# Galactic winds driven by star formation in the local Universe

**Dragan Salak**

Tomonaga Center for the History of the Universe

University of Tsukuba

21 November 2019

# 自己紹介

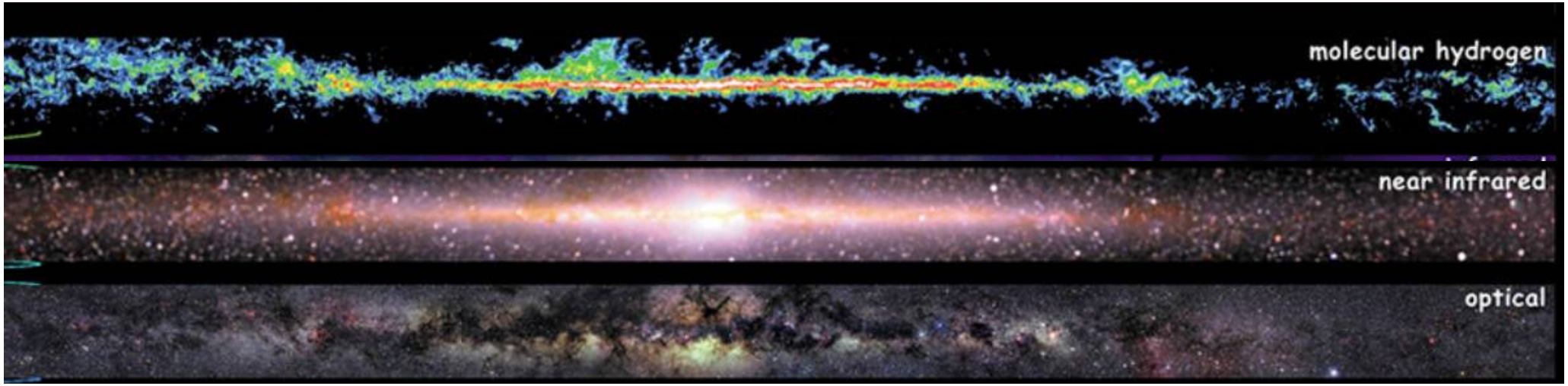
セルビア出身（1983年生まれ）

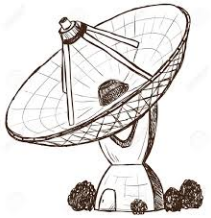
- 2007/6　　Novi Sad大学（物理学科）卒業
- 2011/3　　筑波大学　修士（物理学）
- 2014/3　　筑波大学　博士（理学）
- 2014/4-2015/3　　筑波大学　数理物質系　研究員
- 2015/4-2019/3　　関西学院大学　理工学部　国際修士プログラム　任期制助教
- 2019/6-2019/9　　関西学院大学　理工学部　研究員
- 2019/10-　　筑波大学　宇宙史研究センター　研究員

主なホビー：山登り（日本の山で~100座ぐらい登っています。）

# Star formation and molecular gas

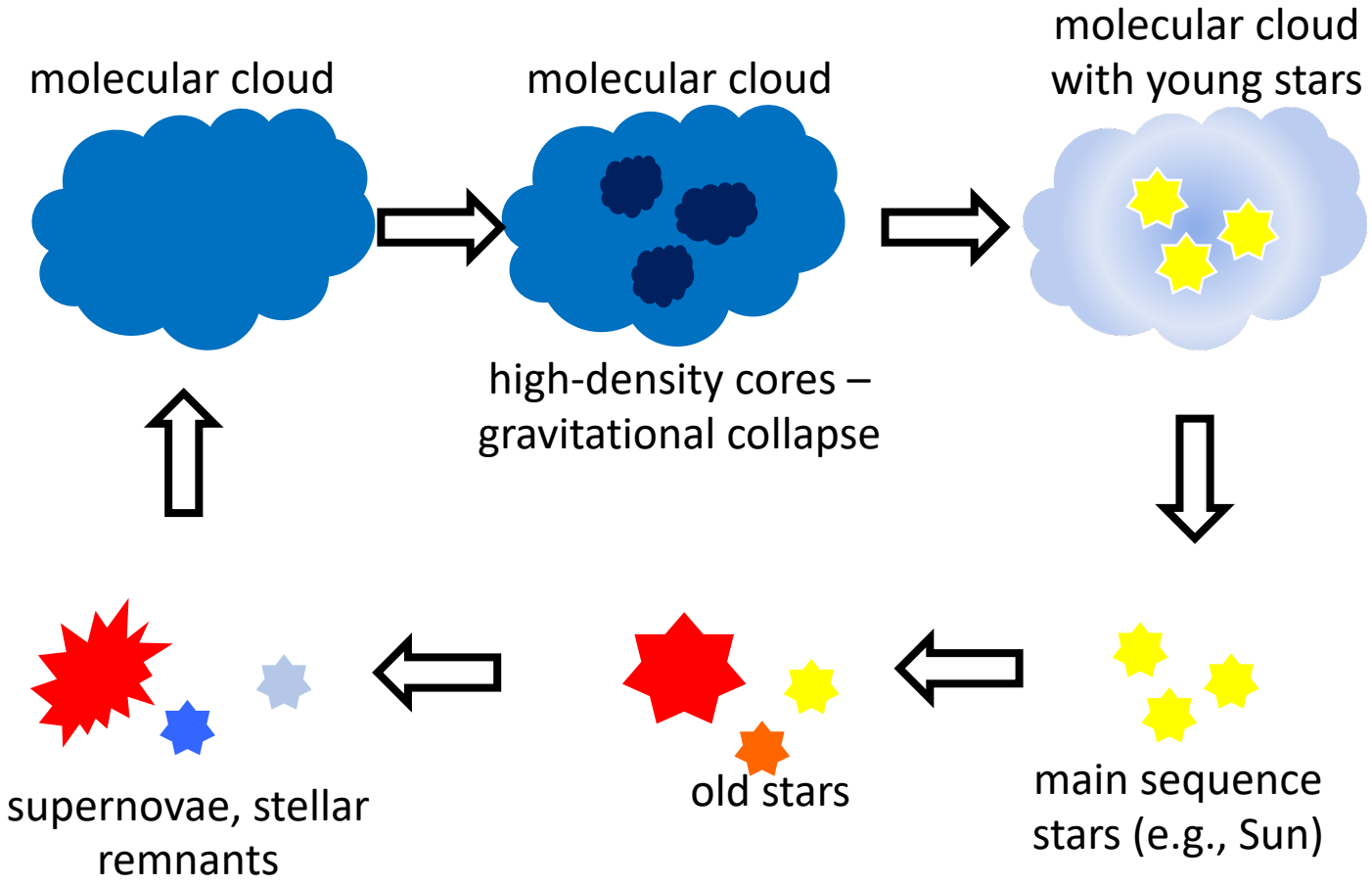
- **Star formation** is observed to take place predominantly in molecular clouds.
- **Molecular clouds** are giant gaseous bodies (size 10-100 pc) that consist mostly of $H_2$ gas and dust particles (size ~0.1 μm).
- Cold (T ~ 10 K) and low density (n ~ $10^3$ $cm^{-3}$), so many **molecular rotational lines** (e.g., CO *J*=1-0) can be detected at μm~mm wavelengths by radio telescopes.

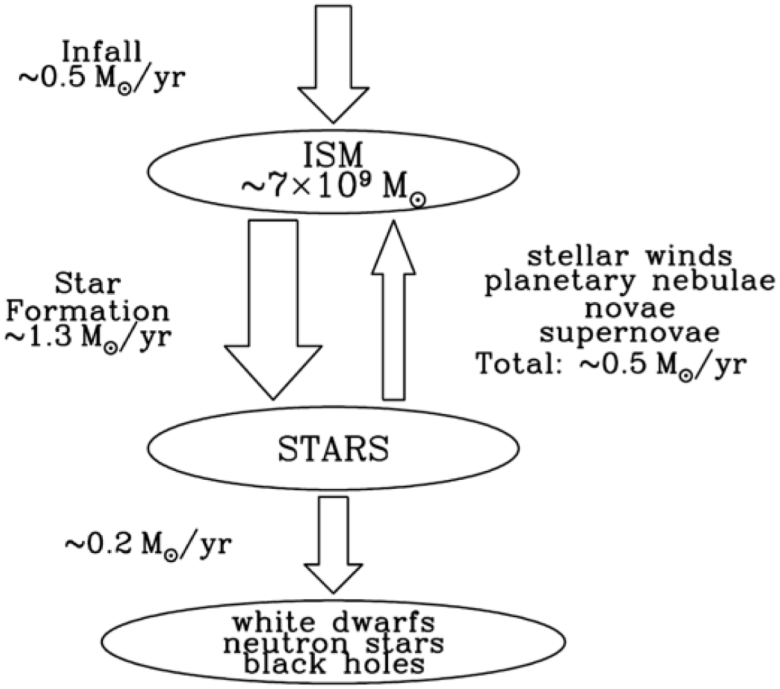


Milky Way galaxy (NASA)

# Formation and evolution of stars

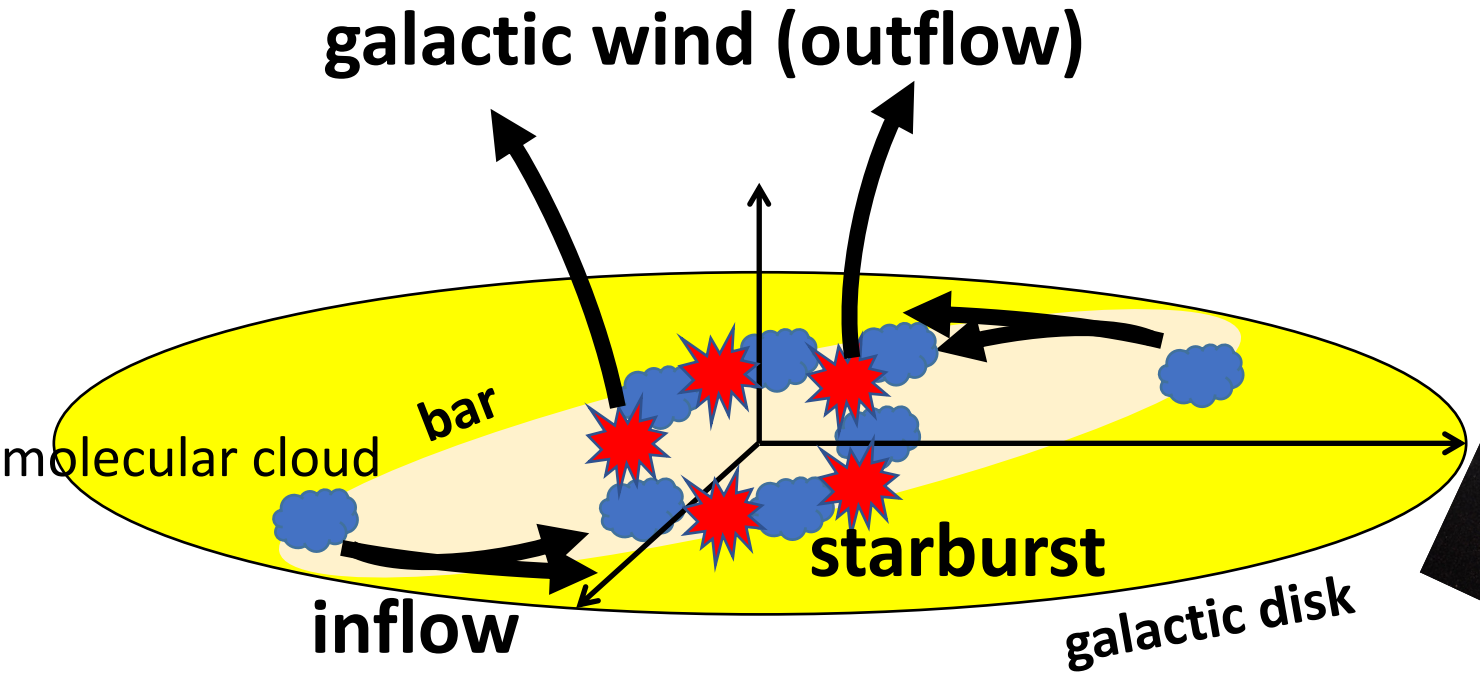


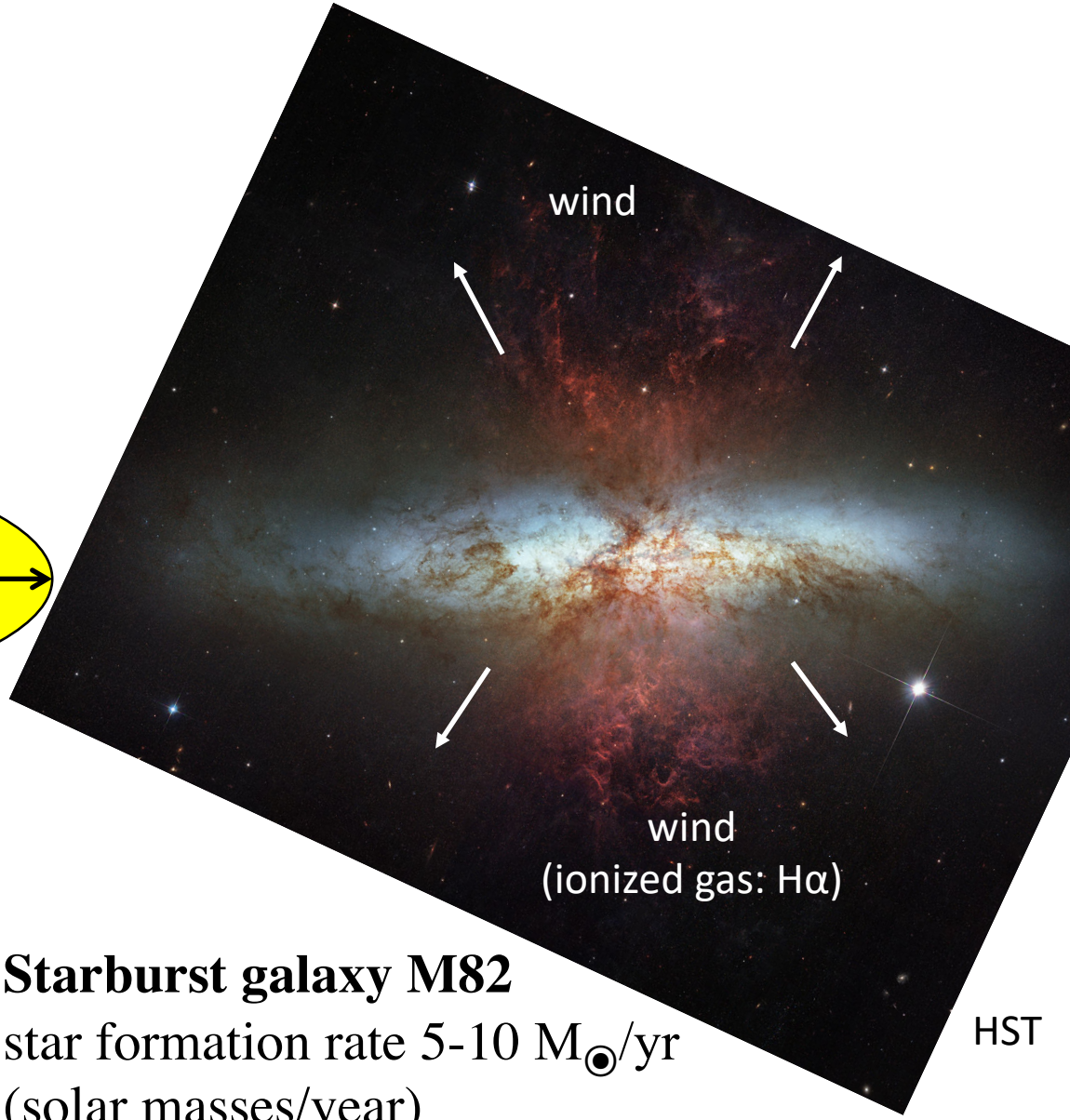

**total Milky Way galaxy**

*"Physics of the ISM and IGM"* Draine

# Baryon cycle in galaxies




e.g., Veilleux+ (2005)

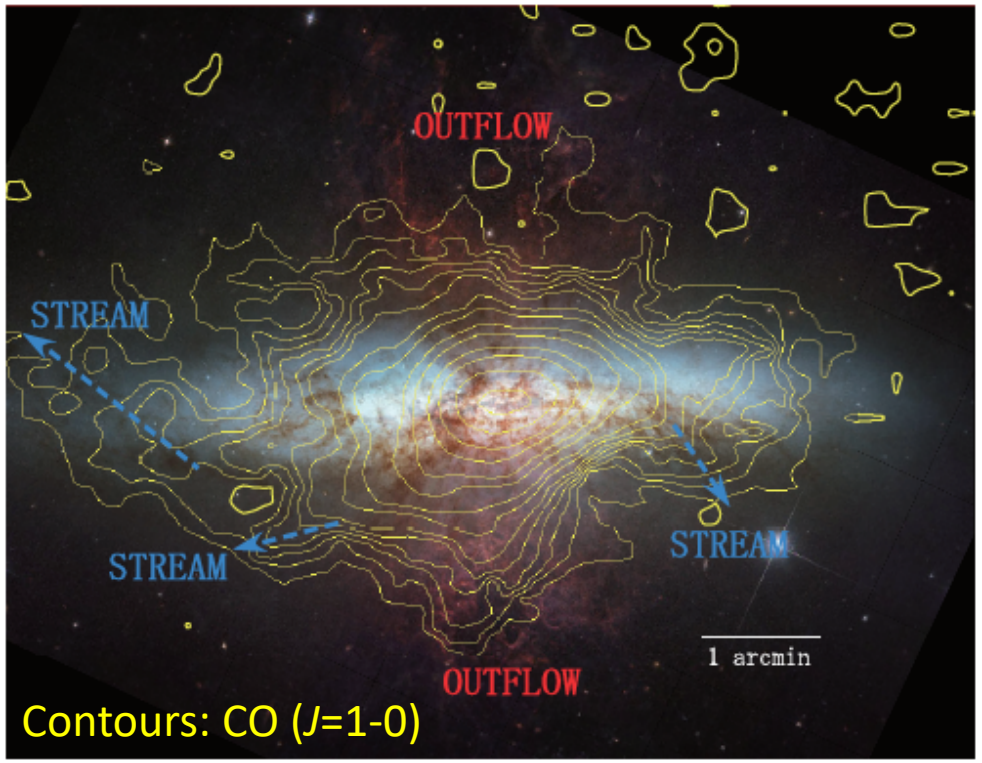



HST

**Starburst galaxy M82**
star formation rate 5-10 $M_\odot$/yr
(solar masses/year)

# Molecular gas in galactic winds

- Classical example: **starburst galaxy M82**

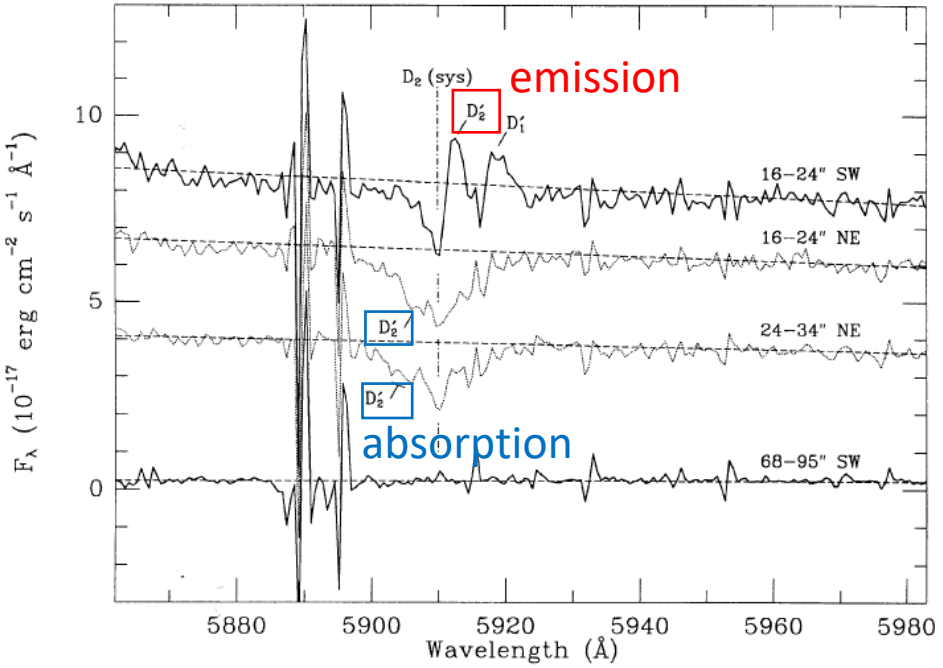



DS+ 2013 PASJ, 65, 66

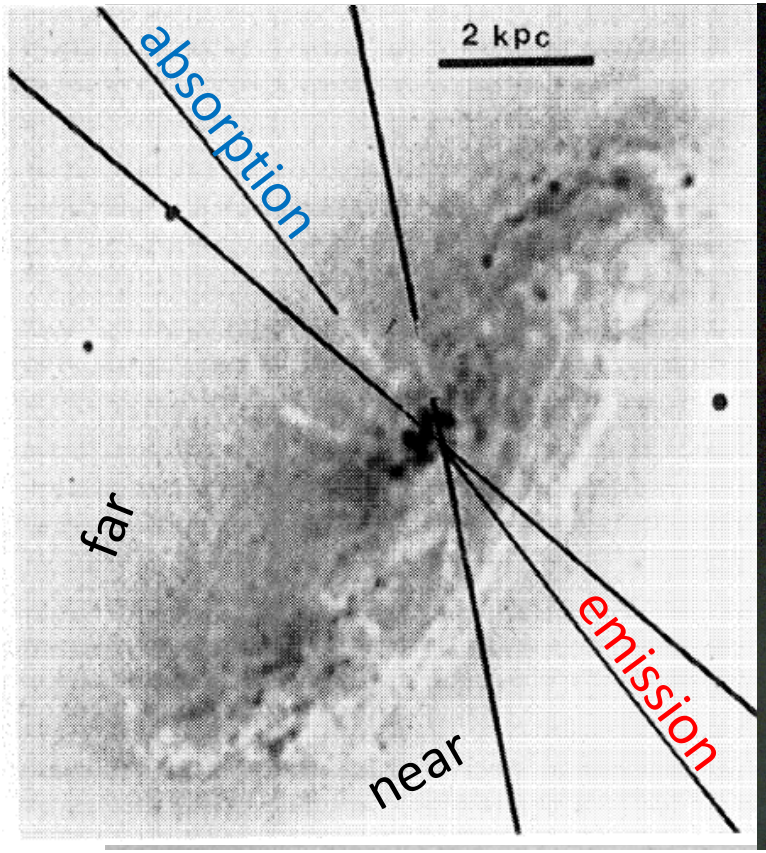
Large-scale molecular gas outflow was detected by the Nobeyama 45-m telescope. Up to 40% of total molecular gas mass in M82 is in the outflow.

# Starburst galaxy NGC 1808

- Nearby (~11 Mpc)
- Starburst in central 500 pc
- Evidence for neutral gas outflow




Na I (Phillips 1993)

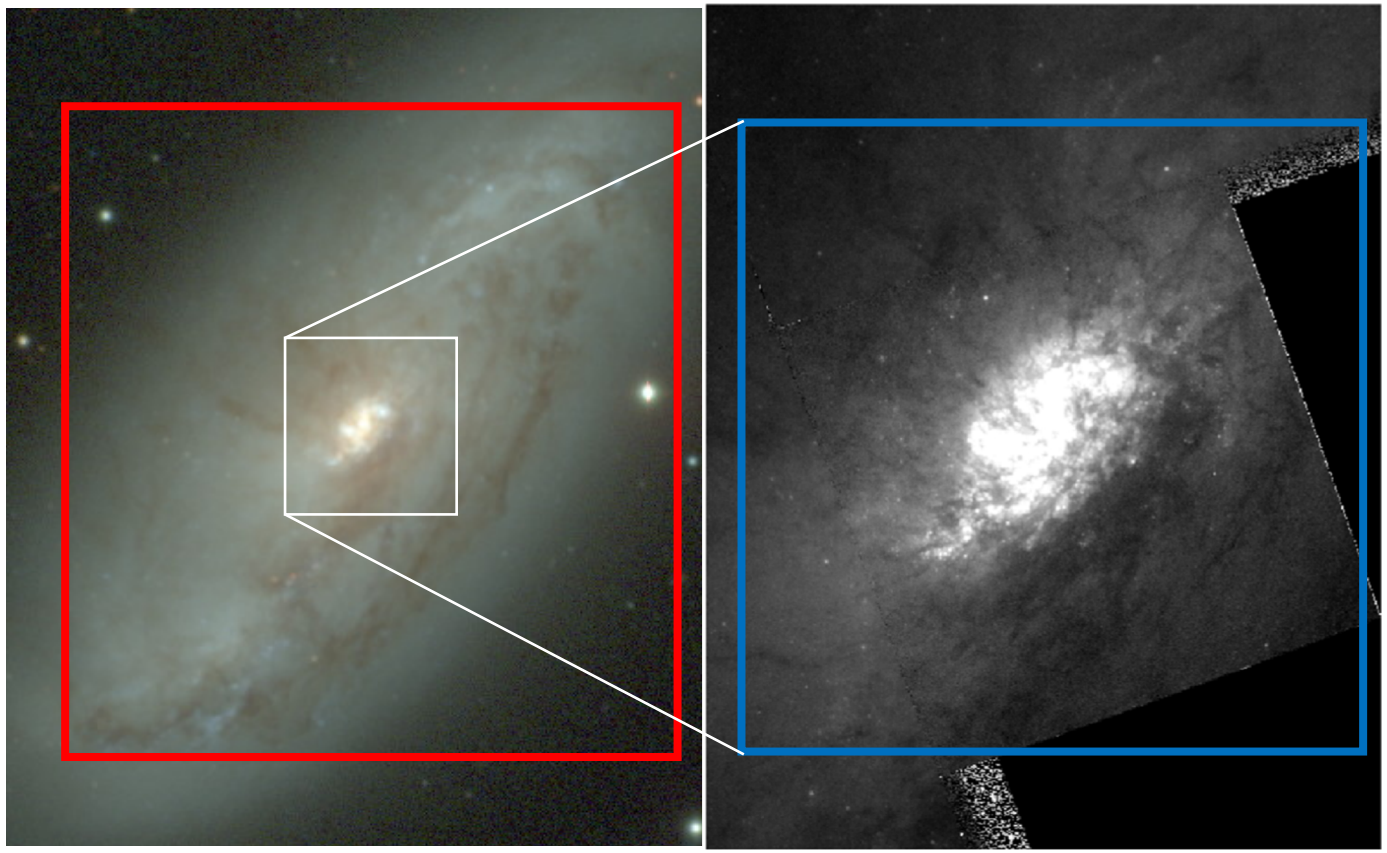



B band negative (Phillips 1993)

Carnegie-Irvine Galaxy Survey (Ho+ 2011)

# ALMA observations of NGC 1808

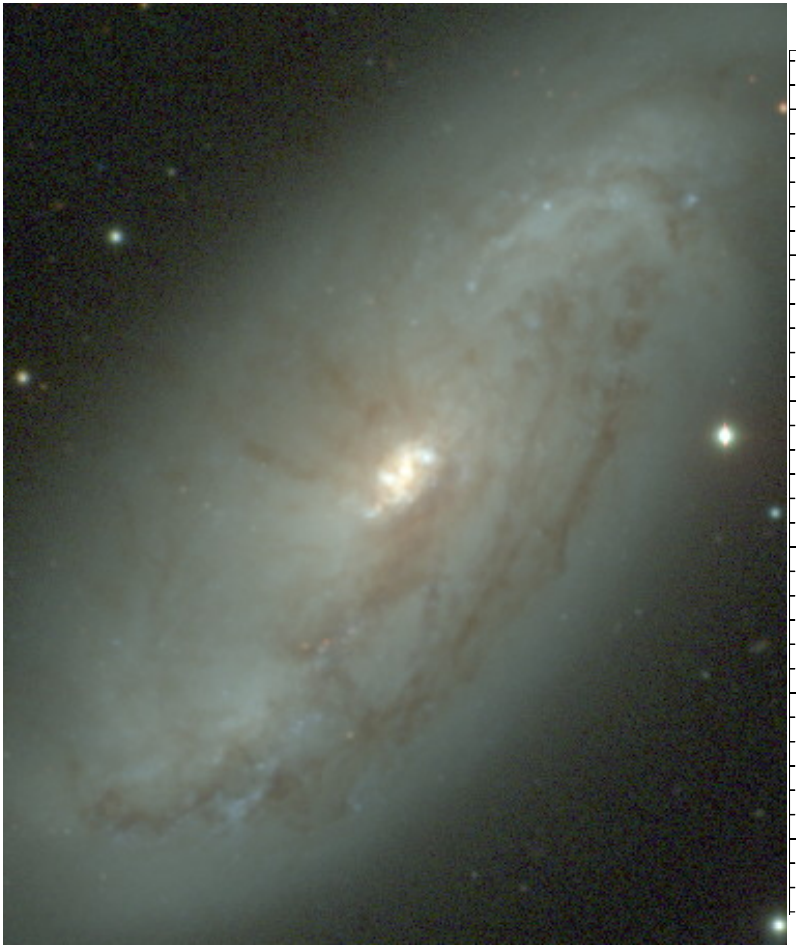

| Cycle | 1 | 2 |
|---|---|---|
| Resolution | 2” (100 pc) | 0.5”-1” (25-50 pc) |
| Spectral line | **CO (1-0)** | **CO (3-2)** |



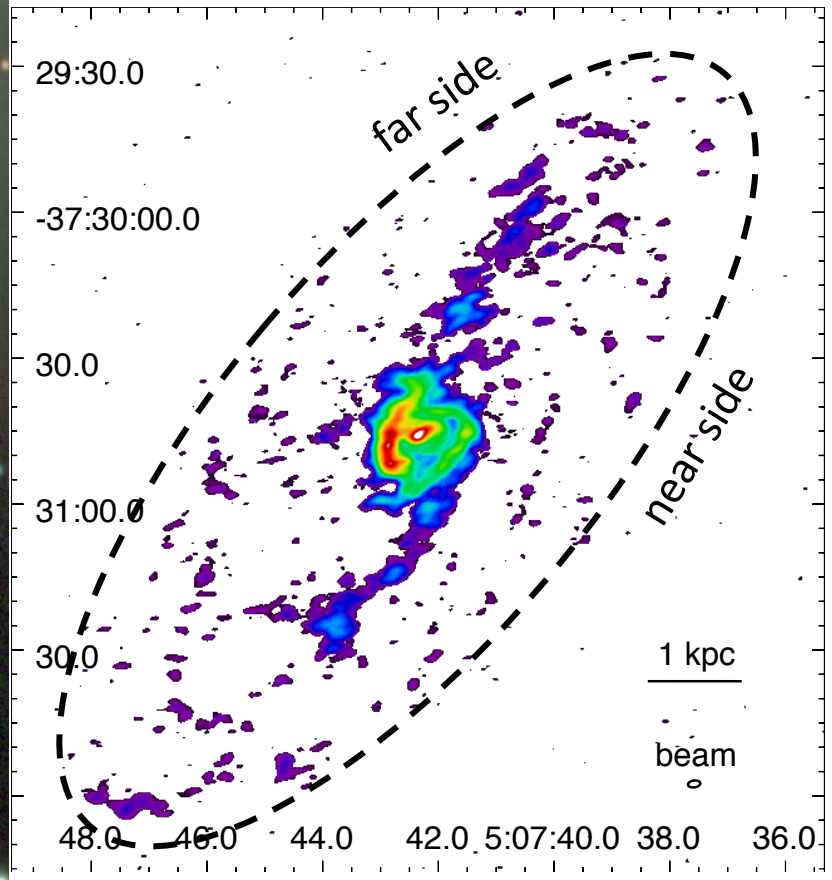
Optical (CGS)

optical
(Hubble Space Telescope)

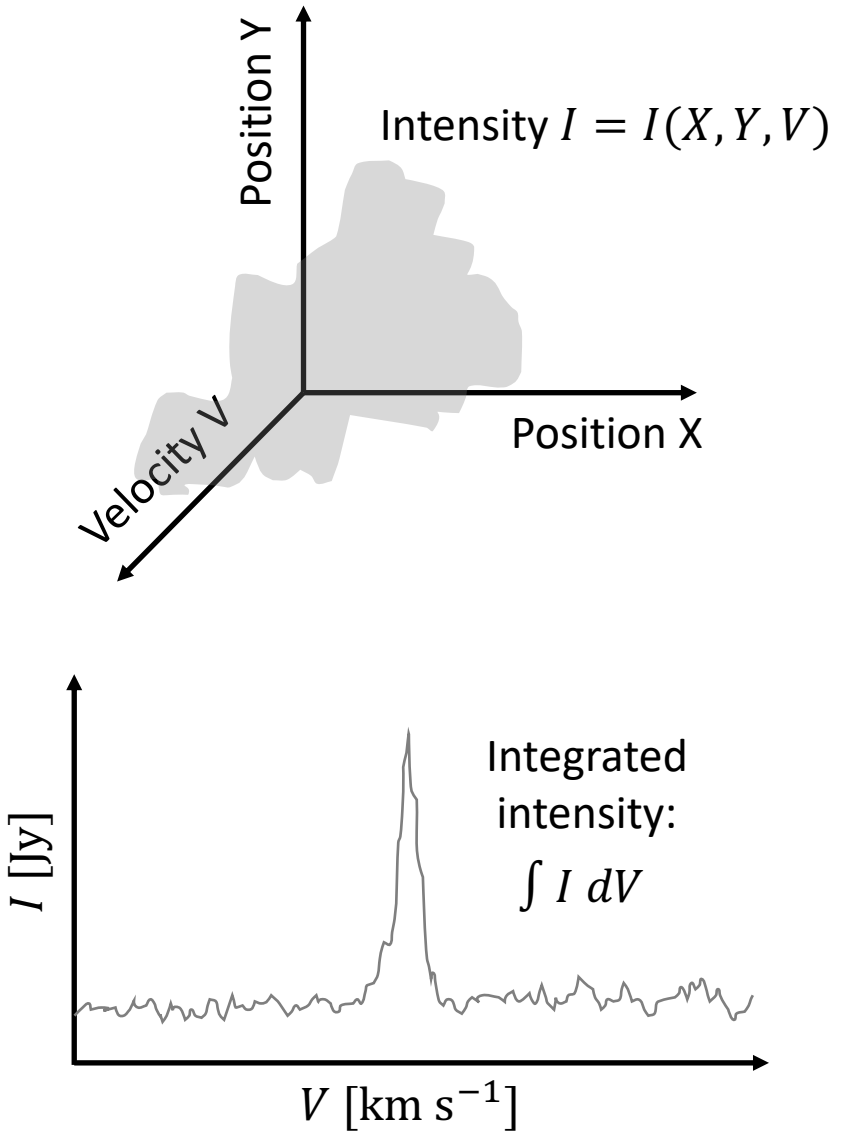
# Molecular gas distribution



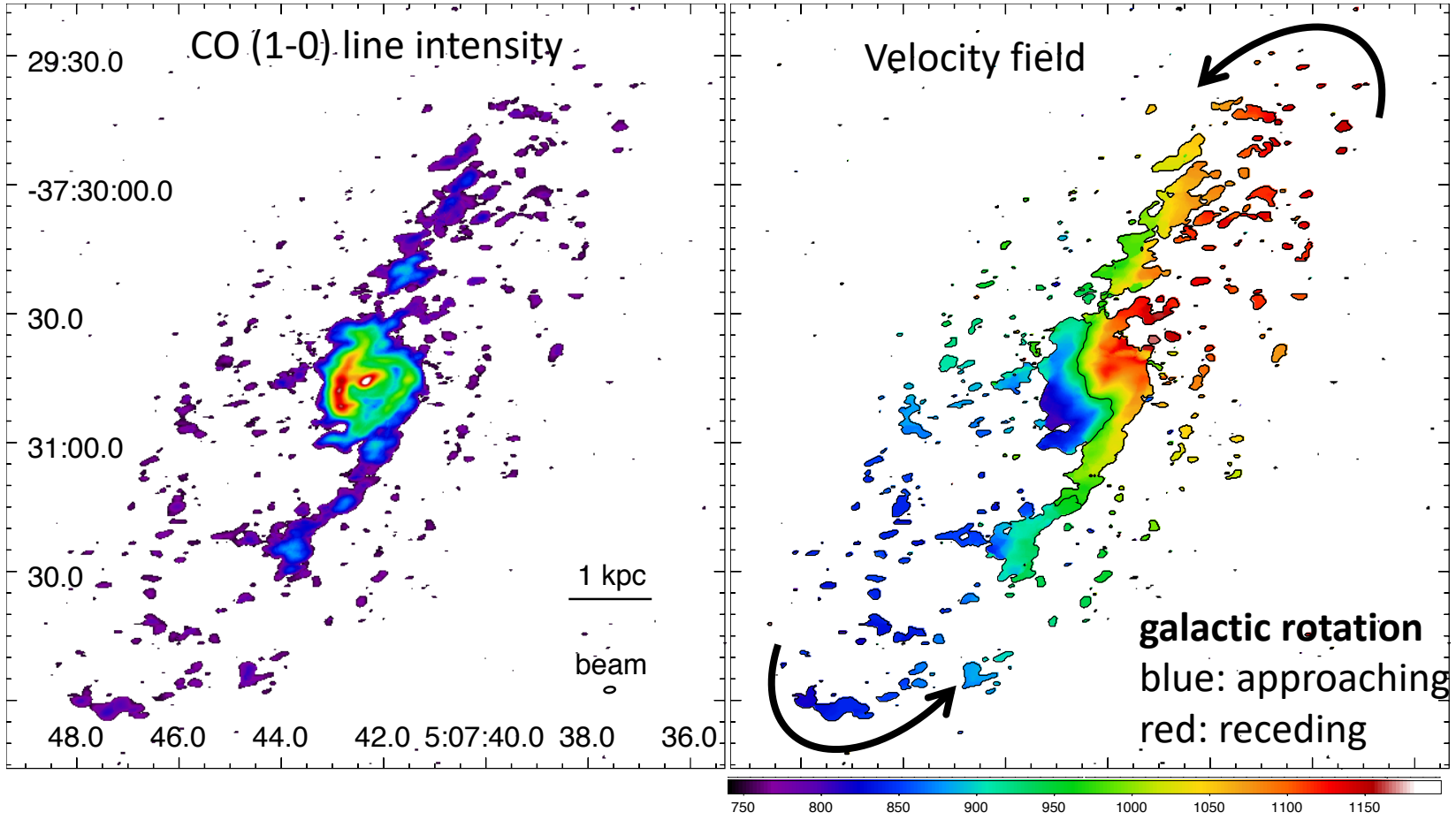
Optical (CGS)




CO (1-0) integrated intensity (DS+ 2016)



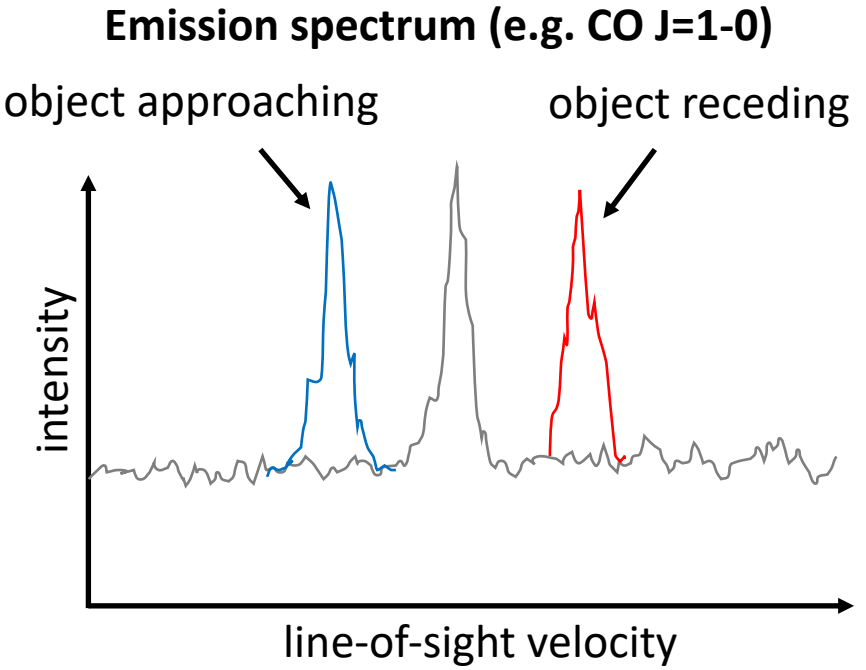
# Molecular gas kinematics





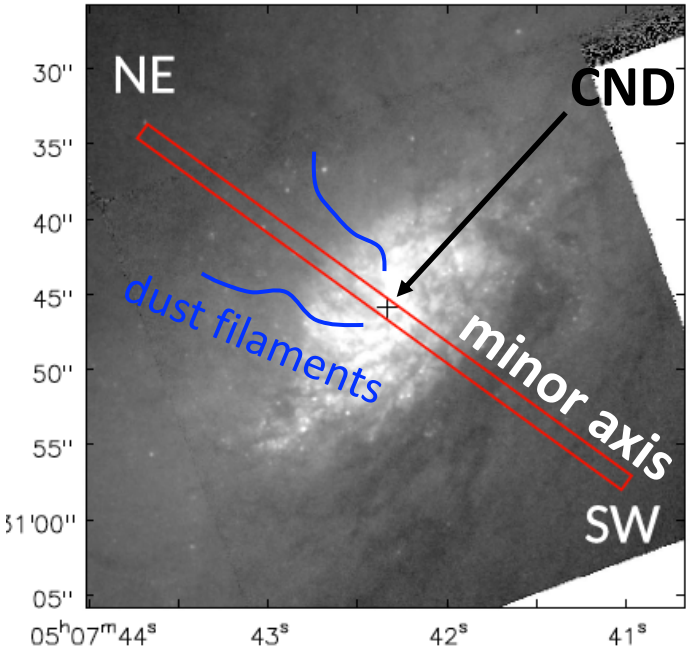


DS+ 2016

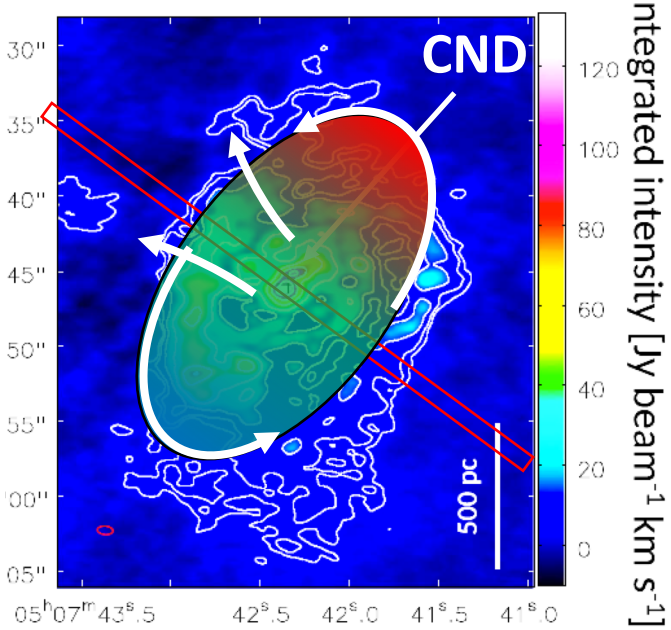


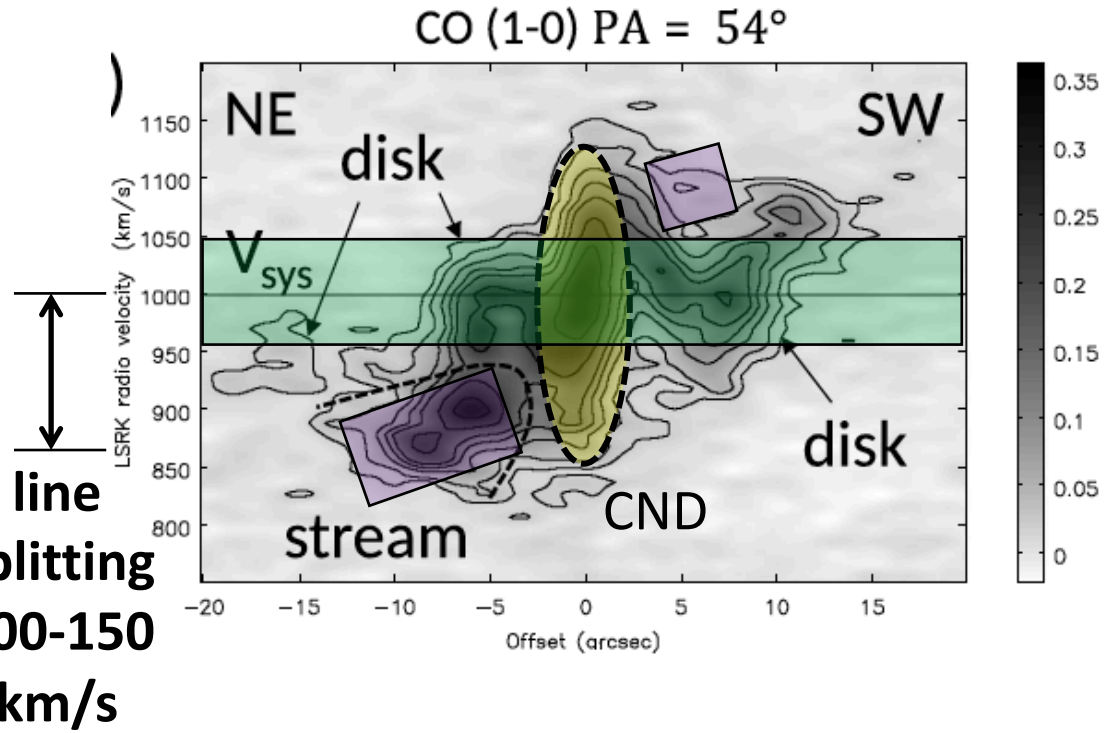
# Molecular wind in NGC 1808

Optical




CO gas




DS+ 2017

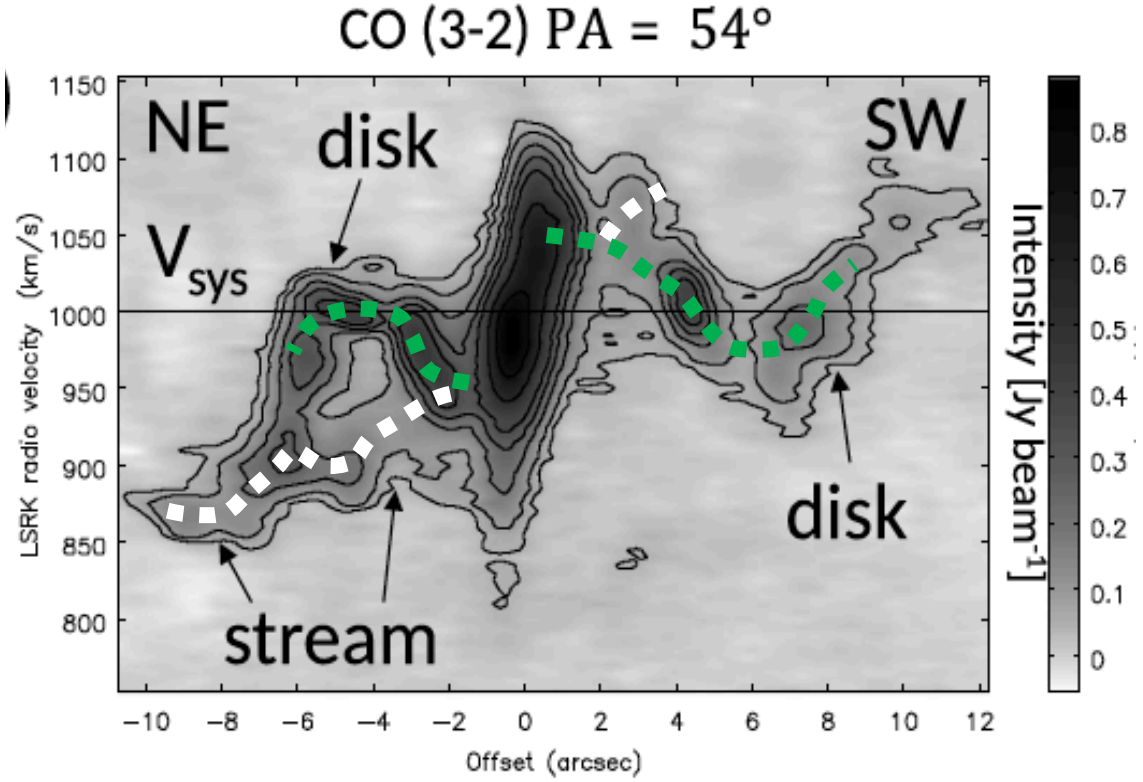
# Outflow dynamics

- **Velocity**

Outflow velocity ~200 km/s at radius 1 kpc

- **Mass outflow rate** $dM/dt$ ~1-10 $M_\odot$/yr

~ total star formation rate ($R$<500 pc) ~5 $M_\odot$/yr

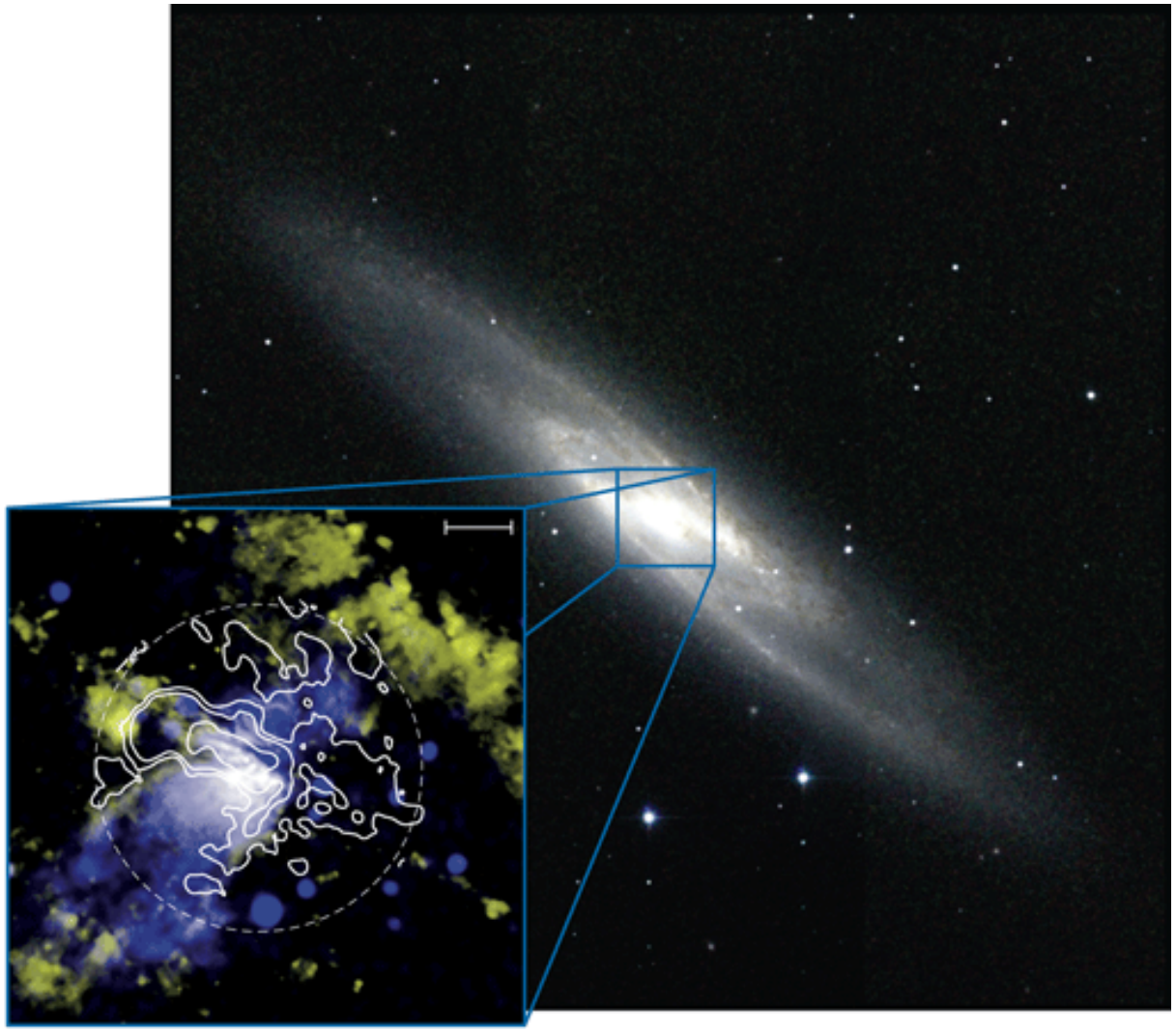



DS+ 2017

# Molecular wind in NGC 253

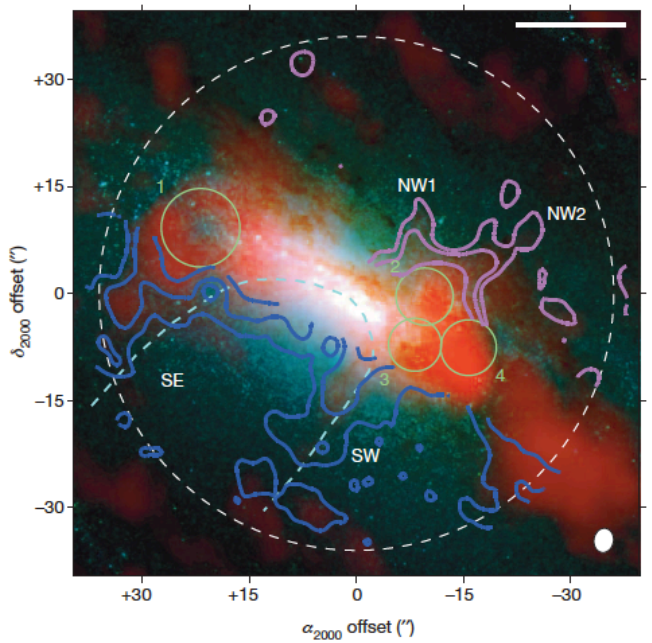
White: molecular gas (intensity of emission line CO J=1-0 na 2.6 mm) captured by ALMA
Blue: ionized gas (X-rays)

Bolatto+ (2013)

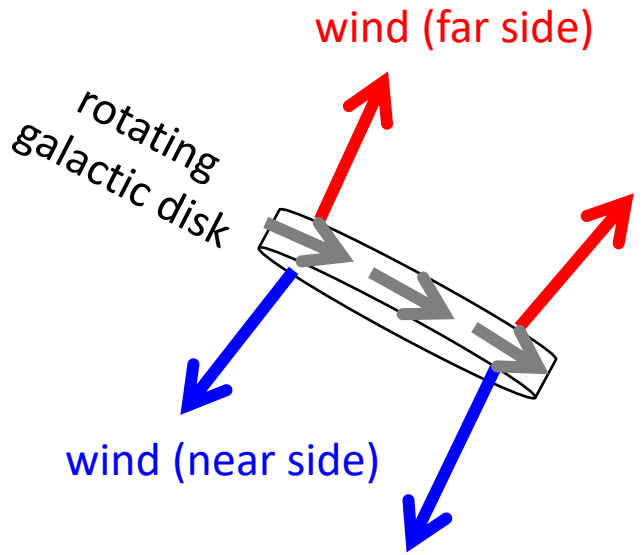


# Molecular wind in NGC 253

- The **molecular wind speed** ~60 km/s relative to the center of the galaxy
- **Mass outflow rate** (3-9 solar masses/year) > **star formation rate** (1-3 solar masses/year)
- Conclusion: Star formation suppressed by the wind




Bolatto+ (2013)



# Conclusions

- Galactic winds remove molecular gas and thus affect star formation activity and galaxy evolution.
- CO observations by ALMA revealed molecular winds in nearby galaxies NGC NGC 1808 and NGC 253.
  - NGC 1808: mass outflow rate ~ star formation rate
  - NGC 253: mass outflow rate ~> star formation rate

  → suppressing star formation?

- Future work: How molecular winds form and evolve?
- In progress: ALMA observations of NGC 1482

Green: stars
Violet: hot gas