Study of the ISM in nearby molecular cloud regions based on the optically thick HI

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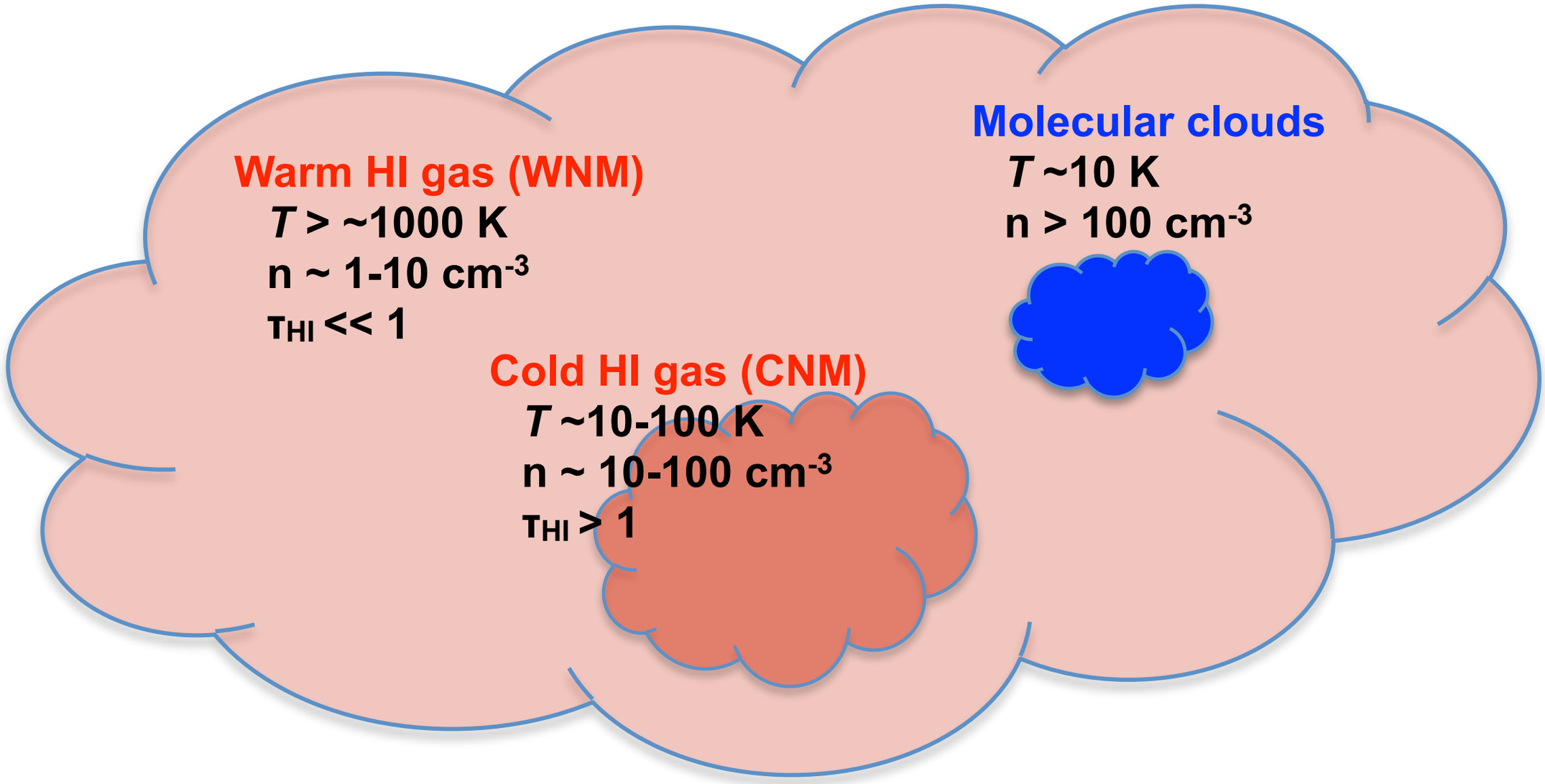
Outline

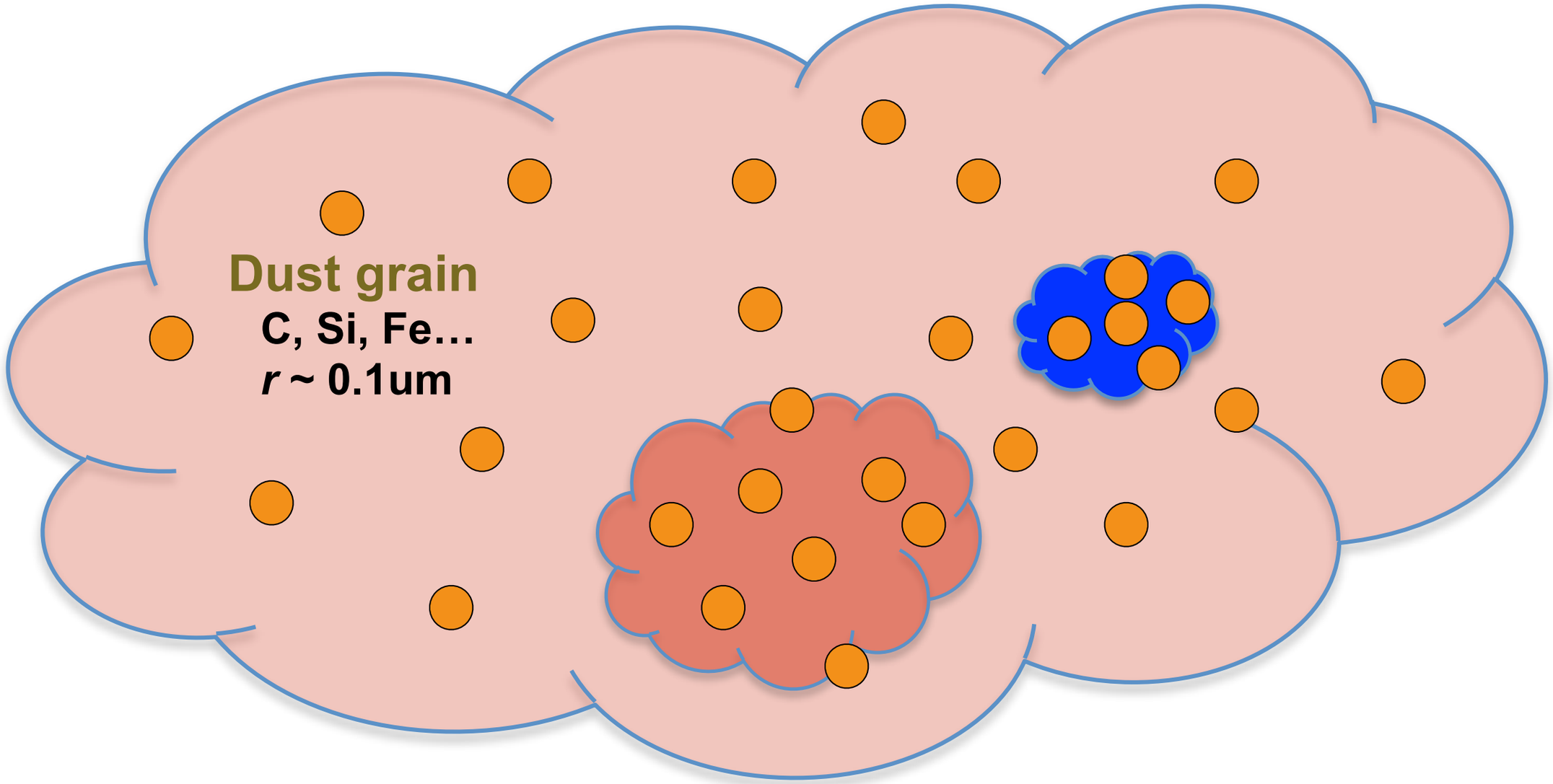
- Introduction of the local ISM
- Total gas column density model
- Target molecular clouds (Perseus and Chamaeleon)
- Optically thick HI in the local ISM

Local Inter Stellar Medium



- **HI**: 21 cm line, $N_{HI} = 1.823 \times 10^{18} \times W_{HI}$ (optically thin approximation)
- **H_2**: 2.6 mm CO line, gas mass inferred by using $X_{CO} = N_{H2}/W_{CO}$

Dust Grains

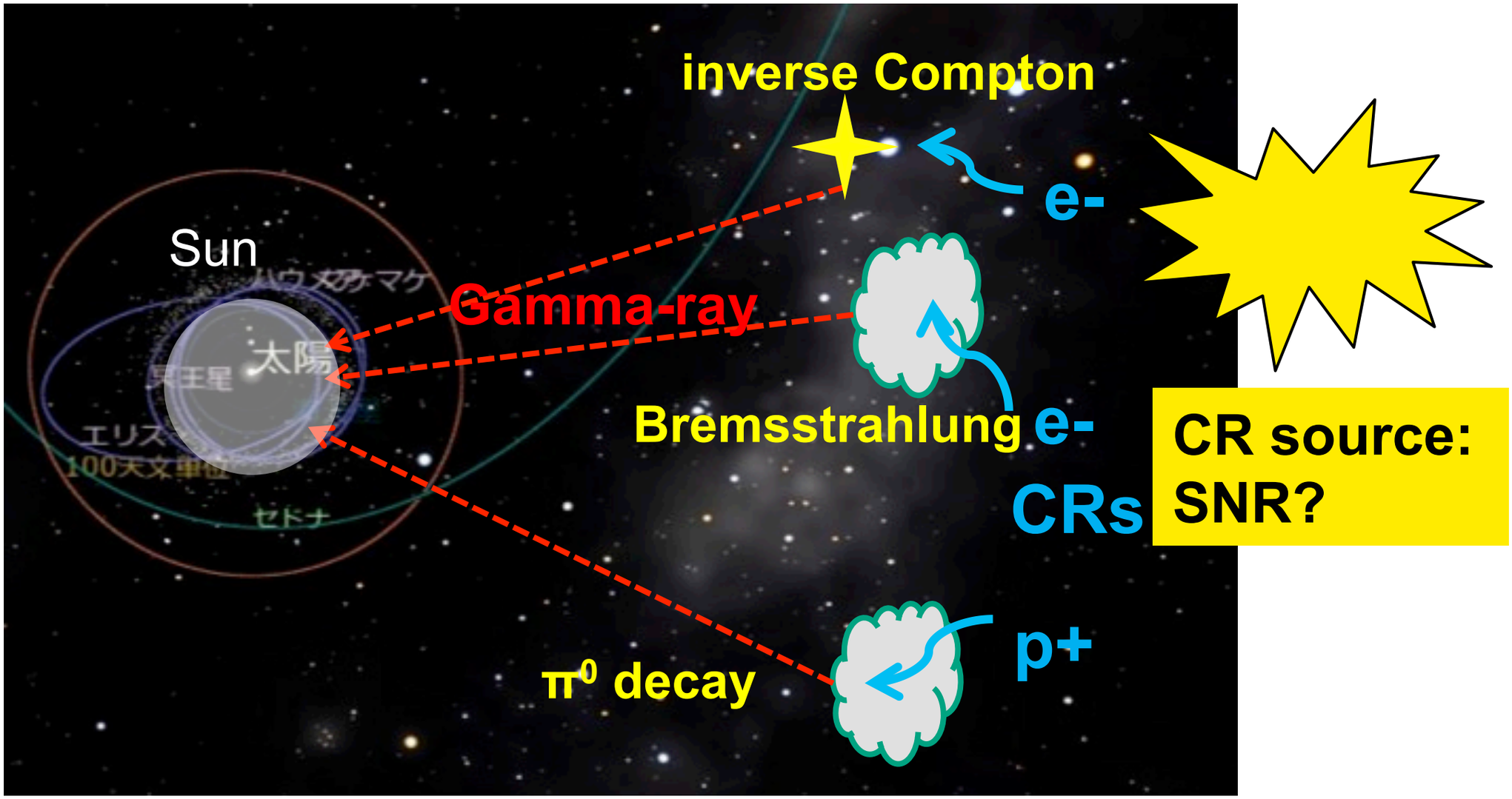


- **Mixed with gas components**
- **Promotes constructions of molecular clouds => evolution of the ISM**
- **Correlation between gas and dust => total gas column density model**
- **Many studies of dust properties (e.g., dust optical depth at 353 GHz: τ_{353}) by Planck**

(e.g., ; Planck Collaboration XIII, 2014; Planck collaboration XXVIII, 2015)

Diffuse γ-ray Emission

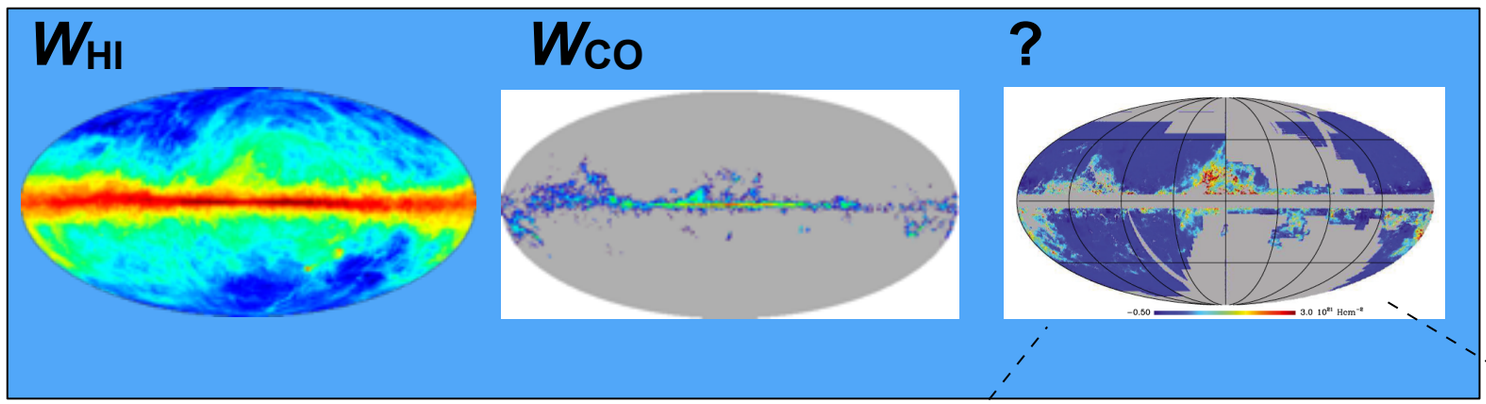
γ-rays ～ CRs x ISM (or ISRF)

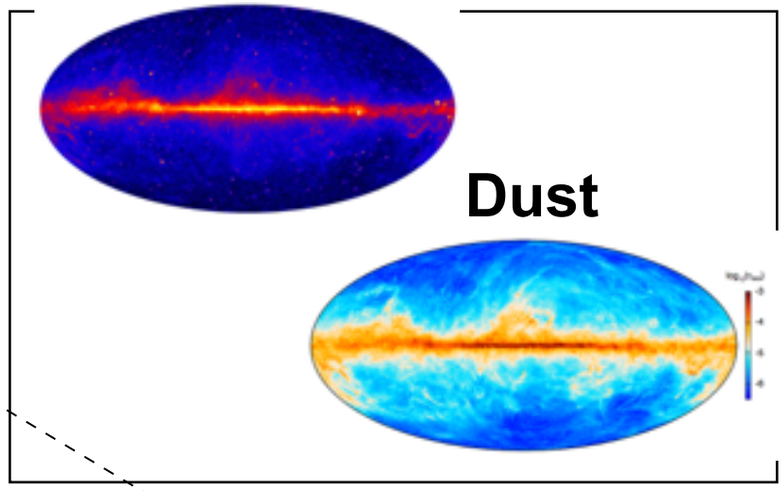


- **ISM distribution measured by other wavelengths => CR density and spectrum "measured" CRs => gas distribution, volume and property**
- **Many studies of diffuse gamma-rays by Fermi-LAT**

(e.g., Ackermann+12, ApJ, 755, 22; Casandjian+15, ApJ, 806, 240; Planck collaboration XXVIII, 2015)

Dark Gas

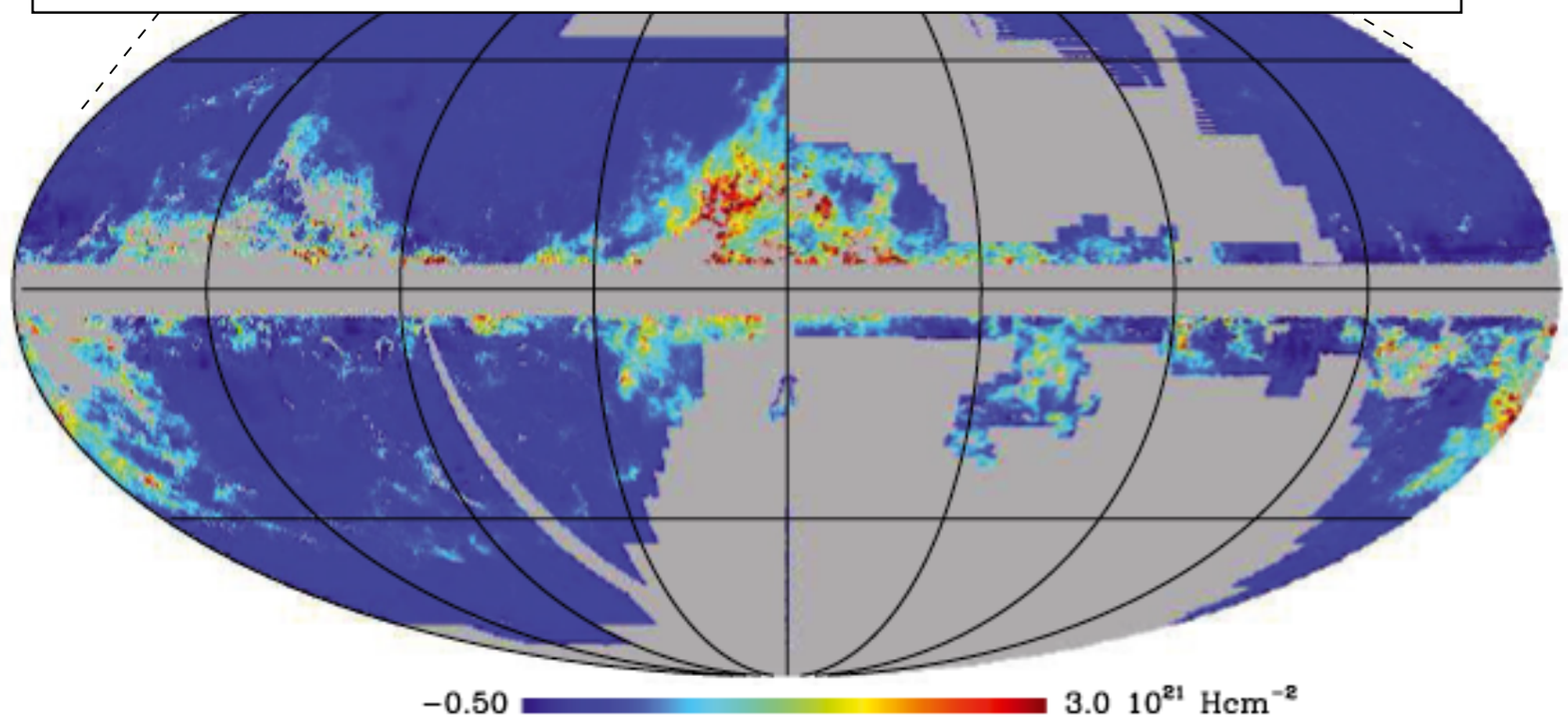




e.g., Grenier+15, Sci, 307, 1292; Ackermann+12, 755, 22; Planck Collaboration XIII, 2014

Dark gas (DG)

- Not traced well by HI and CO surveys
- Interface between the HI/H_2 phases
- Similar gas mass to that of traced by CO



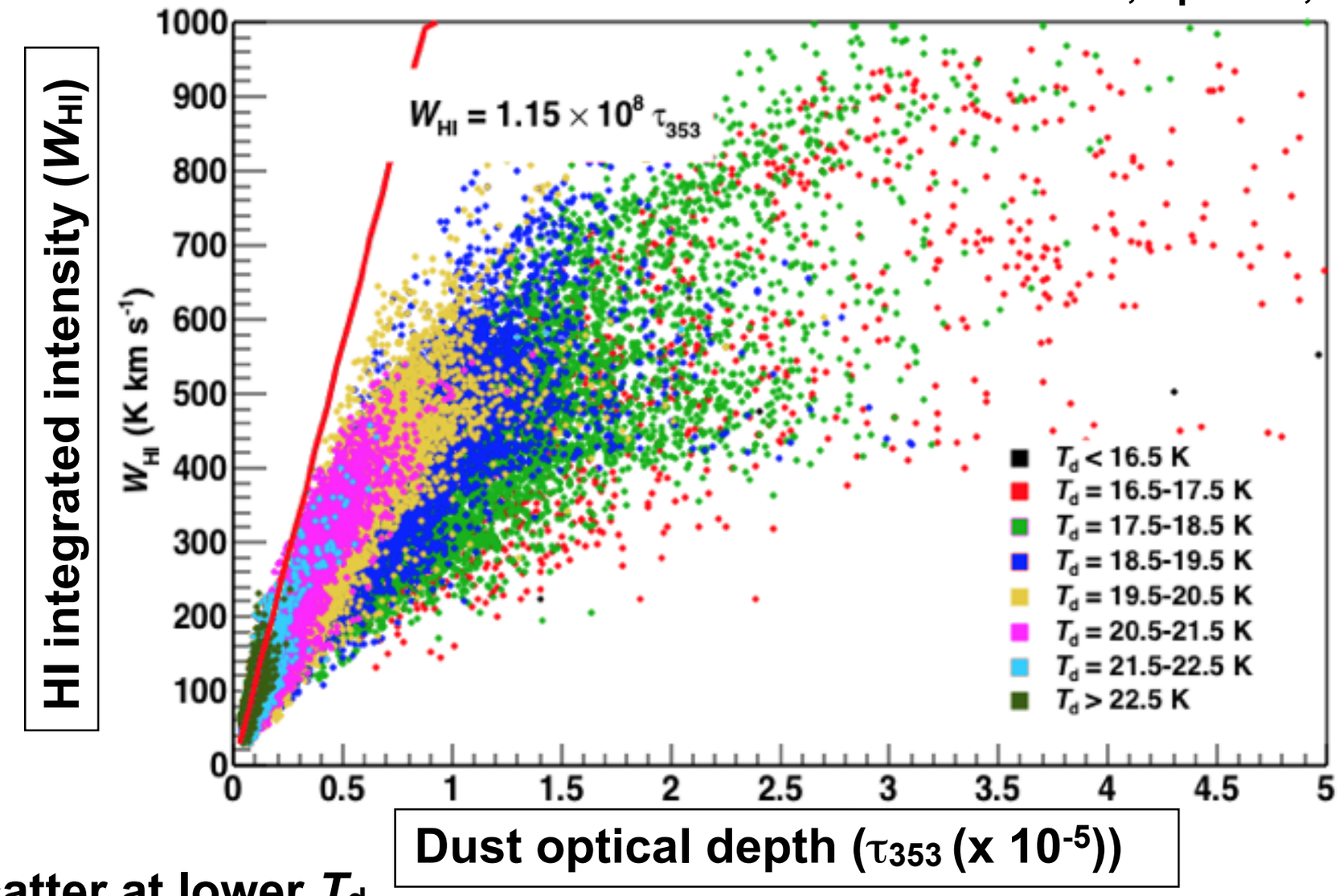
CO-dark H_2 or cold HI (optically thick HI)

e.g., Wofire+10, ApJ, 716, 1191; Fukui+15, ApJ, 798, 6

τ_{353}-W_{HI} Relation

All-sky in the local ISM (|*b*| > 15°)

Fukui+14, ApJ 796, 56
Fukui+15, ApJ 798, 6



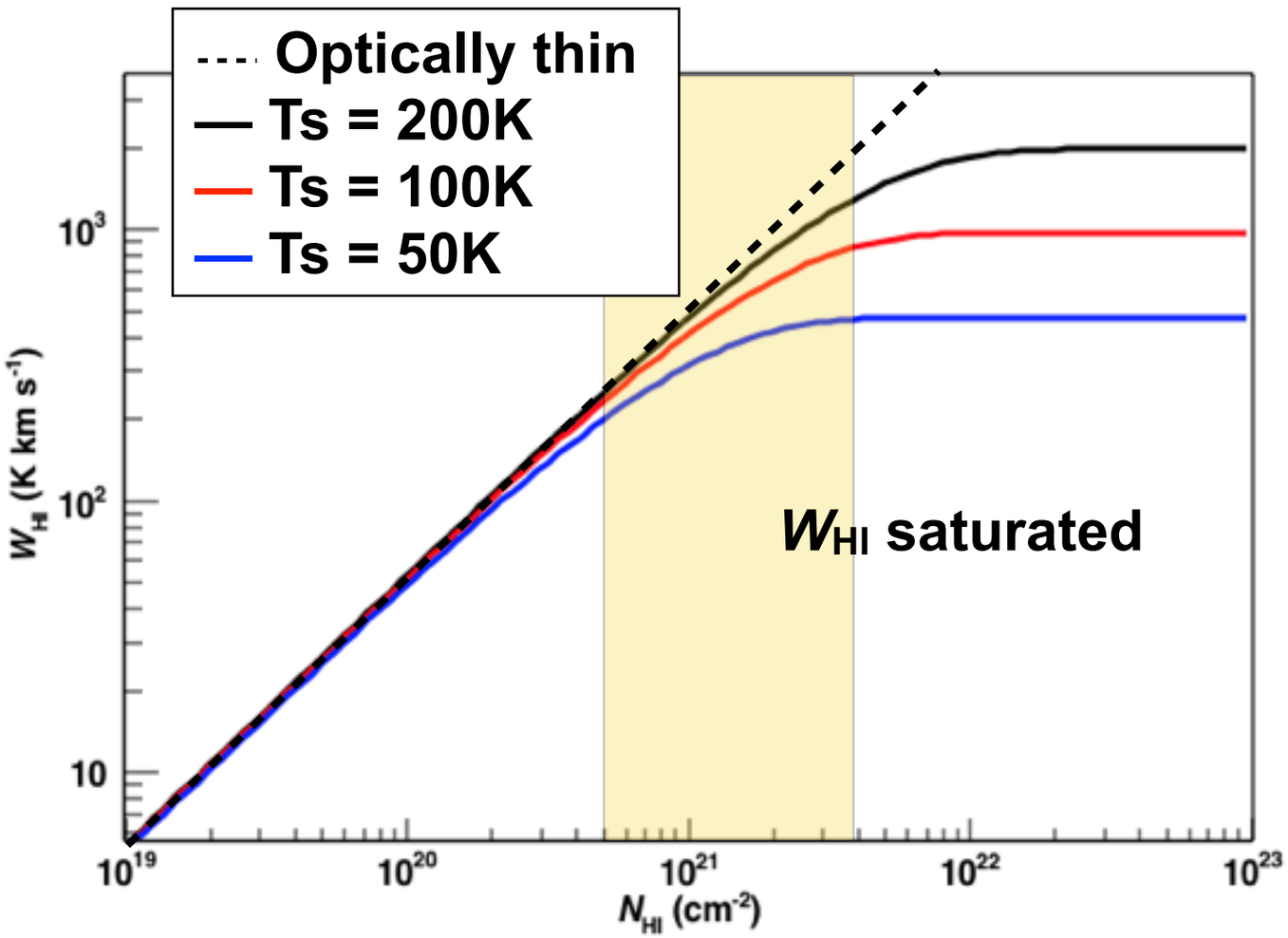
- Larger scatter at lower T_d
  - "Dust property evolution" or HI emission is saturated ? = "optically thick HI"
- Assuming uniform dust property in the local ISM and the optically thin at higher T_d
  - N_H model with linear relation → ~2-2.5 times larger HI density
  - Alternative interpretation of DG (optically thick HI hypothesis)

$N_H = 1.82 \times 10^{18} \times (1.15 \times 10^8 \times \tau_{353})$

Optically thick HI

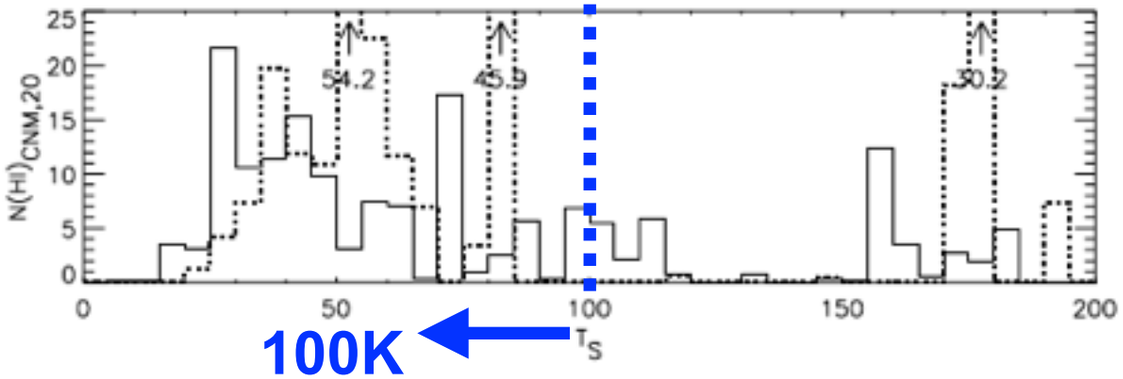
$$W_{\rm HI}({\rm K\ km\ s^{-1}}) = [T_{\rm s}({\rm K}) - T_{\rm bg}({\rm K})] \cdot \Delta V_{\rm HI}({\rm km\ s^{-1}}) \cdot [1 - \exp(-\tau_{\rm HI})]$$

$$\tau_{\rm HI} = \frac{N_{\rm H}({\rm cm^{-2}})}{1.82 \times 10^{18}} \cdot \frac{1}{T_{\rm s}({\rm K})} \cdot \frac{1}{\Delta V_{\rm HI}({\rm km\ s^{-1}})}$$

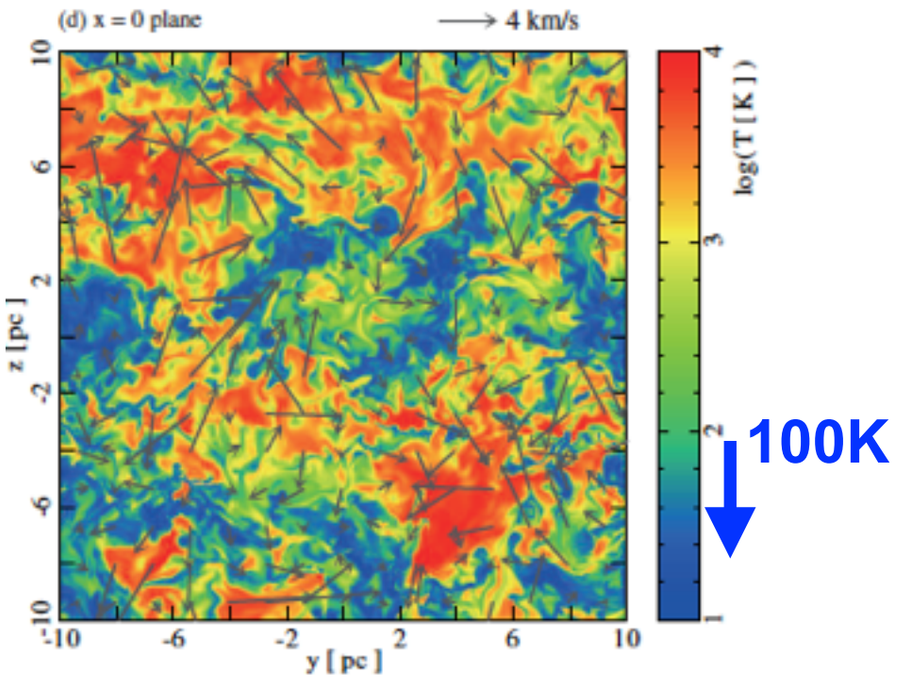


Possible saturation of $W_{\rm HI}$
→ HI gas with lower Ts (optically thick HI)

21 cm absorption line
(Heiles & Troland 03)

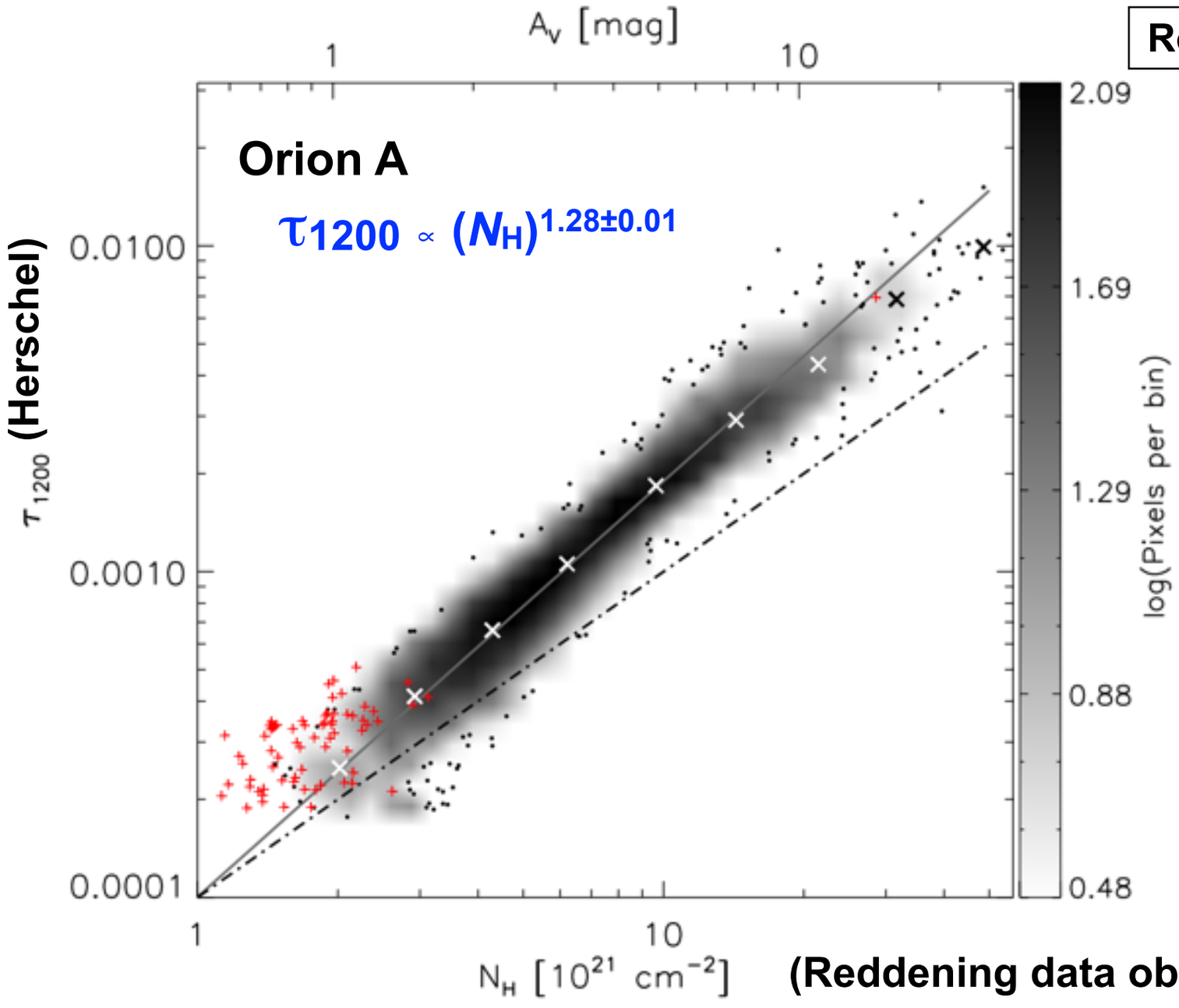


MHD simulation to form molecular clouds (Inoue & Inutsuka 12)



Non-linear Relation

Roy+13, ApJ, 763, 55



(Reddening data obtained with 2MASS)

- **Non-linear relation b/w N_H and dust optical depth**
  - **Evidence for grain evolution in dense gas by aggregation processes**

Motivation

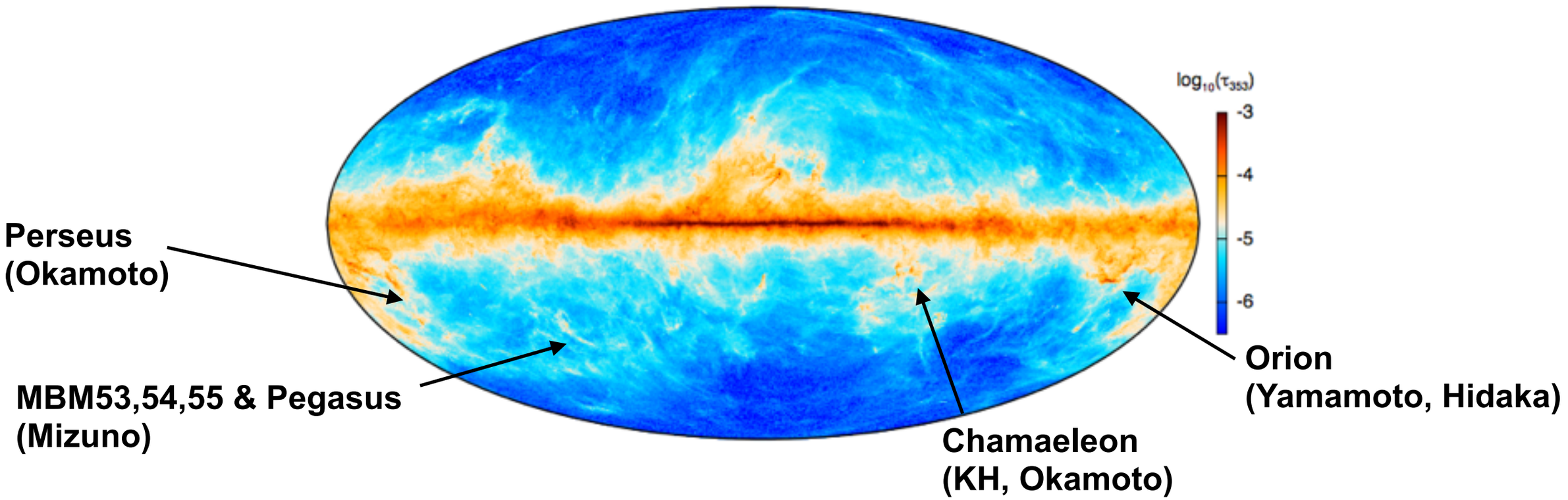
Accurate measurements of the local interstellar hydrogen

Total column density (N_H) model based on dust optical depth (τ_{353})

- **τ_{353}: transparent to the interstellar gas even in dense core regions => accurate measurements of the interstellar gas**

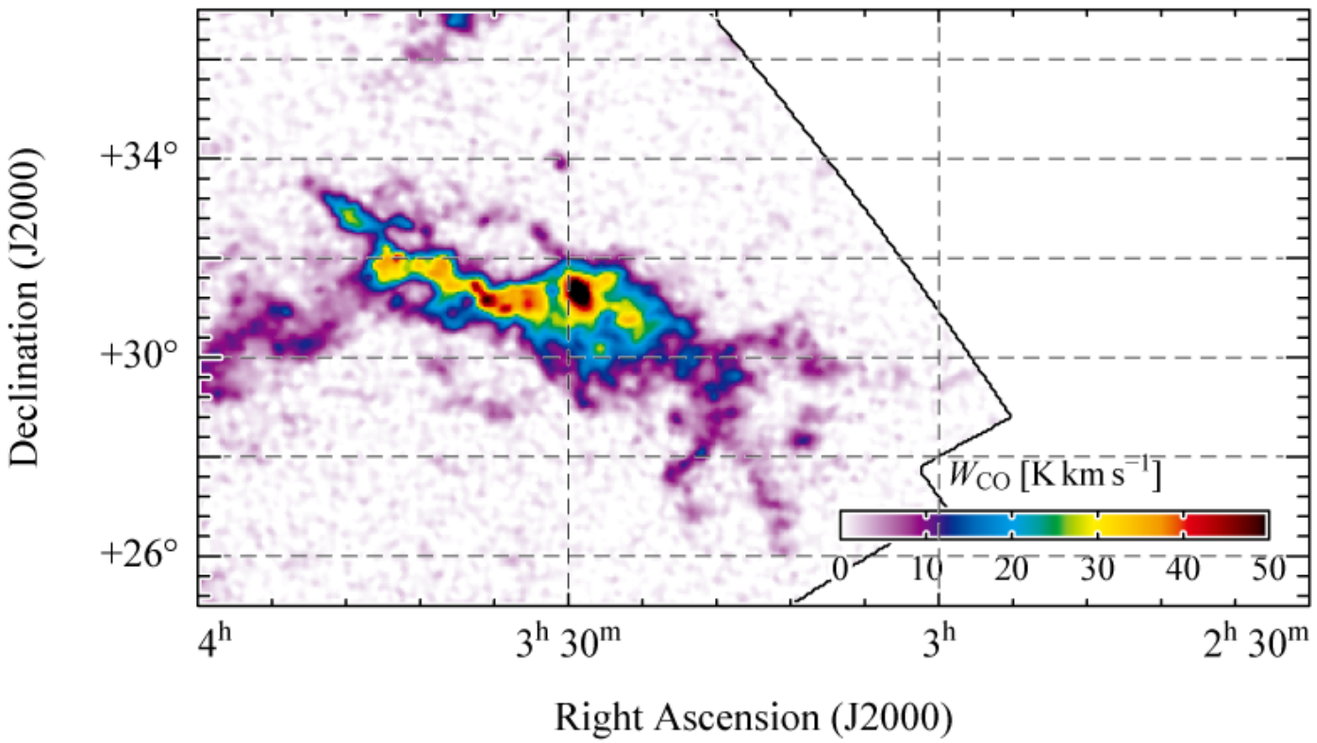
Explore possibility of the optically thick HI, taking into account dust evolution effects

- **Correlation with gamma-rays**
- **=> CR density/spectrum and gas properties (Xco, gas mass) in the local ISM**

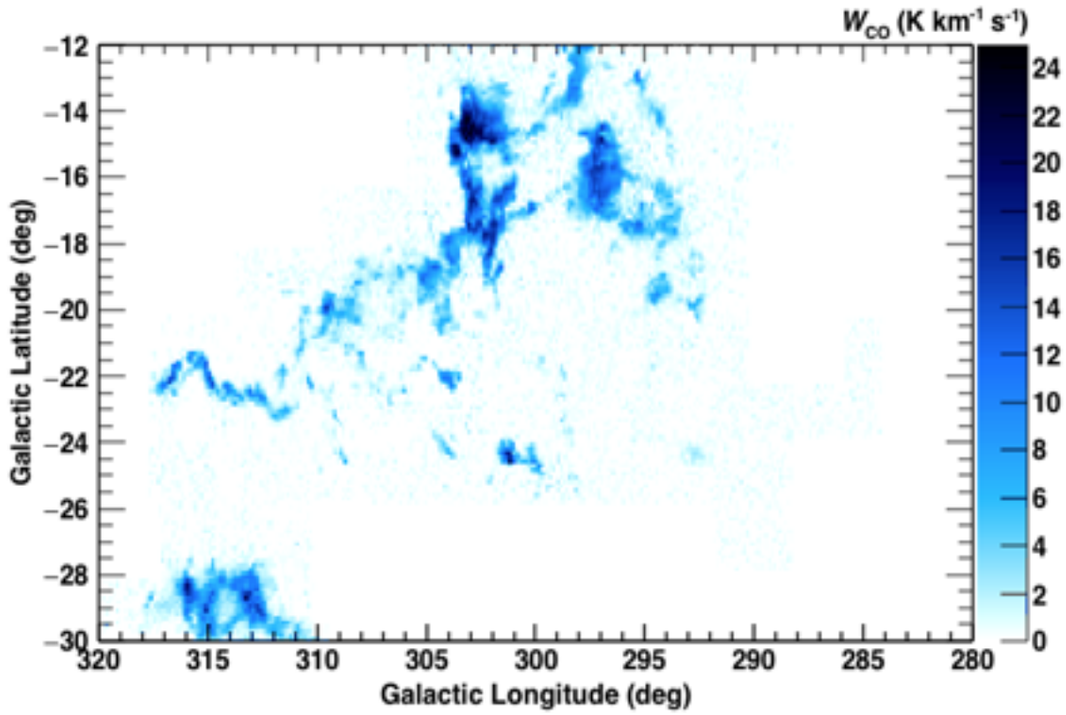


Target Molecular Clouds

Perseus



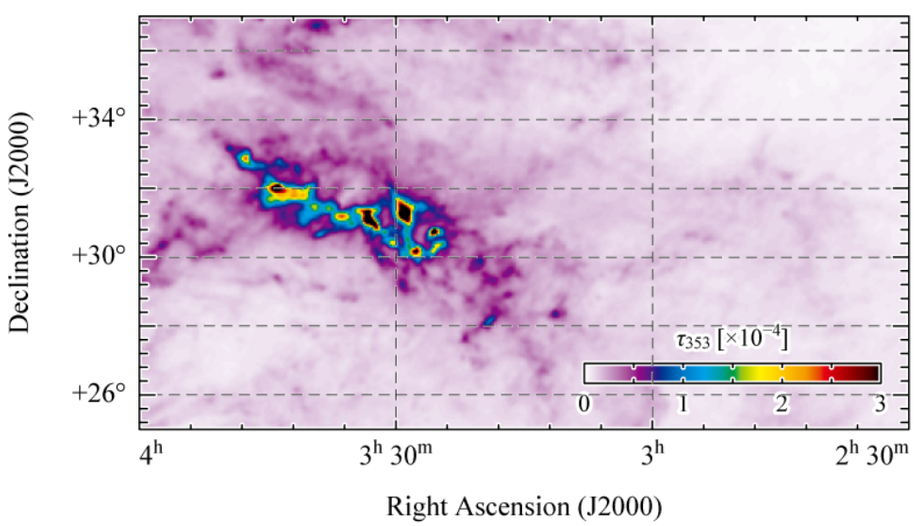
Chamaeleon



	Perseus	Chamaeleon
Distance	~300 pc	~170 pc
Diameter	~50 pc	~30 pc
Mass (H_2)	~3x10^4 Msolar	~1x10^4 Msolar
star-forming regions	IC348, NGC1333	

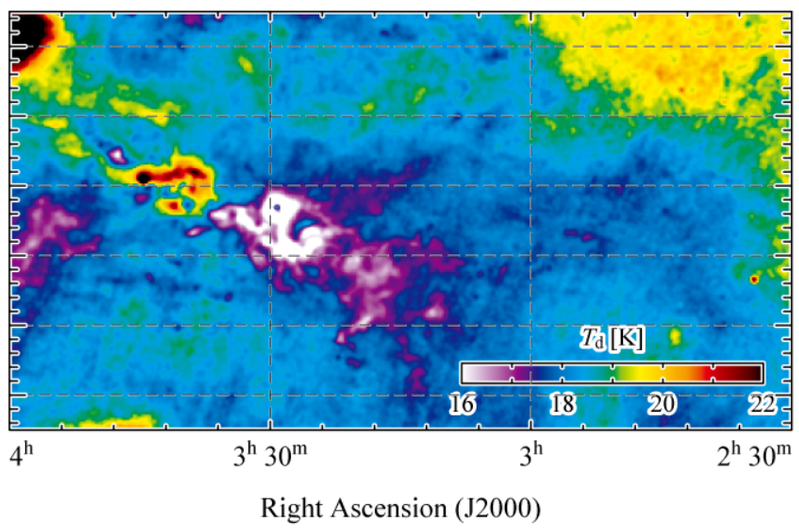
Dataset / Physical properties / ROI

τ353



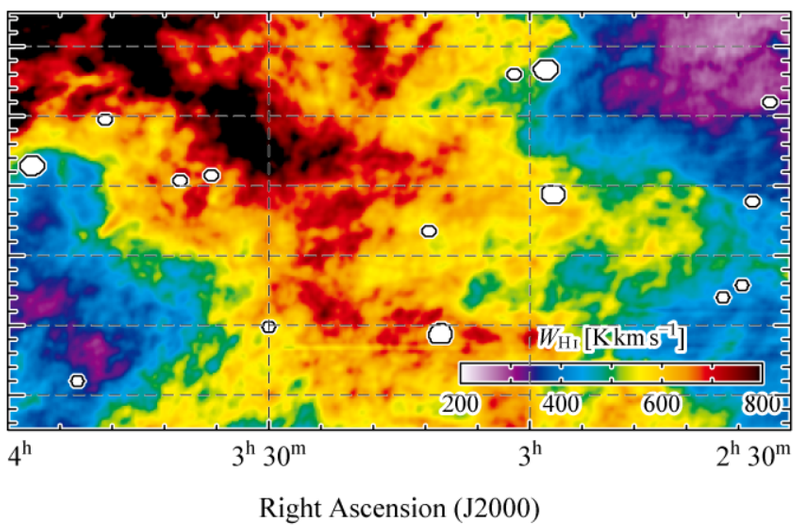
Planck

***T*d**



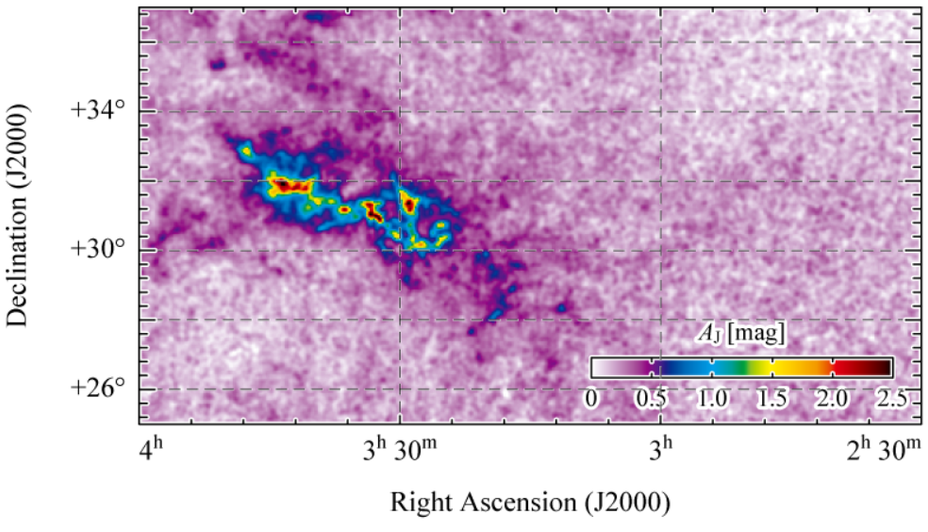
Planck

***W*HI**



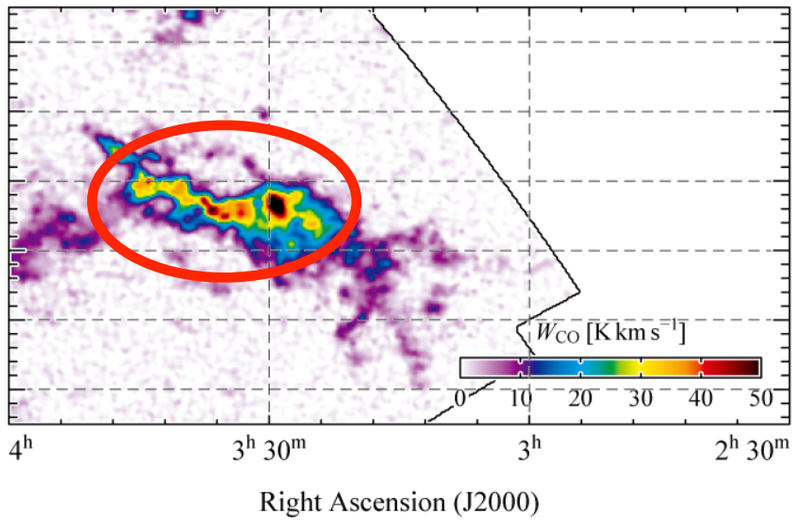
GALFA HI Survey

***A*J (NIR extinction)**



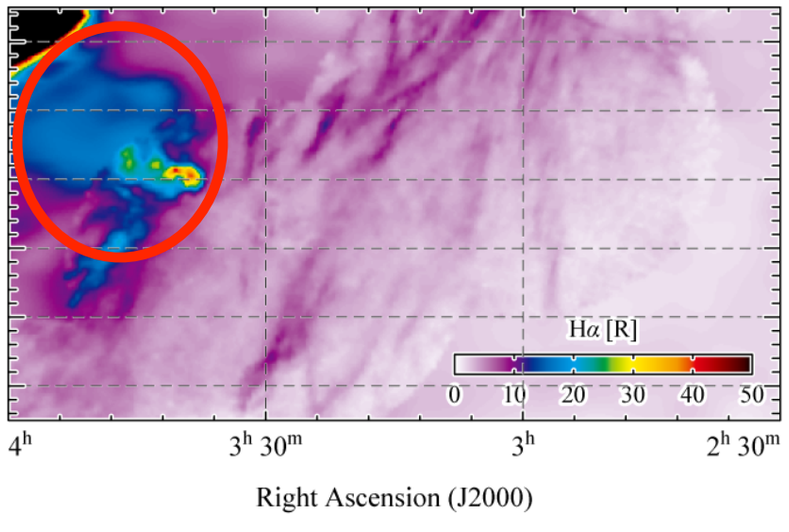
2MASS(NICEST)

***W*CO**



Dame+01 (^{12}CO (J=(1-0)))

Hα

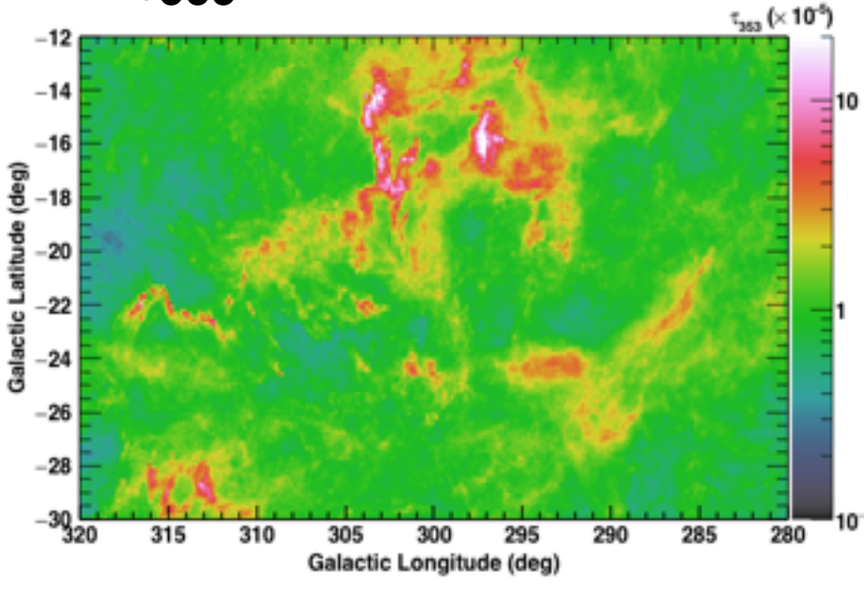


Finkibeiner+03

Masking: *W*CO > 3 σ, Hα > 10 R

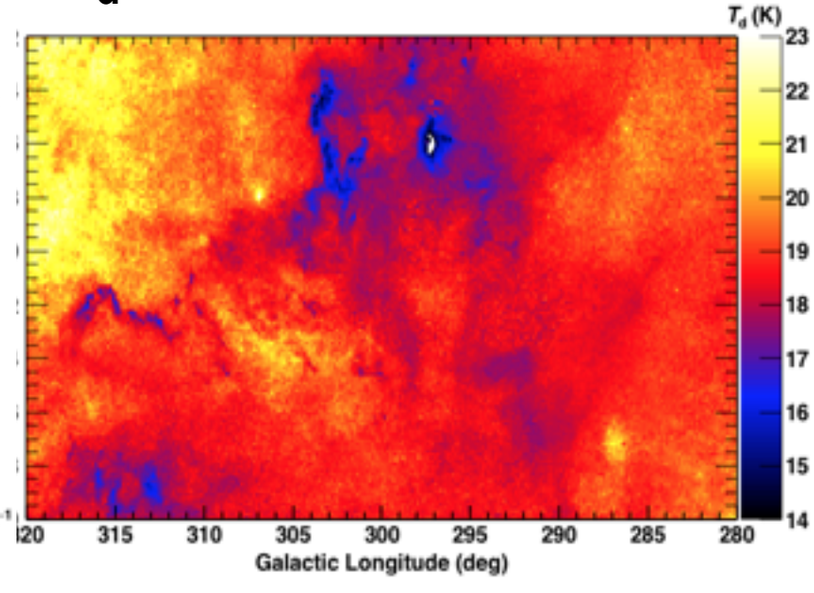
Dataset / Physical properties / ROI

τ353



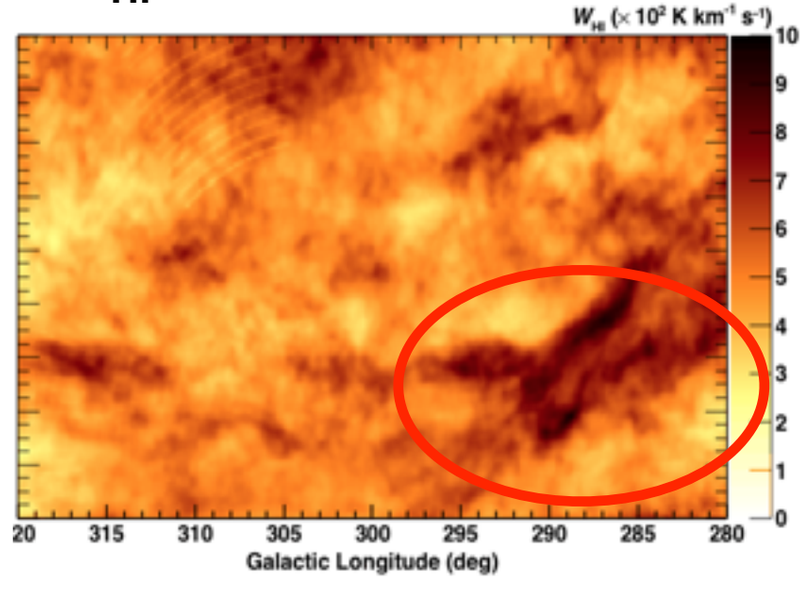
Planck

T_d



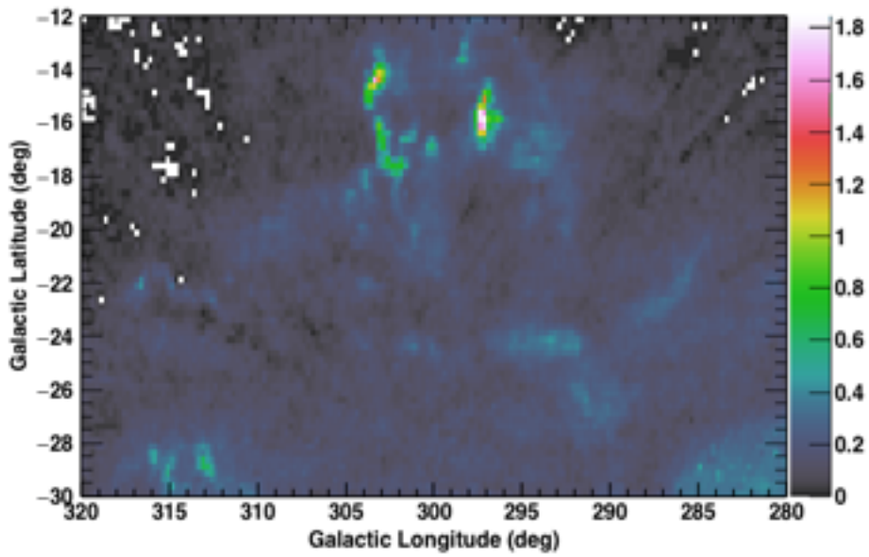
Planck

W_{HI}



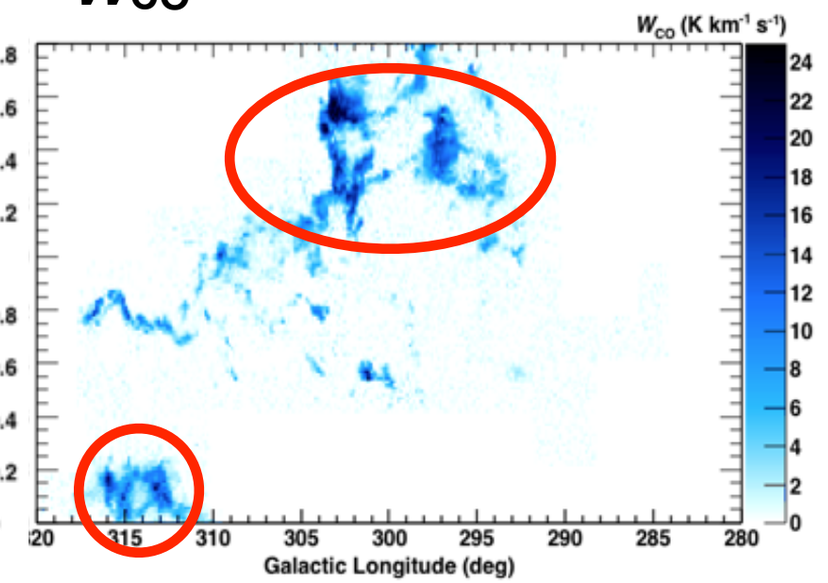
GASS (Parkes Galactic All Sky Survey)

A_J (NIR extinction)



2MASS(NICEST)

W_{CO}



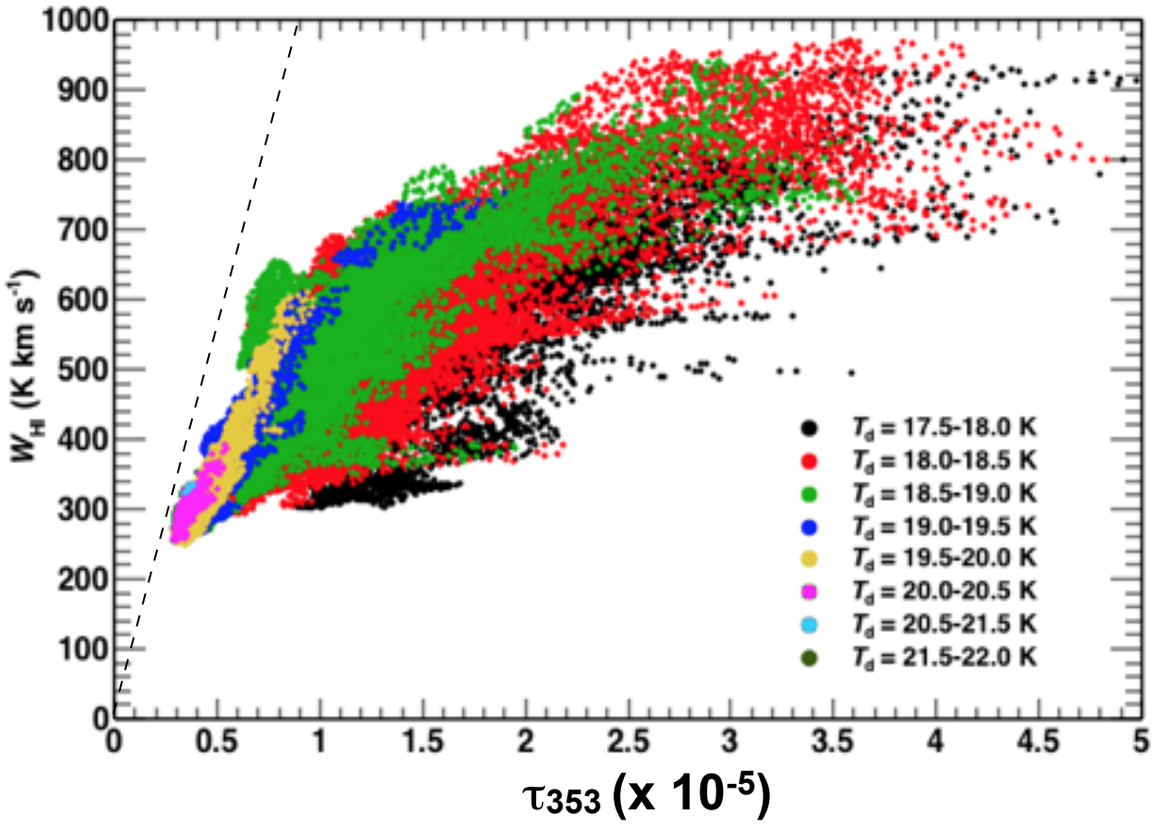
NANTEN (^{12}CO (J=(1-0)))

Masking:

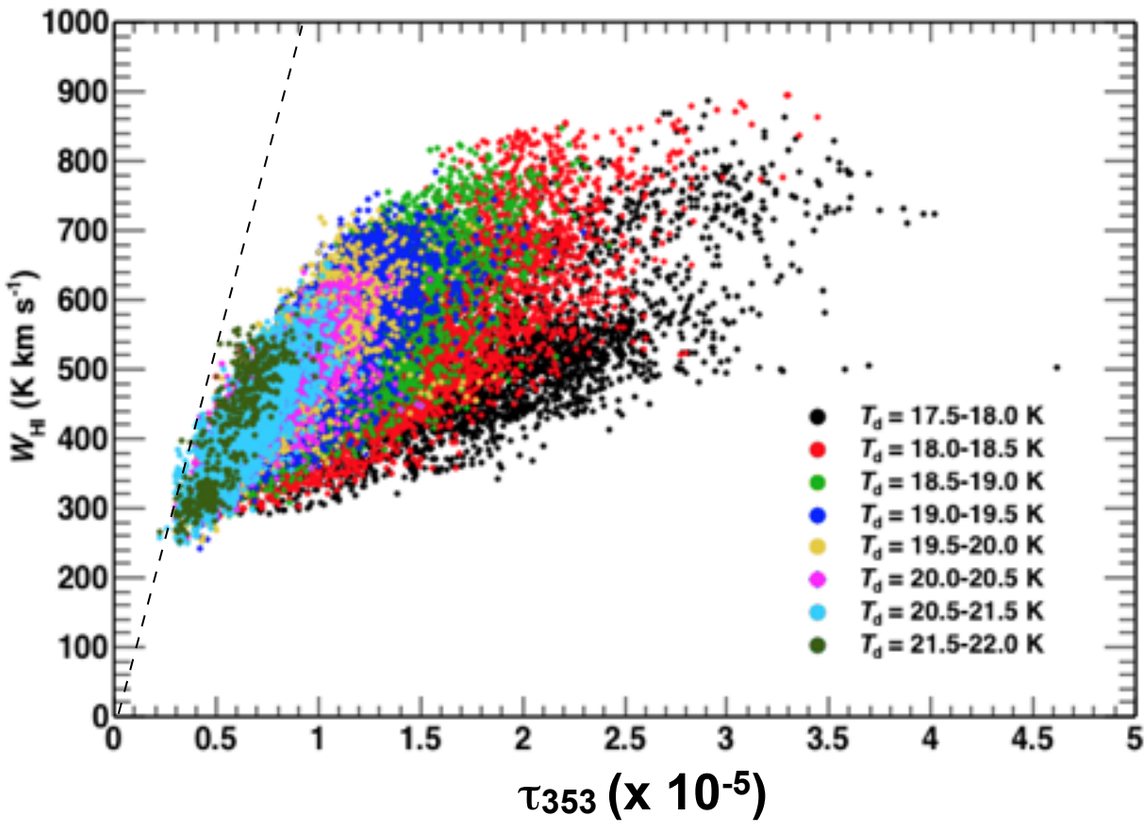
- **W_{CO} > 3 σ**
- **IVA: intermediate clouds may not be associated with local clouds**

τ_{353}-$W_{\rm HI}$ (Perseus and Chamaeleon)

Perseus



Chamaeleon

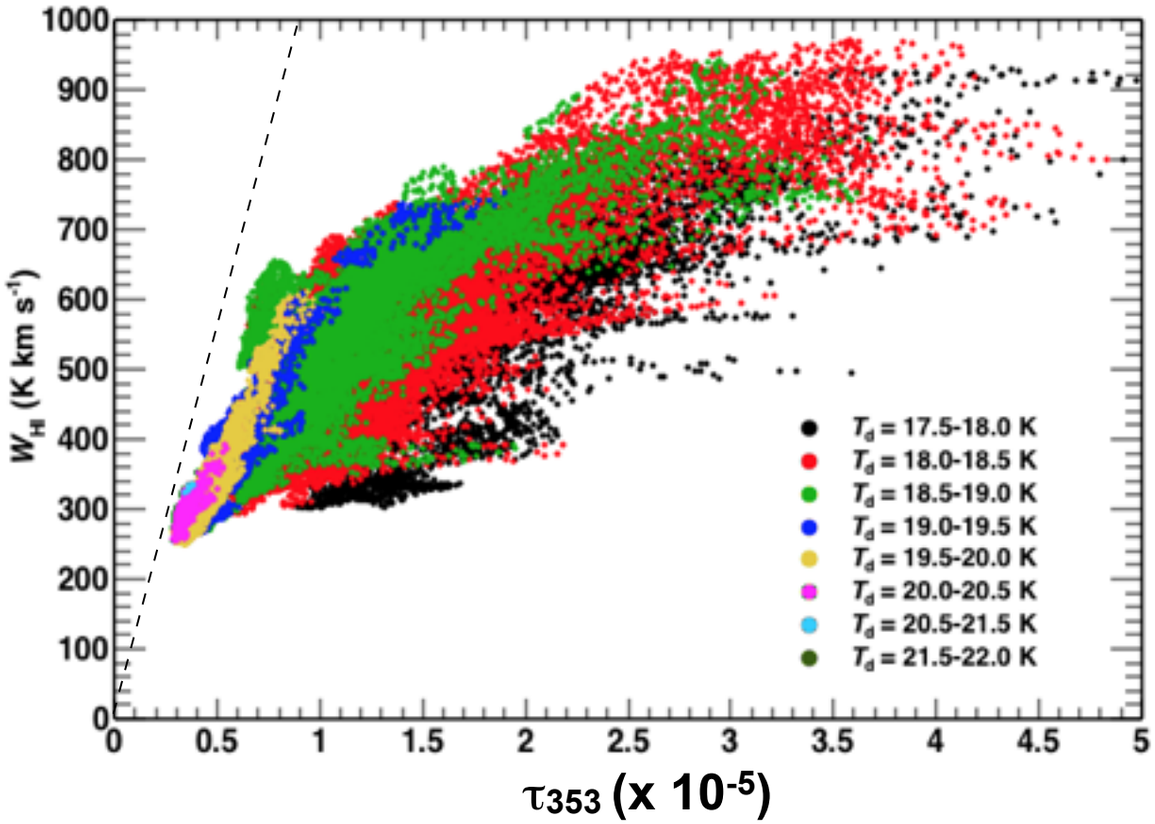


Scattering characterized by $T_{\rm d}$ distribution

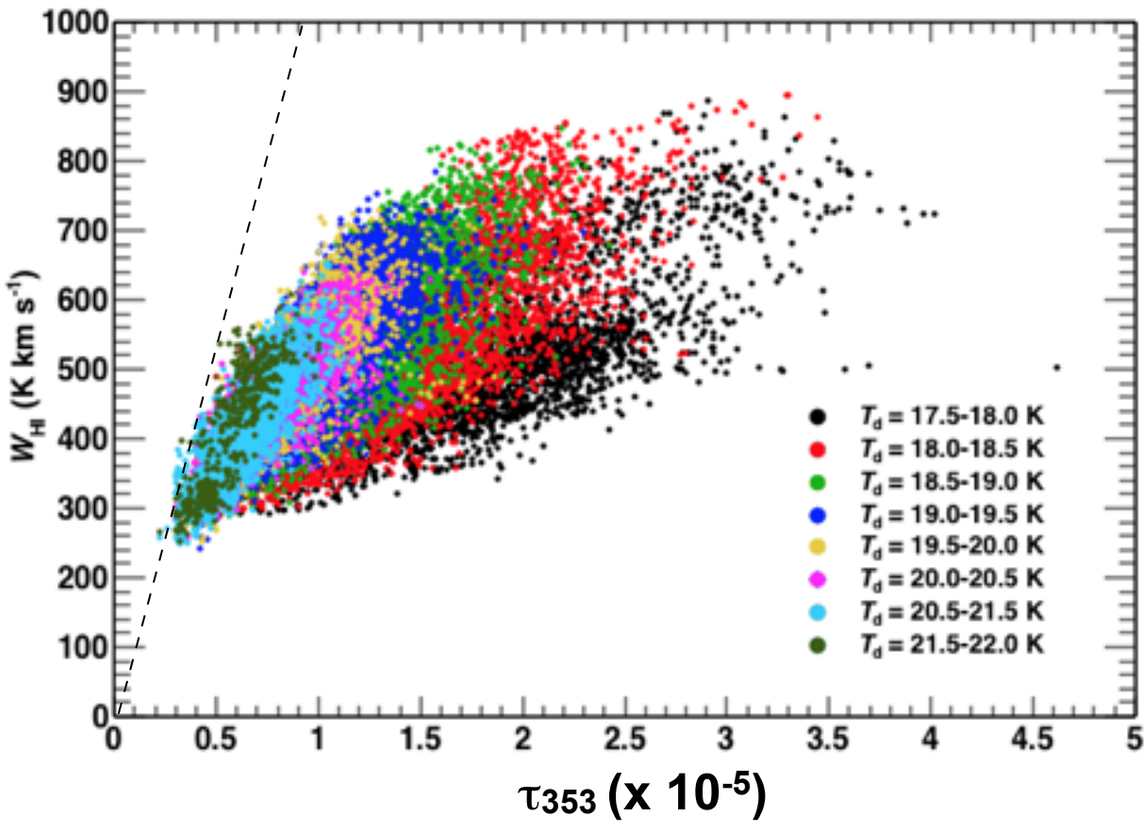
Linear relation b/w $N_{\rm H}$ and τ_{353} in all sky (Fukui+15)

τ_{353}-$W_{\rm HI}$ (Perseus and Chamaeleon)

Perseus



Chamaeleon



Scattering characterized by $T_{\rm d}$ distribution

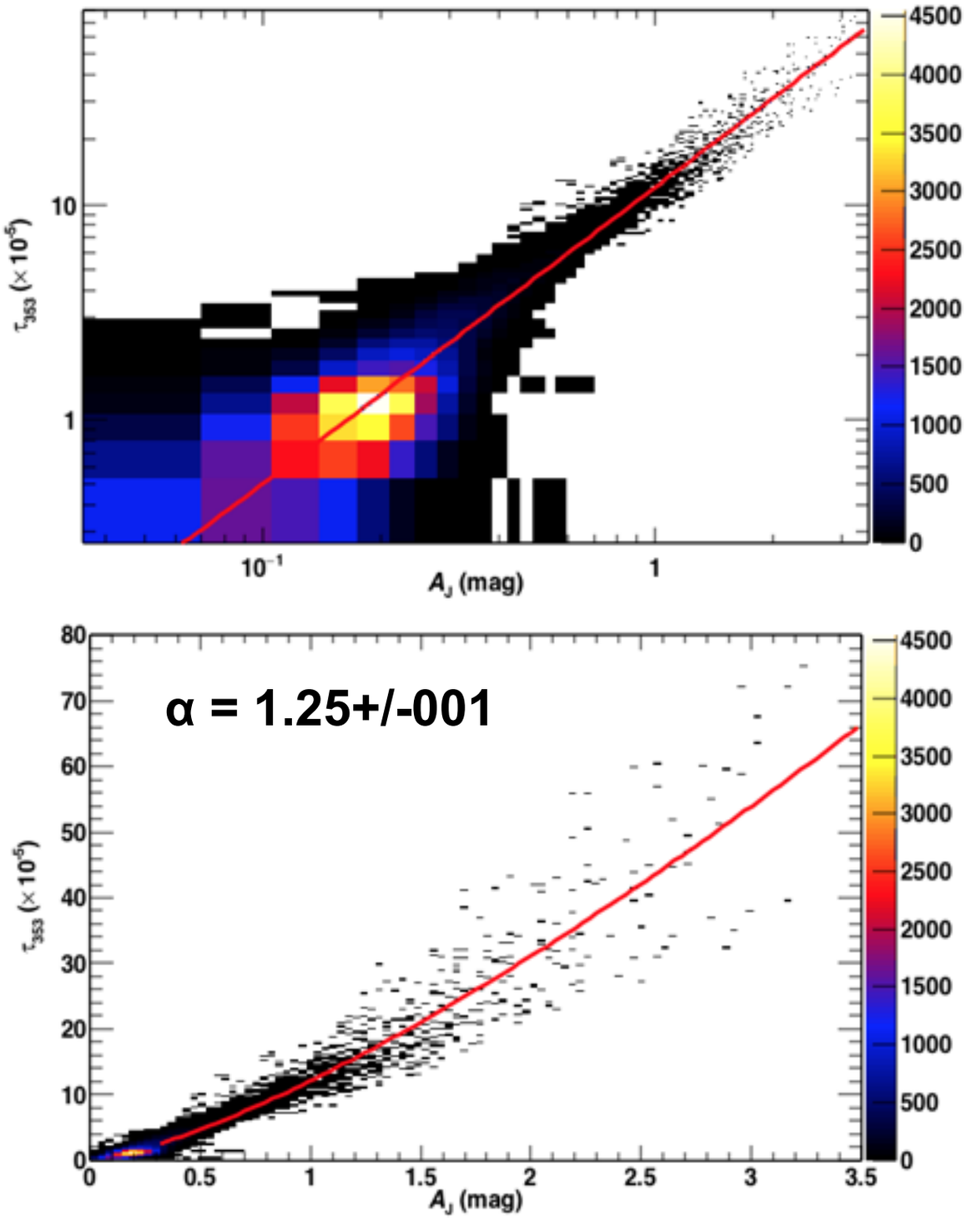
Linear relation b/w $N_{\rm H}$ and τ_{353} in all sky (Fukui+15)
Possible non-linear relation b/w $N_{\rm H}$ and τ_{353}
e.g., α ~1.3 in Orion (Roy+13)

$$\frac{N_{\rm H}(l,b)}{N_{\rm H,ref}} = \left(\frac{\tau_{353}(l,b)}{\tau_{353,\rm ref}}\right)^{1/\alpha}$$

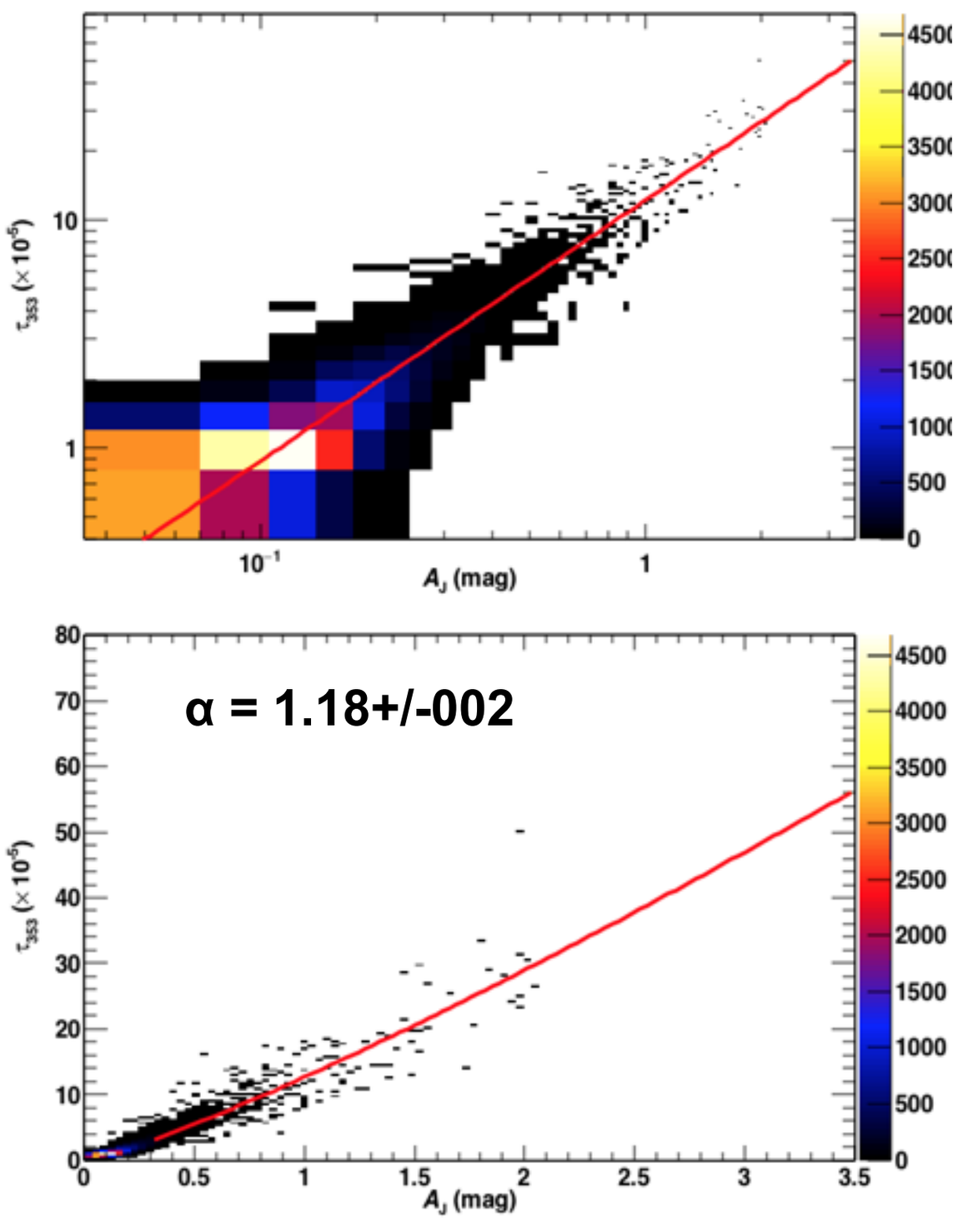
If dust grows with density in time, what is α?
Correlation between τ_{353} and $A_{\rm J}$ based on the assumption that $A_{\rm J}$ represents $N_{\rm H}$

A_J vs. τ_{353}

Perseus

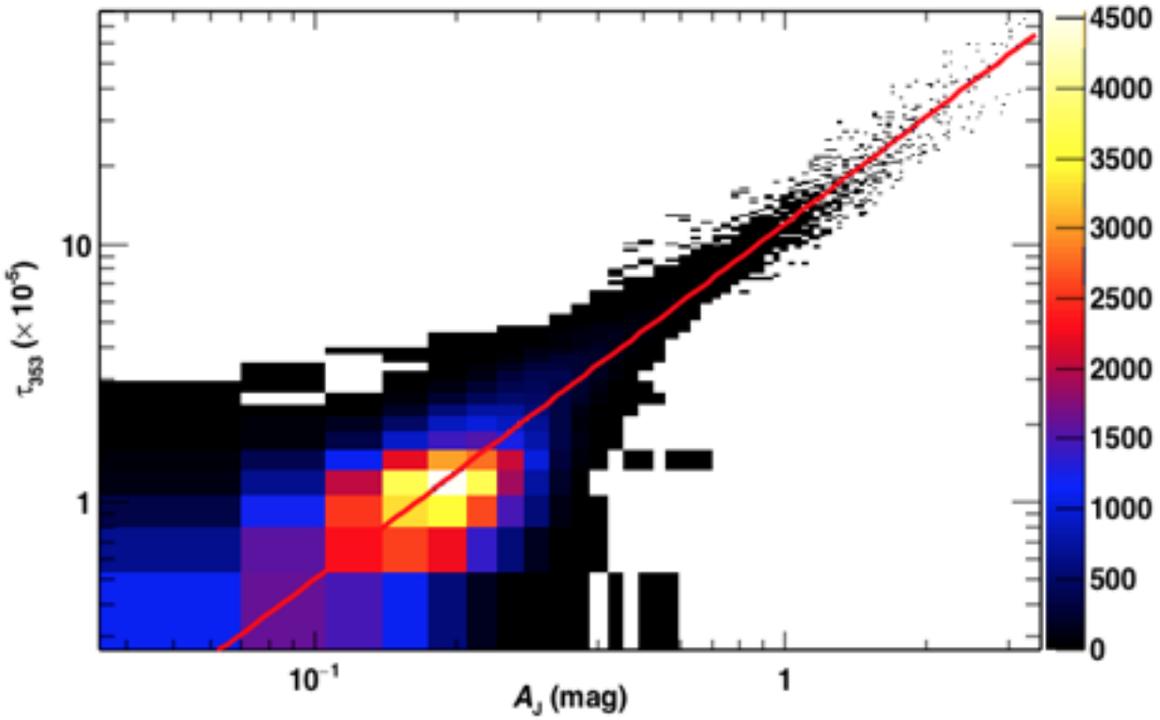


Chamaeleon

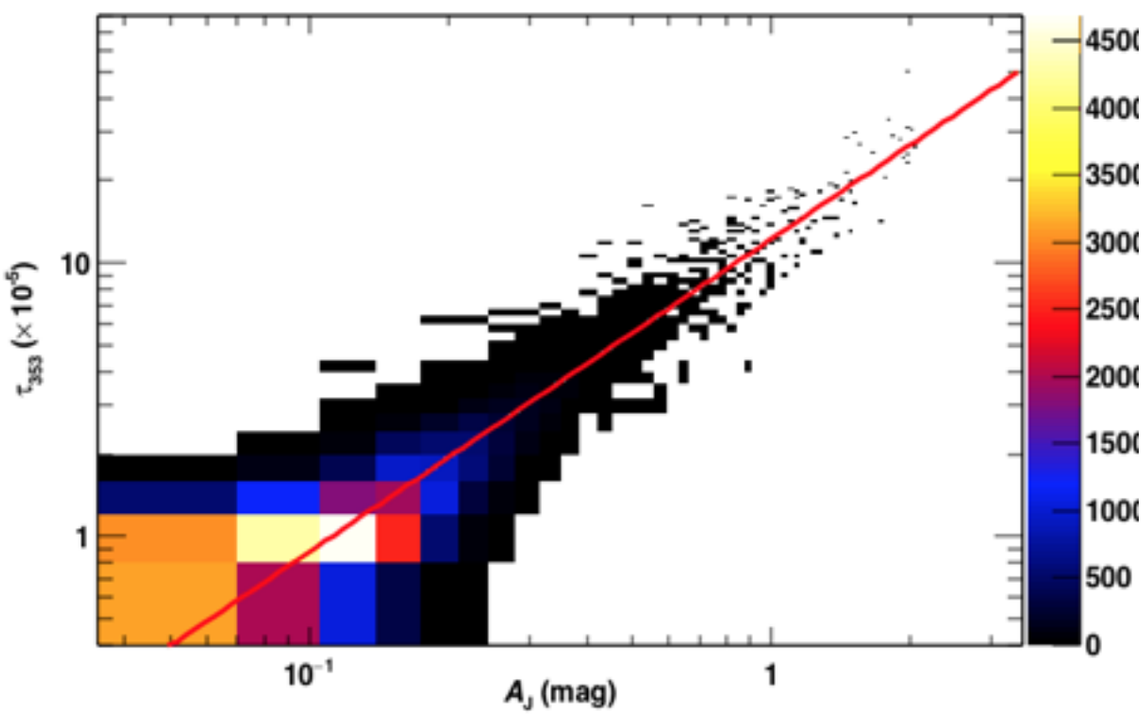


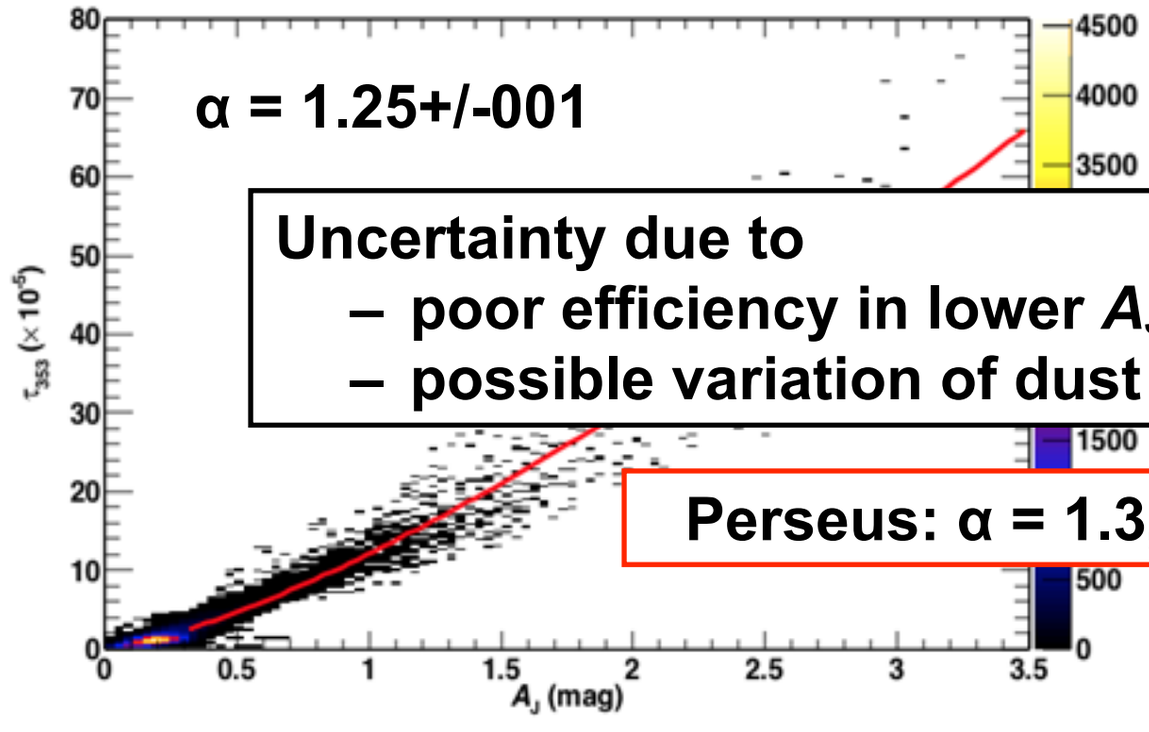
A_J vs. τ_{353}

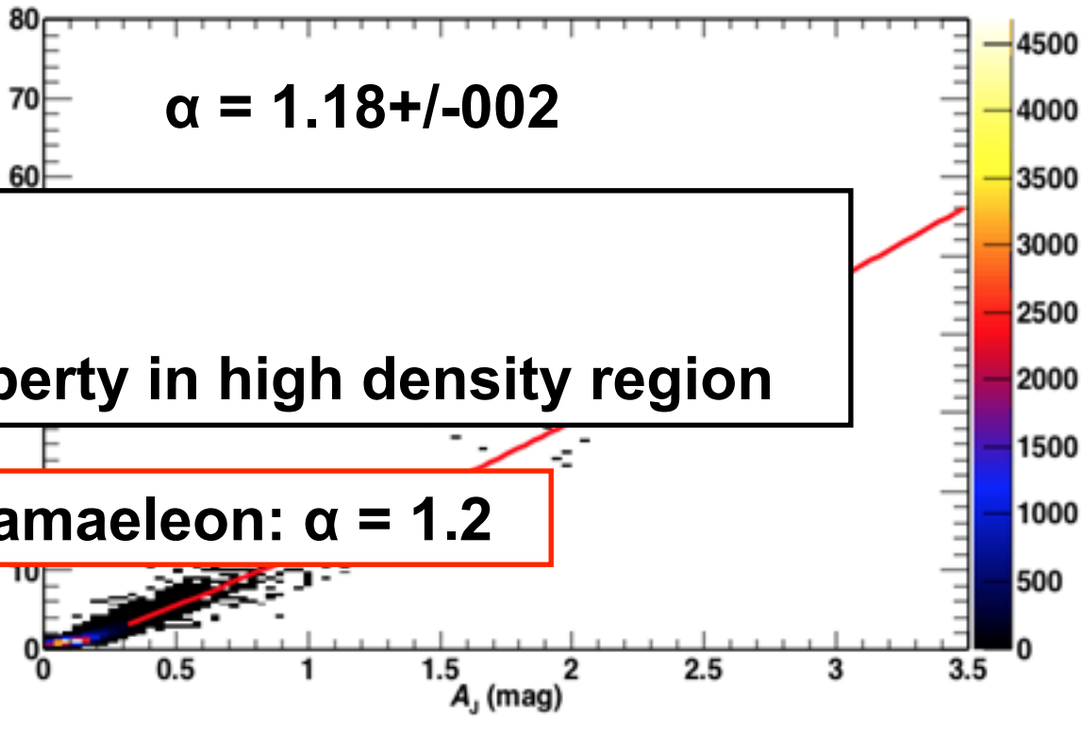
Perseus



Chamaeleon





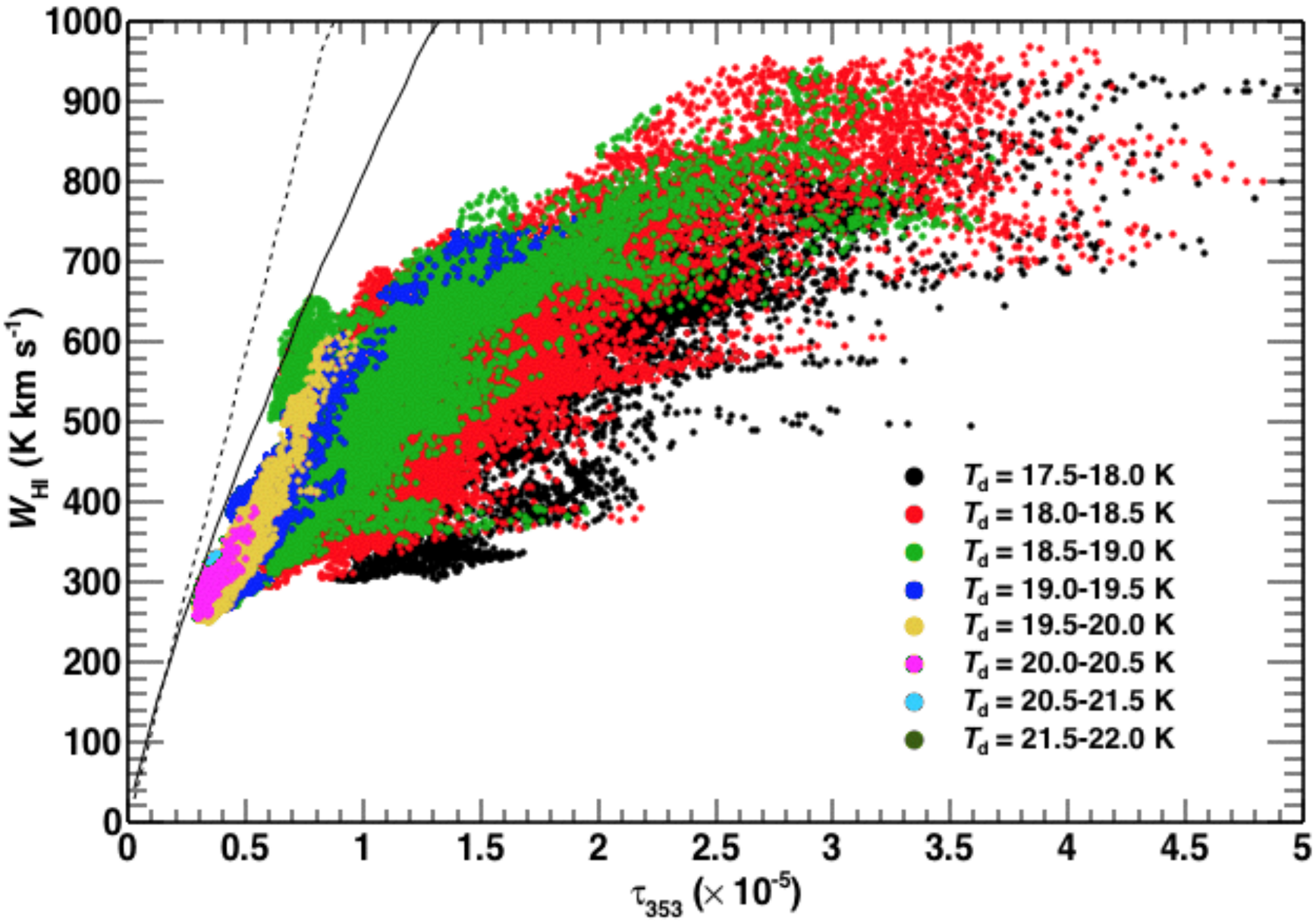


Uncertainty due to
- **poor efficiency in lower A_J**
- **possible variation of dust property in high density region**

Perseus: α = 1.3, Chamaeleon: α = 1.2

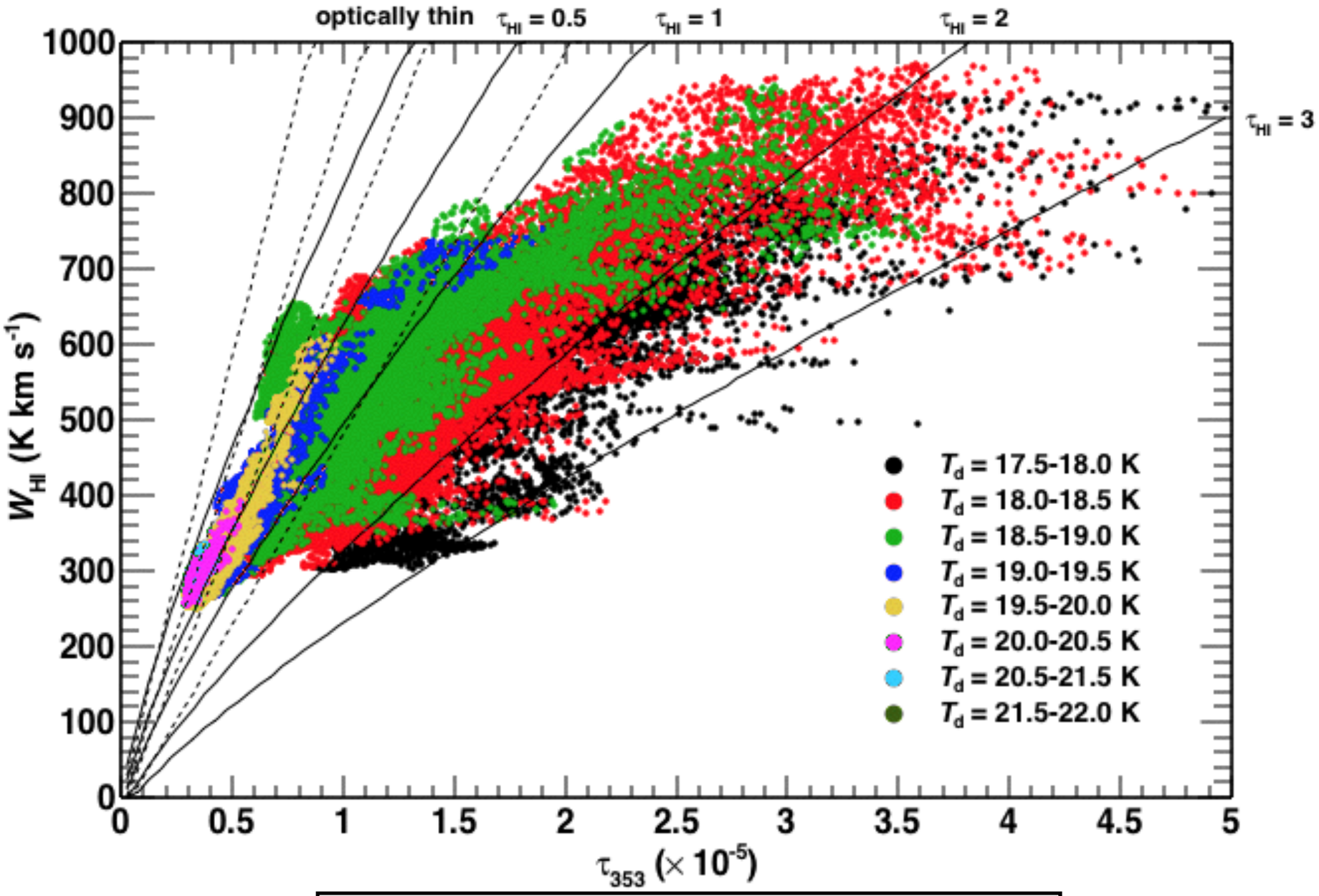
τ_{353}-$W_{\rm HI}$ (Perseus)

α = 1.0 α = 1.3



$$W_{\rm H\,I} = \left\{ \left(\frac{\tau_{353}}{\tau_{353,\rm ref}} \right)^{1/\alpha} \frac{N_{\rm H,ref}}{X_{\rm H\,I}} \frac{1}{\tau_{\rm H\,I}} \frac{1}{\Delta V_{\rm H\,I}} - T_{\rm bg} \right\} \times \Delta V_{\rm H\,I} \{1 - \exp(-\tau_{\rm H\,I})\}$$

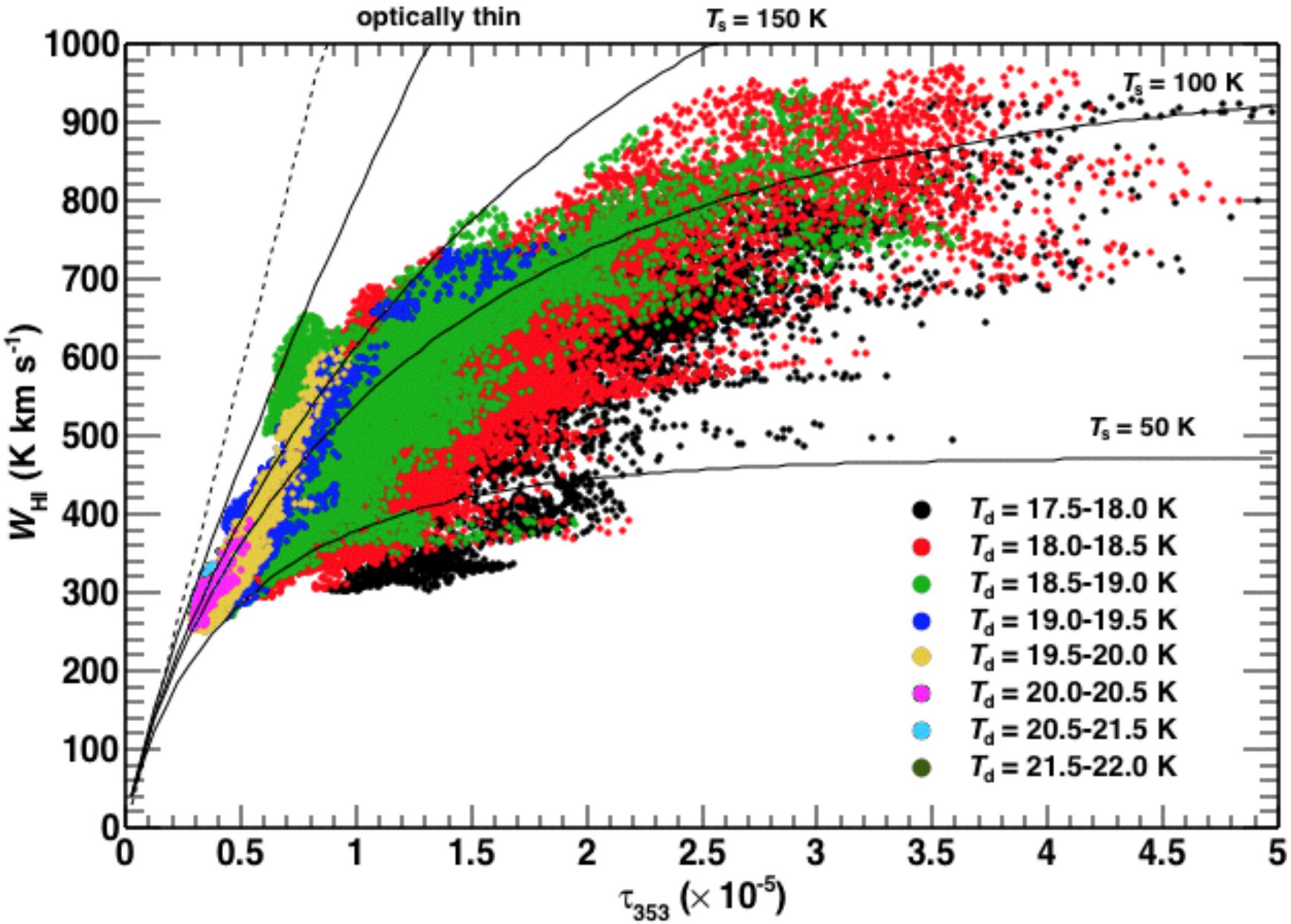
τ_{353}-W_{HI} (Perseus)



dot line: α = 1.0 solid line: α = 1.3

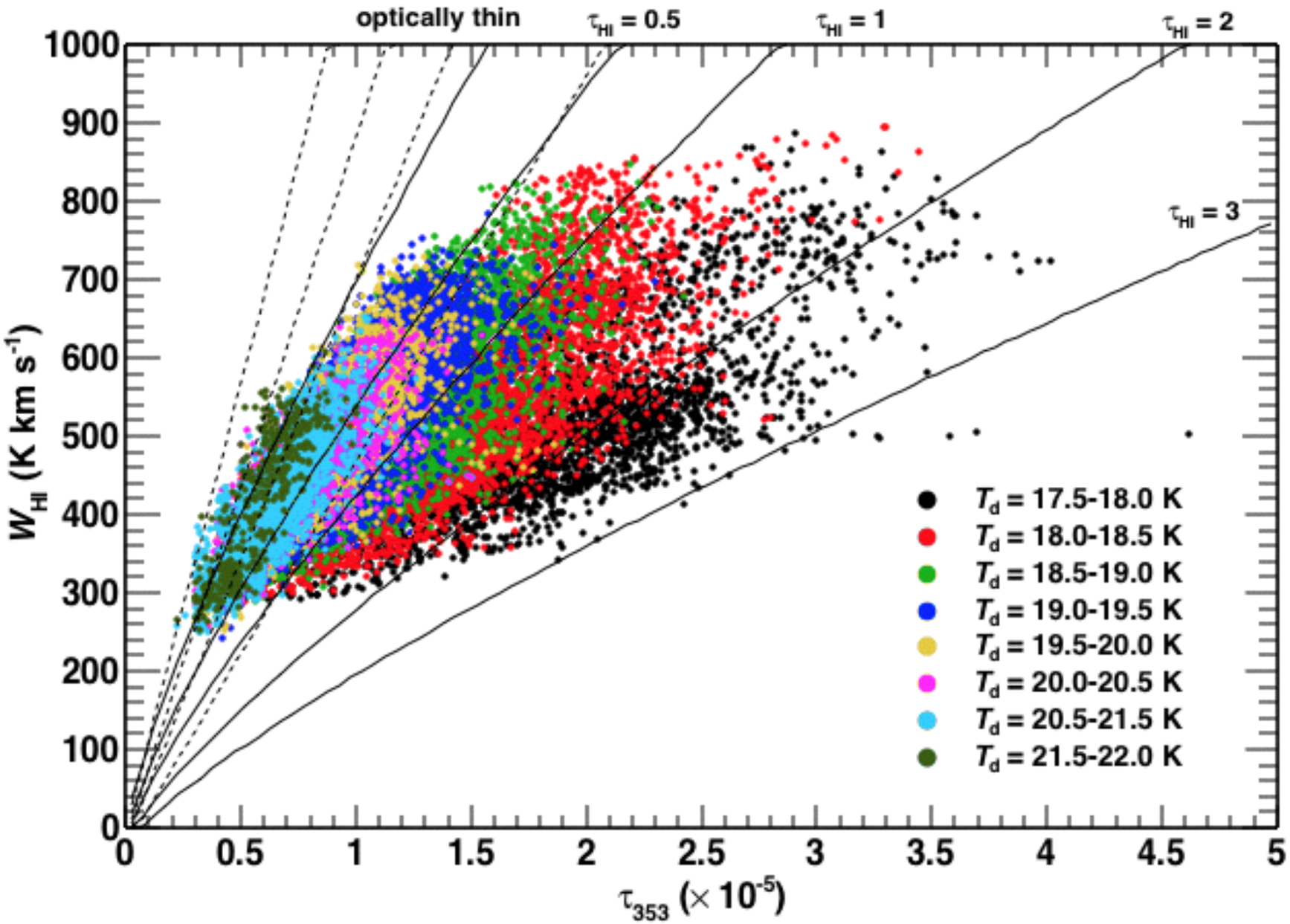
- **Correlation of α = 1.3 is much better than that of α = 1.0**
- **Possible large amount of HI with higher τHI (>~1) characterized by lower Td**

τ_{353}-$W_{\rm HI}$ (Perseus)



Possible large amounts of HI with lower Ts (<100 K) characterized by lower Td

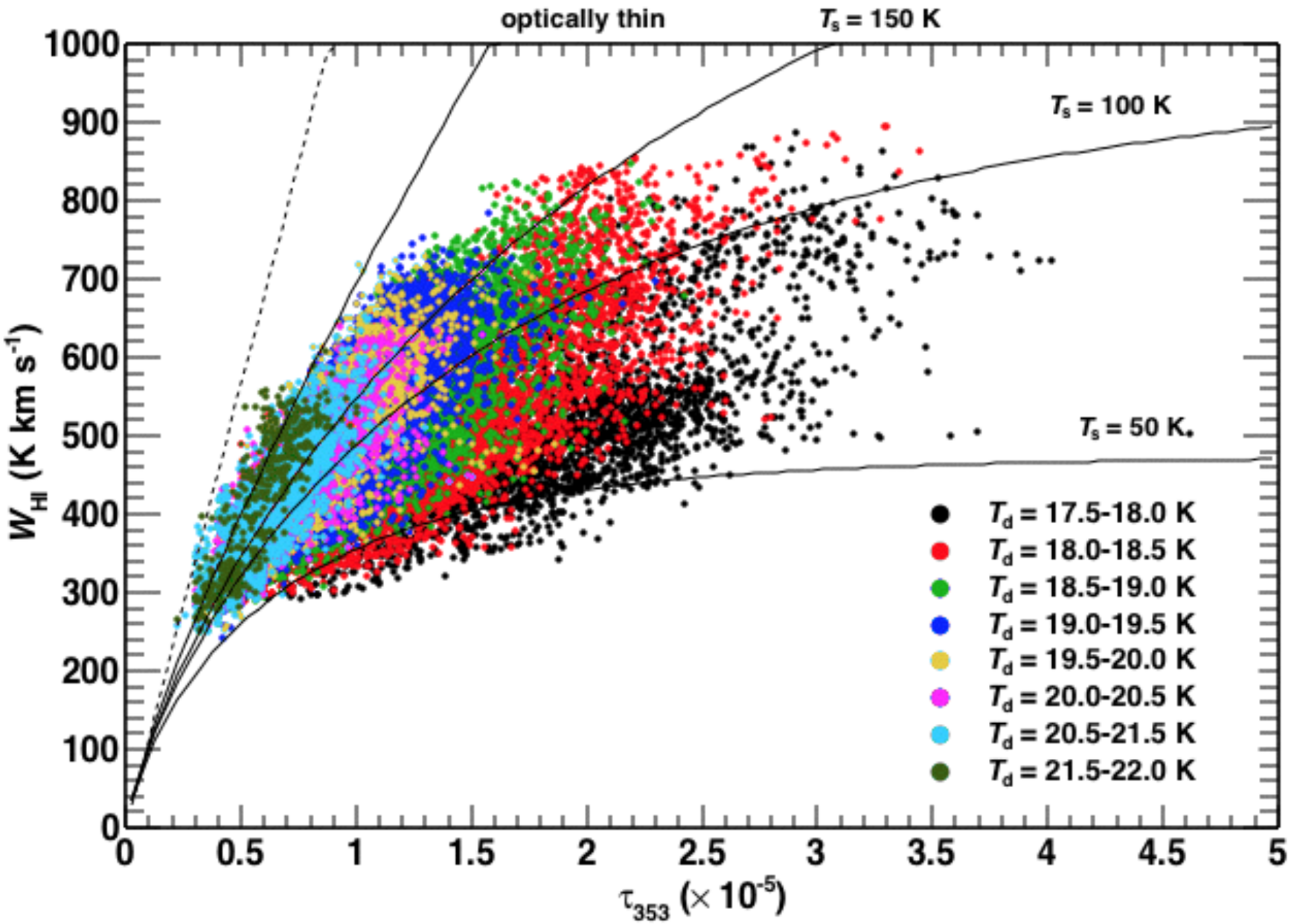
τ_{353}-W_{HI} (Chamaeloen)



dot line: α = 1.0 solid line: α = 1.2

- **Correlation of α = 1.2 is much better than that of α = 1.0**
- **Possible large amount of HI with high τHI (>1) characterized by lower Td**

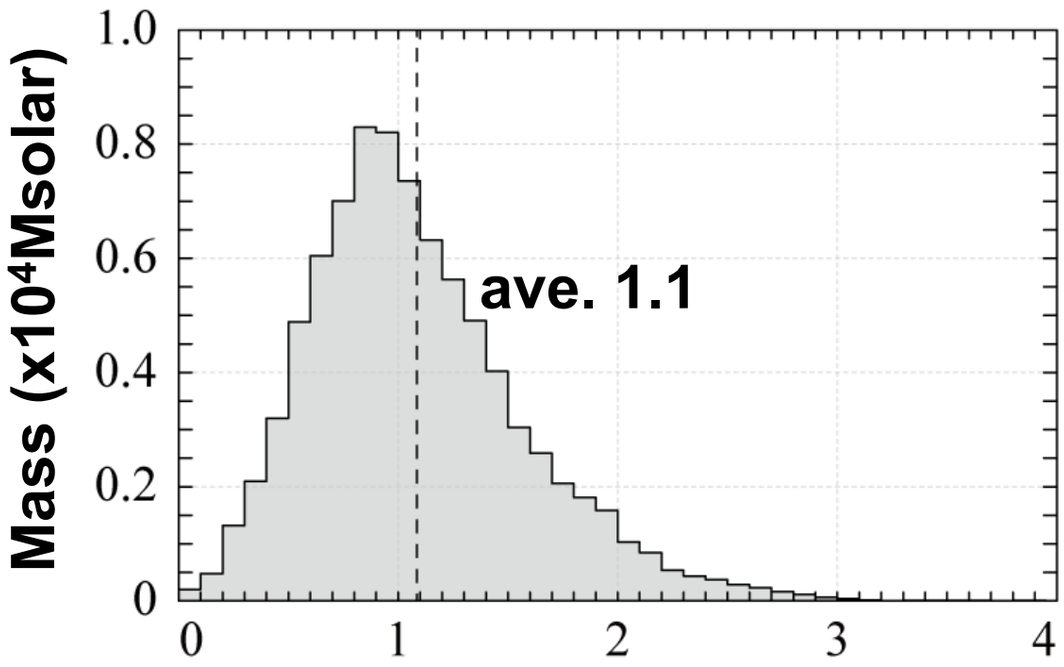
τ_{353}-W_{HI} (Chamaeloen)

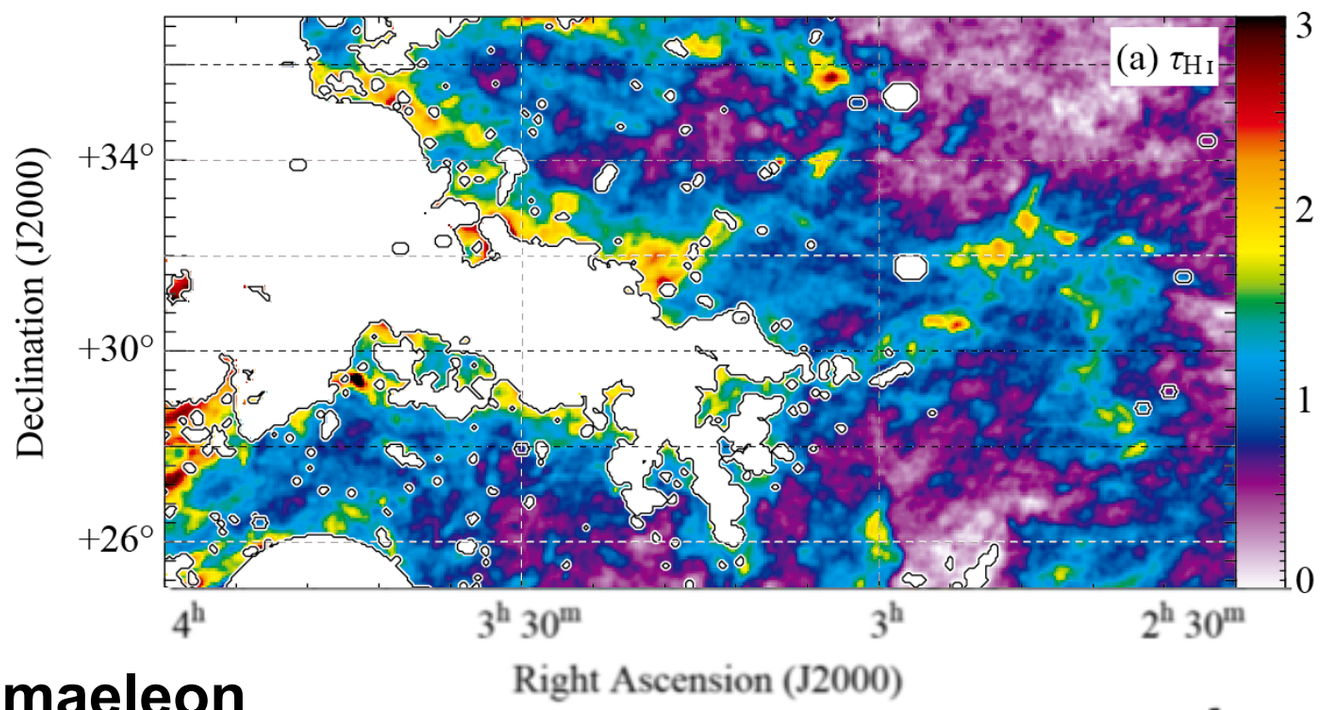


Possible large amount of HI with lower Ts (<100 K) characterized by lower Td

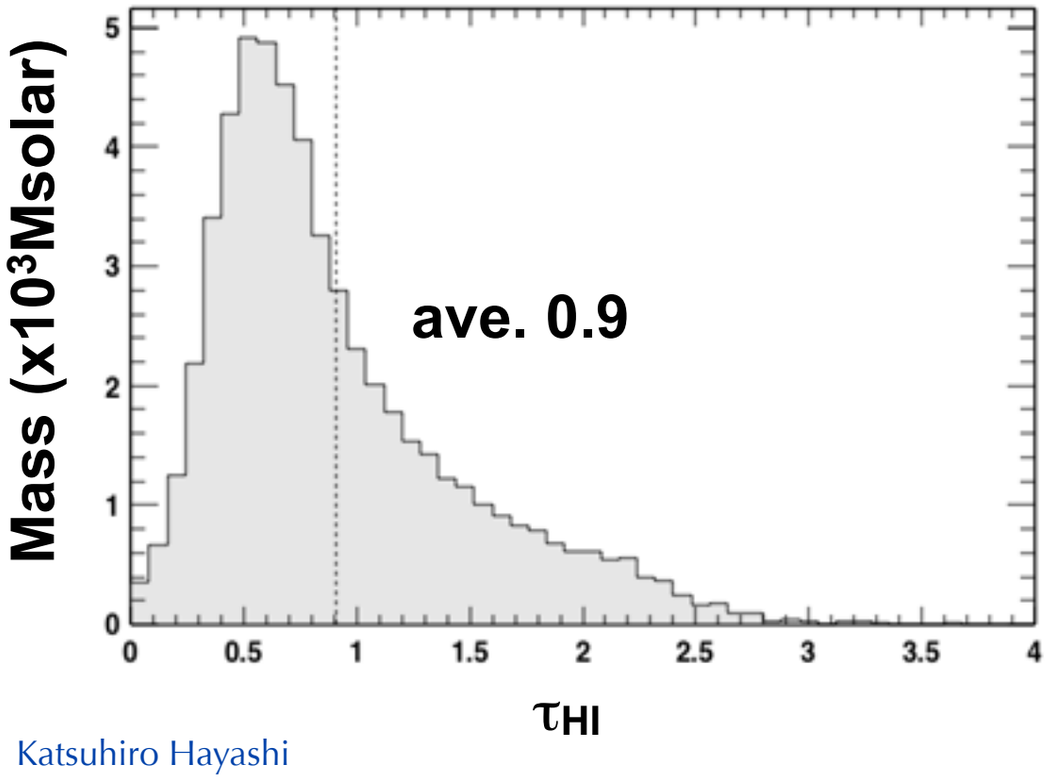
HI Optical Depth (τ_{HI})

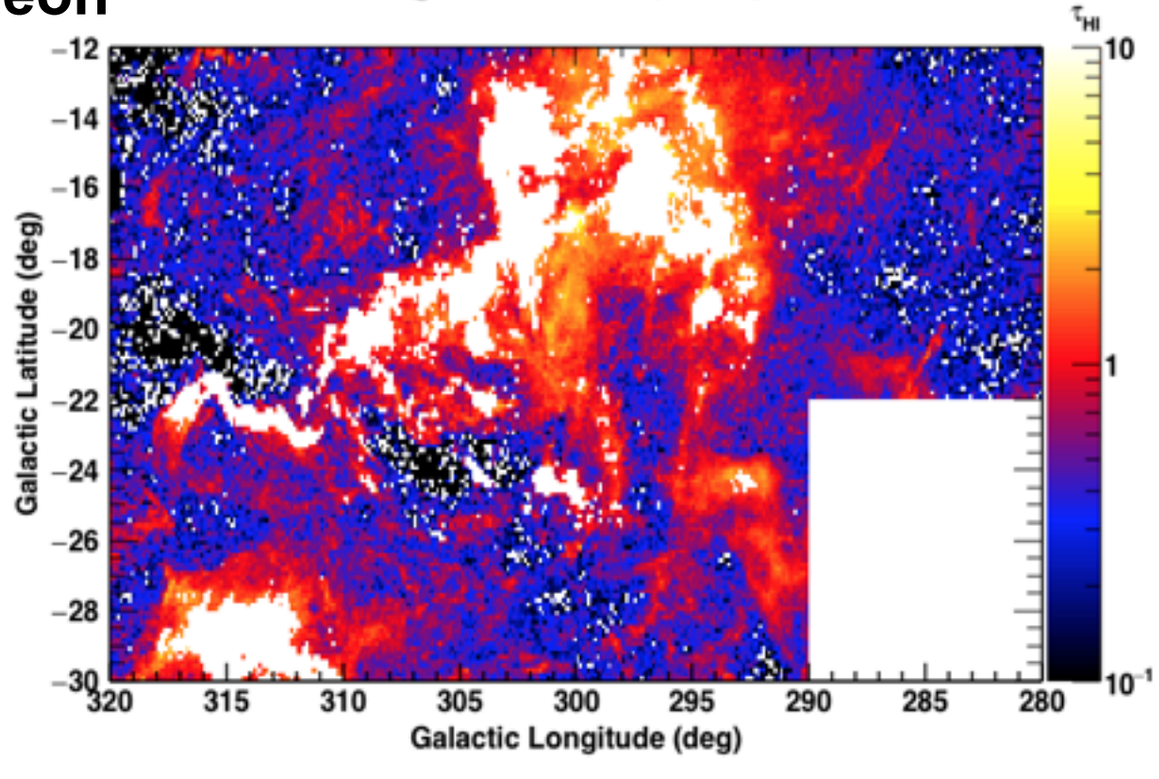
Perseus





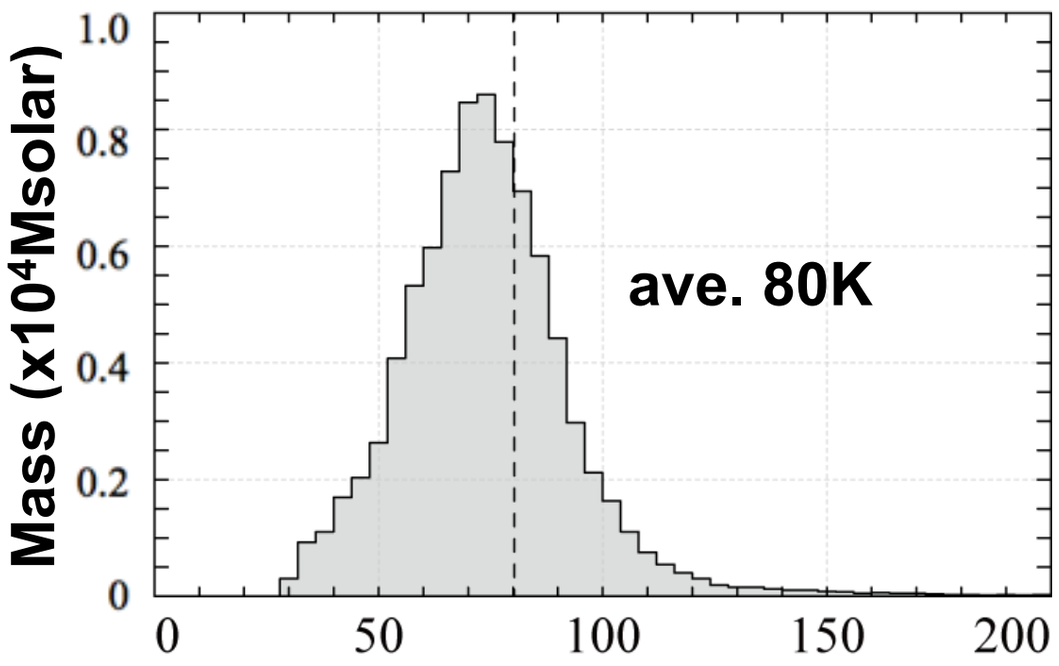
Chamaeleon

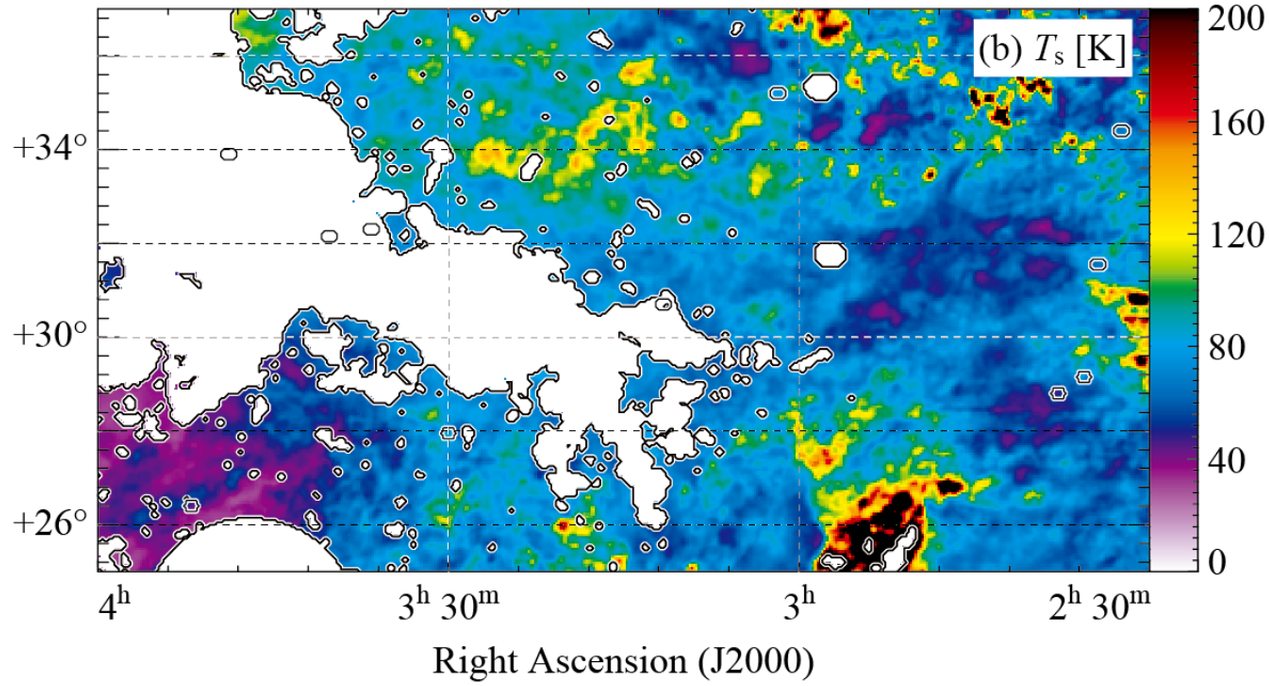




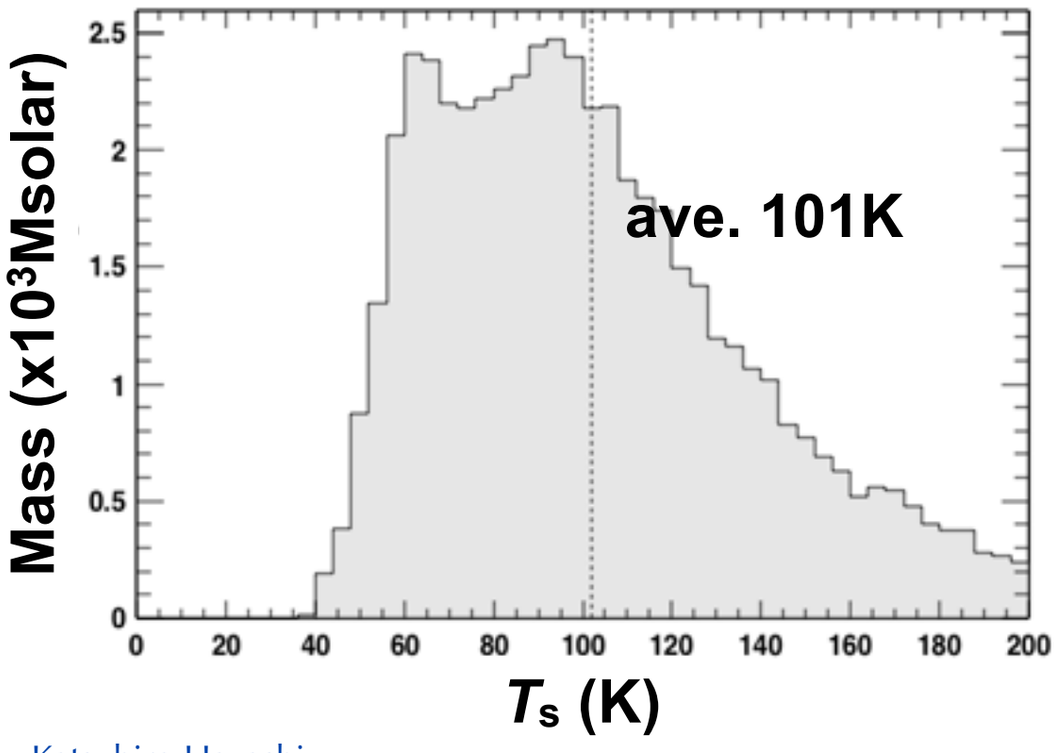
Gas Temperature (T_s)

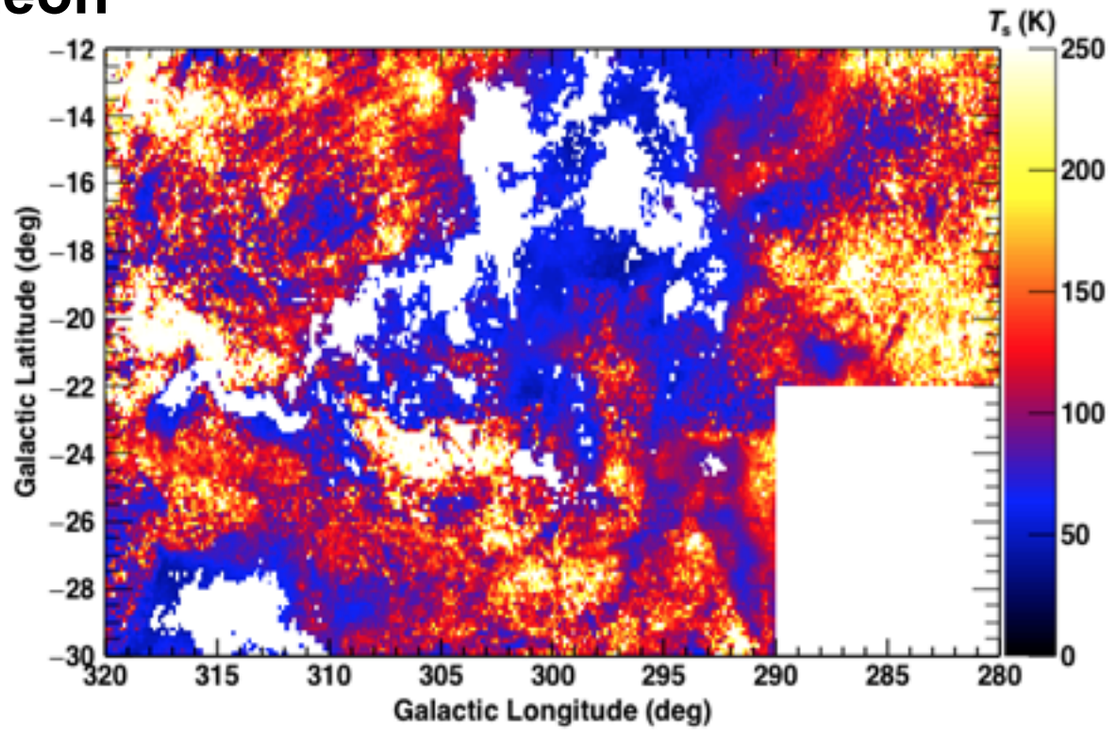
Perseus





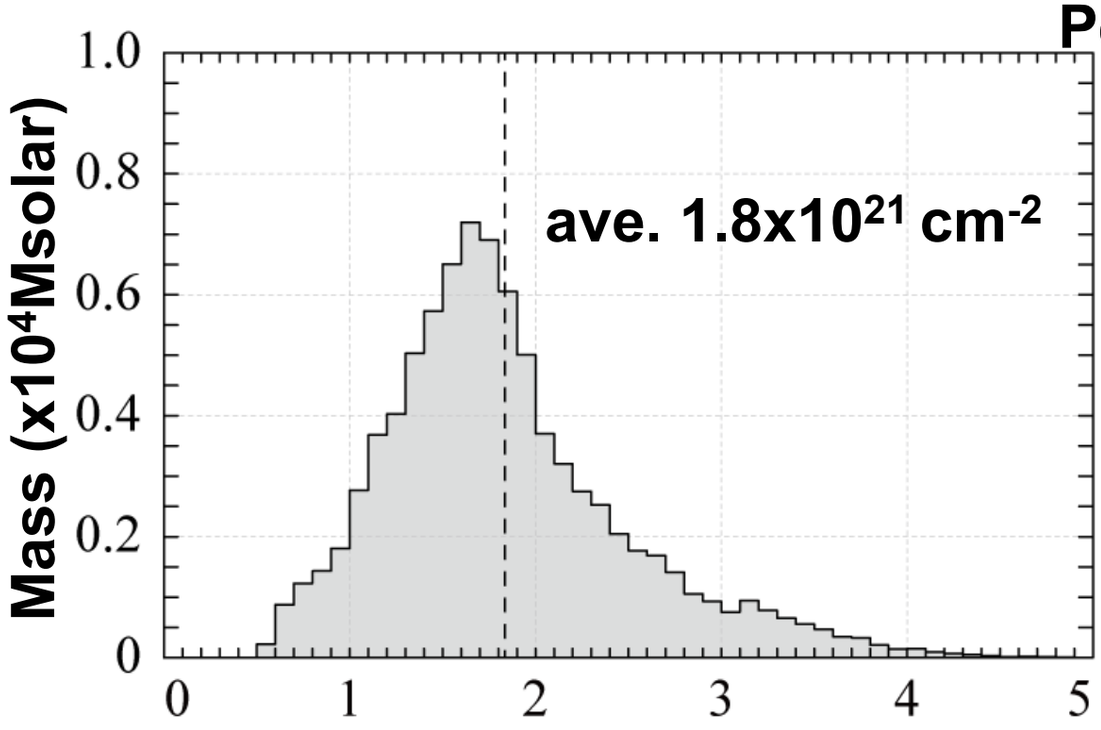
Chamaeleon

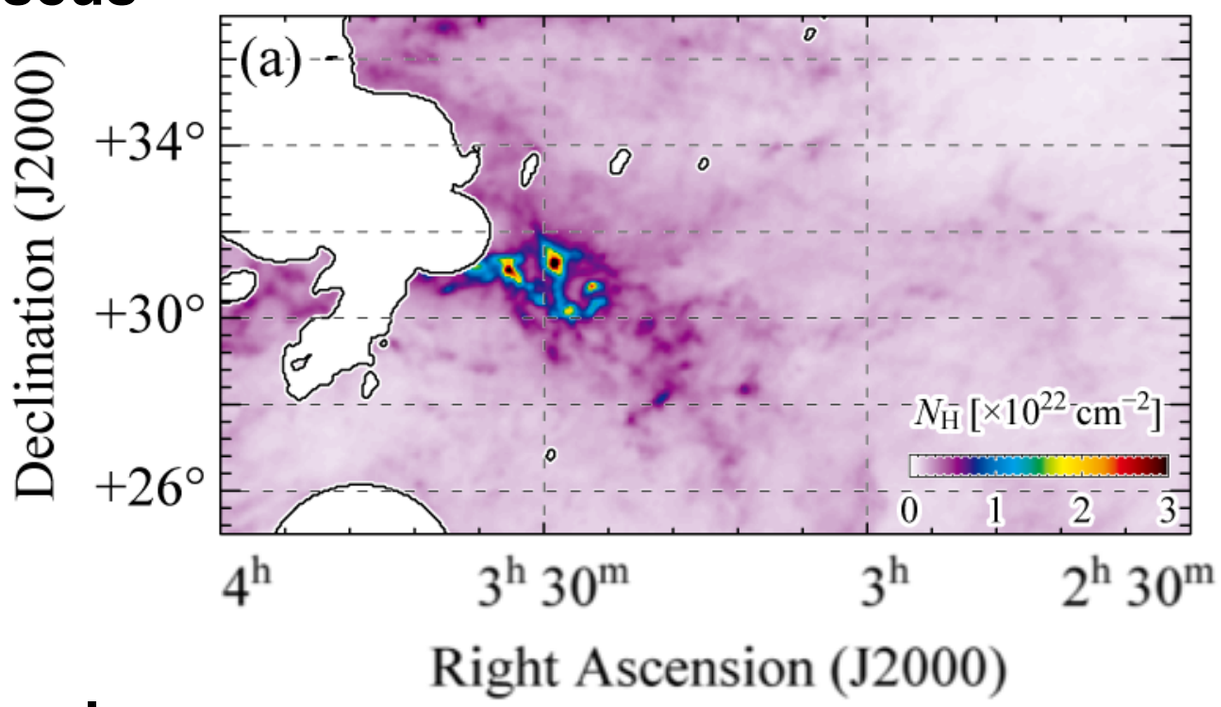




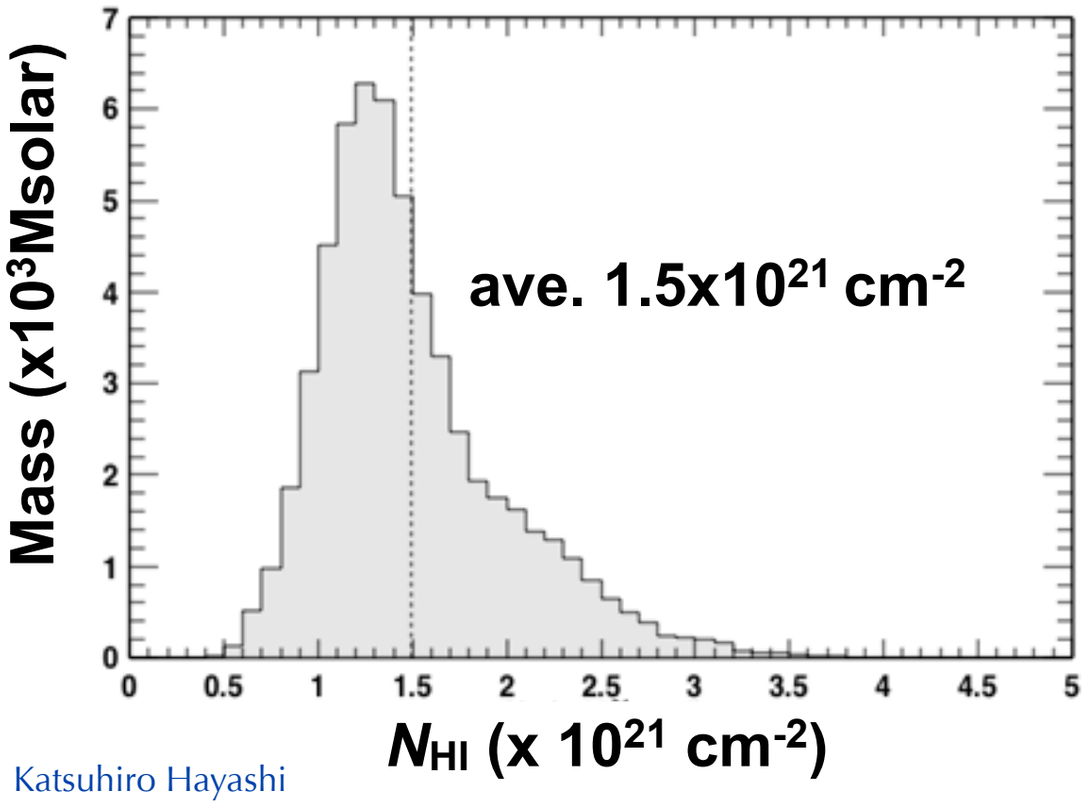
HI Column Density (N_{HI})

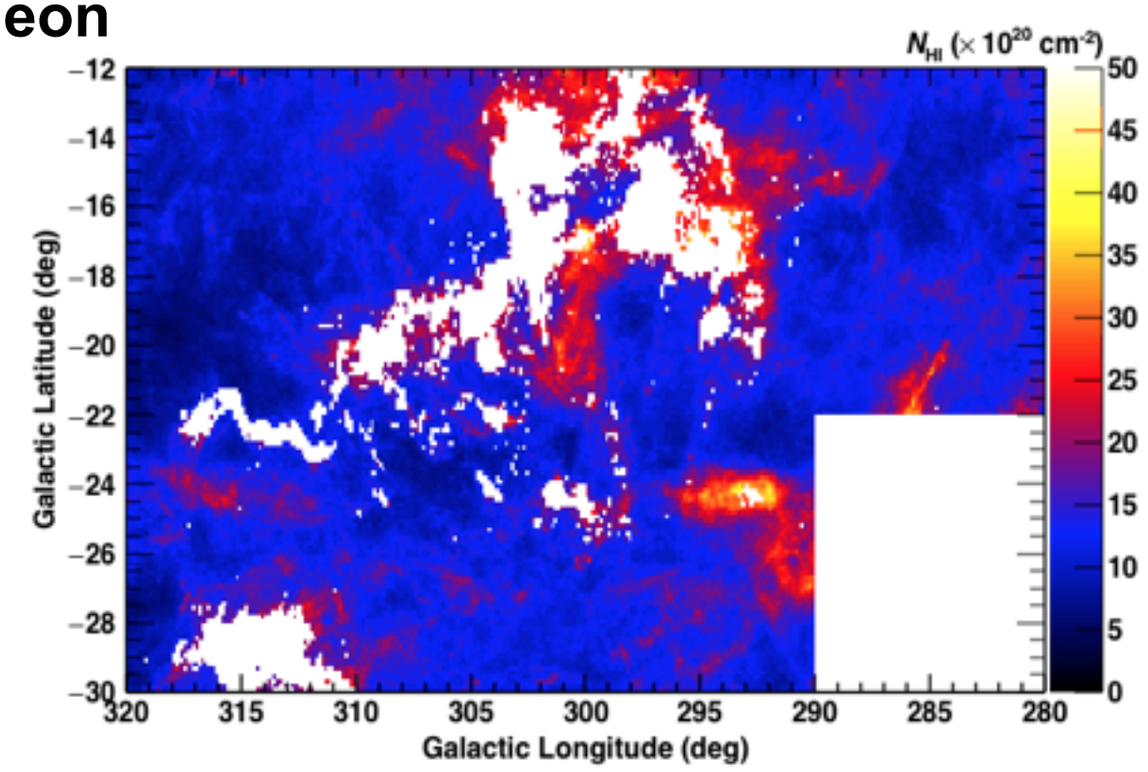
Perseus



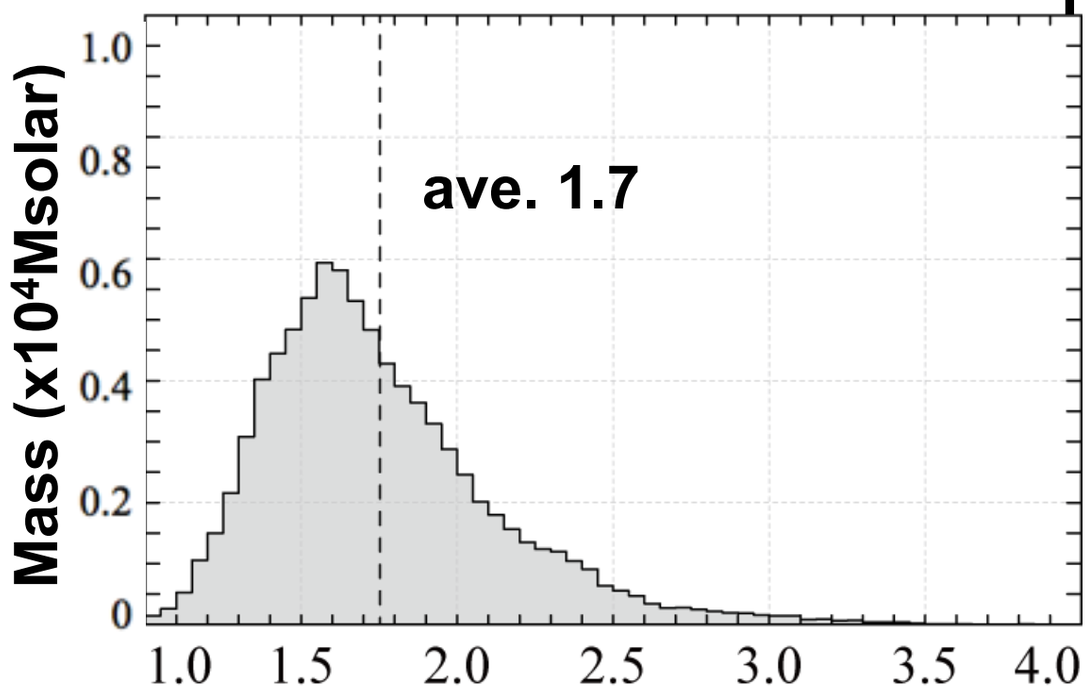


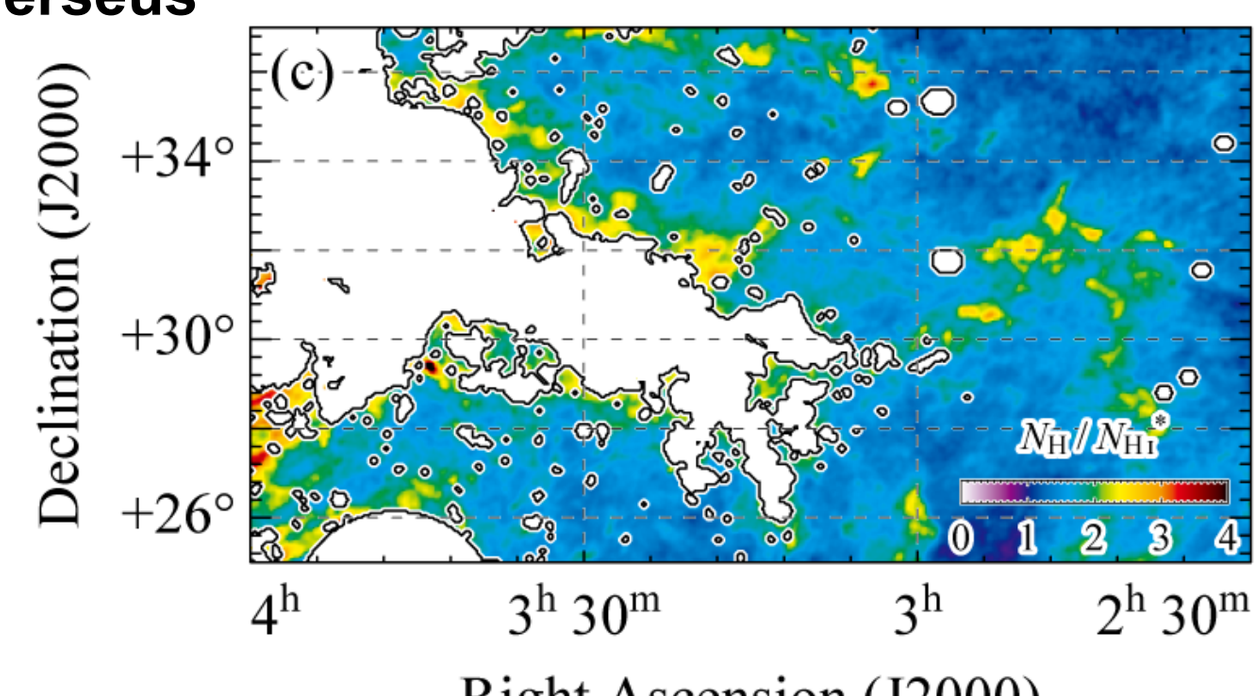
Chamaeleon

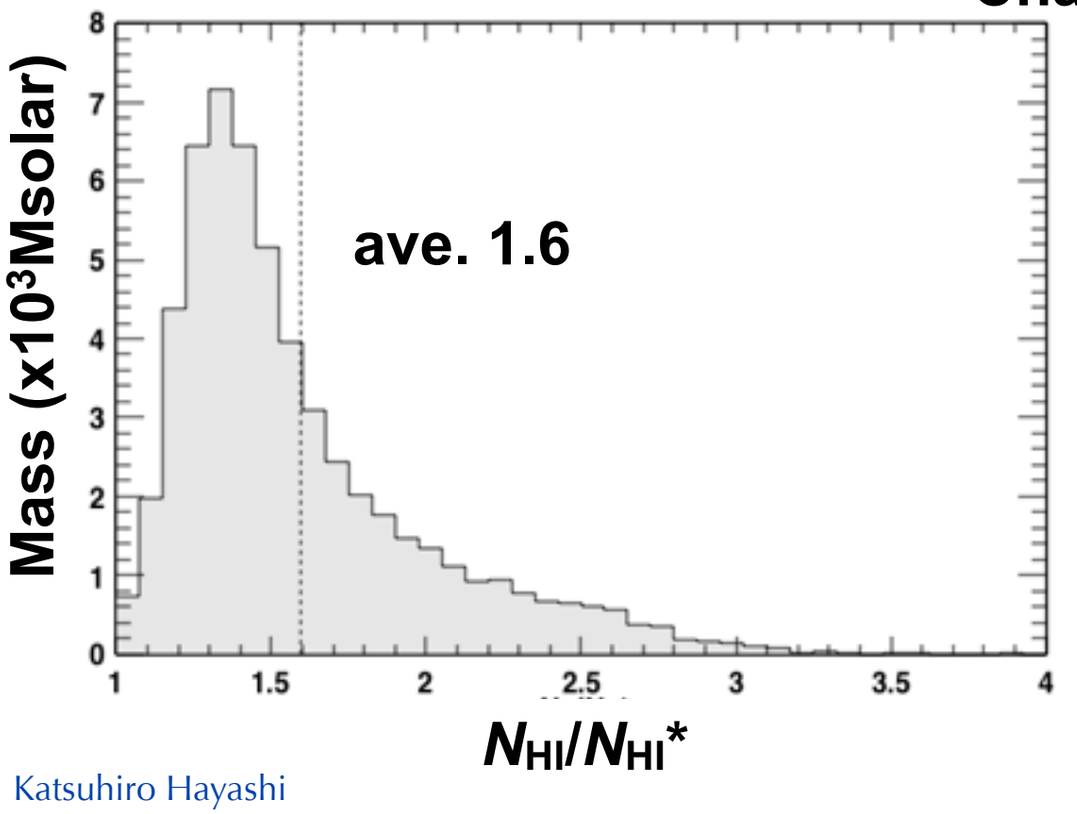


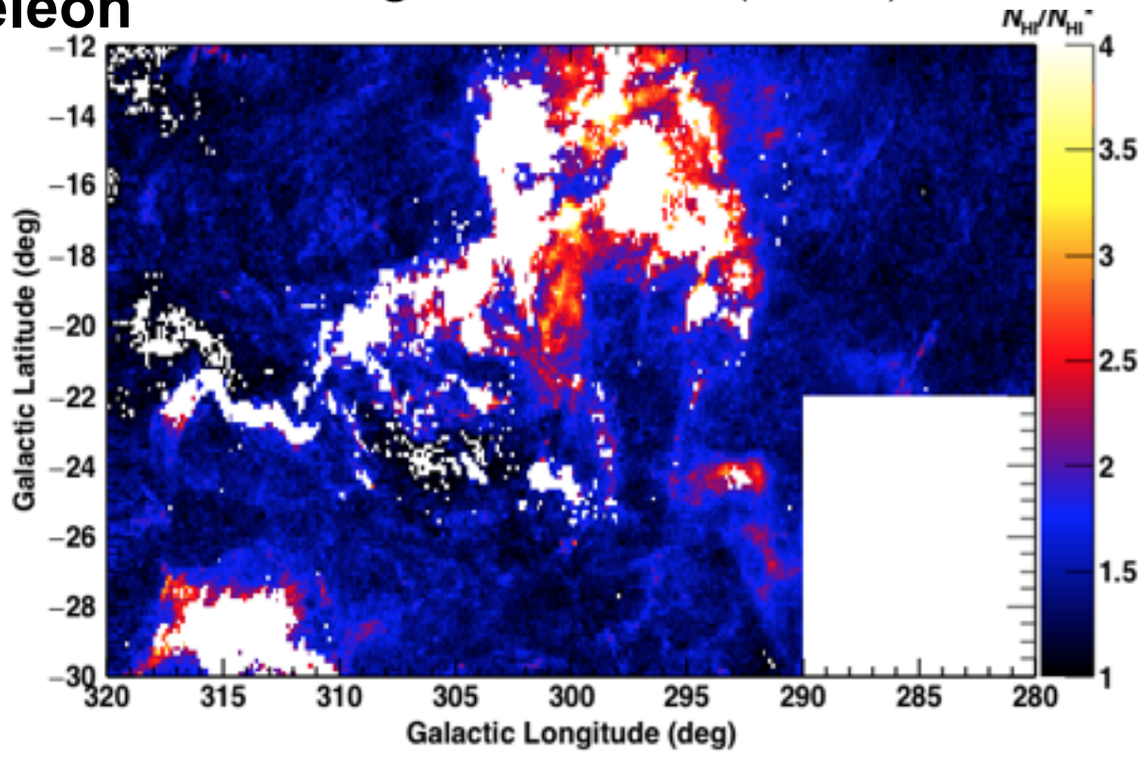


Ratio of N_{HI}/N_{HI}*



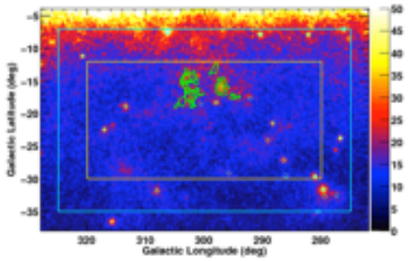




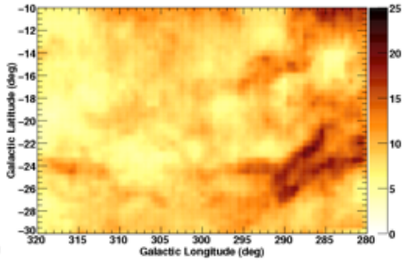


Uncertainty of Recent Gamma-ray Studies

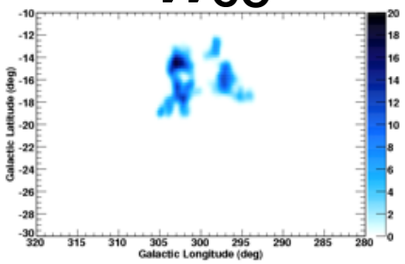
γ-ray



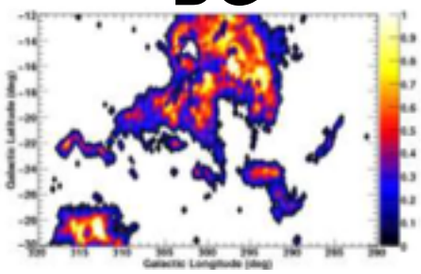
$= q_{HI}(E)$ x N_{HI}



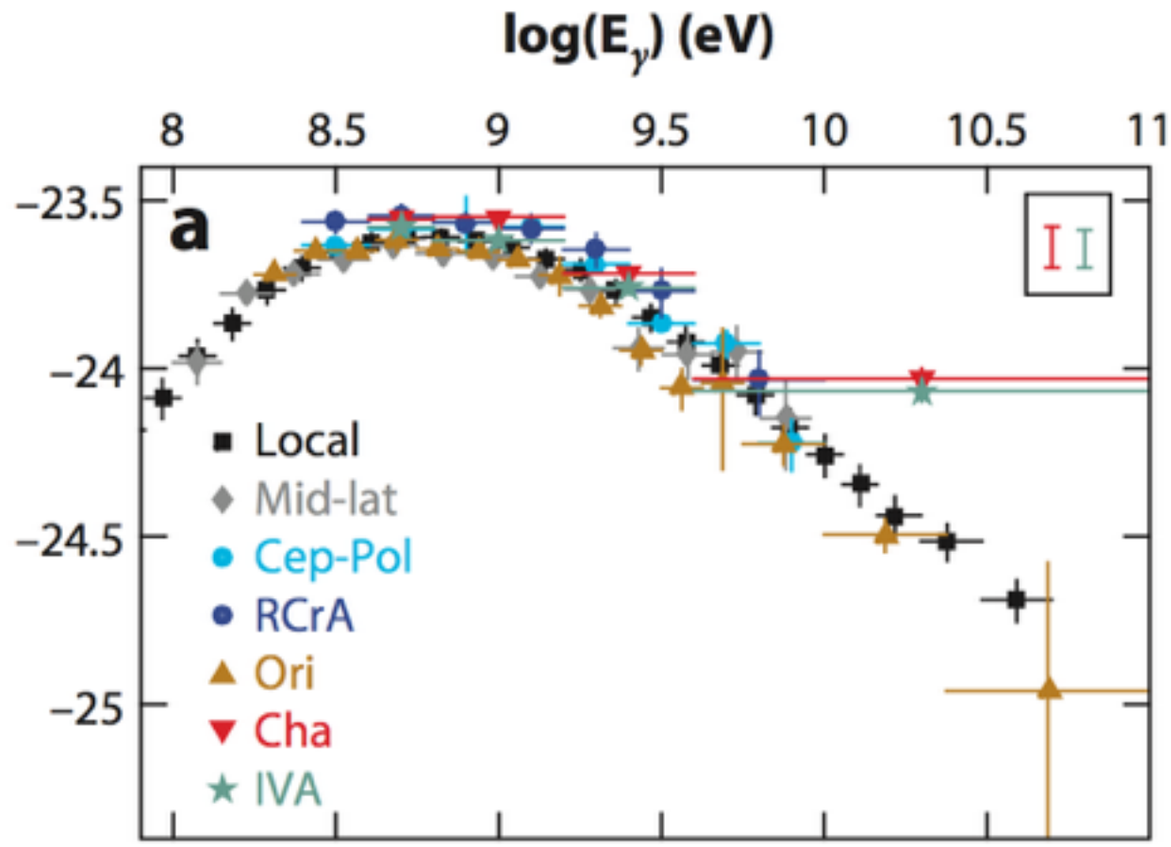
+ $q_{CO}(E)$ x W_{CO}



+ $q_{DG}(E)$ x DG



+ other gamma-ray background



Grenier+15, ARAA, 53, 199

- Interstellar gas divided into HI, H_2 and DG
- Uniform T_s (> 100 K) or optically thin approximation in N_{HI} map
- Uniform and linear gas-to-dust ratio in each phase (HI, H_2, DG)

- Our results show possible large amount of the optically thick HI
  → Re-consider local CR density and gas properties (Xco, gas mass)

Conclusion

- **Infer the HI column density in the local molecular cloud regions (Perseus and Chamaeleon) using dust optical depth (τ_{353}).**

- **Non-linear relation ($\alpha \sim 1.25$) between gas and dust (A_J and τ_{353}) possibly due to dust evolution effects.**

- **Even if we take account of the non-linear effects, a large amount of HI gas (~1.6 times larger that that of the optical thin approximation) with higher τHI (>~1) can be suggested.**

Future work

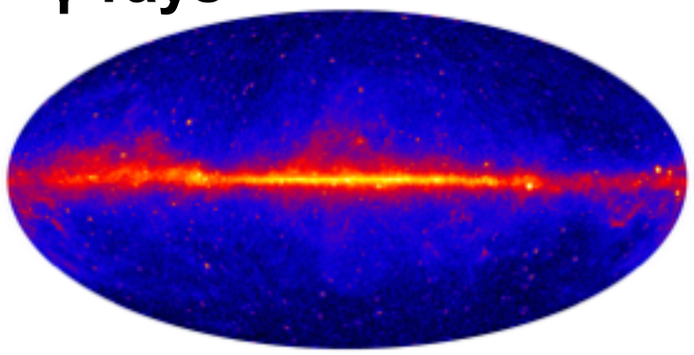
- **More detailed evaluation of uncertainty in the HI column density model due to dust property effects**

- **Studies of local CRs and gas properties using diffuse gamma-ray emission, taking into account the possible uncertainty in the column density model**

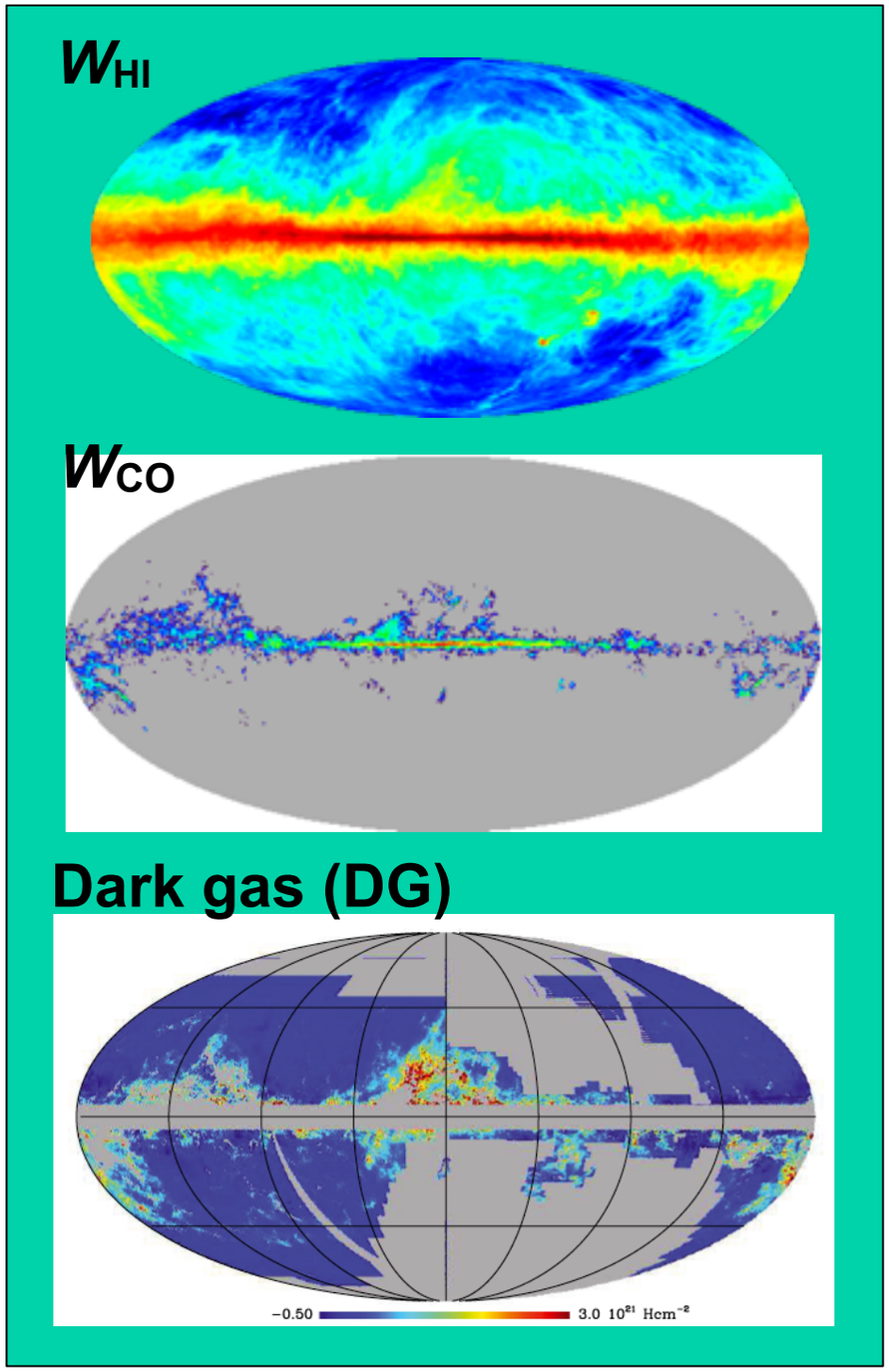
Back up

Gas Tracer

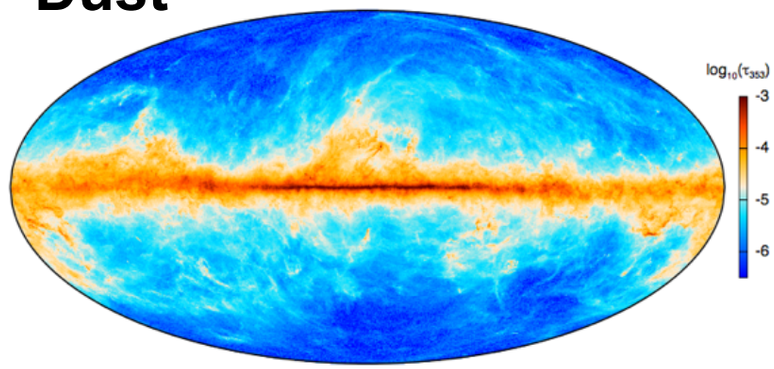
γ-rays



- CRs x ISM
- high energy photos transparent to interstellar gas
- Good gas tracer under the uniform CR density



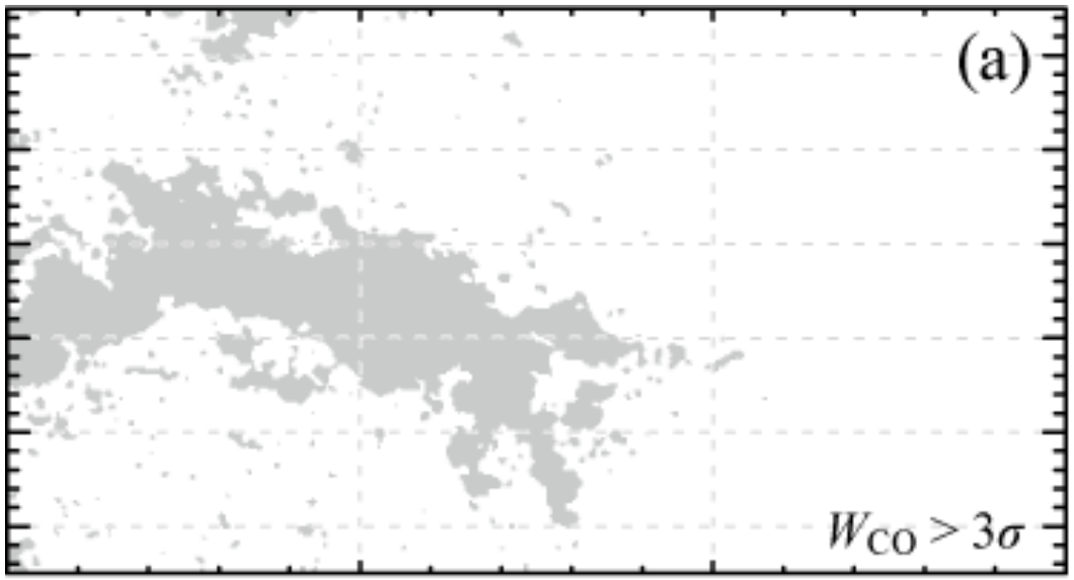
Dust

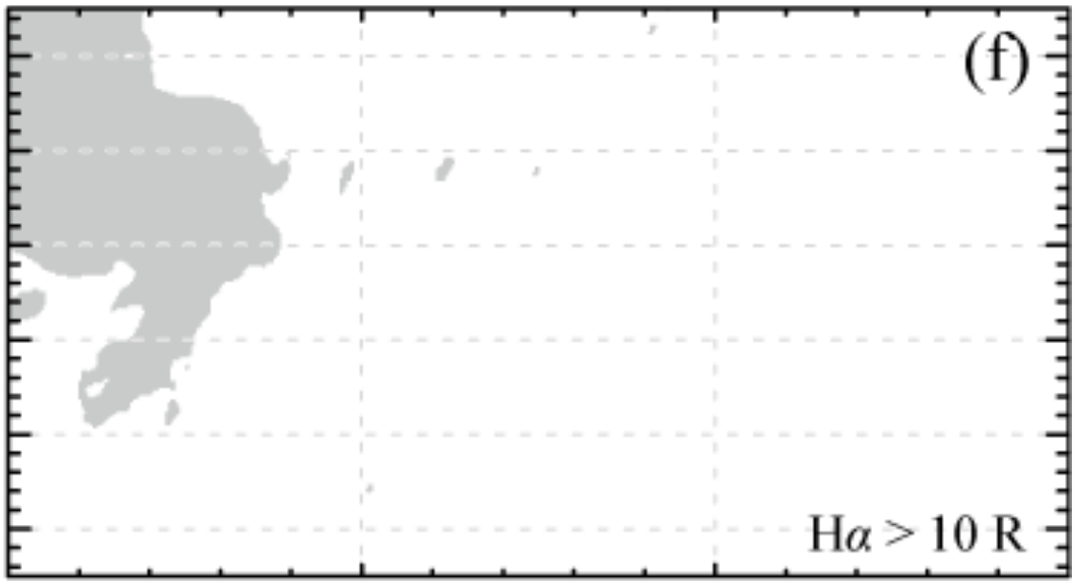


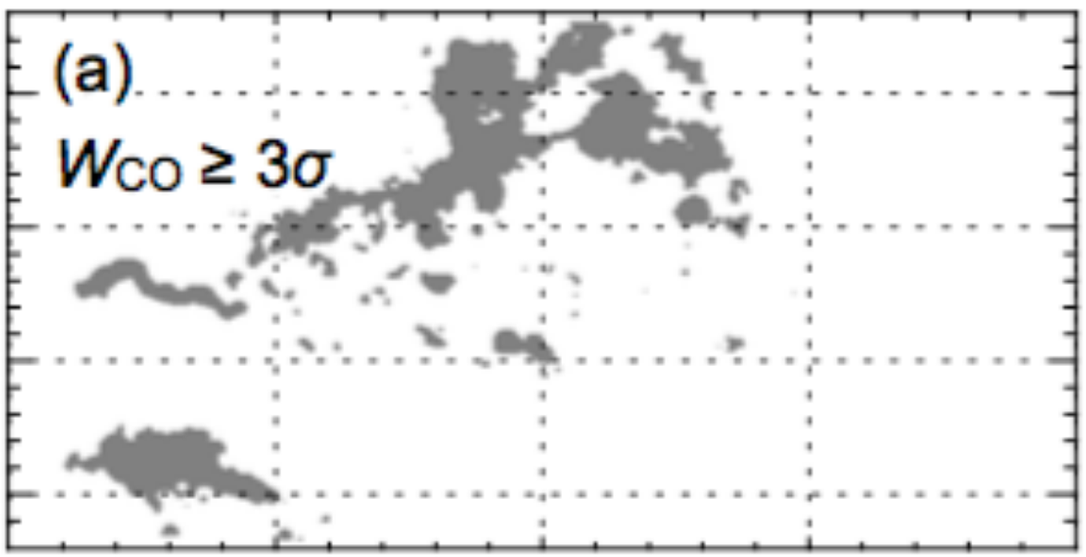
- τ_{353}: dust optical depth at 353 GHz
- Small optical depth: ~10^{-5} transparent to the interstellar gas
- Mixed with gas
- Good gas tracer

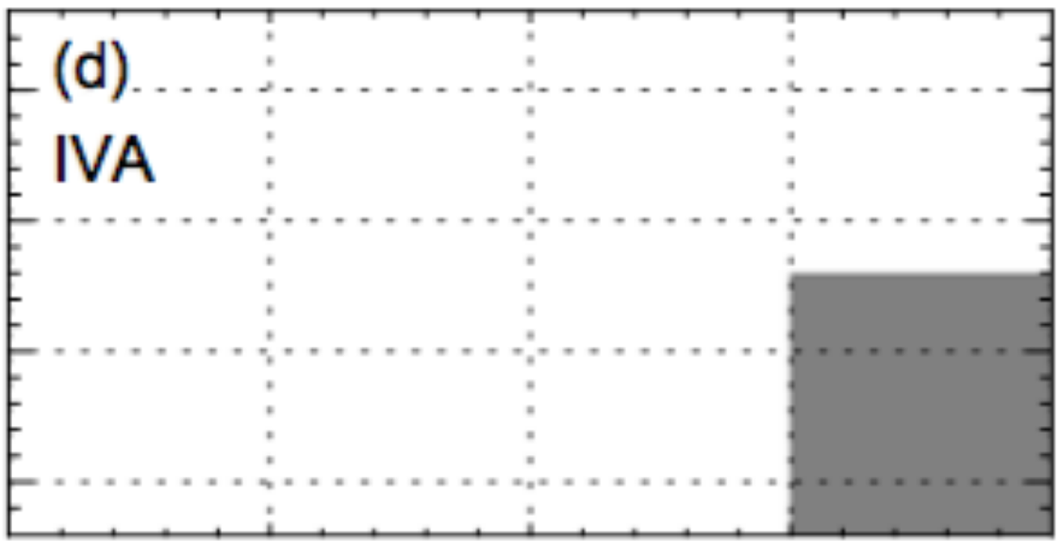
Good spatial correlation between γ-rays and dust emission

Masking





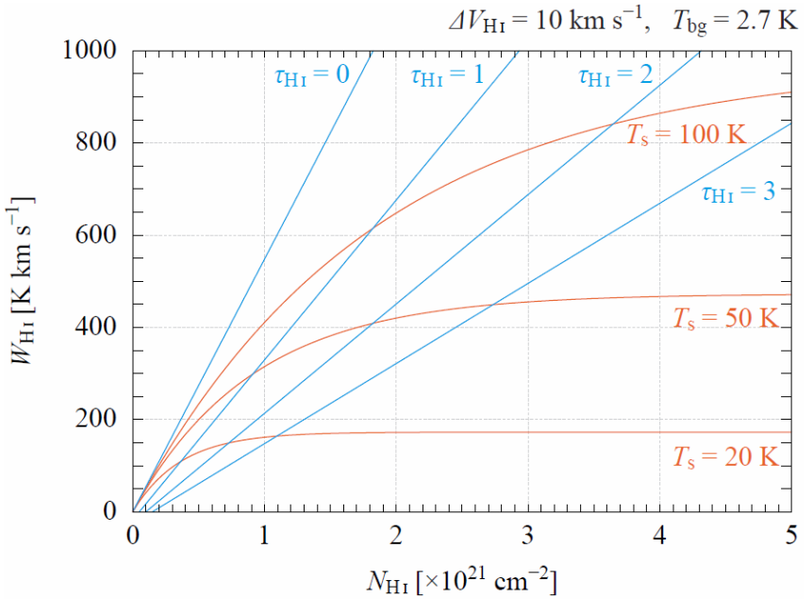




W_{HI}: GASS (Parkes Galactic All Sky Survey)

W_{CO}: NANTEN (^{12}CO (J=(1-0)))

NH model (t353,ref/NHref)



$$\left(\frac{N_{\rm H}(l,b)}{N_{\rm H,ref}}\right)^{\alpha} = \frac{\tau_{353}(l,b)}{\tau_{353,\rm ref}}$$