Catching sub-kpc scale AGN feedback in the act in the Compact Steep Spectrum source 4C 31.04

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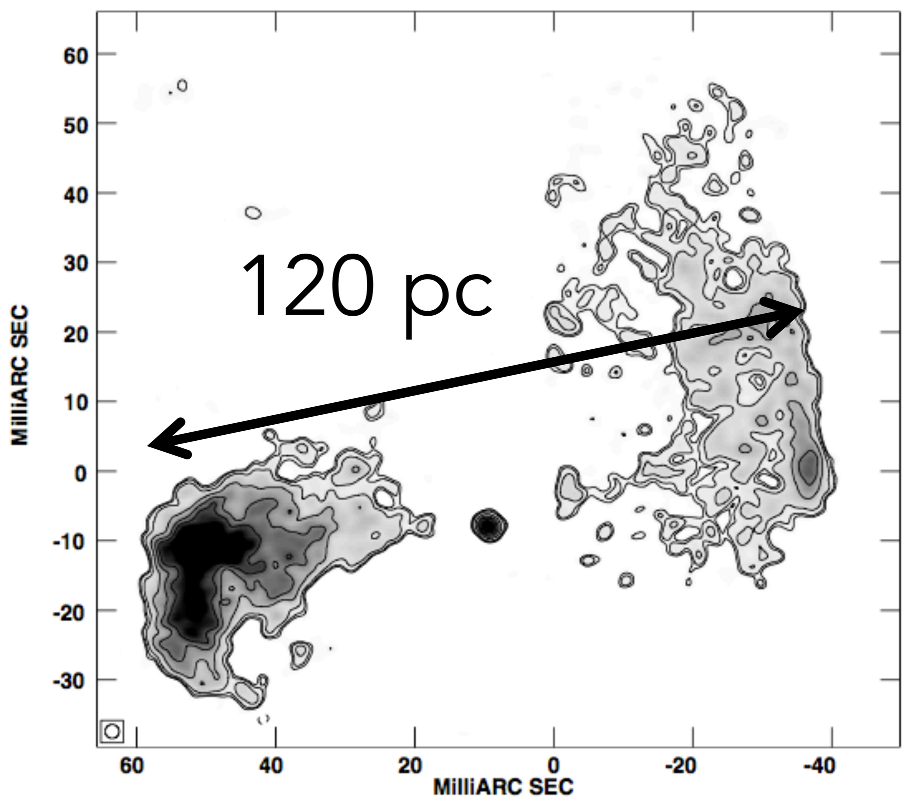
Gigahertz Peak Spectrum and Compact Steep Spectrum sources

Gigahertz Peak Spectrum and Compact Steep Spectrum sources are **young radio galaxies** with compact jets interacting strongly with a dense, inhomogeneous interstellar medium (ISM) [2, 8]. Therefore they are ideal targets in which to study jet-ISM interaction on sub-kpc scales. **We observed the Compact Steep Spectrum source 4C 31.04 with the Near-Infrared Integral Field Spectrometer (NIFS)** in the *H* & *K* bands on the 8-metre Gemini North telescope, in order to investigate sub-kpc jet-ISM interaction.

The Radio Galaxy 4C 31.04

- **4C 31.04 is a Compact Steep Spectrum source** at $z = 0.0602$ [4] with a spectral peak at 400 MHz. It is a Compact Symmetric Object ~120 pc across, with asymmetric radio lobes indicating strong jet-ISM interaction.
- **It is a very young radio AGN.** Synchrotron spectral decay indicates the lobe plasma is 3000-5000 yr old [5].
- The host is a giant elliptical with a **~10^{10} $M_\odot$ circumnuclear disc of dust, atomic and molecular gas** [3,4,9,10,11]. It shows signs of an interaction >10^8 yr ago [10].

Fig. 1: 5 GHz VLBA image of 4C 31.04 [6].



Gemini/NIFS observations

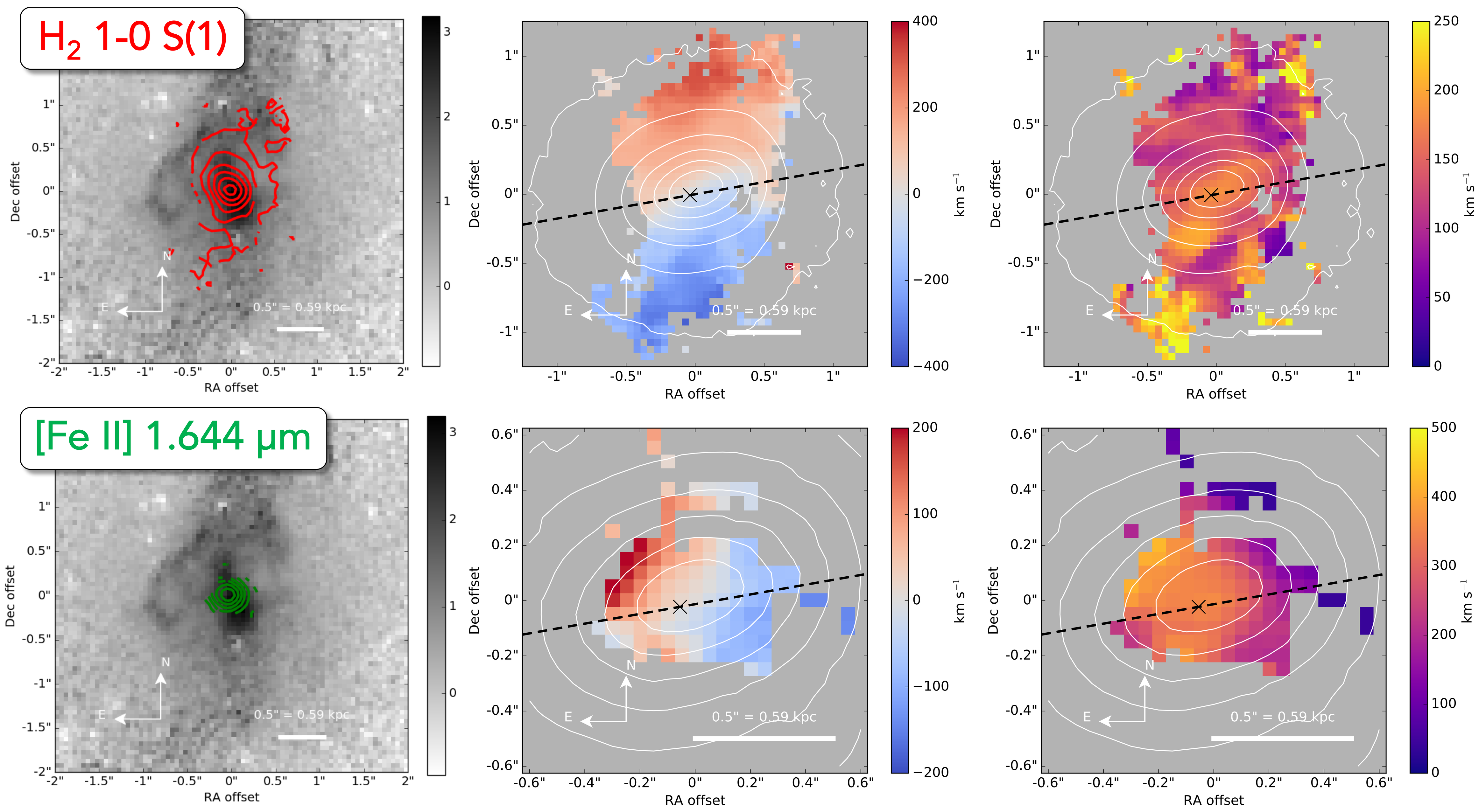
H_2 emission: accretion

- We detect ro-vibrational transitions of H_2 that trace **warm (~10^3 K) molecular gas.**
- **Solid-body rotation** & **high σ: a 'ring'**
- **Lack of Brγ suggests heating by slow shocks.**
- The ring is too far from the nucleus to be caused by AGN. We conclude the **slow shocks are associated with gas accretion from past merger.**

[Fe II] emission: radio jets

- We detect [Fe II] 1.644 μm, which traces **fast shocks that destroy dust grains.**
- **Bipolar radial velocity field & high σ: an expanding bubble ~300-400 pc in diameter**
- We rule out supernova & AGN, meaning the fast shocks are likely caused by radio jets…
- **But the [Fe II] emission is ~3 times more extended than the radio lobes (Fig. 1) – how can this be explained?**

Fig. 2: from left to right: emission line flux overlaid onto Hubble Space Telescope R-H image, radial velocity, and velocity dispersion.



Why is the bubble so much larger than the radio lobes?

To understand why the [Fe II] bubble is so much larger than the radio lobes visible in VLBI imaging, we compare our observations to hydrodynamical simulations (Fig. 3). Using our observations, we create a model of 4C 31.04 (Fig. 4).

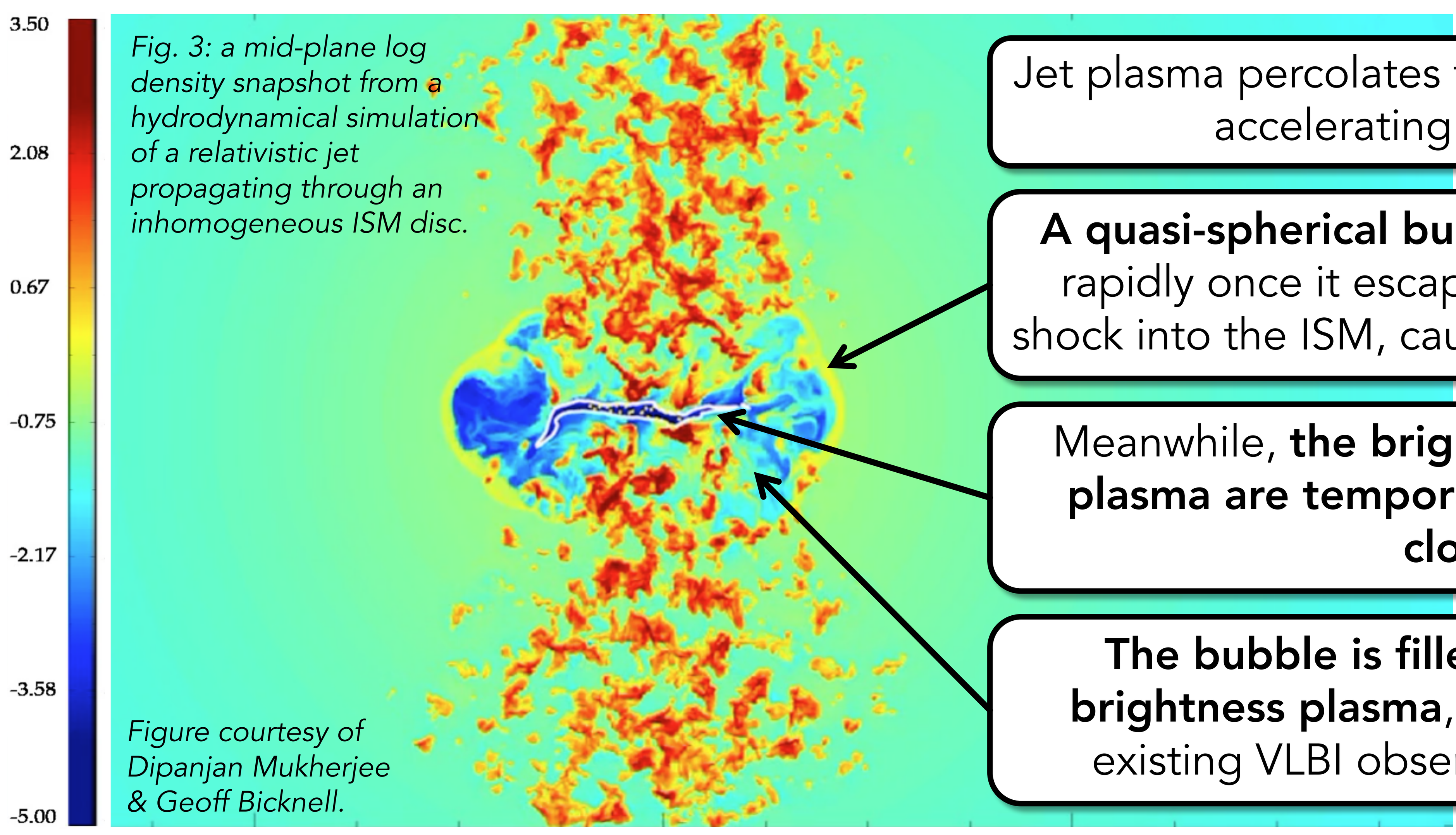


Fig. 3: a mid-plane log density snapshot from a hydrodynamical simulation of a relativistic jet propagating through an inhomogeneous ISM disc.

Figure courtesy of Dipanjan Mukherjee & Geoff Bicknell.

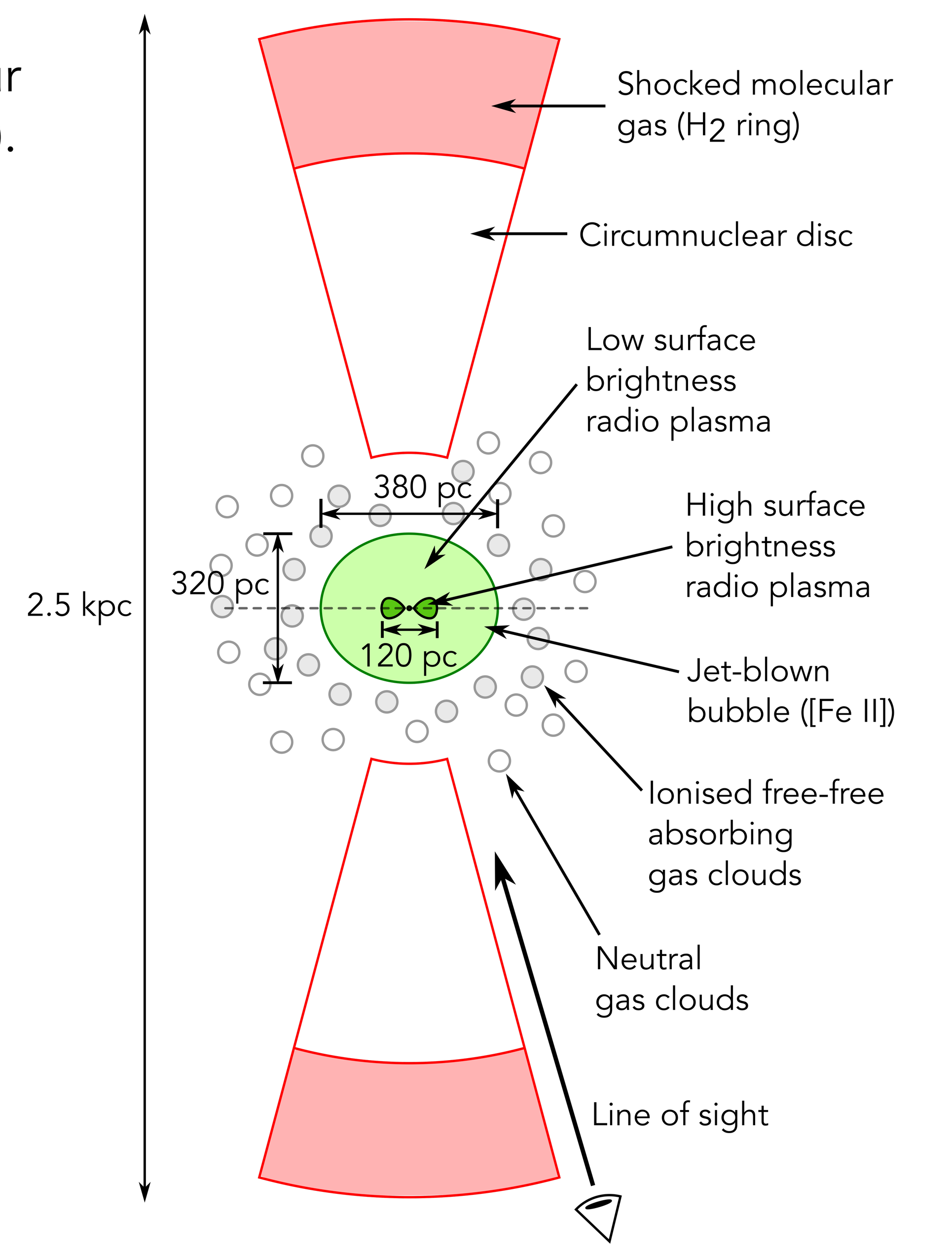
Jet plasma percolates through the clumpy ISM, accelerating gas outwards.

A quasi-spherical bubble forms, expanding rapidly once it escapes the disc. It drives a shock into the ISM, causing the [Fe II] emission.

Meanwhile, **the brightest regions of radio plasma are temporarily halted by dense clouds.**

The bubble is filled with low surface brightness plasma, which is not visible in existing VLBI observations of 4C 31.04.

Fig. 4: a top-down cross-section of our model of 4C 31.04.



How old are the radio jets?

Existing VLBI observations of 4C 31.04 do not reveal the true extent of the jet plasma. To find the *true* age of the radio source, we calculate the time taken for a jet-driven bubble to adiabatically expand to the radius of the [Fe II] emission [1]:

$$t_{\rm jet} = \left(\frac{384\pi}{125}\right)^{1/3} \rho_a^{1/3} F_E^{-1/3} R_{\rm [Fe\ II]}^{5/3} \approx \mathbf{17}\ \mathrm{kyr}$$

~3 times older than previously thought!

- $t_{\rm jet}$: Age of bubble
- ρ_a: Ambient ISM density (0.1 cm^{-3})
- F_E: Jet energy flux (~10^{44} erg s^{-1})
- $R_{\rm [Fe\ II]}$: Bubble radius

Conclusion

We detect a jet-blown bubble in the nucleus of 4C 31.04 that is ~3x larger than the radio lobes detected in VLBI. We calculate the radio source to be 17 kyr old, ~3x older than previously thought. This research shows that **optical/near-infrared tracers of jet-ISM interaction can be crucial in estimating the true ages of young radio sources.**

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