A New Mass Conversion Law for CO Data in Disk Galaxies

Peter Barnes[1,2], Erik Muller[3], Audra Hernandez[4], Ana Duarte-Cabral[5], Frederic Schuller[6]

[1] University of Florida; email: pjb@ufl.edu [2] University of New England [3] National Astronomy Observatory of Japan [4] University of Wisconsin [5] University of Exeter [6] Max-Planck-Istitut für Radioastronomie

We describe new mass conversion laws, from CO molecular line data to inferred mass column, based on observations of several transitions of CO isotopologues in four different large-scale mapping surveys. The new conversion laws replace the use of the single "*X*-factor" in widespread use, with a more physically-based relationship between the CO lines' optical depth, excitation, and column density. The new laws are based on a simple yet robust radiative transfer analysis of the ^{12}CO, ^{13}CO, and C^{18}O line ratios across large areas of the Galactic Plane. These laws have the effect of increasing the inferred mass column over that derived using the single *X*-factor by typically a factor of 2–3. This means that the molecular mass of the Milky Way has probably been substantially underestimated in previous studies, that gas depletion timescales should be correspondingly lengthened, and that scaling laws like the Kennicutt-Schmidt relations may also need to be recalibrated. Because of its statistical basis on a large fraction of our Galaxy's ISM, the new laws are also recommended for use in studies of other Milky-Way-analogue disk galaxies.

The Survey Projects

CHaMP @ Mopra: 300° > l > 280°, J=1→0 lines of HCO$^+$, HCN, N$_2$H$^+$, iso-CO, CN, ~25 others (Barnes et al 2011 *ApJS* **196** 12; 2016 *ApJ* subm.)

ThrUMMS @ Mopra: 360° > l > 300°, J=1→0 lines of CN, iso-CO (Barnes et al 2015 *ApJ* **812** 6)

California Cloud @ SMT: iso-CO J=1→0 (Kong et al 2015 *ApJ* **805** 58)

SEDIGISM @ APEX: l = 18° – 0° – 300°, J=2→1 lines of ^{13}CO and C^{18}O, others (Schuller et al 2016 *A&A* subm.)

The General Law

Together with a metallicity-dependent term from Narayanan et al (2012 *MNRAS* **421** 3127) and a temperature-dependent term from Kong et al (2015 *ApJ* **805** 58), we recommend the following conversion law is applicable to disk galaxies in general, derived from the large-scale CO survey data as explained below:

$$N_{\rm H2} = X_{\rm line}\,(I_{\rm line}/{\rm K\ km\ s^{-1}})^{p}\,(T_{\rm ex}/10\ {\rm K})^{q}\,(Z/Z_{\odot})^{-0.65}$$

where $X_{\rm line}$ = 1.8×10^{24} m^{-2}, p = 1.38, q = –0.7 for "line" = ^{12}CO J=1→0, and
$X_{\rm line}$ = 1×10^{25} m^{-2}, p = 1, q = 0 for "line" = ^{13}CO J=2→1

The Milky Way as a Near-Field Extragalactic Calibrator

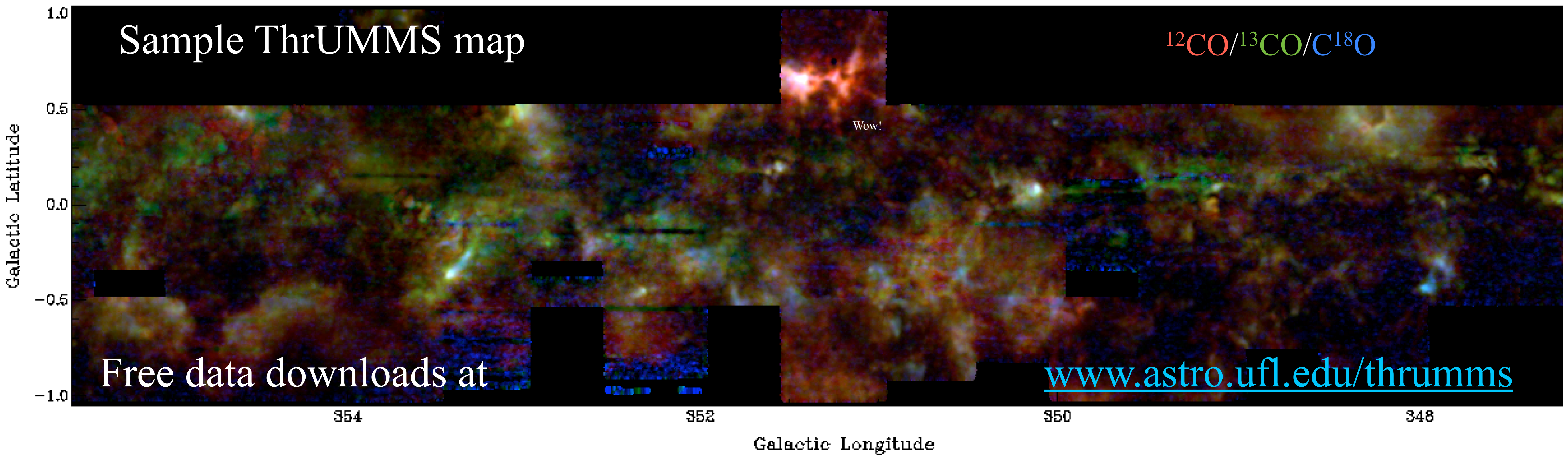

Figure 1 (Barnes et al 2015 ApJ 812 6): Sample 8°×2° map as a colour composite of integrated intensity images from the ThrUMMS data cubes. Note the strong colour variations, indicative of different line ratio, opacity, and excitation environments (see Figs. 2–4) in the molecular material of the Milky Way. ThrUMMS covers 360° > l > 300° at 1′ resolution (see project specs above). CHaMP & SEDIGISM provide similar but much more sensitive and higher-resolution data in their respective areas.

Radiative Transfer Analysis

Both CHaMP & ThrUMMS show dramatic variations in the CO line ratios, indicating a very wide range of optical depth and excitation conditions, from warm and translucent to cold and opaque. The population of cold clouds in particular have optical depths for ^{12}CO easily exceeding 100 in some locations. The same effect is seen in the California Cloud, but on a smaller scale. With the J=2→1 lines, SEDIGISM has extended and confirmed these relationships. Although apparently different, the conversion laws' functional forms (a power law for ^{12}CO J=1→0, flat for ^{13}CO J=2→1) are a direct consequence of the different opacities in the two lines (~hundreds for ^{12}CO J=1→0, and ~a few for ^{13}CO J=2→1). All the conversion laws can be placed on a consistent footing, agreeing also with theoretical studies from (e.g.) Narayanan et al (2012 *MNRAS* **421** 3127), which adds a scaling for metallicity.

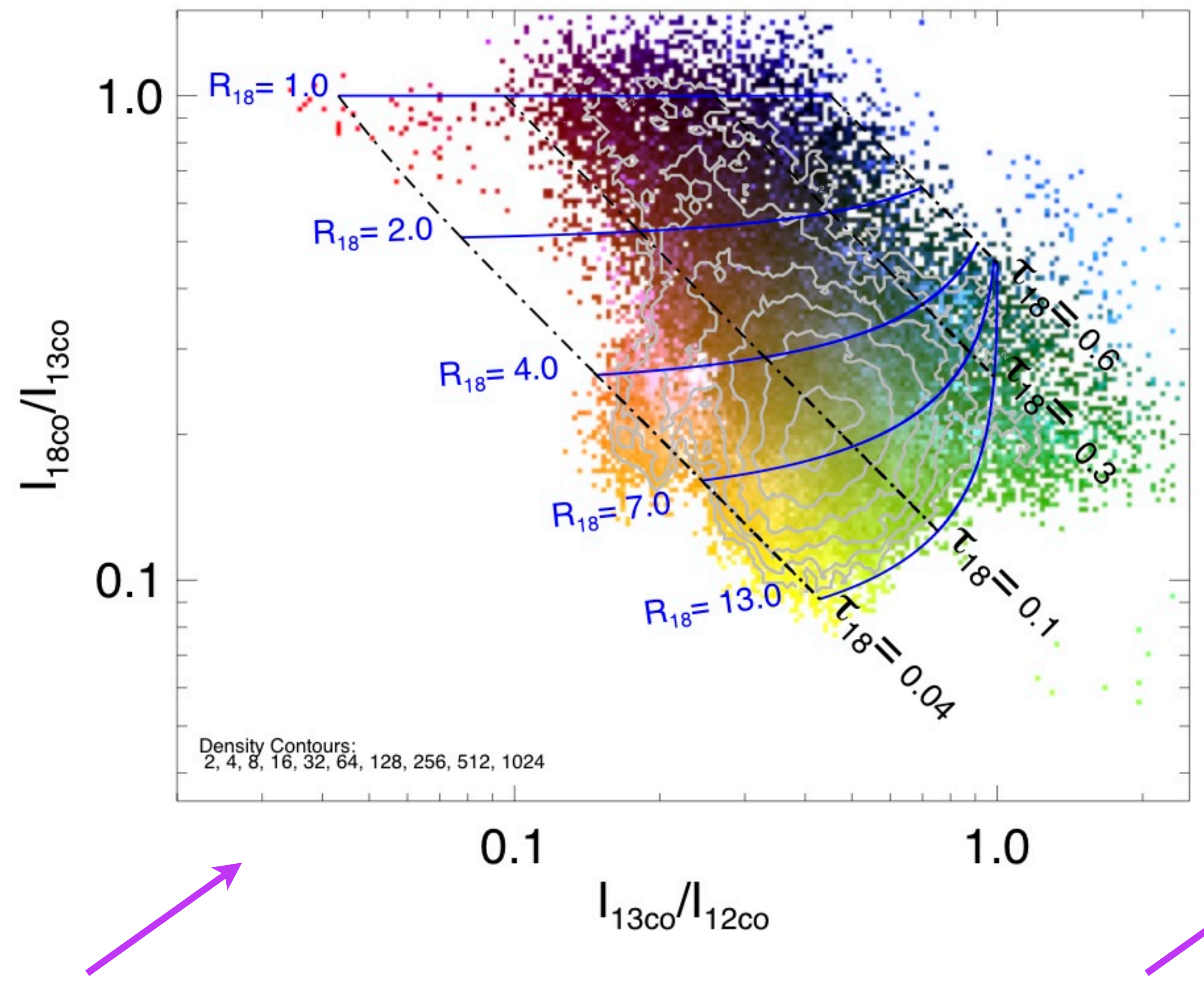

Figure 2 (Barnes et al 2015 ApJ 812 6): CO line ratio "colour-colour" diagram for all ThrUMMS data (~10^9 voxels!). The colours in this plot represent the relative line ratios as shown in the 3-colour image of Figure 1. Overlaid here are radiative transfer models labelled by intrinsic ratio R_{18} = [^{13}CO]/[C^{18}O], and C^{18}O optical depth τ_{18}. This shows that there are many clouds in the Milky Way with previously unrecognised high optical depth, and consequently higher column density than suggested by the standard "*X*-factor" approach.

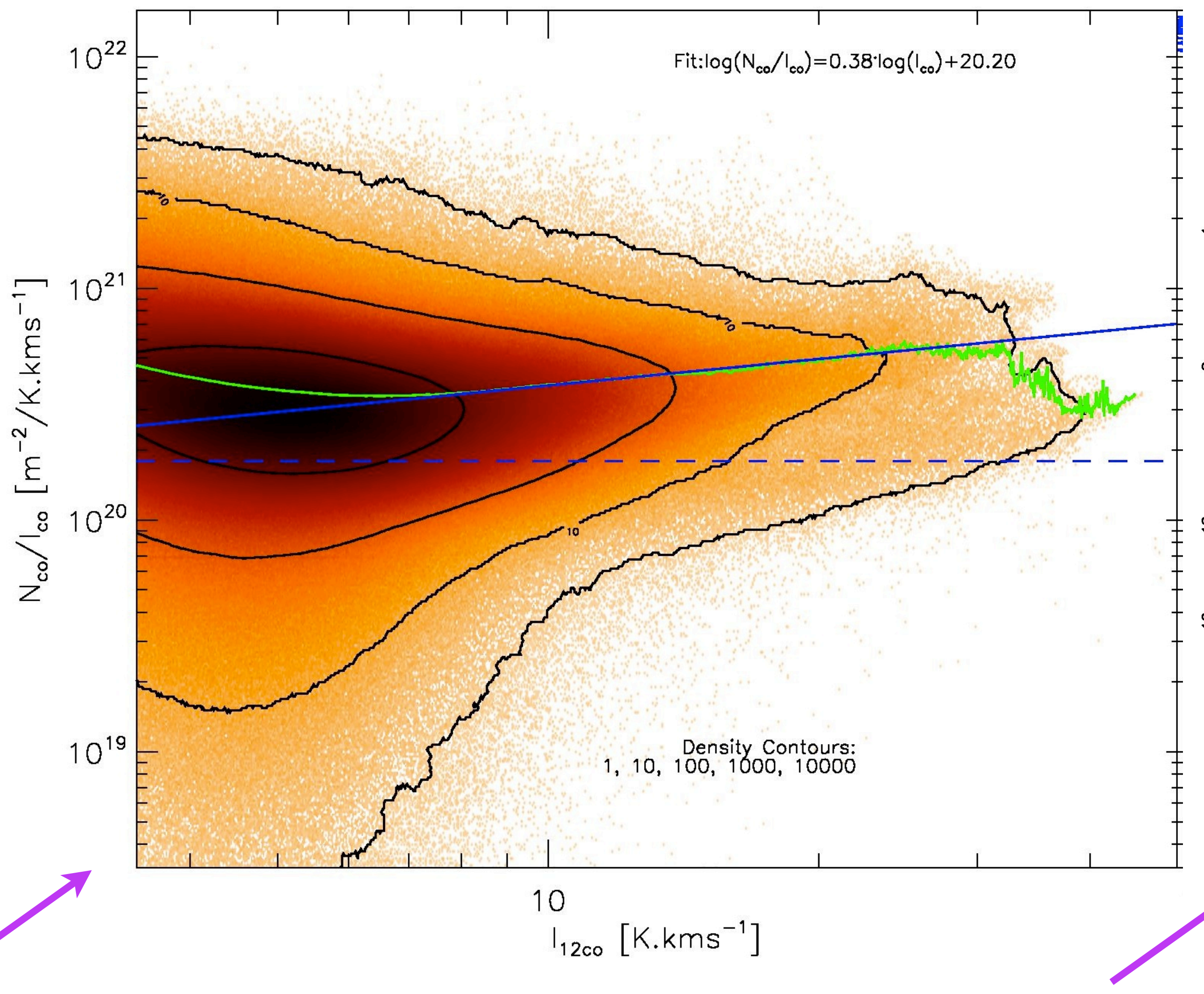

Figure 3 (Barnes et al 2015 ApJ 812 6): Derived conversion from $I_{\rm CO}$ to $N_{\rm CO}$, based only on the plane-parallel radiative transfer model, applied to the data shown in Figures 1 & 2. (The green line connects median N/I ratios over narrow bins in I; the blue line is a power-law fit to the statistically significant data.) Including a [H$_2$]/[CO] abundance ratio of 10^4, this is equivalent to a nonlinear conversion law,

$$N_{\rm H2} = 1.6\times10^{24}\ {\rm m^{-2}}\ (I_{\rm 12CO,1\text{-}0}/{\rm K\ km\ s^{-1}})^{1.38\pm0.15}$$

and suggests that the molecular mass of the Milky Way may have been substantially underestimated.

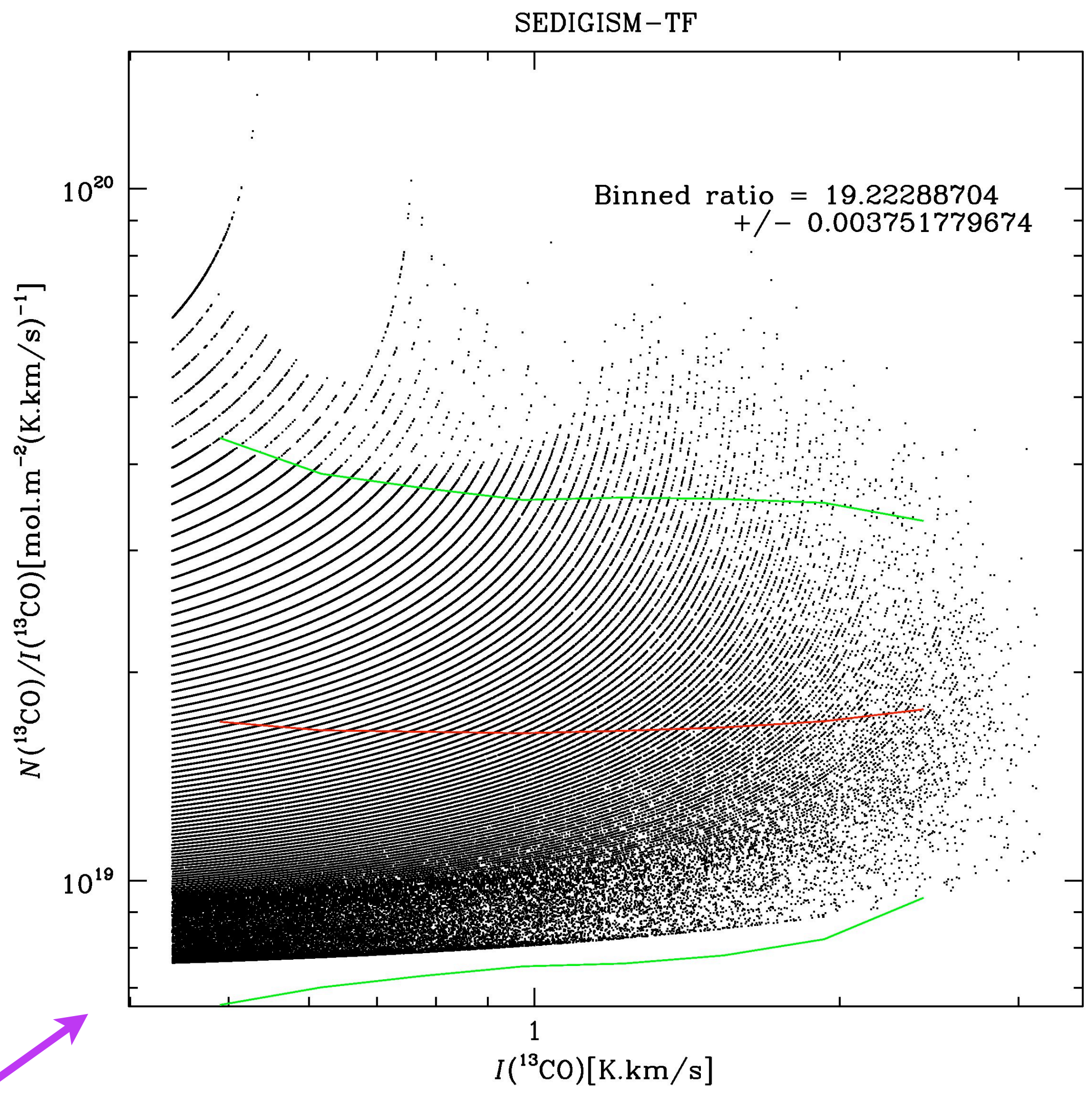

Figure 4 (Schuller et al 2016 A&A submitted): Derived conversion from $I_{\rm 13CO}$ to $N_{\rm 13CO}$, based only on the same plane-parallel radiative transfer model as used in ThrUMMS, but applied to the SEDIGISM ^{13}CO J=2→1 data (red line = binned medians; green lines = 2σ bands). Including [^{12}CO]/[^{13}CO] and [H$_2$]/[^{12}CO] abundance ratios of 60 and 10^4, resp., this is equivalent to a "flat" conversion law,

$$N_{\rm H2} = 1\times10^{25}\ {\rm m^{-2}}\ (I_{\rm 13CO,2\text{-}1}/{\rm K\ km\ s^{-1}})$$

but is consistent with both the ThrUMMS law and independent measurements of the dust-derived mass column from Hi-GAL data.

Pending Applications for CHaMP, ThrUMMS, and SEDIGISM Data

- Fully 3D gas temperature, opacity, column density, abundance, structural, and kinematic cubes of GMCs, & comparison with Hi-GAL based SED fits/dust temperatures
- Kinematic distances & detailed dynamics of all major ISM & Galactic-scale structures on large & small scales, from a ThrUMMS/SEDIGISM/GASKAP (HI) comparison
- Dependence of astrochemistry, cloud structure, internal physics, kinematics, arm-interarm comparisons, and the radio-FIR correlation, on Galactocentric distance and other environmental factors