The Multi-Messenger Astrophysics of the Galactic Centre
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The Galactic Center compared with nuclei of nearby galaxies

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Abstract. Understanding our Galactic Center is easier with insights from nearby galactic nuclei. Both the star formation activity in nuclear gas disks, driven by bars and nuclear bars, and the fueling of low-luminosity AGN, followed by feedback of jets, driving molecular outflows, were certainly present in our Galactic Center, which appears now quenched. Comparisons and diagnostics are reviewed, in particular of $m = 2$ and $m = 1$ modes, lopsidedness, different disk orientations, and fossil evidences of activity and feedback.

Keywords. Galaxy: center – Galaxy: kinematics and dynamics – Galaxy: nucleus – galaxies: active – galaxies: jets

1. Introduction

It is now well established that our Galactic center is very quiet, both on the point of view of star formation, and of nuclear activity. The luminosity of Sagittarius A* is only of 10^{-9} the Eddington luminosity (or 300 $L_\odot$) (e.g. Genzel *et al.* 2010), and the star formation rate is 10 times lower than expected from the high molecular surface density in the CMZ (Central Molecular Zone), e.g. Longmore *et al.* (2013). The reason of this low activity, and low efficiency of star formation might be transient, since there are evidences of recent past activity (e.g. Ponti *et al.* 2010; Carretti *et al.* 2013). Our Galactic center appears to have been quenched by some feedback effect, which has raised the turbulence of the gas to a high level. The velocity dispersion, the radiation field and magnetic field are all very high in this environment (Ferrière *et al.* 2007), and these might be clues from the recent quenching.

The Galaxy is a common barred spiral, with strong non-axisymmetries, both of $m = 2$ and $m = 1$ types, which are powerful engines to fuel gas to the nuclear regions. The gas is present, and certainly other activity episodes are expected in the future.

2. Bars in galaxies to fuel AGN and star formation activities

As shown in Figure 1, our Galaxy has a box/peanut shape bulge, which is attributed to the vertical resonance of the bar (e.g. Combes & Sanders 1981, Ness *et al.* 2012), and a strong bar inside a spiral structure, which is evolved dynamically, so that its pattern speed has relaxed to a low value, allowing two Lindblad resonances (e.g. Binney *et al.* 1991, Rodriguez-Fernandez & Combes 2008). It is also possible that the weakening of the bar, due to the perpendicular orbits inside the two ILRs, and the bulge thickening towards the center, has or will lead to the decoupling of a secondary bar, a faster embedded bar (e.g. Friedli & Martinet 1993, Alard 2001). This nuclear bar would exist at $\sim$ 100pc scale.

These dynamical features help to understand the gas flows in the Galaxy, and the possible formation of gaseous rings, like the CMZ at radii ~150-200pc. It can be shown

Figure 1. Comparison between the Milky Way and nearby galaxies with similar morphology and dynamics: on the left panel, the COBE satellite near-infrared image is compared to the edge-on spiral NGC 4565, showing a boxy-peanut bulge; on the right panel, the artist view of the face-on Milky Way is compared to the barred spiral NGC 3992.

that the bar exerts torques on the gaseous disk, and the sign of the torques change at each resonance. The torques are negative inside corotation, and can drive the gas towards the inner Lindblad resonance (ILR), where it accumulates in a ring. For usual rotation curves, where the rate of orbit precession inside the ILR ($\Omega - \kappa/2$) is incresing with radius, spirals arms are leading inside the ILR, and the torques are negative, so that the gas is stalled. It has to wait viscous torques to infall. When the central region is under the gravitational influence of the central black hole, the precessing rate decreases with radius, and the spirals are trailing, which reverses the sign of the torques, and the gas is driven in. This is a case recently observed with ALMA in NGC 1566 (Combes *et al.* 2014).

Torques have been computed in more than 20 nearby galaxies showing low-luminosity nuclear activity (Seyfert, Liners), with gaseous maps at high interferometric resolution, and forces computed with red images at HST resolution (e.g. Garcia-Burillo & Combes 2012, NUGA project). Suprisingly, only one third of galaxies show gas accretion at $\sim$ 100pc scale, due to a nuclear bar, or no ILR in the center. In two thirds of the sample, the gas is stalled in a nuclear ring, or driven outwards by the gravity torques. Given that all these galaxies should have accreted gas at some step of their bar cycle, this result coulbvbe interpreted as a typical galaxy like the Milky Way experiencung gas accretion at that scale only one third of its time.

3. Off-centring, lopsidedness and the example of M31

Closer to the center, and under the influence of the black hole (BH), orbits become quasi-keplerian. With some self-gravity, this can trigger special modes of densiy waves, with $m = 1$ symmetry, provoking an off-centring of the central mass. This mode allows the inner disk to lose angular momentum, and the gas to fall onto the central BH (cf Reichard *et al.* 2009). This $m = 1$ mode appears clearly in the center of our neighbor M31, which shows a double nucleus: two stellar components P1 and P2, P1 being the brightest.

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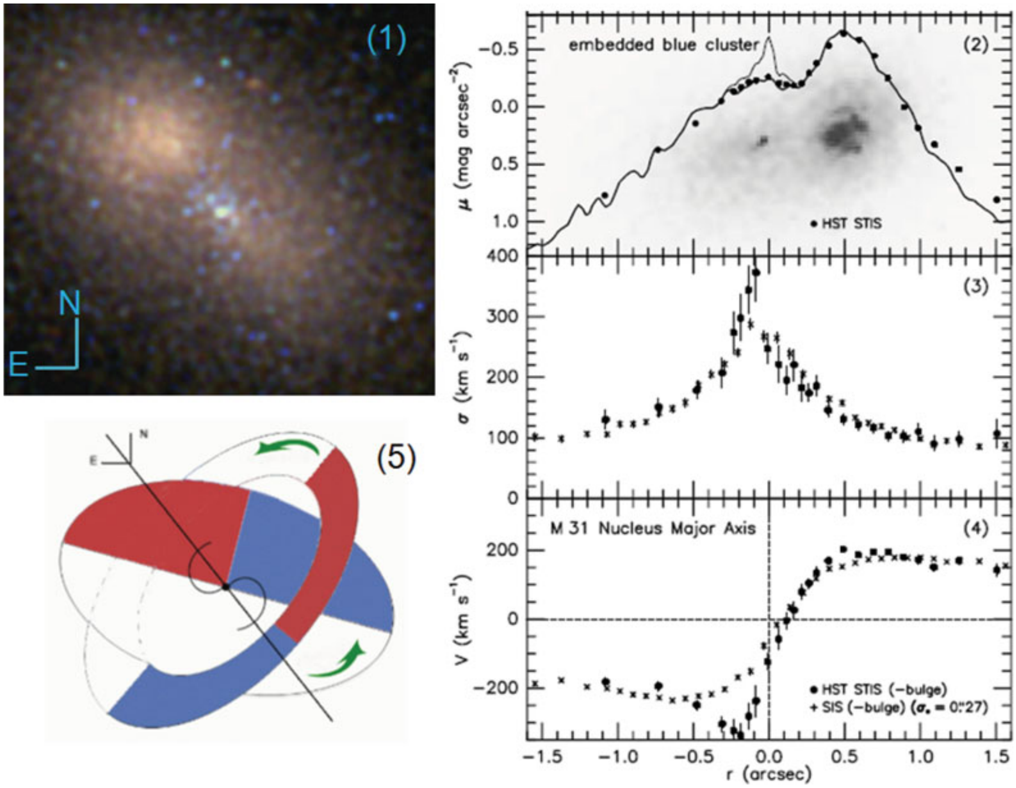

Figure 2. The nucleus of the most nearby spiral galaxy M31 (Andromeda) show features very similar to the Galactic center: (1) the nuclear stellar structure can be decomposed in three components: P1 and P2 with yellow/red color (P1 being the brightest at NE), and P3 closed to the very center, i.e. the supermassive black-hole, with blue color (from Lauer *et al.* 2012); (2) the radial profile of stellar surface density in red light (HST, thick line), and the peak of P3 visible only in ultraviolet (light line); (3) and (4) show the velocity dispersion and the radial velocity profiles, from Bender *et al.* (2005). The last panel (5) is a schematic interpretation of he molecular gas distribution, in different disks (Melchior & Combes 2011).

In fact, the P1-P2 ensemble is part of the same disk, which is lopsided and off-centered through the $m = 1$ mode (Bacon *et al.* 2001). The BH mass is 30 times higher than in our Galaxy, and the zone of influence wider. The nuclear stellar disk has a typical size of 10pc in diameter. The excentric disk model was shown to reproduce the observations, both by a mass-less experiment (Peiris & Tremaine 2003), and a self-consistent N-body model (Bacon *et al.* 2001). The $m = 1$ pattern speed is 3km/s/pc, and the life-time of the wave is at least 3000 rotations. This configuration was shown to be able to drive the angular momentum away (Saha & Jog 2014).

More recently, it was shown in the ultraviolet that a third stellar component, P3, dominates close to the BH. Contrary to P1-P2 which is an old-stellar disk, P2 is a blue young population, corresponding to a 200 Myr old starburst. Figure 2 shows the light distribution along the major axis, together with the velocity dispersion, indicating that P3 corresponds to the BH position, and the asymmetric velocity profile. P3 is a small stellar cluster, of typical size 0.4pc, with a different orientation (inclination, position angle) from the P1-P2 disk. Like in our Milky Way, showing at least two nuclear stellar disks with two different orientations. As far as the molecular gas is concerned, two different disks are also observed (Melchior & Combes 2011).

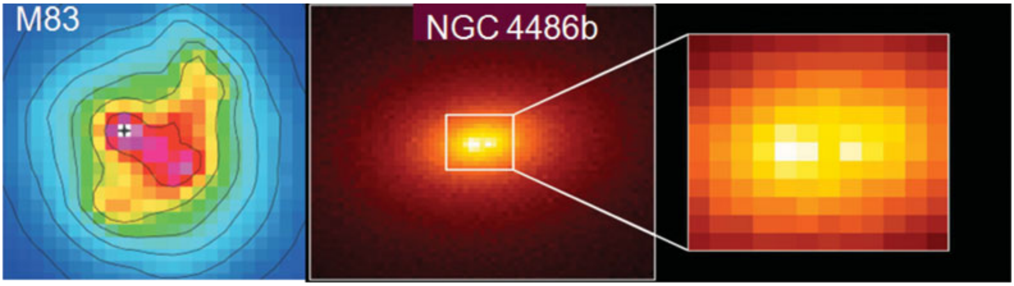

Figure 3. Left: The nucleus of Messier 83, seen in the near-infrared at 3.6 μm, showing a pronounced lopsidedness (Knapen *et al.* 2010). **Right:** HST image of NGC 4486b, showing a double nucleus similar to M31 (Lauer *et al.* 1996).

The existence of a 10Myr young stellar disk (of size 0.4pc) in our Milky Way has raised the paradox of youth (e.g. Genzel *et al.* 2010). To form stars, a gas cloud is required to be dense enough to resist the strong tidal force, which leads to 6 10^{10} cm^{-3} at a radius of 0.1pc, but the gas observed is far from this density. This paradox has led to several hypotheses, like inwards migration of the star cluster after formation far from the center, or stars rejuvenated by collisions. But the most likely is the formation in a dense disk, in situ.

For M31, the same paradox is raised. How could the 200Myr young P3 cluster have formed? The stellar cluster has a surprisingly high compactness (radius 1pc), and cannot come only from BH-stripped giants. It must be possible to form stars in the strong tidal field of the 10^8 $M_\odot$ BH. The migration scenario is even less likely than in the GC, since the mass of the BH is much higher.

A scenario has been proposed by Chang *et al.* (2007). Some gas is released by stellar mass loss from the P1+P2 disk. The latter is experiencing an $m = 1$ mode, with a pattern speed $\sim$ 3-10 km/s/pc. This fixes the size of P3. Outside a certain radius, the gas clouds participating to the $m = 1$ wave are located on crossing orbits, which creates dissipation and infall, until a radius of $\sim$ 1pc. The radius of P3 is thus the last non-crossing orbit. The gas mass available for P3 is about 10^5 $M_\odot$, compatible with the mass loss from a disk P1+P2 of 10^7 $M_\odot$. The stellar mass loss rate of 10^{-4} $M_\odot$/yr fills P3 in about 500Myr. This scenario should produce repeated star bursts, at that frequency.

The $m = 1$ wave and off-centring exists also in our Galaxy. The well-known asymmetry of the molecular parallelogram in the l-v diagram means that 3/4th of the gas mass is at positive longitude, and 1/4th at negative longitude. The phenomenon of lopsided disk is also frequently observed in external galaxies, when there is sufficient spatial resolution: for instance M83 and NGC 4486b (see Figure 3, Thatte *et al.* 2000; Knapen *et al.* 2010, Lauer *et al.* 1996) or also VCC128, showing a double nucleus (Debattista *et al.* 2006).

4. Disks with different orientations

In M31 as well as in our Galaxy, nuclear disks have a different orientation than the main disk, and also there can exist several different nuclear disks. How can they form? During a high-resolution simulation of a Milky-Way-like galaxy, such a phenomenon has been observed (see Figure 4). The bar gravity torques progressively drive the gas inwards. After some time, the gas accumulation in the center triggers a mini-starburst, and the associated supernovae feedback ejects some gas perpendicular to the plane. The latter can fall down in random directions, with different orientations. In the simulation, the gas

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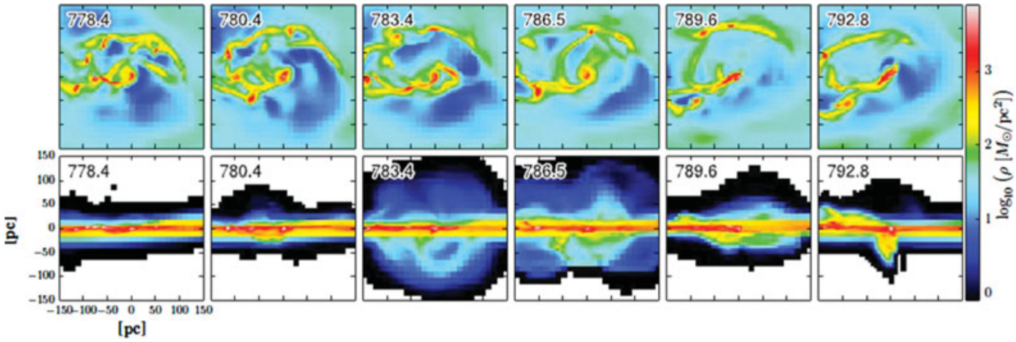

Figure 4. N-body and hydrodynamical simulations of a Milky-Way like galaxy, developing a bar, and showing gas inflow towards the center. When the gas has sufficiently accumulated, the consequent starburst and feedback associated have ejected gas above the plane, which falls back in a fountain. It settles in a polar plane, which may explain the various orientation of gas and stellar disks in galaxy nuclei (from Renaud *et al.* 2015 and Emsellem *et al.* 2015). The top row shows 6 snapshots face-on, and the bottom row edge-on, from 778 Myr to 792 Myr.

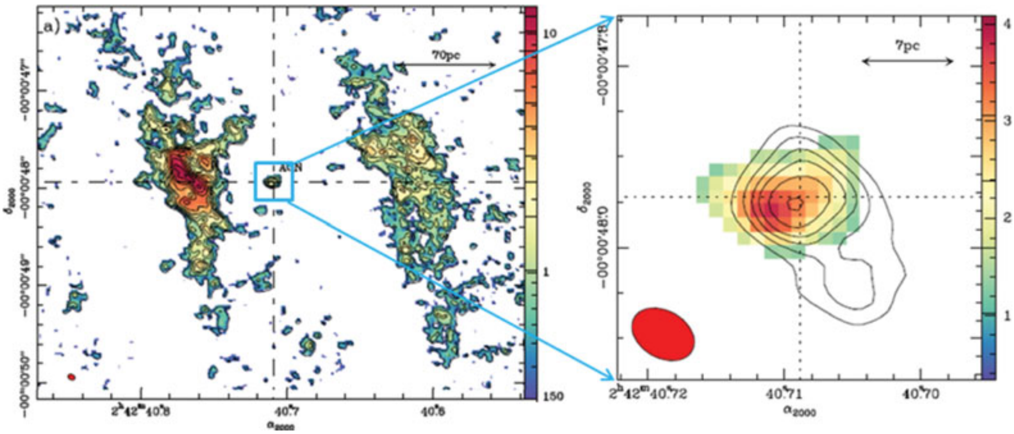

Figure 5. Left: ALMA CO(6-5) map of the nucleus of NGC 1068, showing the circum-nuclear disk (CND) of ∼300pc scale, and the off-centered molecular torus around the AGN. **Right:** Zoomed view of the torus, with the CO(6-5) emission in colors, and the dust emission in contours. From Garcia-Burillo *et al.*(2016).

settled in a polar ring, the only orientation stable with respect to differential precession. Certainly many other orientation can occur in the real world.

The non-alignment of nuclear disks with the host disk is frequent, as shown by radio jets which are not perpendicular to their main disks (e.g. Schmitt & Kinney 2002, Jog & Combes 2009). In NGC 4258, the maser disk of 0.2pc in size, is misaligned by 119° from its galaxy disk, and the radio jet grazes the plane. This is also the case in NGC 1068 (Garcia-Burillo *et al.* 2014). The spatial resolution brought by the ALMA interferometer allows to distinguish molecular tori in nearby galaxies. In NGC 1068, the CO(3-2) torus appears more inclined than the water maser disk, and subject to the Papaloizou-Pringle instability (see Figure 5).

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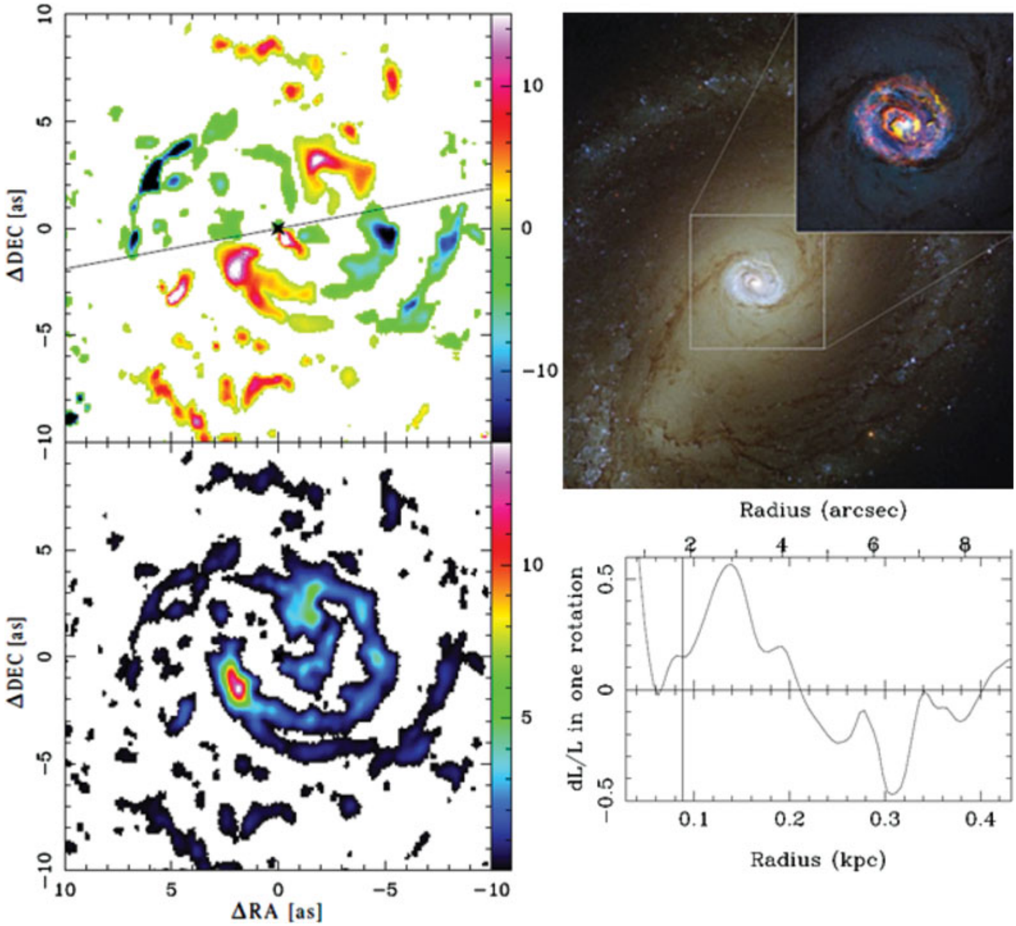

Figure 6. Top right: CO(3-2) ALMA map of the nuclear disk in NGC 1433, superposed to the optical image (Combes *et al.* 2013). The deprojected molecular map is reproduced at the **bottom left**, and the derived torque map is at **top left** (Smajic *et al.* 2014). The torques change sign as expected in a four-quadrant pattern (or butterfly diagram), following the nuclear bars orientation (full line). **Bottom right:** relative loss of angular momentum per rotation, versus radius, in the the galaxy NGC 1433. The gas is stalled in a 200pc ring (the central 50pc is perturbed by a molecular ouflow).

5. Intermittent feedback and quenching

The fueling of gas towards the inner regions has been studied through zooming re-simulations by Hopkins & Quataert (2010a,b). The gas is driven inwards successively by a cascade of non-axisymmetries, first by $m = 2$ waves, and then $m = 1$. At small scales, clumps and turbulence cancontribute, through dynamical friction, and viscous torques. Gas is indeed piling up into the center, but intermittently. The time fluctuations reproduce themselves self-similarly at various scales, in a fractal behaviour. Even when driven by a bar, the gas flow is intermittent, moderated by the feedback. It is then expected that activity periods are also intermittent, as observed in the Milky Way for instance.

Feedback can occur also in low-luminosity AGN, like in the Seyfert 2 galaxy NGC 1433 (see Figure 6). The torques inside the nuclear ring are positive, and the gas is stalled there, at $\sim$ 100pc scale. Inside, at 10pc scale, a molecular outflow is detected on the

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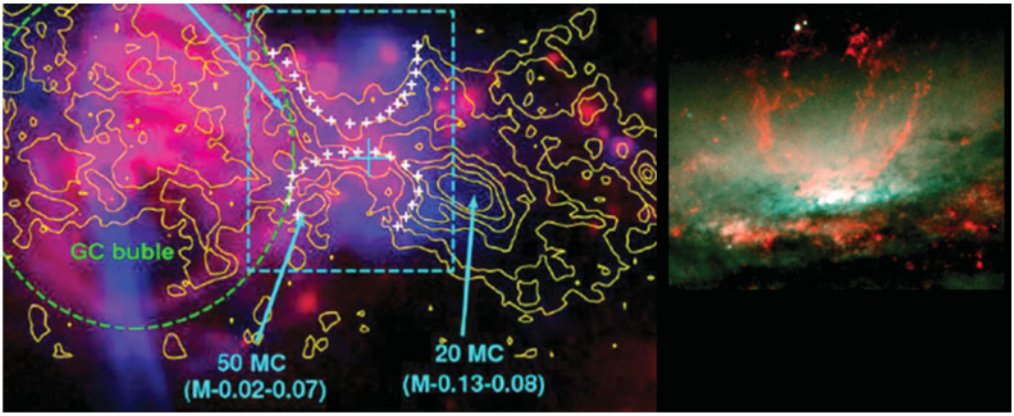

Figure 7. Left: Evidence of a past explosion close to the Galactic center, with two opposite flows of ionized gas (from Hsieh *et al.* 2016). **Right:** Comparison with the tulip-like bipolar outflow in NGC 3079 (Cecil *et al.* 2001).

minor axis, corresponding to 7% of the mass. This is the smallest outflow rate detected in a nearby galaxy.

In the Milky Way, there is several pieces of evidence of past activity, stopped by feedback. Bubbles have been detected in gamma-rays with Fermi, extending 10 kpc above and below the plane (Su *et al.* 2010). These bubbles correspond also to synchrotron emission in cm and mm wavelength (WMAP, Finkbeiner 2014). Radio emission with Parkes-64m has been detected by Carretti *et al.* (2013). These bubbles might have been created by supernovae feedback. Hsieh *et al.* (2016) have recently found evidence of a past explosion through a typical bipolar morphology of the ionized gas (see Figure 7). The time-scale derived is of 0.5 Myr. This corresponds to the hour-glass shape defined by the CS emission, and the polar arc is in the alignment.

6. Conclusions

The dynamical processes in the Milky Way can be derived by analogy of those occuring in nearby galaxies. At large-scale, the primary bar drives gas inwards from 10kpc to R $\sim$ 100pc. Then a possible nuclear bar can continue the action from 100pc to 10pc. Statistically, gas is driven in about one third of the time, in the life of the galaxy.

At scales 1-10pc, other processes, invoking viscous turbulence, clumps, warps, bending, dynamical friction, formation of thick disks/torus, will fuel the center, when there is gas. Under the black hole influence, the $m = 1$ instabilities are frequent in nuclear stellar disks.

The gas fueling is moderated by feedback, either from supernovae or the active nucleus. Activity periods are intermittent, and a majority of the time, the nuclear region is quenched, as is the Milky way today.

The gas ejected by the feedback outside the plane, can fall back in random orientations. There are frequent mis-alignment between small scales and large scales disks. The decoupling of the various scales is also expected, due to different dynamical time-scales.

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