Wide-Field Line Ratio Analysis:
High Dynamic Range Column Density Maps of the Milky Way

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and Frederic Schuller *and the rest of the* SEDIGISM team

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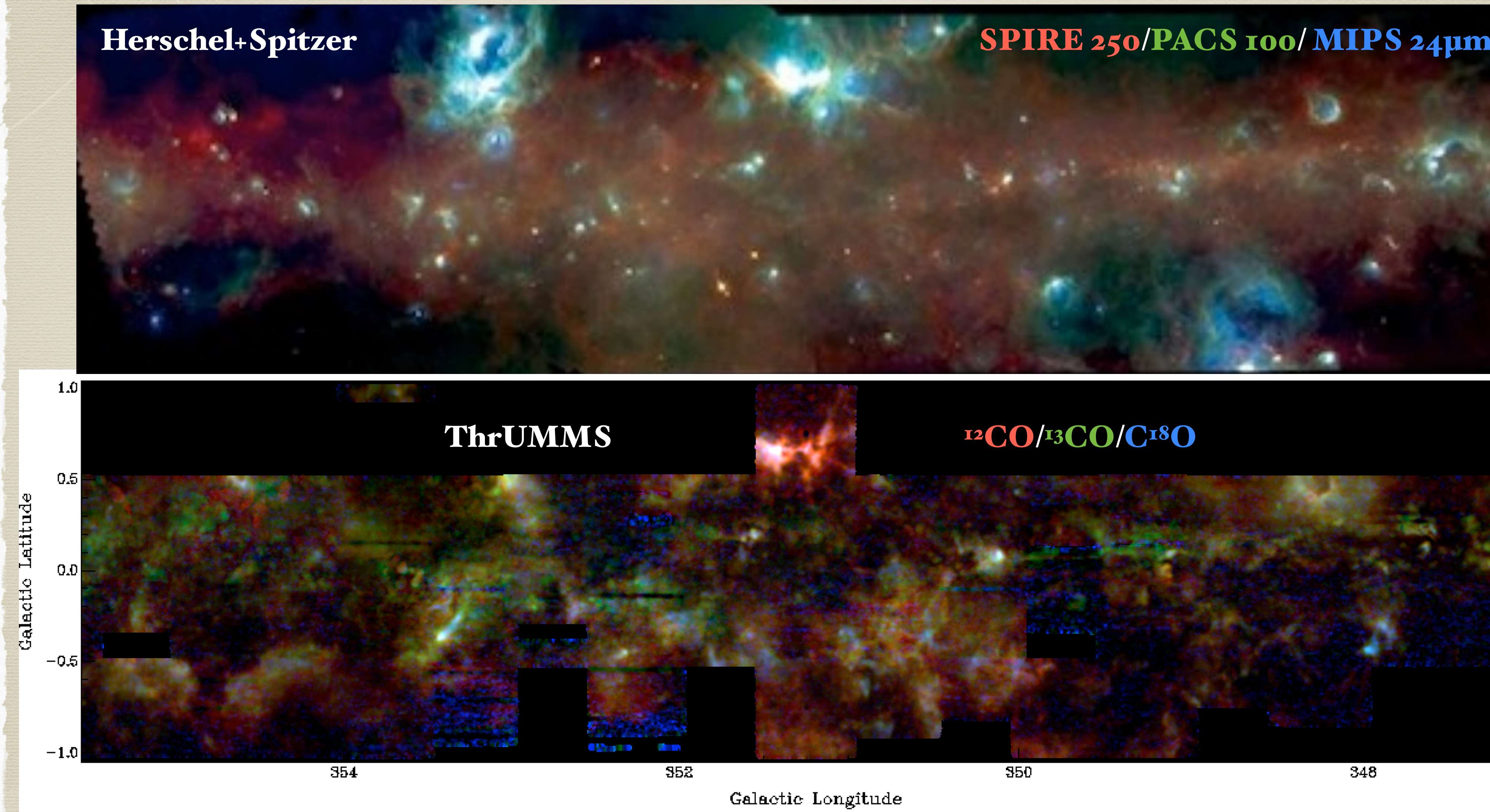
The Basic Problem



* How do we turn data into physics?

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 and 2 unknowns:

Quo vadis?

* Want physical quantities, like mass distribution, excitation conditions

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

* **Emissivity ≠ Mass**

SEDIGISM at APEX

- With SEDIGISM, we also have J=2→1 for ^{13}CO & C^{18}O: how does this help?

- **1st approach**: combine ^{13}CO J=2→1 from SEDIGISM with ^{13}CO J=1→0 from ThrUMMS:

2× →

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

- 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: $\tau_{2\text{-}1}/g_2 = (\tau_{1\text{-}0}/g_1)e^{-h\nu_{2\text{-}1}/kT_{\rm ex}}$.

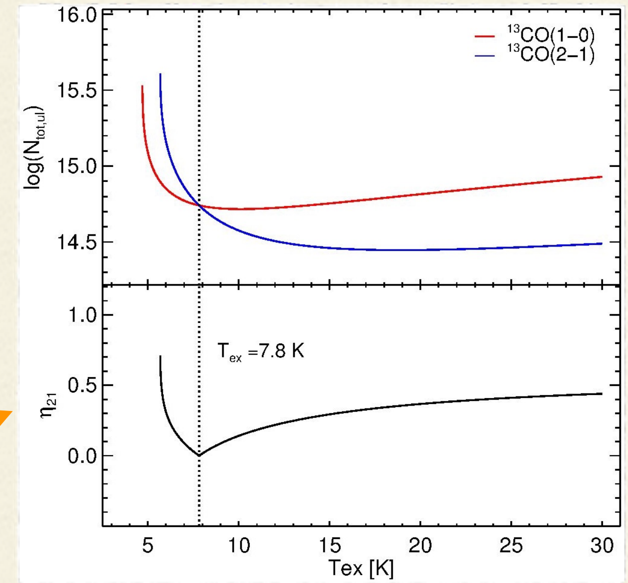
- Equivalent to iteratively solving for 2 versions of N, and matching them, as in Schuller et al 2017 (SED. Paper I)

Iterative Approach

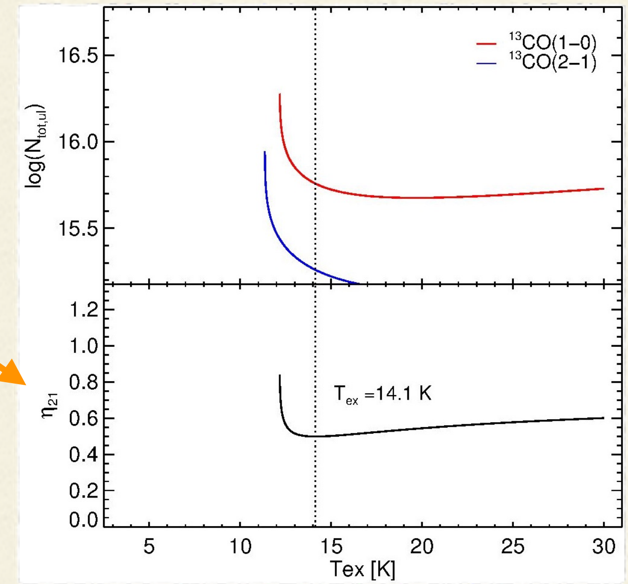
* In Test Field (TF):

* Form a ratio of two *N*s calculated from each line, $\eta_{21}(T_{ex}) = \left|\log\left(\frac{N_{tot,21}}{N_{tot,10}}\right)\right|$, then find T_{ex} where η=0

* Example 1: solvable voxel



* Example 2: not solvable (more on this later)

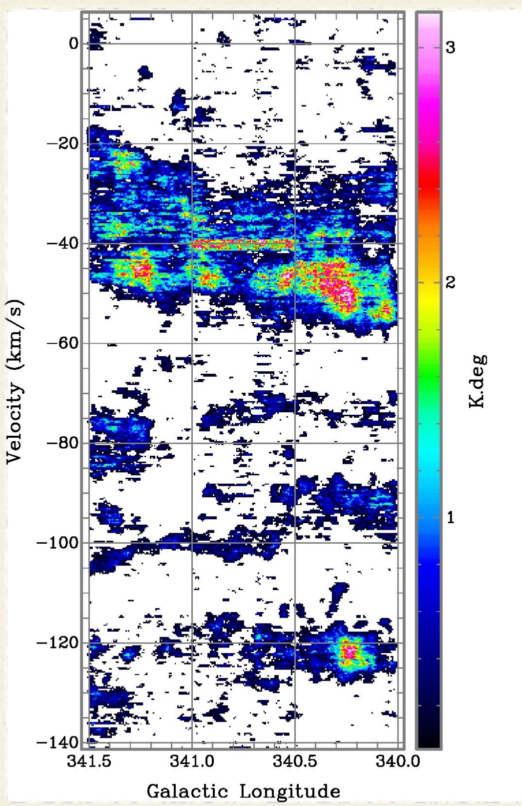


* Most voxels solvable for $\tau_{2\text{-}1}$, $\tau_{1\text{-}0}$, T_{ex}, and $N_{total}(^{13}CO)$

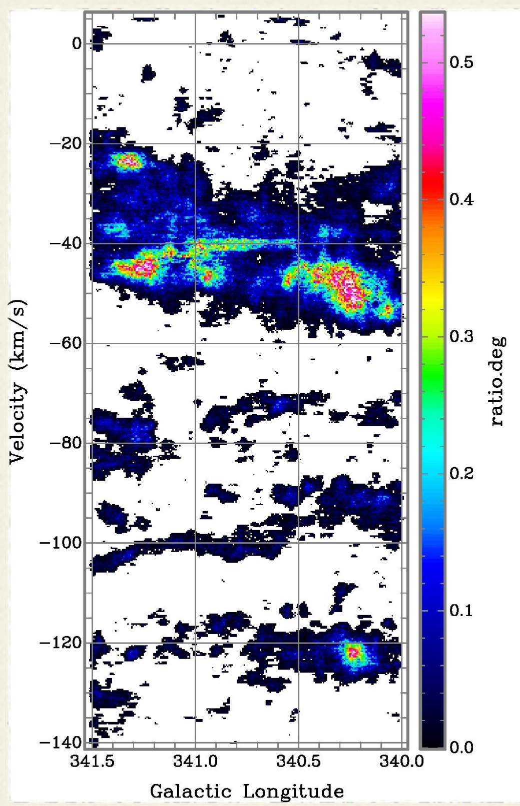
Test Field Recap

* Again, *N* distribution is more clumpy than *I*
* Work continuing in 4Q with Sebastian Lopez & Audra Hernandez

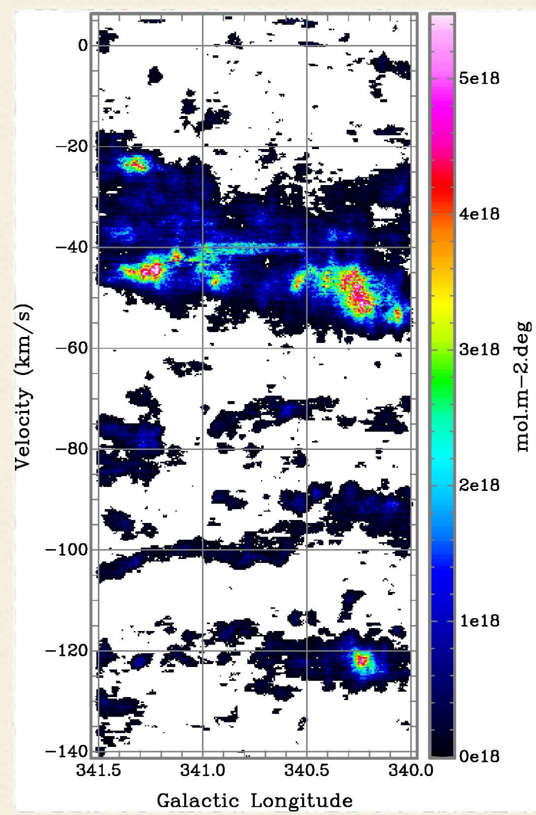
T_{ex}



$\tau_{2\text{-}1}$

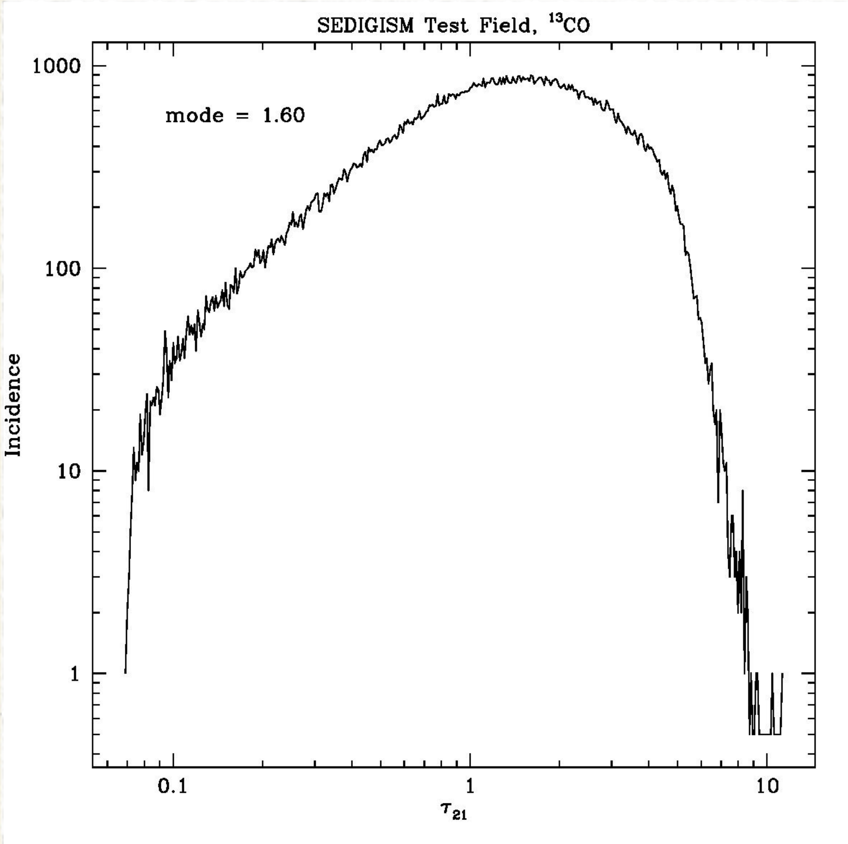


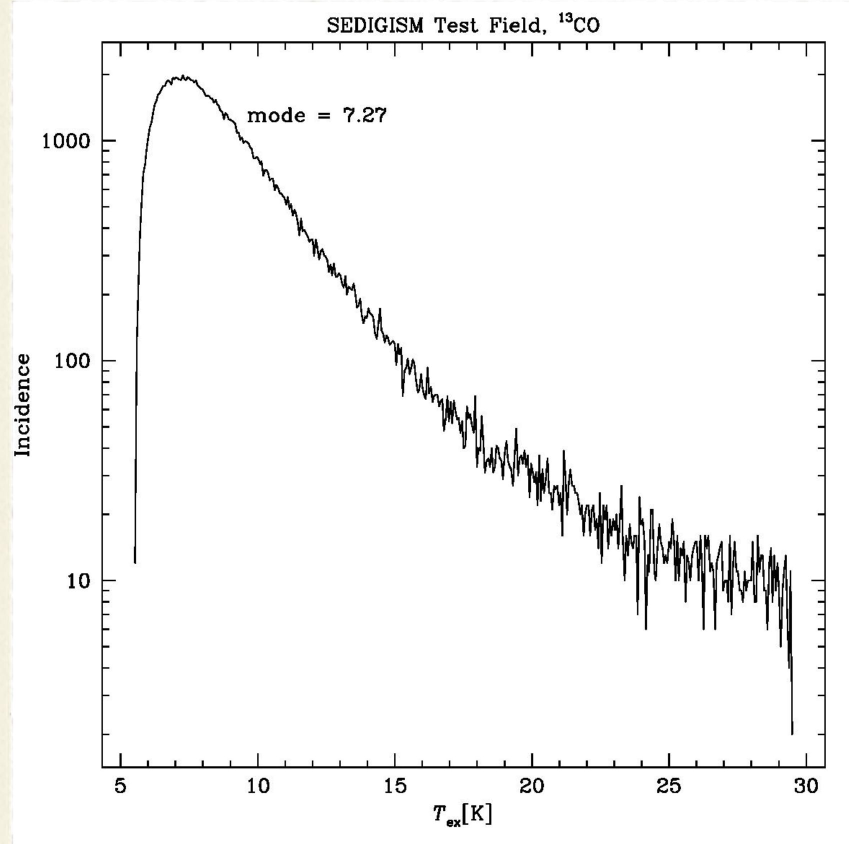
$N_{total}(^{13}CO)$



Unexpected Results

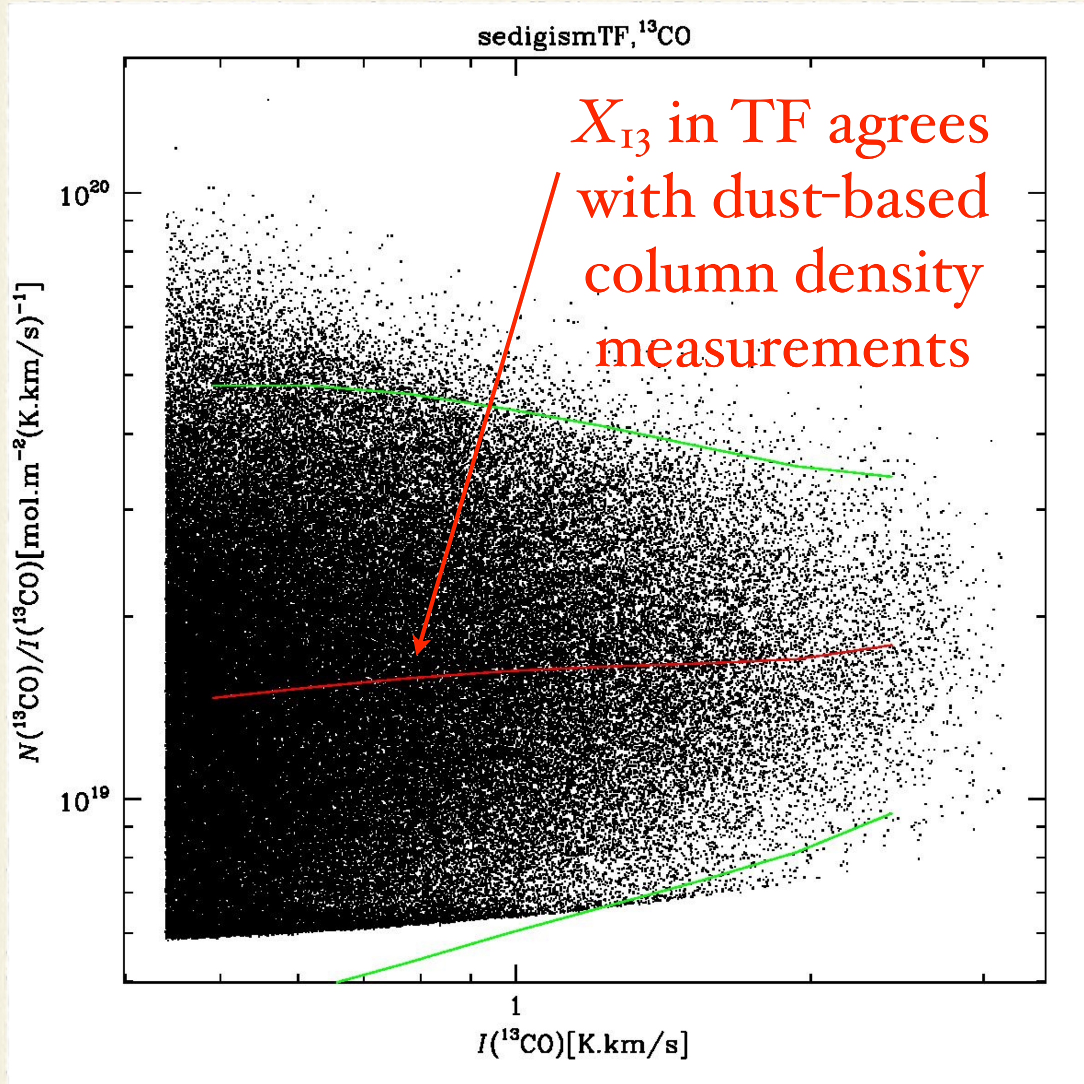
* Most voxels are high opacity ($\tau_{2\text{-}1}$ = 0.4–4) and low excitation (T_{ex} = 6–9 K)
* Assuming τ << 1 should be avoided





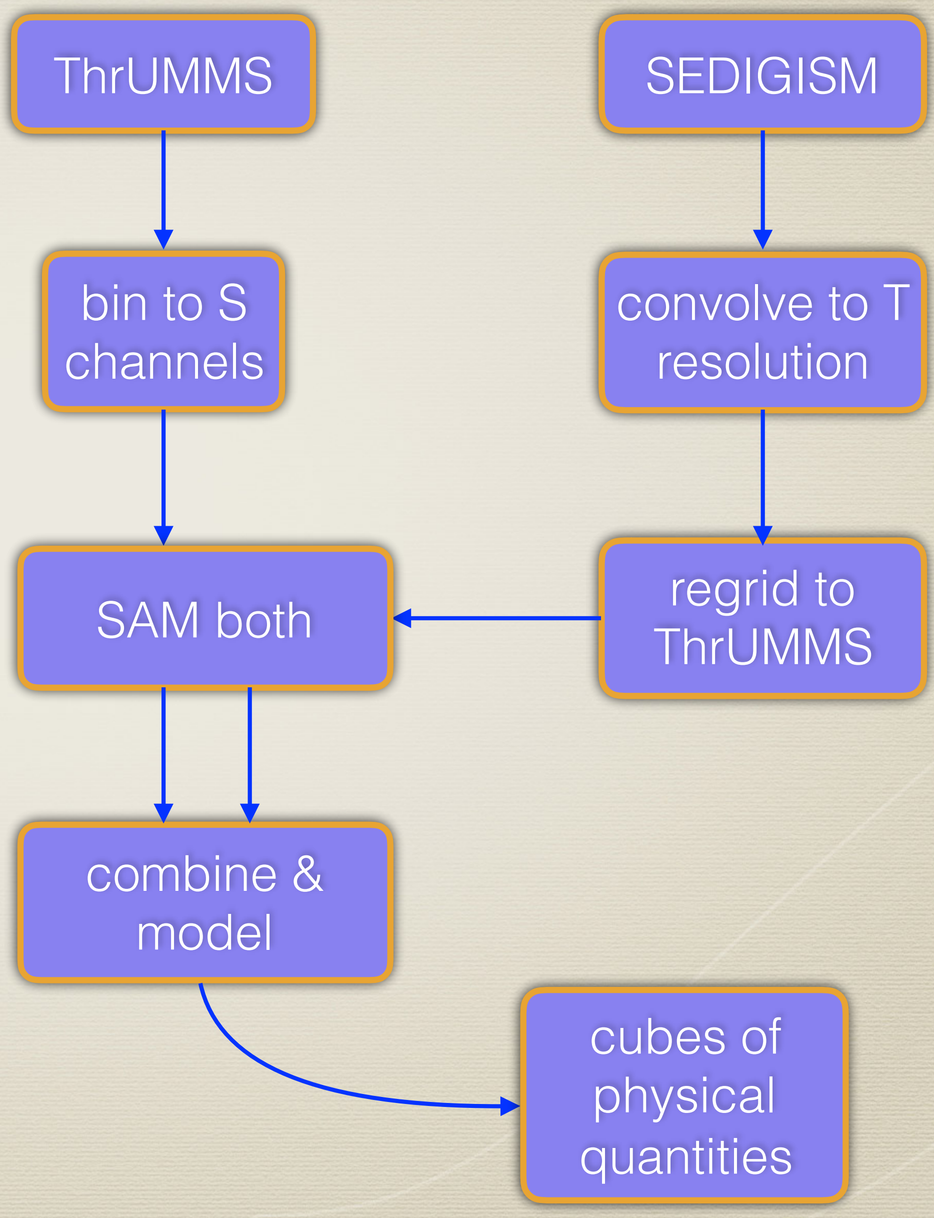
X factors and other questions

- Can also compute ^{13}CO *X*-factor: flat with $I(^{13}CO)$
- Is X_{13} constant outside the TF? Does it have the same value?
- Implications for Dark Molecular Gas, and extragalactic work



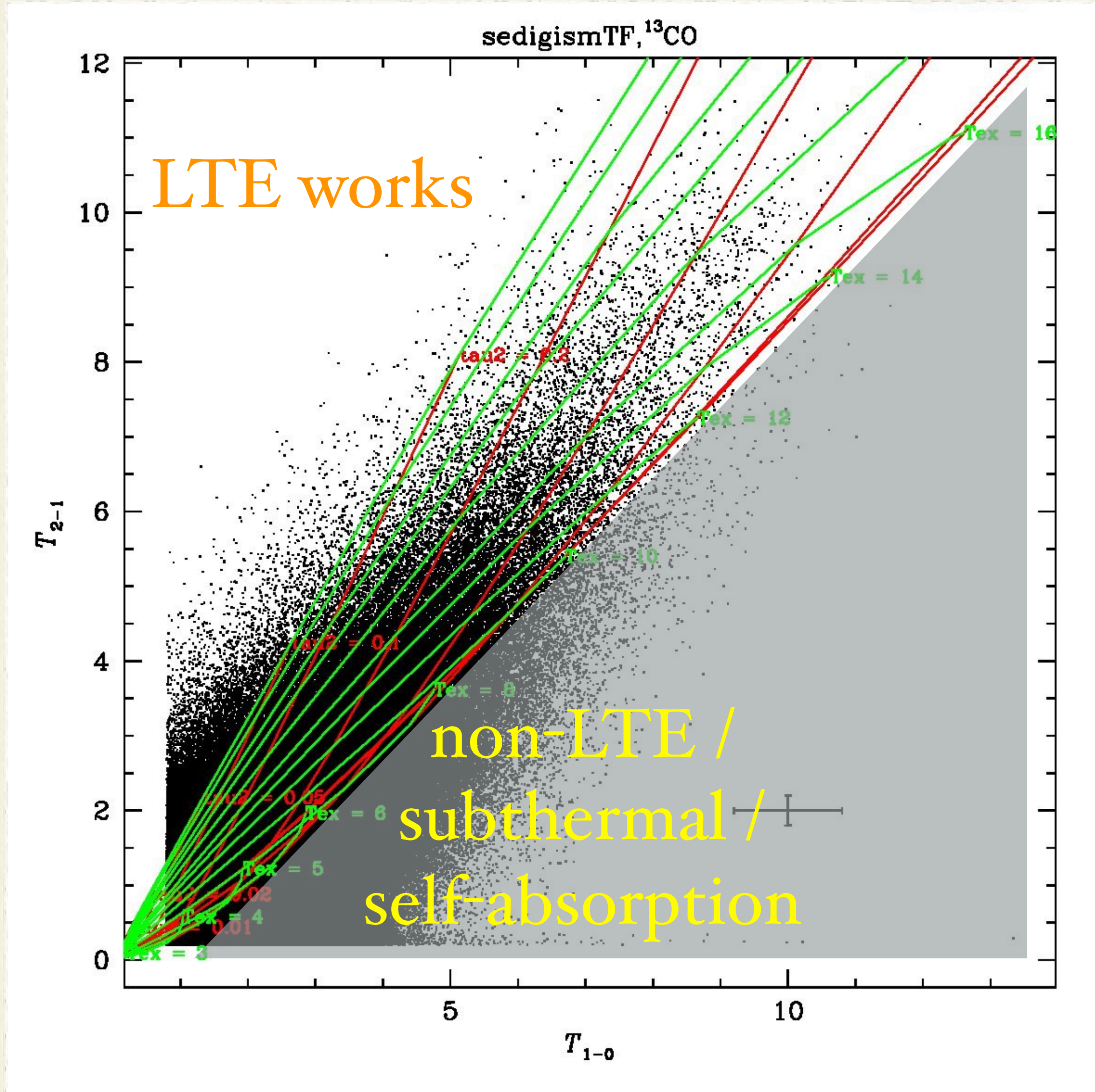
Progress on DR1b

- Work is continuing on a faster (Newton's method) and cleaner algorithm than in TF
- Convergence remains tricky
- First results soon (~1 month); SED Paper III (?) coming later this year



Line Ratios are … Interesting

* There are a minority of voxels with T_2/T_1 very low



* Eventually, look at non-LTE analysis for new subthermal physics

More Applications

- **2nd approach**: iteratively solve between SEDIGISM J=2→1 ^{13}CO and C^{18}O lines' τ and $T_{\rm ex}$ (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 just begun with Prerak Garg, Audra Hernandez in an l=13° test map (1Q)

A "Simpler" Example

* As in ThrUMMS and CHaMP (J=1→0):
  * Have ^{12}CO, ^{13}CO, and C^{18}O data, so 5 equations in 8 unknowns (3×τ, 3×$T_{\rm ex}$ plus abundance ratios R_{13}, R_{18})
  * Assume single, common $T_{\rm ex}$, and R_{13} = 60 (both reasonable) → now 5 equations in 5 unknowns
  * Final convenience: $T_{\rm ex}$ = $T_{\rm mb}$(^{12}CO)+2.73 (since τ_{12}>>1)
  * Now solve **directly**:

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

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

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

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

Side benefit: in this case, column density is **very** HDR, since we can peel away the iso-CO layers

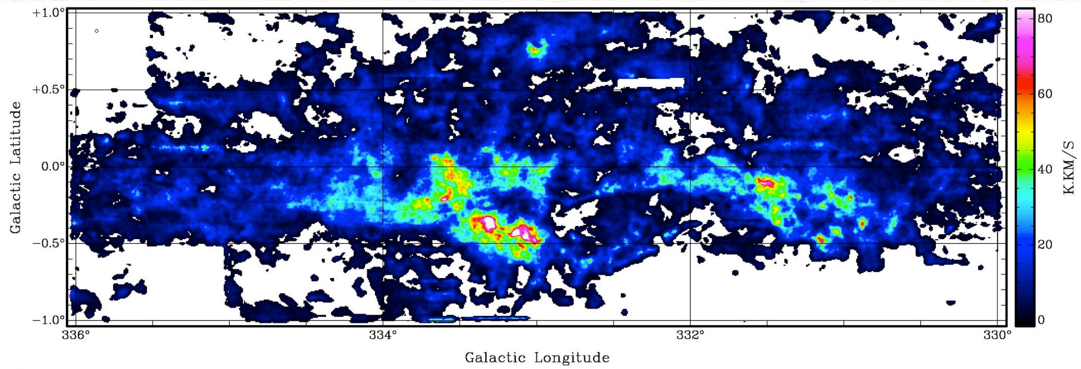
Physics to Come

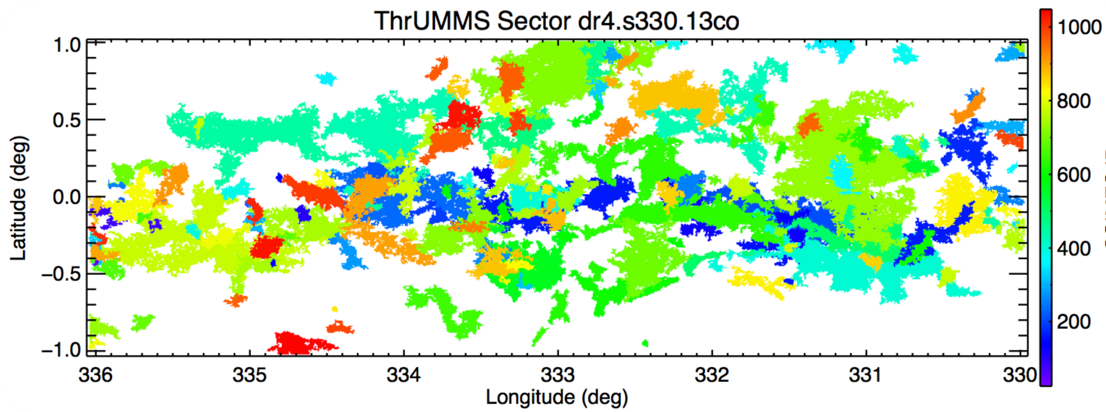
ThrUMMS Sector:
330°-336°
^{13}CO (1-0)
(dv=-150-50 km s^{-1})

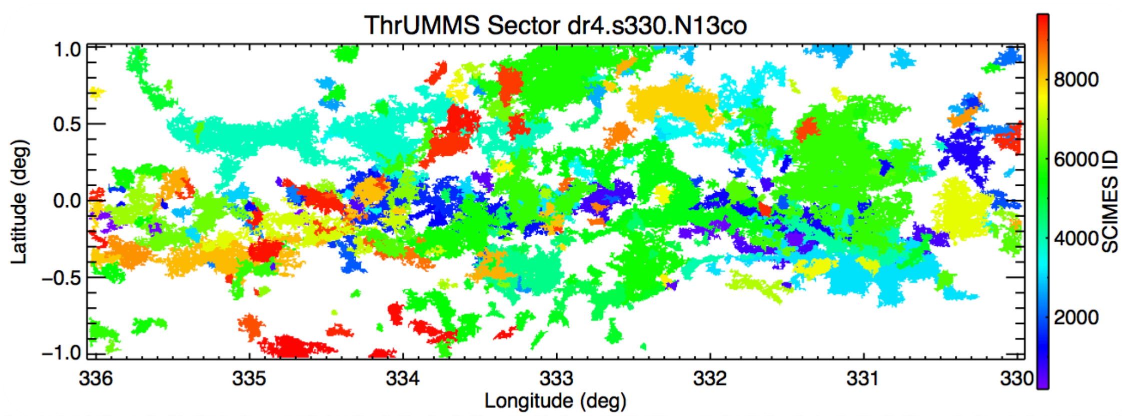
Intensity Based Extraction:

- 2.5σ detection limit
- 4σ minimum separation difference

Column Density Based Extraction





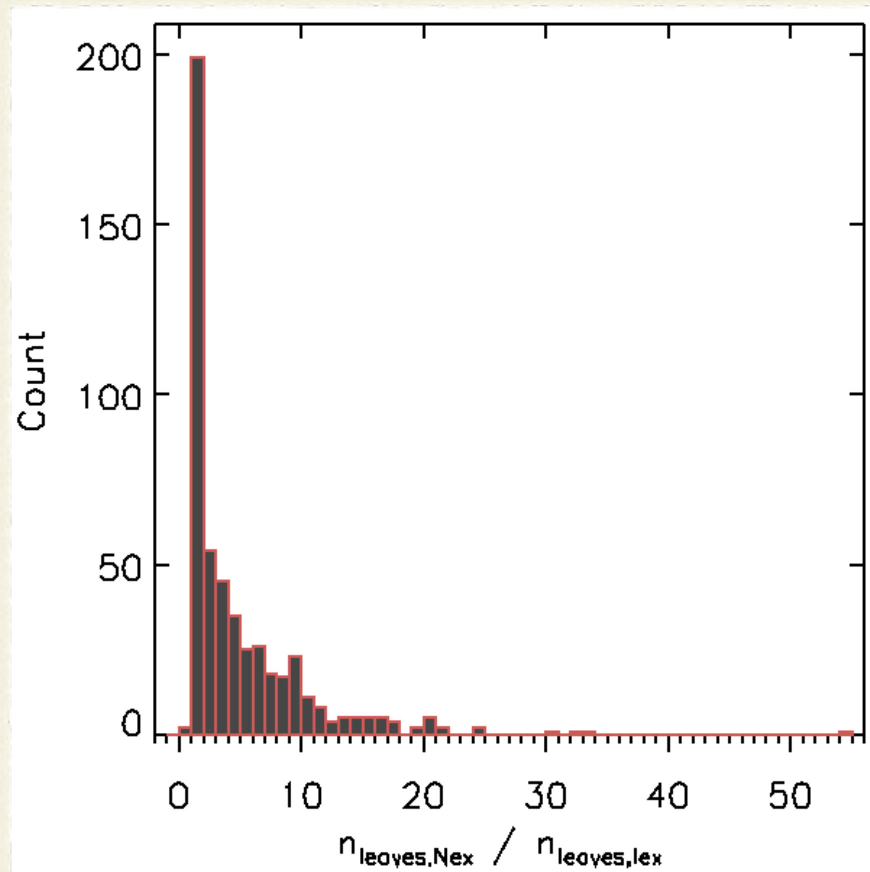


Mass distribution is much clumpier than emission:

Thousands of clouds!

Sensitivity to Clumpiness

* Because of the HDR column density sensitivity, we can see more structure
* Clumpiness is most extreme at the highest column densities, i.e. where $\tau >> 1$



Conclusions

* SEDIGISM on APEX is/will be a major contributor to the revolution in understanding the physics of the molecular ISM
* Exciting new results coming from multi-line radiative transfer analysis over the very wide fields of SEDIGISM at APEX, plus CHaMP & ThrUMMS, others
* Final word: *N*-based physics is different than *I*-based physics. Ignoring this risks the validity of your science