The Hierarchy of the Molecular ISM as Probed by CO

Physics & Demographic of Molecular Clump Evolution from CHaMP, ThrUMMS, & SEDIGISM

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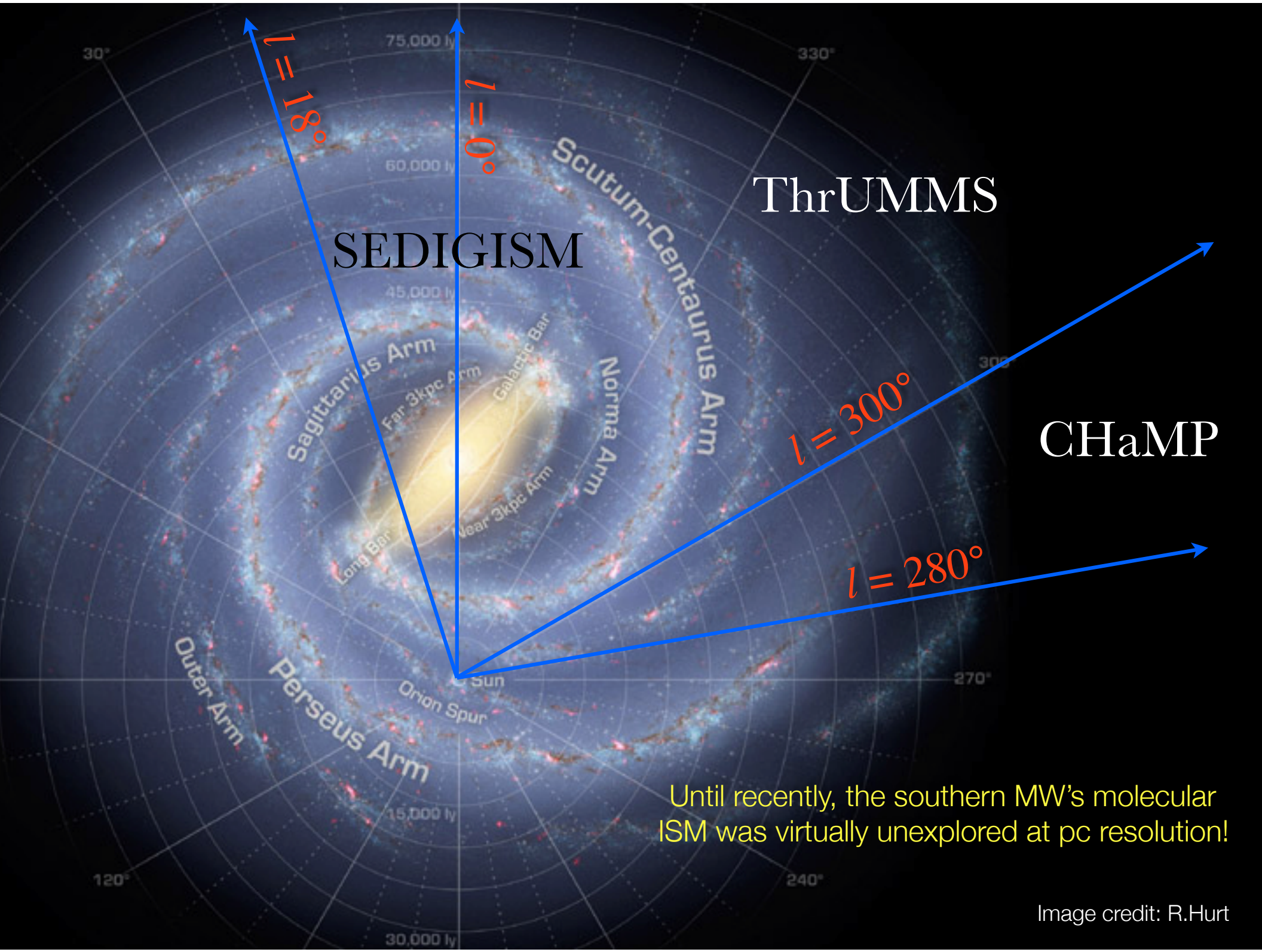
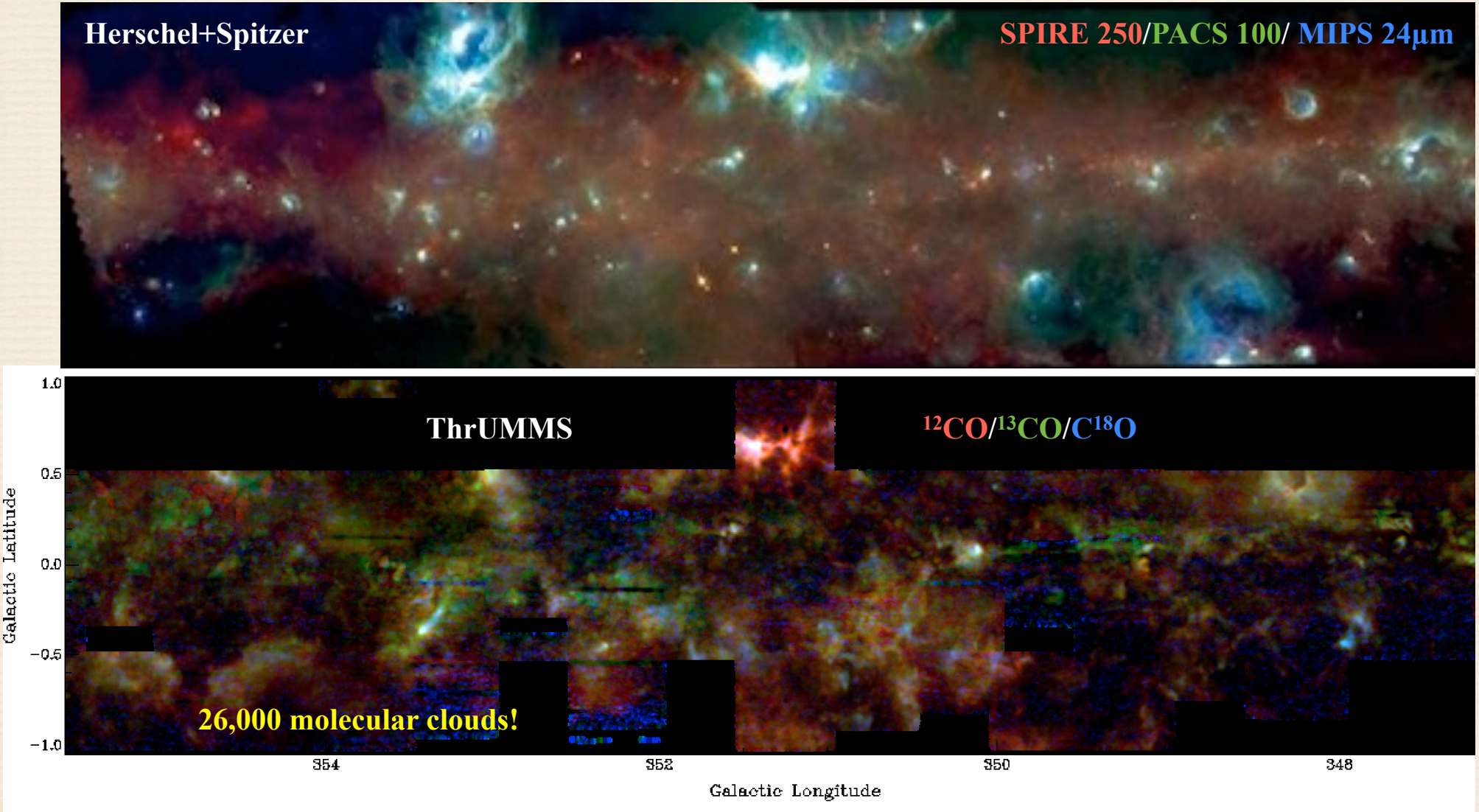
Surveys

- Continuum surveys (GLIMPSE, Hi-GAL, ATLASGAL, BLAST, etc.) provide important SED information on clump masses & luminosities
- **Key point 0:** ***Kinematic information absent*** without spectroscopy. Need molecular, atomic lines
- **Key point 1:** **Resolution!** At 3 kpc, 1′~ 1 pc ***resolves cloud evolution on the scale of cluster formation*** (at 8′, CfA-^{12}CO can't do this)
- **Key point 2:** ***Multi-species*** maps enable entirely new science (GRS-^{13}CO can't do this)
- **Key point 3:** ***Wide field coverage.*** Small maps lack context
- A major motivator for CHaMP & ThrUMMS is **demographics** of clumps (including lifetimes) plus other physics


l = 18°
l = 0°
SEDIGISM
ThrUMMS
CHaMP
l = 300°
l = 280°
Until recently, the southern MW's molecular ISM was virtually unexplored at pc resolution!
Image credit: R.Hurt
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
30°
330°
270°
240°
120°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
Orion Spur
Sun

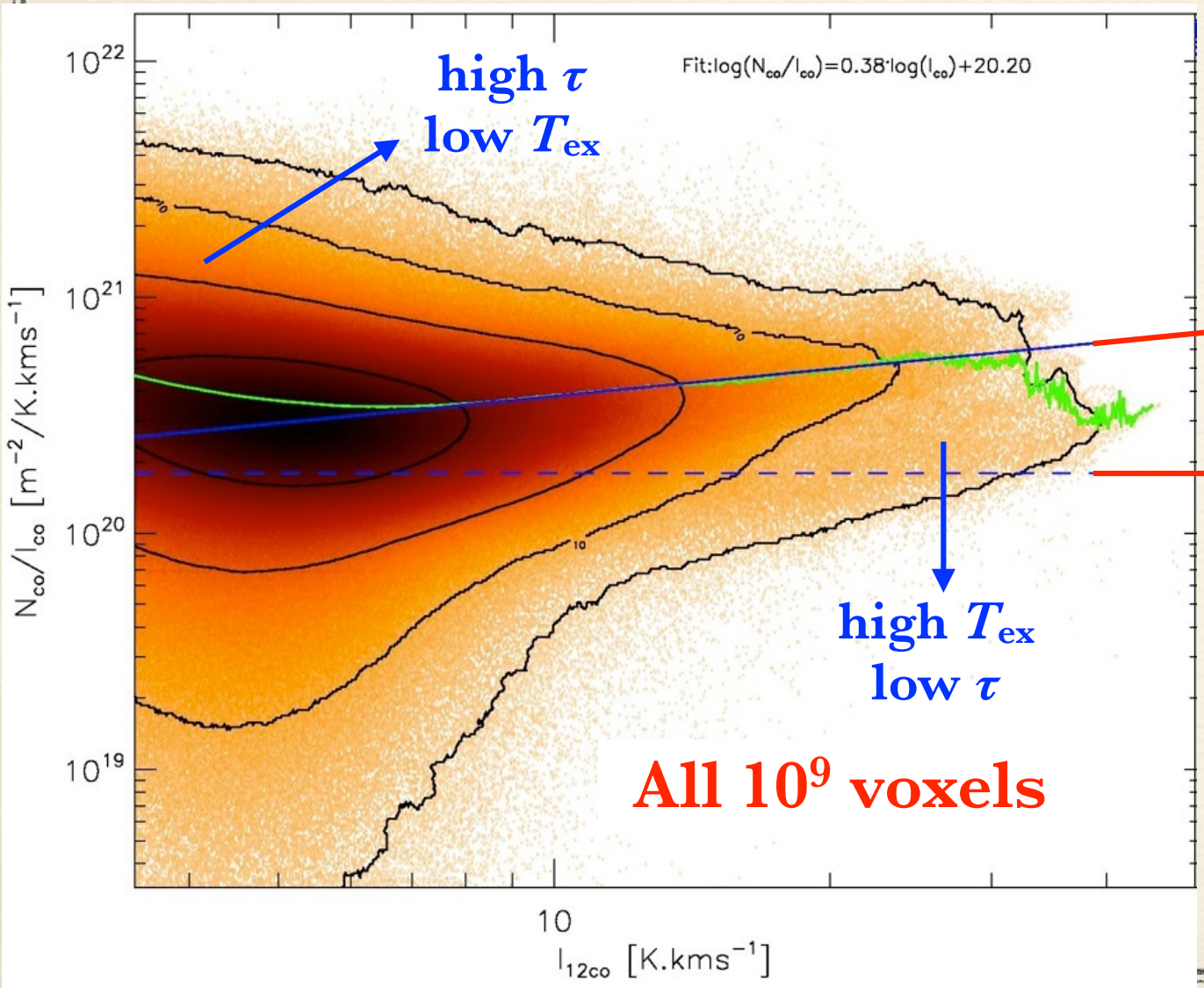
ThrUMMS eye candy



- Similar to dust continuum, but with more physics, and kinematics! Eg, line ratios can be analysed with radiative transfer physics.

ThrUMMS conversion law (BM+2015)

- Averaged across 4Q, the conversion law is $N_{CO} \propto I_{CO}^{1.4}$
  → **~2× as much molecular mass** as standard X factor



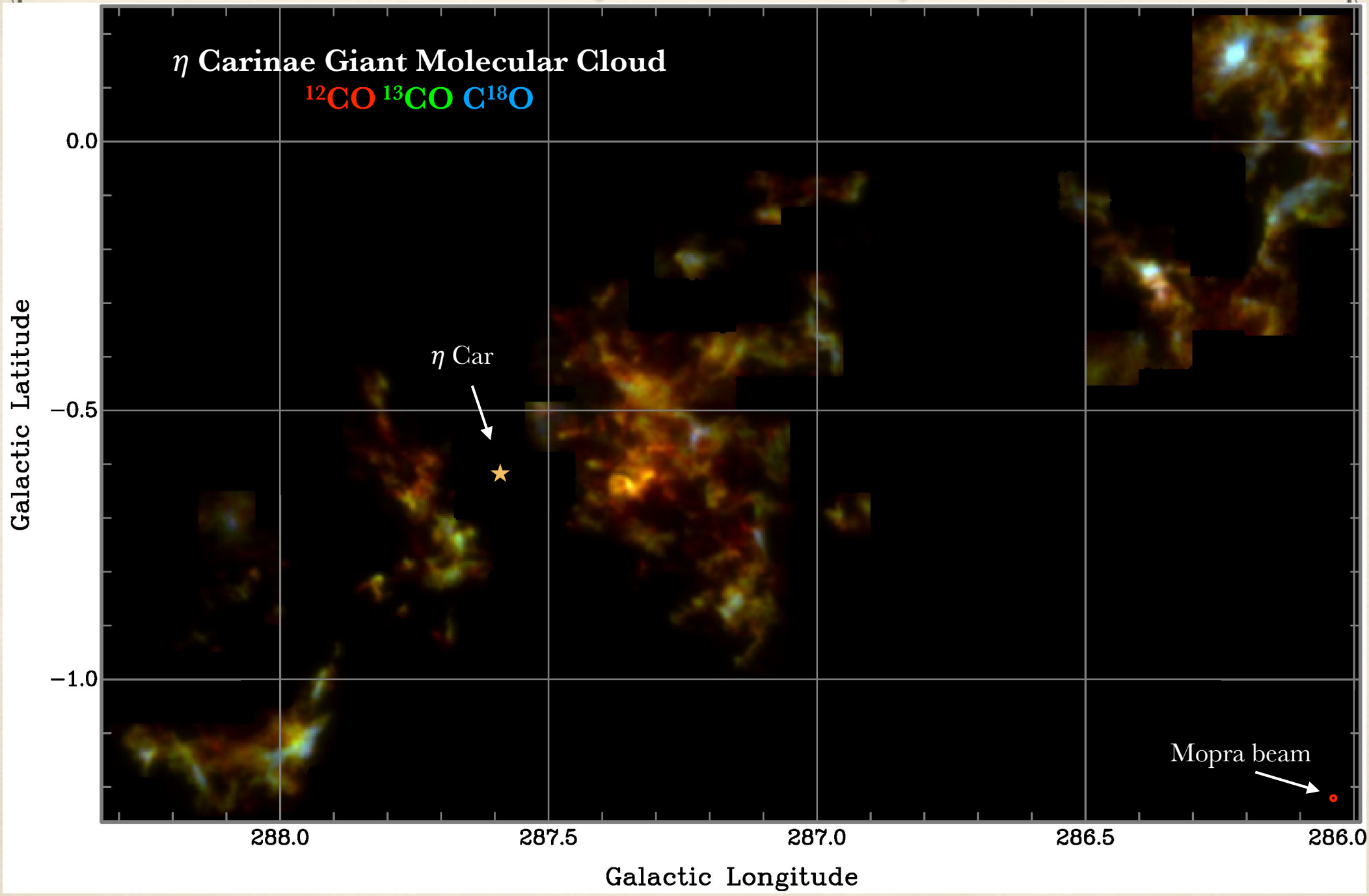
- **Gas depletion timescales** in MW-analogue disks also ~2× longer
- Schmidt-Kennicutt laws may need recalibration

power law

constant X factor: no good!

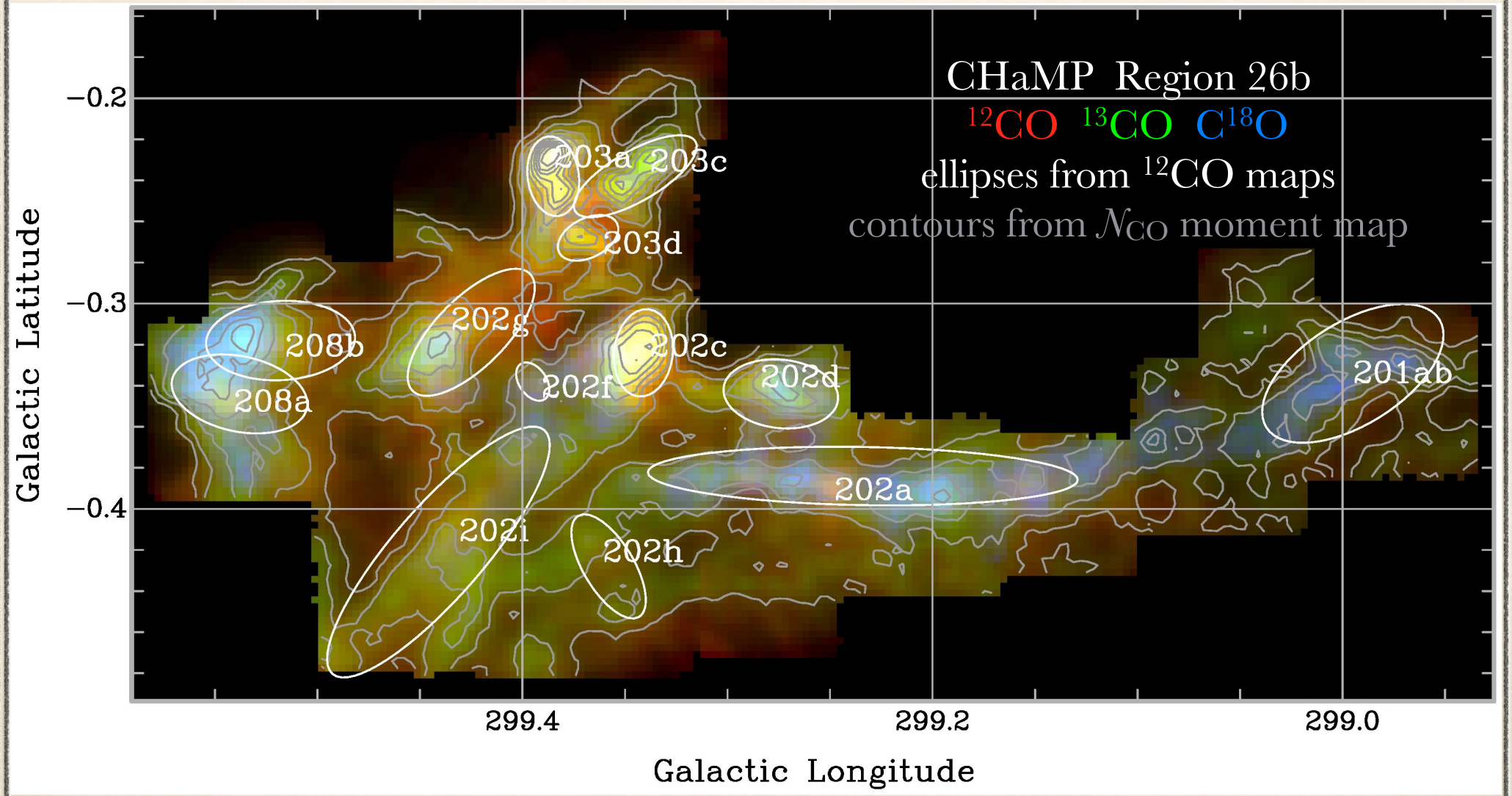
- Comes from large amounts of **high-τ, low T_{ex}** gas
- Old X factor prescription underestimates τ, mass
- Independently check this with CHaMP

CHaMP eye candy (BHM2017)



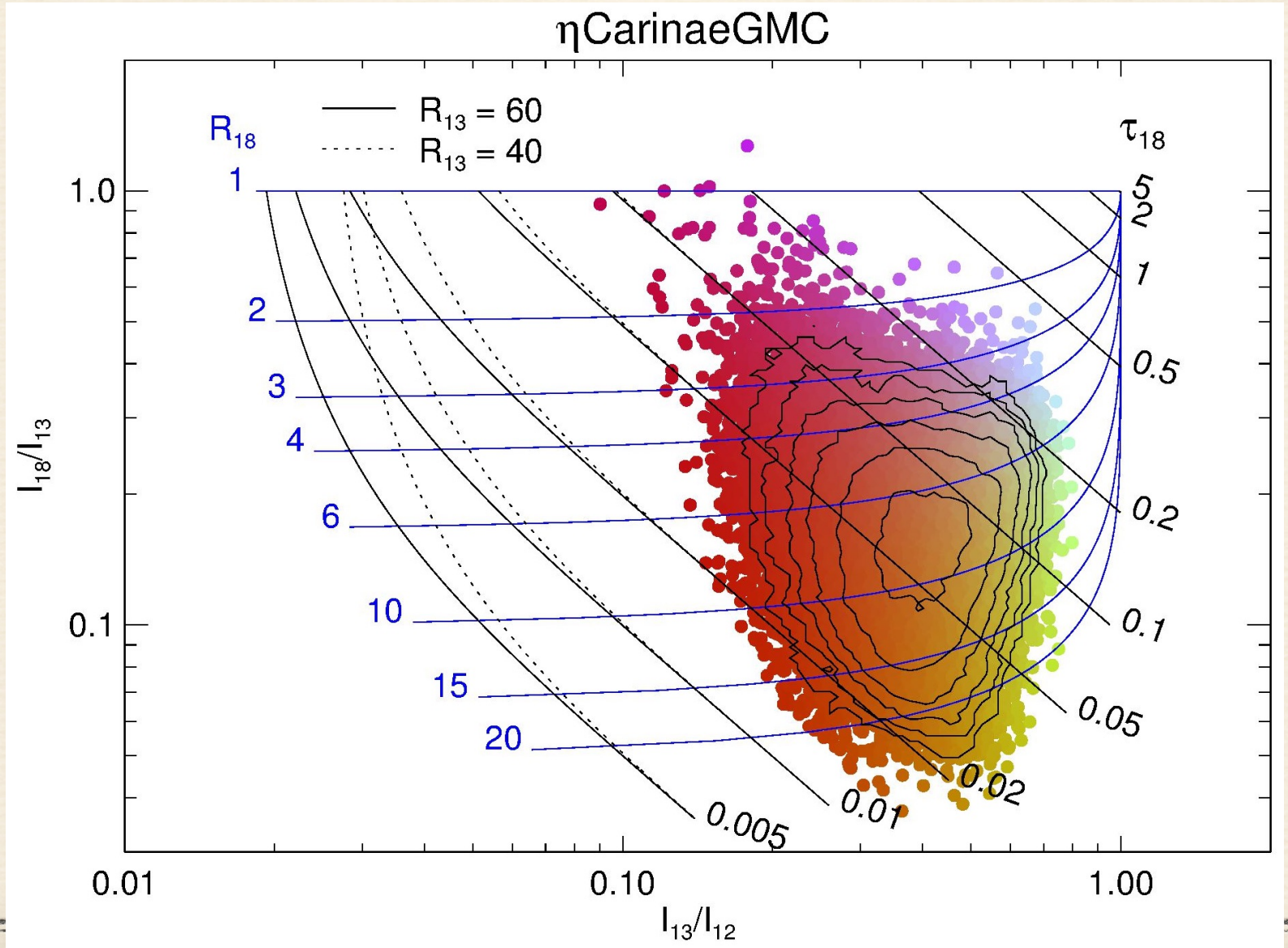
From line ratios to column densities

- Re-examine conversion laws with high-sensitivity CHaMP iso-CO data (BHM 2017, submitted)



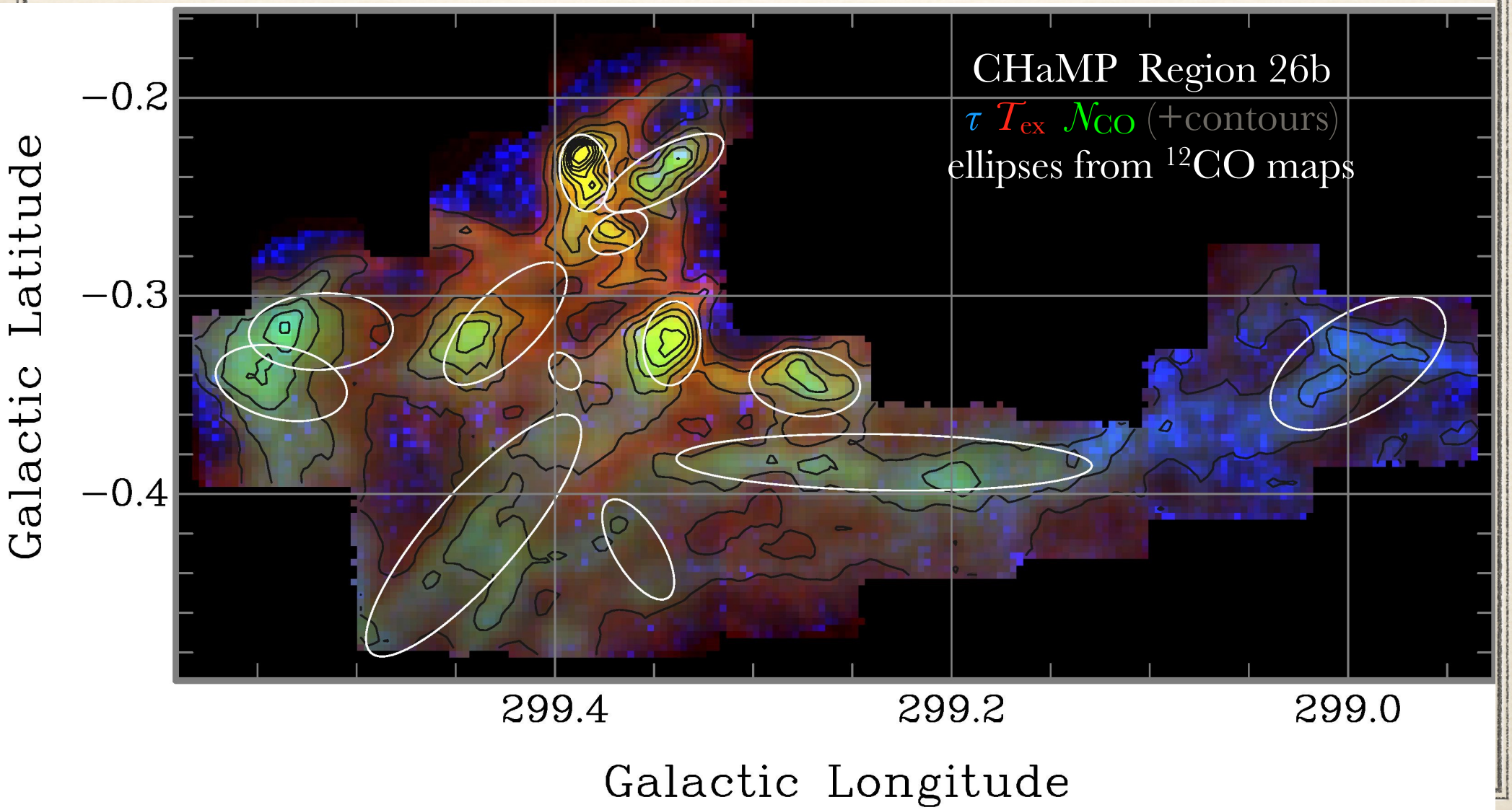
From line ratios to column densities

- CHaMP emission line data 3× more sensitive than ThrUMMS, so radiative transfer analysis more robust



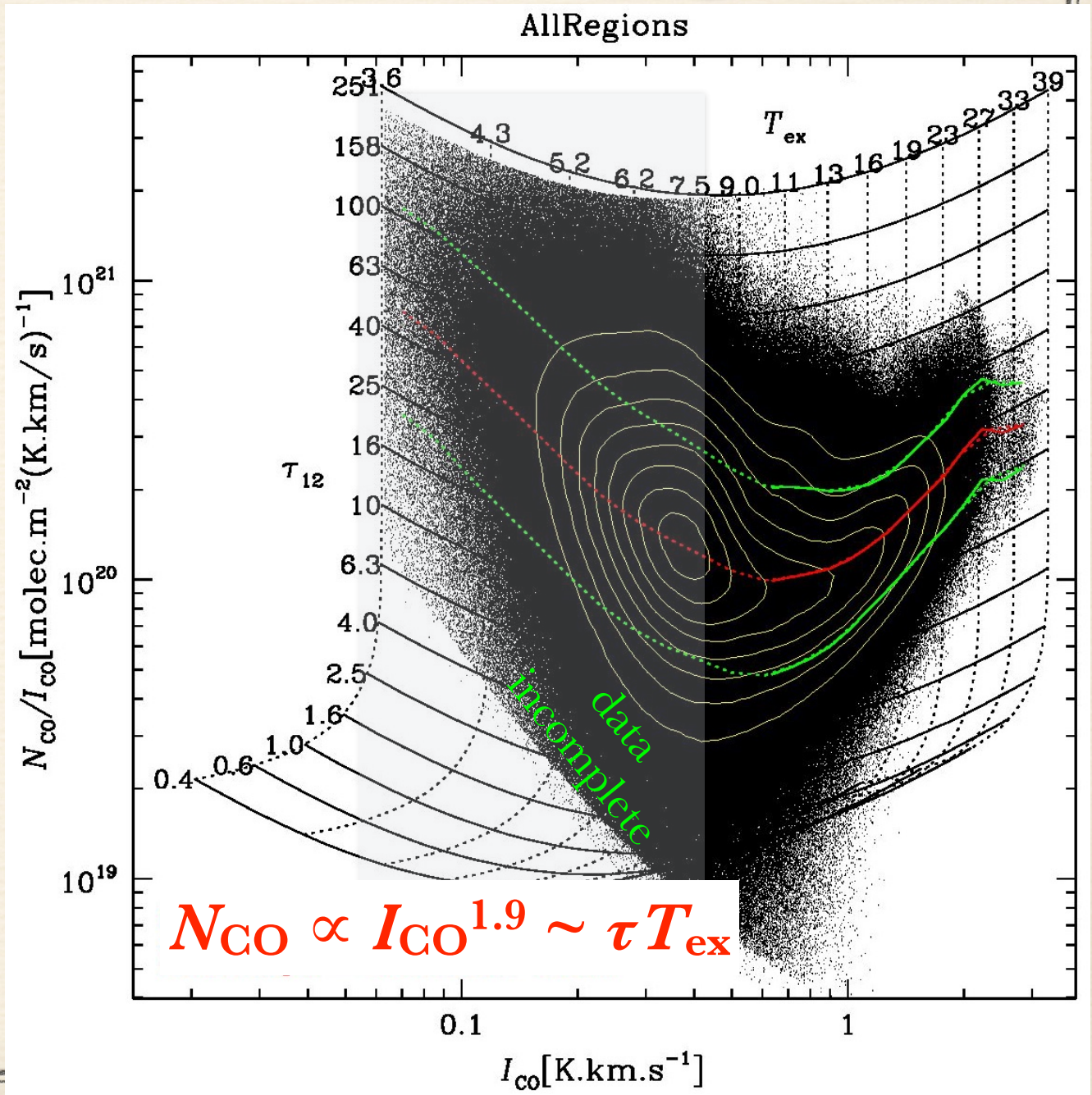
From line ratios to column densities

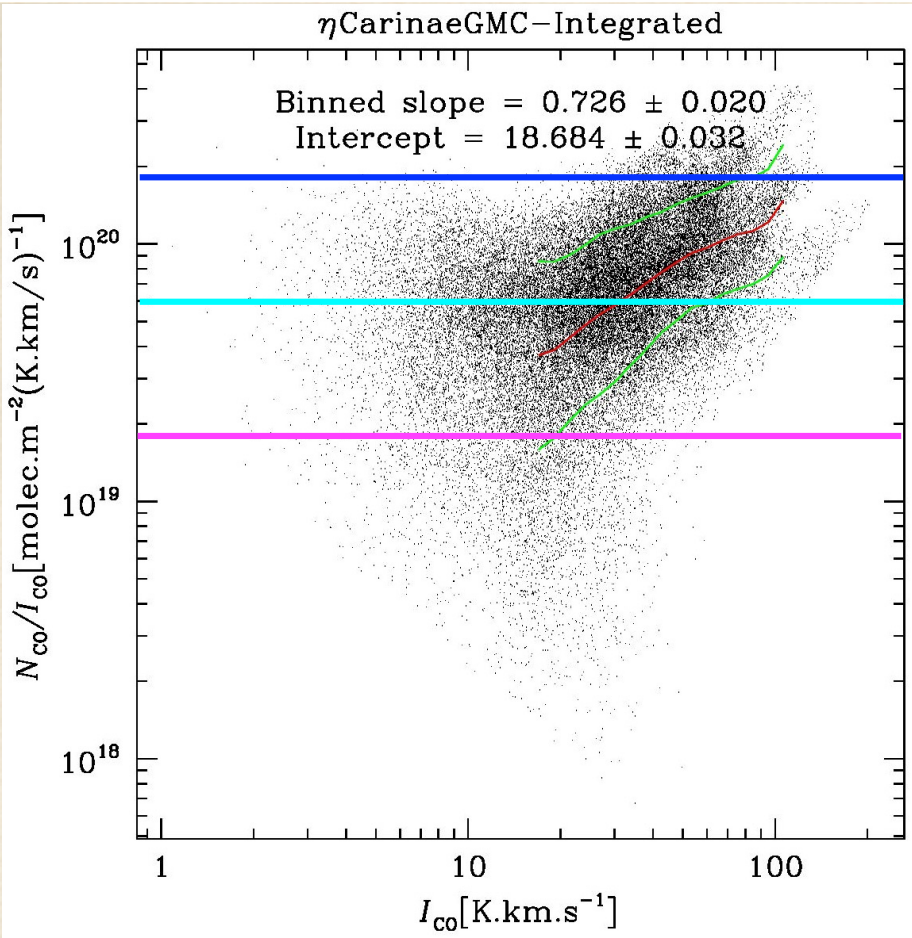
- Physical parameters spatially variable
- Column density depends on **both** τ and T_{ex}



Conversion laws re-imagined

- From CHaMP: conversion laws are even more extreme, and depend on velocity resolution.
- **Conclusion:** integrating ^{12}CO for a cloud gives the wrong $\mathcal{N}_{CO}$ (i.e., method of calibrating X-factor at high $\mathcal{N}$ is wrong) — ***should compute each channel!***





Conversion law if $[CO]/[H_2]$ =

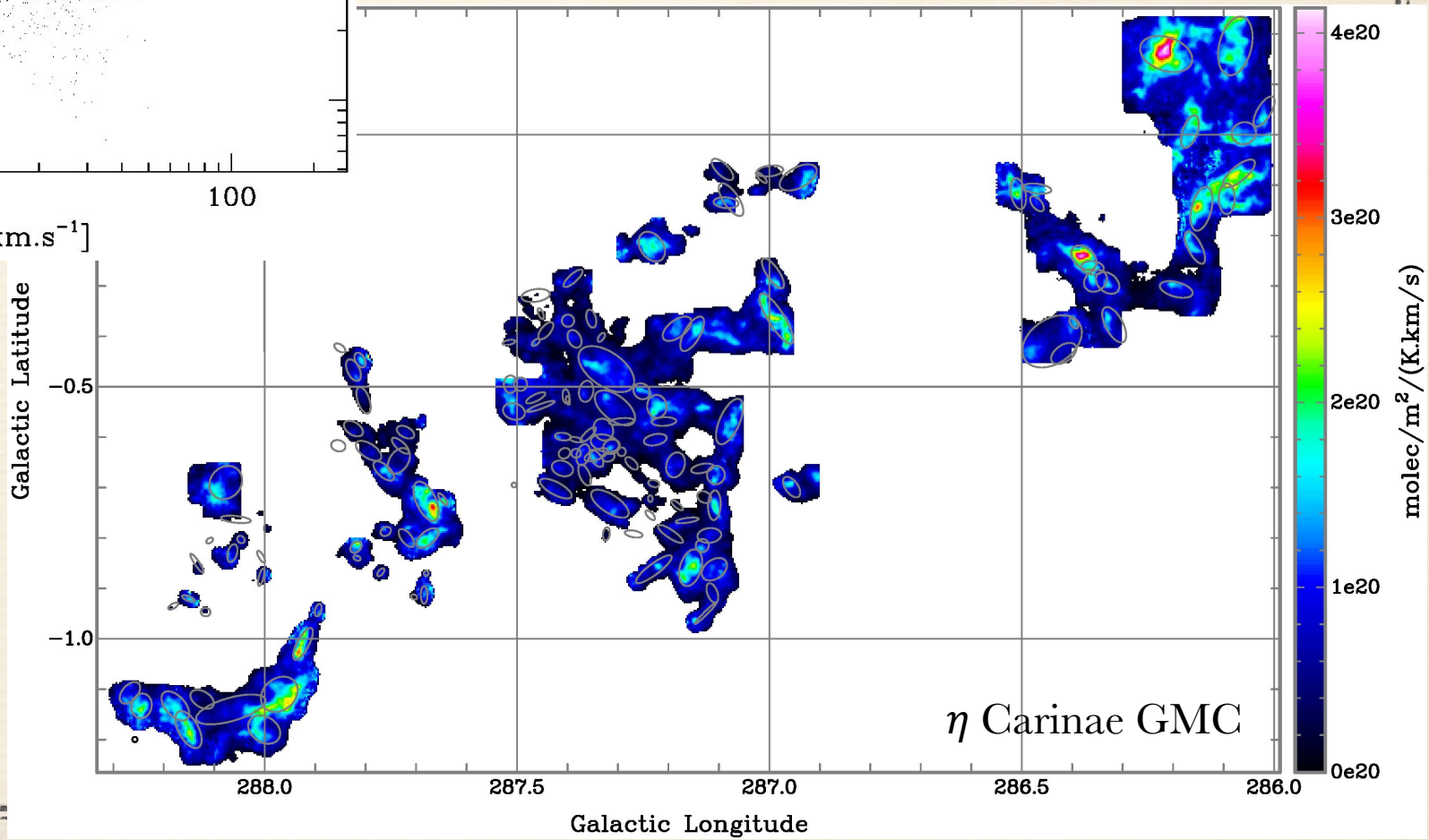
1×10^{-4}

3×10^{-5}

1×10^{-5}

Which is it?

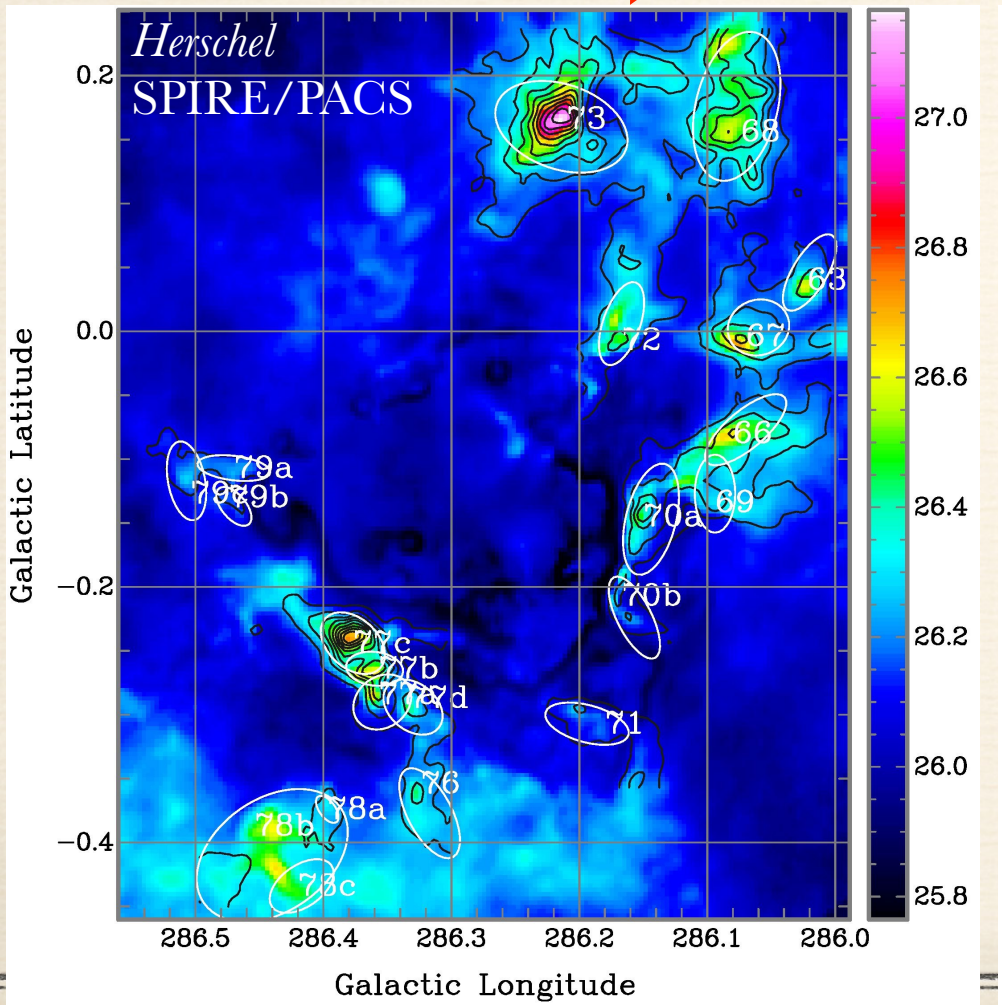
But N_{CO}/I_{CO} also spatially variable:

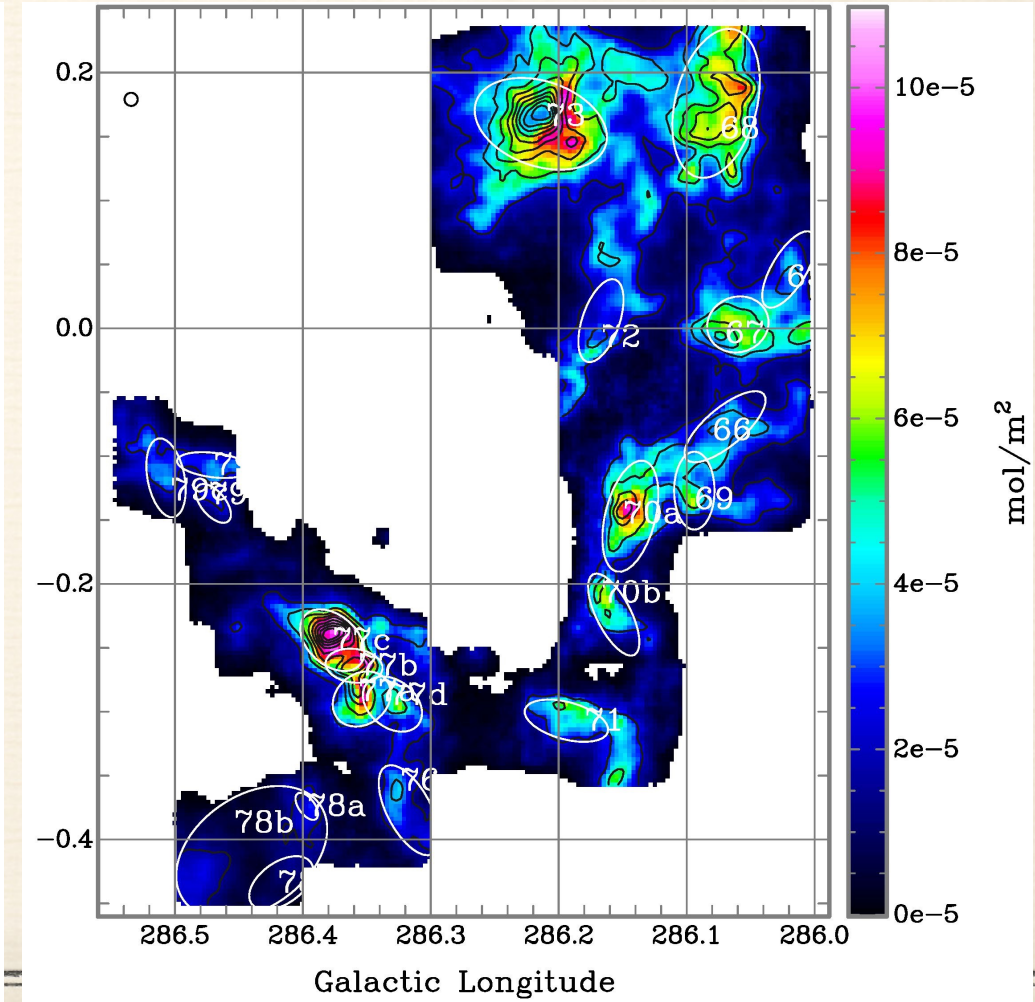


So what's going on?

Both X and [CO]/[H_2] vary

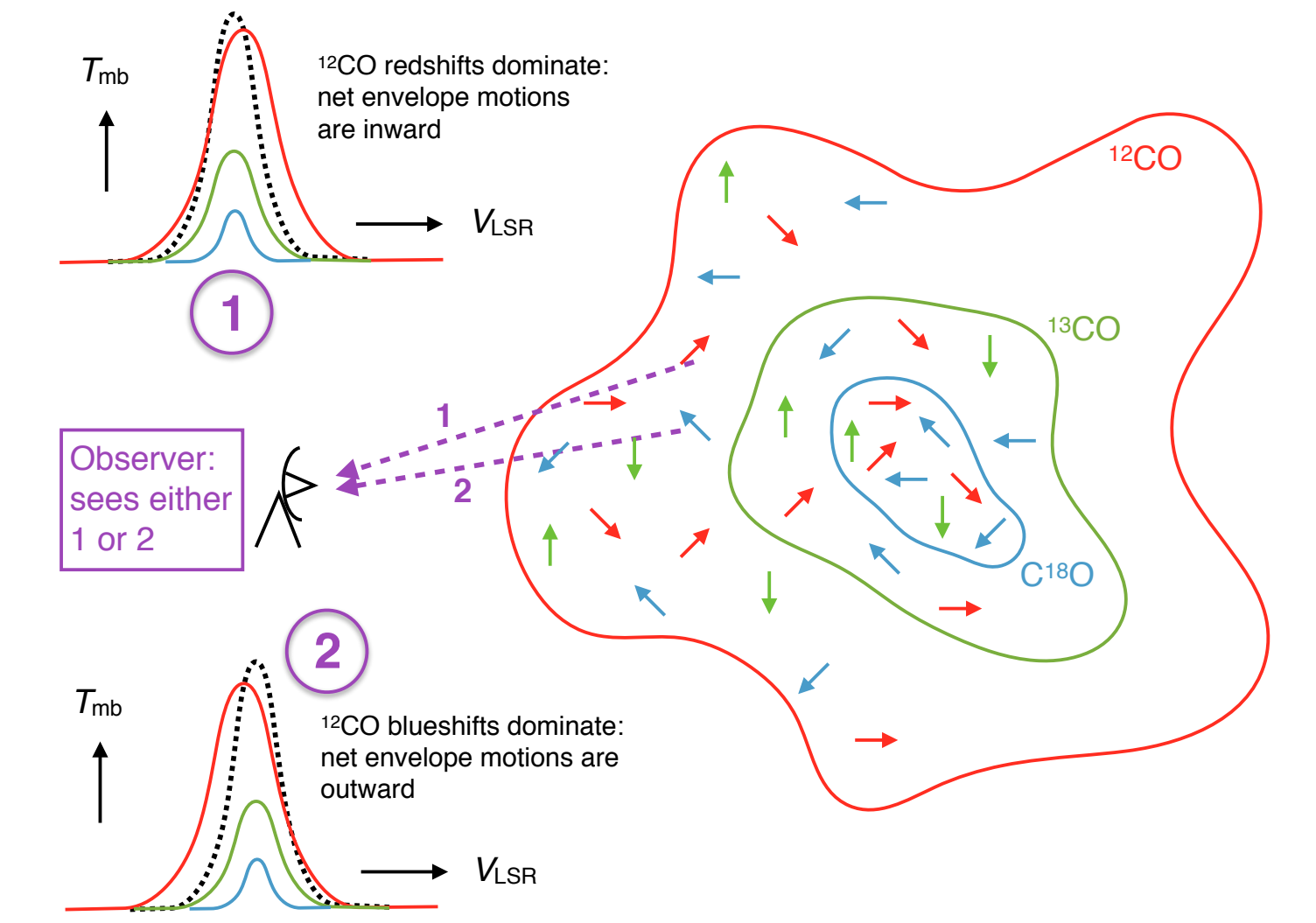
- Compare $\mathcal{N}_{CO}$ with $\mathcal{N}_{dust} \rightarrow \mathcal{N}_{H2}$: derive [CO]/[H_2] (Pitts et al, in prep.)
- Astrochemical models predicting CO abundance variations, from 10^{-5} to 10^{-4}, strongly confirmed



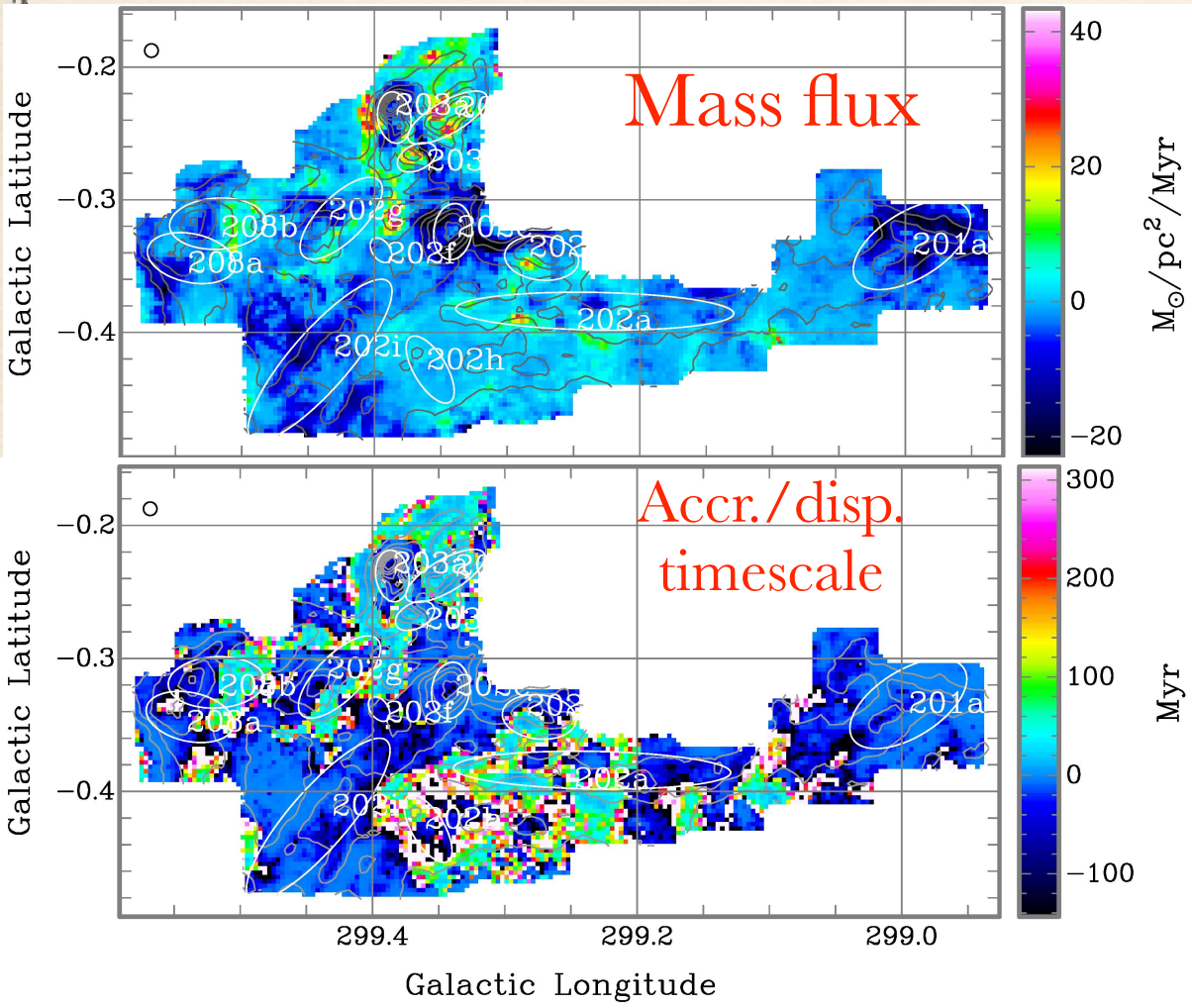


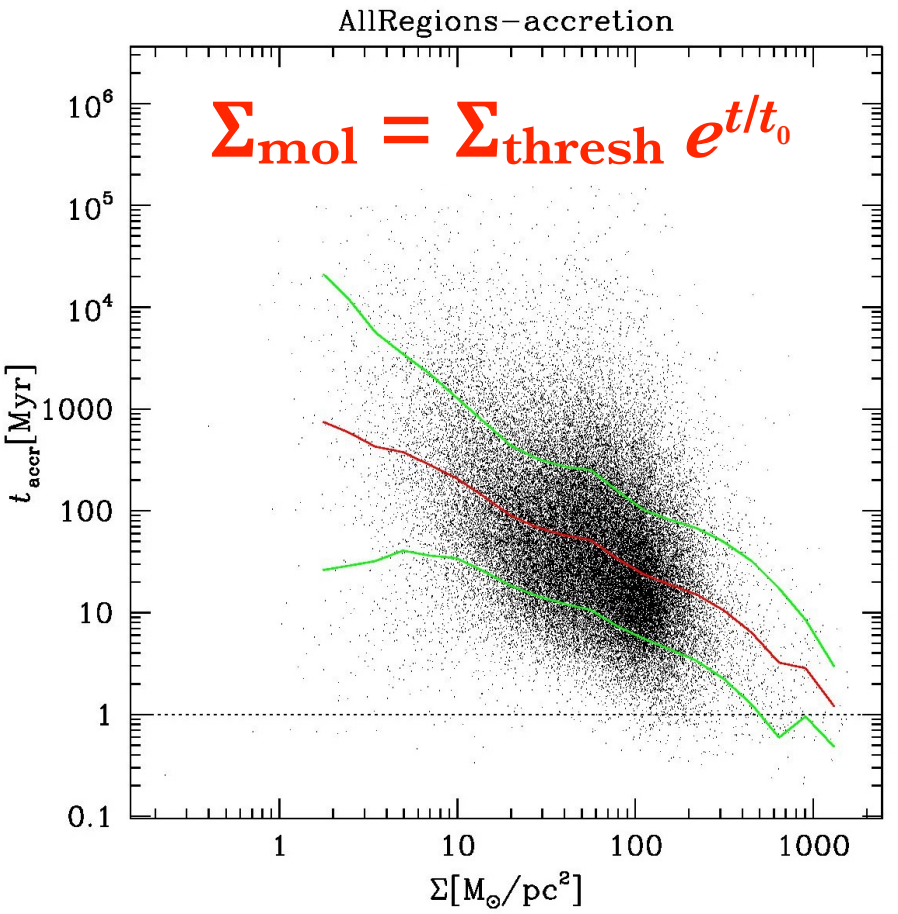
Envelopes vs. interiors

- What about differential dynamics? Compare ^{12}CO envelope material with interior (BHM17, subm.):



Differential dynamics (BHM17, subm.)



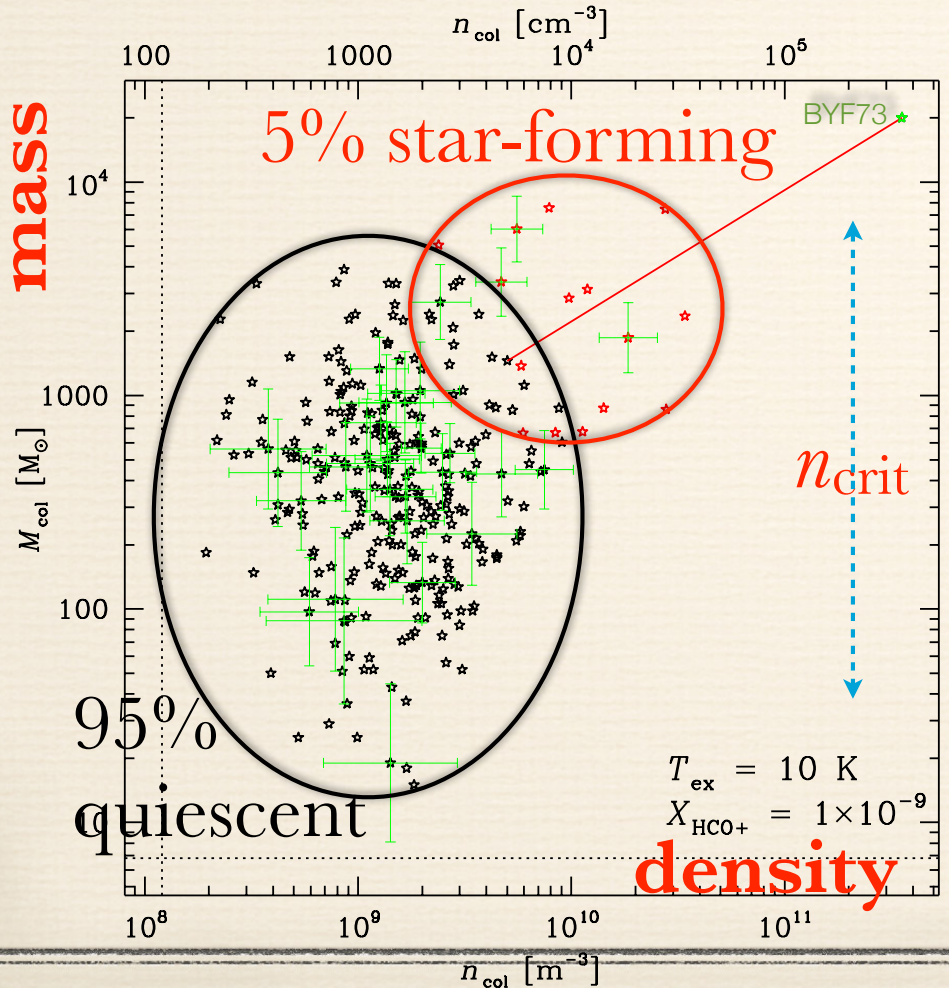


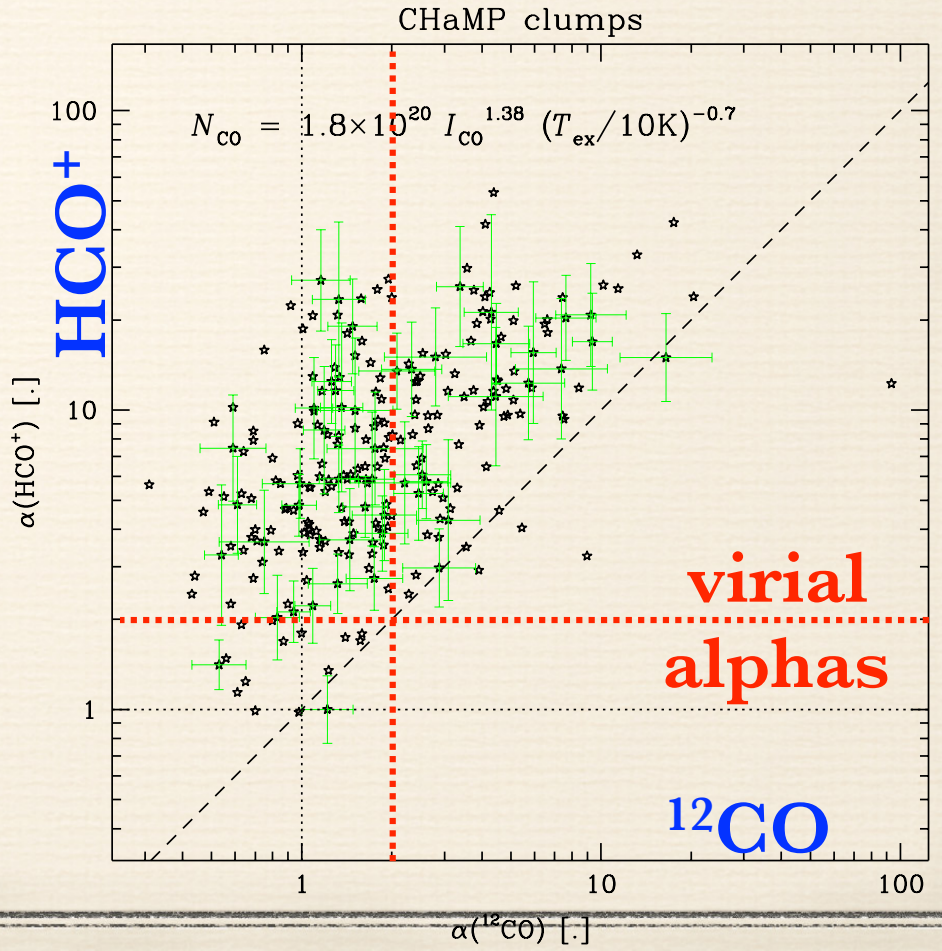
- Although this is just a snapshot, we see direct evidence of cloud ***mass assembly and dispersal***
- All this points to a larger gas reservoir, longer depletion/SF timescales, and other consequences: e.g., L/M unlikely to be an evolutionary indicator for clumps, if M keeps changing

Demographics

- Combine these with prior CHaMP results:

1. A vast population of subthermally-excited, quiescent clouds, implying long latency periods for SF (BYF+2011)
2. Pressure-stabilisation by massive envelopes (BH+2016)





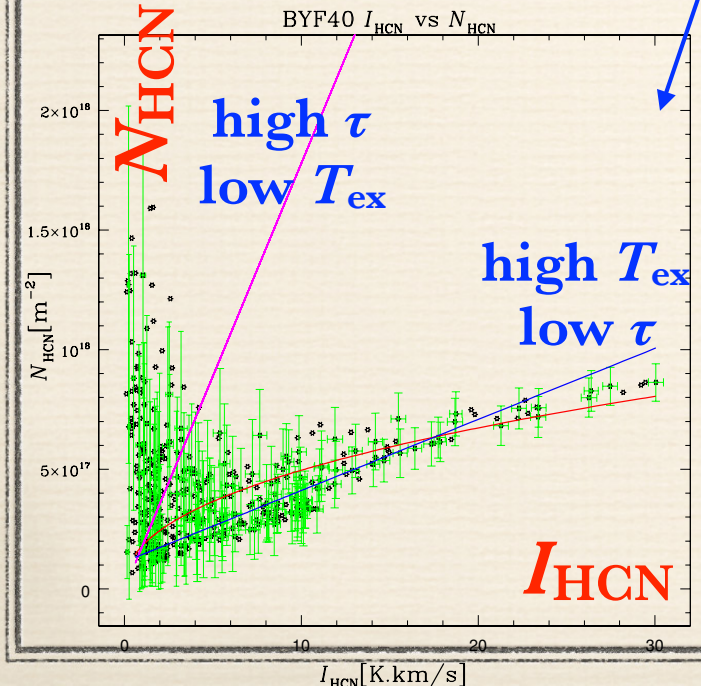
Demographics 2

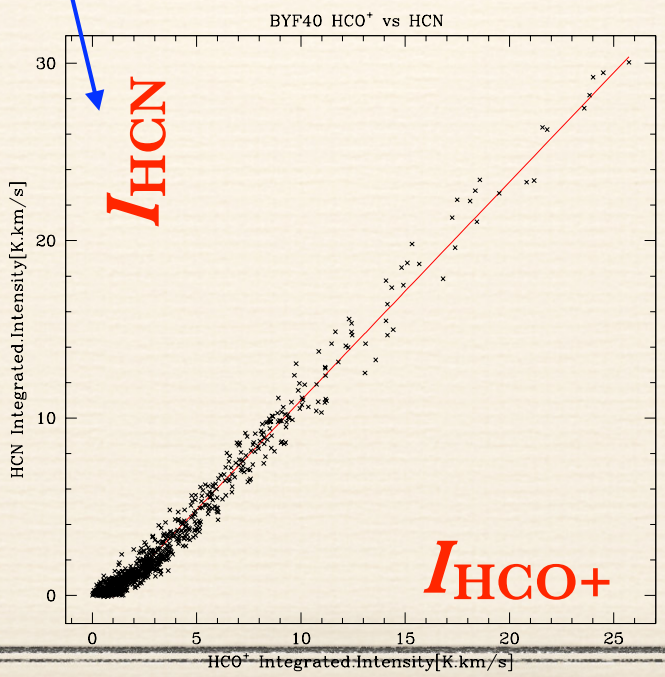
3. "Dense gas" tracers **don't trace dense gas** — they're ***"post-SF feedback indicators"***

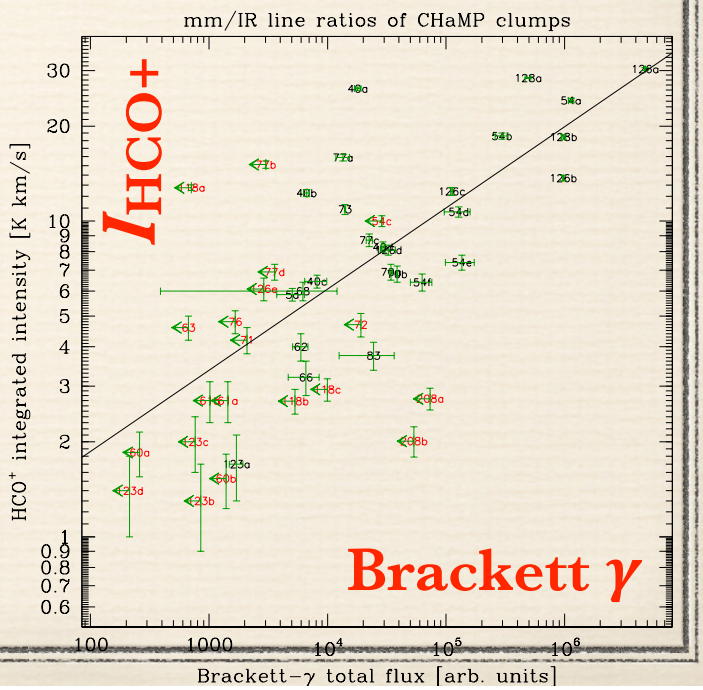
emissivity ≠ mass

Schap et al 2017 – HCN hyperfine line ratio analysis

BYR+2013

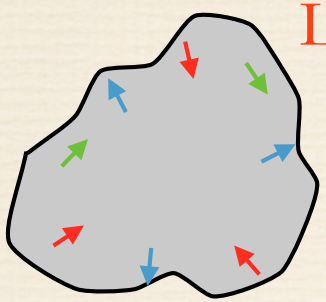




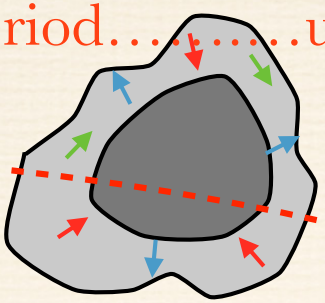


A revised paradigm

Long latency period……up to 100 Myr

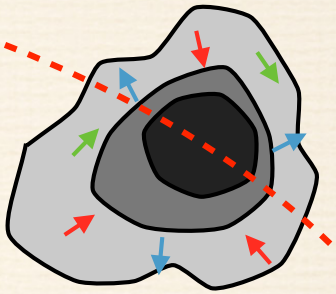


Marginally bound molecular clump forms, **stochastically** accumulates/disperses mass from larger flows, becomes **base unit** of SF



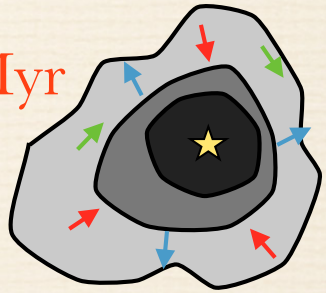
"Denser" clump forms, **pressure-stabilised** by overlying massive envelope; gas mostly **sub-thermal & opaque**, slow accumulation maintains turbulence from exterior

Lower mass protostellar cores form, help maintain interior turbulence; cloud remains cold, "quiescent"



Low- & medium-mass SF **accelerates** during last few Myr

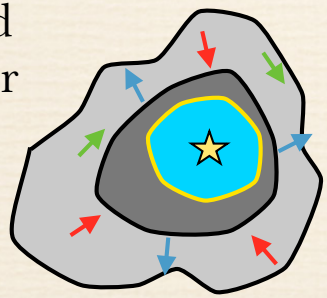
~0.3 Myr



Final, rapid mass inflow, massive protostar(s) & protocluster form

Hot core phase, "**dense gas**" tracers become bright, gas **warms, opacity drops**

~1 Myr



Classic HII region, molecular cloud disperses, cluster revealed

~5 Myr