Dynamical Models of Disc Galaxies and Fueling of the Central SMBH

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Special thanks to Nuria Piñol-Ferrer, Javier Blasco-Herrea, Michael Gatchell, Roland Karlsson

Outline

- What processes could generate flows in discs
- Where can we find signatures of such processes
- Can we unveil flows in discs
- How do we observe the observables
- Applying the models to data to close in to the SMBH

Flows in galaxies

Gas transport to galaxy centers means losing momentum

On galactic scales, this can be initiated and driven by

- Rotational magnetic instabilities (Sellwood & Balbus 1999)
- Minor Mergers (Hernquist & Mihos 1995)
- Turbulence (Lynden-Bell & Pringle 1974)
- Shocks (Roberts 1969)
- Sheared gravitational instabilities (Goldreich & Lynden-Bell 1965)
- Density waves (Lindblad 1964; Lin & Shu 1964)

Nuclear spirals correlate with nuclear activity

- Flocculent or Grand-design

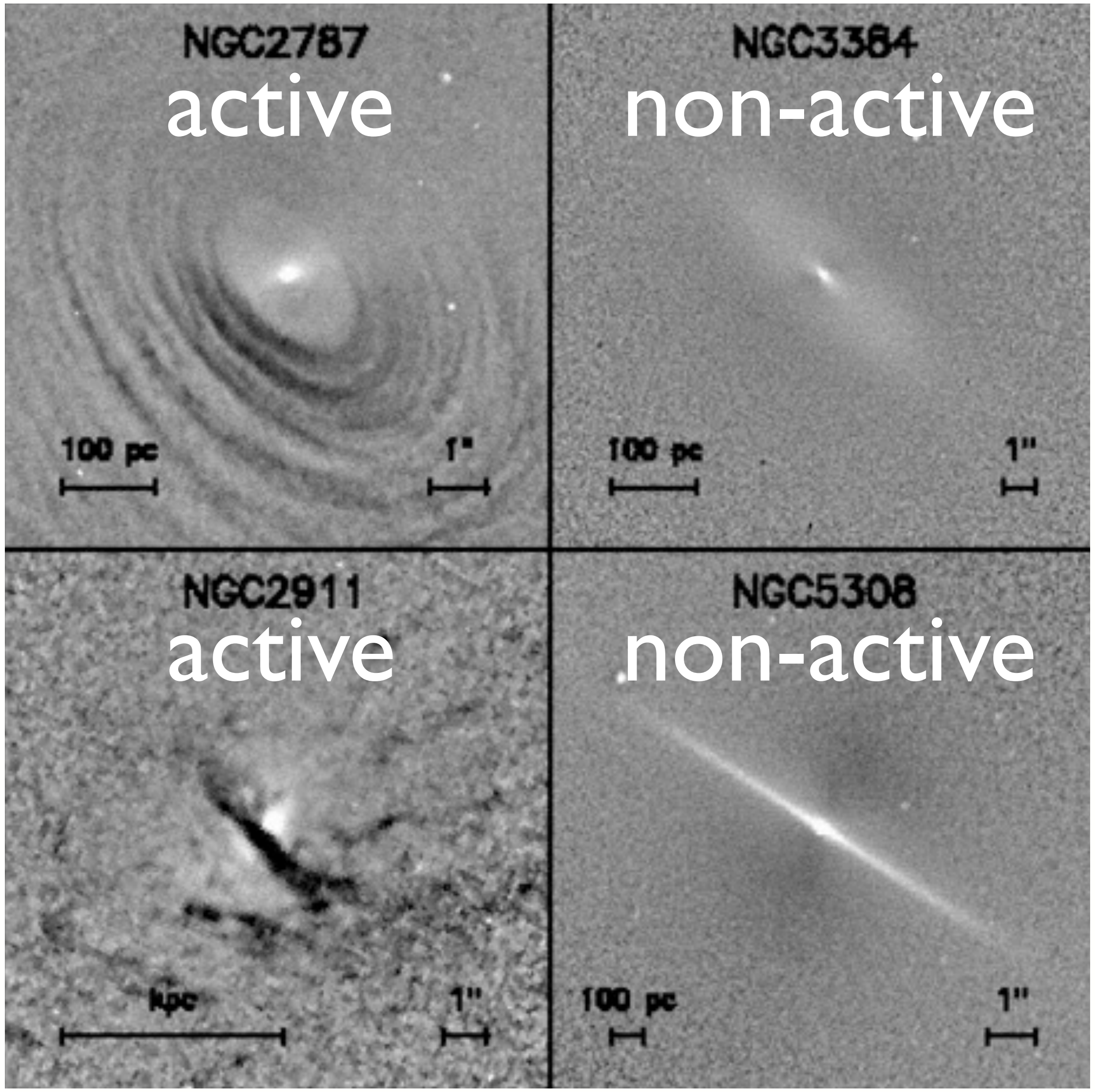
  e.g., Elmegreen et al. (1998)
  Montenegro (1998)
  Englmaier & Shlosman (2000)
  Maciejewski (2004)

- Deviations in density ~ 5-10 %

  e.g., Lou et al. (2001)
  Prieto et al. (2005)
  Fathi et al. (2011)

- Non-circular motions are significant

  e.g., Fathi (2004)
  Storchi-Bergmann et al. (2007)

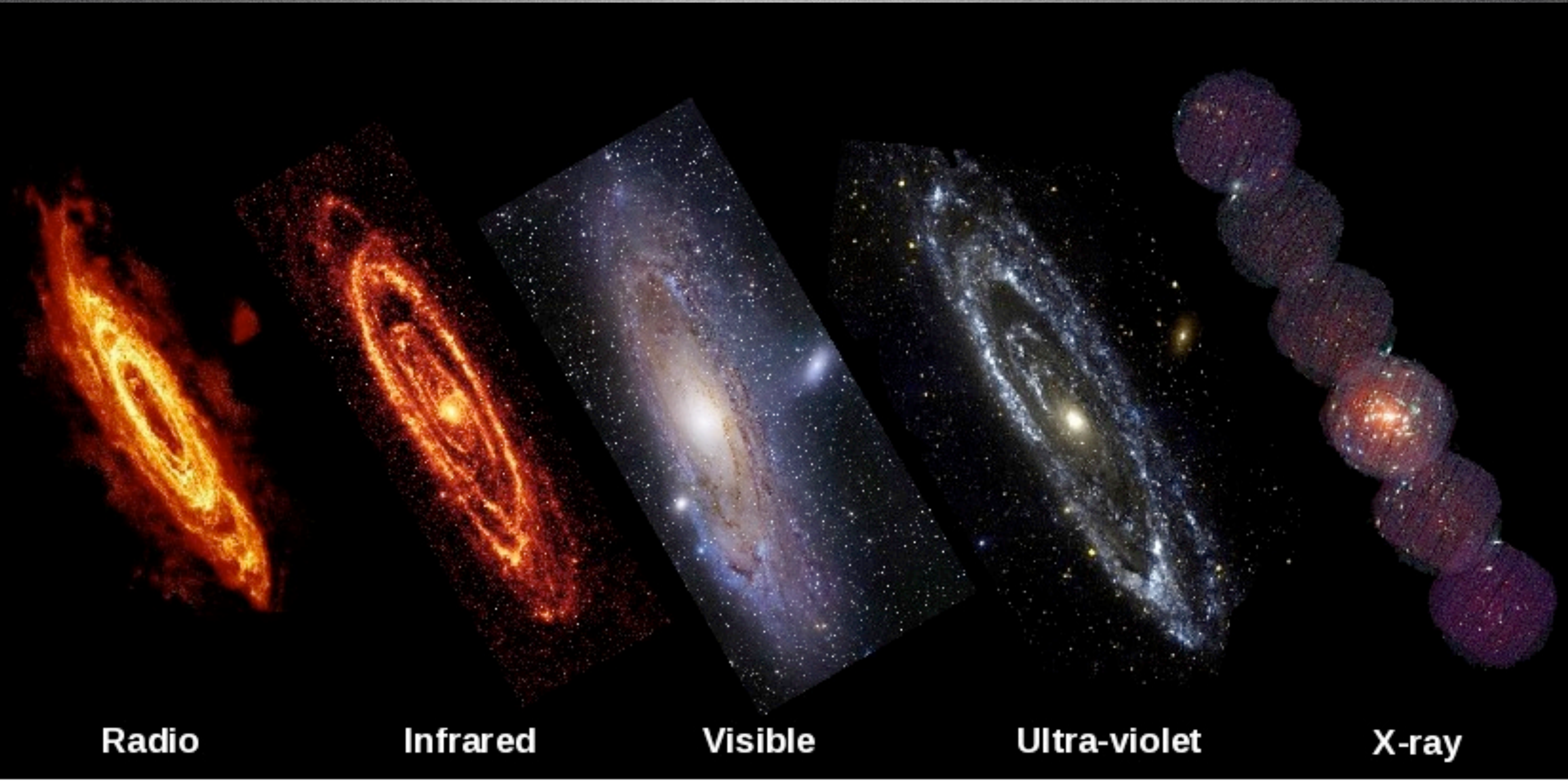


Martini & Pogge (1999)
Regan & Mulchaey (1999)

Density wave theory

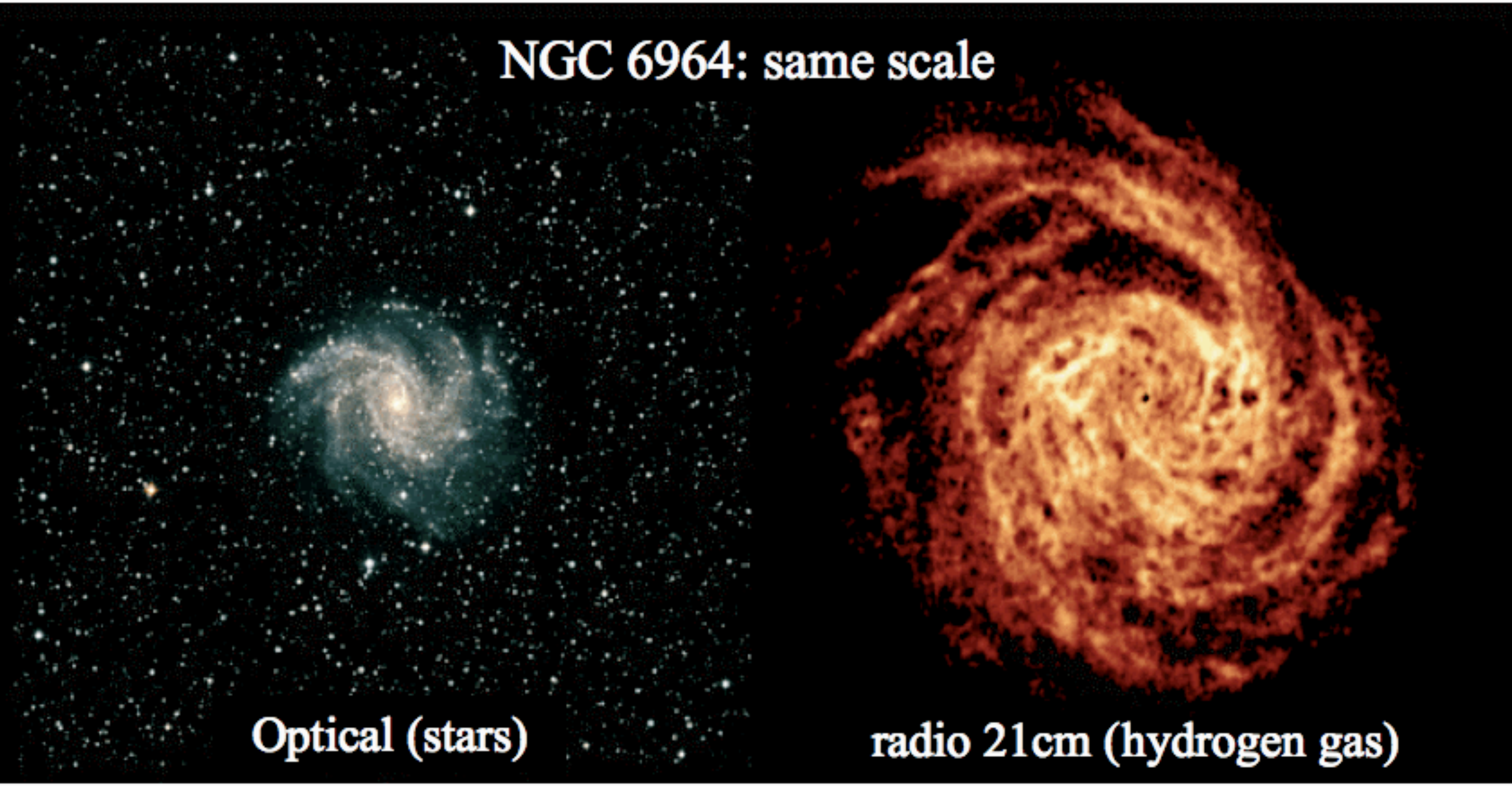
ttt.astro.su.se/~po

The importance of observing different tracers



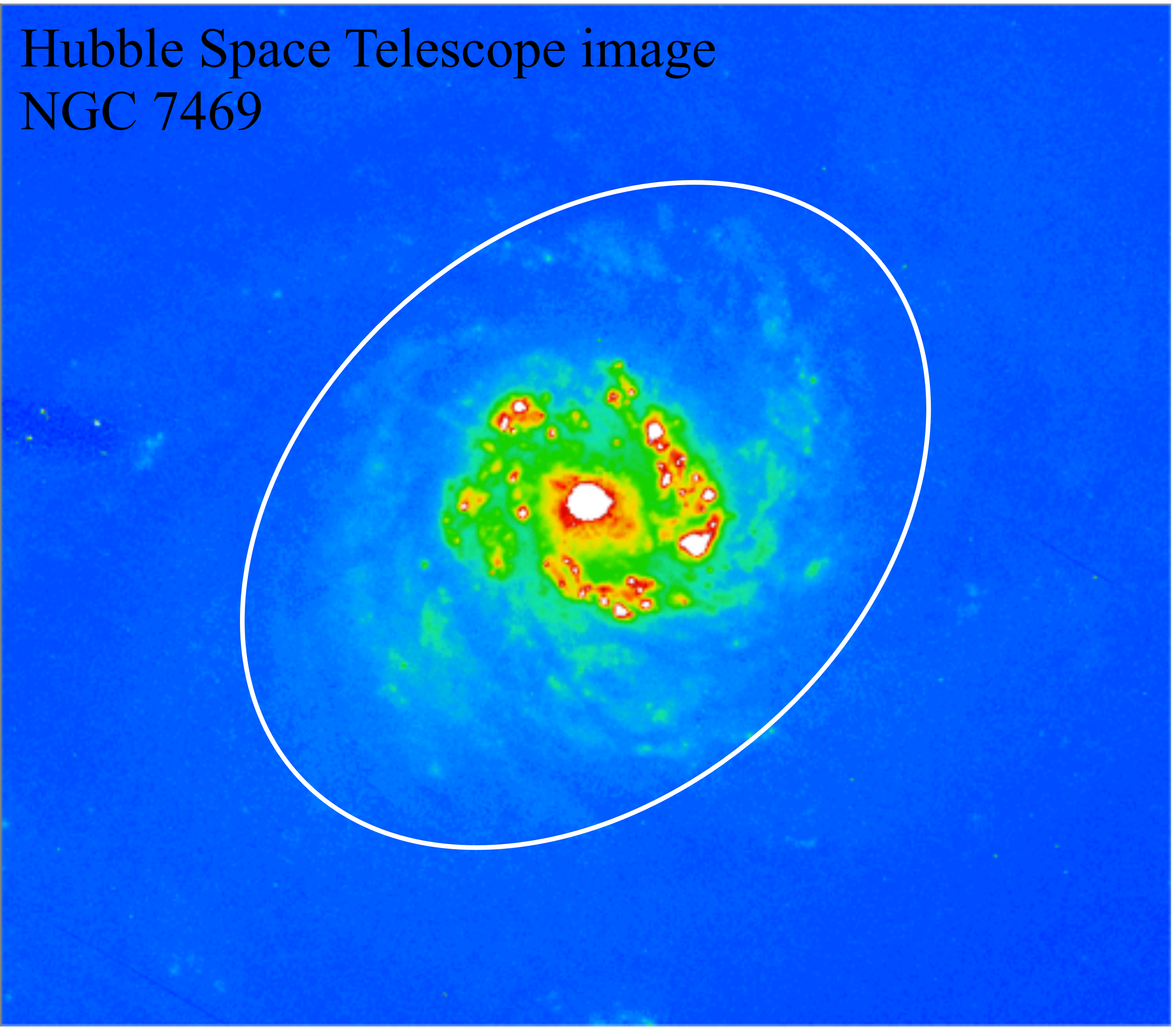
Radio:WSRT/R. Braun; Infrared:NASA/Spitzer/K. Gordon; Visible: R. Gendler; Ultraviolet: NASA/GALEX; X-ray: ESA/XMM/W. Pietsch

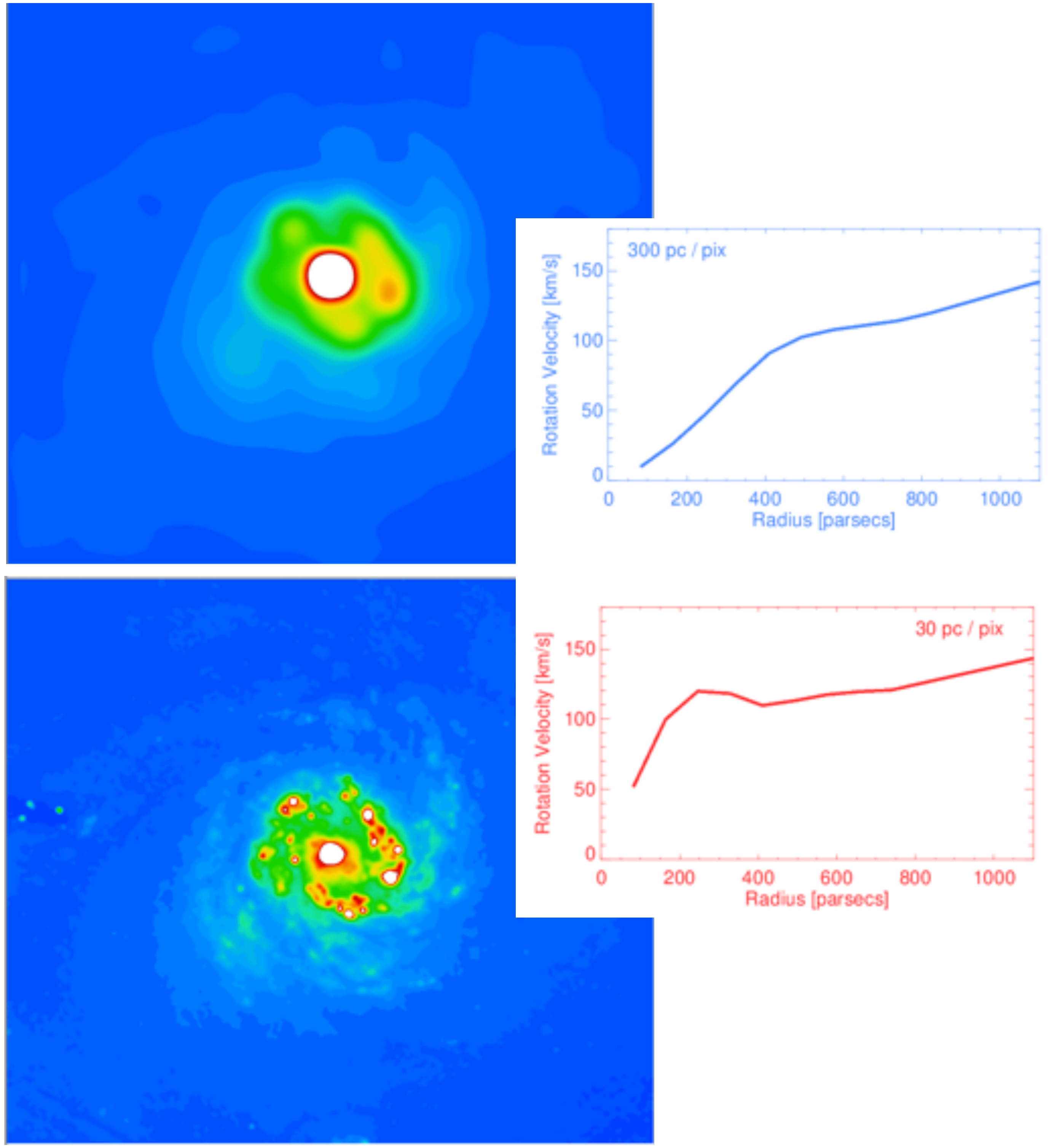
The importance of observing different tracers



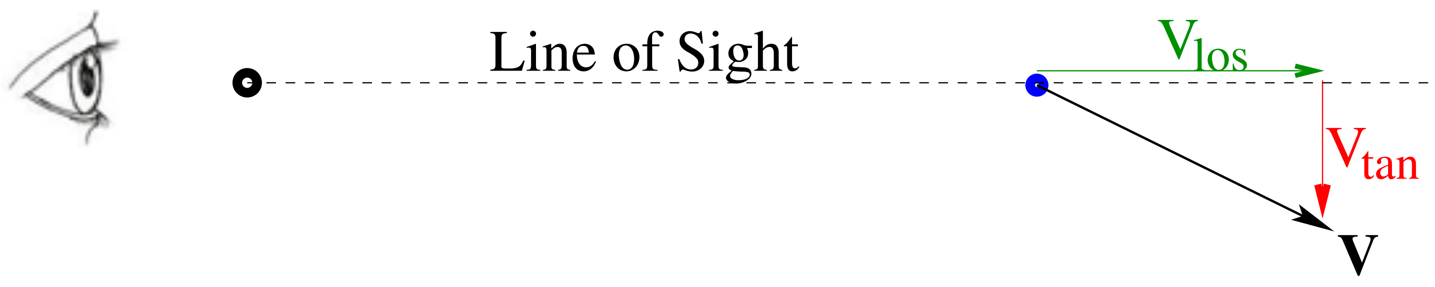
Boomsma (2008)

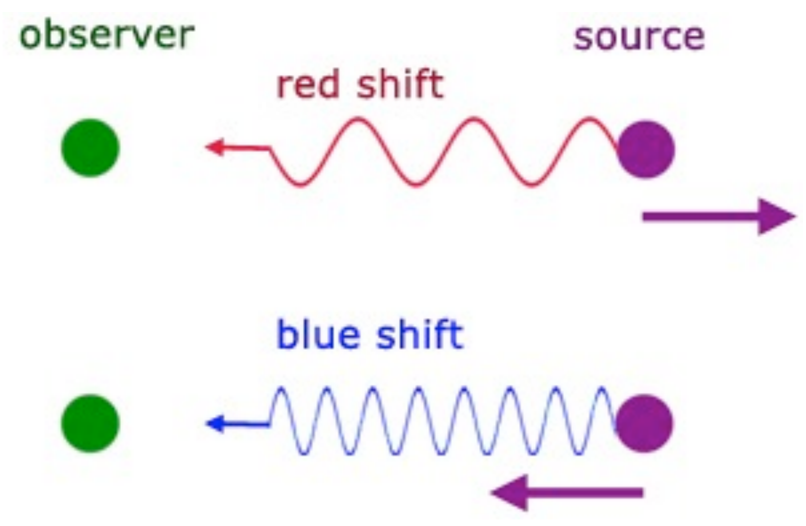
The importance of high-resolution data

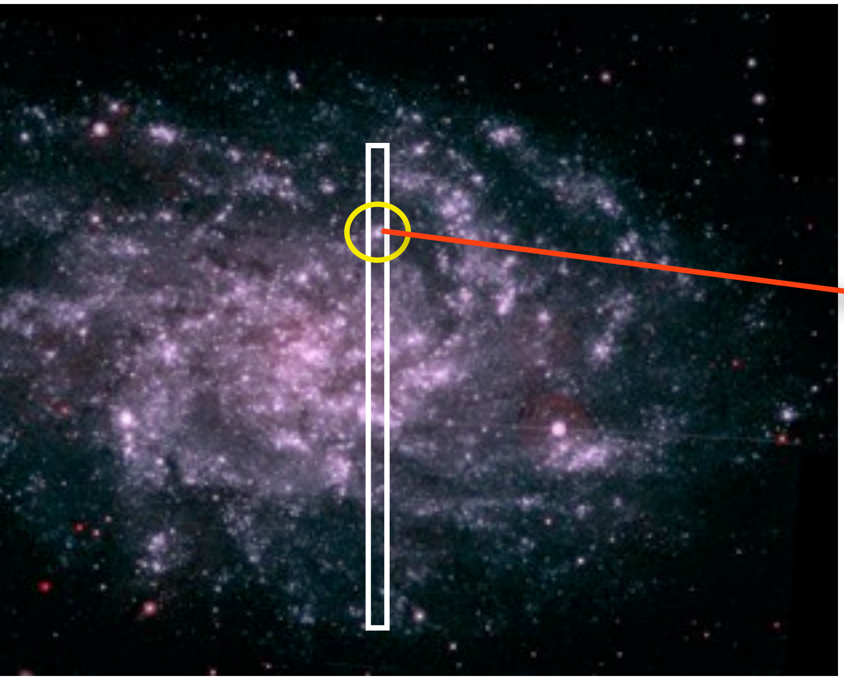


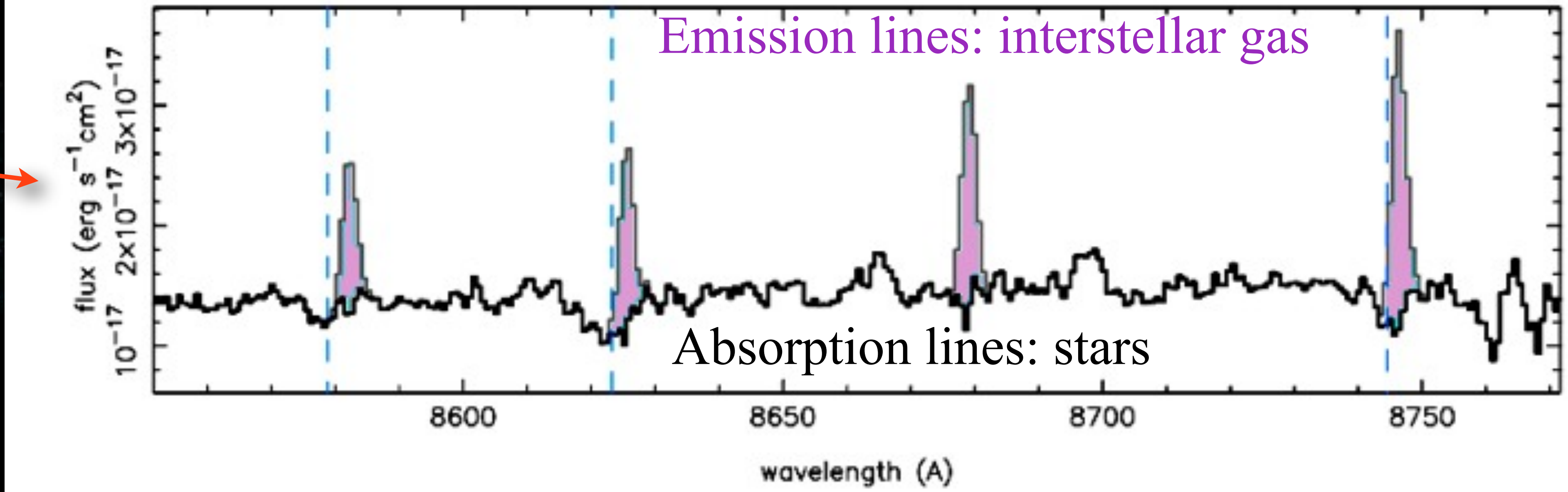


Principles of observing kinematic features

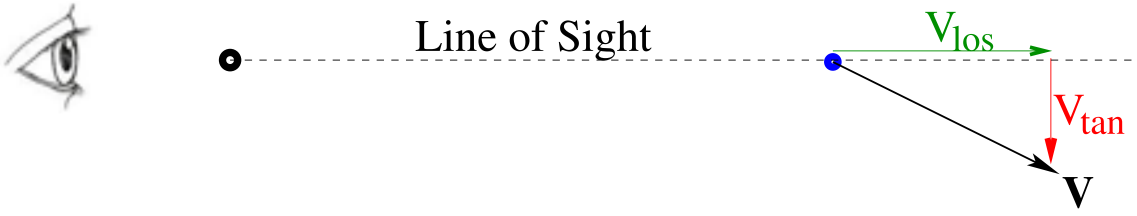


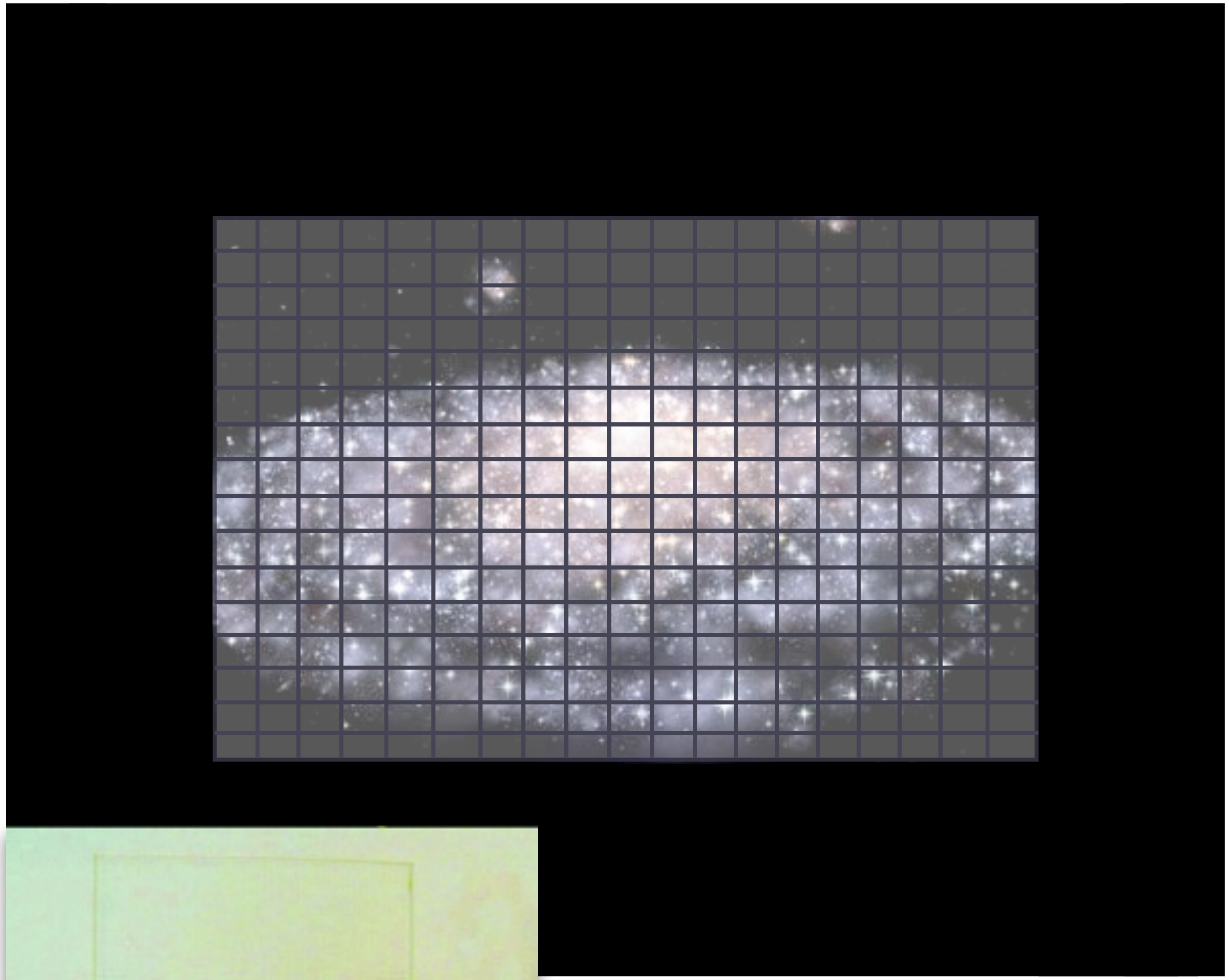




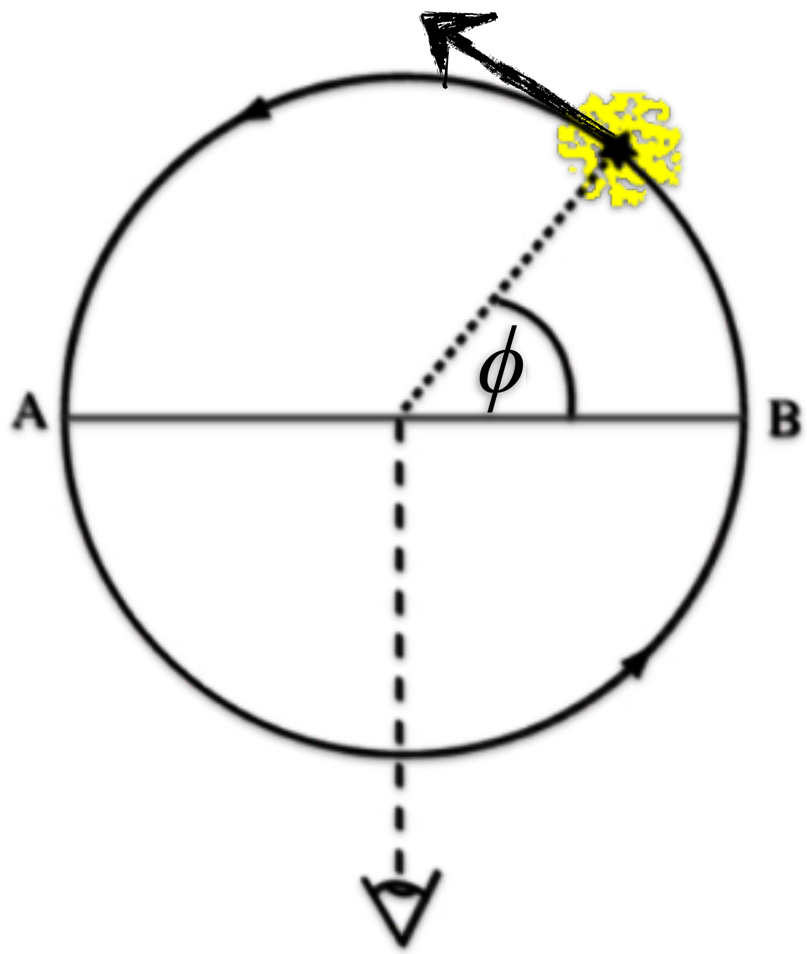


Two-dimensional spectroscopy

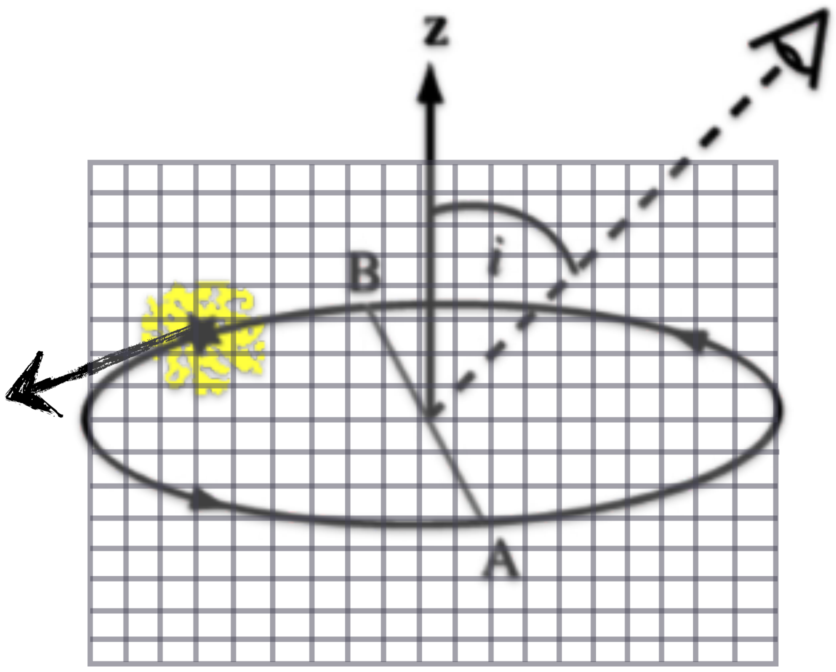


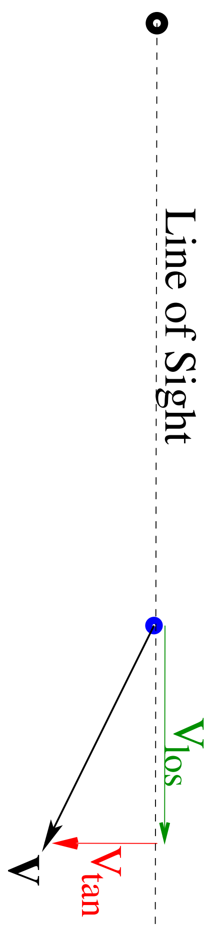


Interpreting kinematic observations



(V_{sys} = systemic velocity of the galaxy)
(i = inclination of the galaxy)





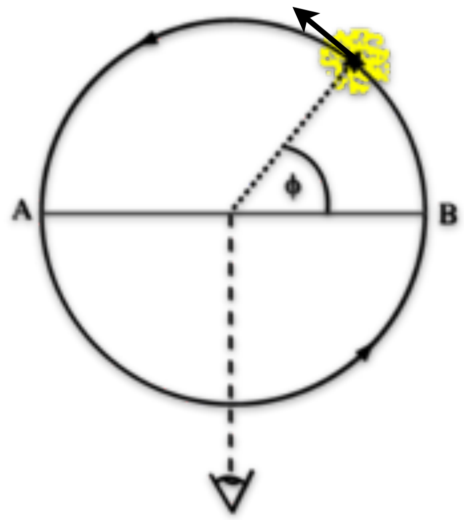
Viewed edge-on:

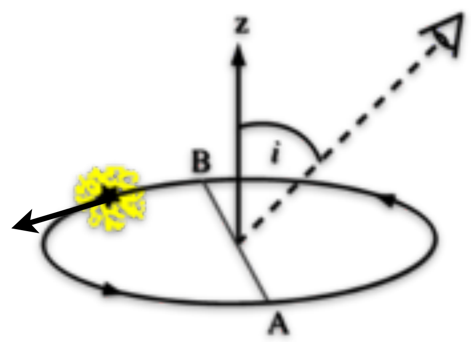
$$V_{los}(R, i = 90^{\circ}) = V_{sys} + V(R)\cos\phi$$

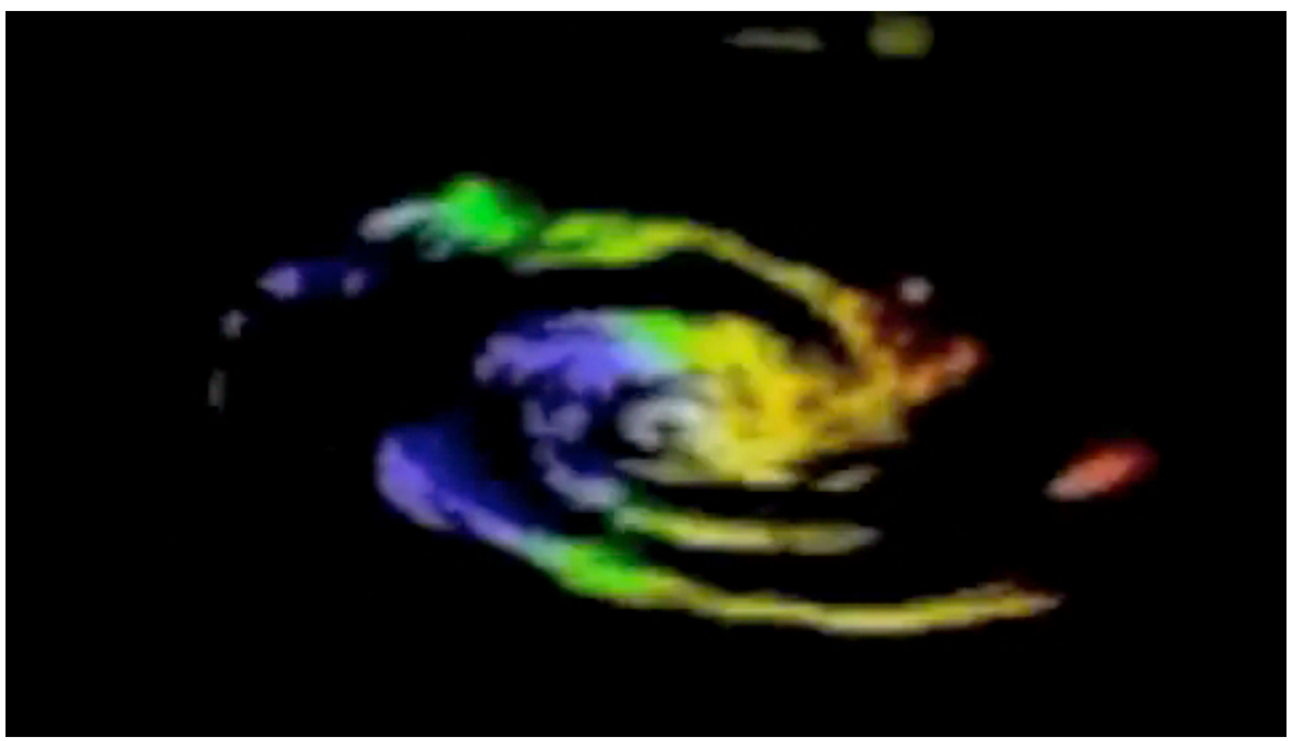
Viewed at an angle:

$$V_{los}(R, i) = V_{sys} + V(R)\cos\phi\sin i$$

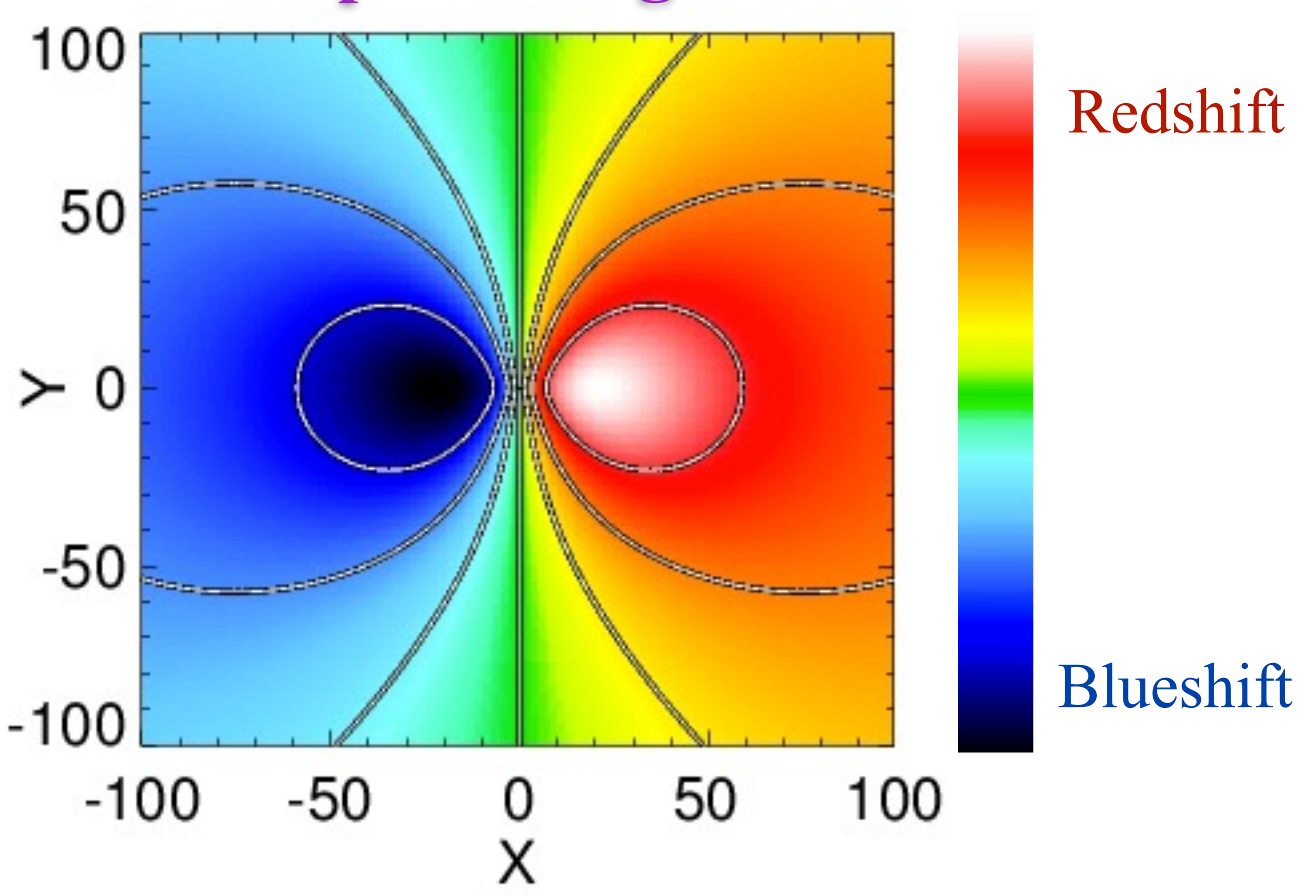
Two dimensional velocity fields



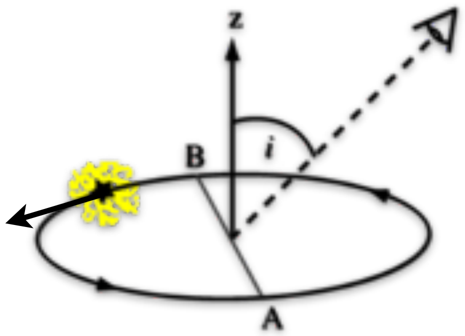




A Spider Diagram

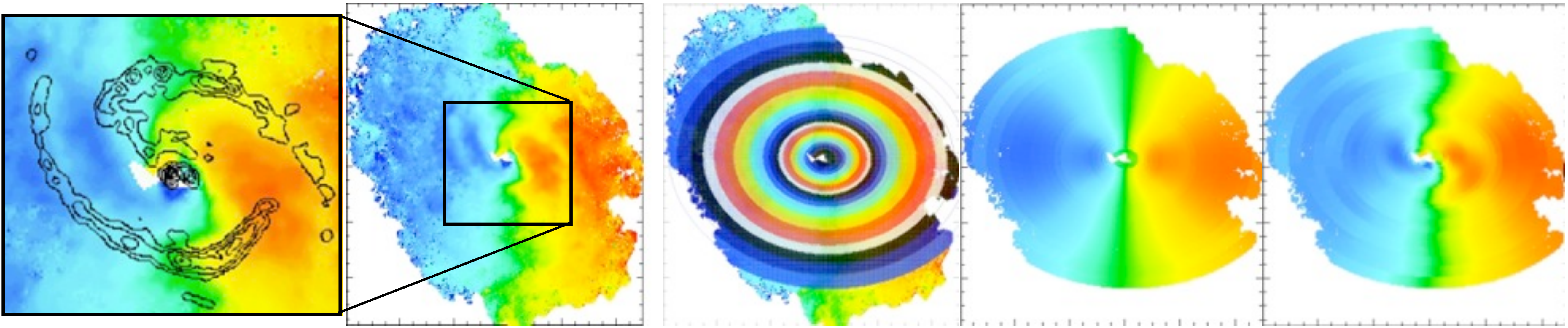


Analysing high-resolution data



$$V_{los}(R,i) = V_{sys} + V(R)\cos\phi\sin i$$

Assuming differential rotation, we section a velocity field into concentric rings and fit the disk centre, inclination, PA, systemic and rotation velocity



$$V_{\rm los} = V_{\rm sys} + \sum_{n=1}^{k} (c_n \cos(n\phi) + s_n \sin(n\phi)) \sin i$$

Fathi et al. (2005; 2007; 2008); van de Ven & Fathi (2010)

Modelling a weakly perturbed gravitational potential

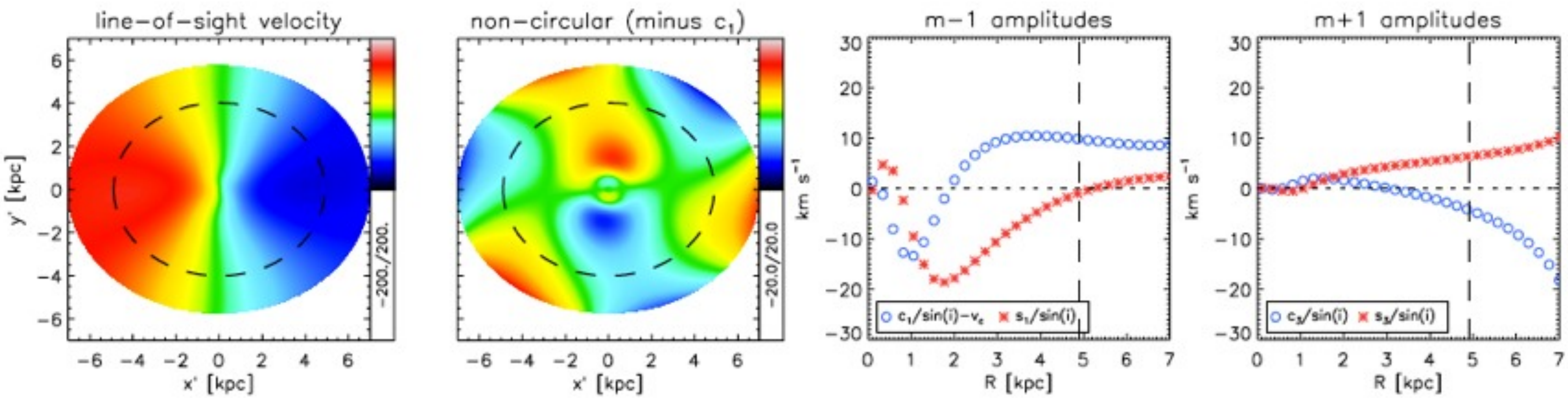
$$\Phi(R,\theta) = \Phi_0(R) + \Phi_m(R)\cos[m(\theta - \Omega_p t)]$$

where Φ_0 is the axisymmetric potential, Ω_p is the angular speed of the rotating potential, and m is the harmonic number of the distortion. For the case of $m = 2$ the potential is barred. The equations of motion are written as

$$-\frac{\partial\Phi}{\partial R} = \ddot{R} + 2\lambda\dot{R} + (\dot{\phi} + \Omega_p)^2 R$$

$$-\frac{\partial\Phi}{R\partial\phi} = R\ddot{\phi} + 2(\dot{\phi} + \Omega_p)\dot{R}$$

$$\ddot{R}_1 + 2\lambda\kappa_0\dot{R}_1 + \kappa_0^2 R_1 = -R_0(A\cos\eta + B\sin\eta)$$



Shlosman & Noguchi (1993); Wada (1994); Fathi (2004); van de Ven & Fathi (2010)

More elaborate analytic dynamical models

- Apply the formalism of Lindblad et al. (1996)

  see also Wada (1994) and Sakamoto et al. (1999)

$$\Phi(r,\theta) = \Phi_0(r) + \Phi_1(r,\theta) = \Phi_0(r) - \sum_{m=1}^{n} \Psi_m(r) \cos m(\theta - \vartheta_m(r))$$

- We advance the method by treating the bar and spiral perturbation simultaneously
- Solve the linearised equations of motion in polar coordinates

$$\ddot{\xi} + 2\lambda\dot{\xi} - 2\Omega\dot{\eta} - 4\Omega A\xi = -\frac{\partial\Phi_1}{\partial r} = \sum_{m=1}^{n}[C_m \cos m(\theta - \vartheta_m) + E_m \sin m(\theta - \vartheta_m)]$$

$$\ddot{\eta} + 2\Omega\dot{\xi} + 2\lambda\dot{\eta} + 4\lambda A\xi = -\frac{1}{r}\frac{\partial\Phi_1}{\partial\theta} = -\sum_{m=1}^{n} D_m \sin m(\theta - \vartheta_m),$$

- Calculate the orbits in an arbitrary gravitational potential and for given viewing angle, damping efficiency, bar speed and strength and spiral pitch angle)

Deriving flows in the disc

$$V_{\rm los} = \sin i \left[v_\phi(R, \psi) \cos\psi + v_R(R, \psi) \sin\psi \right]$$

$$v_R(R, \psi) = v_c(R)[c_R \cos m\psi + s_R \sin m\psi]$$

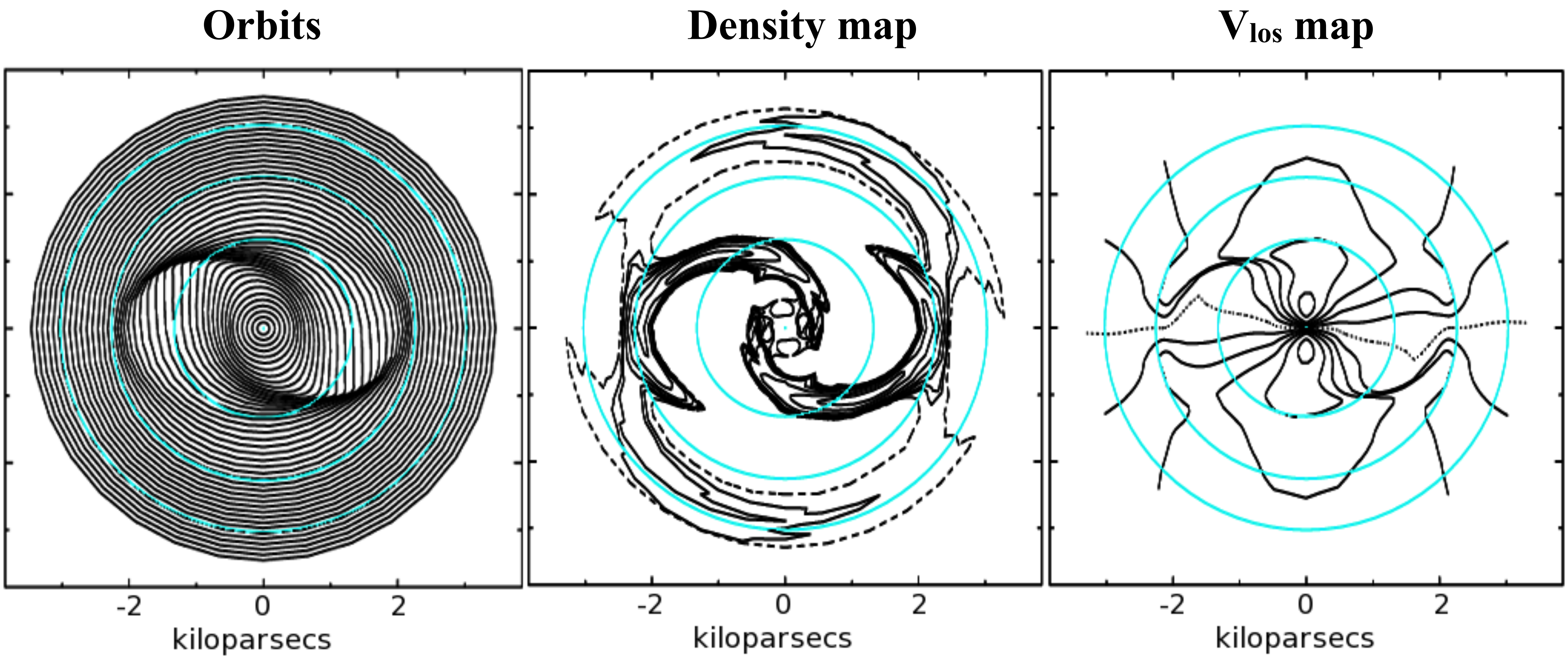
$$v_\phi(R, \psi) = v_c(R)[1 + c_\phi \cos m\psi + s_\phi \sin m\psi]$$

$$v_{\rm flow} = \left(\frac{\Lambda^2}{\Delta^2 + \Lambda^2} \right)^{1/2} v_R$$

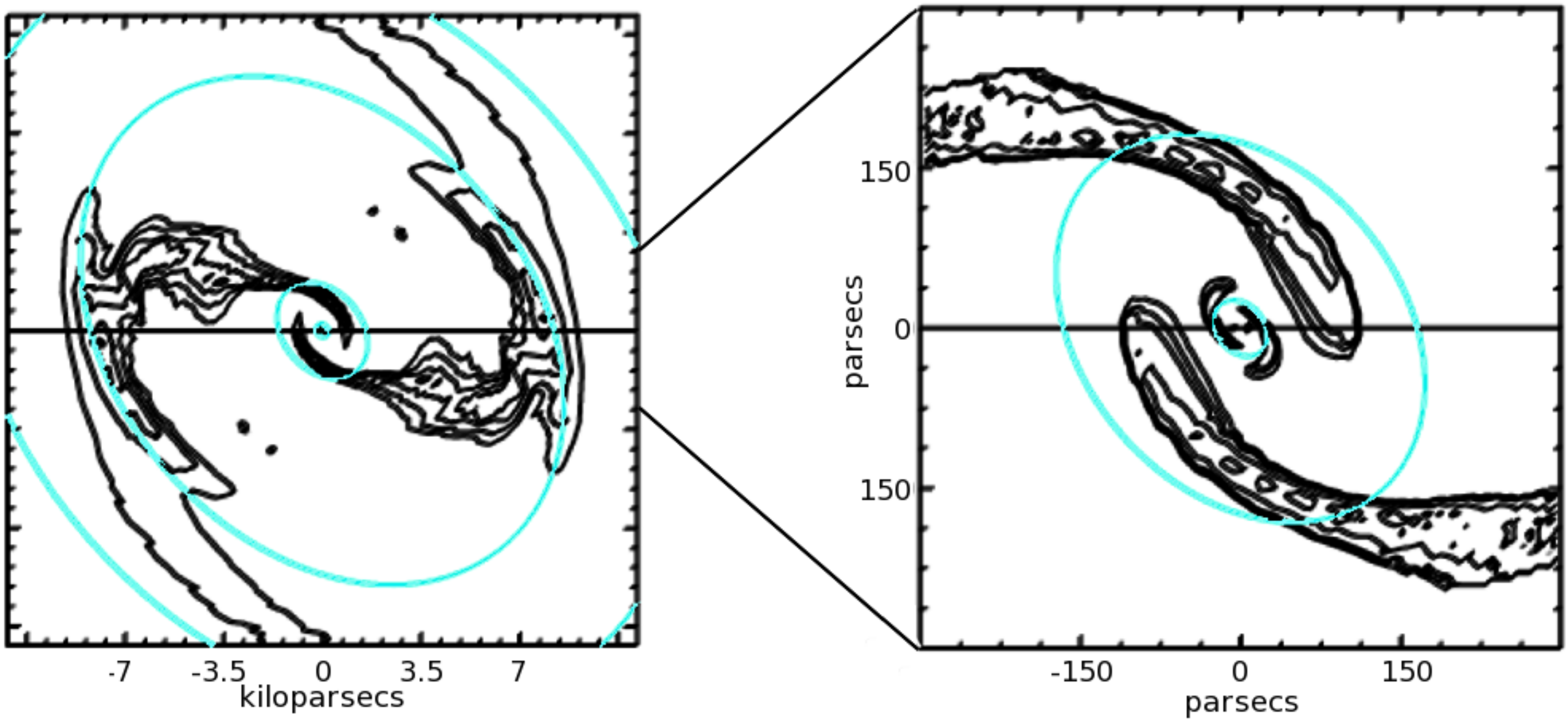
$$\Delta = \kappa^2 - m^2(\Omega - \Omega_p)^2, \quad \Lambda = 2\lambda\kappa m(\Omega - \Omega_p)$$

functions of $\Omega(R)$ and $\kappa(R)$

Orbits, densities and line of sight velocities

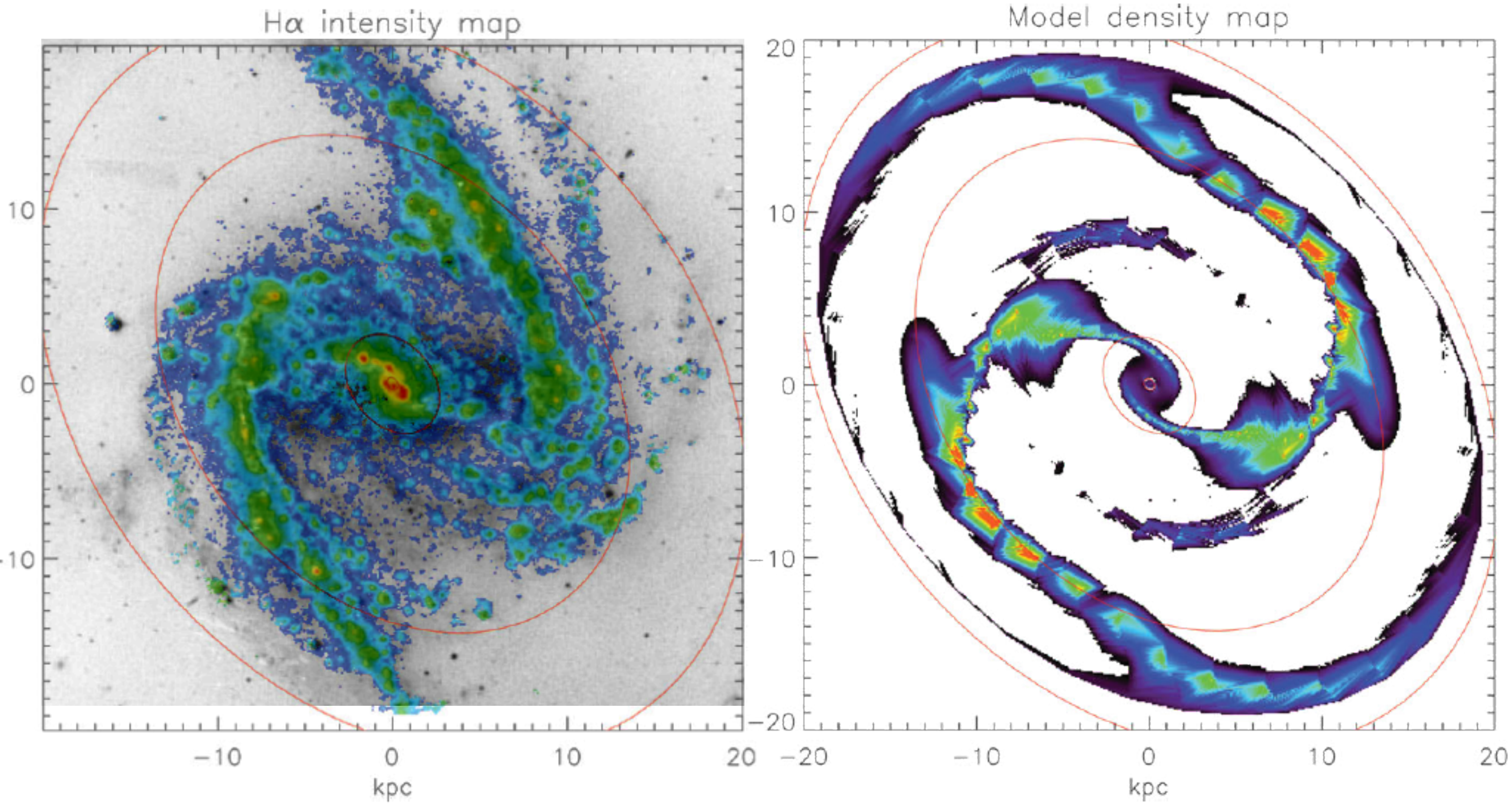


Zooming into the centre



Modelling observational data: ionized gas

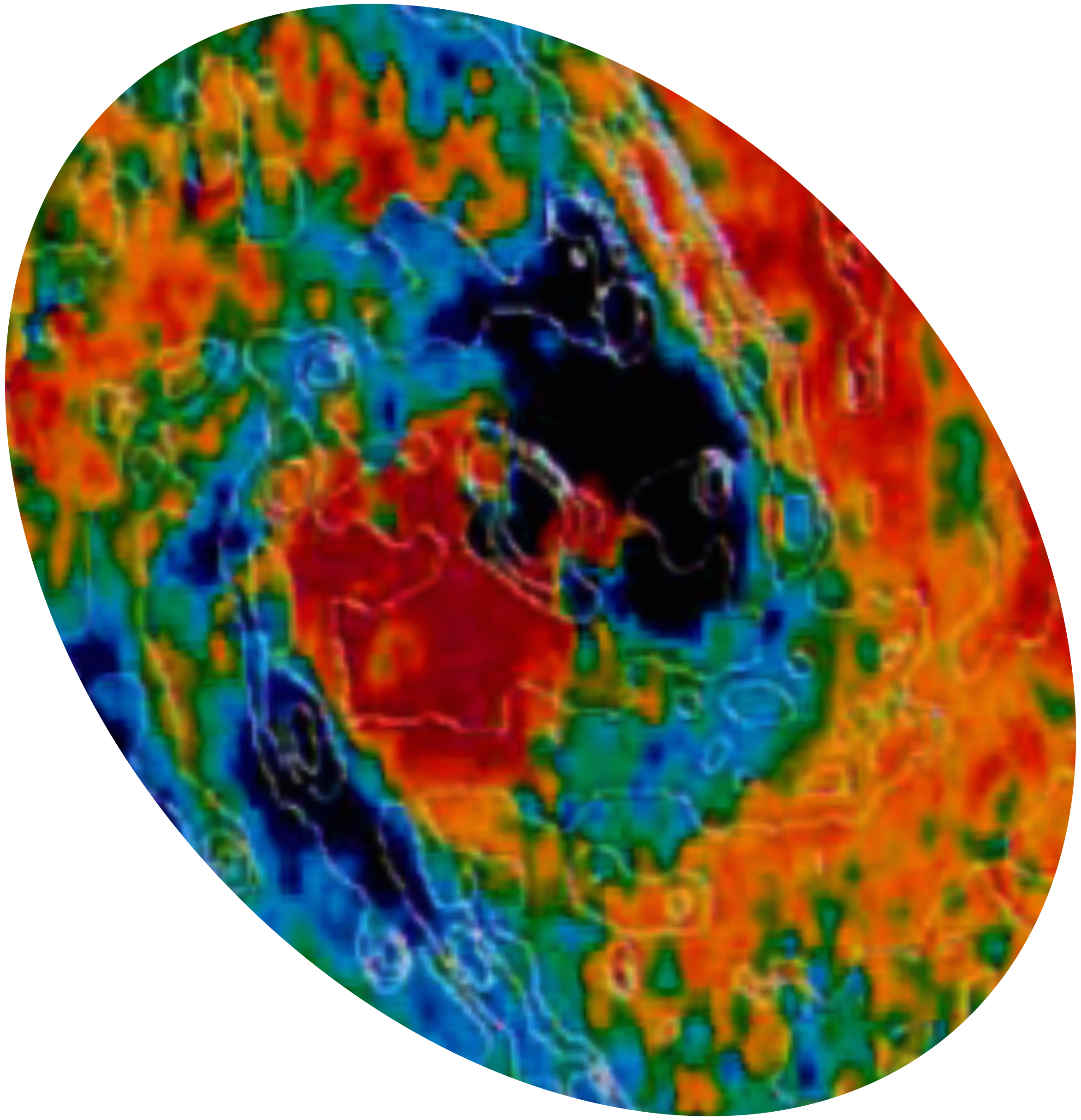
NGC 1365 @ 17 Mpc distance



Piñol-Ferrer, Lindblad, Fathi (2012)

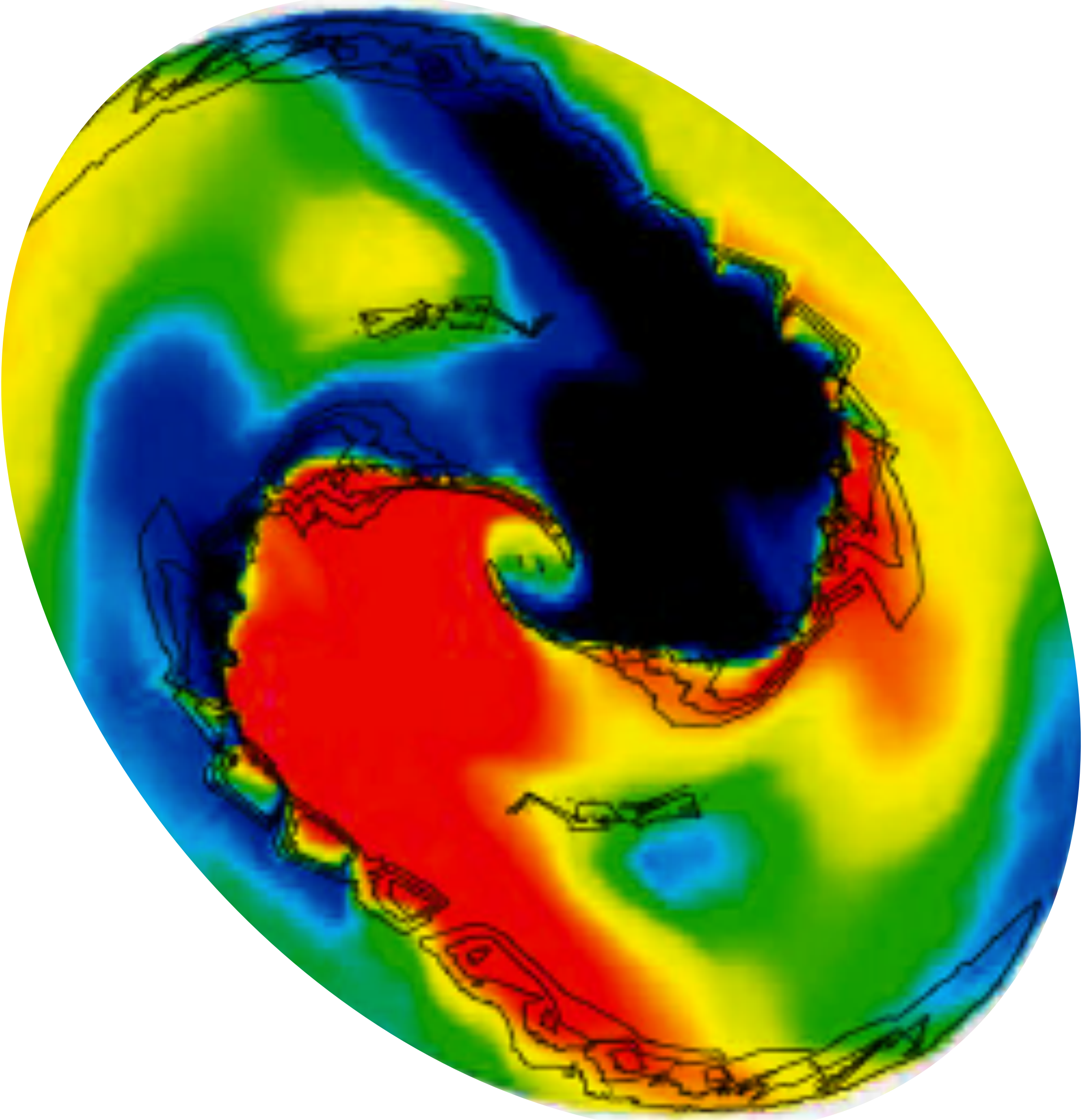
Modelling observational data: neutral gas

DATA



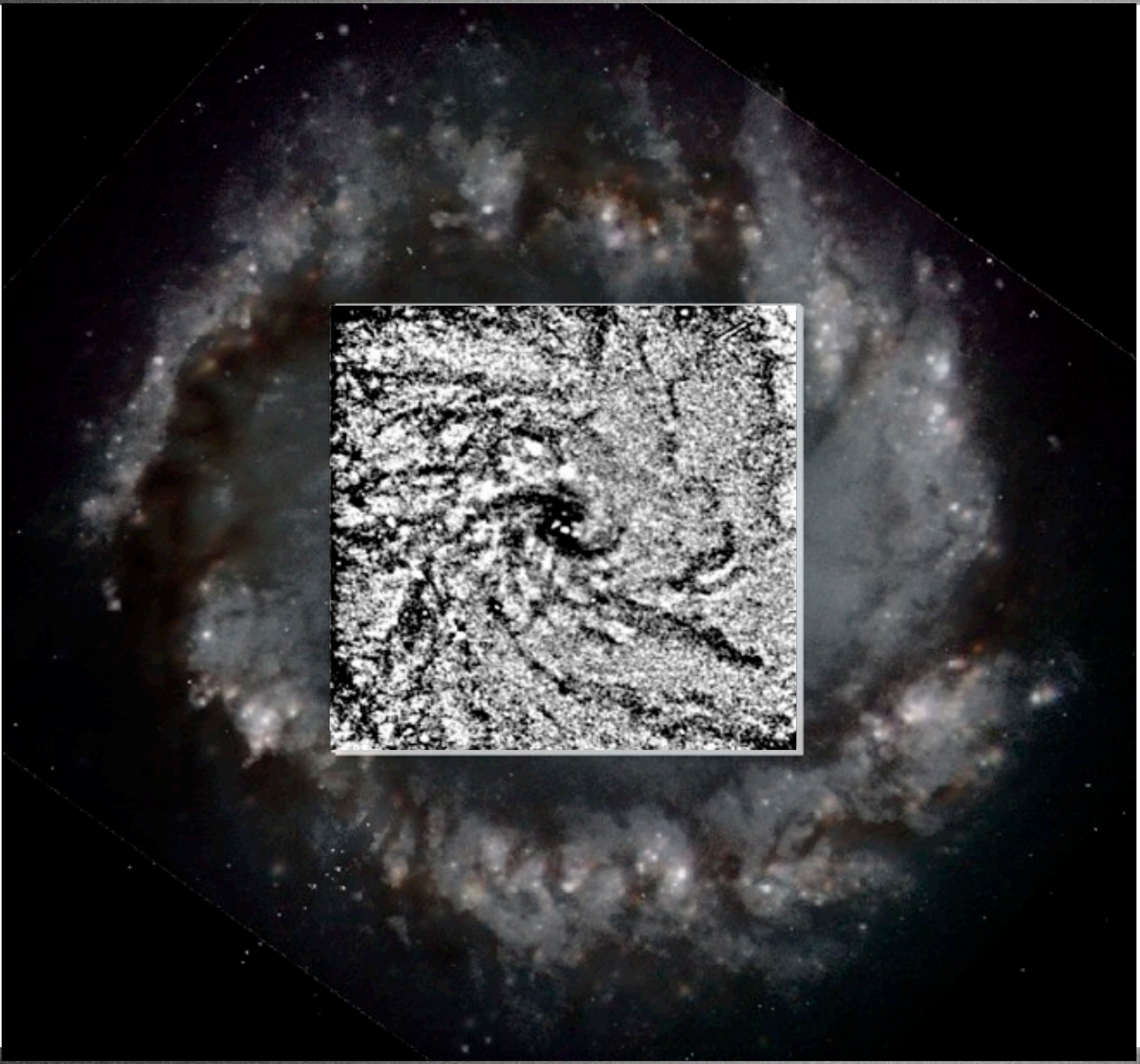
Jörsäter & van Moorsel (1996)

MODEL



Piñol-Ferrer, Lindblad, Fathi (2012)

NGC 1097: 20 kpc to 40 pc / in optical to radio



NGC 1097 @ 14.5 Mpc distance

Large-scale dynamics:
Fabry-Perot data
VLA data

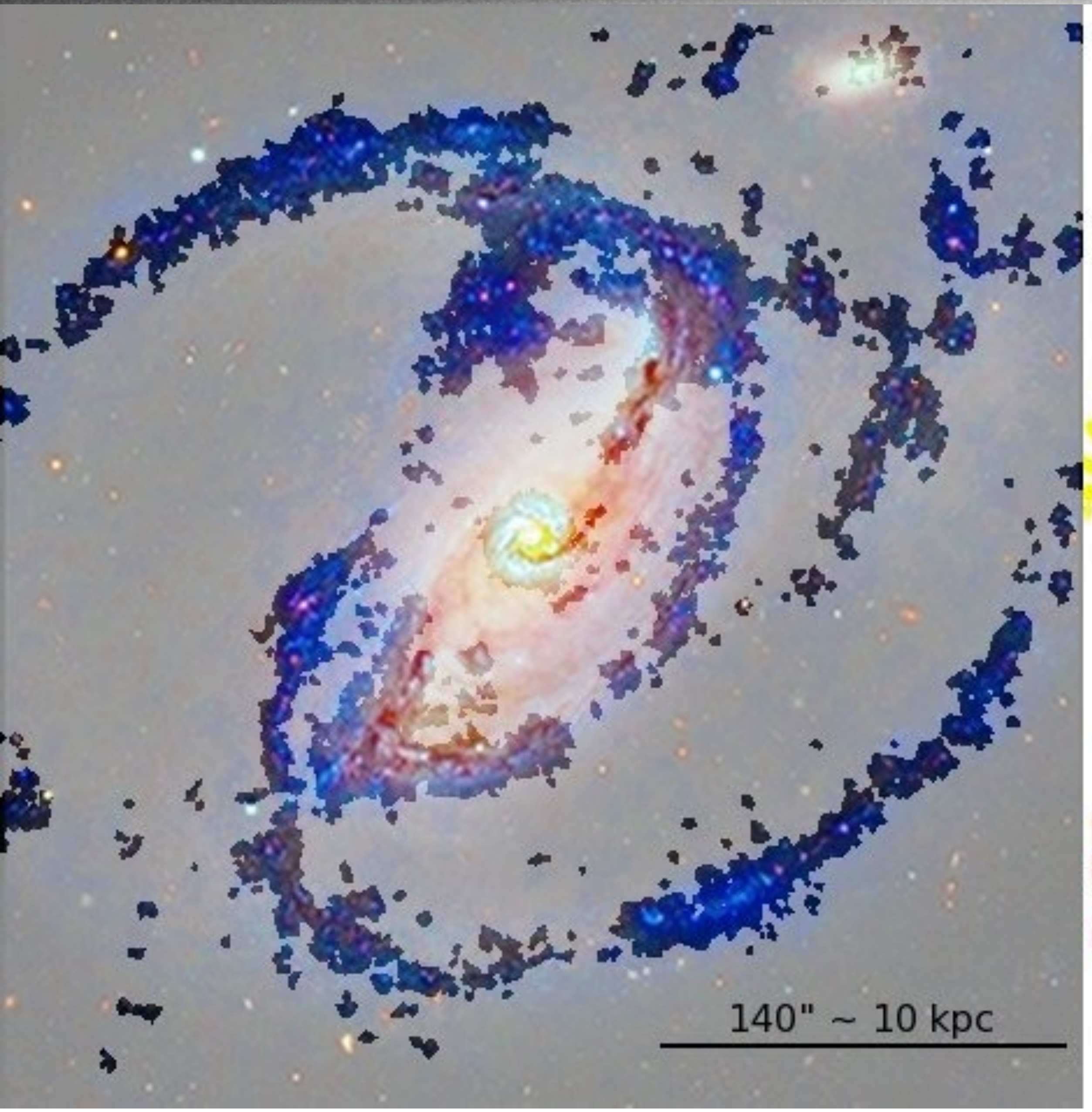
Small-scale dynamics:
8-m Gemini 2D spectra
SMA data (archival)
ALMA (Cycle 0 and 1)

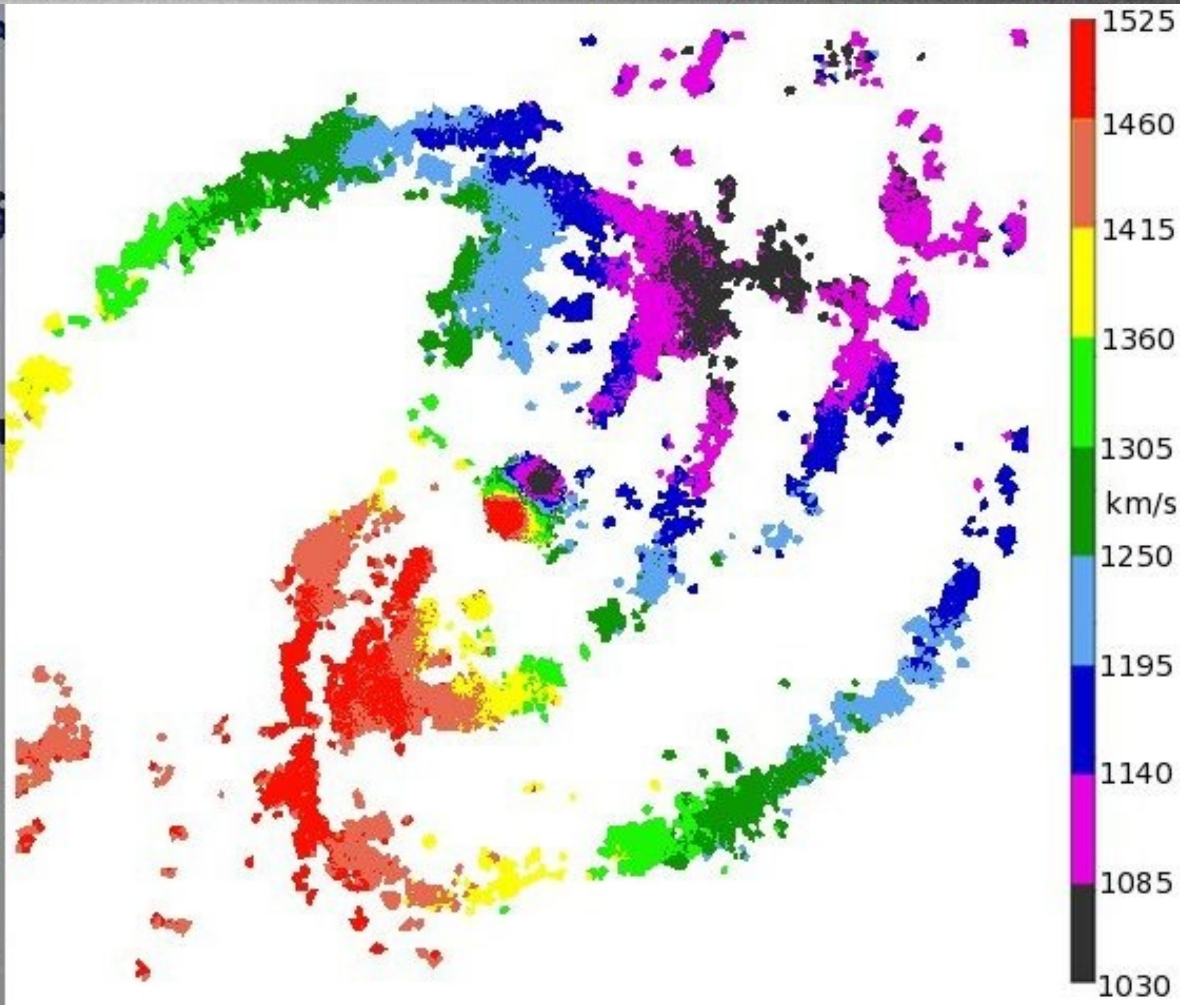
Single-dish:
APEX, JCMT, IRAM

+ our own Hubble Space Telescope images and spectra (GO 9872)

Fathi et al. (2006)

NGC 1097: 20 kpc to 40 pc / in optical to radio

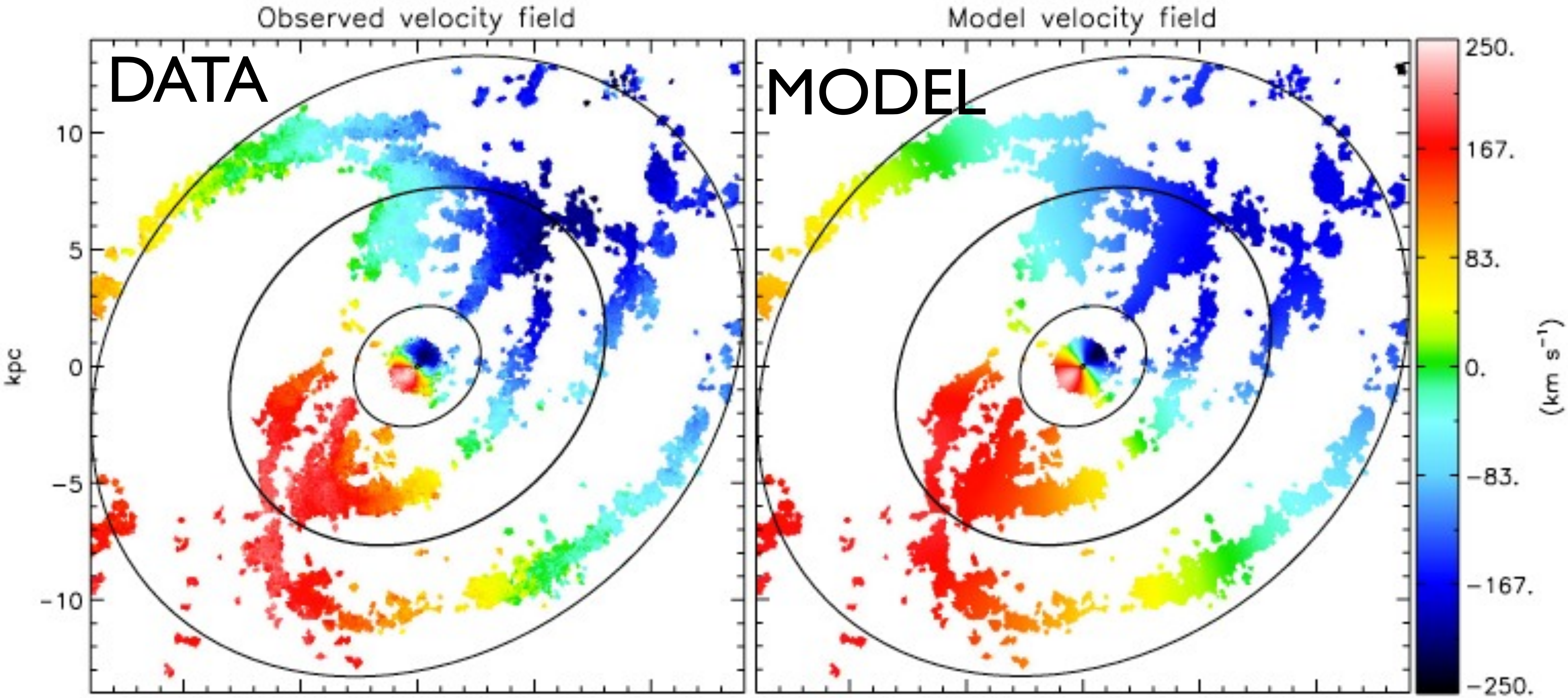




Hα line observed with our Fabry-Perot Interferometer covering 8′x8′ field at 0.8"/pix with a velocity sampling = 15 km/s

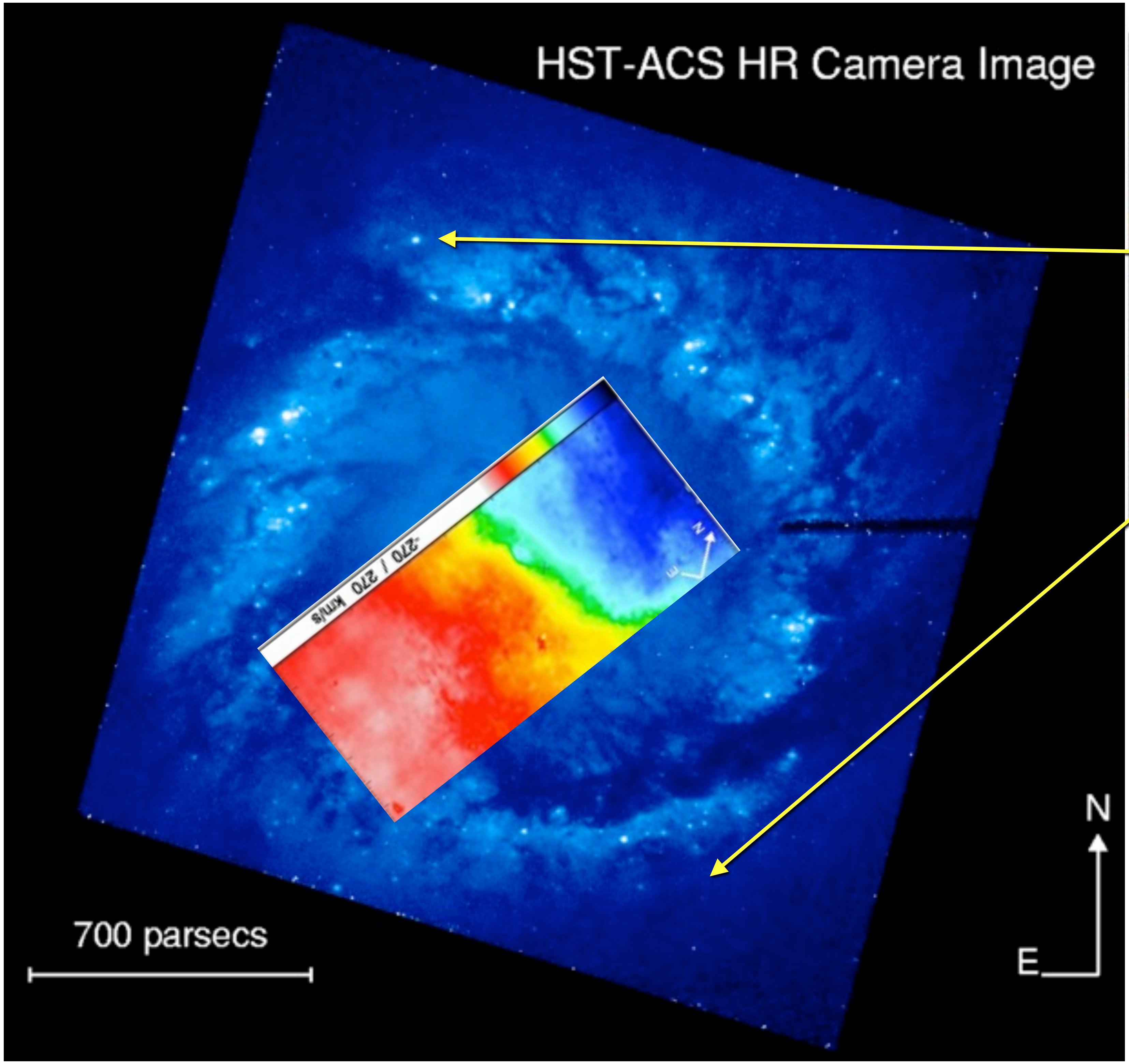
VLA DnC configuration data at 21 km/s and beam FWHM of 56"

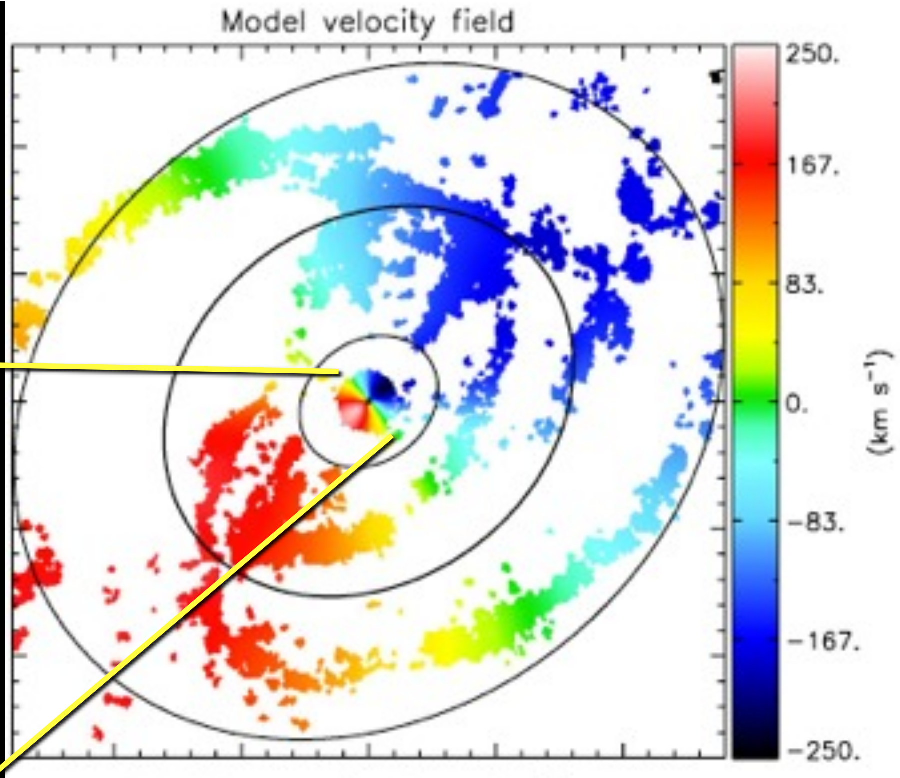
NGC 1097: 20 kpc to 40 pc / in optical to radio



Piñol-Ferrer, Fathi et al. (2014)

NGC 1097: 20 kpc to 40 pc / in optical to radio



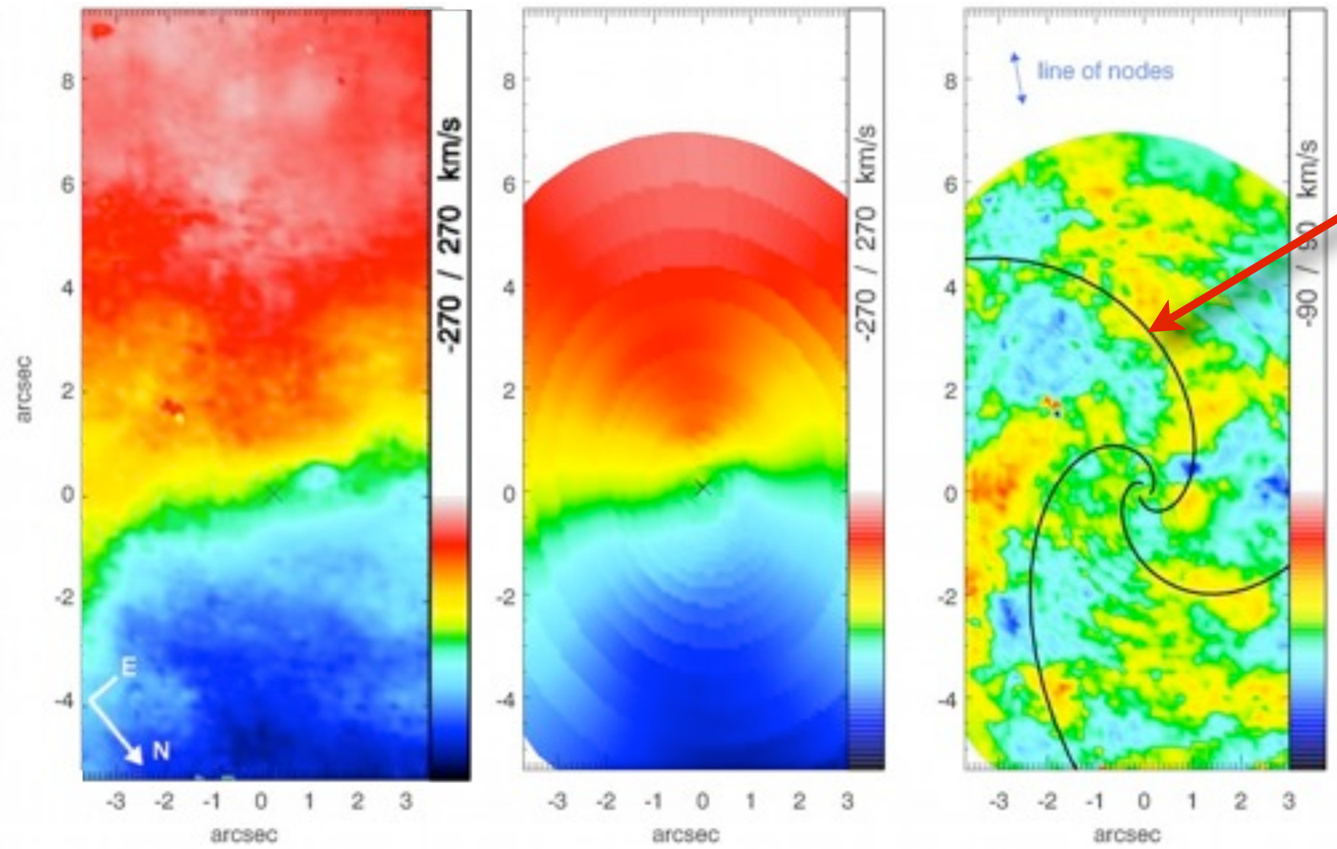


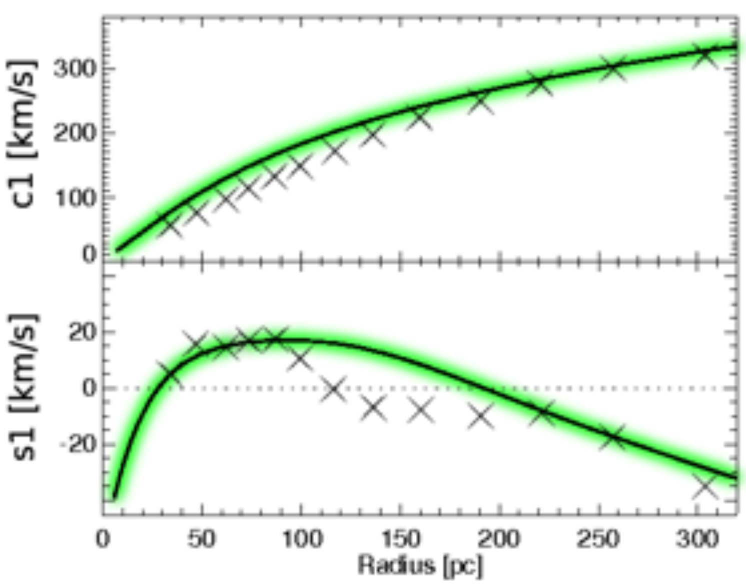
GMOS-2D spectra cover Hα, [NII], [SII] lines at 0.1"/pix (0.8" / pix in big map) at 85 km/s (FWHM)

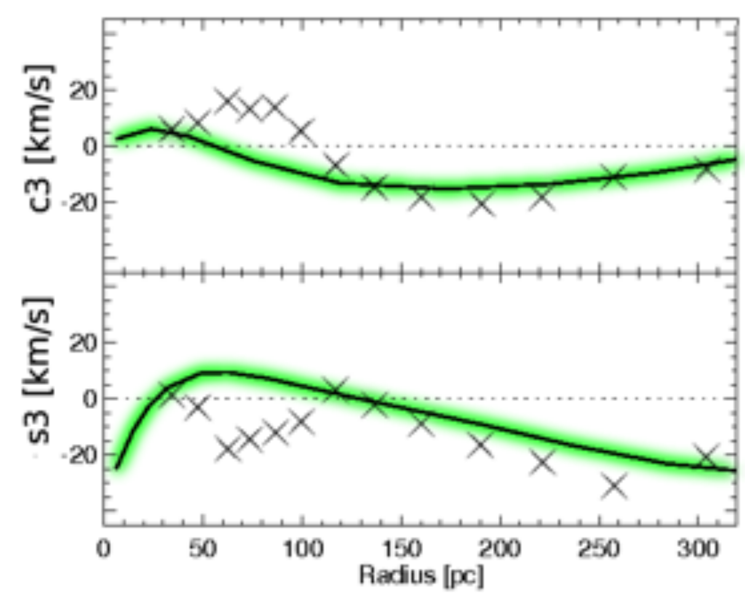
Fathi et al. (2006)

Direct evidence for flows along nuclear spiral arms

Kinematic arms, not density arms

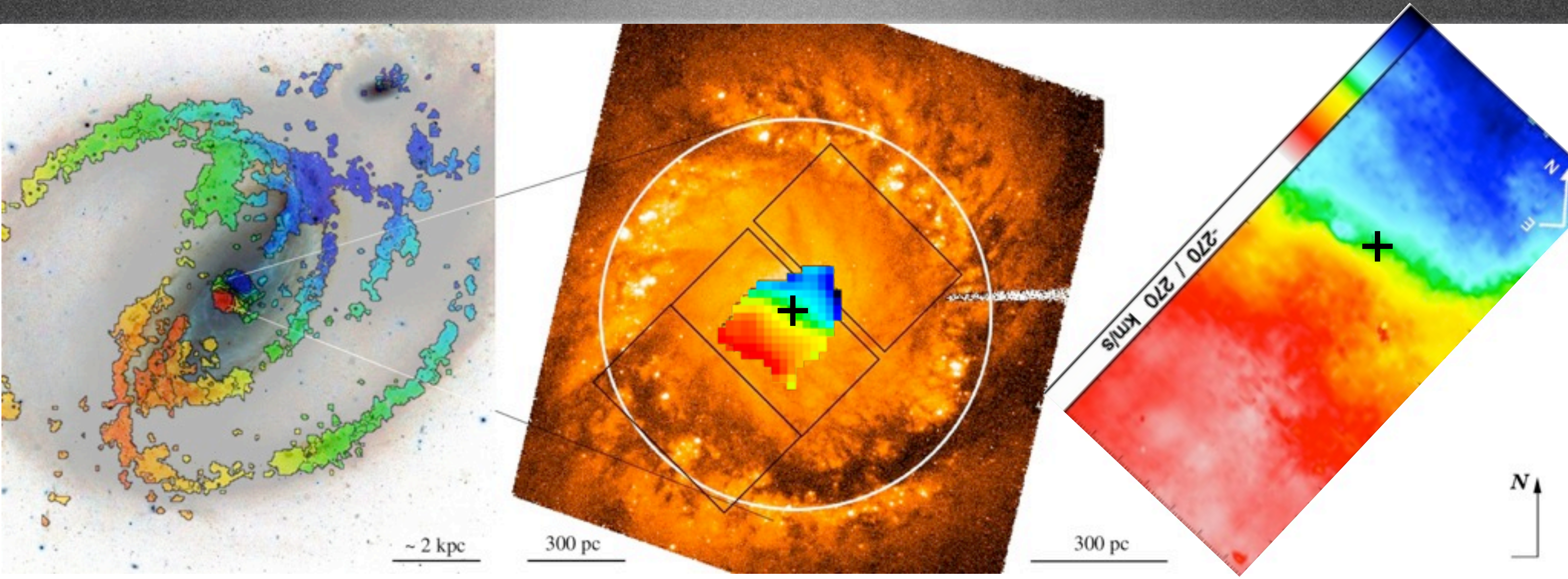






Fathi et al. (2006); van de Ven & Fathi (2010)

Synergy between optical, mm and radio observations

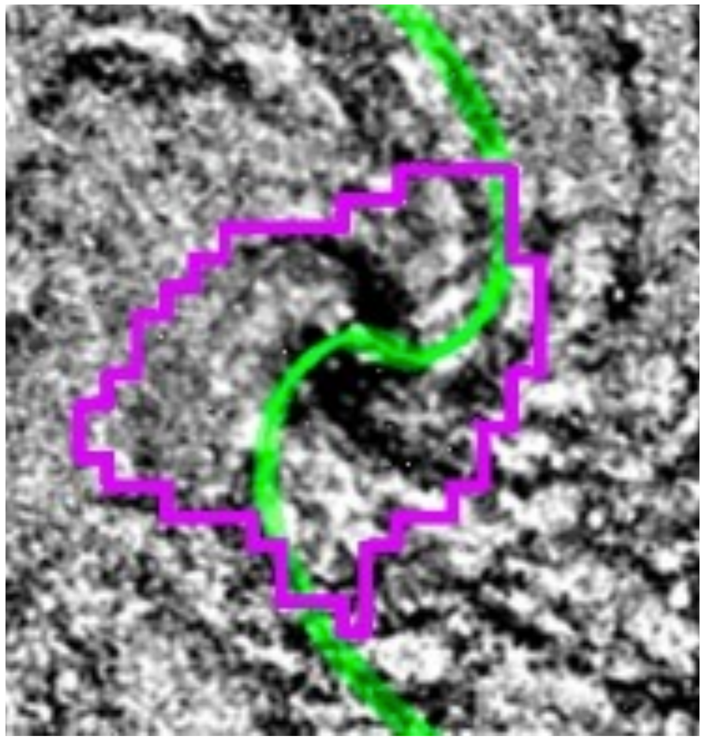


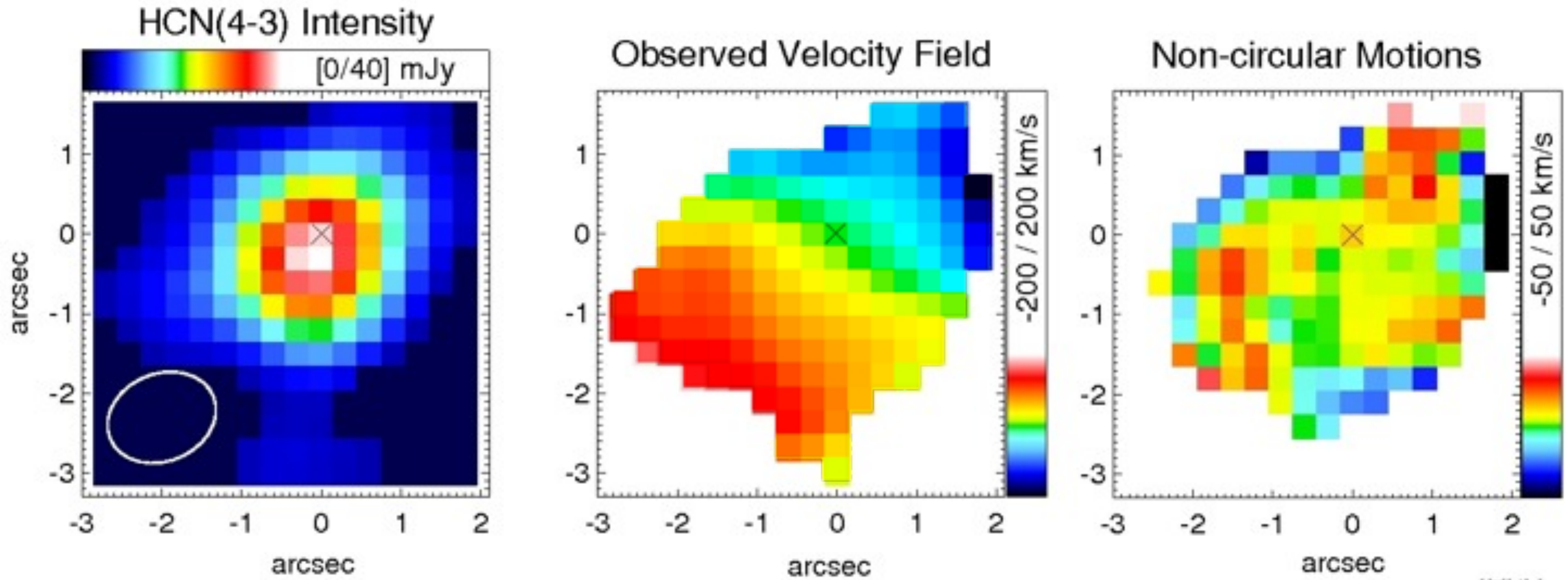
- ALMA Band 7 observations with 15 antennas (Cycle-0 data: PI - Kotaro Kohno)
- HCN(4–3) line at rest frequency of 354.505 GHz (488.28125 kHz)
- Primary beam of 18.1"
- Synthesized beam of 1.5" x 1.2" (105 x 84 pc) sampled at 0.3"/pix (56"/pix with VLA)

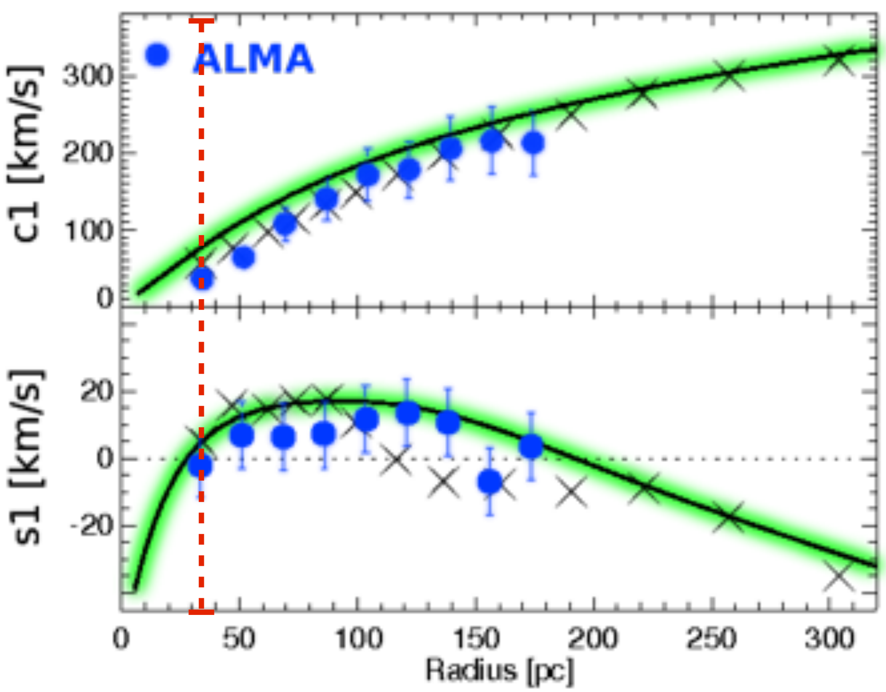
Fathi et al. (2013)

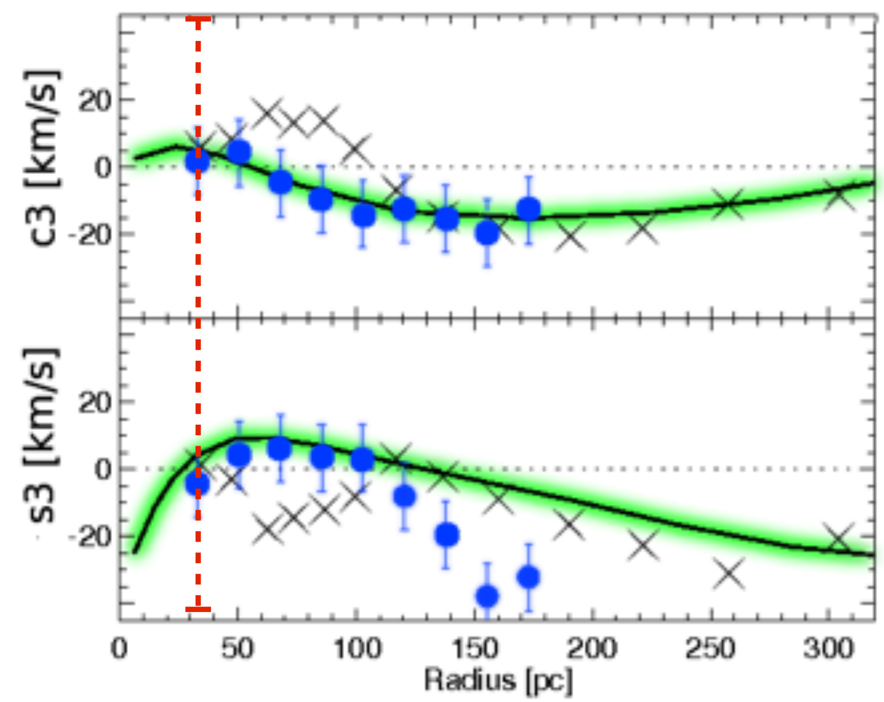
Fuelling the Supermassive Black Hole in NGC 1097

with model density arms









Ionised and molecular gas inflow rates

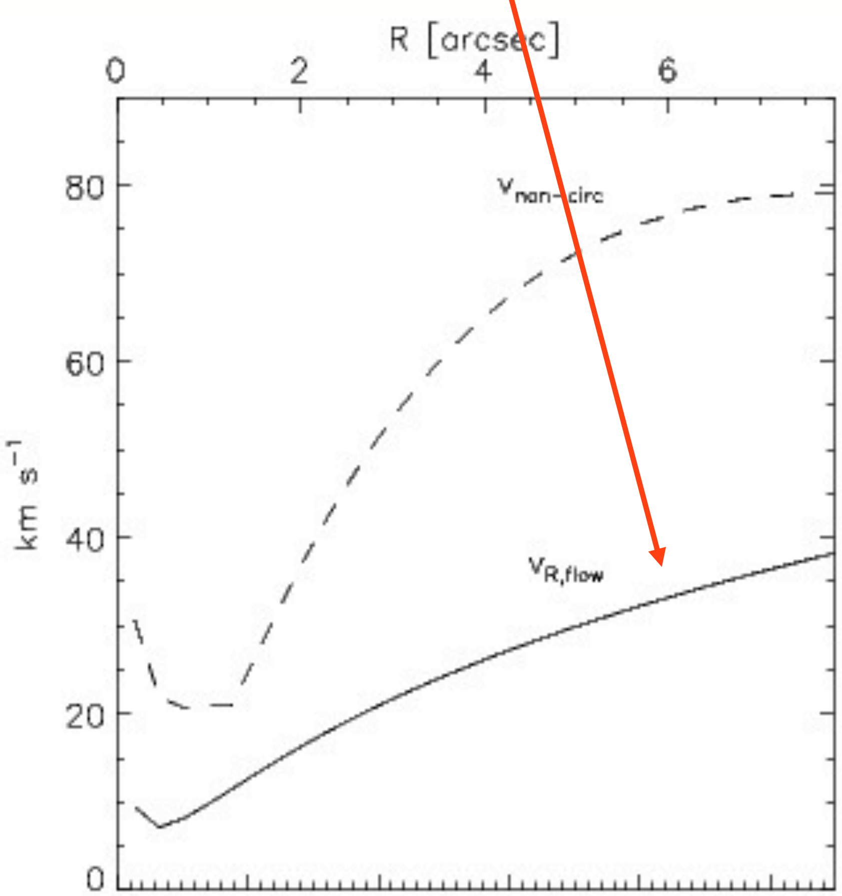
$$\dot{M} = m\, v_{\rm inflow}\, \Delta\rho_{\rm gas}\, \pi R^2\, \frac{h}{R}\, \frac{1}{4m}$$

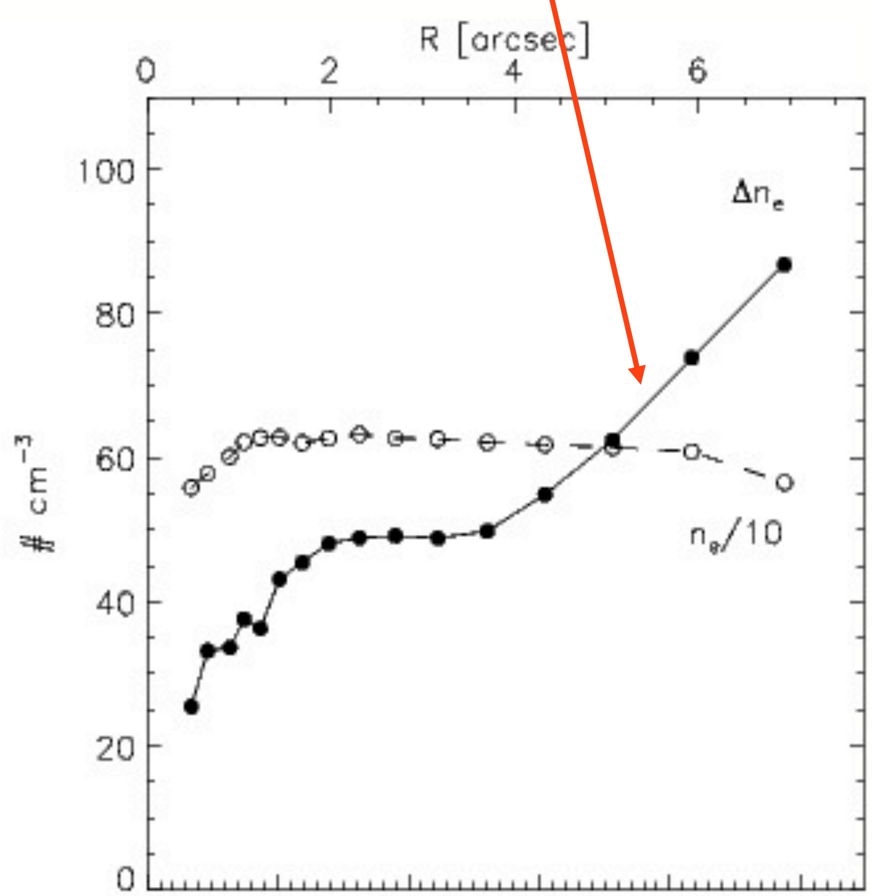
# of arms

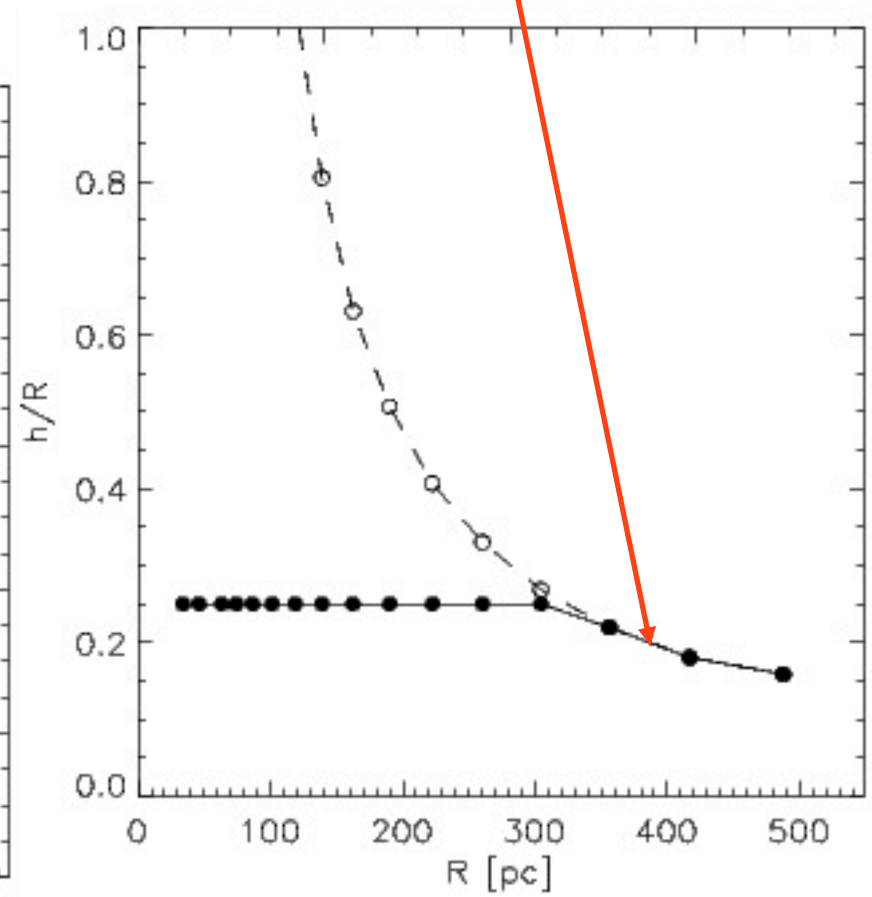
inflow velocity
spiral model

gas (over)density
[SII] doublet ~6700Å

geometric area
Toomre's Q=1



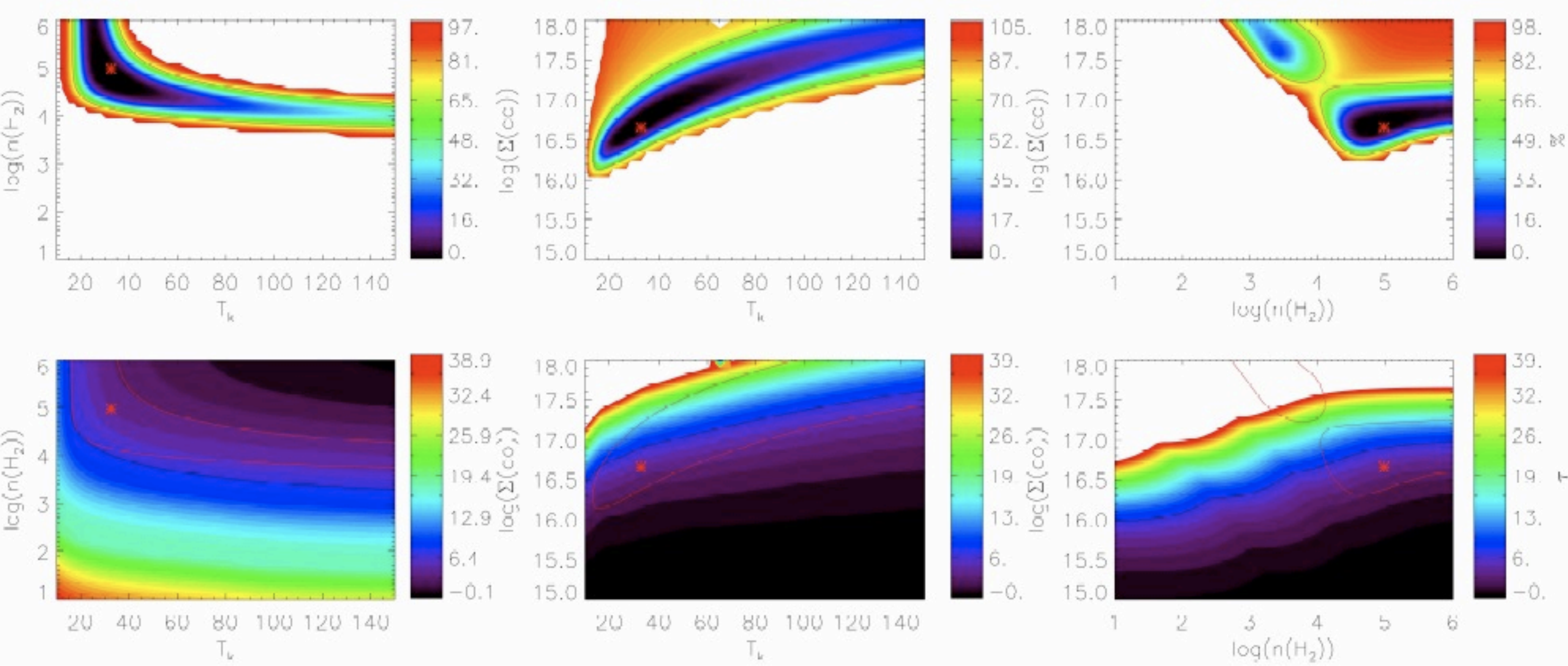




van de Ven & Fathi (2010)
Piñol-Ferrer et al. (2011)
Fathi et al. (2013)

Ionised and molecular gas inflow rates

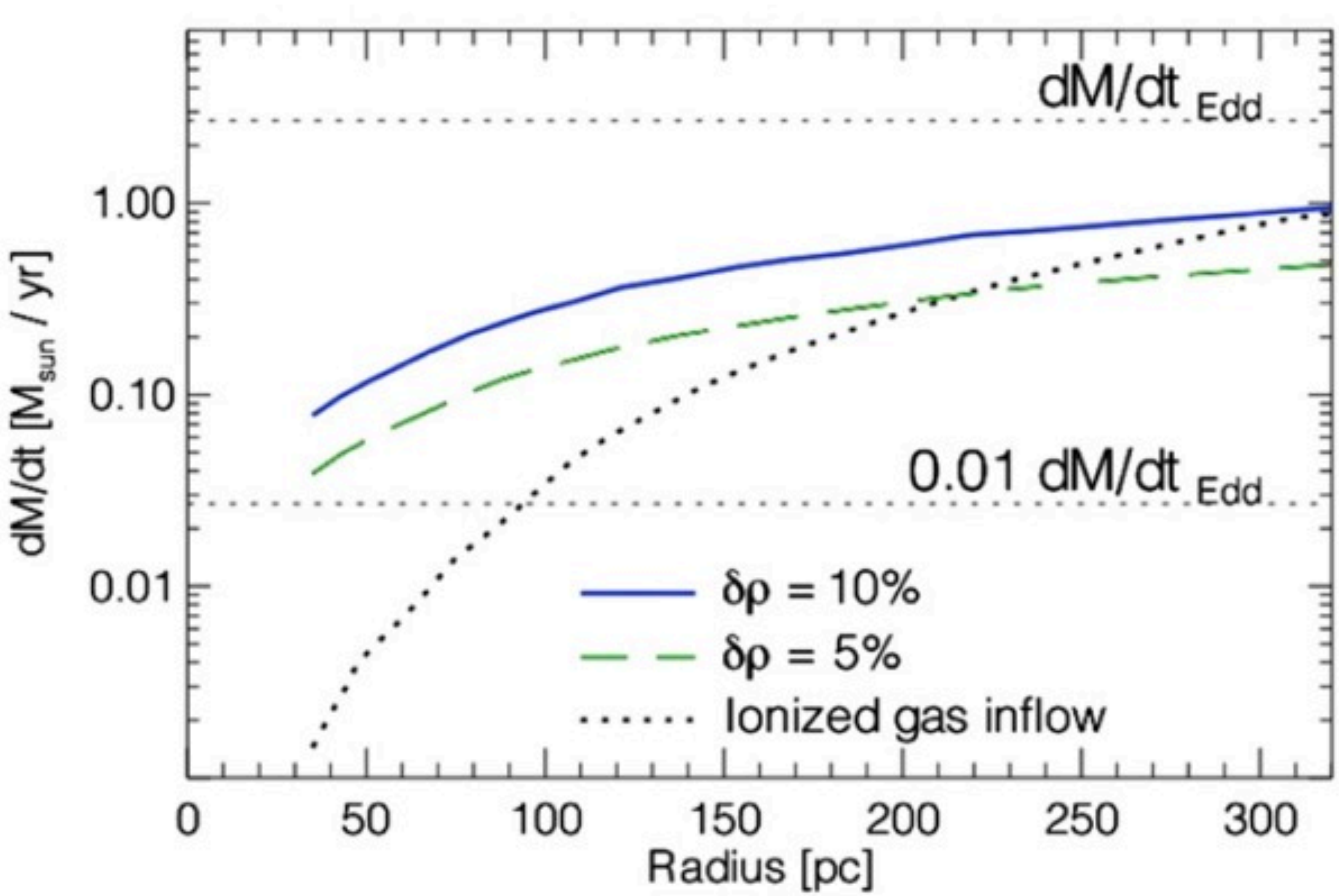
- [SII] lines to measure the ionised gas
- CO isotopologues to measure the molecular gas (Local thermal equilibrium method)
- HCN to measure the densest cores



Piñol-Ferrer et al. (2011); Fathi et al. (2013)

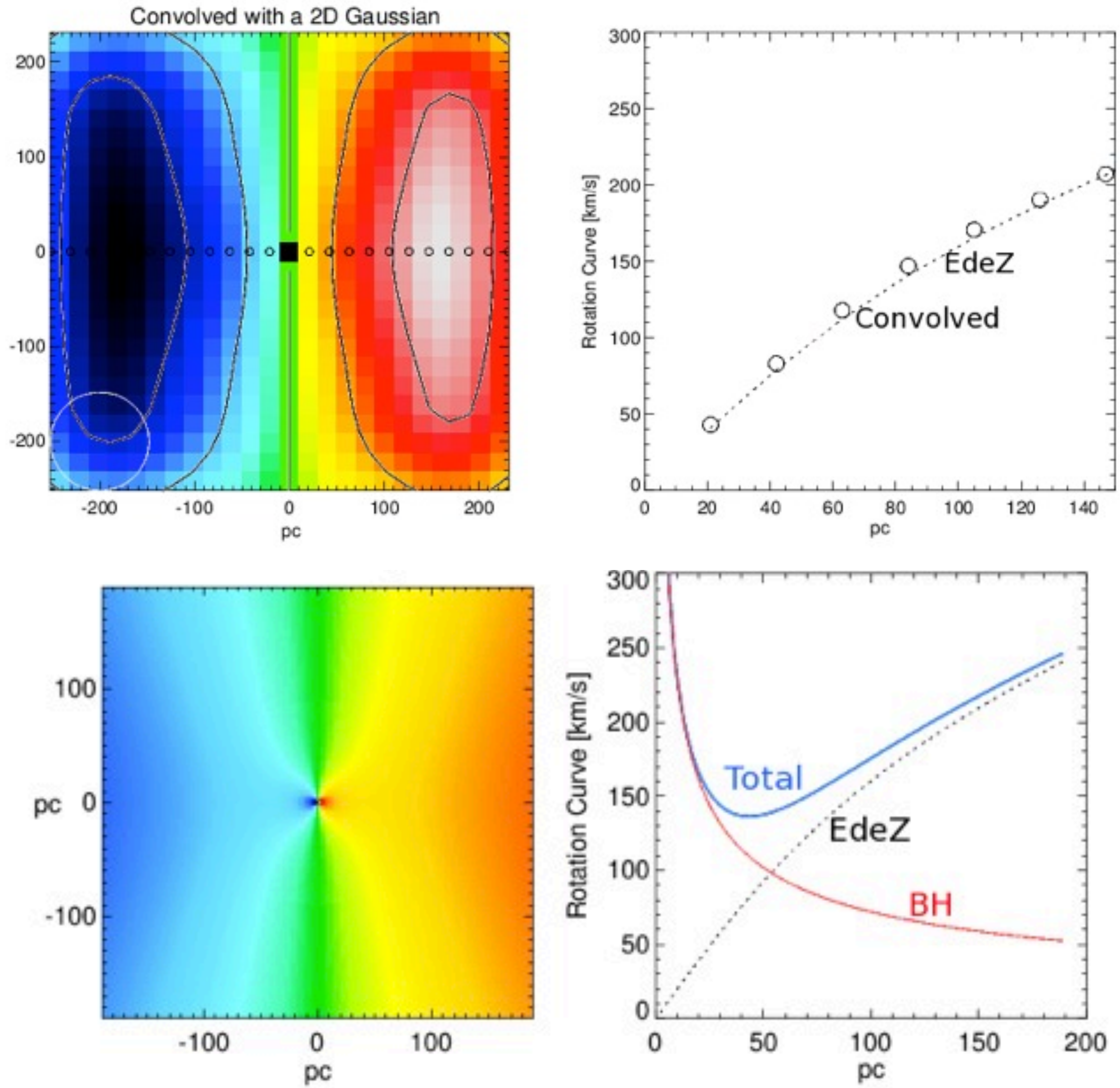
Ionised and molecular gas inflow rates

- NGC 1097 hosts a 1.2×10^{8} M⊙ Supermassive Black Hole
- This implies an Eddington accretion rate (ε=0.1) = $(dM/dt)_{Edd}$ = 2.7 M⊙/yr



Piñol-Ferrer et al. (2011); Fathi et al. (2013)

How close are we to the Supermassive Black Hole



Fathi et al. (2013)

Summary

- Interstellar gas flows and galactic scale dynamics are best studied using a multiwavelength approach (and using 2D spectroscopy)
- The tools that we have built and developed over the past 15 years have proven successful in a number of observed galaxies
- Our new analytic approach reproduces all main observed features seen in various wavelengths: outer arms, main bar and the nuclear spirals (for the first time)
- ALMA Cy-0 observations kinematically confirm the nuclear spirals down to 40 pc from the 10^8 $M_\odot$ Supermassive Black Hole in NGC 1097
- Gas inflow rate upper limit = 0.2 $M_\odot$/yr (0.07 M_{Edd}) at 40 pc distance

Thank you