Class 9: Giant molecular clouds

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Outline

- Measuring GMC mass
  - Optically thin lines
  - Optically thick lines
  - Cross-checks
- GMC properties
  - Cloud decomposition and its challenges
  - Mass distribution
  - Virial parameter and density
- Timescales

Measuring GMCs

Basic considerations

- Dust is most conceptually straightforward, but too faint to use much beyond ~1 kpc from the Sun; big surveys rely almost exclusively on CO, ^{13}CO, HCN
- Some big surveys:
  - CfA (CO 1-0, Galactic — Dame+ 2001)
  - FCRAO (^{13}CO and CO 1-0, Galactic — Roman-Duval+ 2010)
  - PHANGS-ALMA (CO 2-1, extragalactic — Sun+ 2018)
  - EMPIRE (HCN 1-0, extragalactic — Bigiel+ 2016)
- The most basic quantity we want to extract is mass, but even this can be challenging, as we will see

Deriving mass from ^{13}CO

A somewhat simplified version that captures the basic idea

- Given both CO and ^{13}CO, can derive the mass exploiting the fact that CO is almost always optically thick, while ^{13}CO is usually optically thin
- For gas in LTE, emitted intensity obeys $I_\nu = [1 - \exp(-\tau_\nu)]\, B_\nu(T)$
- For CO $\tau_\nu \gg 1$, so $I_\nu \approx B_\nu(T)$; for ^{13}CO, $\tau_\nu \ll 1$, so $I_\nu \approx \tau_\nu B_\nu(T)$; measure I_ν for CO, and assume same T for ^{13}CO → measured I_ν for ^{13}CO immediately gives τ_ν
- In LTE, optical depth given by

Line wavelength

$$\tau_\nu = \frac{\lambda^2}{8\pi}\left(\frac{g_0}{g_1} N_0 - N_1\right) A_{10}\phi(\nu)$$

Line shape function

Columns in states 0 and 1

Degeneracy ratio

Deriving mass from ^{13}CO

Part II

- Since $N_1 = (g_1/g_0)\, N_0\, e^{-E/kT}$, two equations in two unknowns, solve for N_0, N_1
- These are columns of ^{13}CO in states 0 and 1; get total ^{13}CO column assuming LTE, so $N_{tot} = N_0 / Z(T)$, where $Z(T)$ = partition function
- Get total gas column from assumed abundance of ^{13}CO relative to H

Exercise: think of some possible sources of error / uncertainty in this method, and describe the sign of the error (i.e., do you underestimate or overestimate the mass as a result of the error)?

Optically thick lines

Basic considerations

- *A priori*, the idea that you can measure mass using an optically thick line seems crazy: can you measure the thickness of a brick wall by looking at its surface?
- The only reason this works at all is that spectral lines contain a lot more information than the continuum — in particular, they contain information about the velocity distribution
- Conceptual idea: for an optically thick line, integrated brightness is mostly set by the width in velocity, and the width in velocity should be roughly what is required for virial balance. A more massive cloud needs a higher velocity dispersion for virial balance, so mass ↔ velocity width ↔ line brightness

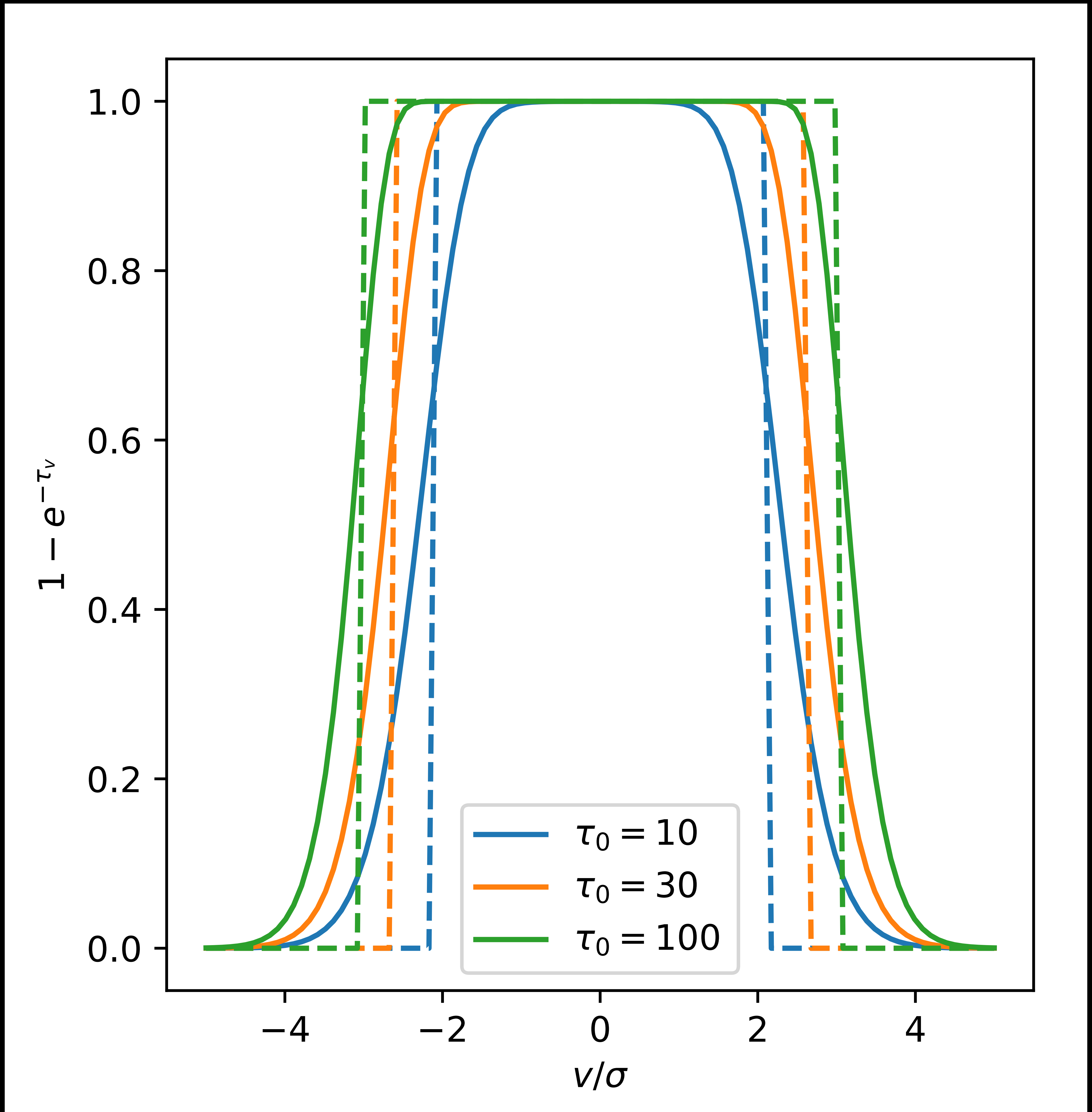
Optically thick lines
Qualitative derivation I

- Consider gas with temperature T and Gaussian velocity distribution of width σ
- Frequency-integrated intensity of emission produced by gas in LTE is given by $\int I_\nu \, d\nu = \int [1 - \exp(-\tau_\nu)] \, B_\nu(T) \, d\nu$
- In radio, usually use brightness temperature and velocity instead of intensity: $W = \int T_{B,\nu} \, dv = \int [1 - \exp(-\tau_v)] \, T \, dv$; second step holds in LTE and RJ-limit
- Given assumed velocity distribution, we have $\tau_v = \tau_{v,0} \exp[-v^2 / 2\sigma^2]$; where $\tau_{v,0}$ is the optical depth at line centre (zero velocity)

Optically thick lines

Qualitative derivation II

- For $\tau_{v,0} \gg 1$, we can approximate $1 - \exp(-\tau_v)$ as a top hat function
- Put jump in top hat at velocity where $\tau_v = 1 \rightarrow v/\sigma = (2 \ln \tau_{v,0})^{1/2}$
- In this case integral is trivial to evaluate: $W = 2\,(2 \ln \tau_{v,0})^{1/2}\,\sigma T$
- Thus W depends linearly on σT, and almost not at all on $\tau_{v,0}$



Optically thick lines

Qualitative derivation III

- Now suppose cloud being observed has mass M, radius R
- Velocity dispersion related to these by $\sigma^2 = \alpha_{\mathrm{vir}} GM / 5R$, so we have line luminosity $W = 2\,[2\,(\ln \tau_{v,0})\,\alpha_{\mathrm{vir}} GM / 5R]^{1/2}\,T$
- Rewrite M and R in terms of surface density $\Sigma = M / \pi R^2$ and number density $n = 3M / 4\pi R^3 \mu m_{\mathrm{H}}$: result is $W = [6\pi G\,(\ln \tau_{v,0}) / 5\mu m_{\mathrm{H}}]^{1/2}\,(\alpha_{\mathrm{vir}}/n)^{1/2}\,\Sigma T$
- Implication: W traces gas surface density with weak dependence on α_{vir}/n, linear dependence on gas temperature (but this varies little)

Optically thick lines

Conversion factors: α and X

- This is usually expressed in terms of the conversion factor: $\alpha_{\rm CO} = \Sigma \,/\, W_{\rm CO}$ and $X_{\rm CO} = N \,/\, W_{\rm CO} = (\Sigma/\mu m_{\rm H}) \,/\, W_{\rm CO}$; same idea for HCN
- Conversion factors depend only on $\alpha_{\rm vir}/n$ and T; conversion factors should be relatively constant, as long as these vary little
- Problems in two regimes:
  - At low metallicity, CO may not be abundant enough to be optically thick
  - In starburst / merging galaxies, gas density and temperature may be higher, and velocity dispersion may be super-virial

Cross-checking the conversion factors

Two main methods

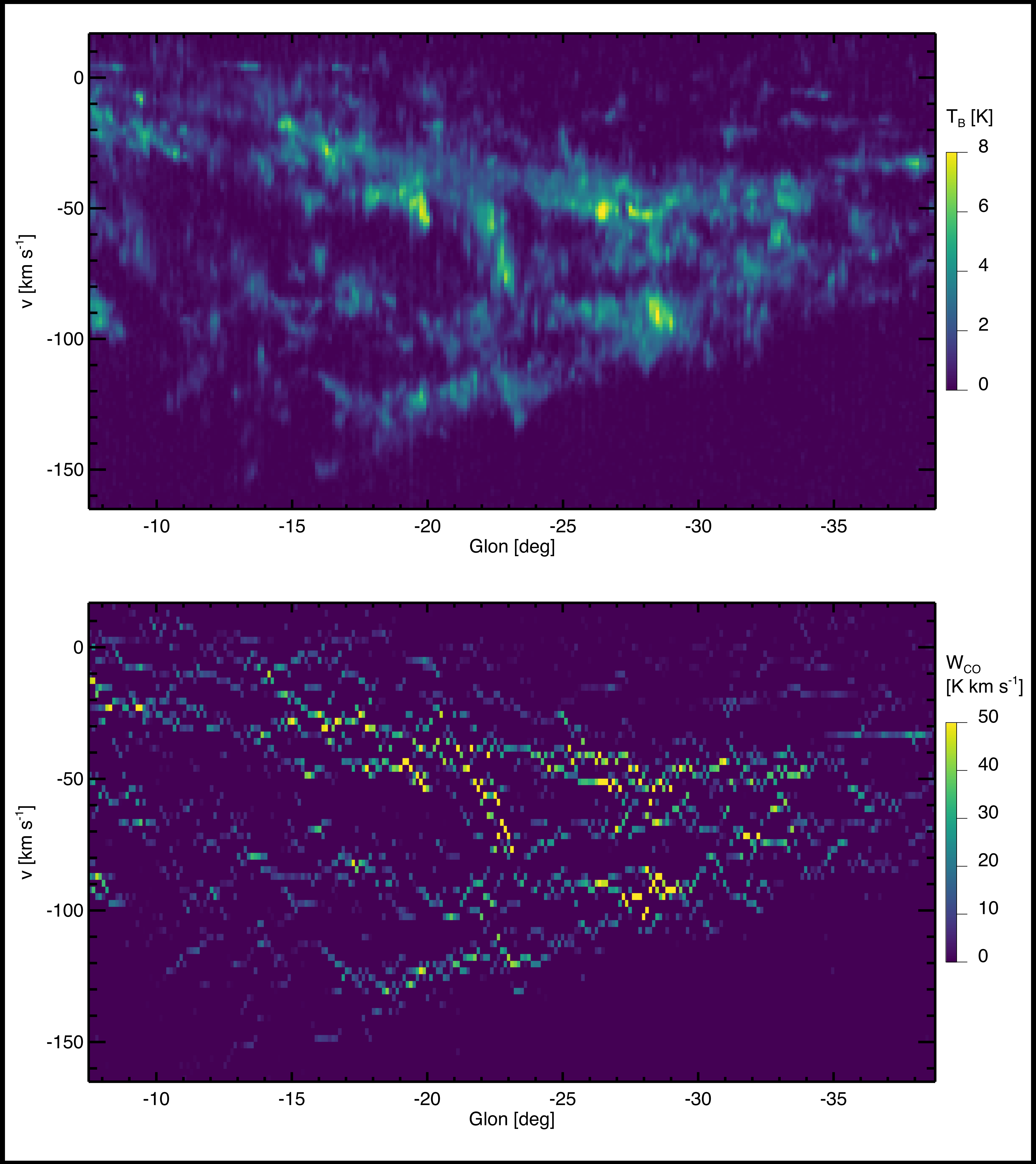
- In nearby clouds, can compare column inferred from conversion factor to value inferred from dust emission
- γ-rays produced by CR interactions with gas; CR density in Galaxy fairly constant, so γ-ray brightness along a given line of sight just scales with number of H nuclei; thus γ-ray brightness measures column density
- Values in Milky Way from both methods fairly consistent: $\alpha_{CO} \approx 4\ M_\odot\ \mathrm{pc}^{-2}$ / (K km s^{-1})
- Higher in low metallicity galaxies, lower in starbursts

Exercise: try plugging some reasonable values into our theoretically-derived estimates of the conversion factor. How do they compare to the empirical calibrations?

Results from surveys

A starting caution

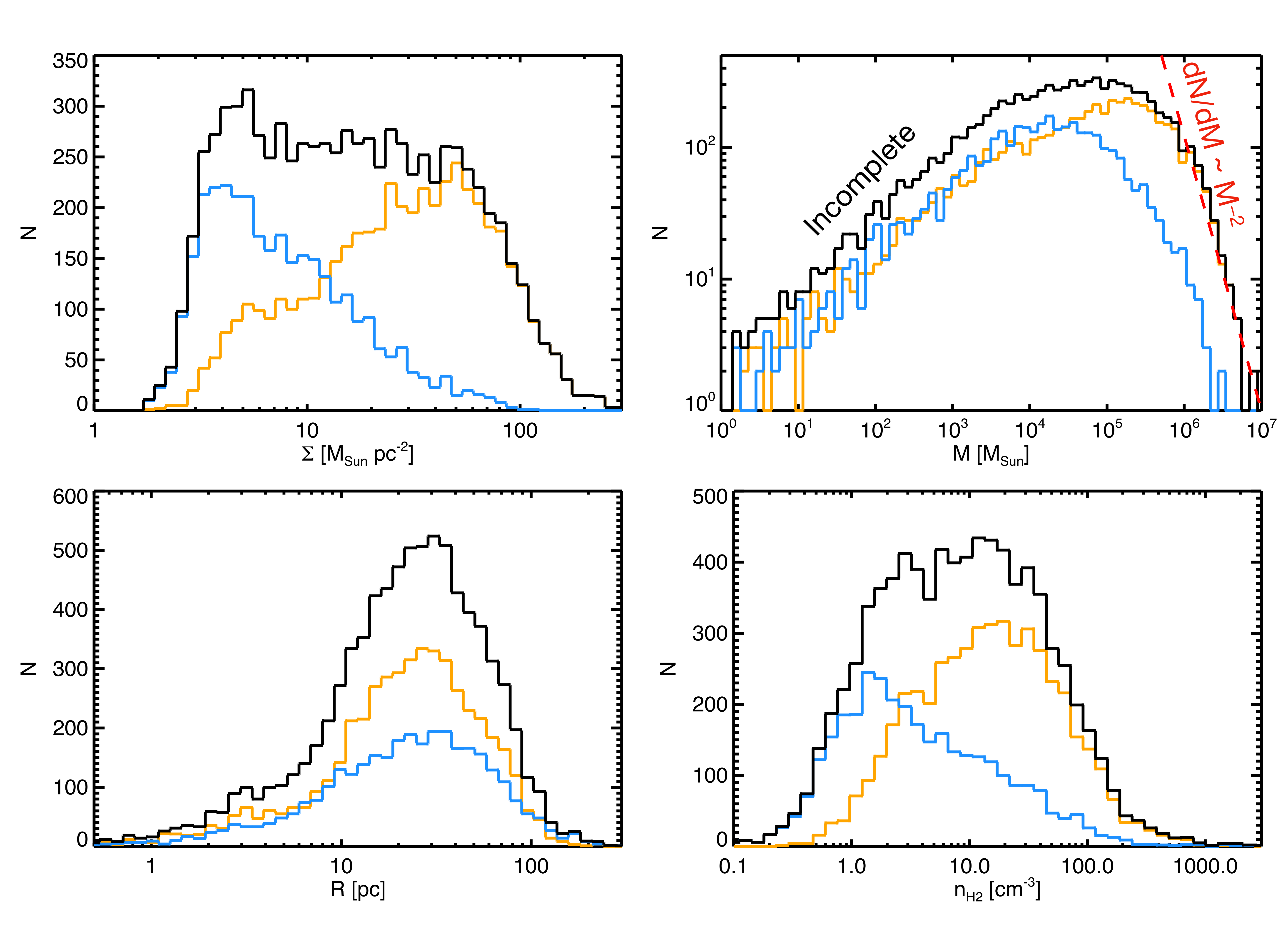
- We will now discuss basic empirical results of GMC studies
- Fundamental problem: decomposing the observed CO emission into GMCs is very uncertain, particularly in molecule-rich regions
- Decomposition usually done in PPV space, but structures are complicated, partly overlapping



Miville-Deschênes+ 2017; top is observed CO distribution, bottom is decomposition into discrete clouds.

Basic results for the Milky Way

- Σ ~ 10s of $M_\odot$ pc^{-2}; varies with environment, so ~100 in inner Galaxy, ~10 in outer
- Mass function $dN/dM \sim M^{-2}$ or slightly shallower at high mass end; most mass in big clouds, $M \gtrsim$ few $\times$ 10^5 $M_\odot$
- Typical size ~30 pc
- Typical density ~30 H_2 cm^{-3}; corresponds to free-fall time ~ 10 Myr

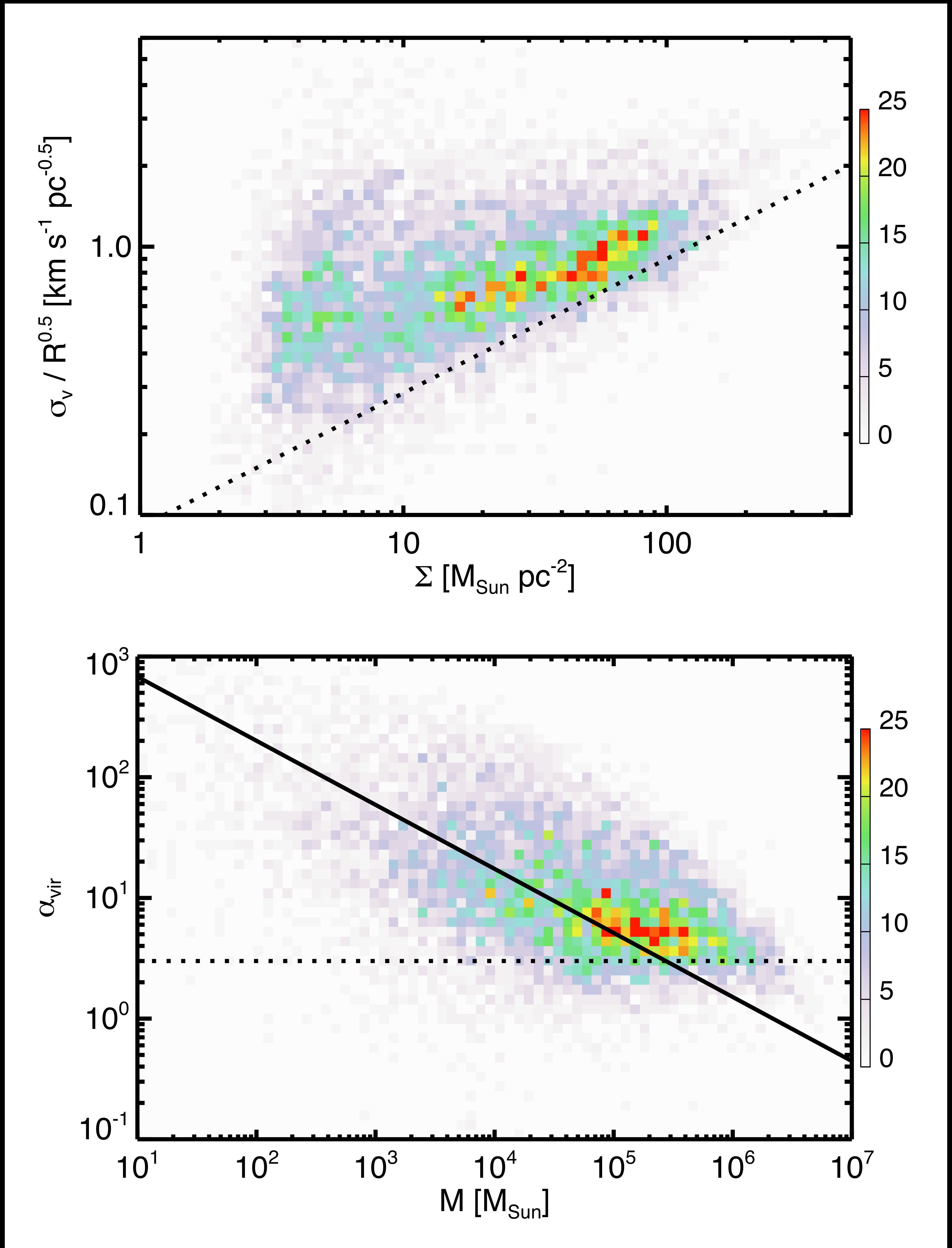


Miville-Deschênes+ 2017; blue = outer Galaxy, orange = inner Galaxy

LWS and Virial Parameter

For the Milky Way

- Clouds follow a linewidth-size relation σ / $R^{1/2}$ ~ constant, weak dependence on Σ
- Massive clouds have virial parameters close to unity; low-mass clouds are super-virial
- However, recall that most mass is in massive clouds; thus most molecular gas in the Galaxy is in molecular clouds with α_{vir} ~ few



Miville-Deschênes+ 2017

Timescales for GMCs

- Most basic timescale is free-fall:

M / 10^6 $M_\odot$ Σ / 100 $M_\odot$ pc^{-2}

$$t_{\rm ff} = \sqrt{\frac{3\pi}{32 G\rho}} = \sqrt{\frac{\pi^2}{8G}} \frac{M^{1/4}}{\Sigma^{3/4}} = 7 M_6^{1/4} \Sigma_2^{-3/4} \text{ Myr}$$

- Crossing time is closely related to this: $t_{\rm cr} = \frac{R}{\sigma} \approx \frac{2}{\sqrt{\alpha_{\rm vir}}} t_{\rm ff}$
- Two more timescales of great interest:
  - Depletion time = time that would be required to convert all of the gas into stars
  - Lifetime = time for which an individual GMC lives; somewhat nebulous, depends on definition of "live", but interesting nonetheless
- We want to know ratios of these timescales to free-fall / crossing time

Gas depletion time

Definitions and global considerations

- Define depletion time $t_{\mathrm{dep}} = M_{\mathrm{gas}}$ / SFR and star formation efficiency per free-fall time $\varepsilon_{\mathrm{ff}} = t_{\mathrm{ff}} / t_{\mathrm{dep}}$; $\varepsilon_{\mathrm{ff}}$ = fraction of mass converted to stars per t_{ff}

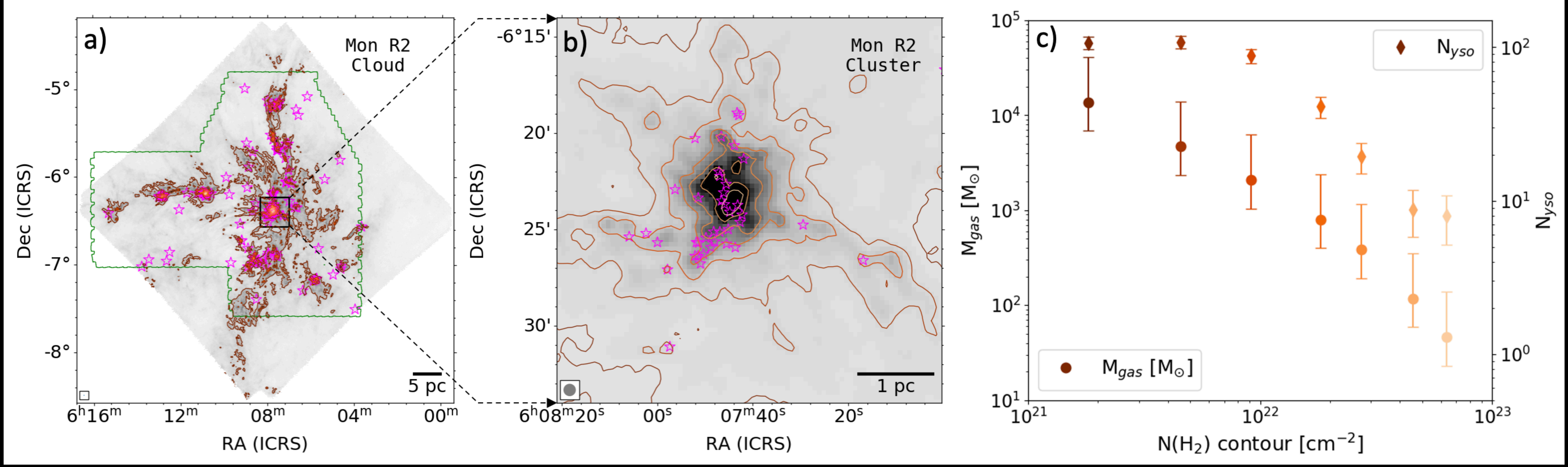
- For Milky Way, total GMC mass ≈ 10^9 $M_\odot$ and total SFR ≈ 1 $M_\odot$ yr^{-1}, so $t_{\mathrm{dep}} \approx$ 1 Gyr; for mean GMC free-fall time $t_{\mathrm{ff}} \approx$ 1 Myr, we have mean $\varepsilon_{\mathrm{ff}} \approx 0.01$

- However, this does not necessarily mean that this value applies to all clouds; could be that most clouds don't form stars at all ($\varepsilon_{\mathrm{ff}} = 0$), while some small fraction have much larger $\varepsilon_{\mathrm{ff}}$

- Investigation tricky due to timescale issues: short enough so that one can't assume tracers like Hα or IR are reliable

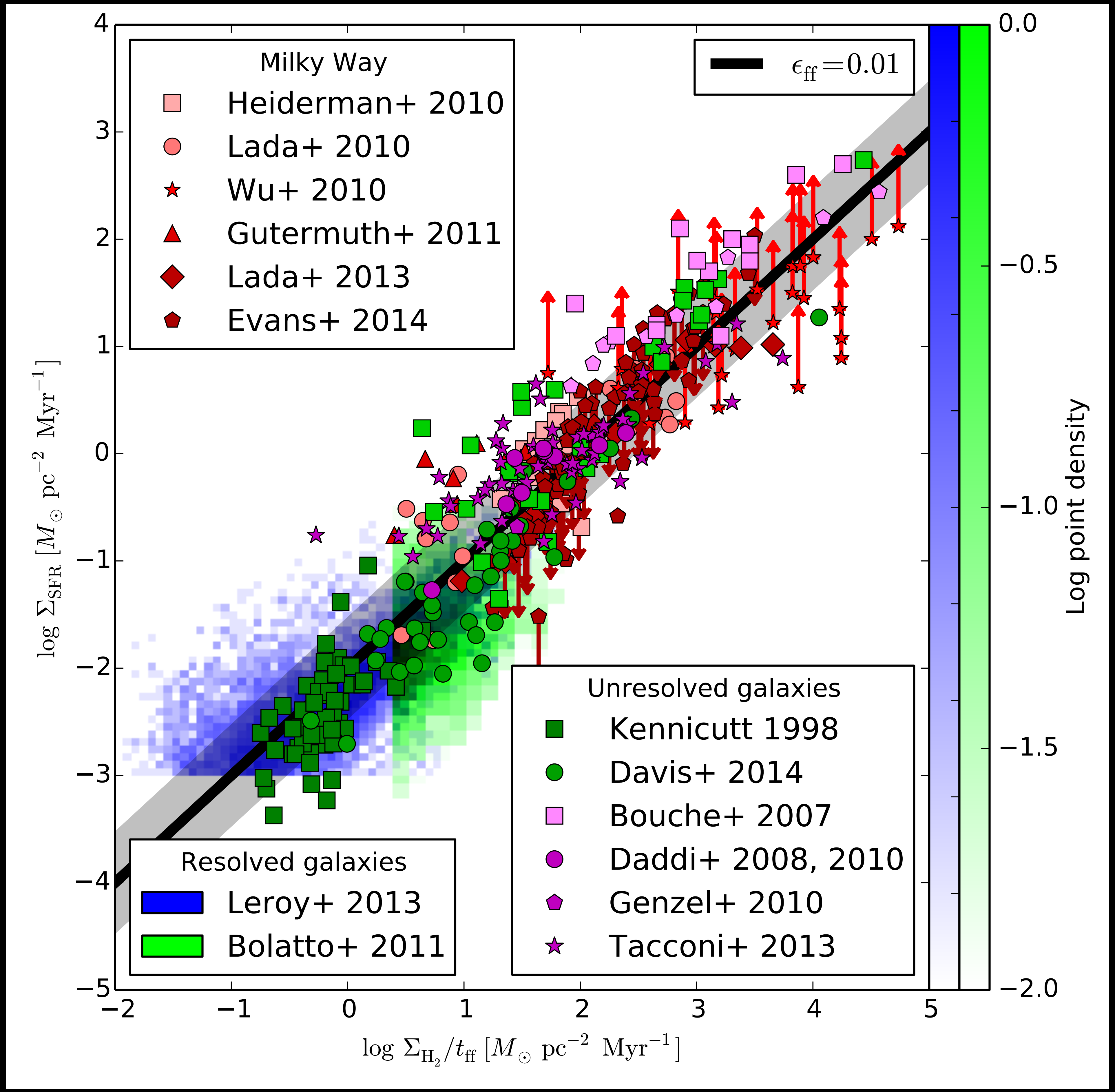
Measuring cloud depletion times

- Most reliable method is counting class 0/I YSOs: lifetime $t_{YSO} \approx 0.5$ Myr, mean mass $m_{YSO} \approx 0.5\ M_\odot$ (from IMF), so SFR $\approx N_{YSO}\, m_{YSO} / t_{YSO}$
- Draw column density contours on clouds; measured enclosed mass M_{gas} from dust, enclosed area, estimate t_{ff} by assuming depth along LOS ~ (area)$^{1/2}$
- Resulting estimate: $\varepsilon_{ff} = (M_{gas}/\mathrm{SFR}) / t_{ff}$

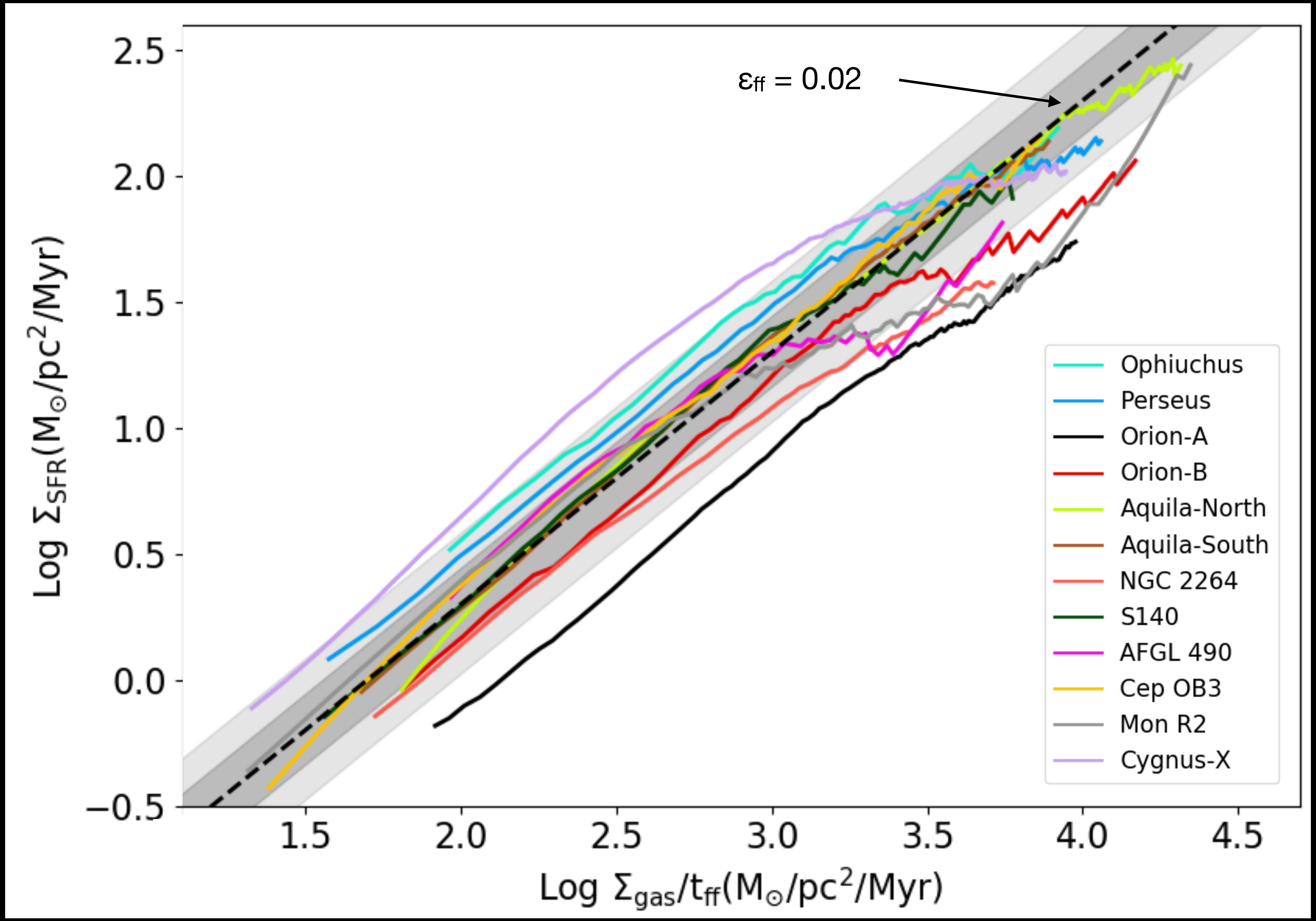


Pohkrel+ 2020, in prep

Results for ε_{ff} measurements



Krumholz 2014 — each red point represents one cloud



Pokhrel+ 2020 in prep — each line shows different contour levels within a single cloud

Lifetimes of GMCs

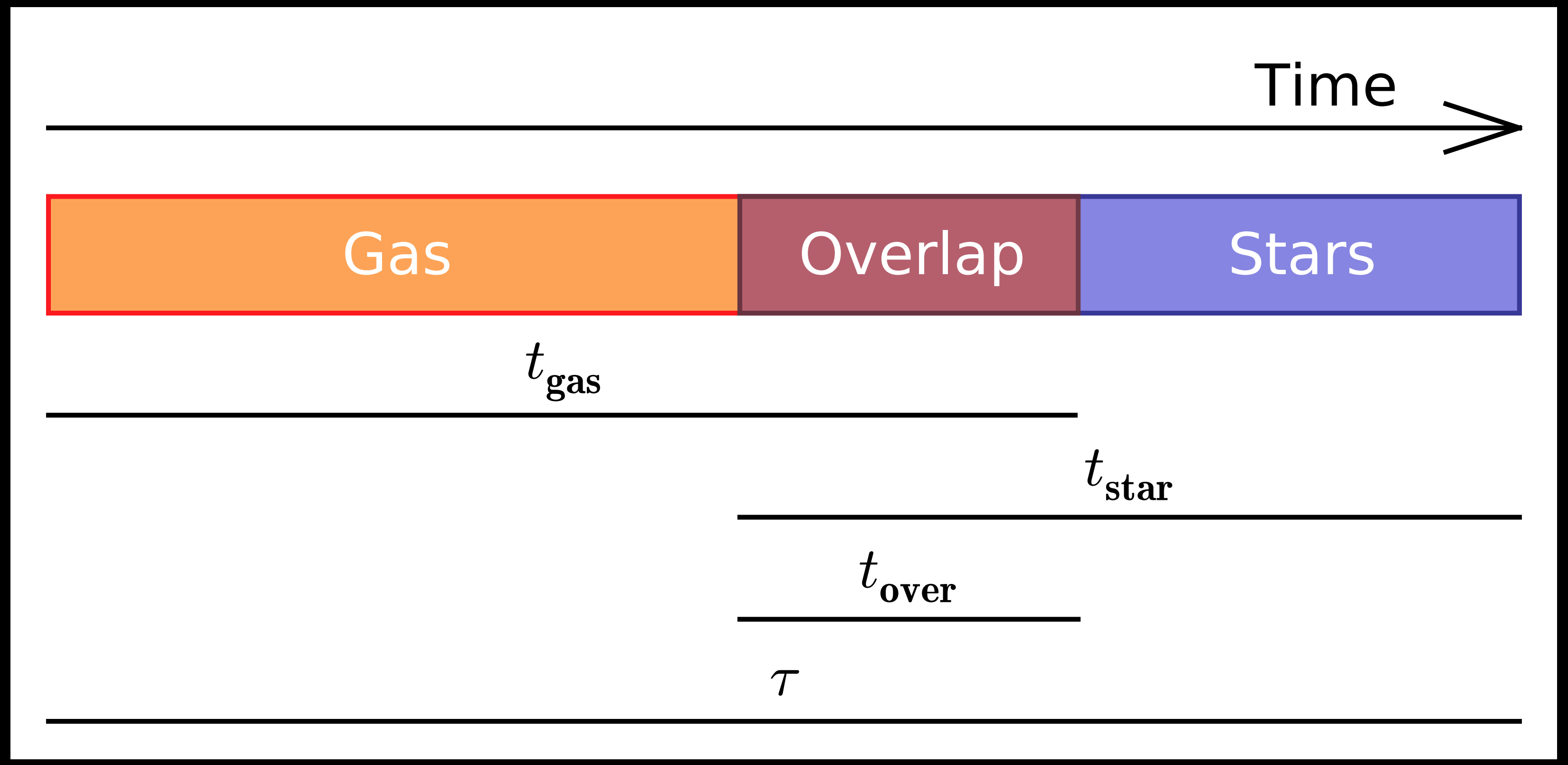
A tricky thing to measure

- Gas depletion times ~1 Gyr — but do clouds live this long, or are they disrupted by stellar feedback or something else first?
- Measuring lifetime is hard, since we can't just wait and watch (most PhD students are not willing to wait 1 Gyr to get their PhDs)
- No intrinsic "clocks" in GMCs — but stars do represent a clock, since we understand (we think) stellar lifetimes
- Basic idea: use statistical correlation between stars (or things that stars produce, like Hα) and gas to estimate GMC lifetimes

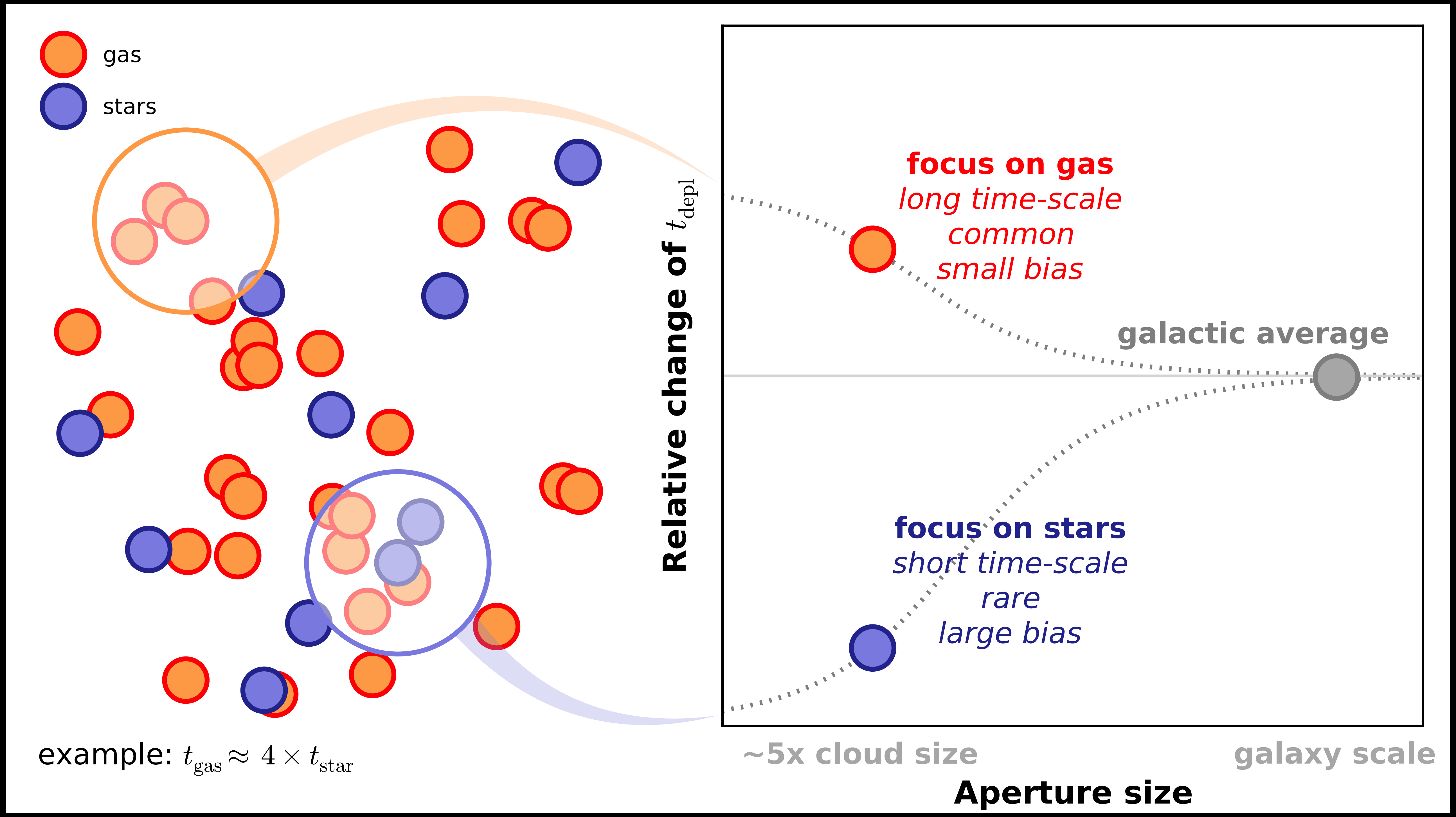
Statistical method

A cartoon version

- Measure ratio of M_{gas} to SFR in a big aperture — ratio gives mean value of t_{dep} for galaxy
- As aperture shrinks, measured t_{dep} changes:
  - Larger if aperture catches a gas cloud that has not yet formed many stars
  - Smaller if it catches a region where many stars have formed and cloud is disappearing



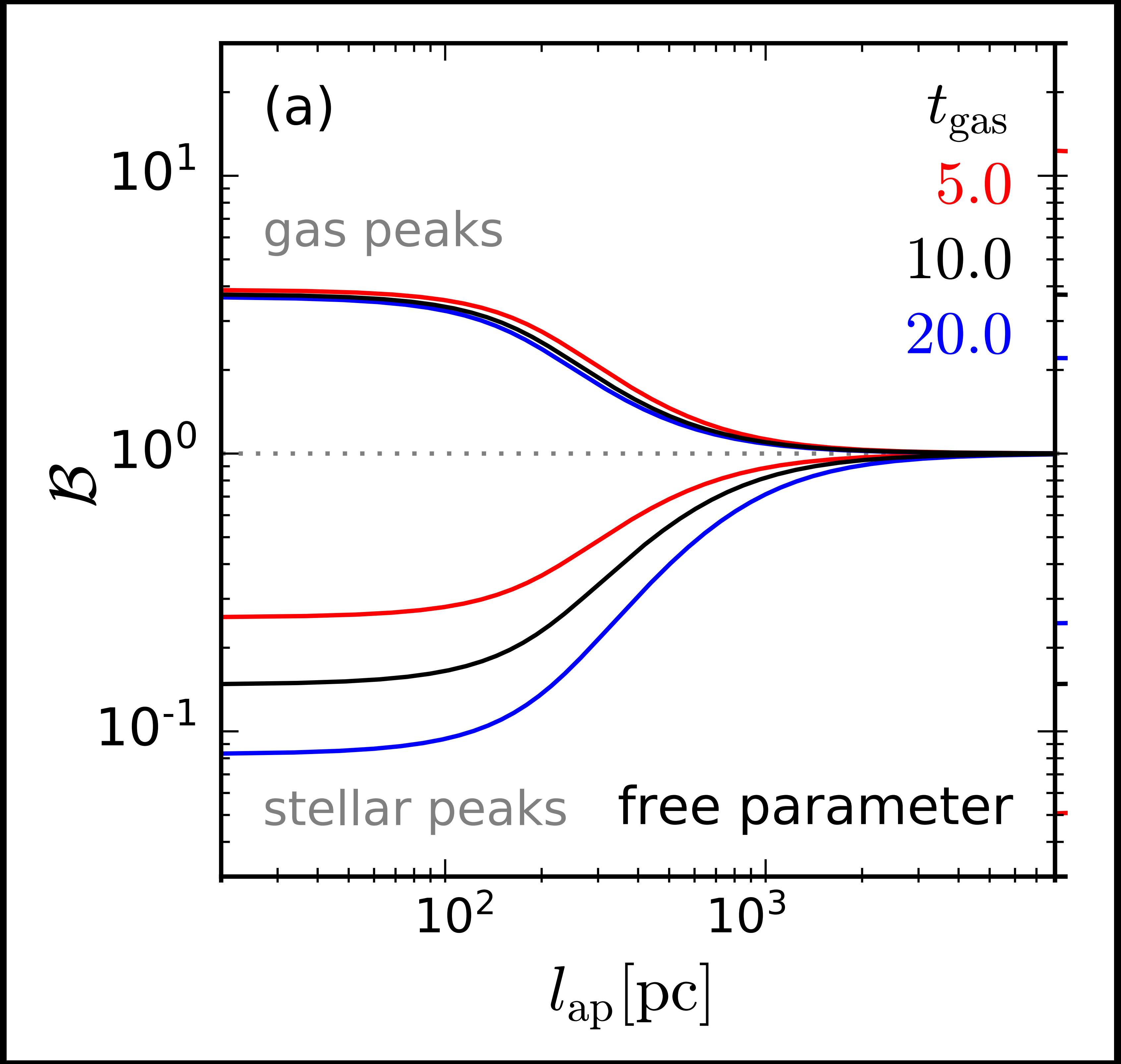
Kruijssen+ 2018



Statistical method

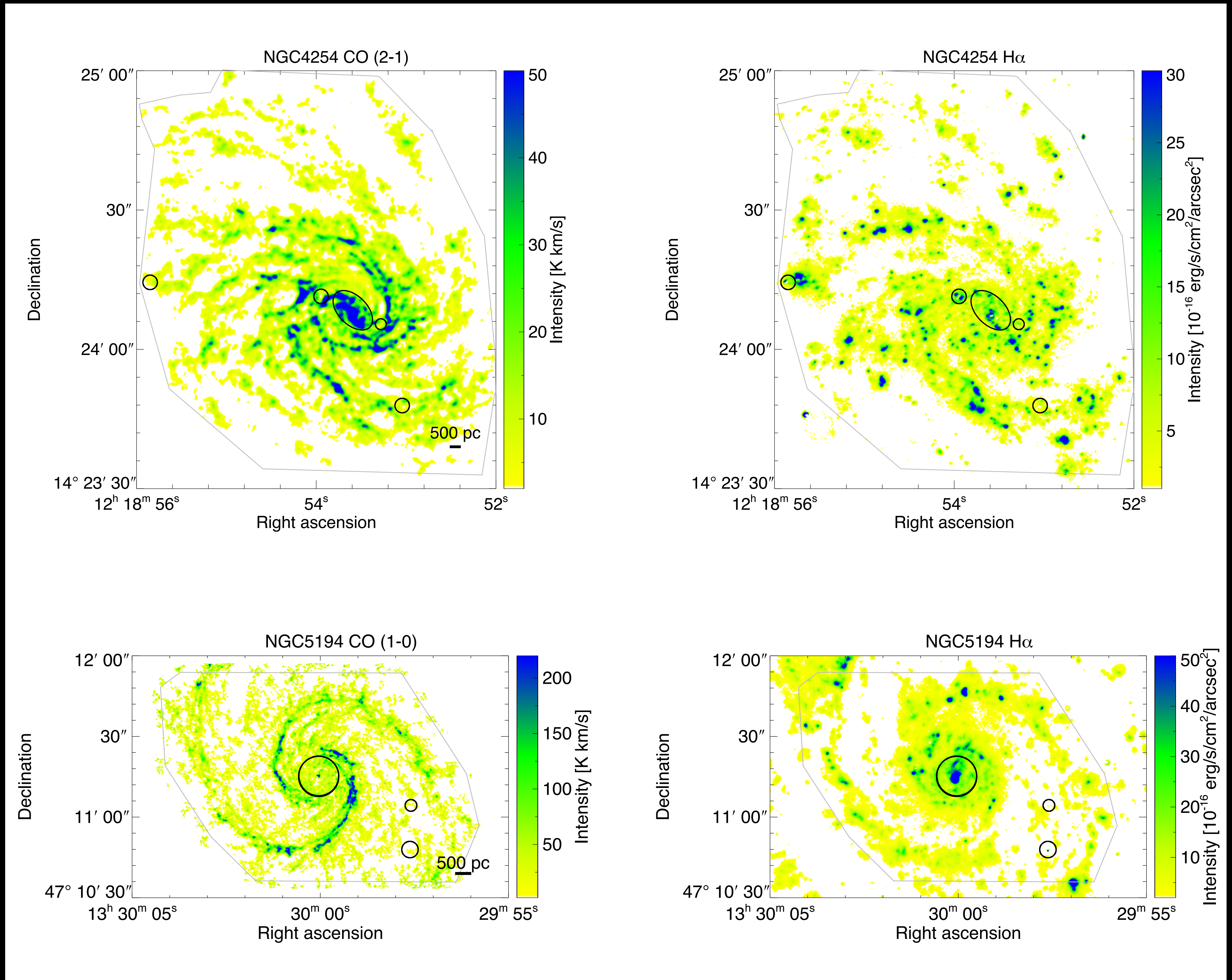
Cartoon version II

- Time for which “star clusters” are “on” is set by stellar evolution
- As gas lifetime gets longer relative to this, clouds get more common relative star clusters
- Apertures focused on star clusters must show smaller $t_{\rm dep}$ relative to mean of galaxy in order to compensate for larger number of gas clouds
- Fit $\mathscr{B} = t_{\rm dep}(\ell) / \langle t_{\rm dep} \rangle$ as a function of aperture size ℓ to constrain cloud lifetime

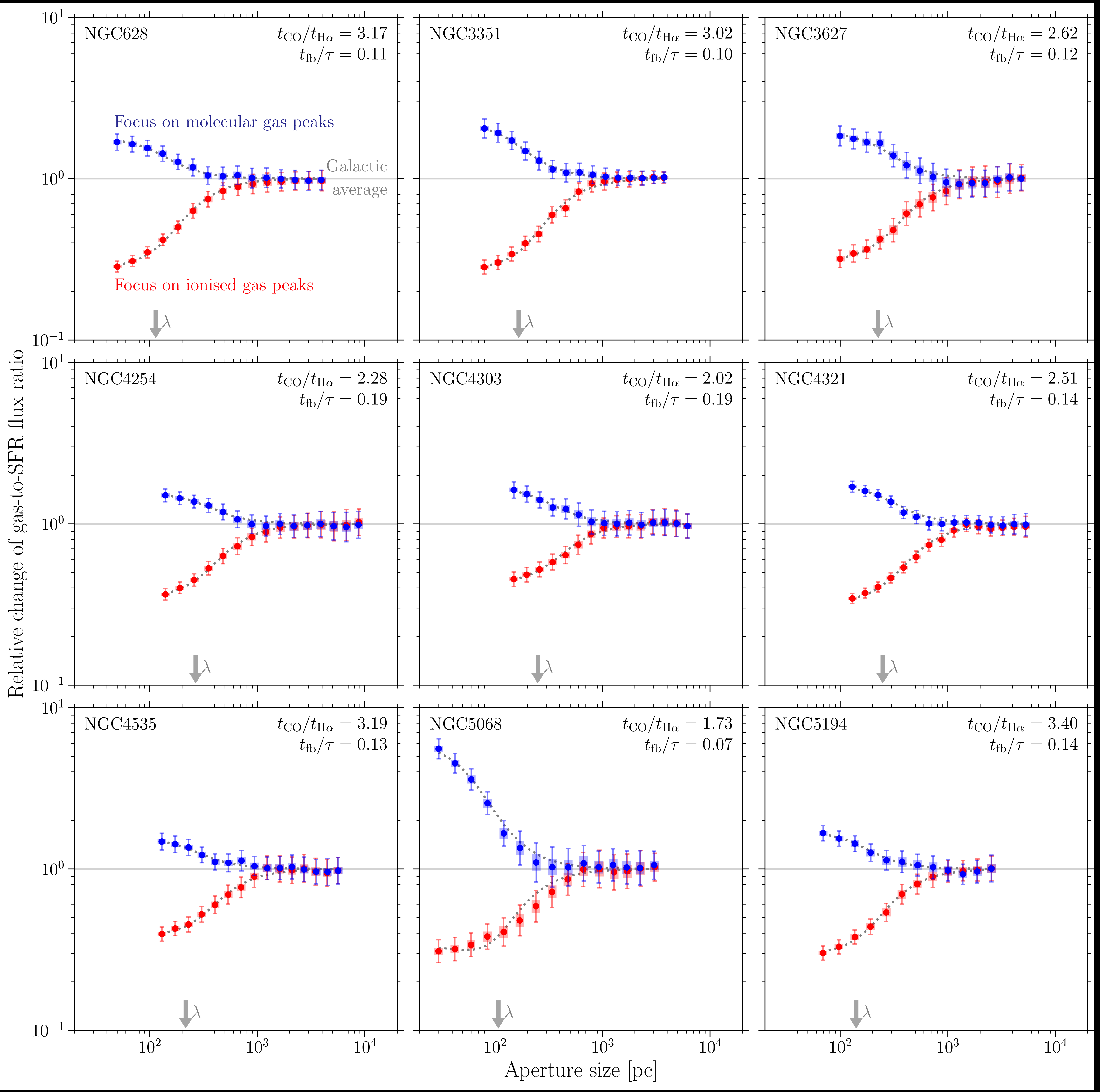


Kruijssen+ 2018

The statistical method in practice



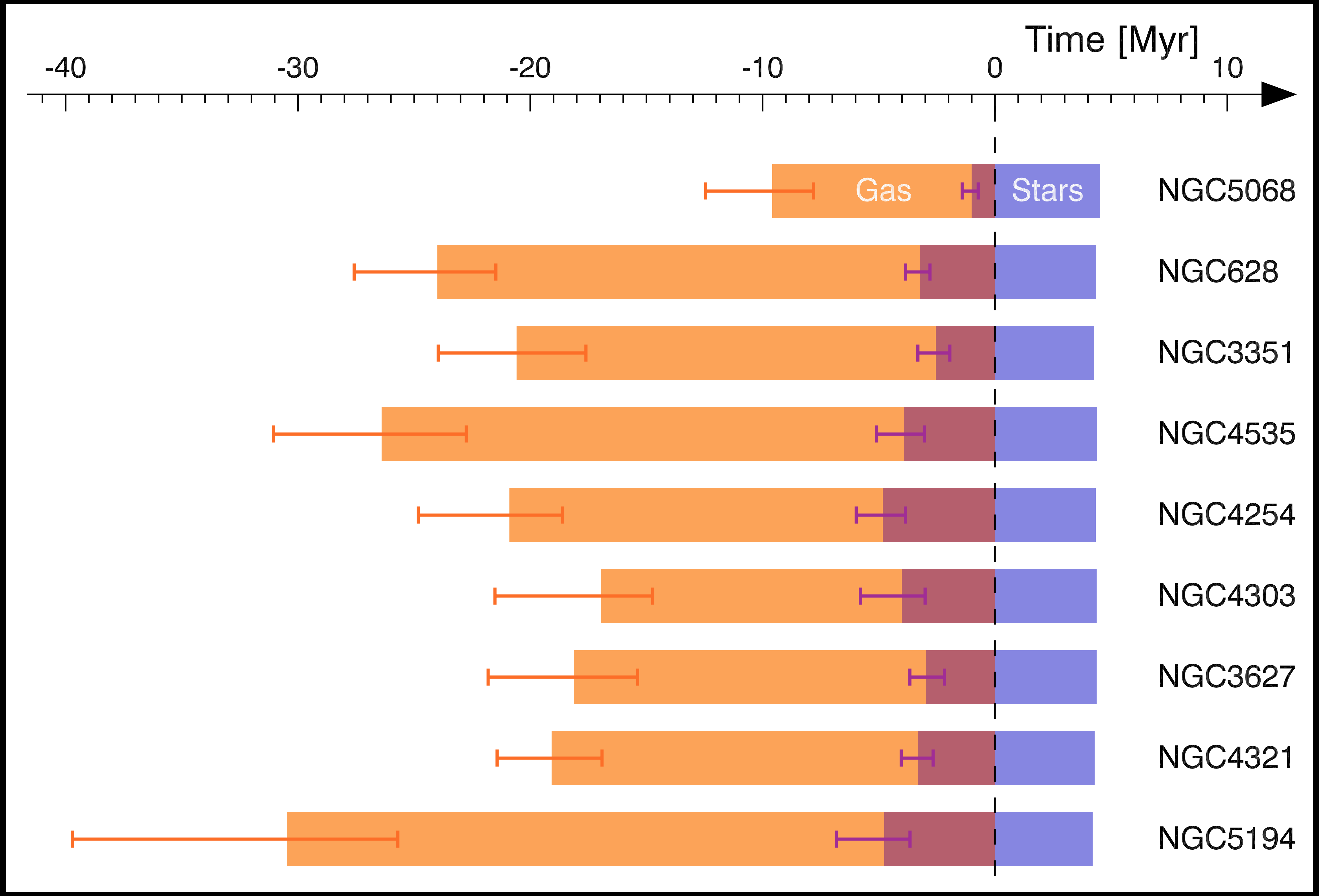
Chevance+ 2020



GMC lifetimes

Results and implications

- Mean GMC lifetime is ~20-25 Myr, which is a few × $t_{\rm ff}$
- Short lifetime means GMCs only have time to convert ~5% of their mass to stars before dying
- Short “overlap” phase means GMCs disrupted quickly once (massive) stars form



Chevance+ 2020