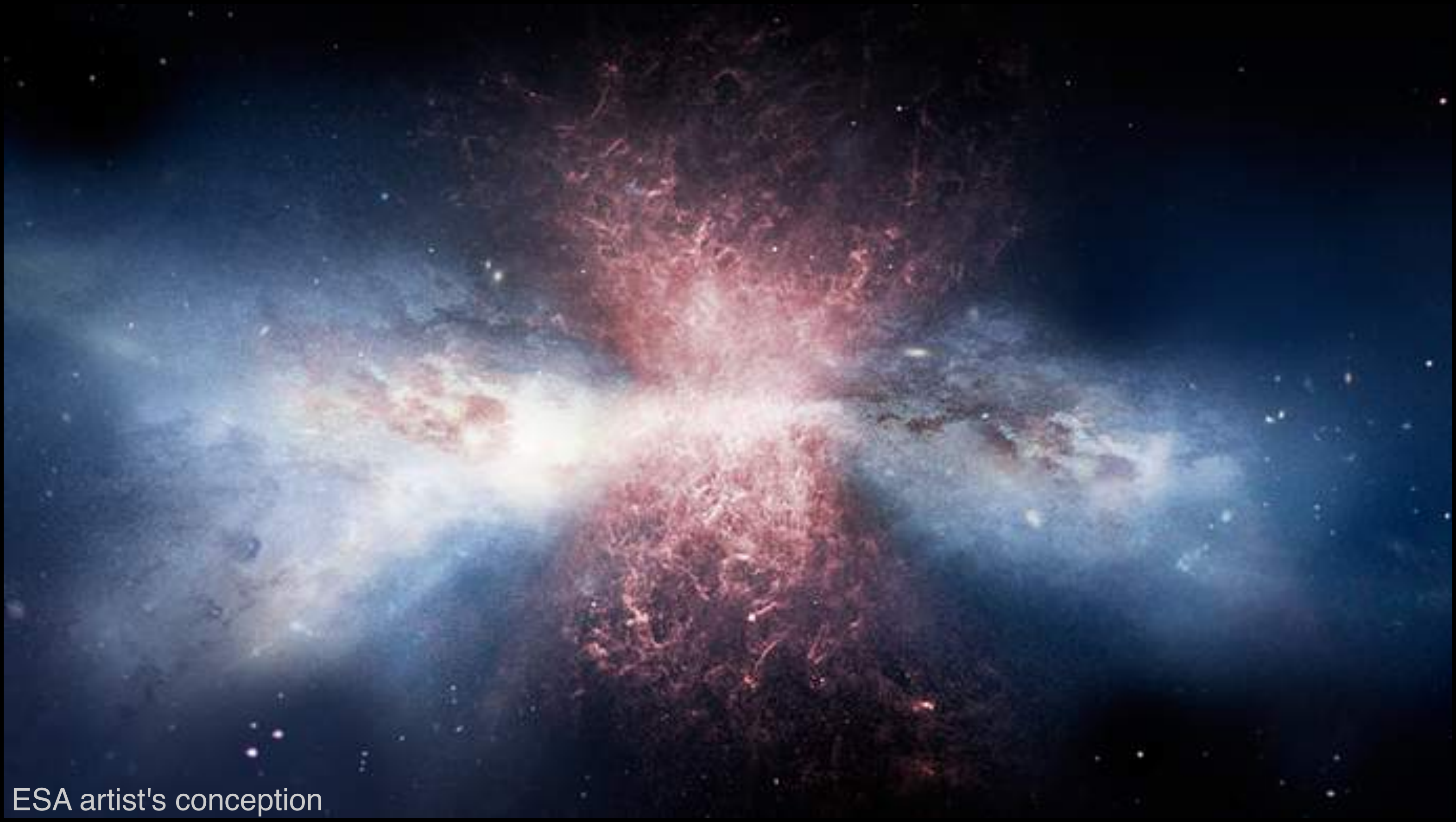
# The Physics, Observational Signatures, and Consequences of AGN-Driven Galactic Winds


ESA artist's conception

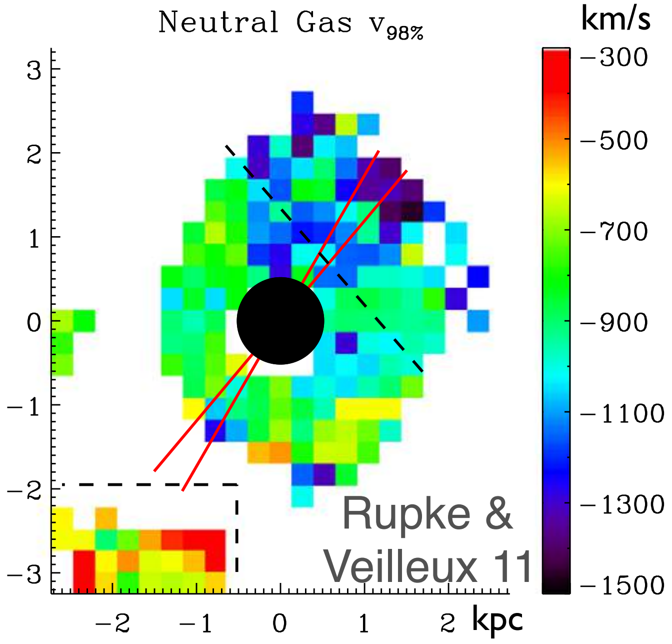
Claude-André Faucher-Giguère
Northwestern University I CIERA

With Eliot Quataert, Alex Richings, Paul Torrey, Daniel Anglés-Alcázar, Phil Hopkins,
Norm Murray, Jonathan Stern, Nadia Zakamska, Joe Hennawi, & Jesse Nims

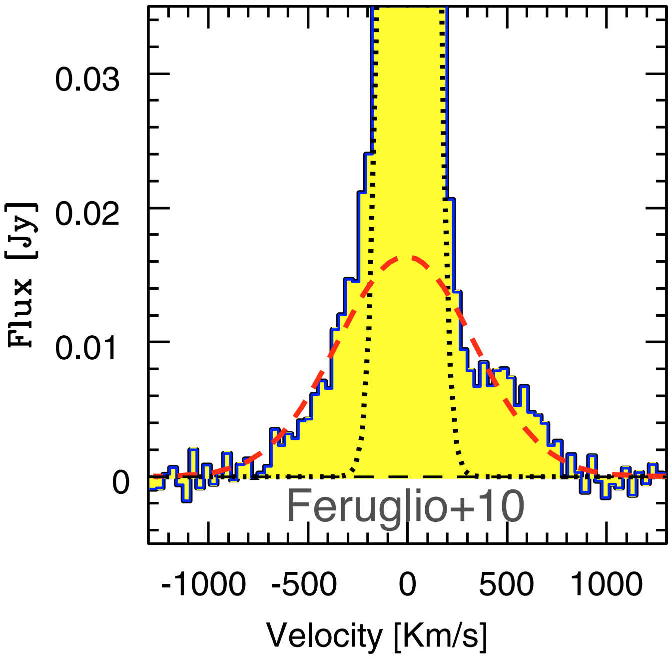
# Wide-angle, galaxy-scale outflows driven by AGN

- Now detected in atomic+molecular (CO, OH, HCN, ..) gas in luminous QSOs at $z$~0-6 (Moe+09, Feruglio+10, Fischer+10, Sturm+11, Rupke & Veilleux 11, Aalto+12, Greene+11, Maiolino+12, …)
- $R$~1-10 kpc, $v$~1,000 km/s, d$M$/d$t$~1,000 $M_{sun}$/yr, ⇒ $L_{kin}$ ~ few % $L_{AGN}$
- Distinct from radio jets acting in clusters

**Mrk 231**



Rupke & Veilleux 11

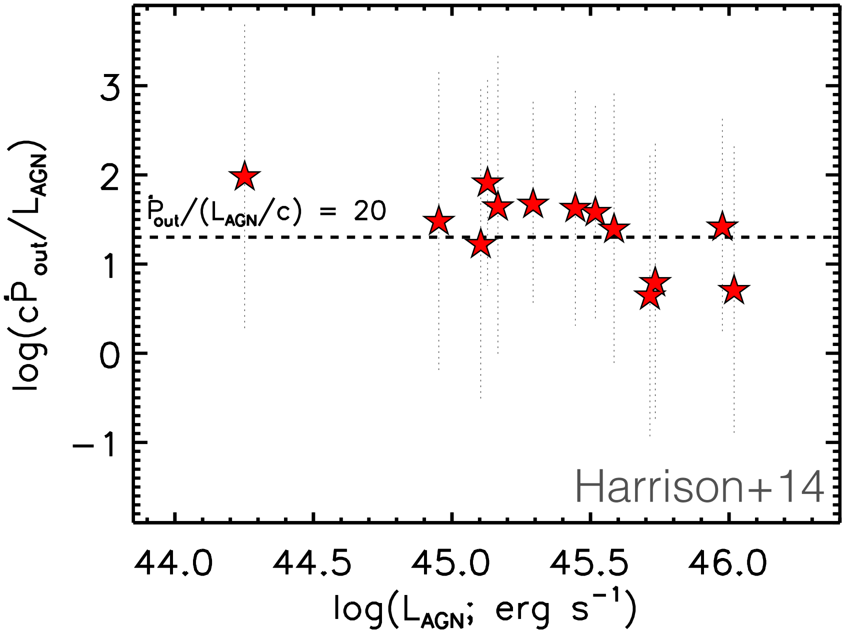


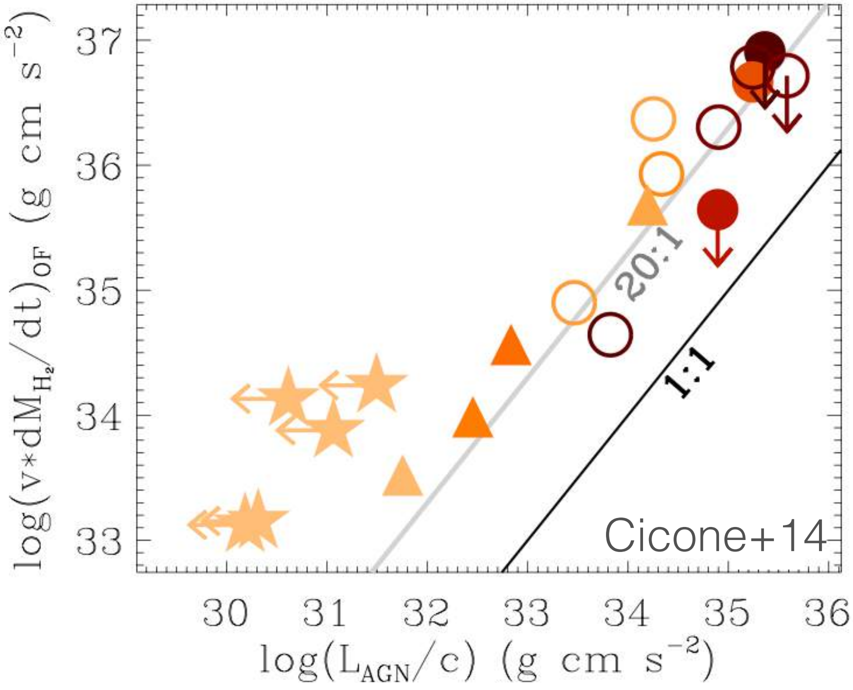
Feruglio+10

# Outline

- Spherically-symmetric dynamics of AGN-driven galactic winds
    - ➡ energy-conserving ⇒ momentum fluxes $\gg L_{\rm AGN}/c$
- Observational signatures
    - ➡ molecule formation at wind shocks
- Effects on galaxies: 3D simulations with stellar+AGN feedback

# AGN outflow momentum fluxes ≫$L_{\rm AGN}/c$





- If all photons scatter once & *P* is conserved,

$$\dot{P} \sim L_{\rm AGN}/c$$

- Observations indicate

$$\dot{P} \sim 20 L_{\rm AGN}/c$$

FG, Quataert & Murray 12; FG & Quataert 12

## Momentum conserving

$t_{cool} \ll t_{flow}$

No thermal pressure

$P_{final} \sim P_{start}$

e.g., evolved star wind

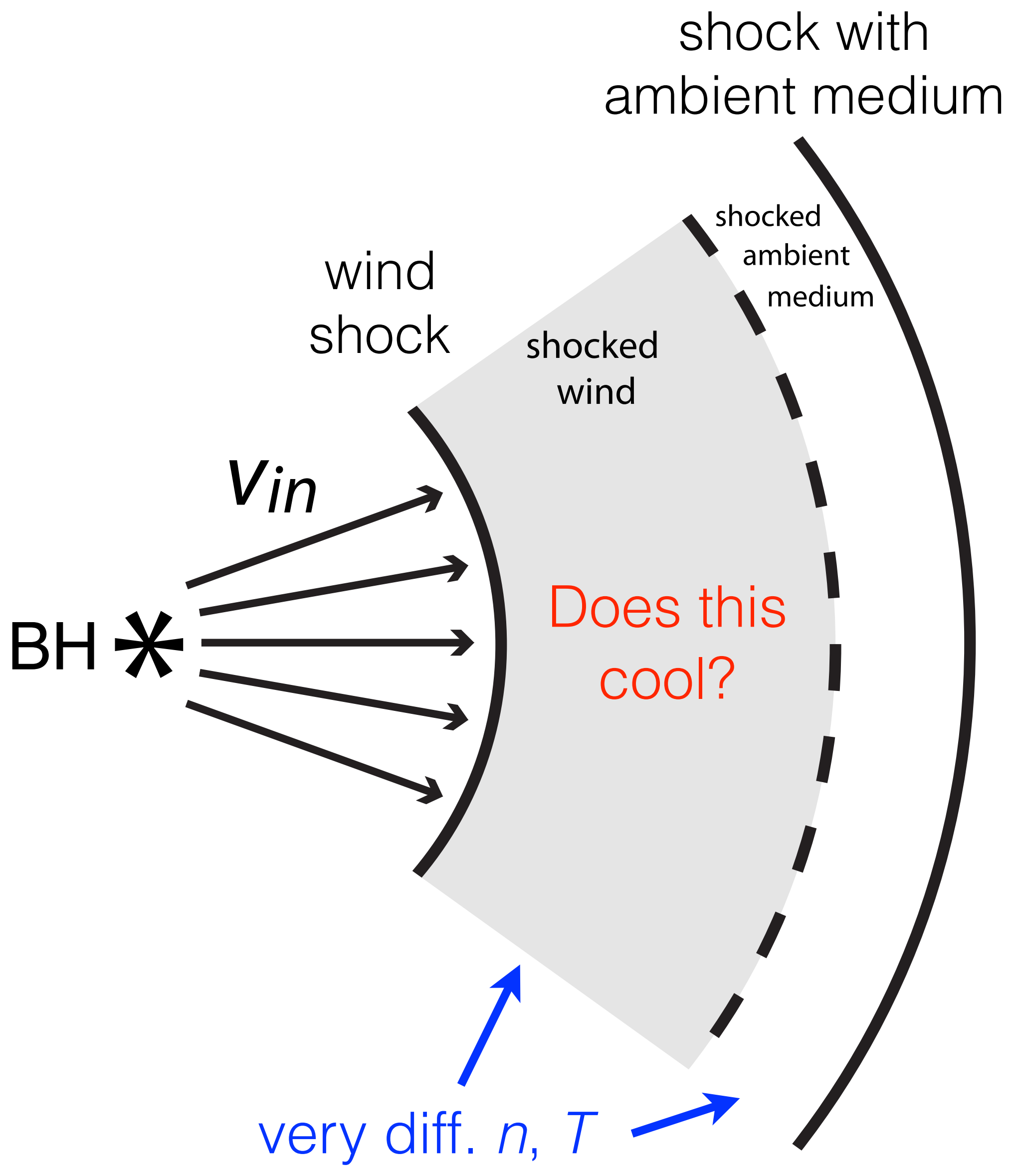
## Energy conserving

$t_{cool} \gg t_{flow}$

Shocked gas does $pdV$ work

$P_{final} \gg P_{start}$

e.g., Sedov-Taylor SN remnant



FG & Quataert 12 (s.a. King 03, Costa+14)

# AGN-driven galactic winds are energy-conserving

1) Radiation pressure accelerates nuclear wind with $\dot{P} \sim L_{\rm AGN}/c$

(assume, traced by broad absorption lines (BALs) with $v_{\rm in}$~0.1$c$)

2) Energy-conserving phase boosts $\dot{P}$ by factor ~20

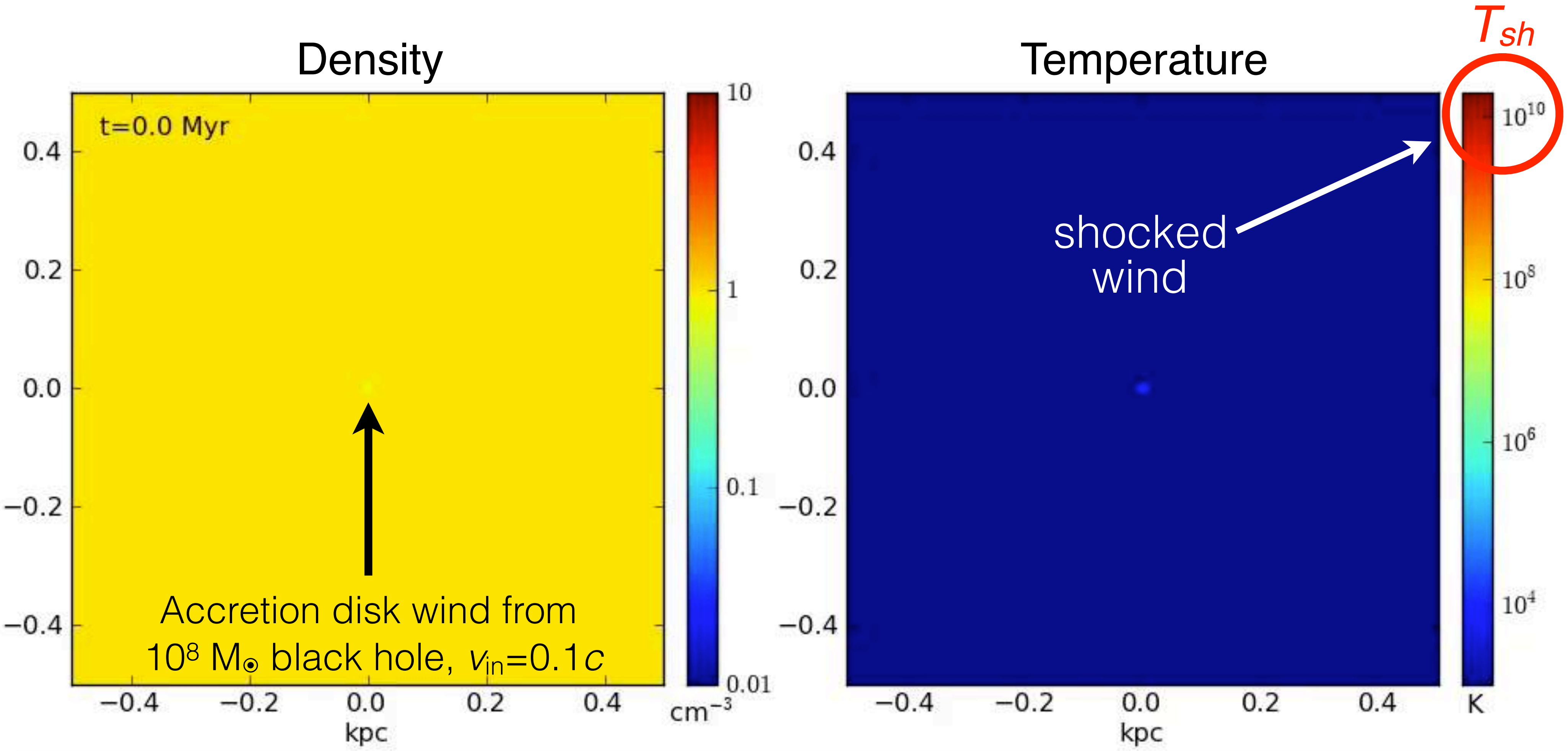
(show)

- Several previous studies predicted AGN-driven outflows to be momentum-conserving because of the short cooling times expected in galactic nuclei (e.g., Silk & Nusser 2010)

- Important heating and cooling physics missed in most simulations

FG & Quataert 12 (s.a. Zubovas & King 12)

# Wind shock structure evolution



$T_{sh}$

shocked wind

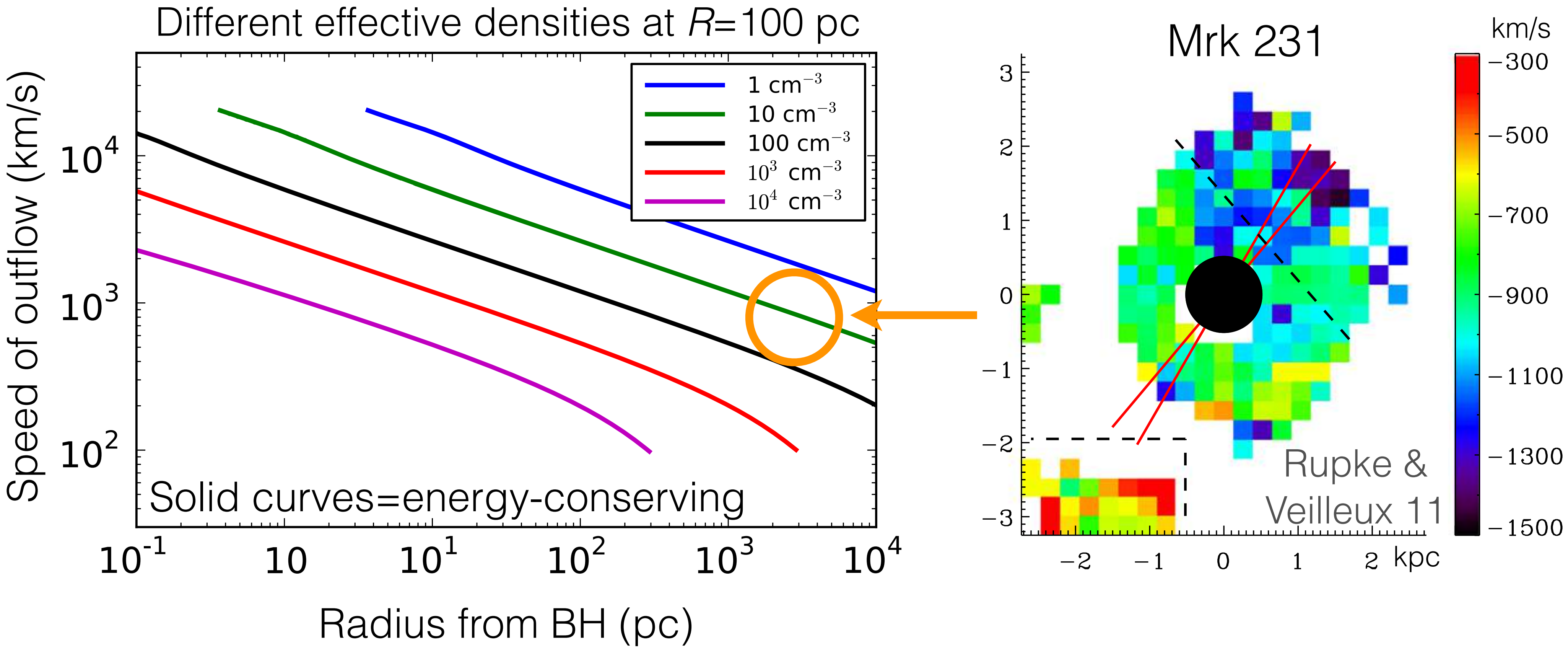
Accretion disk wind from $10^8$ $M_\odot$ black hole, $v_{in}=0.1c$

Cooling dominated by inverse Compton scattering with BH radiation,

but slowed by factor ~50 due to weak $p^+$, $e^-$ coupling

FG & Quataert 12

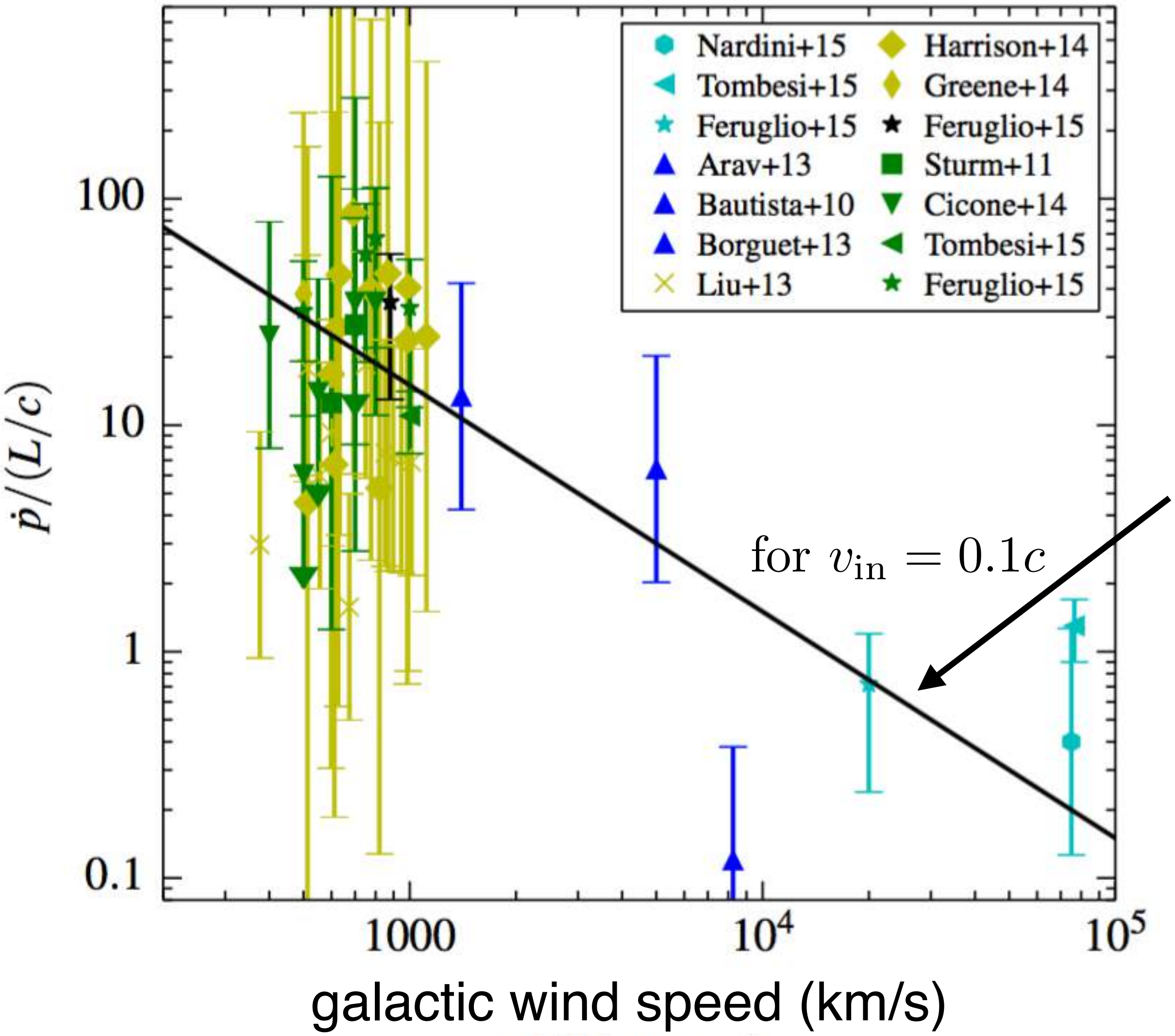
# Dynamical models for spherical galactic nuclei



⇒ Black hole-driven galactic winds are in energy-conserving

FG & Quataert 12

# Energy conservation naturally explains measured QSO outflow momentum boosts



$$\frac{\dot{P}}{L_{\rm AGN}/c} \sim \frac{1}{2}\left(\frac{\text{nuclear wind speed}}{\text{galactic wind speed}}\right)$$

FG & Quataert 12; Stern, FG+16

# Outline

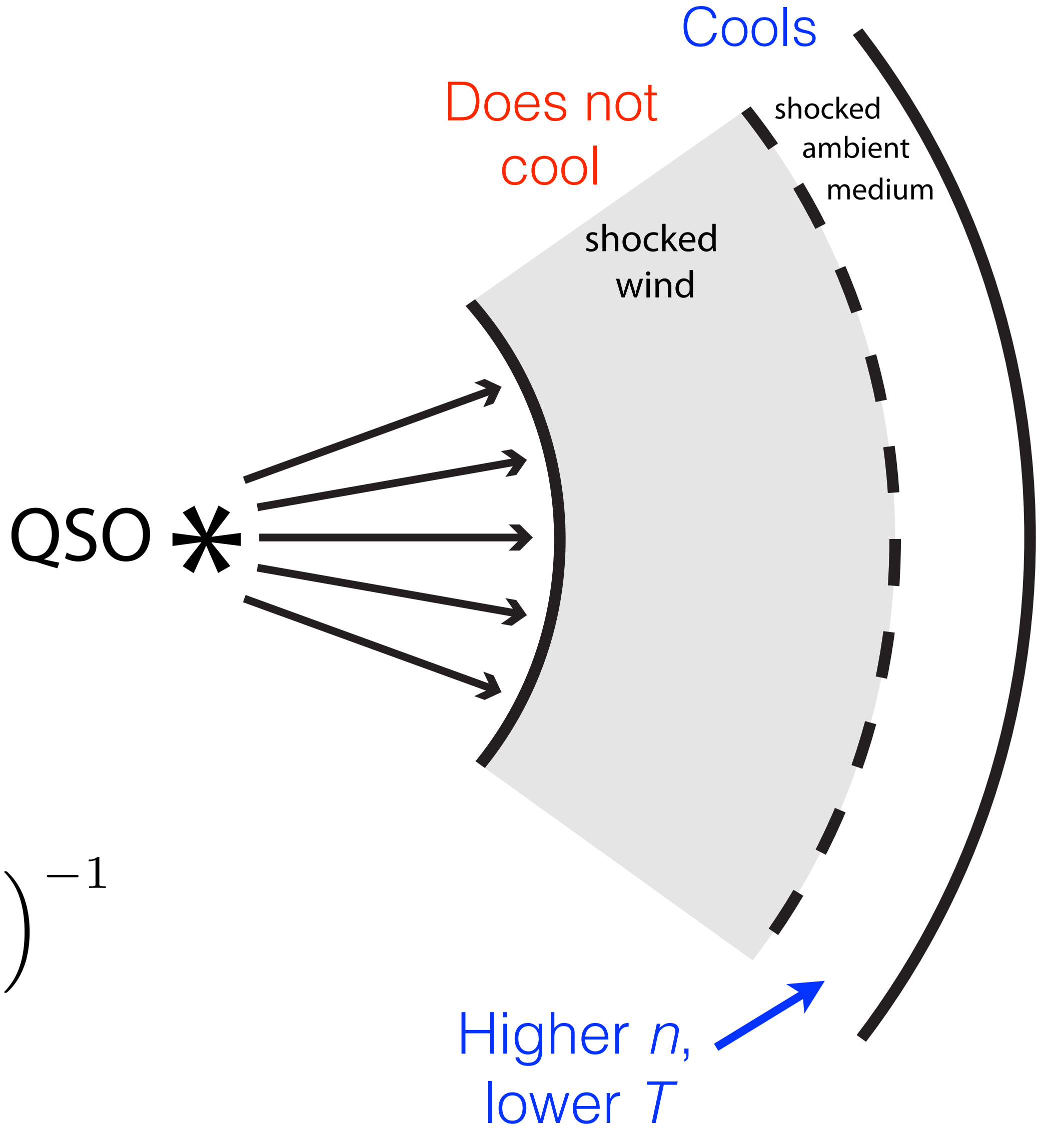
- Spherically-symmetric dynamics of AGN-driven galactic winds
  - ➡ energy-conserving ⇒ momentum fluxes $\gg L_{\mathrm{AGN}}/c$
- **Observational signatures**
  - ➡ molecule formation at wind shocks
- Effects on galaxies: 3D simulations with stellar+AGN feedback

# Cooling of the forward shock

- Shocked wind properties set by jump conditions at (inner) wind shock ($v$~0.1$c$)

- Shocked ambient medium properties set by jump conditions at forward (outer) shock ($v$≲1,000 km/s):

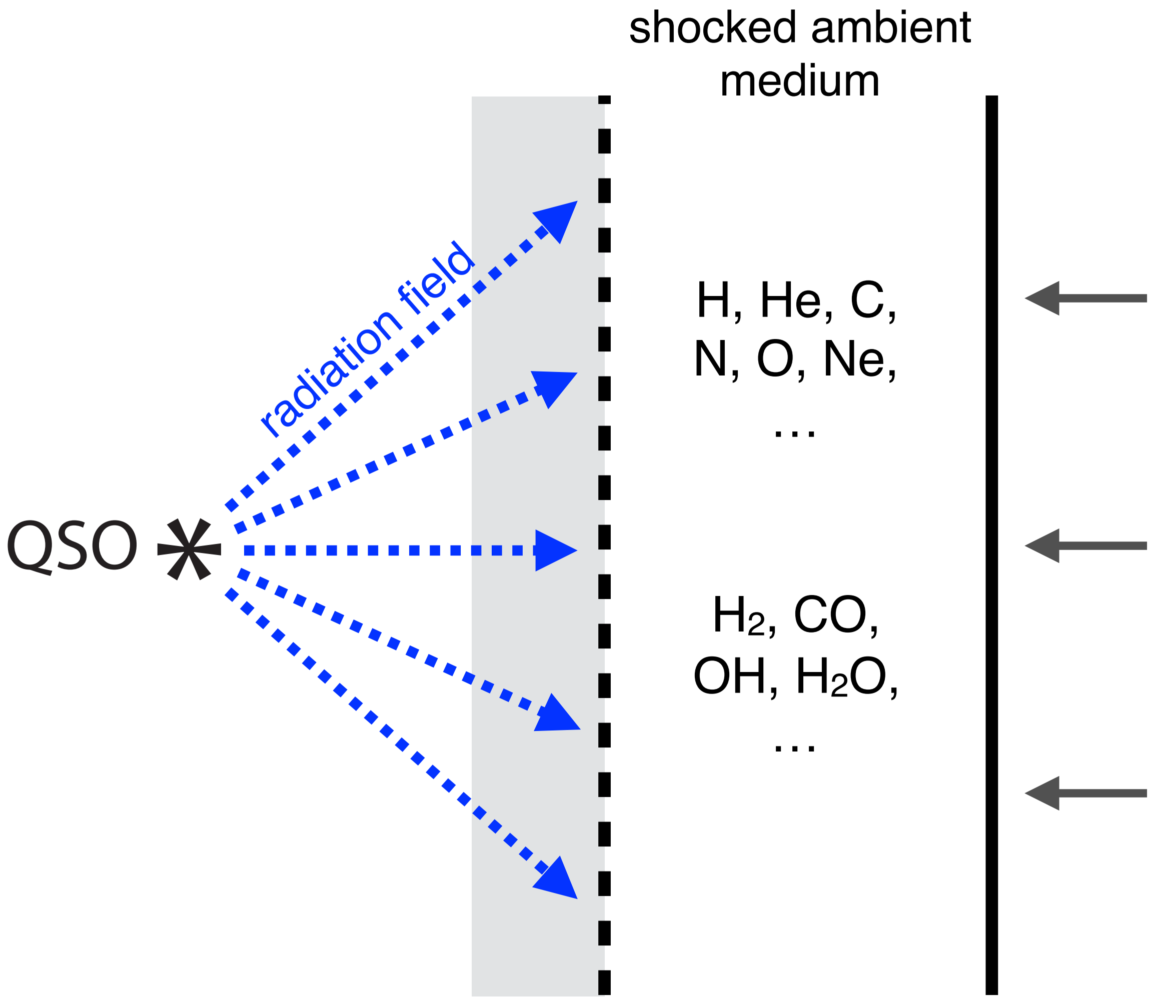
$$t_{\rm cool} \approx 2 \times 10^4 \ {\rm yr} \left( \frac{n_{\rm ambient}}{10 \ {\rm cm}^{-3}} \right)^{-1} \times \left( \frac{v_{\rm outer \ shock}}{500 \ {\rm km \ s}^{-1}} \right)^2$$



FG & Quataert 12 (s.a. Zubovas & King 14, Costa+15)

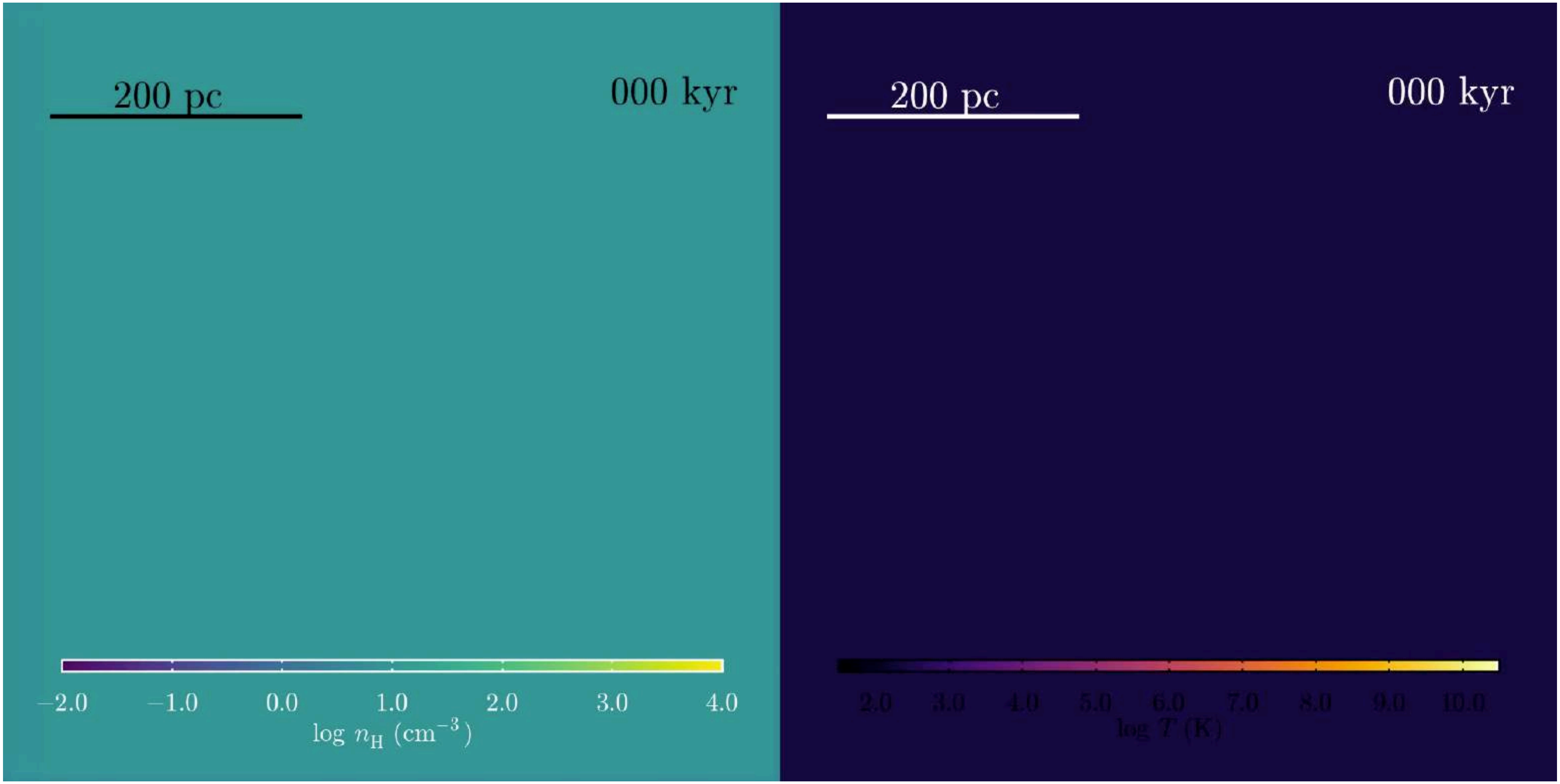
# Time-dependent chemistry in forward shock cooling layer

- 3D hydro
  - illuminated by QSO
  - confined by pressure of wind bubble
- Time-dependent chemistry including:
  - standard cooling/heating + Compton from AGN + cosmic rays
  - 11 atoms, 20 molecules
  - dust-mediated reactions (assume constant dust)
  - self-shielding



Richings & FG, in prep. (using CHIMES chemical network from Richings+14ab)

# Example hydro-chemical simulation



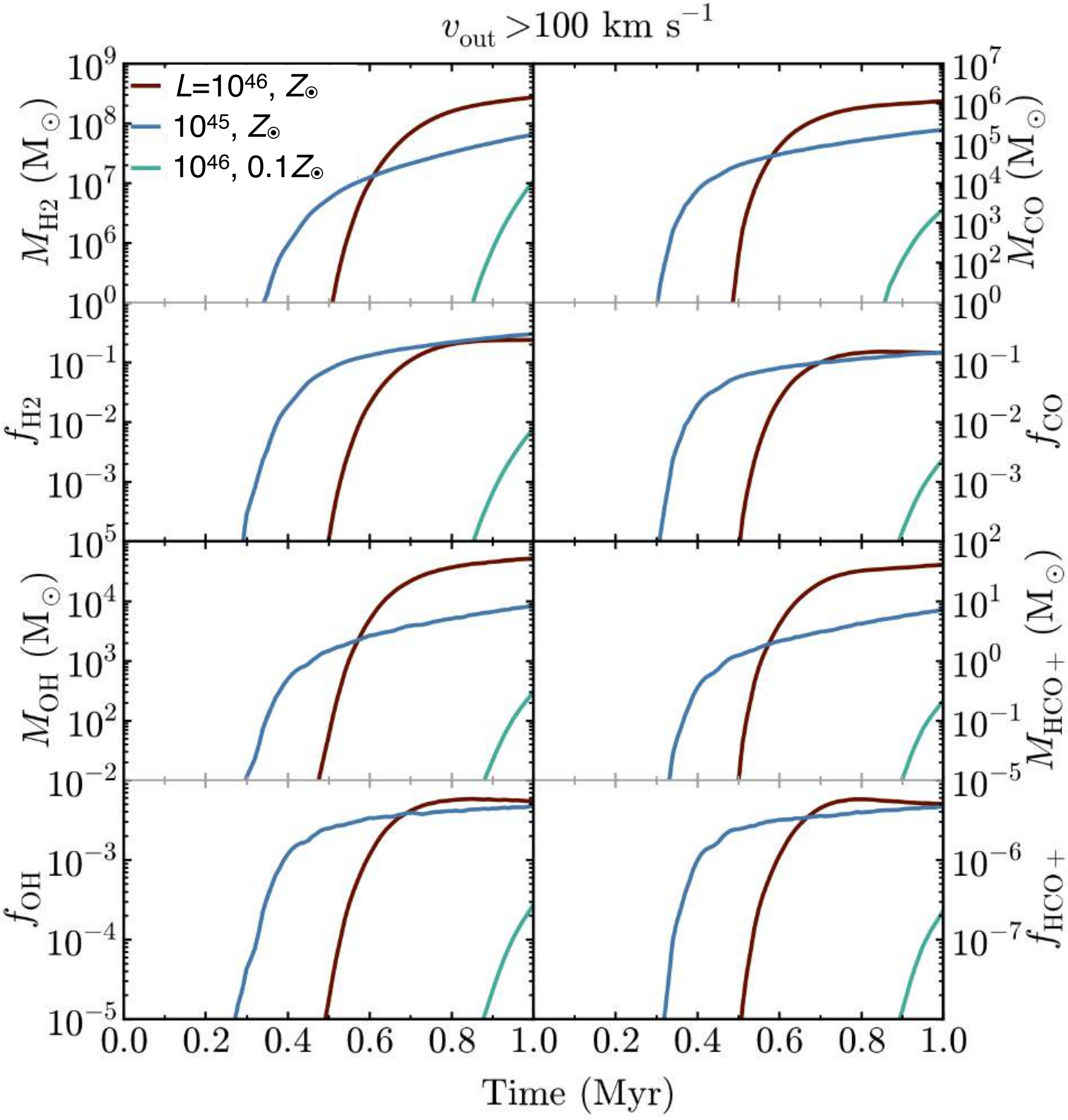
$L_{\rm AGN}$=10$^{45}$ erg s$^{-1}$, $v_{\rm in}$=0.1c, $P_{\rm in}$=$L_{\rm AGN}/c$,
$n_{\rm ambient}$=10 cm$^{-3}$, $Z_{\odot}$, MW dust-to-metals, $\sigma$=200 km/s potential

Richings & FG, in prep.

# Molecule formation in cooling forward shock

- As post-shock layer cools
  - pressure from wind bubble compresses it
  - density increases
  - molecules form quickly
  - (stars form in wind?)

- Molecular abundances increase with metallicity, AGN power, dust-to-metals ratio

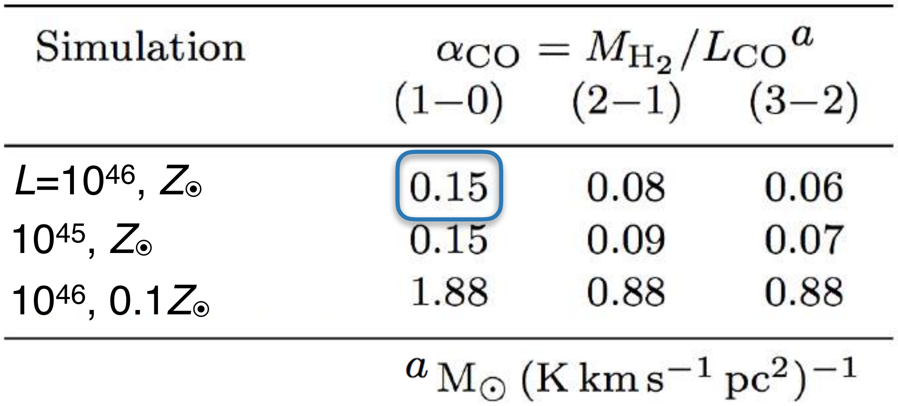


All other parameters as on previous slide

Richings & FG, in prep.

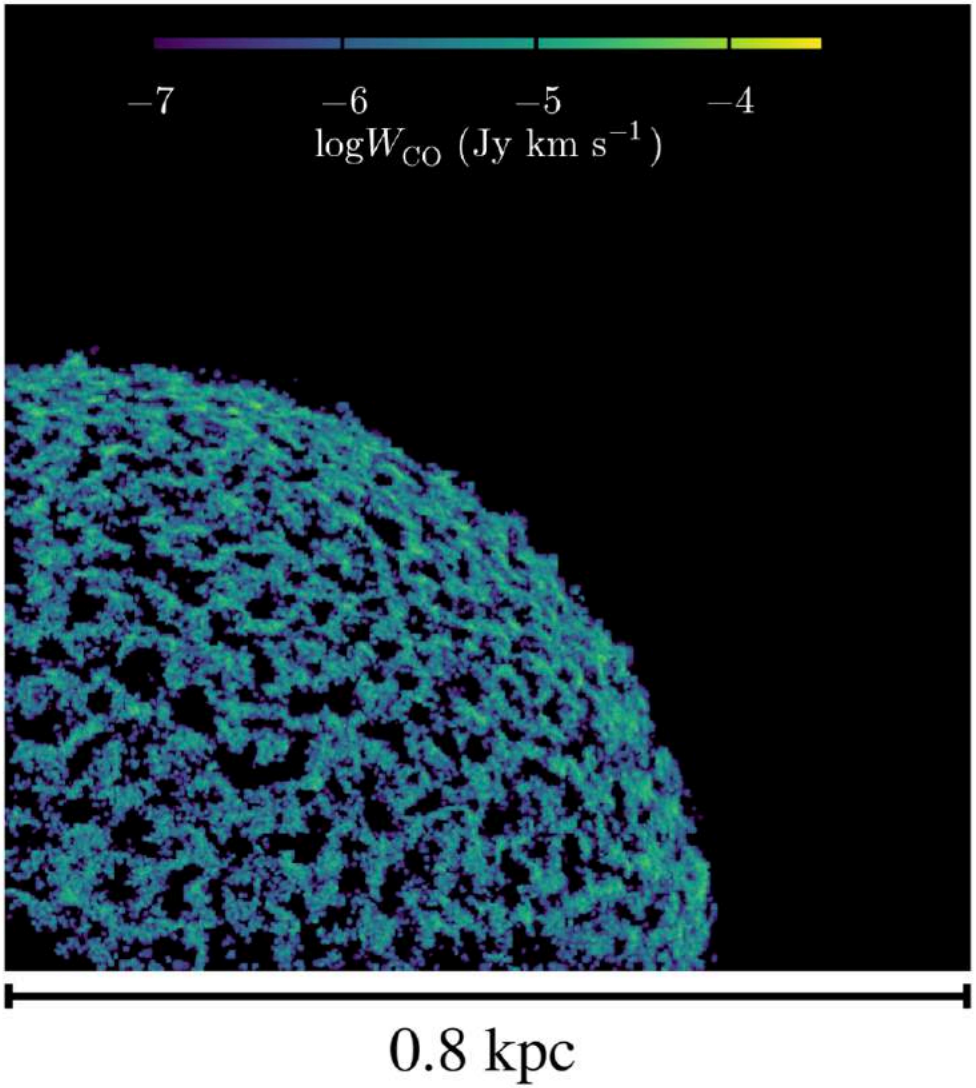
# Predictions for molecular tracers: CO conversion

- Radiative transfer with RADMC-3D
    - line transfer
    - thermal dust emission, absorption, and scattering



| Simulation | $\alpha_{\mathrm{CO}} = M_{\mathrm{H_2}}/L_{\mathrm{CO}}{}^{a}$ | | |
|---|---|---|---|
| | (1–0) | (2–1) | (3–2) |
| $L$=$10^{46}$, $Z_\odot$ | 0.15 | 0.08 | 0.06 |
| $10^{45}$, $Z_\odot$ | 0.15 | 0.09 | 0.07 |
| $10^{46}$, 0.1$Z_\odot$ | 1.88 | 0.88 | 0.88 |

$^{a}$ $\mathrm{M_\odot\,(K\,km\,s^{-1}\,pc^2)^{-1}}$



- Standard ULIRG value: $\alpha_{\mathrm{CO(1\text{-}0)}}$=0.8
    - observed outflow rates could be biased high by factor ~5 (additional factor ~5 if using standard MW value)

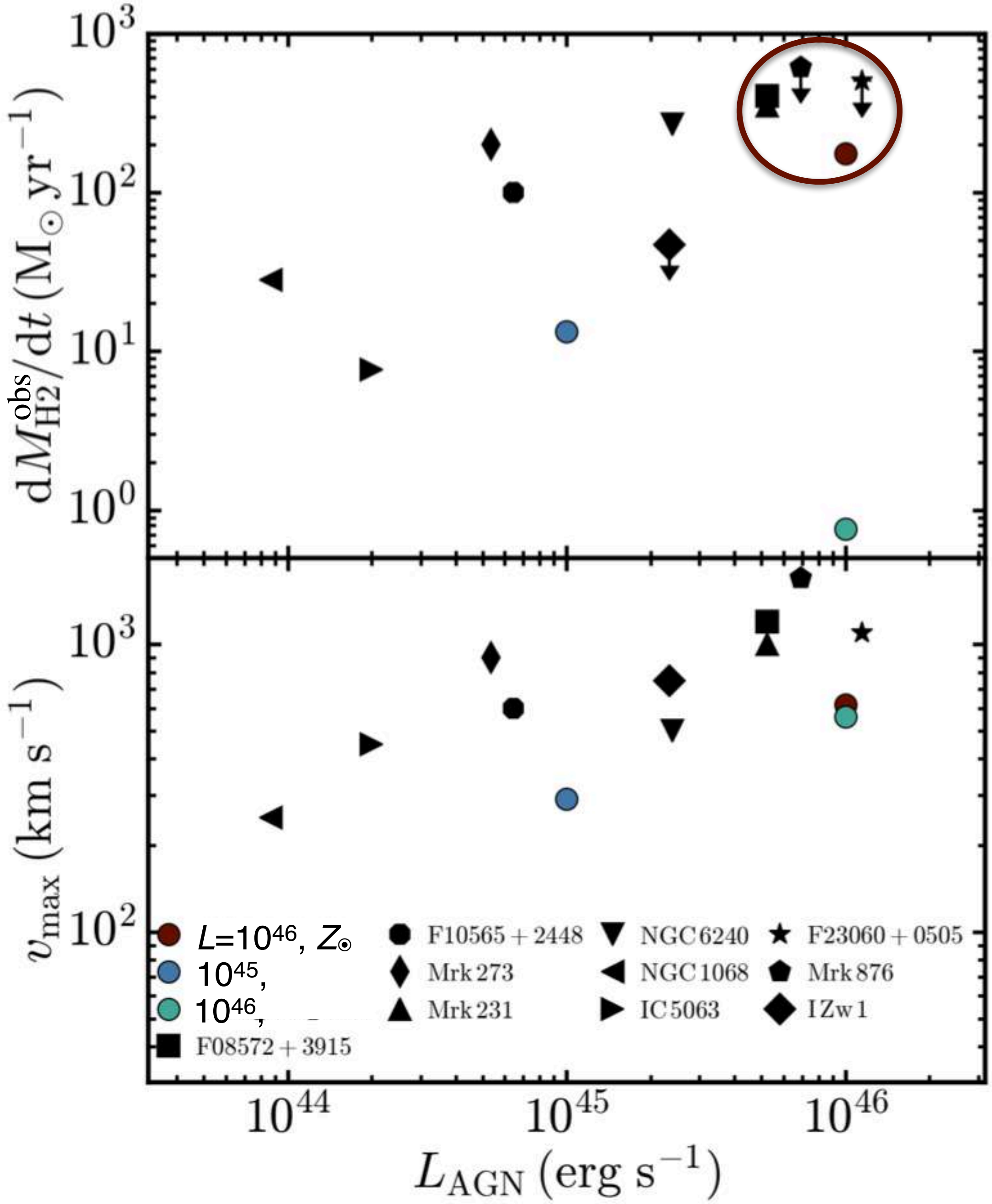
Richings & FG, in prep.

# Comparison with observed outflows

- Seyfert 1 and 2 CO observations compiled in Cicone+14

- To compare fairly with simulations, apply observational $\alpha_{CO}$ to simulated CO spectra

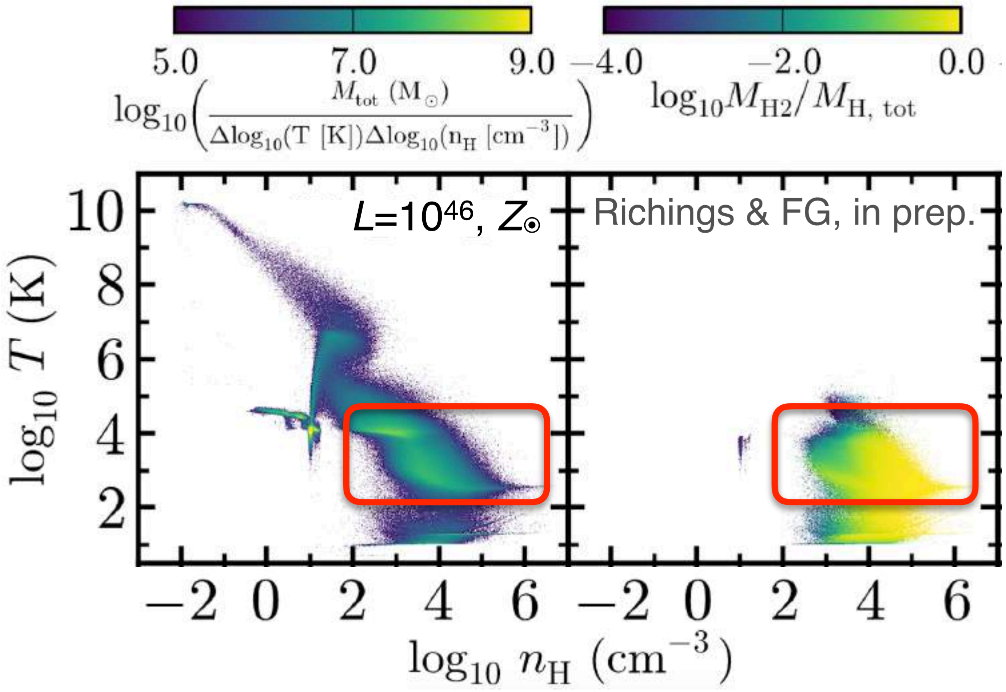
→ reasonable agreement with observed molecular outflow rates for $Z_{\odot}$ sims



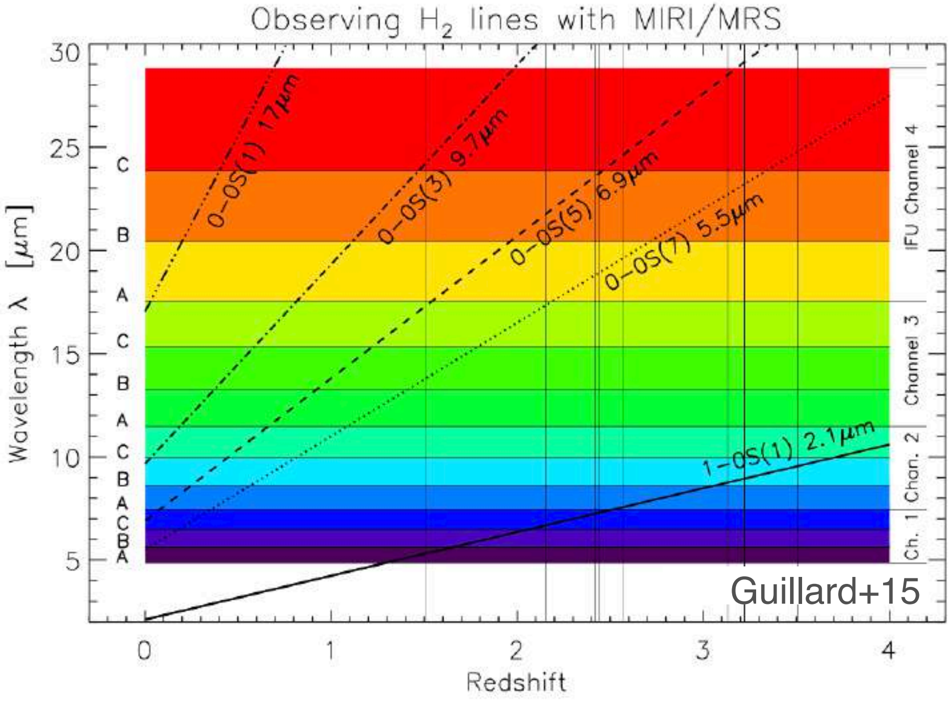
Richings & FG, in prep.

# Warm $H_2$: mapping AGN winds with JWST era

- >70% of $H_2$ is warm (~$10^2$-$10^4$ K) in sims
- Emits in NIR and MIR ro-vibrational lines
- Existing AGN wind detections by Spitzer, ground-based IFUs (e.g., Ogle+07, Rupke & Veilleux 13, Hill & Zakamska 14)
- JWST MIRI and NIRSPEC will observe with IFU capability out to cosmic noon (*z*~1-3)



Richings & FG, in prep.

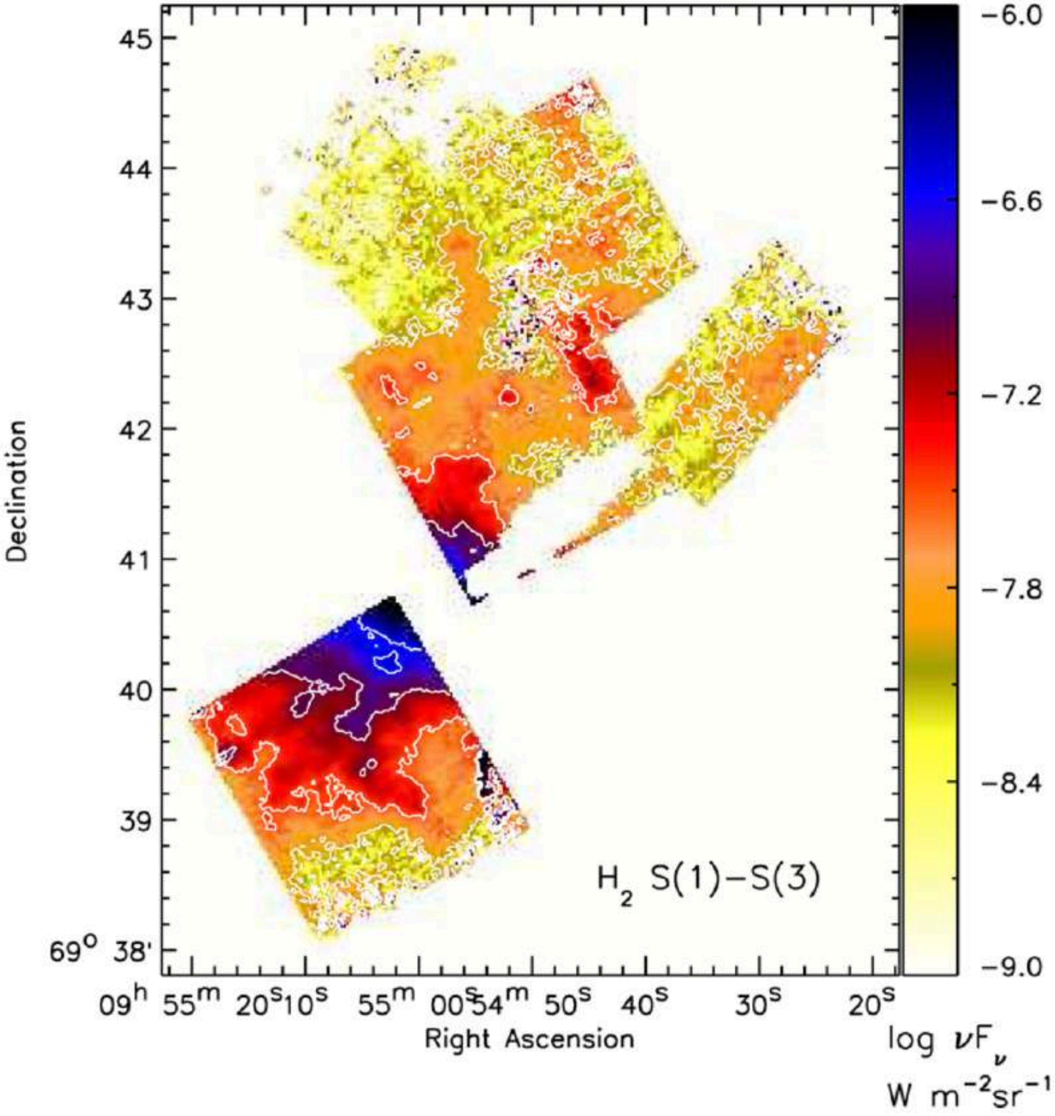


Guillard+15

# Preview: dust+$H_2$ in M82's star formation-driven wind

Dust (Spitzer IRAS)

$H_2$ (Spitzer IRS)



Engelbracht+06

Beiraio+15

# Outline

- Spherically-symmetric dynamics of AGN-driven galactic winds

  ➡ energy-conserving ⇒ momentum fluxes $\gg L_{\mathrm{AGN}}/c$

- Observational signatures

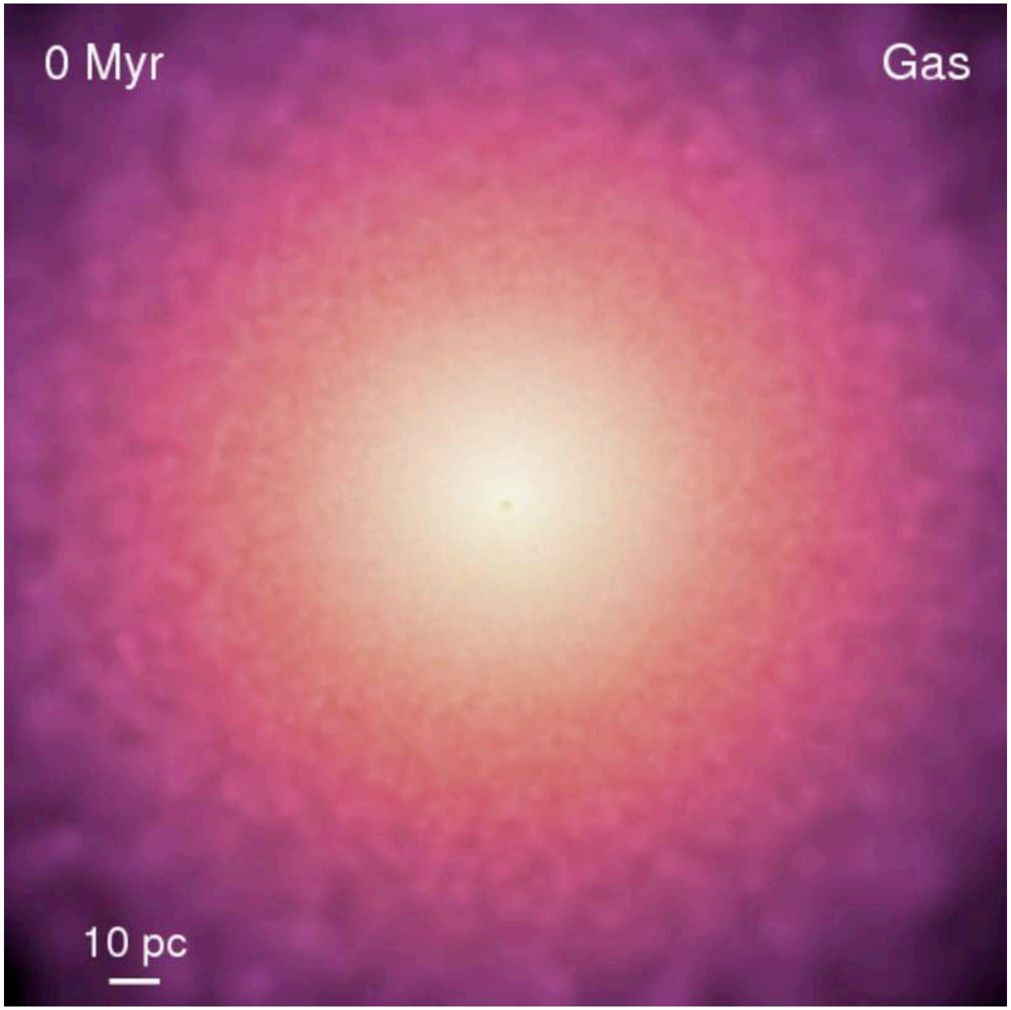
  ➡ molecule formation at wind shocks

- Effects on galaxies: 3D simulations with stellar+AGN feedback

# To capture effects of AGN feedback on galaxies, need realistic ISM and stellar feedback

- AGN winds
    - often launched at center of disk
    - expand in multiphase ISM
- We use the GIZMO (FIRE) code:
    - dark matter, gas + stars
    - cooling to $T \sim 10$ K
    - SNe, photoionization, stellar winds, radiation pressure

~0.01 pc res. gas-rich nucleus, SF only

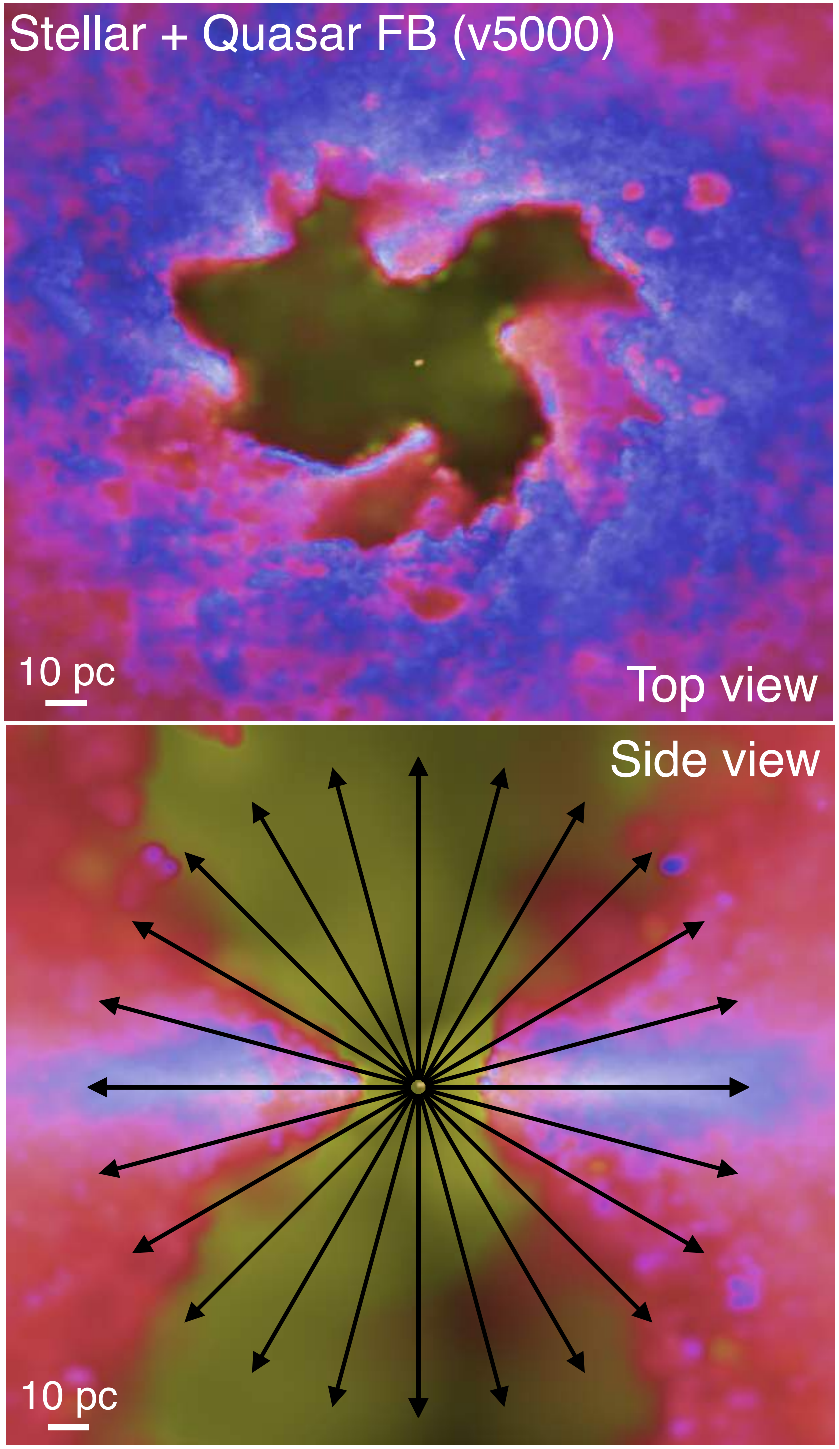


**Blue ≲1,000 K, pink ~$10^4$-$10^5$ K, yellow ≳$10^6$ K**

Hopkins, Torrey, FG+16

# Turning on the AGN

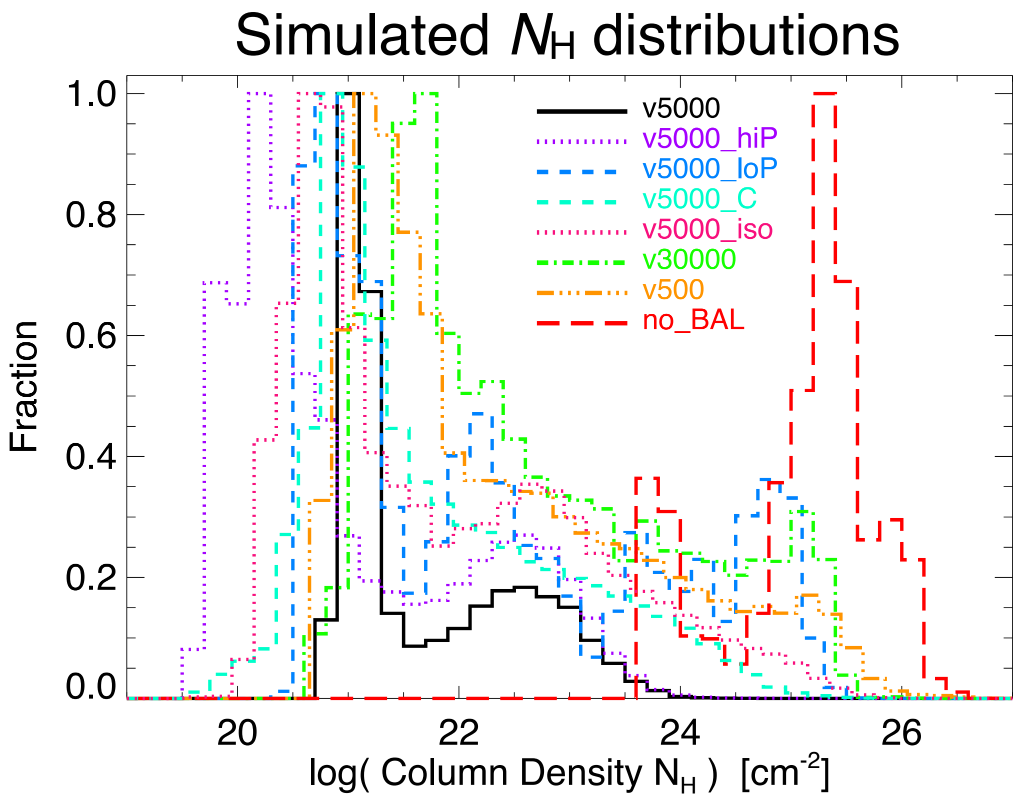
- BAL wind feedback
  - outflow rate $\propto$ accretion rate
  - parameterized by initial wind velocity, momentum loading
- Shocked wind expands along paths of least resistance
- Origin of the torus?



**Blue $\lesssim$1,000 K, pink ~$10^4$-$10^5$ K, yellow $\gtrsim 10^6$ K**

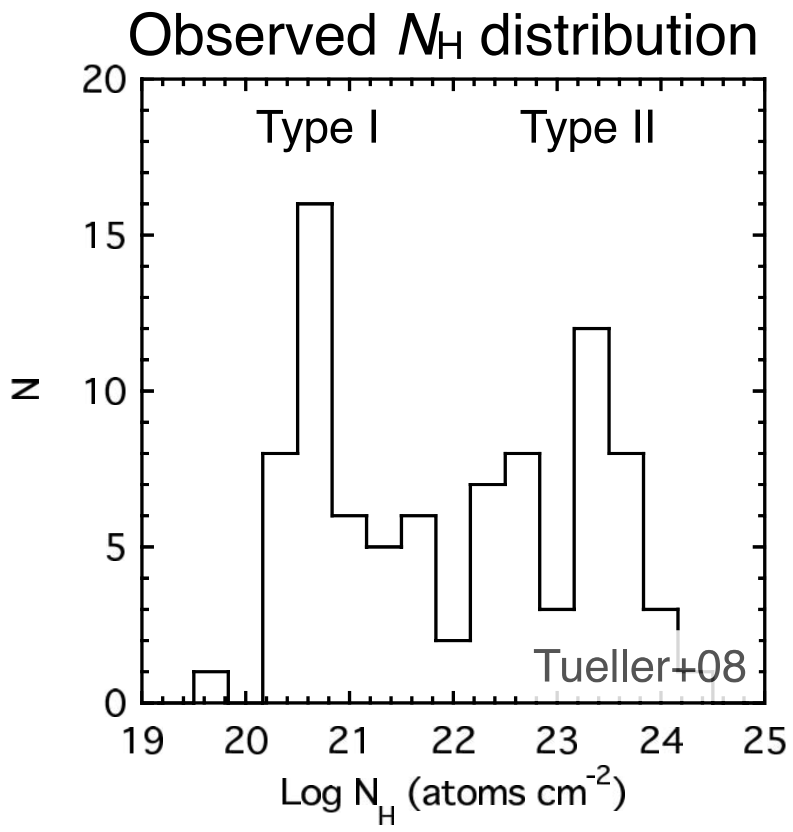
Hopkins, Torrey, FG+16

# BAL wind-induced torus may explain observed column density distribution


Simulated $N_H$ distributions

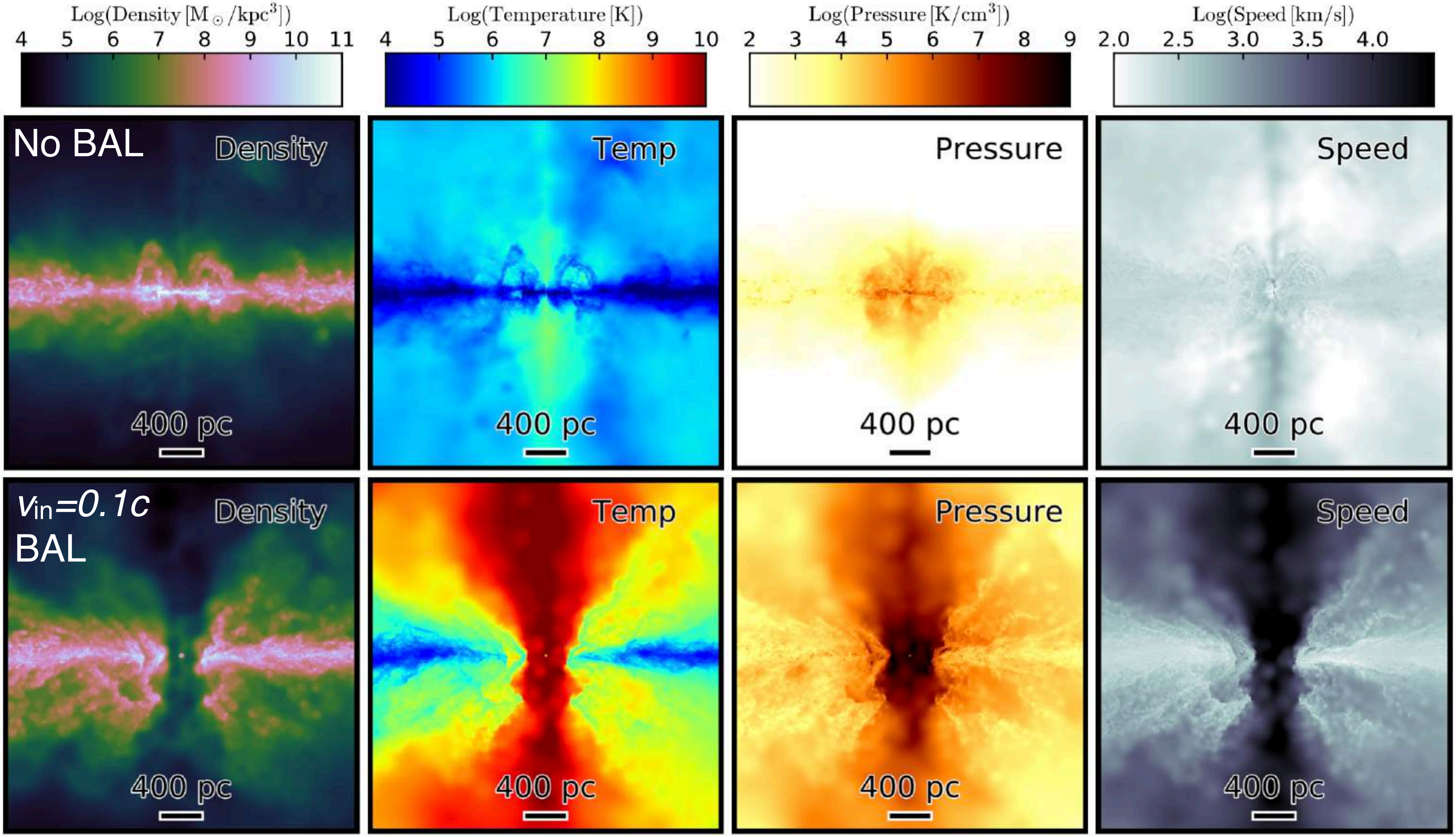
low columns cleared by BAL feedback

no BAL ⇒ too obscured


Observed $N_H$ distribution

Hopkins, Torrey, FG+16

# Larger scales: full galaxy simulations



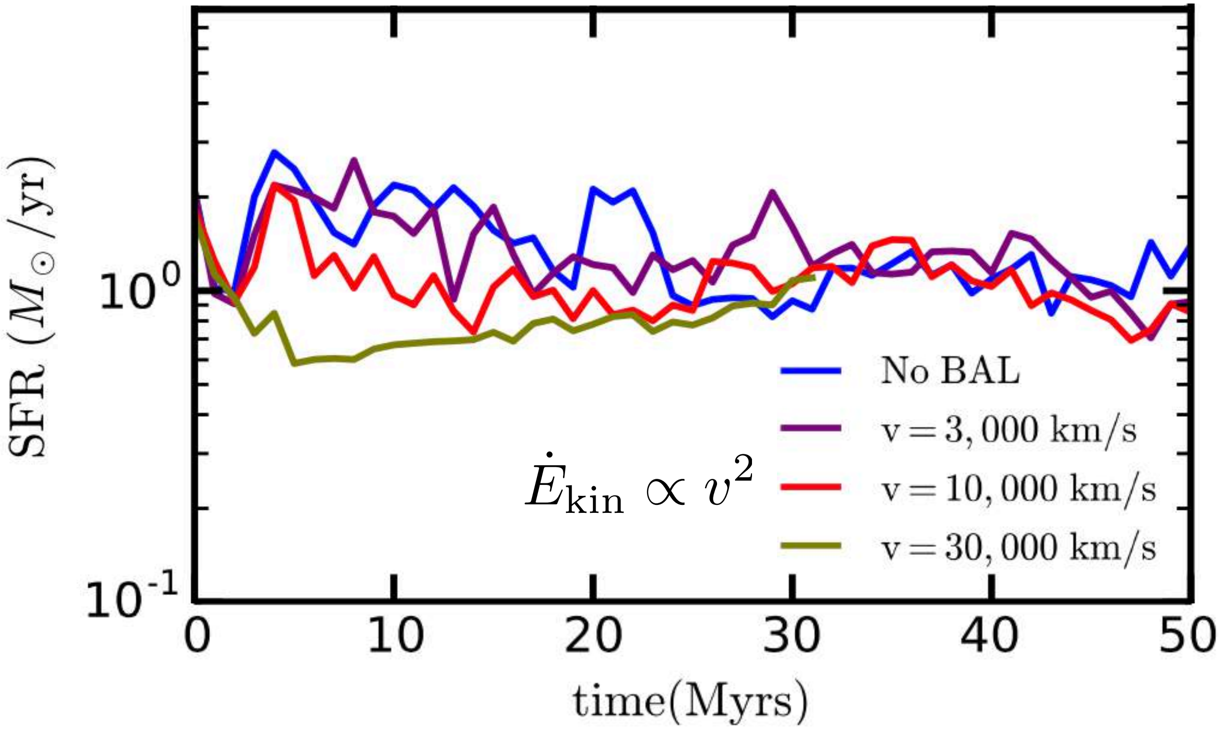
$L_{AGN}=10^{45}$ erg s$^{-1}$, $v_{in}$=0.1c, $P_{in}=L_{AGN}/c$ (time steady)

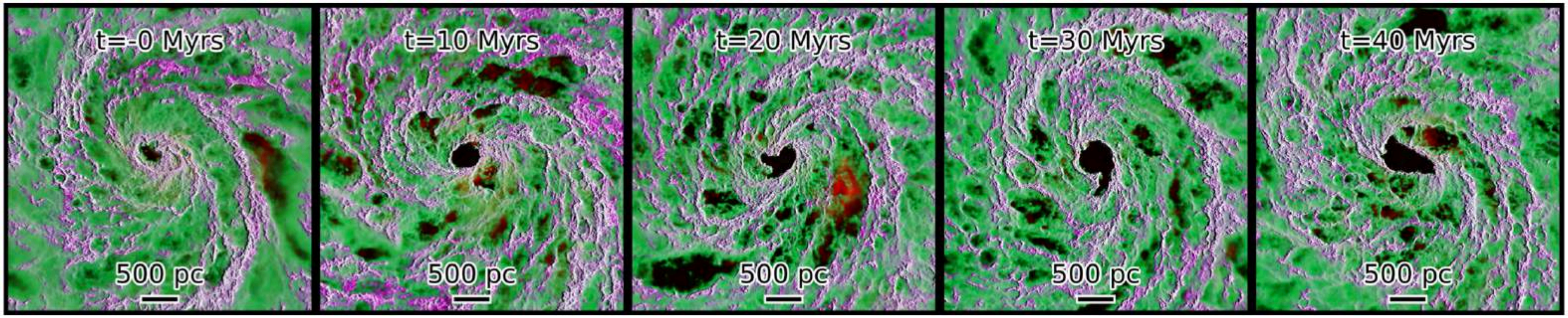
Torrey, FG+, in prep.

# Effects of moderate-luminosity AGN on disk galaxies

- Hot wind vents out normal to disk plane once nuclear cavity is opened
- Steady-state SFR negligibly affected by BAL wind
- Effects could be larger in luminous QSOs, especially those with messy inner regions obstructing wind escape

$L_{\rm AGN}=10^{45}$ erg s$^{-1}$, $P_{\rm in}=L_{\rm AGN}/c$





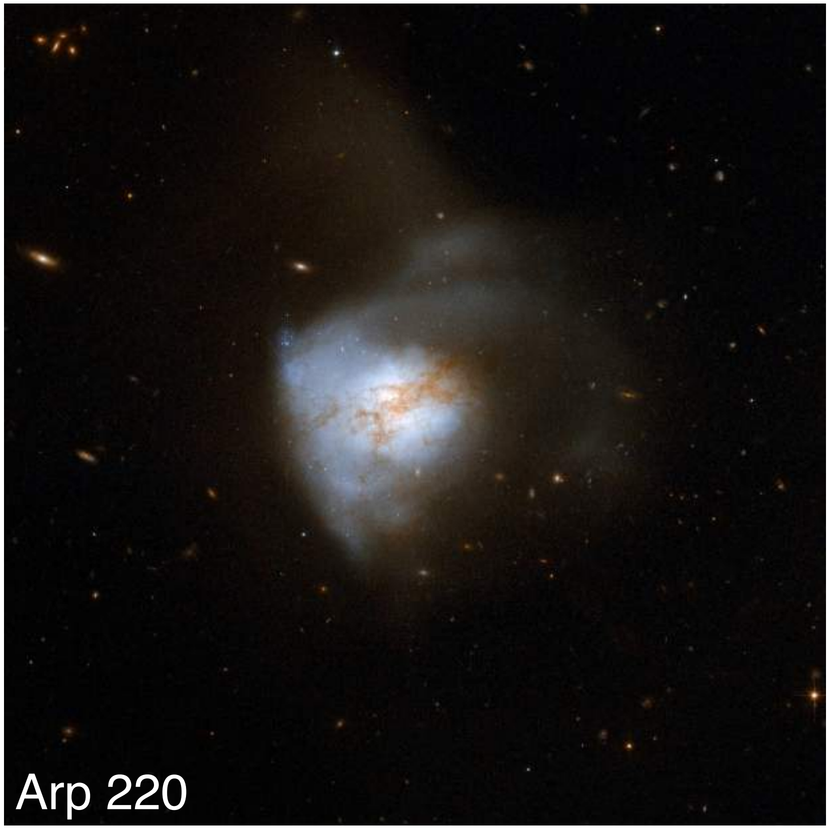
$v_{\rm in}=0.1c$ BAL

Torrey, FG+, in prep.

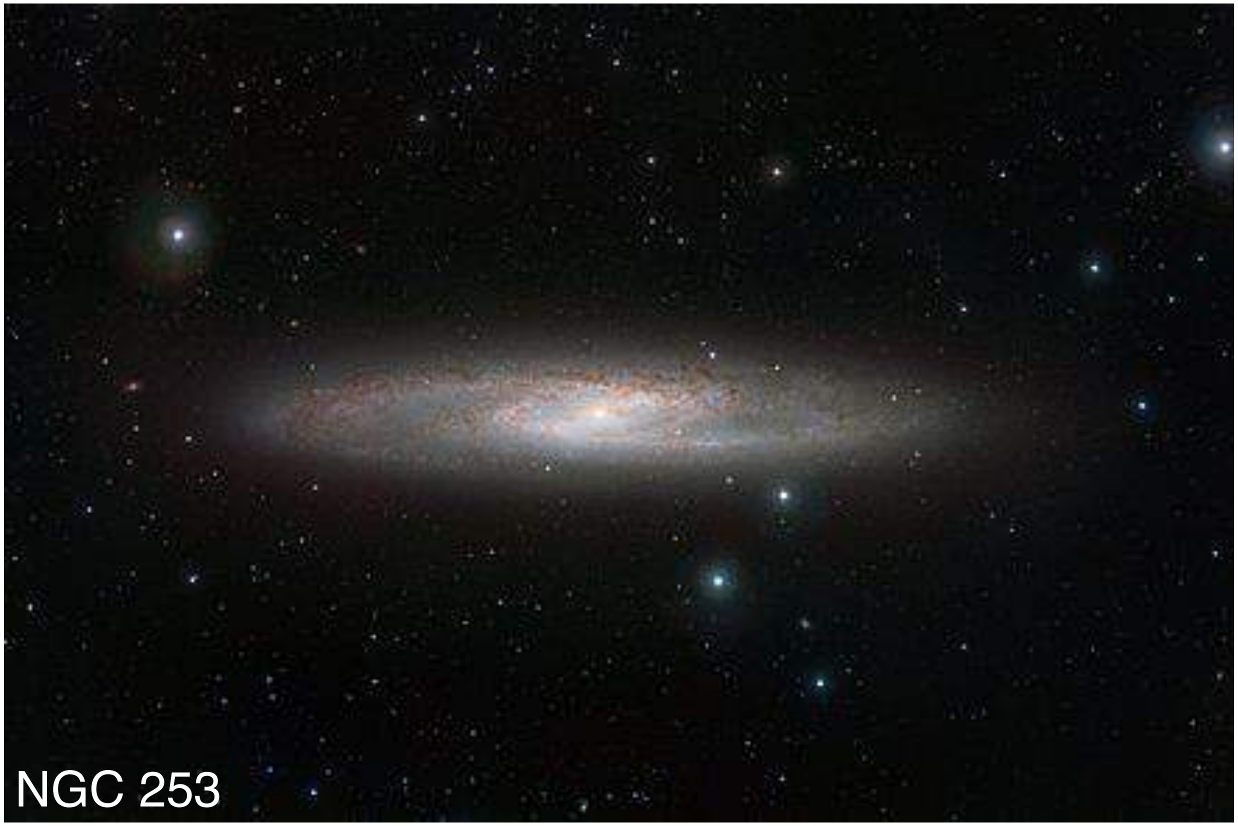
# Galaxy-scale feedback hypothesis

For significant direct AGN wind feedback on galactic SFR, need energetic wind (~ galaxy binding energy) *and* quasi-isotropic covering of the nucleus for efficient coupling, e.g. in major mergers that concentrate gas in galaxy centers.

E.g., if/when a luminous AGN turns on…



is likely to be strongly affected.



is unlikely to have its SFR significantly changed.

Note: Early galaxies ($z \gtrsim 2$) have thicker disks & messier gas morphologies, so they may be in general more affected by AGN feedback than local galaxies.

# Summary

- Energy-conserving AGN outflows ⇒ momentum fluxes $\gg L_{\mathrm{AGN}}/c$
- Forward shocks can cool and form molecules
- Realistic ISM, stellar feedback, and large-scale gas geometry needed to capture effects of AGN-driven winds on galaxies

➡ BAL winds from moderate-luminosity AGN have weak effect on the SFR of disk galaxies

➡ effects of AGN winds likely enhanced in galaxies with messy nuclear geometries, e.g. in galaxy mergers or high-redshift galaxies