Bursts of star formation and gas outflows in galaxies

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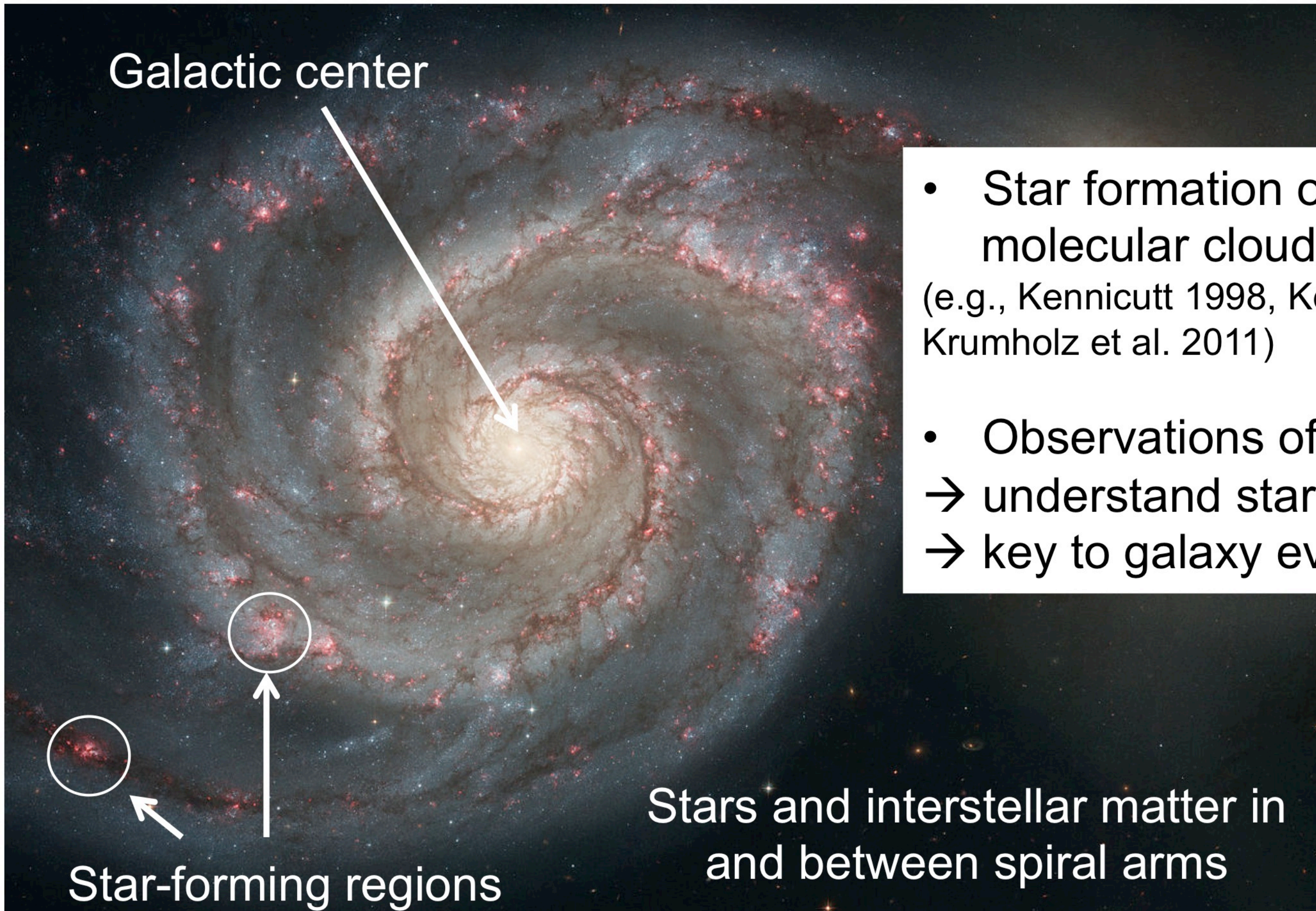
Outline

1. **Star formation and starburst galaxies**
2. **Superwinds and galaxy evolution**
3. **Case study**
   - Observations of the galaxy M82

Star formation in galaxies



- Star formation occurs in molecular clouds

(e.g., Kennicutt 1998, Kennicutt et al. 2007; Krumholz et al. 2011)

- Observations of molecular gas

→ understand star formation
→ key to galaxy evolution

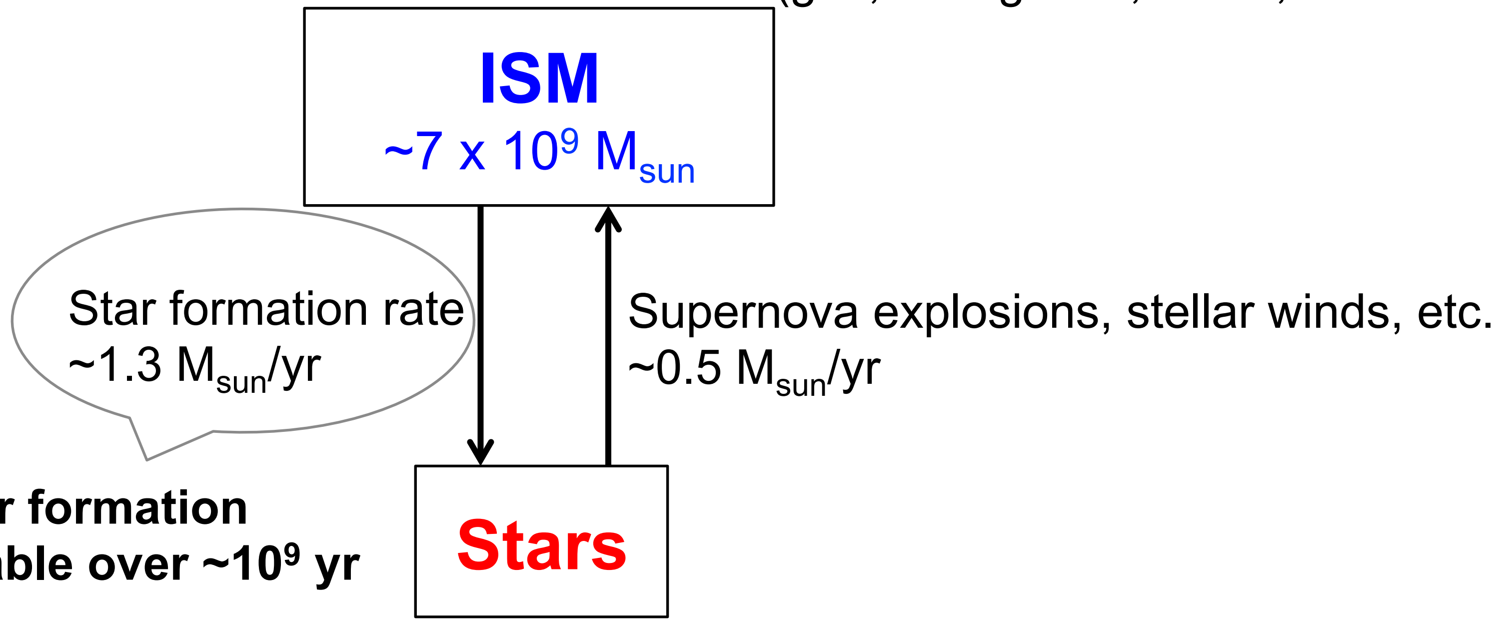
Spiral galaxy M51 (Credit: HST)

Baryon flow in a typical disk galaxy

Mass budget in our Galaxy:

- Dark matter
- Baryons (~10%) = visible matter

~90% of baryons in stars, ~10% in interstellar medium (ISM)
(gas, dust grains, PAHs, cosmic rays)

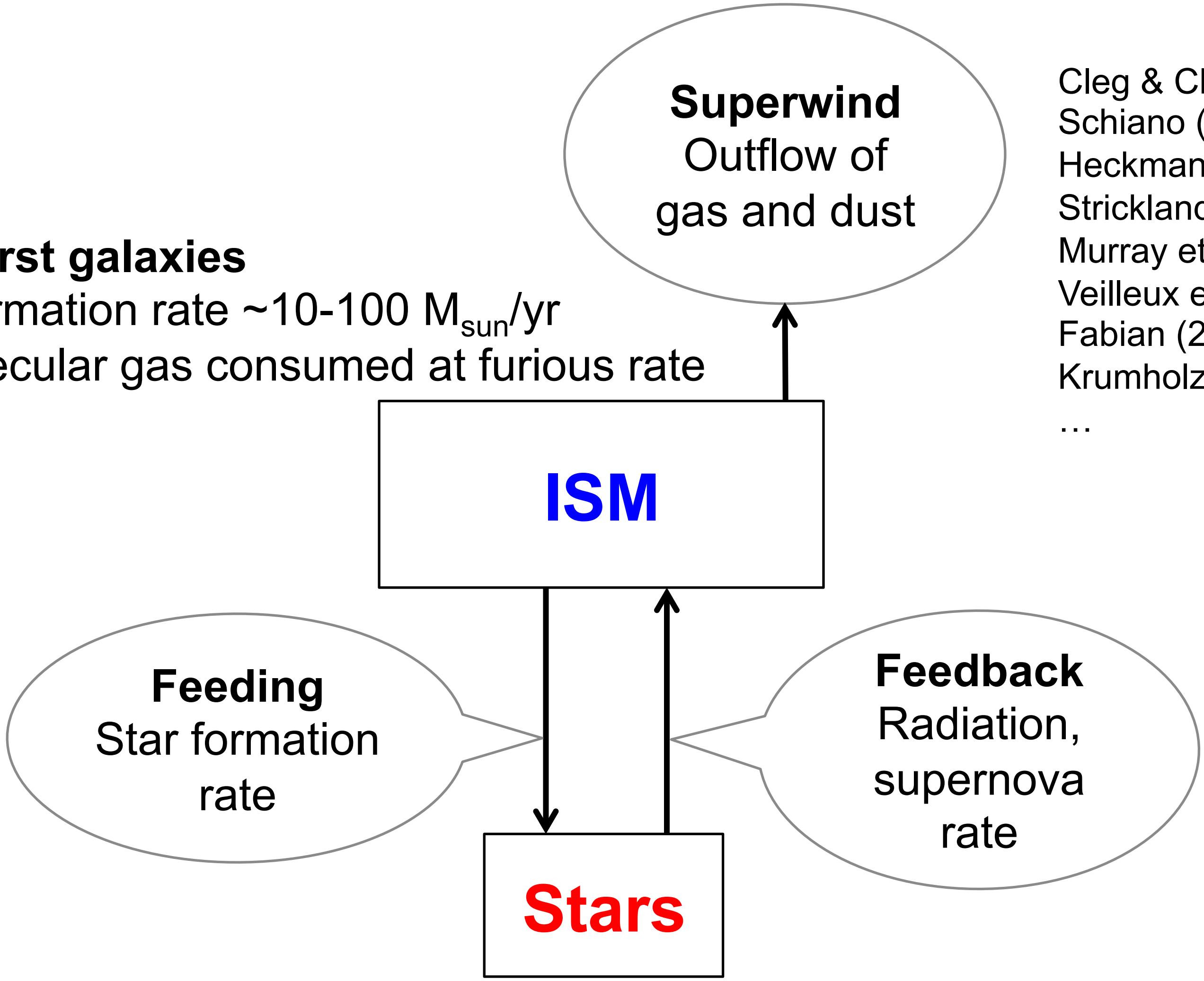


Star formation sustainable over ~10^9 yr

Star formation feedback in starburst galaxies

Starburst galaxies
Star formation rate ~10-100 M_{sun}/yr
→ molecular gas consumed at furious rate

Cleg & Chevalier (1985)
Schiano (1985)
Heckman et al. (1990)
Strickland et al. (2004)
Murray et al. (2005, 2011)
Veilleux et al. (2005)
Fabian (2012)
Krumholz & Thompson (2013)
…



Superwinds and galaxy evolution

M82
(Credit: Chandra, HST)

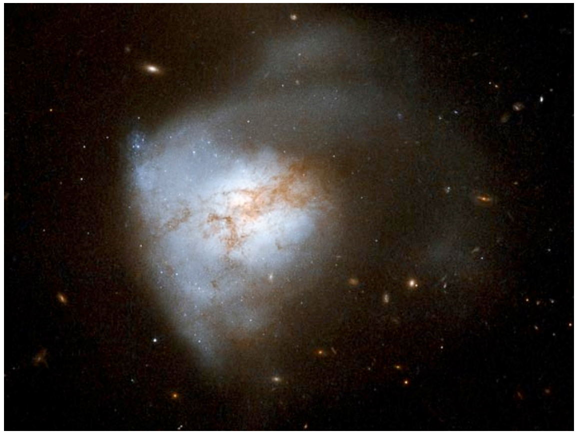
Interaction/merging of gas-rich galaxies

↓

Starburst
(high star formation rate)

↓

Superwind

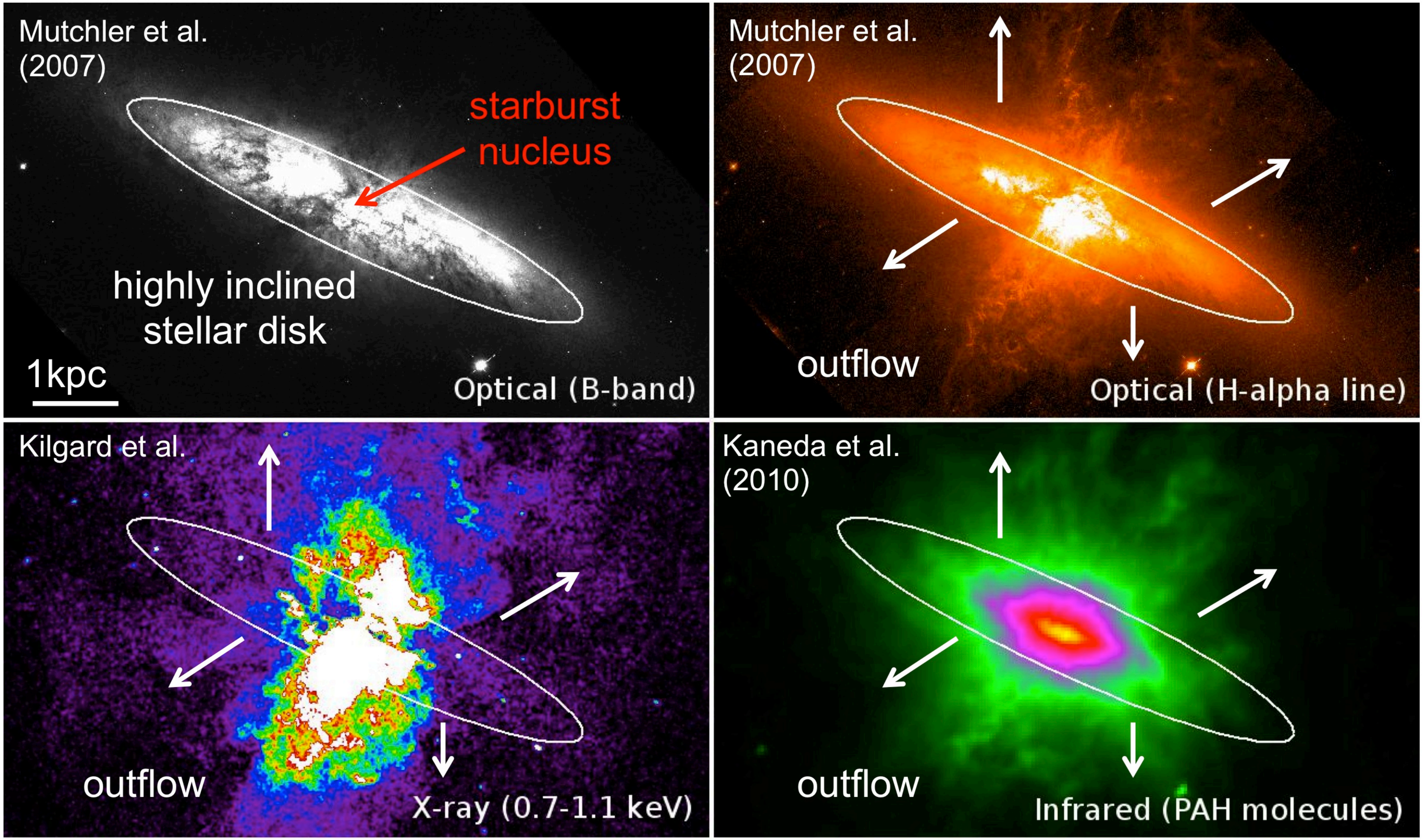


Arp 220
(Credit: HST)

Suppress star formation

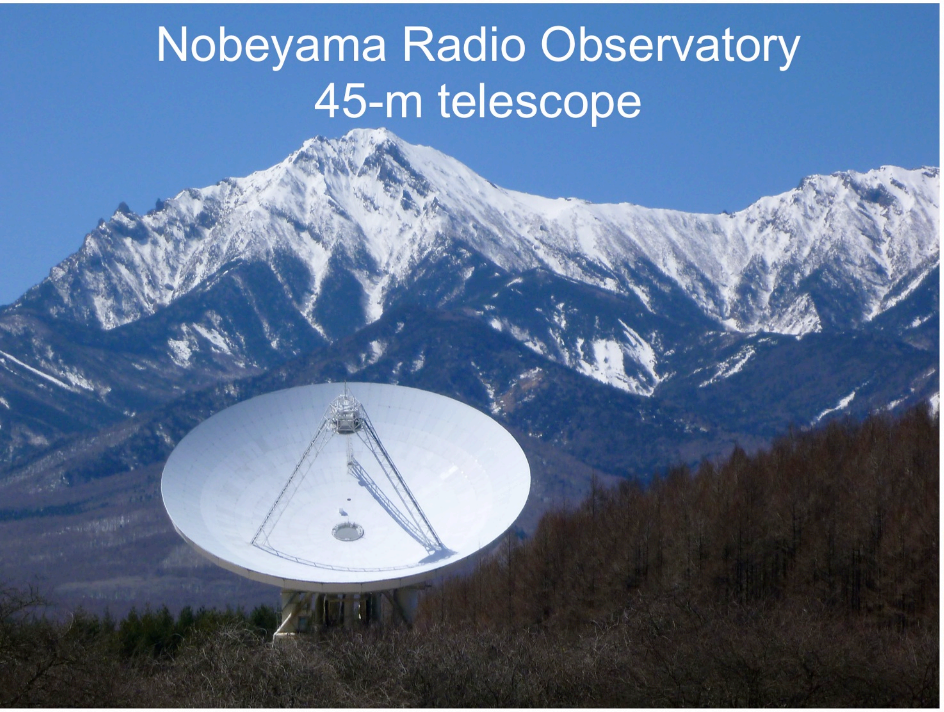
Transport heavy elements (Z>2) to intergalactic space

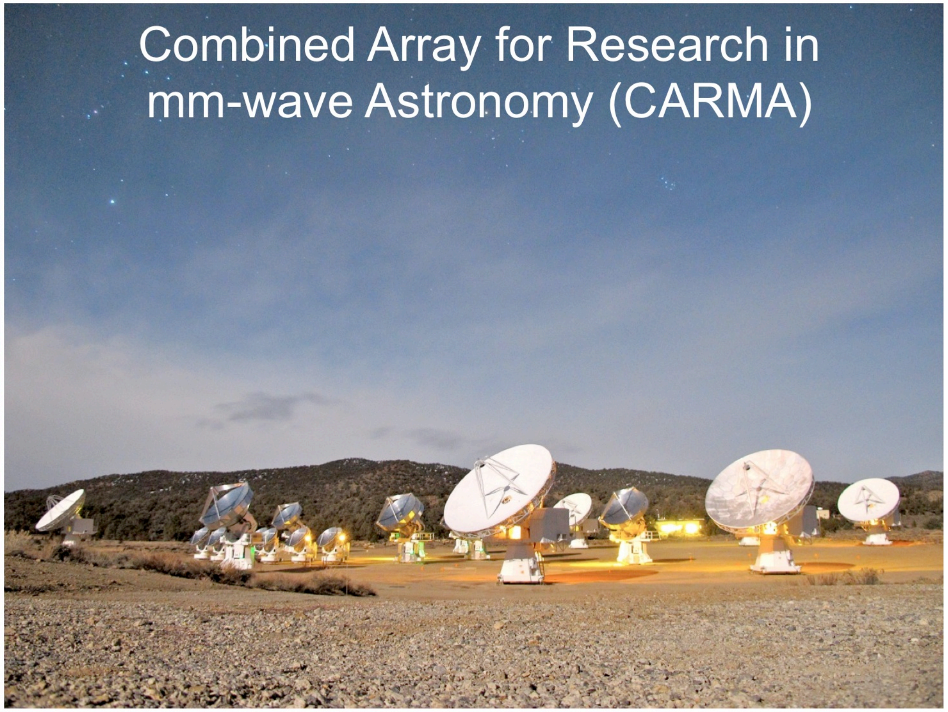
Multi-phase outflows: M82 case study



Observations of molecular gas

How is molecular gas affected by the superwind?
Interstellar molecular gas is cooled by CO (J=1→0) λ=2.6 mm
(J : rotational quantum number)

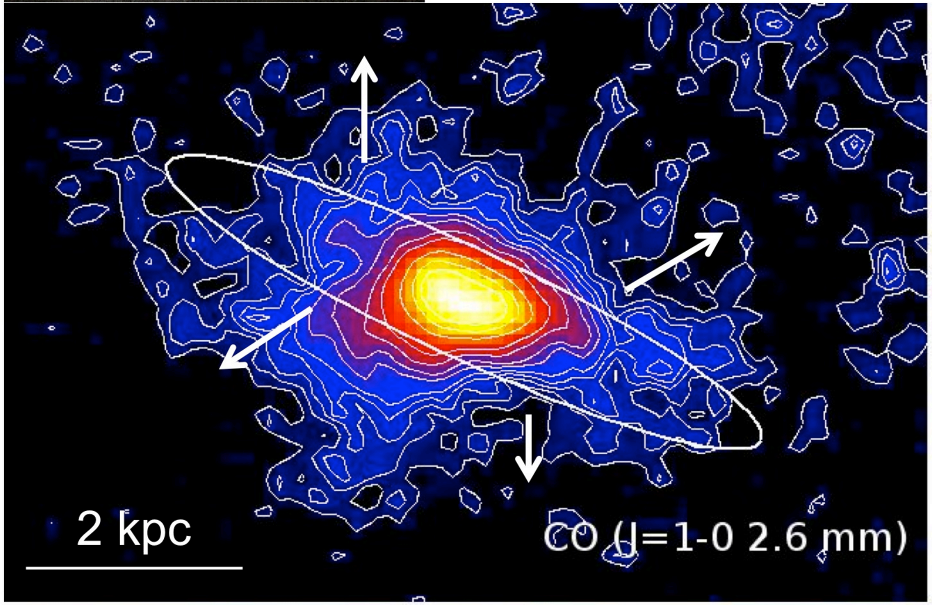


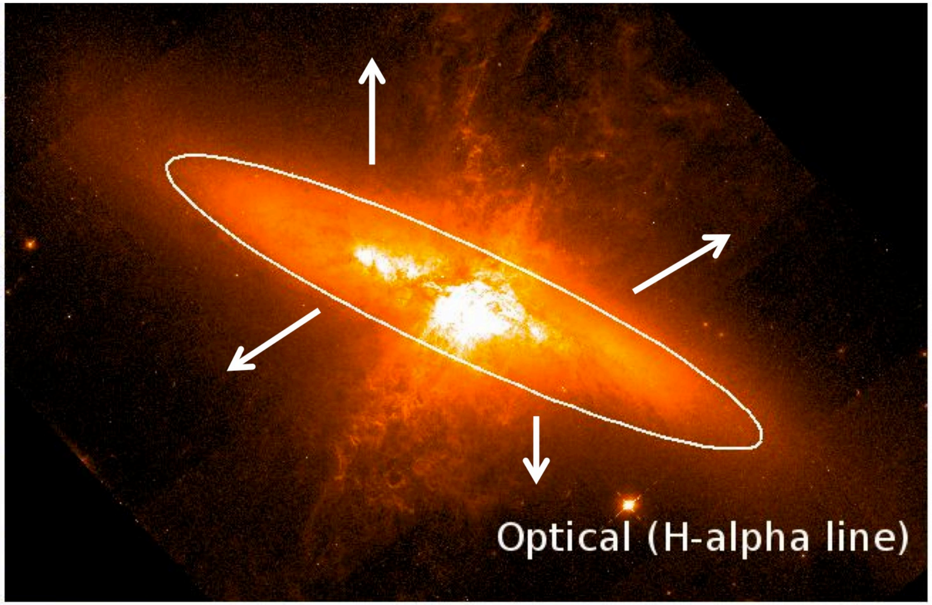


Antenna diameter = 45m
→ high sensitivity

Array of 6-m and 10-m antennas
→ high angular resolution

Molecular gas outflow





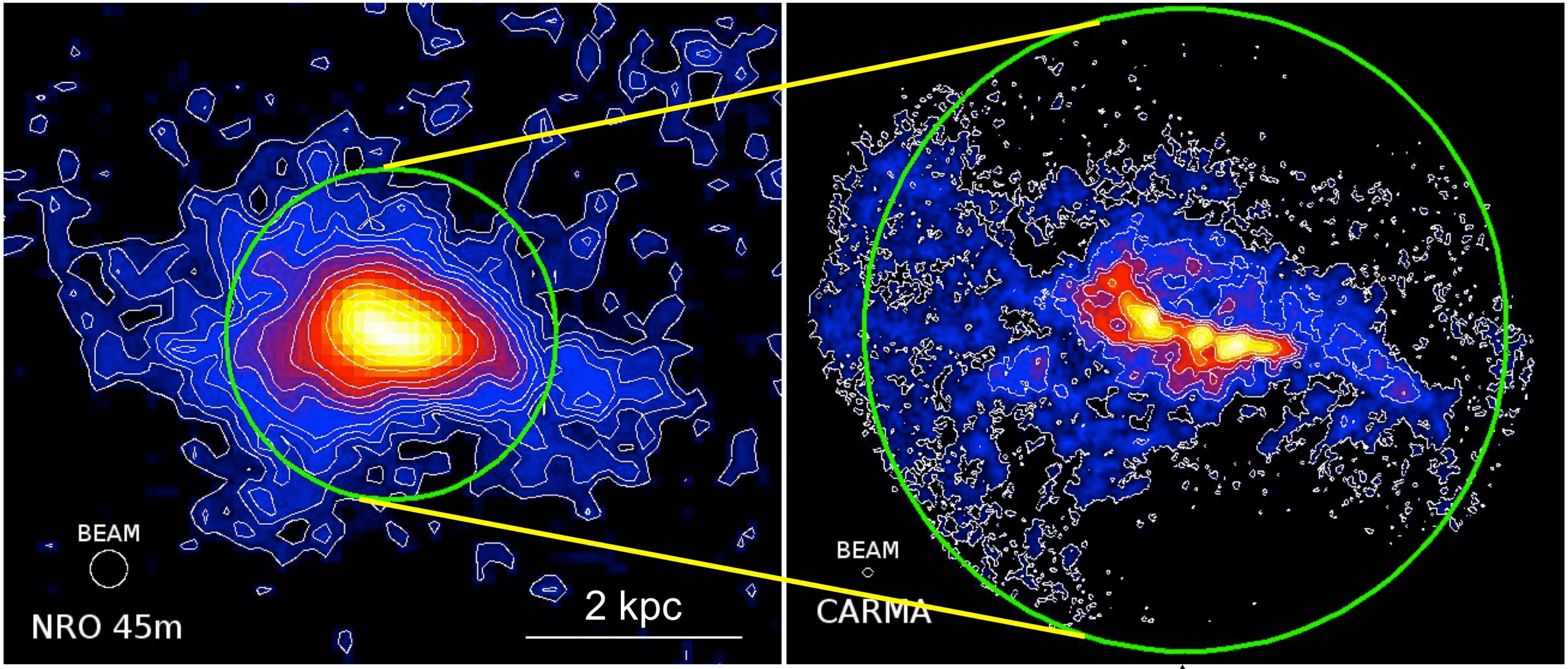
Salak et al. (2013) ↑ Mutchler et al. (2007)

Observations with Nobeyama 45-m telescope

- Large-scale molecular gas outflow >2 kpc above the galactic plane

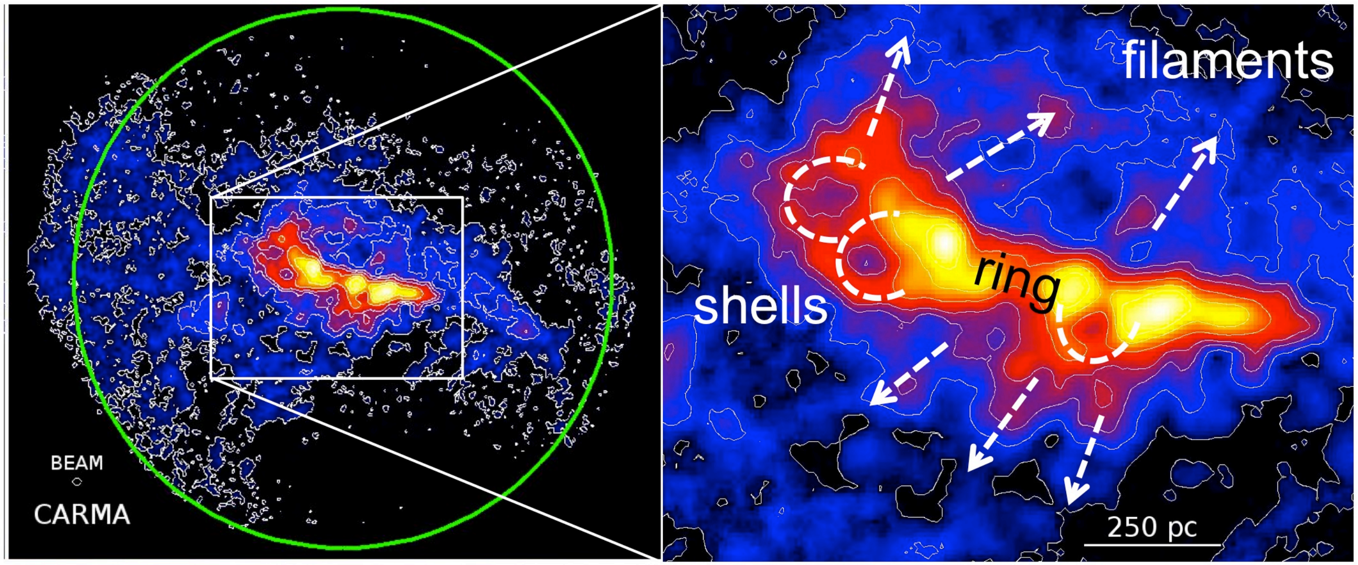
(1 pc = 3.1 x 10^{13} km)

High-resolution CO observations

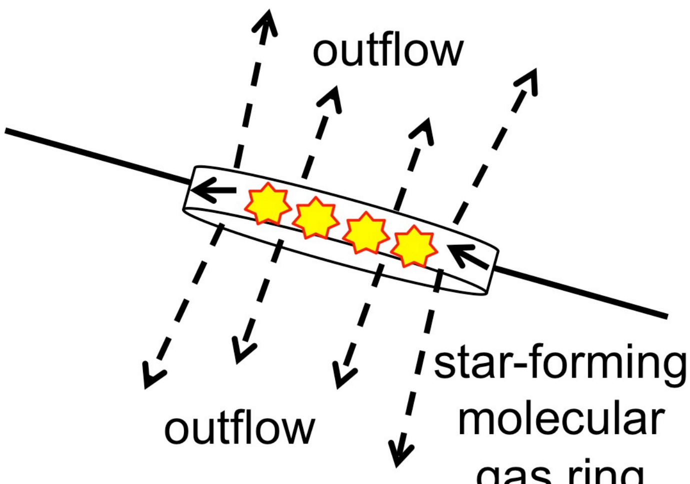


CARMA + Nobeyama 45m map
highest-resolution CO map (CANON project)
(2.8 x 2.5 $arcsec^2$ equivalent to ~45 pc)

Close-up of the molecular gas outflow

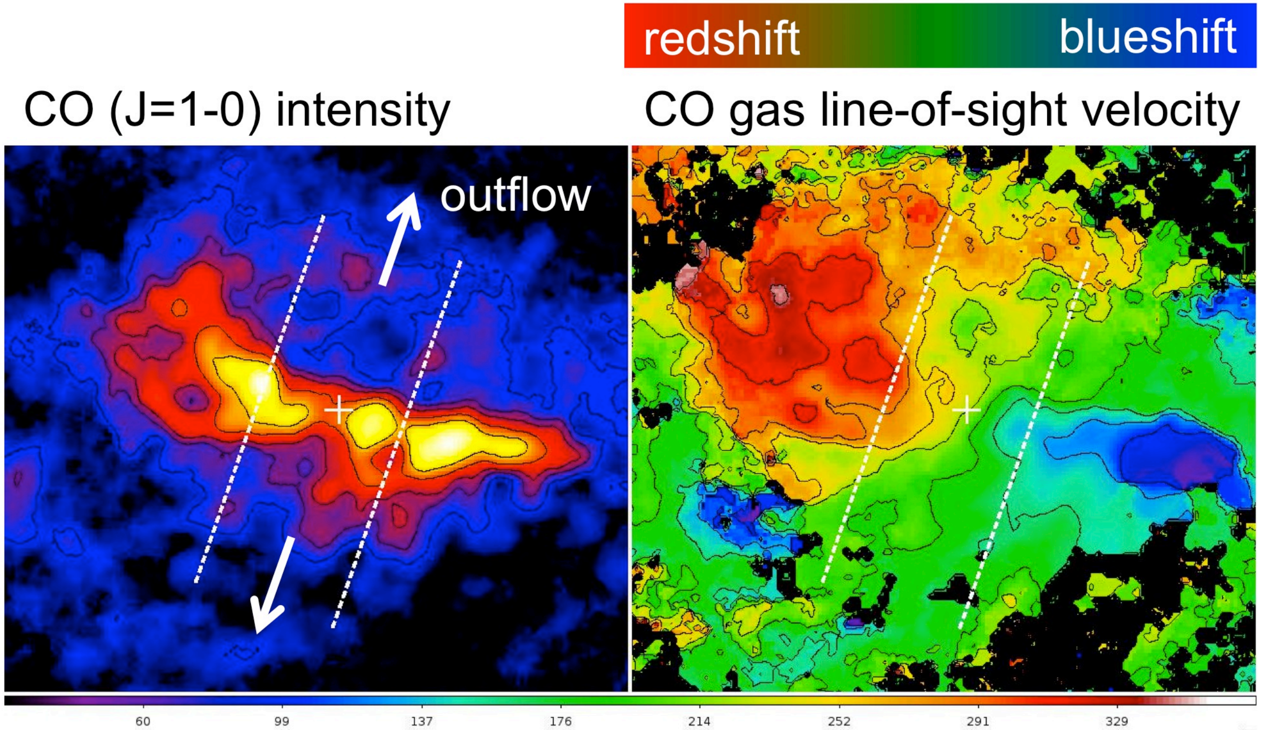


Molecular gas outflows launched from the 300-pc ring

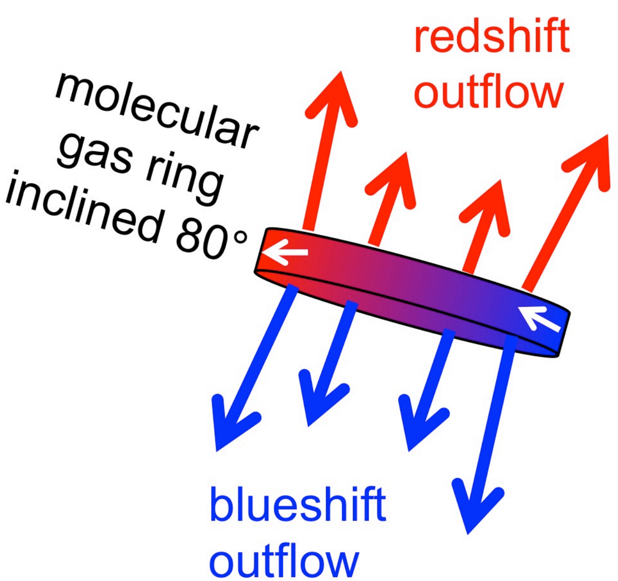


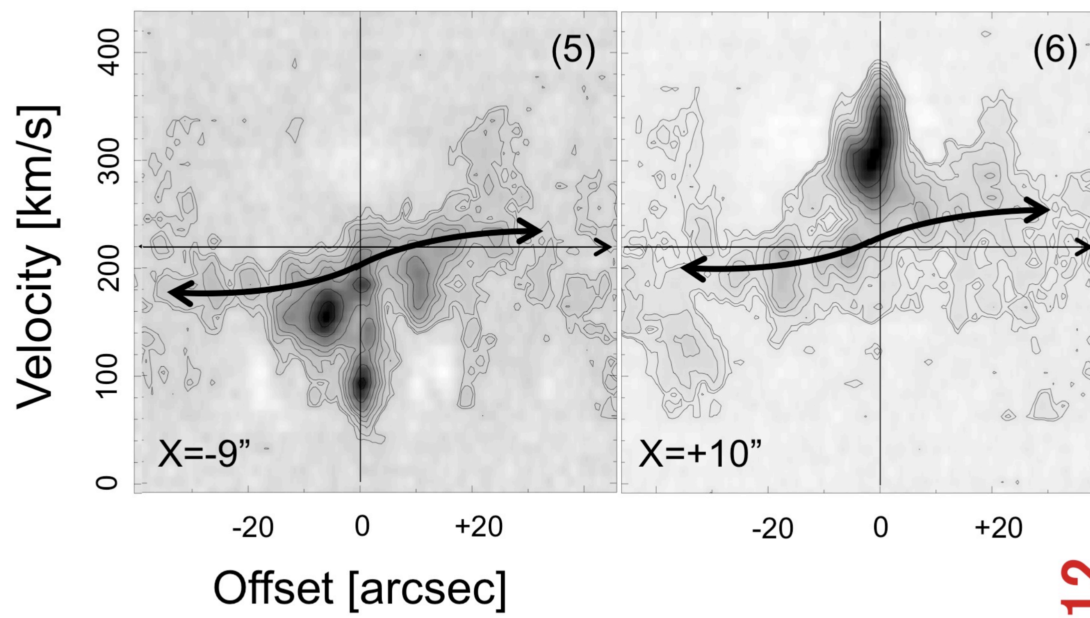
→ **How does the superwind affect star formation?**
→ **Can molecular gas escape?**

- Outflow velocity from CO spectra
- H_2 gas mass from CO line flux
- Mass outflow rate



Mean outflow velocity ~100 km/s





Superwind and the evolution of ISM in M82

Molecular gas outflow:

Mean velocity	100 km/s	< escape velocity (~300 km/s)
Mass outflow rate	30 M_{sun}/yr	≥ star formation rate (~10 M_{sun}/yr) (e.g. Förster Schreiber et al. 2003)
Momentum rate =(mass outflow rate) x (velocity)	3 x 10^3 M_{sun}/yr km/s	~ starburst input (radiation pressure, supernovae)

→ Molecular gas blown out within <10^7 yr
→ Strong suppression of star formation

Conclusions

- **Star formation in starburst galaxies triggers the superwind feedback**
- **Superwinds play essential role in galaxy evolution**
- **Observations of M82 show outflow of hot and cold gas**
  - Molecular gas will be depleted within $<10^7$ Myr
  - Star formation will be suppressed by the superwind
- **Observations of galactic superwinds with new instruments (e.g., ALMA in Chile) are promising to probe starburst feedback across cosmic history**

Thank you!