Survival of molecular gas in a stellar feedback-driven outflow seen with MUSE and ALMA

Ryan Leaman (MPIA)

Francesca Fragkoudi, Miguel Querejeta,
Gigi Y.C. Leung, Dimitri A. Gadotti, Bernd Husemann,
Jesus Falcon-Barroso, Patricia Sanchez-Blazquez,
Glenn van de Ven, Taehyun Kim, Paula Coelho,
Mariya Lyubenova, Adriana de Lorenzo-Caceres,
Marie Martig, Inma Martinez-Valpuesta,
Justus Neumann, Isabel Perez, Marja Seidel

15th Potsdam Thinkshop

NGC 3351

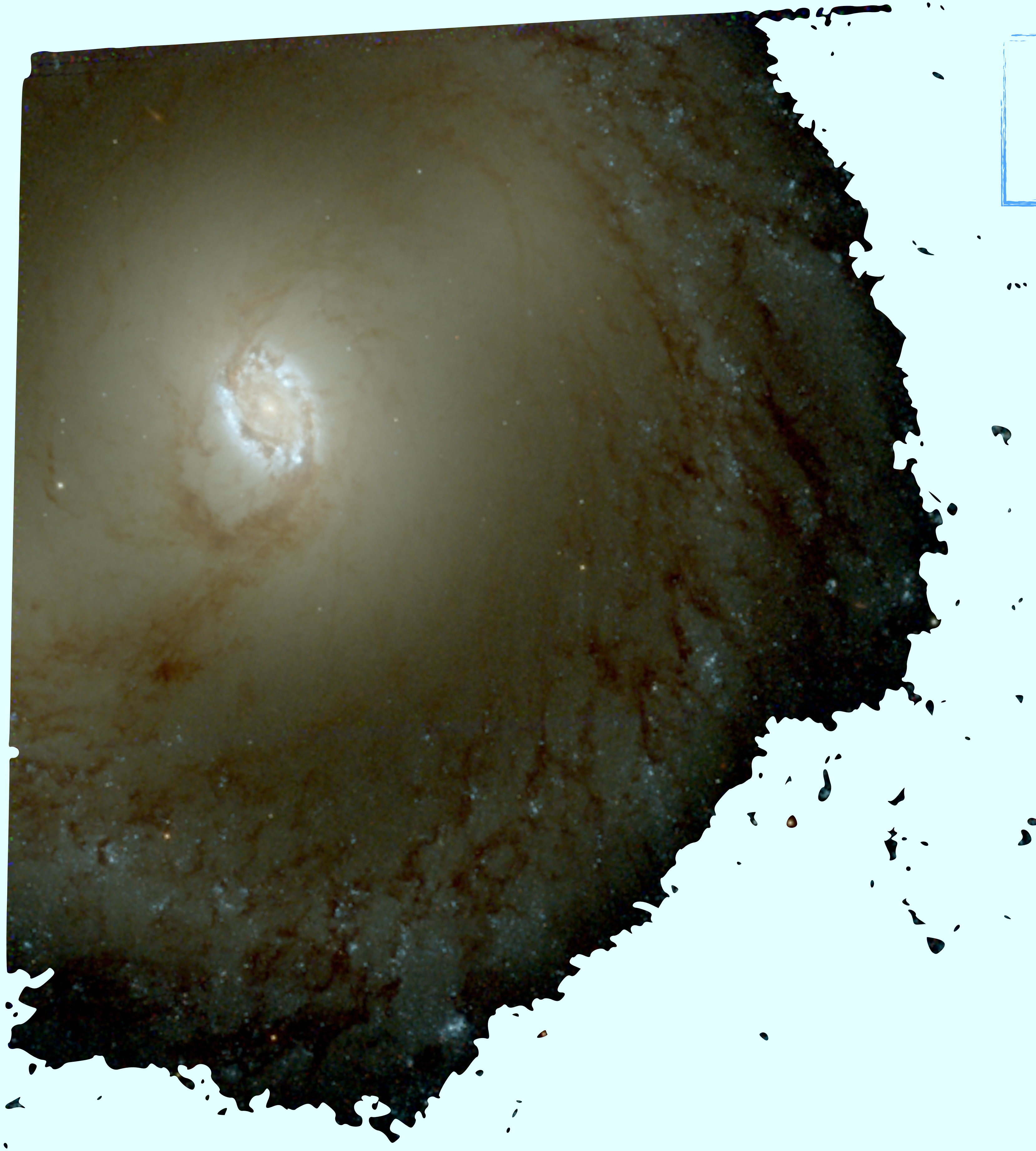


Image Credit: LEGUS Survey

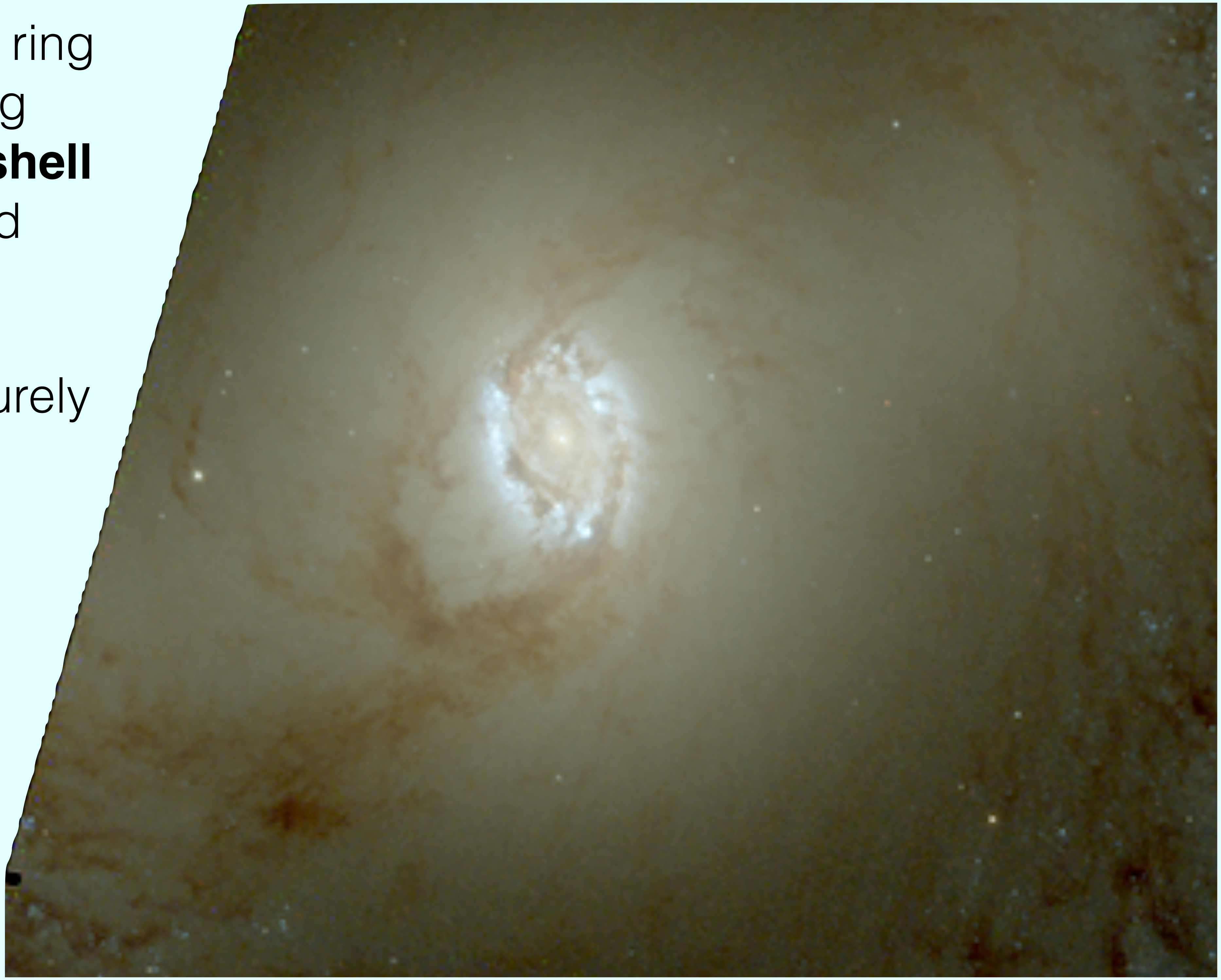
- Ionised gas and stars observed with MUSE as part of **TIMER** survey (PI: Gadotti)
- Archival **HST** (PI: Calzetti) and **ALMA** data (PI: Sandstrom)
- D = 10 Mpc, $M_* \sim M_{MW}$, SFR in nuclear ring ~ 1 M_{sun}/yr. **No AGN**.

NGC 3351

- In addition to nuclear ring and linear gas feeding lanes, a **transverse shell of molecular gas** and dust is present

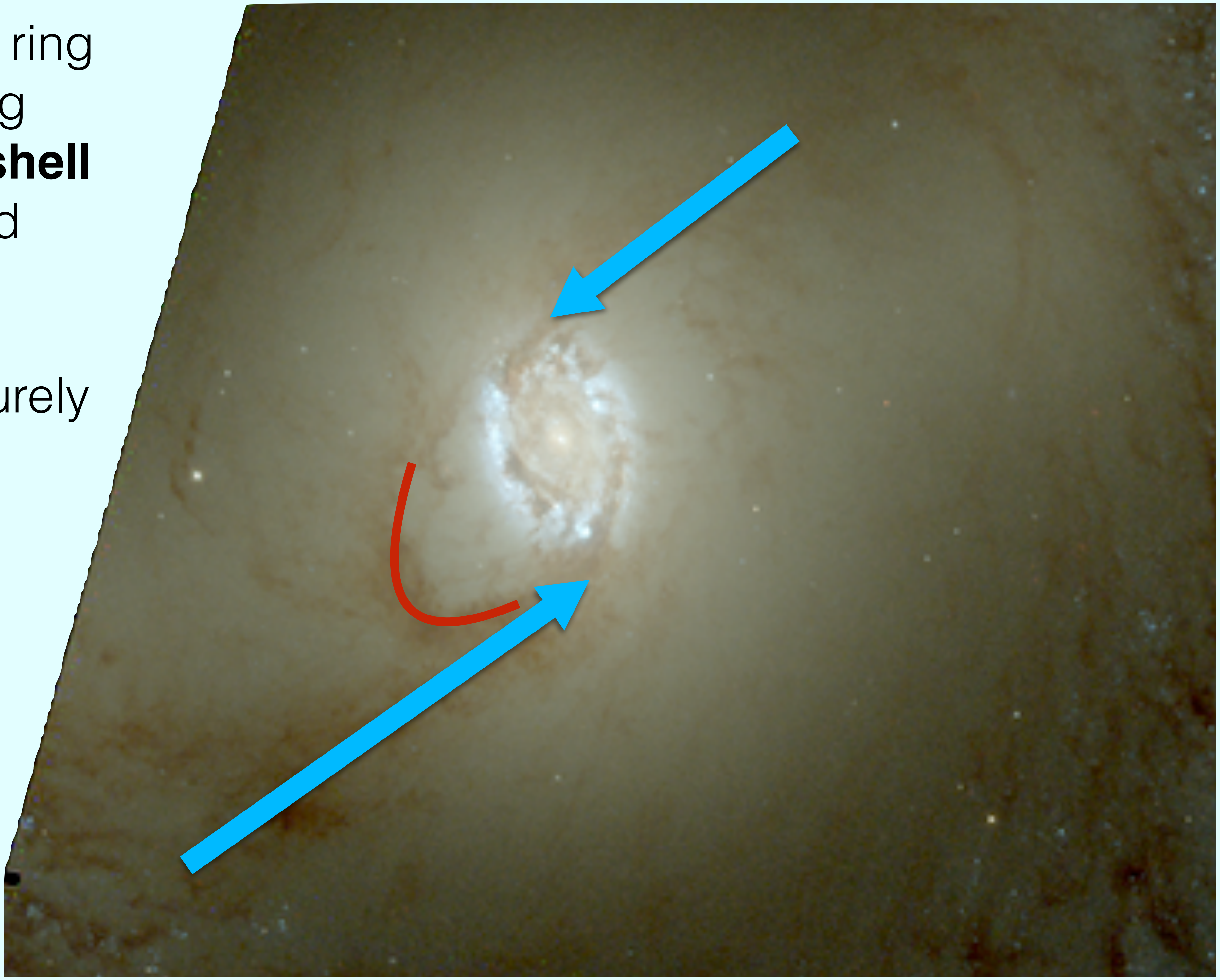
- Not expected from purely gravitational effects

- Can we use peculiar morphology as a **boundary condition to help constrain** efficiency of stellar feedback?



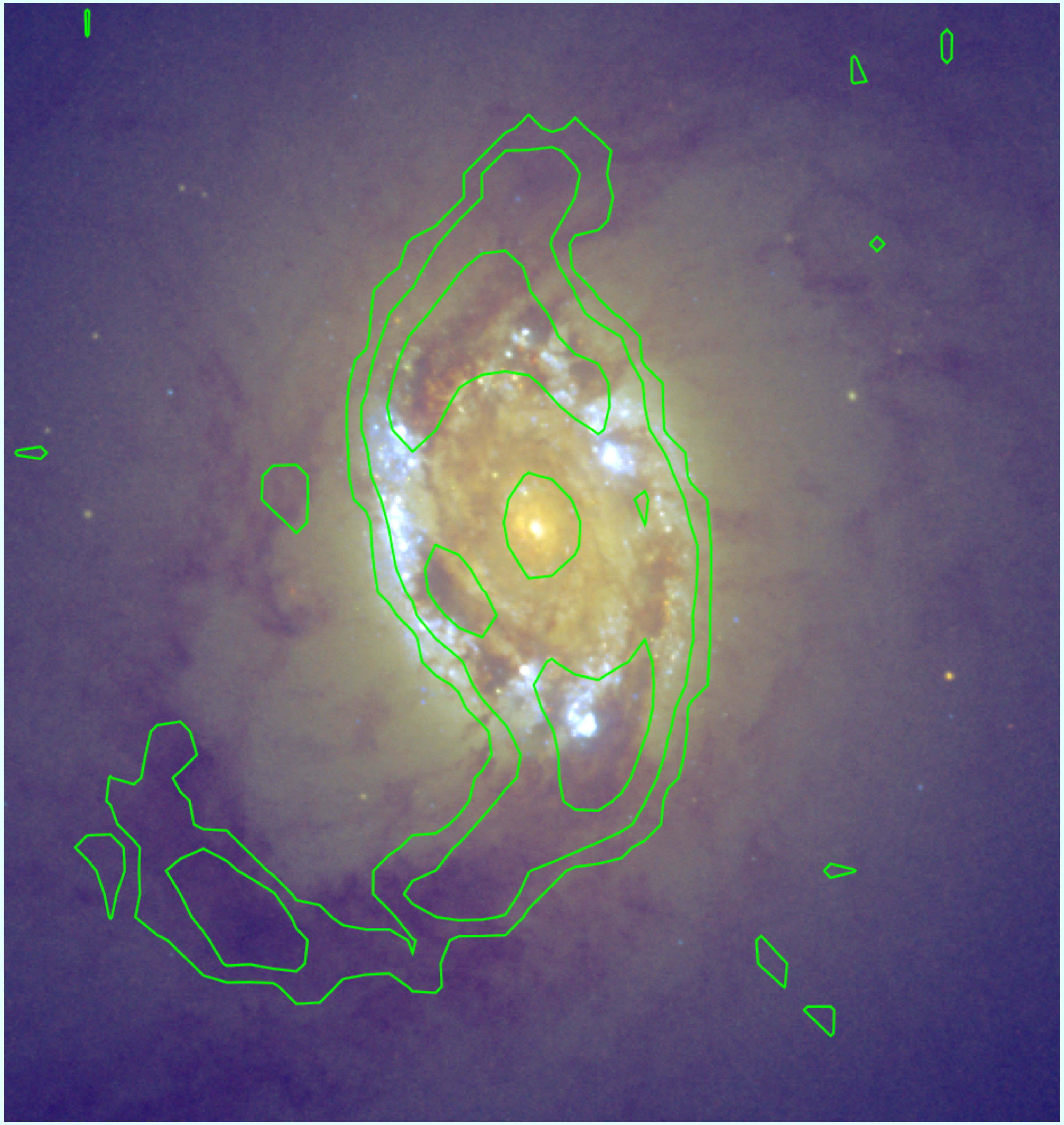
NGC 3351

- In addition to nuclear ring and linear gas feeding lanes, a **transverse shell of molecular gas** and dust is present
- Not expected from purely gravitational effects
- Can we use peculiar morphology as a **boundary condition to help constrain** efficiency of stellar feedback?



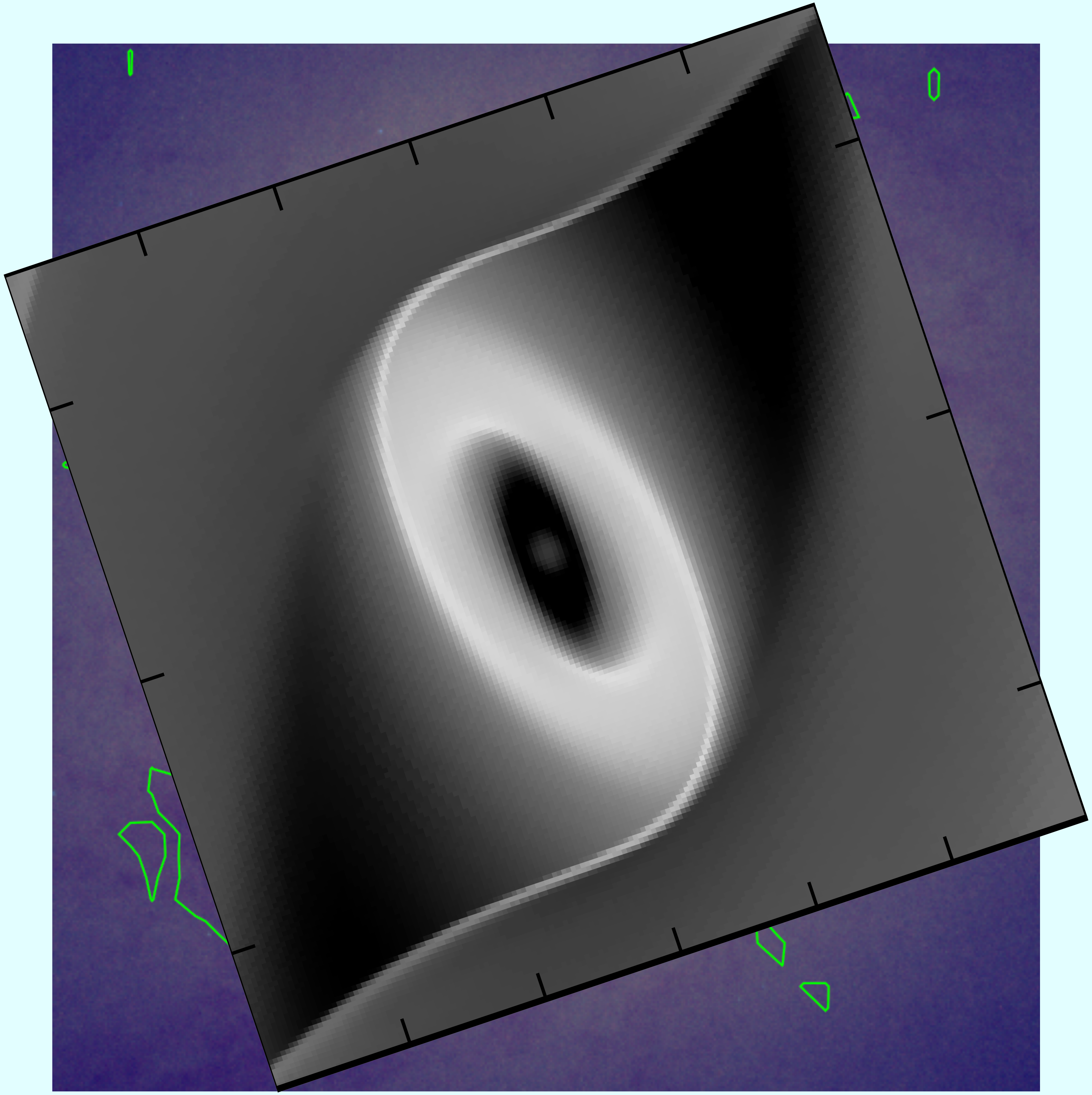
Molecular Gas Morphology

- Hydrodynamic simulations tailored to the potential of NGC 3351 confirm that this dusty molecular shell **is not expected solely from gravity**



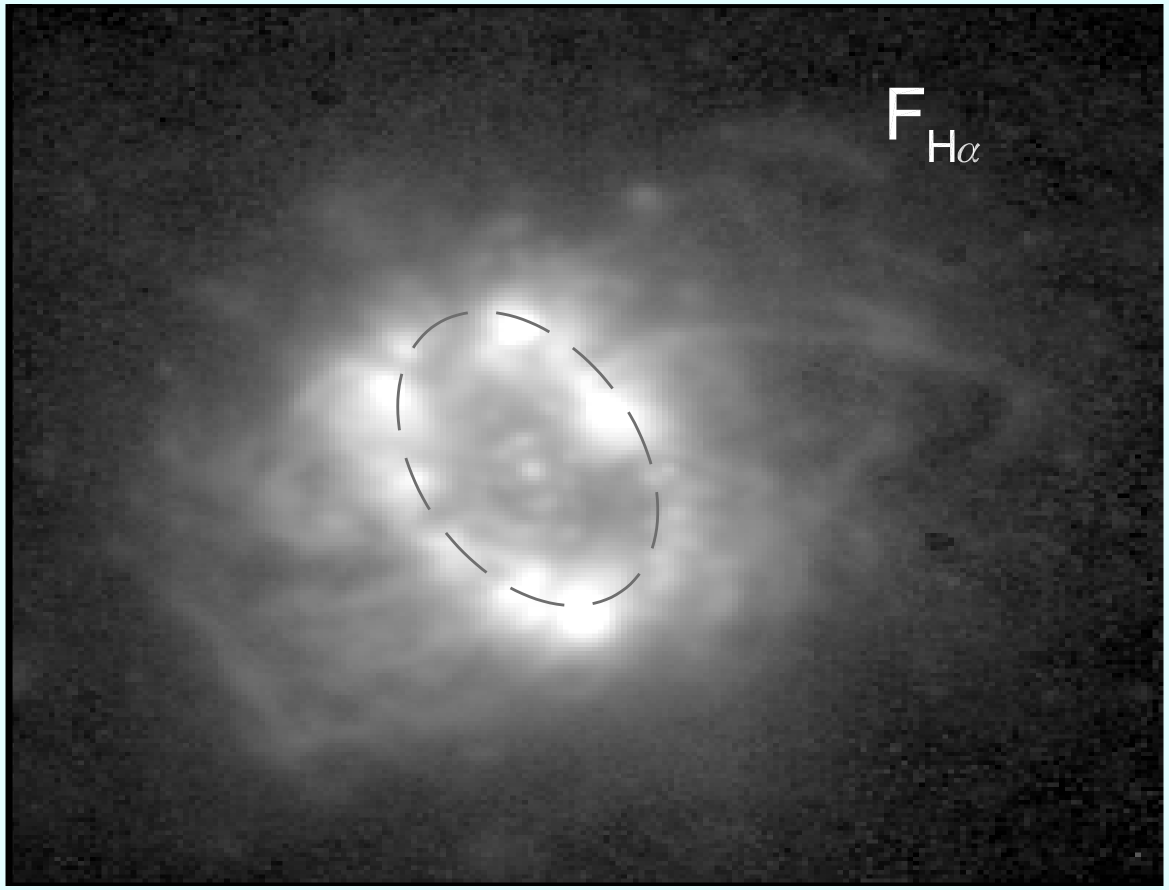
Molecular Gas Morphology

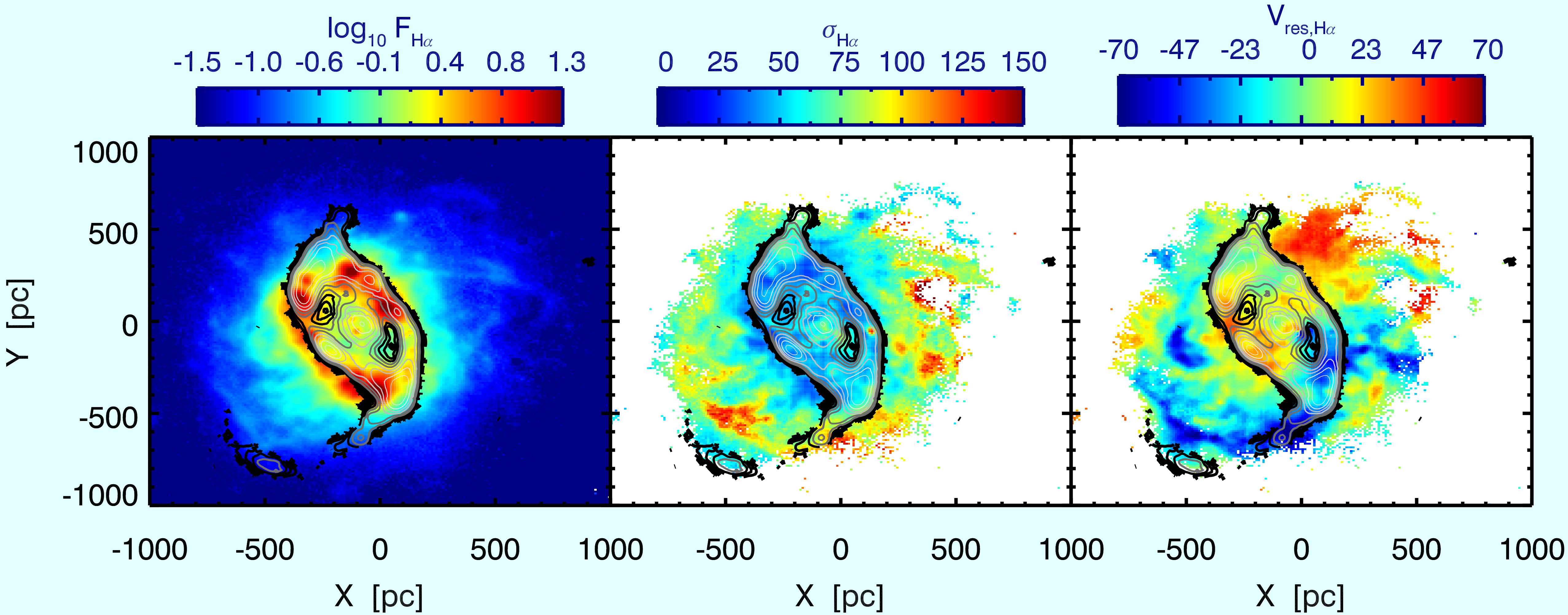
- Hydrodynamic simulations tailored to the potential of NGC 3351 confirm that this dusty molecular shell is not expected solely from gravity
- Can it be **due to feedback** from the star forming nuclear ring?



Ionised Gas Kinematics

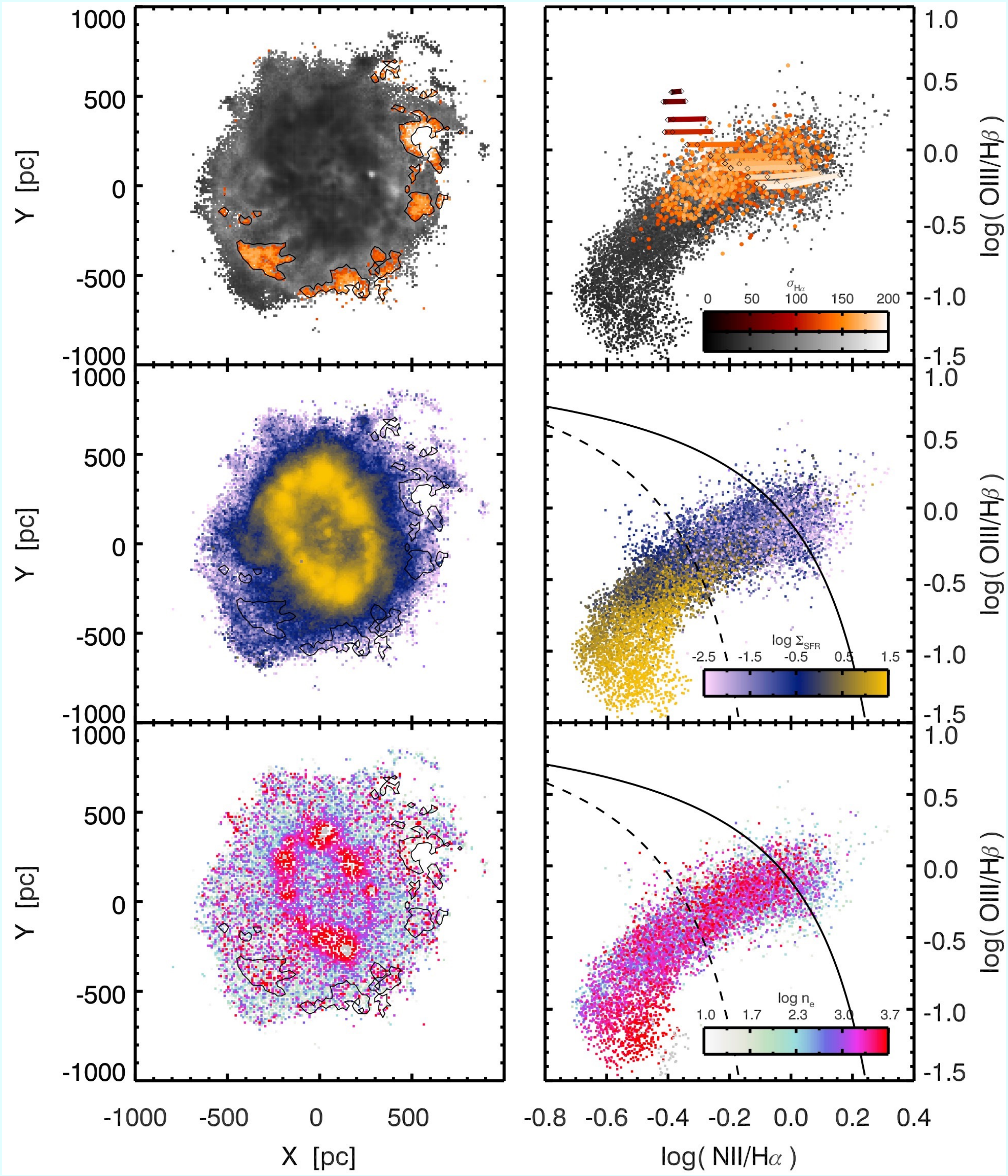
- Hα emission in MUSE cube shows **ionised gas radially expanding** from ring, bounded in cavity by dusty gas shell.





Emission Line Diagnostics

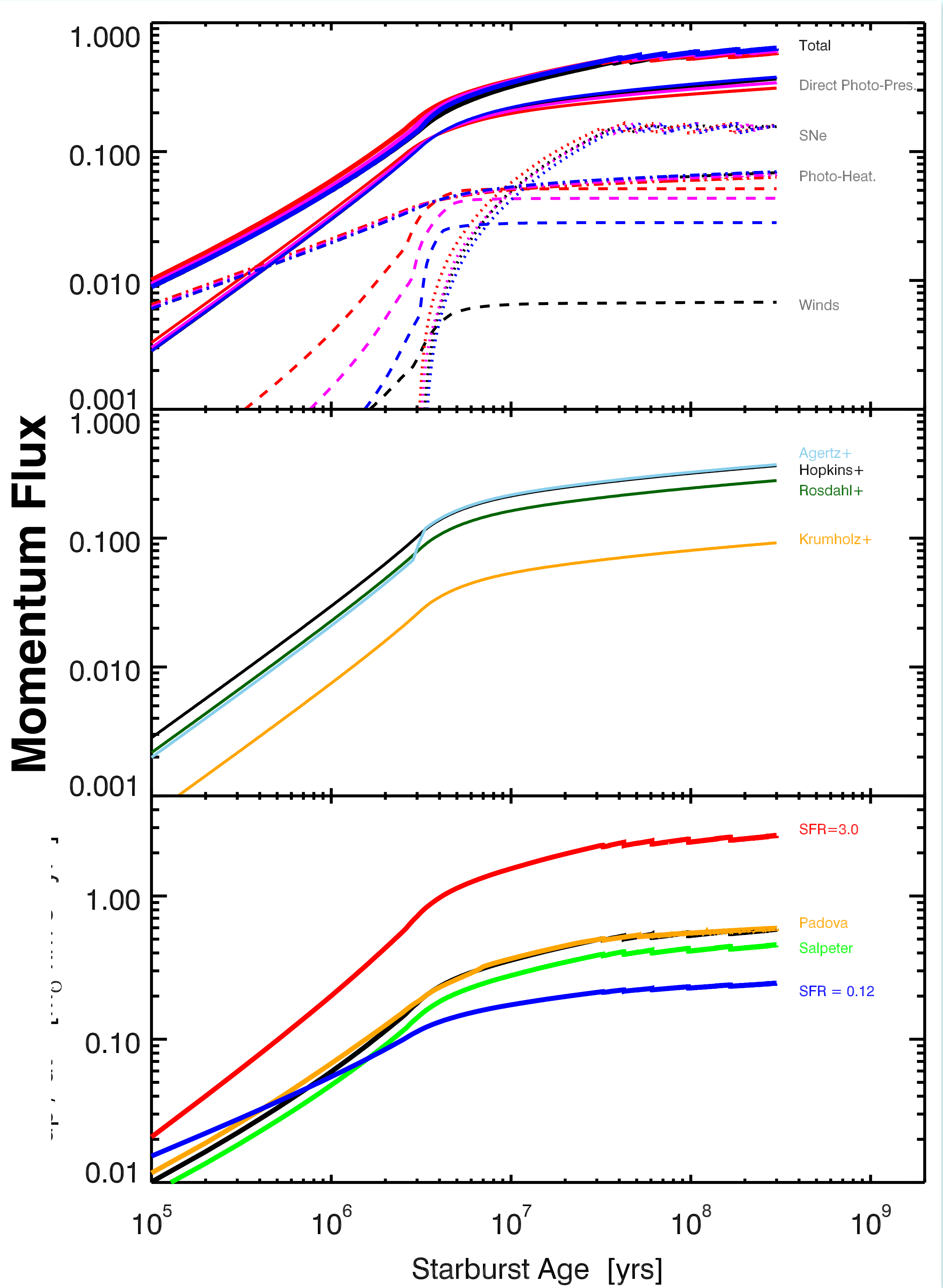
- Emission line ratios are **consistent with a shock origin** in the cavity.
- Observed velocity dispersion is consistent with fast shock model predictions for line ratios



Feedback Energetics

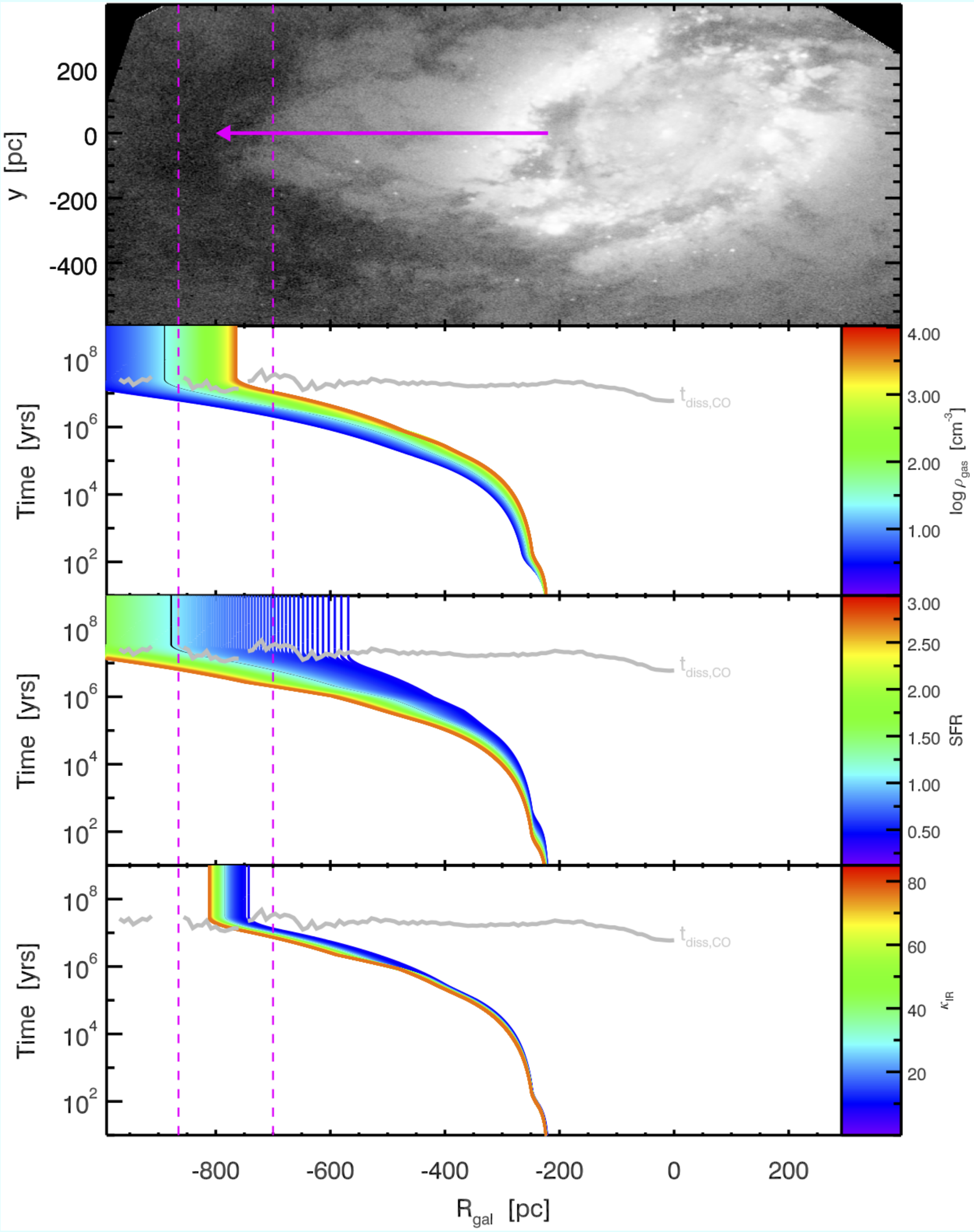
- Use STARBURST99 models together with analytic sub-grid feedback prescriptions to model momentum injection to the gas due to:

  - **Direct photon pressure**
  - **Supernovae**
  - **Stellar Winds**
  - **Photoionisation heating**



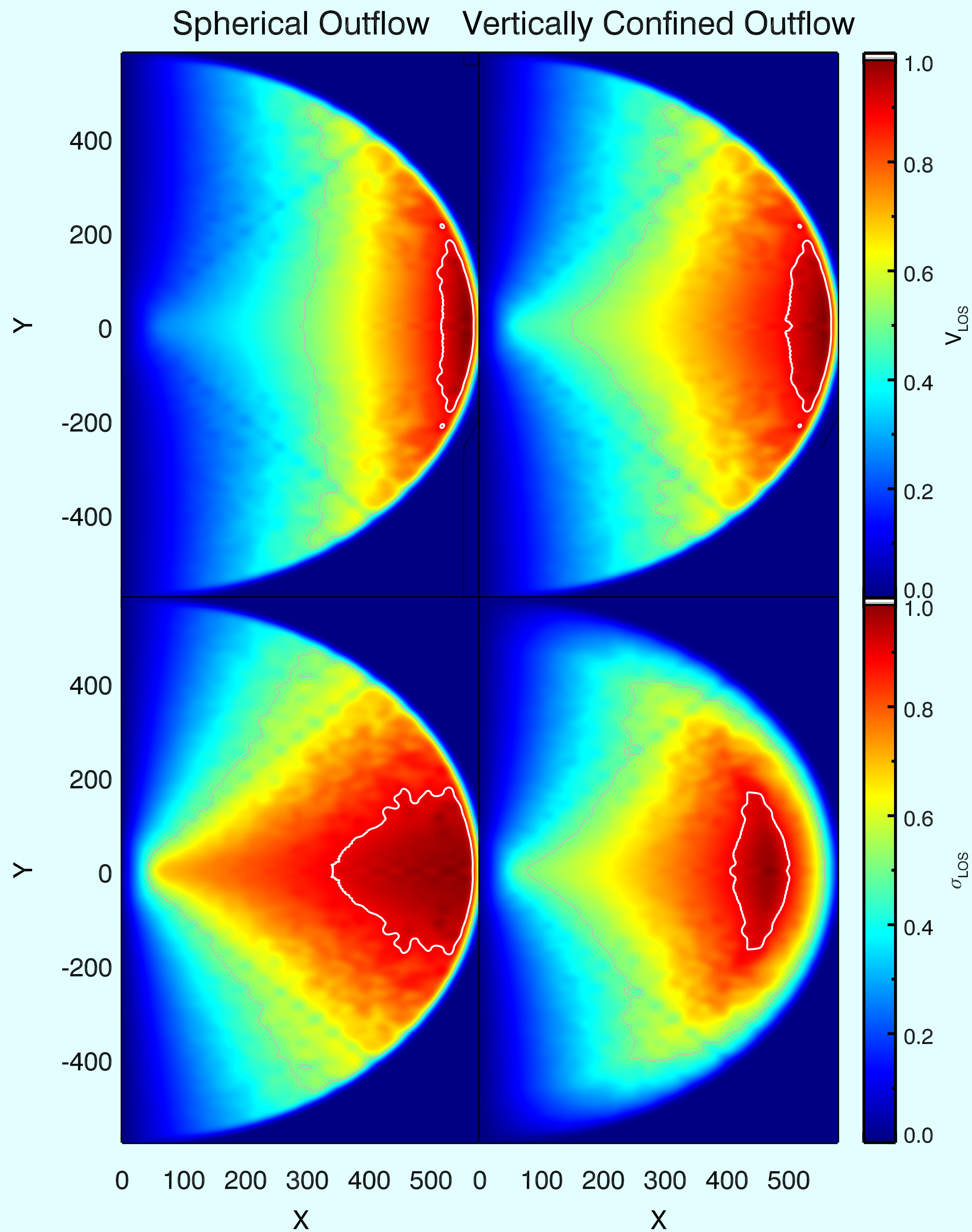
Shell Expansion

- Is there **enough energy** from the star forming nuclear ring to **move the molecular gas shell** from the ring to its present day location?
- STARBURST99 + analytic prescriptions for feedback and bubble expansion model, suggest energy is sufficient to reproduce the morphology over **an expansion time of ~10^7** years

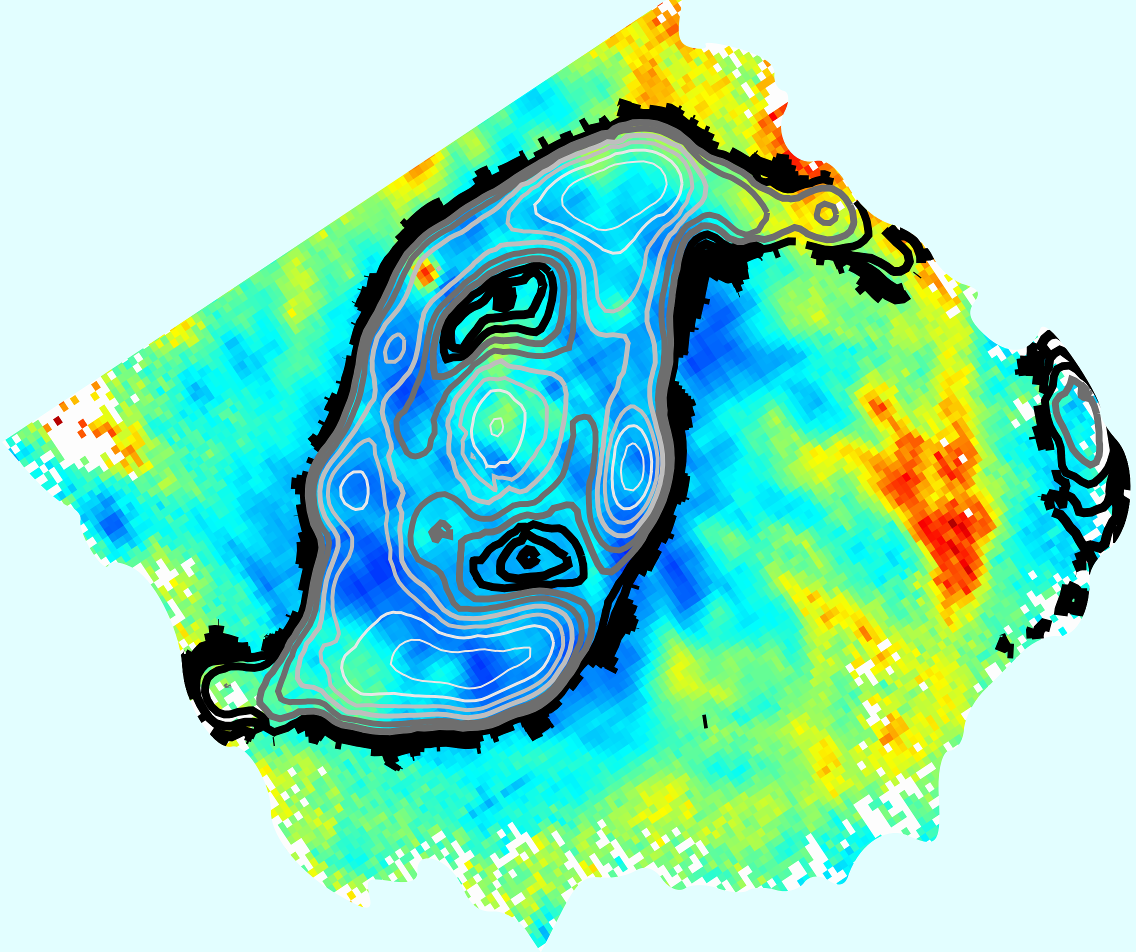


Outflow Geometry

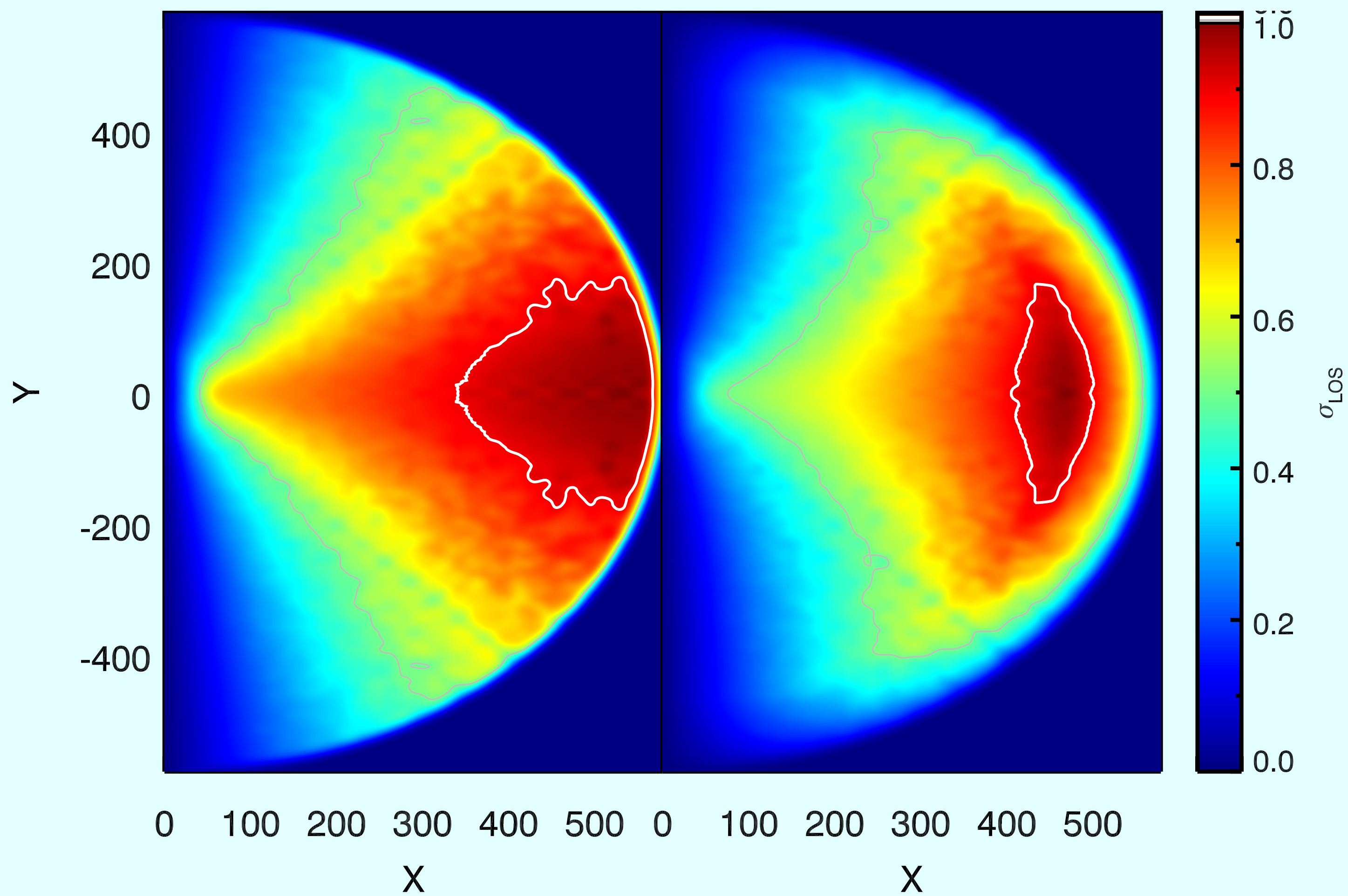
- Create mock kinematic maps corresponding to a **spherical** outflow or **vertically confined** outflow
- Velocity dispersion map is most consistent with a planar expansion, with **opening angle of ~35 degrees**



Outflow Geometry

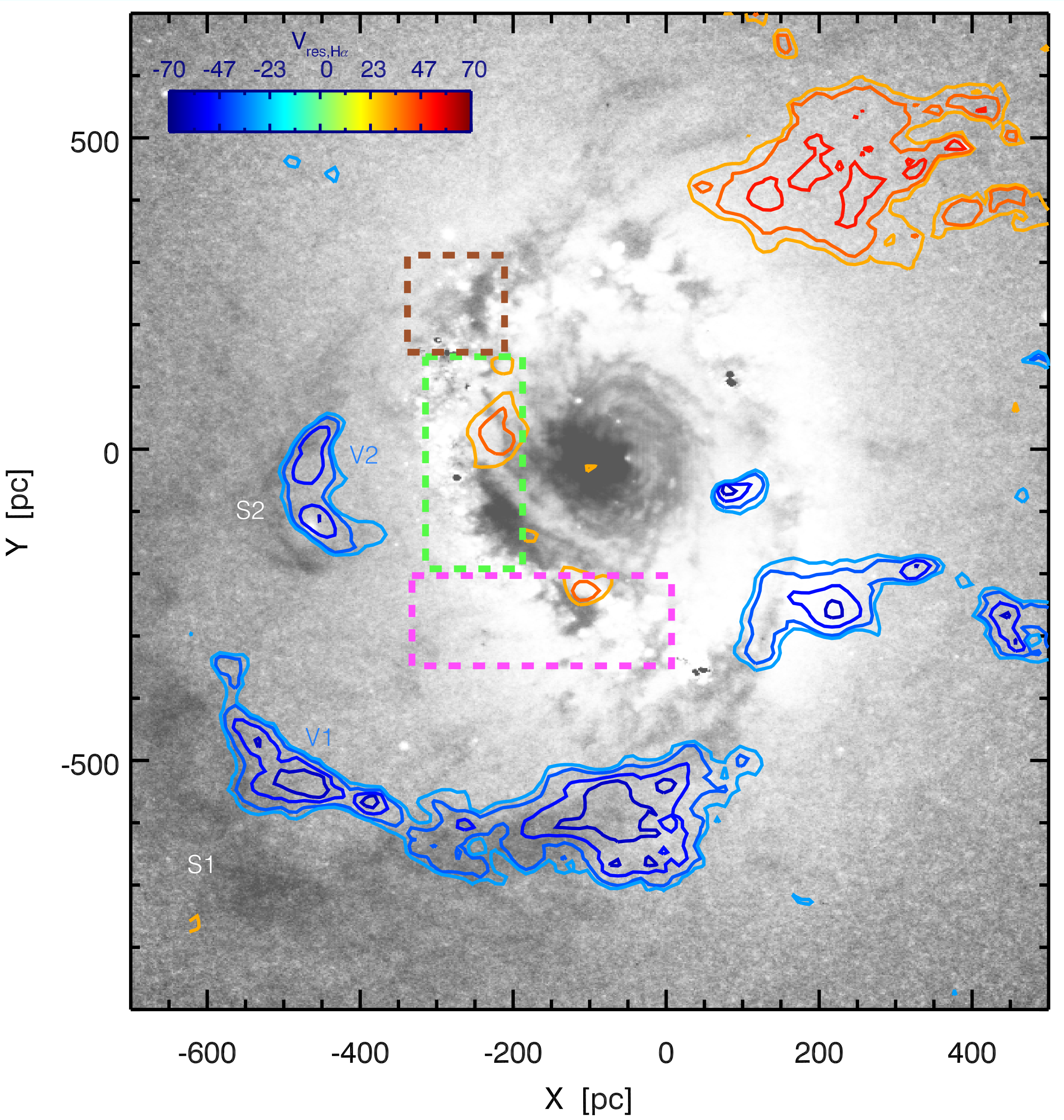


- Create mock kinematic maps corresponding to a **spherical** outflow or **vertically confined** outflow
- Velocity dispersion map is most consistent with a planar expansion, with **opening angle of ~35 degrees**

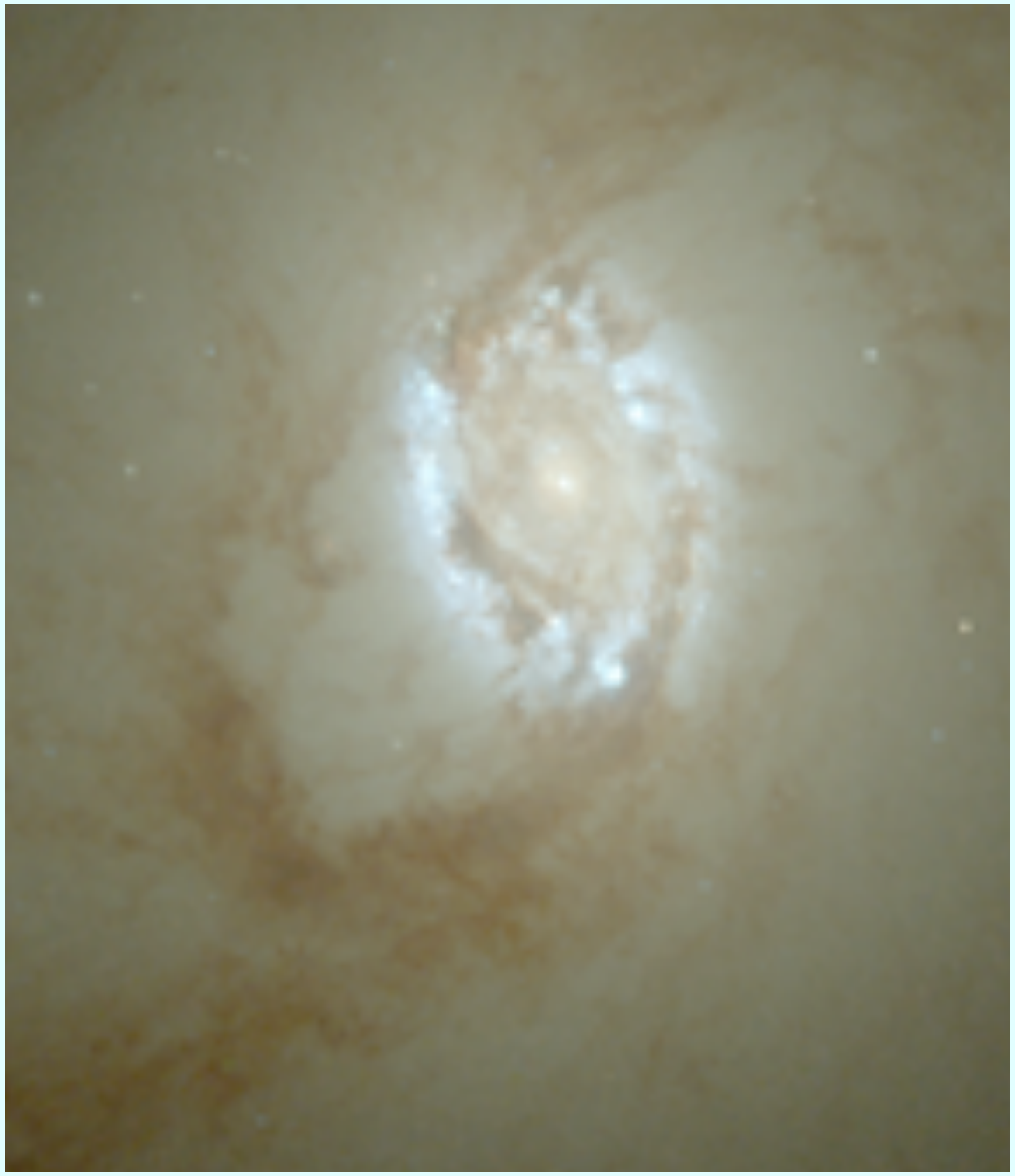


A consistent scenario?

- Direct photon pressure from SF ring could be responsible for moving the dusty molecular gas shell out from the ring initially.
- Sustained SF/SNe maintains hot, low density ionised gas outflow in the cavity, which shocks when crossing underlying galaxy velocity field.
- Signatures of multiple episodes evident in co-located kinematic/morphological features

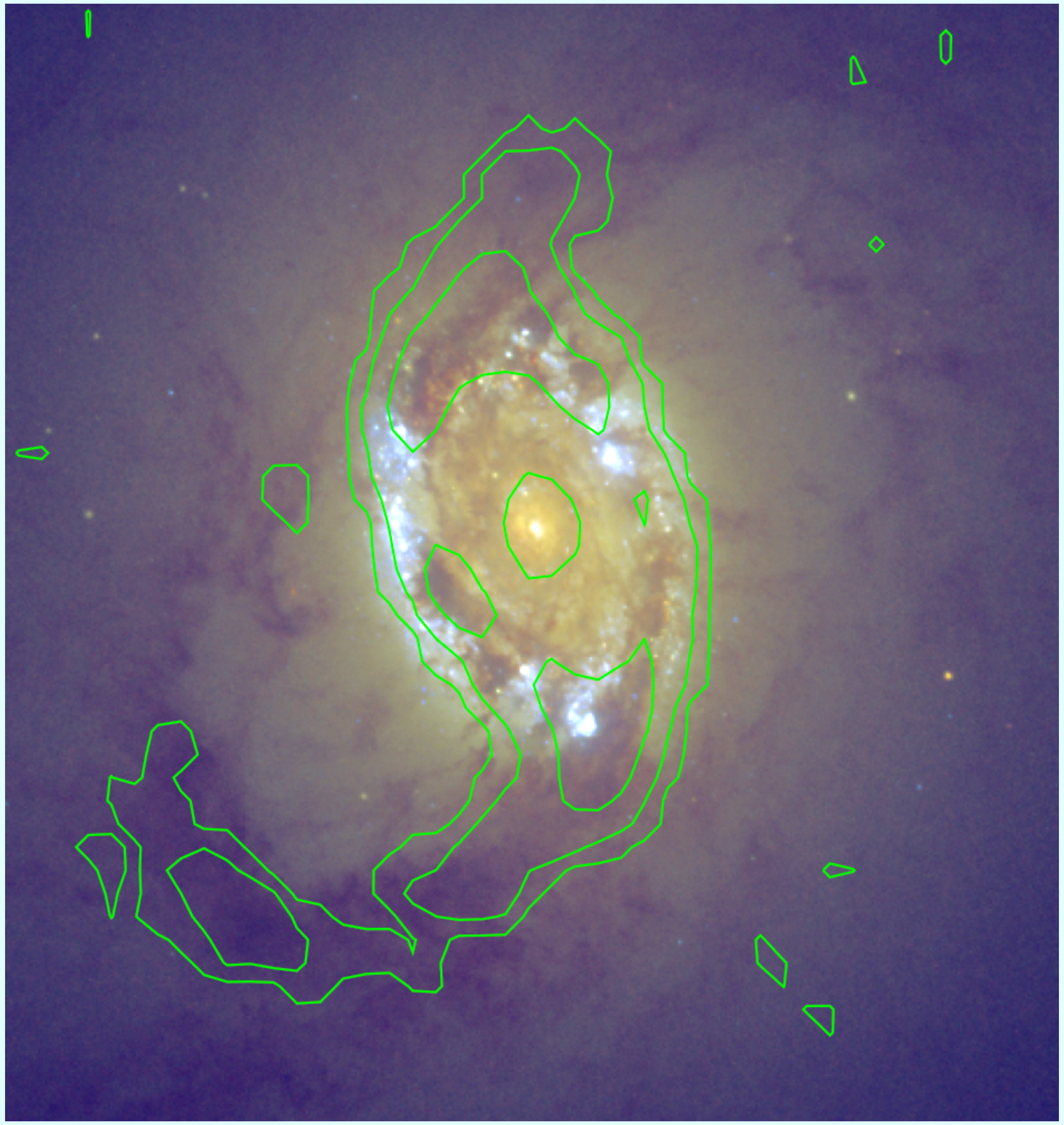


Survival of the molecular gas



- Molecular and neutral gas shells and ‘streamers’ seen in larger galactic-scale winds (e.g., Walter et al. 2017) .
- Naively might expect the gas to be destroyed or heated on short timescales.
- **Can the molecular gas survive the hot, energetic outflow generated in our favoured feedback scenario?**
- Lets evaluate three scenarios from literature…

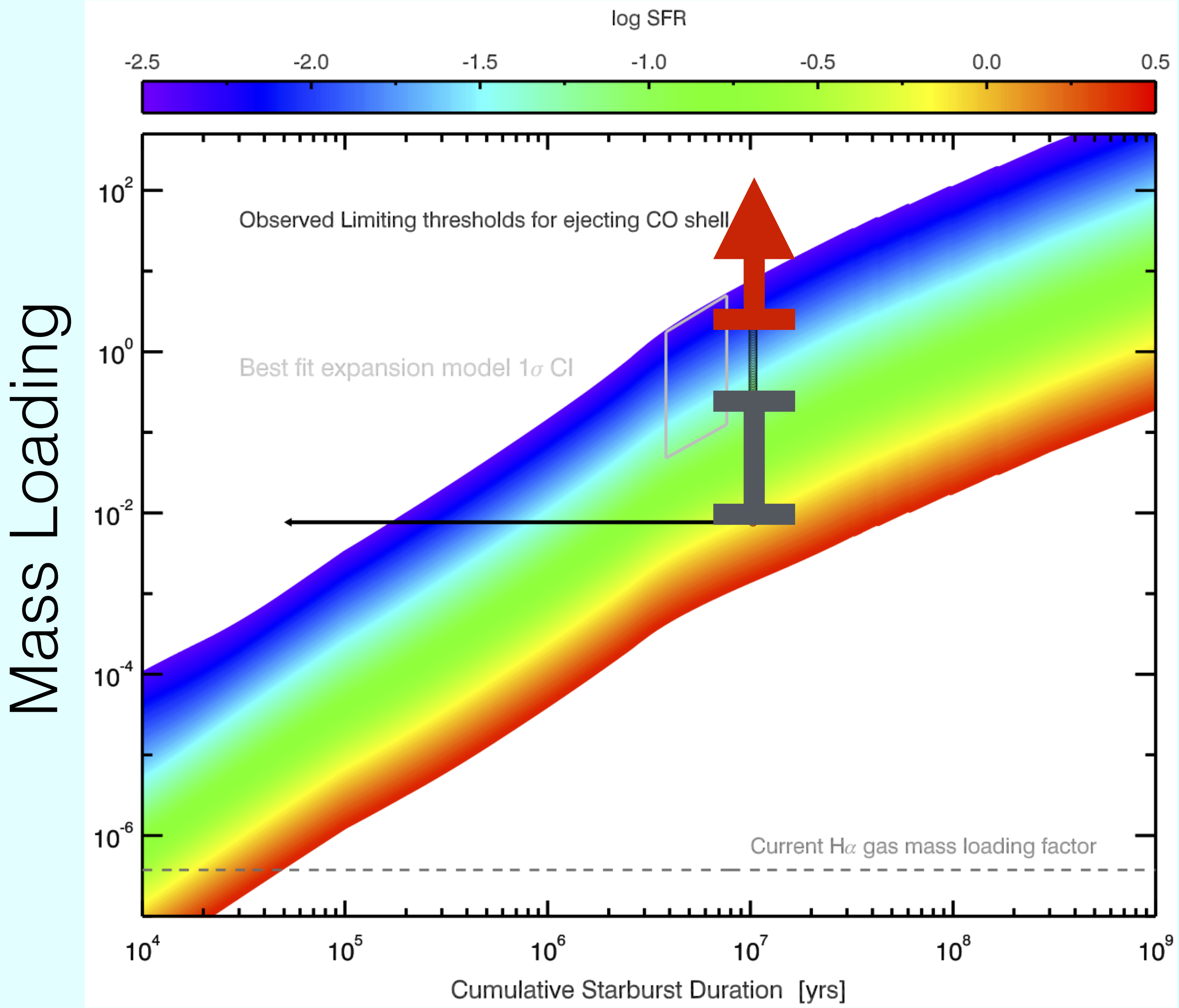
Survival of the molecular gas



Condensation Scenario: Hot gas shatters into droplets, which cool isobarically even in outflows. Get "fog" of cold gas **condensing in the outflow** (e.g., McCourt et al. 2018)

- Only gets you to neutral phase. As outflow is supersonic, the cooling time is longer than 'crushing' and entrainment timescales. *in-situ* condensation **not likely in this system**.

Survival of the molecular gas



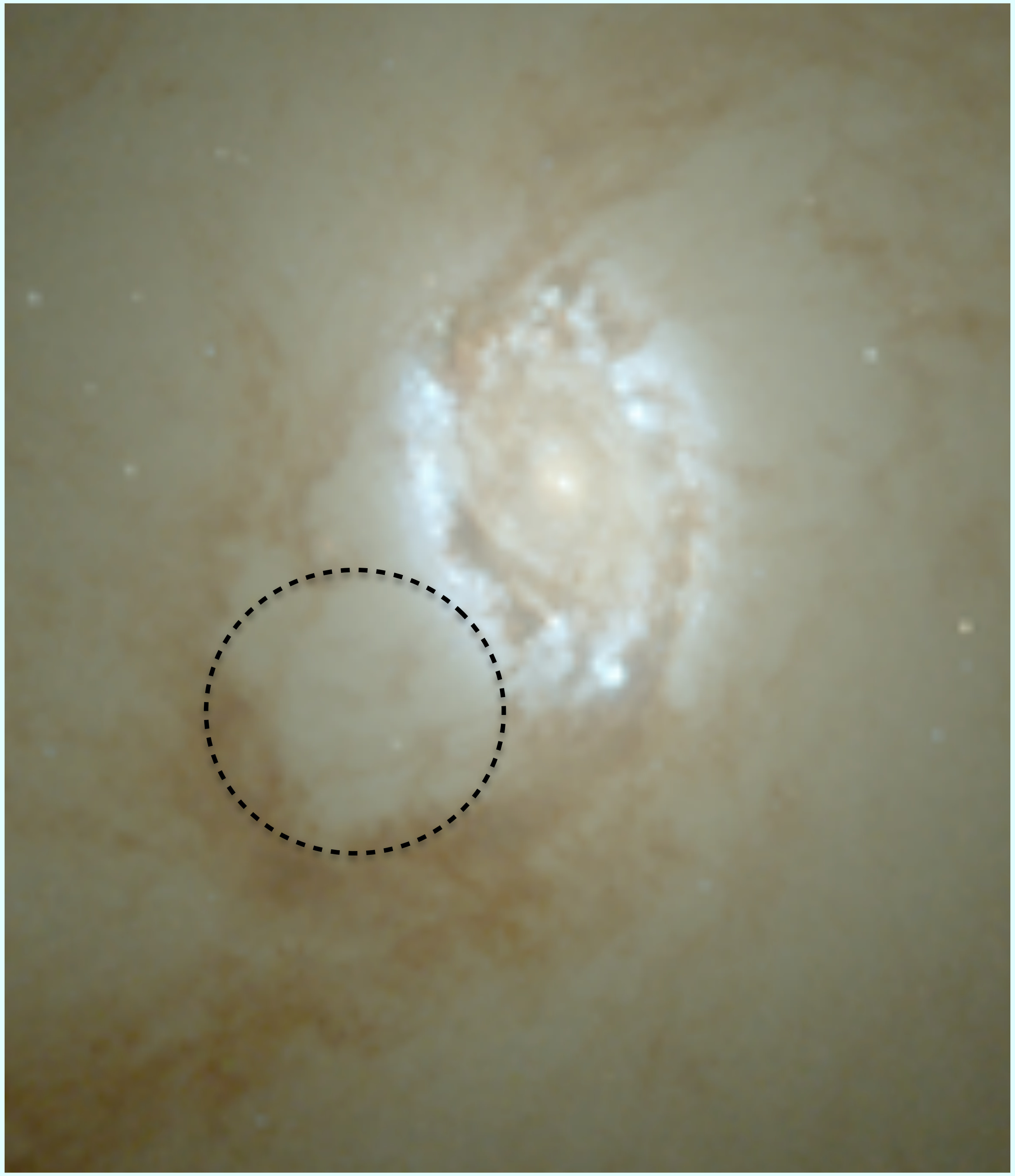
Radiative Scenario: Certain mass loading factors are conducive to radiative cooling at radius R_{cool} (Thompson et al. 2016)

- For cooling to occur at observed radius need:

$$\eta_{crit} \propto R_{CO,obs}^{0.342} R_i^{0.613} SFR^{-0.27} \geq 2.5$$

- Possible, but requires **higher mass loading** than limits implied by expansion model and escape velocity curve (< 0.13)

Survival of the molecular gas



Magnetic Scenario:
Magnetic field lines permeating through dusty cold gas, help keep it from disrupting, and prevent conductive heating (McCourt et al. 2015)

-*B*-field produces drag force on expanding gas shell, imparts radius of curvature. From imaging, can measure R_{curve}, yields estimate of: *B* ~ 330 μG.

$$R_{curve} \sim \left(\frac{V_{Alfvén}}{V_{outflow}}\right)^2 R_{cloud}$$

Summary and Implications

- Stellar feedback can have substantive effect on underlying gas morphology and dynamics. In this system the central region has an energy budget comparable to low luminosity AGN.
- Survival of the molecular gas in this energetic outflow is possibly aided by magnetic fields.
- Similar features in other systems may allow for differential constraints on stellar feedback efficiency as a function of host galaxy SFR, mass.