A first comprehensive analysis of the distributions of the ISM, γ-rays, and X-rays over the Large Magellanic Cloud

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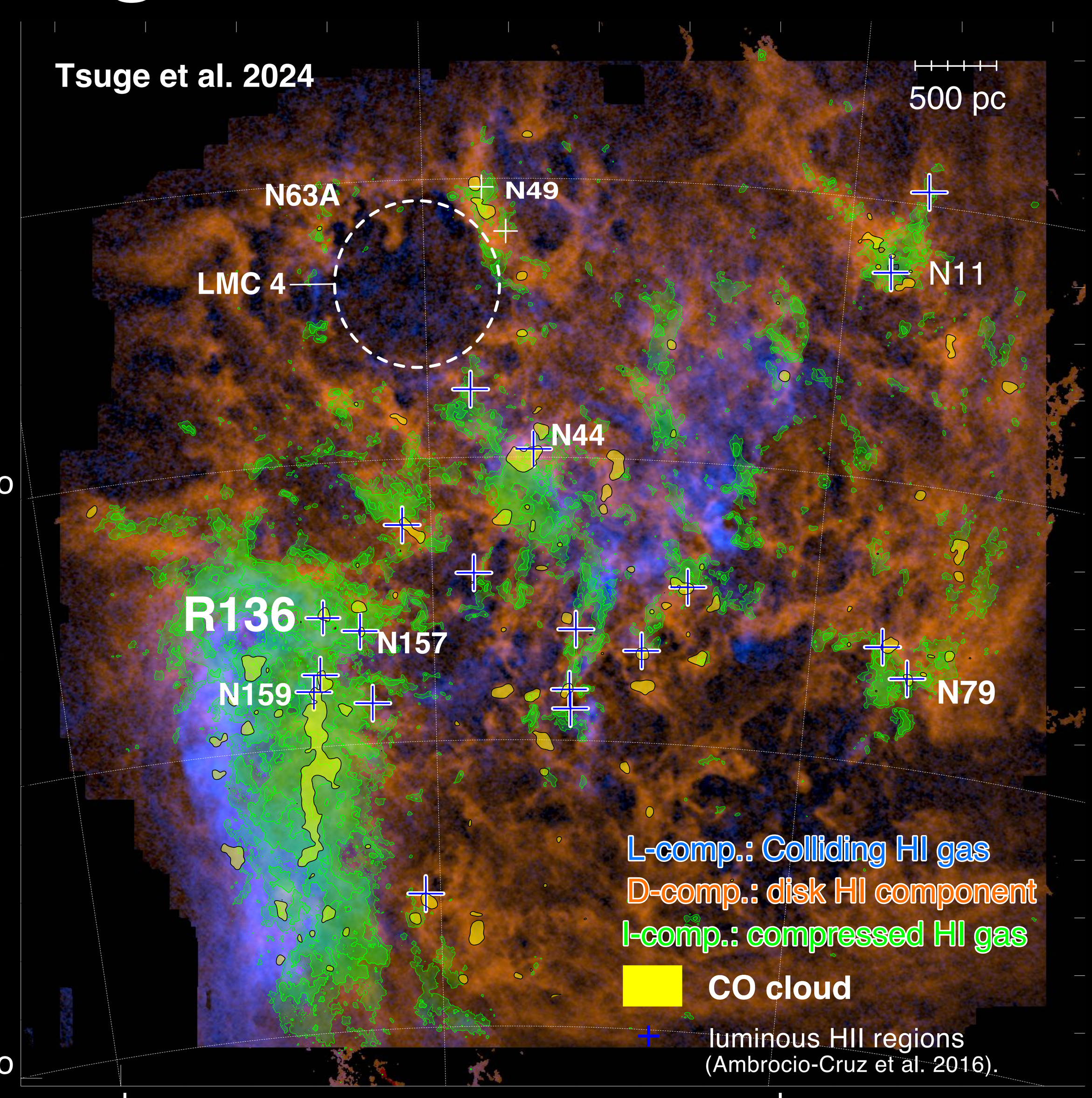
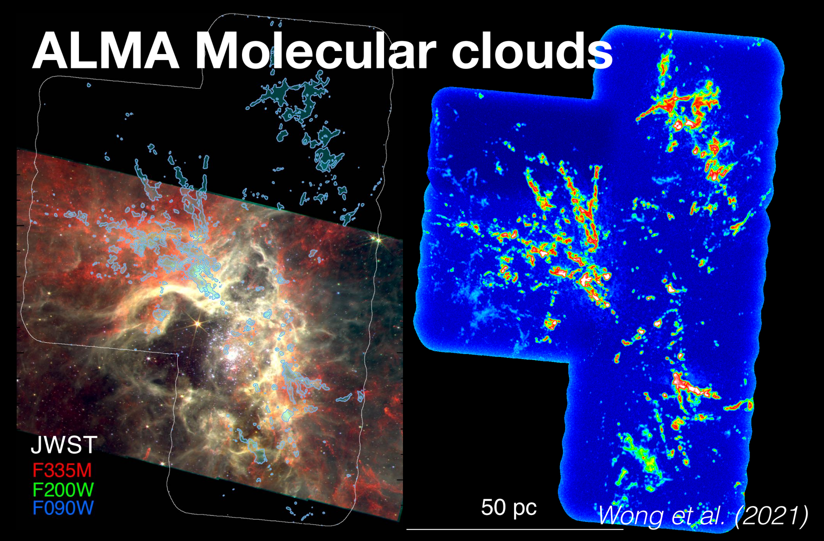
Abstract

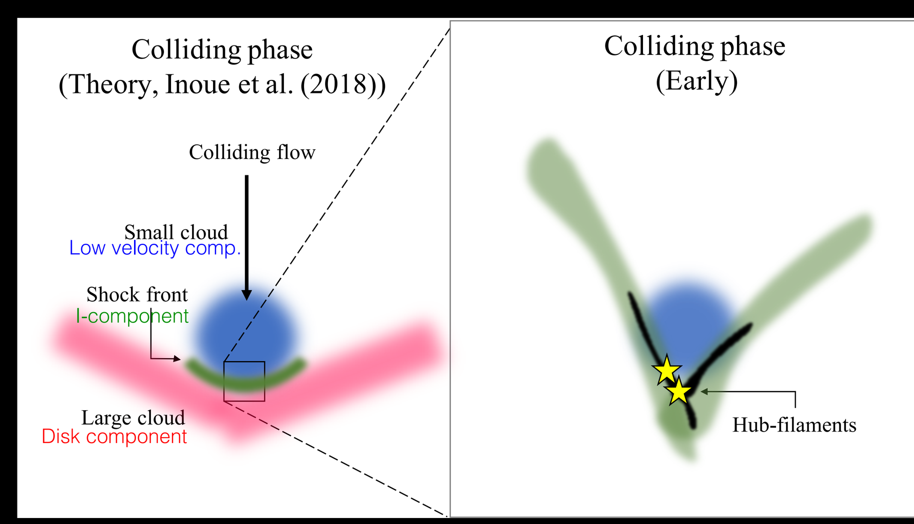
Diffuse γ-ray emission is thought to be primarily produced by interactions between cosmic-ray protons and interstellar protons via hadronic processes. Therefore, it provides a valuable opportunity to obtain a comprehensive understanding of cosmic-ray distribution and the interstellar gaseous medium. We present the first analysis of the spatial distributions of GeV and TeV γ-rays, hard and soft X-rays, and interstellar molecular/atomic clouds over the whole Large Magellanic Cloud (LMC). We have found the global distribution of Fermi γ-rays closely resembles that of interstellar molecular and atomic hydrogen gas, as revealed by the NANTEN CO and ATCA & Parkes HI. Locally, γ-rays excesses are spatially coincident with the positions of X-ray bright supernova remnants observed with eROSITA. We also found that there are no X-ray and CO/HI counterparts for the γ-ray excess inside LMC 4, suggesting that localized ionized gas may also act as a target for cosmic-ray protons. In addition, we will discuss the origin of diffuse soft X-rays in the LMC as produced by the supersonic gas collisions as driven by the tidal interaction between the LMC and the SMC. The present comparisons mark a first step toward a full understanding of the interplay between the high energy radiations and the cool ISM in a galaxy.

High-mass star formation triggered by galactic tidal interaction in the LMC



- Tidal interaction induce collisions of HI gas on the kpc scale, creating a high-density environment enough to form star clusters over the whole LMC (incl. N44, N11, N79) (Fukui et al. 2017; Tsuge et al. 2019; 2024).
- The I-component is thought to be formed by deceleration of the gas due to the collision of the L- and D-components. → Observational trace of gas collisions (Tsuge et al. 2024).





The collisions have triggered the formation of the molecular clouds as well as the super-star cluster R136 and N44 together with the surrounding high-mass stars including the progenitor of SN1987A.

This process, supported by theoretical studies

Supersonic cloud collisions compress HI gas and enhance turbulence, thereby increasing the mass accretion rate, leading to the formation of massive clumps that have the potentiall to evolve into young massive clusters (e.g., Inoue et al. 2018;Maeda et al. 2021; 2024).

↑ **Figure 1**: Hi intensity map of the I-component by contours superposed on the L- and D-components image. The integration velocity range is V_{offset}=−101.1– −30.5 km s^{-1} for the L-component, V_{offset}=−10.4 – 9.7 km s^{-1} for the D-component, and V_{offset}=−30.5– −10.4 km s^{-1} for the Icomponent. V_{offset} is defined as the relative V_{LSR} with respect to the rotation velocity.The contour levels are 300, 500 and 1000 K km s^{-1}. Plus signs show the positions of luminous Hii regions (SHα > 1 x 10^{4} erg cm^{-2} s^{-1} sr^{-1}; Ambrocio-Cruz et al. 2016). Molecular clouds of N48 and N49, which are located between two SGSs, LMC 4 and LMC 5 are also shown by crosses.The shaded areas in yellow are the the regions where ^{12}CO(J=1–0) intensity obtained with NANTEN is greater than 1.5 σ (1.48 K km s^{-1}) with the same velocity range.

Multi-wavelength view of the ISM in the LMC

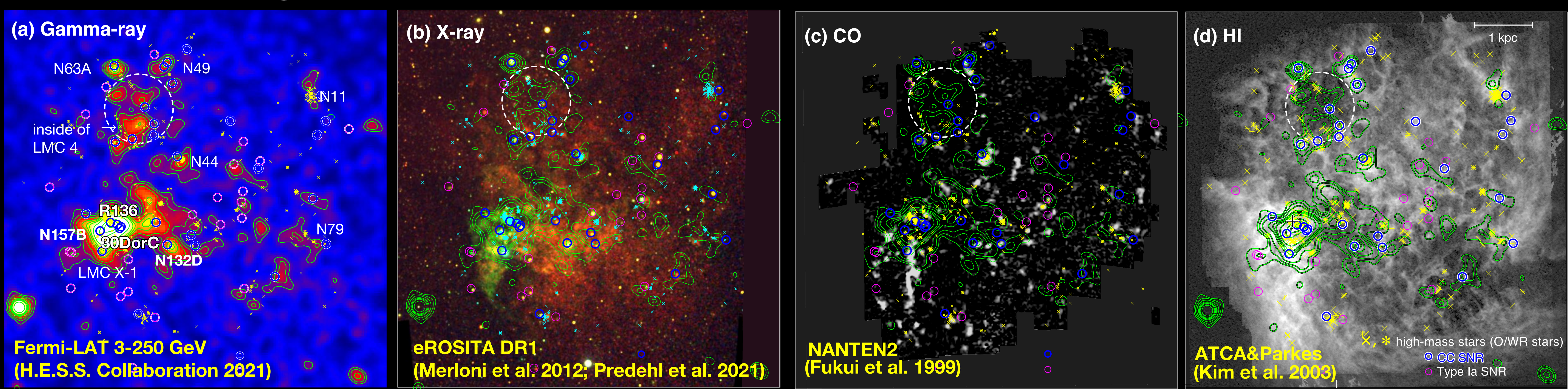


Figure 2: (a) Gaussian (σ = 0.2) kernel smoothed Fermi-LAT count map cen- tered on the position of N132D for the energy range 3–250 GeV. The bright Fermi-LAT sources at the eastern edge of the LMC-30 DorWest region are N157B and PSR B0540-69 (H.E.S.S. collaboration et al. 2021). (b) A three-color composite image of eROSITA DR1 X-ray emission (Merloni et al. 2012; Predehl et al. 2021): red represents 0.2-0.5 keV, green represents 0.5-1.0 keV, and blue represents 1.0-2.0 keV emission. (c) ^{12}CO(J=1–0) total integrated intensity obtained with NANTEN (e.g., Fukui et al. 1999). (d) The total HI integrated intensity maps obtained with ATCA & Parkes telescopes (Kim et al. 2003). Crosses and asterisks are O-type and WR stars, respectively (Bonanos et al. 2009). The blue and magenta circles represent CC-type SNRs and type Ia SNRs, respectively (Maggi et al. 2016).

ISM around R136 and 30DorC

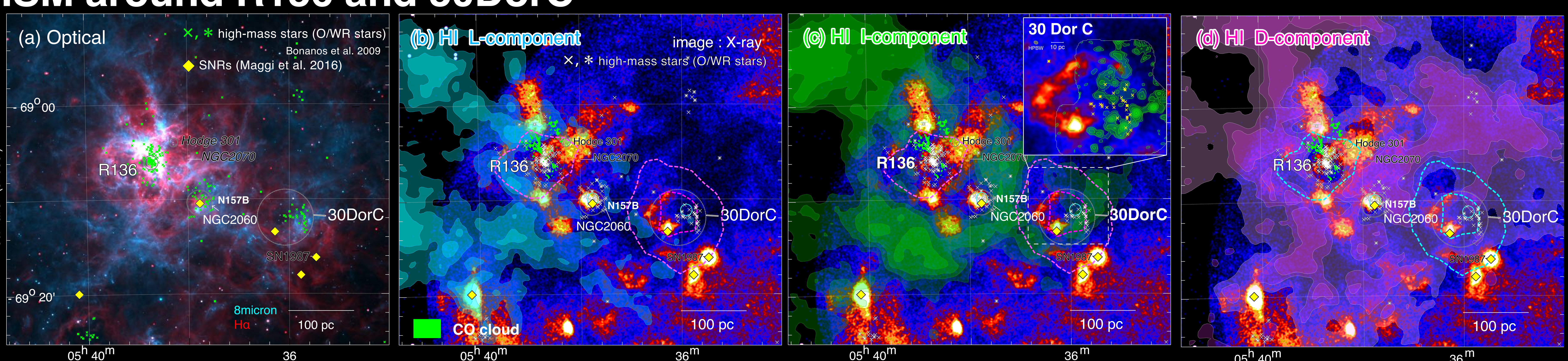


Figure 3: (a) Optical and infrared image with Hα in red (e.g., Meixner, M. et al. 2006) red) and 8 micron in cyan (Smith et al. 2005) of 30 Doradus region. Green crosses are O-type and WR stars (Bonanos et al. 2009). The Hi integrated intensity map of (b) the L-component, (c) the I-component, and (d) the D-component (Fukui et al. 2017) overlaid with X-ray emission (0.5–0.7 keV) obtained with the early data release of the eROSITA (Predehl et al. 2021; Sasaki et al. 2022). The integration velocity range is Voffset = −101.1–−30.5 km s–1 for the L-component, V_{offset} = −10.4– 9.7 km s^{-1} for the D-component, and V_{offset} = −30.5– −10.4 km s^{-1} for the I-component. The lowest contour level and intervals are 300 K km s^{-1} and 200 K km s^{-1} for (b) and 850 K km s^{-1} and 250 K km s^{-1} for (c) and 700 K km s^{-1} and 300 K km s^{-1} for (d). Crosses and asterisks are O-type and WR stars, respectively (Bonanos et al. 2009). Yellow diamonds are SNRs (Maggi et al. 2016). Dashed lines in panels (b) - (d) show gamma-ray flux of residual emission after subtraction of the emission from N 157B predicted by the best-fit ROI model. Contours of at (1.5, 3.0) x 10^{-8} cm^{-2} s^{-1} sr $^{-1}$(Aharonian et al. 2024).

- Diffuse gamma-ray radiation was detected toward the HII regions (e.g., R136, N44, N11, N79), in addition to the several gamma-ray SNRs (e.g., N132D, N63A, N49).
- Almost diffuse gamma-rays are associated with atomic and molecular hydrogen gas as well as thermal X-ray plasma.
- Hadronic gamma-rays may be produced in the HII regions and superbubble? (Past supernova events and/or stellar clusters possibly accelerate cosmic-ray protons?)