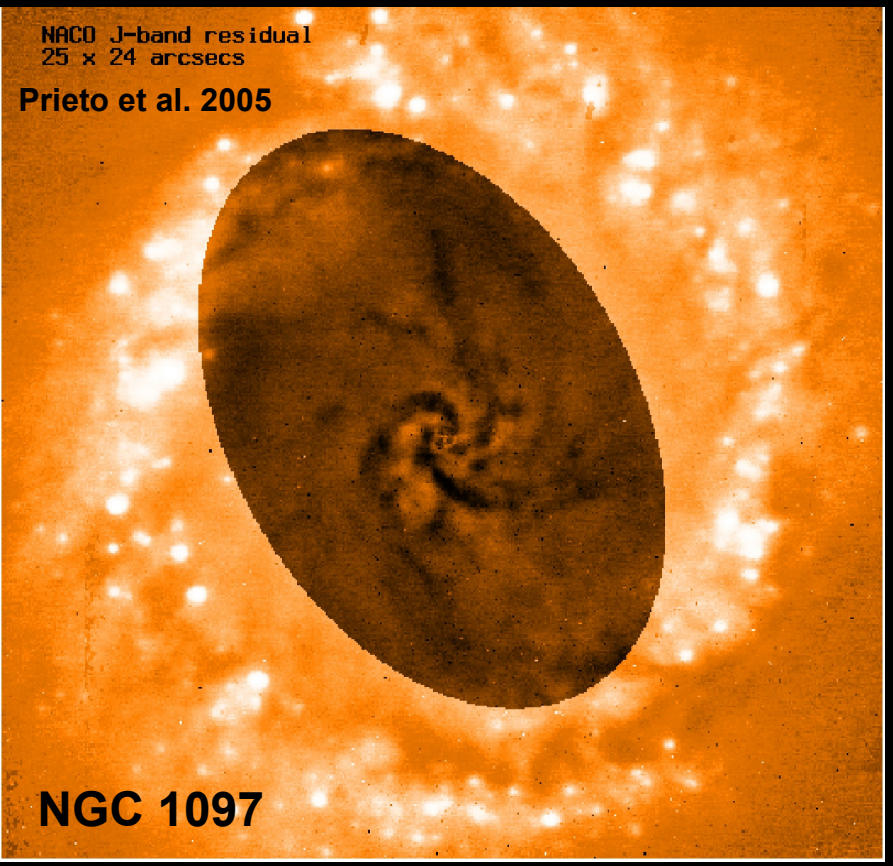
Feeding the central black hole and nuclear starbursts: gas inflow in nuclear spirals



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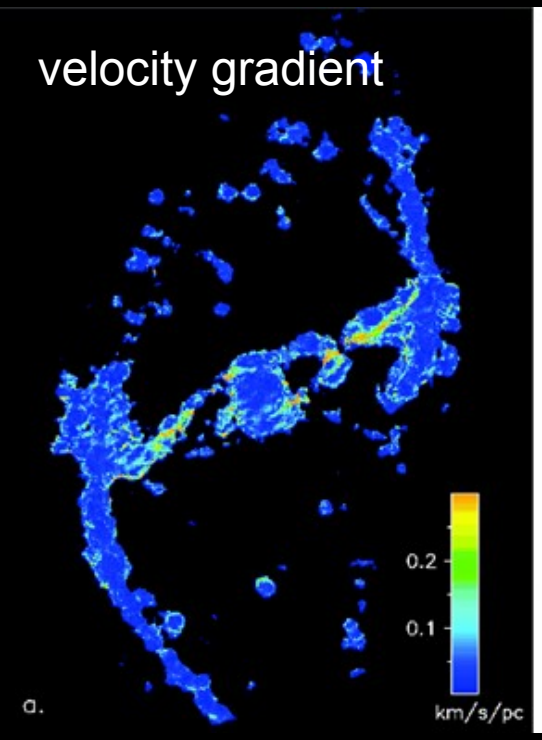
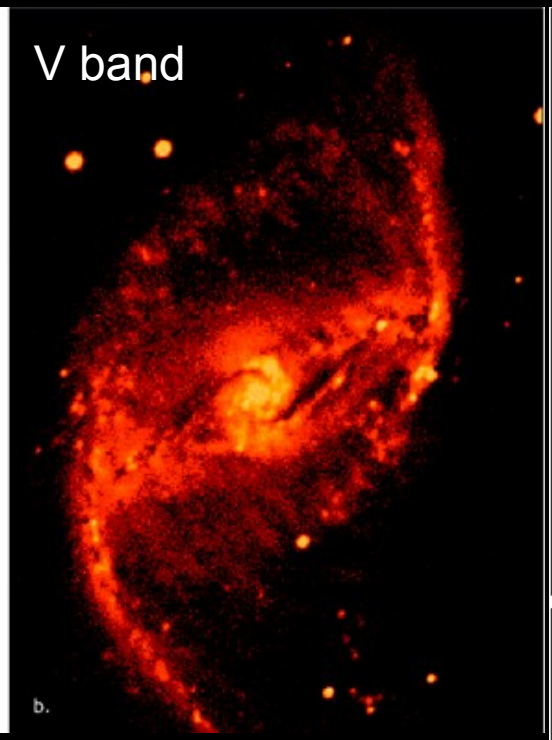
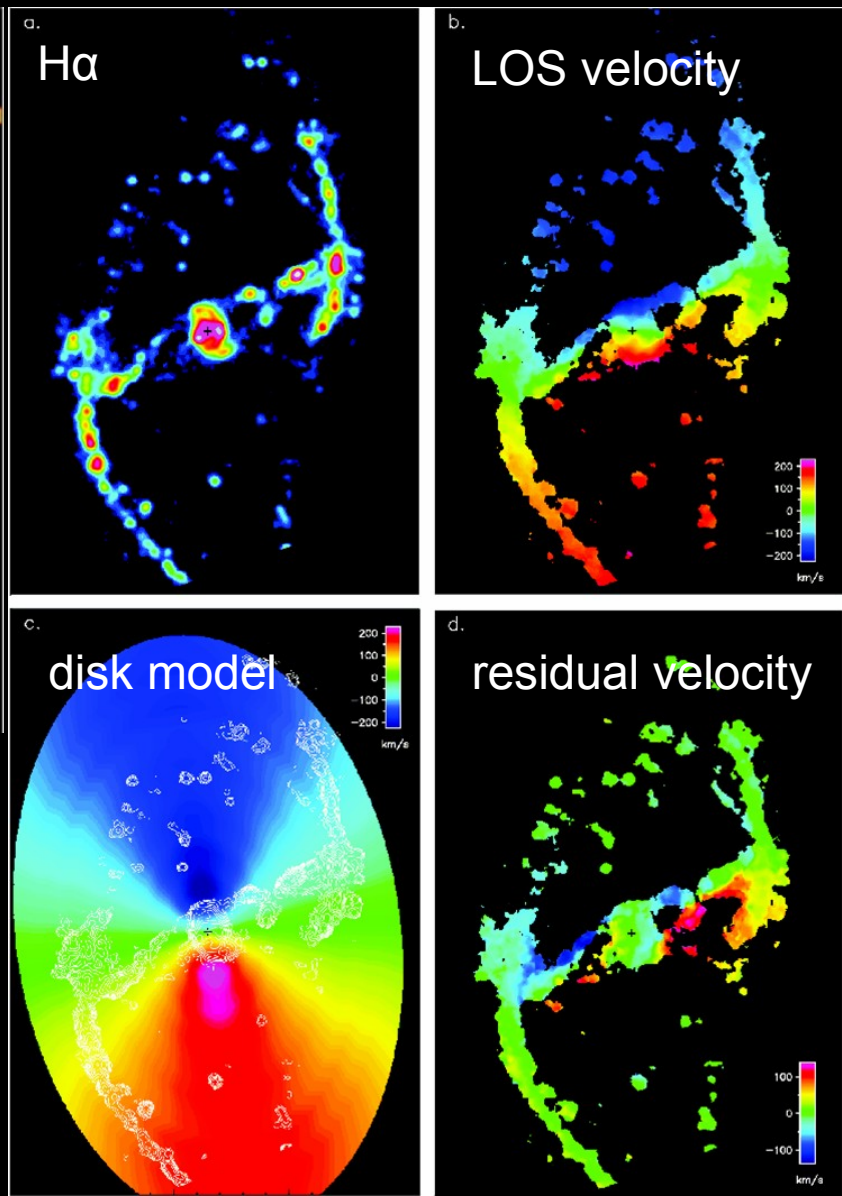
Bars as efficient drivers of inflow on large scales





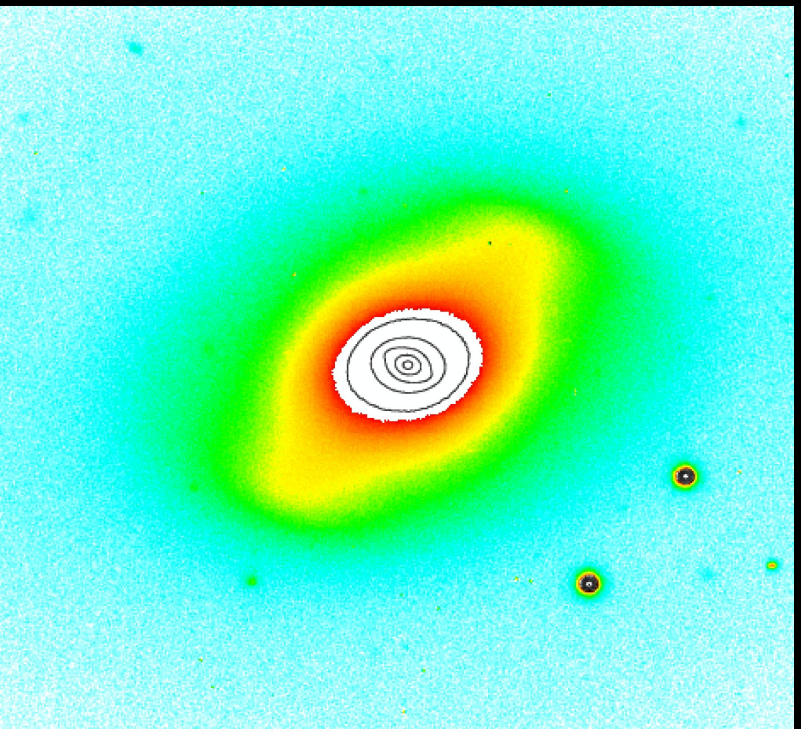


NGC 1530

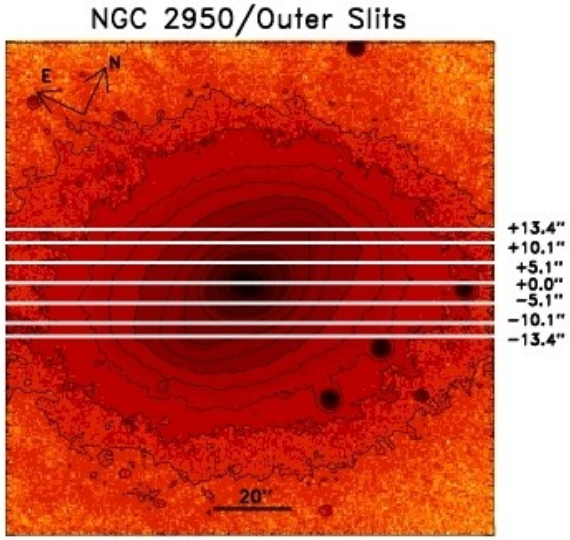
Zurita et al. 2004

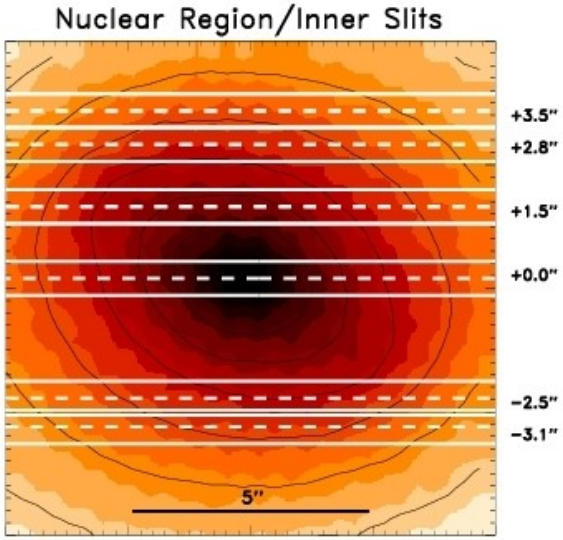
- but inflow stagnates in the innermost kpc

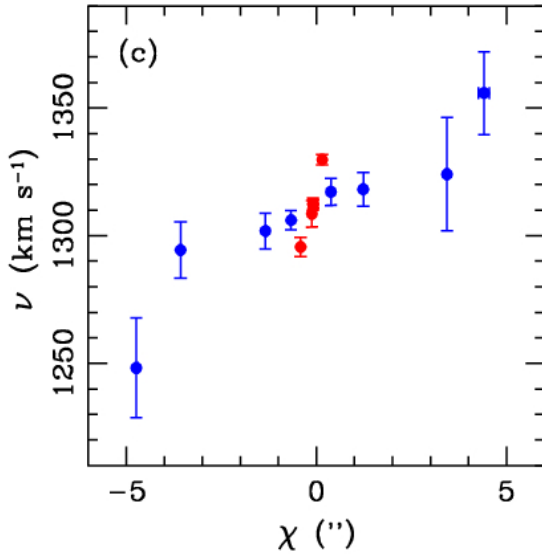
Possible drivers of inflow in the central kpc: I. Nuclear bars



- 25-30% of barred galaxies host nested bars *(Erwin & Sparke 2002, Laine et al. 2002)*
- the two bars rotate with different angular velocities *(Corsini et al. 2003)*
- but it remains unclear whether nested bars can drive gas inflow







Possible drivers of inflow in the central kpc: II. Nuclear spirals

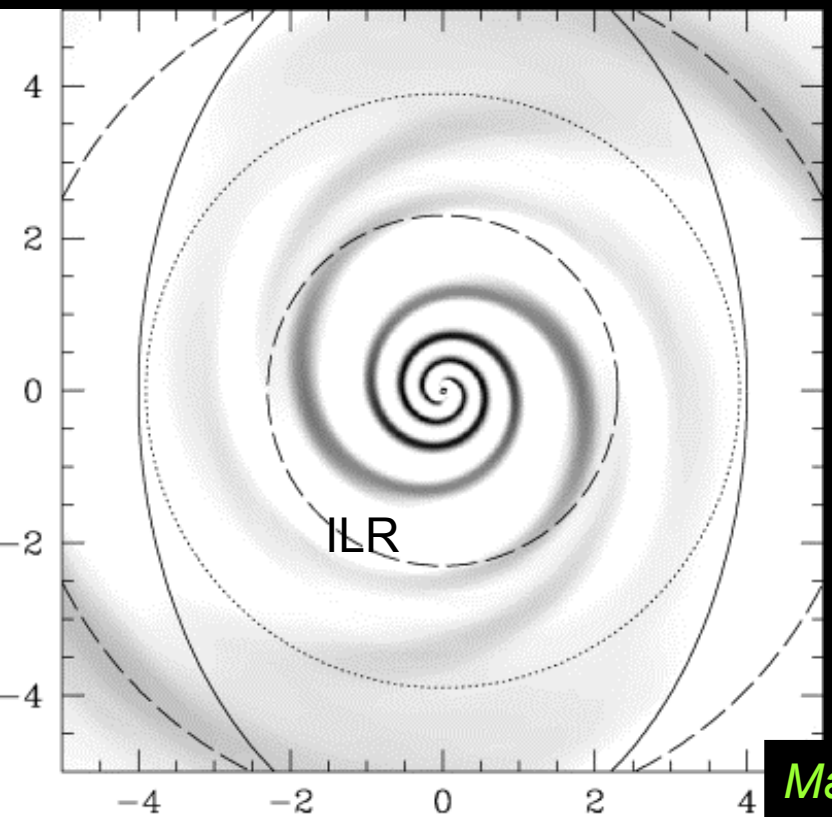
Linear dispersion relation for waves in a disc:

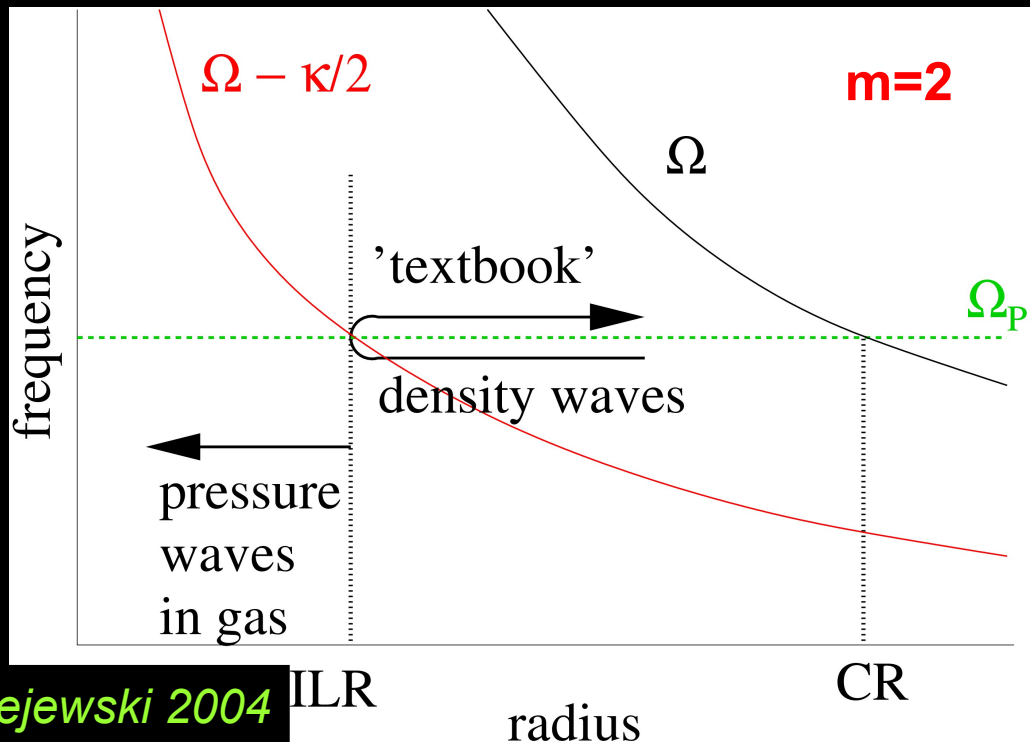
$$m^2(\Omega - \Omega p)^2 - \kappa^2 - k^2c^2 + 2\pi G\, F\, |k|\, \rho = 0$$

rotation curve — gas pressure — self-gravity

$$(\Omega + \kappa/m - \Omega p)\,(\Omega - \kappa/m - \Omega p) = (kc/m)^2 > 0$$

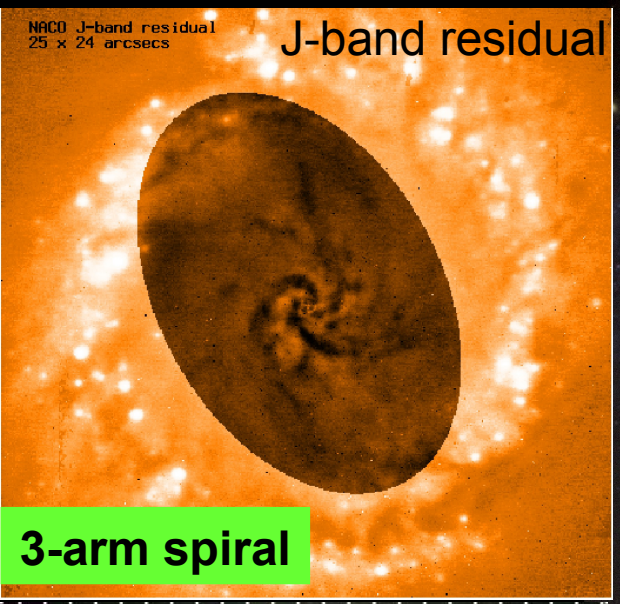
$$= -\,2\pi G\, F\, |k|\, \rho / m^2 < 0$$

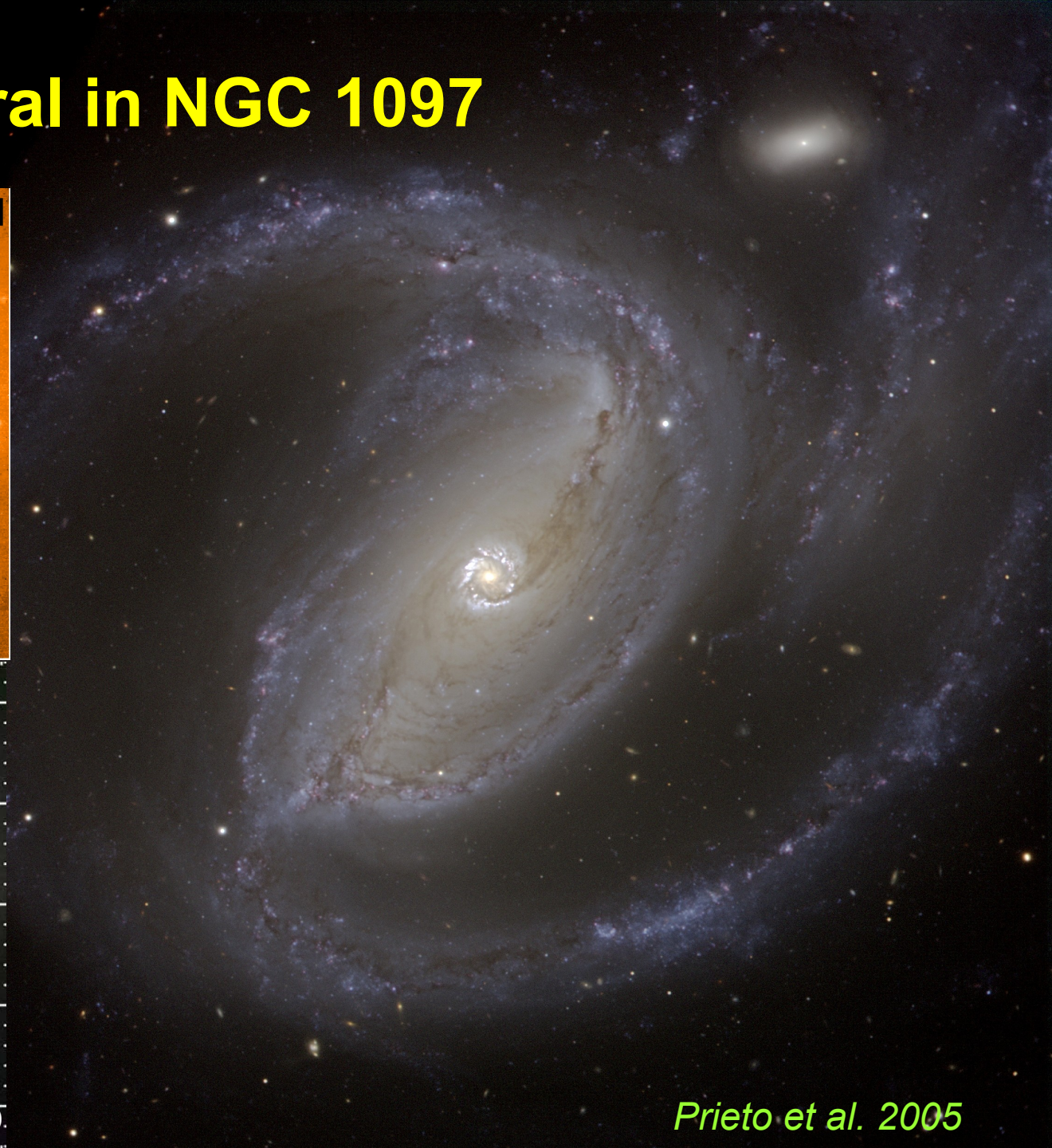




Maciejewski 2004

Nuclear spiral in NGC 1097

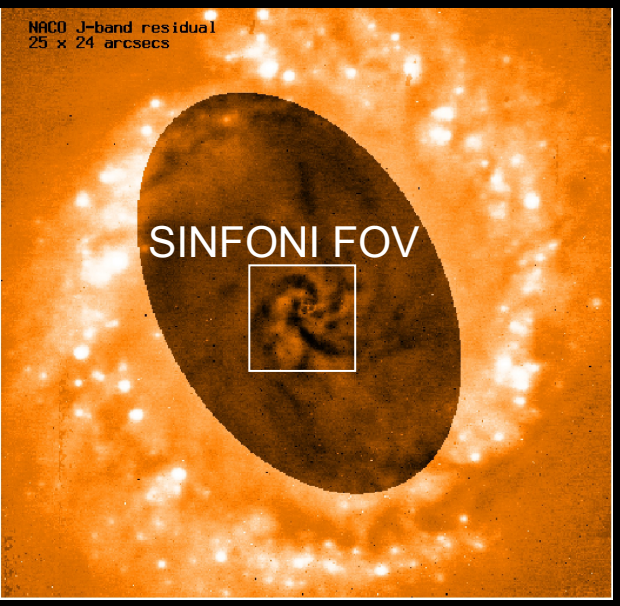


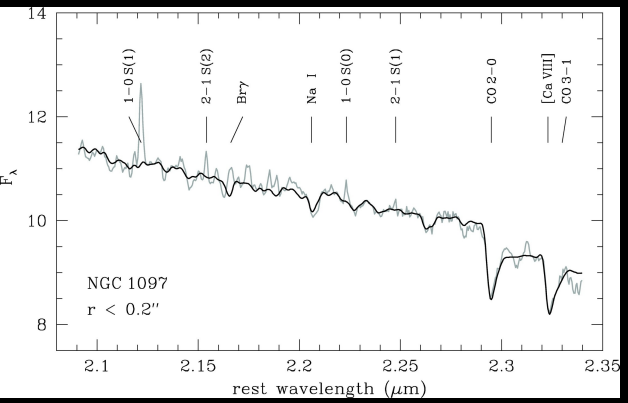


Prieto et al. 2005

SINFONI observations of NGC 1097

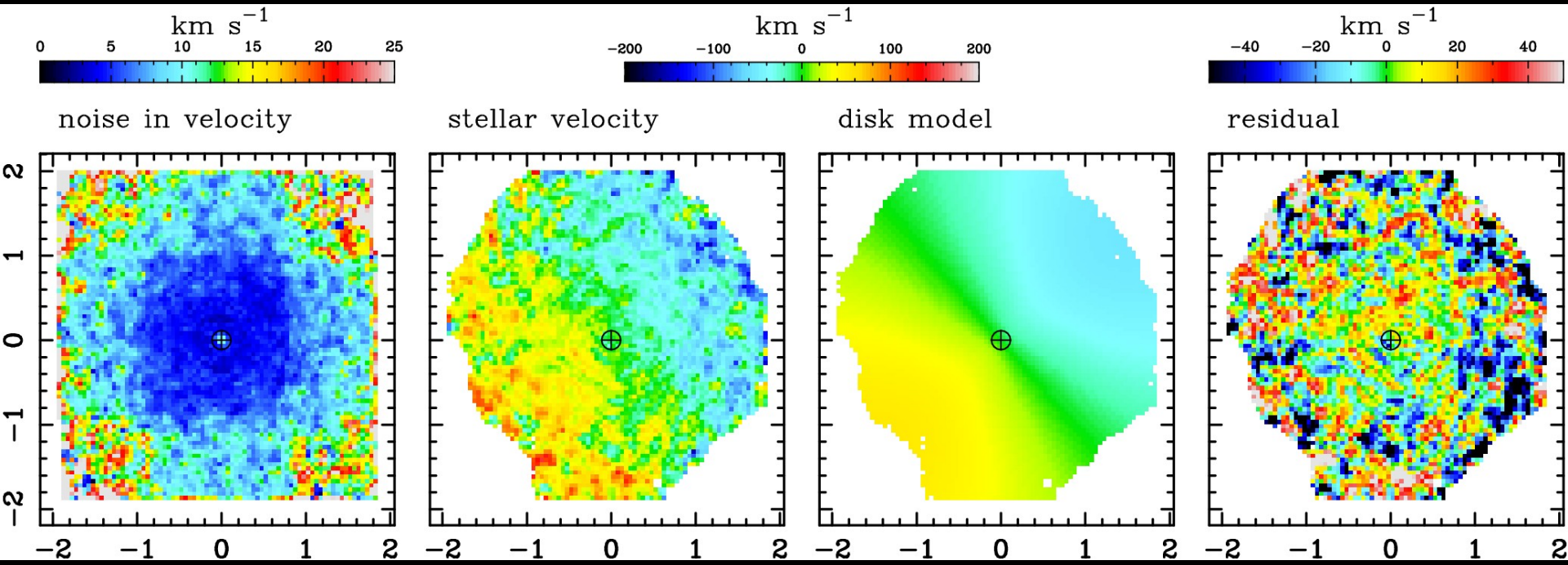
(Davies, Maciejewski, Hicks et al. 2009)





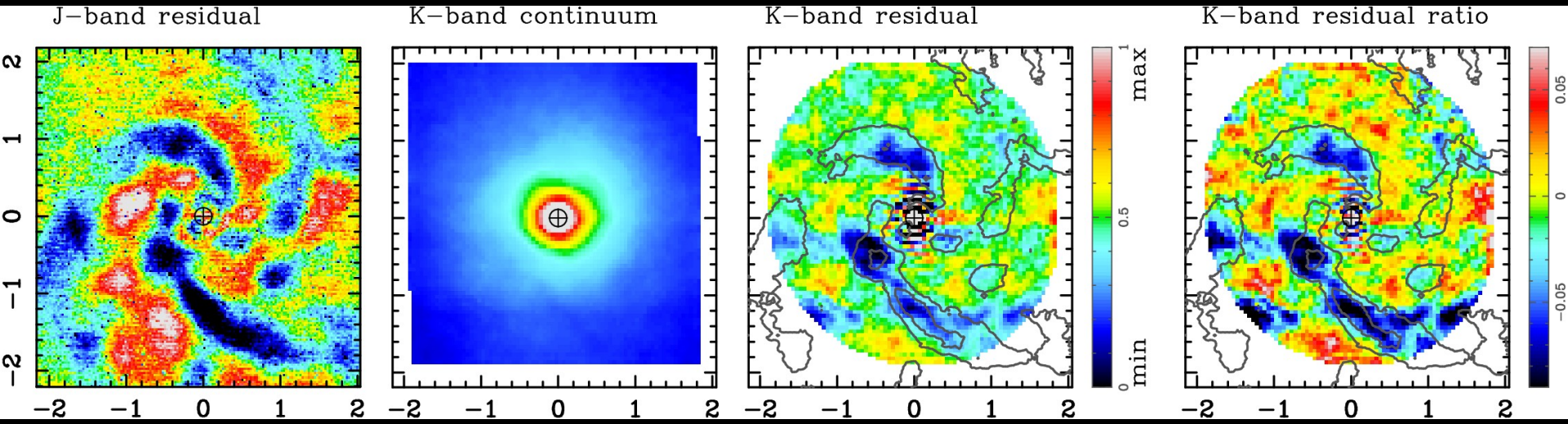
- SINFONI: AO NIR IFU (integral field unit) at the VLT, 4”x4” FOV
- data taken with the H+K grating, R~1500 resolution
- pixel scale: 0.05”x0.1” observed, 0.05”x0.05” of processed data cube
- total on-source integration time 40 mins
- PSF fitted with a Moffat function yield a K-band (non-stellar continnum) FWHM of 0.25” with 75% of the flux within the ‘core’
- kinematics of absorption and emission lines derived with LINEFIT *(Davies et al. 2009 & in prep)*

Stellar kinematics

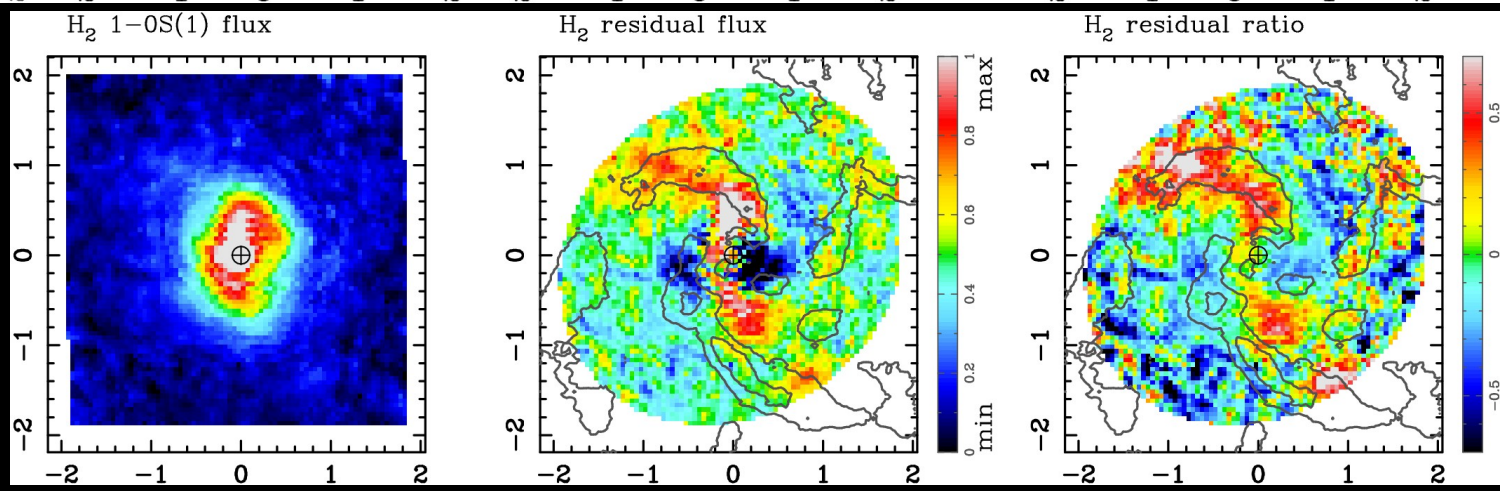


- subtracting from stellar velocity a simple axisymmetric disc model (DYSMAL code, *Cresci et al. 2009*) gives residual velocity
- no coherent structure in residual velocity – no peculiar bulk motions of stars in bulge and disc
- stellar velocity dispersion σ~150 km/s > v_circ

Absorption in continuum and molecular emission



NACO



2.12 μm 1-0 S(1) H2 emission line traces warm molecular gas

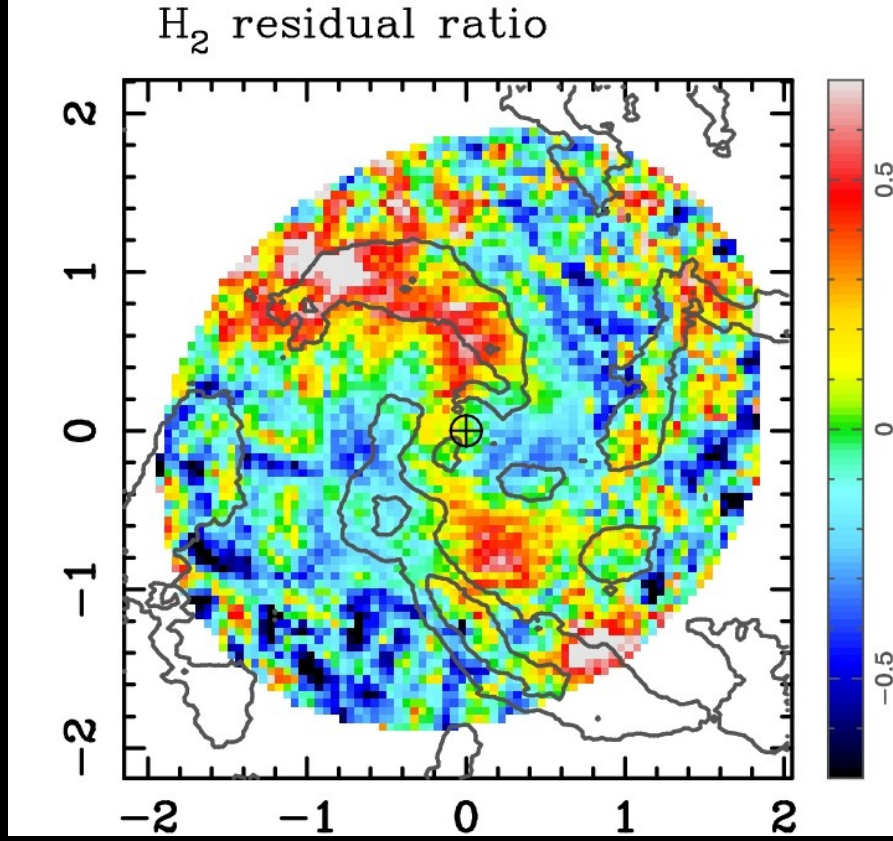
- same 3-arm spiral structure in NACO J-band residuals and SINFONI K-band residuals
- low continuum coincides with H2 emission → absorption

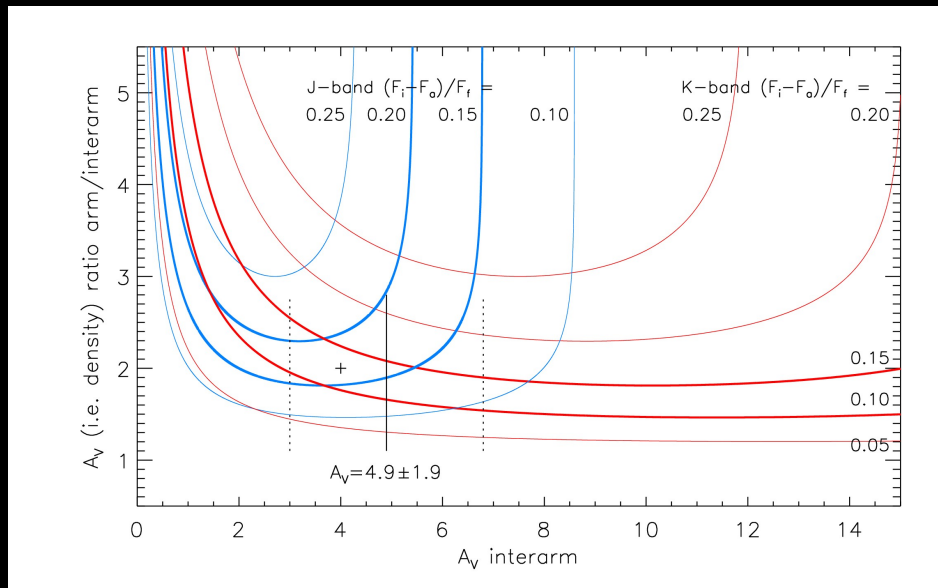
- brightest H2 emission along the inside edge of the negative stellar residuals (gas entering the arm heated in the shock?)
- molecular spiral of arm-width 0.4” can be traced to within 0.2” of the centre (resolution limit)
- extinction Av = 4.9 ± 1.9 from comparing K-band slope with stellar templates (screen approximation)
- extinction in the arm Av = 8.0 ± 2.3 with arm/interarm extinction ratio 2.0 ± 0.3 from J- and K-band contrasts
- gas surface density

  140 ± 40 Msun/pc² in the arms and

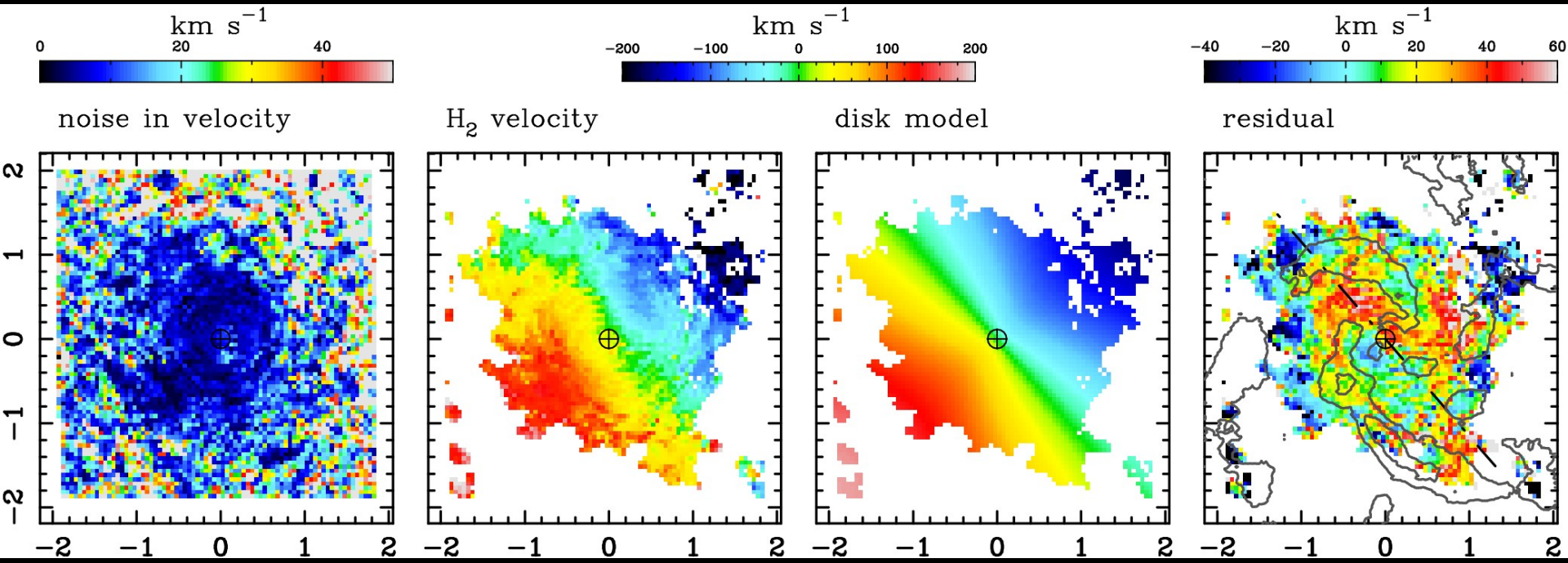
  70 ± 17 Msun/pc² between arms

  up to 4x smaller than CO estimates

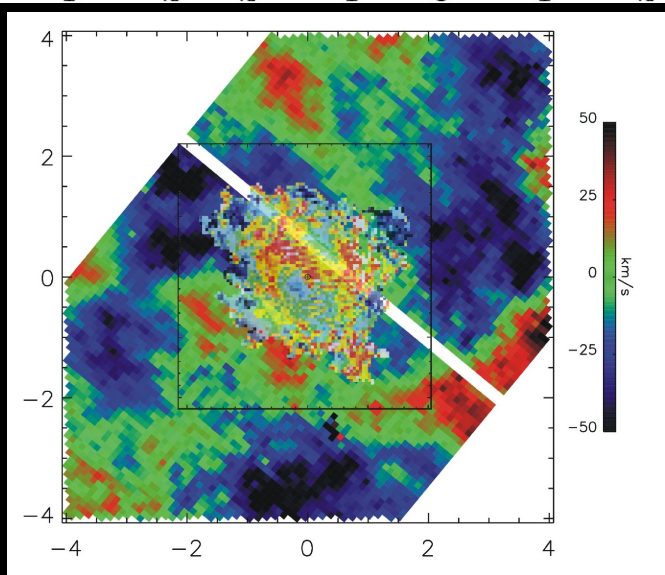




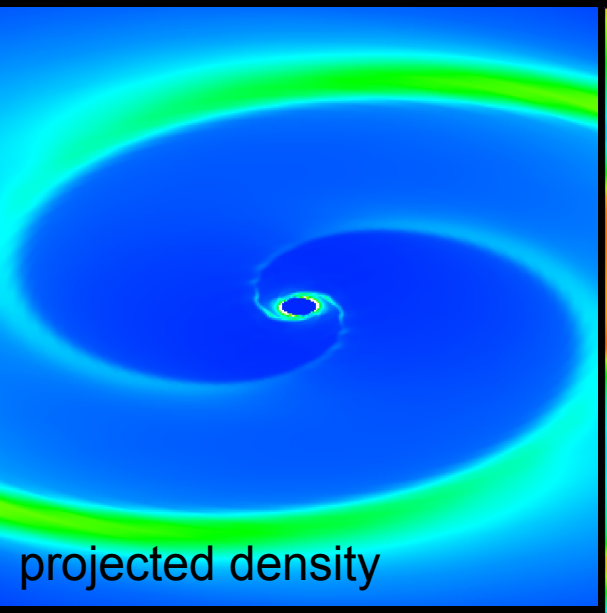
H2 kinematics

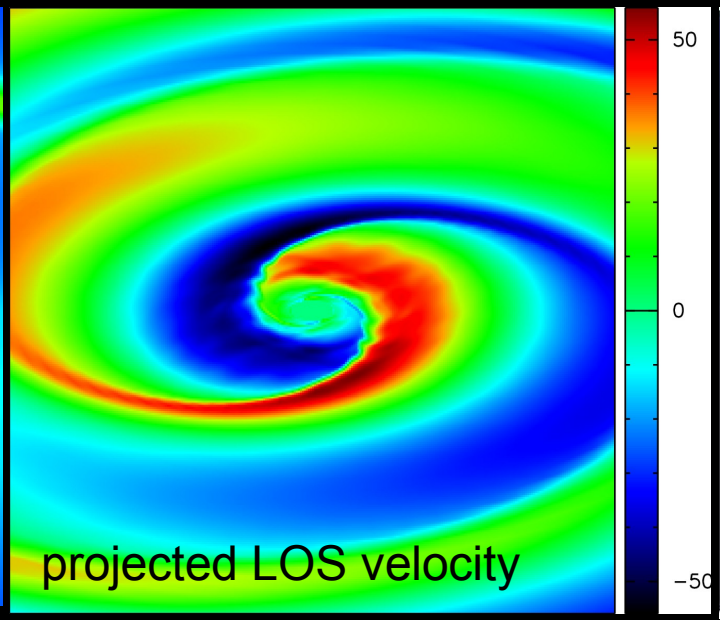


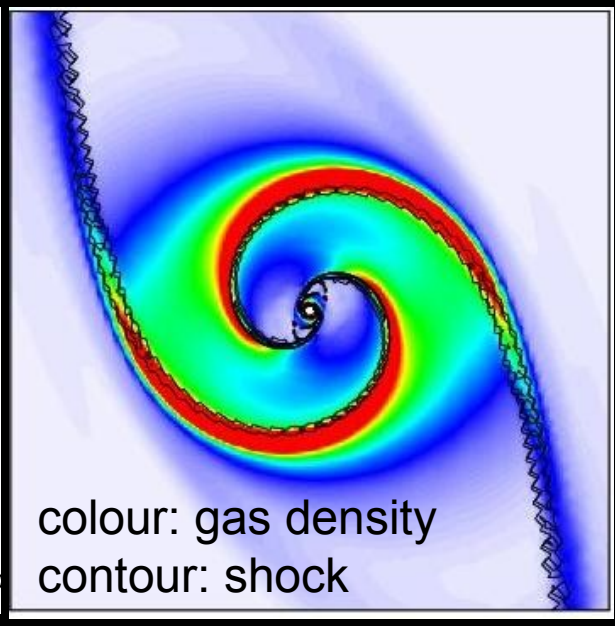
- subtracting disk model (fixed PA & axial ratio) from H2 velocity gives residual velocity
- 2-arm kinematic spiral in residual velocity, projected amplitude 40 km/s
- consistent with ionized gas kinematics traced by [NII] emission (GMOS, *Fathi et al. 2006*)



Kinematics and dynamics of spiral density waves

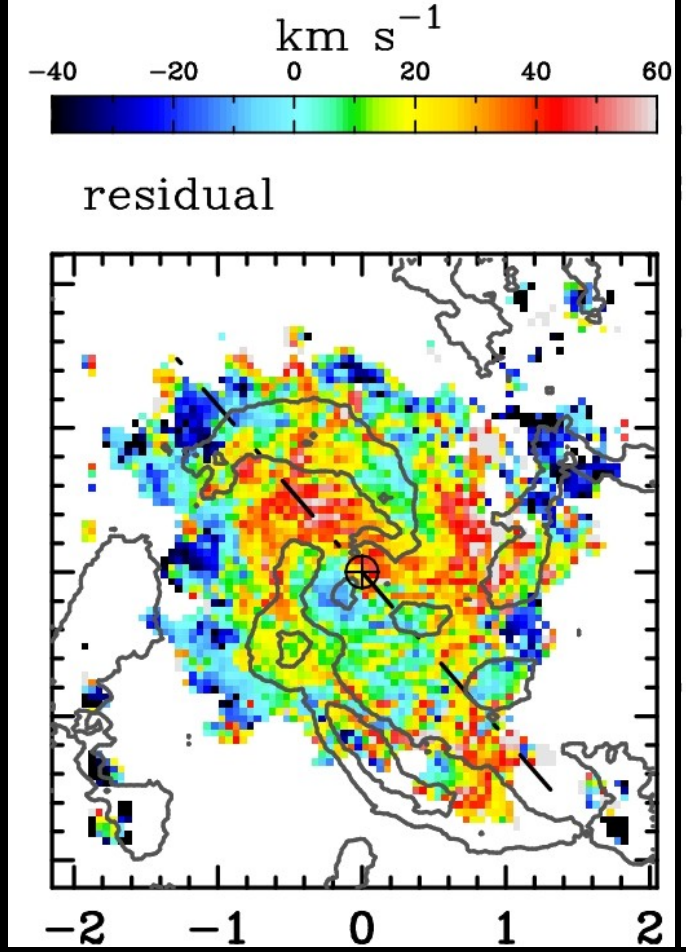


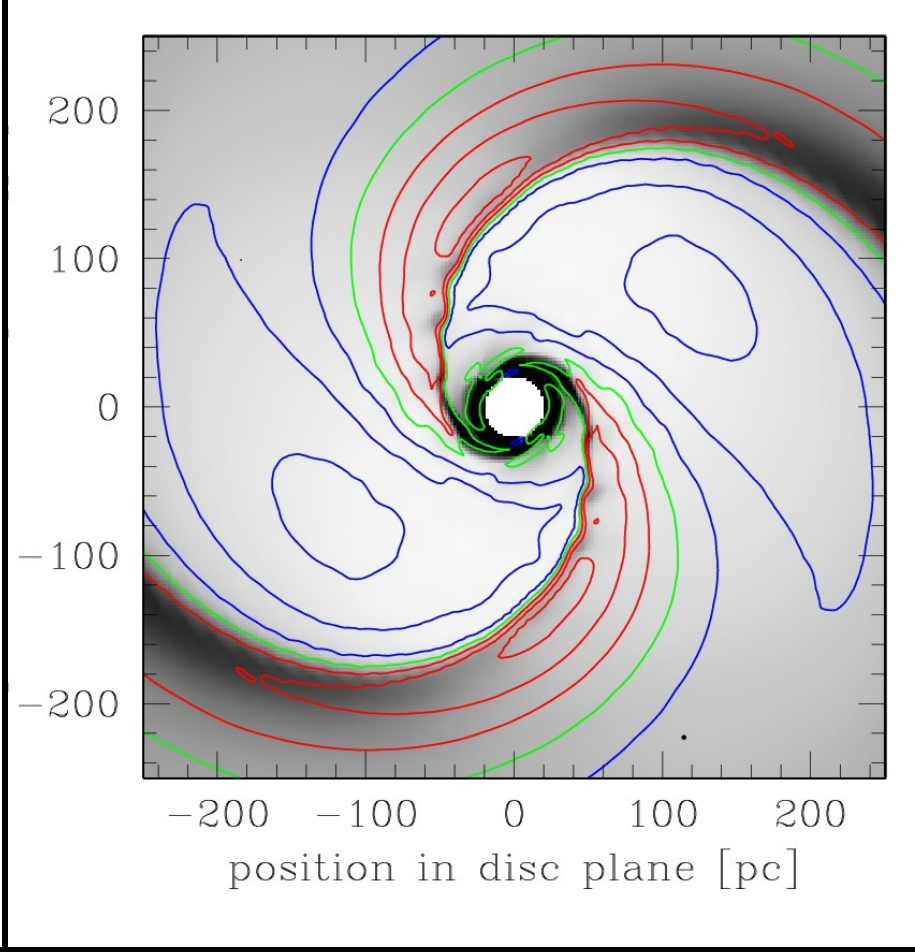




- velocity residuals of an m-arm spiral take shape of (m-1)-arm spiral inside corotation *(Canzian 1993)*
- gaseous inner disk in NGC 1097 gravitationally stable → the spiral most likely pressure wave driven by bar or other mass asymmetry
- intrinsic velocity dispersion in H2: 30-45 km/s; intrinsic amplitude of radial motion: 75 km/s → **spiral is a shock in gas**
- shock on the inside of the arm in models of nuclear spiral shocks *(Maciejewski 2004)*

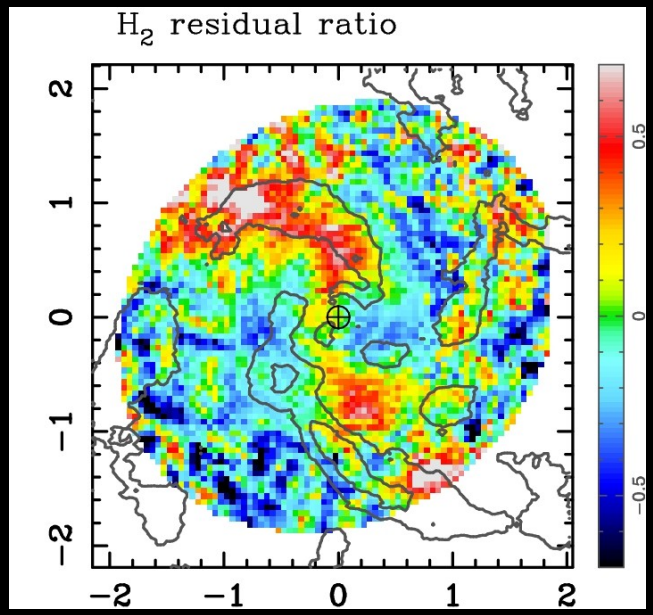
Gas inflow in nuclear spiral shock

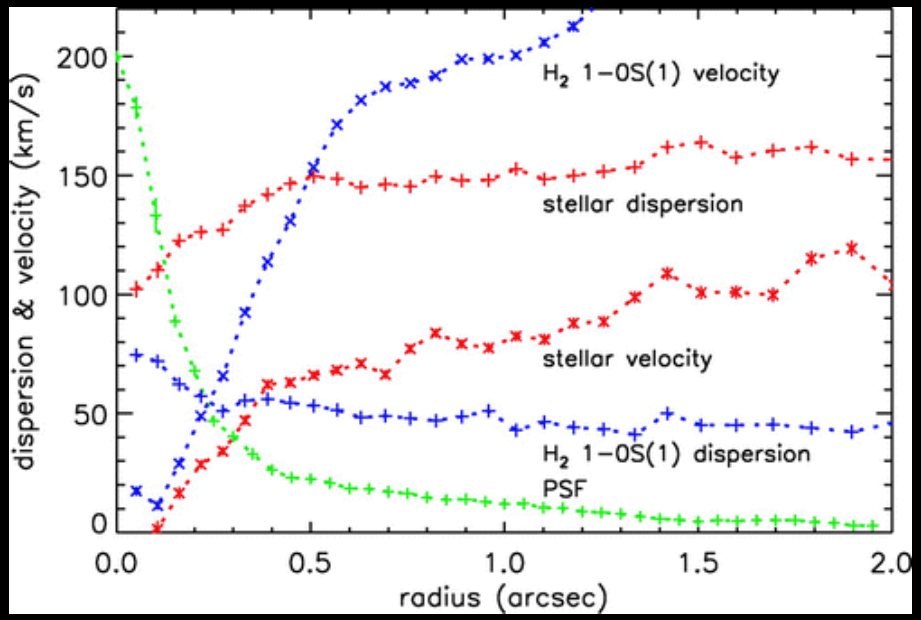




- naive estimate of inflow from molecular gas density and radial velocity: 1.23 ± 0.35 Msun/yr – LARGE!
- models show that inflow in the arms balanced by outflow between the arms
- in the model most similar to gas kinematics in NGC 1097 the inflow is 0.1 Msun/yr while the naive estimate gives 2 Msun/yr
- after correction, the net inflow in the nuclear spiral in NGC 1097 is ~0.06 Msun/yr

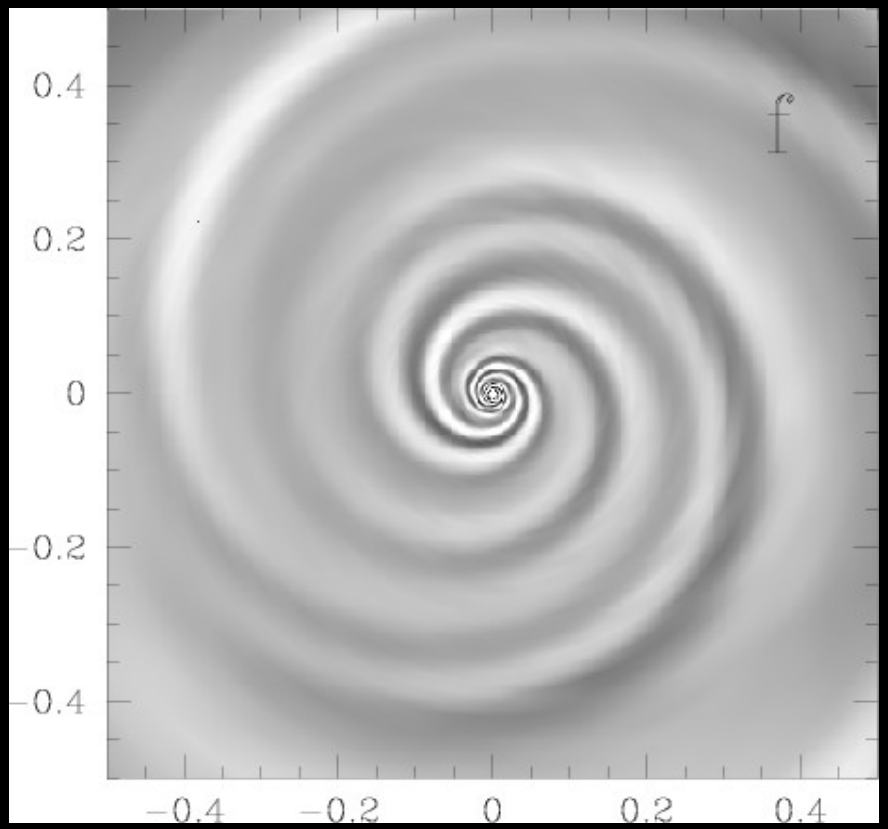
Inside the 0.2” or 17 pc radius



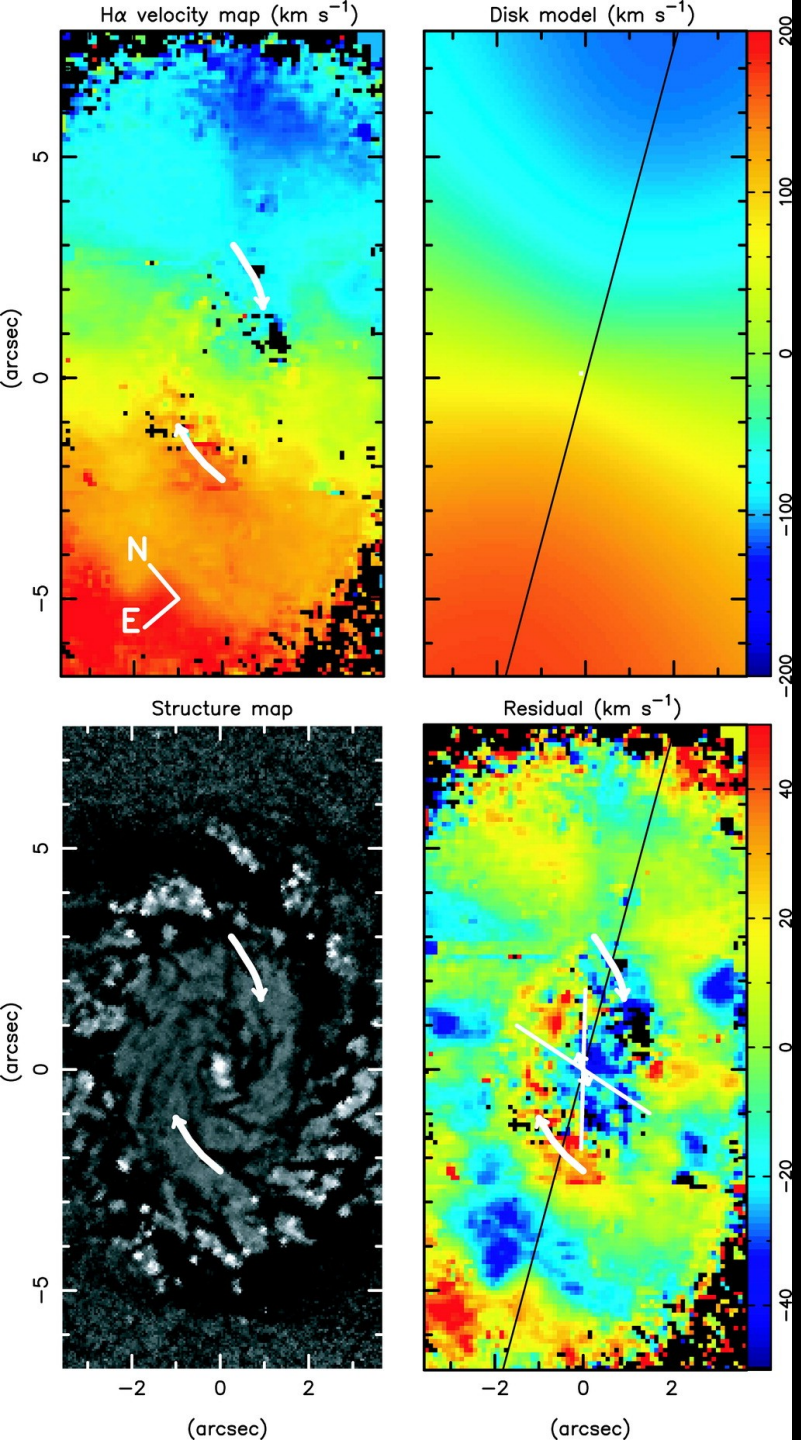


- gas velocity dispersion exceeds its rotation velocity – disk approximation no longer valid
- nuclear starburst *(Storchi-Bergmann et al. 2005, Davies et al. 2007)* → nuclear spiral feeds gas reservoir that gives rise to nuclear starburst?
- 0.06 Msun/yr inflow rate consistent with the mass (10^6 Msun) and age (8 Myr or less) of starburst
- at this rate, ~2 Gyr is needed to drain all gas inside the nuclear ring → nuclear spiral in quasi-equilibrium (refilling from nuclear ring?)

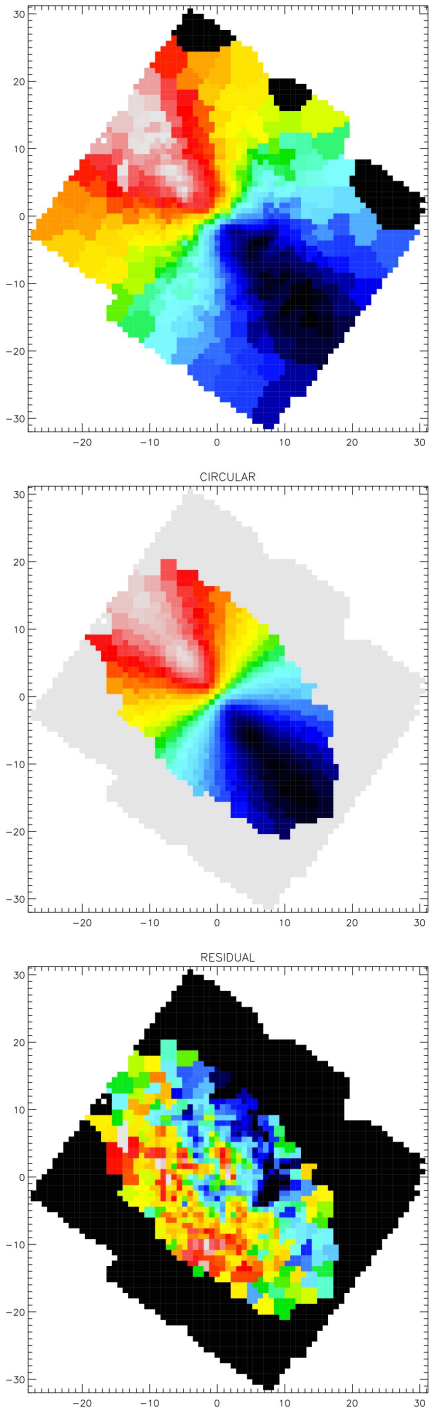
Outstanding questions and future work



- why 3 arms? orbiting object *(Etherington & Maciejewski 2006)* or coupling of waves from 2 bars?
- nuclear spirals seen in extinction only in IR – search for kinematic signatures instead?



NGC 6951
(GMOS
Storchi-Bergmann et al. 2007)



NGC 2974
(SAURON
D. Krajnovic - priv. comm.)

Conclusions

- 3-arm spiral inside the nuclear ring in NGC 1097 extends in to radius of 17 pc (resolution limit)
- the spiral indicates shock in gas: shocked H2 on inside edge of the arms, radial velocity amplitude, 2-arm kinematic spiral in residual velocity
- gas surface density in arms ~70 Msun/pc^2, inflow rate 0.06 Msun/yr
- nuclear spiral can feed recurrent episodes of star formation in the innermost ~17 pc radius for ~1 Gyr
- gas dynamics within the ~17 pc radius probably dominated by energy input from star formation