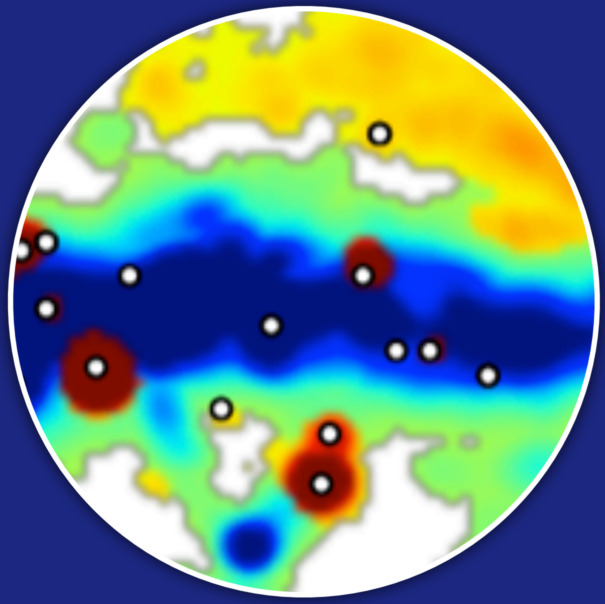
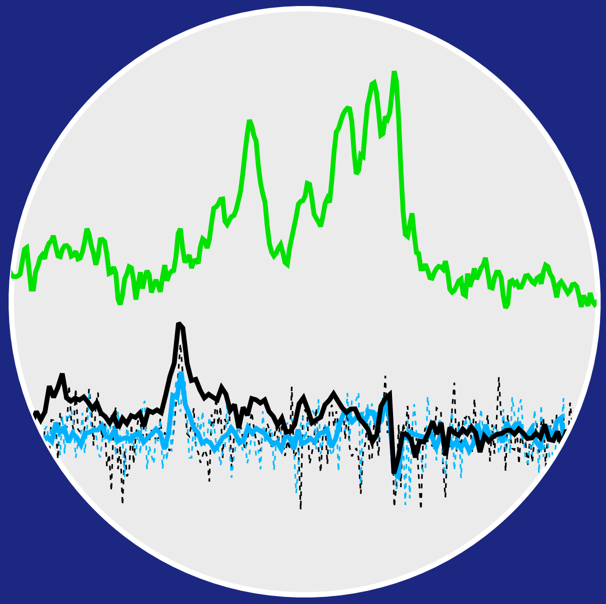
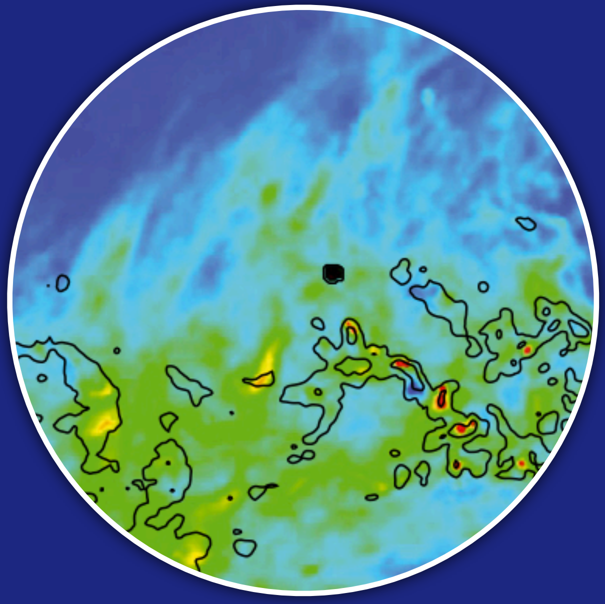
Shining Light on the Dark ISM:

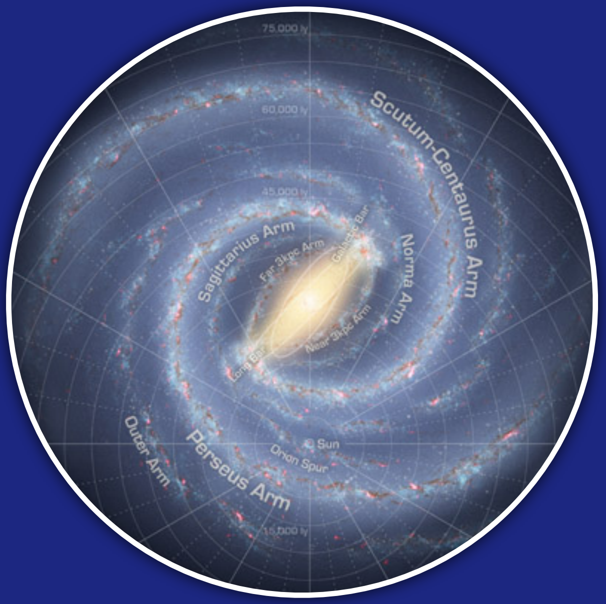
Tracing the HI-H_2 Transition Through the Dark Zone

Joanne Dawson | Macquarie University / CASS

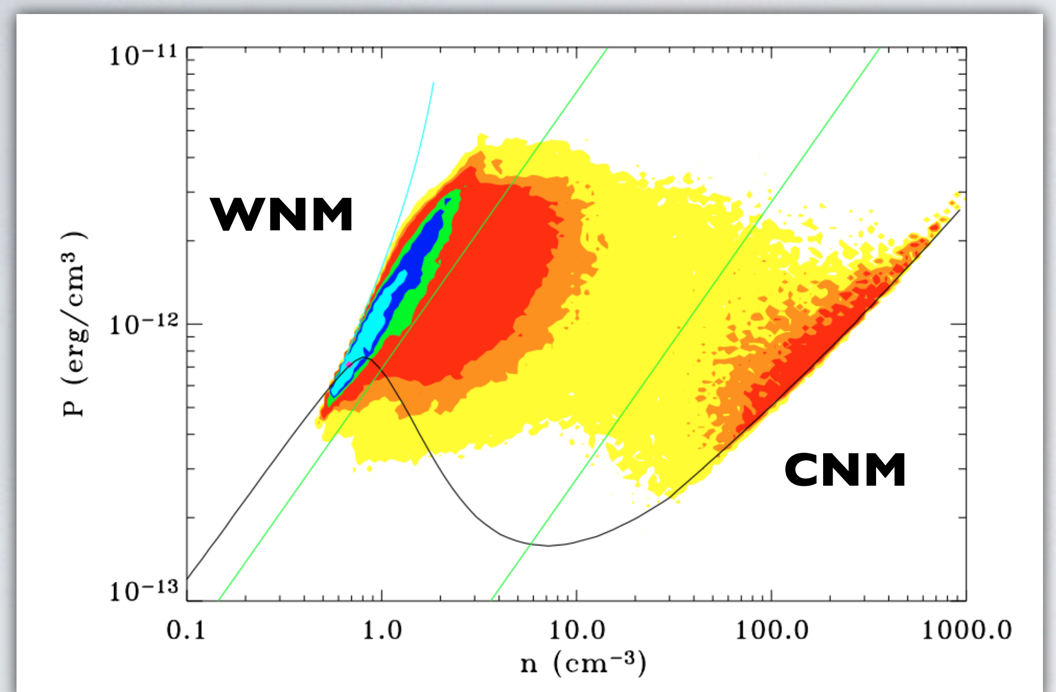


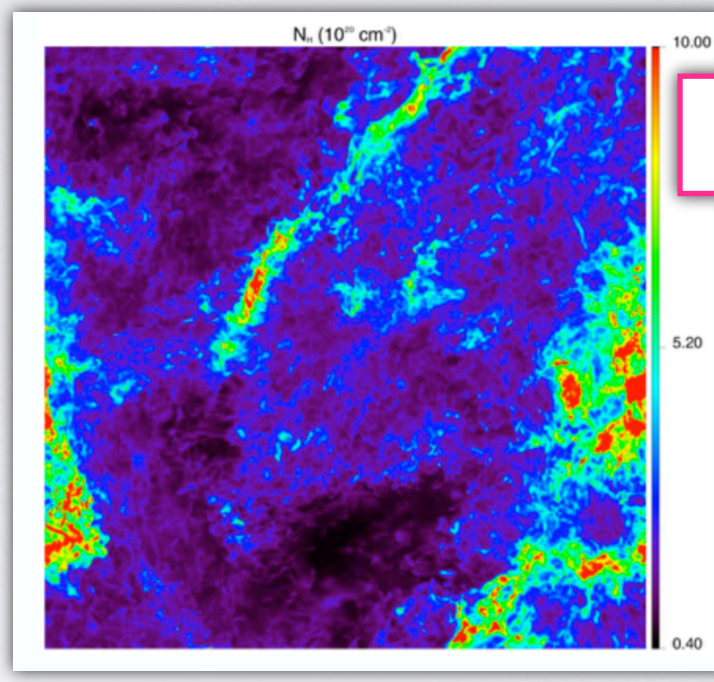






Atomic Gas Bistability: From WNM to CNM



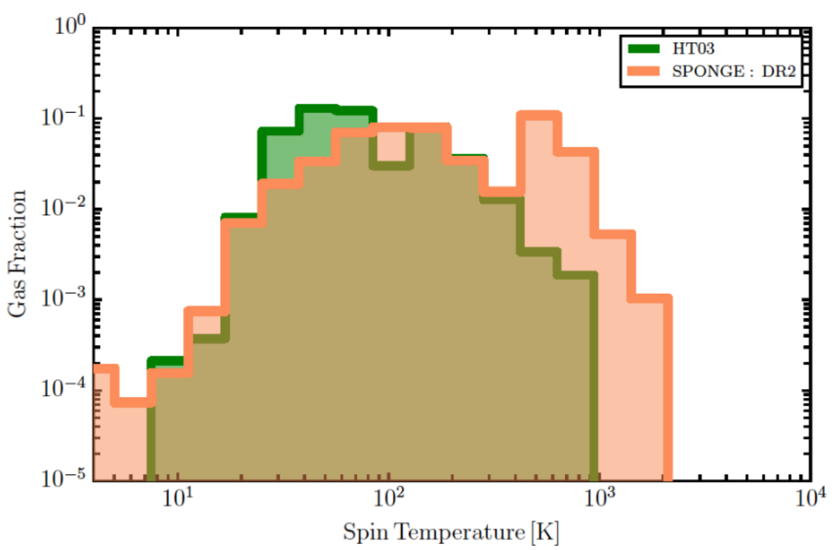


Marc-Antoine

Eva

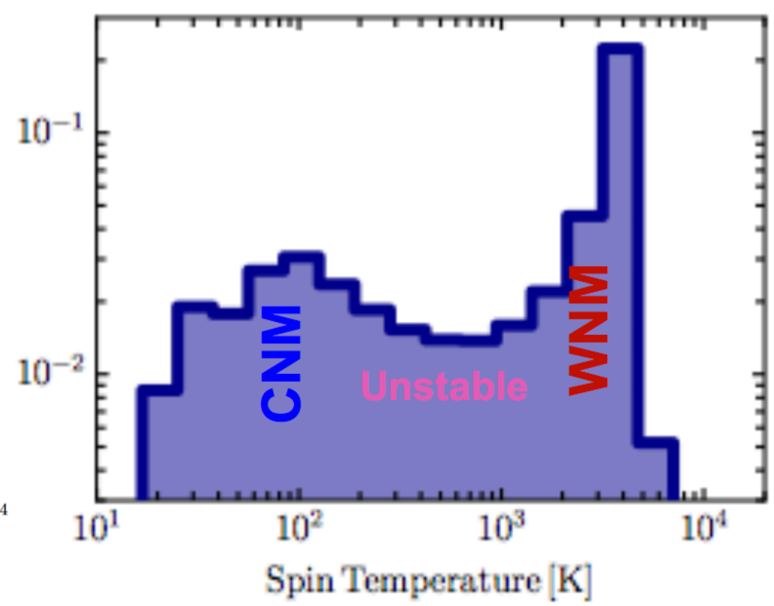
Snez

Arecibo Millennium Survey
21-SPONGE (full survey)



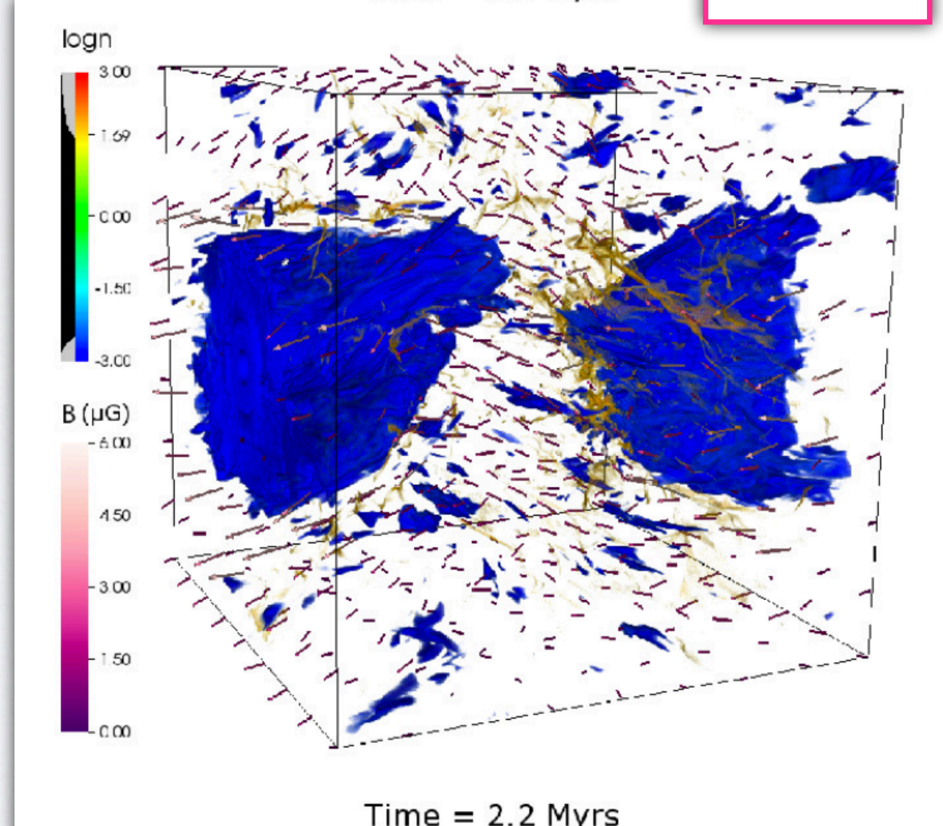
Unstable fraction ~40% (preliminary)

Heiles & Troland 2003a
Murray et al. 2015, 2017



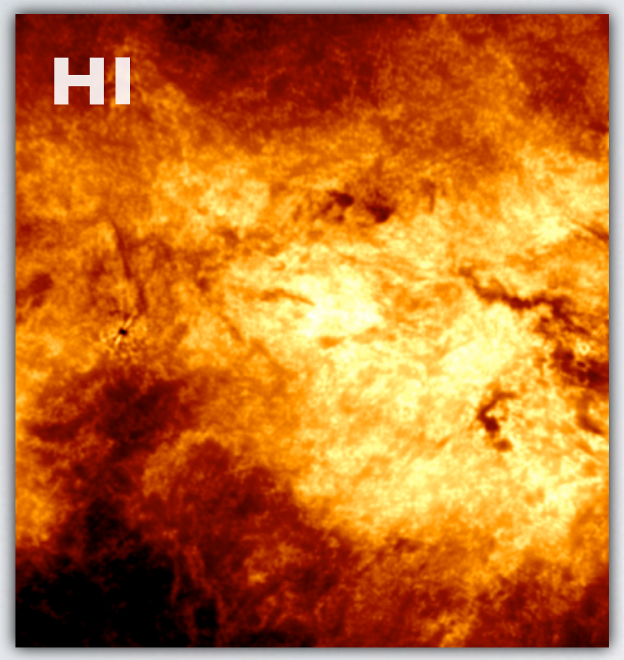
3D HD numerical simulations
Kim et al. 2014, ApJ, 786, 64

16



From Gas to Stars...

Atomic Gas



Molecular Clouds

Stars & Stellar feedback

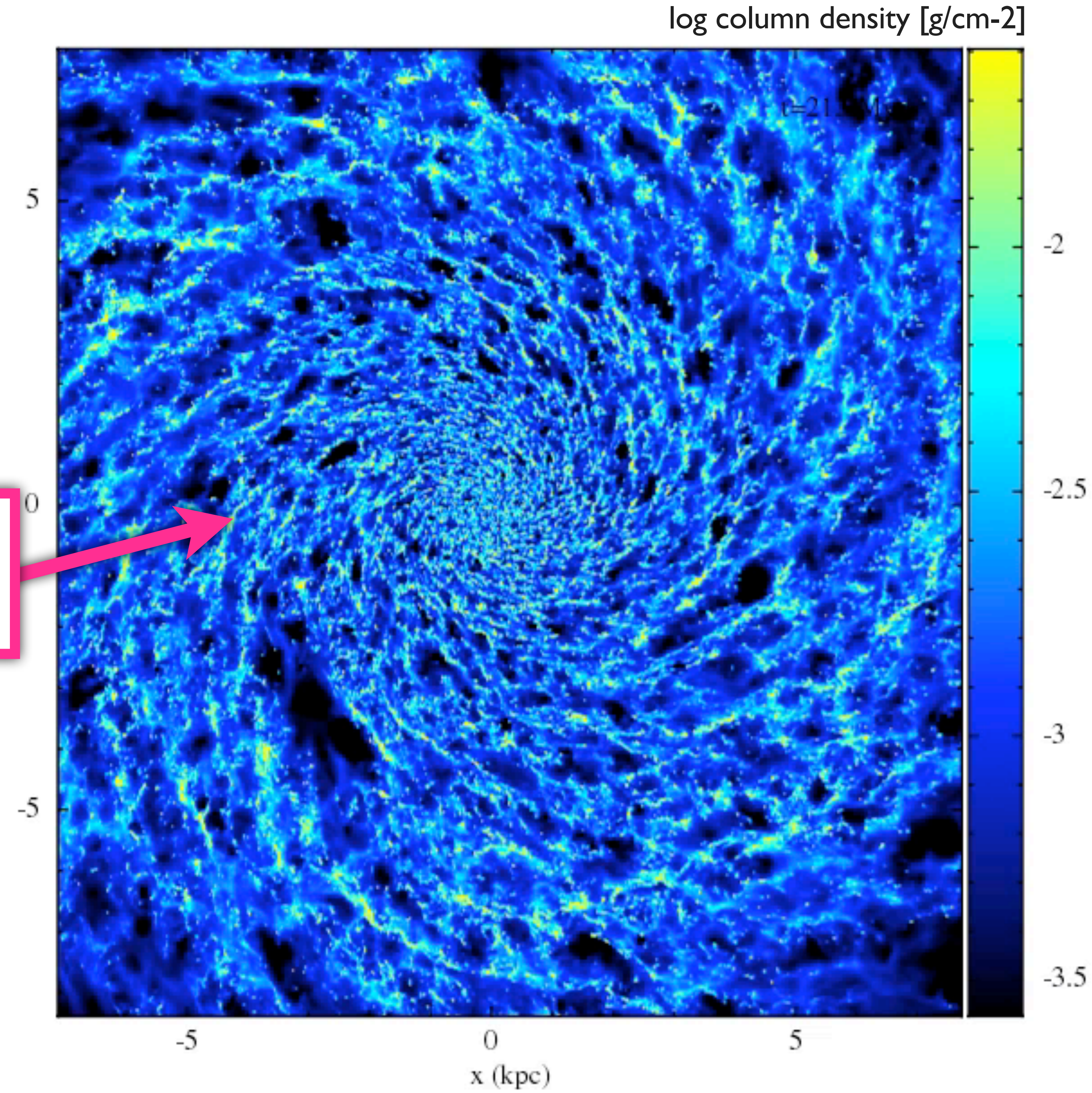
Molecular cloud complexes (MCCs) are highly structured and "turbulent." Observational evidence suggests that MCCs are dynamically dominated systems, rather than quasi-equilibrium entities. The observed structure is more likely a consequence of the formation process than something that is imprinted after the formation of the MCC. Converging flows provide a natural mechanism to generate MCC structure. We present a detailed numerical analysis of this scenario. Our study addresses the evolution of an MCC from its birth in colliding atomic hydrogen flows up until the point when H_2 may begin to form. A combination of dynamical and thermal instabilities breaks up coherent flows efficiently, seeding the small-scale nonlinear density perturbations necessary for local gravitational collapse and thus allowing (close to) instantaneous star formation. Many observed properties of MCCs come as a natural consequence of this formation scenario. Since converging flows are omnipresent in the ISM, we discuss the general applicability of this mechanism, from local star formation regions to galaxy mergers.

Heitsch et al. (2006)

Molecular Cloud Formation in Galaxy Disks

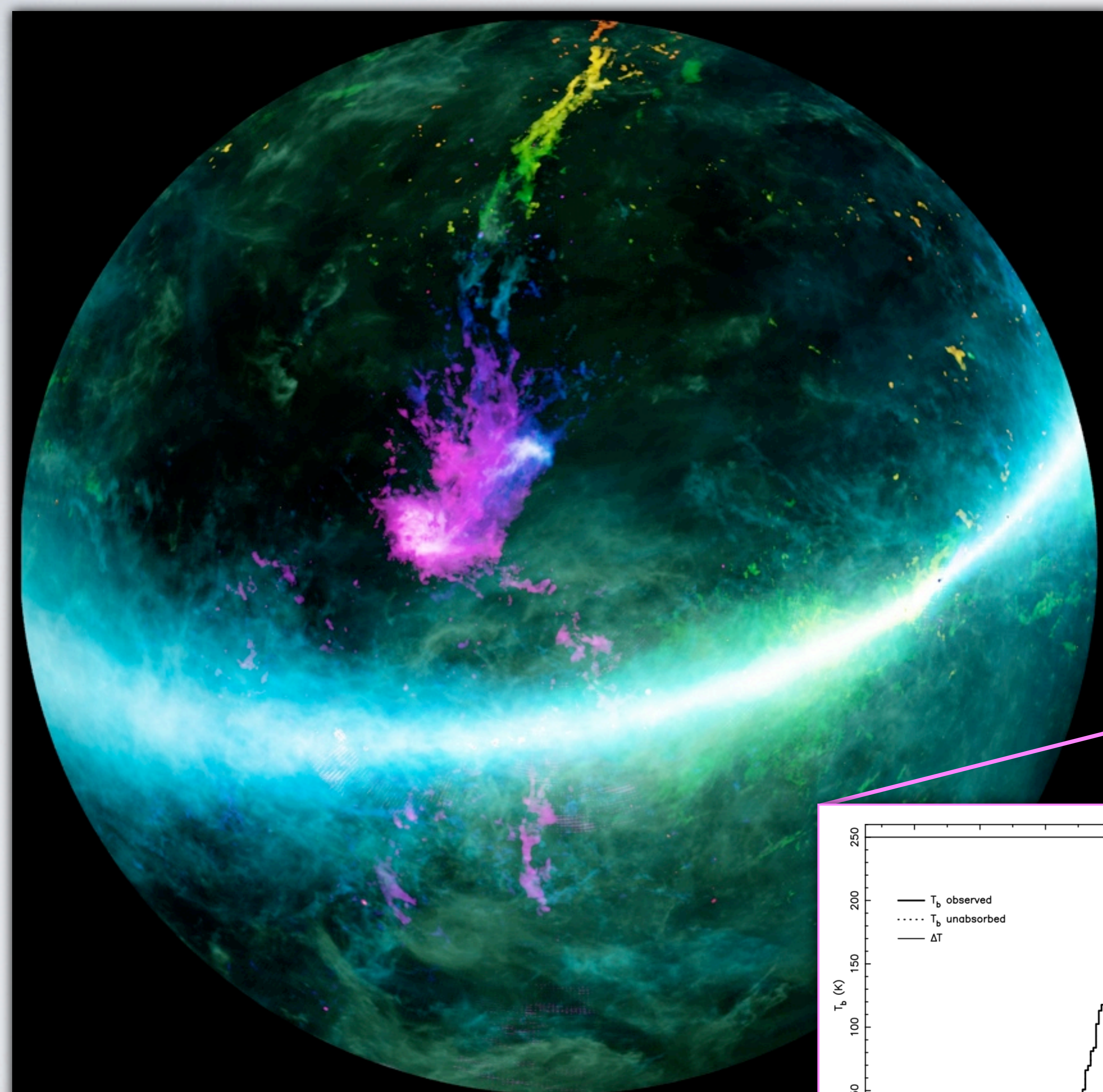
- Large-scale **gravitational/ magnetic/thermal instabilities**
- Plus additional over-pressurisation from spiral potential and stellar feedback?

You are here



Movie: Simulation of molecular cloud formation in galaxy disk (Dobbs et al. 2011)

Atomic Gas From HI

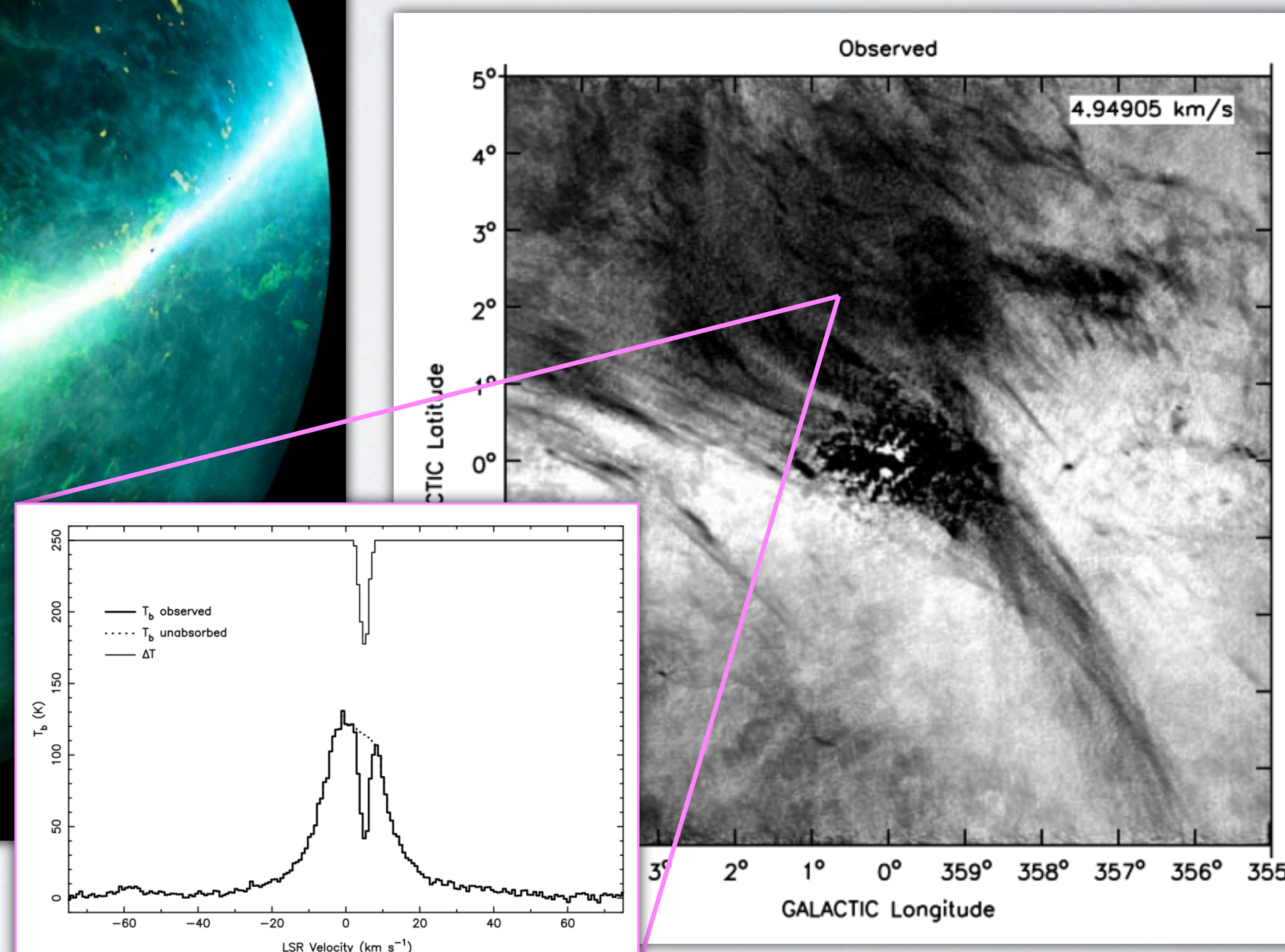


Milky Way in Hydrogen. Credit: S. Janoweicki, N. McClure-Griffiths & GASS team

$$N_{\rm HI} \geq 1.8 \times 10^{18} \int T_v \, dv$$

Optically thin limit

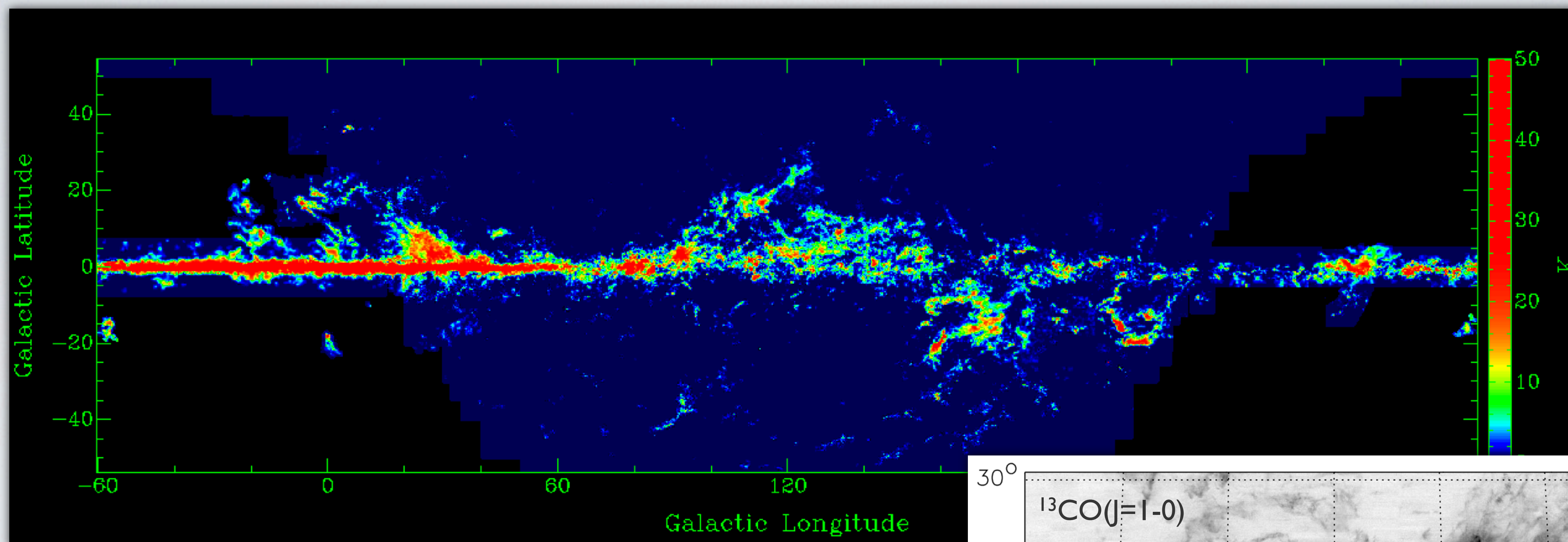
McClure-Griffiths et al. (2006)



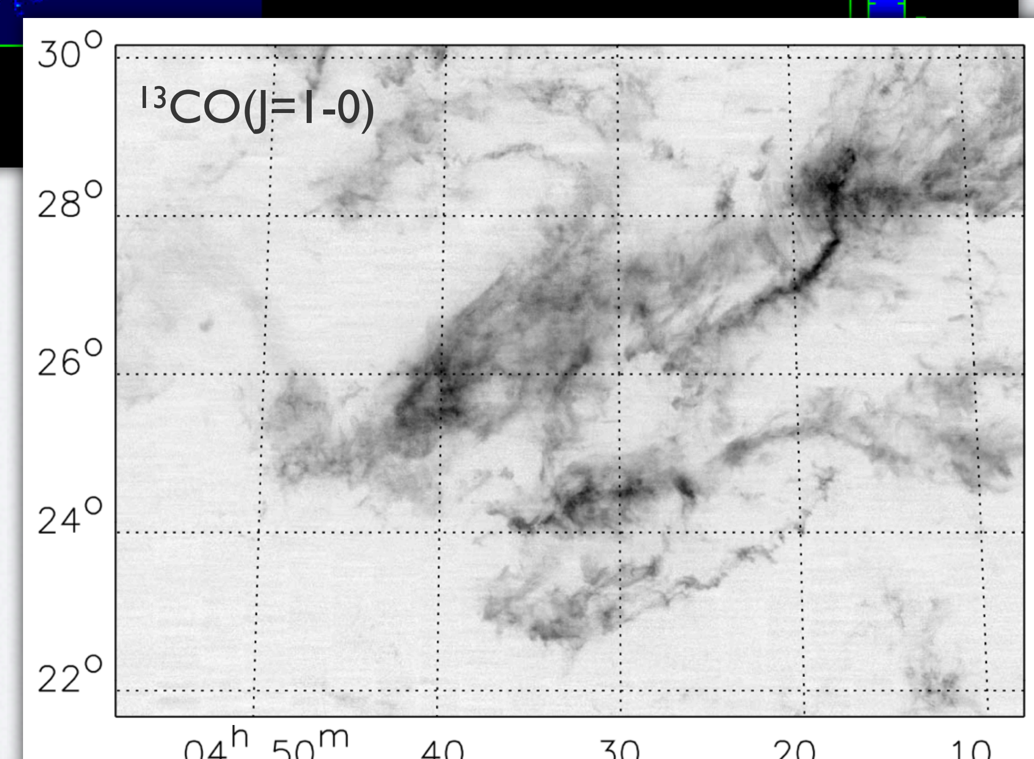
Molecular Gas From CO

CO lines as a proxy for H_2.

All sky $^{12}CO(J=1-0)$ survey (Tom Dame, unpublished)



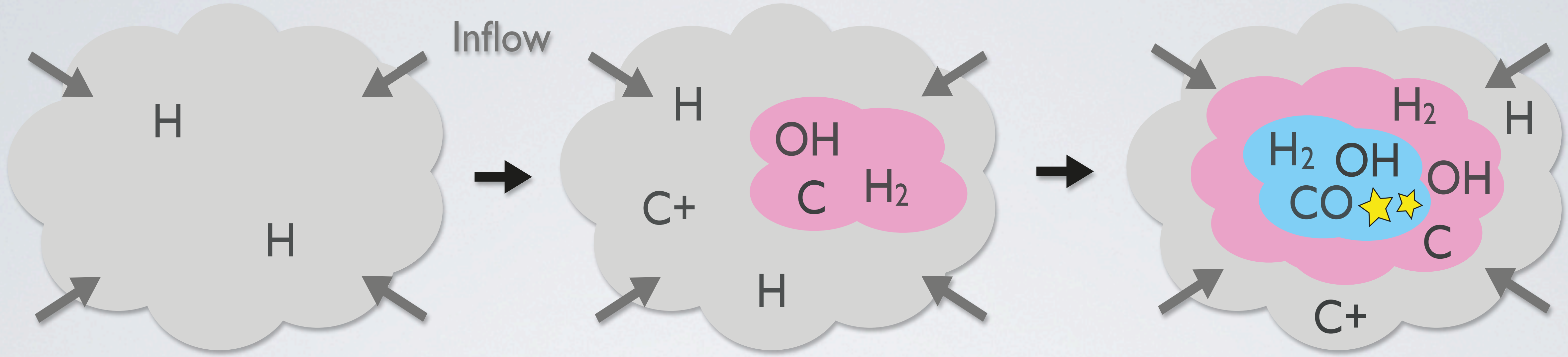
Right: Taurus molecular cloud in CO(J=1-0), Goldsmith et al. (2008)

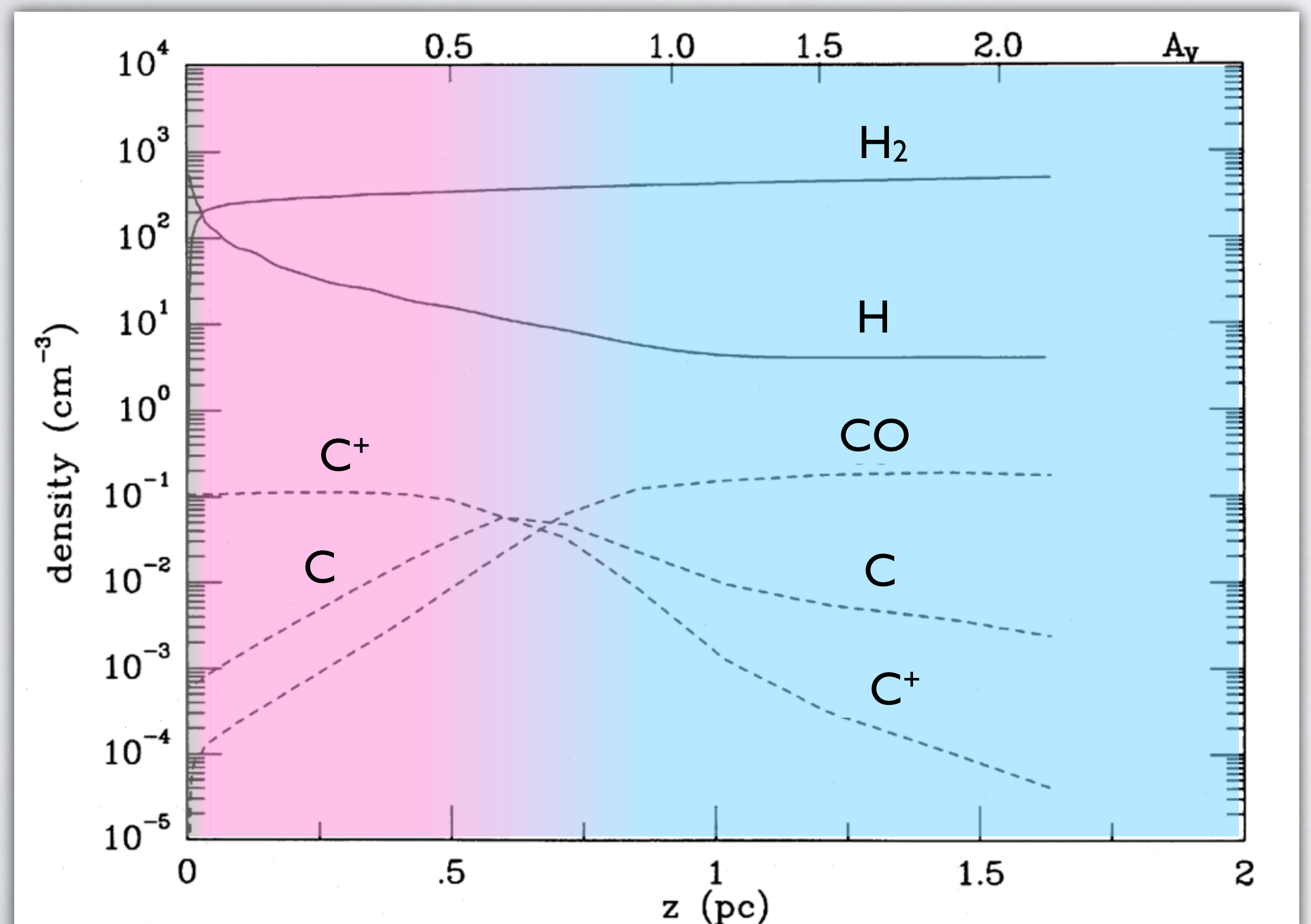


$$N(\mathrm{H_2}) = X_{\mathrm{CO}} \times \int T_b[^{12}\mathrm{CO}(J{=}1{-}0)]\, dv$$

Alternatively, assume LTE (and T_{ex} and CO/H_2 ratio) and derive $N(H_2)$ from $^{13}CO(J=1-0)$

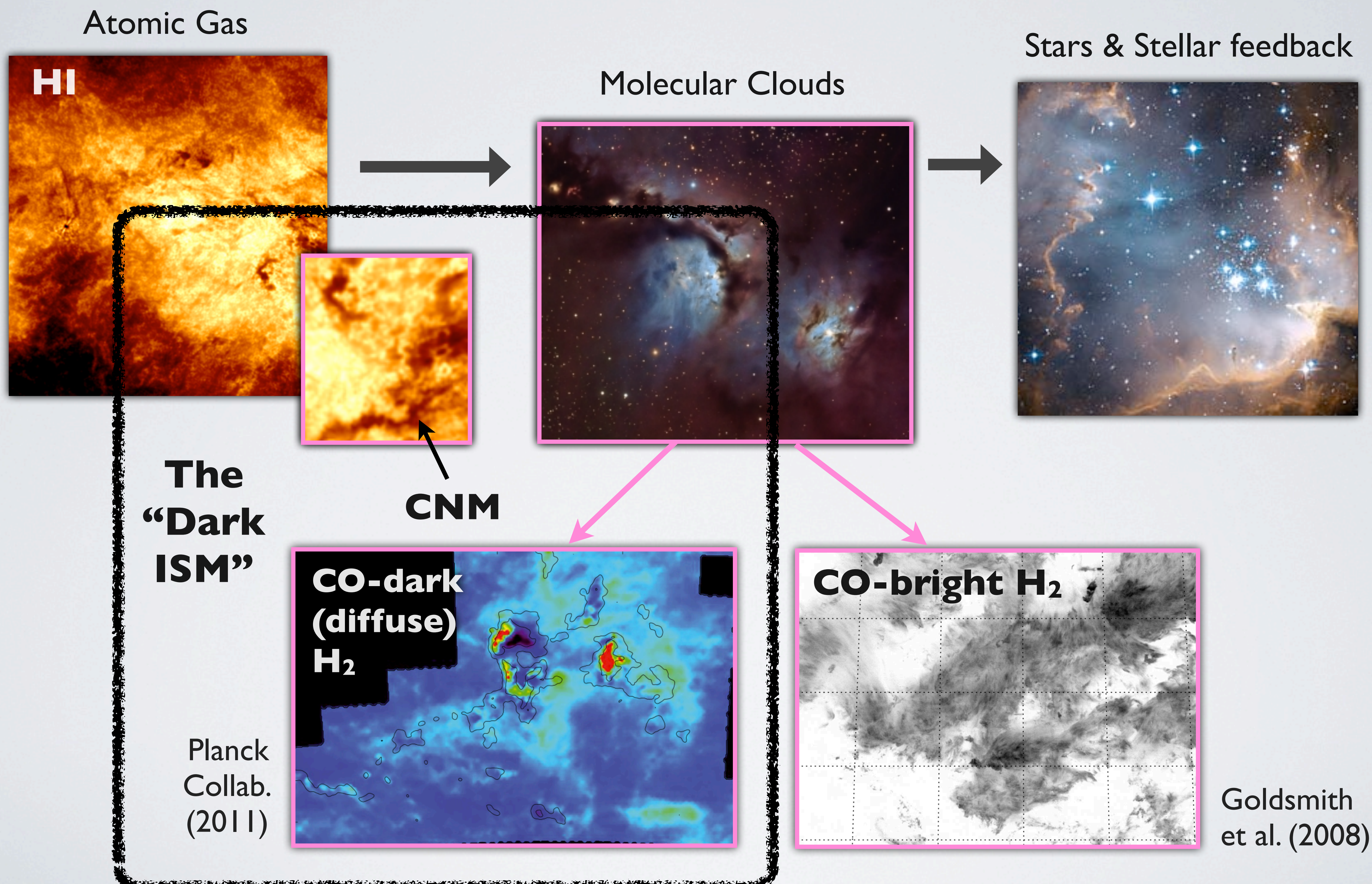
Molecular Gas From CO





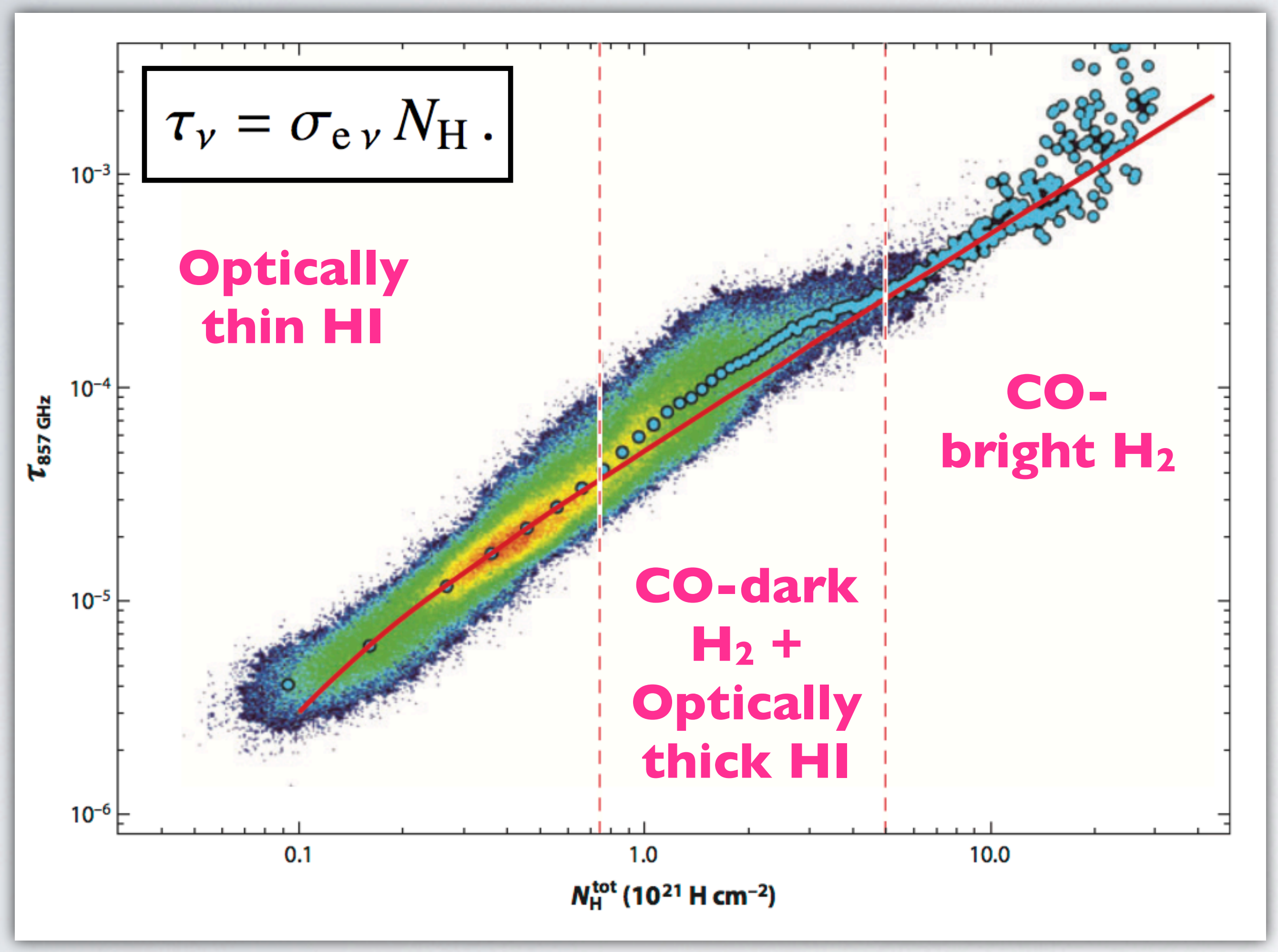
- *"A map of CO emission is a map of CO abundance and CO chemistry first, and only secondarily a map of the mass"* – Liszt, Pety & Lucas (2010)
- Only abundant (= readily detectable) in moderately dense, highly-molecular regions with $A_V \gtrsim 1$ → **Misses diffuse H_2 altogether**

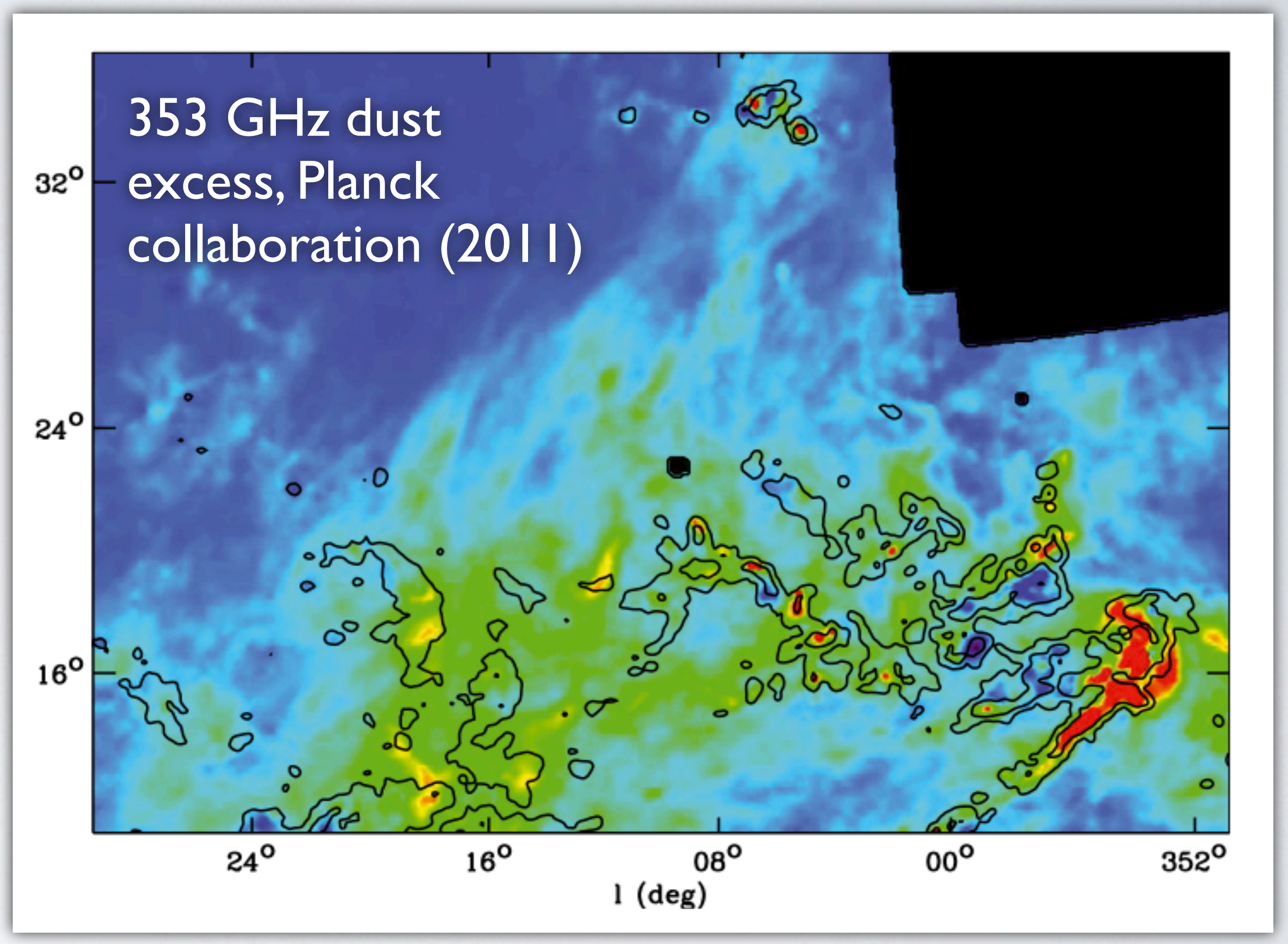
Welcome to the Dark Zone...



The Dark ISM: Dust-based estimates

The Dark ISM: Neutral gas "not seen" in HI and CO





Planck Collaboration (2011, XIX)

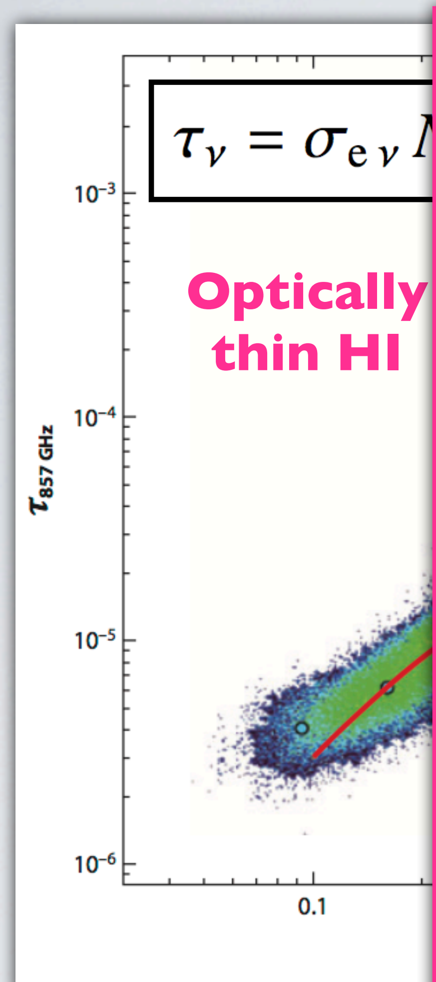
How much gas is "dark"?

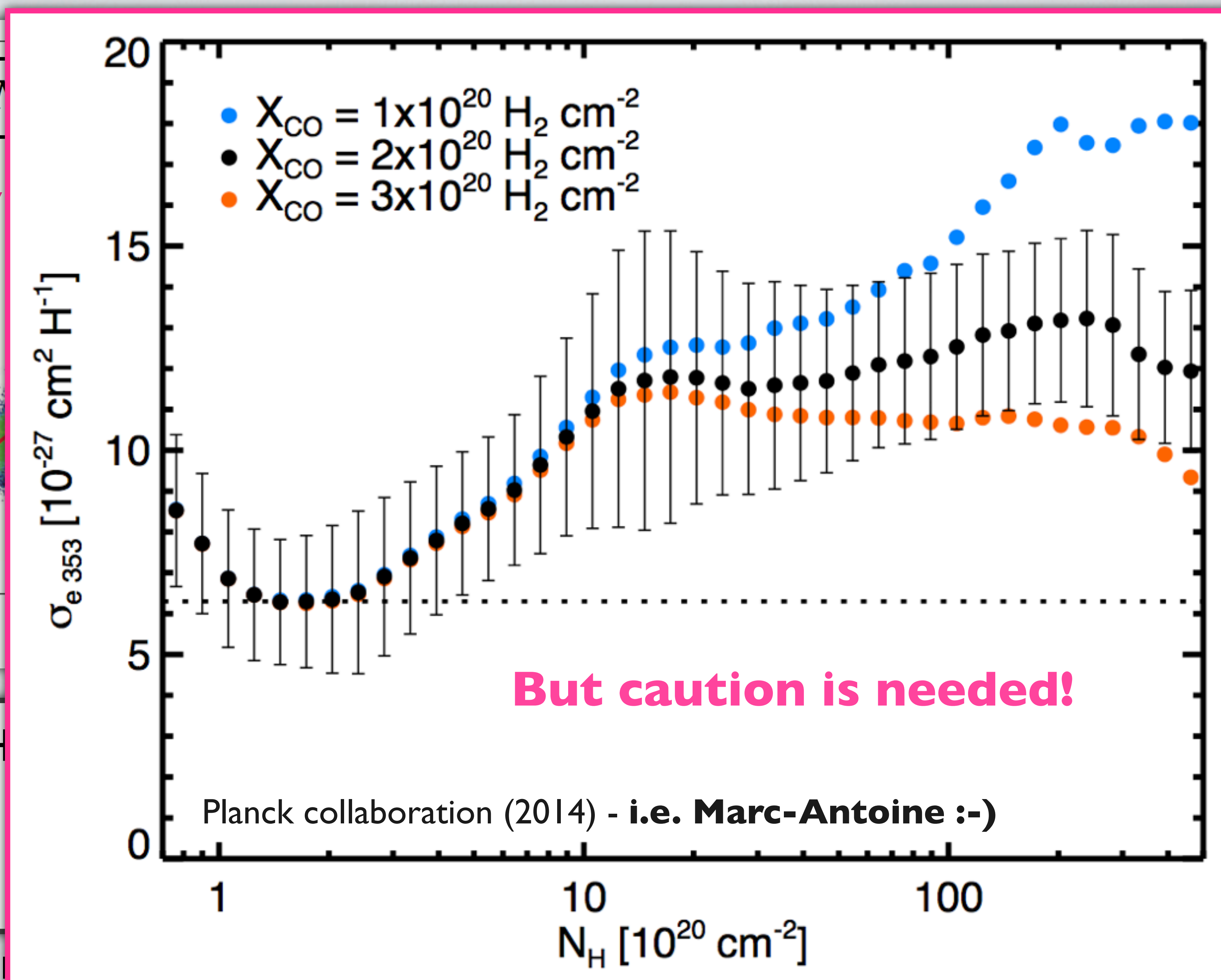
- ≲ **50% in local IR cirrus clouds** (Reach et al. 1994)
- **~20% in solar neighbourhood** (Planck collaboration 2011)

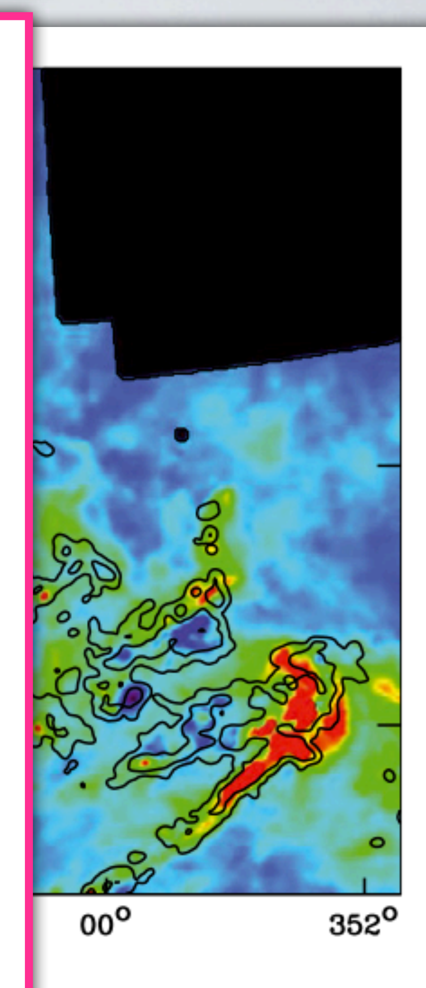
See also: Blitz et al. (1990), Reach et al. (1998), Douglas & Taylor (2007), Dawson et al. (2011)

The Dark ISM: Dust-based estimates

The Dark ISM: Neutral gas “not seen” in HI and CO







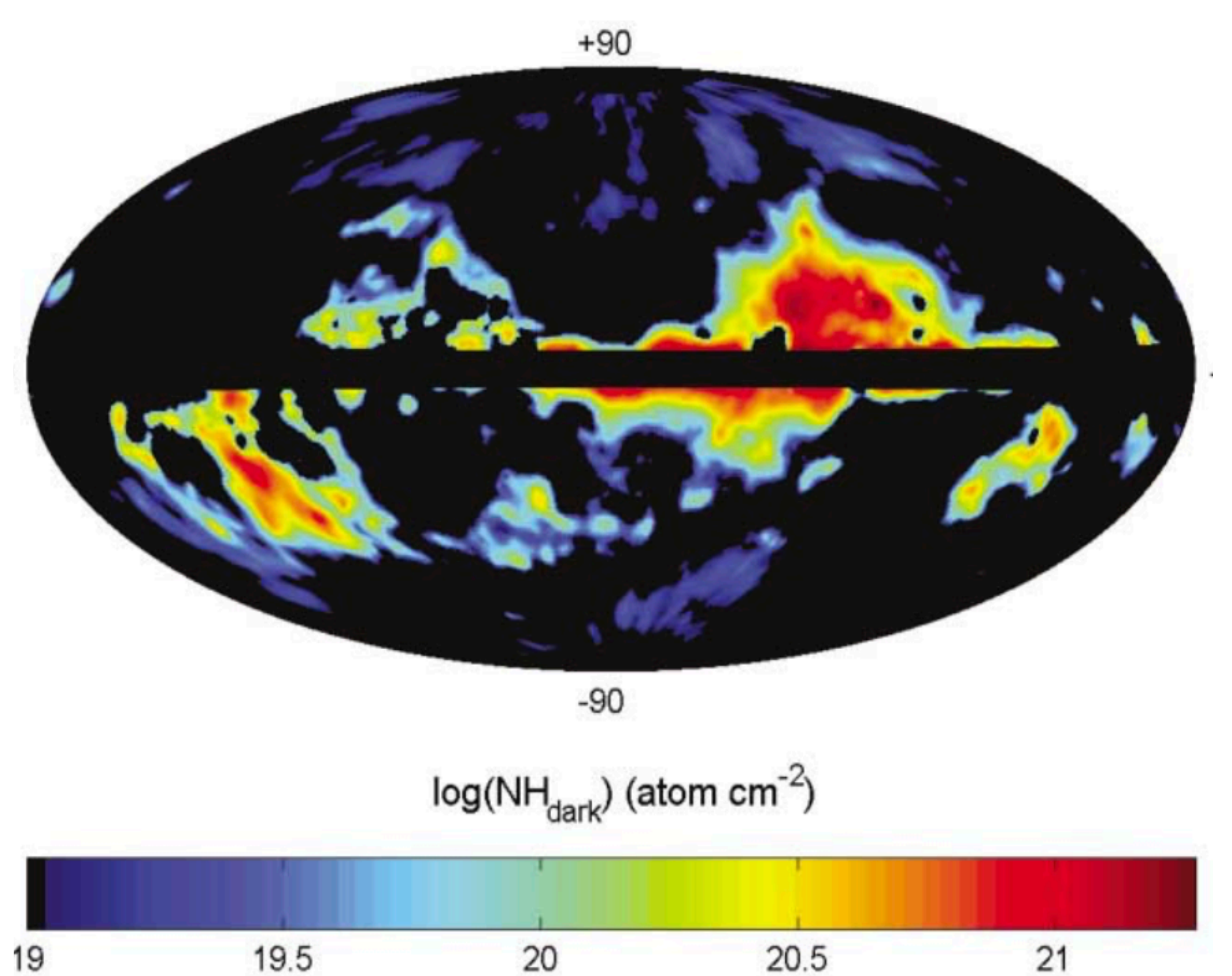
Planck Collaboration (2011, XIX)

H

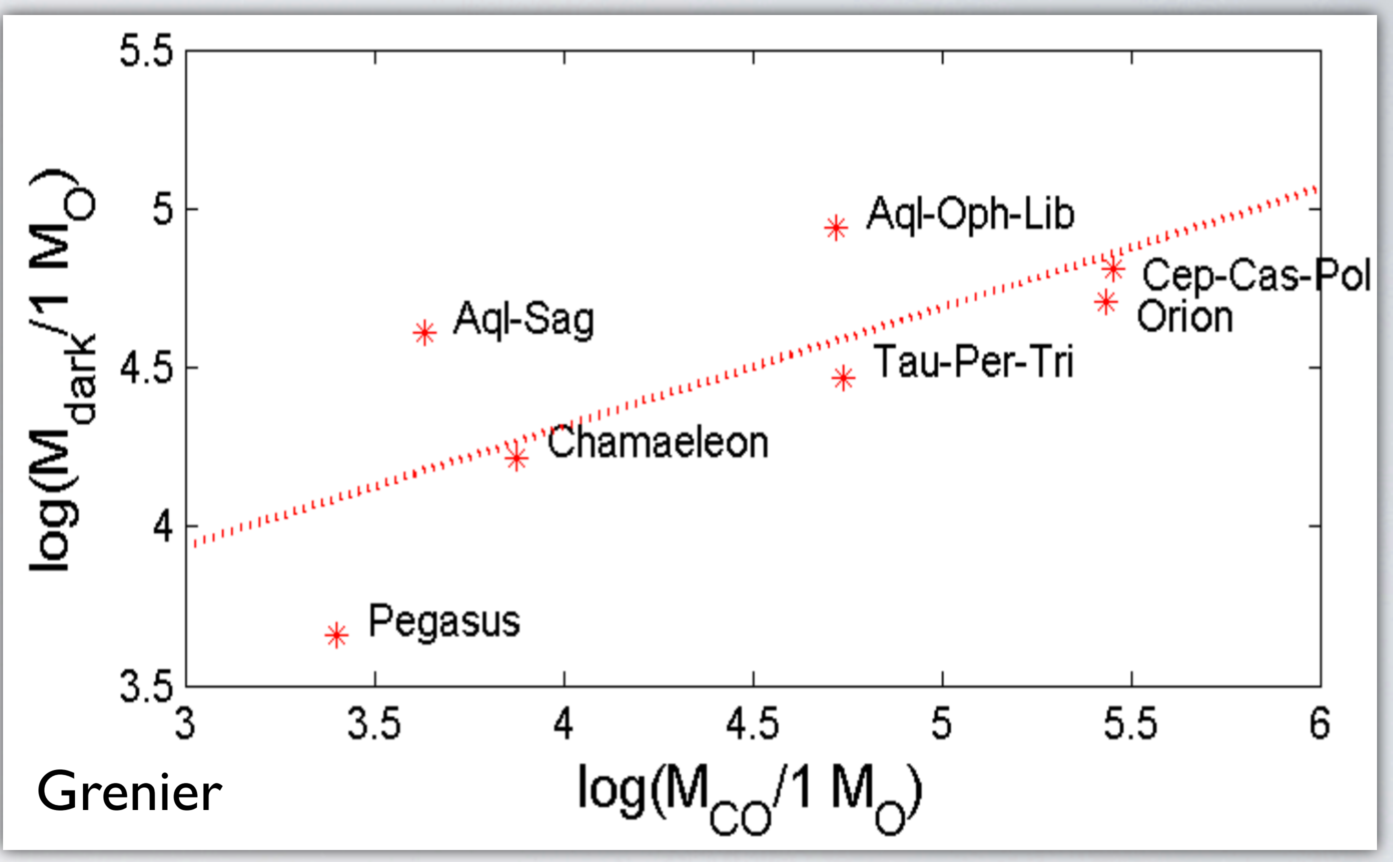
)

See also: Blitz et al. (

The Dark ISM: Gamma Rays



Grenier et al. (2005)



Region	H_2:dark:HI
Cepheus-Cassiopeia-Polaris	7.5:1:7.3
Orion	8.6:1:7.3
Aquila-Ophiuchus-Libra	0.8:1:1.0
Taurus-Perseus-Triangulum	2.3:1:3.1
Aquila-Sagittarius	0.2:1:0.5
Chamaeleon	0.9:1:3.7
Pegasus	0.7:1:3.4

How much gas is "dark"?

- **6~60% in solar neighbourhood cloud complexes**

The Dark ISM: A Handy Naming Guide

“Dark ISM”

CO-dark H_2

“Dark molecular gas”

“Diffuse molecular gas”

H_2 not recovered by CO-based estimates

“Transition-state gas”

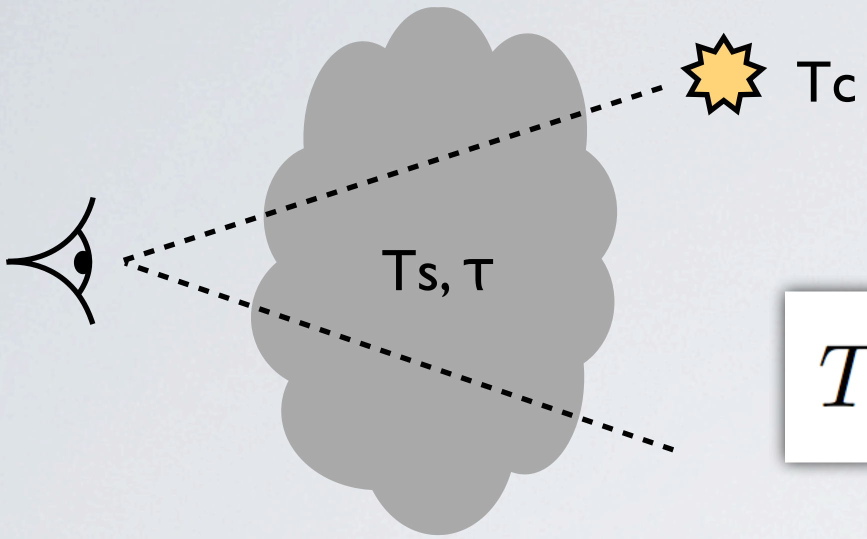
CNM

Optically thick HI

Cold HI

HI not recovered by 21cm emission

The Dark ISM: CNM From HI Absorption



$$T_\mathrm{b}(\mathrm{off}) = T_\mathrm{bg}e^{-\tau_v} + T_\mathrm{s}(1 - e^{-\tau_v})$$

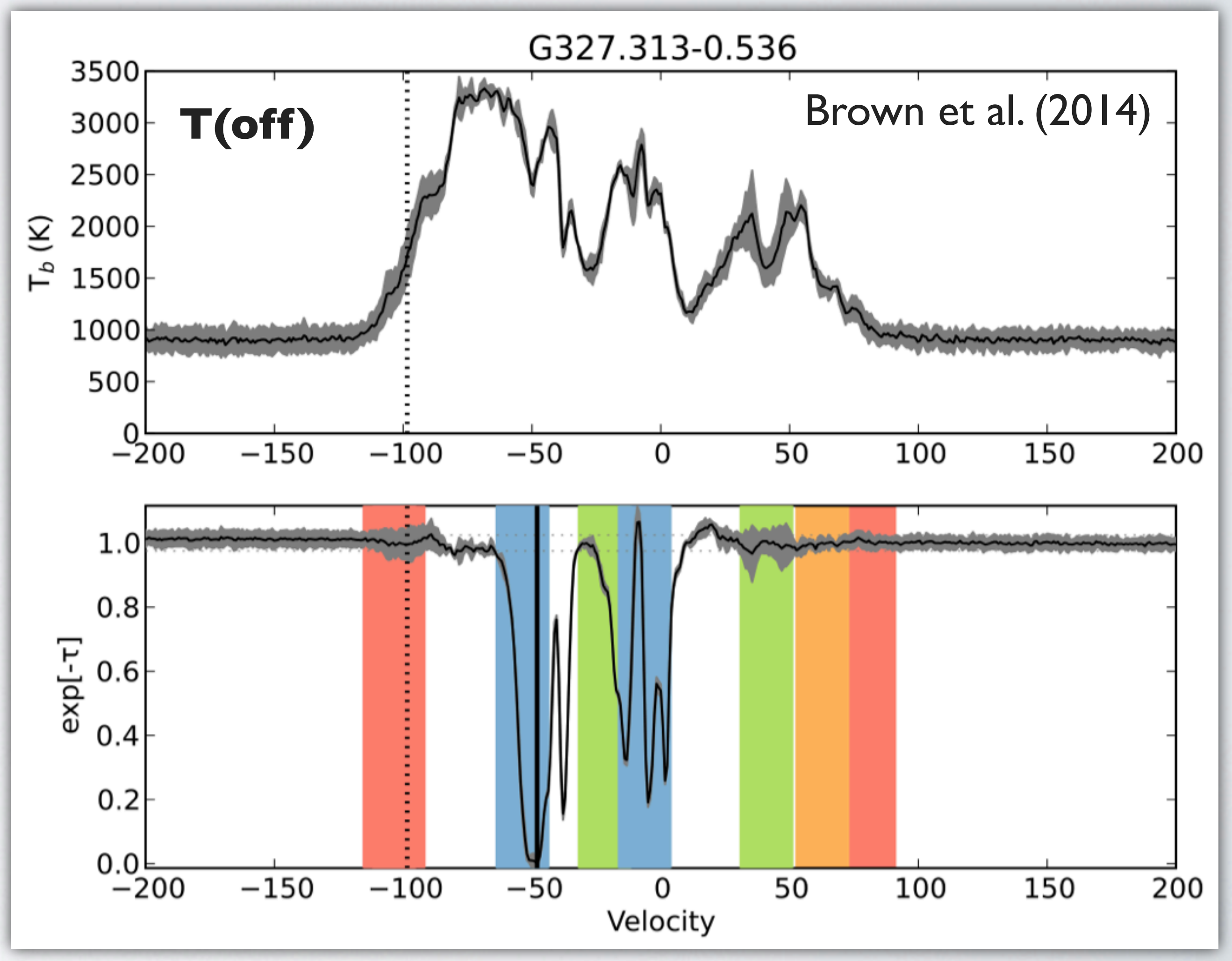
* Simplest single component case

$$T_\mathrm{b}(\mathrm{on}) = (T_\mathrm{bg} + T_\mathrm{c})e^{-\tau_v} + T_\mathrm{s}(1 - e^{-\tau_v})$$

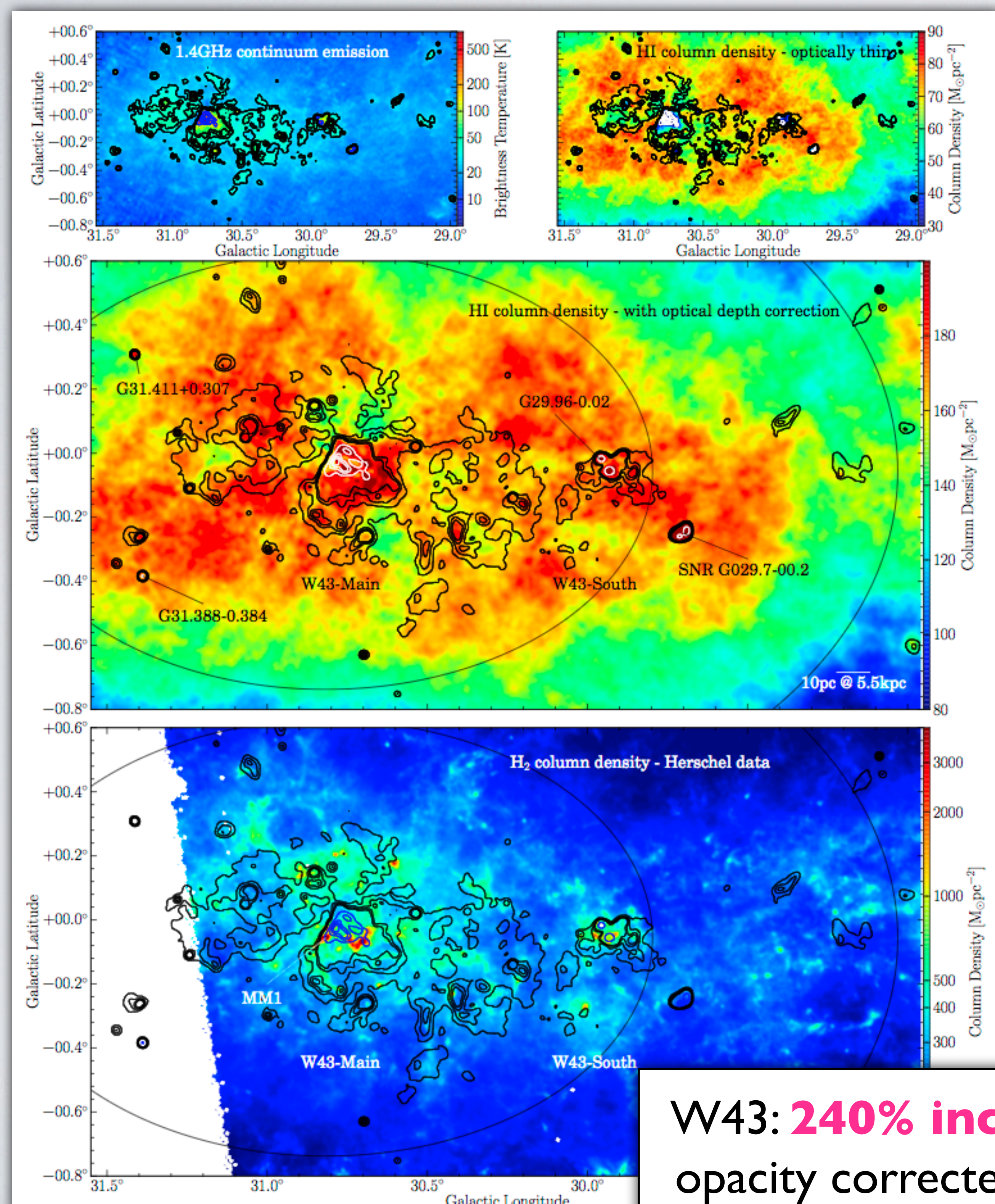
How much material is missed by assuming optically thin HI?

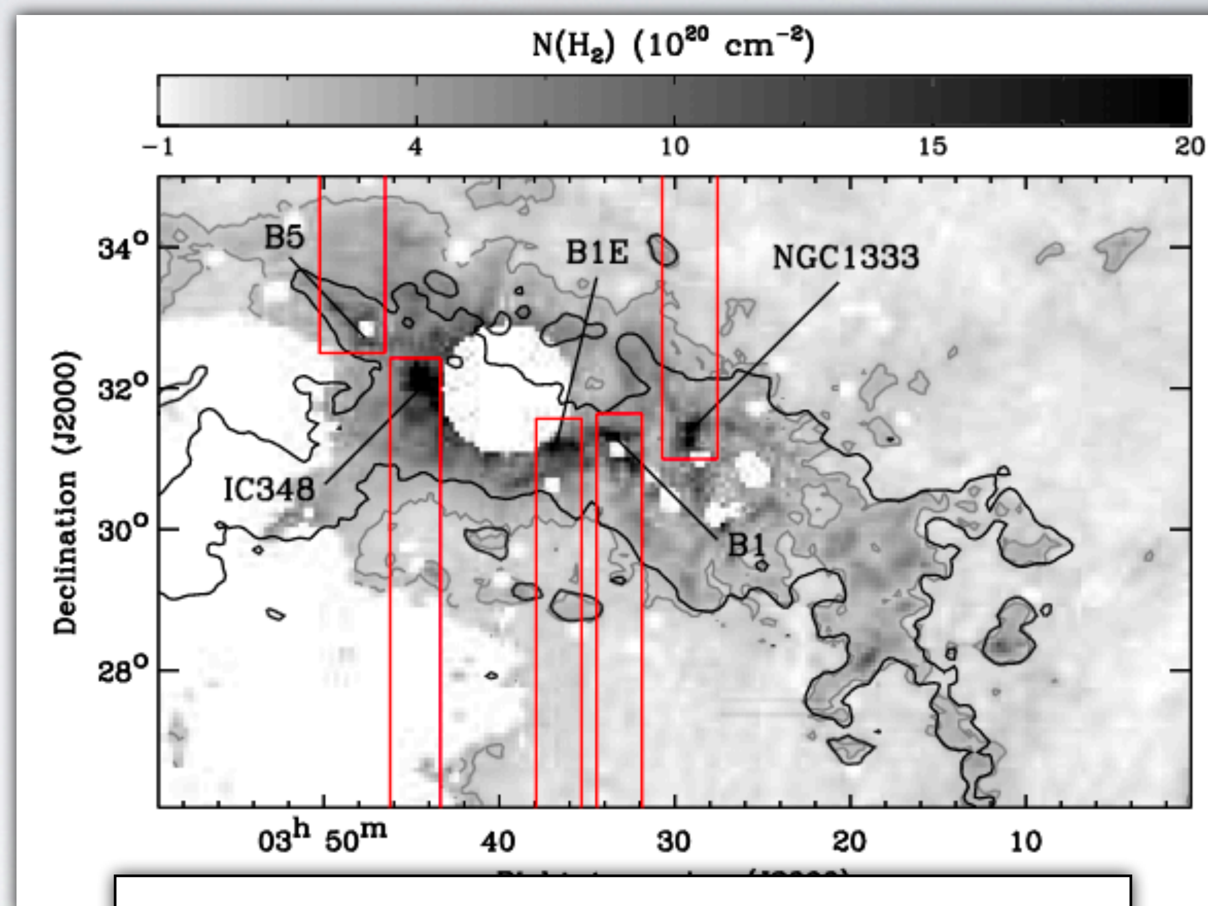
- **~25% in the local ISM** (Heiles & Troland 2003)
- **~30–40% in the inner Galaxy** (Dickey et al. 2003)
- **~10–30% in the outer Galaxy** (Dickey et al. 1983)

Along a few 10s of sightlines



The Dark ISM: Environmental Variation



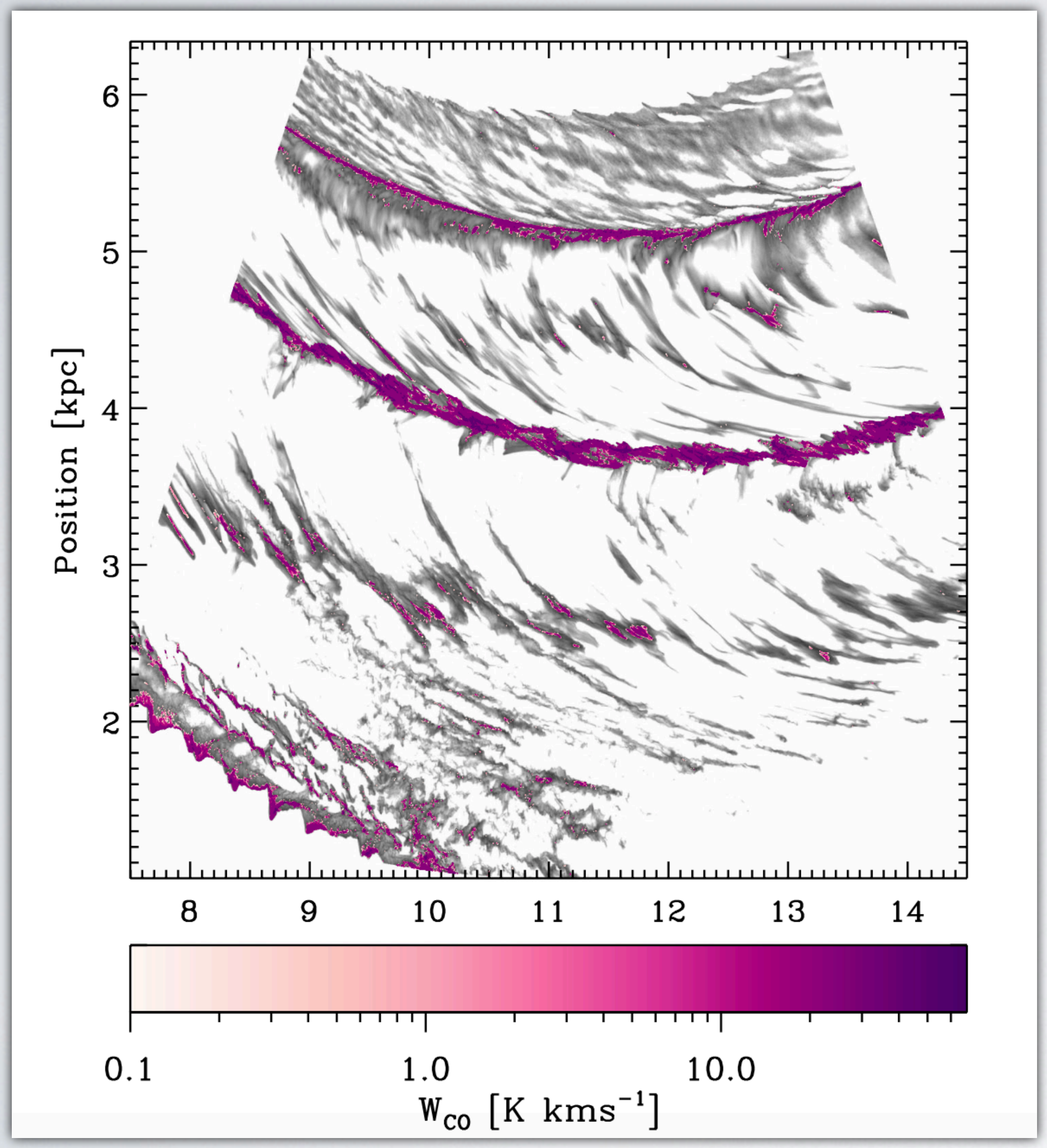


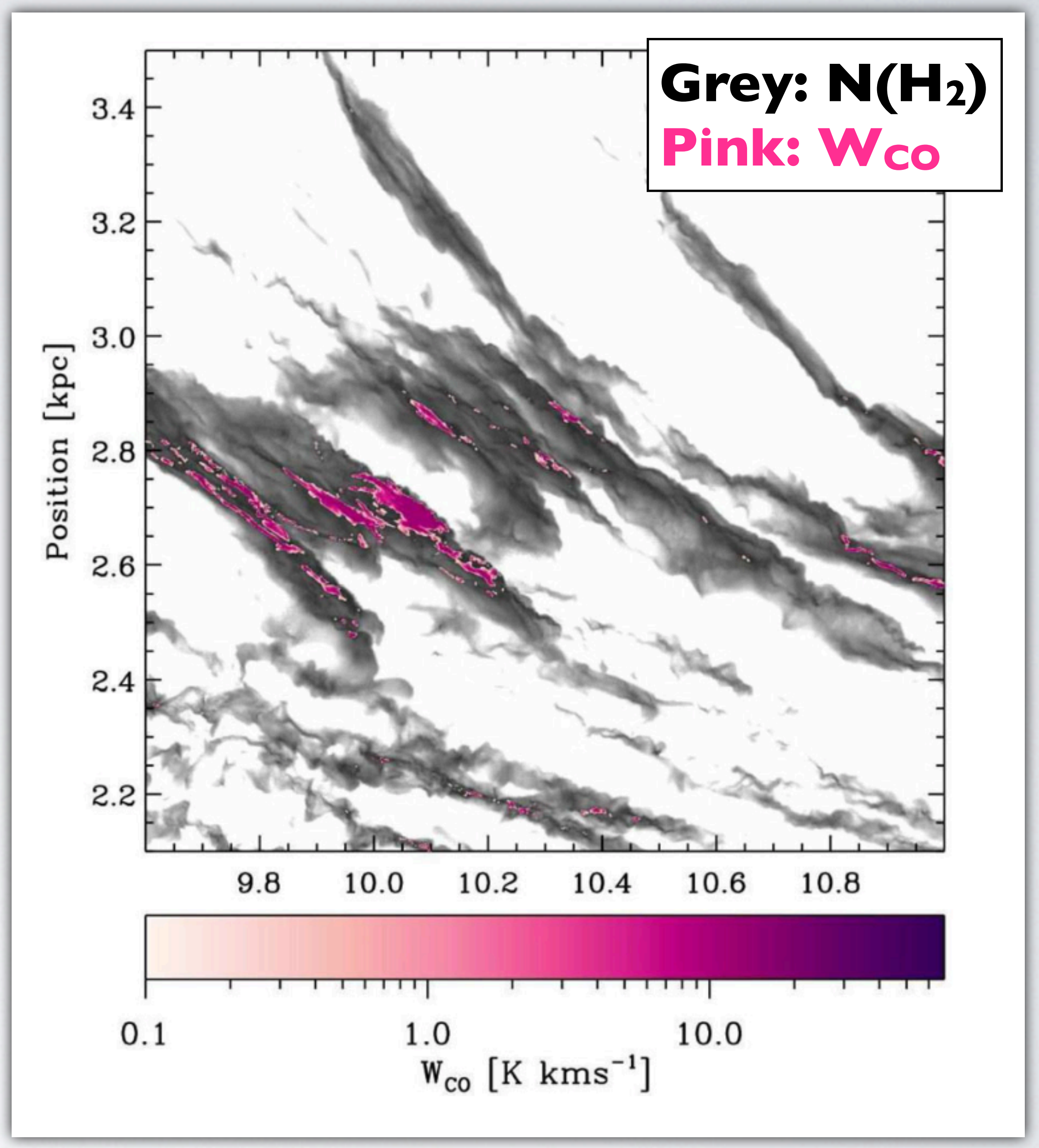
Perseus: Only **10% increase in HI mass** when opacity corrected; **~80% of dark gas is H_2**

(Stanimirovic et al. 2014; Lee et al. 2015)

W43: **240% increase in HI mass** when opacity corrected (THOR; Bihr et al. 2015)

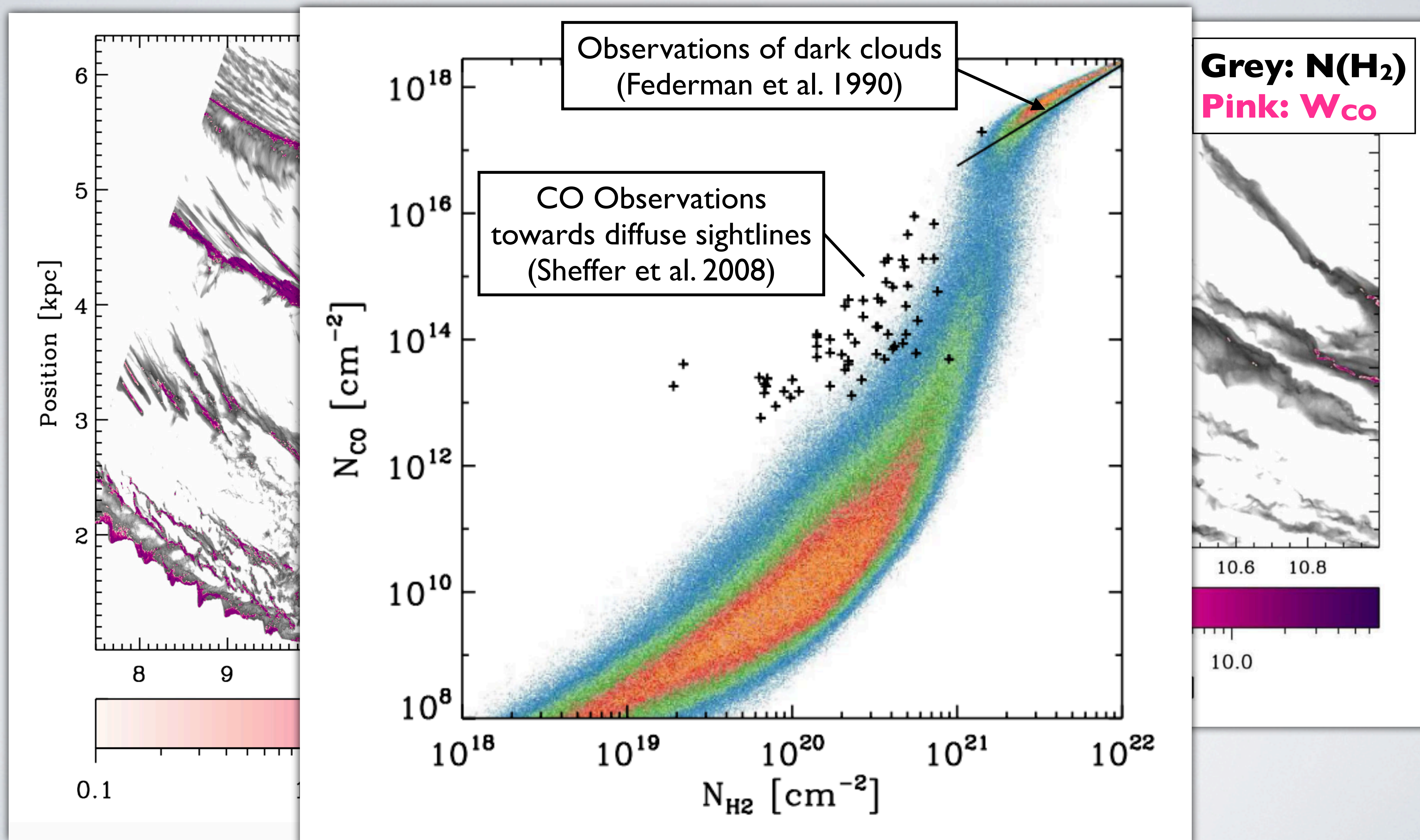
The Dark ISM: Numerical Simulations





Smith et. al. (2014)

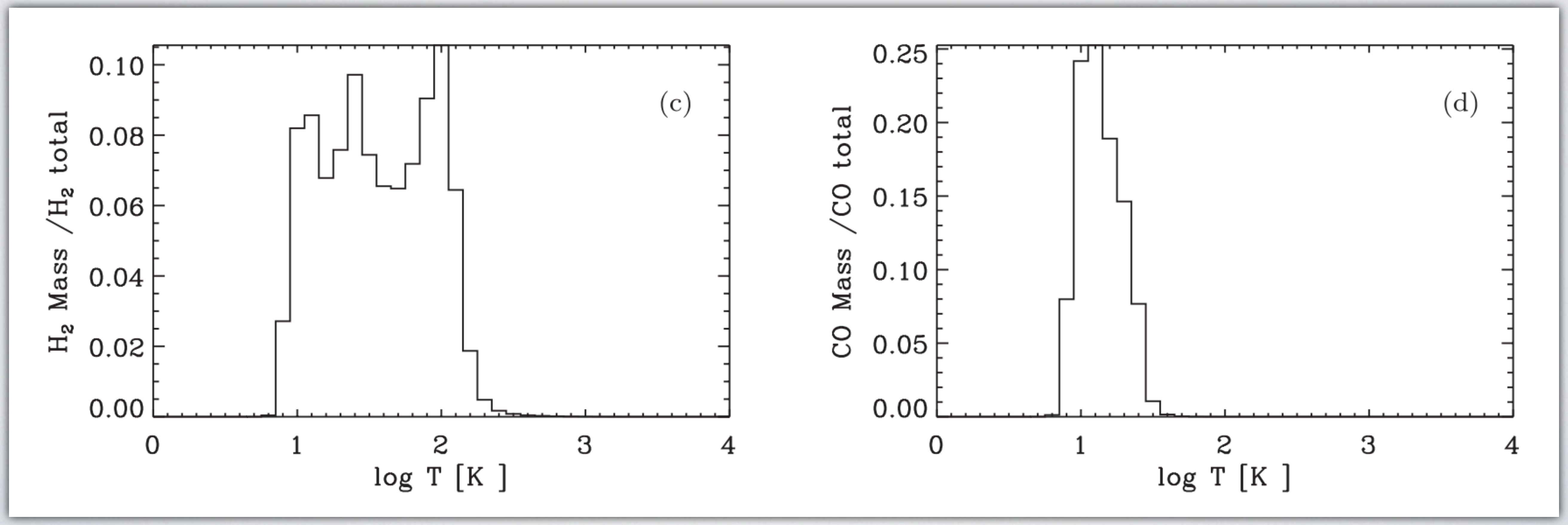
The Dark ISM: Numerical Simulations



The Dark ISM: Numerical Simulations

We investigate the temperature distribution of CO-dark molecular hydrogen (H_2) in a series of disc galaxies simulated using the AREPO moving-mesh code. In conditions similar to those in the Milky Way, we find that H_2 has a flat temperature distribution ranging from 10 to 100 K. At $T < 30$ K, the gas is almost fully molecular and has a high CO content, whereas at $T >$ 30 K, the H_2 fraction spans a broader range and the CO content is small, allowing us to classify gas in these two regimes as CO-bright and CO-dark, respectively. The mean sound speed in the CO-dark H_2 is $c_{\rm s,\,dark} = 0.64\,{\rm km\,s^{-1}}$, significantly lower than the value in the cold atomic gas ($c_{\rm s,\,CNM} = 1.15\,{\rm km\,s^{-1}}$), implying that the CO-dark molecular phase is more susceptible to turbulent compression and gravitational collapse than its atomic counterpart. We further show that the temperature of the CO-dark H_2 is highly sensitive to the strength of the interstellar radiation field, but that conditions in the CO-bright H_2 remain largely unchanged. Finally, we

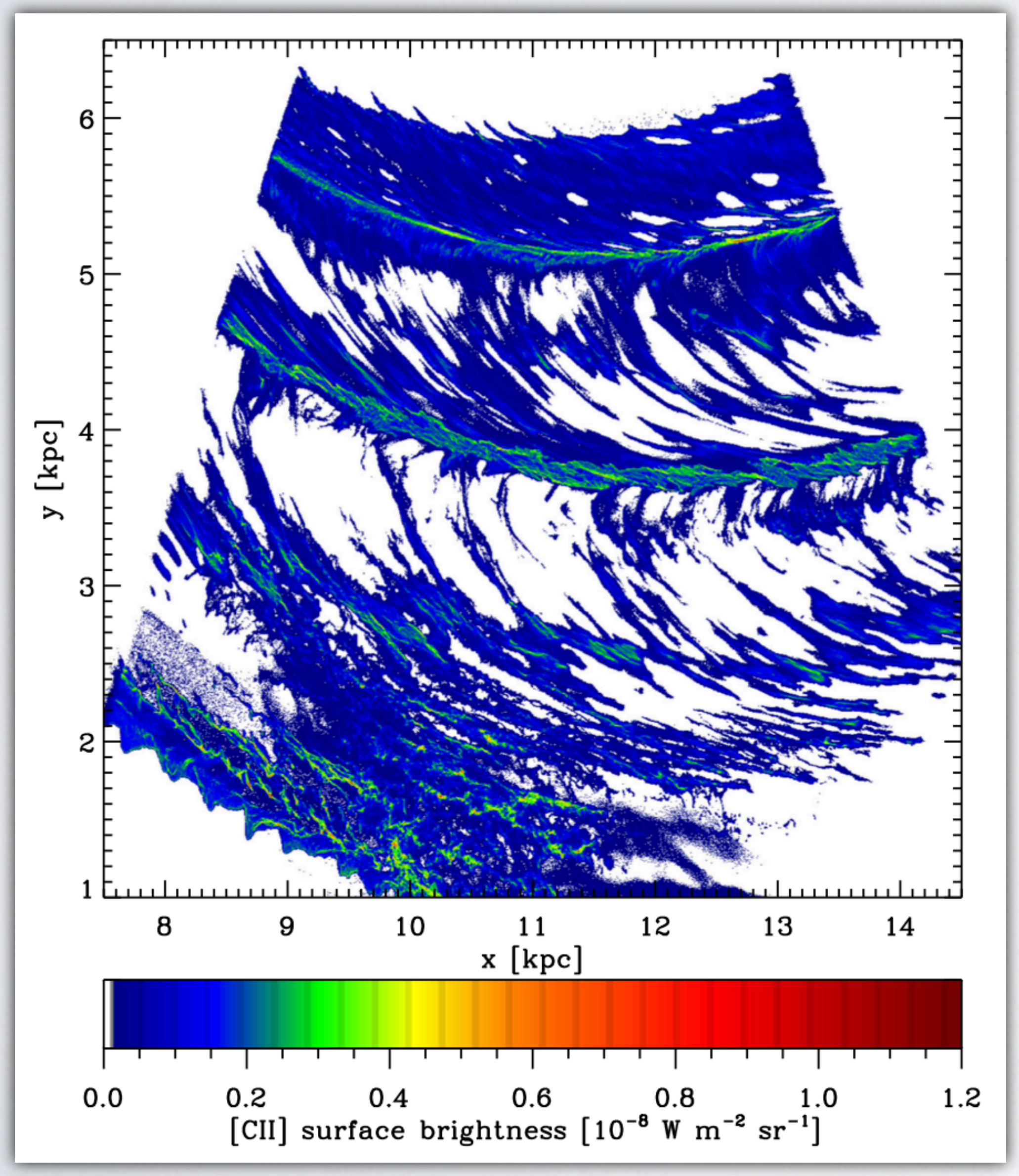
Glover & Smith (2016)

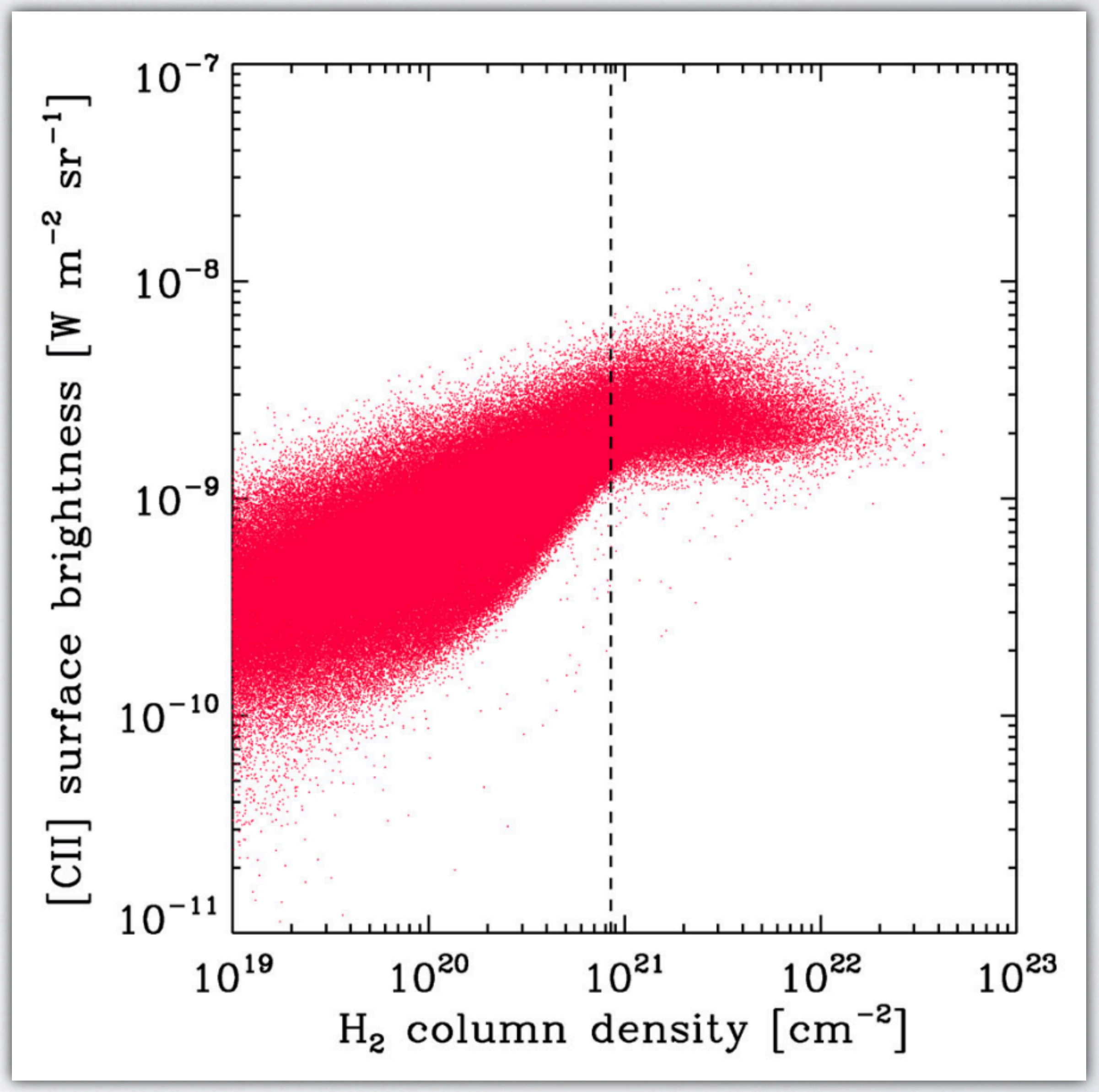


The Dark ISM: Numerical Simulations

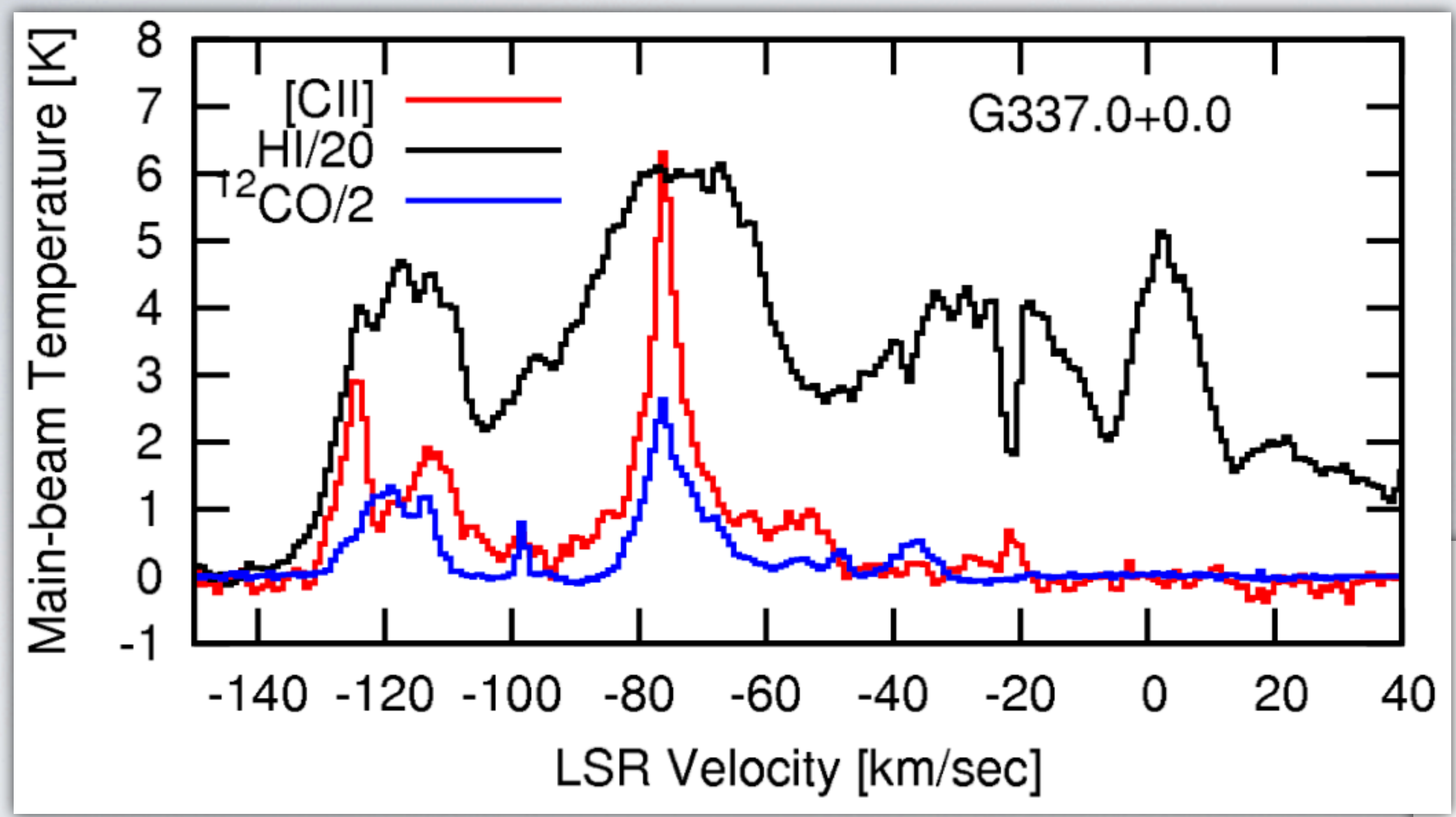
radiation field, but that conditions in the CO-bright H_2 remain largely unchanged. Finally, we examine the usefulness of the [C II] and [O I] fine-structure lines as tracers of the CO-dark gas. We show that in Milky Way-like conditions, diffuse [C II] emission from this gas should be detectable. However, it is a problematic tracer of this gas, as there is only a weak correlation between the brightness of the emission and the H_2 surface density. The situation is even worse for the [O I] line, which shows no correlation with the H_2 surface density.

Glover & Smith (2016)

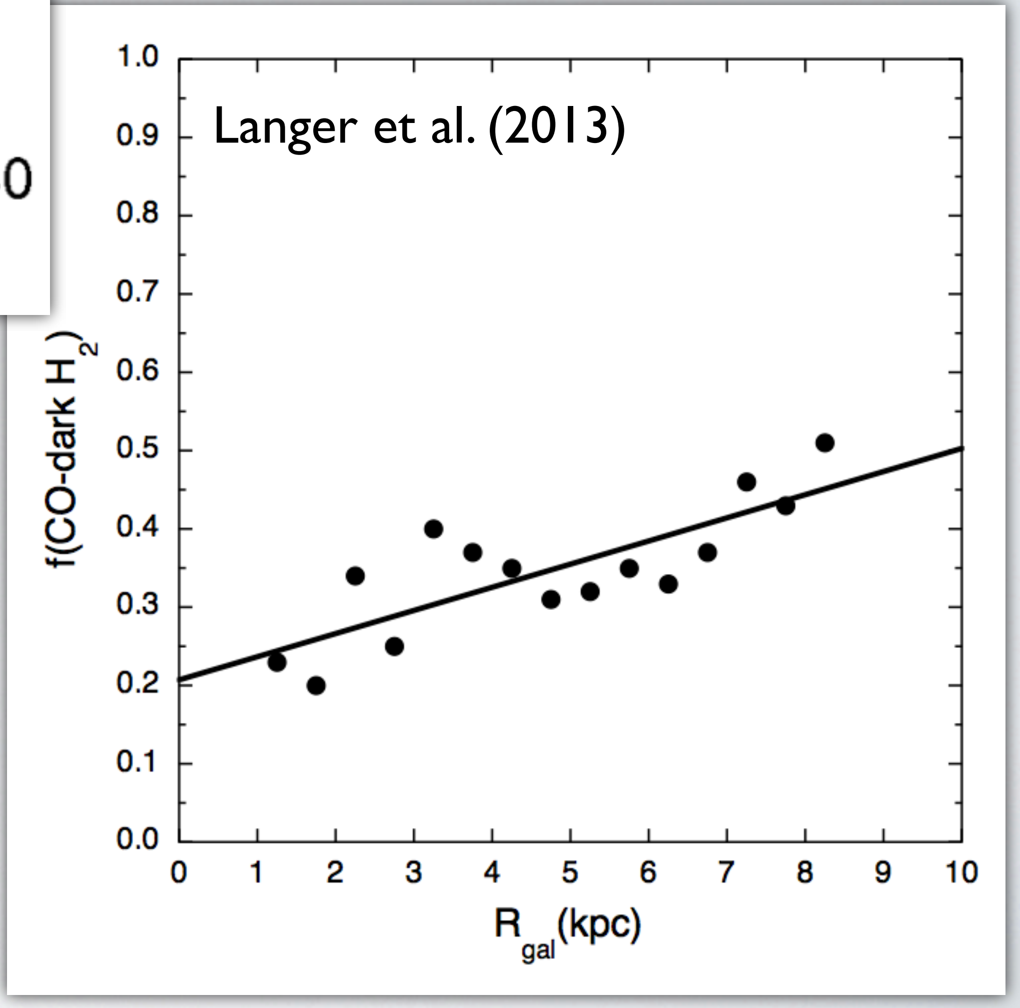




The Dark ISM: CO-Dark H_2 from C+



GOT C+ Survey Results



How much H_2 is CO-dark?

- **~20-50% in the inner Galaxy?** (Pineda et al. 2013, Langer et al. 2013)

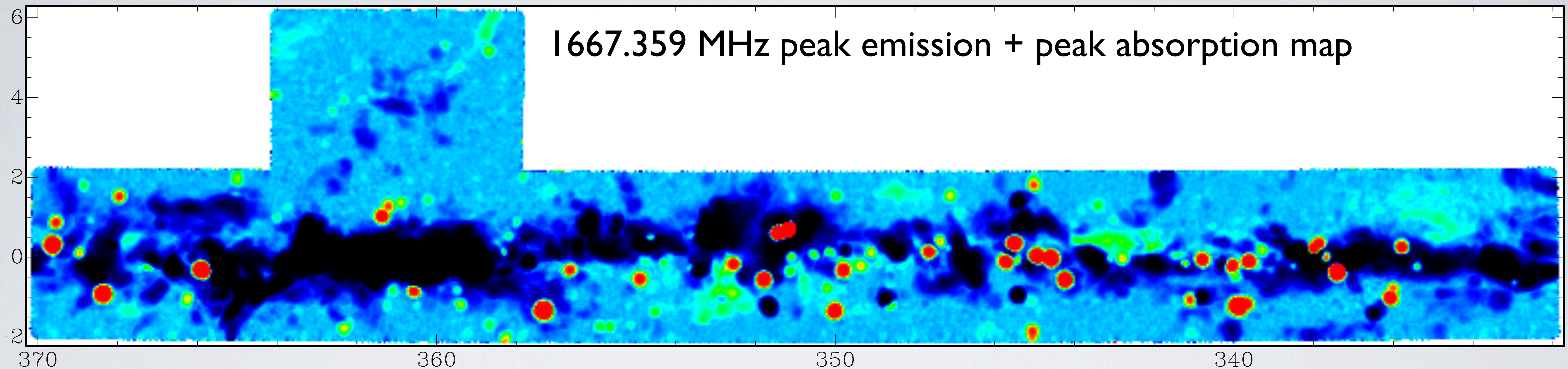
  Along 320 sightlines!

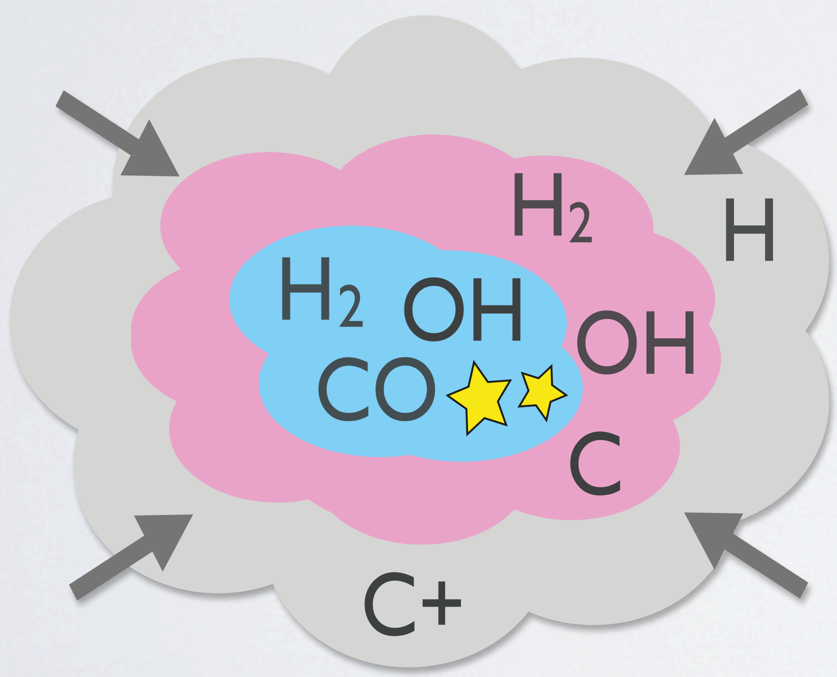
The Dark ISM: Outstanding Questions

"[All] tracers have different limitations and comparing them is essential to map and weigh the main gas reserves of the Milky Way." - *Grenier et al. (2004)*

- How do the fractional abundances of HI, cold HI, diffuse H_2 and CO-bright H_2 vary throughout the Galaxy?
- How is dark/diffuse H_2 distributed on Galactic scales and locally within CNM/molecular cloud complexes?
- How well is dark/diffuse H_2 mixed with the CNM? (And WNM??)
- What is its chemical profile?
- What is its temperature/density distribution?
- How much mass is contained in this phase?

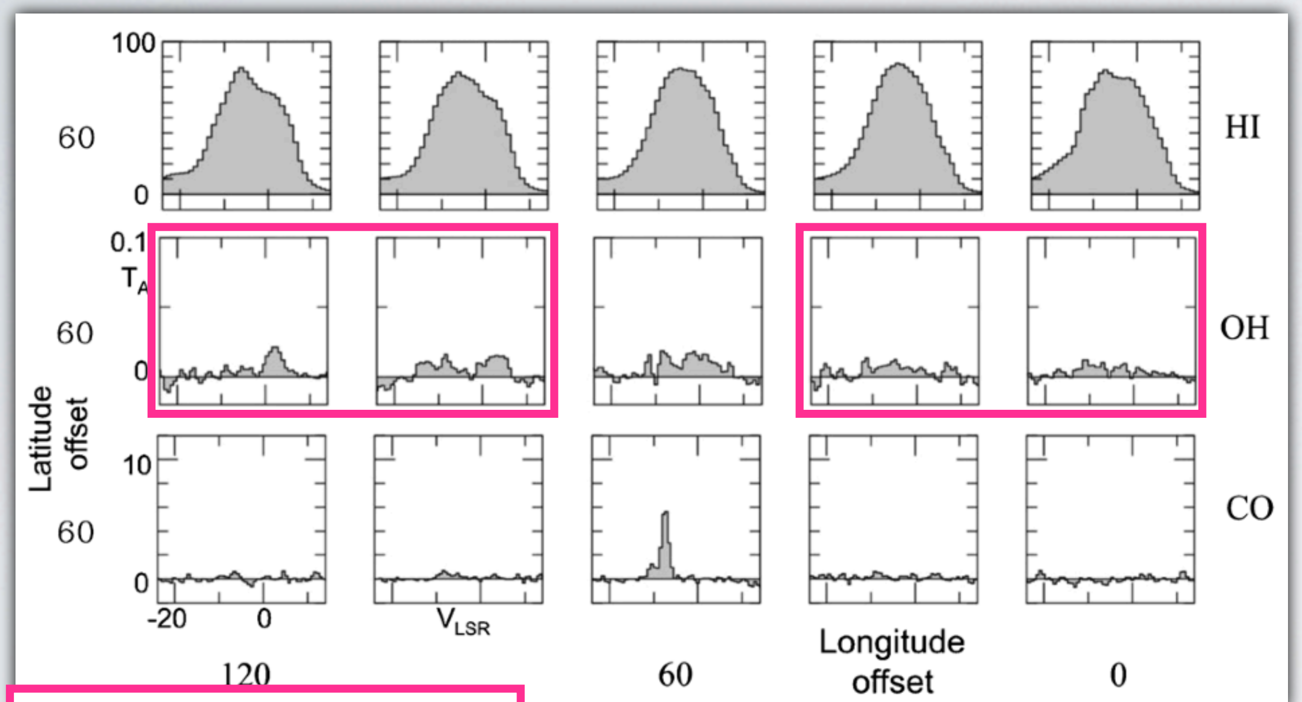
OH What a Lovely Molecule





- **Abundant** and **observable** in diffuse, CO-poor molecular gas (e.g. Wannier et al. 1993, Allen et al. 2012)
- **Stable abundance ratio** from Av ~0.25 to ~10 (Crutcher 1979, Liszt & Lucas 1996)
- Readily observed in **absorption & emission**
- **4-line system** can be modelled to constrain gas properties (temperature, density, IR field...)

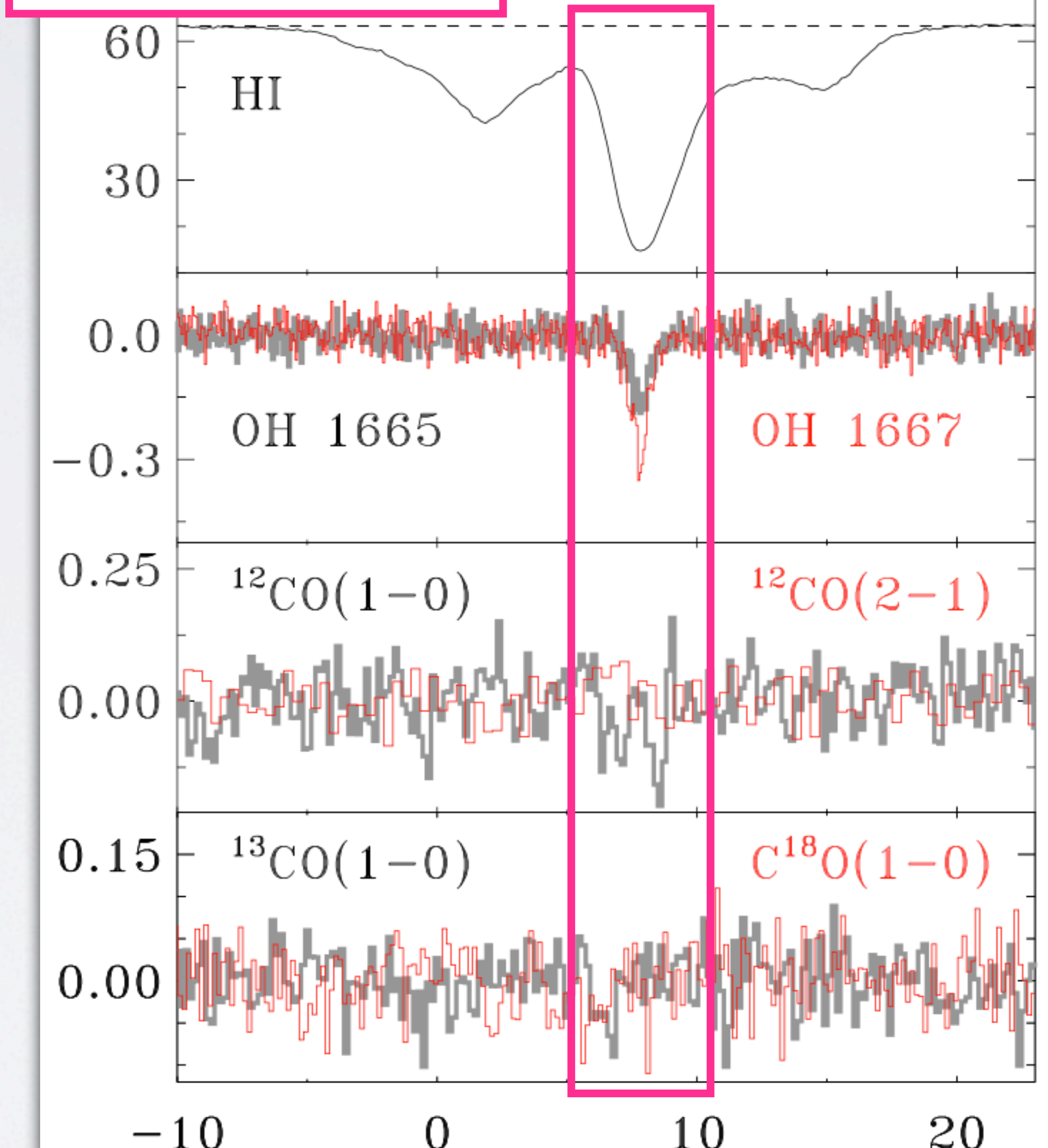
OH What a Lovely Molecule



OH where no CO

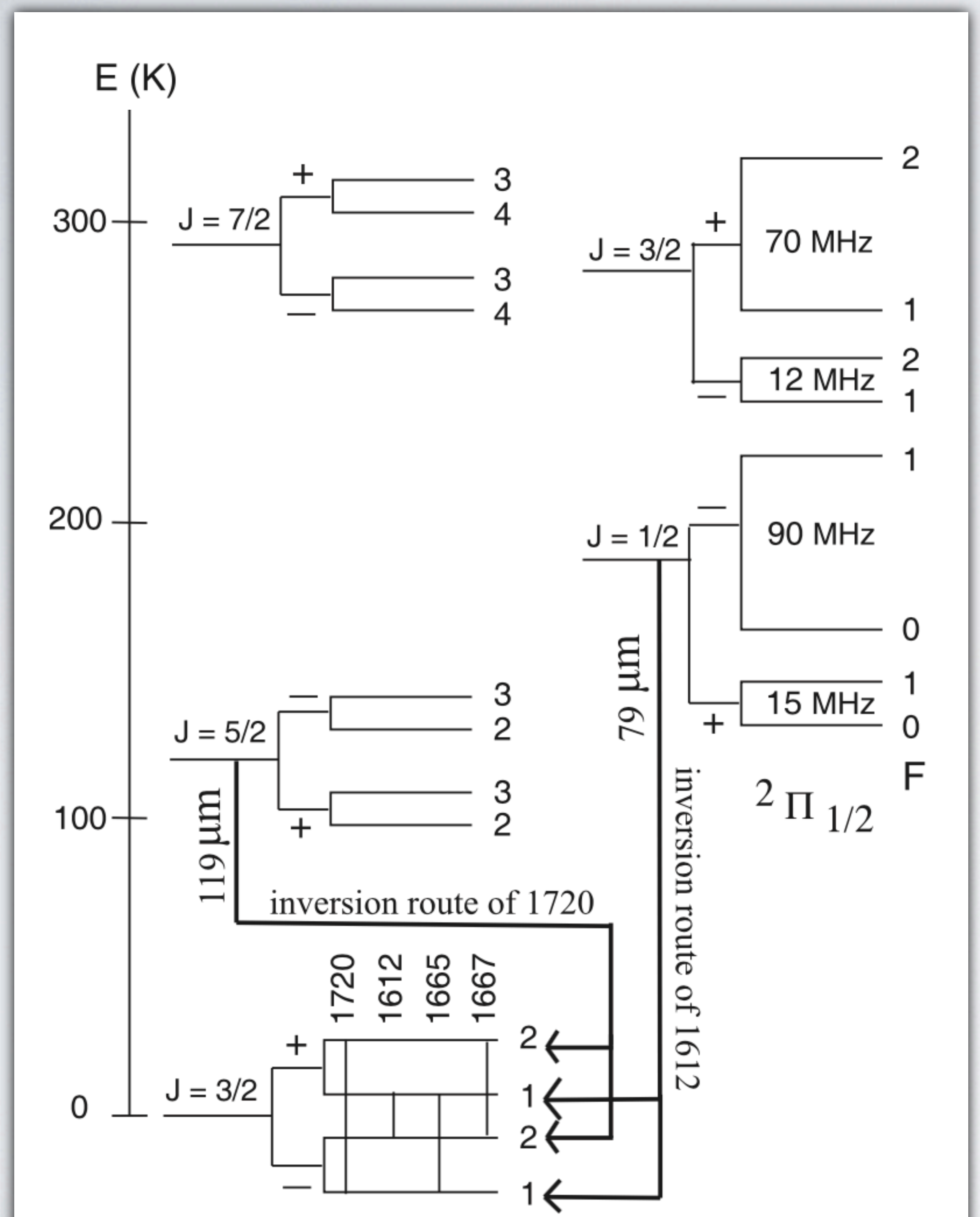
Allen et al. (2012)

OH where no CO

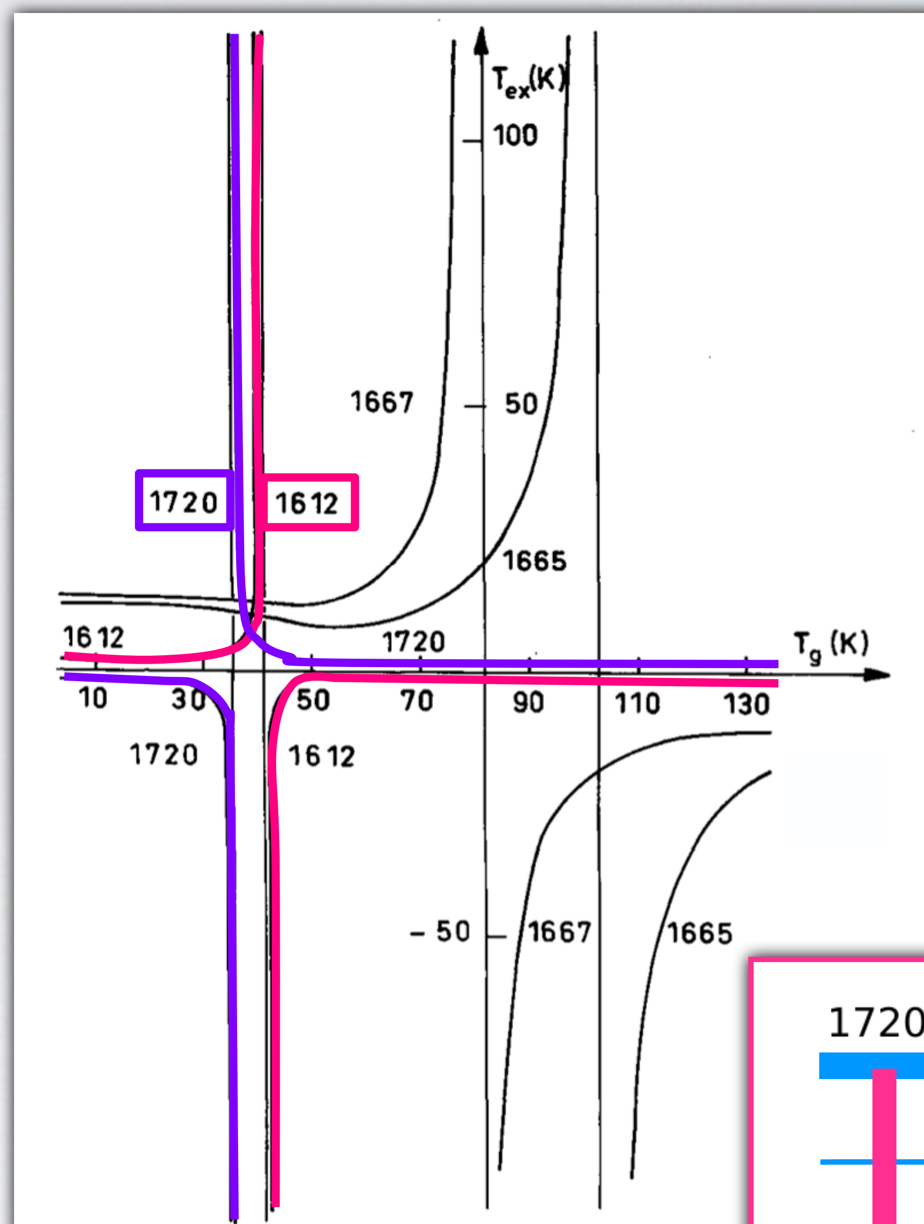


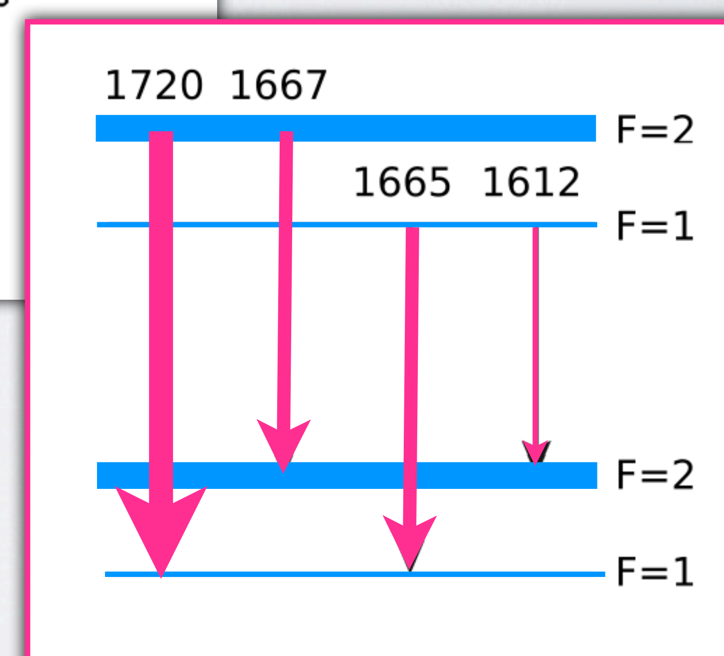
Tang, Nguyen, Li, Dawson et al. (in prep)

OH What a Lovely Molecule



Reproduced from Du et al. (2016)



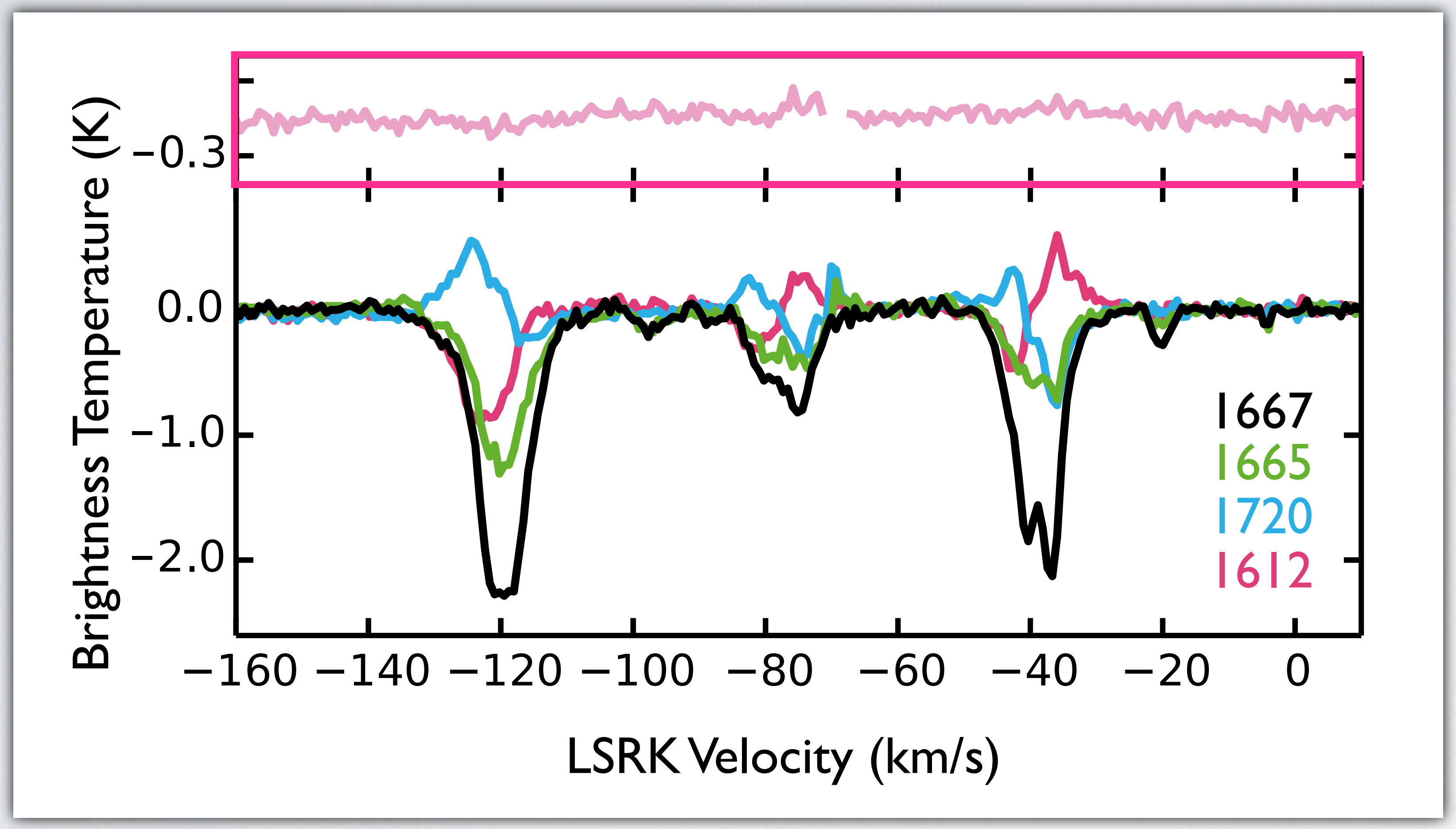


Variation of OH excitation temperature with dust temperature

(LVG models by Guibert et al. 1979)

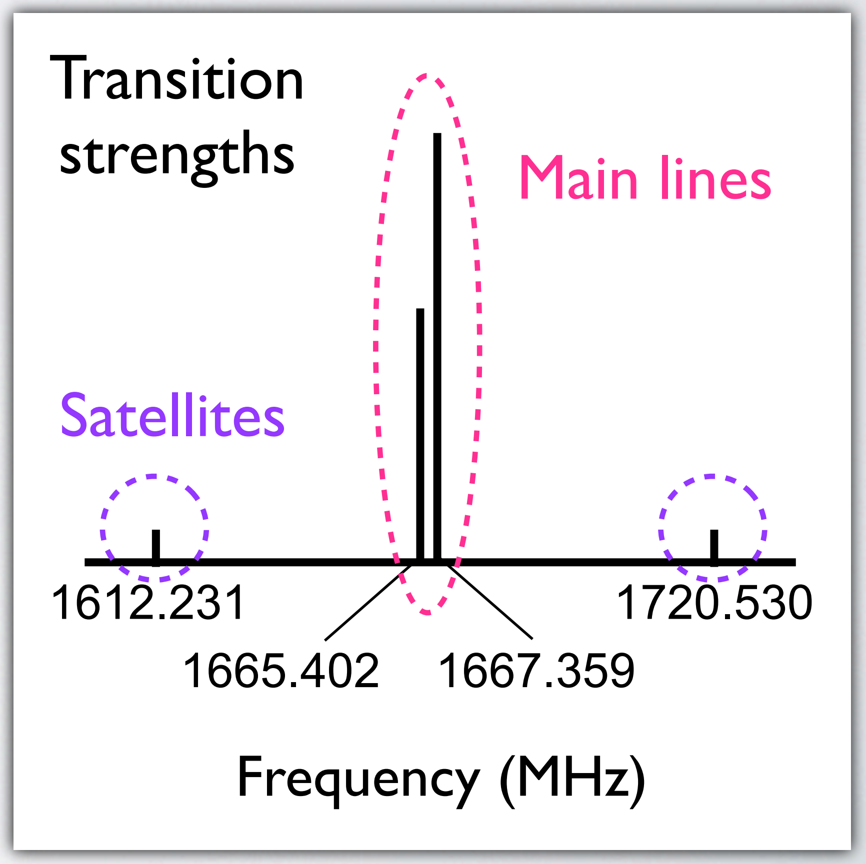
OH What a Lovely Molecule

$$[T_\mathrm{b}(1612) + T_\mathrm{b}(1720)] - [T_\mathrm{b}(1667)/9.0 + T_\mathrm{b}(1665)/5.0] = 0$$



True when:

- Optical depth $\tau \ll 1$
- Continuum background $T_c(\nu)$ is constant
- $h\nu / kT_{ex} \ll 1$



The Dark ISM from SPLASH & GASKAP

GASKAP

The Galactic ASKAP Survey

PIs: Naomi McClure-Griffiths & John Dickey

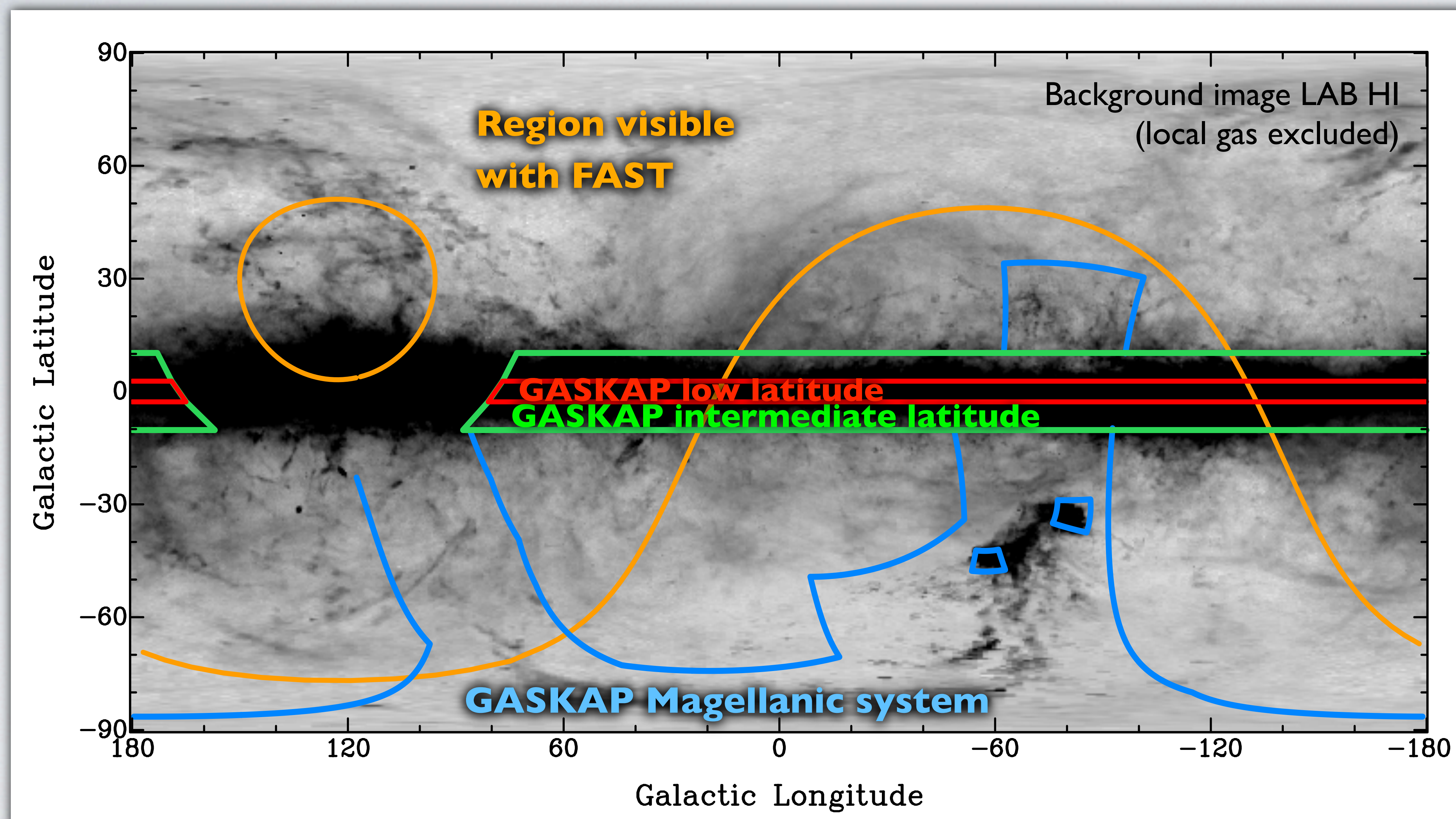
SPLASH

The Southern Parkes Large Area Survey in Hydroxyl

PIs: Joanne Dawson & Andrew Walsh

GASKAP: Galaxy Evolution Begins at Home

Aim: To study the evolution of the Milky Way and Magellanic Clouds through their interstellar gas and star formation



HI 21cm emission & absorption: **WNM & CNM**

OH 18cm diffuse emission & absorption (1612, 1665, 1667 MHz): **Molecular gas**

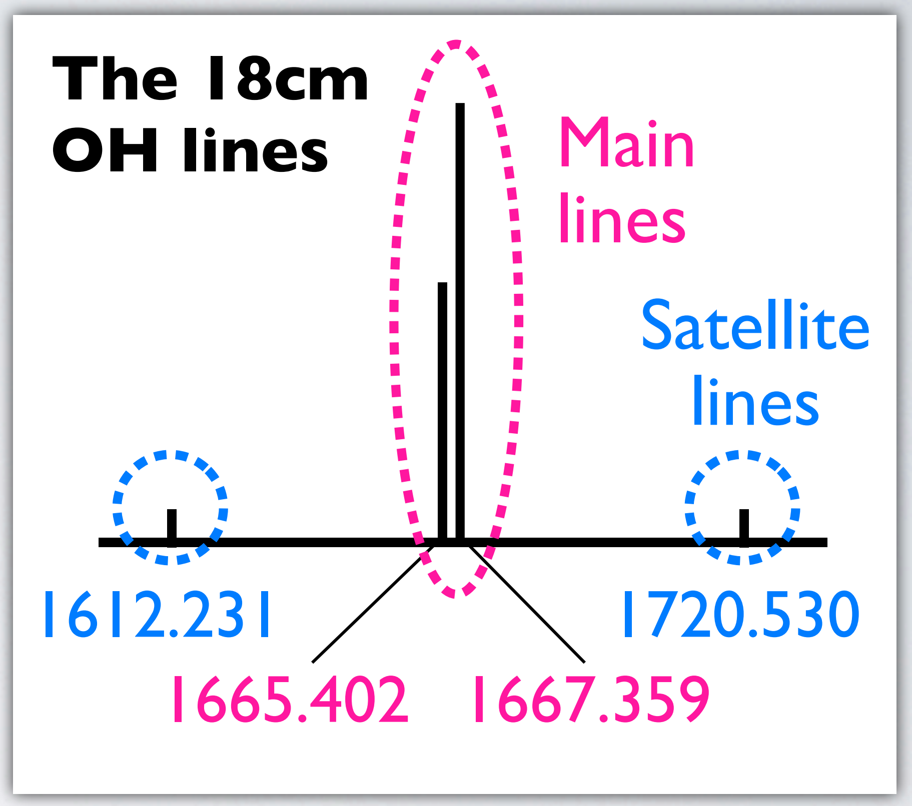
OH 18cm masers: **Star formation & evolved stars**

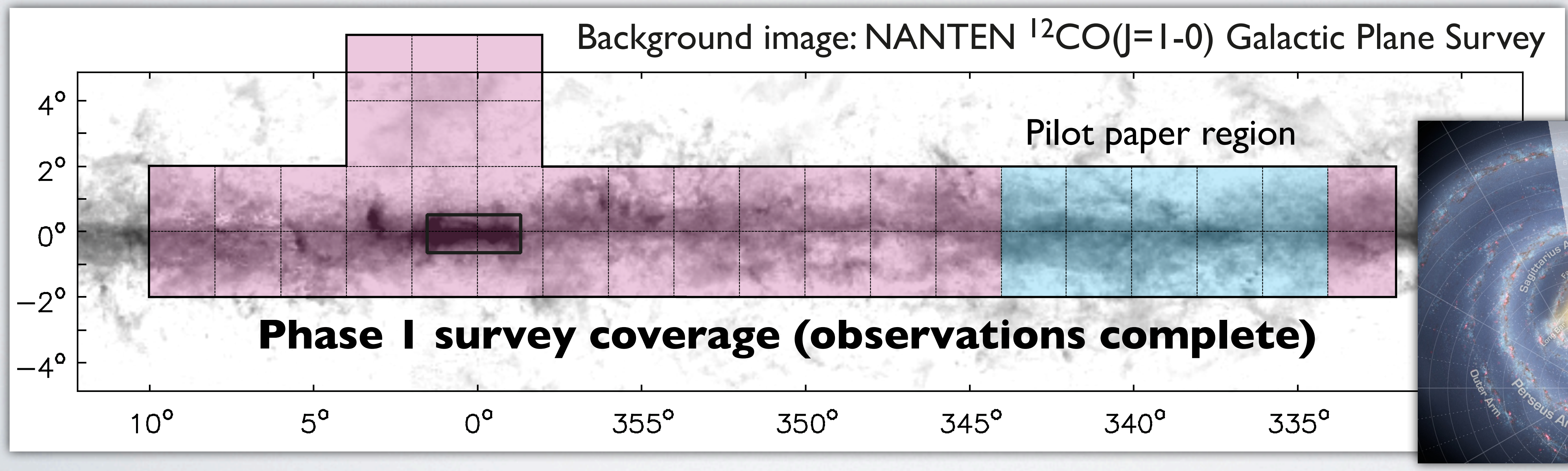
Dickey et al. (2013)

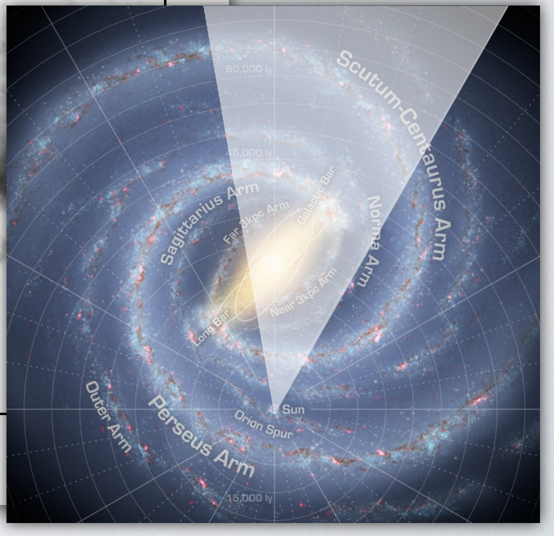
First ASKAP zoom-mode data expected ~~imminently~~! **This year.**

SPLASH: Survey Overview

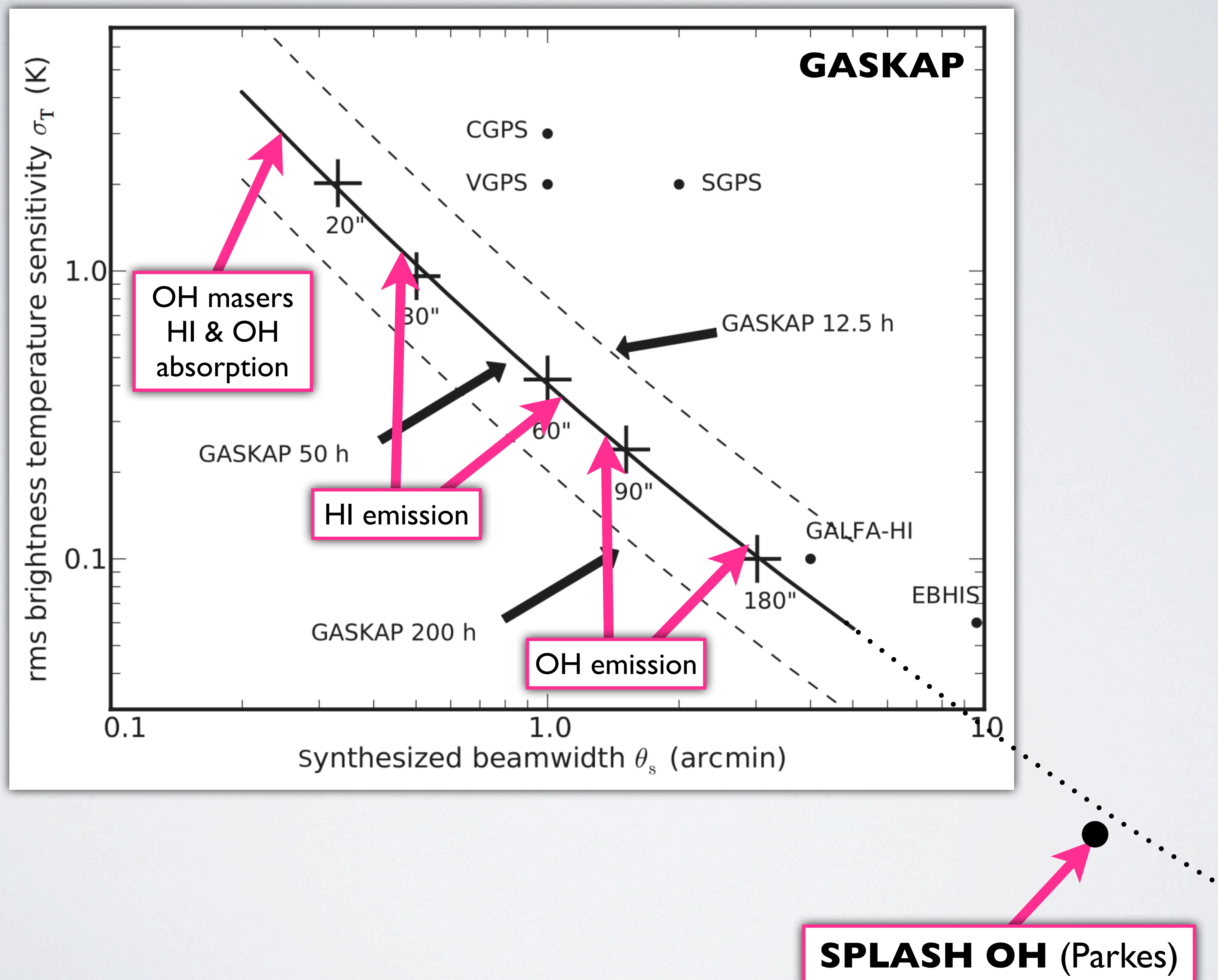
- Parkes single-dish survey
- **All four ground state transitions of OH**
  - 1612, 1665, 1667, 1720 MHz **+ 1.6-1.7 GHz continuum**
- **Low resolution, high sensitivity:**
  - Effective **HPBW = 15’**, **σ = 15-20 mK** (for δv = 0.7 km/s), raw δv = 0.18 km/s





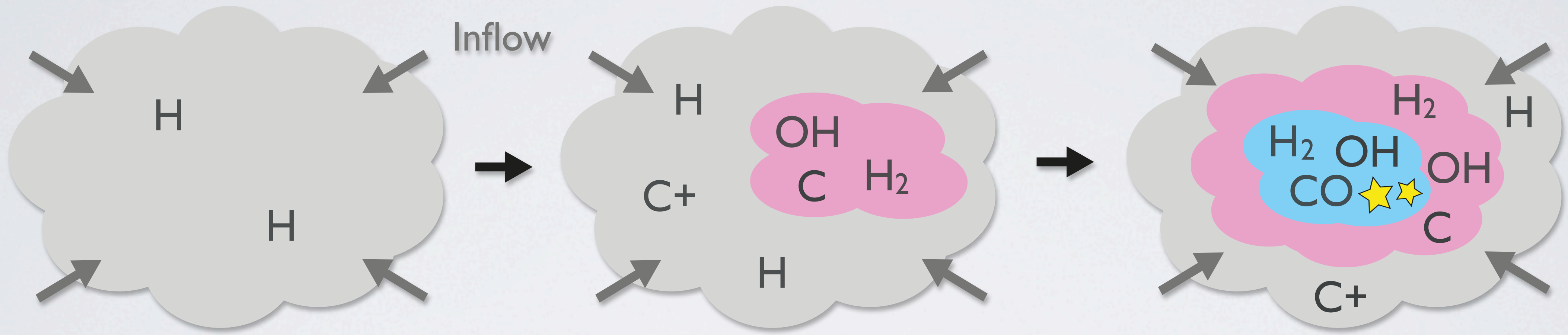


GASKAP vs SPLASH: Sensitivity & Resolution



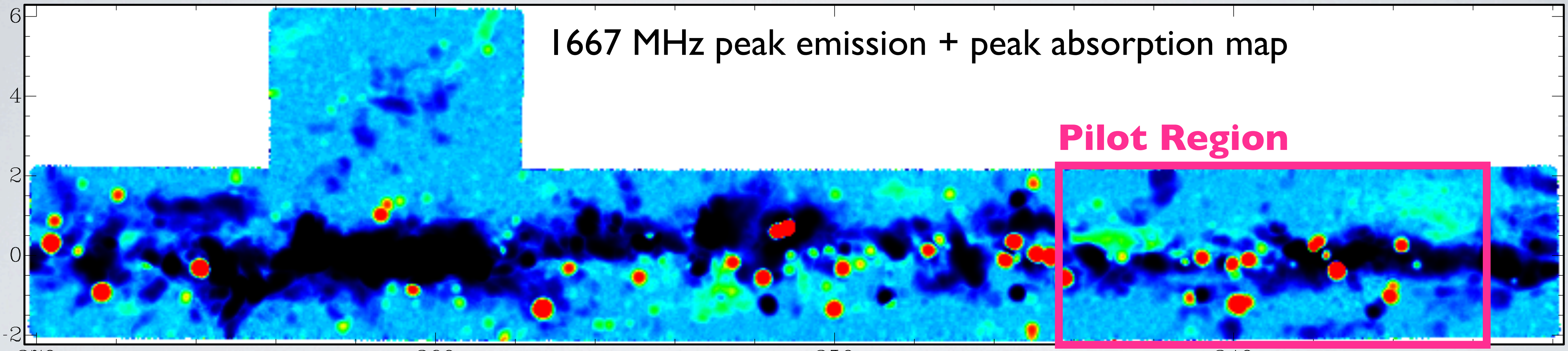
SPLASH Science Aims

- **Map CO-dark H_2**
  - OH present where CO is not - recover the Milky Way's hidden molecular gas



- **Environmental conditions in the OH-bright ISM**
  - Excitation modelling gives local IR field, density, kinetic temperature...
- **Mapping the Central Molecular Zone**
  - Combining OH and CO to build up a 3D map of the Galactic Centre region
- **Deep OH maser survey**
  - Positions and polarisation properties (ATCA)
  - Star formation, SNR shocks, evolved stars, magnetic field studies...

SPLASH: Current Status



- **Data status:**
  - Data reduction pipeline complete!
  - First-pass datacubes produced
  - Some refining of baselining/RFI-cleaning parameters outstanding
- **Science Underway!**
  - Diffuse OH analysis & maser detection stats in the pilot region - Jo Dawson, Andrew Walsh (*Dawson et al. 2014*)
  - OH maser followup with ATCA - Haihua Qiao, Andrew Walsh (*Qiao et al. 2016*)
  - Structure and dynamics of the CMZ - Qingzeng Yan, Andrew Walsh (*Yan et al. submitted*)
  - Evolved star maser statistics - Kosuke Shinano, Hiroshi Imai *(Imai et al. in prep)*
  - CO-dark molecular gas & diffuse OH excitation modelling - Jo Dawson, Mark Wardle

GASKAP: Finest Ever Grid of Absorption Data

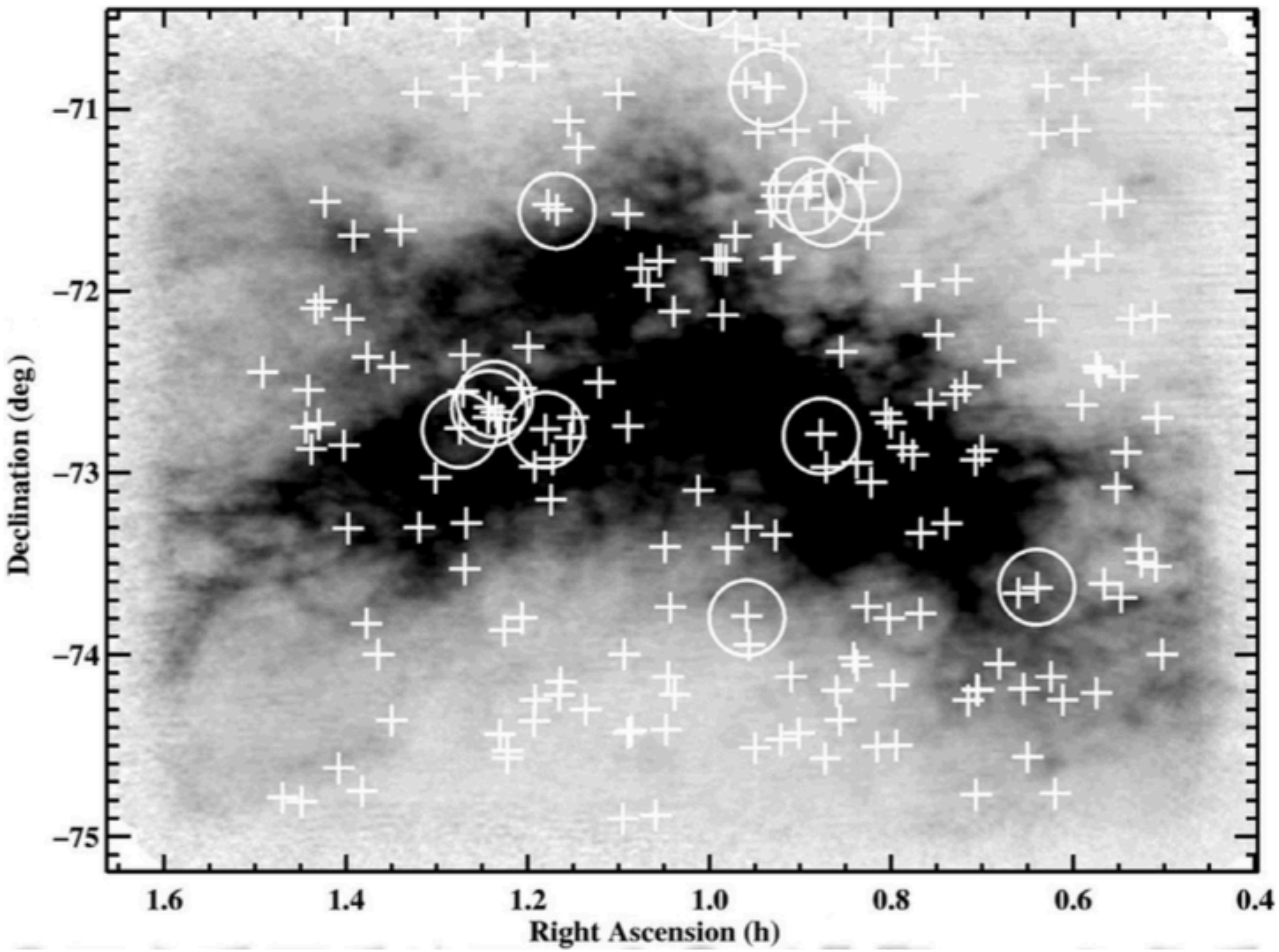


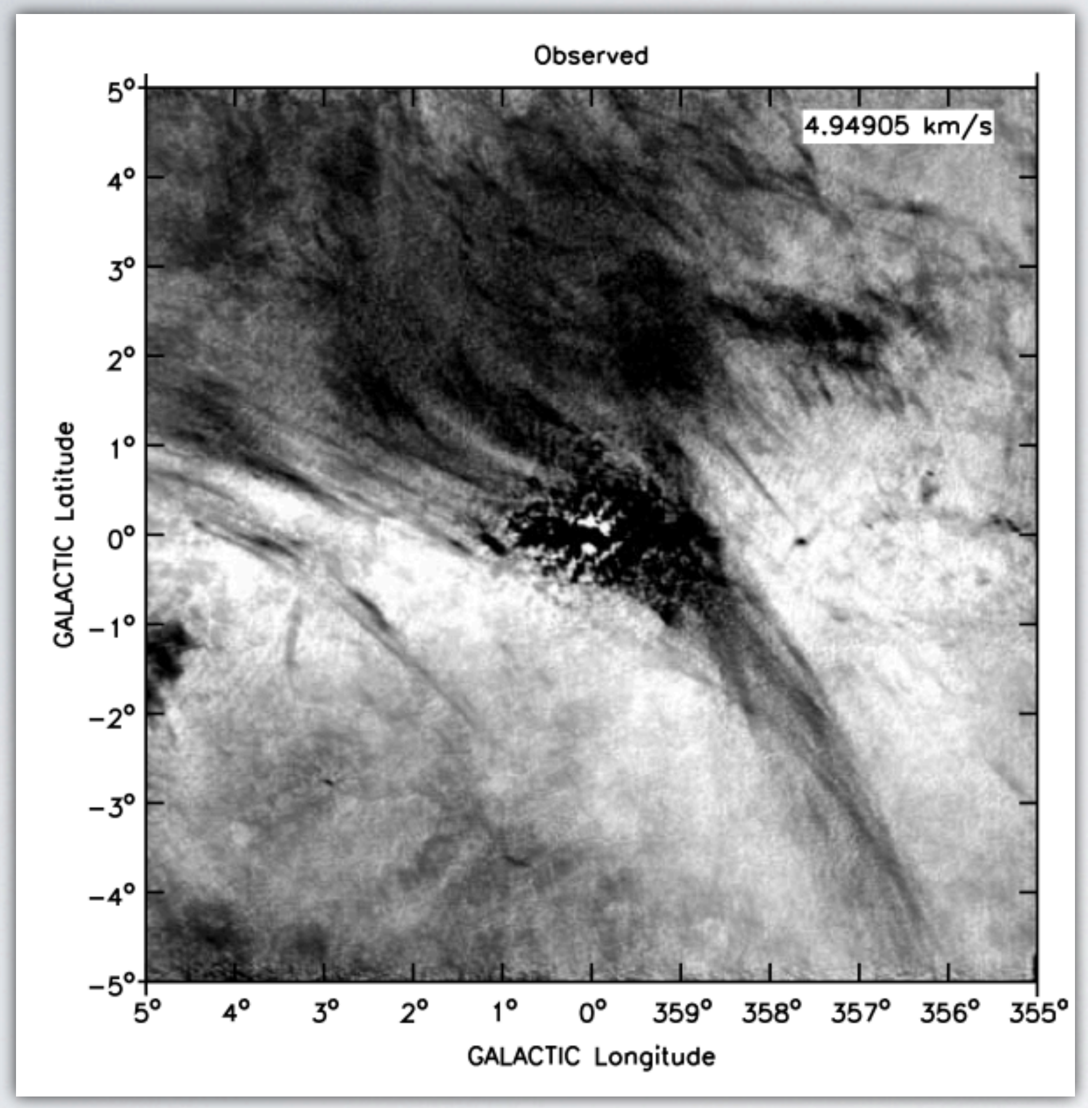
Figure 5. Locations of background continuum sources toward the SMC. The circles show directions for which the H I absorption spectra have already been measured. The crosses show locations of sources bright enough to give good quality absorption spectra with GASKAP.

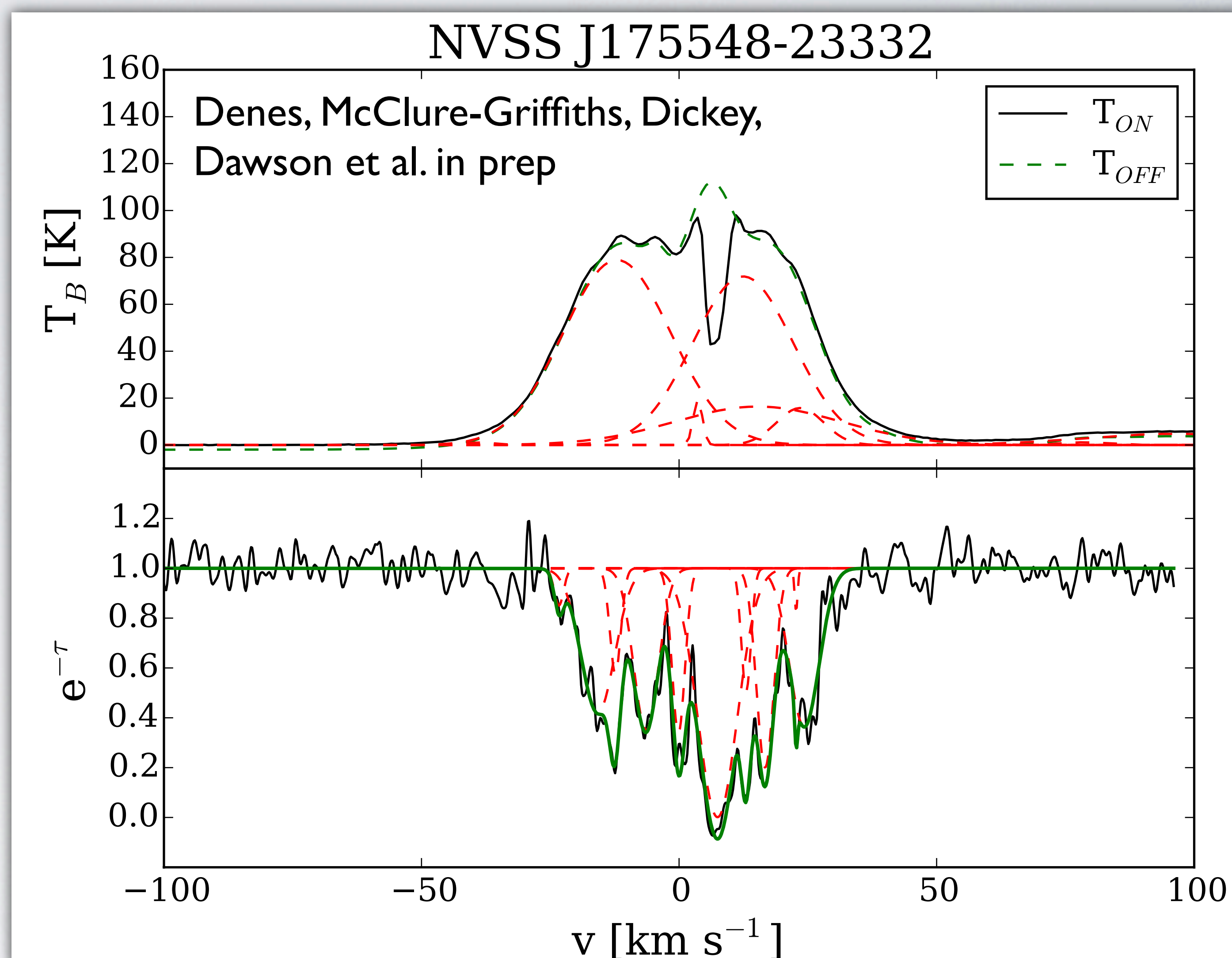
GASKAP will **vastly increase the number of background sources** available for HI absorption measurements.

~ 3 sources per square degree in the GP

Tighter constraints on **Galactic CNM fraction** + its **environmental variation!**

GASKAP: Calibrating the HISA Galaxy





- Sensitivity & resolution of GASKAP → **increased population of HISA** clouds
- HISA gives morphological information, but (usually) T_S and τ are degenerate
- Use new background source population to finely sample multiple sightlines through HISA clouds → **independent calibration of T_S and τ** → bootstrap to all clouds??

GASKAP OH Absorption Meausurements

Tang, Nguyen, Li, Dawson et al. (in prep)

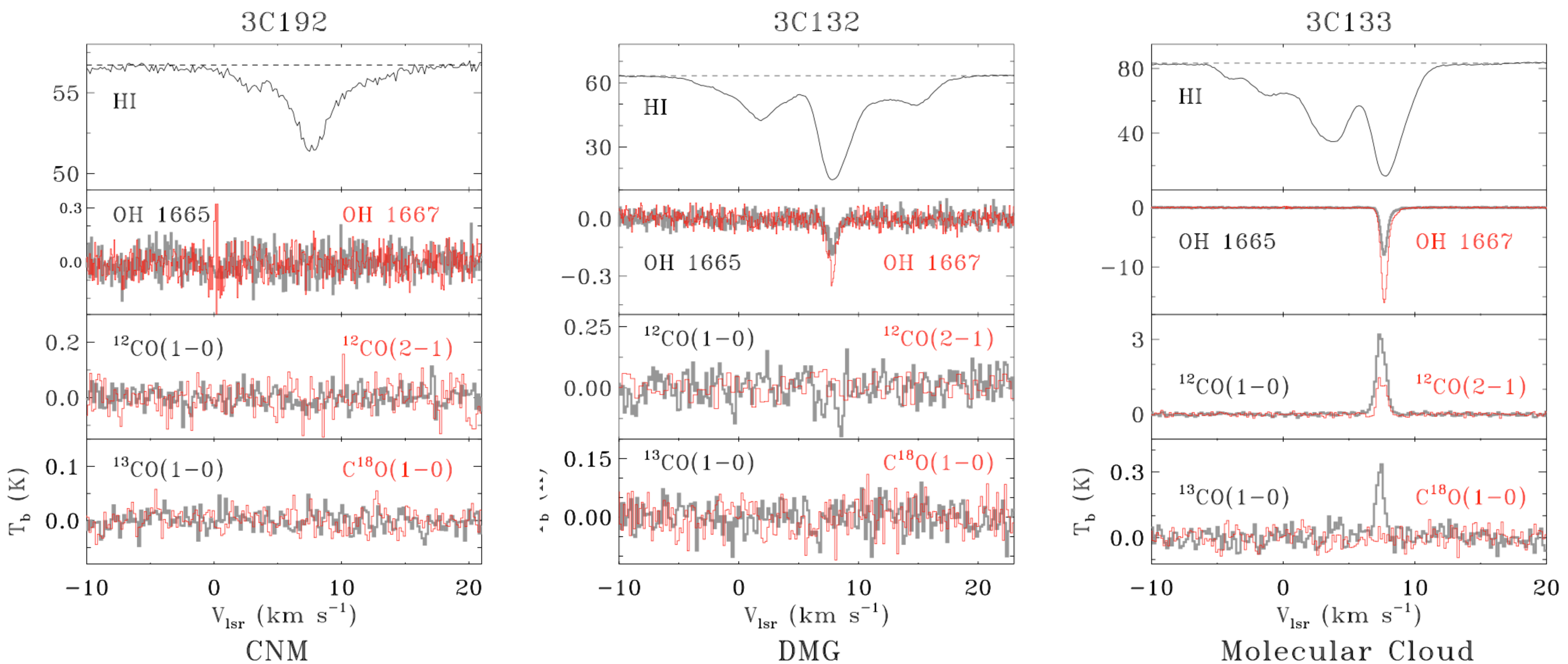
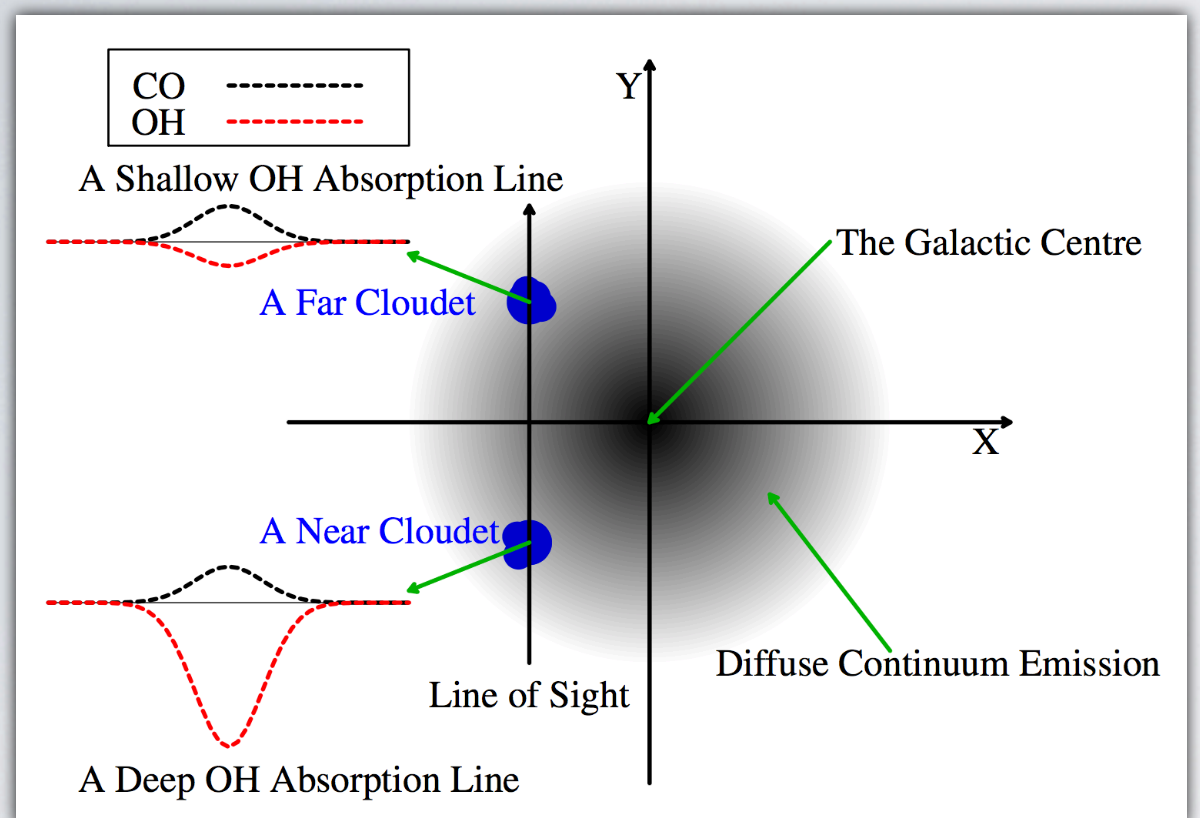


FIG. 9.— Representative spectra. 3C192 sightline has only HI seen in absorption. One component of 3C133 sightline has OH and HI in absorption and CO and its isotopologues in emission. 3C132 sightline has one gas component with both OH and HI , but no detectable CO transitions.

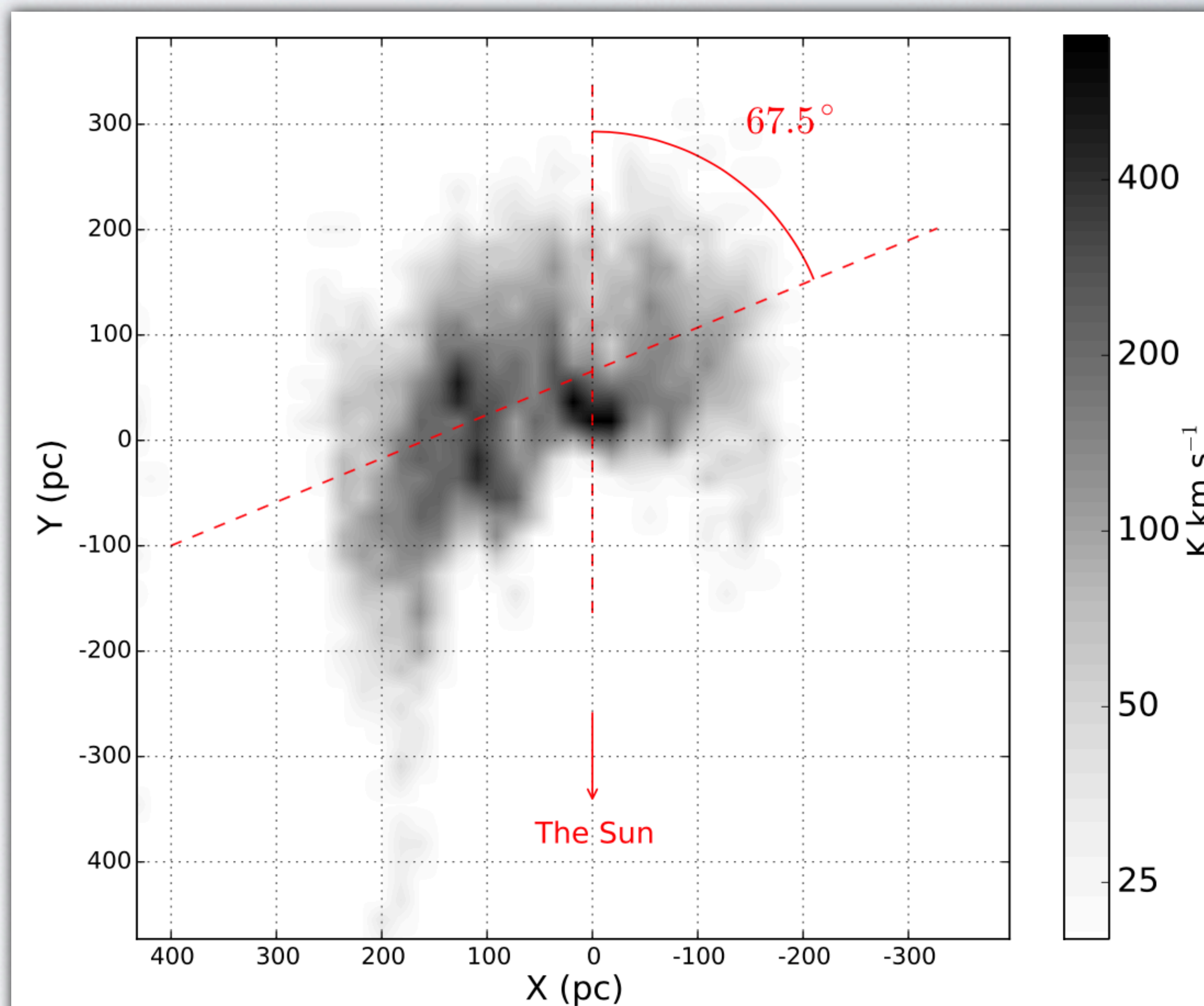
- **GASKAP** HI absorption & emission: **T_S, τ_{HI} and N(HI)**
- **GASKAP** OH absorption + **SPLASH+GASKAP** OH emission: **T_{ex}, τ_{OH}, N(OH), N(H_2)**
- Combine with **Mopra** surveys etc for **N(CO)**, **CO-bright N(H_2)**

SPLASH: 3D Structure of the CMZ



In a nutshell: Relative strengths of OH absorption and CO emission place a cloud along the line of sight

Yan, Walsh, Dawson et al. (submitted)



New face-on map of the CMZ derived from SPLASH & Mopra data:

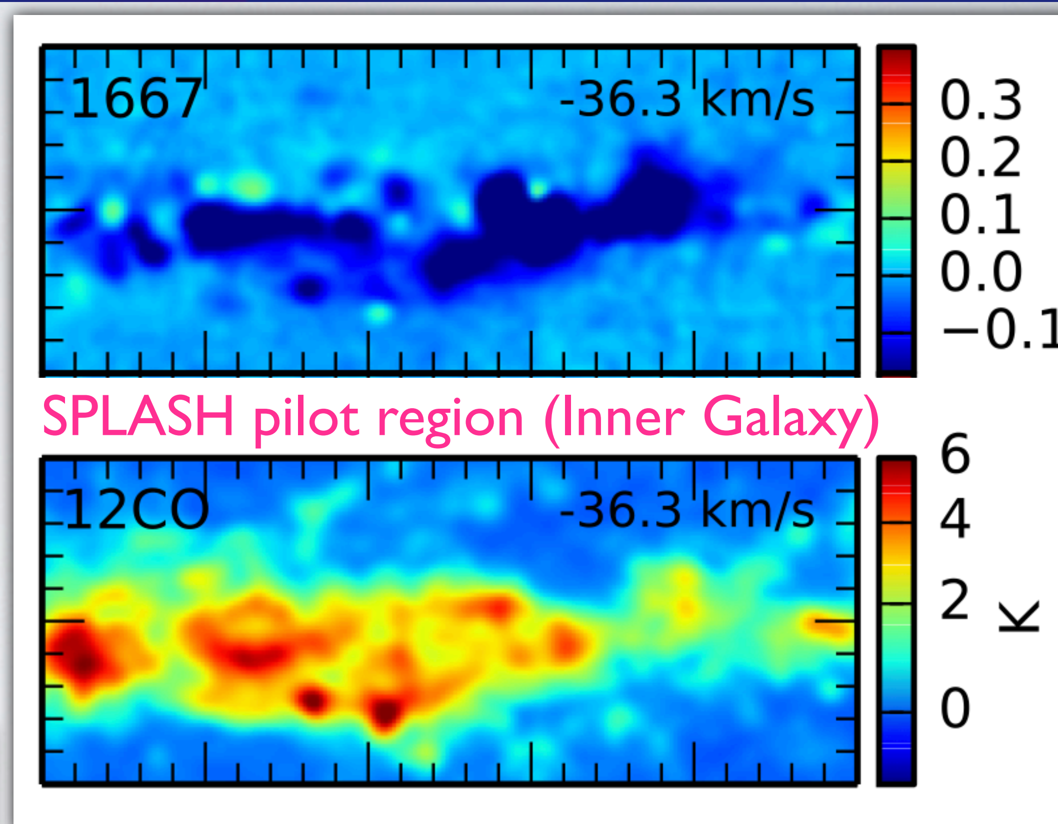
- **Bar-like structure** with inclination angle of 67.5 ± 2.1deg with respect to the line of sight.
- **No ring-like structure** seen (due to low resolution?)

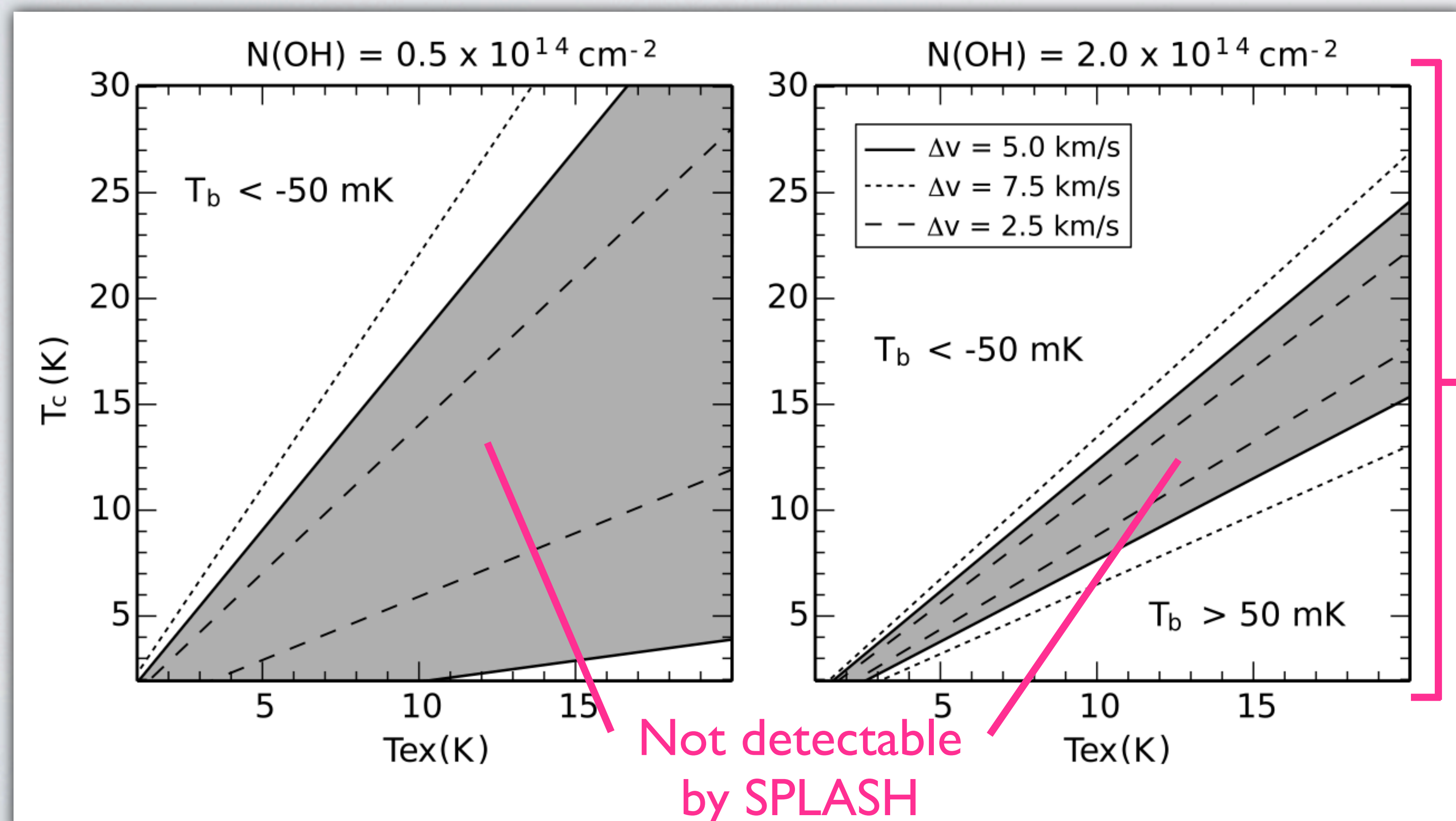
SPLASH: Where is the Dark ISM?

Only 1% of voxels CO-dark (?!)

- Spatially-extended CO-dark layers not seen
- In contrast to Outer Galaxy *(e.g. Wannier et al. 1993)* & local clouds *(e.g. Allen et al. 2012, 2015)*

i.e. OH and CO appear spatially well-mixed on scales of Parkes beam (5~50 pc)





Why?

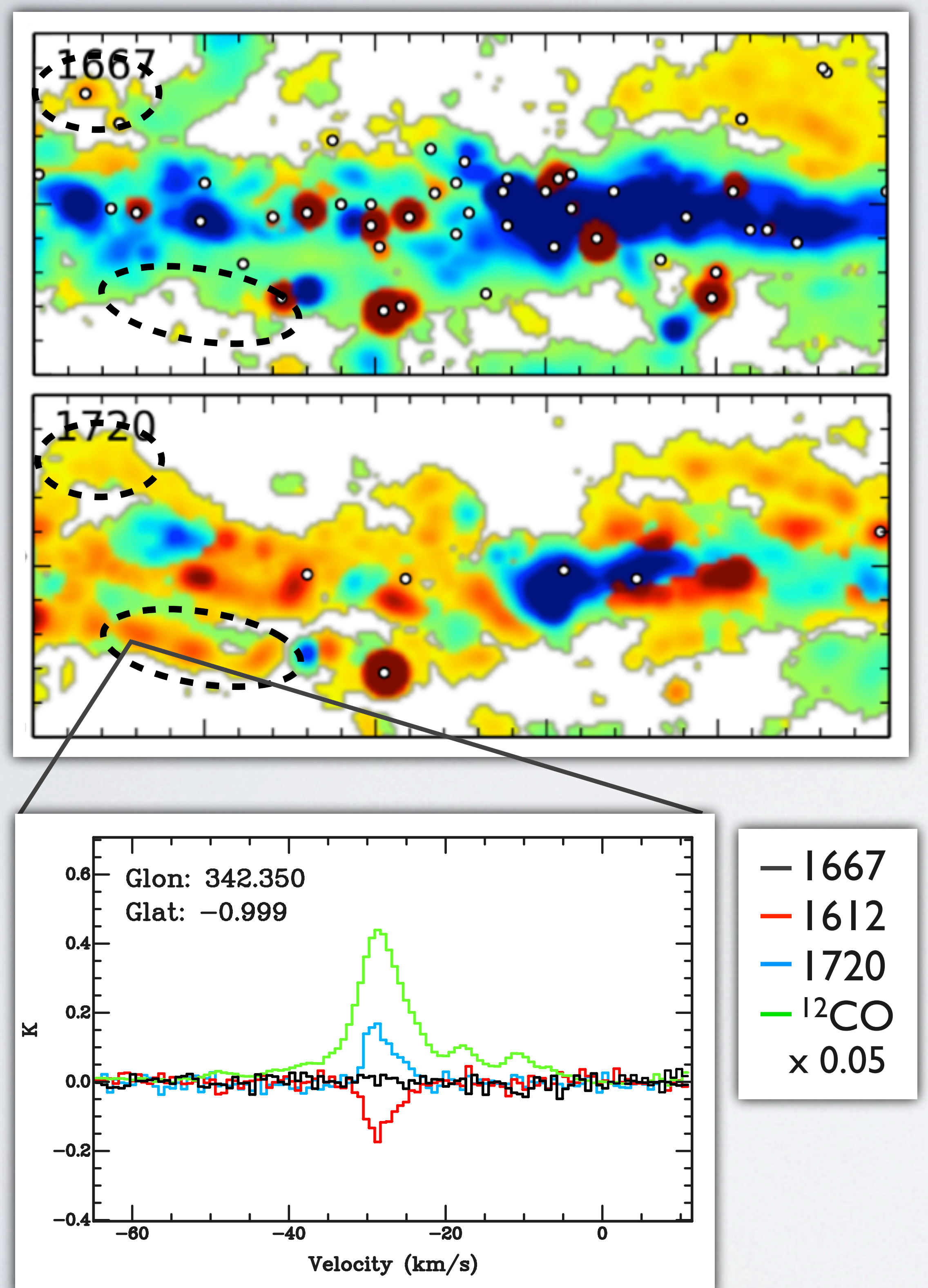
Insufficient sensitivity? No...

Insufficient contrast (T_{ex} - T_C)? Definitely in places...

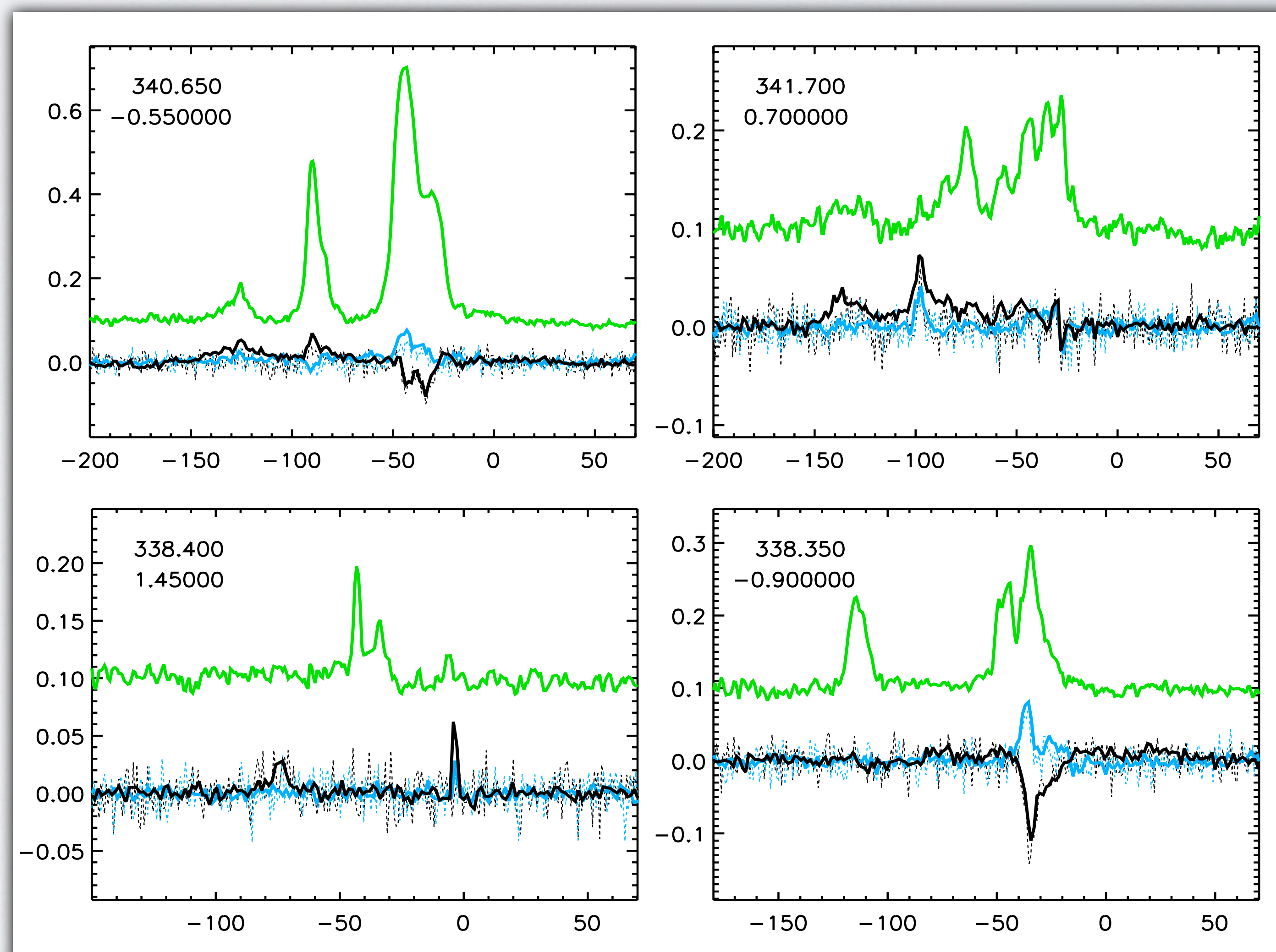
$$T_b(1667) = \boxed{(T_{ex} - T_c)}(1 - e^{-\tau_{1667}})$$

Inner/Outer Galaxy differences? Smaller abundance? Thinner envelopes? Embedded pockets?

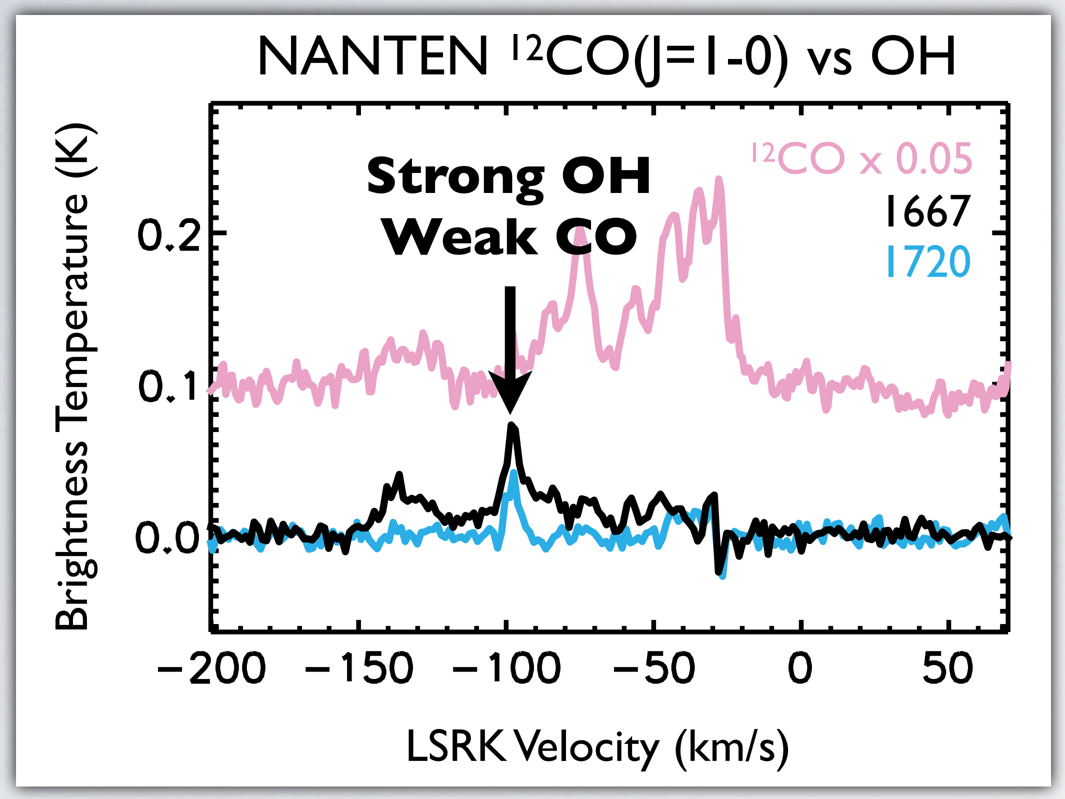
SPLASH: Where is the Dark ISM?



- Small $|T_{ex} - T_c|$ can definitely be an issue: **12% of OH detections are satellite-line only**
- Some OFF spectra show CO-dark OH (oops!)
- Deep Parkes observations do recover more OH, but questions remain...

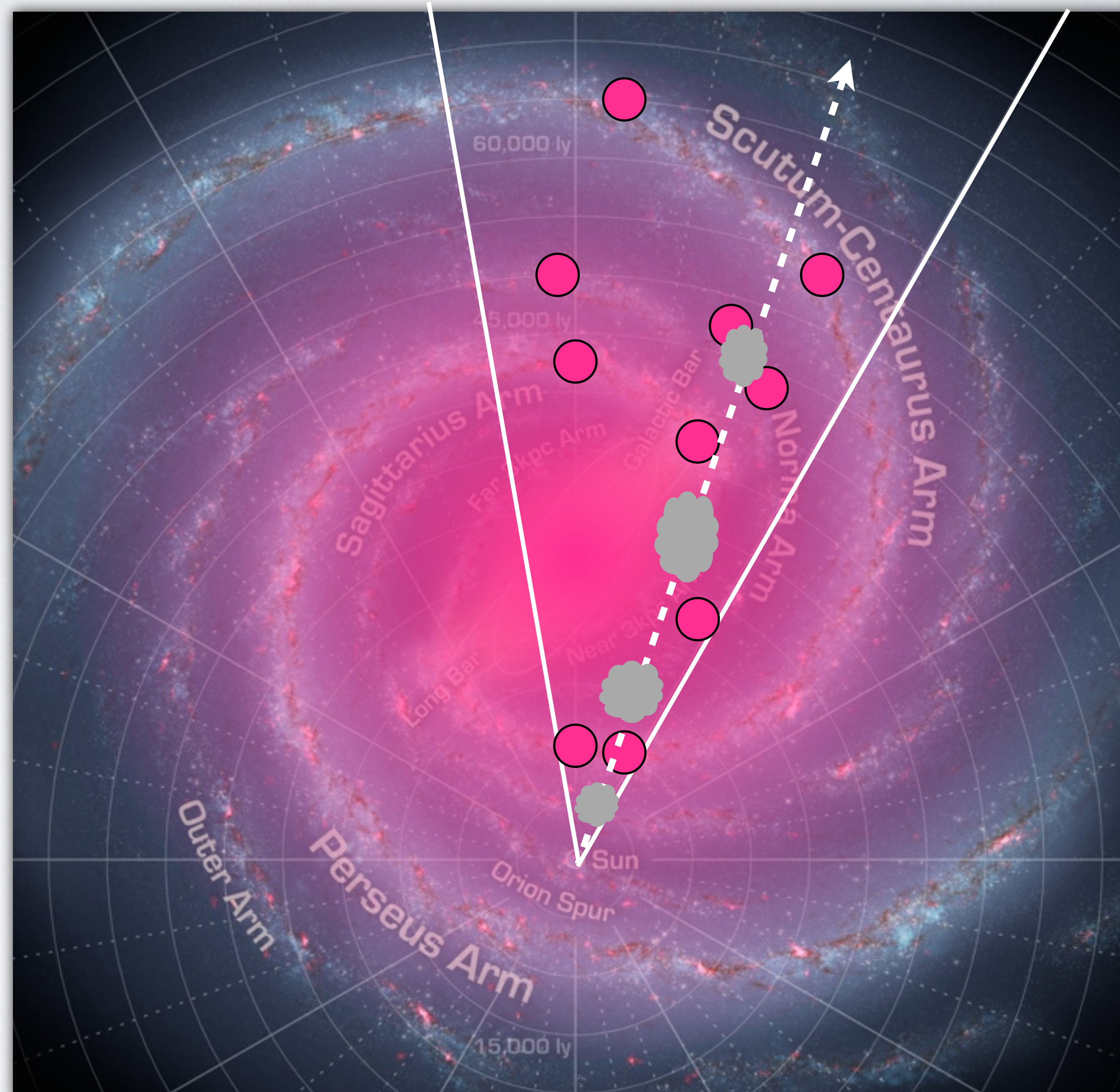


SPLASH: Disentangling the Dark ISM

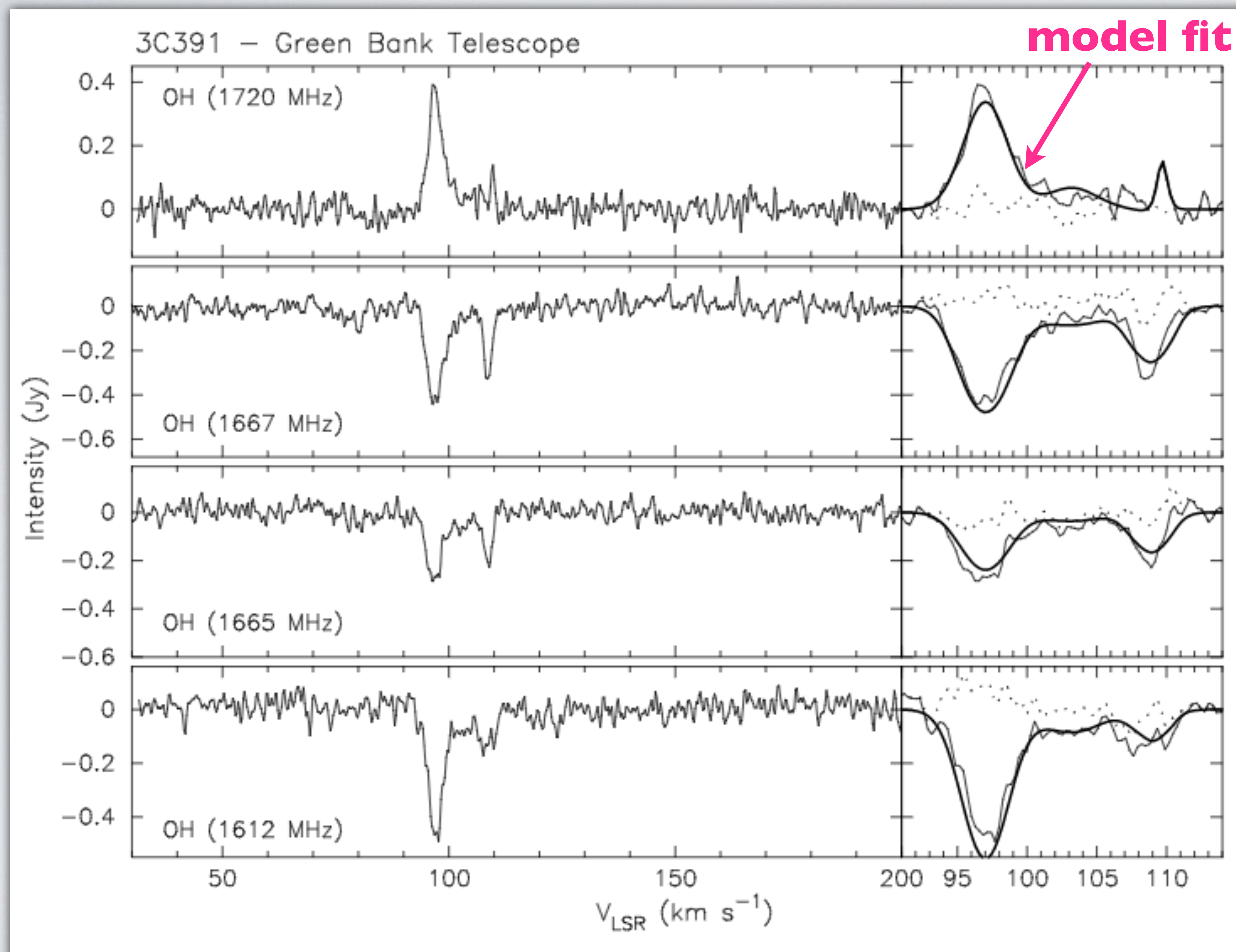


- Focus on **high-contrast midplane** ($T_c > T_{ex}$)
- **Calibrate T_{ex}** using **GASKAP** absorption data (+ATCA)
- Compare CO- and OH-derived columns to **recover CO-dark H_2**
- Requires some "fun" modelling of the continuum and OH cloud distribution

Diffuse Galactic continuum
Discrete HII regions



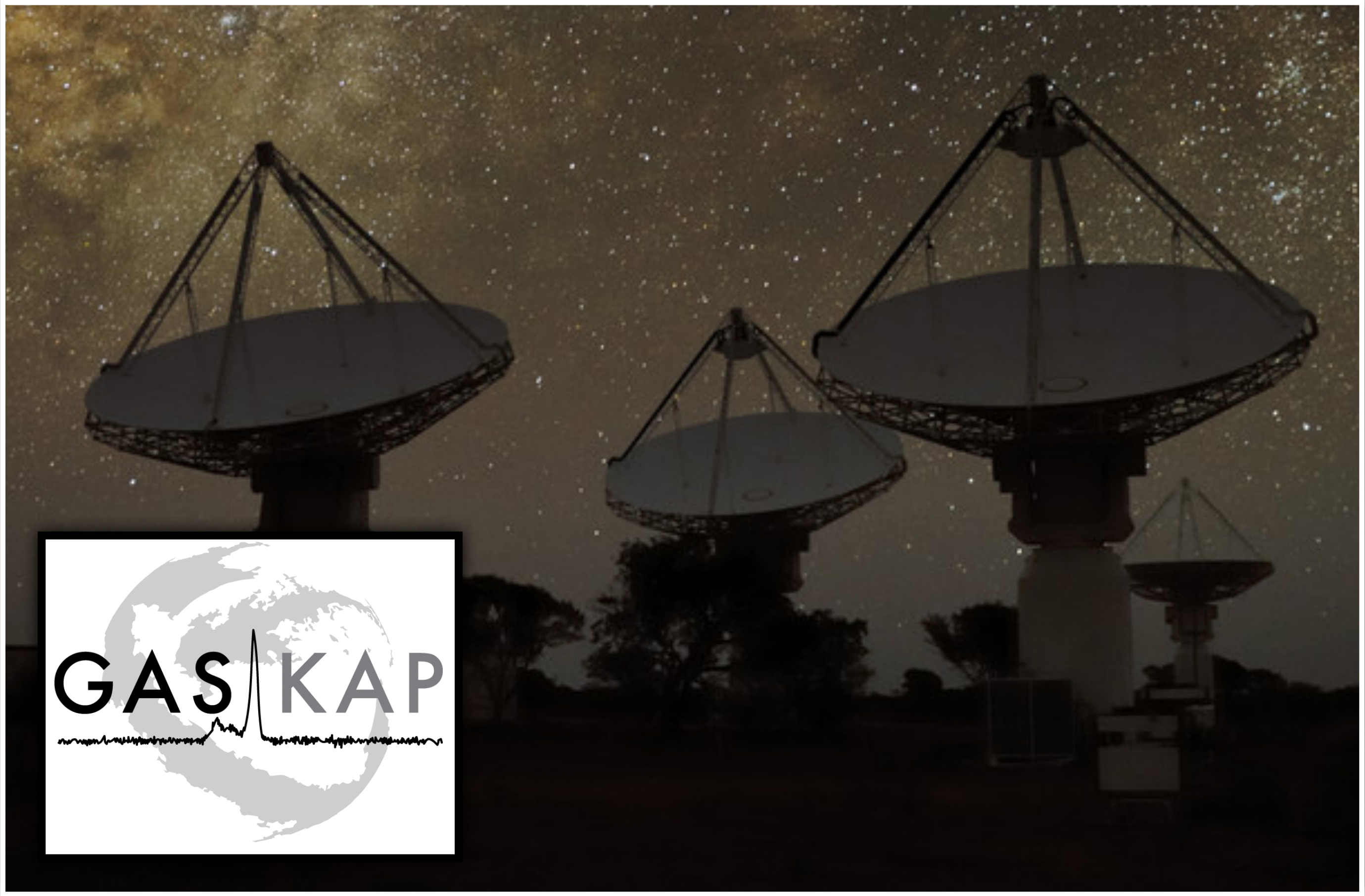
SPLASH: OH Excitation Modelling

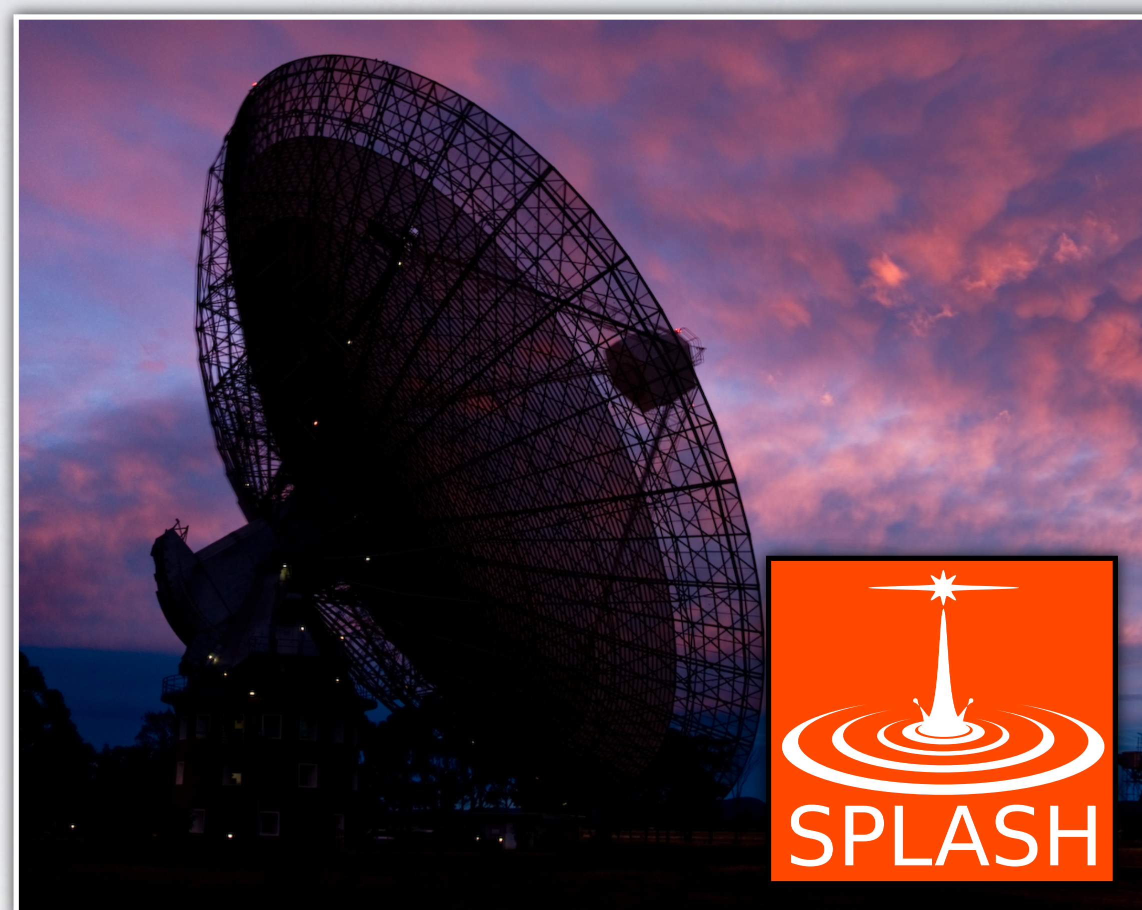


Hewitt, Yusef-Zadeh & Wardle (2008)

- **Full set of all four OH lines** has immense potential
- Translate to measurable physics via **excitation / radiative transfer models**
- T_{ex}, T_k, IR field, $n(H_2)$, τ...
- **Probe physical state of the CO-dark H_2!** (And all OH-bright gas)

Summary





The Galactic ASKAP Survey

HI 21cm emission & absorption, OH 18cm emission, absorption & masers

The Southern Parkes Large Area Survey in Hydroxyl

High-sensitivity 18cm OH (single dish)

Both will **improve our knowledge of the Milky Way ISM**, particularly the **nature and distribution of the "dark" ISM**