Wide-Field Line Ratio Analysis:

High Dynamic Range Column Density Maps of the Milky Way

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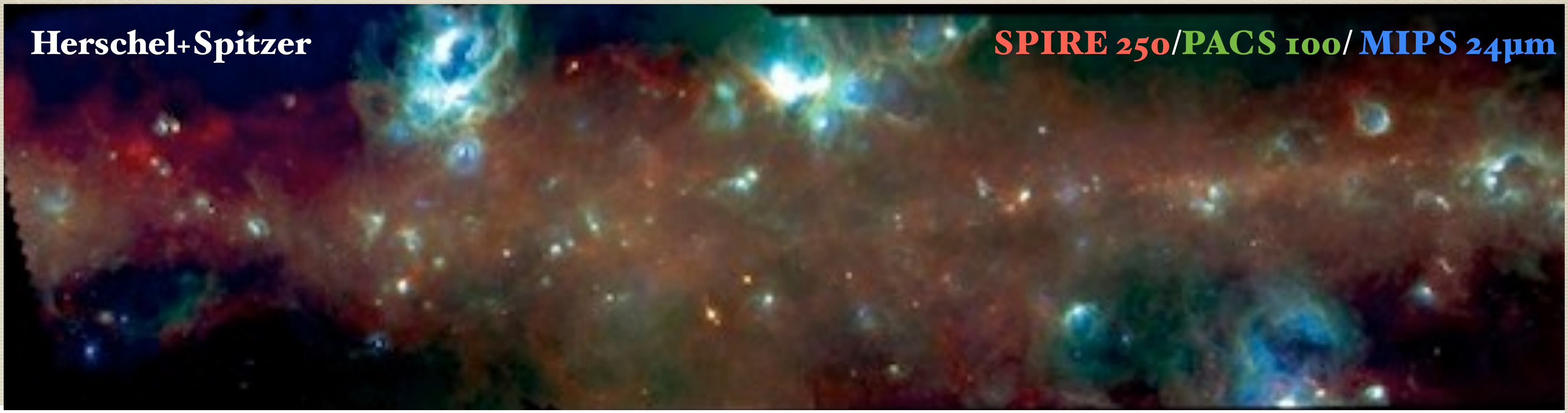
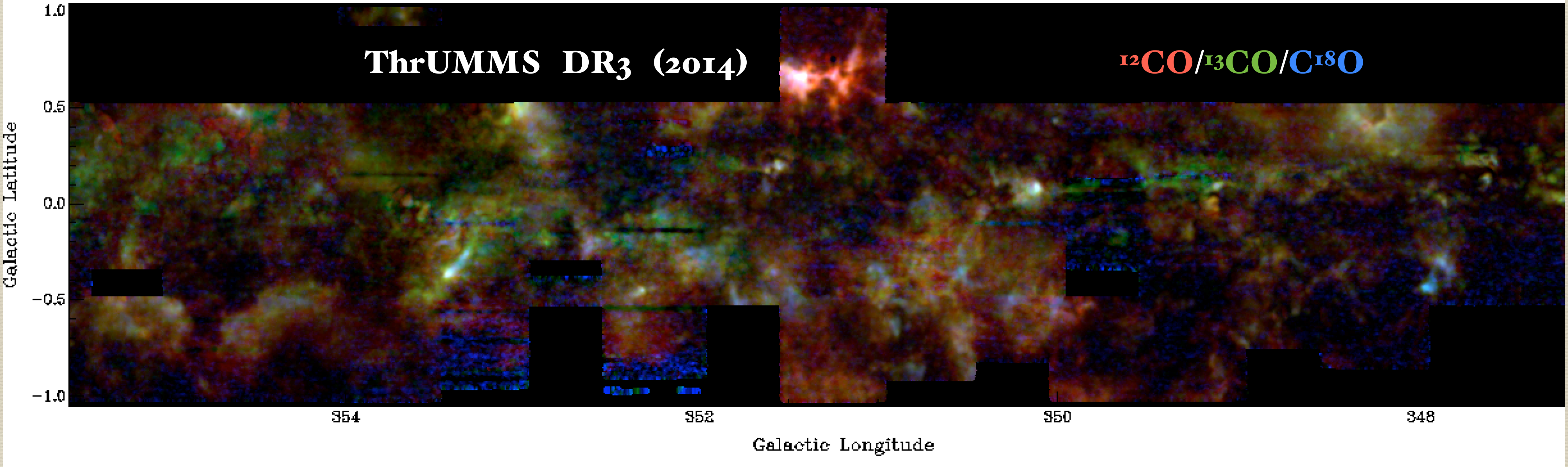
Threads

1. **Nature of the problem**, i.e. going from T_b to $N_{\mathrm{col}}/T_{\mathrm{ex}}/\tau$
2. **Ongoing projects:**
    a. ThrUMMS, three iso-CO J=1→0 lines, very large contiguous area = 120 deg^2, including lessons from CHaMP
    b. ^{13}CO with SEDIGISM J=2→1 and ThrUMMS J=1→0, large overlap area = 60 deg^2
    c. SEDIGISM ^{13}CO + C^{18}O J=2→1, only possible over small areas (~0.01 deg^2) where T_b(C^{18}O) $\gtrsim$ 2–3 K
3. **Future projects:**
    a. Mutually reconciling 2a–2c, e.g. abundance variations, non-LTE conditions
    b. Connecting τ, T_{ex}, N_{col} cubes to SCIMES catalogues, Galactic structure, other topics (eg, CODEX project with GUSTO mission)

The Basic Problem





- How do we turn data into fundamental physics? E.g., molecular mass + excitation, detailed comparisons with cold dust?

The Basic Problem

- Observe line emission

$$T_{\rm mb} = [S_\nu(T_{\rm ex}) - S_\nu(T_{\rm bg})](1 - e^{-\tau})$$

With a single line, we have 1 equation with 2 unknowns, τ and $T_{\rm ex}$:

- We want physical quantities, like mass distribution, excitation conditions

Quo vadis?

- **Emissivity ≠ Mass** (see later)

$$N = \frac{3h}{8\pi^3\mu^2}\ \frac{Q(T_{\rm ex})e^{E_u/kT_{\rm ex}}}{J_u(e^{h\nu/kT_{\rm ex}} - 1)} \int \tau {\rm d}V$$

ThrUMMS: a "simple" example

- For J=1→0, have $^{12}\mathrm{CO}$, $^{13}\mathrm{CO}$, and $\mathrm{C^{18}O}$ data, so 5 equations (3 radxfer + 2 abundance ratios R_{13}, R_{18} connecting species) in 9 unknowns: $3{\times}\tau$, $3{\times}T_{\mathrm{ex}}$, $3{\times}N_{\mathrm{col}}$
- Assume single, common T_{ex} (LTE) and $R_{13} = 60$ (both reasonable) so 3 more → 8 equations
- Final relation: $\tau_{12} >> 1$, giving (e.g.) $T_{\mathrm{ex}} \approx T_{\mathrm{mb}}(^{12}\mathrm{CO}) + 2.73$
- Now solve **directly**:

$$\frac{T_{13}}{T_{12}} = \left[\frac{S_{13}(T_{\mathrm{ex}}) - S_{13}(T_{\mathrm{bg}})}{S_{12}(T_{\mathrm{ex}}) - S_{12}(T_{\mathrm{bg}})}\right] \frac{1 - e^{-\tau_{13}}}{1 - e^{-R_{13}\tau_{13}}} ,$$

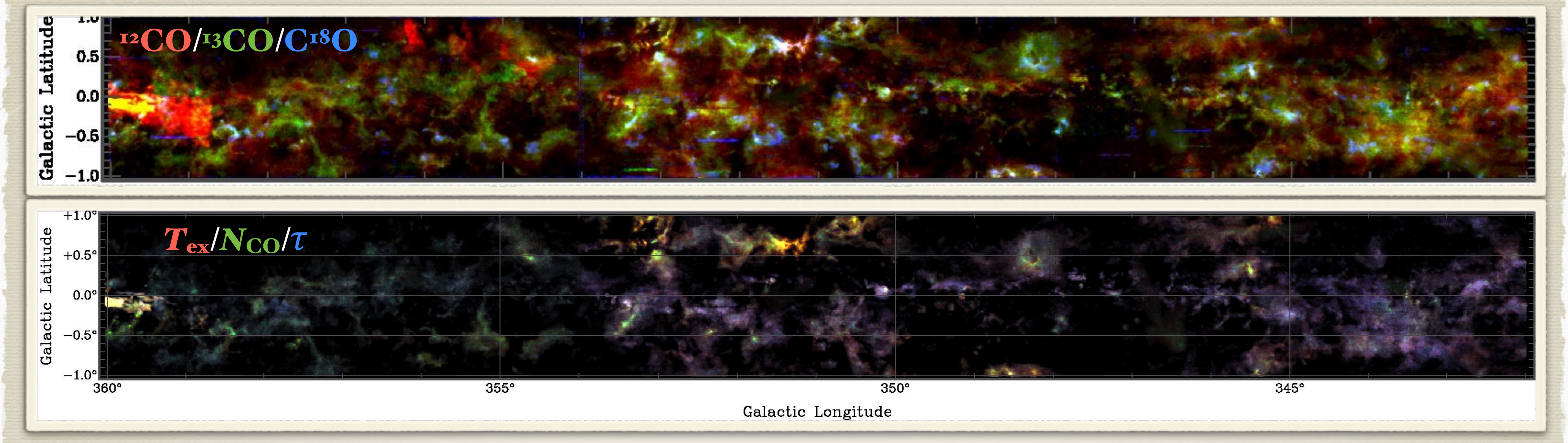
$$\frac{T_{18}}{T_{13}} = \left[\frac{S_{18}(T_{\mathrm{ex}}) - S_{18}(T_{\mathrm{bg}})}{S_{13}(T_{\mathrm{ex}}) - S_{13}(T_{\mathrm{bg}})}\right] \frac{1 - e^{-\tau_{18}}}{1 - e^{-\tau_{13}}} ,$$

$\tau_{12} = R_{13}\tau_{13}$, and

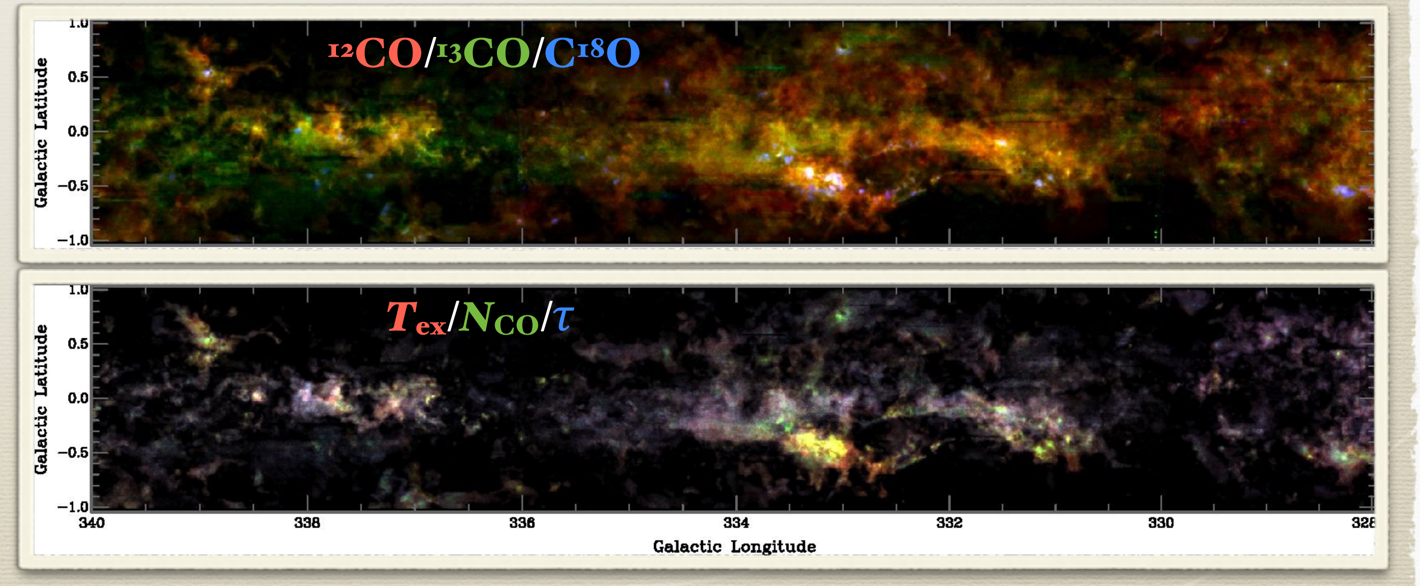
$\tau_{13} = R_{18}\tau_{18}$,

Side benefit: in this case, column density is **very** HDR (high dynamic range) effectively peeling away the iso-CO layers

Results from DR6 (pending)



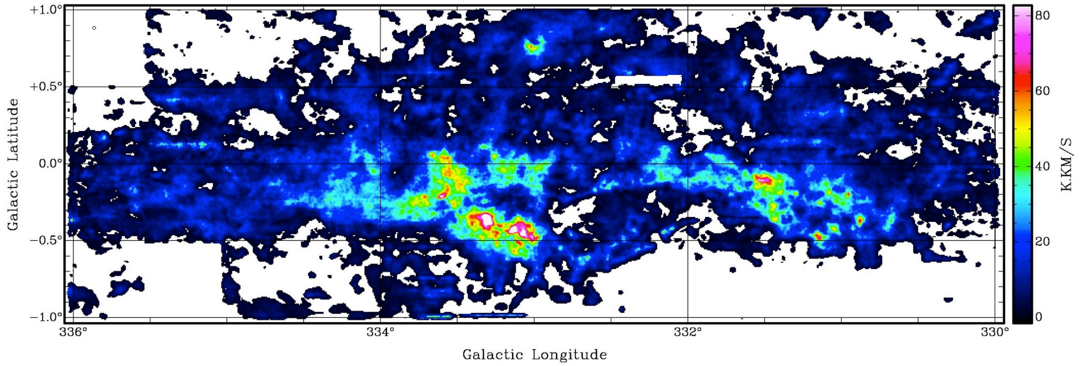
- Eyeball physics (with Dylan Barnes): lots of cold (low T_{ex}), opaque (high τ) clouds, high N_{CO} rare (B+2021, in prep.)



SCIMES Analysis

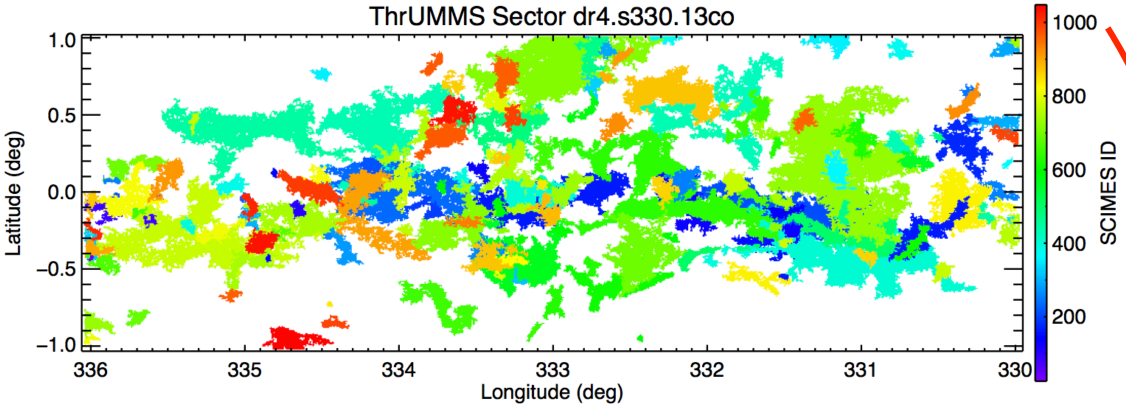
(with Sebastian Lopez, B+2021, in prep.)

ThrUMMS Sector:
330°-336°
^{13}CO (1-0)
(dv=-150-50 km s^{-1})

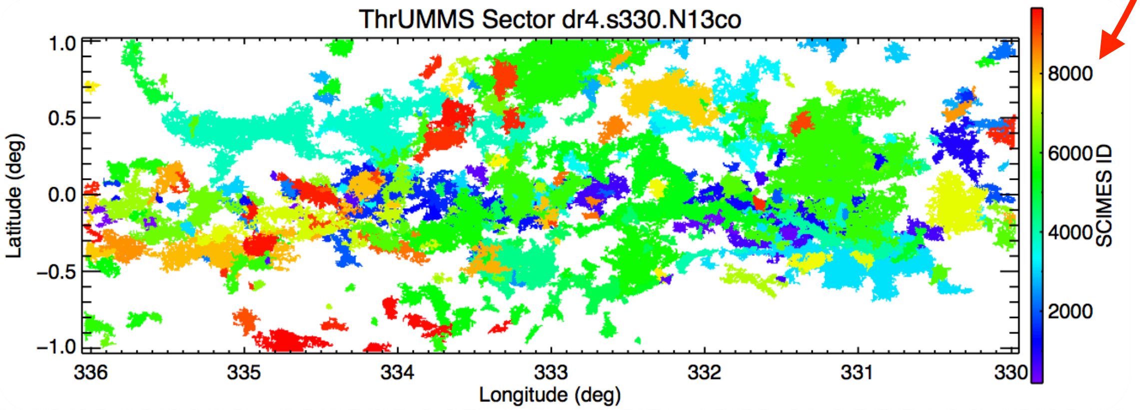


Intensity Based Extraction:

- 2.5σ detection limit
- 4σ minimum separation difference


ThrUMMS Sector dr4.s330.13co

Column Density Based Extraction

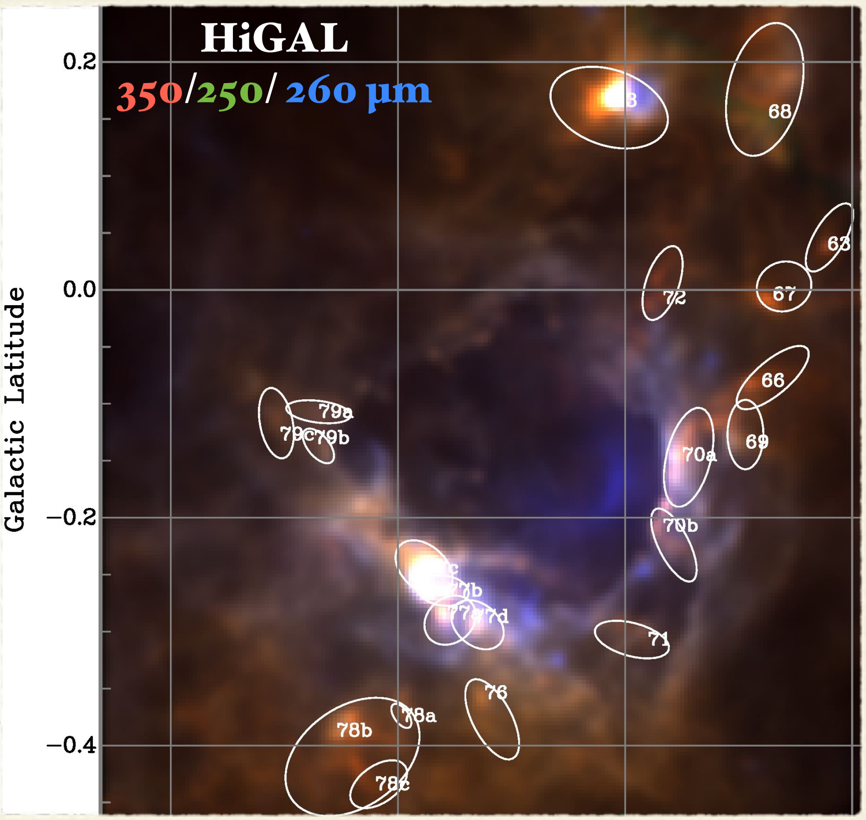

ThrUMMS Sector dr4.s330.N13co

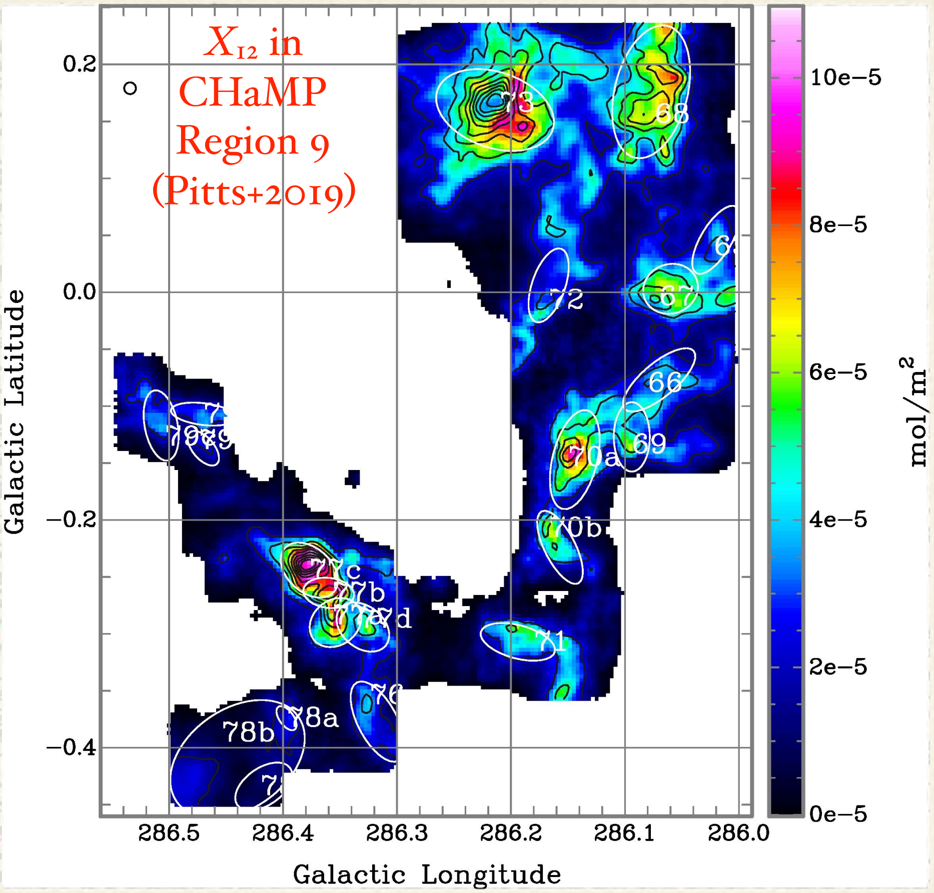
Mass distribution is much clumpier than emission distribution
$I \neq N$

Thousands of clouds!

Other lessons from CHaMP

- Use *Herschel* data to compute dust-based N_{H_2} map
- Derive $[^{12}CO]/[H_2]$ abundance map: it's mostly ***much lower*** than expected, and varies ***a lot*** too!

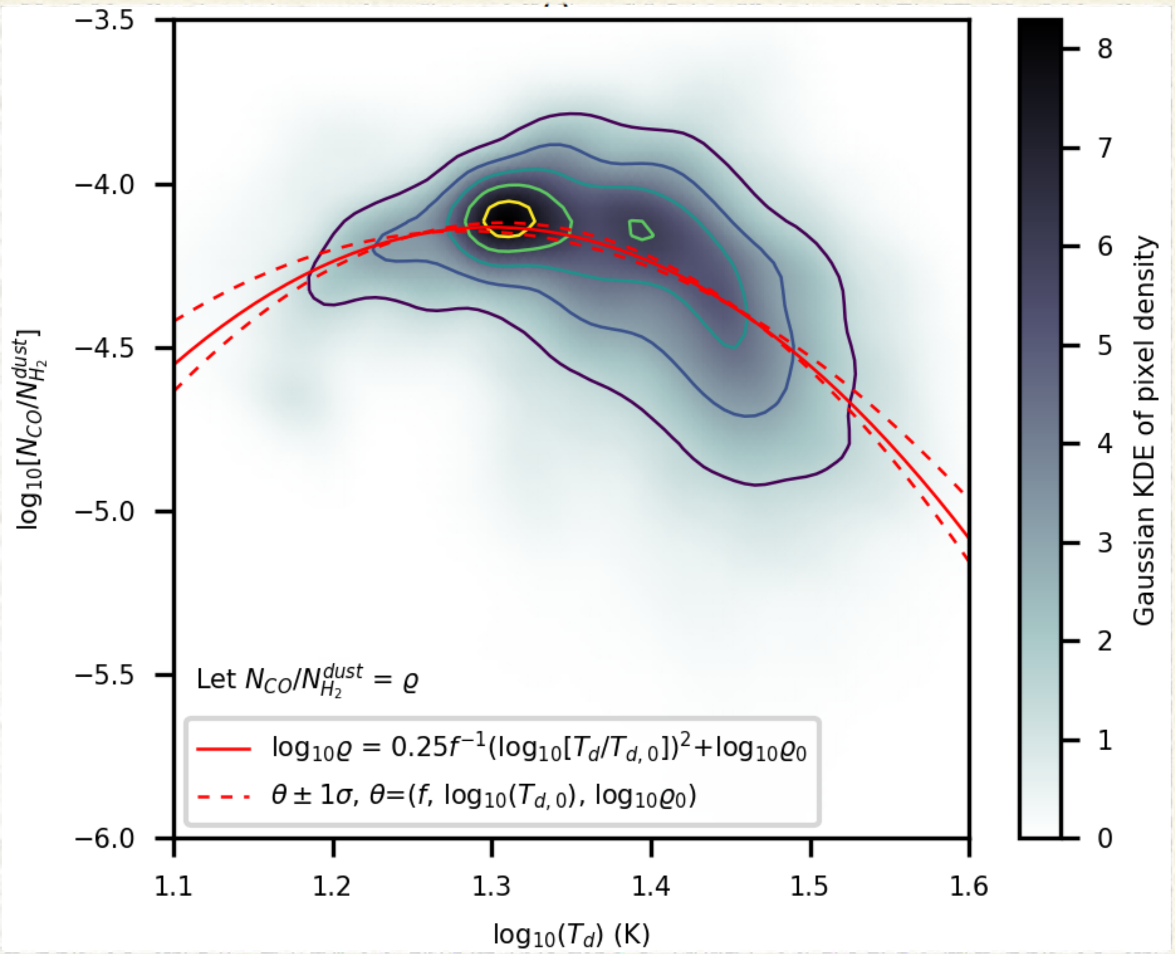




A ^{12}CO abundance law

$$\log_{10}(N_{\rm CO}/N_{\rm H2,dust}) = -10\,[\log_{10}(T_{\rm d}/20.0\ {\rm K})]^2 - 4.13$$

- All CHaMP data (Paper V, Pitts & Barnes 2021):
- Median abundance ≈ 7.4×10^{-5} per H_2 or about 1/3 canonical
- Caveats: LTE, GDR; otherwise, pretty straightforward



SEDIGISM: ***slightly*** messier

- With SEDIGISM, we also have $J=2\rightarrow1$ for ^{13}CO + C^{18}O: how does this help?

- **1st approach**: combine ^{13}CO $J=2\rightarrow1$ from SEDIGISM with ^{13}CO $J=1\rightarrow0$ from ThrUMMS:

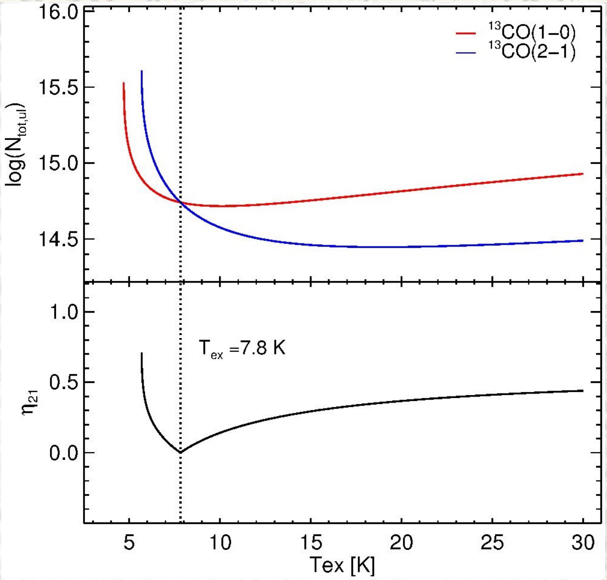
$$2\times \rightarrow \quad \boxed{T_{\rm mb} = [S_\nu(T_{\rm ex}) - S_\nu(T_{\rm bg})](1 - e^{-\tau})}$$

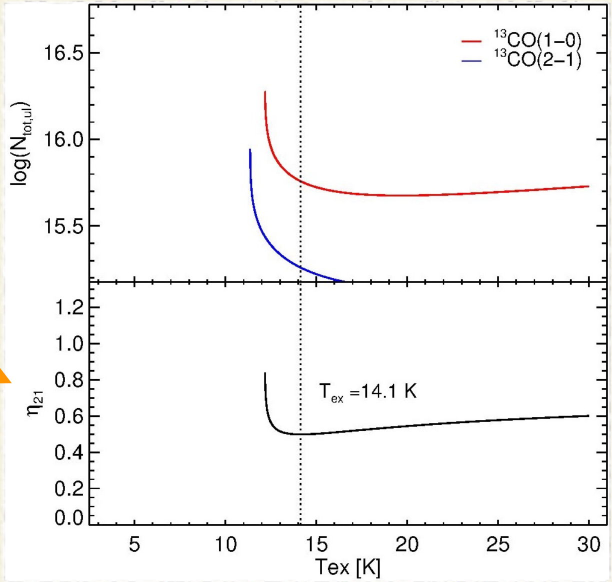
- Then we have to **iteratively** solve for the 2 lines' τ and common $T_{\rm ex}$ (2 equations in 3 unknowns) by connecting them through detailed balance: $\tau_{2\text{-}1}/g_2 = (\tau_{1\text{-}0}/g_1)e^{-h\nu_{2\text{-}1}/kT_{\rm ex}}$.

- Equivalent to iteratively solving for 2 versions of N, and matching them, as in Schuller et al 2017:

Iterative Approach

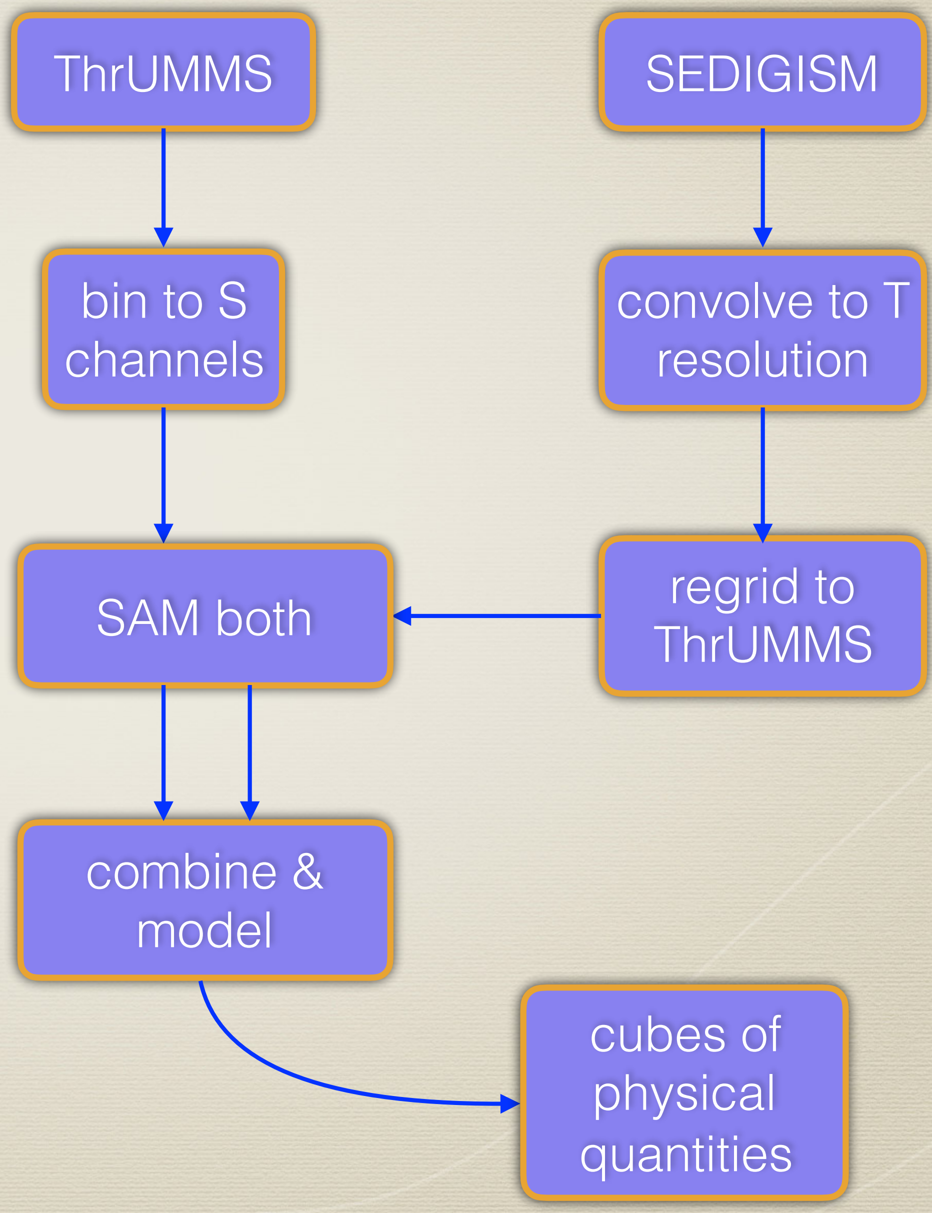
- In Test Field (TF, with Audra Hernandez):
- Form a ratio of two *N*s calculated from each line, $\eta_{21}(T_{ex}) = \left|\log\left(\frac{N_{\text{tot},21}}{N_{\text{tot},10}}\right)\right|,$ then find T_{ex} where η=0
- Example 1: solvable voxel
- Example 2: not solvable (more on next slide)
- Most (well, ~half) voxels solvable for $\tau_{2\text{-}1}$, $\tau_{1\text{-}0}$, T_{ex}, and $N_{\text{total}}(^{13}\text{CO})$





Progress…

- Work is continuing (with Sebastian Lopez) using a faster Newton's method and cleaner algorithm than in TF
- The physics is non-trivial: even LTE modelling has intrinsic numerical issues…


ThrUMMS

SEDIGISM

bin to S channels

convolve to T resolution

SAM both

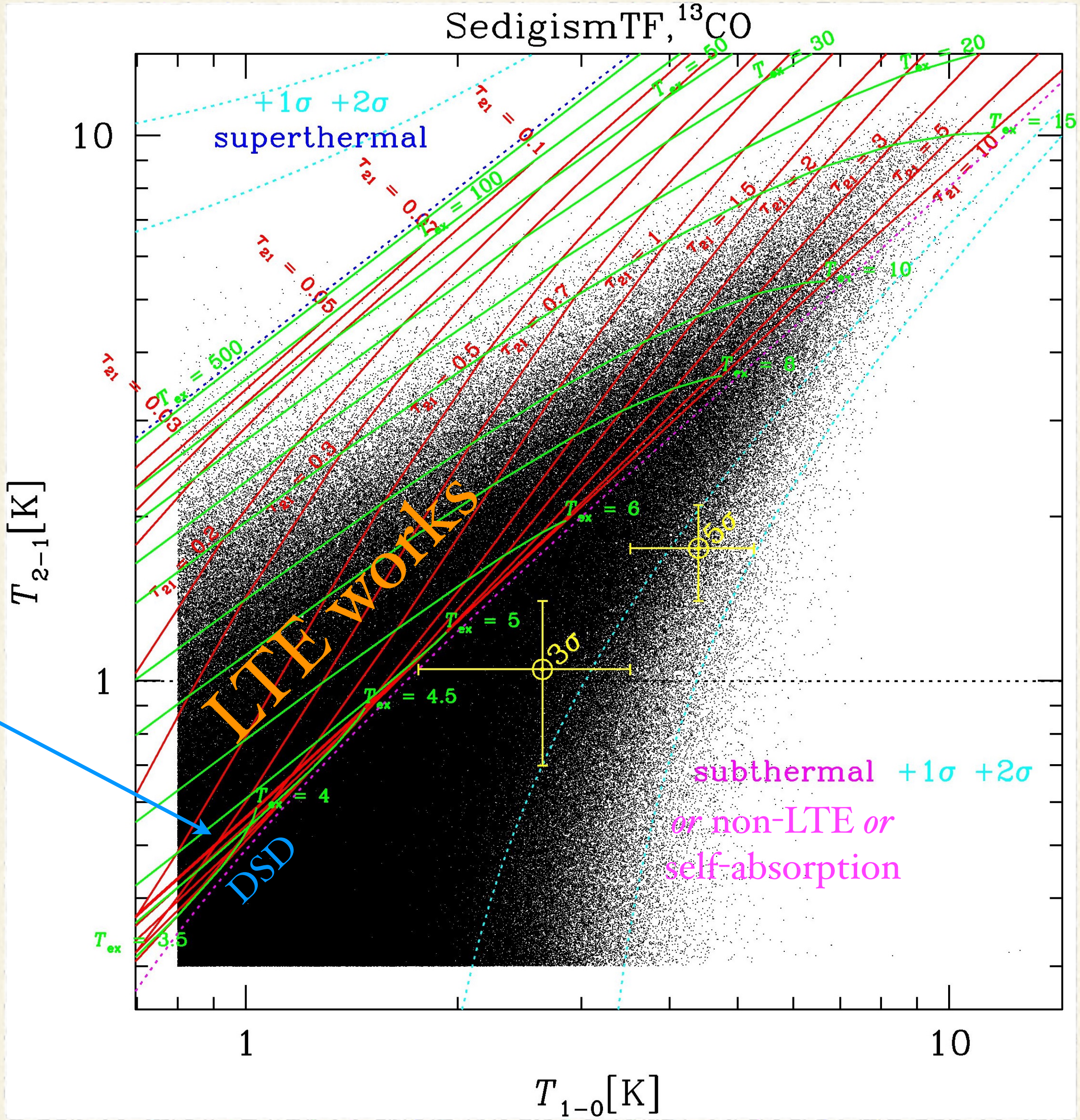
regrid to ThrUMMS

combine & model

cubes of physical quantities

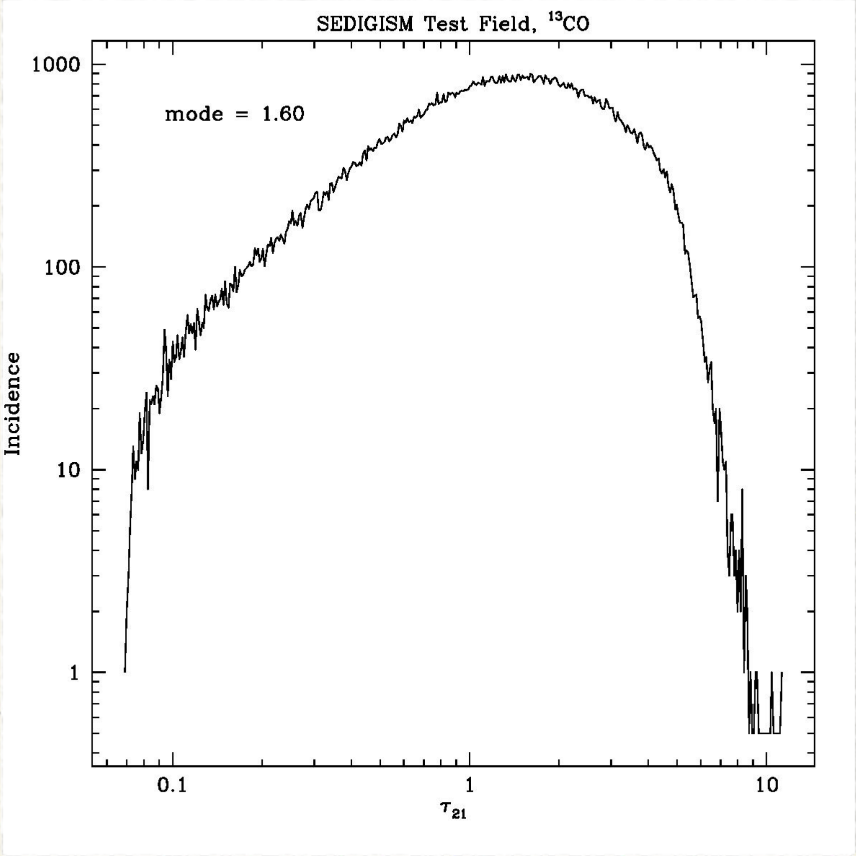
Line Ratios are … Interesting

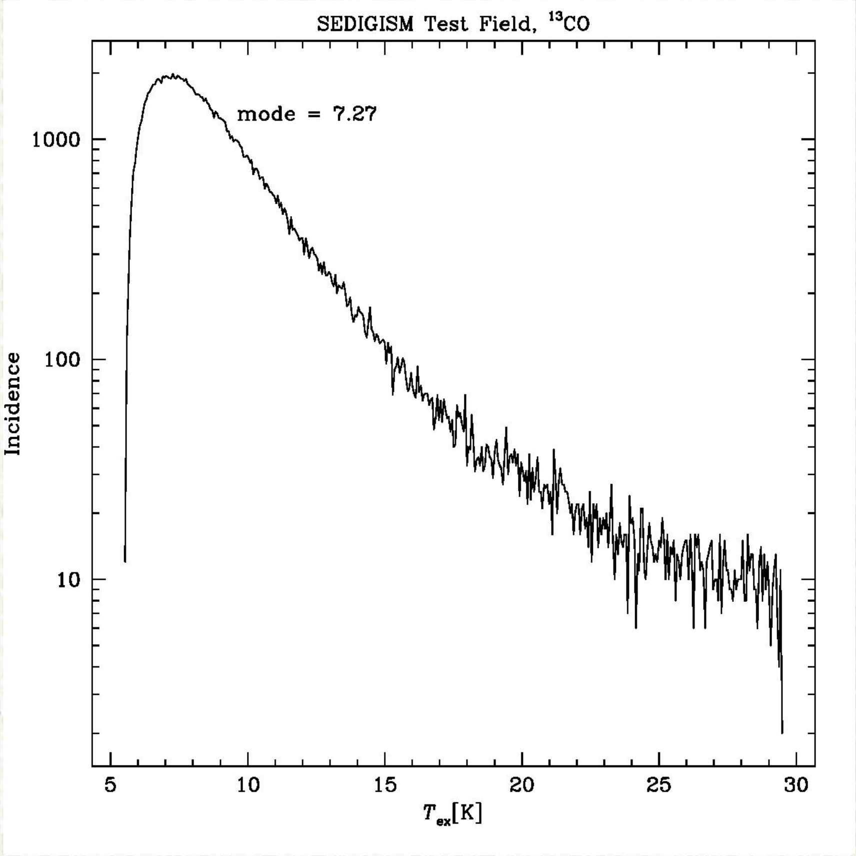
- ~Half the voxels have very low T_2/T_1 ratio: subthermal(?) excitation
- Convergence remains tricky, especially in low-T_{ex}/high-τ DSD (double solution domain) near subthermal limit
- Eventually, will need non-LTE analysis for new physics



Unexpected Results

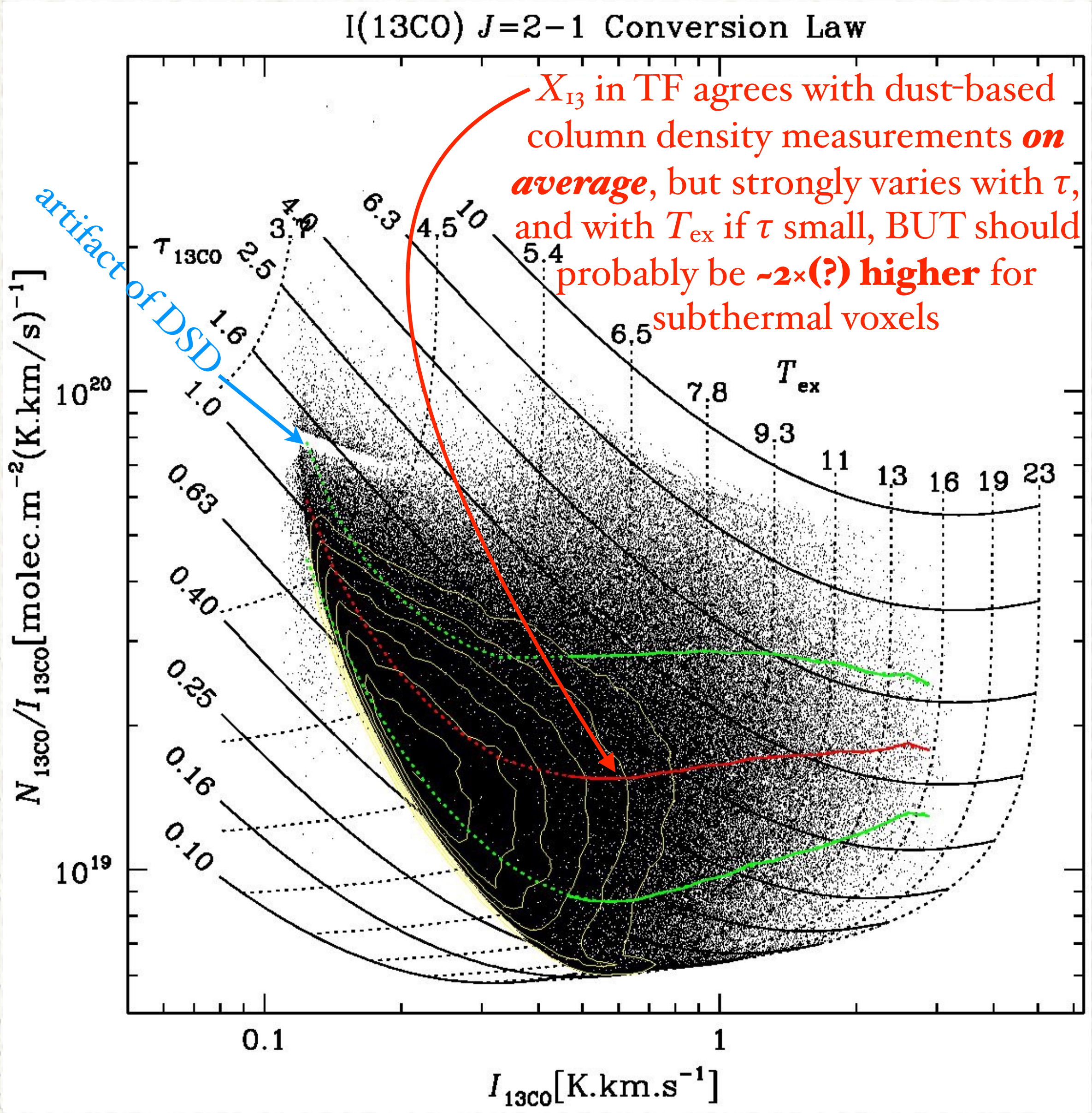
- Of the voxels which have LTE solutions, most are high opacity ($\tau_{2\text{-}1} = 0.4$–4) and low excitation ($T_{\mathrm{ex}} = 6$–9 K)
- Assuming $\tau << 1$ should be avoided





X factors and other questions

- Can also compute ^{13}CO X-factor: ~flat with I(^{13}CO) in TF, but probably only because of Central Limit Thm.
- X_{13} hides a multitude of sins, e.g. ***no provision*** for subthermal voxels!
- Inside & outside the TF, X_{13} varies regionally & globally; need to map its value
- Implications for Dark Molecular Gas & N_{H_2}, extragalactic work, etc.



artifact of DSD

X_{13} in TF agrees with dust-based column density measurements ***on average***, but strongly varies with τ, and with T_{ex} if τ small, BUT should probably be **~2×(?) higher** for subthermal voxels

More Applications

- **2nd approach**: iteratively solve between SEDIGISM J=2→1 ^{13}CO & C^{18}O lines' τ & $T_{\rm ex}$ (again, 2 equations in 3 unknowns)

$$\frac{T_{18}}{T_{13}} = \left[\frac{S_{18}(T_{\rm ex}) - S_{18}(T_{\rm bg})}{S_{13}(T_{\rm ex}) - S_{13}(T_{\rm bg})}\right] \frac{1 - e^{-\tau_{18}}}{1 - e^{-\tau_{13}}}$$

- Need to also assume R_{18}: will investigate how this works, given the CHaMP result that R_{18} varies... a lot!

- Work (with Prerak Garg) in an l=13° test map (1Q), but only over small areas (~few arcmin^2)

Future Work

- Connect N_{CO} catalogues from SCIMES (T:1-0, S:2-1) with properly segmented dust-based $N_{\mathrm{H_2}}$ structures (CODEX project)

- Map abundances $[^{13}\mathrm{CO}]/[\mathrm{H_2}]$ and $R_{13} = [^{12}\mathrm{CO}]/[^{13}\mathrm{CO}]$ across 4Q by combining N_{13} maps with dust-based $N_{\mathrm{H_2}}$ maps (still need to assume a single GDR)

- Re-analyse Galactic distribution of $N_{\mathrm{H_2}}$, X_{13}, T_{ex}, etc. with respect to spiral arms (globally) or filament/cloud structure & properties (locally)

Conclusions

- Main takeaway: *N*-based physics is different than *I*-based physics, affecting inferences of mass, structure, excitation, other derived cloud properties. Ignoring this risks the validity of your science.
- These projects are staff-limited: postdocs, students, please help!