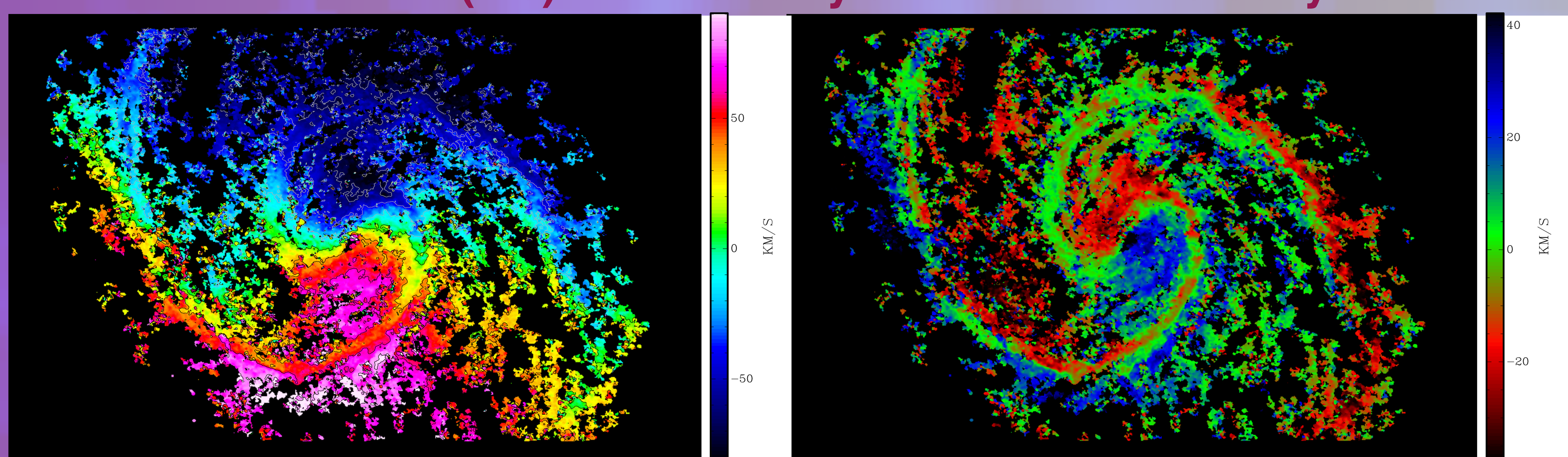
The PdBI Arcsecond Whirlpool Survey (PAWS) II.
Complex dynamics of M51 as driver of Giant Molecular Cloud properties.

D. Colombo (MPIA)*, E. Schinnerer (MPIA), A. Hughes (MPIA), S. Meidt (MPIA),
J. Pety (IRAM), S. Garcia-Burillo (OAN), A. Leroy (NRAO), K. Schuster (IRAM), C. Kramer (IRAM),
G. Dumas (IRAM), C. Dobbs (Exeter) & T. Thompson (OSU)

Abstract: **High resolution (40 pc) CO(1-0) observation from the PdBI Arcsecond Whirlpool Survey (PAWS, PI Schinnerer) reveals a highly complex dynamical scenario in the inner disk of M51. Our harmonic decomposition of the non-circular motion field provides the first kinematic evidence of a three-fold potential perturbation previously postulated by Henry et al. (2003). The origin of this density-wave is uncertain but it appeared closely related to M51's nuclear bar. Given the tight link between CO distribution and underlying stellar potential (Schinnerer et al. 2013), the M51 complex kinematics naturally reflected in the observed environmental dependency of Giant Molecular Cloud (GMC) properties. Massive, bright and large line-width GMCs are preferentially located in the central region and in the density-wave spiral arms. The inter-arm GMCs are more similar to the populations of low-mass galaxies as LMC and M33. A significant fraction of clouds in M51 does not appear to be virialized and the GMC surface density is tightly linked to the environment in which they are observed. We interpret the shapes of the GMC mass distributions via a cloud evolution scenario that includes various formation/destruction mechanisms connected with the galactic structure.**

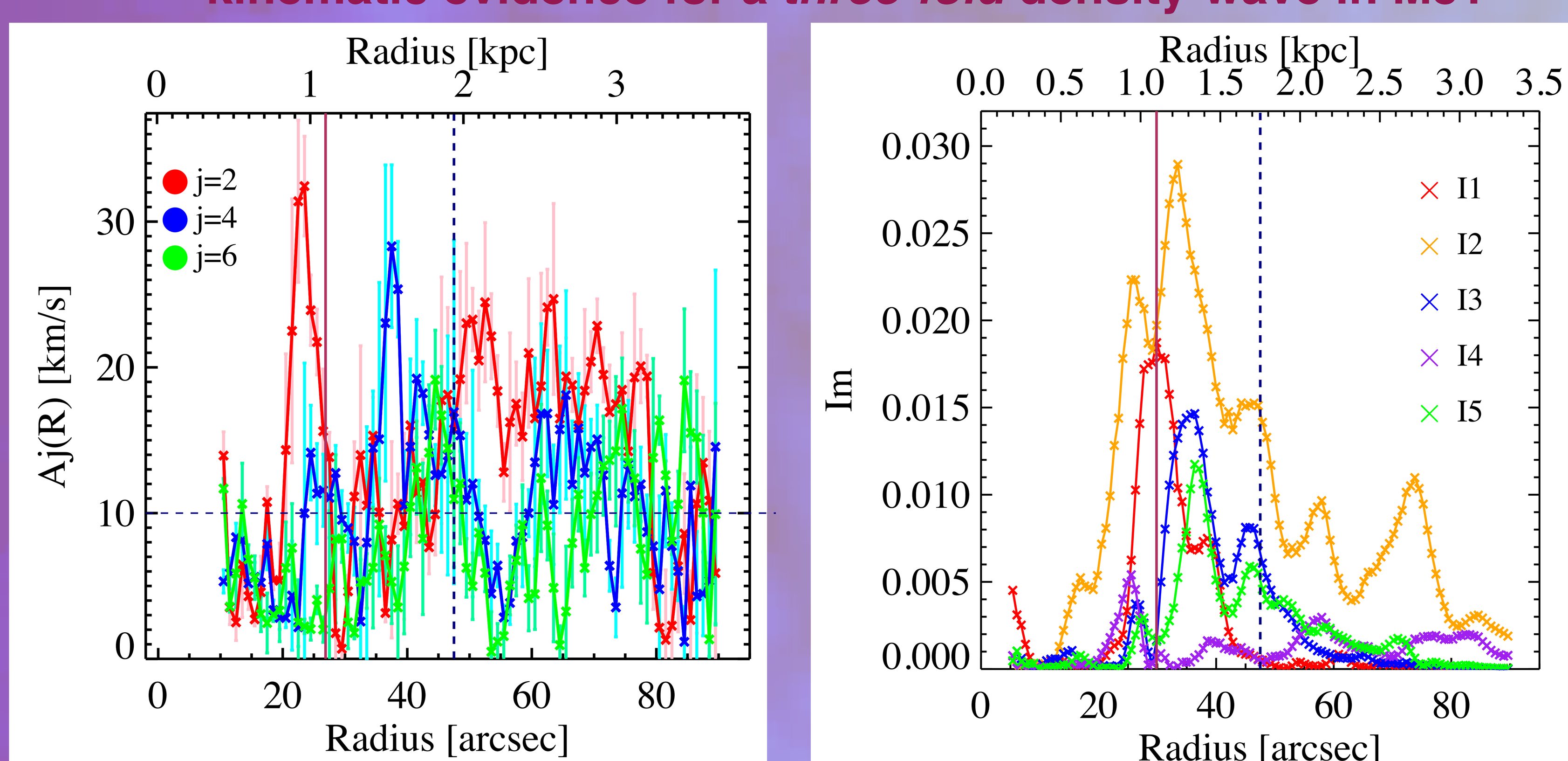
M51's complex dynamical structure

Ia. PAWS $^{12}CO(1-0)$ M51 Velocity and residual velocity fields



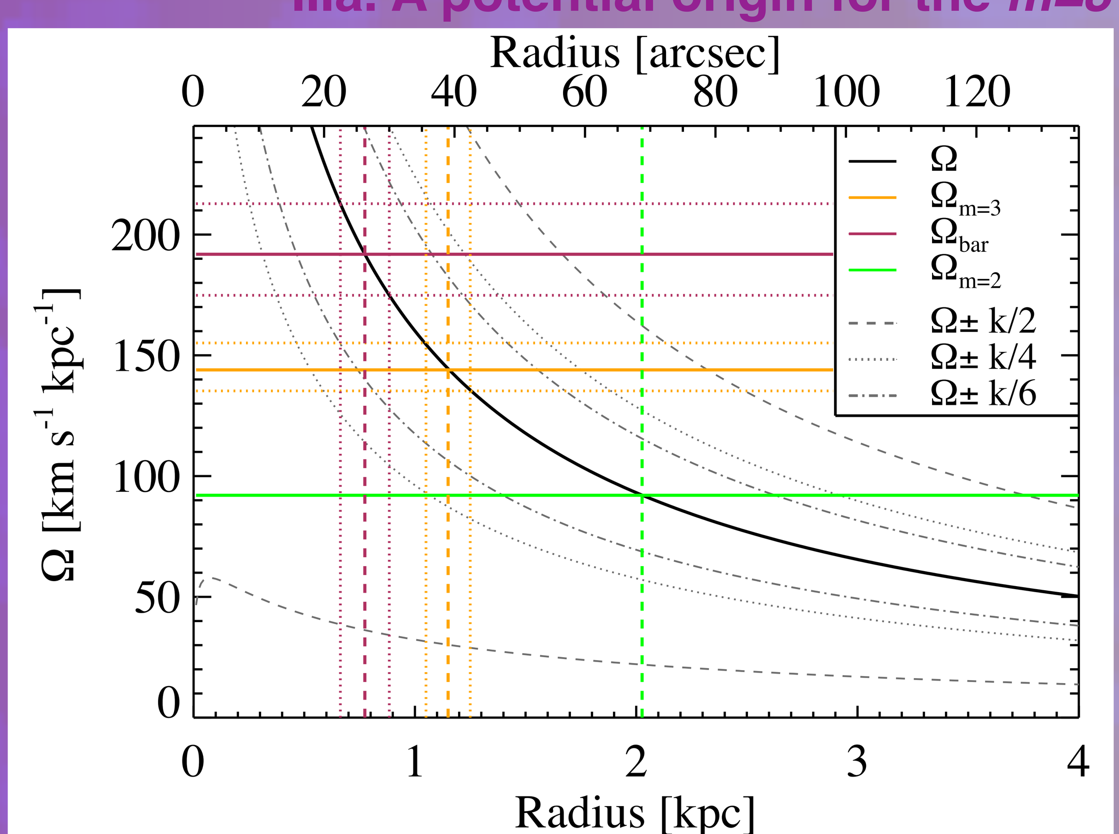
Left: The PAWS CO velocity field of M51 is complex, showing a **twist caused by a central bar, strong streaming motion in the spiral arms, and a red-shifted core**. ***Right***: The residual velocity field is obtained by subtracting a model of pure circular motion from a stellar mass-based (Meidt et al. 2013) and HI data (Walter et al. 2008) rotation curve with *PA*=173° and *i*=22°. The non-circular motions in M51 are now apparent. The **"butterfly" pattern of the nuclear bar and gas inflow along the souther spiral arm** are manifested.

IIa. Harmonic decomposition: kinematic evidence for a *three-fold* density-wave in M51



Left: Even terms of the residual velocity field harmonic decomposition. An m-fold potential perturbation introduces j=m±1 components in the residual velocity field (Canzian & Allen 1997). These components switch in dominance at the corotation radius of the mode. We observe a strong j=2 centered at R~0.9 kpc that loses power at R~1.1 kpc ("m=3 corotation", red vertical line) in favor of a j=4 component. The j=2 regains power at R~1.7 kpc (dashed blue vertical line). This is evidence for the **existence of m=3 and m=1 perturbations of the potential, responsible for the lobsidedness of M51 at small and large radii**. ***Right***: Harmonic decomposition of the integrated intensity map. In the presence of linear coupling between the dominant m=2 and m=3, we see a boosting in the I1 and I5 terms in the Fourier decomposition of the CO brightness as predicted (Masset & Tagger 1997).

IIIa. A potential origin for the *m=3* perturbation



Angular frequency curves derived from the stellar-based rotation curve of M51: Ω (black full), Ω±k/2 (grey dashed), Ω±k/4 (grey dotted), Ω±k/6 (grey dashed-dotted). Pattern speed estimates for the nuclear bar (red), main spiral arms (green), and m=3 mode (yellow) together with the their corotation radius at R~0.8±0.1 kpc (Zhang & Buta 2012), R~2 kpc (Meidt et al. 2013), R~1.1±0.1 kpc, respectively.

The bar corotation overlaps with the ultra harmonic resonance (UHR) 6:1 of the ***m=3*** pattern speed. In light of this evidence **we argue that the nuclear bar of M51 may be the main driver of the m=3 density-wave.** This scenario is supported by the fact that the ***m=3*** mode extends out to R~1.7 kpc which is very close to the bar's OLR, its outermost extent gravitational influence. However we note that the corotation of the ***m=3*** mode corresponds to the inner UHR 4:1 of the main spiral arms suggesting a possible interaction with this structure and reinforcing its density-wave nature.

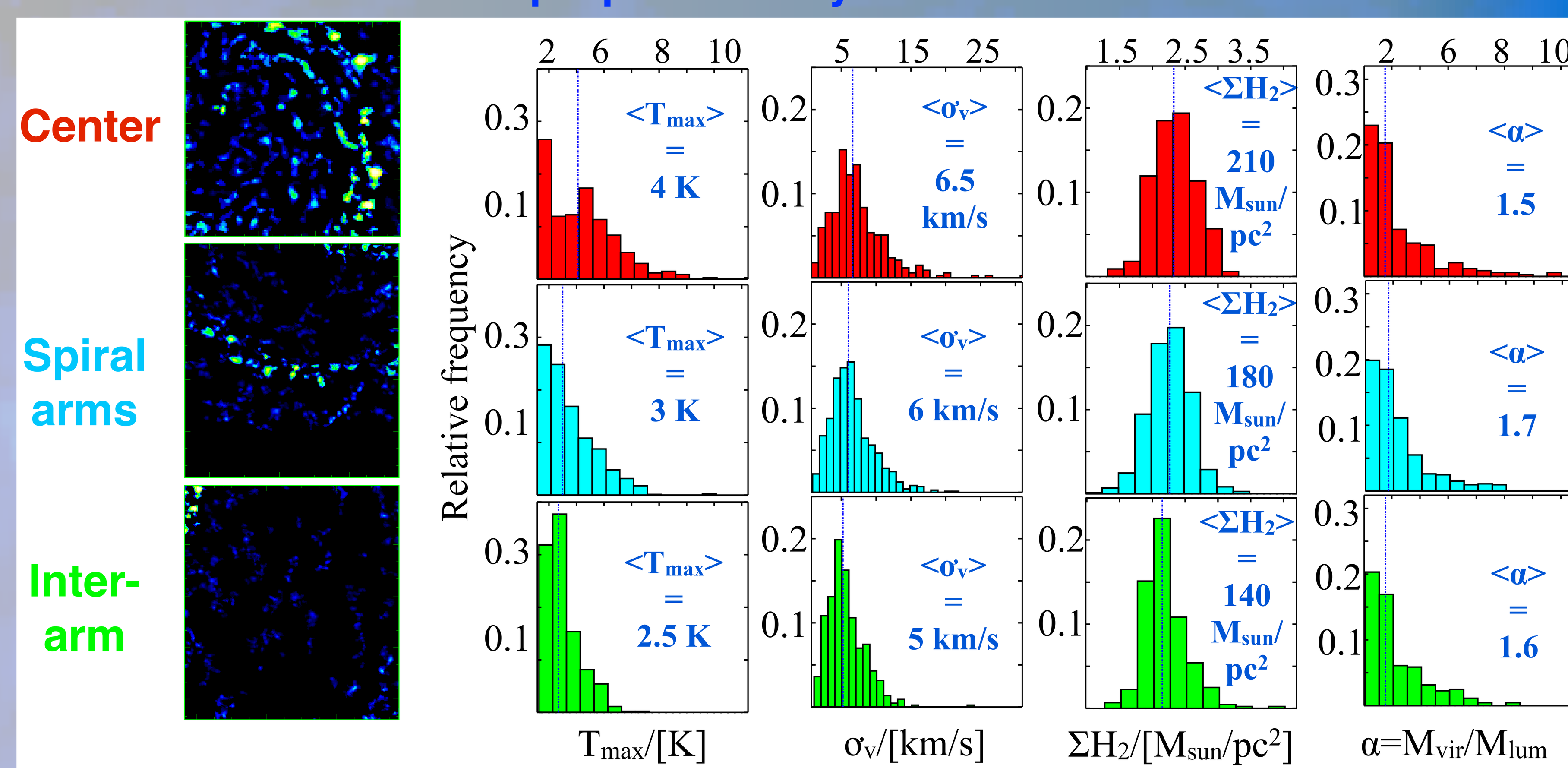
References:

Bolatto et al 2008, ApJ, 686, 948-965
Canzian & Allen 1997, ApJ, 479-723C
Henry et al 2003, AJ, 126-2831
Masset & Tagger 1997, AAP, 322-442
Meidt et al. 2013, ApJ in press
Schinnerer et al. 2013, ApJ in press
Solomon et al 1987, ApJ, 319, 730-741
Walter et al. 2008, AJ, 136-2563
Zhang & Buta 2012, arXiv:1203.5334

Email:** **colombo @ mpia.de

Environmental dependence of GMC properties

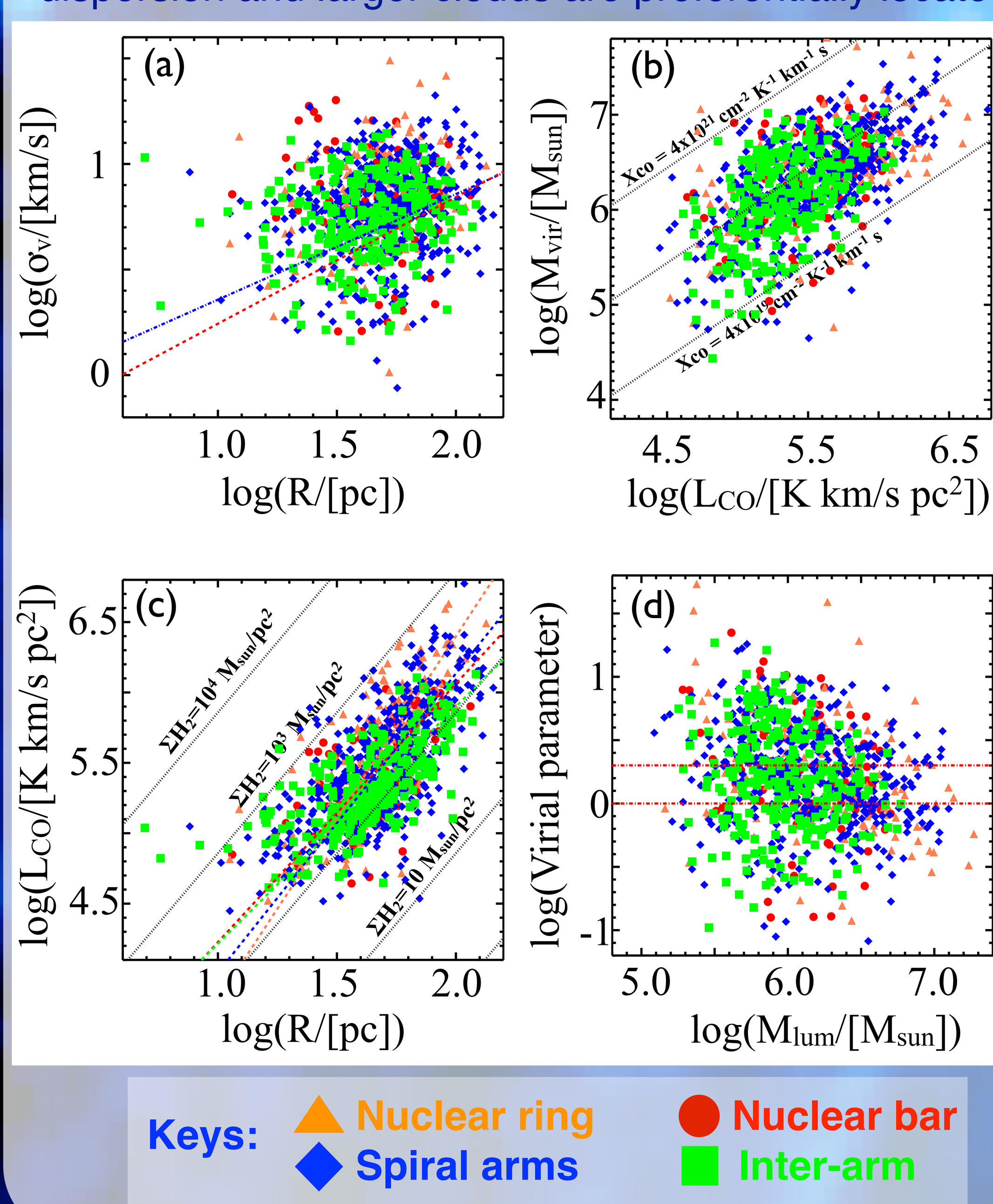
Ib. GMCs properties vary with environment



The 1507 GMCs contain 55% of the total PAWS CO(1-0) flux in M51. Left panels show a representative sample of GMCs in the center, spiral arm and inter-arm region of M51. Vertical blue lines in the plots indicate the property median. **Distinct changes as a function of environment are observed. Clouds in the center and spiral arms are brighter, with higher velocity dispersion and surface density than objects in the inter-arm region.**

IIb. GMC scaling relations as function of environment

(a) Size-velocity dispersion:
Large scatter and no obvious relation in M51. The bulk of points lies above both Galactic (blue line, Solomon ea 1987) and extragalactic (red line, Bolatto ea 2008) fits. High velocity dispersion and larger clouds are preferentially located in the center and spiral arms.



(b) CO luminosity-virial mass: The data points are scattered around Xco = 4x10^{20} cm^{-2} K^{-1} km^{-1} s. If M51's GMC population is, on average, self-gravitating (α~1), then the average Xco must be similar to the Galactic value.
(c) Size-CO luminosity: The data points lie slightly above an isosurface H_2 density of 100 M_{sun}/pc^2. Fits (in same color as data points) of center (especially in the nuclear ring) and spiral arm GMCs, are steeper with respect to the inter-arm cloud one. This suggests that the H_2 surface density of clouds is related to the environmental pressure, that is higher in the center and spiral arms due to a deeper stellar potential.
(d) Luminosity mass-virial parameter: The median virial parameter α~1.6 suggests that M51's GMCs are mostly bound. However a significant fraction of unbound objects is present.

IIIb. GMC formation and evolution in M51

Differences in GMC properties are reflected in their cumulative mass functions that suggest a **cloud evolution scenario**. Population **upstream is composed of small clouds**, when this population enters the density wave larger and more massive GMCs are formed due to **agglomeration and self-gravity**. Once these **GMCs leave the spiral arm (downstream) shear and SF destroy** the massive objects until they resemble the upstream mass function. In the **molecular ring, gas stalls and accumulates** due to a dynamical resonance, thus the processes present in the spiral arms are enhanced. **The sharp truncation of the nuclear bar mass function** could be caused by a combination of shear due to the stellar bar, enhanced interstellar radiation field and AGN.