.65	3.4×10^{-5}	5×10^{5}
CS	$1 \to 0$	48.99	1.7×10^{-6}	5×10^{4}
CS	$2 \to 1$	97.98	1.7×10^{-5}	3×10^{5}
HCO^+	$1 \to 0$	89.19	4.3×10^{-5}	2×10^{5}

Rotational excitation of a diatomic-molecule

- Eigenvalue of energy (Quantum mechanics)

$$E = \frac{\hbar^2}{2I} J(J+1) = \frac{h^2}{8\pi^2 I} J(J+1)$$

- Rotational quantum number, J $(J = 0,1,2,3,\ldots)$
- $\Delta J = \pm 1$

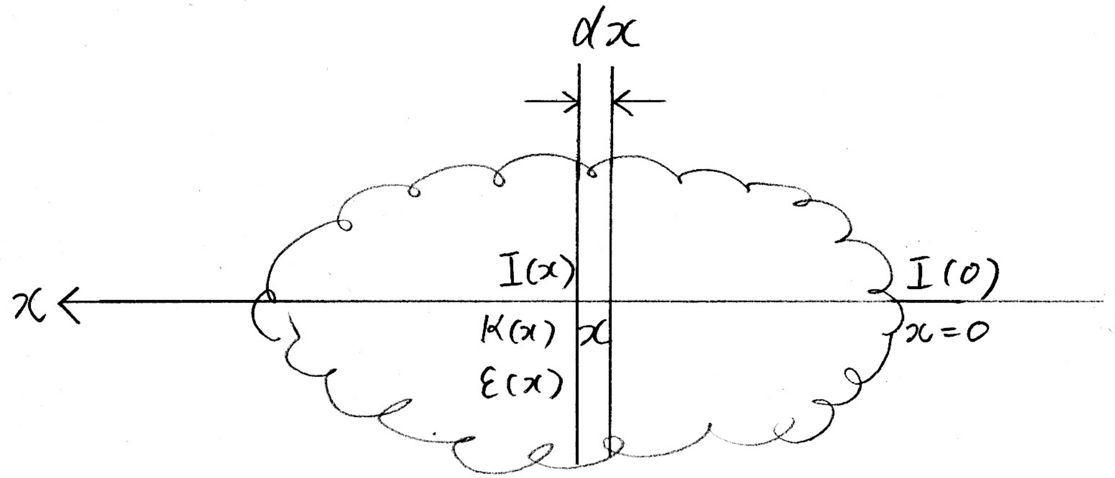
$$\nu_{J+1 \to J} = 2B(J+1) \quad (B \equiv \frac{h}{8\pi I})$$

- A coefficient

$$A_{J+1,J} = \frac{64\pi^4}{3hc^2} \nu^3_{J+1,J} \,|\, \mu_{J+1,J} \,|^2$$

$$|\, \mu_{J+1,J} \,|^2 = \frac{J+1}{2J+1} \mu^2$$

Radiative transfer



$$dI_\nu = -\kappa_\nu I_\nu dx + \epsilon_\nu dx$$

($\varepsilon_\nu(x)$: Emission coefficient, $\kappa_\nu(x)$: Absorption coefficient)

$$I_\nu = I_\nu(0)\exp(-\tau_\nu) + \frac{\epsilon_\nu}{\kappa_\nu}(1 - \exp(-\tau_\nu))$$

Optical depth: $\tau_\nu = \int \kappa_\nu dx$

Absorption coefficients

$$\kappa_\nu = \frac{h\nu}{4\pi}(B_{12}n_1 - B_{21}n_2)\varphi(\nu') \qquad \longleftarrow \quad g_1 B_{12} = g_2 B_{21}$$

$$= \frac{h\nu}{4\pi}\left(\frac{g_2}{g_1}n_1 - n_2\right)B_{21}\varphi(\nu') \qquad \longleftarrow \quad A_{21} = \frac{2h\nu^3}{c^2}B_{21}$$

$$= \frac{c^2 g_2 n_1}{8\pi\nu^2 g_1}\left[1 - \exp\left(-\frac{h\nu}{kT}\right)\right]A_{21}\varphi(\nu')$$

$\varphi(\nu)$: line profile function

$$\left(\int \varphi(\nu)d\nu = 1\right)$$

- When $\varphi(\nu)$ takes a Gaussian function.

$$\varphi(\nu_0) = \frac{2\sqrt{\ln 2}}{\sqrt{\pi}}\frac{1}{\Delta\nu} \approx \frac{1}{\Delta\nu}, \ (\Delta\nu : \text{FWHM line width})$$

Excitation temperature & Optical depth

- ^{13}CO J=1-0 (LTE assumption)
  - Radiation (Observed) Temperature, $T_R{}^*$

(*Back ground of spectral line is removed)

$$\frac{2\nu^2 k}{c^2} T_R^* = [B_\nu(T_{ex}) - B_\nu(T_{bg})](1 - \exp(-\tau_\nu))$$

$$T_R^* = T_0[f(T_{ex}) - f(T_{bg})](1 - \exp(-\tau_\nu))$$

$$T_0 = h\nu/k; \quad f(T) = (\exp(T_0/T) - 1)^{-1}$$

- Since τ_{12CO}(optical depth of ^{12}CO J=1-0) ≥ 1

$$T_{ex} = T_0^{12}\left\{\ln\left(1 + \frac{T_0^{12}}{T_{R,12CO}^* + T_0^{12} f(T_{bg} = 2.7\ [\mathrm{K}])}\right)\right\}^{-1}$$

- Then, derive τ_{13CO} (optical depth of ^{13}CO J=1-0)

Column density

$$\kappa_\nu = \frac{c^2 g_{J+1} n_1}{8\pi\nu^2 g_J}\left[1-\exp\left(-\frac{h\nu}{kT_{\text{ex}}}\right)\right]A_{J+1,J}\varphi(\nu')$$

$$= \frac{8\pi^3\nu\mu^2}{3hc}\left[1-\exp\left(-\frac{h\nu}{kT_{\text{ex}}}\right)\right]n_J\frac{J+1}{2J+1}\frac{1}{\Delta\nu}$$

- Partition function, Q

$$n_J = n\frac{g}{Q}\exp\left(-\frac{E_J}{kT_{\text{ex}}}\right) \qquad Q=\sum_{J=0}^{\infty} g_J\exp\left(-\frac{E_J}{kT_{\text{ex}}}\right)\approx\frac{kT_{\text{ex}}}{hB}\quad (hB << kT_{\text{ex}})$$

$$\kappa_\nu = \frac{8\pi^3 B\mu^2}{3ckT_{\text{ex}}}\left[1-\exp\left(-\frac{h\nu}{kT_{\text{ex}}}\right)\right]\exp\left(-\frac{hBJ(J+1)}{kT_{\text{ex}}}\right)\frac{2J+3}{2J+1}\frac{J+1}{2J+1}\frac{1}{\Delta\nu}n$$

$$\tau_\nu = \int\kappa_\nu dx = \frac{8\pi^3 B\mu^2}{3ckT_{\text{ex}}}\left[1-\exp\left(-\frac{h\nu}{kT_{\text{ex}}}\right)\right]\exp\left(-\frac{hBJ(J+1)}{kT_{\text{ex}}}\right)\frac{2J+3}{2J+1}\frac{J+1}{2J+1}\frac{1}{\Delta\nu}N$$

$$N(^{13}\text{CO}) = 2.42\times10^{14}\left(\frac{\tau_{^{13}\text{CO}}T_{\text{ex}}\Delta v}{1-\exp([5.29/T_{\text{ex}}])}\right)$$

Physical parameters from CO emission

- Mass: $$M_{\rm CO} = u m_{\rm H} \sum [D^2 \Omega N({\rm H_2})]$$

u: mean molecular weight, $m_{\rm H}$: H atom mass,
D: distance to object, Ω: solid angle, $N(\rm H_2)$: H_2 column density

- ^{12}CO
  - Optically thick ($\tau \geq 1$)
  - Can trace only envelopes.
  - X-factor (empirical): $$N({\rm H_2}) = X_{\rm CO} \times W_{\rm CO}$$

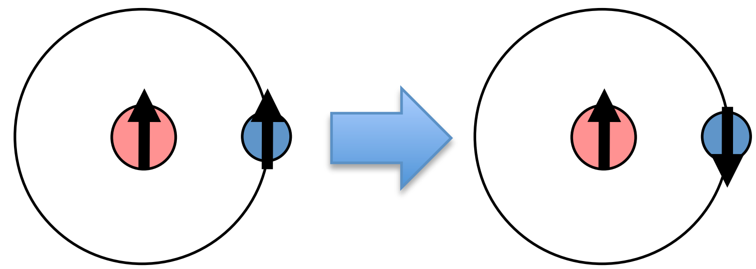
$W_{\rm CO}$: ^{12}CO integrated intensity

0.7×10^{20} cm^{-2} (K km s^{-1})$^{-1}$ (Torii et al. 2011, the Galactic centre)

2.0×10^{20} cm^{-2} (K km s^{-1})$^{-1}$ (Bertsch et al. 1993, disk average)

HI 21cm line

hyperfine levels of the
hydrogen 1s ground state



- Spin angular momentum
  Upper: $1/2 + 1/2 = 1$ $(1 = \pm 1, 0)$, $g_2 = 3$
  Lower: $1/2 - 1/2 = 0$, $g_1 = 1$
- $\Delta E = 9.4\times10^{-25}$ J ($T = \Delta E/k = 0.068$ K)
- $\nu = 1420.405$ MHz, $\lambda = 21.106$ cm
- $A_{21} = 2.85\times10^{-15}$ s^{-1} (Optically thin)

Derivation of physical parameters

- Rayleigh-Jeans approximation

$$\tau_\nu = \frac{c^2 h g_2}{8\pi\nu g_1 k}\frac{A_{21}}{T}\varphi(\nu')\int n_1 dx \equiv \frac{c^2 h g_2}{8\pi\nu g_1 k}\frac{A_{21}}{T}\varphi(\nu')N_1$$

- Column density: $N_1 = \int n_1 dx$

- τ << 1 case

$$T_b = T_b(0)\exp(-\tau_\nu) + T(1-\exp(-\tau_\nu)) \approx T_b(0) + \tau_\nu T$$

$$\Delta T_b = \frac{c^2 h g_2}{8\pi\nu g_i k}A_{21}N_1\varphi(\nu') \quad (\Delta T_b \equiv T_b - T_b(0))$$

$$\int \Delta T_b d\nu' = \frac{\nu}{c}\int \Delta T_b dv = \frac{c^2 h g_2}{8\pi\nu g_i k}A_{21}N_1$$

$$N_1 = \frac{8\pi\nu^2 g_1 k}{c^3 h g_2 A_{21}}\int \Delta T_b dv$$

HI 21cm line

- In the thermodynamic equilibrium

$$\frac{N_2}{N_1} = \frac{g_2}{g_1}\exp\left(-\frac{h\nu}{kT}\right) \approx \frac{g_2}{g_1} = 3$$

(Rayleigh-Jeans approx.)

$$N_{\rm HI} = N_2 + N_1 = 4N_1$$

$$N_{\rm HI} = 4 \times \frac{8\pi\nu^2 g_1 k}{c^3 h g_2 A_{21}} \int \Delta T_b dv$$

$$= \boxed{1.82 \times 10^{18} \int \Delta T_b dv \quad ({\rm cm}^{-2})}$$

How to measure ISM protons (H_2)

- ^{12}CO emission and X-factor

$$N(\mathrm{H_2}) = X_{\mathrm{CO}} \times (\mathrm{CO\ integrated\ intensity})$$

$$X_{\mathrm{CO}} \approx 2 \times 10^{20}\ \mathrm{cm^{-2}}\ (\mathrm{K\ km\ s^{-1}})^{-1}$$

- ^{13}CO C^{18}O vs. Extinction

$$N(^{13}\mathrm{CO})(\mathrm{cm^{-2}}) \approx (1-2) \times 10^{15} A_V(\mathrm{mag})$$

$$N(\mathrm{C^{18}O})(\mathrm{cm^{-2}}) \approx (2-3) \times 10^{14}\ A_V(\mathrm{mag})$$

$N(\mathrm{H_2})/A_\mathrm{V} = 9.4\times10^{20}$ (cm^{-2} mag^{-1}) gives

$$N(\mathrm{H_2}) \approx 10^6 N(^{13}\mathrm{CO}) \approx 6 \times 10^6\ N(\mathrm{C^{18}O})$$

How to measure ISM protons (HI)

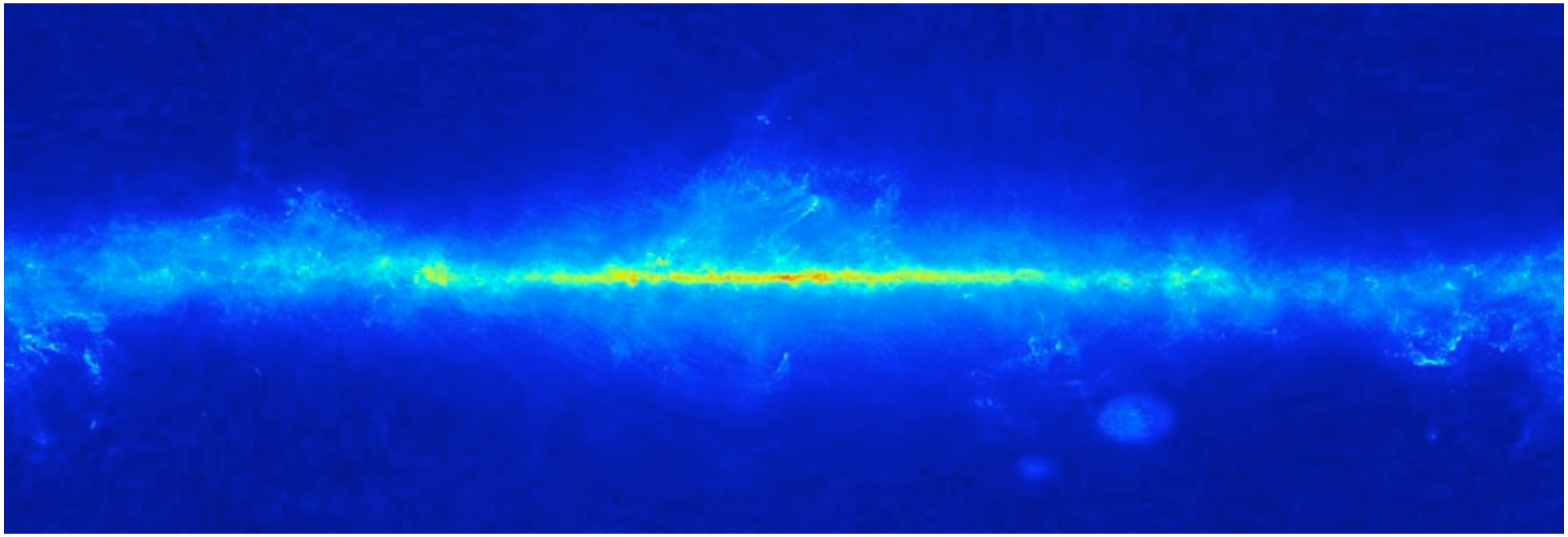
$$N(\mathrm{HI}) = \frac{32\pi \nu k}{3c^2 h A_{\mathrm{ul}}} \int_{\nu_1}^{\nu_2} \int_0^l T_{\mathrm{s}} \kappa_\nu \, dx \, d\nu = \frac{32\pi \nu^2 k}{3c^3 h A_{\mathrm{ul}}} \int_{v_1}^{v_2} T_{\mathrm{b}} \, dv$$

$$= 1.823 \times 10^{18} \times (\text{HI integrated intensity in K km s}^{-1})$$

- HI emission:

  usual assumption is "optically thin"
  - caveat: sometimes this assumption fails
    e.g., dark gas, HISA (cold HI in self-absorption)

Dust optical/near IR extinction



Dobashi+ 2005, 2011

How to measure ISM protons

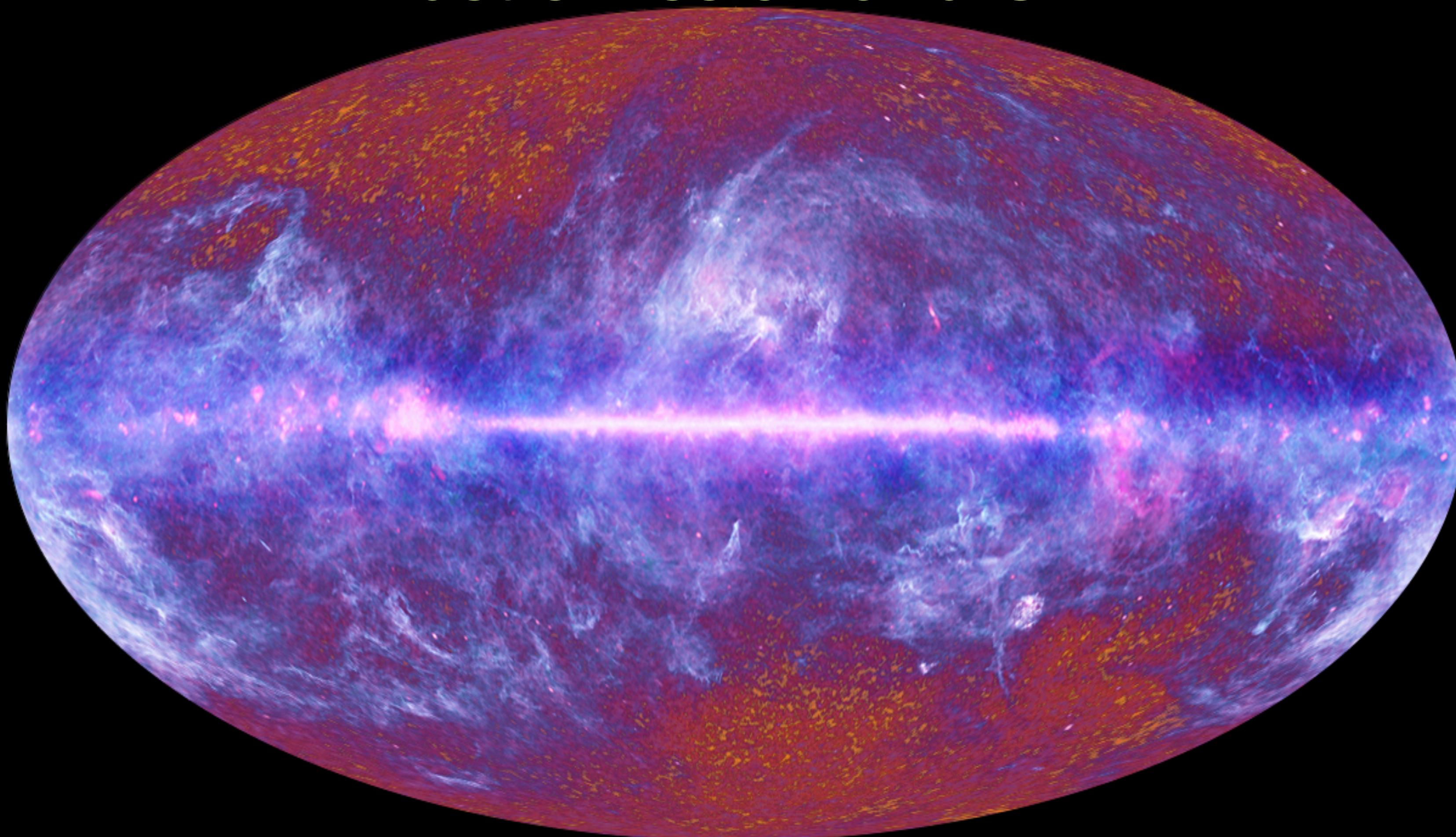
- N(HI+H_2)/E(B-V) ratio derived from the observations of the *Copernicus* satellite (Bohlin+ 1978)

$$\frac{N(\mathrm{H\,I} + \mathrm{H_2})}{E(B-V)} = 5.8 \times 10^{21}\,\mathrm{cm^{-2}mag^{-1}}$$

- adopting $R_V = A_V / E(B\text{-}V) = 3.1$ and assuming all hydrogen in dense clouds is in the molecular form, we have

$$\frac{N(\mathrm{H_2})}{A_V} = 9.4 \times 10^{20}\,\mathrm{cm^{-2}mag^{-1}}$$

Dust emission and CMB



The Planck one-year all-sky survey

esa

(c) ESA, HFI and LFI consortia, July 2010

ISM protons from dust emission

$$N(\mathrm{H_2}) = \frac{S_\nu^{\mathrm{beam}}}{\Omega_{\mathrm{beam}} \mu m_{\mathrm{H}} \kappa_\nu B_\nu(T_{\mathrm{dust}})}$$

S_ν^{beam}	flux density per beam
Ω_{beam}	Beam solid angle
$\mu = 2.8$	Mean molecular weight
$m_{\mathrm{H}} = 1.67 \times 10^{-24}$ g	Mass of H atom
$\kappa_\nu \propto \nu^{-\beta}$	Mass absorption coefficient per gram
$B_\nu(T_{\mathrm{dust}})$	Planck function at the dust temperature T_{dust}

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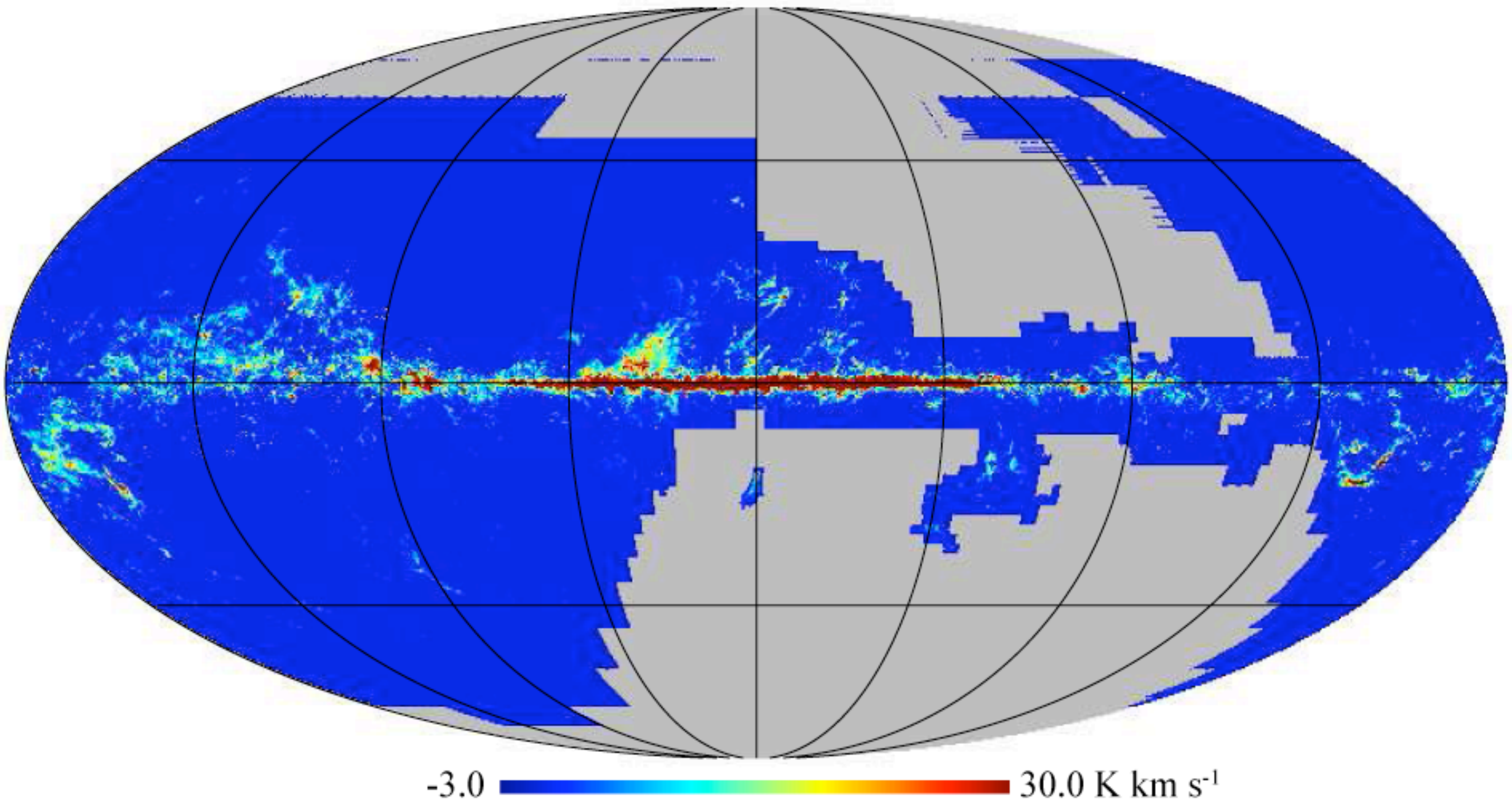
CO surveys : CfA + NANTEN



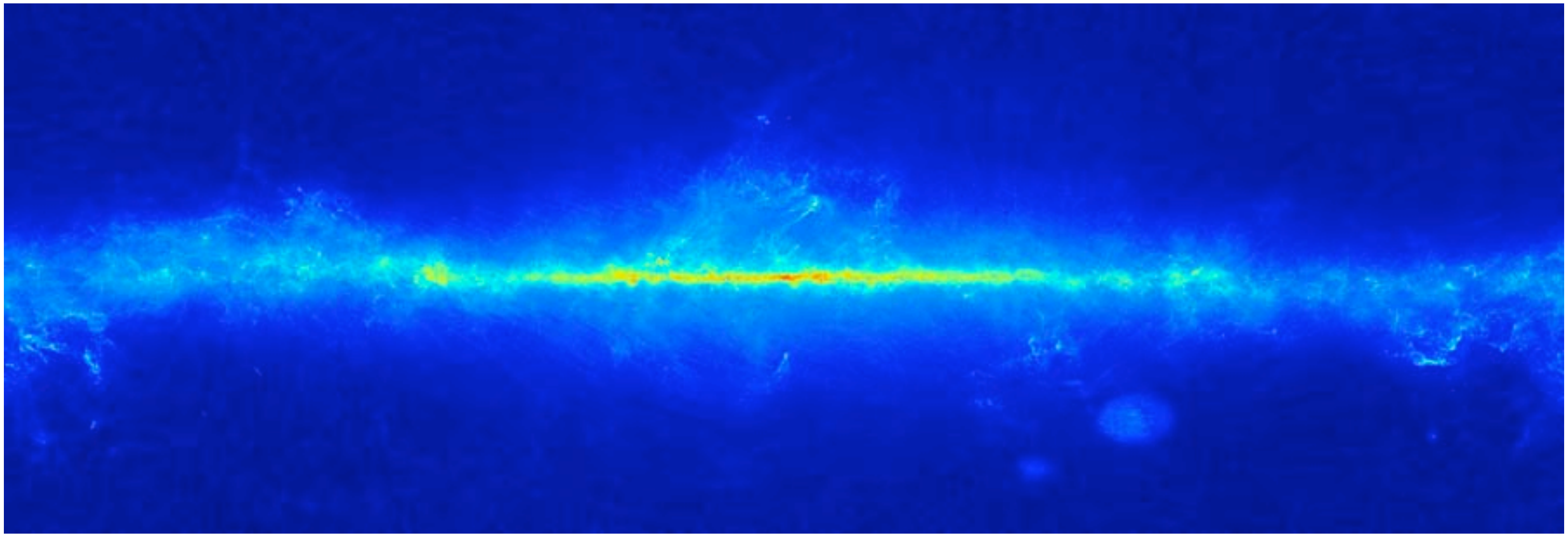
Planck Collaboration, arXiv:1101.2029

NANTEN & NANTEN2

@Las Campanas, alt.2400m

@Atacama, alt.4800m

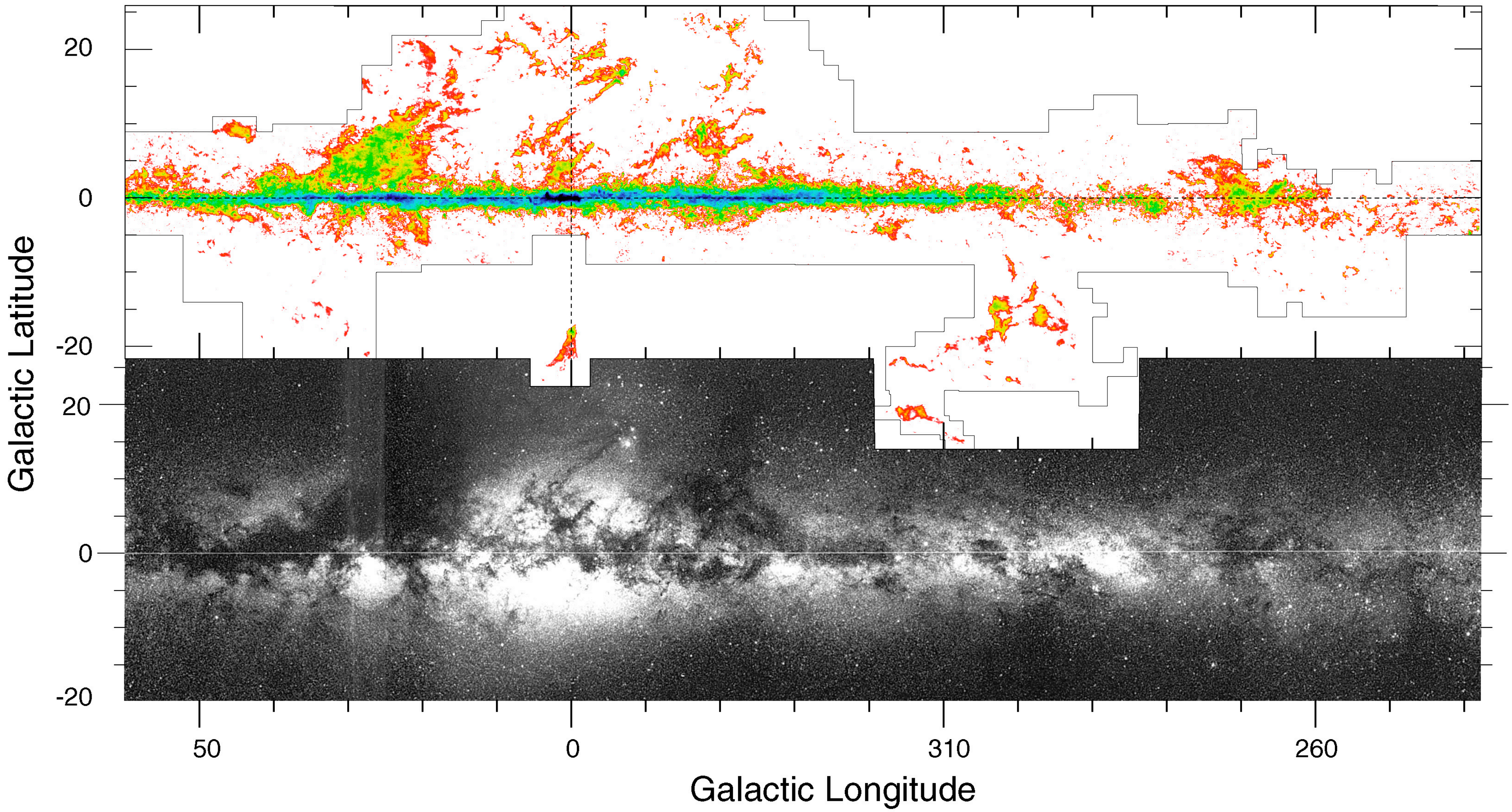
Dust optical/near IR extinction



Dobashi+ 2005, 2011

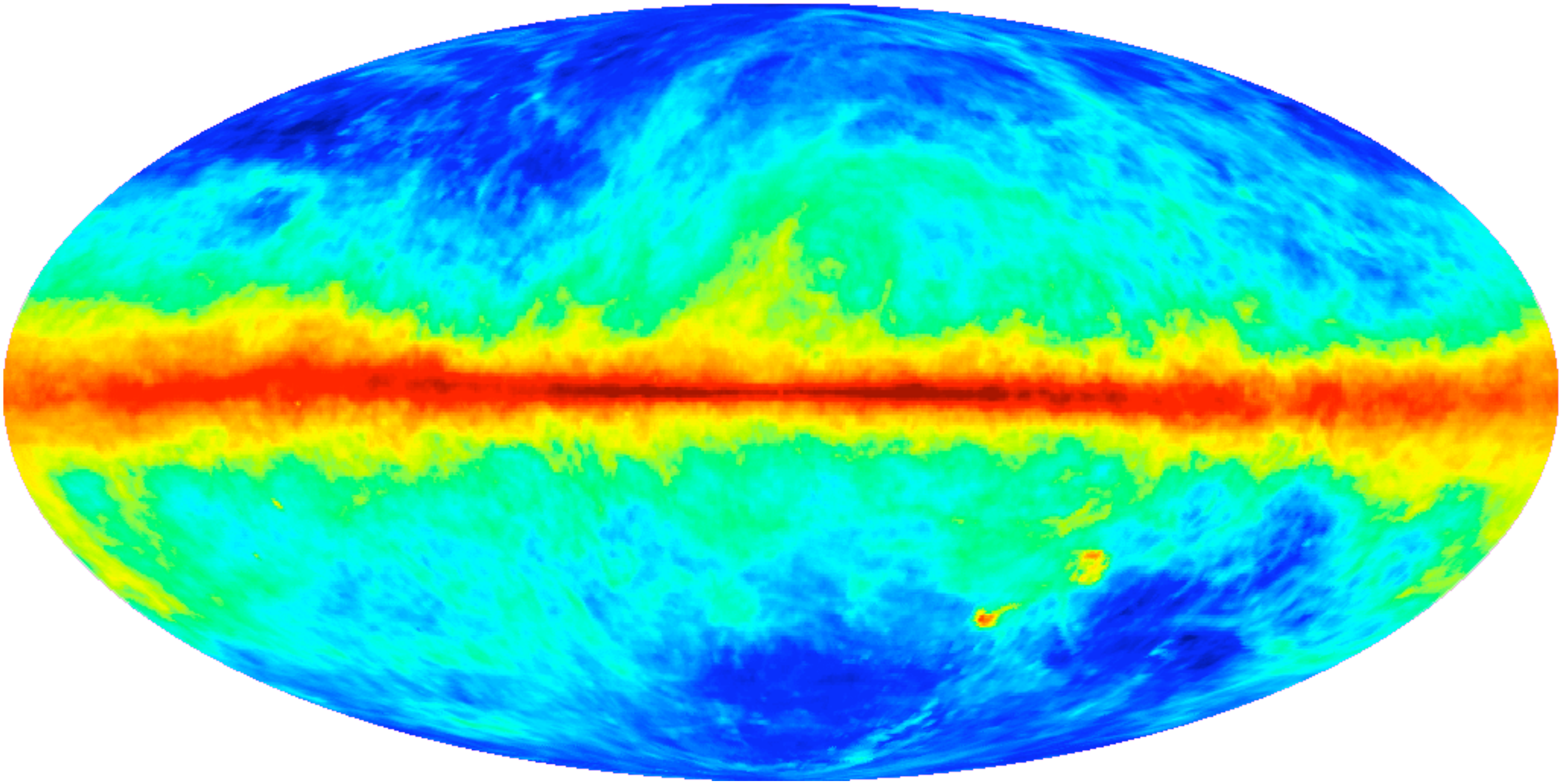
Galactic Plane Survey

- ^{12}CO(J=1-0), Grid size ~ 4′ (|b|<5°), 8′ (5°<|b|<10°)
- Integ. time (typ) ~5sec/point,   1,100,000 observed points



写真：EXPLORING THE SOUTHERN SKY (1988)

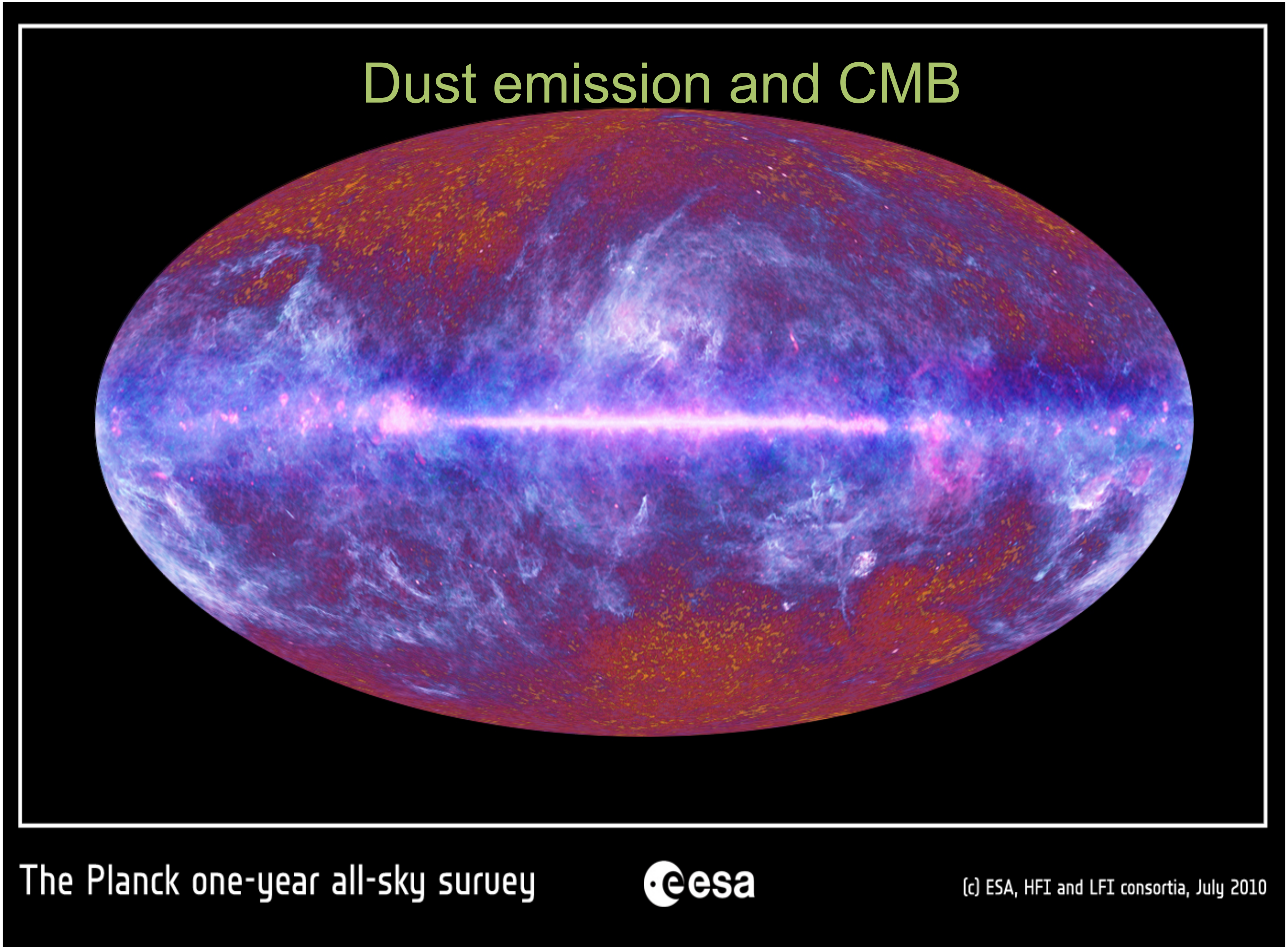
HI LAB



The Leiden/Argentine/Bonn Galactic HI Survey

Kalberla+ 2005
Courtesy of Legacy Archive for Microwave Background Data Analysis

Dust emission and CMB



The origin of cosmic ray protons

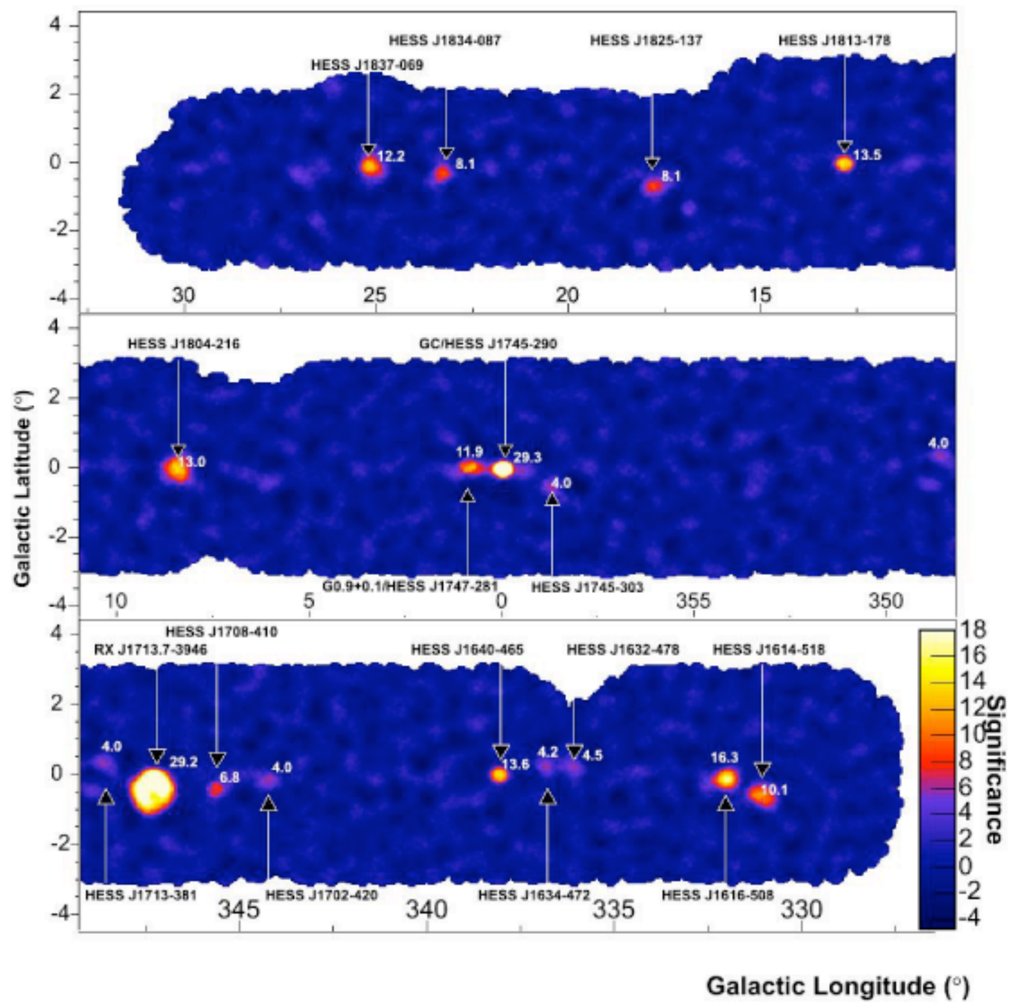
Hadronic vs. leptonic (electron's inverse Compton etc.)
Hadronic $p + p \Rightarrow \pi^0 \Rightarrow 2\gamma$ seems promising
energy spectrum by HESS, Fermi, AGILE

TeV γ SNR RXJ1713.7-3946, brightest HESS source
If hadronic we need target ISM protons,
we need to know target protons
in order to estimate CR proton energy

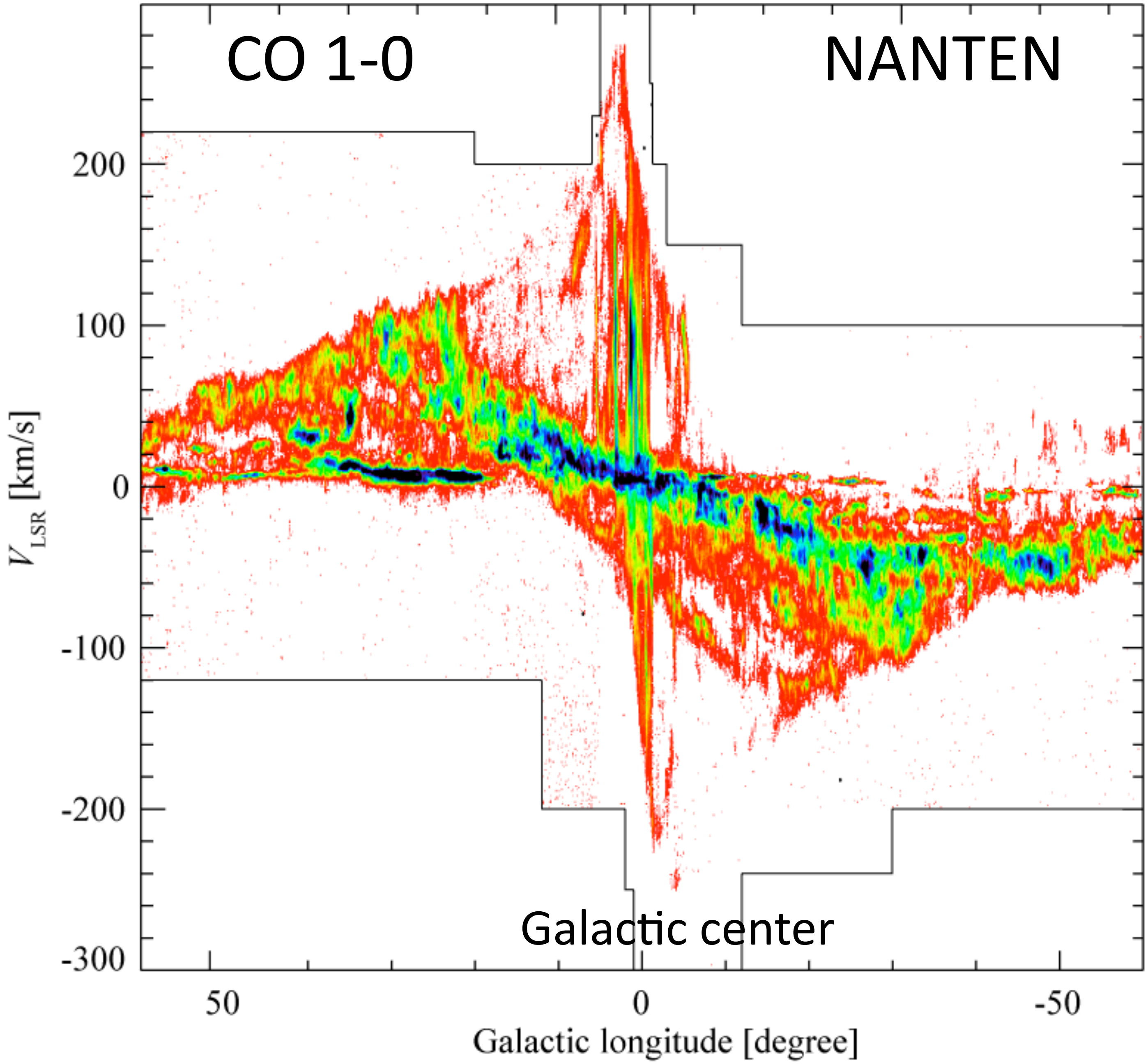
Collaborators

- HESS team: F. Aharonian, G. Rowell +
- HI: N. McClure-Griffiths +
- MHD: Inutsuka +

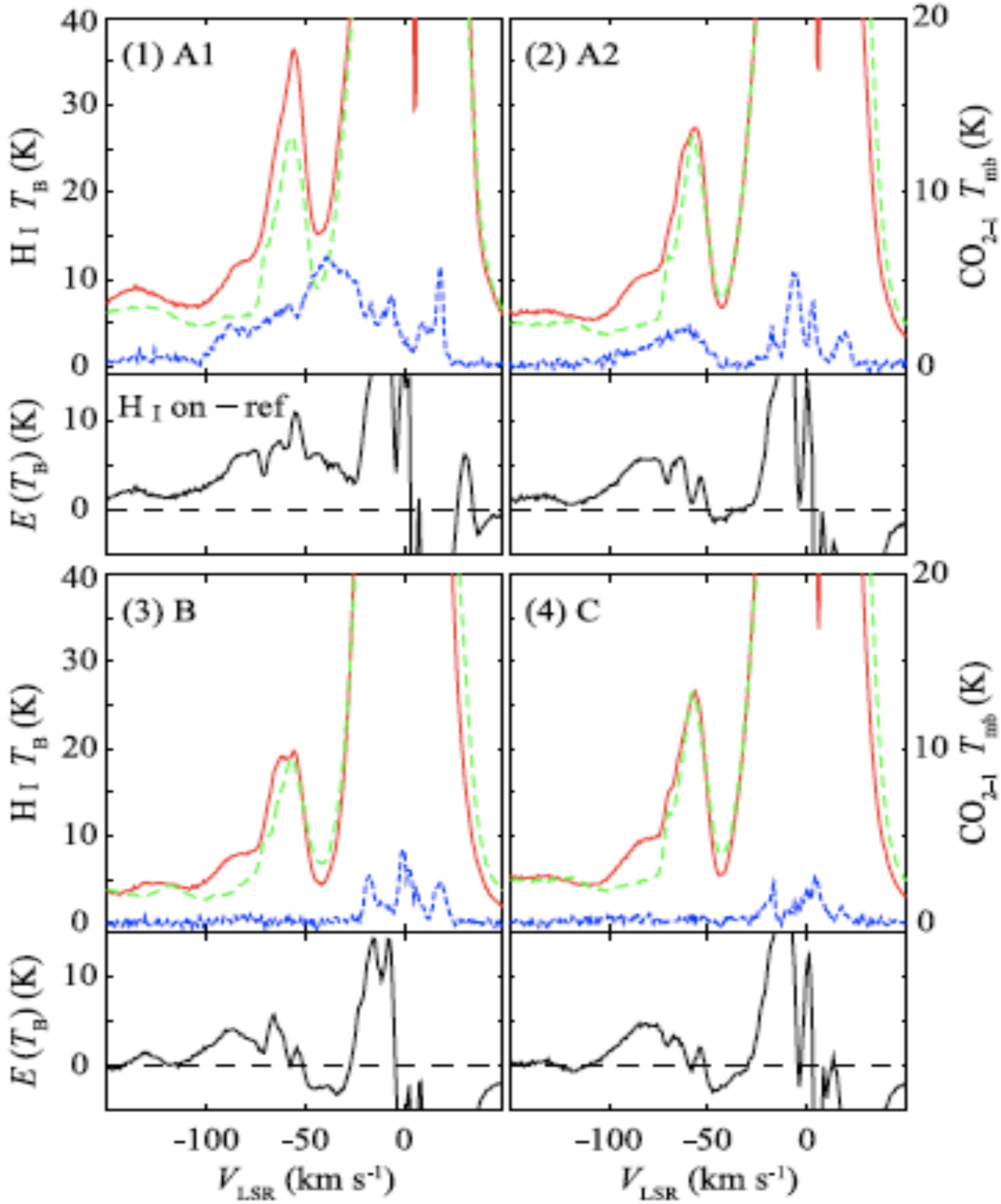
HESS TeV gamma-ray sources



Aharonian+ (2006)



CO 1-0
NANTEN
Galactic center
200
100
0
-100
-200
-300
V_{LSR} [km/s]
50
0
-50
Galactic longitude [degree]



Galactic centre

Red On source HI

Green Reference HI

Blue CO

Black Subtracted HI
[Cold dense HI]

Hayakawa et al. 2011

Supernova remnant (SNR) W28(G6.4-0.1)

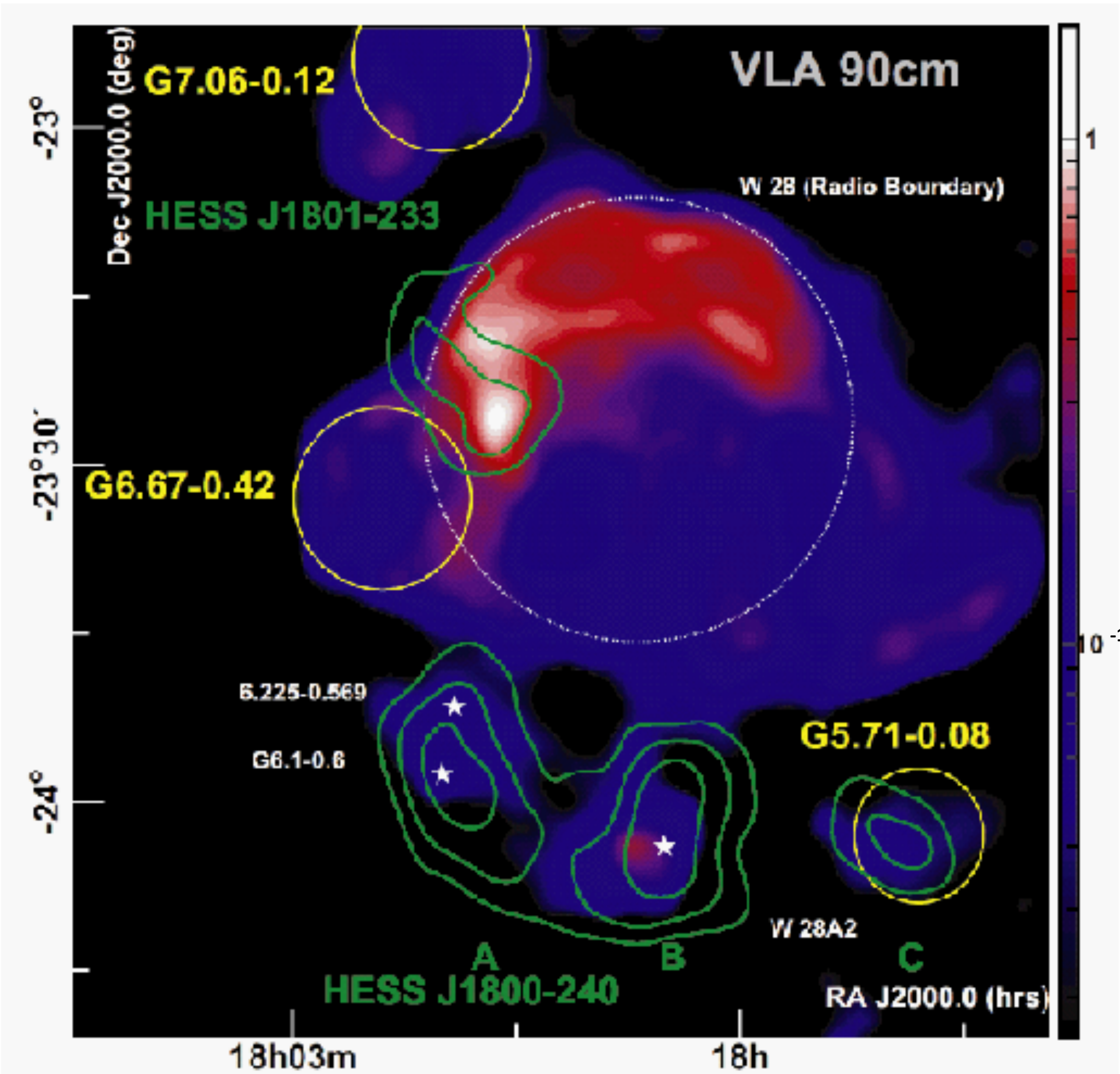
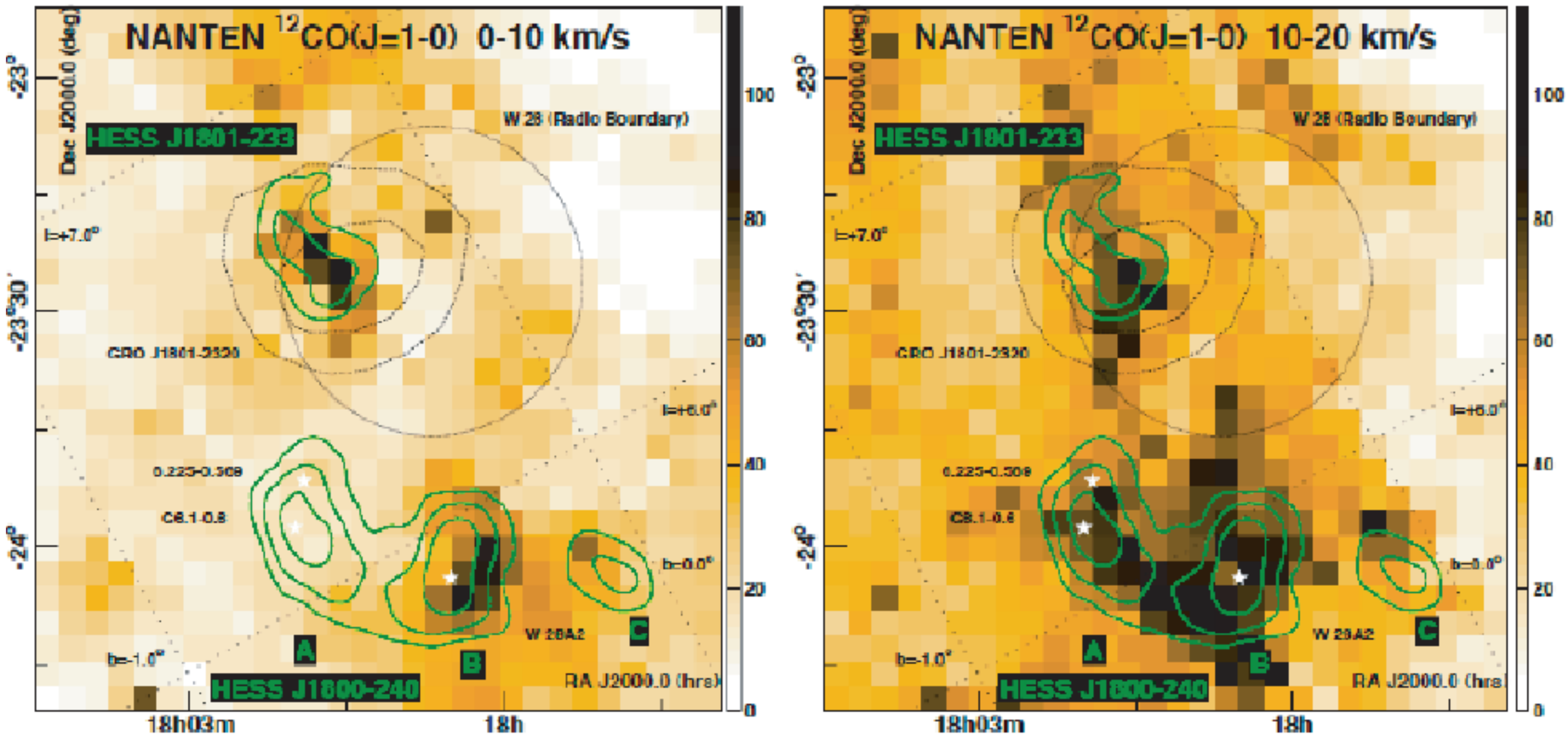


Fig: VLA 90cm radio image from Brogan et al.(2006). Overlaid are solid green contours of TeV gamma-ray significance levels of 4 ,5 and 6 σ. White stars indicate HII region.

Aharonian et al. (2008)

TeV γ vs. CO(J=1-0)

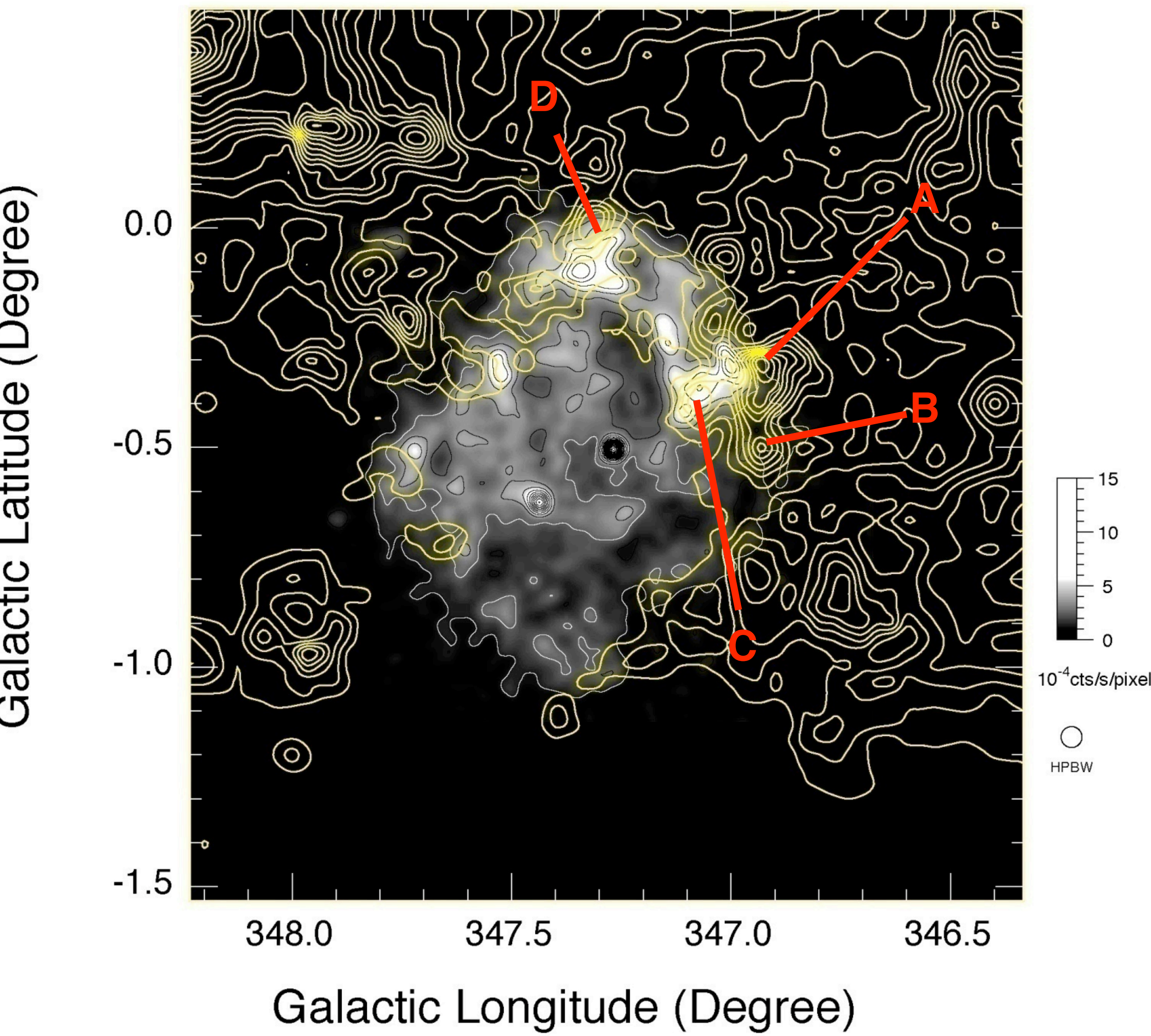


Left: NANTEN 12CO(1-0) image (beam size : 2.7’) of the W 28 region for VLSR=0 to 10 km/s with VHE γ ray significance contours overlaid (green) -levels 4,5,6σ. The radio boundary of W 28, the 68% and 95% location contours of GRO J1801－2320 and the location of the HII region W 28A2 (white stars) are indicated.

Right: NANTEN 12CO(1-0) image for VLSR=10 to 20 km/s.

(Aharonian et al. 2007)

RXJ1713.7-3946: ^{12}CO(J=1-0) with X-ray



<u>molecular hole</u>
surrounding boundary of the SNR

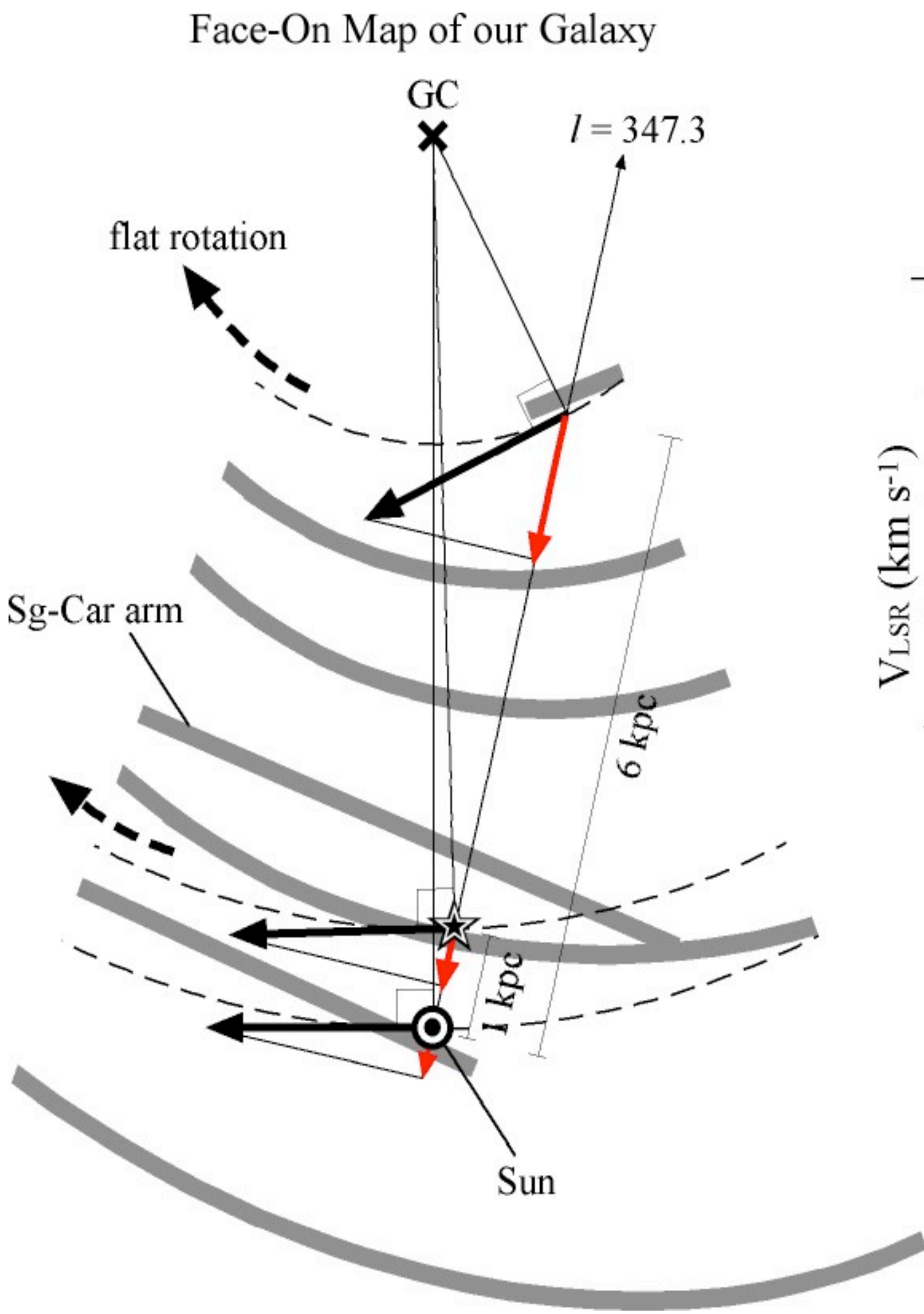
CO peaks⇔X-ray peaks show good spatial correlation (northwestern bright rim)

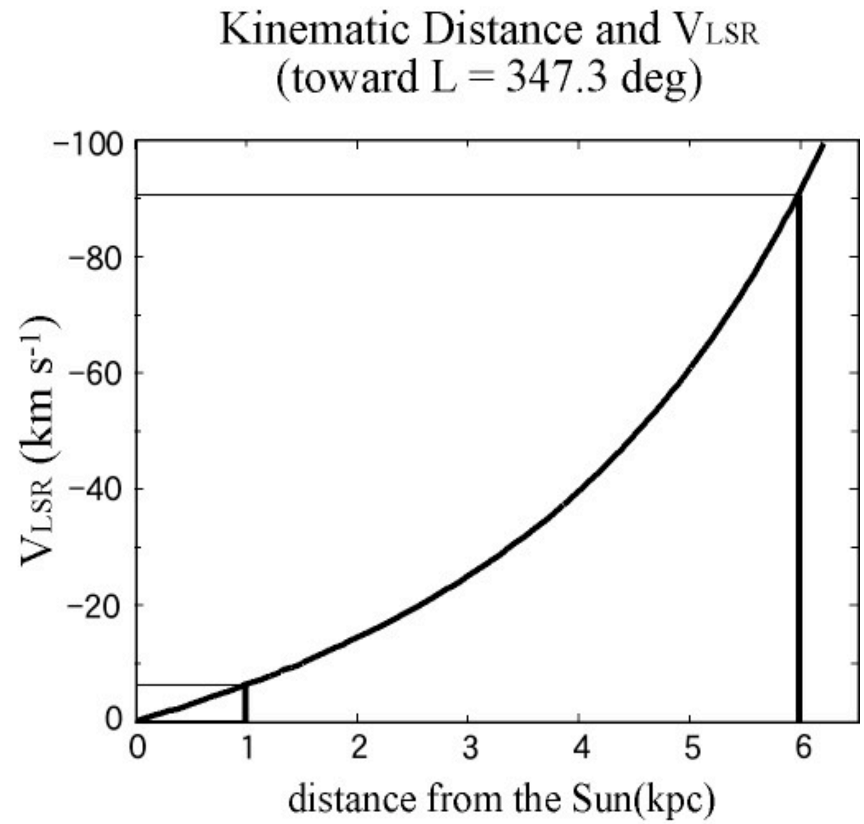
↓

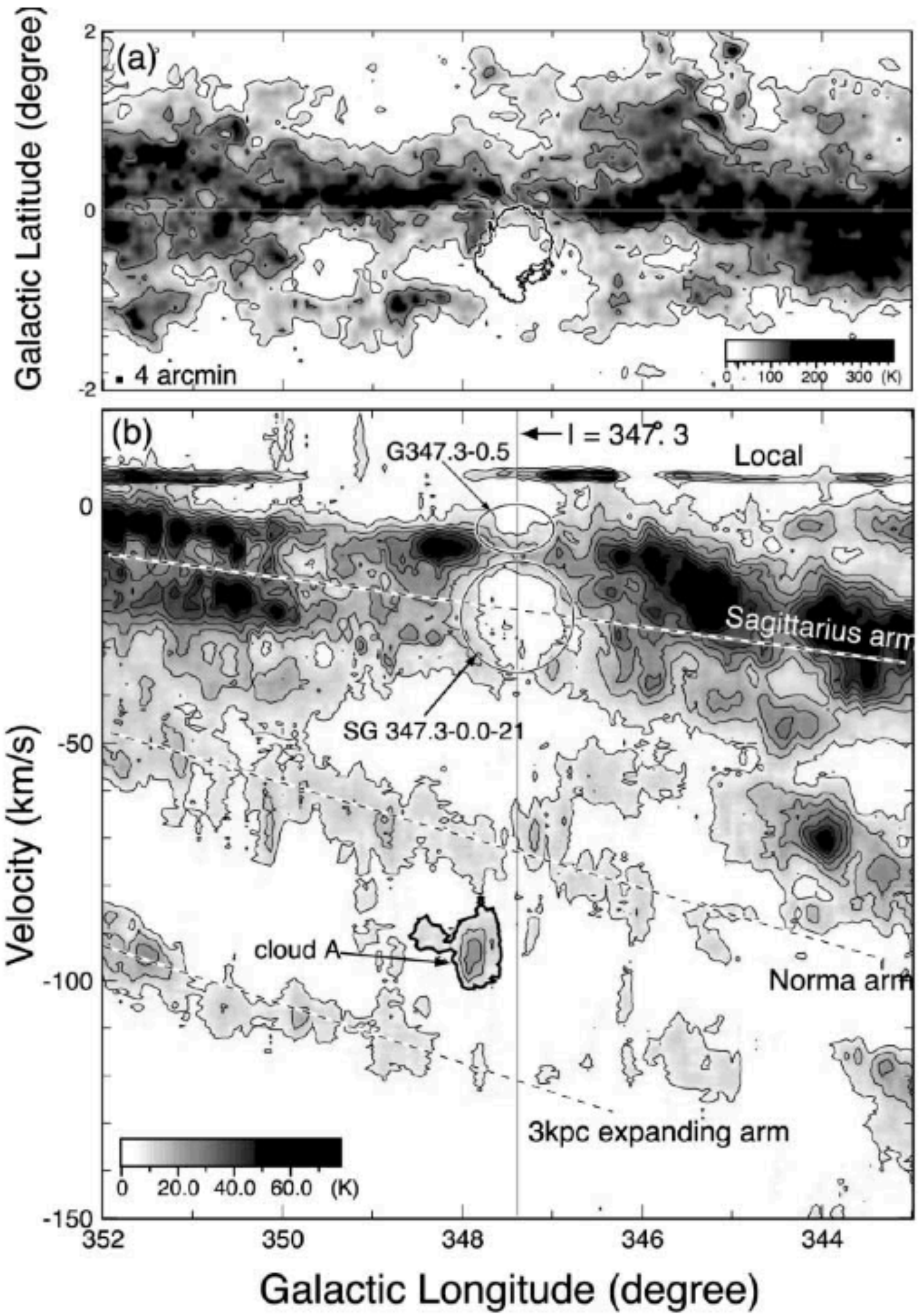
indicates interaction of the SNR with molecular clouds.

SNR at 1kpc, 1600yrs

Fukui et al. 2003


Face-On Map of our Galaxy
GC
l = 347.3
flat rotation
Sg-Car arm
6 kpc
1 kpc
Sun

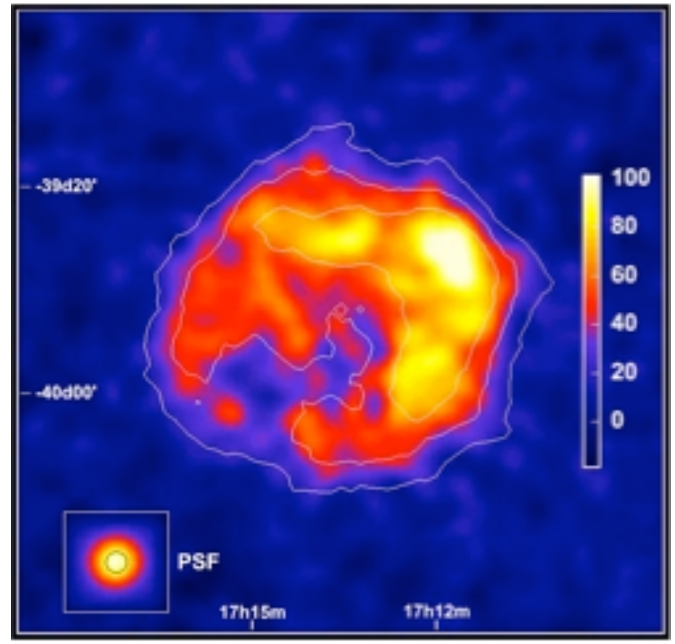

Kinematic Distance and VLSR
(toward L = 347.3 deg)
VLSR (km s-1)
-100
-80
-60
-40
-20
0
0
1
2
3
4
5
6
distance from the Sun(kpc)



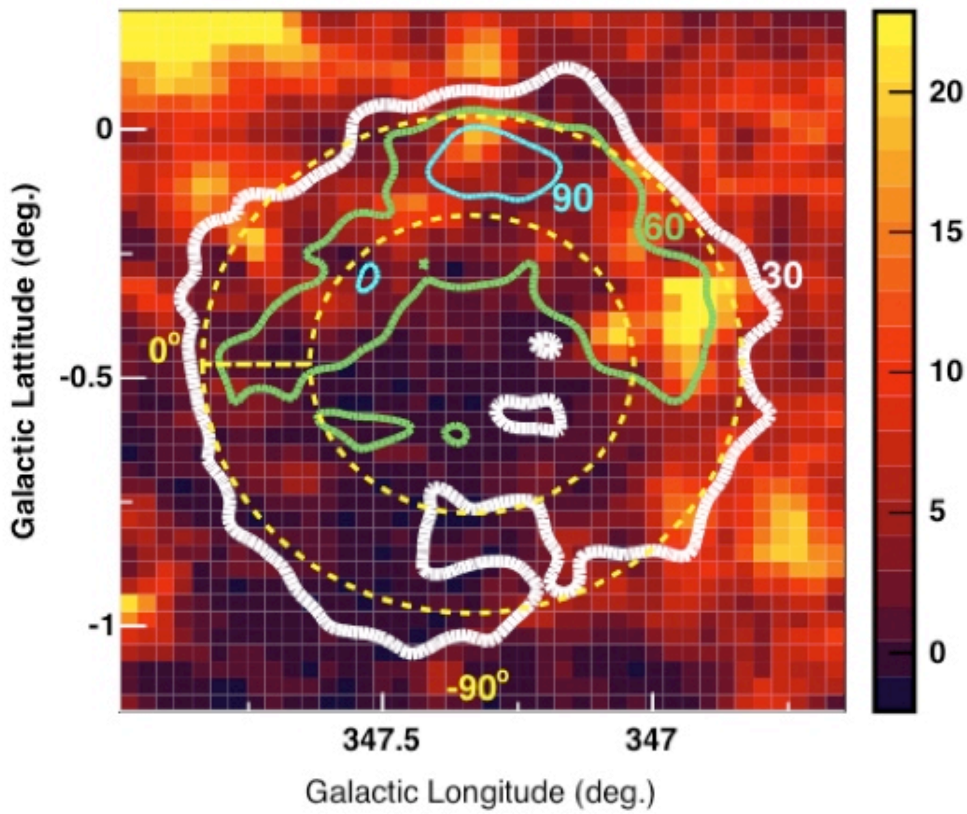
Moriguchi+05

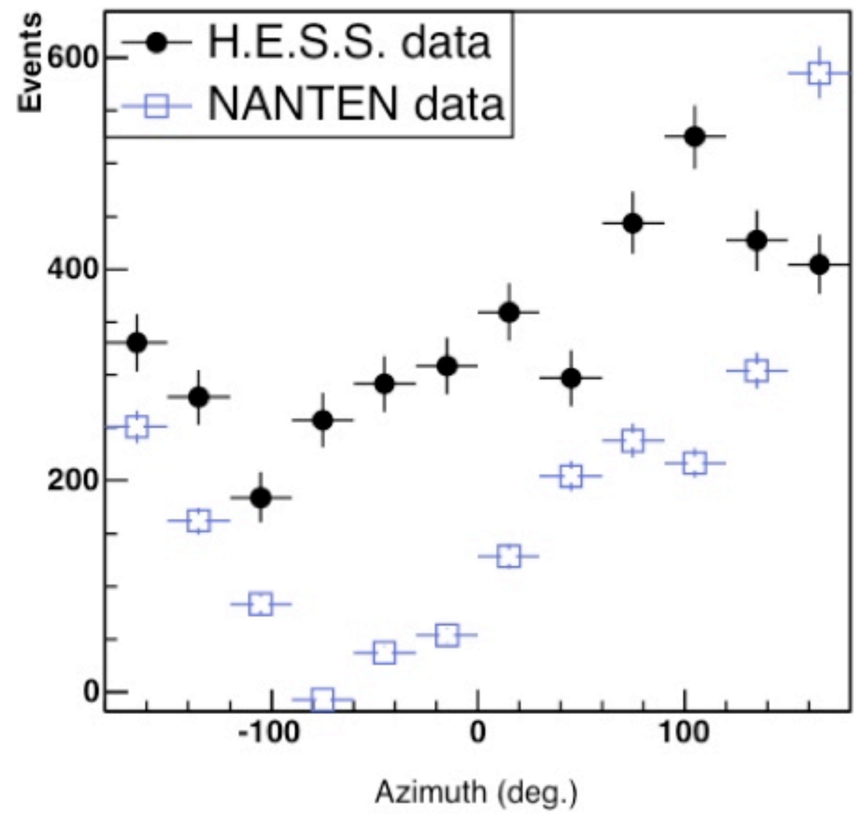
SNR G347.3-0.5 (RXJ1713.7-3946)

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

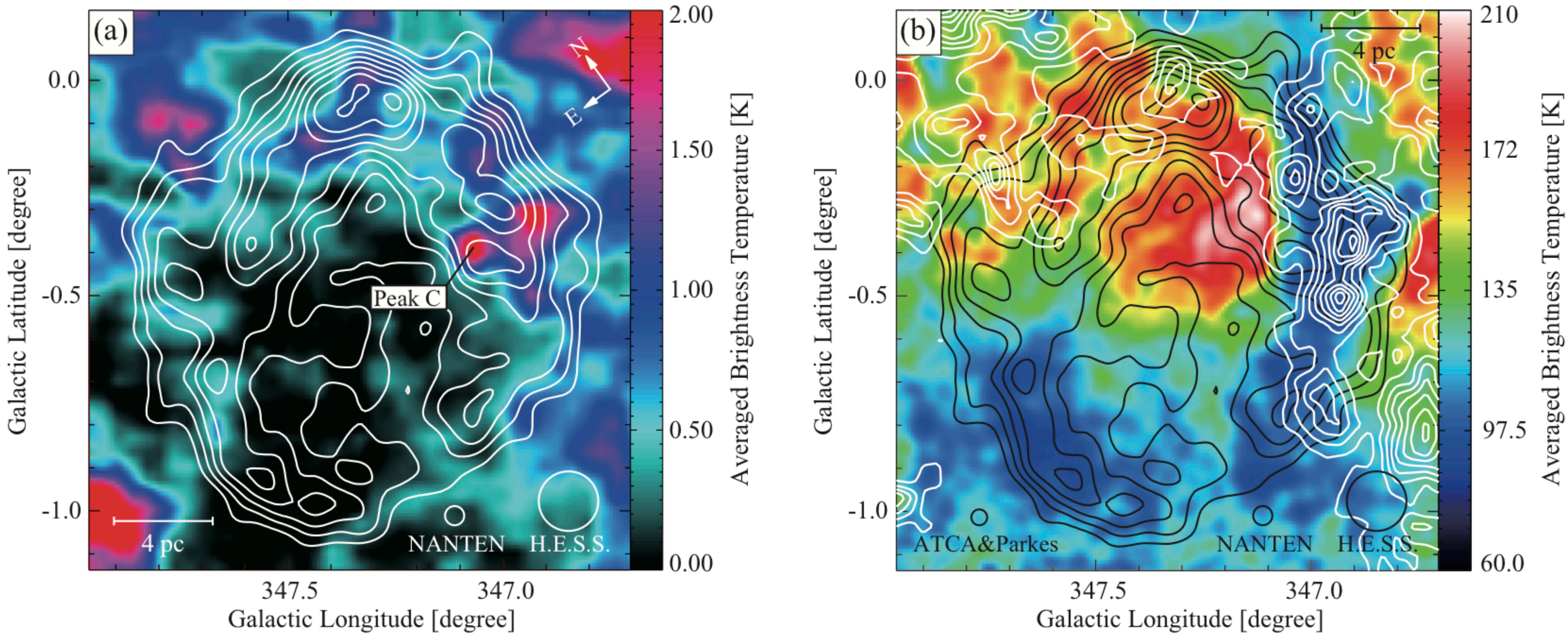


Aharonian et al. 2005

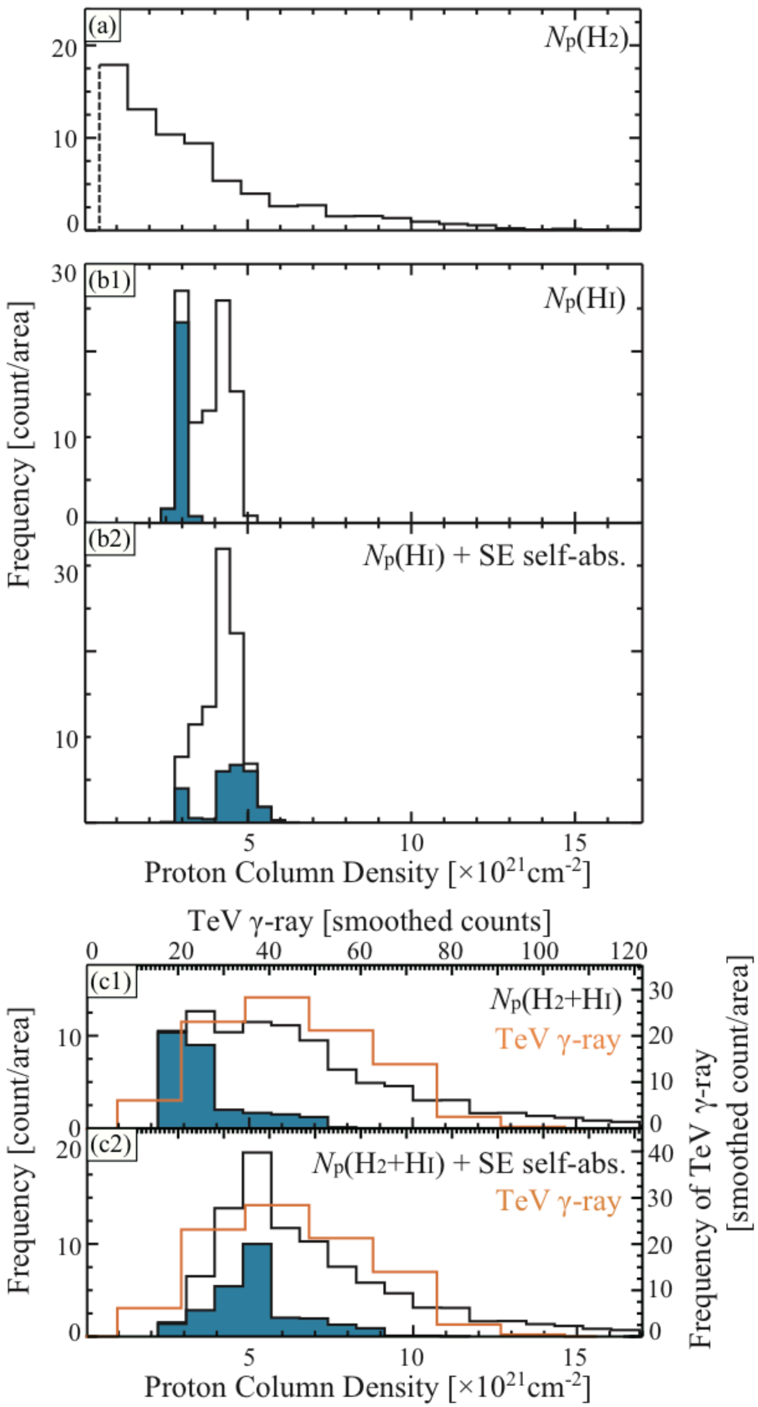




CO, HI & TeV γ-ray Distributions

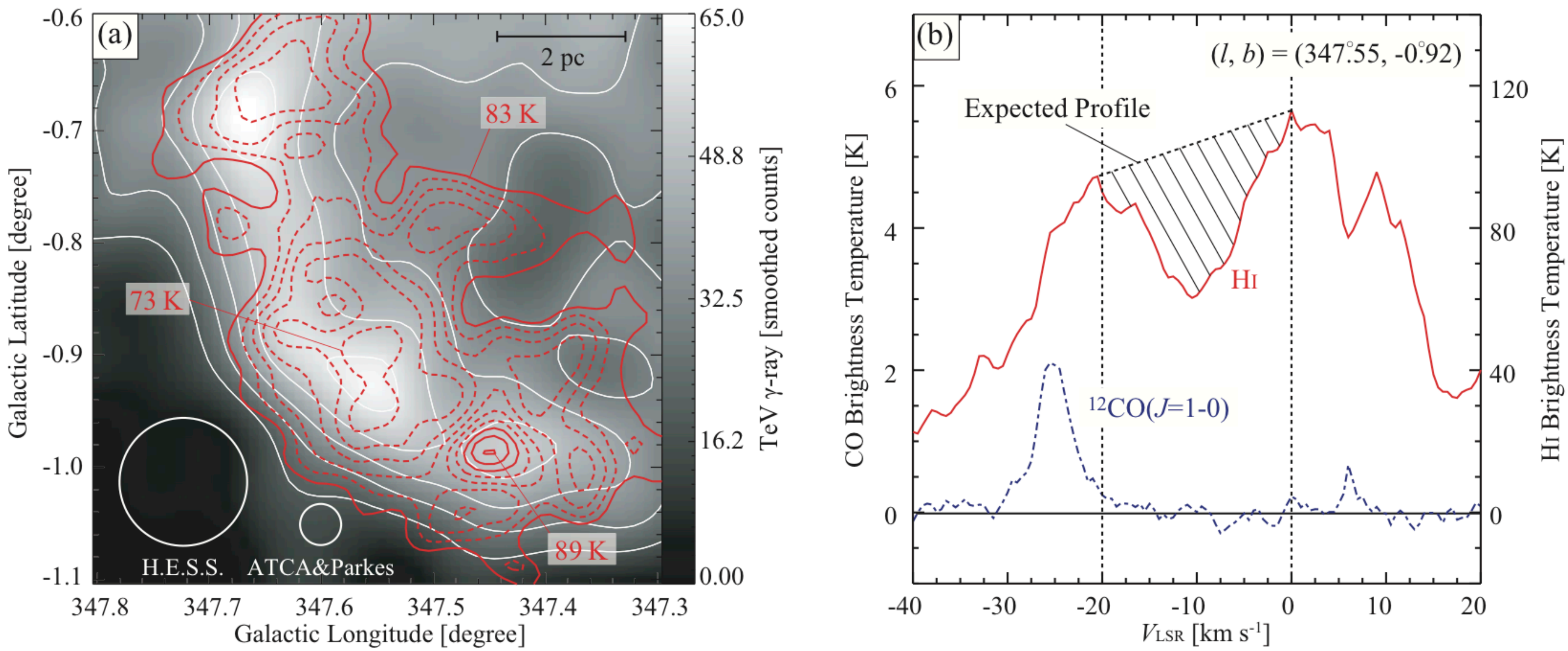


Fukui et al. 2011

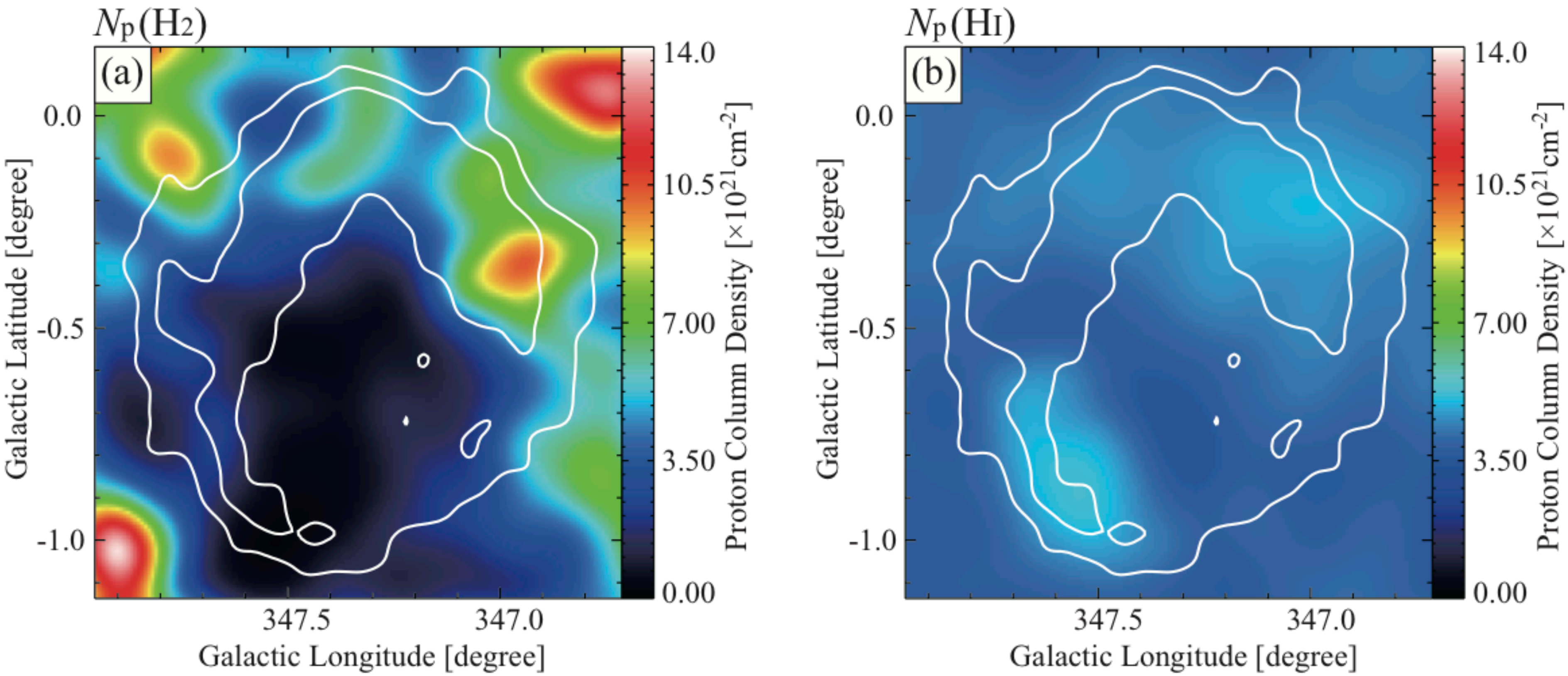


Histograms of ISM Proton Column Density & TeV γ-rays

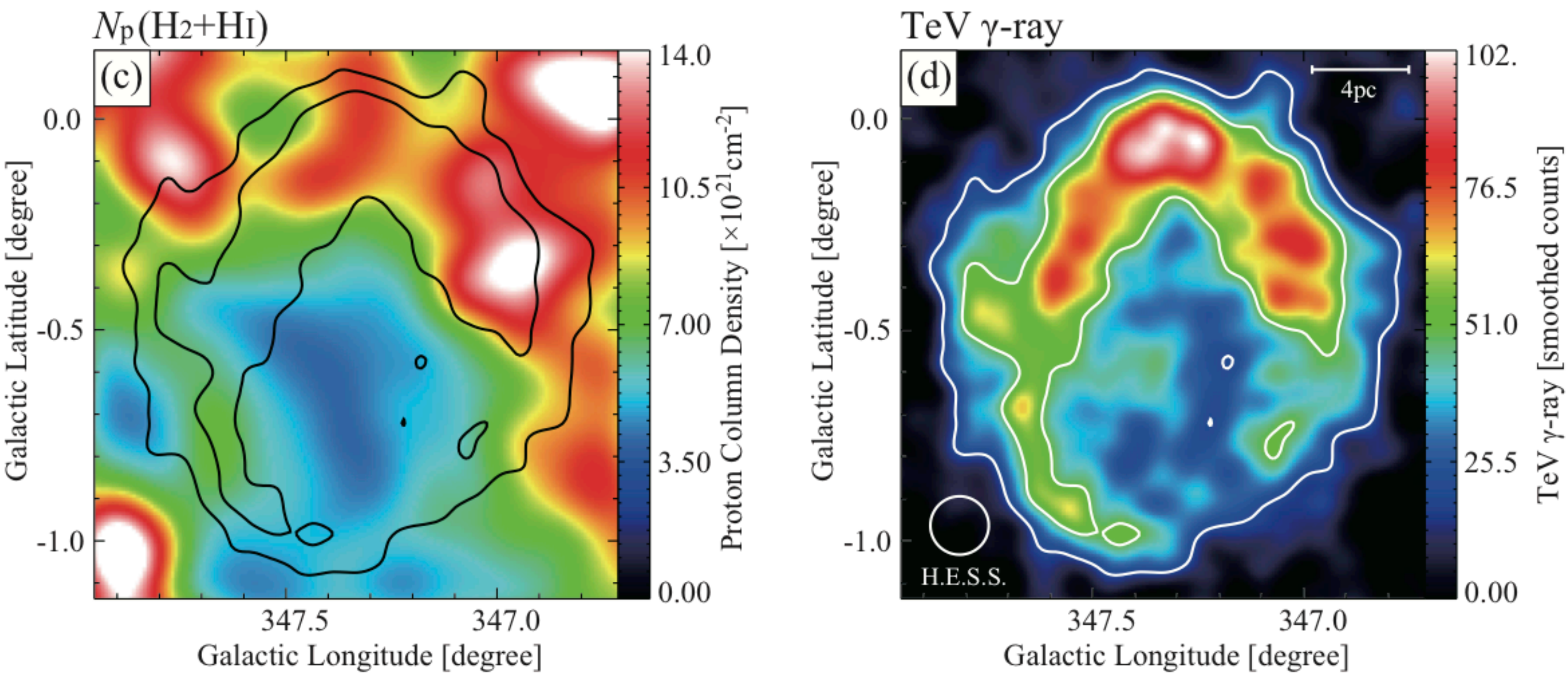
Dark HI SE Cloud (Self-Absorption)



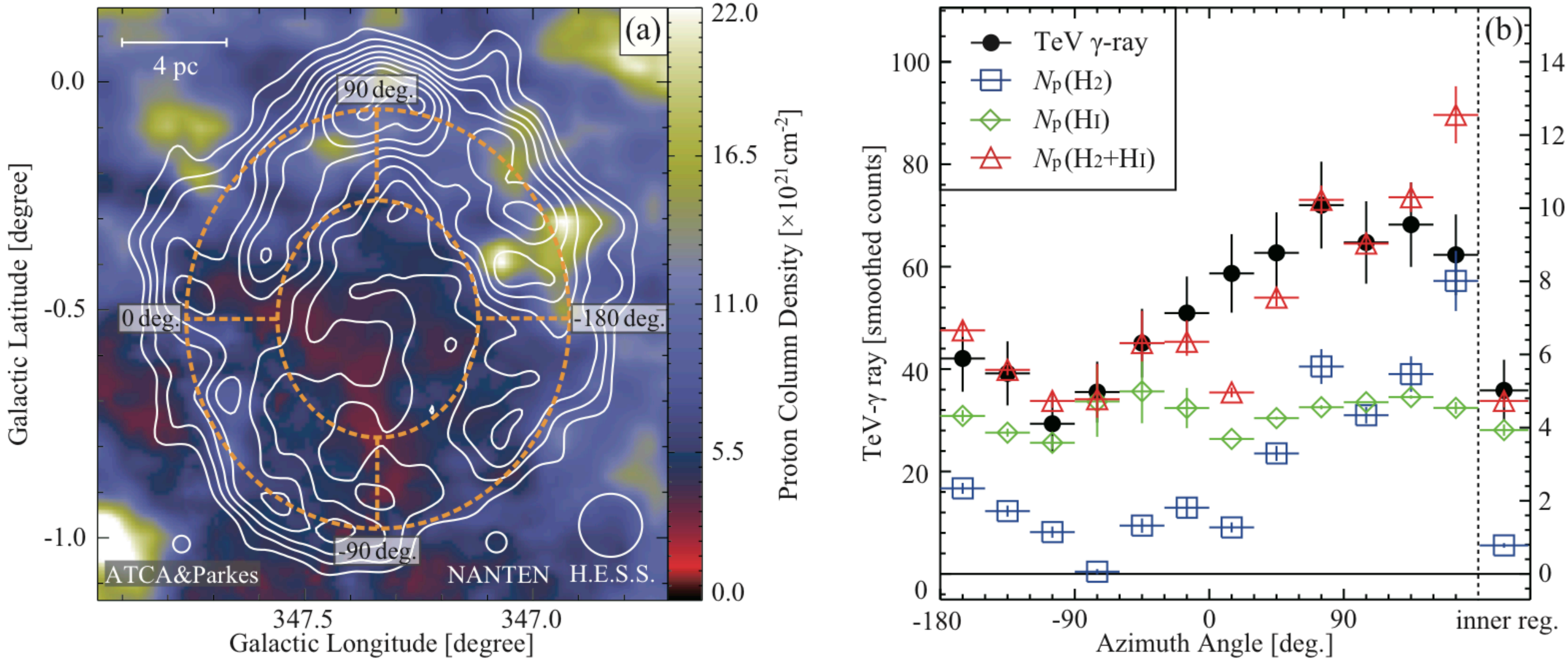
ISM Proton Column Density Distributions



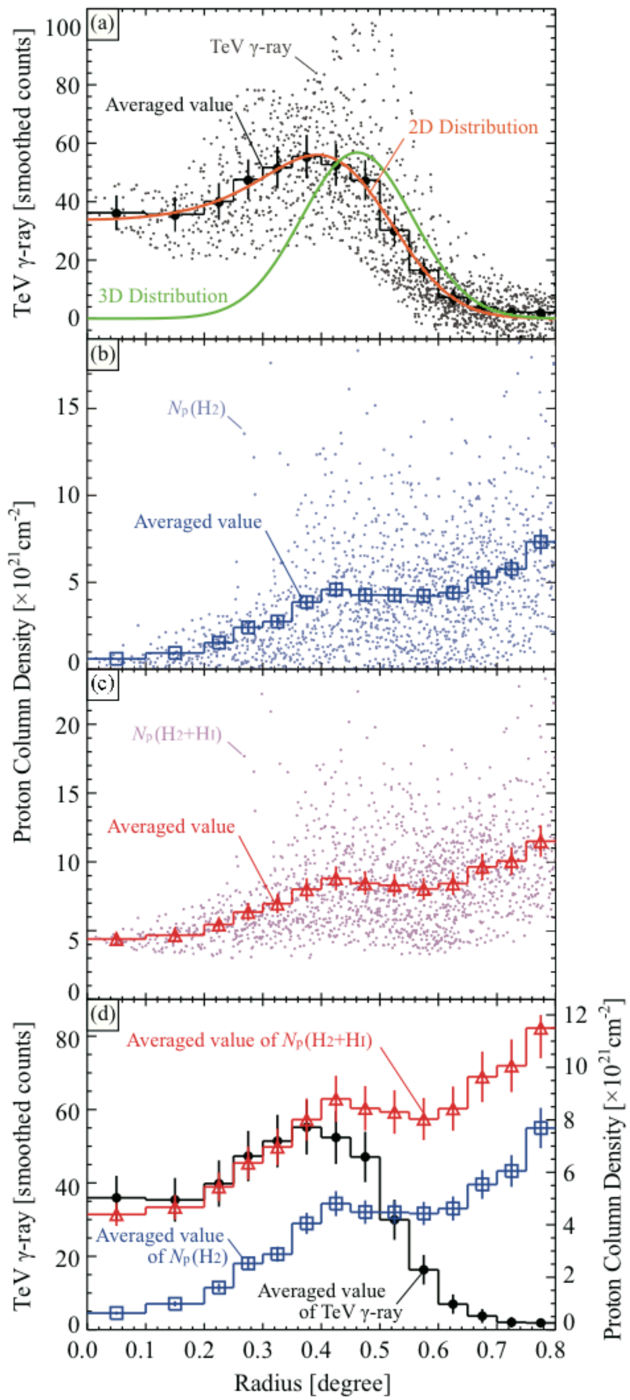
ISM Proton Column Density Distributions



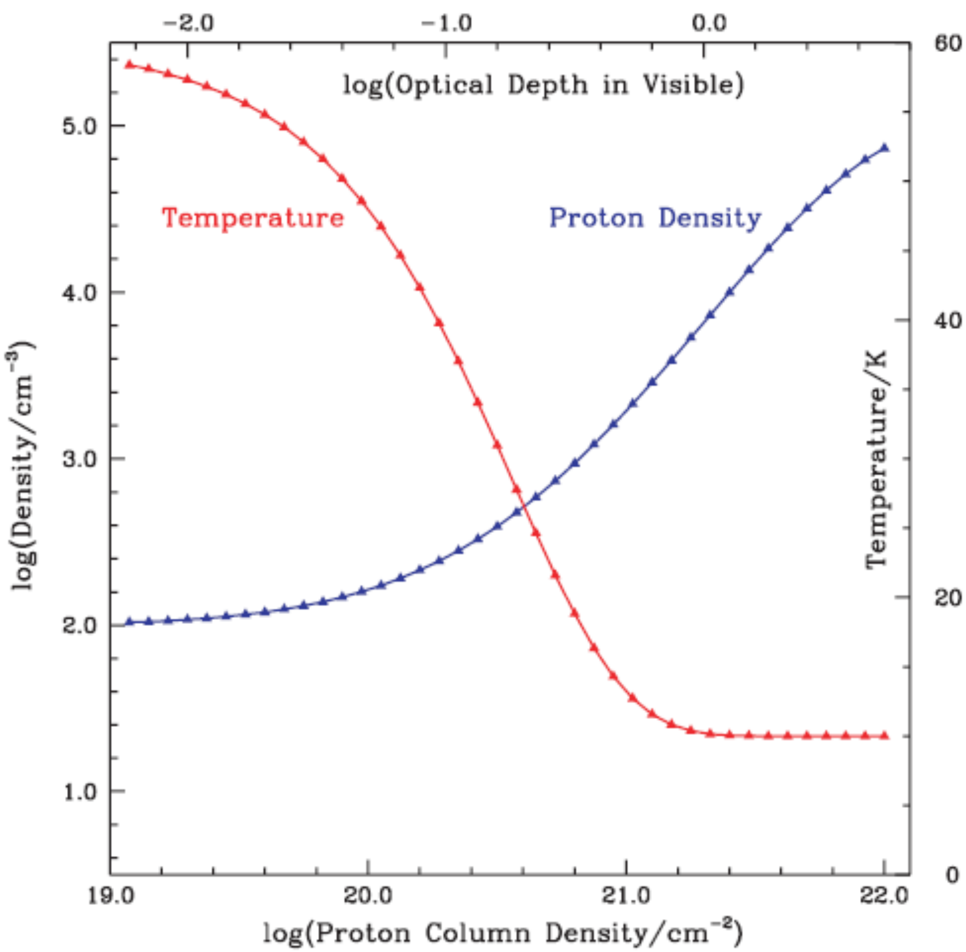
Annular Distribution of
Proton Column Density & TeV γ-ray



Radial Profile Plot of TeV γ-ray & ISM Protons



HI becomes dark at higher density



Goldsmith et al. 2007

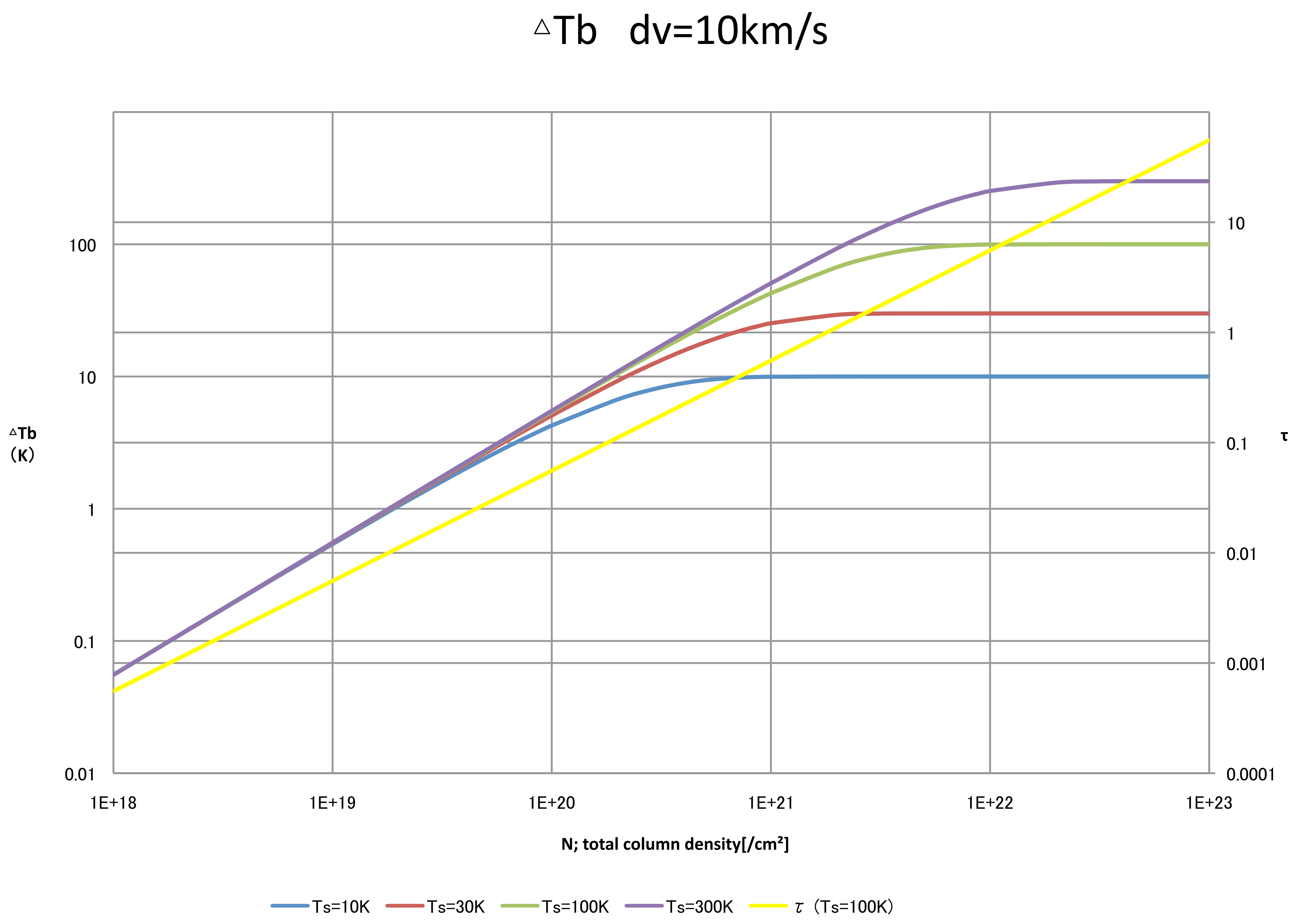
How to measure ISM protons (HI)

$$N(\text{H I}) = \frac{32\pi\nu k}{3c^2 h A_{\text{ul}}} \int_{\nu_1}^{\nu_2} \int_0^l T_{\text{s}} \kappa_\nu \, dx \, d\nu = \frac{32\pi\nu^2 k}{3c^3 h A_{\text{ul}}} \int_{\nu_1}^{\nu_2} T_{\text{b}} \, dv$$

$$= 1.823 \times 10^{18} \times (\text{H I integrated intensity in K km s}^{-1})$$

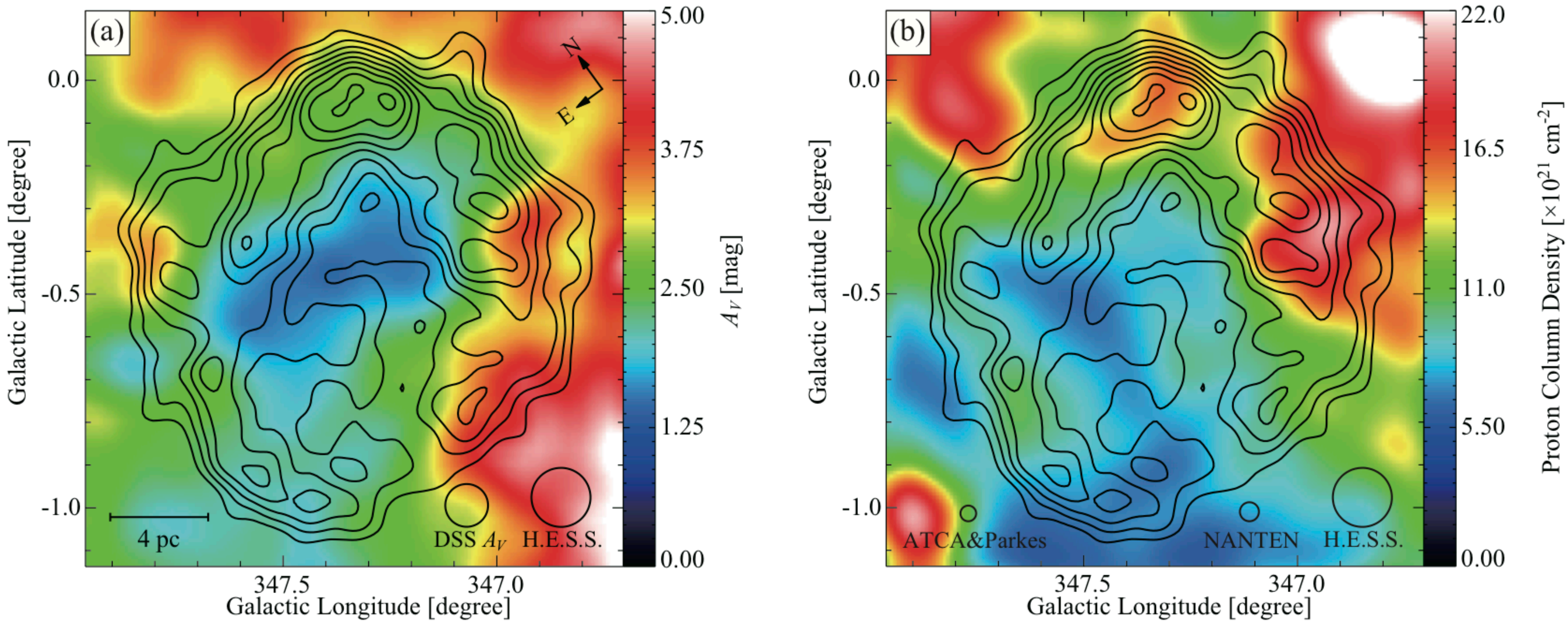
- HI emission usual assumption is optically thinness
  - caveat: sometimes this assumption fails
    e.g., dark gas, HISA (cold HI in self absorption)

$$\tau(v) = \int \kappa(v) dl = \frac{3c^3 h A_{\text{ul}}}{32\pi\nu^2 k T_{\text{s}}} \frac{N(\text{H I})}{\Delta V} = \frac{1}{1.823 \times 10^{18}} \left[\frac{T_{\text{s}}}{\text{K}}\right]^{-1} \left[\frac{N(\text{H I})}{\text{cm}^{-2}}\right] \left[\frac{\Delta V}{\text{km s}^{-1}}\right]^{-1}$$

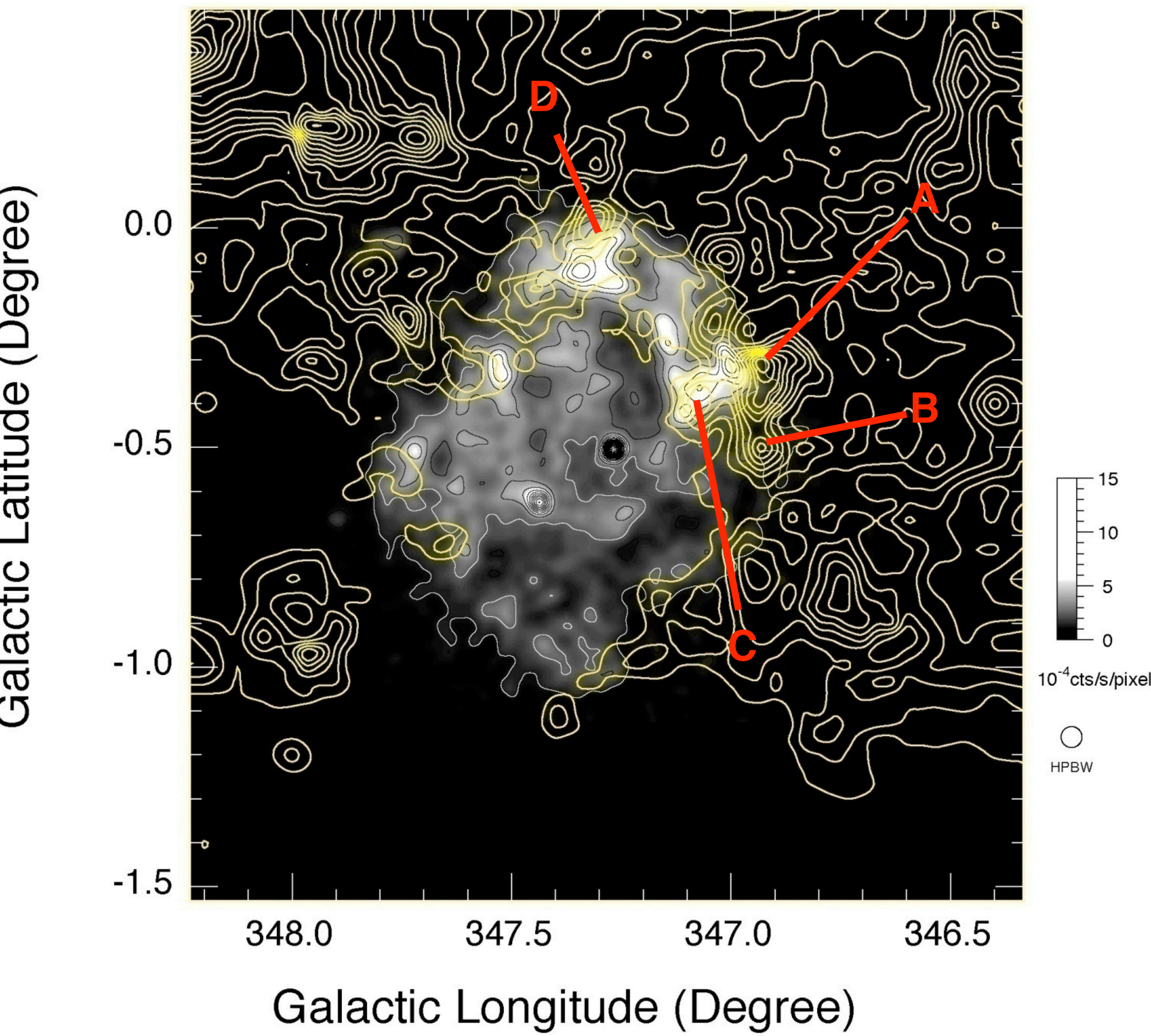


△Tb dv=10km/s
△Tb
(K)
100
10
1
0.1
0.01
τ
10
1
0.1
0.01
0.001
0.0001
1E+18
1E+19
1E+20
1E+21
1E+22
1E+23
N; total column density[/cm²]
Ts=10K
Ts=30K
Ts=100K
Ts=300K
τ (Ts=100K)

Distributions of
A_V & Proton Column Density



RXJ1713.7-3946: ^{12}CO(J=1-0) with X-ray



<u>molecular hole</u>
surrounding boundary of the SNR

CO peaks⇔X-ray peaks show good spatial correlation (northwestern bright rim)

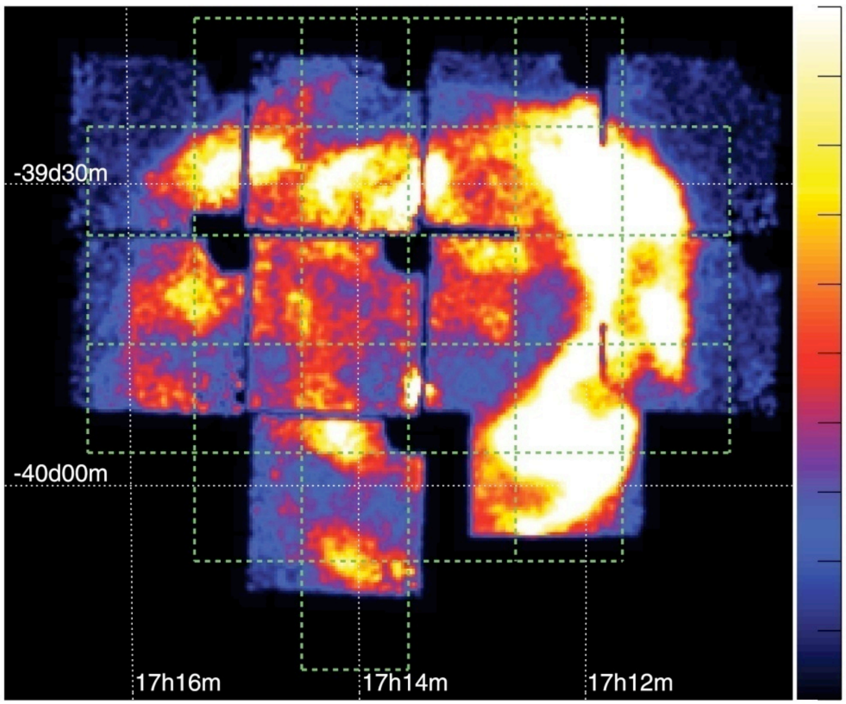
↓

indicates interaction of the SNR with molecular clouds.

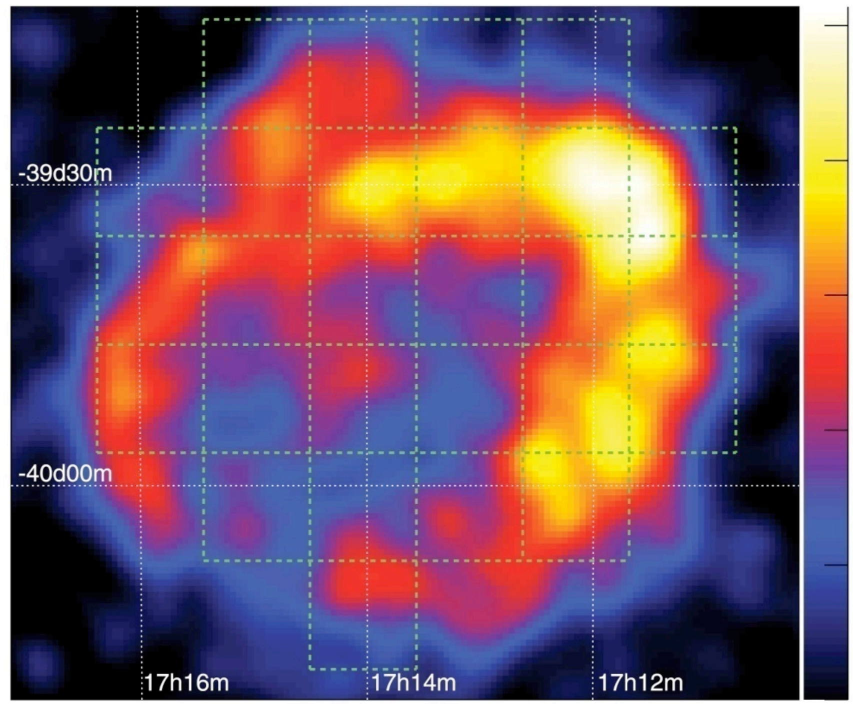
SNR at 1kpc

Fukui et al. 2003

TeV γ ray SNR RXJ1713.7-3946

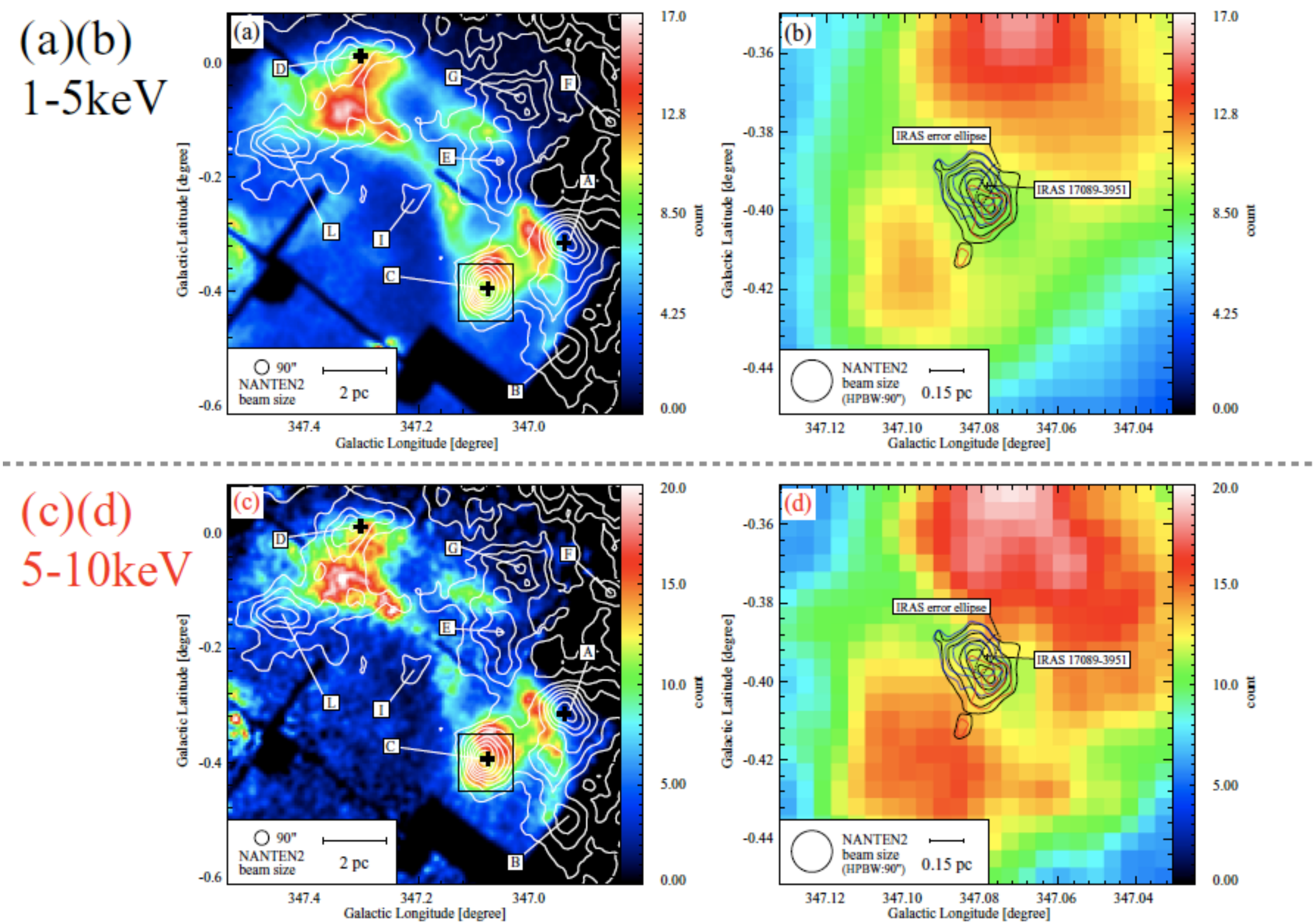


Suzaku shychrtoron X rays
10TeV electrons



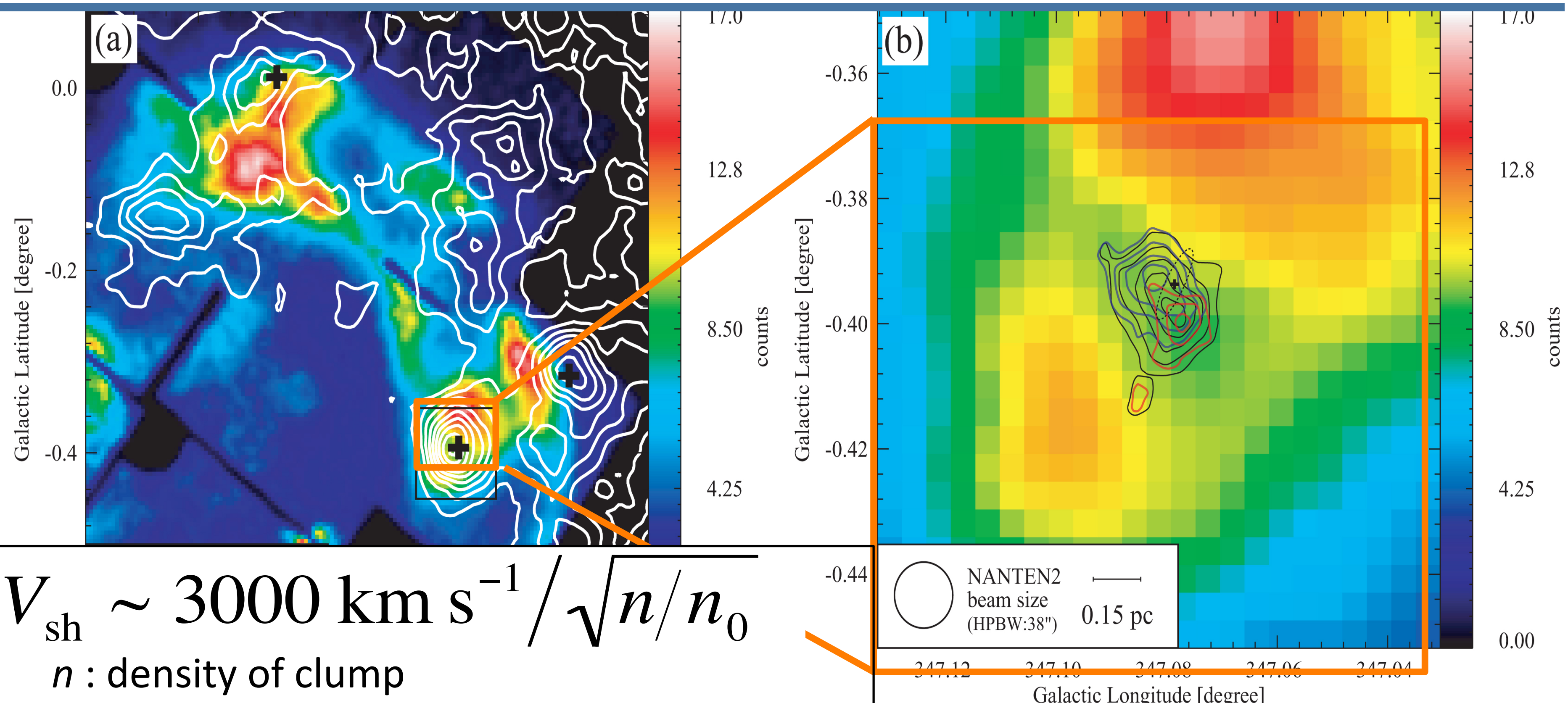
HESS TeV γ rays
100TeV protons

Tanaka et al. 2008



Sano et al. 2011, ApJ in press

Shock propagation into dense gas



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

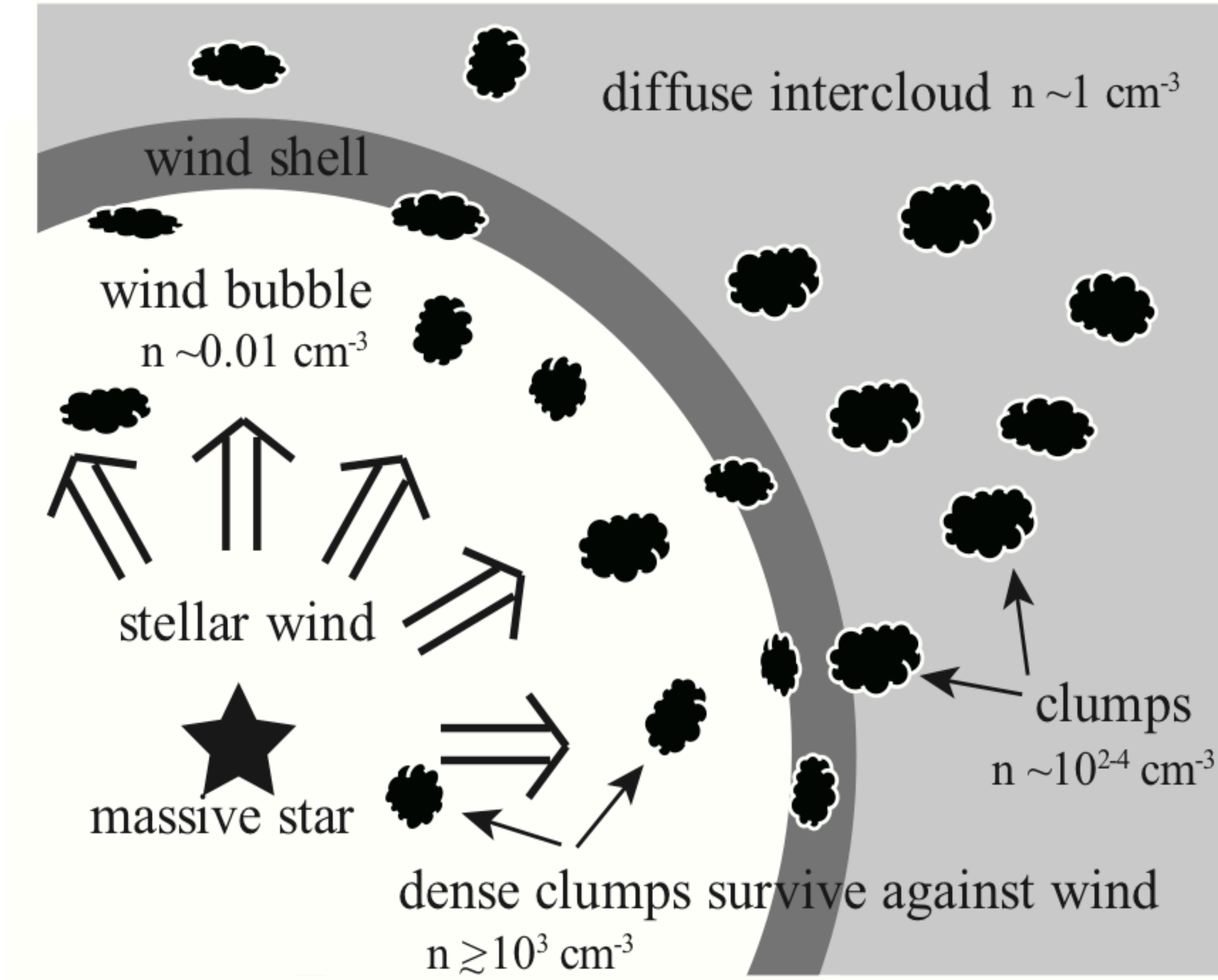
n : density of clump

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

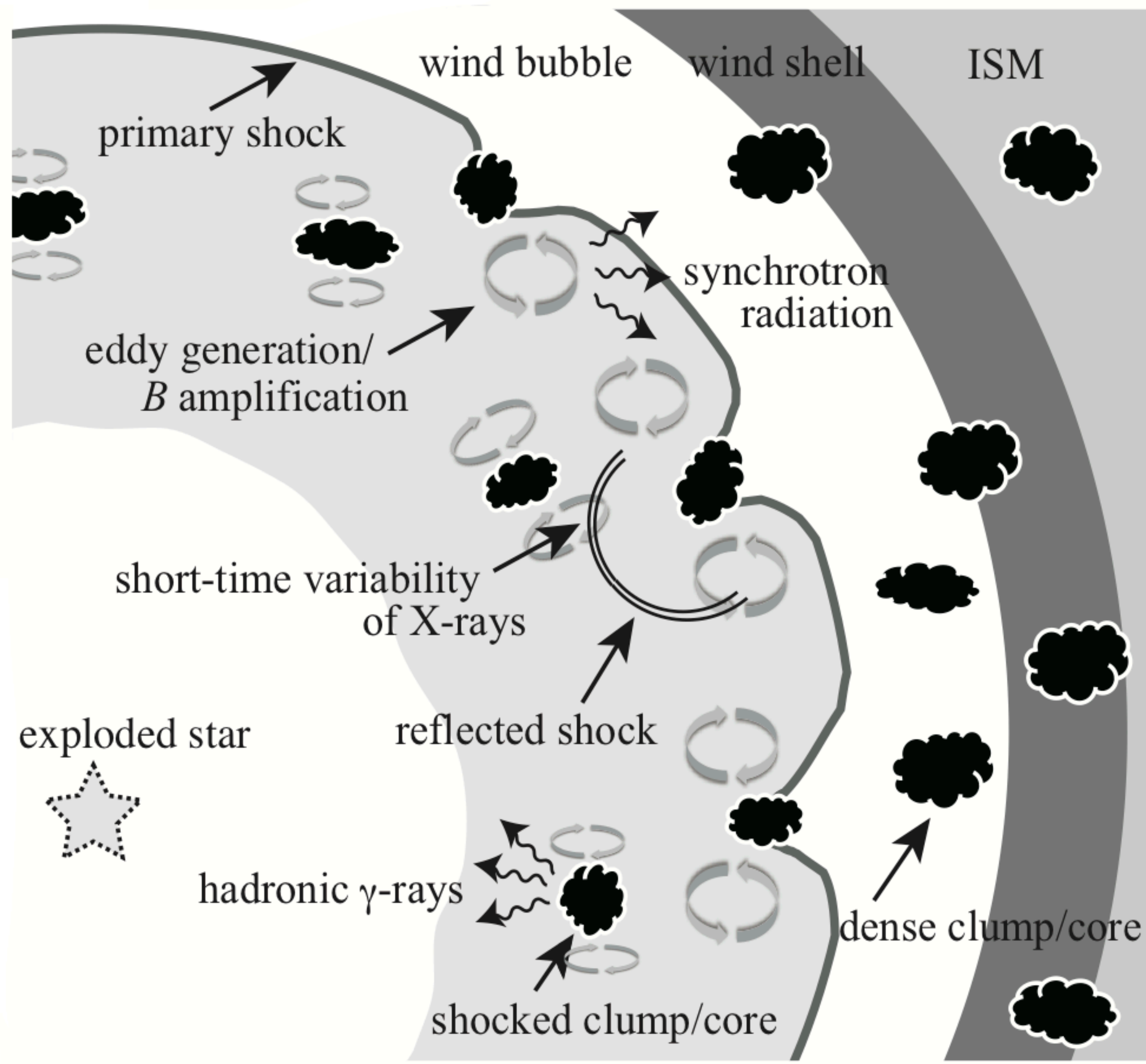
10^4 cm^{-3}, t~1000yrs

Penetrating Depth = 0.03 pc

Sano et al. 2010



Inoue et al. 2011



Inoue et al. 2011

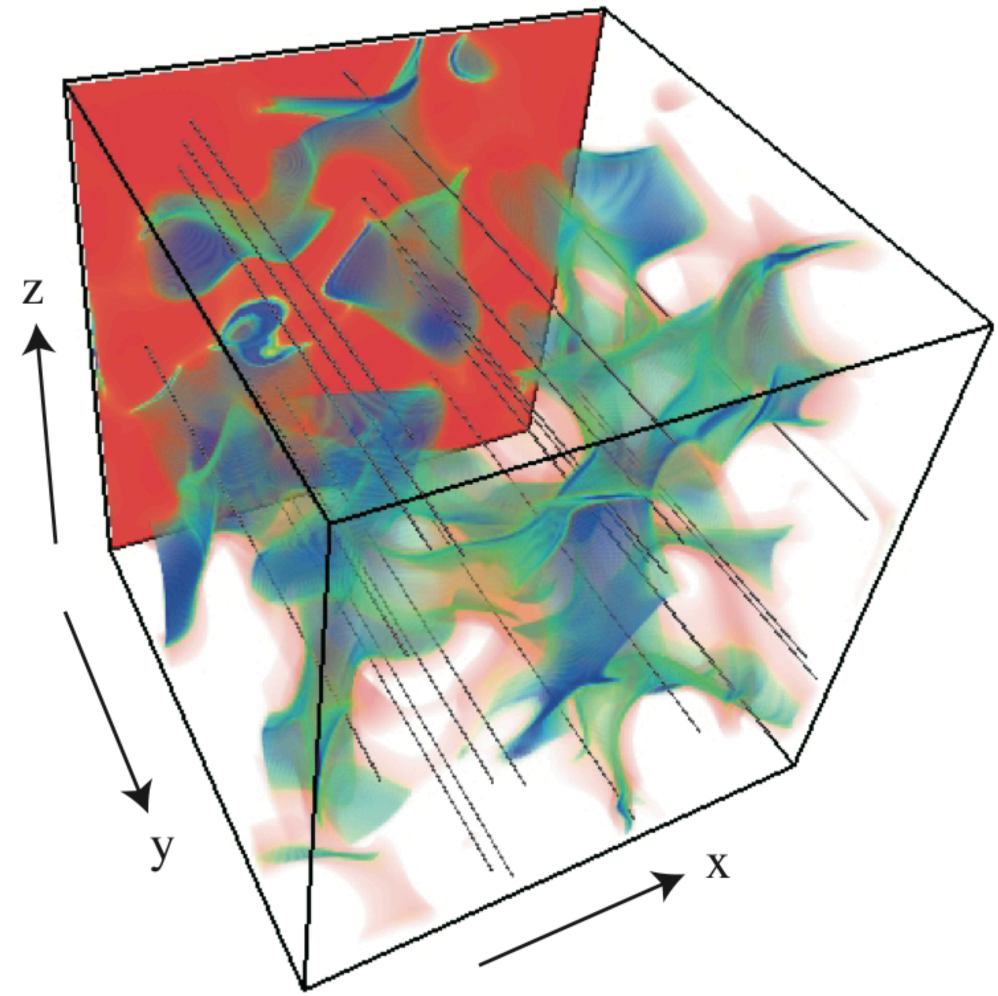


FIG. 2.— Number density volume rendering of the resulting cloudy medium as a consequence of the thermal instability after 3.0 Myr of evolution (a few cooling times). The mumber density map in the $y = 0.0$ pc plane is overplotted. Regions in green and blue indicate the density $n \sim 10$ cm^{-3} and $n \gtrsim 30$ cm^{-3}, respectively, and the region in red shows the diffuse intercloud gas with $n \lesssim 1$ cm^{-3}. Magnetic field lines are represented as gray lines.

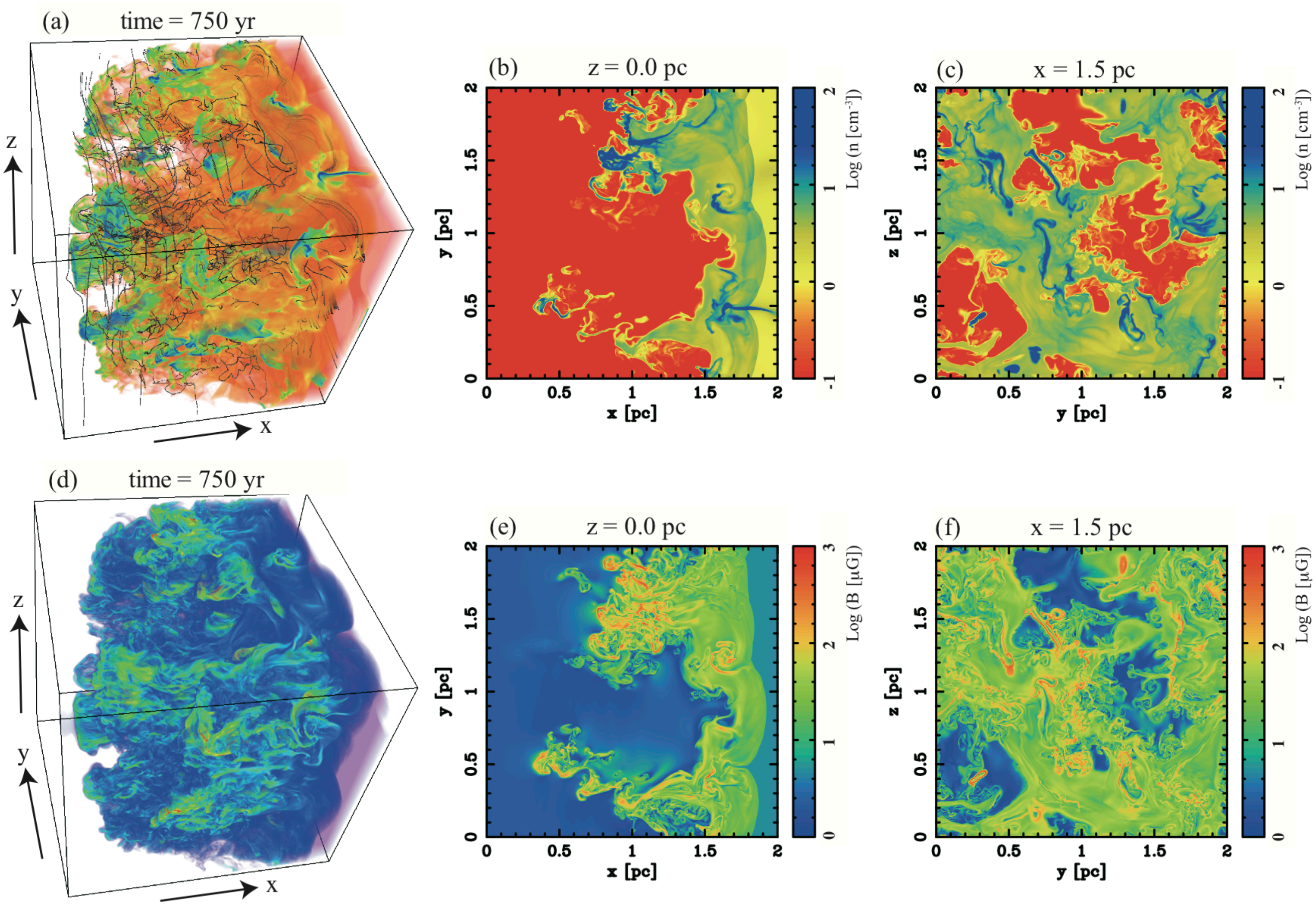


FIG. 3.— Result of the perpendicular shock case at t = 750 yr after the shock injection. Panel (a): number density volume rendering. Regions in green and blue indicate the density $n \sim 10$ cm^{-3} and $n \gtrsim 30$ cm^{-3}, respectively, and the regions in warm colors show the shocked diffuse gas with $n \lesssim 4$ cm^{-3}. Magnetic field lines are represented as gray lines. Panel (b): two-dimensional number density slice at $z = 0.0$ pc. Panel (c): slice of number density at $x = 1.5$ pc. Panel (d): volume rendering of magnetic field strength. Regions in blue, green and red indicate the regions with $B \lesssim 100$ μG, $B \gtrsim 100$ μG, and $B \gtrsim 500$ μG, respectively. Panel (e): slice of magnetic field strength at $z = 0.0$ pc. Panel (f): slice of magnetic field strength at $x = 1.5$ pc.

Ellison et al. 2010 paper

- Uniform model, to account for gamma rays
  we need high proton density like 100 cm^{-3}
- Then we have too strong thermal X rays, contradicting no thermal X rays (Suzaku)
- This is not a problem if the ISM is highly clumpy; cavity (0.1 cm^{-3}) and dense clumps (1000 cm^{-3})

SNR RXJ1713 summary

Gamma-rays correlate well with ISM H nuclei, CO+HI, allowing detailed identification of target protons in a density range from 100 to 10^3 cm^{-3}.

The gas is highly clumpy. Wp ~ 10^{48}erg for average ISM density 100$cm^{-3.}$ [Sano et al. 2010; Fukui et al. 2011]

- ISM protons estimated by careful analysis of dense atomic and molecular gas, HI (self-absorption) and CO. [Fukui et al. 2011] Such gas can account for dark gas.
- No thermal X rays are emitted because of low density gas in the evacuated cavity. Gamma-rays become hard, due to energy-dependent interaction with dense gas. [Zirakashivili and Aharonian 2010; Inoue, Yamazaki, Inutsuka, Fukui 2011; cf Abdo et al. 2011]

“Dark gas”

- Dark gas: not detected either in CO or HI

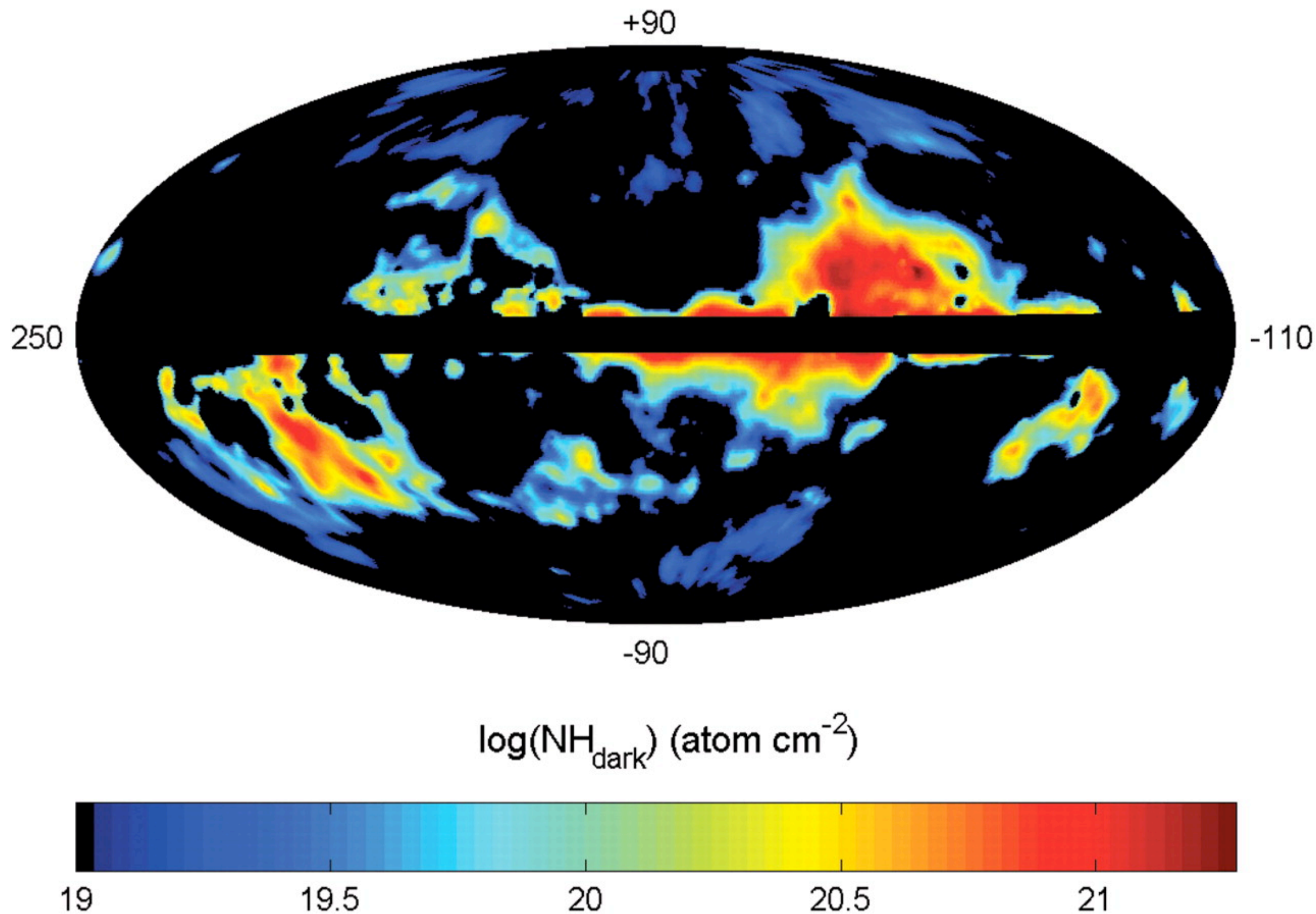
  deteted in γ rays and dust emission/absorption

  typical column density 10^{20}-10^{21} $cm^{-2,}$

  density 10^{2}-10^{3} cm^{-3}
- Either cool dense atomic or less dense molecular gas
- H_2 formation time is long, 10^{7} yrs , and low density gas may not yet be converted into molecular gas

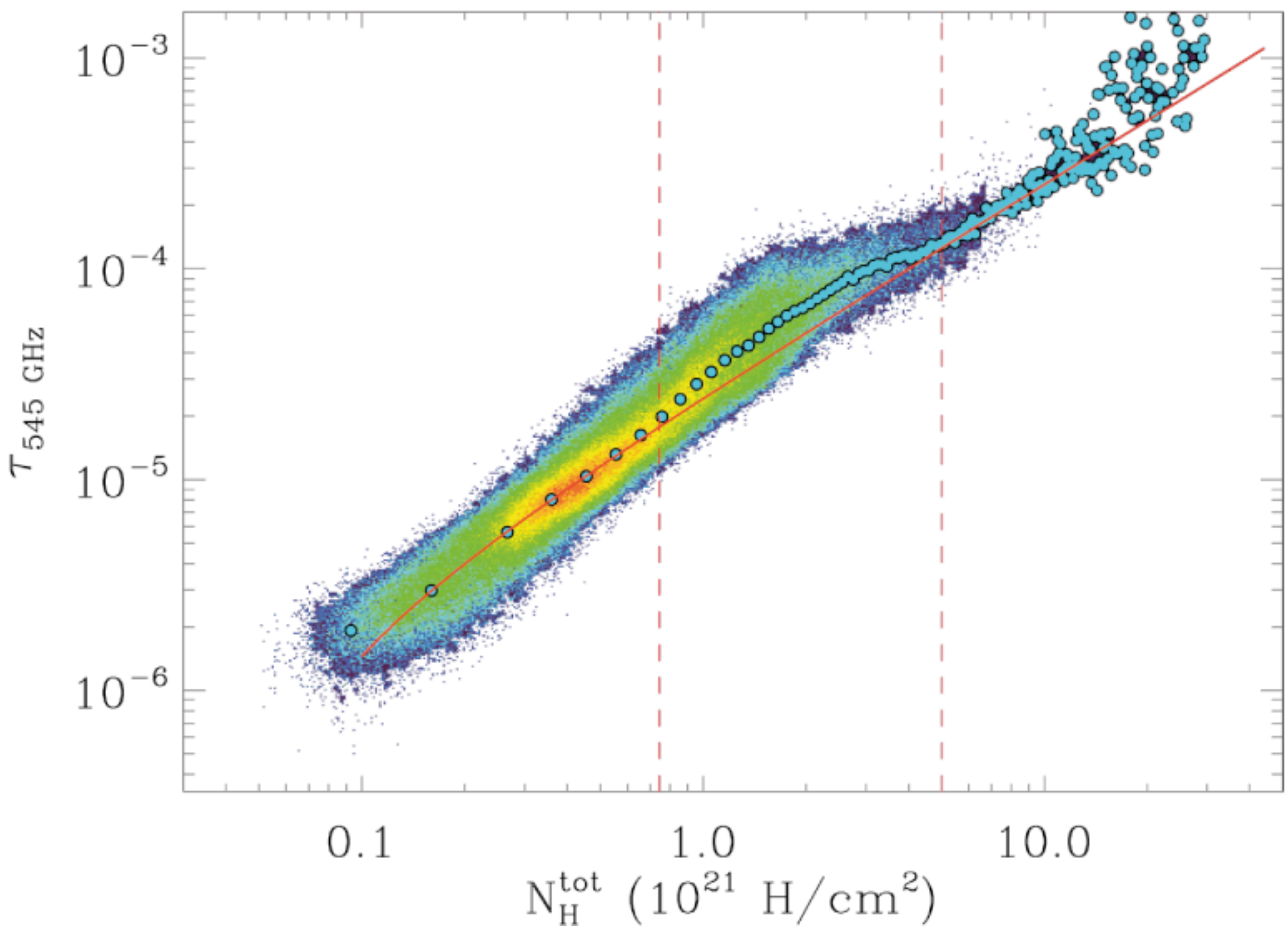
  ref. Grenier et al. 2005, Wolfire et al. 2010, Burgh et al. 2010, Glover et al. 2010, Planck collaboration 2011

Fig. 4. Map, in Galactic coordinates centered on l = 70°, of the column densities of dark gas found in the dust halos, as measured from their γ-ray intensity with the reddening map.



I A Grenier et al. Science 2005;307:1292-1295

Published by AAAS



(Planck Collaboration, arXiv:1101.2029)

Molecular clouds and gamma-rays

Interstellar Medium ISM

- Molecular clouds: dense neutral gas H2
  - density 10^3 cm-3 or higher, Tk=10-20K
- Atomic clouds: dense atomic gas HI
  - density 1-100 cm-3, Ts=30-100K

Gamma-rays produced by

1) Hadronic scenario
   - cosmic ray proton - ISM proton reaction, neutral pions decay into gamma rays
2) Leptonic scenario
   - Inverse Compton (IC) effect, CMB etc.

   Gamma-rays (0.1GeV-100TeV) observed by HESS, MAGIC, VERITAS, Fermi, AGILE[2005-] and CTA[2013-]