The cool Galactic ISM and star formation

Zooming in on the Physical Processes Driving Star-Formation and Galactic Evolution

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Outline

1. Tracers of the ISM
2. Phases of the ISM
3. The properties of Galactic molecular clouds
4. Distribution of molecular gas in the Milky Way
5. The turbulent properties of molecular clouds
6. The ISM and star formation

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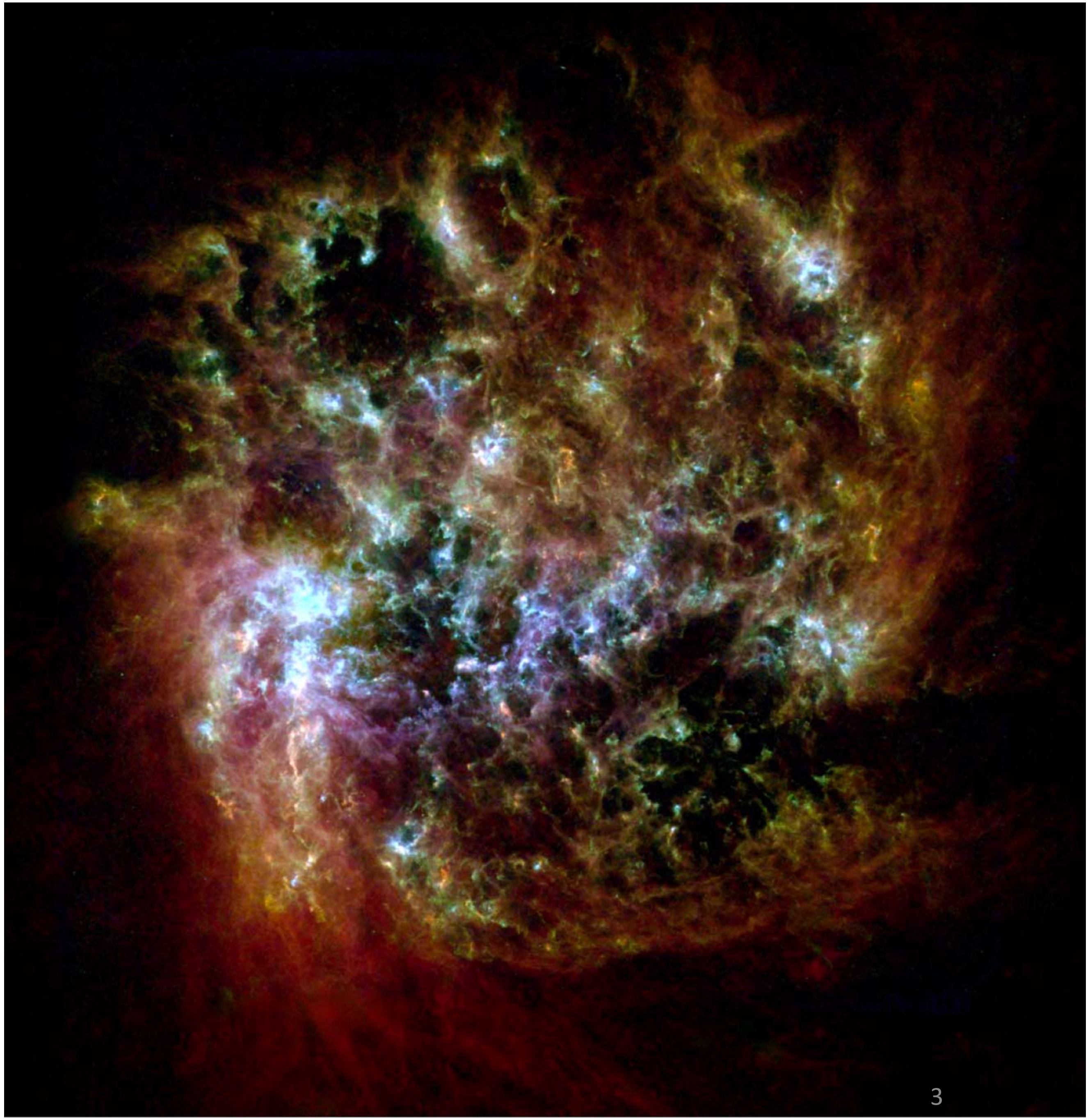
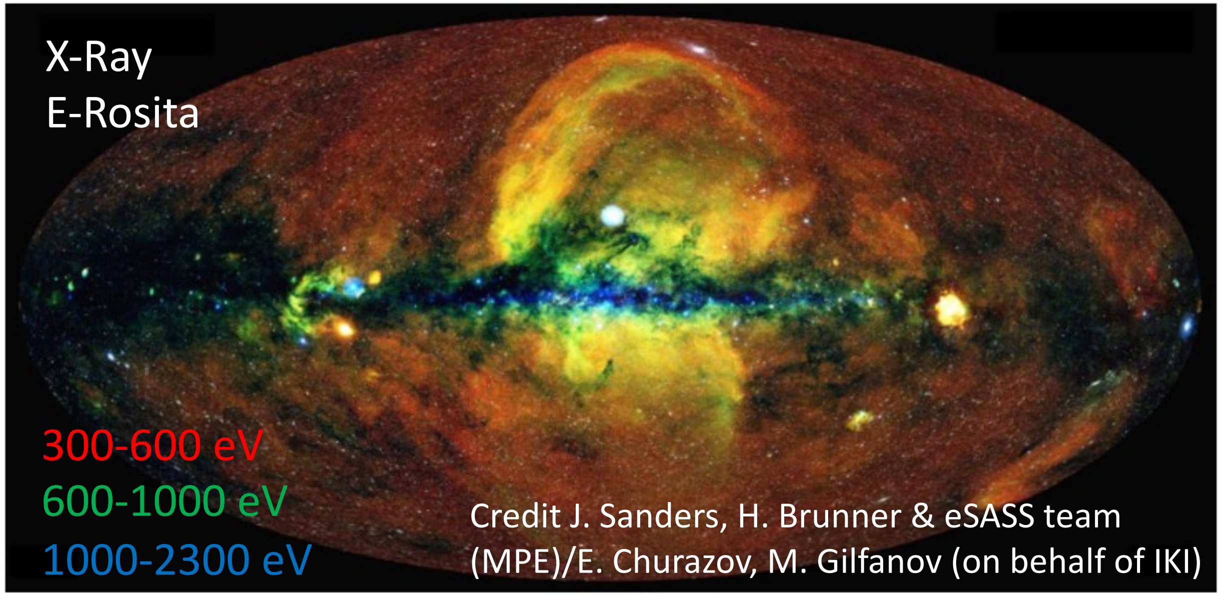
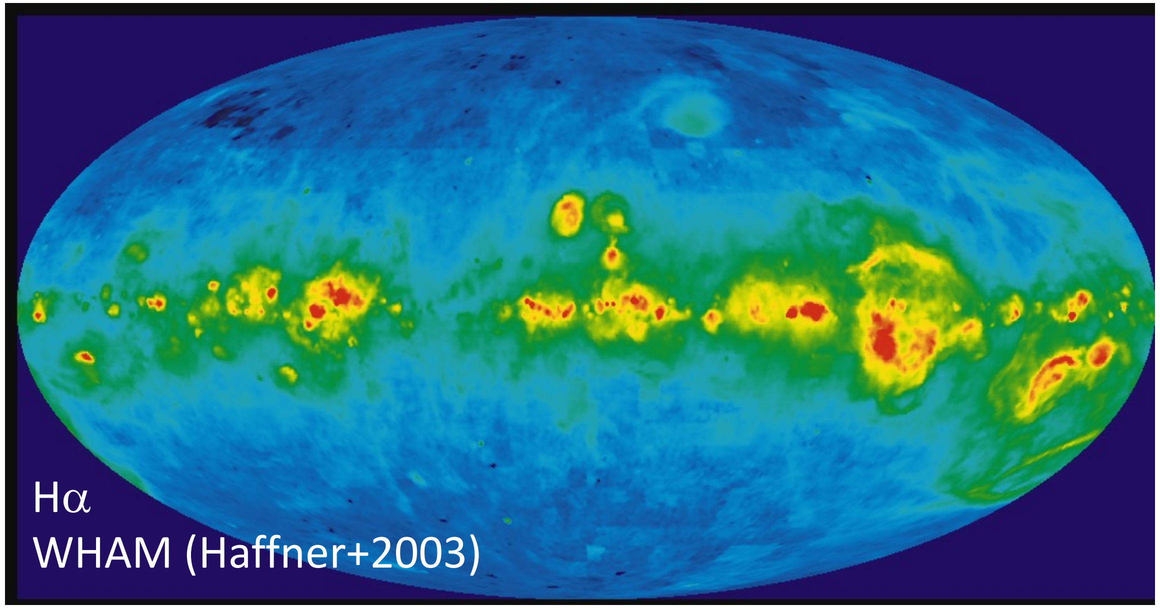
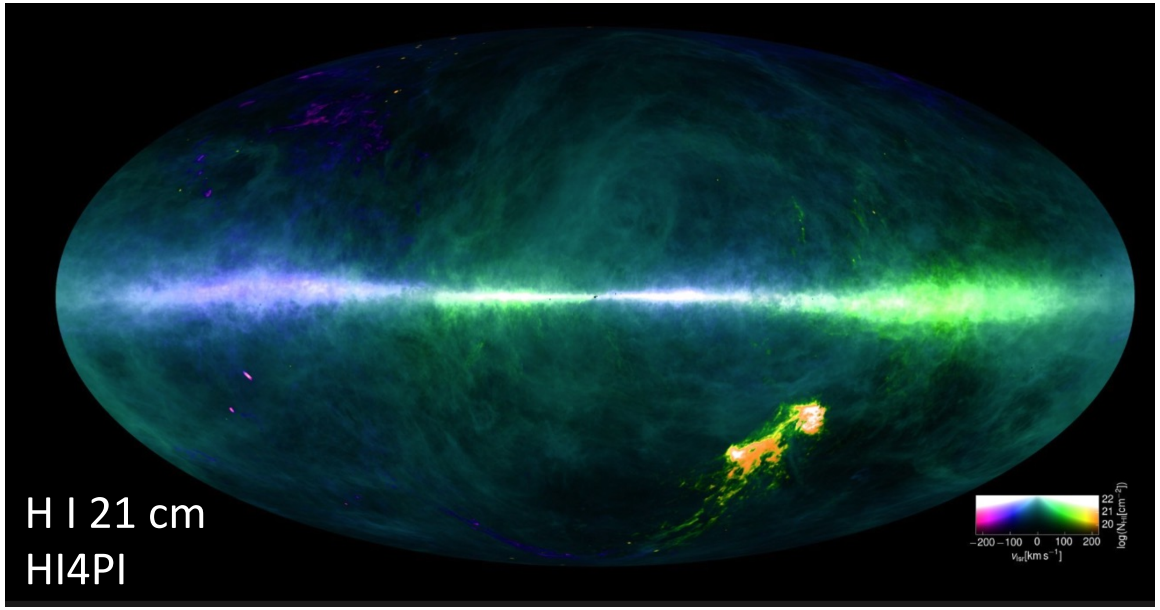
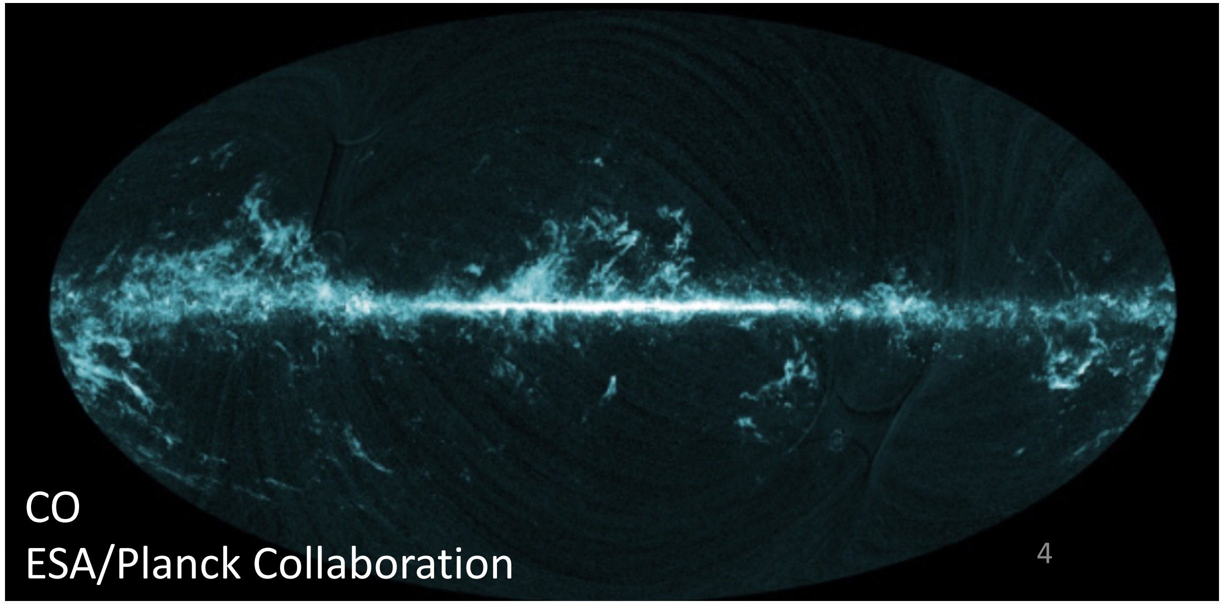


Observing the phases of the Galactic ISM



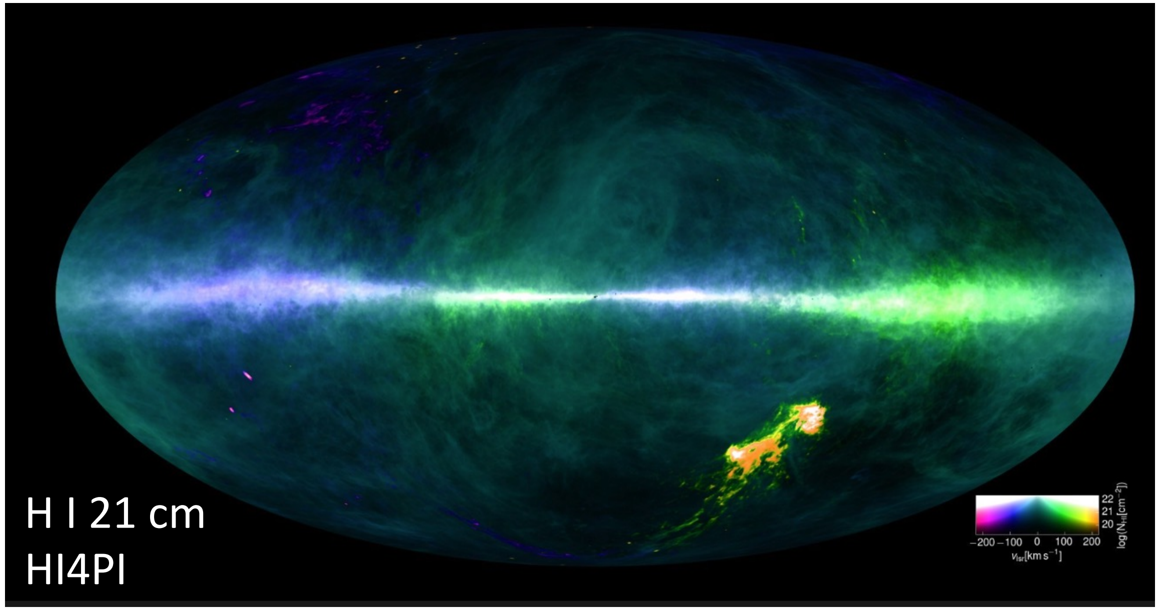


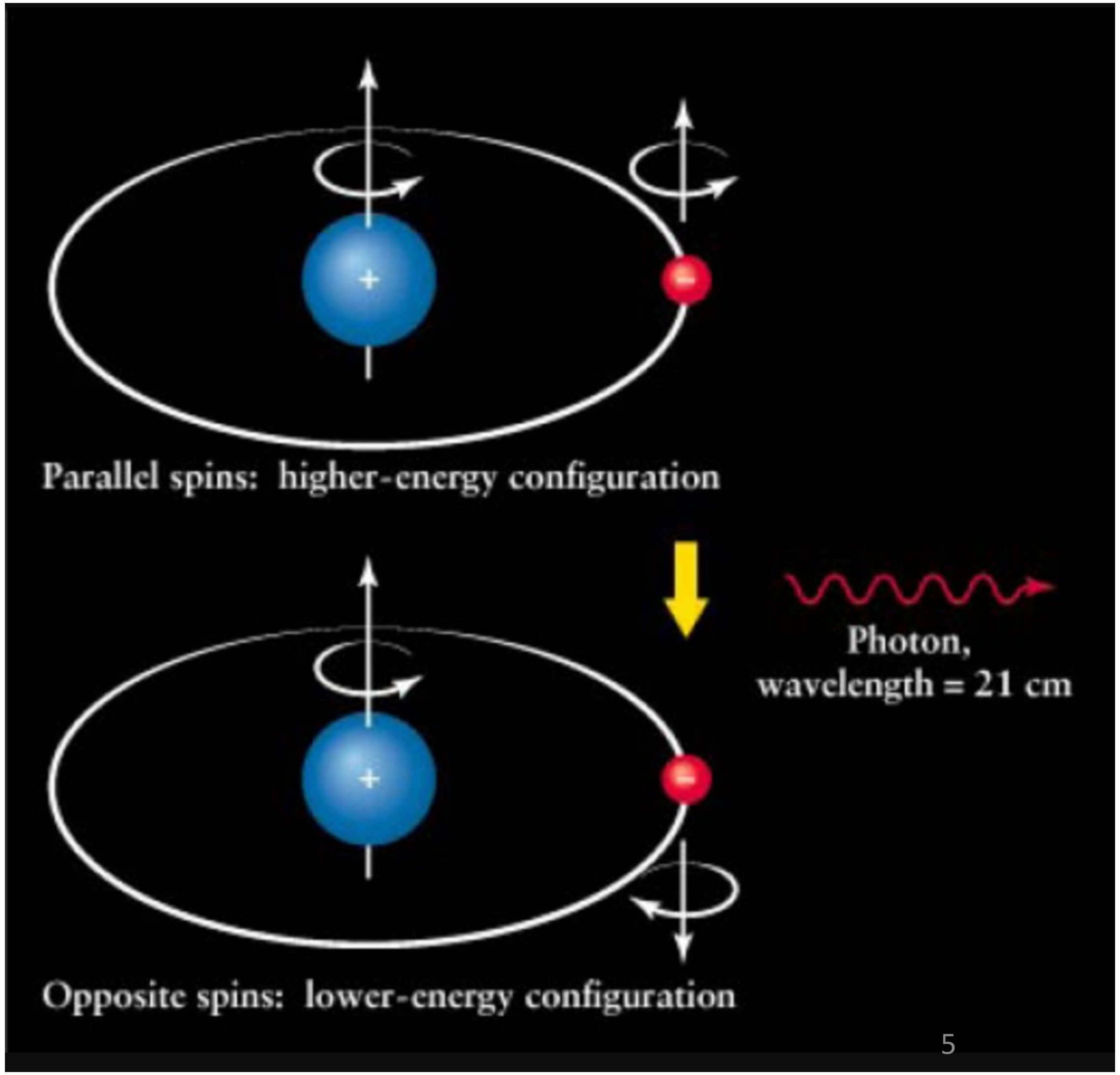




The HI 21cm hyperfine transition

- 21cm hyperfine transition at 1.4 GHz traces atomic hydrogen
- Spin flip transition
- Observed by radio telescopes (e.g., Parkes, VLA)





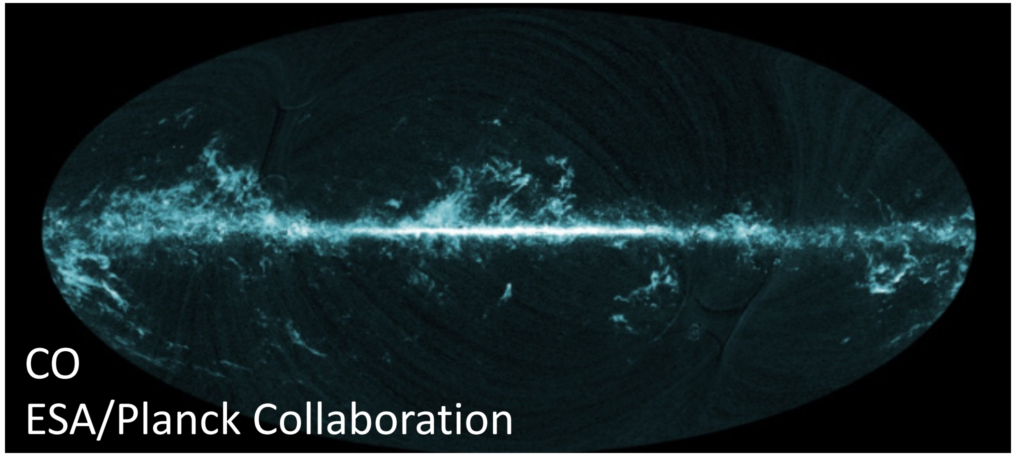
CO rotational transitions

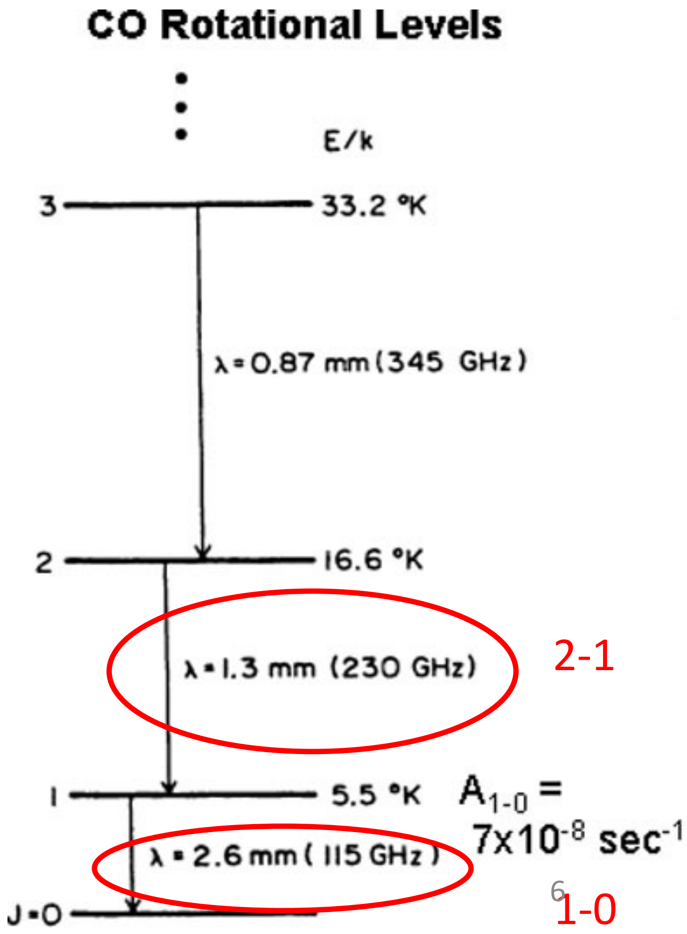
- Rotational levels are quantized with energy $E_{rot} = \frac{J(J+1)\hbar^2}{2I}$
- Transition from J → J-1 has energy

$$E_{J\rightarrow J-1} = \frac{\hbar^2}{2I}(J(J+1) - J(J-1)) = \frac{\hbar^2 J}{I}$$

- Two isotopes: ^{12}CO and ^{13}CO with $\frac{n(^{12}\mathrm{CO})}{n(^{13}\mathrm{CO})} = 6.2 \times R_{\mathrm{gal}} + 18.7$.

- Observable with mm telescopes (ALMA, MOPRA, IRAM, PdBI)





Dust emission as a tracer of the ISM

- Dust absorbs UV/optical stellar light and re-emits it in the far-infrared as a blackbody with a modified emissivity law

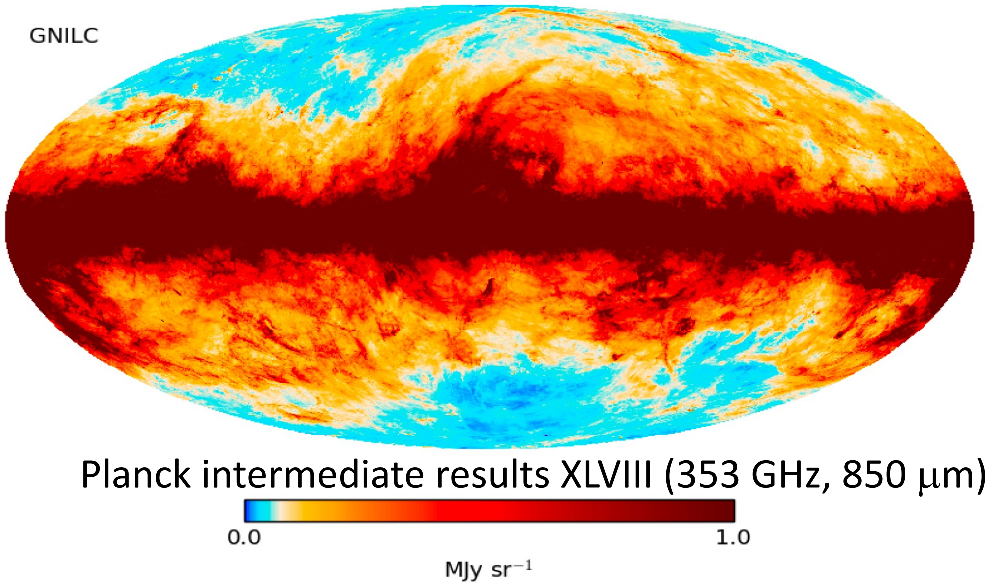
Surface density of dust

$$S_\lambda = (2.0891 \times 10^{-4})\kappa_\lambda \Sigma_d B_\lambda$$

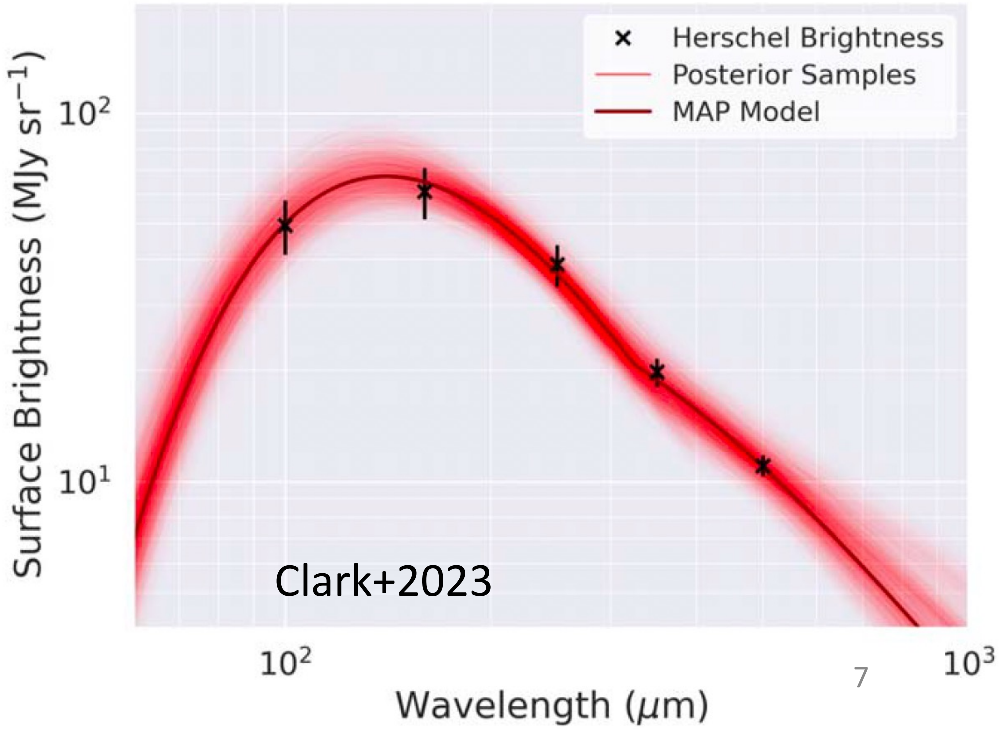
Surface brightness · Opacity · Planck Function

$$\kappa_\lambda = \frac{\kappa^{\mathrm{BE}}_{\mathrm{eff},160}}{160^{-\beta_{\mathrm{eff},1}}} E(\lambda)$$

- Dust FIR spectral energy distribution (SED) can be modeled to measure the properties of dust (column density, temperature)



Planck intermediate results XLVIII (353 GHz, 850 μm)

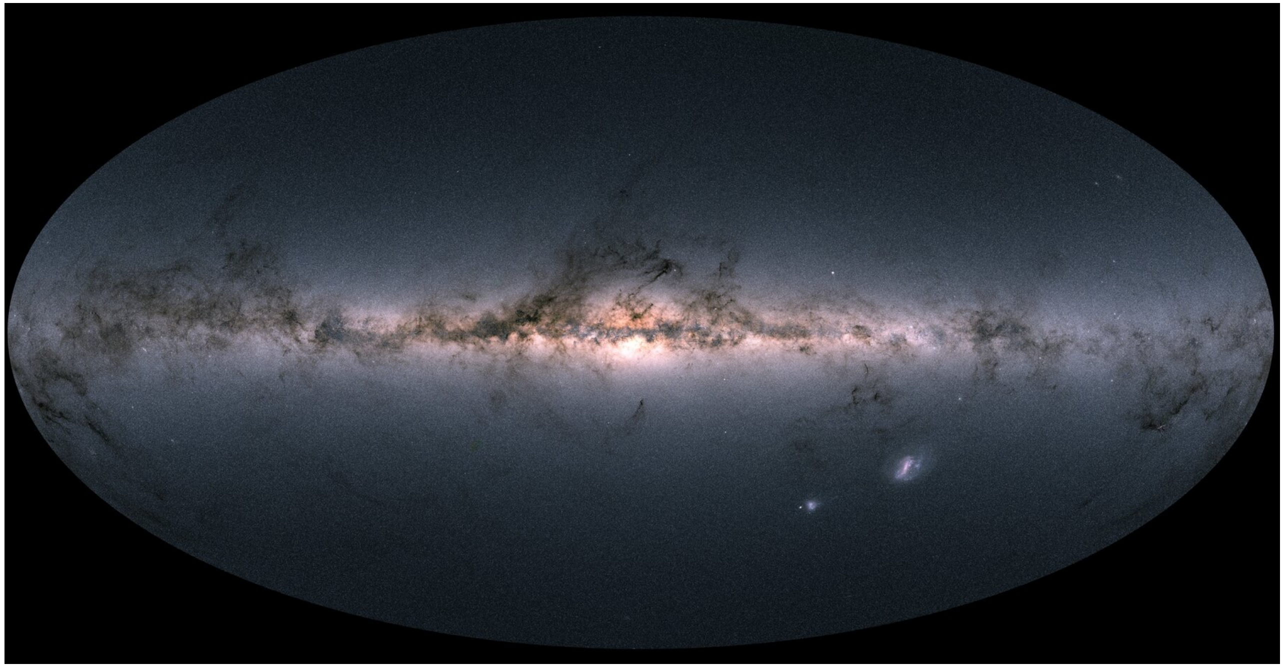


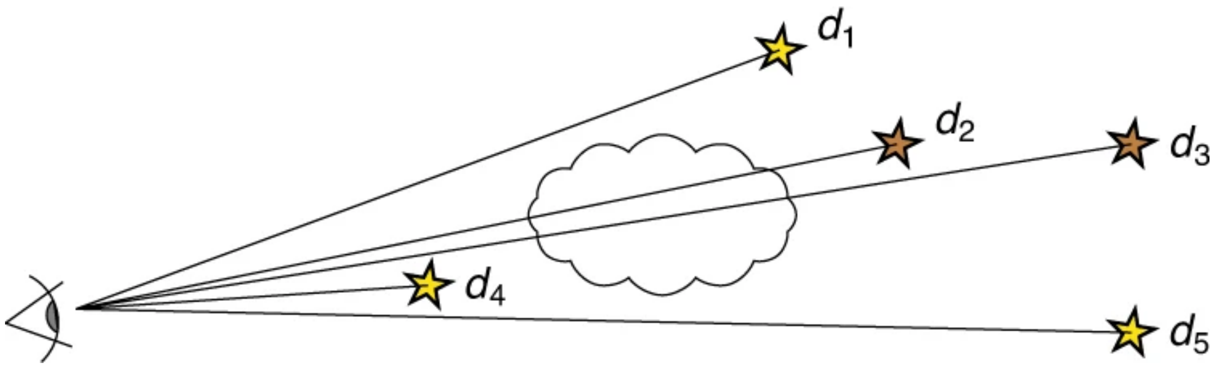
Clark+2023

Dust extinction as a tracer of the ISM

- Dust absorbs and scatters UV/optical stellar light
- Use distance and dust reddening of stars to map ISM clouds

ESA/Gaia map of stellar density





From Leike+2021: a dust cloud is located between distances d4 and d2

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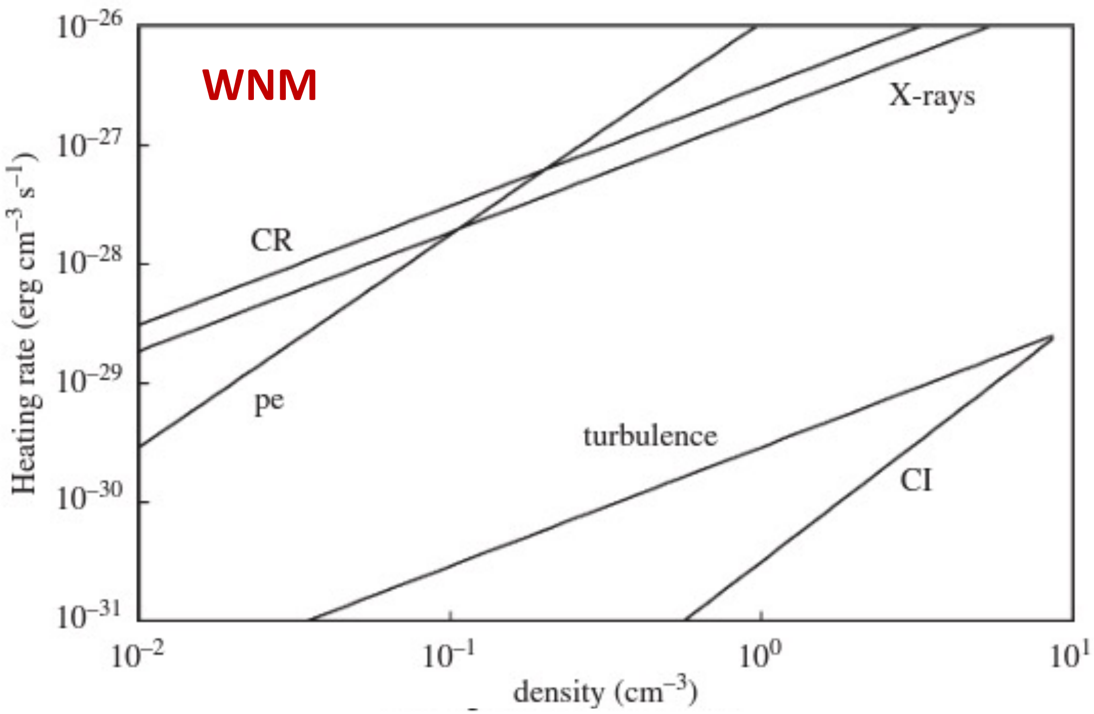
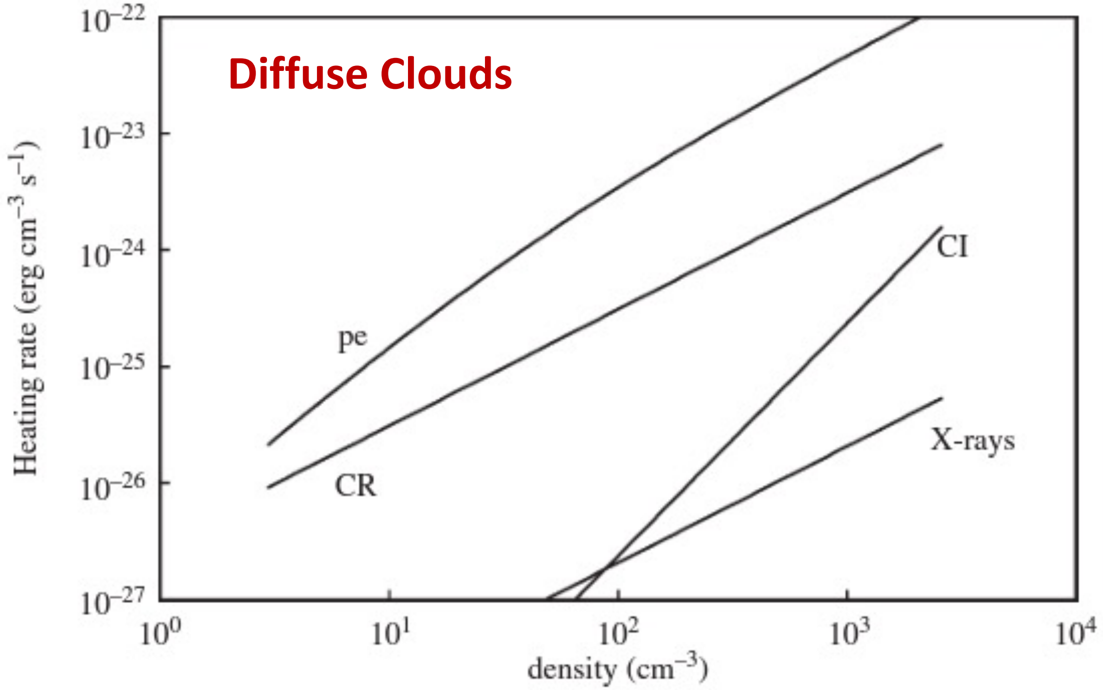
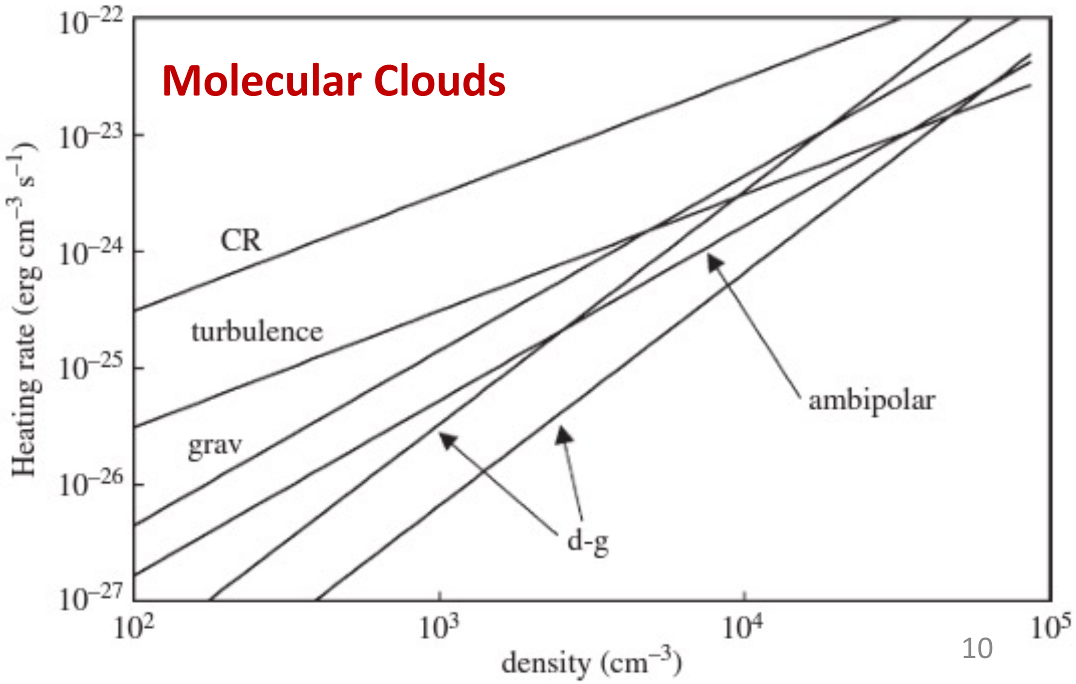
Heating

- Dominant sources of heating (Tielens+2005)
  - Photoelectric effect on dust grains
  - Cosmic rays

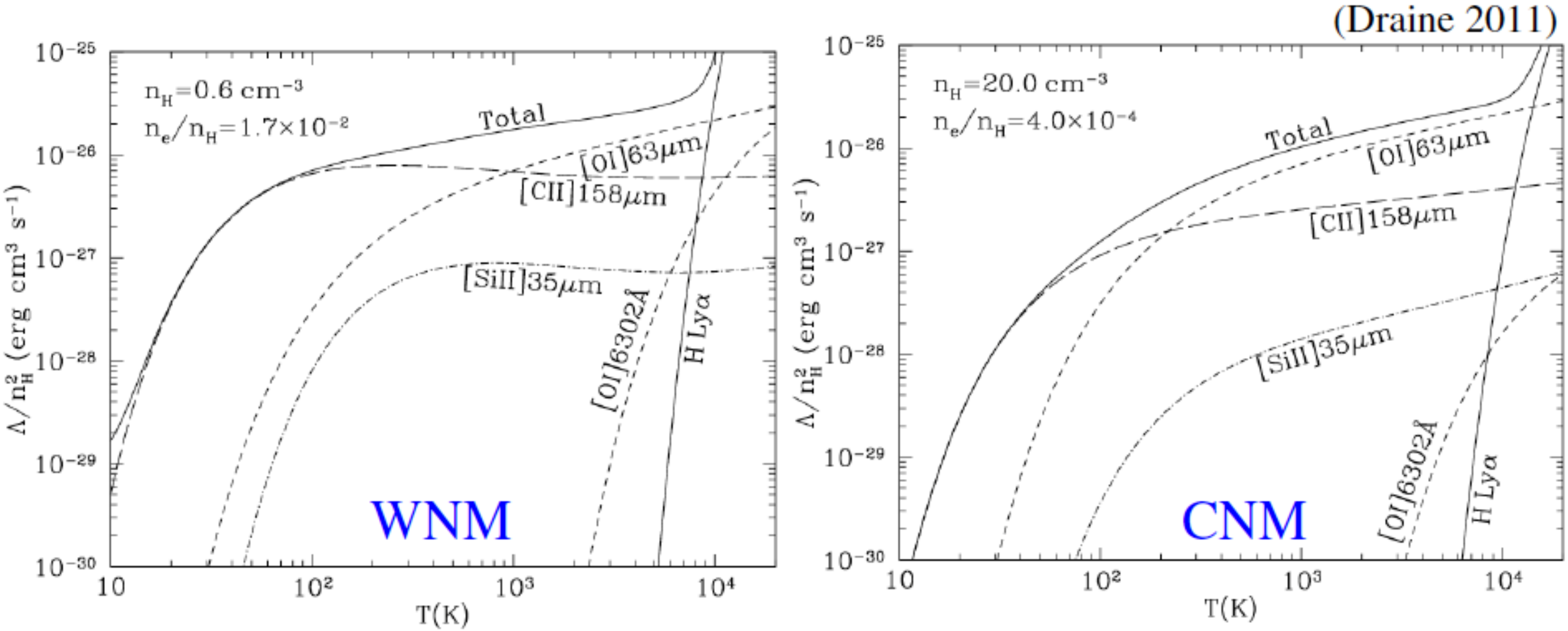






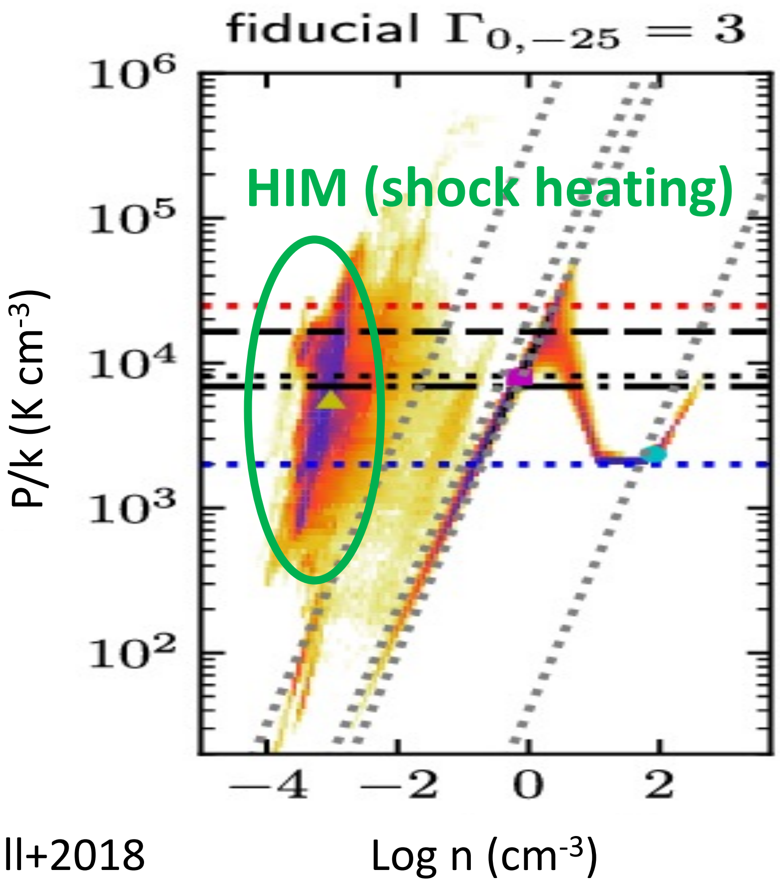
Cooling

- Dominant cooling mechanisms (Draine+2011)
  - Lyman alpha emission (warm-hot medium)
  - Fine structure line emission ([O I], [C II])

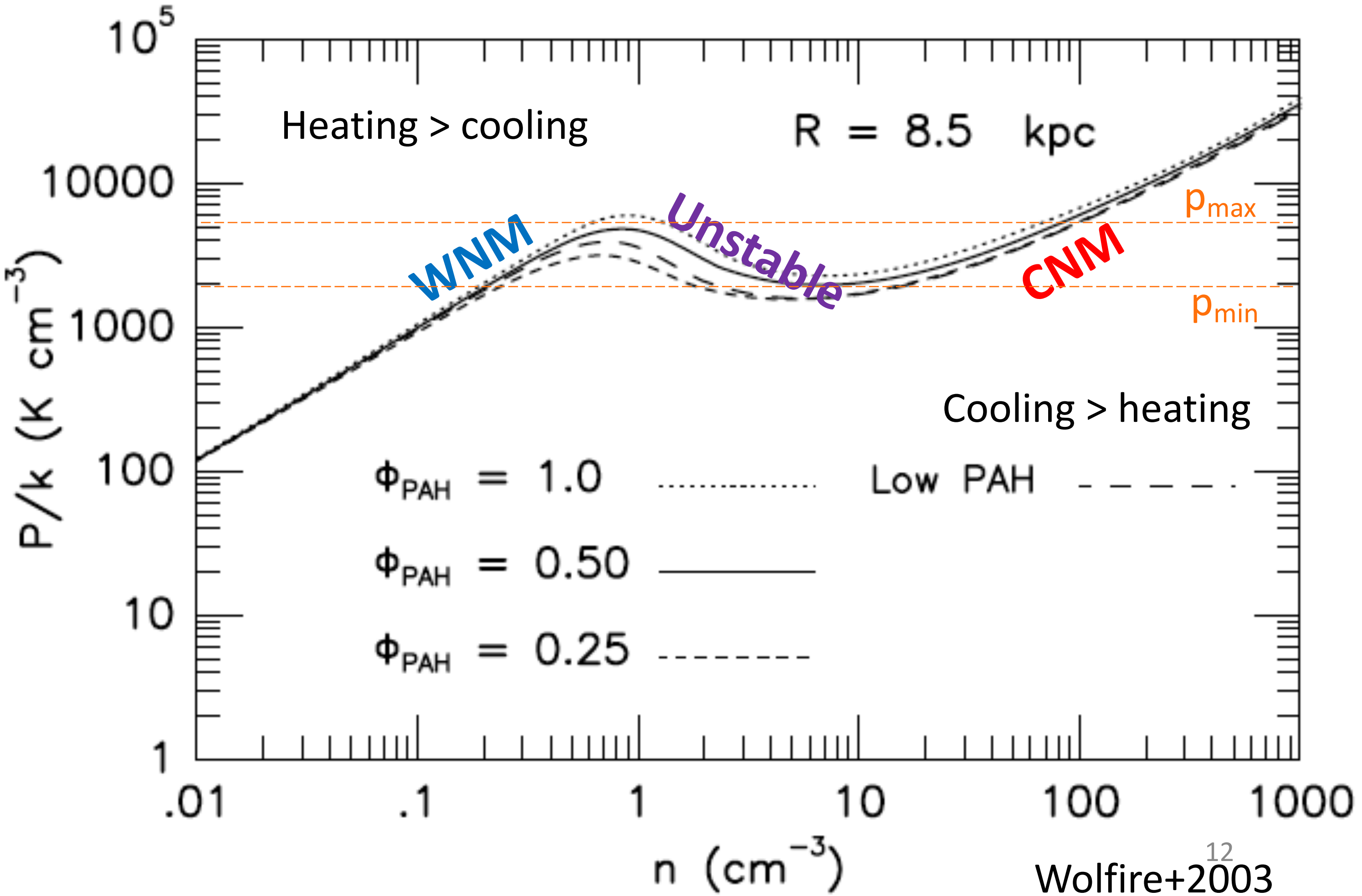


Phase diagrams

- In steady state, heating = cooling
- Phase diagram relating pressure (or temperature) and density defines phases of the ISM



Hill+2018

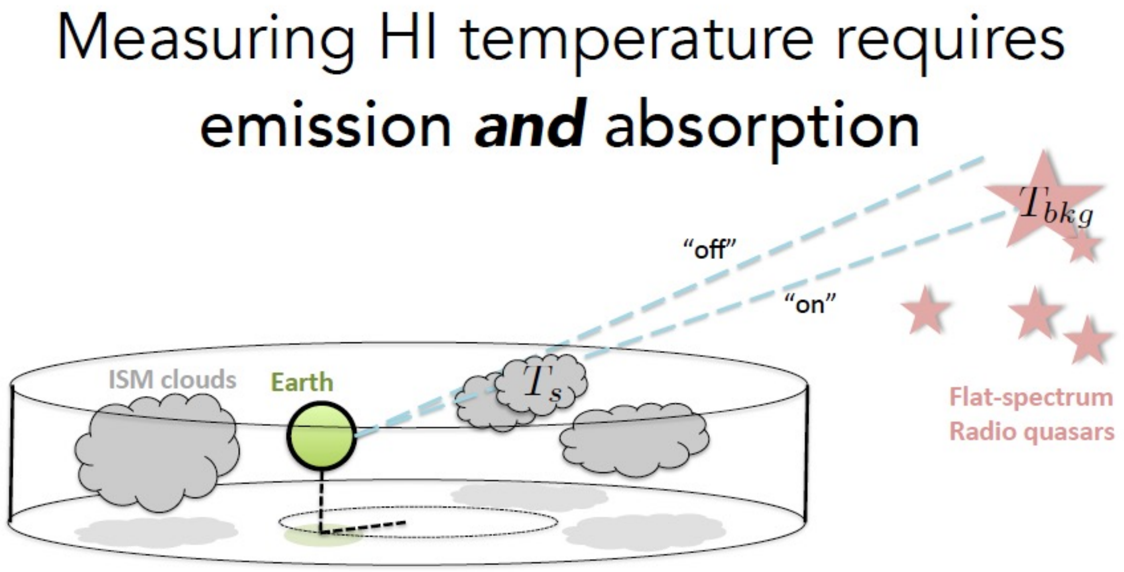


Wolfire+2003

Phase	T (K)	n_H (cm^{-3})	H	Heating/cooling	Observable	Mass
Hot ionized medium (HIM)	$>10^{5.5}$	0.004	2-3 kpc	Shock heated, collisionnally ionized Cooled by adiabatic expansion, X-ray emission	UV, X-ray Radio synchrotron	$2x10^9$ Mo
HII gas	10^4	$0.3\text{-}10^4$	NA	Heated by photoelectrons Cooled by optical line, fine structure line emission, free-free emission	Optical line emission Thermal radio continuum	
Warm Neutral Medium (WNM)	5000	0.6	400 pc	Heated by photo-electrons from dust; ionized by starlight, cosmic rays Cooled by optical line and fine structure line emission	HI 21 cm emission, absorption Optical, UV emission lines	6e9
Cold Neutral Medium (CNM)	100	30	150 pc	Heated by photoelectrons from dust; ionized by starlight, cosmic rays Cooled by fine structure line emission	HI 21 cm emission, absorption Optical, UV emission lines	
Molecular Clouds	10-50	>100	50 pcs	Heating: Cosmic rays; photoelectrons from dust (surface) Cooled by CO emission, C I, C II fine structure line	CO rotational emission HI 21 cm emission, absorption Optical, UV absorption lines Dust FIR emission	2.5e9

Probing the CNM, WNM and unstable phase

- Need HI 21 cm emission and absorption measurements to probe both the spin temperature and column density (optical depth τ)



$$T_b^{on} = T_{bkg} e^{-\tau} + T_s (1 - e^{-\tau})$$
$$T_b^{off} = T_s (1 - e^{-\tau})$$

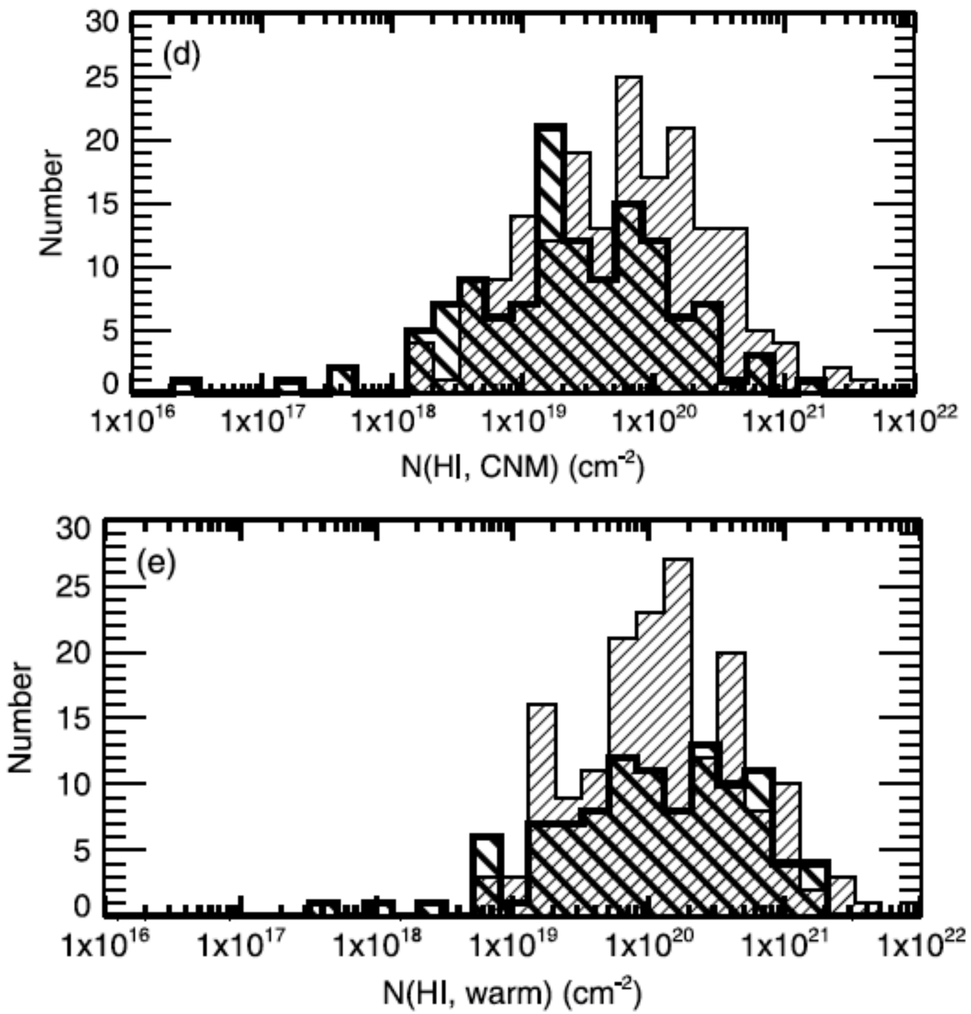
From C. Murray

See work by Claire Murray, Snezana Stanimirovic, John Dickey, Carl Heiles and others

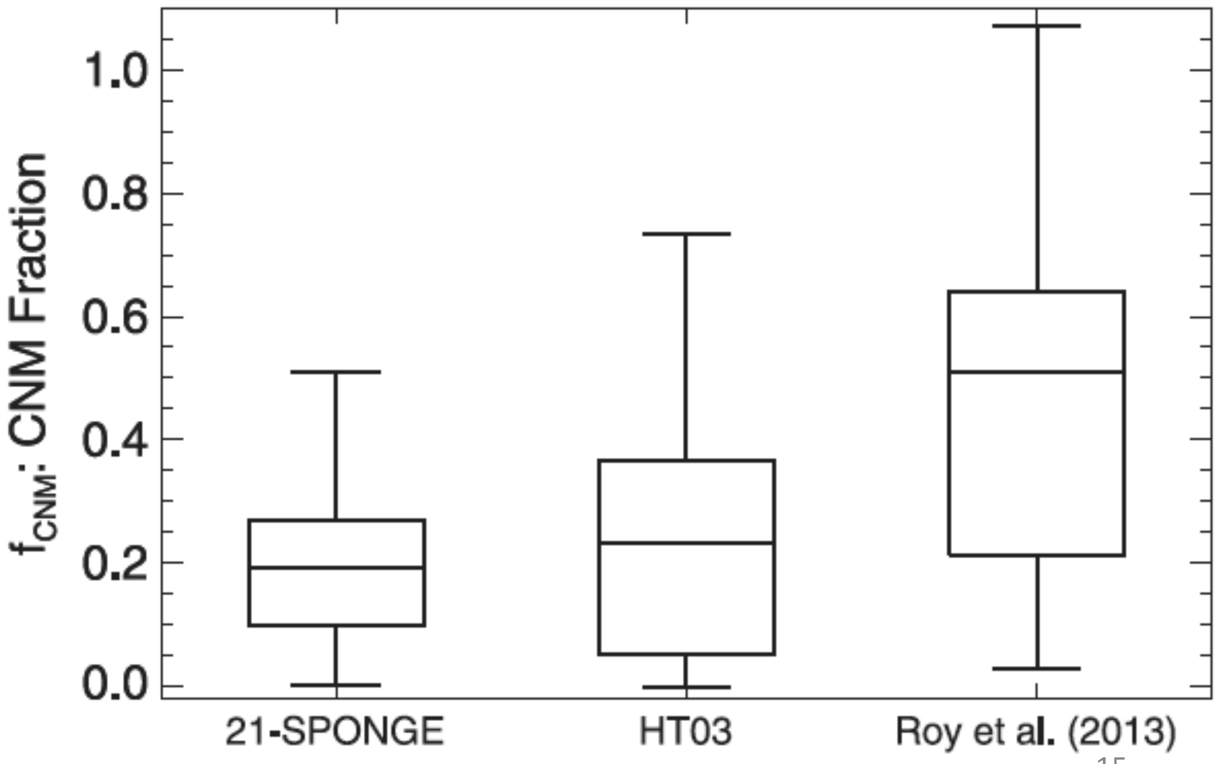
See Rybicki & Lightman or Draine (2011) books for radiative transfer background

Properties of the CNM

- Results from Murray+2015

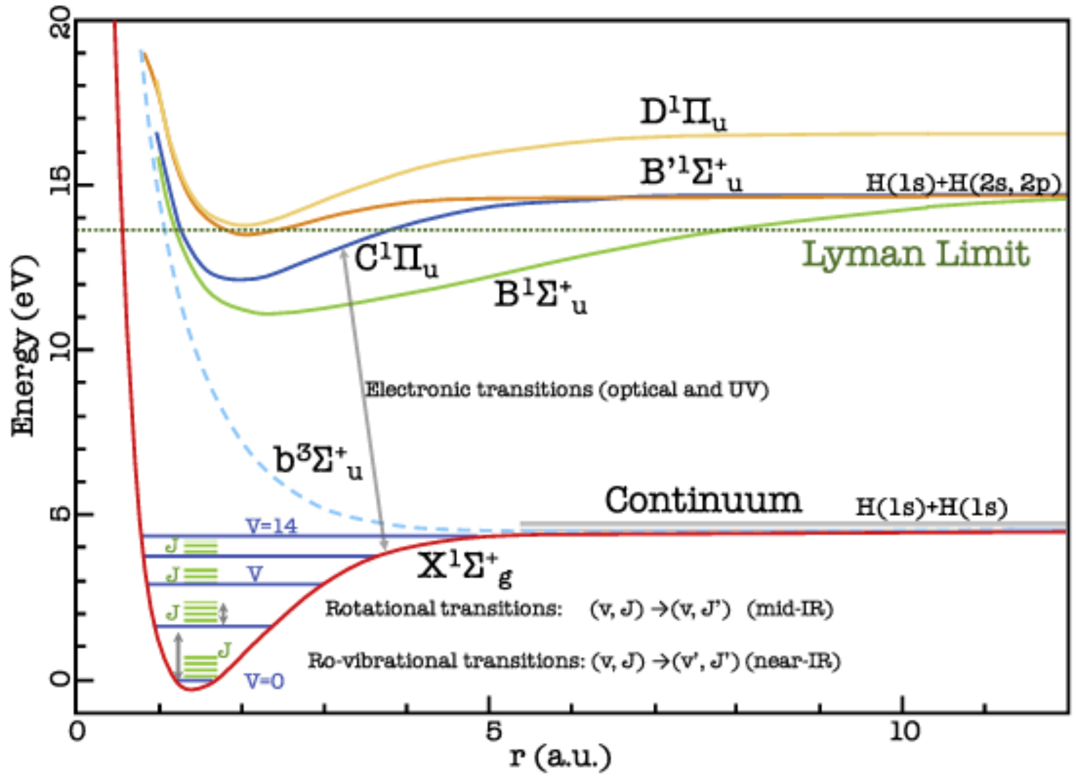


- 20-60% of HI in the CNM (depending on survey)
- 20% of HI in unstable phase in Murray+2015 (compatible with colliding flows in Audit & Hennebelle 2005)

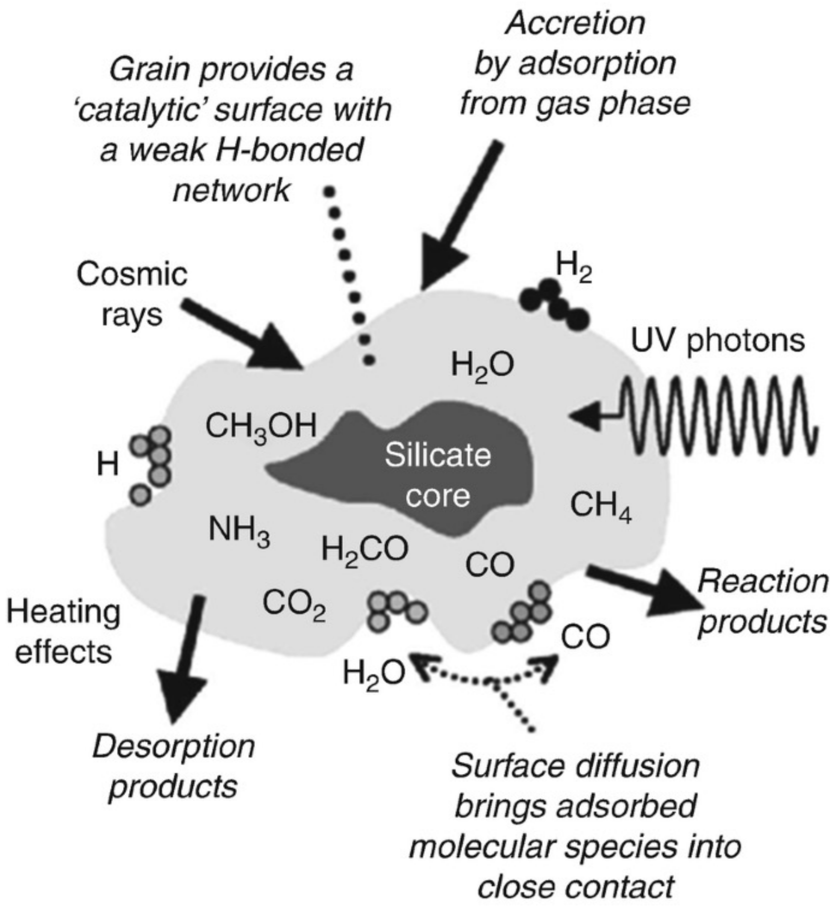


H_2 formation and dissociation

- H_2 forms on dust grains, the catalyst that can absorb the energy released by the formation of the molecule
- H_2 is photo-dissociated by UV photons



Wakelam et al. 2017



Interstellar chemical processes Fraser+2001

Shielding for H_2

H2 needs shielding (by itself and by dust)

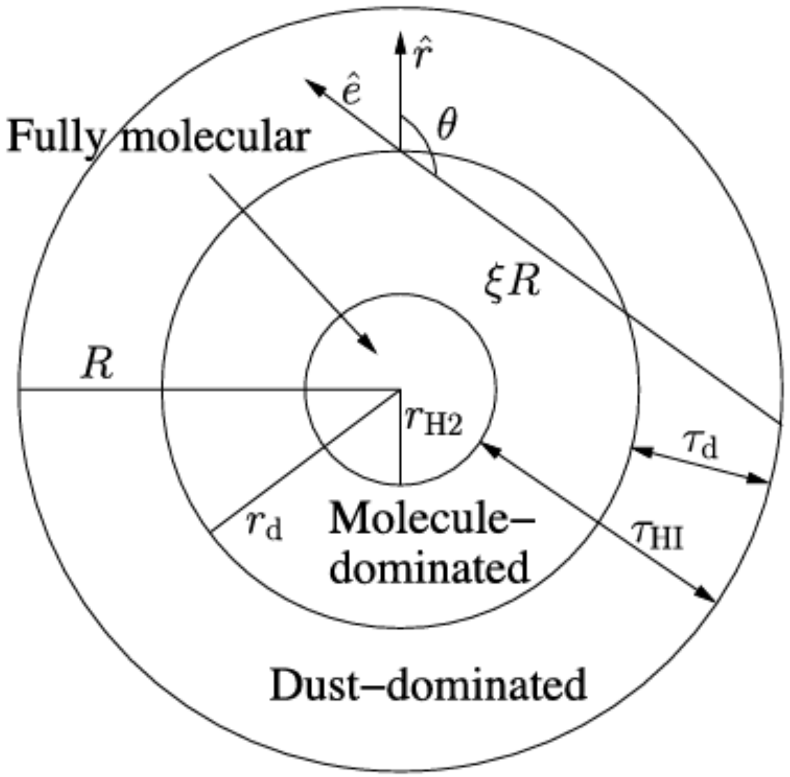
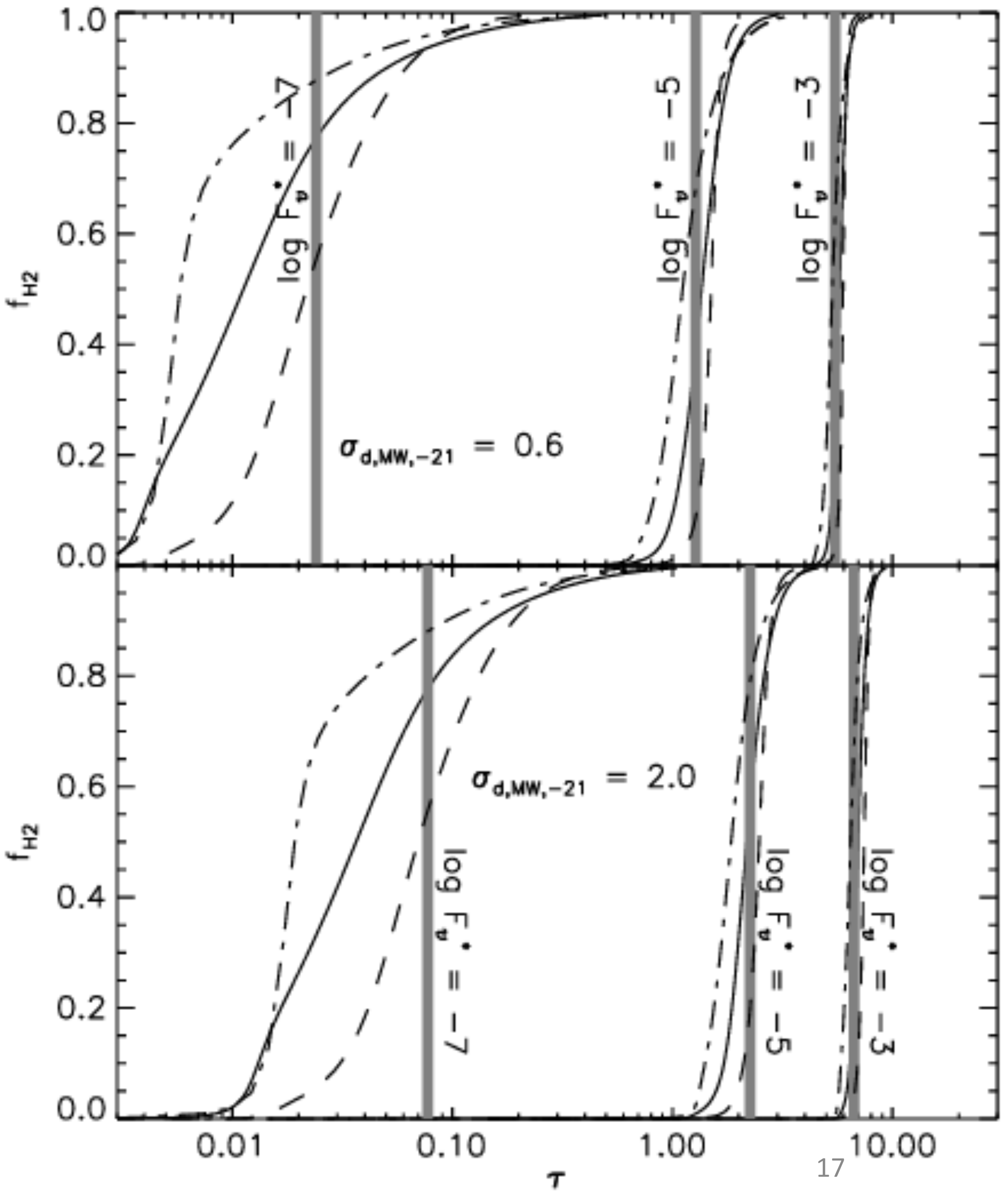


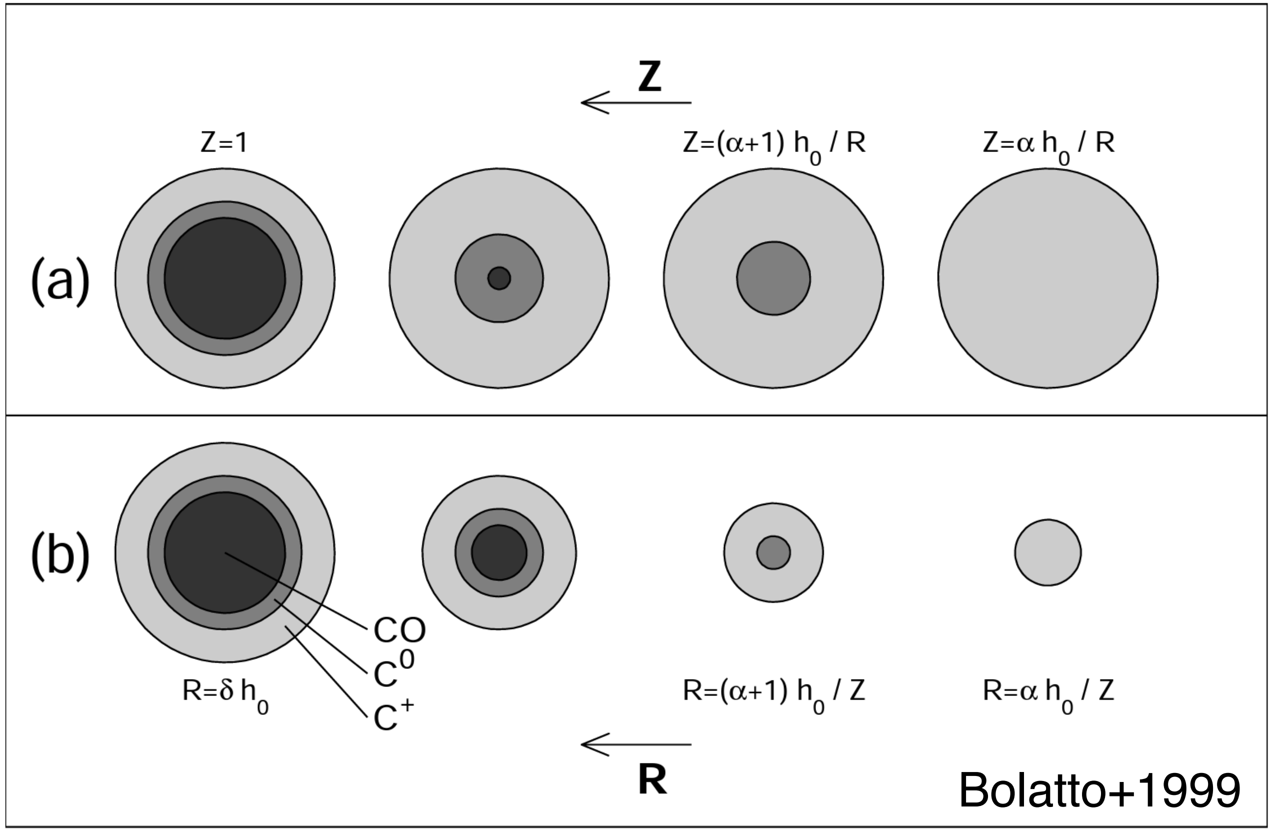
FIG. 3.—Illustration of the two-zone approximation in spherical geometry.



Krumholz+2008

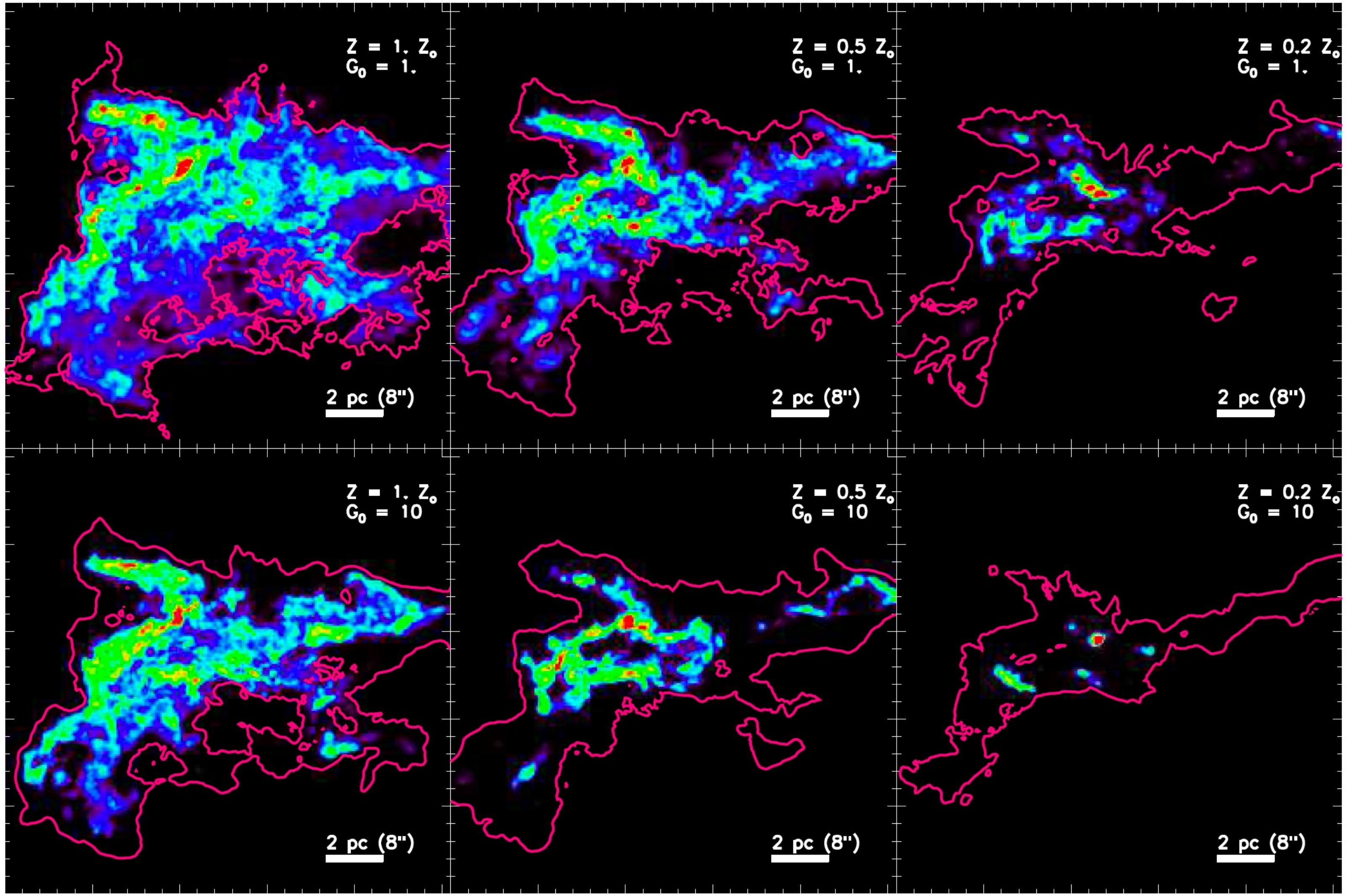
CO as a tracer of H2

- CO is the most abundance molecule after H_2 in molecular clouds
- Traces H_2 relatively well at solar metallicity and standard radiation fields



- CO does not self-shield and therefore requires more dust shielding than H_2
- At low metallicity, the low dust abundance leads to CO-dark H_2

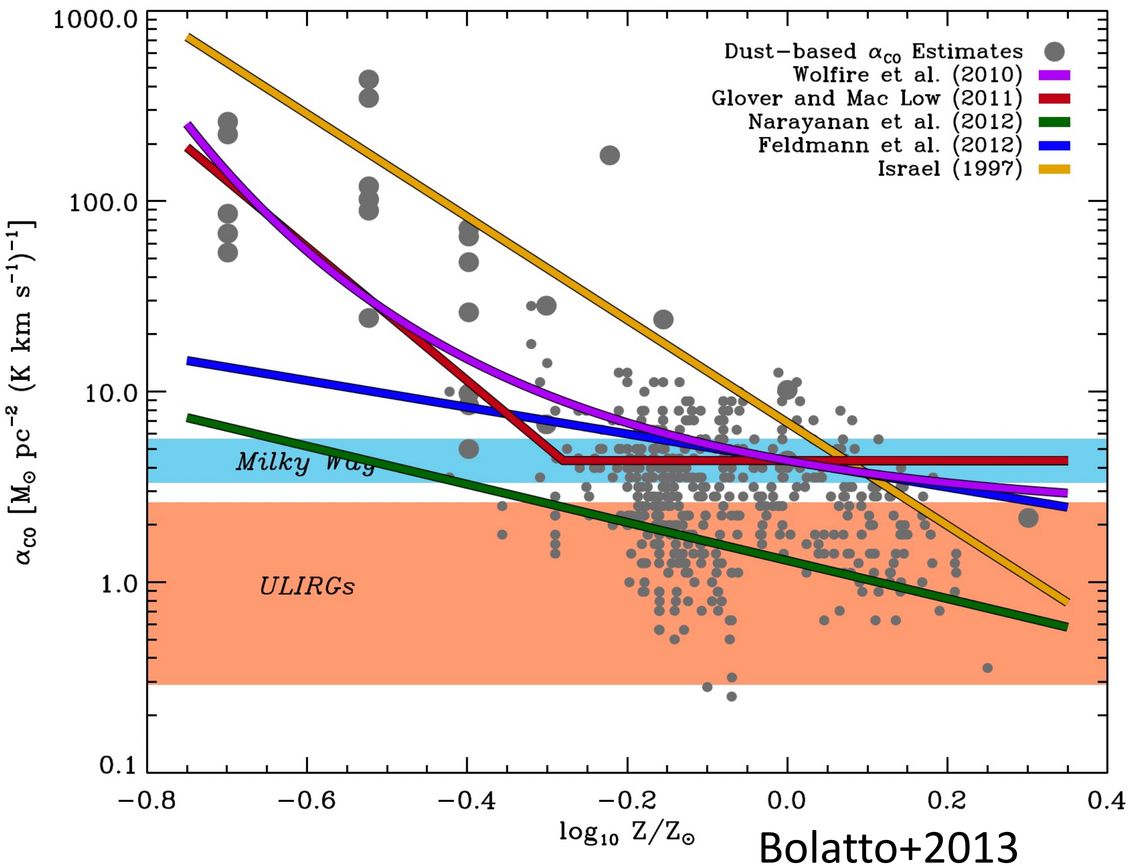
CO as a tracer of H2



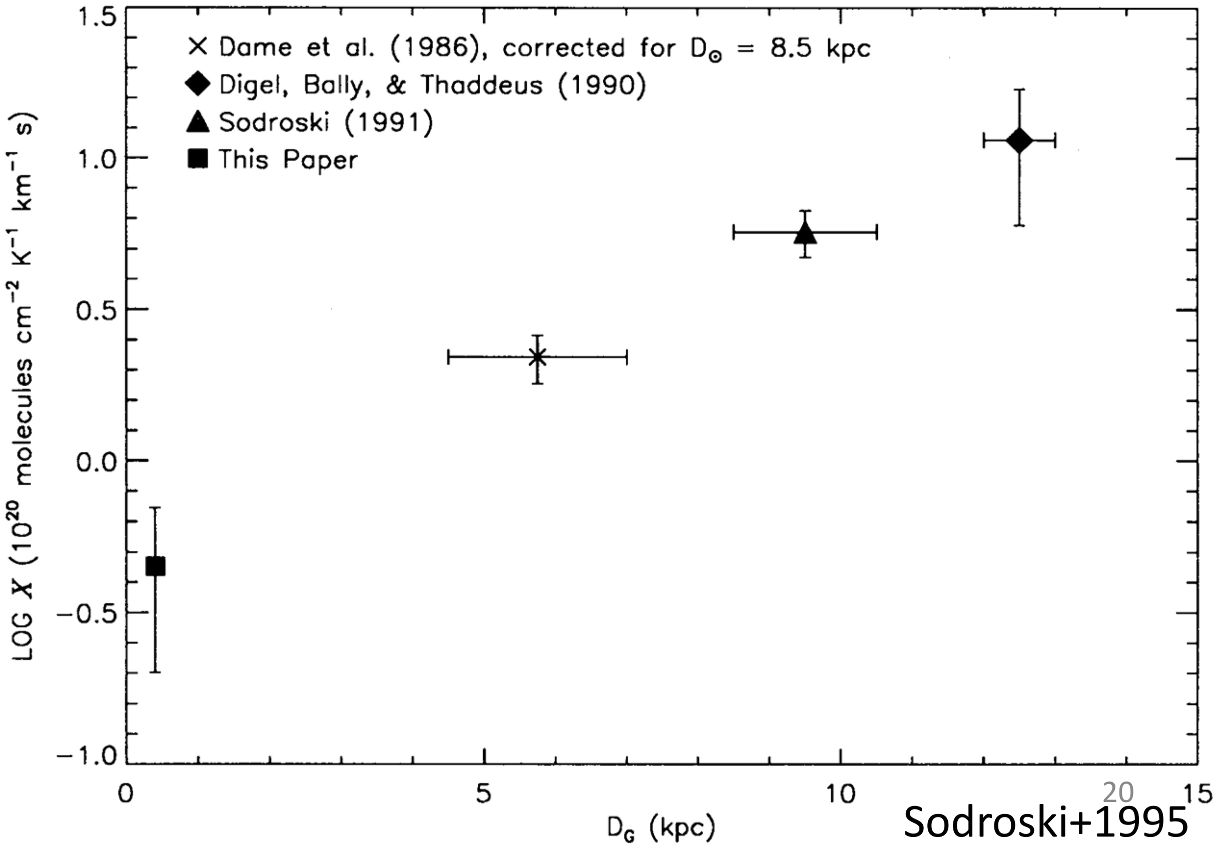
Simulated CO integrated intensity map by Glover & Clark (2012) of a 16 pc molecular cloud at metallicities $Z = Z_\odot$, $Z = 0.5\ Z_\odot$, $Z = 0.2\ Z_\odot$ from left to right, and at radiation fields $G_0 = 1$ (top) and $G_0 = 10$ (bottom). The red contours show the $10\ M_\odot\ pc^{-2}\ H_2$ surface density level.

The CO-to-H2 conversion factor

- X_{CO} = $N(H_2)/I(CO) = 2\times10^{20}$ cm^{-2} K^{-1} km^{-1} s in the solar neighborhood
  - Also expressed as $\alpha_{CO} = \Sigma(H_2)/I(CO) = 4.3$ M_o pc^{-2} K^{-1} km^{-1} s
- Varies with environment (metallicity, dynamical state)



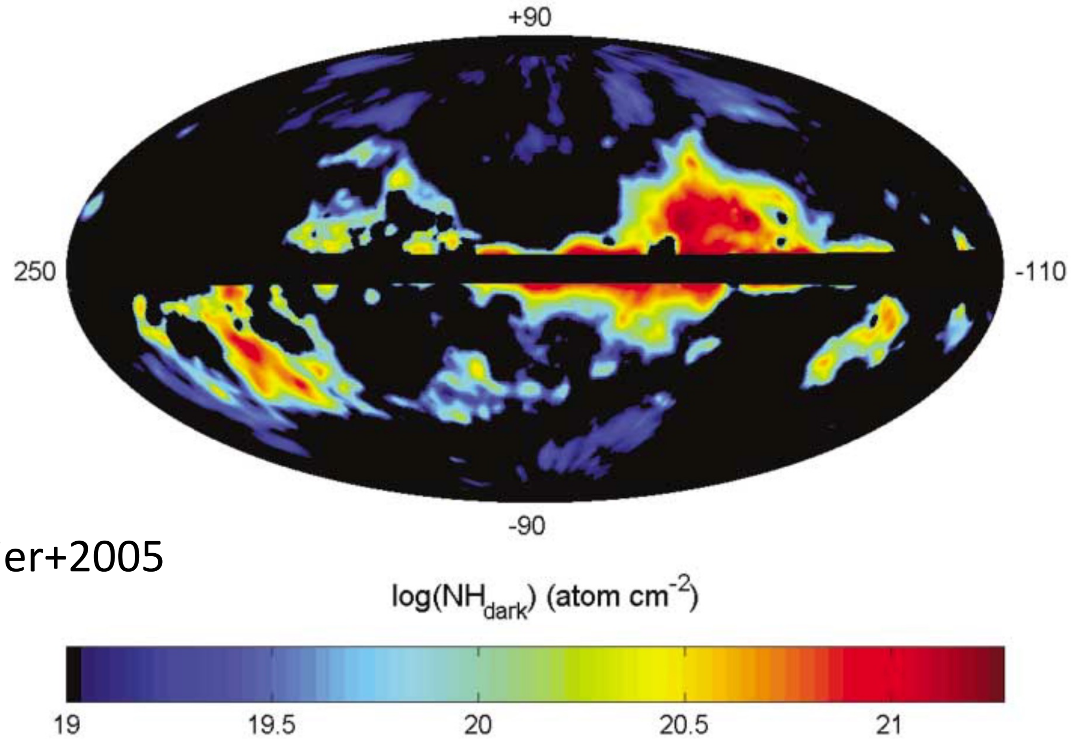
Bolatto+2013



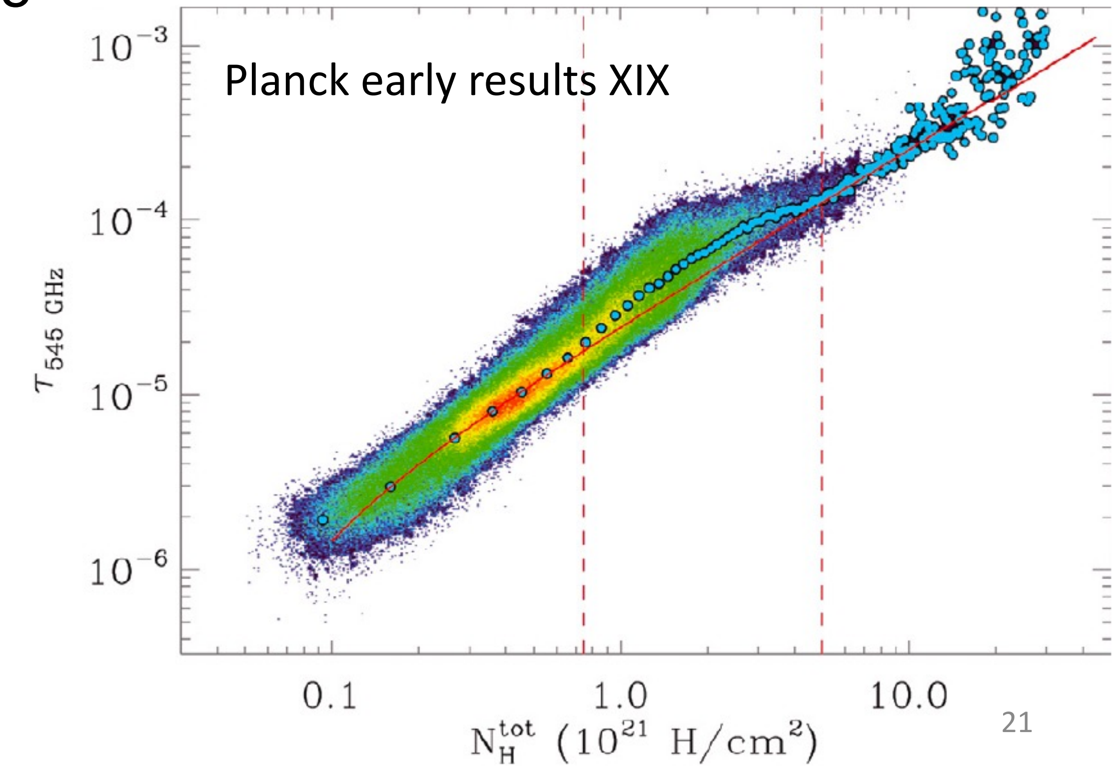
Sodroski+1995

Quantifying CO-Dark gas in the Milky Way

- Planck quantified CO-dark H_2 mass using dust emission → CO-dark H_2 represents 118% of the H_2 mass traced by CO in the Milky Way (Planck early results XIX)
- Analysis of combined HI, CO, dust, γ-rays (Grenier+2005, Planck intermediate results XVIII) also suggest CO-dark mass is 100% of CO-bright H_2
- These results assume constant dust-to-gas ratio

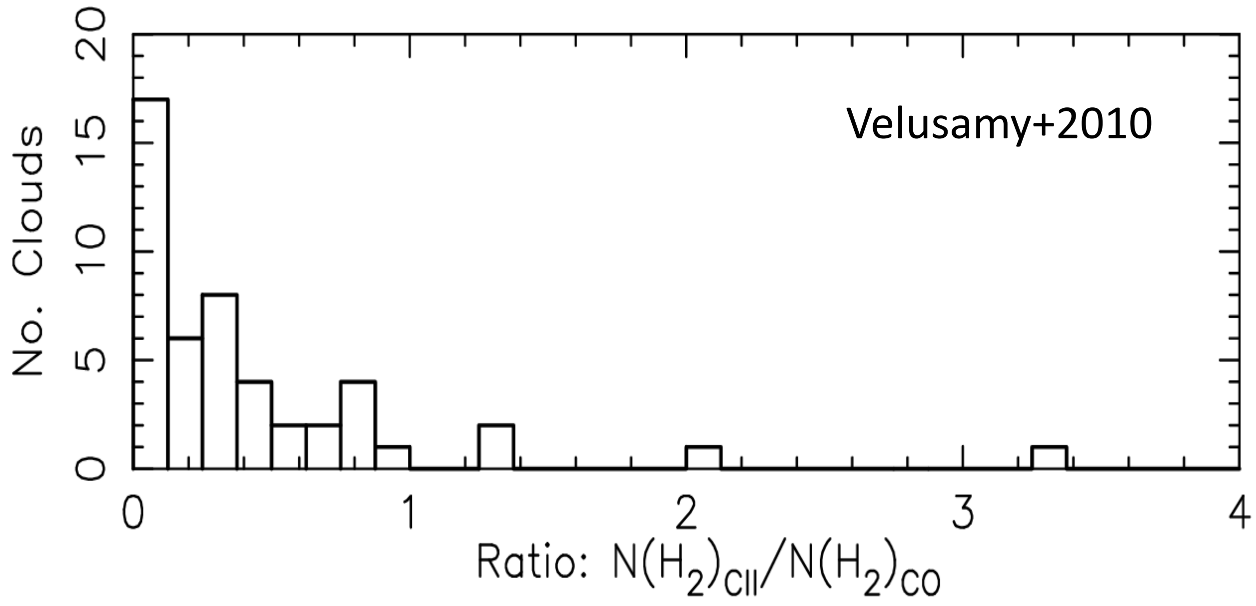


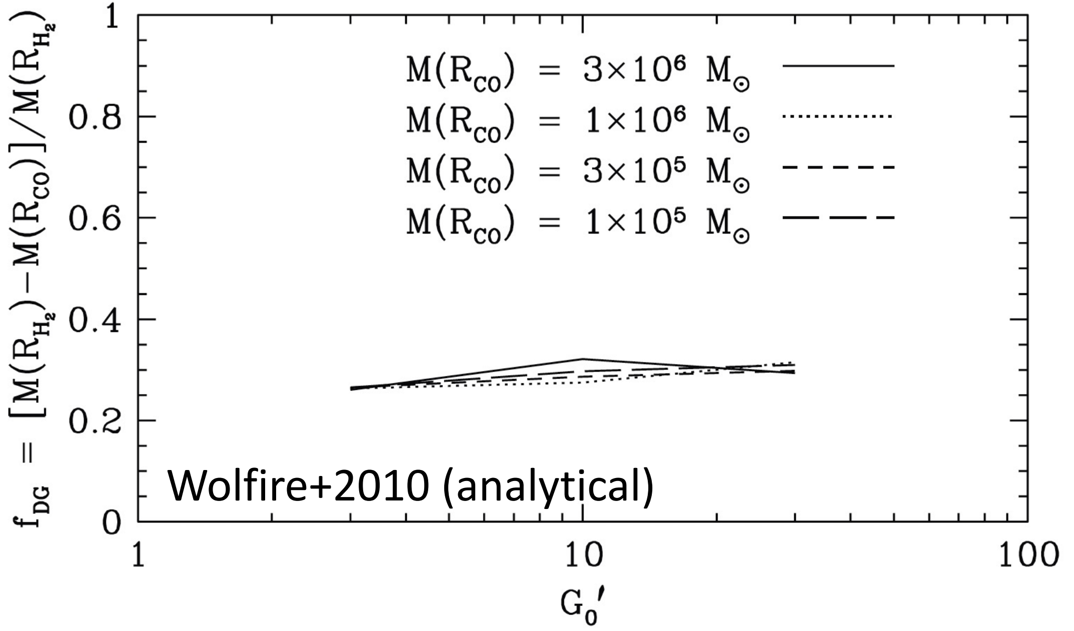
Grenier+2005

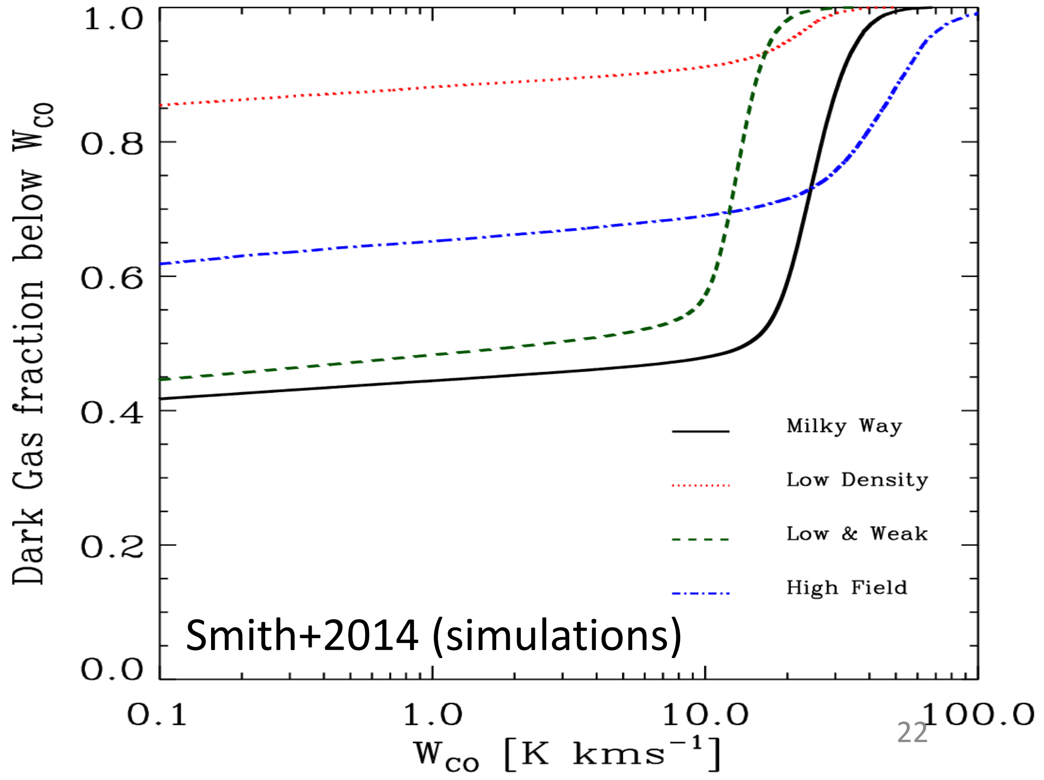


Quantifying CO-Dark gas in the Milky Way

- Fraction of CO-dark gas from C II emission = 0.41 (Velusamy+2010)
- Simulations predict 30-50% H_2 to be CO-dark in the Milky Way (Smith+2014, Wolfire+2010)







Open Questions

- What fraction of HI is in the unstable phase?
- How much CO-dark H_2 is there?
- How does the fraction of CO-dark gas vary with environment (e.g., radiation field)?
- How does the X_{CO} conversion factor vary with environment and spatial scale?

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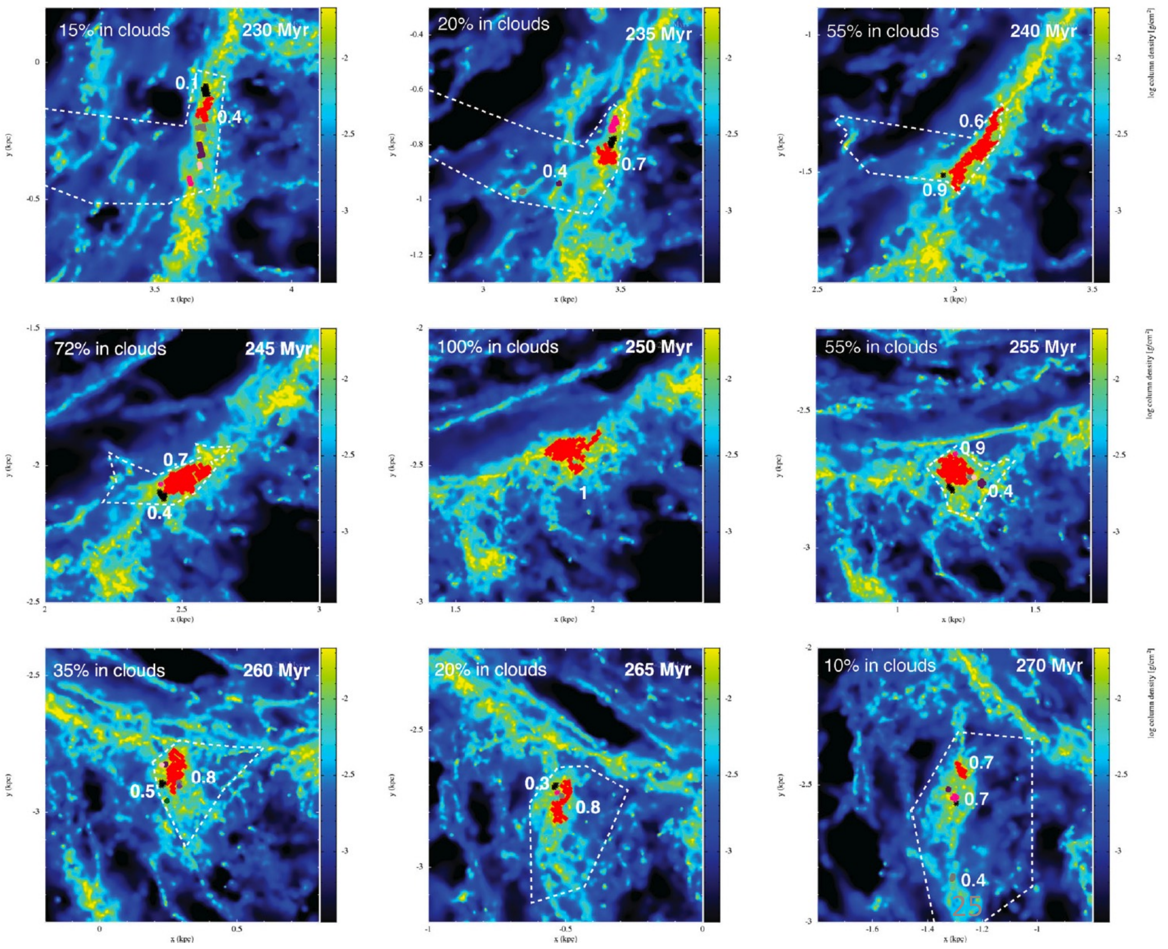
Formation of molecular clouds

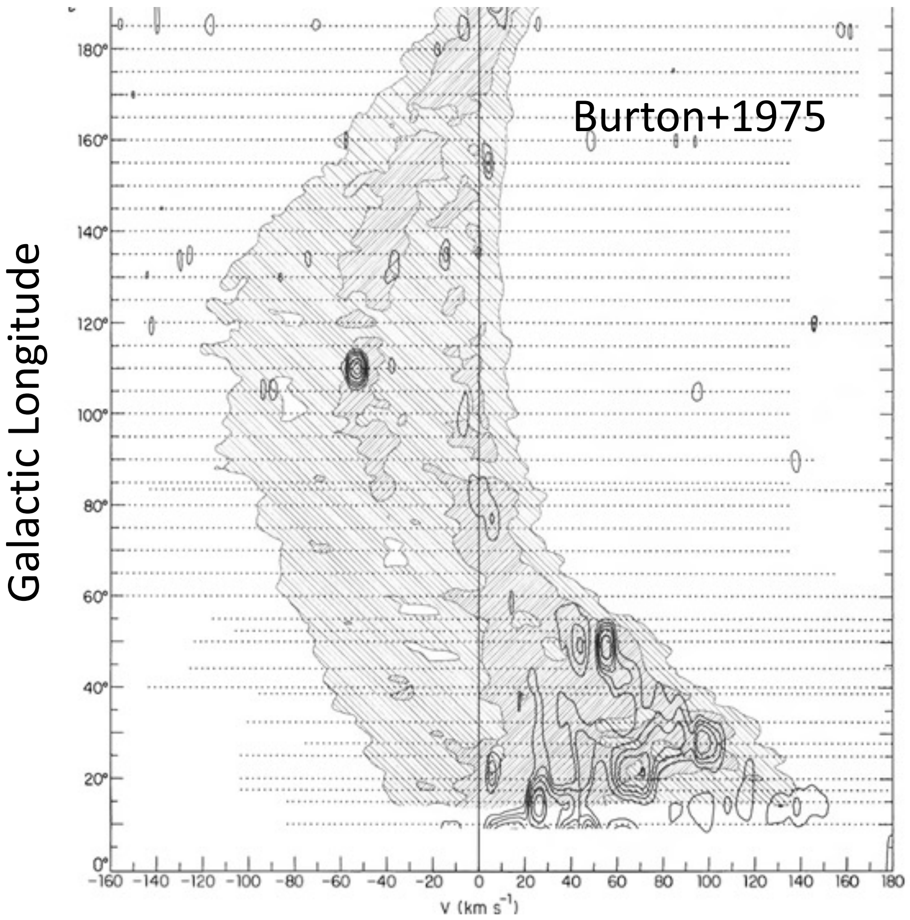
- Localized converging flows (e.g., expansion of HII region or SN shock, e.g., Dawson+2013)
- Cloud-cloud collisions in spiral arms (Dobbs+2008)
    - ➢low surface densities (< 10 Mo pc^{-2})
- Gravitational instability (Julian & Toomre 1966, Kim & Ostriker 2002, 2006)
    - ➢ high surface densities and combined with cloud-cloud collisions
- Magneto-Jeans instability (Kim & Ostriker 2001)
- Parker instability (Mouschovias 1974)
- Lifetimes < 20 Myr (Dobbs & Pringel 2013)

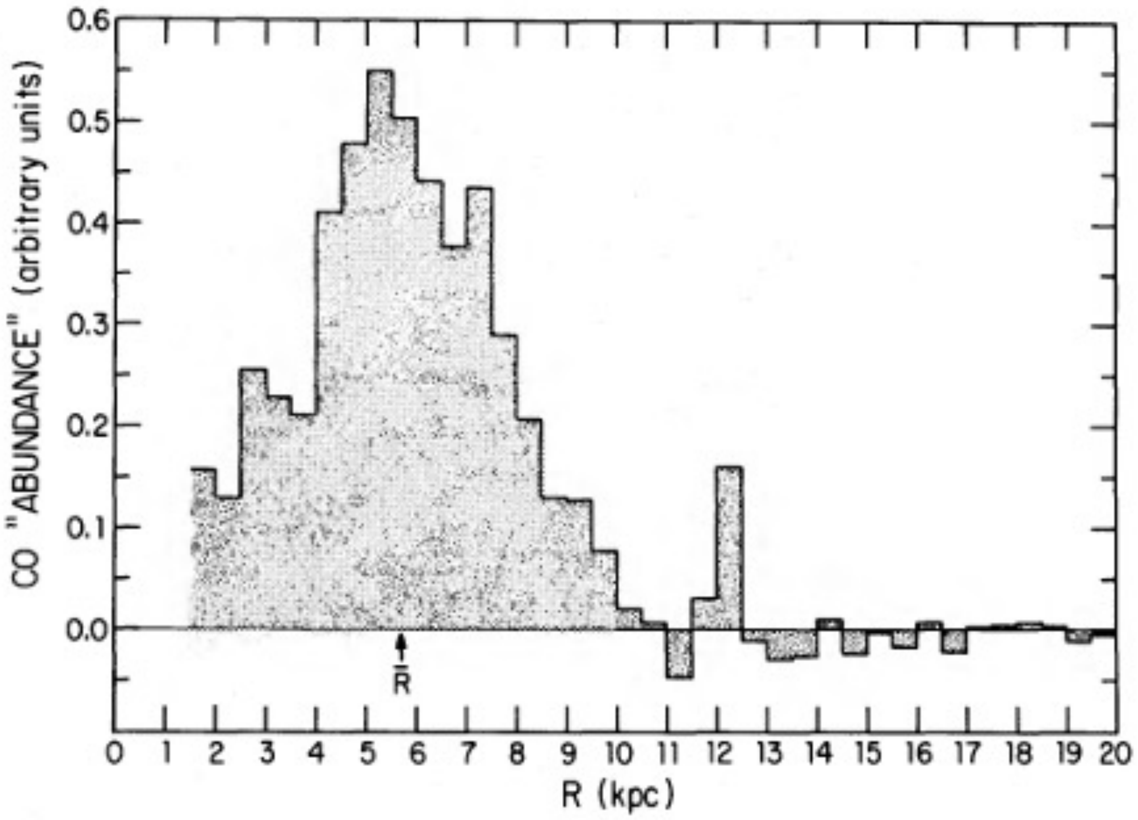
Dobbs & Pringel 2013



History of molecular clouds studies

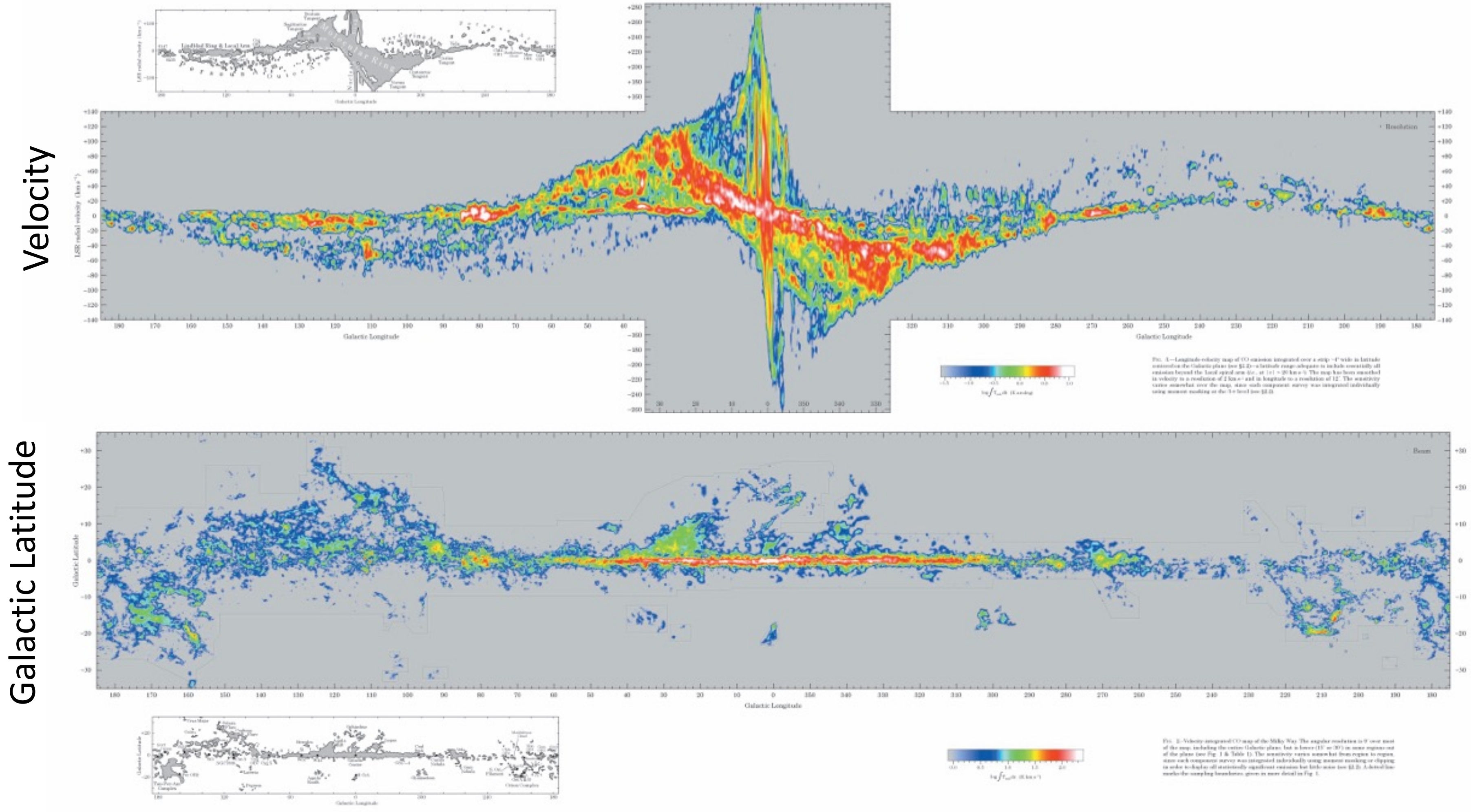
- Detection of H_2 in the UV (Carruthers+1970) and CO emission at 2.6 mm (Wilson+1970)
- Burton+1975 and Dame+1987 surveys performed the first large scale CO surveys in the Milky Way





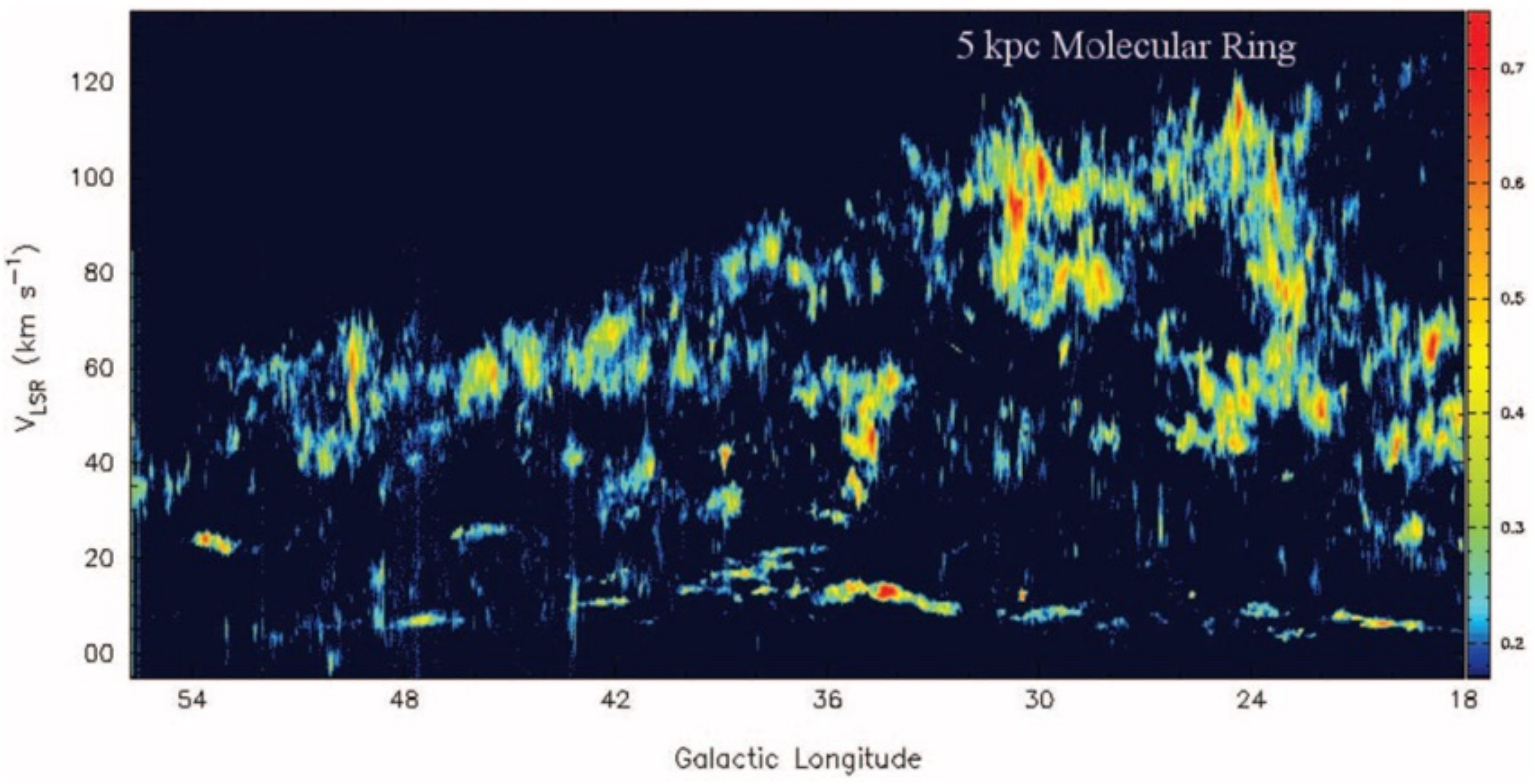
History of molecular clouds studies

- Dame+2001 surveyed the Milky Way plane at 4’ resolution with for ^{12}CO 1-0
- Yoda+2010 surveyed a similar area with ^{12}CO and ^{13}CO (2-1) at 4’



High-resolution ^{13}CO surveys

- Galactic Ring Survey (Jackson+2006, Rathborne+2009) offered high resolution (30”) to resolve molecular clouds in ^{13}CO 1-0
- Outer Galaxy survey by Brunt+2015 in ^{13}CO and ^{12}CO 1-0



History of CO surveys in the Milky Way

- From review by Heyer+2015

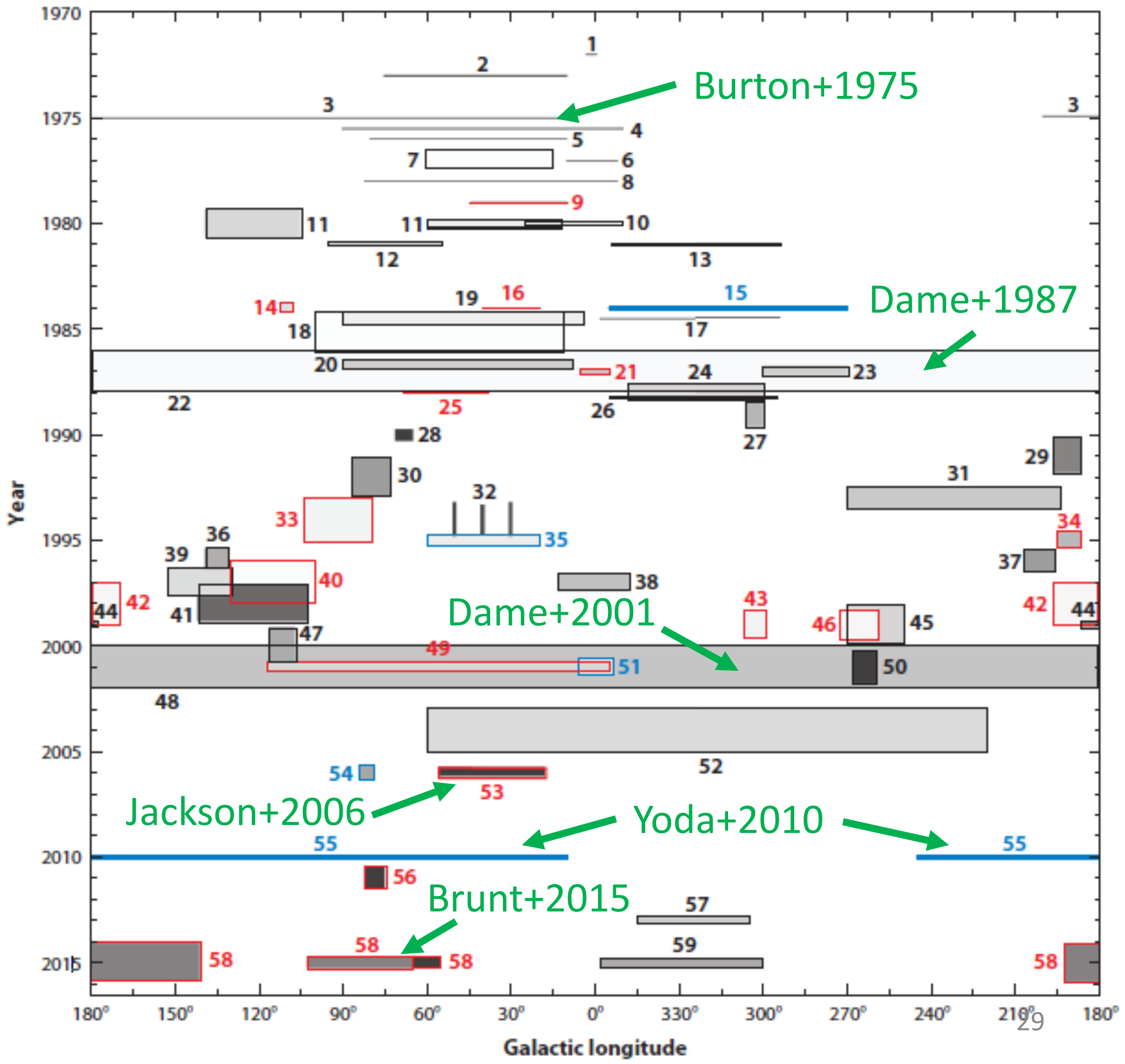
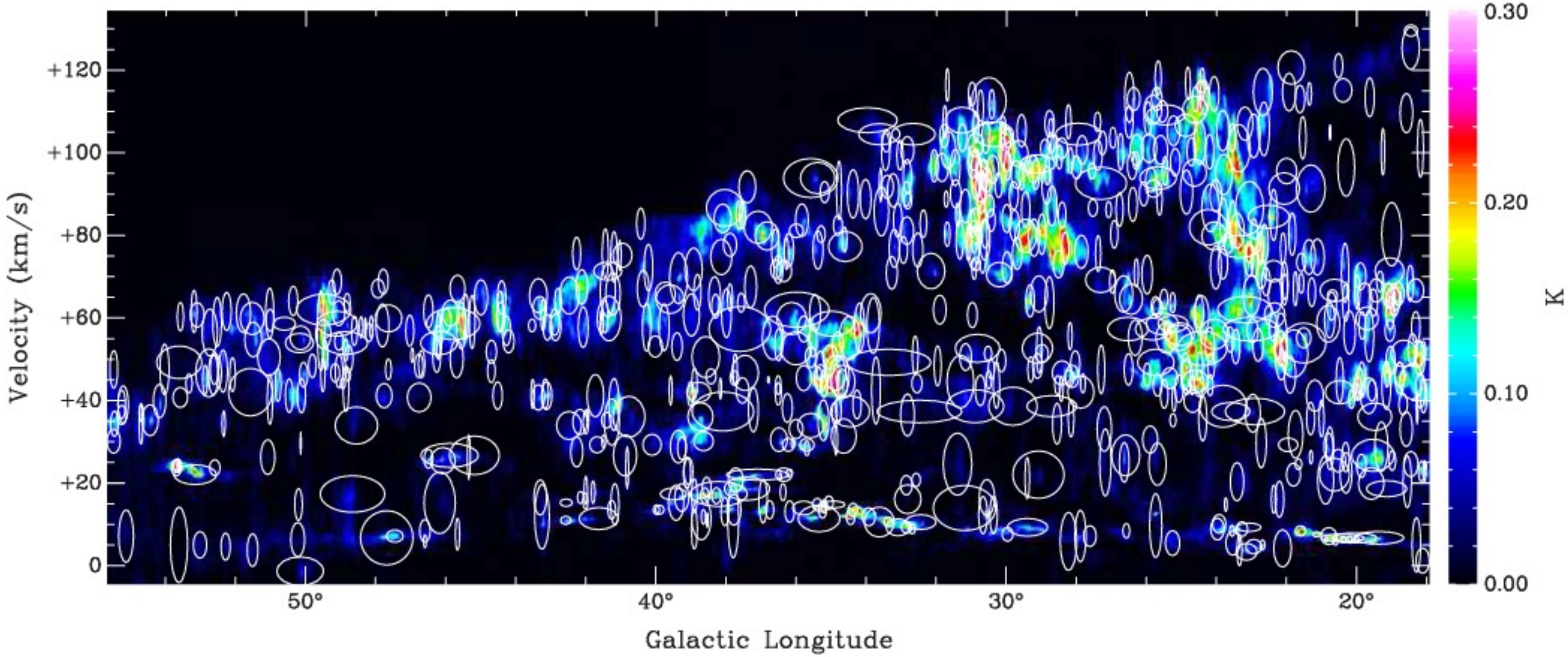


Figure 2

A summary of large CO surveys of the Galactic plane. The numbers are keys to each survey's publication listed at the end of this caption. The limits of each survey are approximated by a rectangle that is positioned vertically at the year of its publication. For clarity, the maximum value of $|b|$ for all surveys is limited to 5°. Surveys outlined in red are in the ^{13}CO line and those in blue are in the ^{12}CO (2–1) line. The grayscale shading indicates sensitivity per unit area and velocity interval; specifically, it indicates the root mean square (rms) at 1 km s^{-1} spectral resolution that one would obtain by averaging all survey spectra within 1 deg^2. The rms sensitivities for ^{13}CO surveys are increased by a factor of five to account for the reduced intensity of that line. The grayscale runs from ~0.01 K rms (*black*) to ~10 K rms (*white*). 1, Solomon & Klemperer 1972; 2, Schwartz et al. 1973; 3, Burton et al. 1975; 4, Scoville & Solomon 1975; 5, Gordon & Burton 1976; 6, Bania 1977; 7, Cohen & Thaddeus 1977; 8, Burton & Gordon 1978; 9, Solomon et al. 1979; 10, Bania 1980; 11, Cohen et al. 1980; 12, Kutner & Mead 1981; 13, McCutcheon et al. 1981; 14, Casoli et al. 1984; 15, Israel et al. 1984; 16, Liszt et al. 1984; 17, Robinson et al. 1984; 18, Dame & Thaddeus 1985; 19, Knapp et al. 1985; 20, Sanders et al. 1986; 21, Bally et al. 1987; 22, Dame et al. 1987; 23, Grabelsky et al. 1987; 24, Bronfman et al. 1988; 25, Jacq et al. 1988; 26, Robinson et al. 1988; 27, Nyman et al. 1989; 28, Digel et al. 1990; 29, Stacy & Thaddeus 1991; 30, Leung & Thaddeus 1992; 31, May et al. 1993; 32, Dame & Thaddeus 1994; 33, Dobashi et al. 1994; 34, Carpenter et al. 1995; 35, Sakamoto et al. 1995; 36, Digel et al. 1996; 37, Oliver et al. 1996; 38, Bitran et al. 1997; 39, Sato 1997; 40, Yonekura et al. 1997; 41, Heyer et al. 1998; 42, Kawamura et al. 1998; 43, Kato et al. 1999; 44, Lee et al. 1999; 45, Yamaguchi et al. 1999; 46, Yamaguchi et al. 1999; 47, Ungerechts et al. 2000; 48, Dame et al. 2001; 49, Lee et al. 2001; 50, Moriguchi et al. 2001; 51, Sawada et al. 2001; 52, Mizuno & Fukui 2004; 53, Jackson et al. 2006; 54, Schneider et al. 2006; 55, Yoda et al. 2010; 56, Schneider et al. 2011; 57, Burton et al. 2013; 58, Brunt et al. 2015; 59, Barnes et al. 2015.

“Extracting” molecular clouds from position-position-velocity cubes

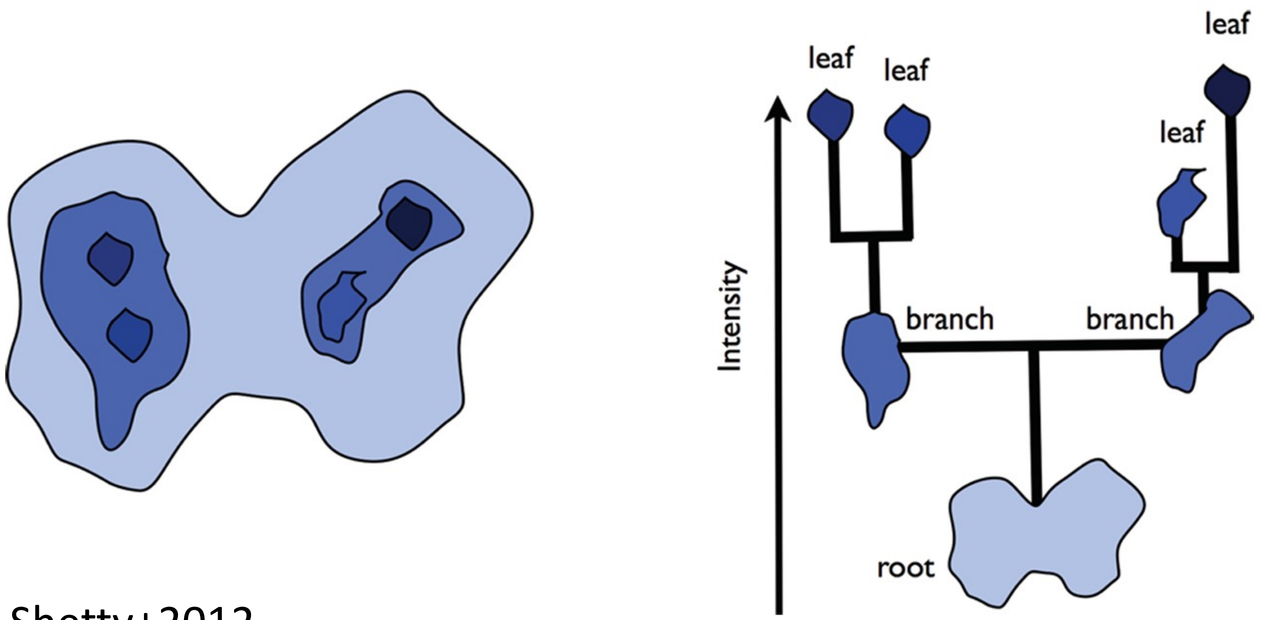
- CLUMPFIND searches through a 3D (l,b,v) position-position-velocity (PPV) data cube using iso-brightness surfaces to identify contiguous emission features without assuming an a priori shape.



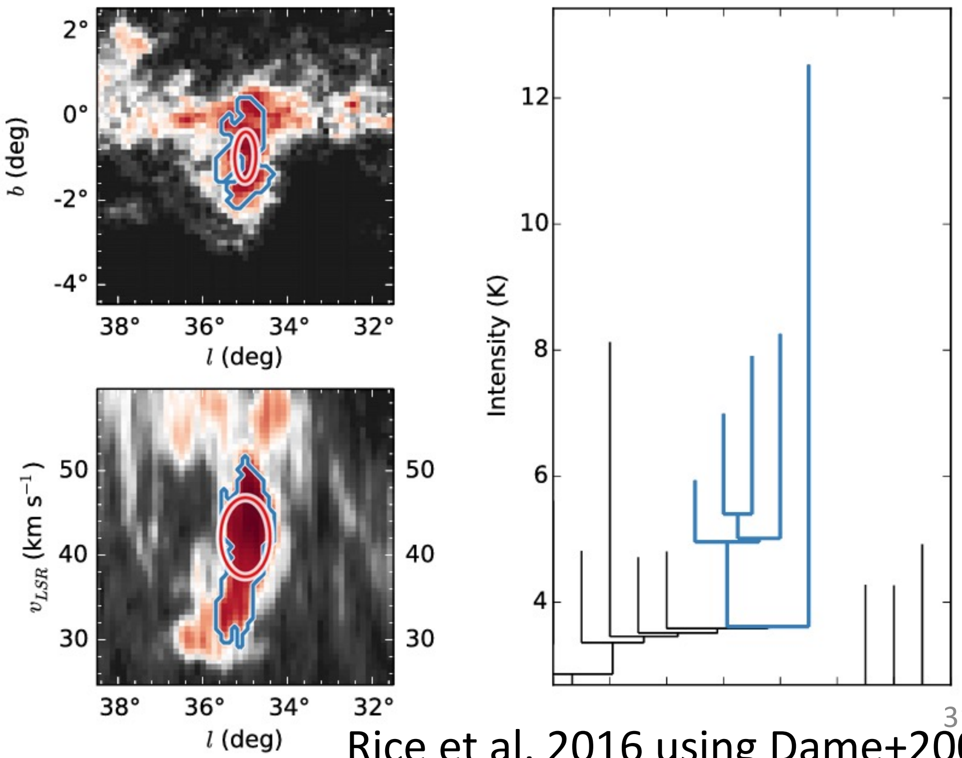
Rathborne+2009

“Extracting” molecular clouds from position-position-velocity cubes

- “Dendrograms represent the essential features of the hierarchical structure of isosurfaces in molecular line data cubes” (Rosolowsky+2008)
- Points in the dendrogram structure correspond to specific volumes in data cubes defined by their bounding isosurfaces



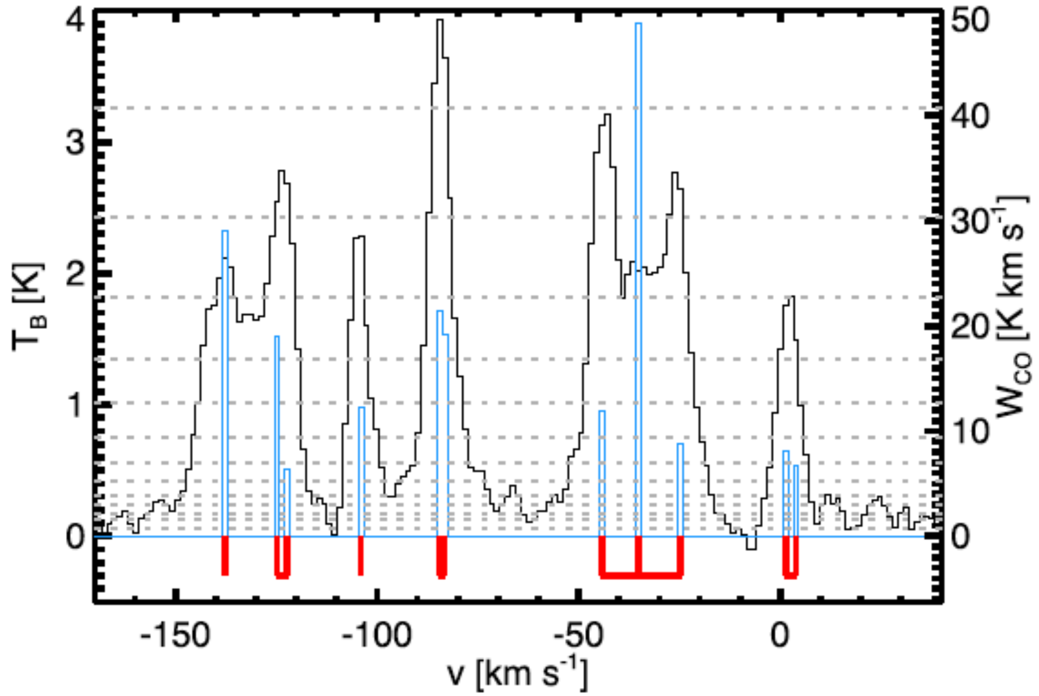
Shetty+2012



Rice et al. 2016 using Dame+2001 survey

"Extracting" molecular clouds from position-position-velocity cubes

- Gaussian decomposition of spectra + clustering analysis (e.g., CLUMPFIND) – Miville-Deschenes+2017
- Captures 98% of emission in Dame+2001 survey



Deriving molecular clouds properties

Based on Rohlfs & Wilson 2004

- CO excitation temperature from ^{12}CO data

From ^{12}CO 1-0 (optically thick)

$$T_{ex} = \frac{5.53}{ln(1 + \frac{5.53}{T_{12}+0.837})}$$

- ^{13}CO optical depth

From ^{13}CO 1-0

$$\tau_{13}(\ell, b, v) = -ln\left(1 - 0.189\, T_{13}(\ell, b, v)\left(\frac{1}{\frac{1}{e^{\frac{5.3}{T_{ex}(\ell,b,v)}}-1} - 0.16}\right)\right)$$

- Mass of H_2 + He (assumes abundance $^{13}CO/H_2$)

$$\frac{M}{M_\odot} = 0.27\,\frac{d^2}{kpc^2}\int_\ell\int_b\int_v \frac{T_{ex}(\ell, b, v)}{1 - e^{\frac{-5.3}{T_{ex}(\ell,b,v)}}}\tau_{13}(\ell, b, v)\frac{dv}{km\ s^{-1}}\frac{d\ell}{arcmin}\frac{db}{arcmin}$$

Deriving molecular clouds properties

- Properties are derived inside iso-surface (e.g., 4σ isophot for Roman-Duval+2010, or T_b > 1 K)
- Radius: Count positions N_{pix} where the ^{13}CO integrated intensity is > 4σ ~ 0.2 K km/s

$$A = N_{pix} d^2 \Delta l \Delta b \qquad R = \sqrt{\frac{A}{\pi}}$$

- Virial parameter: Describes the ratio of kinetic energy to gravitational energy ($\alpha = M_{vir}/M$)

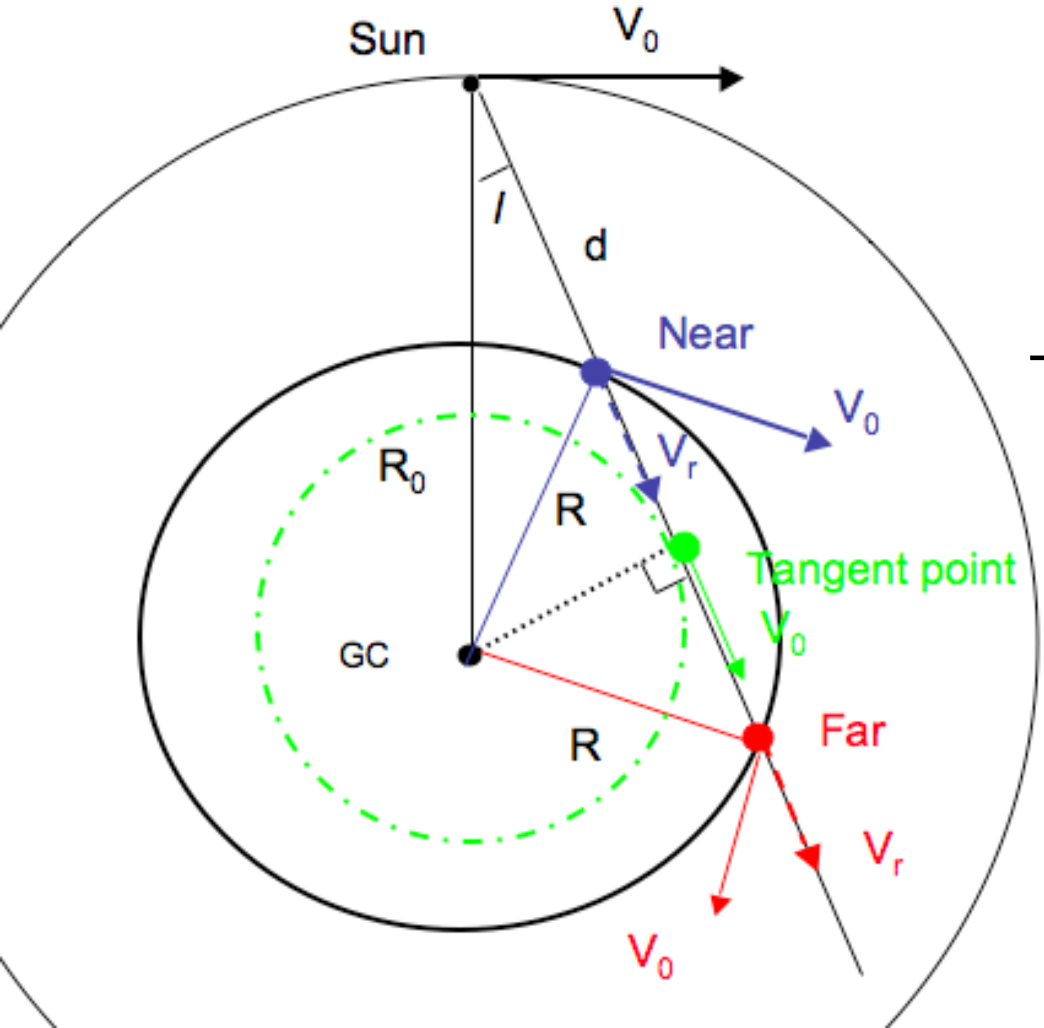
$$\alpha = \frac{5\sigma_v^2 R}{GM} = 1160 \left(\frac{\sigma_{v_{1D}}^2}{km^2 s^{-2}} \right) \left(\frac{R}{pc} \right) \left(\frac{1M_o}{M} \right)$$

- Surface mass density:

$$\Sigma = \frac{M}{\pi R^2}$$

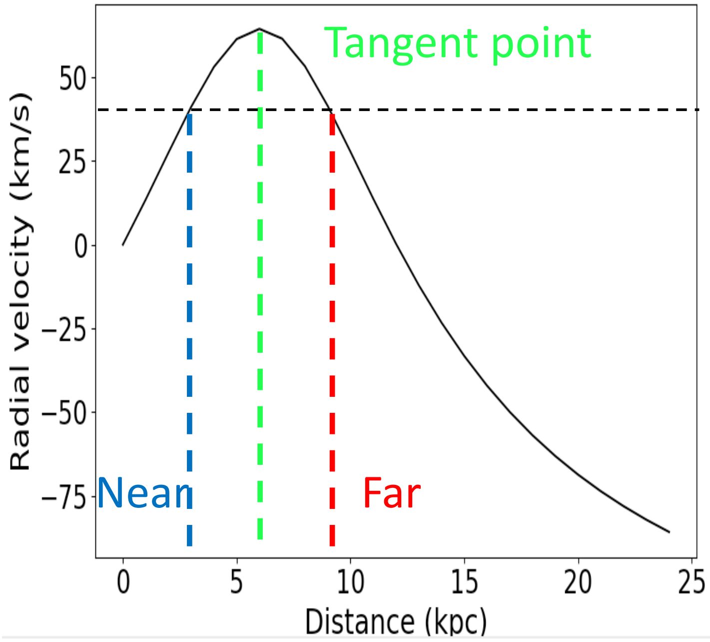
Kinematic distances to molecular clouds

Roman-Duval+2009



- Based on a rotation curve model (e.g., Clemens+1985)
- Large errors where non-circular motions (spiral arms….)
- Unique solution for the galactocentric radius
- Two solutions for the distance inside solar circle
  - "Near"
  - "Far"

→ Kinematic distance ambiguity

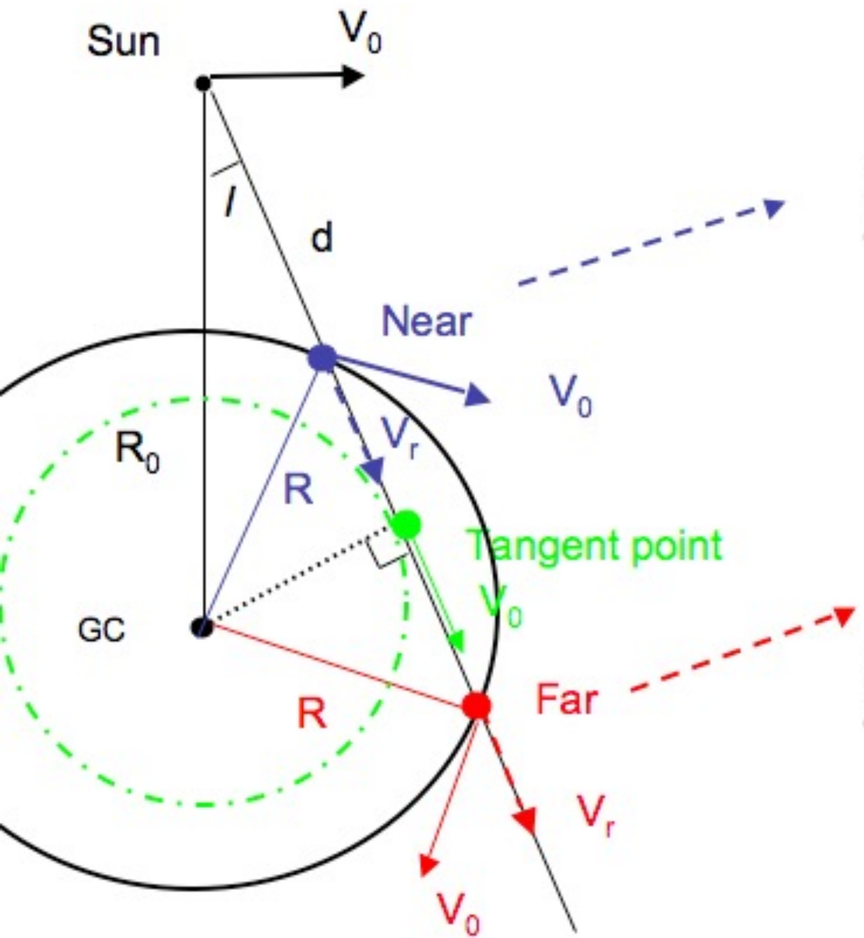


$$V_{radial} = V_0 \sin l \left(\frac{R_0}{R} - 1\right)$$

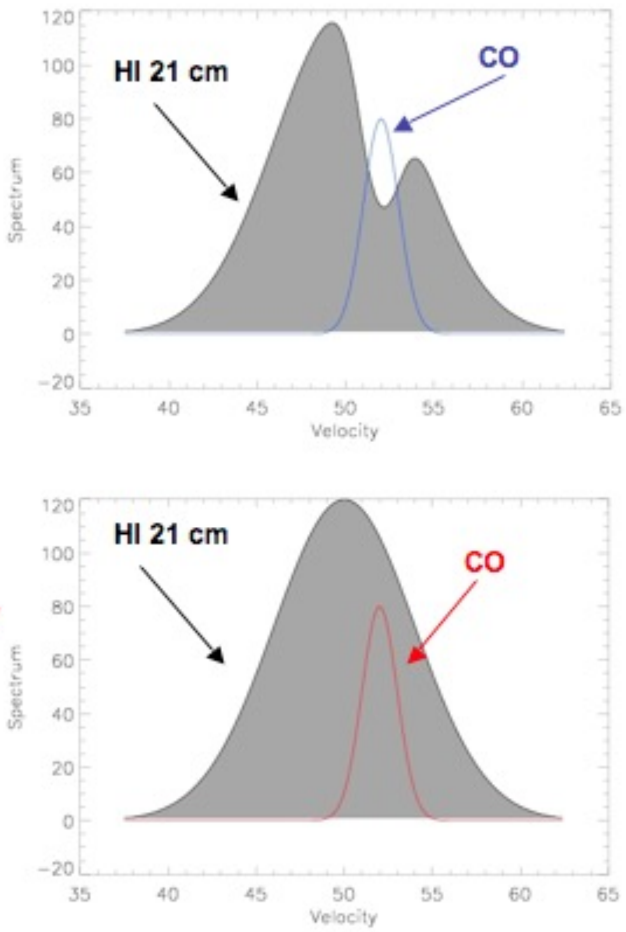
$$R^2 = R_0^2 + d^2 - 2Rd\cos l$$

$$d = R_0 \cos l \pm \sqrt{R^2 - R_0^2 \sin^2 l} = R_0 \cos l \pm \sqrt{R^2 - R_{min}^2}$$

Resolving the kinematic distance ambiguity with HI self-absorption



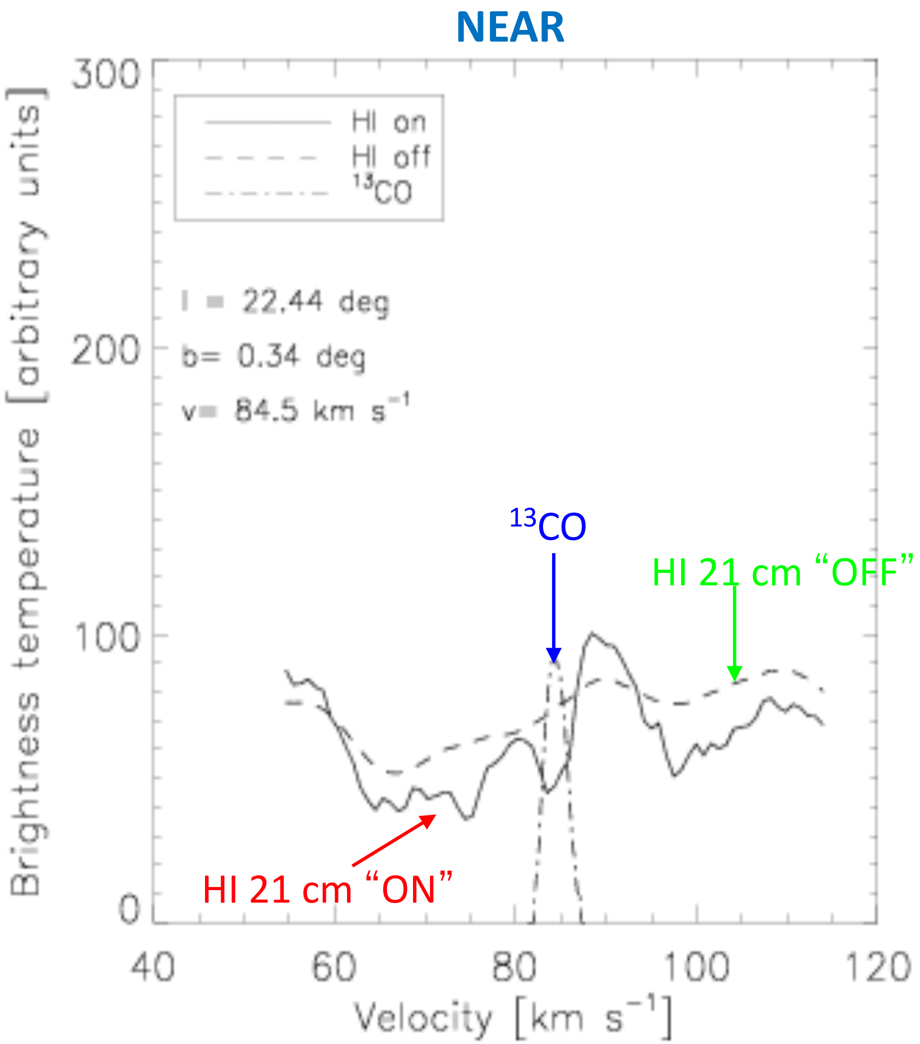
Roman-Duval+2009

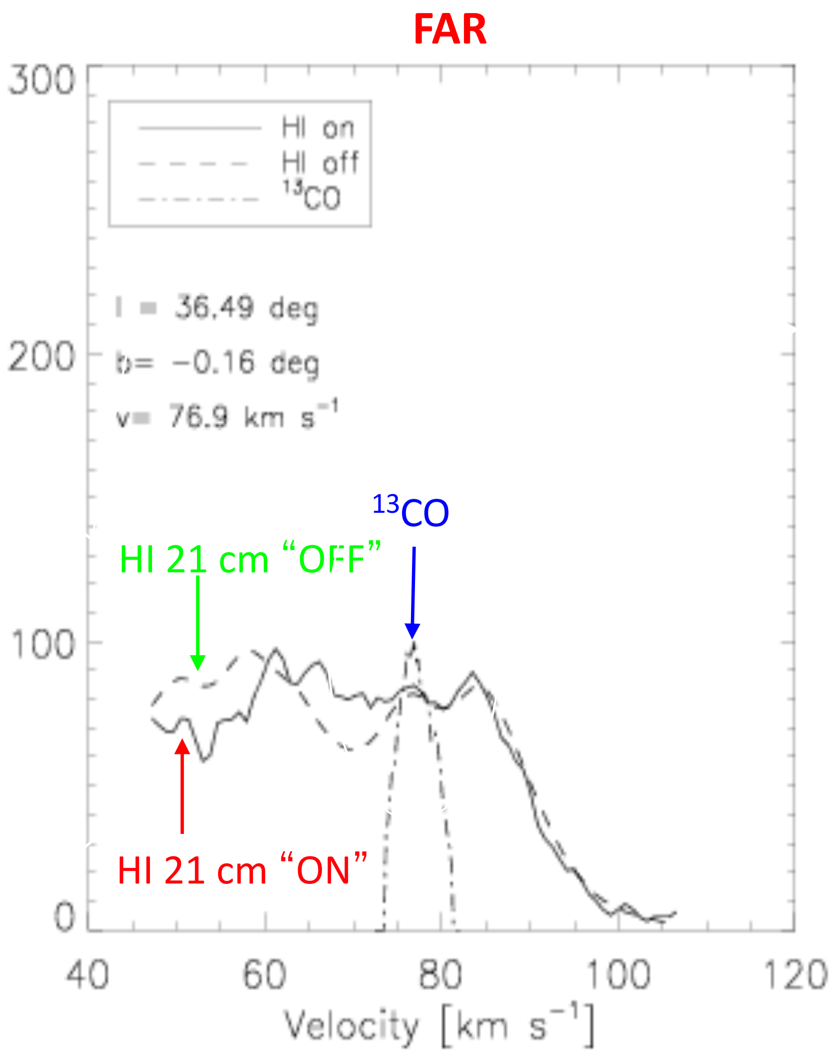


- Warm HI (T_{ex} ~100 - 10000K) everywhere in the Galaxy
- T_{ex} ~ 10 K for HI in clouds + high column density → cold clouds absorb background 21 cm radiation from warm HI

Example from the Galactic Ring Survey

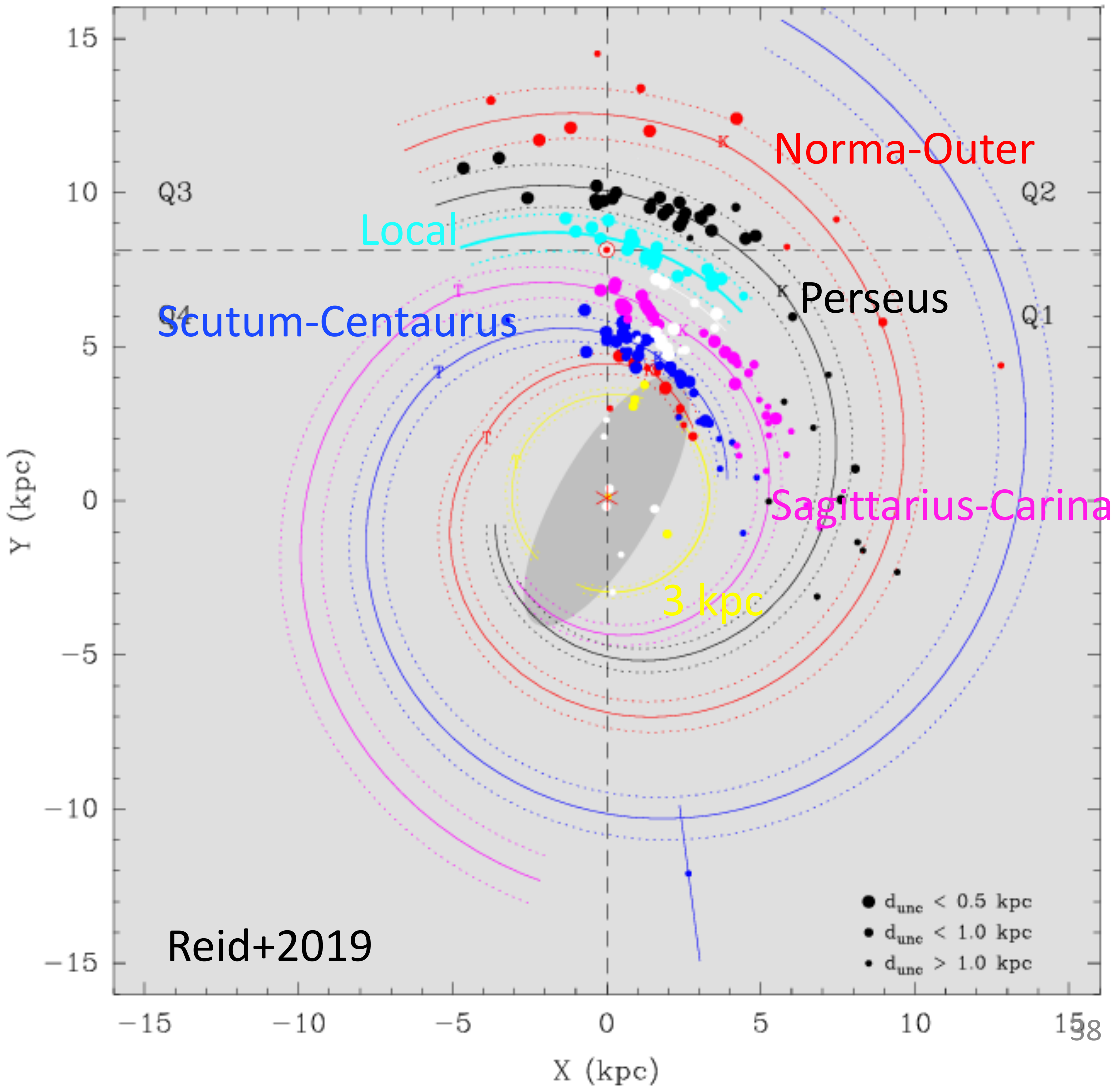
Roman-Duval+2009





Distances from maser parallaxes

- Massive star-forming regions can host masers (=lasers in the microwave wavelength range)
- Those can be observed out to large distances
- Distance derived from parallax of maser measured with high precision using large-baseline interferometry (e.g., VLBI)
- D = 2 AU/ tan(p)



3D Dust maps

- Uses Gaia distances and stellar photometry/reddening (Pan-STARRS, 2MASS)
- See Green+2019 for details

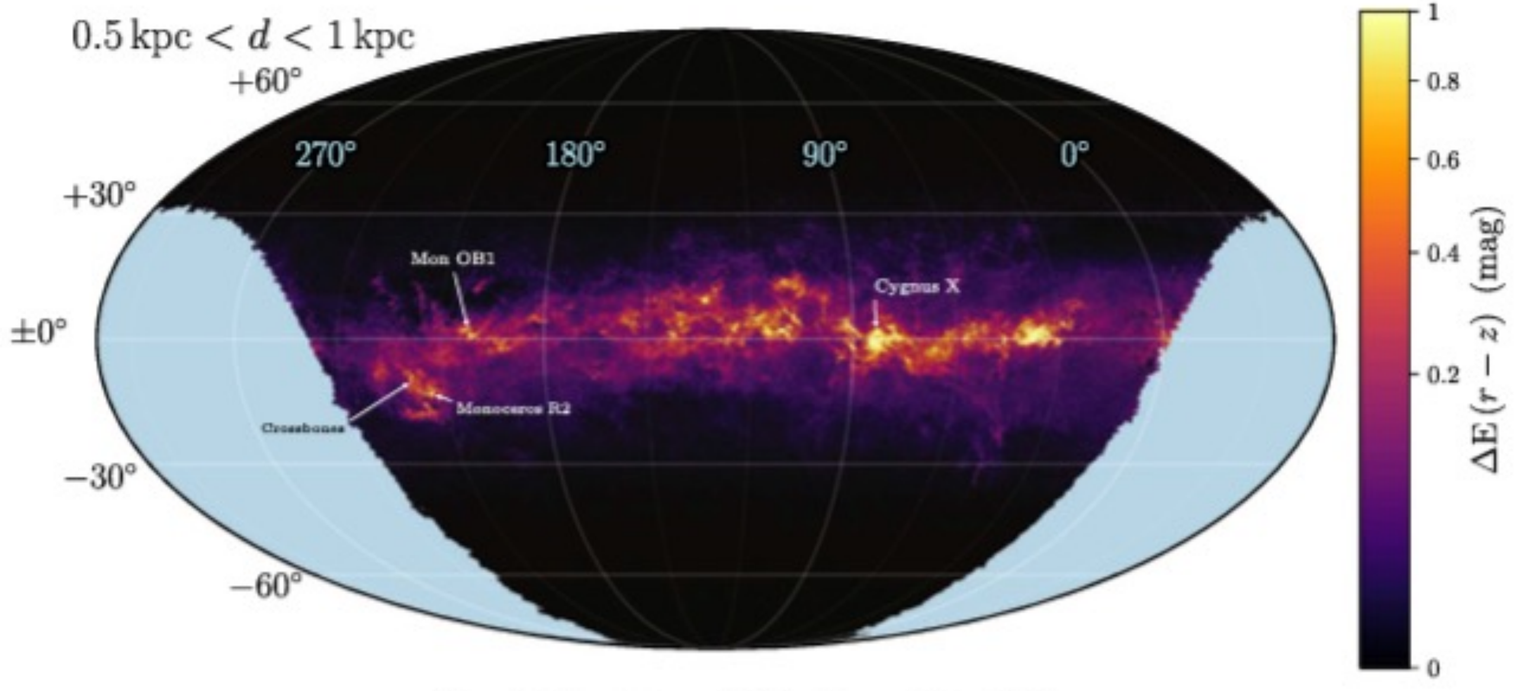
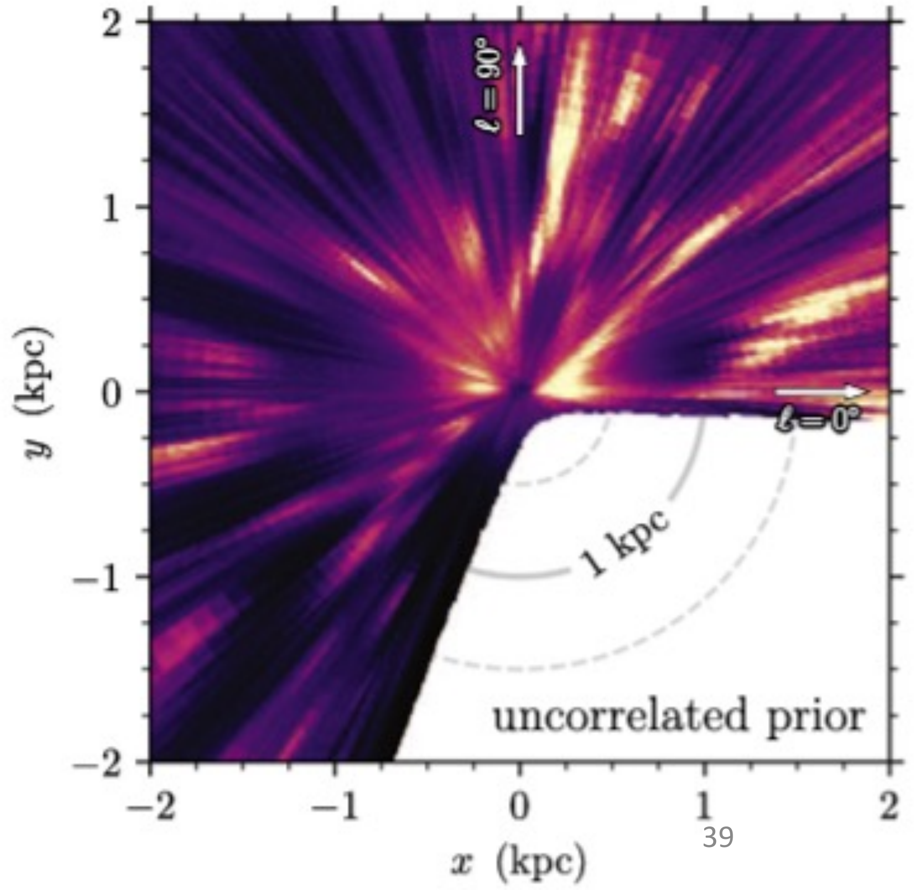
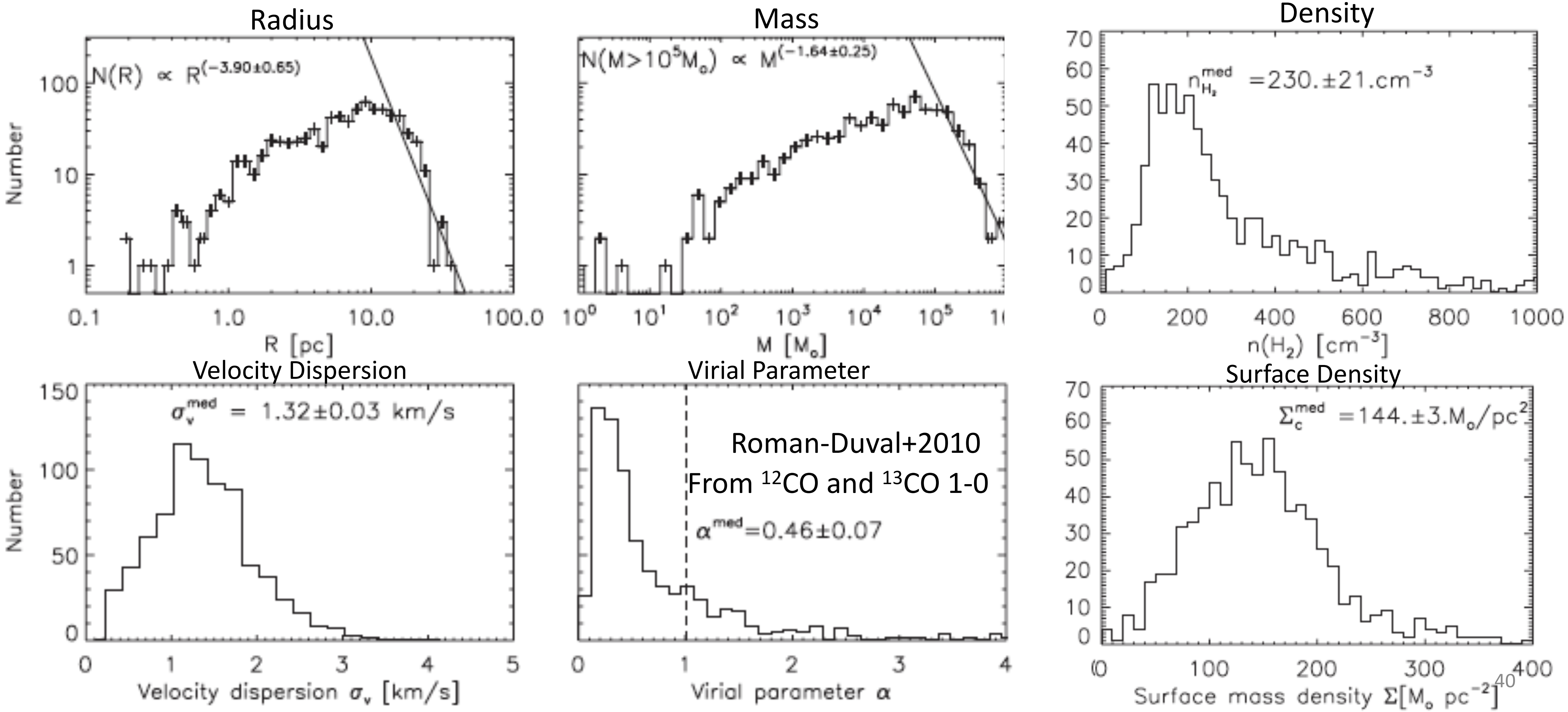


Figure 2. Cumulative reddening between 0.5 and 1 kpc.



Properties of molecular clouds in the MW



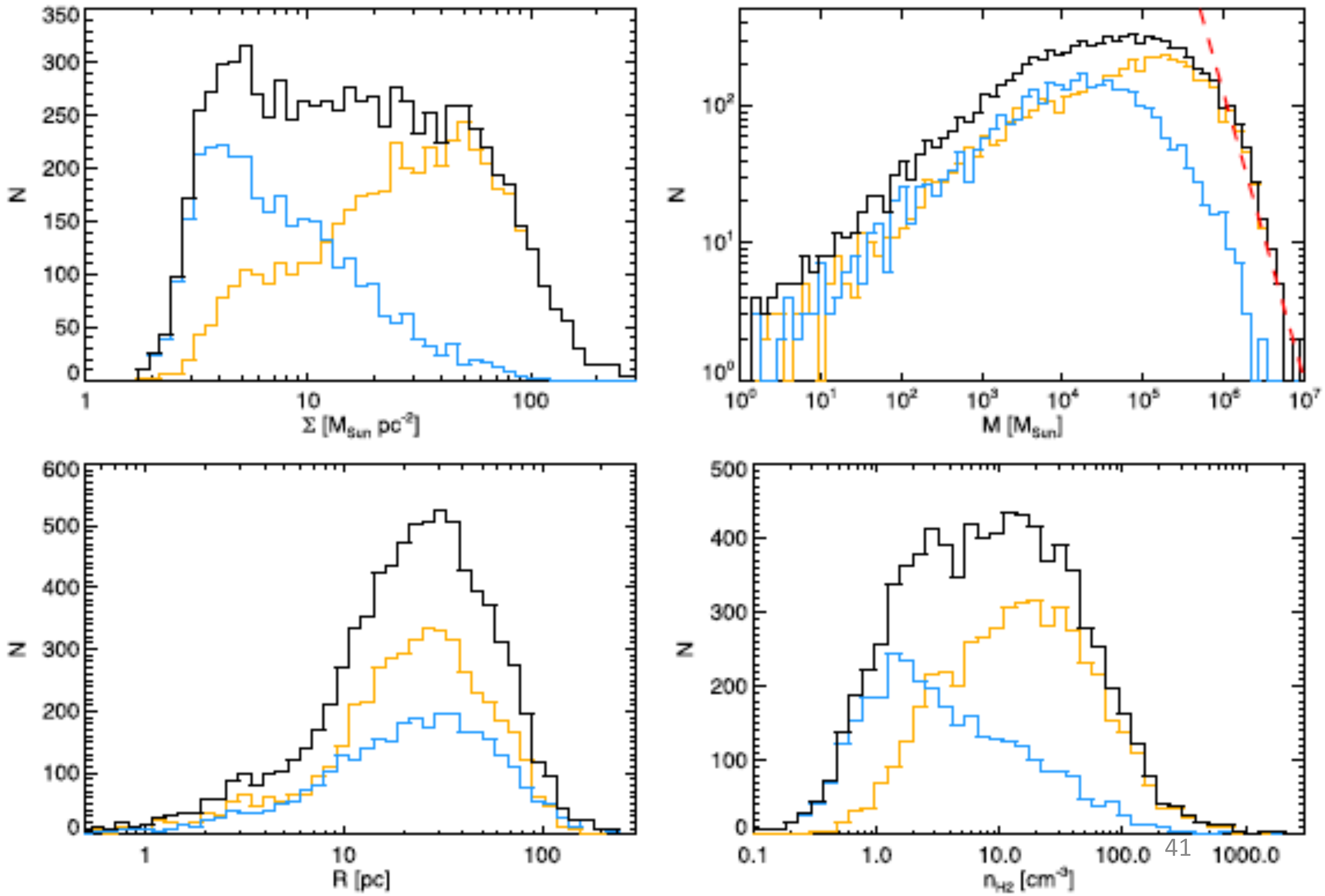
Properties of molecular clouds in the MW

- From Miville-Deschenes (^{12}CO 1-0 survey from Dame+2001)

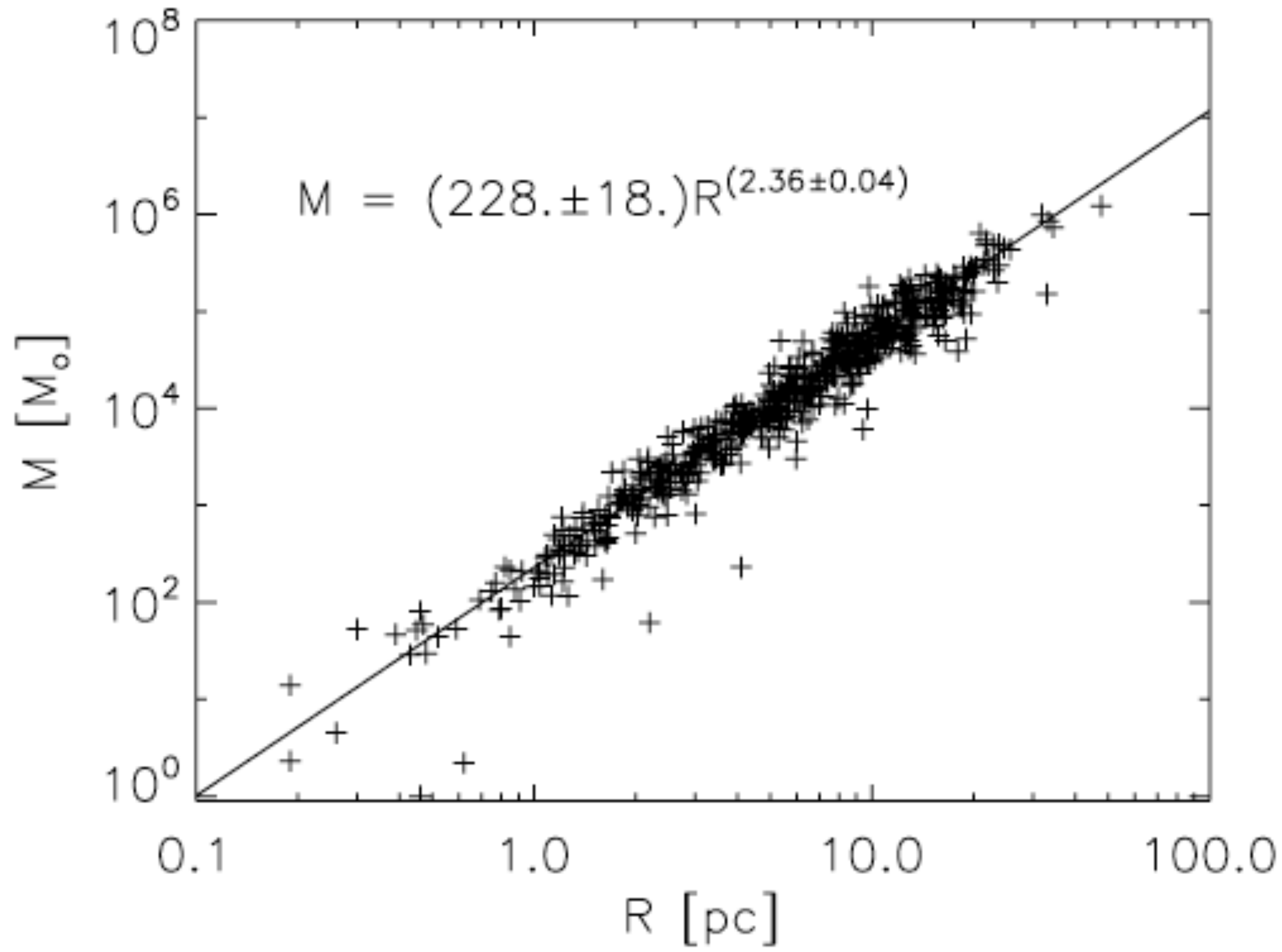
Inner Galaxy

Outer Galaxy

Power-law exponent -2



Properties of molecular clouds in the MW



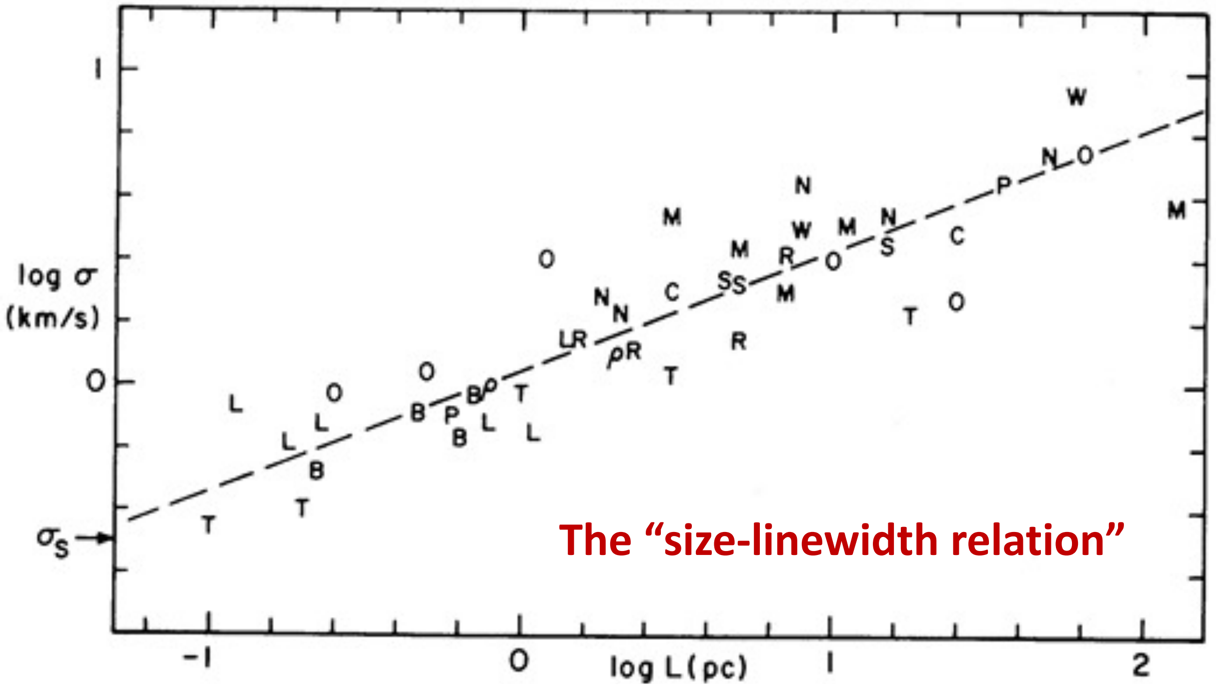
- Fractal dimension = 2.36
- See also Elmegreen & Falgarone 1996
- Can be used to estimate cloud mass from radius (easier to measure)

Roman-Duval+2010

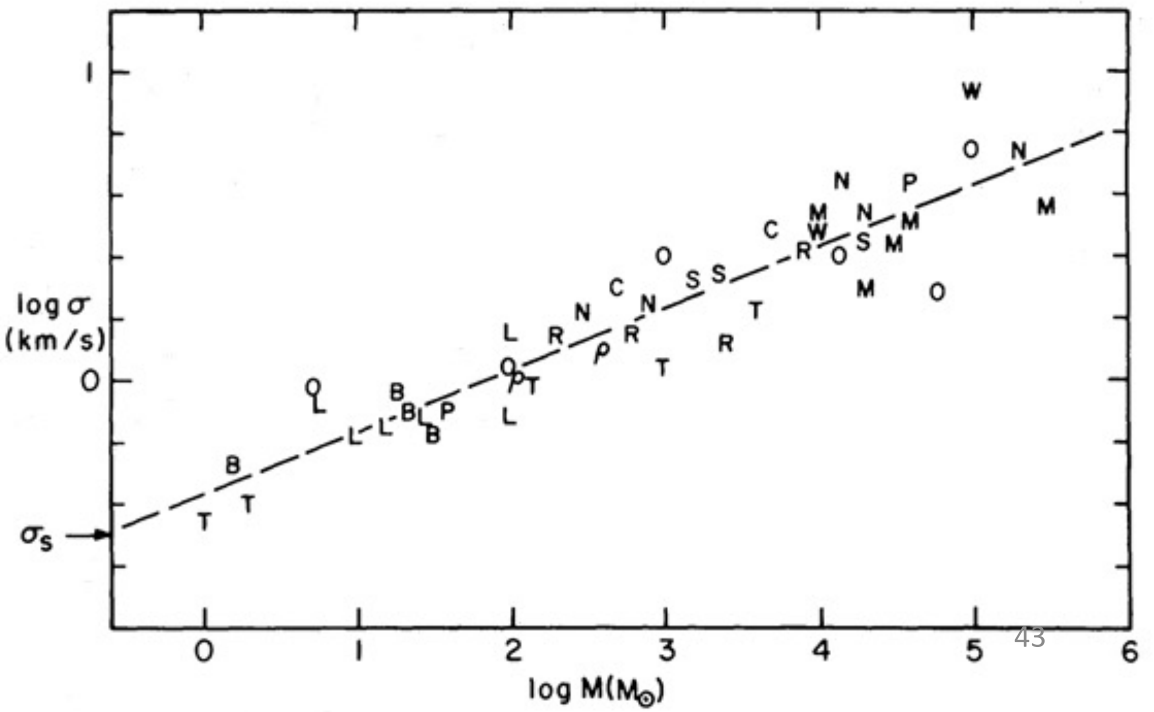
Larson's relations

- Larson (1981) measured three empirical relations from CO observations:
  - ✓ Σ ~ constant

$$\sigma(\mathrm{km\,s^{-1}}) = 1.10\, L\, (\mathrm{pc})^{0.38}$$

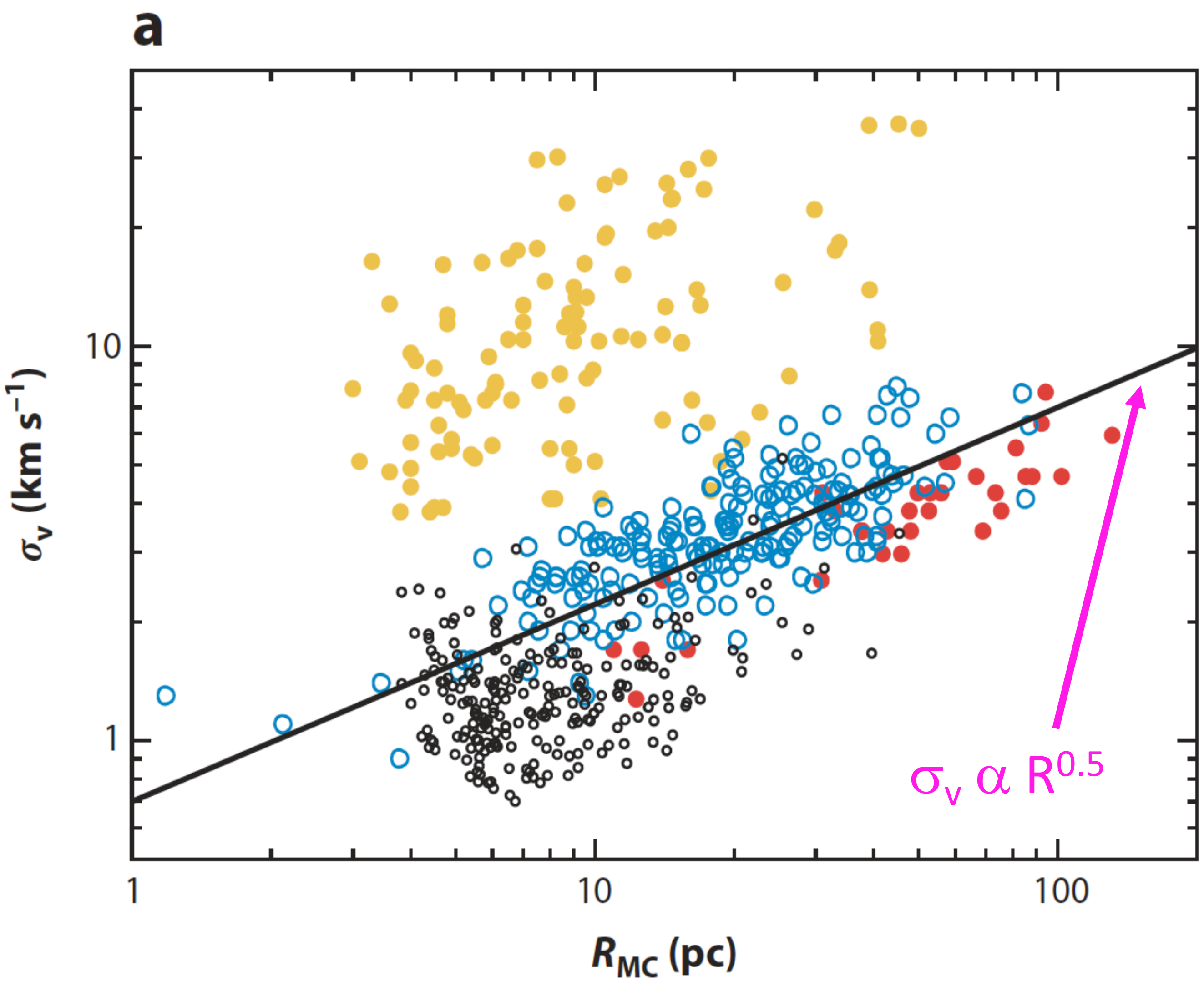


$$\sigma\,(\mathrm{km\,s^{-1}}) = 0.42\, M(M_\odot)^{0.20}$$



→ Motions in molecular clouds stem from turbulence

Larson's relations revisited



Heyer+2015 compiled more recent data on the size-linewidth relation in the Milky Way

Oka+2001 (Galactic Center)
Dame+1986 (l = 12-60 deg)
Solomon+1987 (l = 8-90 deg)
Heyer+2001 (Outer Galaxy)

Equipartition between gravitational and kinetic energy

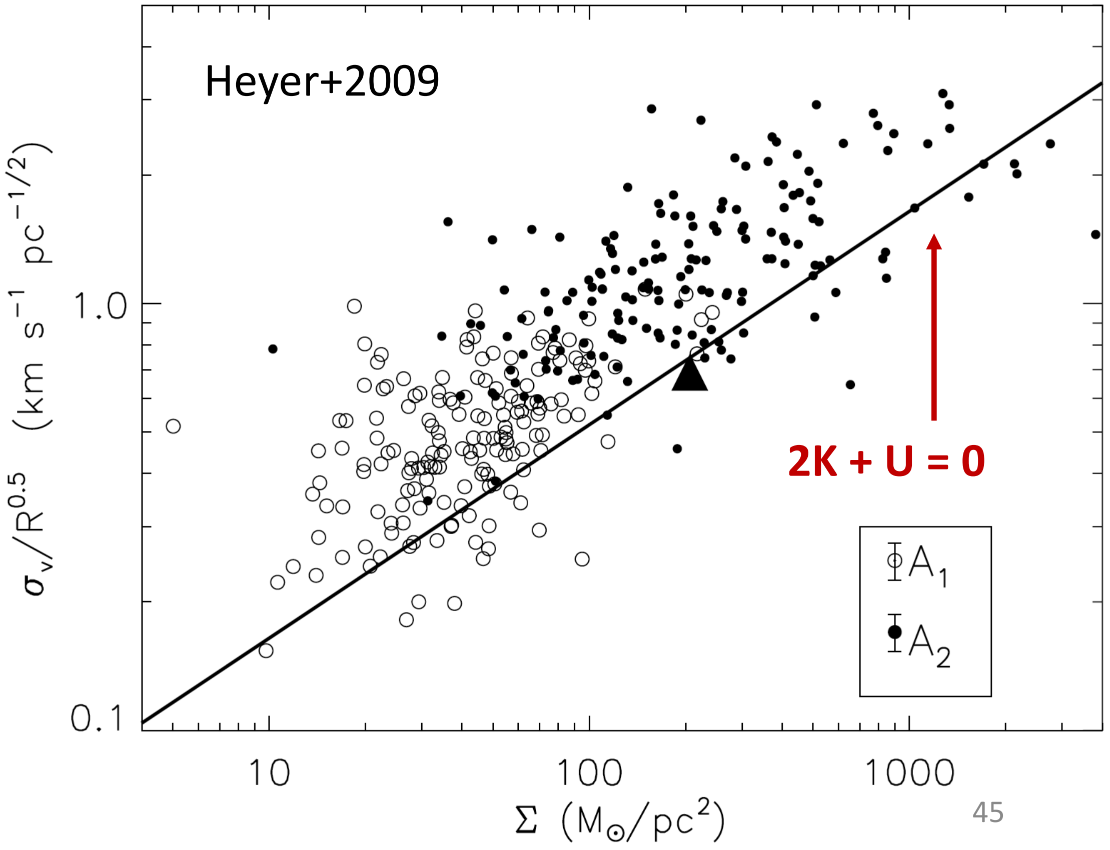
- Often (incorrectly) equated to "virial equilibrium" (2K + U = 0)
- Kinetic energy from turbulence interpreted as source of support

$$K = \frac{M\sigma_v^2}{2} \qquad U = \frac{GM^2}{5R} \qquad M_{vir} = \frac{5\sigma_v^2 R}{G}$$

$$M = M_{vir} \rightarrow \sigma_v = \sqrt{\frac{\pi G}{5}}\Sigma^{\frac{1}{2}} R^{\frac{1}{2}}$$

Heyer+2009 study suggests:

- $M < M_{vir}$
- Σ is not constant

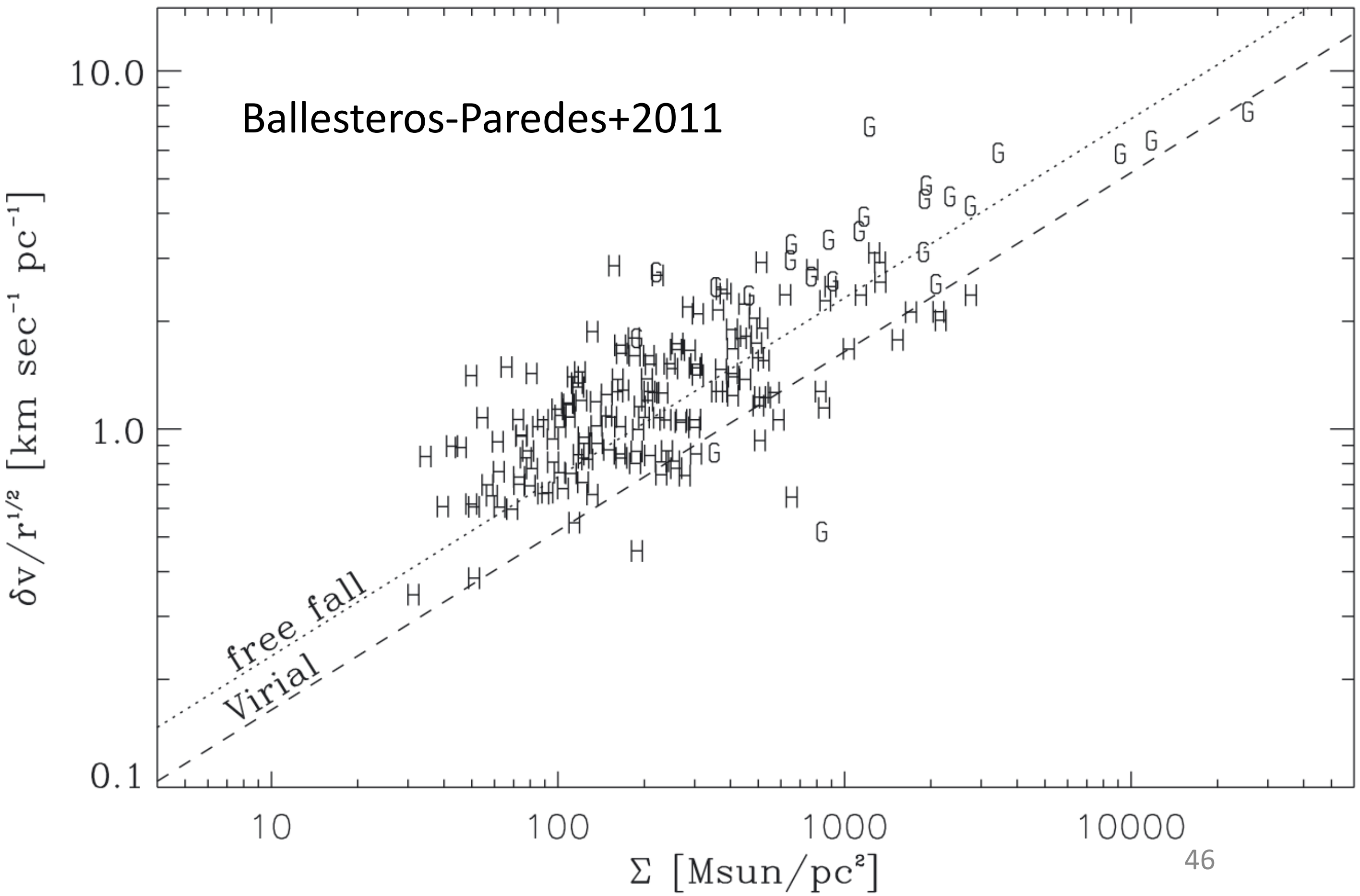


Equipartition between gravitational and kinetic energy

- Another interpretation: Free-fall! Differs only by factor from virial equilibrium

$$\sigma_v^{ff} = \sqrt{\frac{2\pi G}{5}}\Sigma^{\frac{1}{2}} R^{\frac{1}{2}}$$

- In the case of free-fall, kinetic energy is interpreted as source of support while in fact, it is only due to collapse

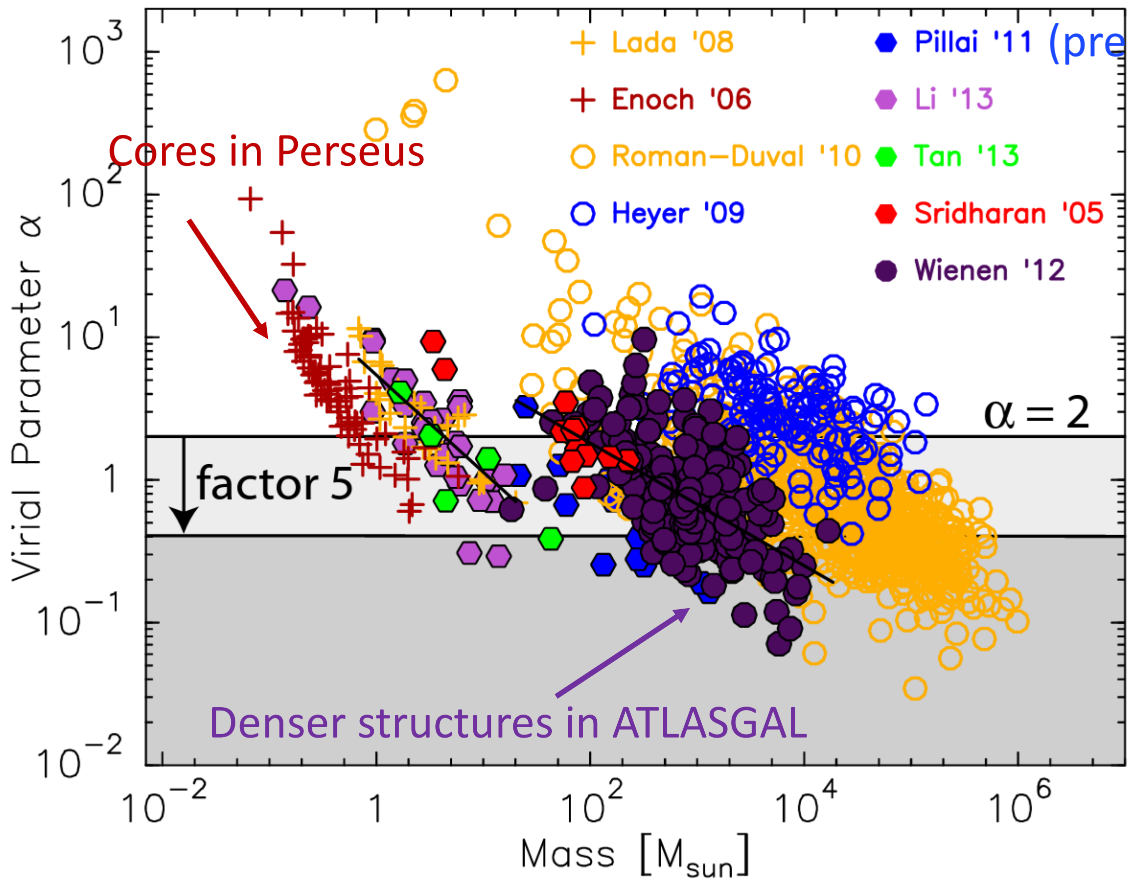


The virial parameter

$$\alpha = \frac{M_{vir}}{M}$$

$\alpha < 1$: gravitationally bound; $\alpha > 1$: unbound

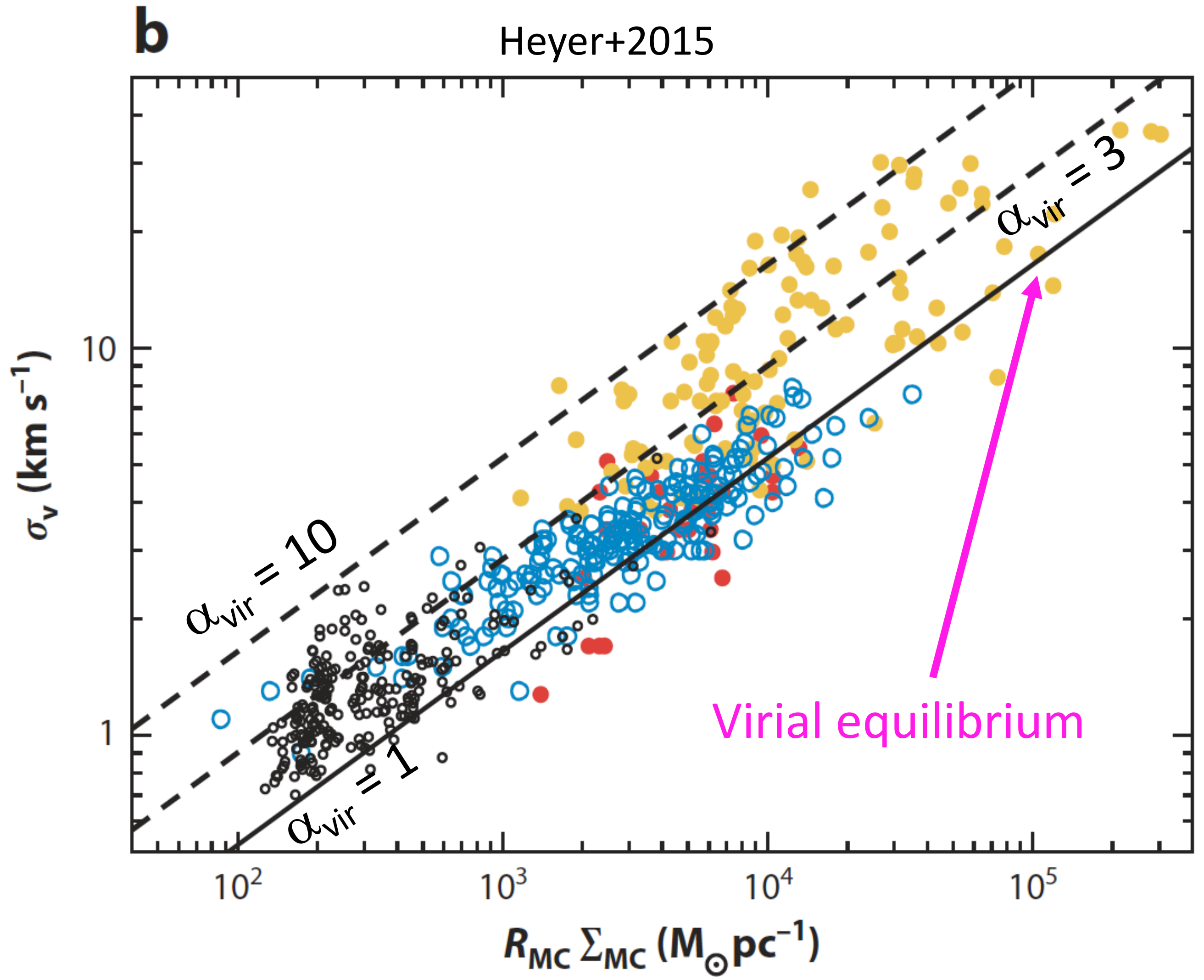
Kauffmann+2013



Many clouds with $\alpha < 1$ suggests:

- Magnetic field needed for support or;
- Rapid collapse (could explain the absence of high-mass starless cores (Kauffmann+2013)

The virial parameter



Clouds in the galactic center have a surplus of support ($\alpha >> 1$)

Oka+2001 (Galactic Center)
Dame+1986 (l = 12-60 deg)
Solomon+1987 (l = 8-90 deg)
Heyer+2001 (Outer Galaxy)

Open Questions

- How do molecular clouds form in different galactic environments (e.g., Galactic center vs spiral arms)?
  → what are the gas flows in/around molecular clouds that result in their assembly?
- What are the lifetimes of molecular clouds?
- How do we get accurate distances to molecular clouds?
- How do we statistically characterize molecular clouds without subjectivity from the segmentation method?
- How big of a role does turbulence vs gravity vs magnetic fields play in the formation and evolution of molecular clouds?

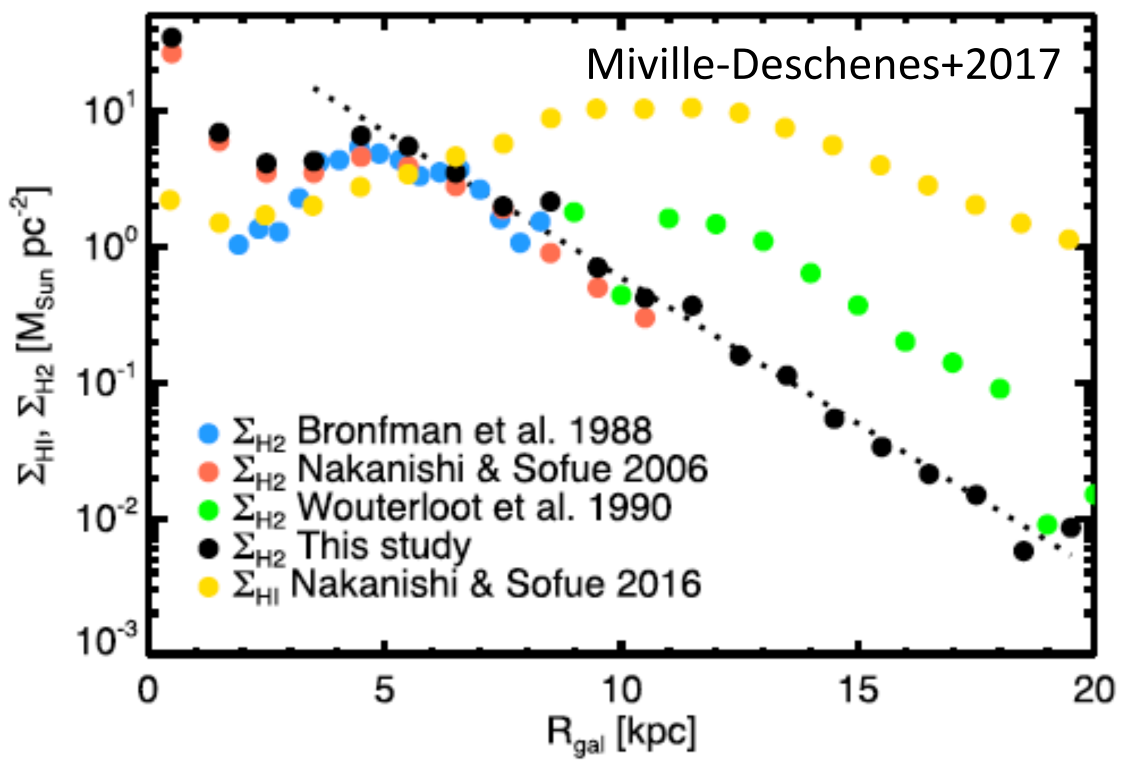
1. Tracers of the ISM
2. Phases of the ISM
3. Galactic molecular clouds
4. **Distribution of molecular gas in the Milky Way**
5. The turbulent properties of molecular clouds
6. The ISM and star formation

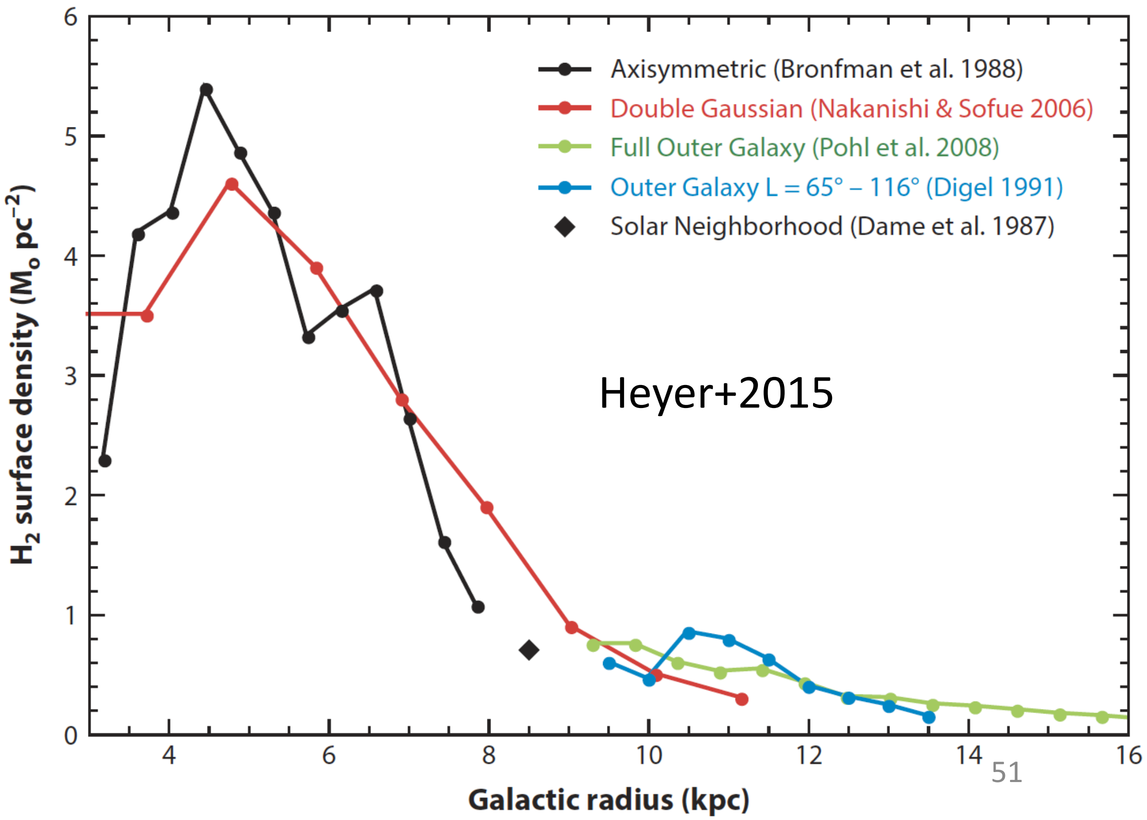
The Galactic surface density of molecular gas

- Derived from Dame+2001 survey (covers the entire Galactic plane)

→ Based on ^{12}CO and assumes $X_{CO} = 2x10^{20}$ cm^{-2} K^{-1} km^{-1} s

- See Heyer+2015 and Miville-Deschenes+2017





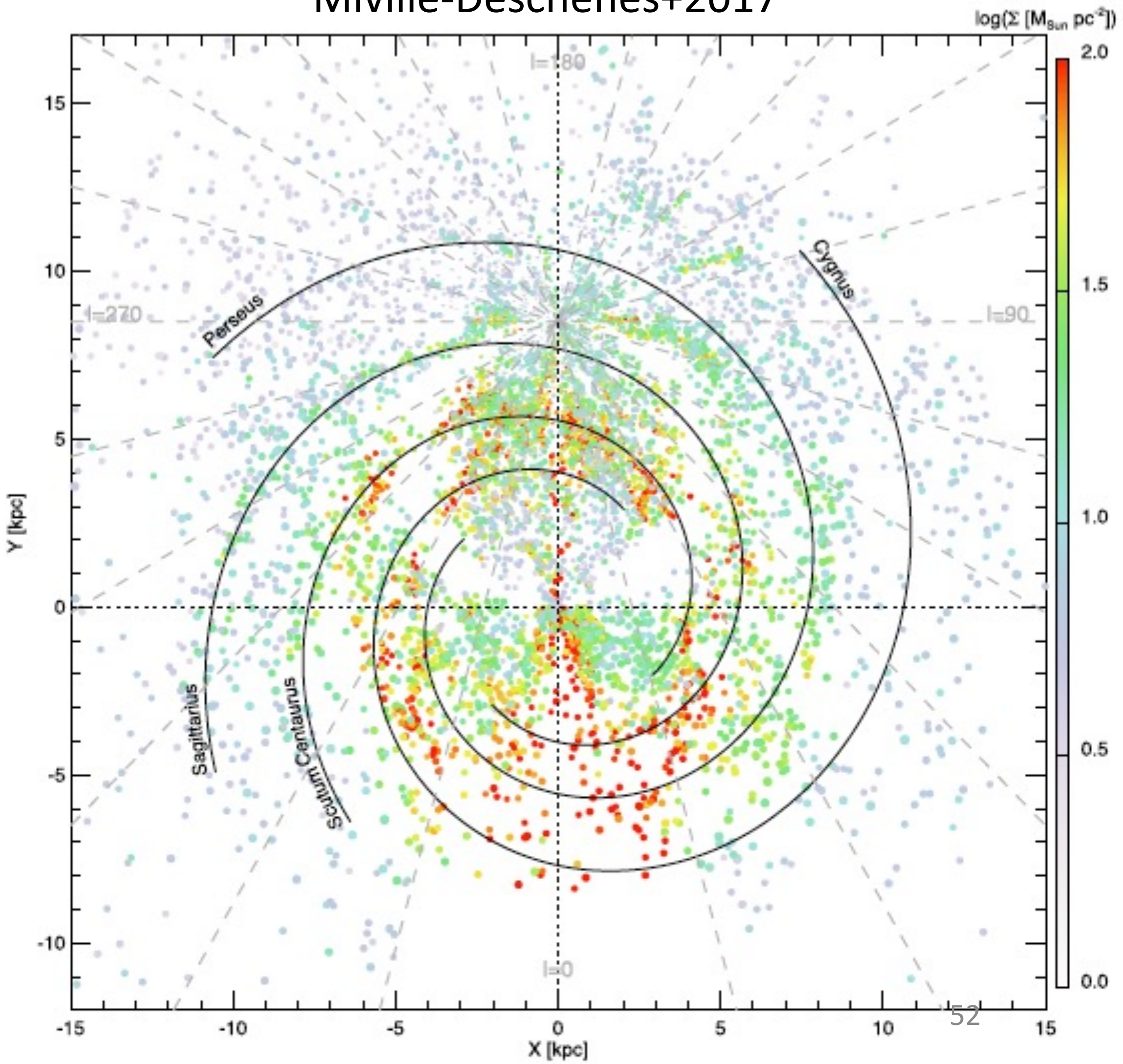
The face-on distribution of molecular gas

- Derived from Dame+2001 survey (covers the entire Galactic plane)

→ Based on ^{12}CO and assumes X_{CO} = 2x10^{20} cm^{-2} K^{-1} km^{-1} s

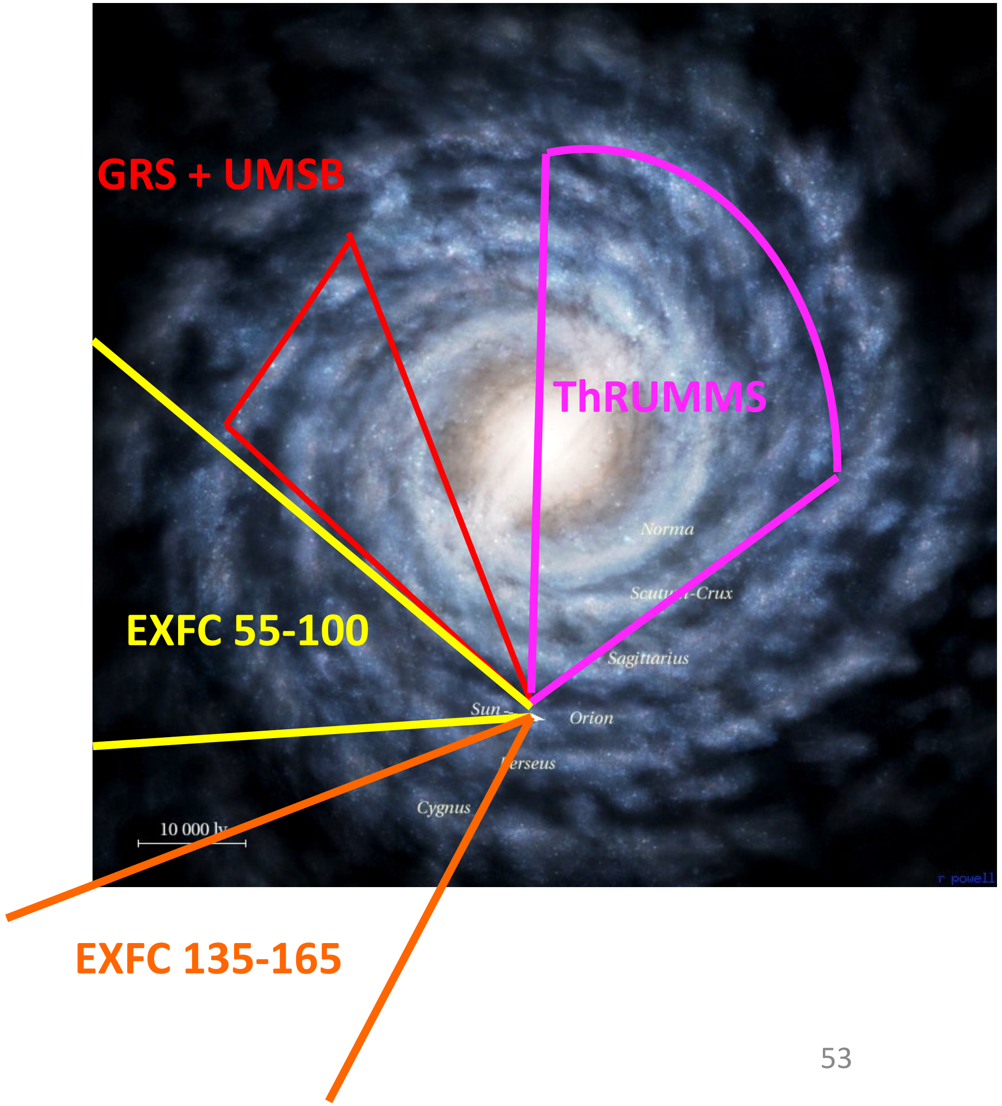
- See Miville-Deschenes+2017

Miville-Deschenes+2017



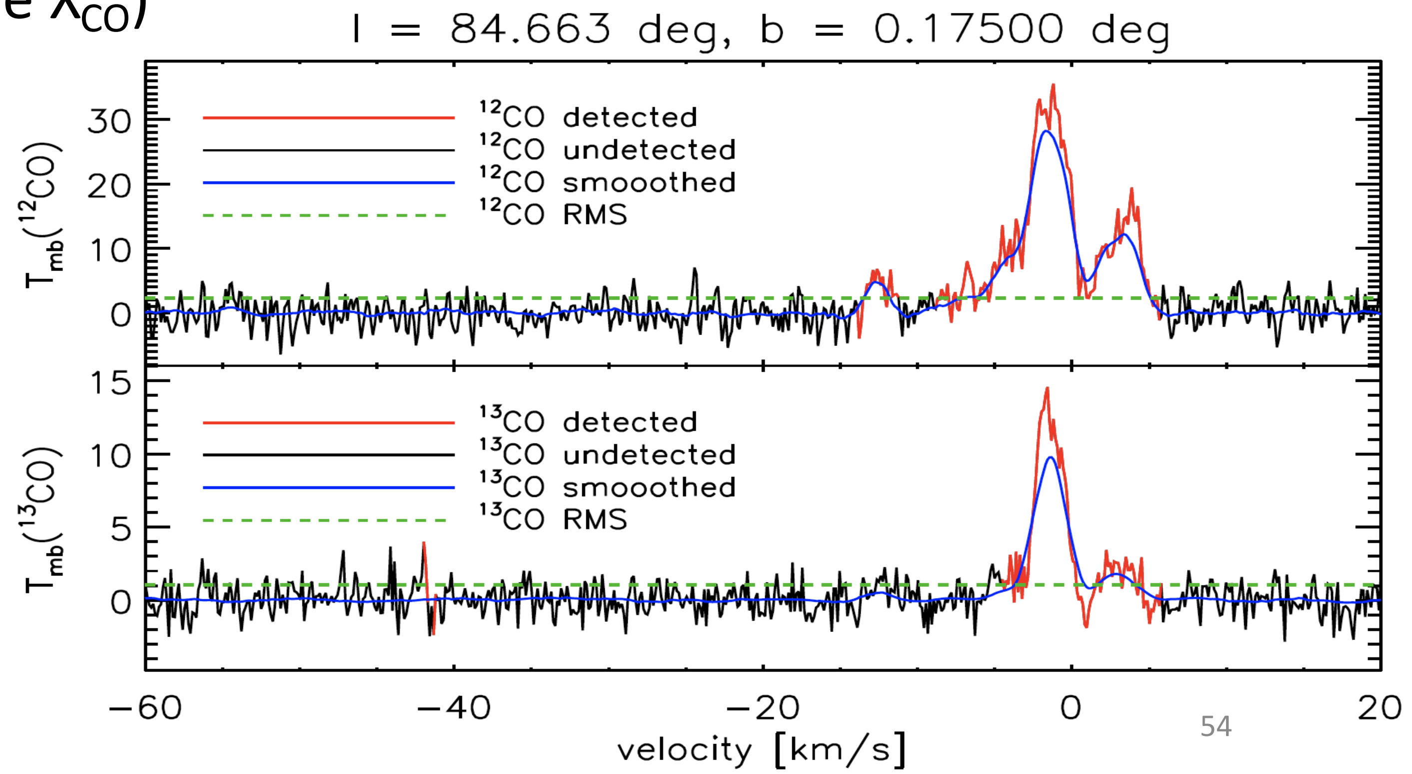
Quantifying the distribution of molecular gas in the milky way

- In the Milky Way, we can spatially resolve different gas components
- We use large-scale surveys of ^{12}CO and ^{13}CO
  - Galactic Ring Survey (GRS, ^{13}CO) – Jackson+2006
  - University of Massachusetts Stony Brook survey (UMSB) in ^{12}CO - Sanders+1986
  - EXeter-FCRAO survey (EXFC) in ^{12}CO and ^{13}CO (outer Galaxy) – Brunt+2015
  - ThrUMMS survey (^{12}CO and ^{13}CO) – Barnes+2015
  - All surveys have 45” beam



Eliminating the concept of “cloud”

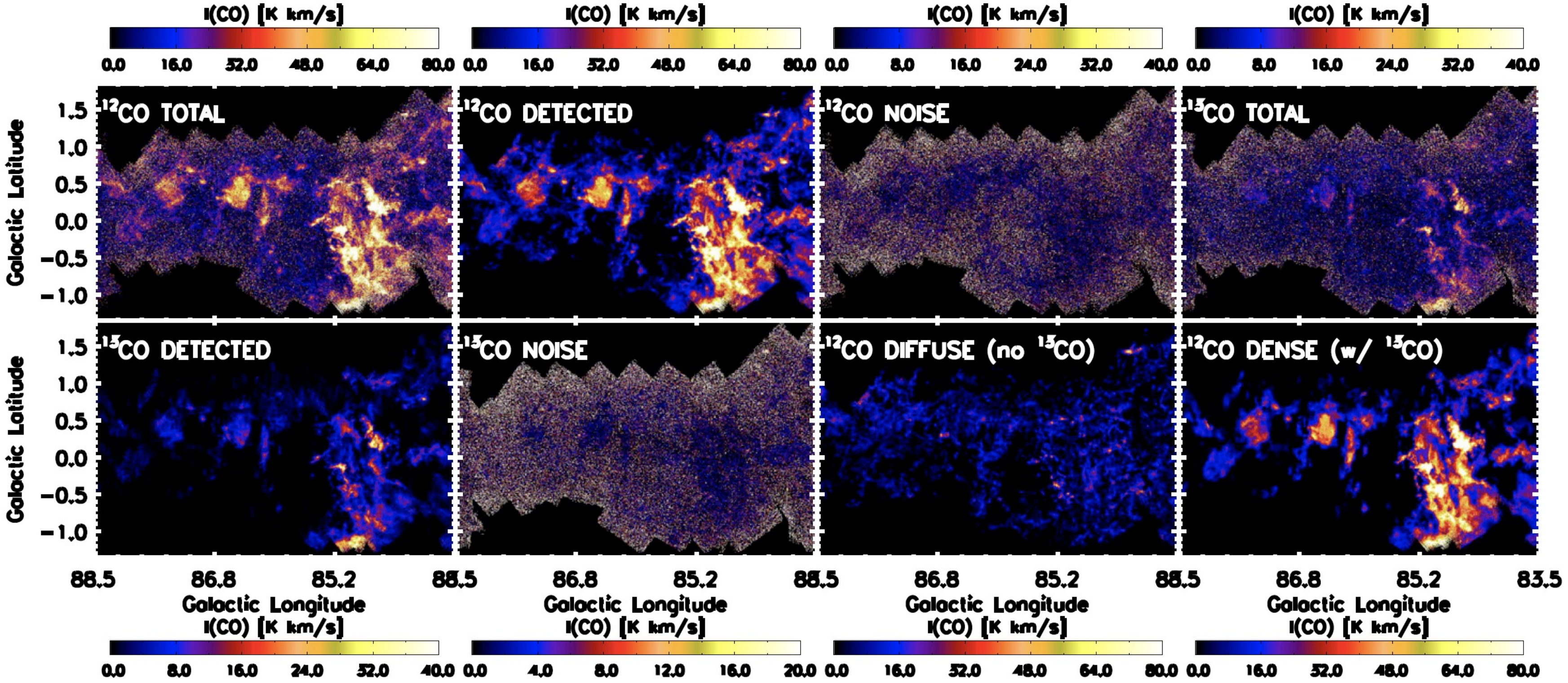
- Work directly with the cube (no decomposition of emission into MC – captures all the emission)
- Uses morphological operations (see Roman-Duval+2016 for details)
- Use ^{12}CO and ^{13}CO (no need to assume X_{CO})



Roman-Duval+2016

Diffuse and dense molecular gas

- Separate diffuse and dense molecular gas
  - ➢ Detect ^{13}CO emission with T_{12}/T_{13} up to 10
  - ➢ Dense CO gas detected in ^{12}CO and ^{13}CO → $\Sigma_v(H_2) > 10\ M_o\ pc^{-2}\ (km\ s^{-1})^{-1}$
  - ➢ Diffuse CO gas detected in ^{12}CO, not ^{13}CO → $\Sigma_v(H_2) < 10\ M_o\ pc^{-2}\ (km\ s^{-1})^{-1}$

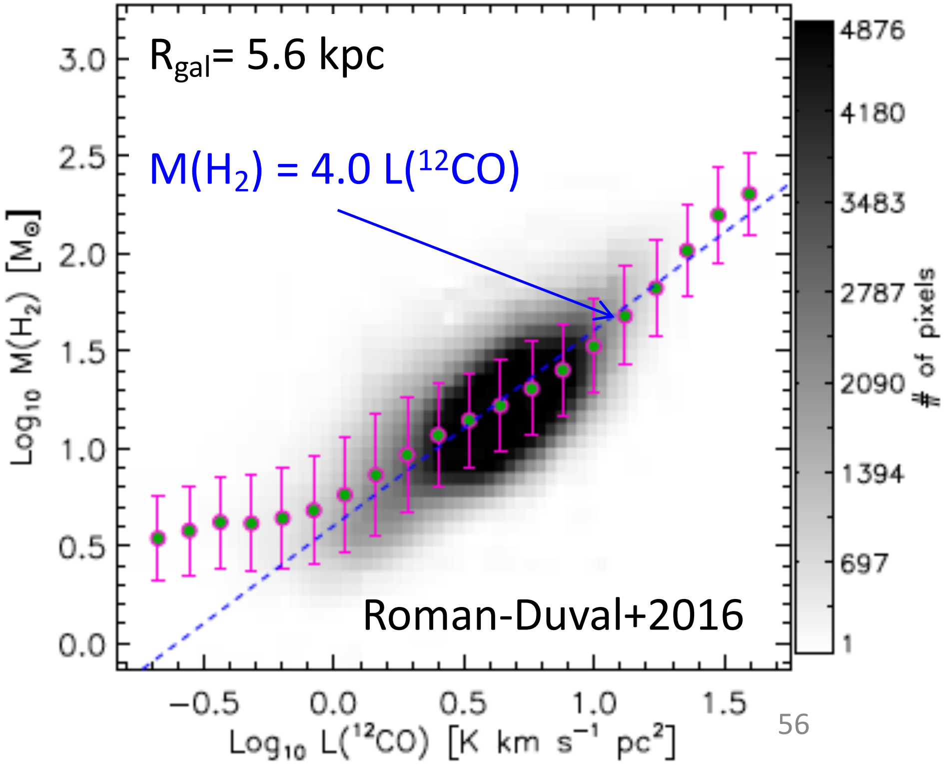


Roman-Duval+2016

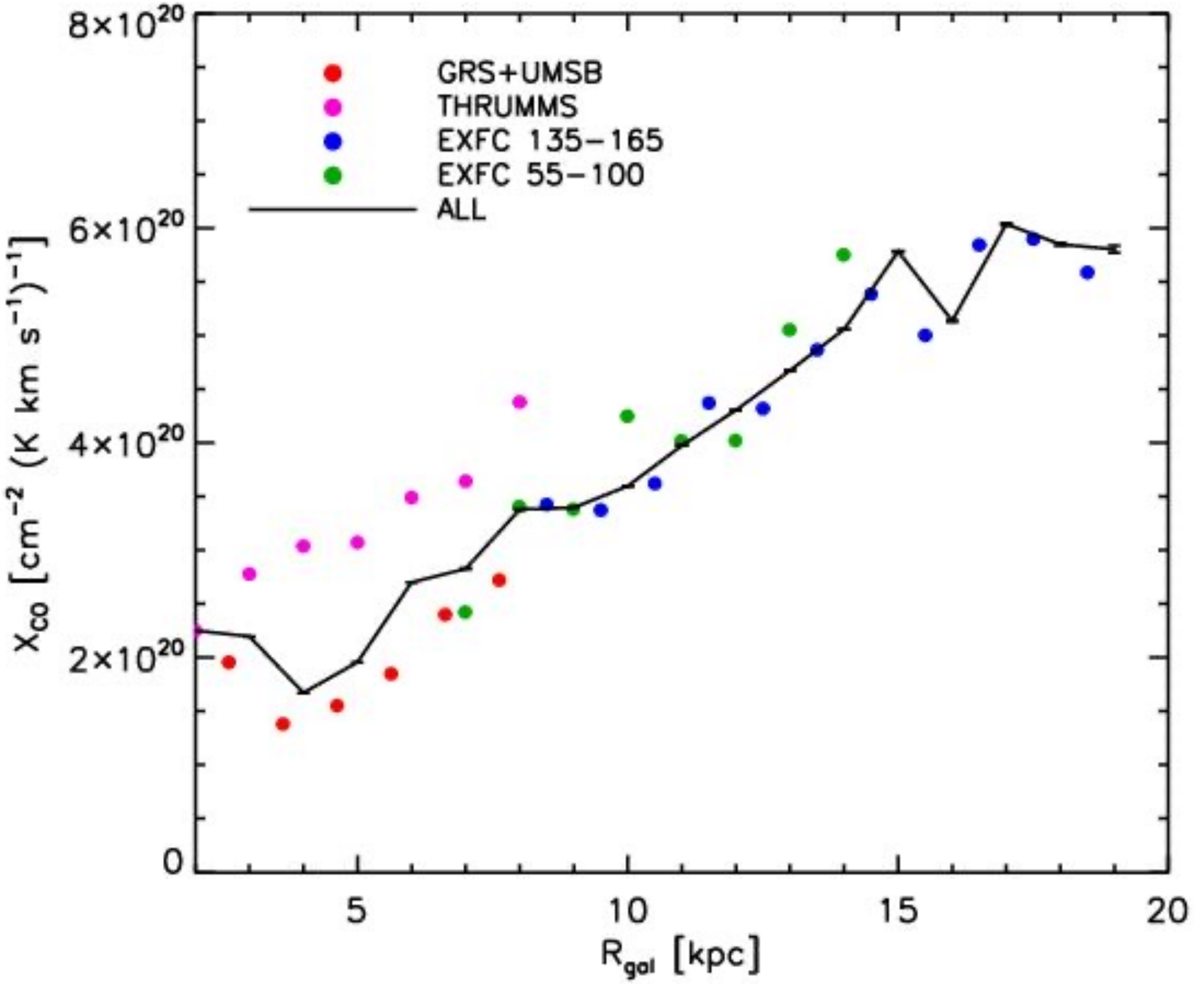
Physical Properties of the gas

- Kinematic distances determined using and Clemens+1985 rotation curve
  - ★In the inner Galaxy, kinematic distance ambiguity
    - Weigh the emission between the near and far distance solutions using a Gaussian with FWHM equal to the scale height of the molecular disk (110 pc)

- T_{ex}, $\tau(^{13}CO)$, $M(H_2)$ determined in each (l, b, v) position where ^{13}CO emission is $>2\sigma$
  - ★Conversion factor between ^{12}CO emission and H_2 mass (X factor) determined in R_{gal} bins of 1 kpc width
  - ★Same X factor is applied to voxels where ^{13}CO emission is $< 2\sigma$ to convert ^{12}CO emission to H_2 mass



Variations of X_{co} conversion factor with Galactocentric radius



$M(H_2)$ calculated from ^{12}CO and ^{13}CO assuming:

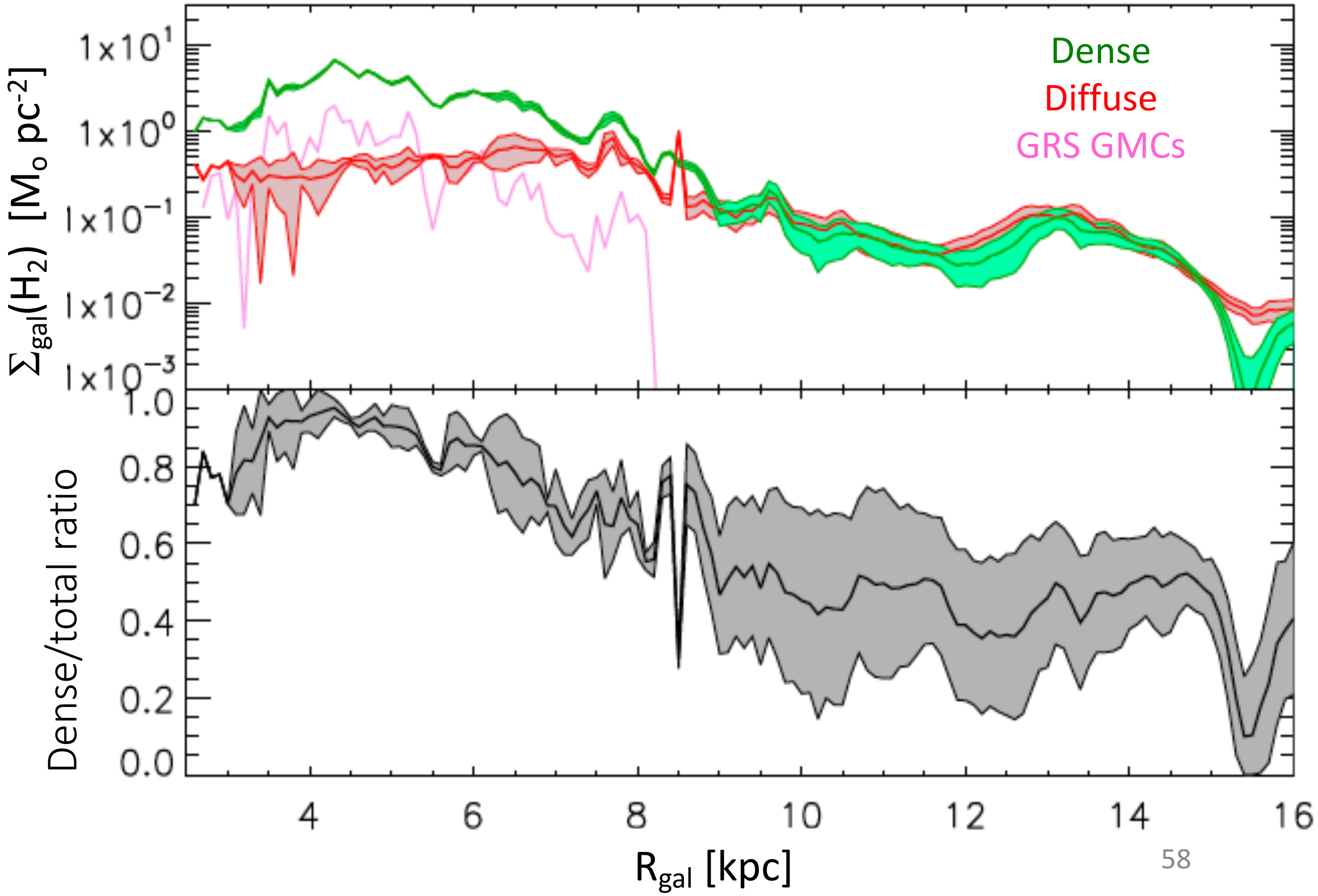
- Constant $^{12}CO/H_2$
- $^{13}CO/^{12}CO$ varying between 50 at R_{gal} = 5 kpc and 100 at R_{gal} = 15 kpc (Milam+2005)
- LTE

GRS+UMSB
ThrUMMS
EXFC 135-165
EXFC 55-100

Roman-Duval+2016

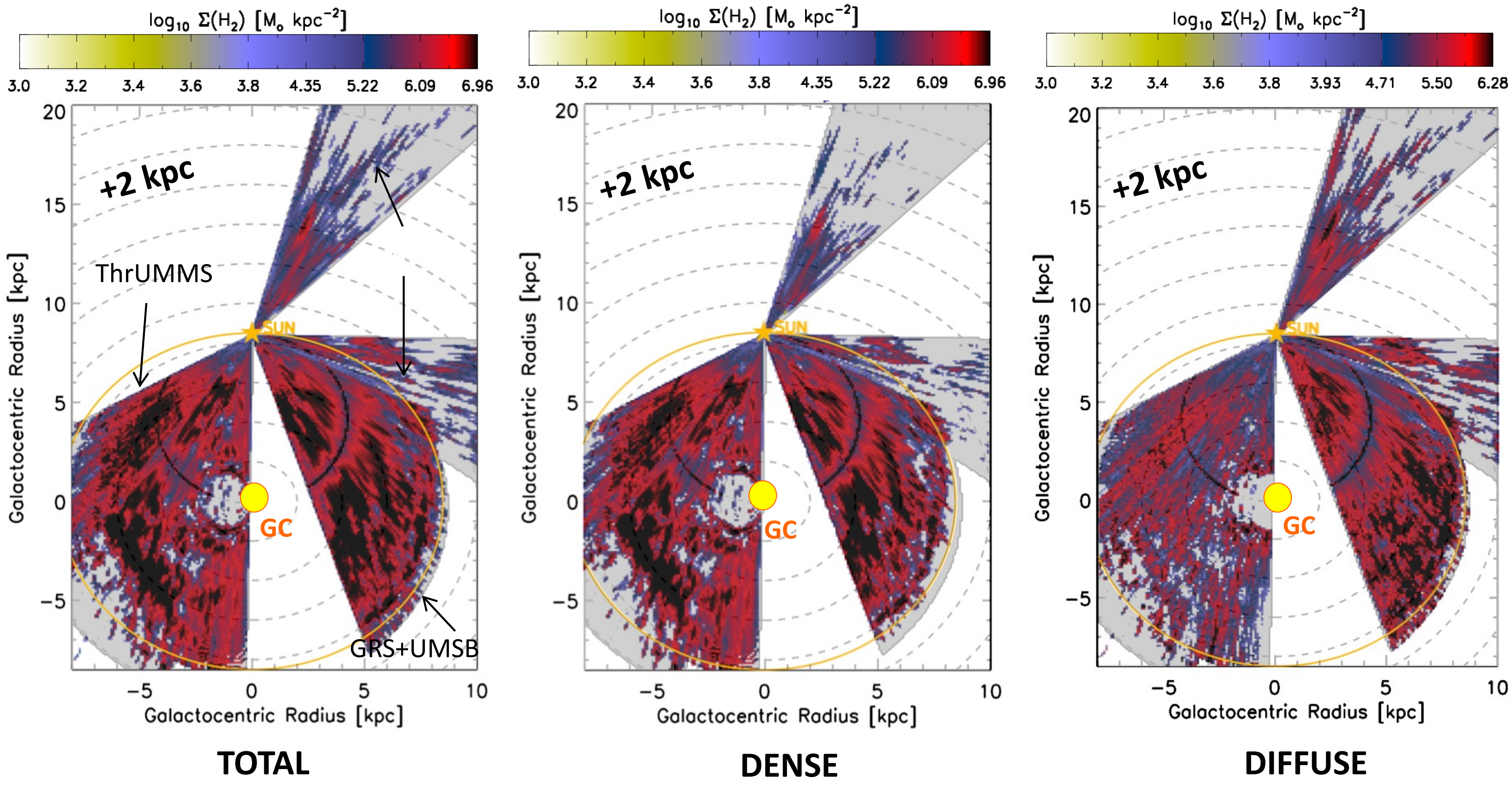
Radial distribution of diffuse and dense gas

- The fraction of diffuse gas increases from 10-20% at R_{gal}=2-6 kpc, to 50% beyond the Solar Circle
- The diffuse CO gas represents 25% of the total H_2 mass (6.5×10^8 M_o)

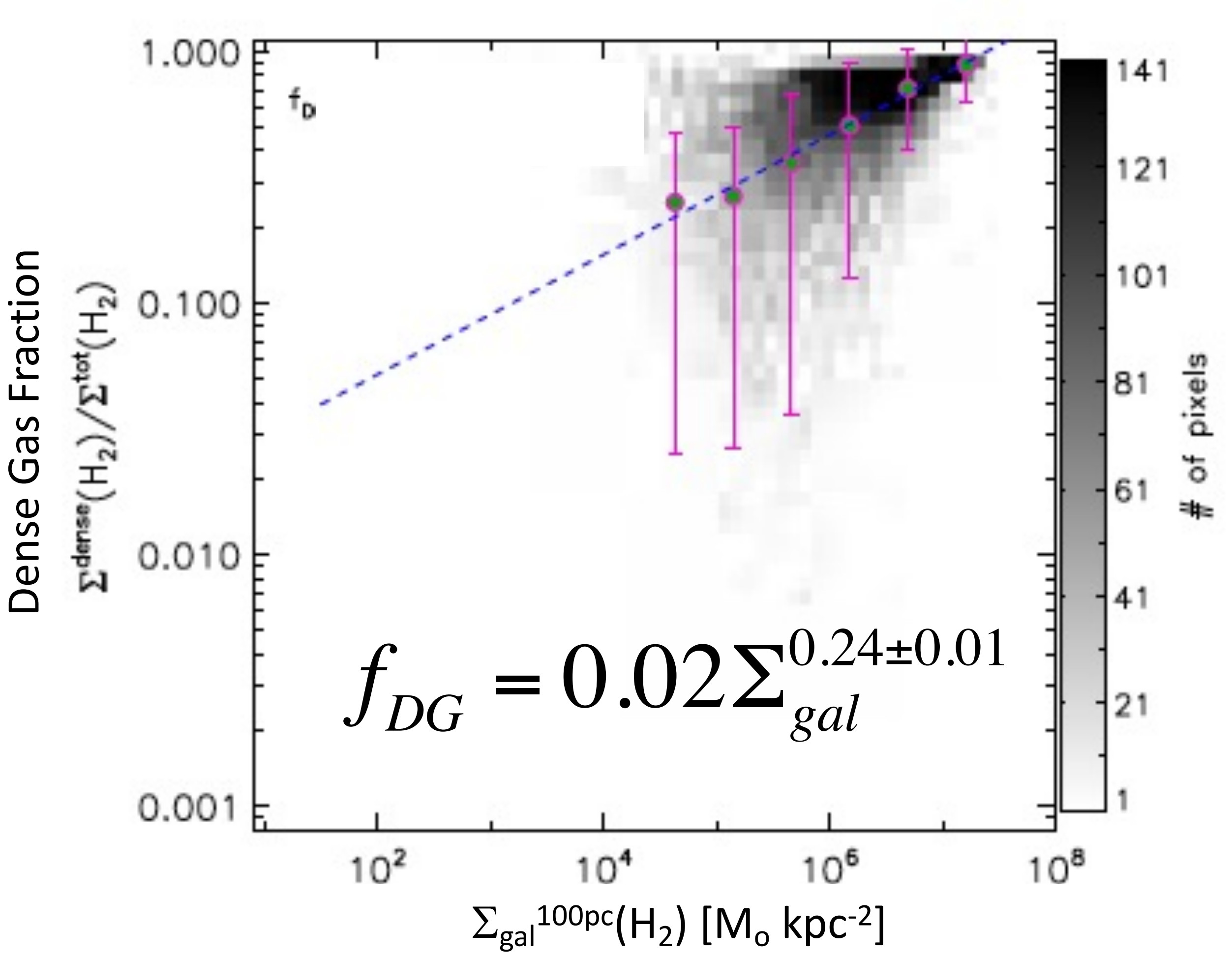


Spatial distribution of CO gas in the Milky Way

Face-on surface density computed on 100 pc scales in the total, diffuse, and dense components



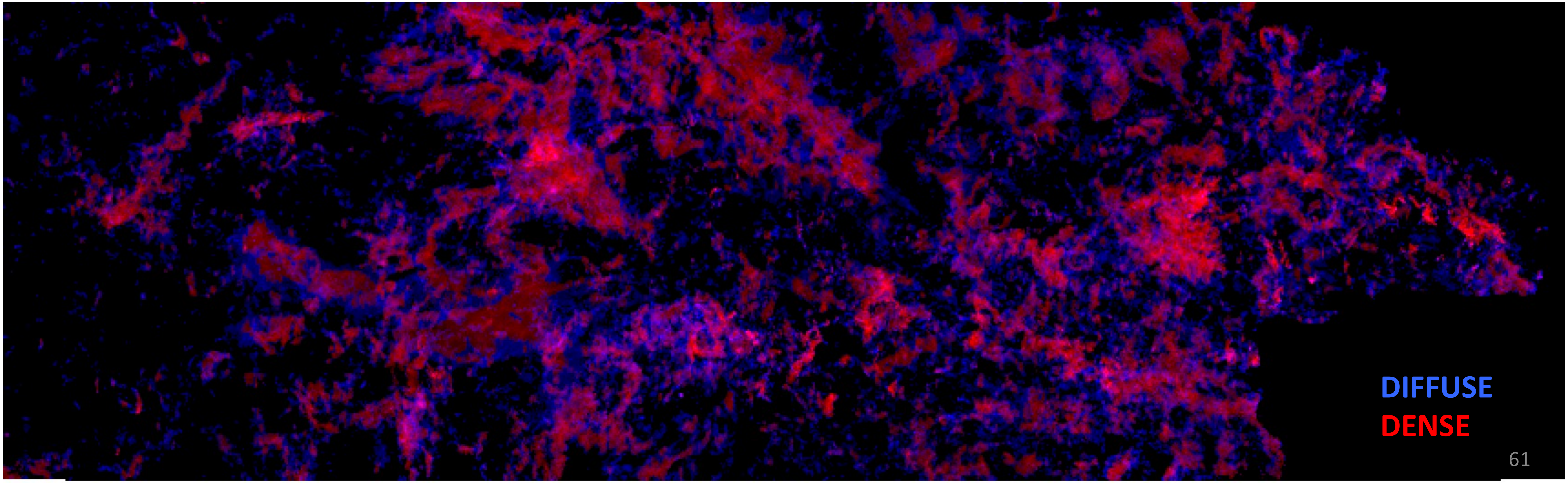
Dense gas fraction vs disk surface density



- Compute face-on disk surface density on 100 pc scale
- Dense gas fraction increases with surface density as $\Sigma^{0.24}$
- Consistent with results on larger scales from Usero+2015, Bigiel+2016

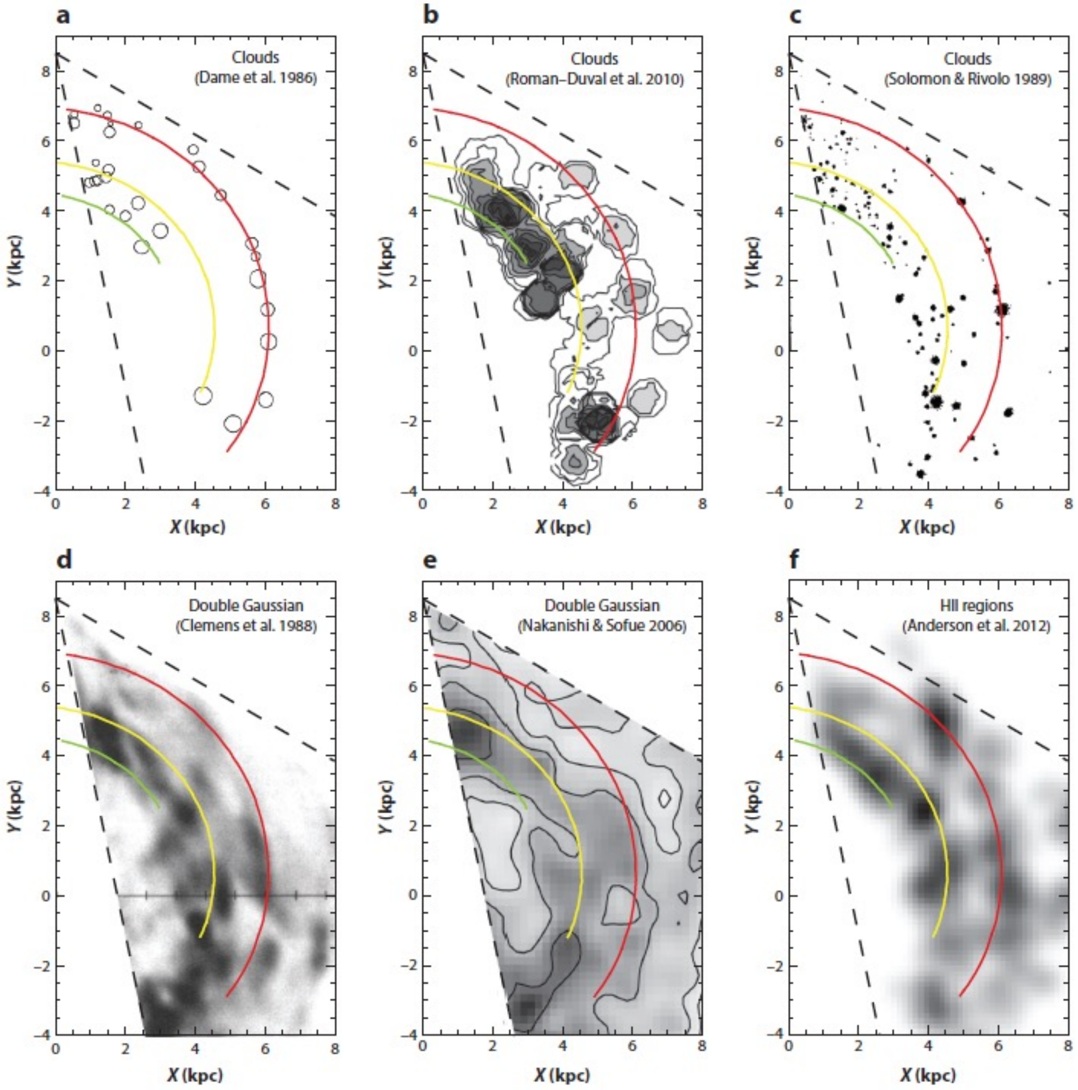
Nature of the diffuse and dense CO gas

- Integrated intensity maps of the diffuse and dense CO gas in the Outer Galaxy (135°<l<165° , -4°<b<5°, clouds roughly 3 kpc away).
- Diffuse CO gas corresponds to the envelopes of denser gas

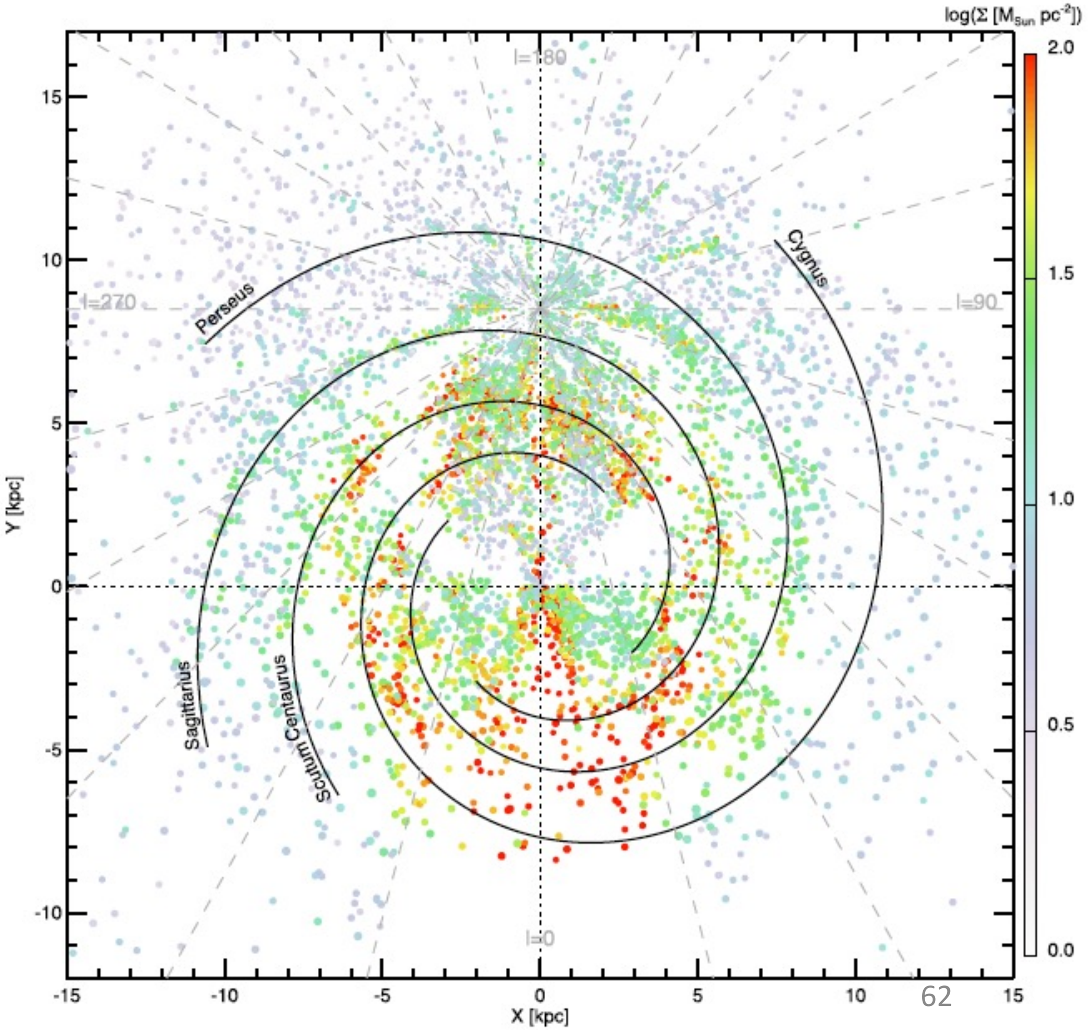


Using MCs to trace the spiral structure of the MW

- Summary of literature in Heyer+2015

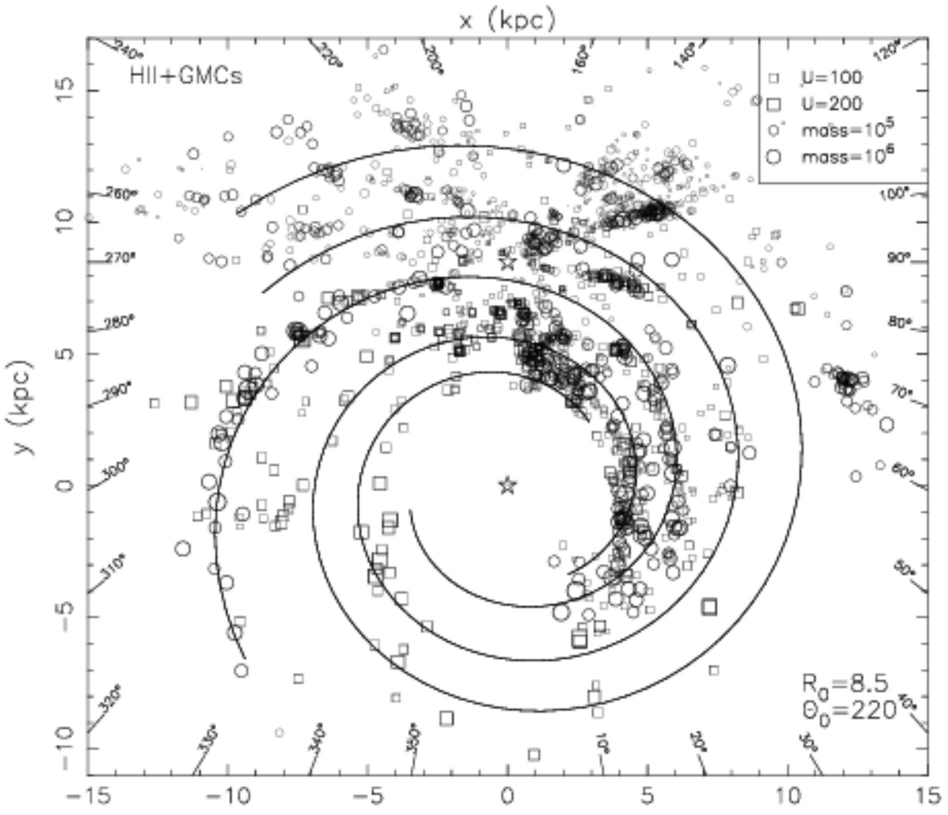


Distribution of MCs (Miville-Deschenes+2017)



Using MCs to trace the spiral structure of the MW

- See also Hou+2009
- They fit 2,3, 4 arm models to the distributions of MCs and HII regions



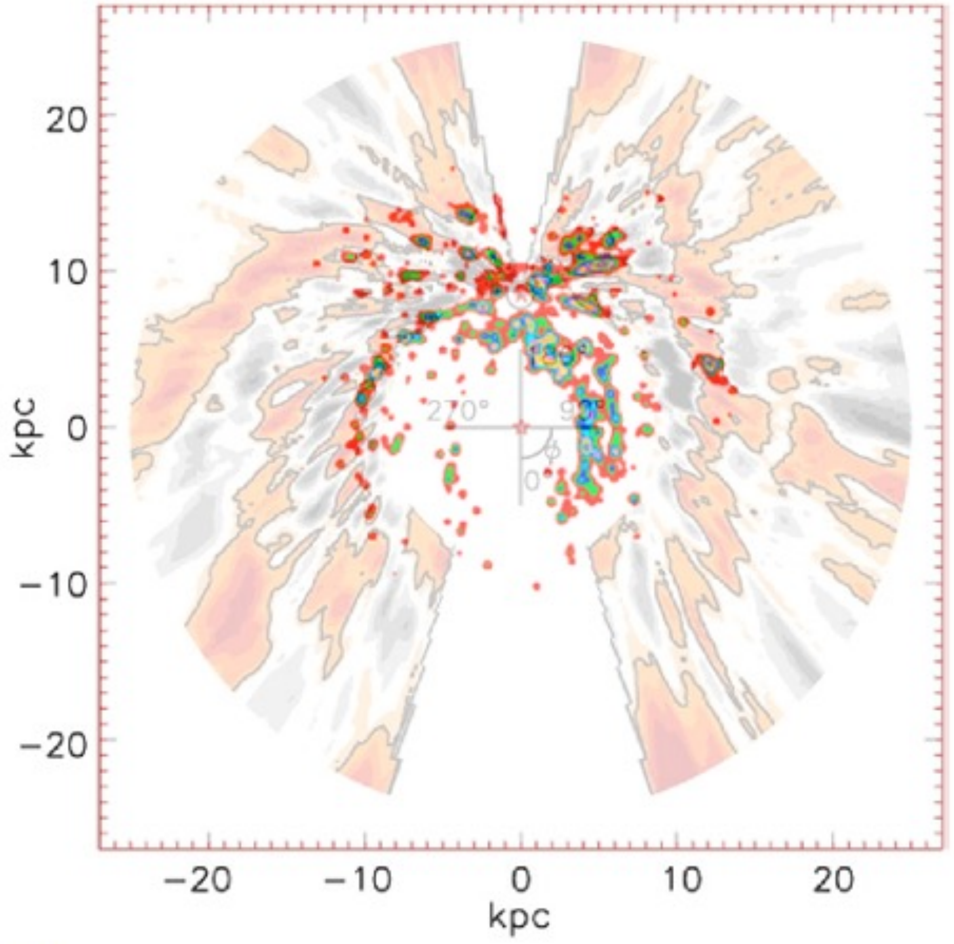
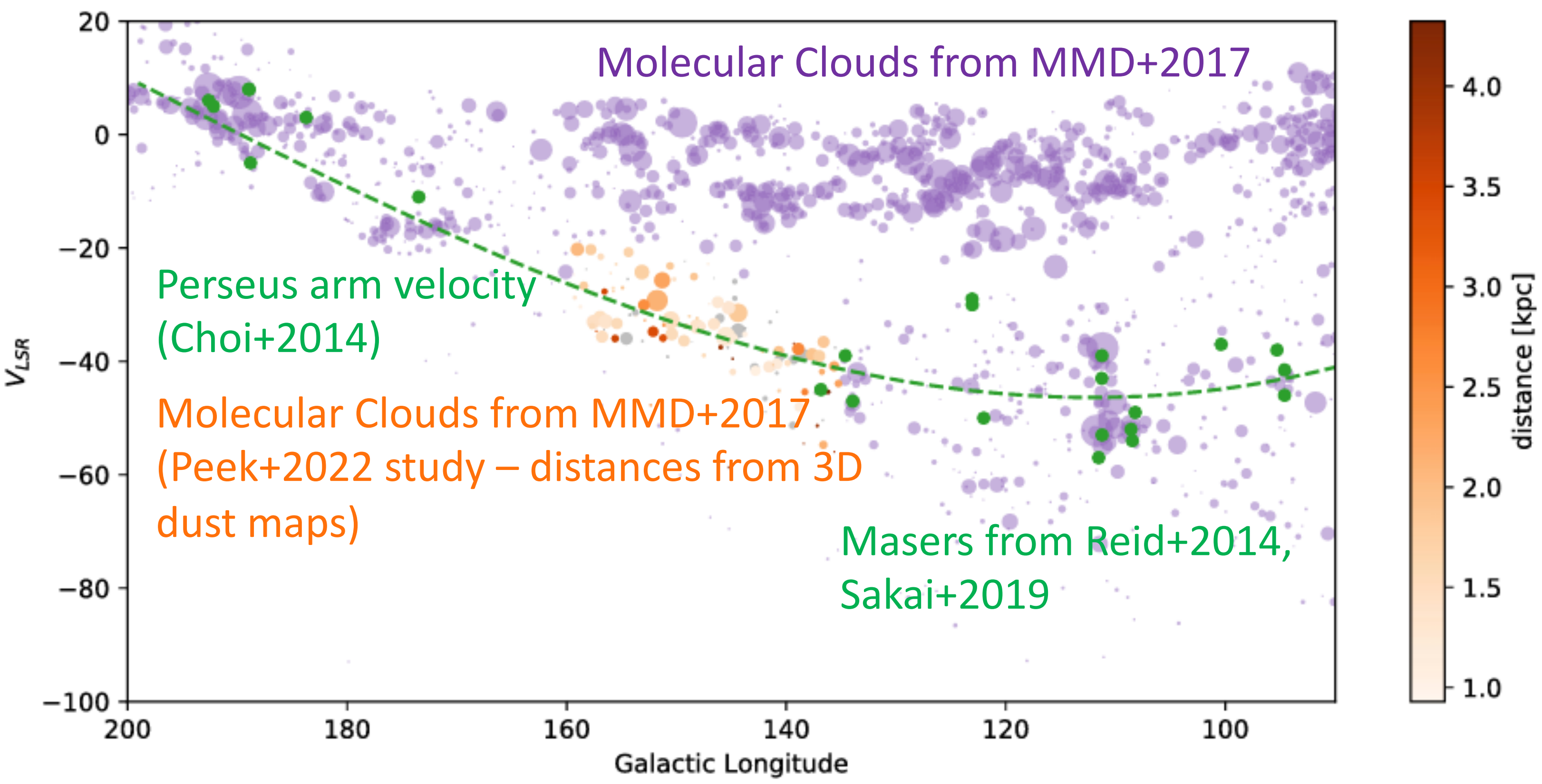


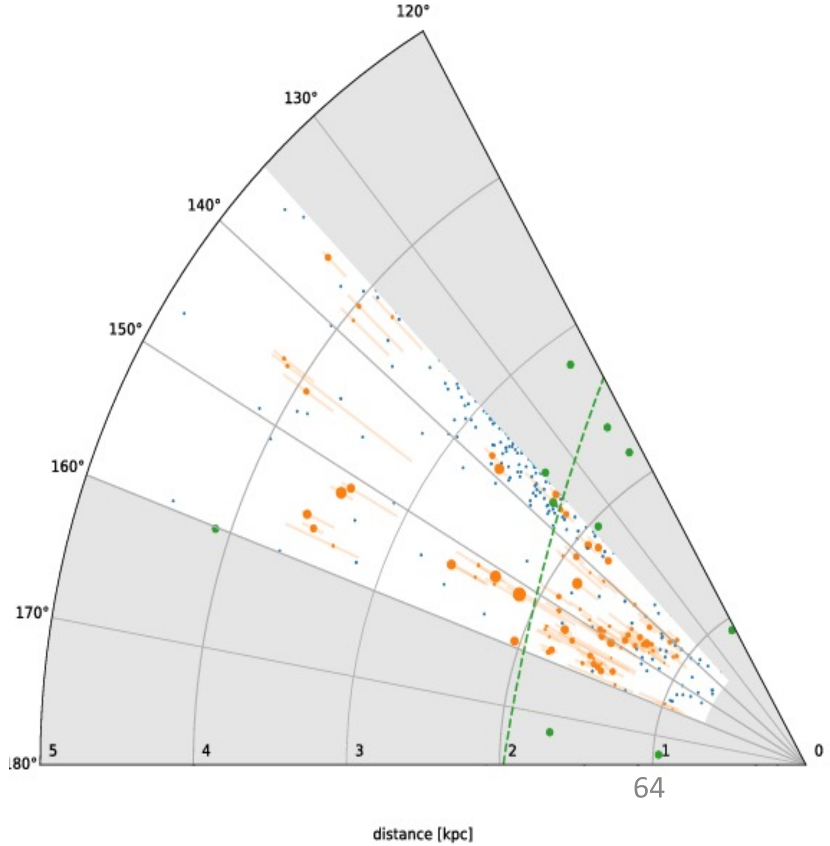
Fig. 4. The spiral structure of HII regions and GMCs (R_0 = 8.5 kpc and Θ_0 = 220 km s^{-1}) is overlaid on the HI map (Levine et al. 2006).

The illusion of the Perseus arm

- Spiral-like structure can be generated using the velocity field expected from the density-wave theory derived in Lin et al. (1969) with no density variation at all (Burton+1971) — velocity crowding
- Measure distance of molecular clouds using 3D dust maps from Green+1019
- Map clouds face-on → Not following a spiral arm

Peek+2022





Open Questions

- How do we retrieve the 3D structure of gas in the Milky Way from emission line cubes?
- How do we probe molecular cloud dynamics?
- What is the structure of the Milky Way in molecular gas?

1. Tracers of the ISM
2. Phases of the ISM
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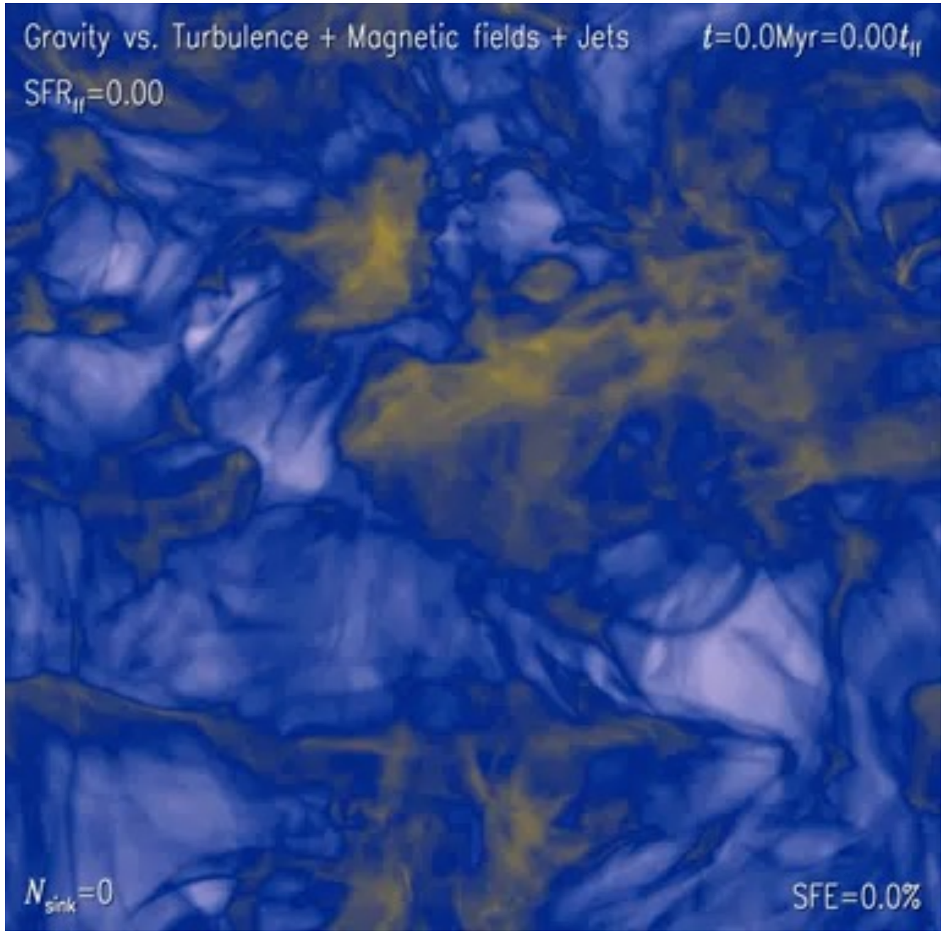
Molecular clouds are turbulent and transient

Simulations from Christoph Federrath



- Ballesteros-Paredes+2011: "*The complex nonlinear, large-scale and anisotropic nature of turbulent motions implies that molecular clouds do not necessarily provide support, but rather cause continuous morphing and reshaping of molecular clouds, and contribute to, or perhaps are even driven by, the clouds' gravitational collapse (Vazquez-Semadeni et al. 2008).*"
- MC dynamical time = $R/\sigma_v \sim 1$ Myr

Solenoidal vs compressive forcing

- Solenoidal turbulence forcing is divergence free: $\nabla . \boldsymbol{V} = 0$
- Expansive forcing (expansion/support against collapse): $\nabla . \boldsymbol{V} > 0$
- Compressive forcing (collapse/compression): $\nabla . \boldsymbol{V} < 0$

Federrath+2010

The density PDF of turbulent gas – effect of forcing

- PDF lognormal for solenoidal forcing
- PDF cannot be well approximated by a log-normal for compressive forcing
  - Requires a skewed log-normal

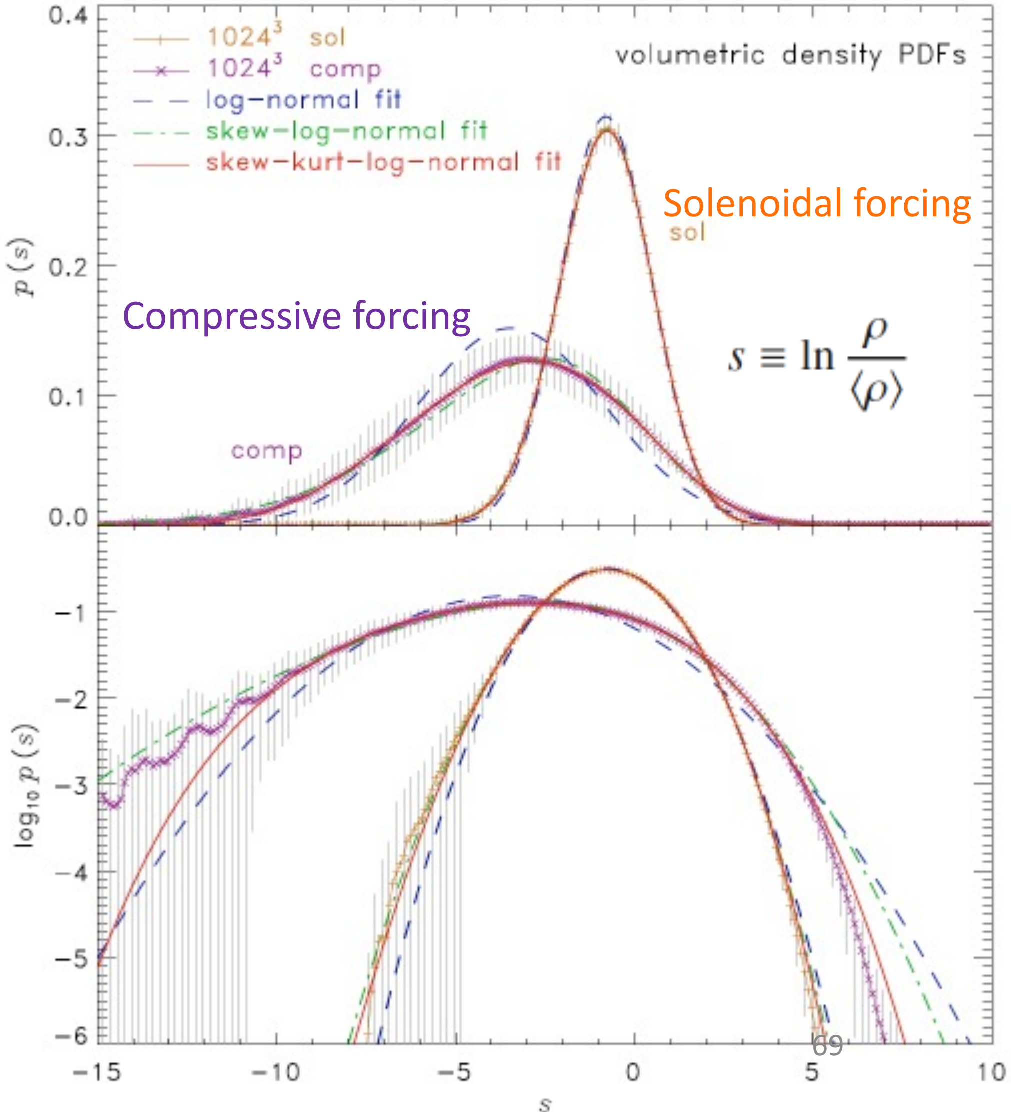
$$p(s) = \frac{1}{\pi\,\omega}\,\exp\left[-\frac{(s-\xi)^2}{2\omega^2}\right]\int_{-\infty}^{(s-\xi)\alpha/\omega}\exp\left(-\frac{t^2}{2}\right)\mathrm{d}t,$$

- The width of the distribution is related to the Mach number

$$\sigma_s^2 = \ln\left(1 + b^2\mathcal{M}^2\right),$$

- The parameter b depends on the type of forcing
  - b = 1 for compressive forcing
  - b = 1/3 for solenoidal forcing

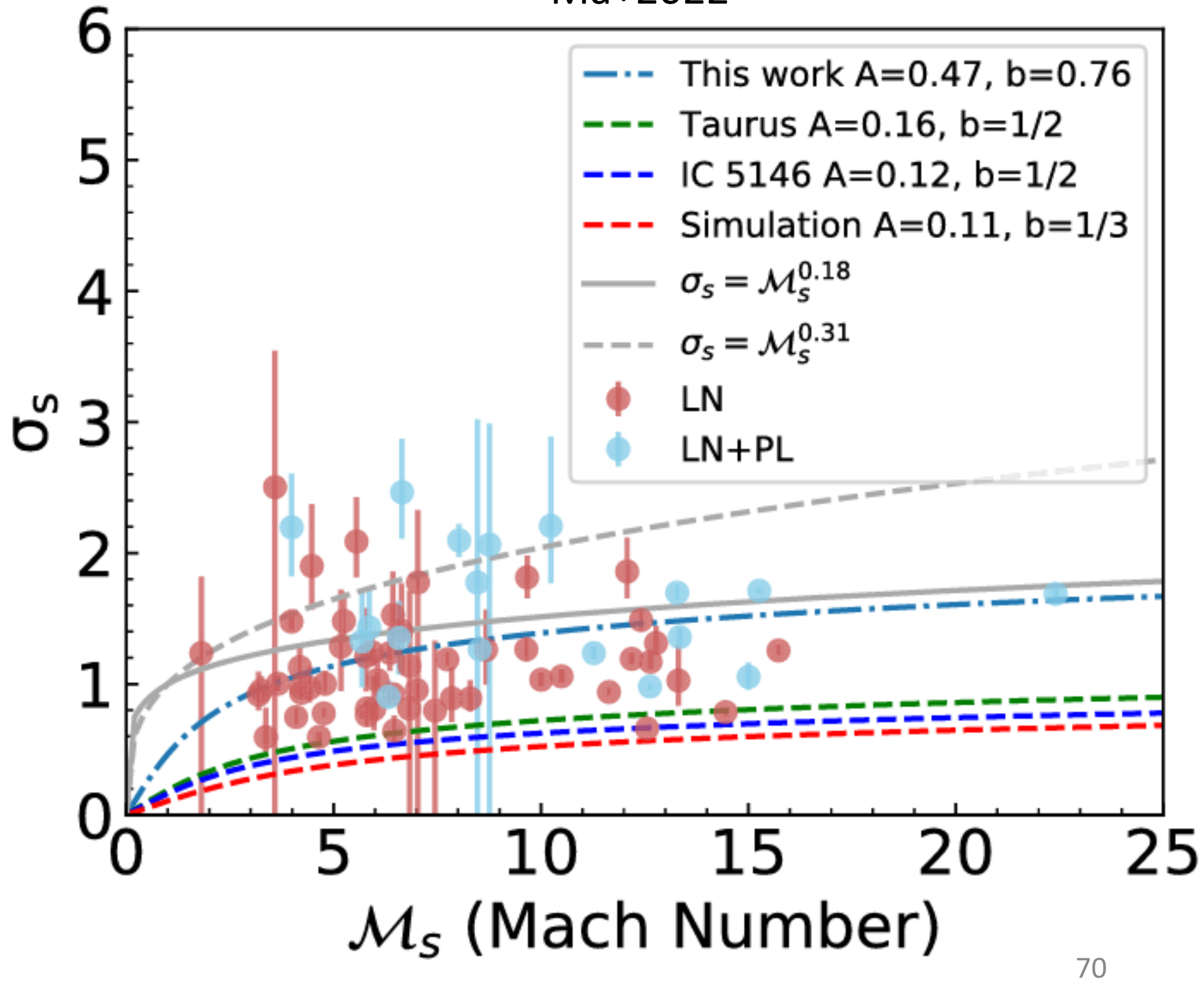
Federrath+2010



The density PDF of turbulent gas – effect of forcing

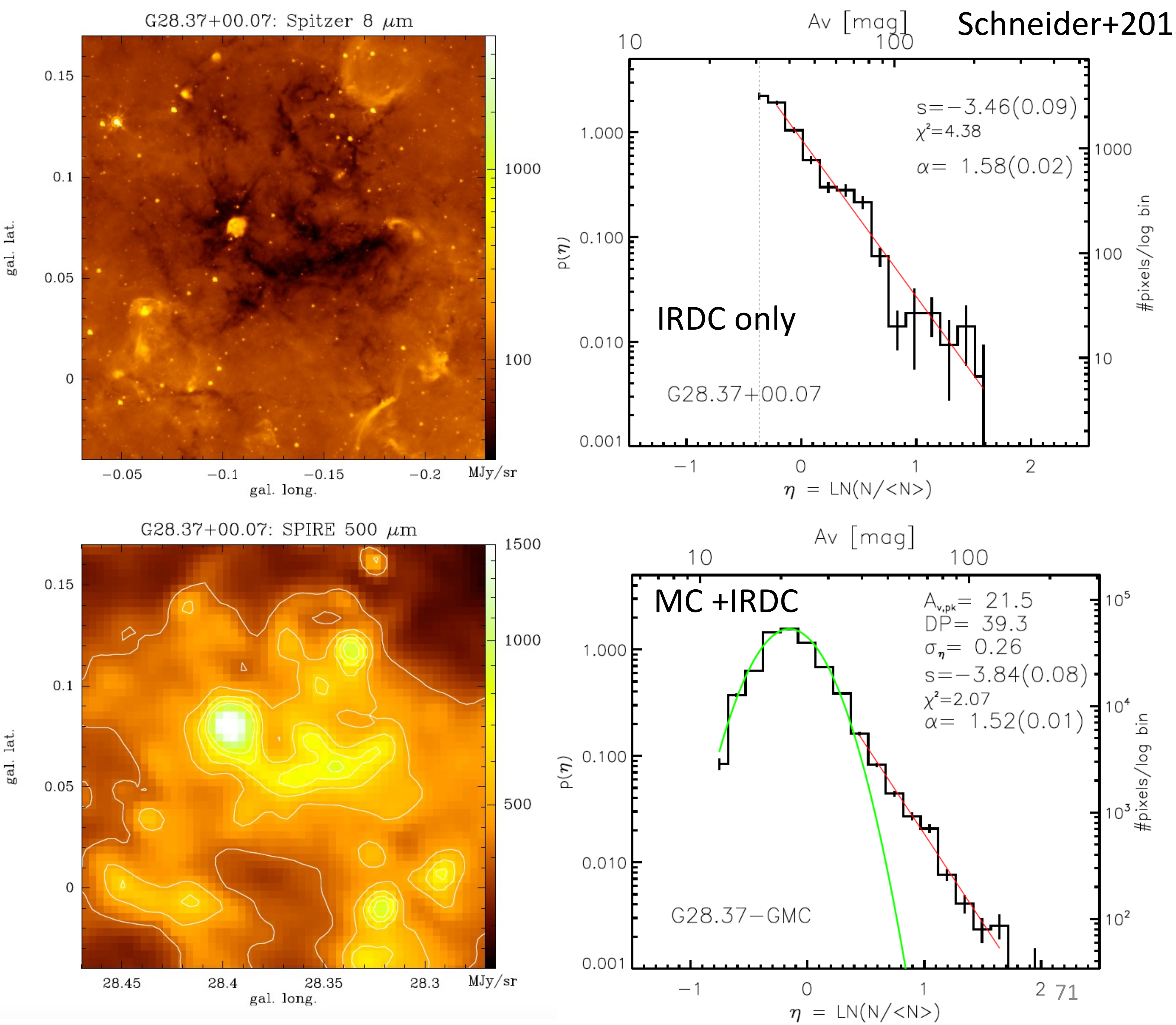
- Measurements of *b* in molecular clouds
  - ➢ *b* = 0.22 in central molecular zone molecular cloud, indicating solenoidal forcing induced by strong shear forces (Federrath+2017)
  - ➢ *b* = 0.76 in sample of 130 MCs in 3rd galactic quadrant, indicating compressive forcing (Ma+2022)

Ma+2022



The density PDF of turbulent gas – effect of gravity

- Gravity and collapse incur a power-law in the density PDF of molecular clouds
- Transition point between the lognormal and power-law column density PDF represents the critical density where turbulent and thermal pressure balance, the so-called “post-shock density” (Burkhart+2017)



Schneider+2015

Energy spectrum of turbulence – subsonic regime

- **Kolmogorov** turbulence applicable to **incompressible fluid $\mathcal{M} < 0.3$**
  - Energy spectrum $E(\mathbf{k}) = k^2 P(\mathbf{k}) = k^2 u^2(\mathbf{k}) \propto \mathbf{k}^{-\beta}$ $\beta = 5/3$
  - Structure function $S_2(l) = \langle |u(\mathbf{x}+\mathbf{l}) - u(\mathbf{x})|^2 \rangle \propto l^{1/3}$
  - Dissipative structures are filaments

Energy spectrum of turbulence – supersonic regime

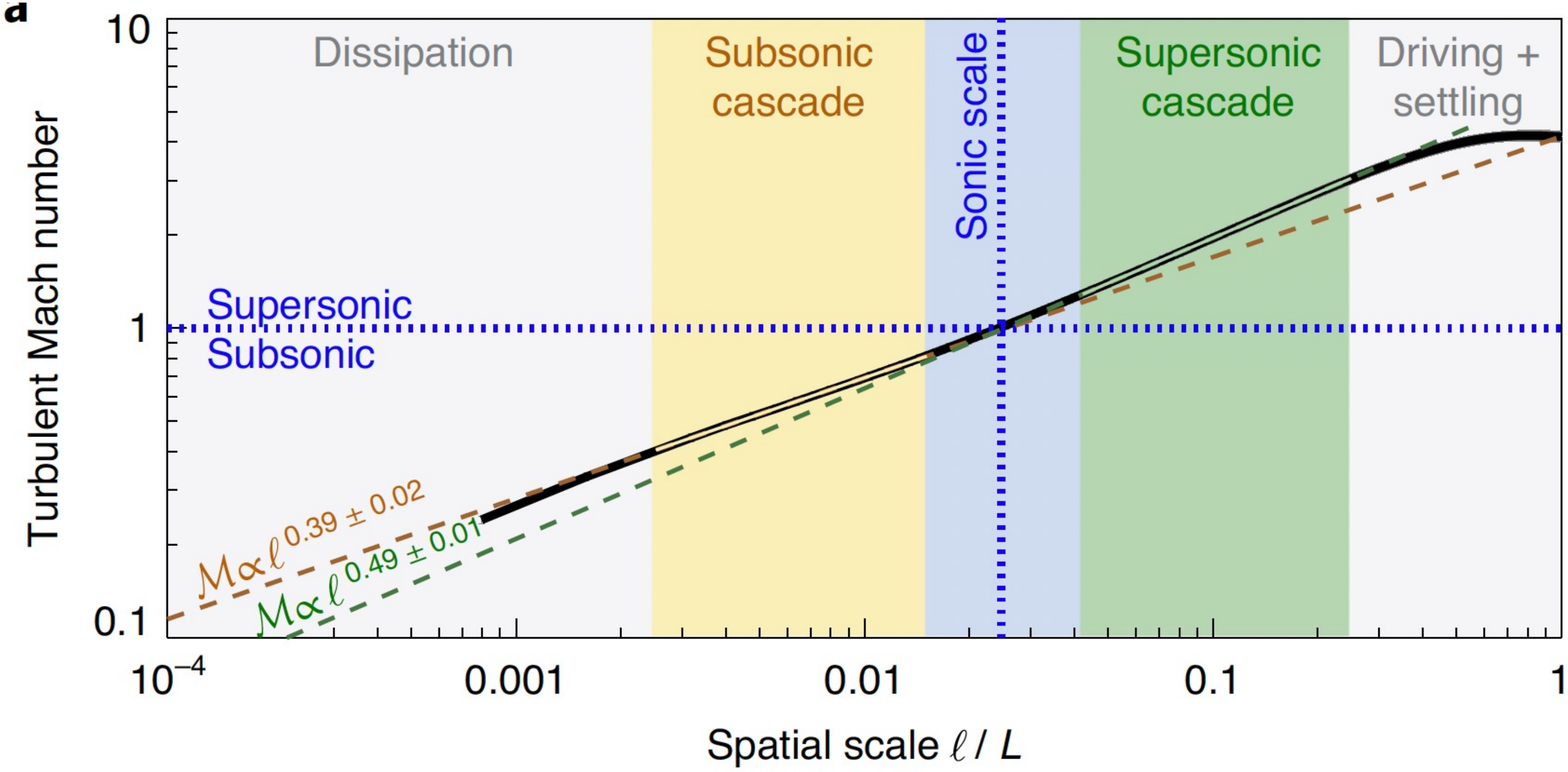
- **ISM turbulence on molecular clouds scales is supersonic, compressible** (at least on scales larger than sonic scale)
  - ➢Intermittent turbulence
  - ➢Kolmogorov-Burgers turbulence (Boldyrev 2002)

$$S_p(l) = \langle |\mathrm{u}(\mathbf{x}+\mathbf{l}) - \mathrm{u}(\mathbf{x})|^{\mathrm{p}} \rangle \equiv l^{\zeta(p)} \text{ and } \zeta(p) = \frac{p}{9} + 1 - \left(\frac{1}{3}\right)^{p/3}$$

  - ➢ ζ(2)= 0.74 (β = 1.74)
  - ➢ Dissipative structures are sheets

Energy spectrum of turbulence

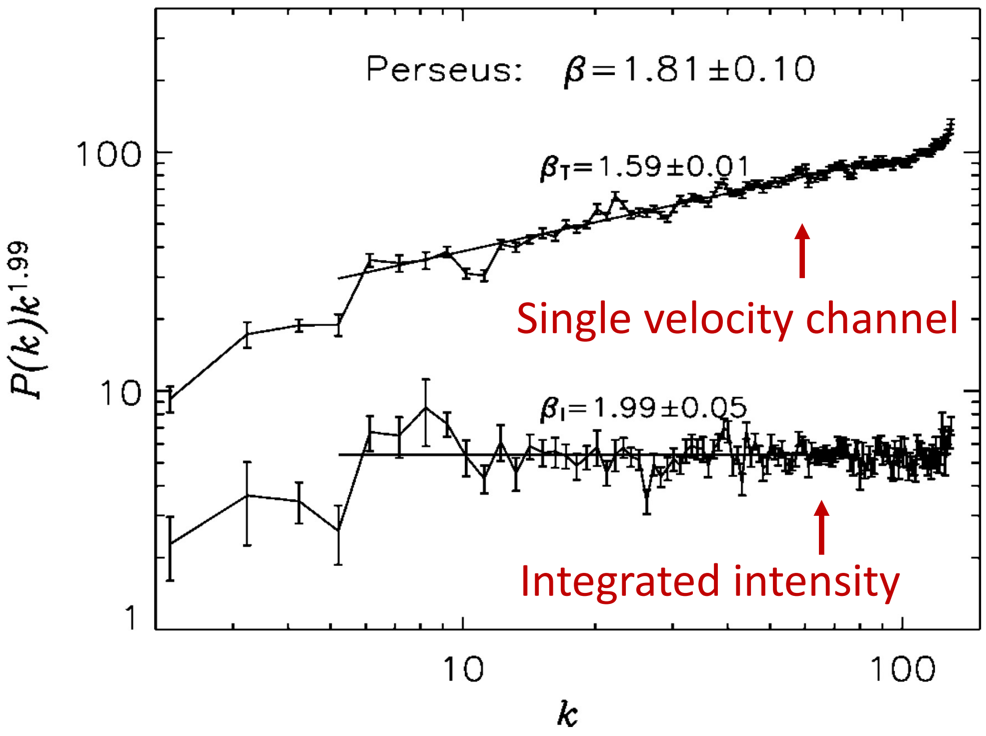
- Second order structure function has slope:
  - 1/3 below sonic scale (Kolmogorov subsonic incompressible turbulence
  - 0.5 above sonic scale (supersonic, compressible Burgers turbulence)



Federrath+2021

Measuring the energy spectrum of MCs – velocity channel analysis

- Difficult problem because 3D velocity field is not accessible (only PPV)
- Each velocity channel contains gas at different densities (emissivity) and locations
- Lazarian+2000, 2004 derived statistical tools (velocity channel analysis, velocity coordinate spectrum) to derive the density and velocity power spectrum in molecular clouds
- Relies on power spectrum of velocity channels and integrated intensity
- Applied to Perseus ^{13}CO observations by Padoan+2006 (β = 1.81)

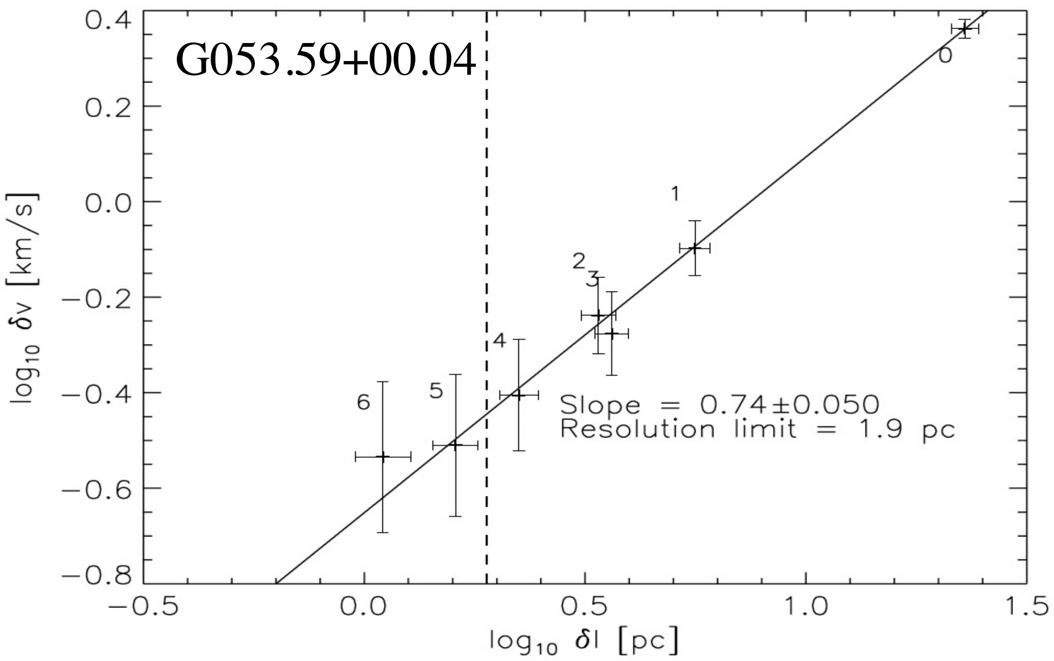


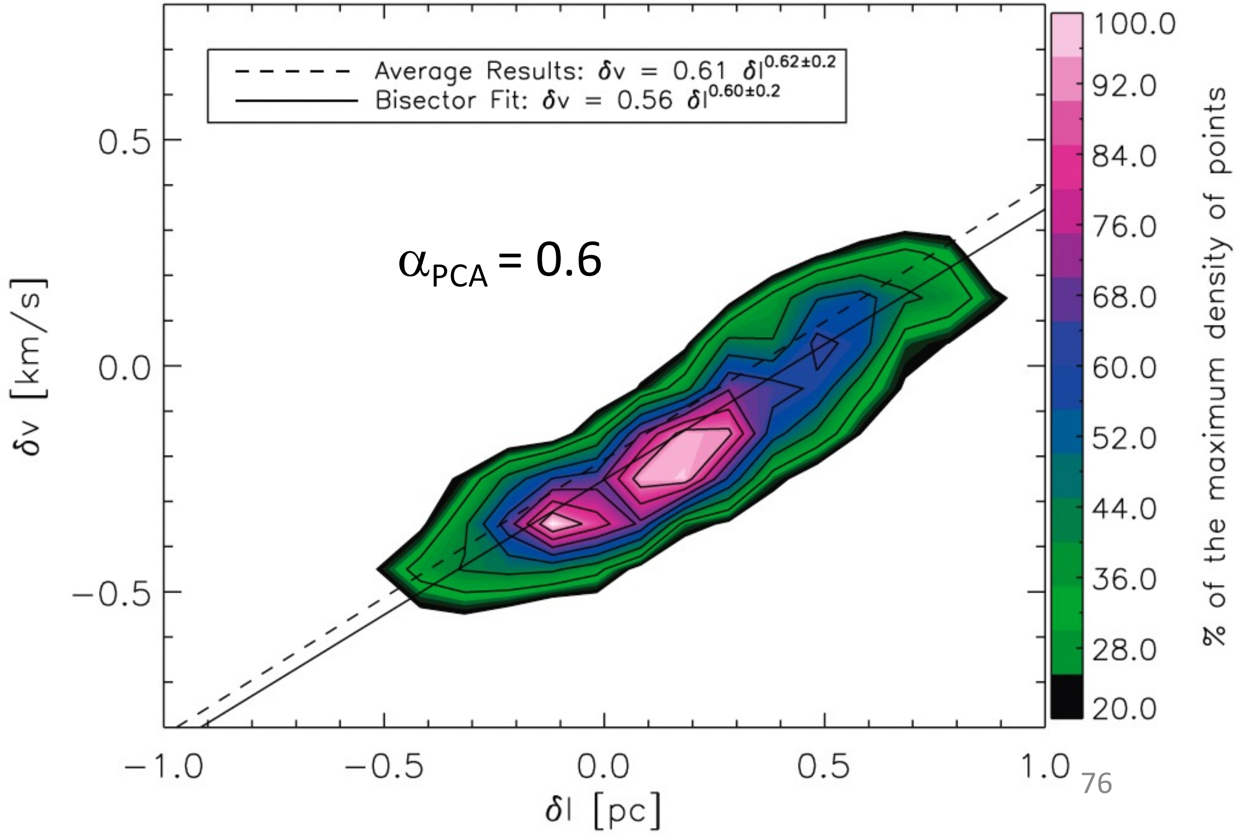
Padoan+2006

Measuring the energy spectrum of MCs - PCA

- Principal component analysis (Brunt+2002, Roman-Duval+2011) of PPV cubes provides a structure function, but requires comparison to simulations to figure out the order of the structure function
- β = 1.9 for GRS molecular clouds (^{13}CO)

$$\beta_v = 0.20 \pm 0.05 + (2.99 \pm 0.09)\alpha_{\mathrm{PCA}}.$$





Consequence of the turbulent nature of MCs

- Turbulent motions carry fluid elements that constantly redistribute their mass — MCs are not static spheres (McKee & Zweibel 1992)
- In this context, it is difficult to argue that MCs are in virial equilibrium (Ballesteros-Paredes+2006)
- Kinetic energy can be both a source of support against gravity ($\nabla.\boldsymbol{V} \geq 0$) and promote collapse ($\nabla.\boldsymbol{V} < 0$)
- Turbulent motions lead to over-densities (from compression) that can further collapse under the effects of gravity

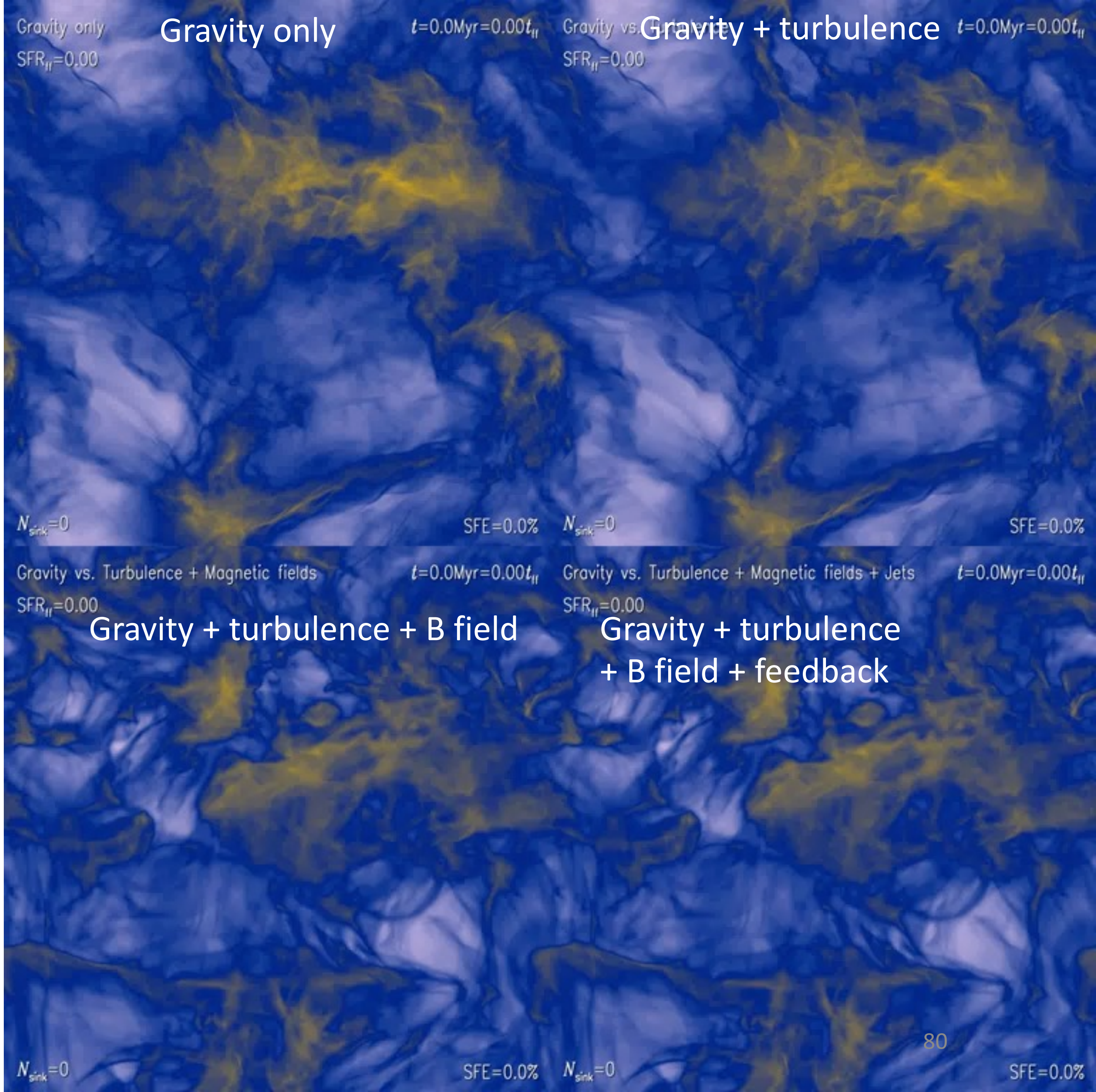
Open Questions

- How do we quantitatively measure the turbulent properties of molecular clouds?
  - ➢ 3D velocity and density field statistics?
  - ➢ What are the relevant metrics? The power spectrum is not sufficient – the phase information is key in the ISM (MHD equations)
- What are the mechanisms injecting turbulence in molecular clouds?

1. Tracers of the ISM
2. Phases of the ISM
3. Galactic molecular clouds
4. Distribution of molecular gas in the Milky Way
5. The turbulent properties of molecular clouds
6. **The ISM and star formation**

The role of turbulence, gravity, magnetic field and feedback on star formation

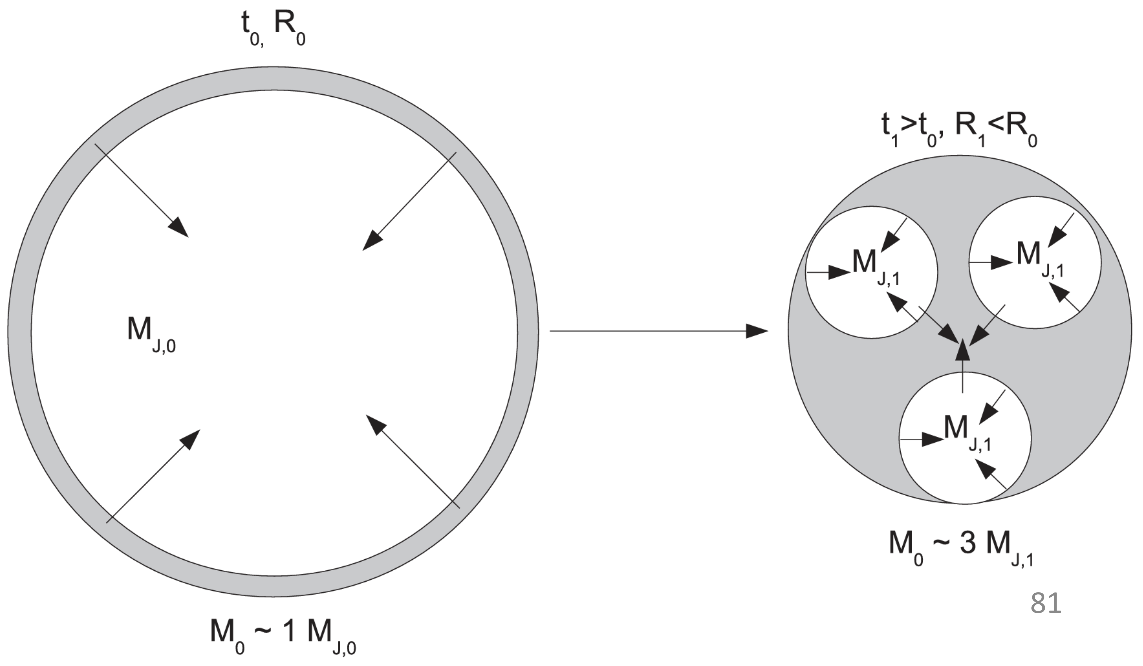
Simulations from Federrath+2015



Interpretation of the equipartition of energy (Ballesteros-Paredes+2011)

- Molecular clouds are formed in large-scale compressions from the warm, diffuse, thermally unstable medium (Vazquez-Semadeni et al. 2007; Heitsch & Hartmann 2008).
- As these clouds accumulate mass and cool rapidly, they become Jeans unstable
- Gravity begins to dominate the motions (→ near equipartition between the gravitational and kinetic energies; Vazquez-Semadeni et al. 2007)

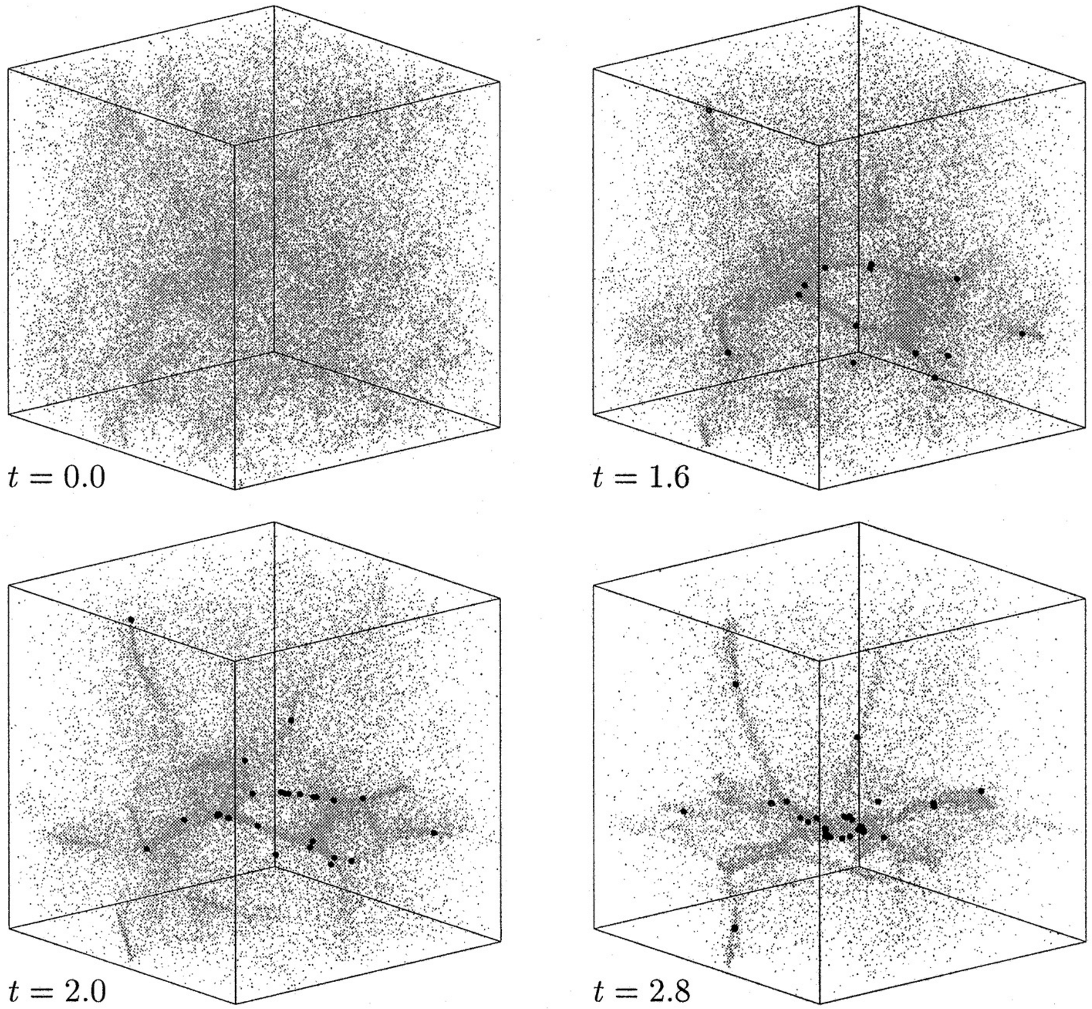
Vazquez-Semadeni+2019



Interpretation of the equipartition of energy

- The initial turbulent fluctuations in density and velocity produce hierarchical fragmentation
- Dense clumps with short free-fall times proceed to a rapid collapse, while at the same time the whole cloud contracts at a slower rate, because of its lower average density

$$M_J \propto \rho^{-\frac{1}{2}} T^{\frac{3}{2}}$$

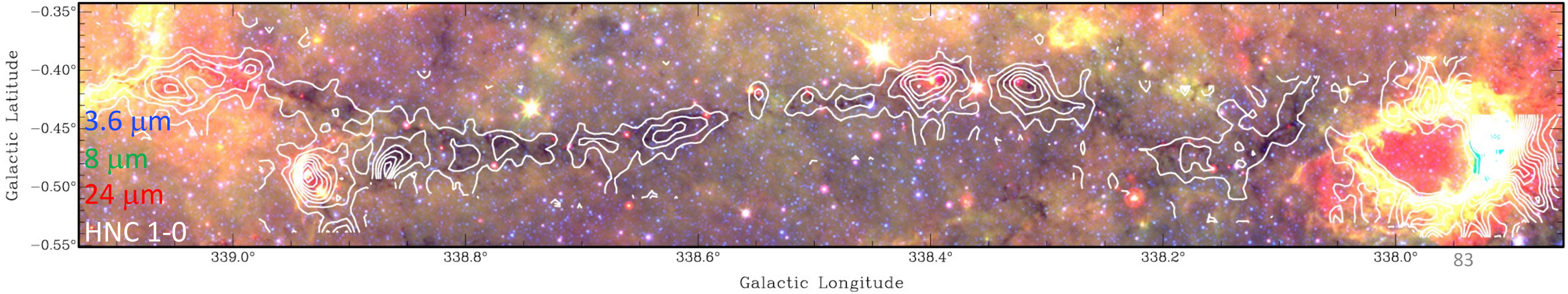


Klessen+1998

Tracers of MW star-formation – Young Stellar Objects

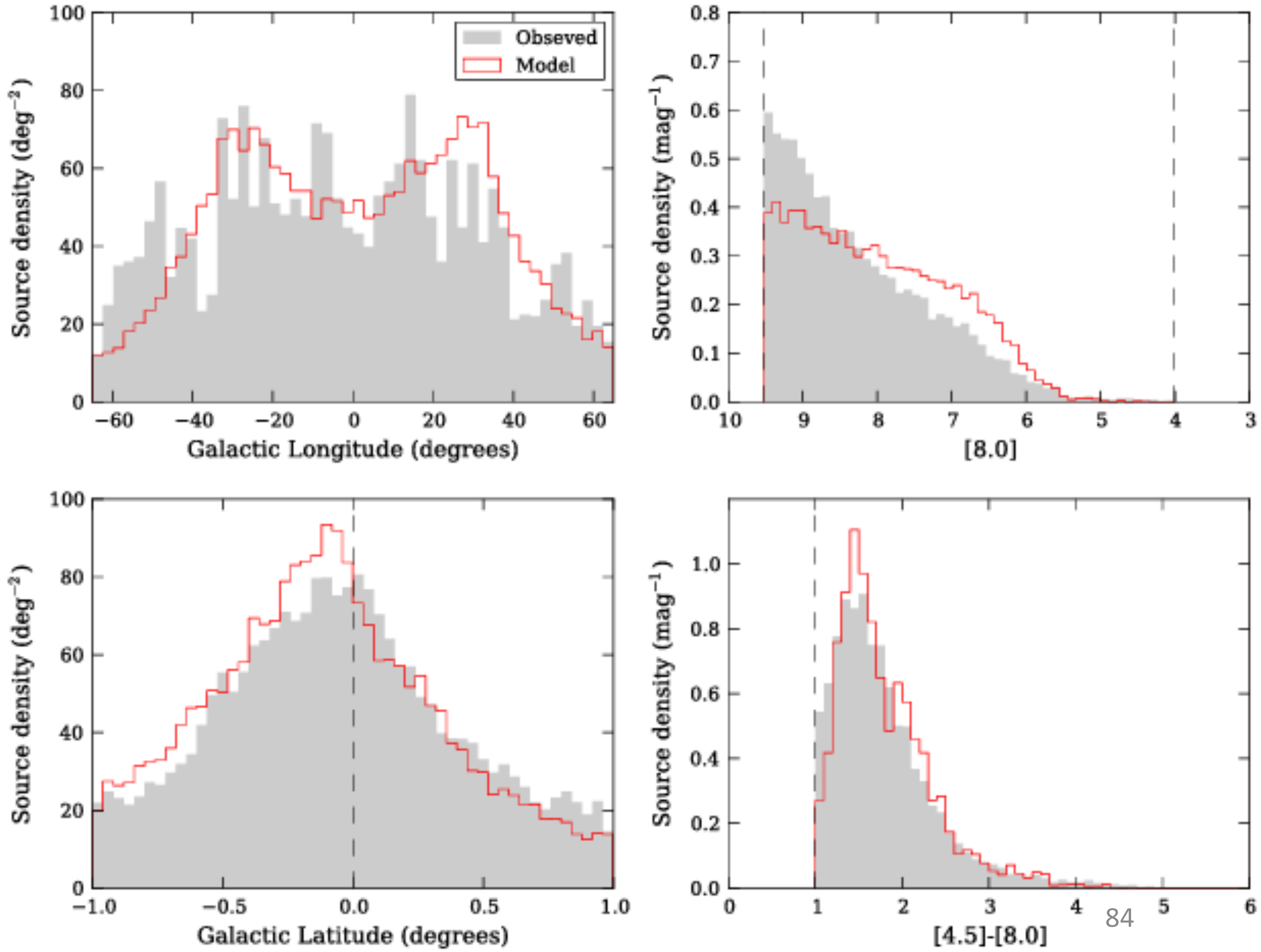
- Star-formation occurs in filamentary (or sheet?) structures called infrared dark clouds (e.g., Simon+2006)
- Protostars forming in IRDCs traced by MIR emission (24 microns) and dense gas (and temperature) tracers (e.g., HNC, HCN, NH3 etc)
- YSO counts in the IR provide estimate of SFR on timescales of 1000 yr – 2 Myr (Robitaille & Whitney 2010)
- This is a resolved SF tracer

Jackson+2010



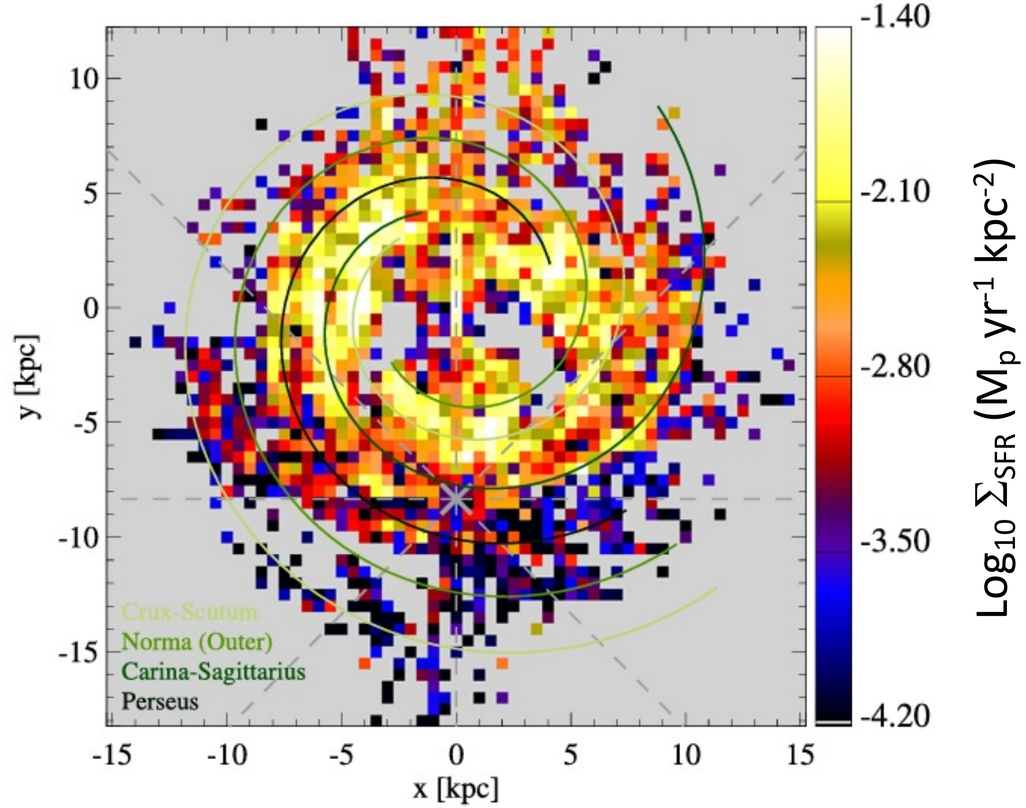
Tracers of MW star-formation – Young Stellar Objects

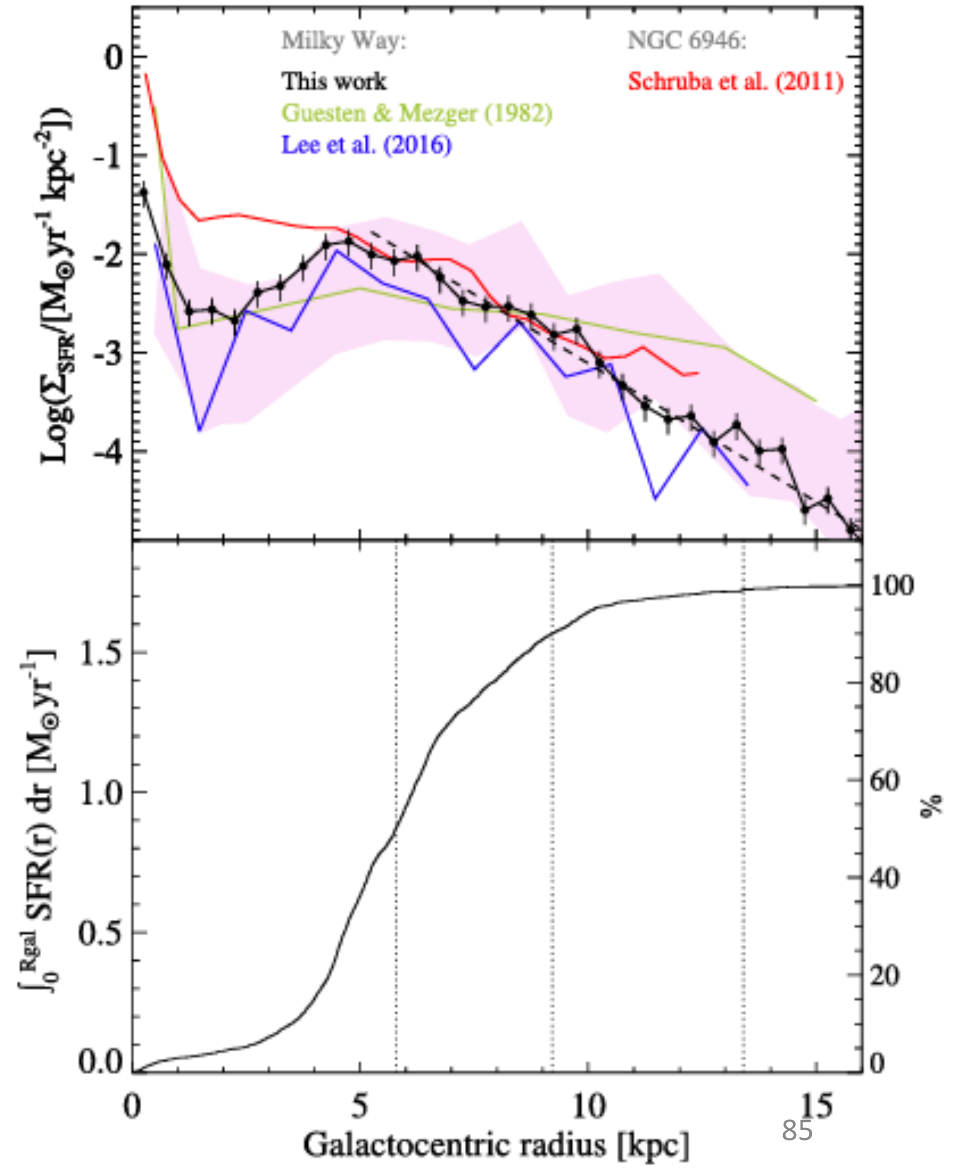
- Robitaille & Whitney modeled the distribution of YSOs observed by Spitzer in the MW and found SFR = 0.68 – 1.45 M_o yr^{-1}



Tracers of MW star-formation – Young Stellar Objects

- Elia+2022 estimated the Galactic SFR from FIR pre-stellar and proto-stellar clumps in the HIGAL survey
- SFR = 2 M_o yr^{-1}





Tracers of MW star-formation – Free-free emission

- An SFR of 1 M_o yr^{-1} produces a Lyman continuum photon rate Nc = 9.26 × 10^{52}photons s^{-1} for the Salpeter (1955) IMF (assuming a mass range of 0.1–100 M_o, see Kennicutt 1994, 1998a, Chomiuk+2011)

- Galactic SFR estimated by calculating the total Lyman continuum photon rate required to maintain the ionization of all Galactic giant HII regions known from radio continuum surveys
- Probes timescales 5-8 Myr (Chomiuk+2011)

Elia+2022

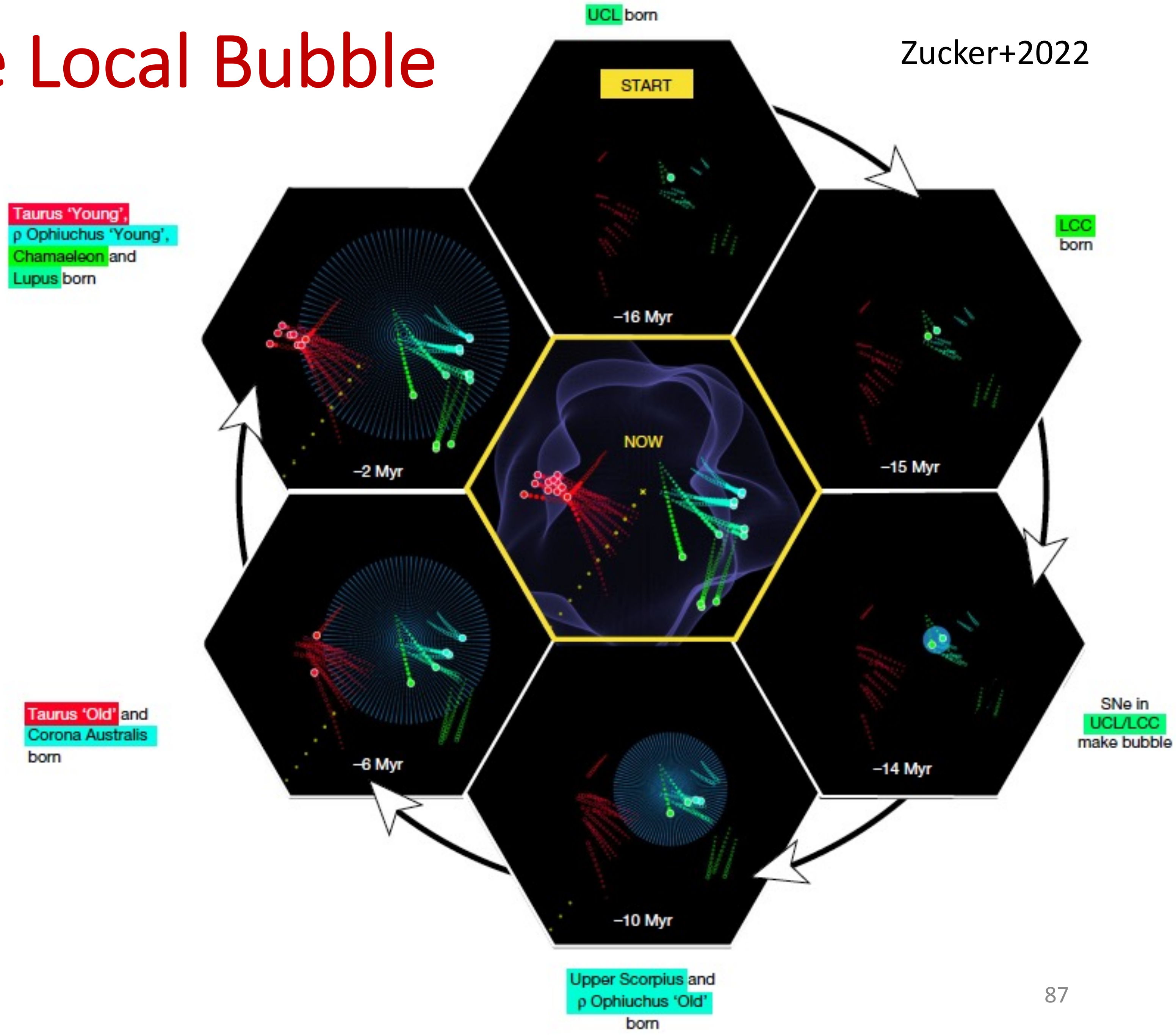
Table 1
Star Formation Rate Estimates for the Milky Way

Method	SFR ($M_\odot$ yr^{-1})	References
Ionization rate from radio free–free	0.35[a]	Smith et al. (1978)
Ionization rate from radio free–free	2.0 ± 0.6[a]	Guesten & Mezger (1982)
Ionization rate from radio free–free	1.6 ± 0.5[a]	Mezger (1987)
Ionization rate from [N II] 205 μm (COBE)	2.6 ± 1.3[a]	Bennett et al. (1994)
Ionization rate from [N II] 205 μm (COBE)	2.0 ± 1.0[a]	McKee & Williams (1997)
O/B star counts	1.8 ± 0.6[a]	Reed (2005)
Nucleosynthesis from ^{26}Al (INTEGRAL)	2.0 ± 1.2[a]	Diehl et al. (2006)
Continuum emission at 100 μm (COBE)	1.9 ± 0.8[a]	Misiriotis et al. (2006)
Ionization rate from microwave free–free (WMAP)	2.4 ± 1.2[a]	Murray & Rahman (2010)
YSO counts (Spitzer)	1.1 ± 0.4[a]	Robitaille & Whitney (2010)
YSO counts (MSX)	1.8 ± 0.3	Davies et al. (2011)
Combination of literature values	1.9 ± 0.4	Chomiuk & Povich (2011)
Continuum emission at 70 μm (Herschel)	2.1 ± 0.4	Noriega-Crespo (2013)
Combination of literature values	1.65 ± 0.19	Licquia & Newman (2015)
FIR clump counts (Herschel)	2.0 ± 0.7	This work

Note.
[a] This value is not taken from the original article, but was rescaled by Chomiuk & Povich (2011) to normalize all literature results to the same IMF (see text).

Star formation in the Local Bubble

Zucker+2022



- With 3D dust maps, gas kinematics, proper motions etc, Zucker+2022 reconstructed the 3D star-formation history in the Local Bubble, a cavity of ionized gas surrounding the Sun
- https://faun.rc.fas.harvard.edu/czucker/Paper_Figures/Interactive_Figure1.html

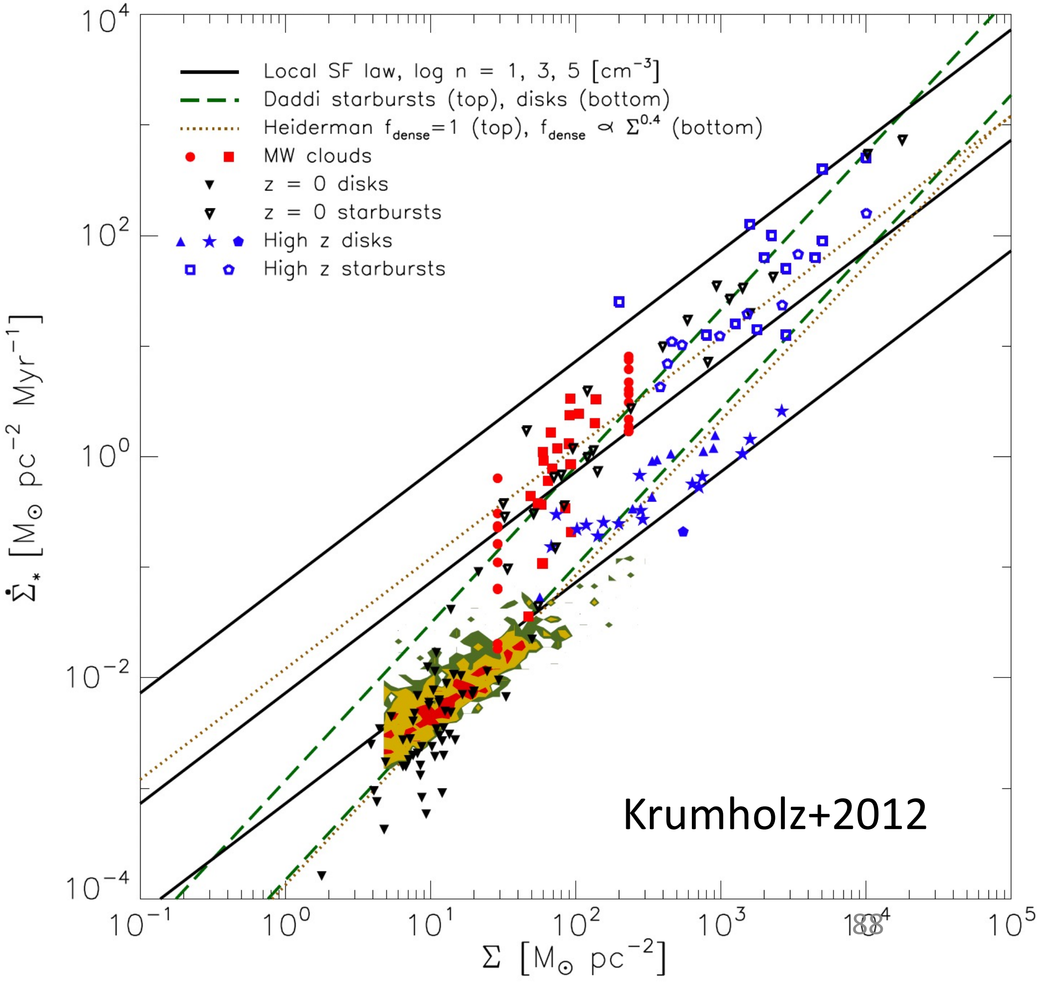
The star-formation "law"

- Correlation between gas surface density and surface density of star-formation rate originally observed by Schmidt 1959, and better constrained by Kennicutt+1998

$$\Sigma_{\mathbf{SFR}} = A\Sigma_{\mathbf{gas}}^{N}$$

N =1.4

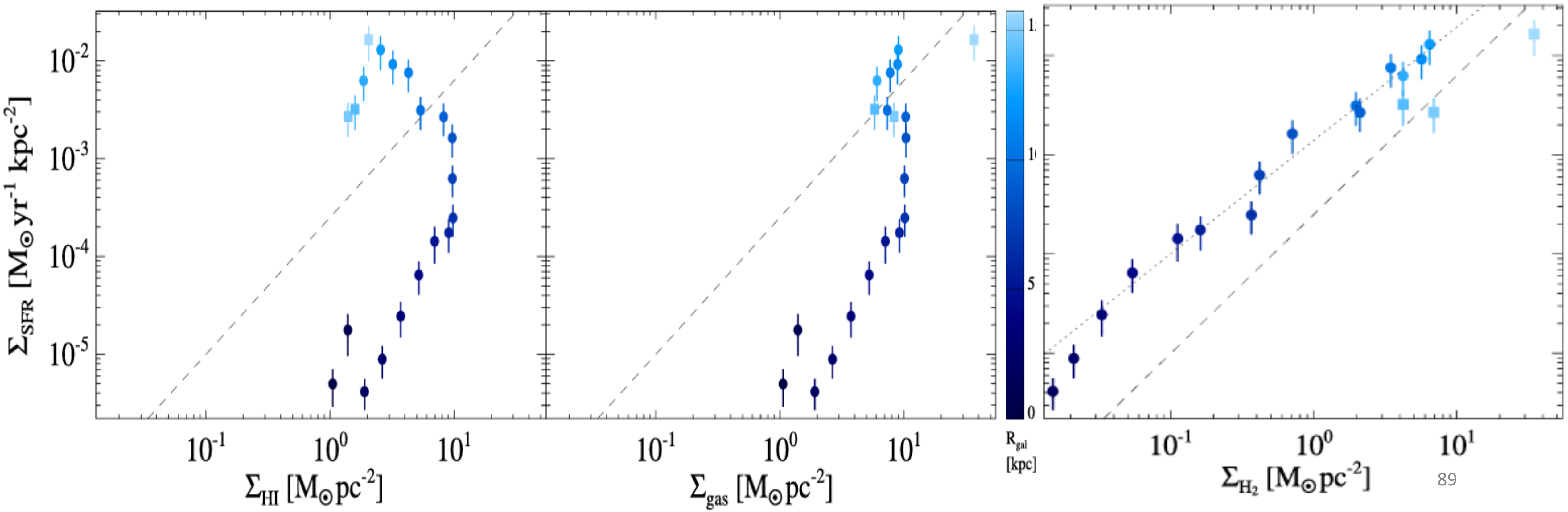
- Compilation of (Σ_{gas}, Σ_{SFR}) by Krumholz+2012
  - ➢ Includes nearby galaxies, higher redshift systems, Galactic clouds
- Relation does not appear to be universal



Star formation law with molecular gas

- Star-formation correlates much better with molecular gas than atomic or total gas
- Conversion of HI → H2 is a bottleneck and the timescale for this conversion depends on galaxy dynamics, metallicity etc.

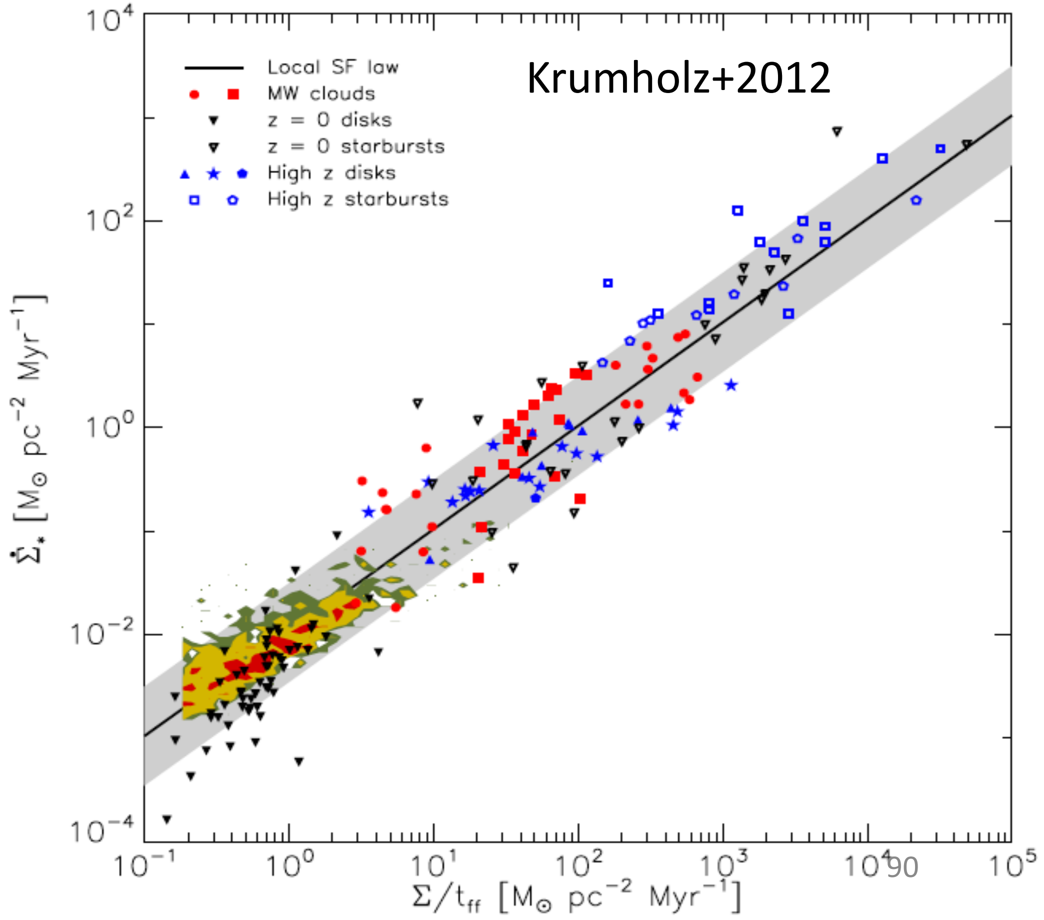
Elia+2022 (Σ_{gas} from Miville-Deschenes+2017)



Volumetric star formation law

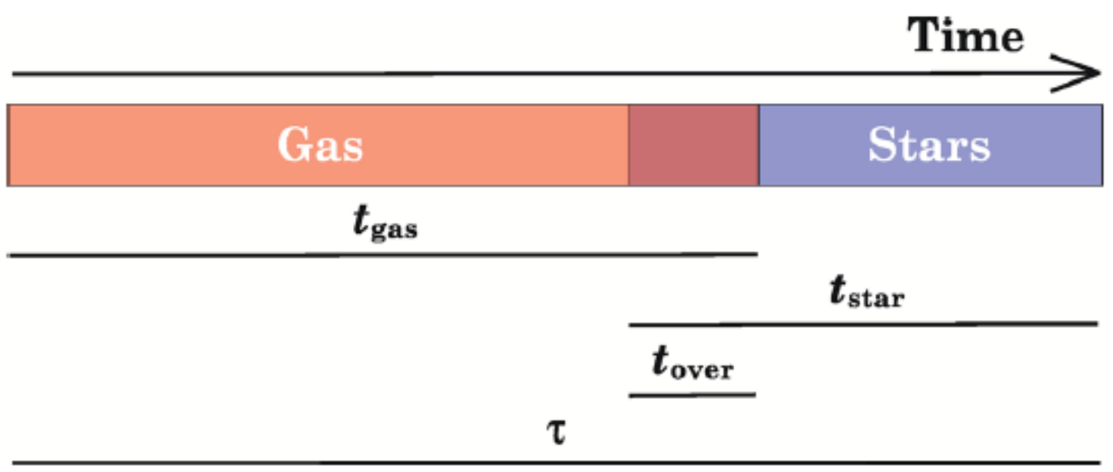
- Local, volumetric star formation law accounts for variety of size scales and volume densities.
    - ➢ A given column density of gas may correspond to a wide range of densities depending on the size scales involved

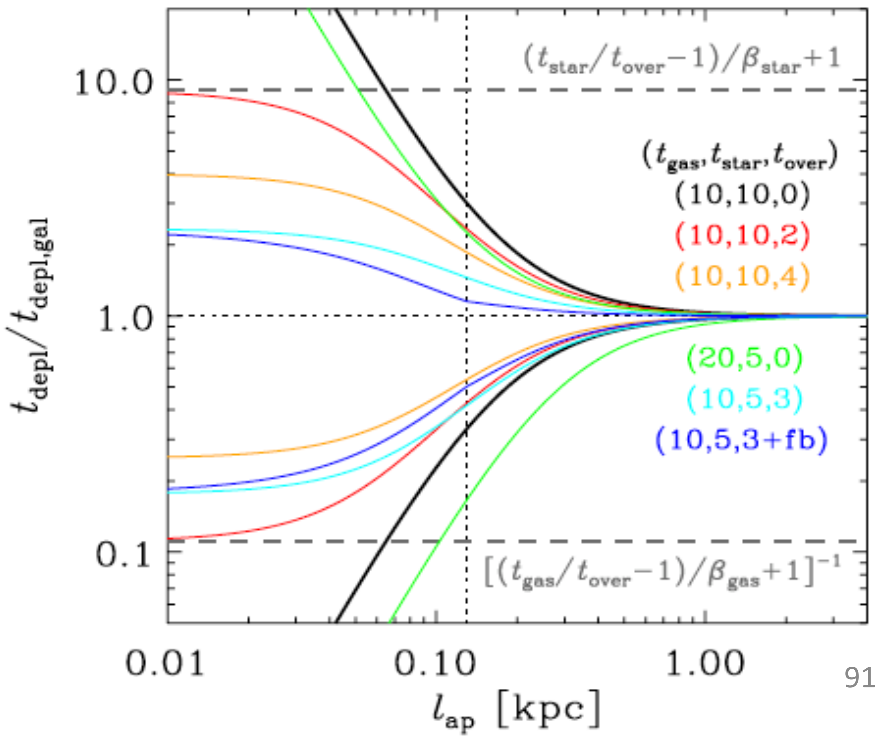
- "All the data, from small solar neighborhood clouds with masses $\sim10^3 M_o$ to submillimeter galaxies with masses $\sim10^{11} M_o$, fall on a single star formation law in which the star formation rate is simply ~1% of the molecular gas mass per local free-fall time" (Krumholz+2012)
- Clouds in the galactic center have a low SFE, but are consistent with a volumetric SFE of 1-a few % per free-fall time (Barnes+2017)



Uncertainty principle for star-formation

- Galactic SF relation breaks down due to the incomplete sampling of independent star forming regions
- The typical size scales above which galactic SF relations hold vary from ∼100 pc in the Central Molecular Zone to almost a kpc in the solar neighborhood (Kruijssen+2014)





Open Questions

- What are the star formation processes and does one process dominate over another in different environments?
- What are the timescales for star formation?

QUESTIONS ?

BACK UP SLIDES

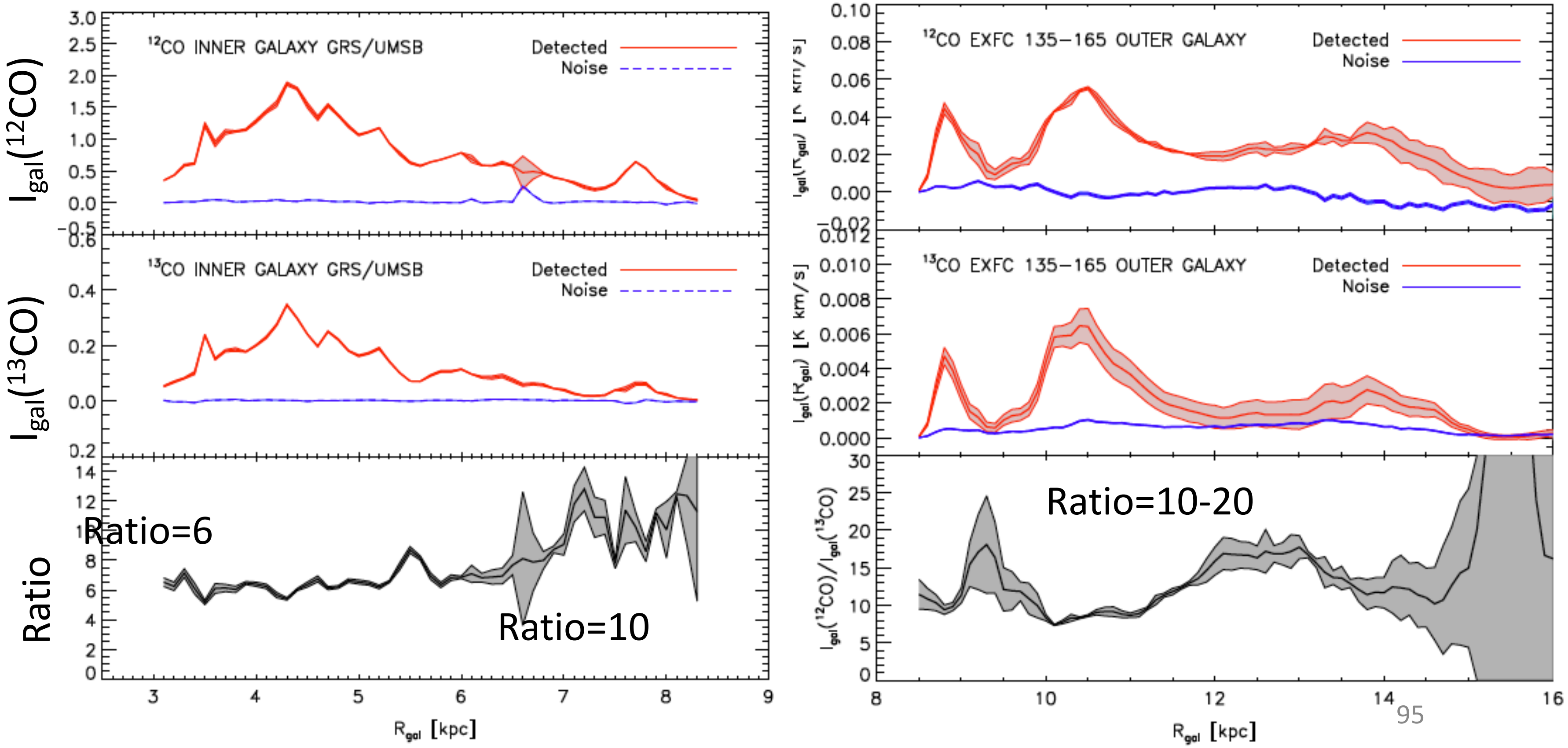
Radial profile of ^{12}CO and ^{13}CO intensities

Knowing distance, “face-on” intensity in each tracer can be computed

- * $I(^{12}CO)/I(^{13}CO)$ ~ 5-10 inside solar circle
- * $I(^{12}CO)/I(^{13}CO)$ ~ 10-20 outside solar circle

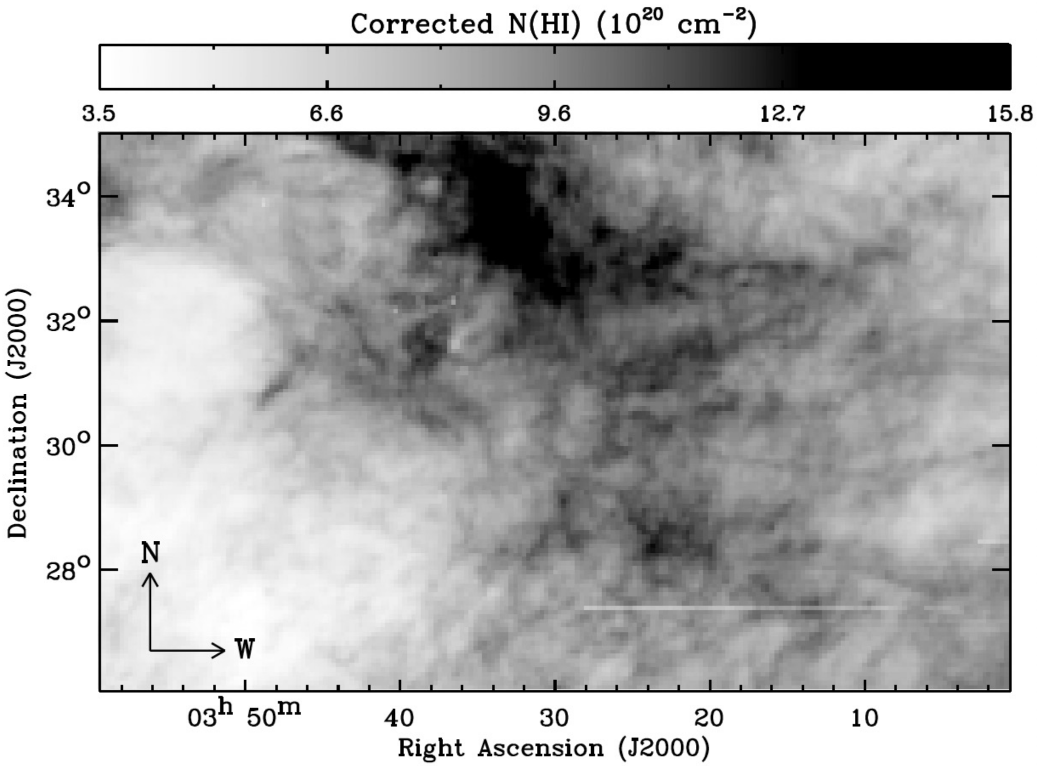
Roman-Duval+2016

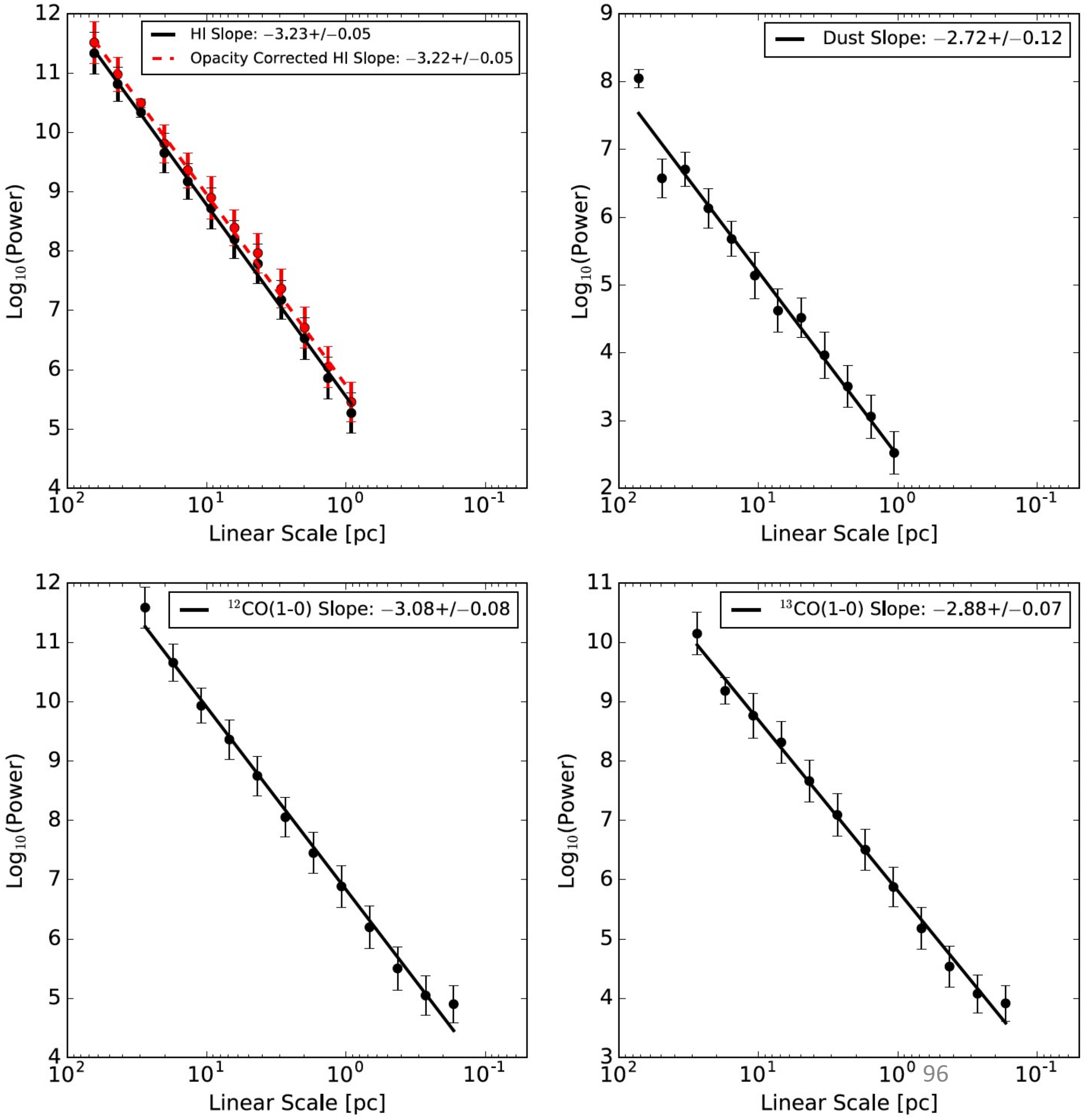
GRS+UMSB (2.5-8.5 kpc) **EXFC 135-15 (8.5-20 kpc)**



Density power spectra

- Turbulent ISM is hierarchical with a power-law density power spectrum
- Example for Perseus (Pingel+2018)





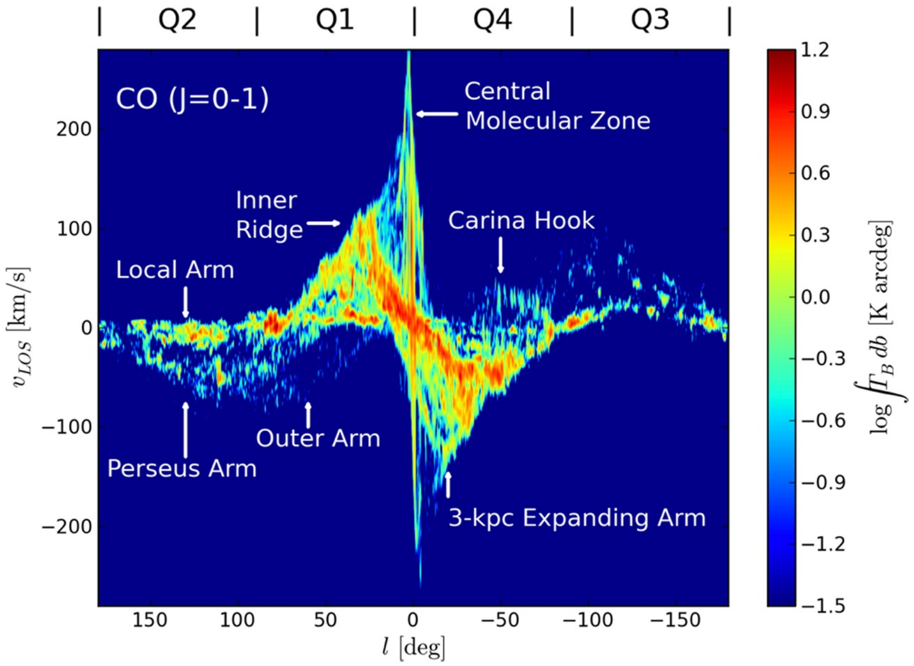


Figure 1. Longitude–velocity map of brightness temperature of the CO ($J = 0$–1) transition (Dame et al. 2001), with major arm features labelled. We integrate the CO emission over latitude in order to show weaker features. Q1-4 indicates the position of Galactic quadrants.

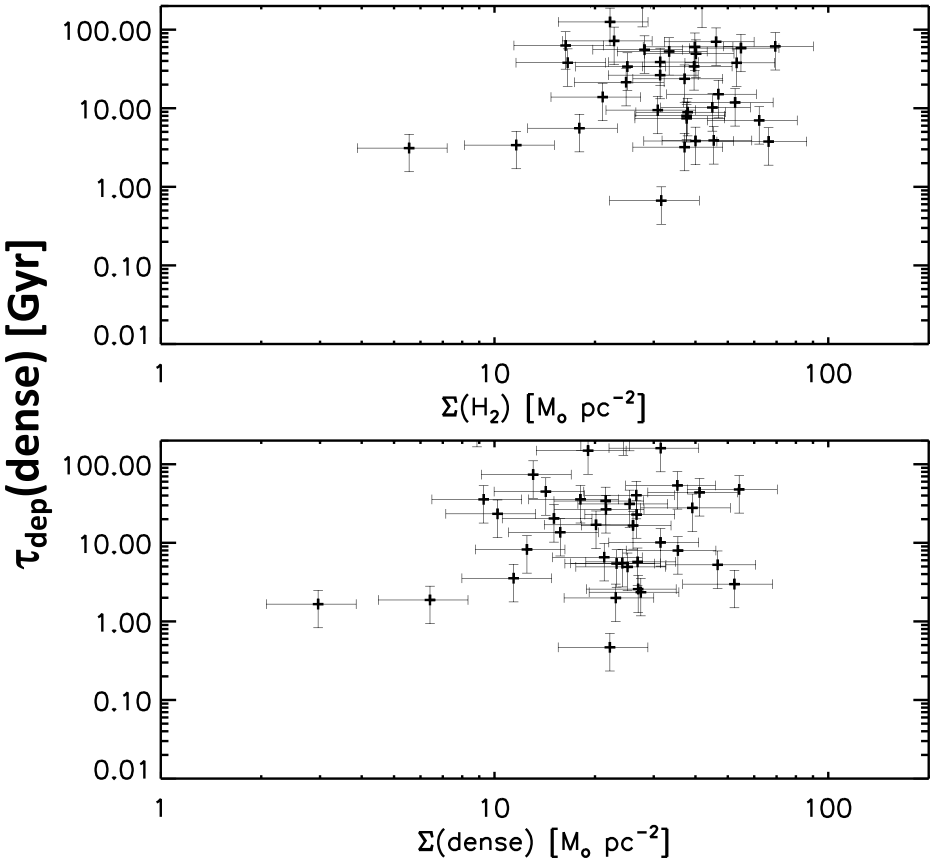
Pettitt+2015

Dense CO gas vs IRIS 25

- Convolve IRIS 25 μm and CO maps to 100 pc resolution and examine molecular depletion times vs surface density of molecular gas

$$\Sigma_{SFR}[M_o yr^{-1} kpc^{-2}] = 2.8 \times 10^{-3} S_{25}[MJy/sr]$$

$$\tau_{dep} = \frac{\Sigma(\mathrm{H}_2)}{\Sigma_{SFR}}$$



τ_{dep} = 10 Gyr implies inefficient SF in outer galaxy?

Star formation law with molecular gas

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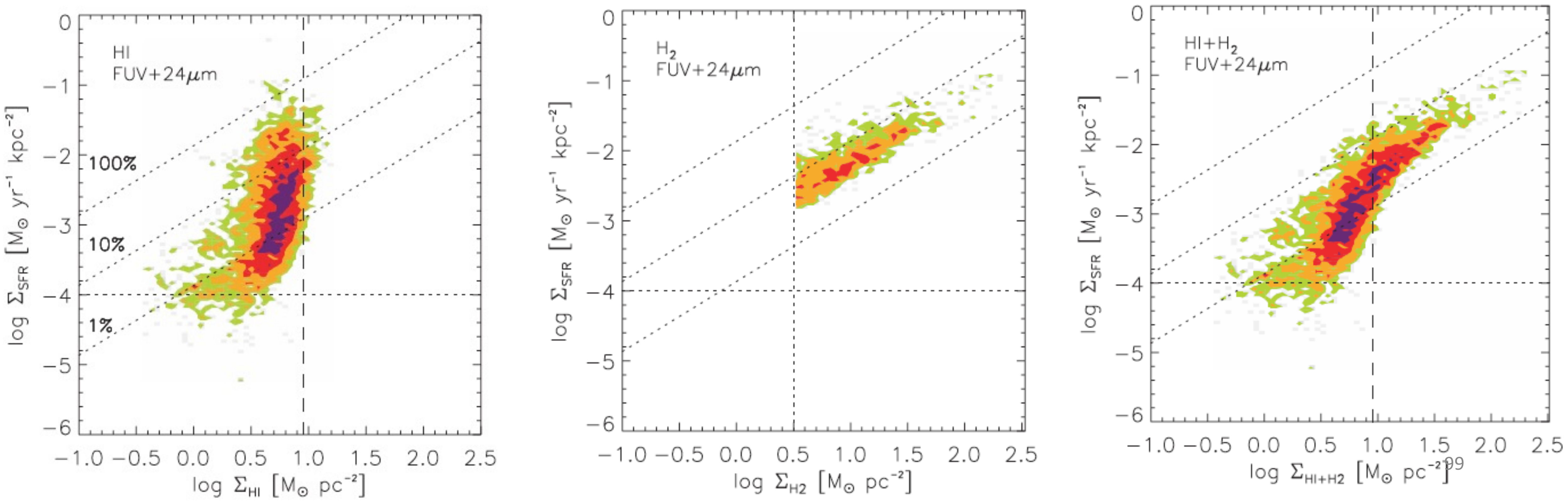
- Conversion of HI → H2 is a bottleneck and the timescale for this conversion depends on galaxy dynamics, metallicity etc.



SFE in galactic center (in rel to virial parameters)