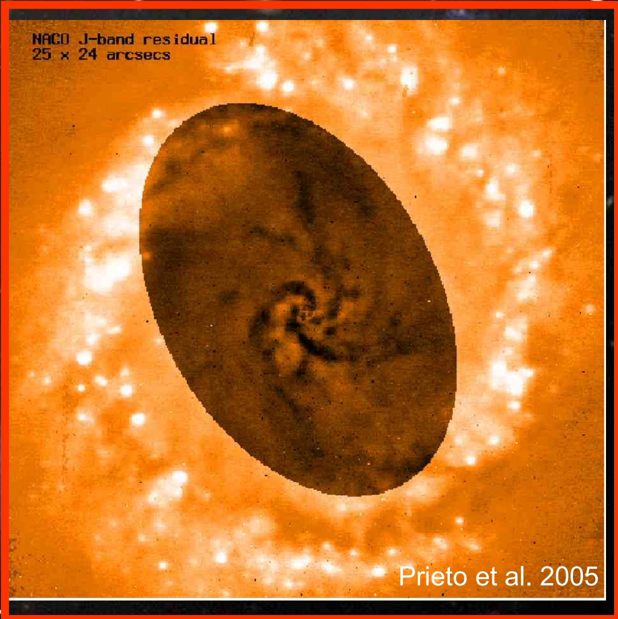
Nuclear spirals: a mechanism of gas inflow to innermost parsecs

Witold Maciejewski

Astrophysics Research Institute

Liverpool John Moores University



Waves in disc in linear theory

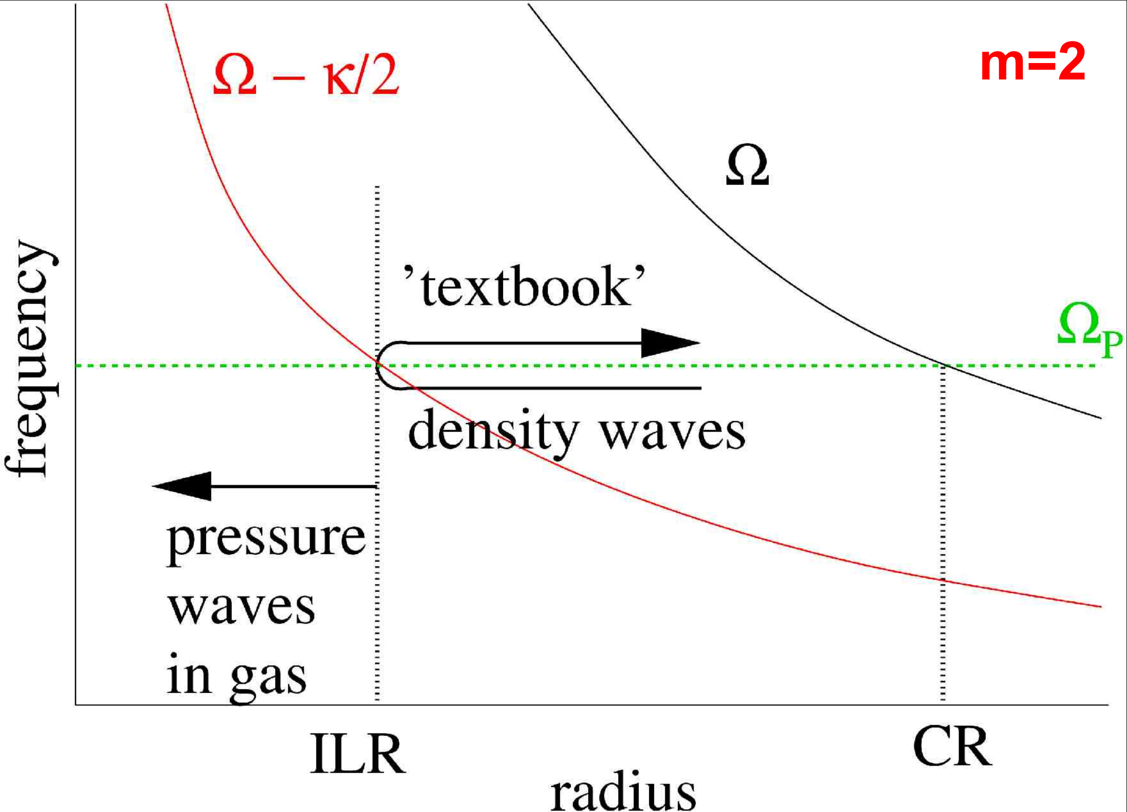
Linear dispersion relation for waves in a disc:

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

rotation curve — gas pressure — self-gravity

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

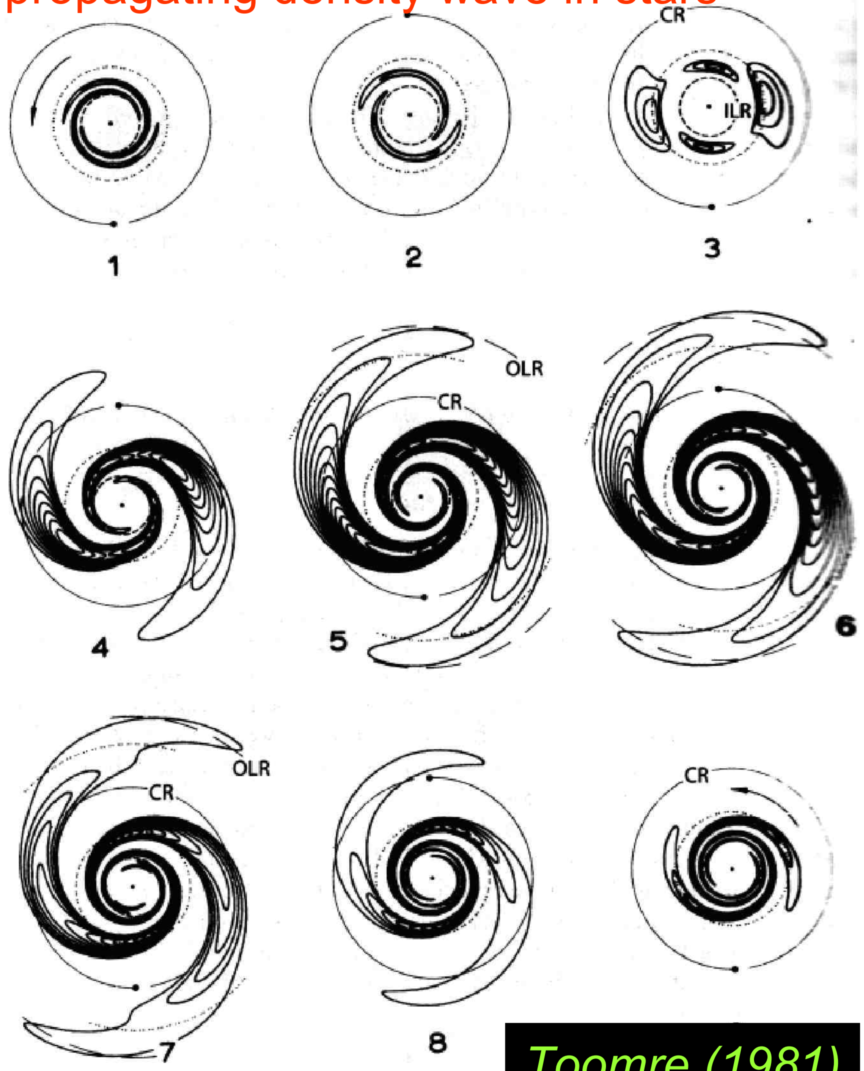
$$= -\,2\pi G\, F\, |k|\, \rho\, /\, m^2 \qquad < 0$$



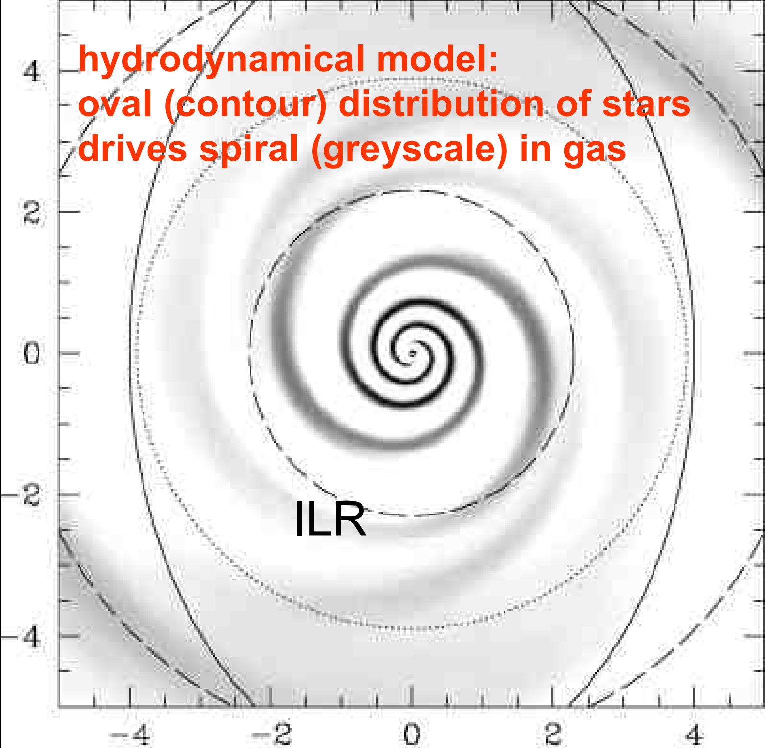
- spiral morphology of the waves
- pressure waves can propagate all the way to the galaxy centre
  → nuclear spirals

Stellar density waves vs. pressure waves in gas

propagating density wave in stars

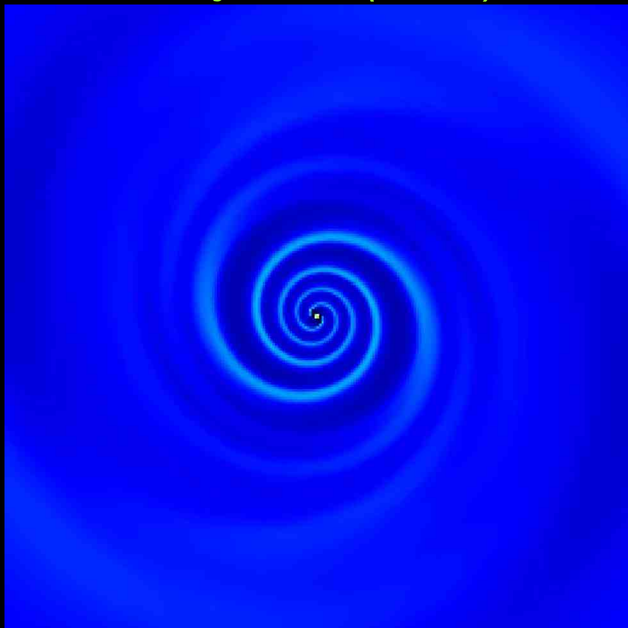


Toomre (1981)

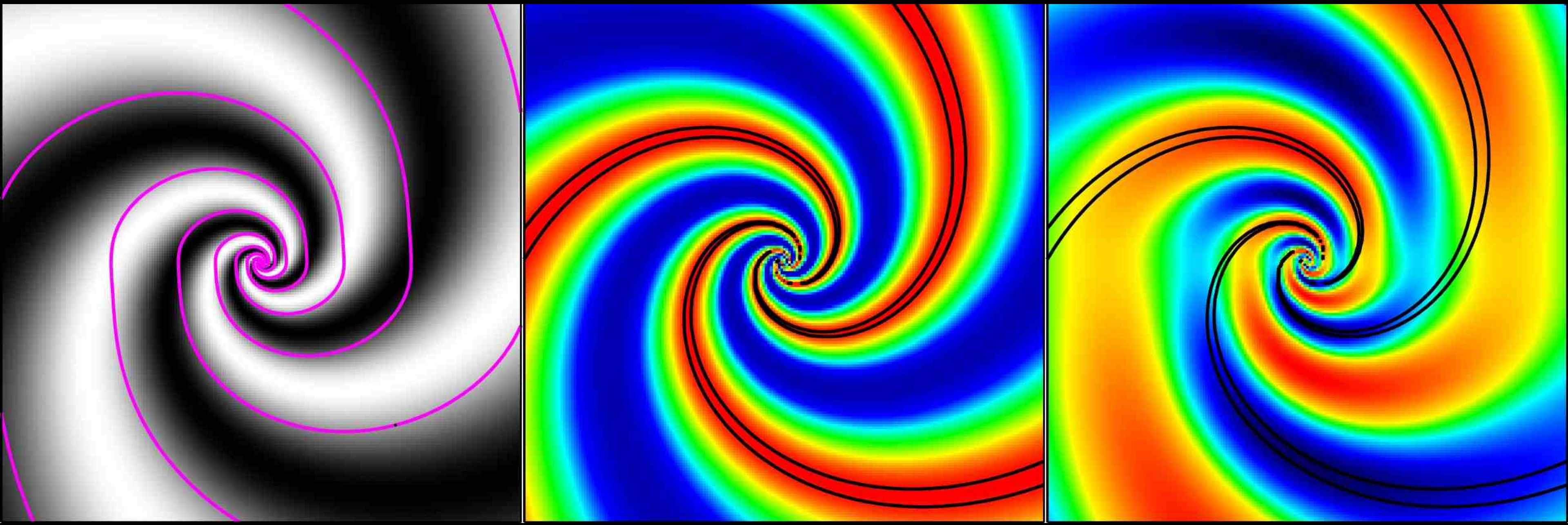


Maciejewski (2004)

- stellar density waves amplified at the ILR
- pressure waves in gas generated at the ILR



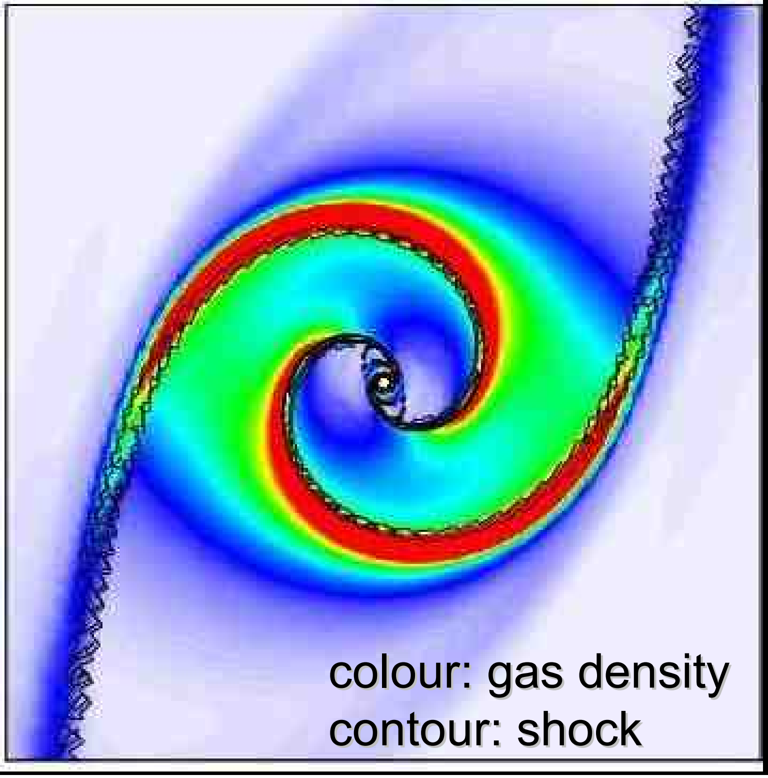
Properties of nuclear spirals in linear approximation



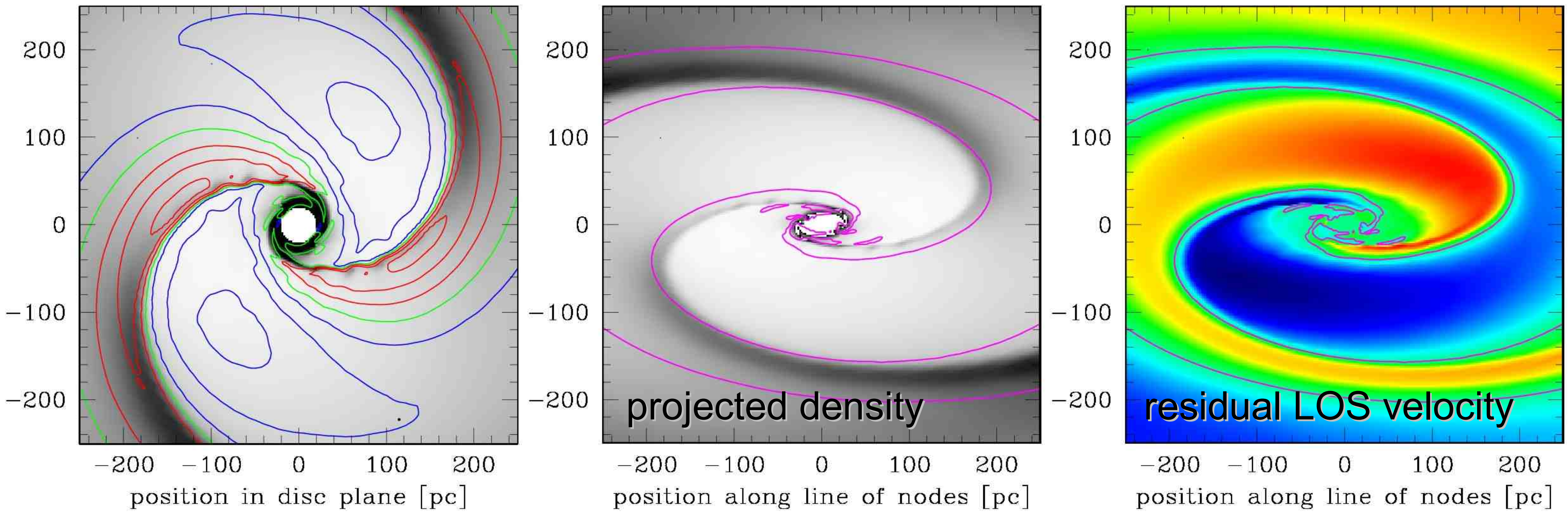
density (3 arms) (high density darker) radial velocity residual LOS velocity (morphological spiral arms in contours)

- radial inflow along the arms, outflow between the arms
- m-arm photometric spiral corresponds to m-1-arm kinematic spiral in LOS velocity residuals *(Canzian 1993)*
- linear analysis limited to $\Delta\rho/\rho << 1$ and residual velocity << sound speed

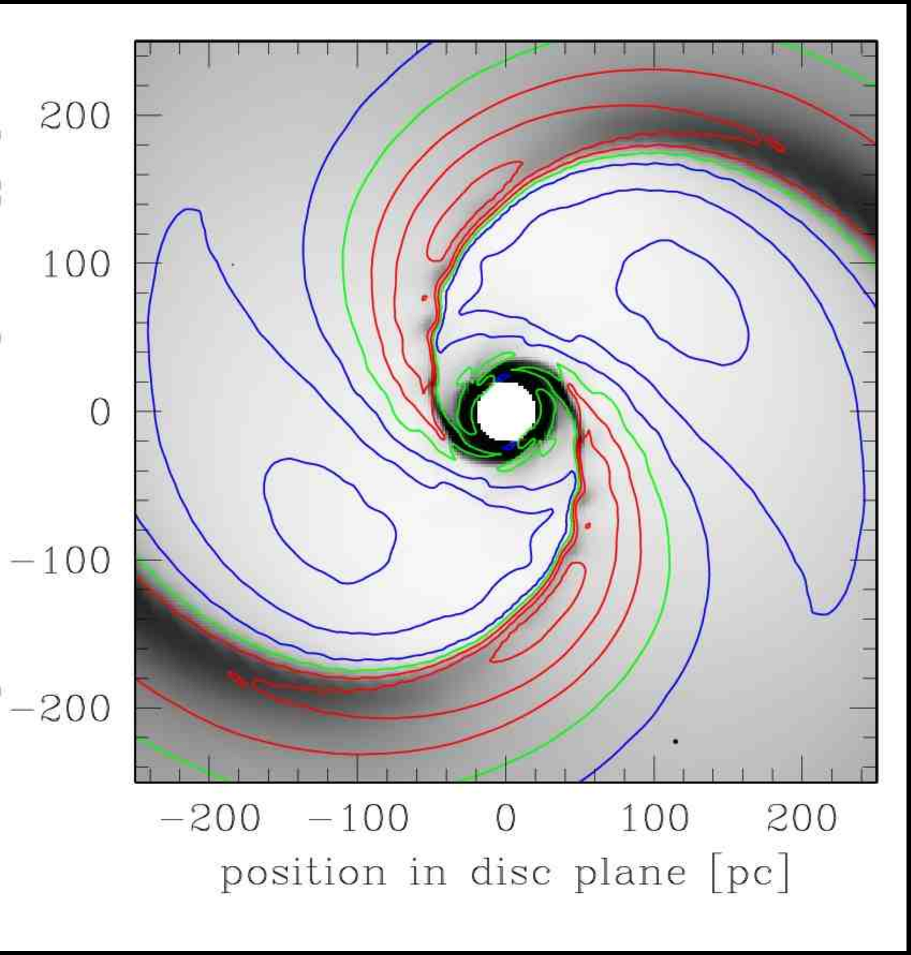
Hydrodynamical model of a nuclear spiral shock driven by a bar



- shock on the inside edges of the arms
- radial velocities up to 60 km/s when sound speed 20 km/s
- location of inflow/outflow and m/m-1 multiplicity of photometric/kinematic spiral like in the linear case



Gas inflow in nuclear spiral shock



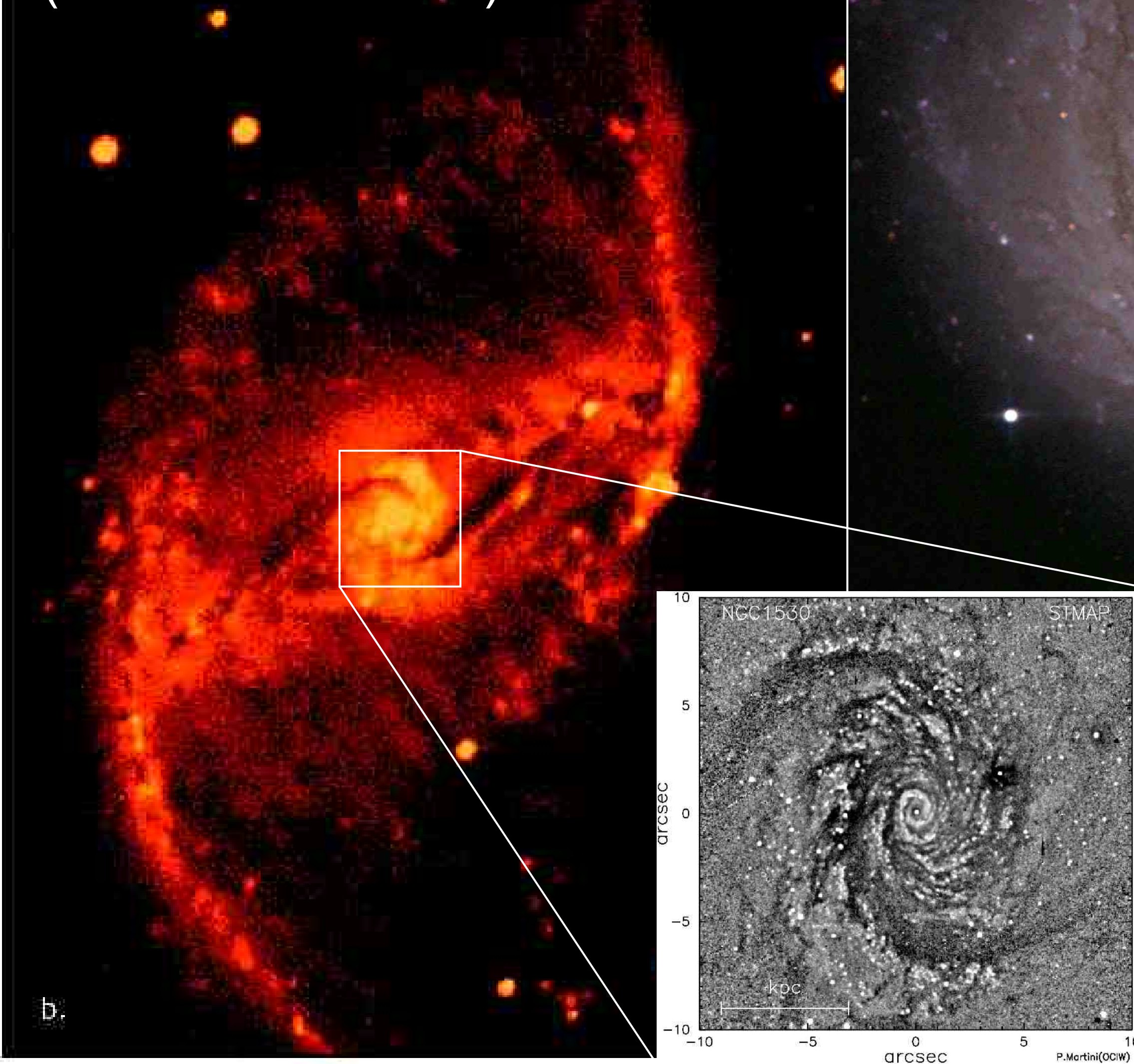
- **because of dissipation in the shock there is inflow**
- naive estimate of inflow from gas density in the arms and radial velocity:

  ~1.2 Msun/yr – LARGE!
- models show that inflow in the arms balanced by outflow between the arms
- hydrodynamical model indicates that the naive estimate must be reduced by a factor of ~20

- nuclear spiral shocks not always associated with star formation

Nuclear spirals in weak and strong bars

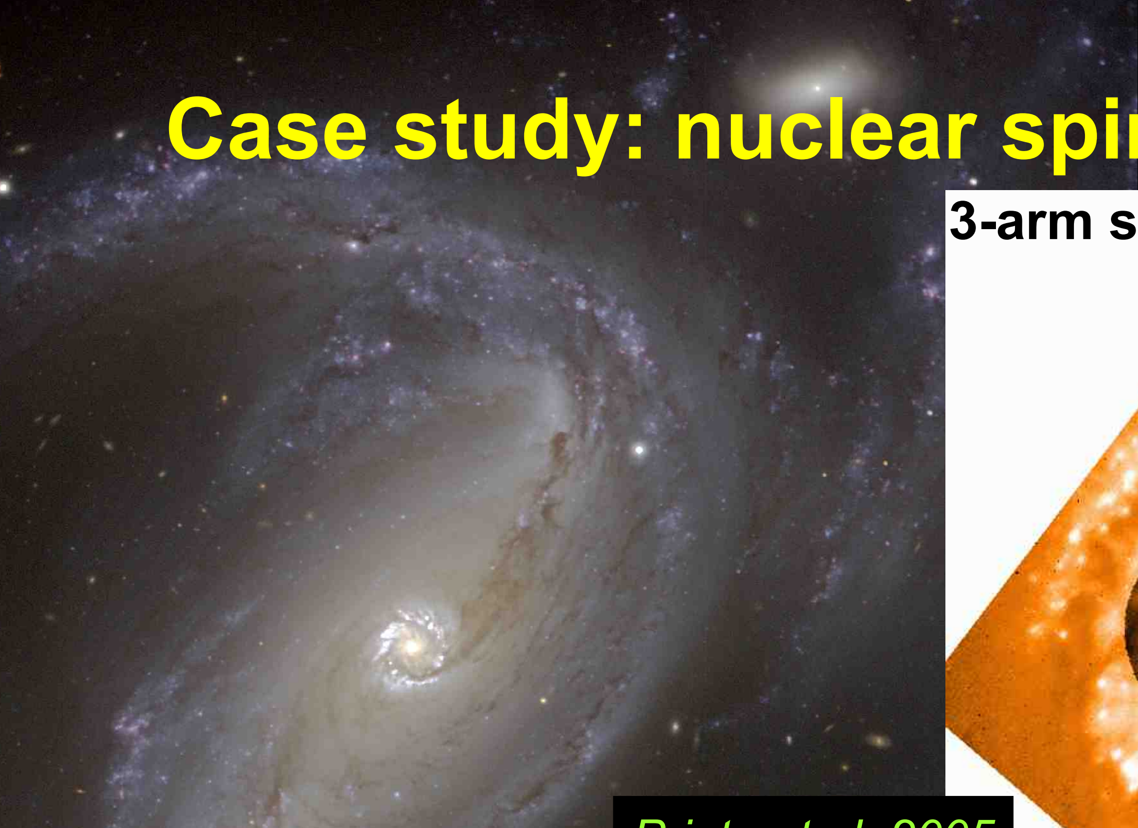
dusty features – seen in majority of disc galaxies
(*Martini et al. 2003*)



M 100, *Allard et al. 2005*

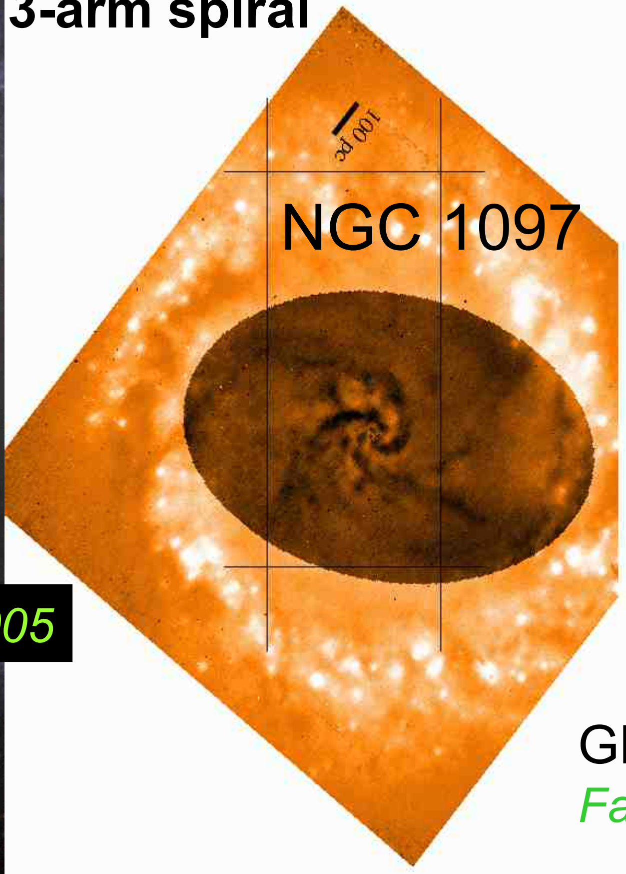
NGC 1530, *Zurita et al. 2004*

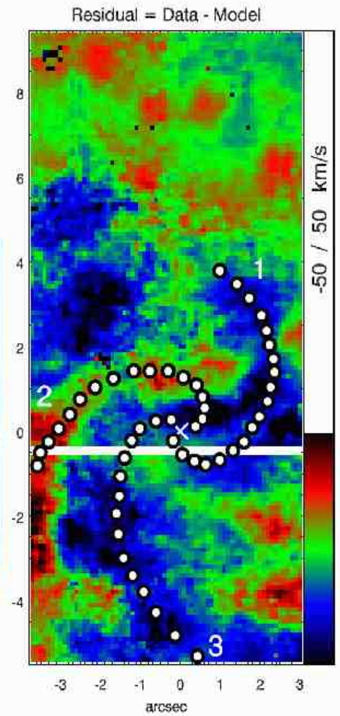
Case study: nuclear spiral in NGC 1097



Prieto et al. 2005

3-arm spiral





GMOS

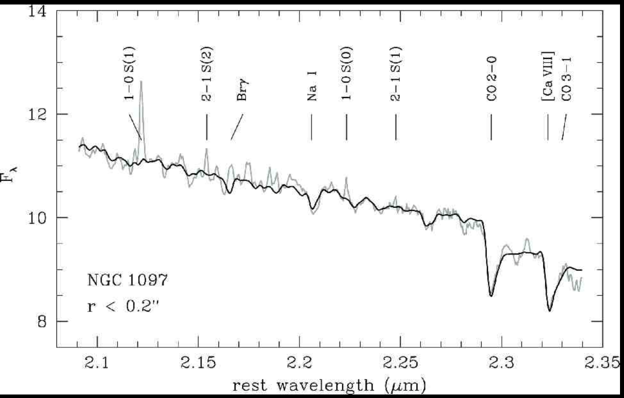
Fathi et al. 2006

- intrinsic gas velocity dispersion: 30-45 km/s
- intrinsic amplitude of LOS velocity residuals: 75 km/s

→ **spiral is a shock in gas**

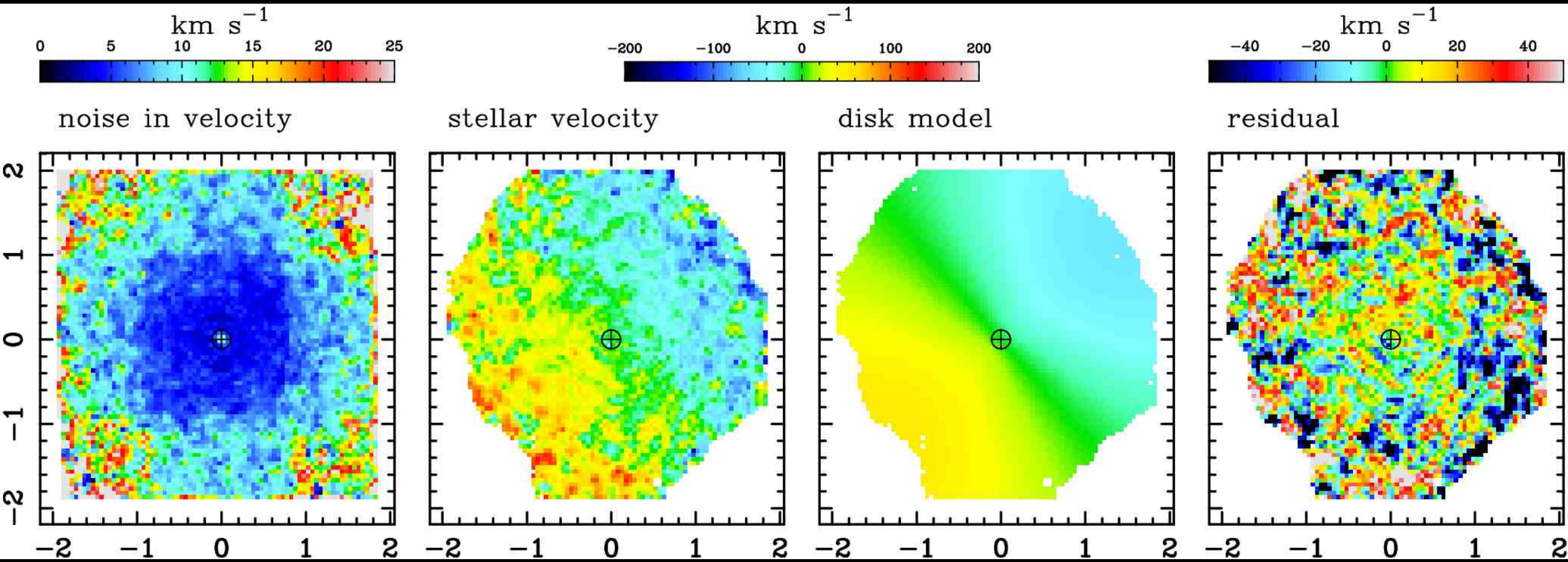
SINFONI observations of NGC 1097

(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)*

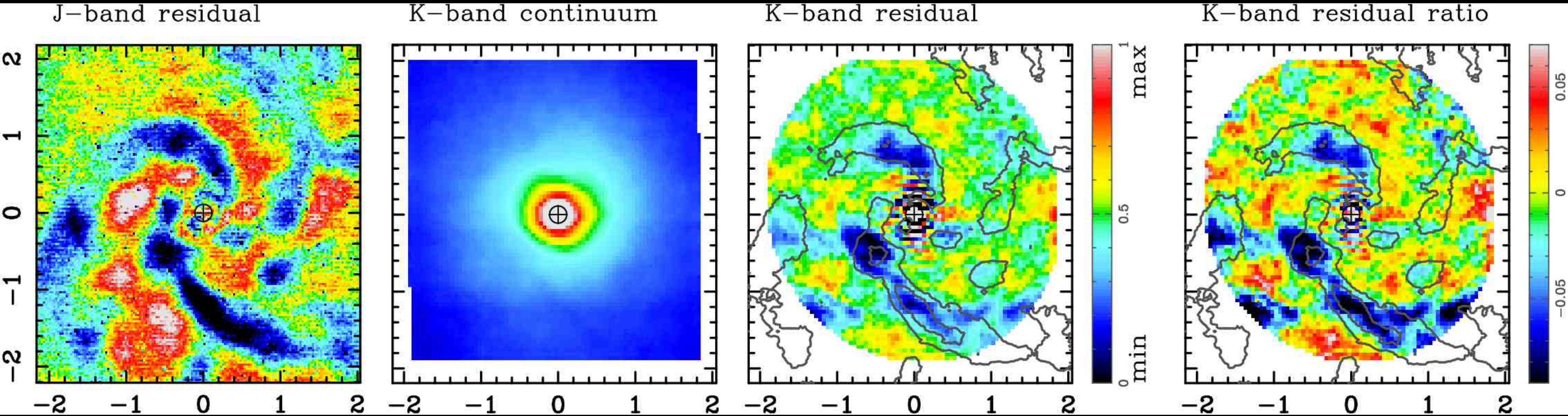
Stellar kinematics



- no coherent structure in residual velocity – no peculiar bulk motions of stars in bulge and disc

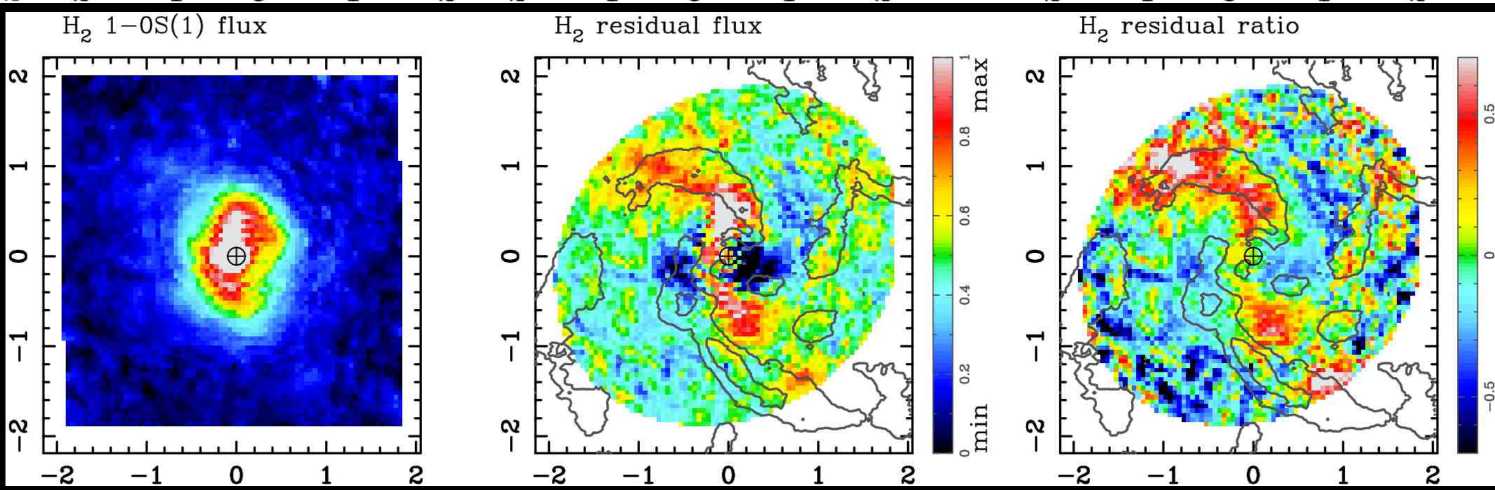
  → stars do not participate in the spiral pattern
- stellar velocity dispersion σ~150 km/s > v_circ

Absorption in continuum and molecular emission



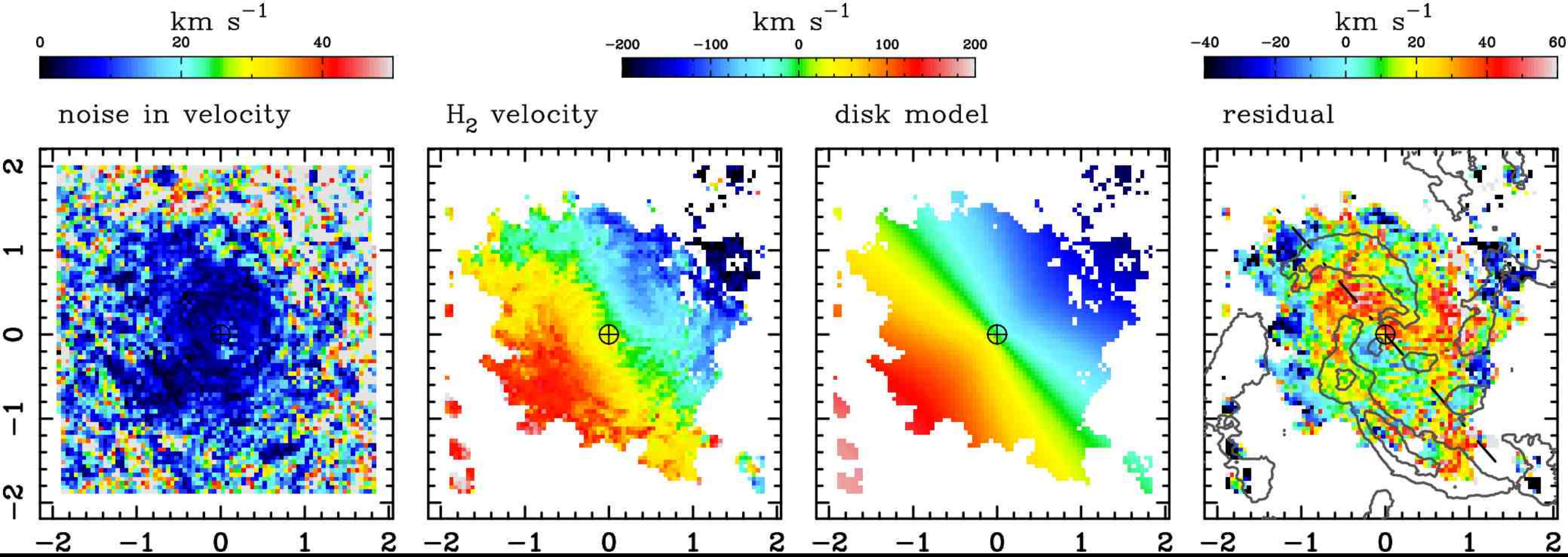
NACO

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

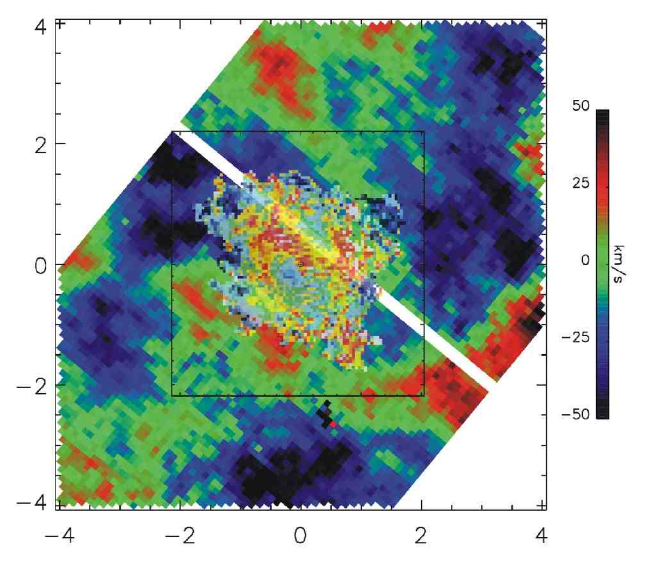


- same 3-arm spiral in NACO J-band residuals and SINFONI K-band residuals
- low continuum coincides with H2 emission → both trace high density of gas
- H2-emission arm inside the extiction arm: gas entering the arm is heated in the shock

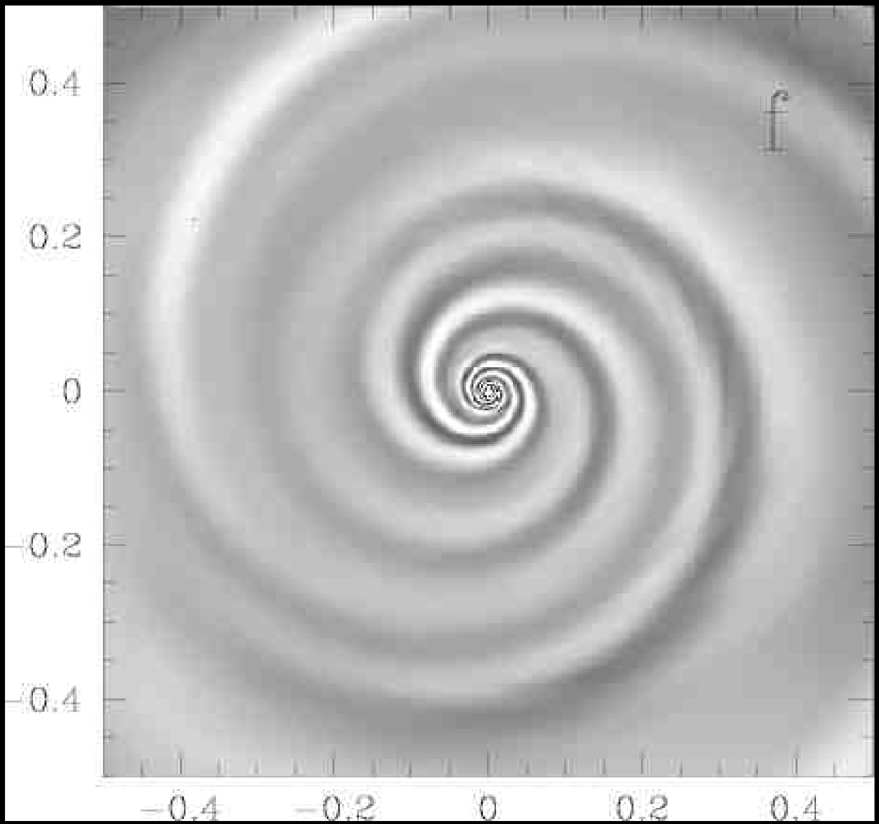
H2 kinematics

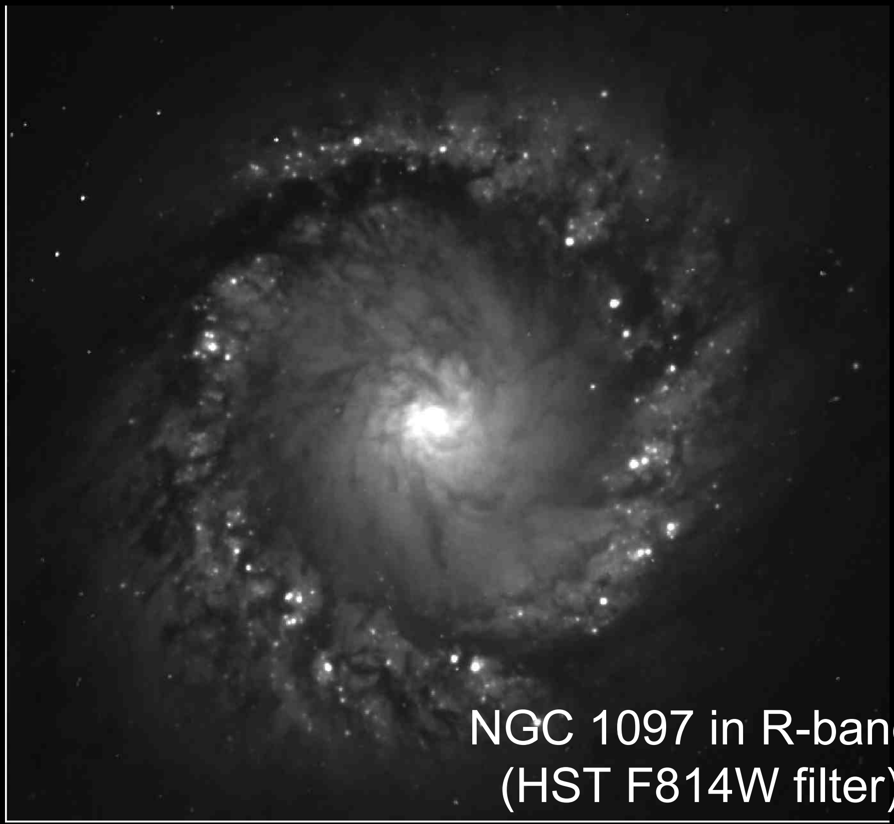


- subtracting disk model (fixed PA & axial ratio) from H2 velocity gives residual velocity
- 2-arm kinematic spiral in residual velocity
- consistent with ionized gas kinematics traced by [NII] emission (GMOS, *Fathi et al. 2006*)

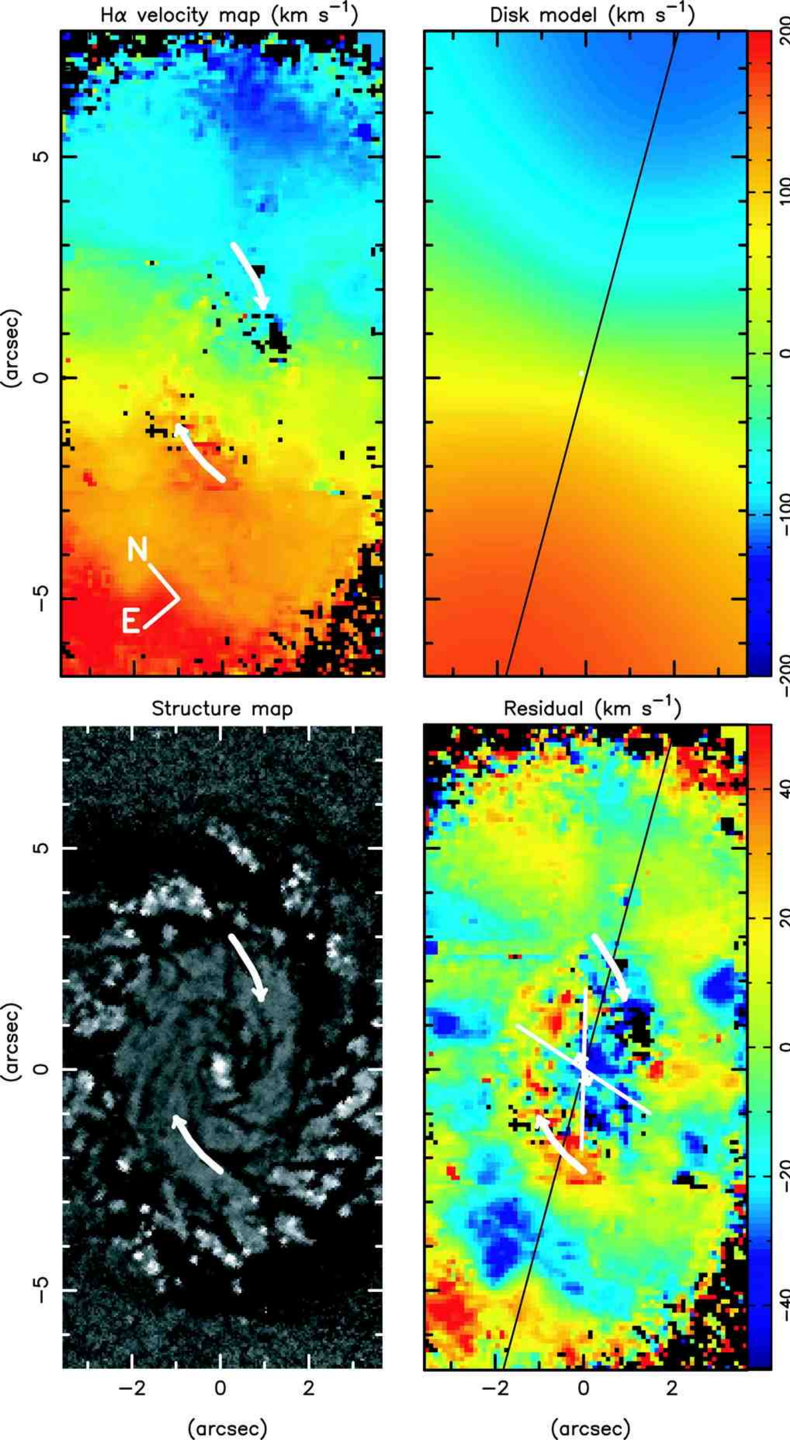


- corrected net inflow in the nuclear spiral in NGC 1097 is 0.06 Msun/yr – consistent with SF history *(Storchi-Bergmann et al. 2005, Davies et al. 2007)*
- ~2 Gyr needed to drain all gas inside the nuclear ring
  → nuclear spiral in quasi-equilibrium (refilling from nuclear ring?)





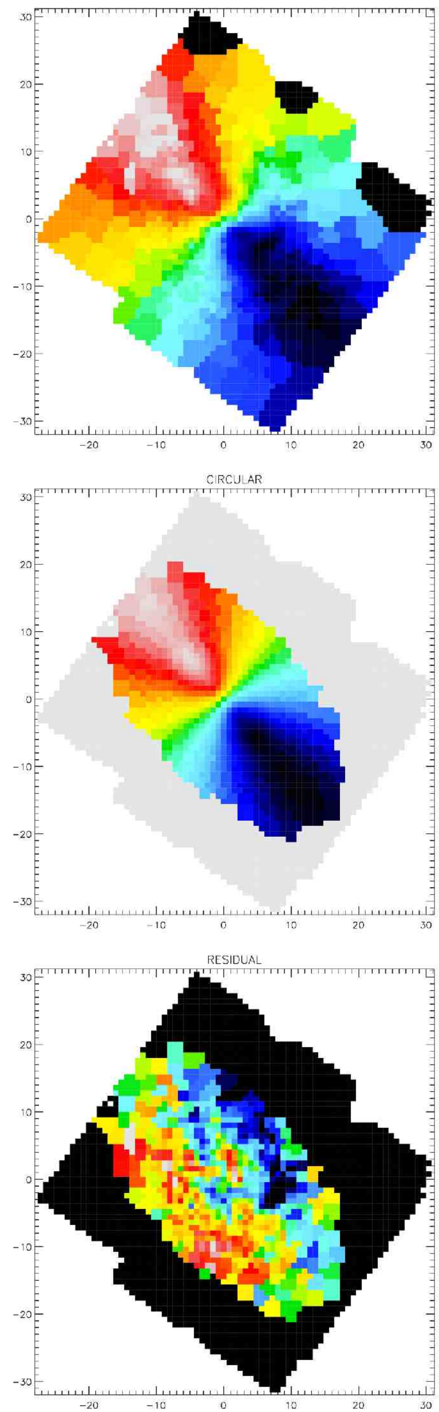
- why 3 arms? orbiting object *(Etherington & Maciejewski 2006)* or coupling of waves from 2 bars?
- nuclear spirals seen in extinction only in IR
  → search for kinematic signatures instead?



Kinematic signatures of other nuclear spirals

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

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



Conclusions

- nuclear spirals as pressure waves in gas, (different from classical stellar density waves)
- nuclear spirals can be shocks in gas, hence dissipation & inflow, but correct for interarm outflow
- stellar & gas morphology & kinematics in the innermost 300 pc of NGC 1097 unveil a spiral shock in gas
- nuclear spiral shock in NGC 1097 can last for Gyrs, and cause gas inflow consistent with SF history