AGN-driven Molecular Outflows

ESA

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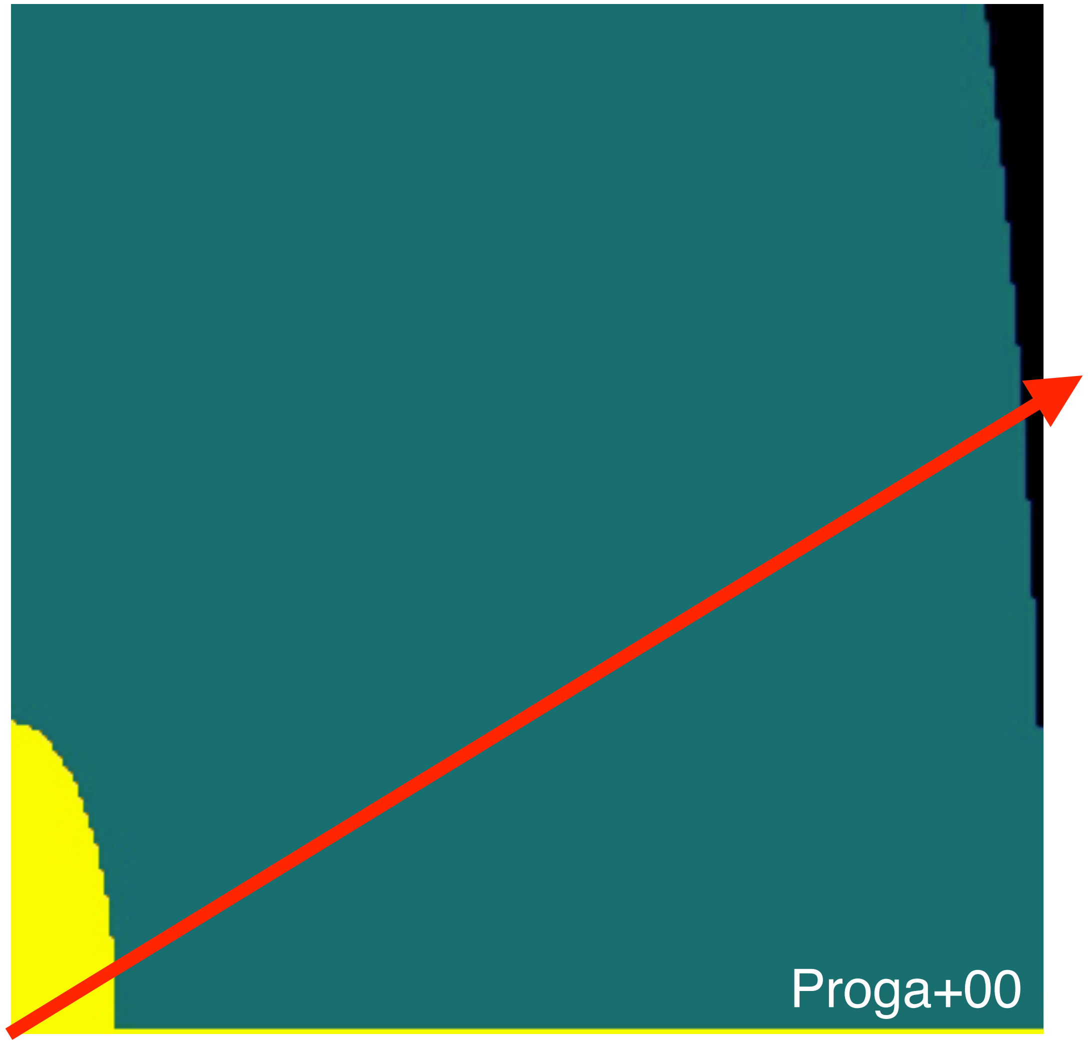
Accretion disk winds

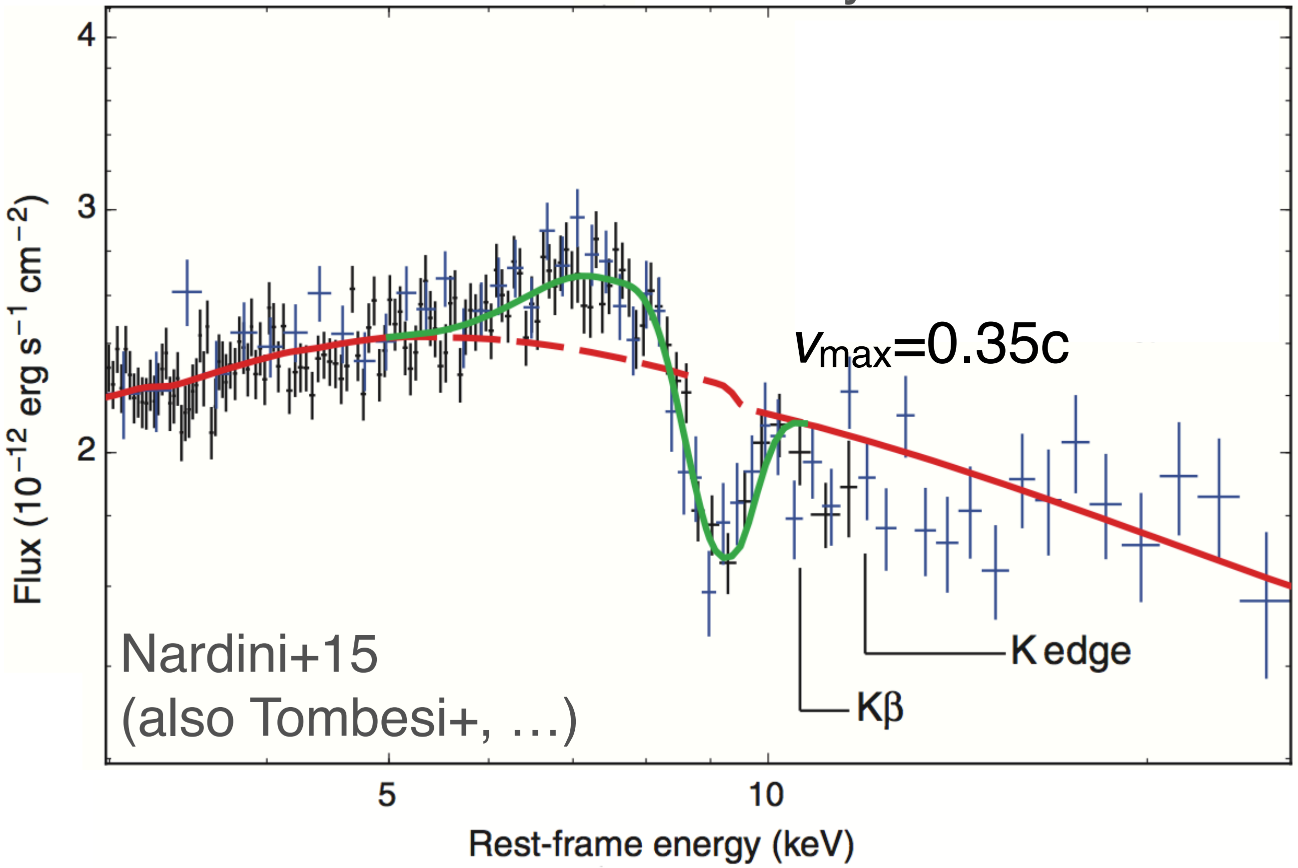
- Likely accelerated by radiation
- Broad absorption lines (BALs) in UV
- Ultra-fast outflows (UFOs) in X-rays
- *v*~10,000-100,000 km/s

→ What are the galaxy-scale manifestations?



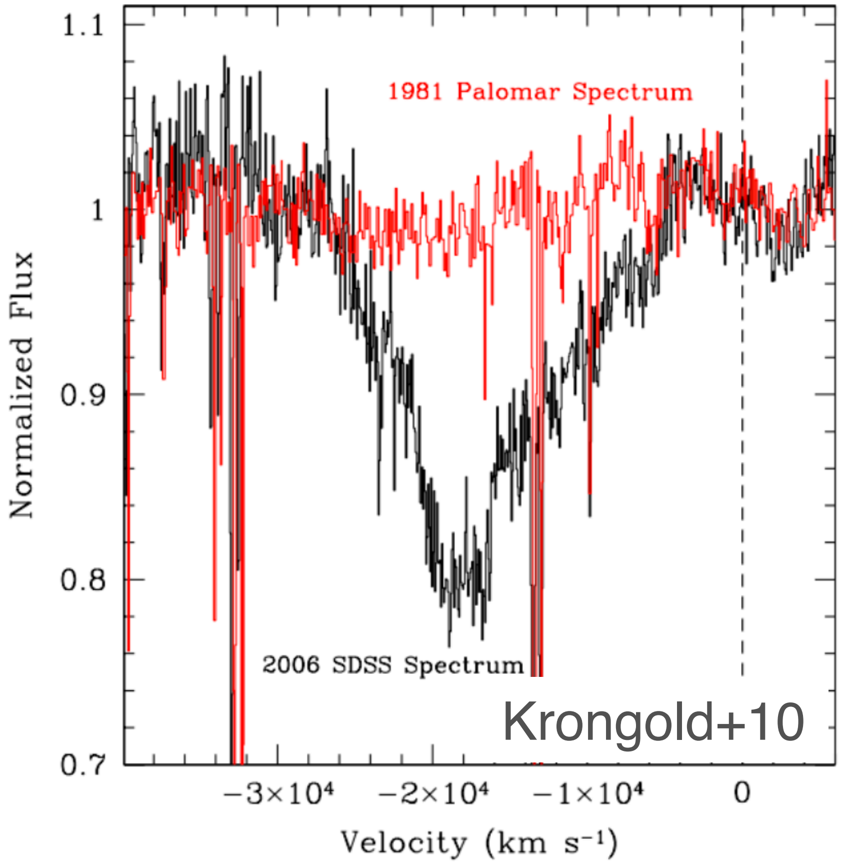
Proga+00

PDS 456 — X-ray UFO



Nardini+15
(also Tombesi+, …)

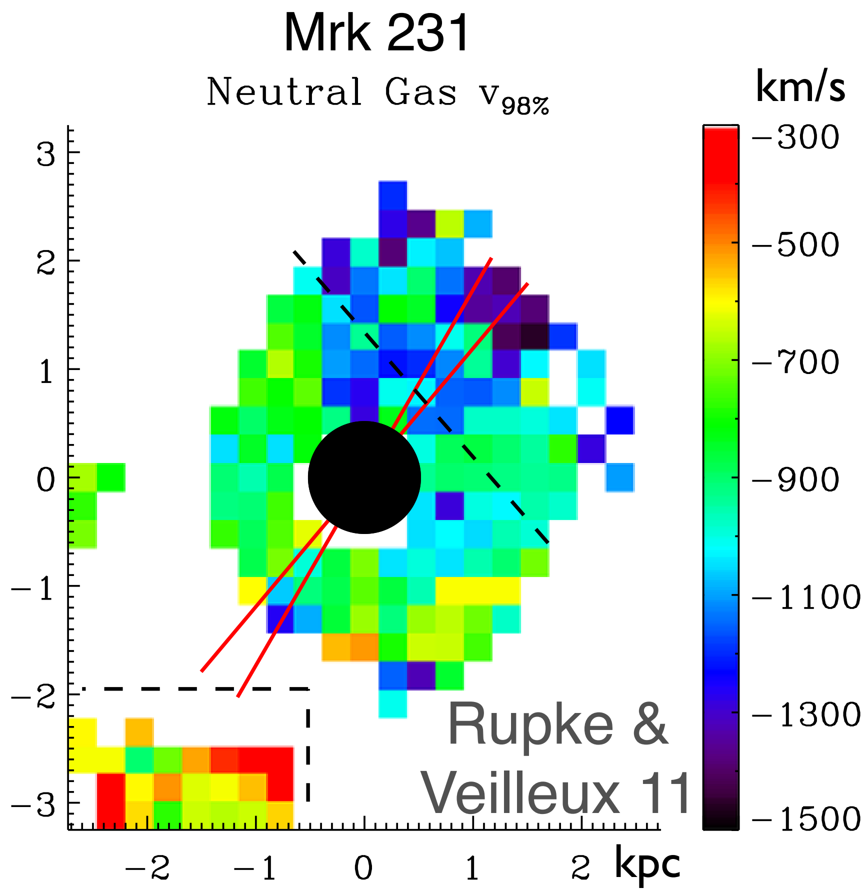
Ton 34 — CVI BAL



Krongold+10

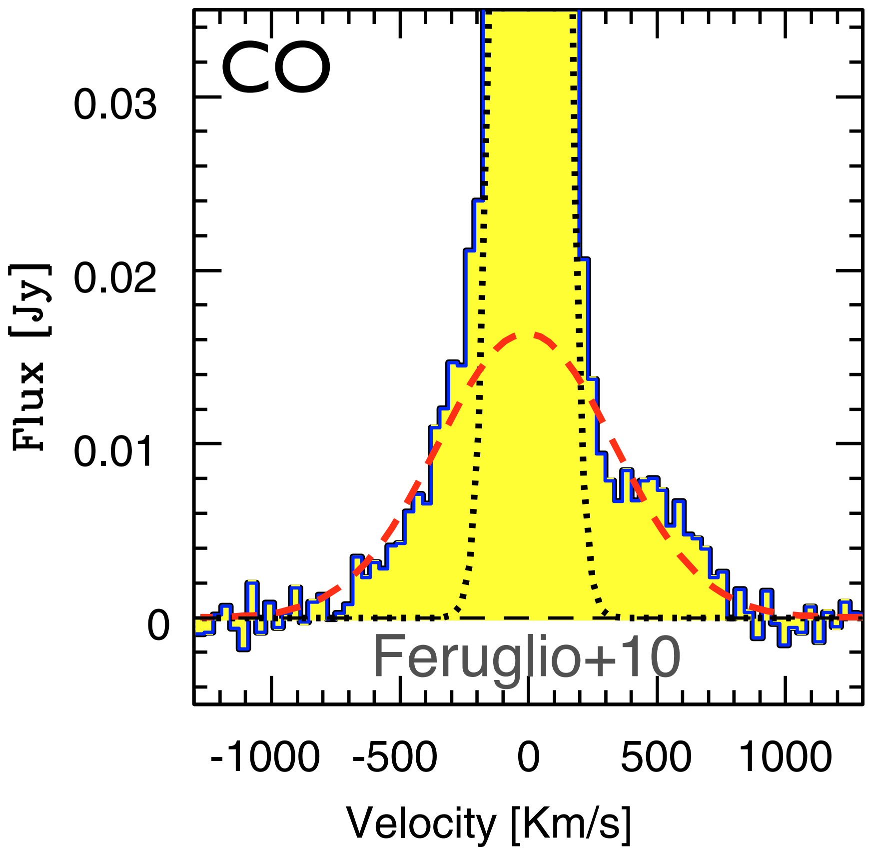
Galaxy-scale, wide-angle outflows driven by AGN

- Detected in atomic+molecular 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, Cicone+14, …)
- R~1-few kpc, v~1,000 km/s, $\mathrm{d}M/\mathrm{d}t$~1,000 M_{sun}/yr, ⇒ L_{kin} ~ few % L_{AGN}, t_{flow} ~ 1 Myr
- Distinct from radio jets


Mrk 231

Neutral Gas $v_{98\%}$

Rupke & Veilleux 11



Feruglio+10

Where does the molecular gas come from?

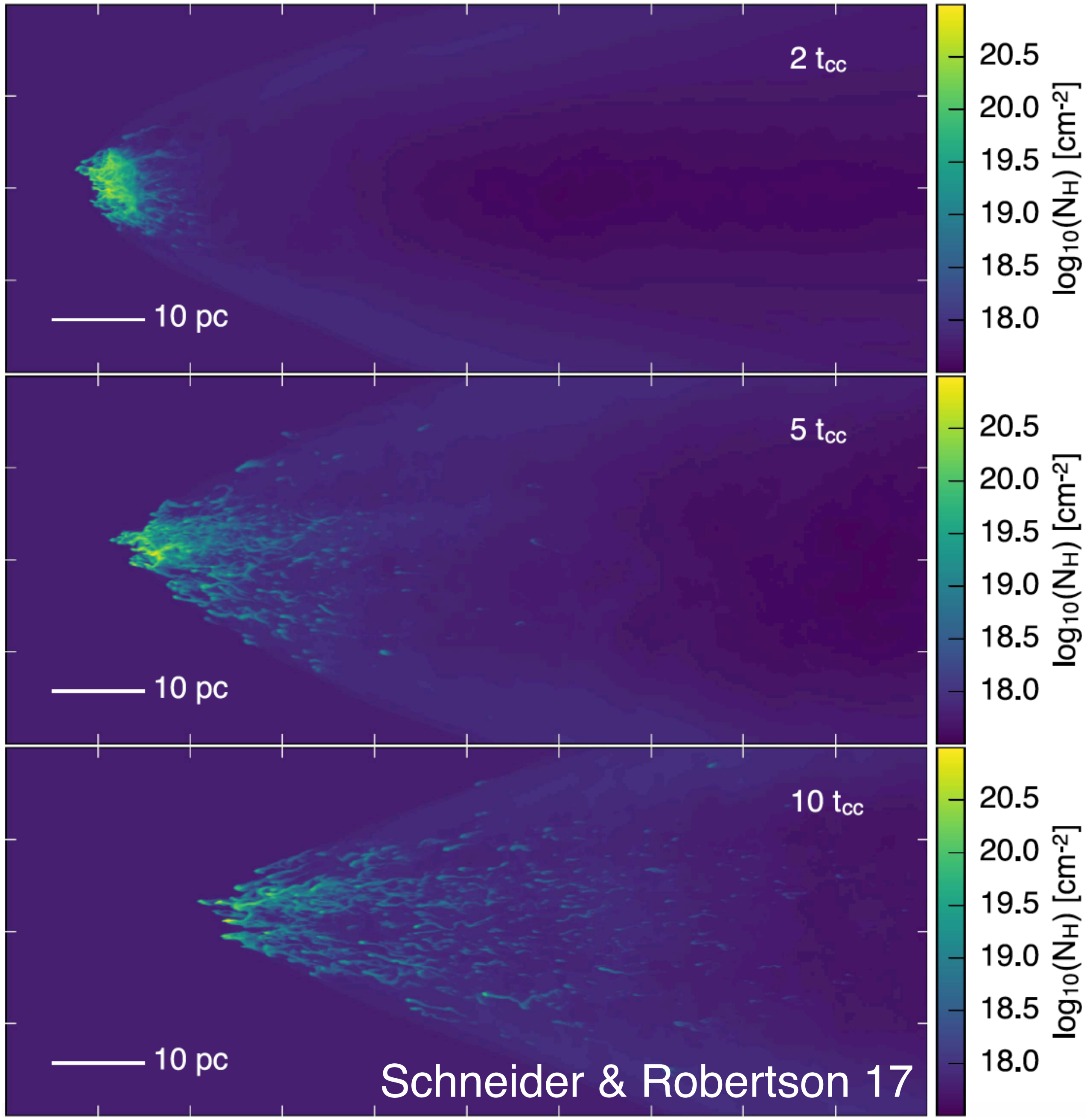
- May dominate outflow energetics

  (depending on assumed conversions)

- Different tracers (CO, OH, HCN, …) cover wide range of densities, up to $n > 10^4$ cm^{-3}

- Severe problems with accelerating molecular clouds:
  - small cross sections
  - mixing by hydro instabilities
  - molecule destruction by shocks

    (e.g., Ferrara & Scannapieco 17)



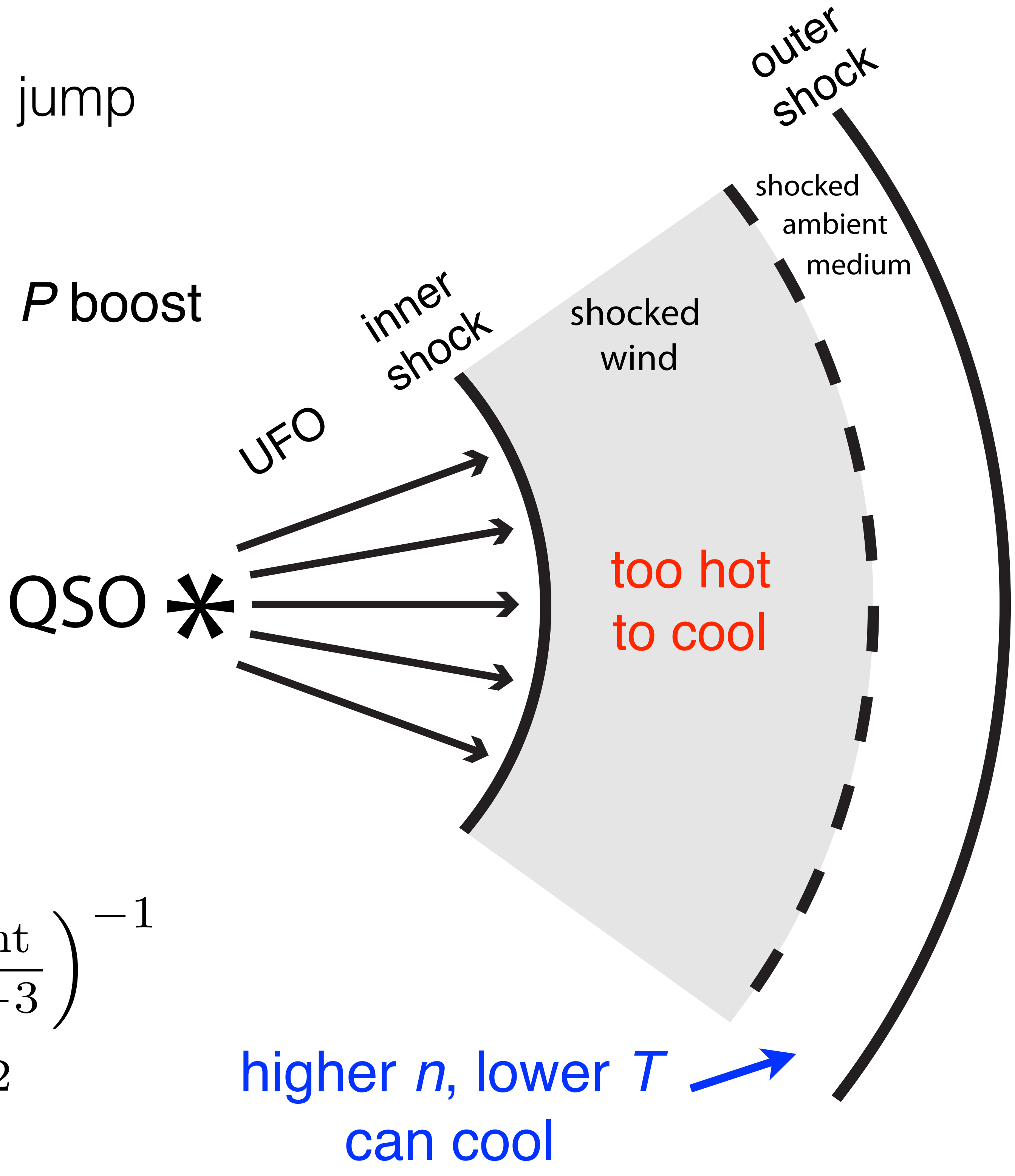
Schneider & Robertson 17

Wind bubble structure

- Shocked wind properties set by jump conditions at inner wind shock ($v_{\rm in}$~0.1c) ⇒ **energy conserving, P boost**

- Shocked ambient medium properties set by jump conditions at outer shock ($v_{\rm s}$≲1,000 km/s):

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



too hot to cool

higher n, lower T can cool

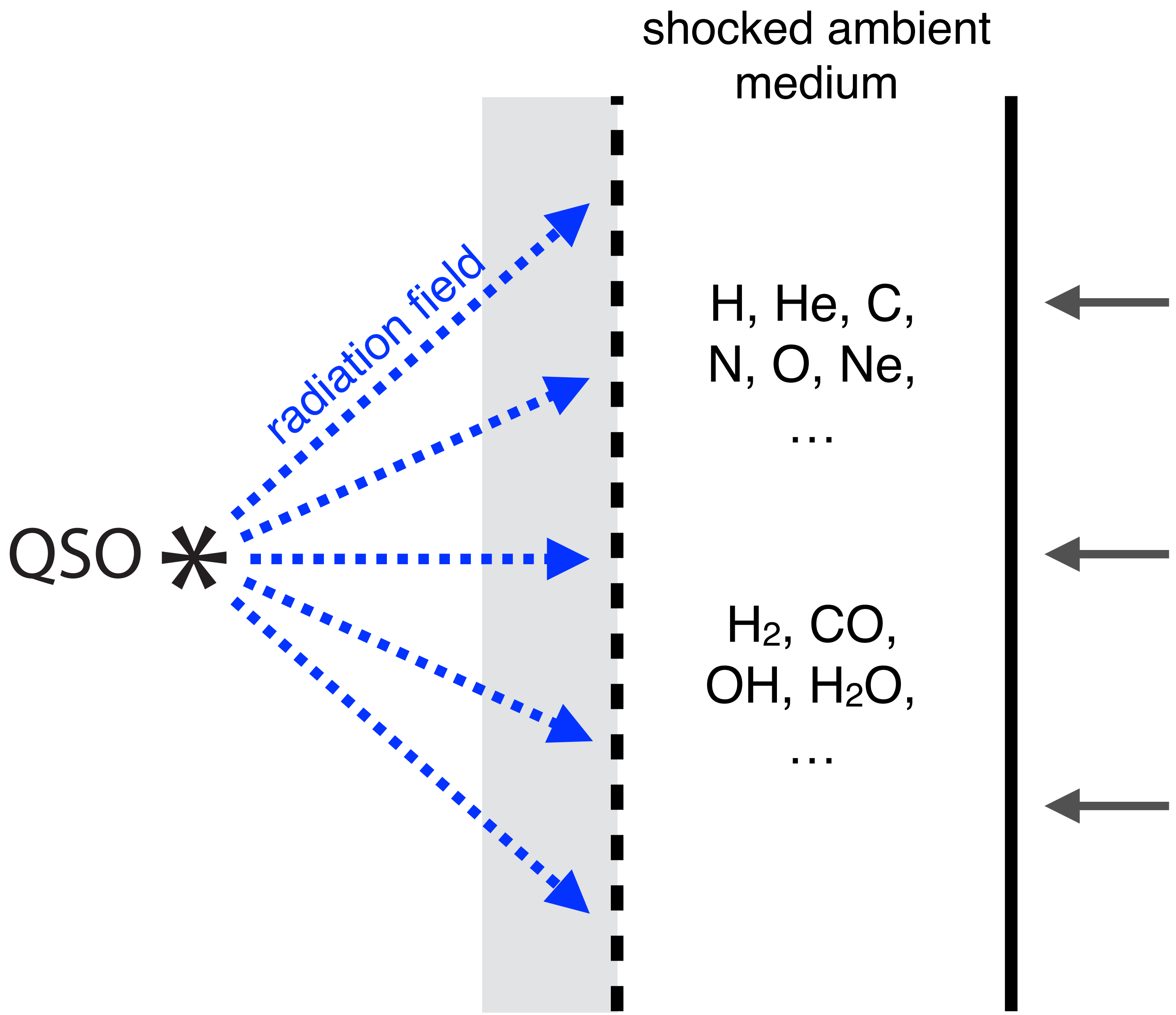
FG & Quataert 12 (also: Zubovas & King 14; Costa+14; Wang & Loeb 18; …)

Time-dependent chemistry in swept-up gas

- 3D hydro (GIZMO/MFM+CHIMES)
  - 11 atoms, 20 molecules
  - standard cooling/heating
  - cosmic ray ionization
  - dust-mediated reactions

    (assume constant dust)
  - illumination by QSO
  - shielding using $L \sim \rho/\nabla\rho$
  - fiducial res. $m_{\rm gas}=30\ \mathrm{M_{sun}}$,

    high res. $m_{\rm gas}=10\ \mathrm{M_{sun}}$



shocked ambient medium

QSO

radiation field

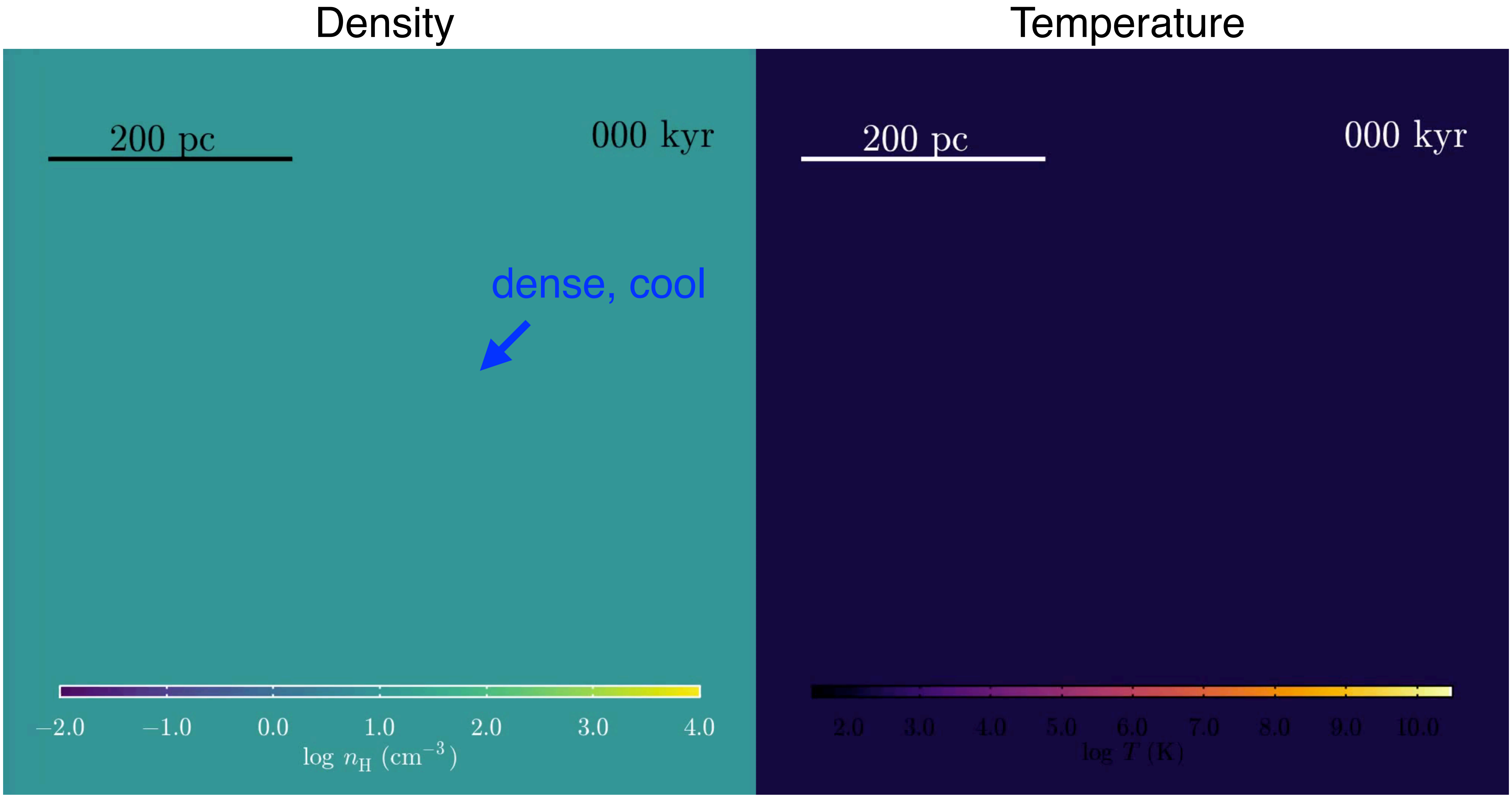
H, He, C,
N, O, Ne,
…

H_2, CO,
OH, H_2O,
…

Richings & FG 18a

Example hydro-chemical simulation

(spherical ICs = proxy for launch in buried nucleus)



Density

Temperature

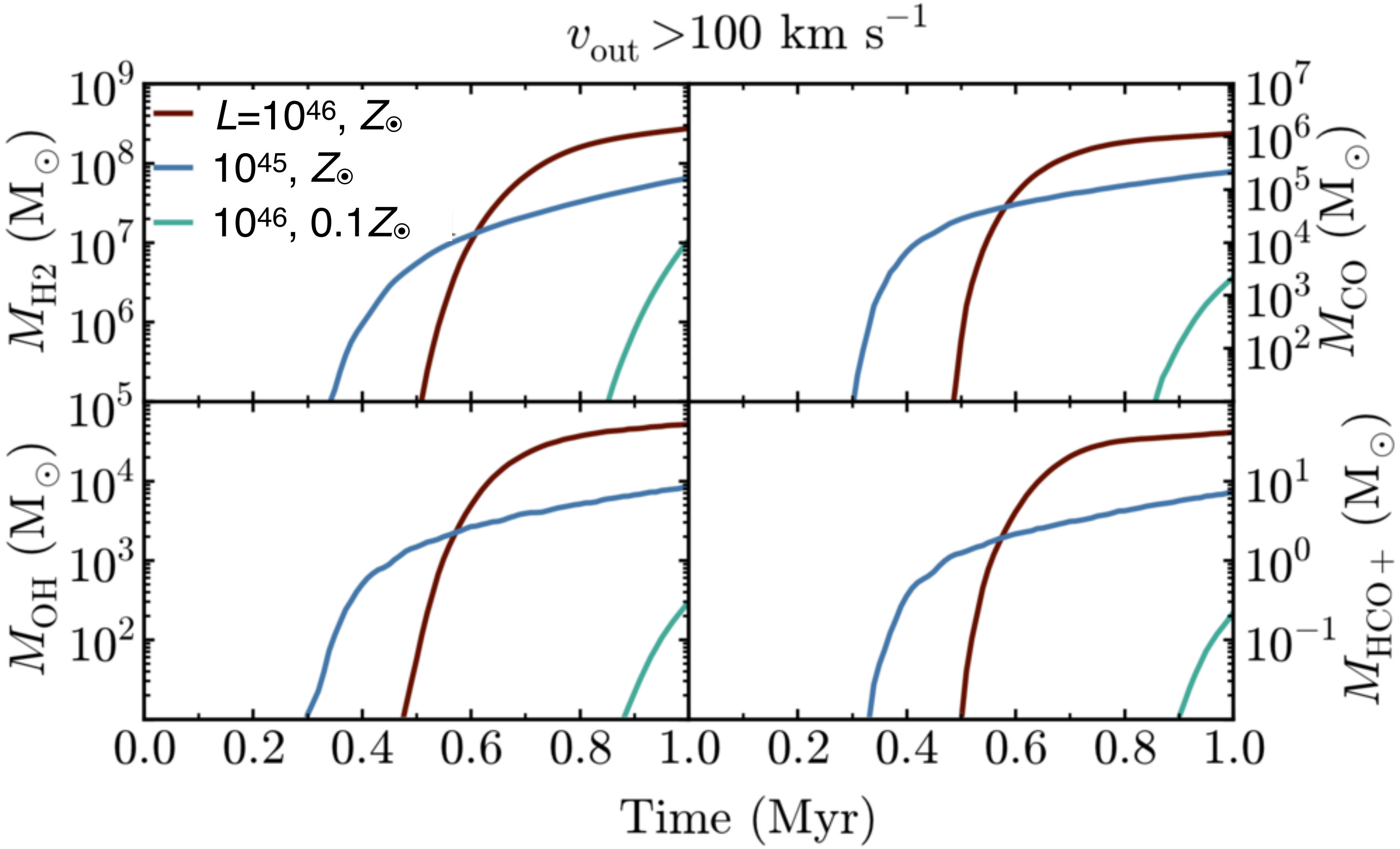
dense, cool

$L_{\rm AGN}$=10^{45} erg s^{-1}, $v_{\rm in}$=0.1c, $({\rm d}P/{\rm d}t)_{\rm in}$=$L_{\rm AGN}/c$,
$n_{\rm ambient}$=10 cm^{-3}, $Z_{\odot}$, MW dust-to-metals

Richings & FG 18a

Molecule formation in swept up gas

- As post-shock layer cools
  - pressure from wind bubble compresses it
  - density increases
  - molecules form quickly
- Molecular abundances increase with metallicity, dust-to-metals ratio



at solar metallicity, ≈20% molecular fraction

All other parameters as on previous slide

Richings & FG 18a

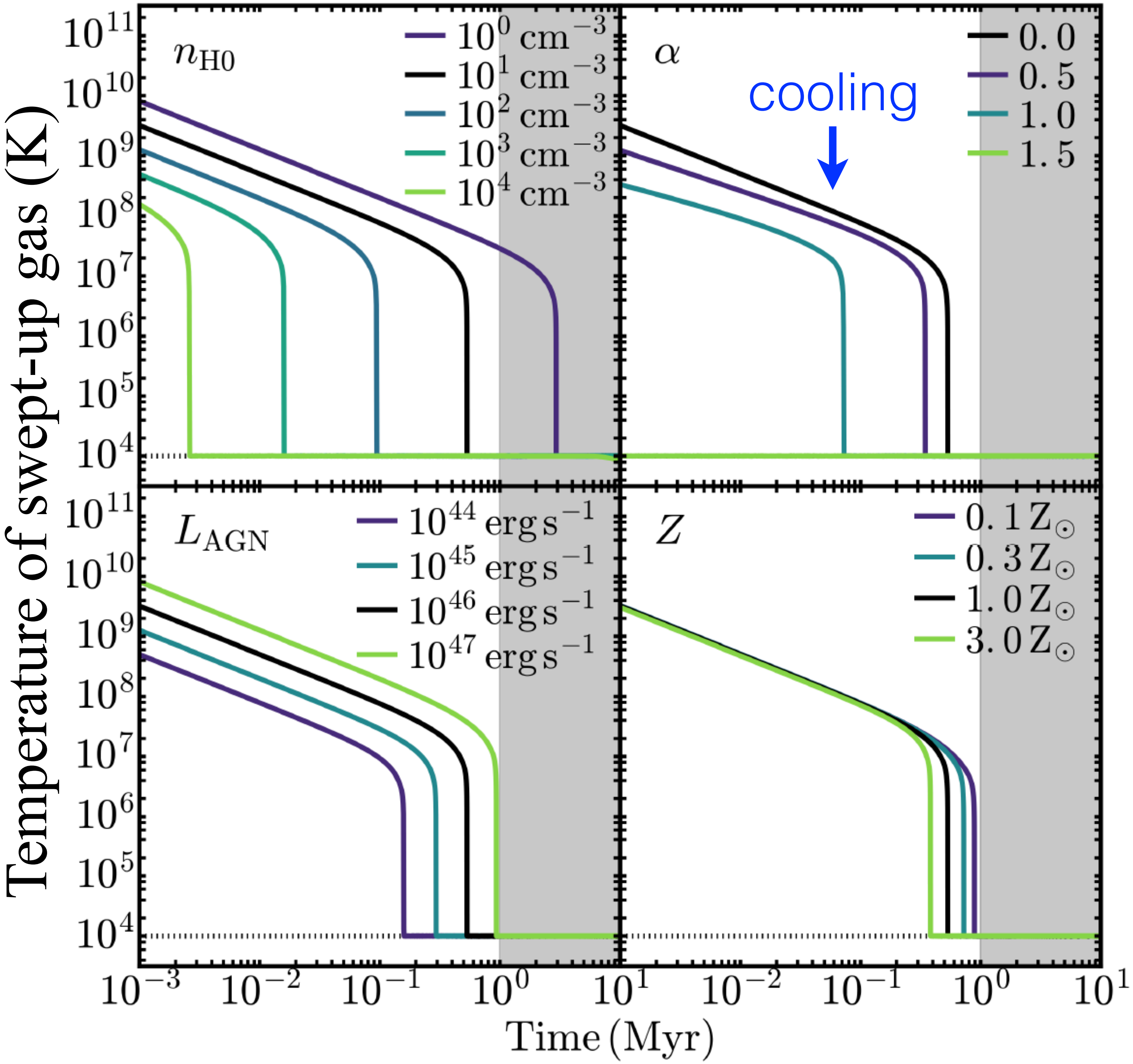
Extrapolating to different systems

- Analytic wind model reproduces dynamics and cooling found in hydro simulations

- Vary ambient density profile, metallicity, and AGN luminosity

$$n_{\rm H} = n_{\rm H0} \left(\frac{R}{100 \ {\rm pc}} \right)^{-\alpha}$$

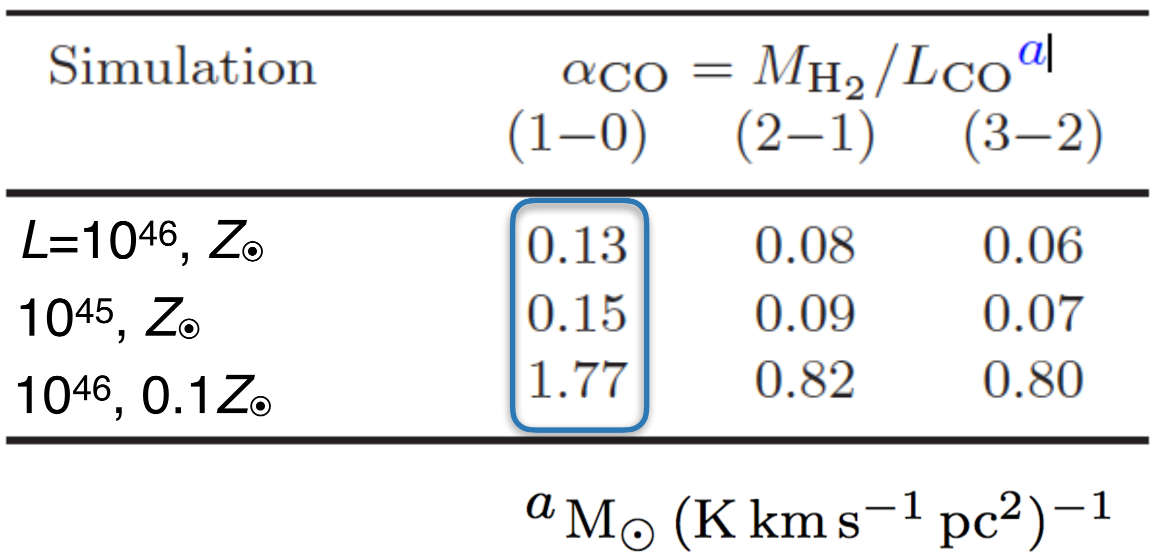
→ swept-up gas **generically** cools within $t_{\rm flow}$ ~ 1 Myr



Richings & FG 18b

CO emission: non-universal α_{CO} in winds

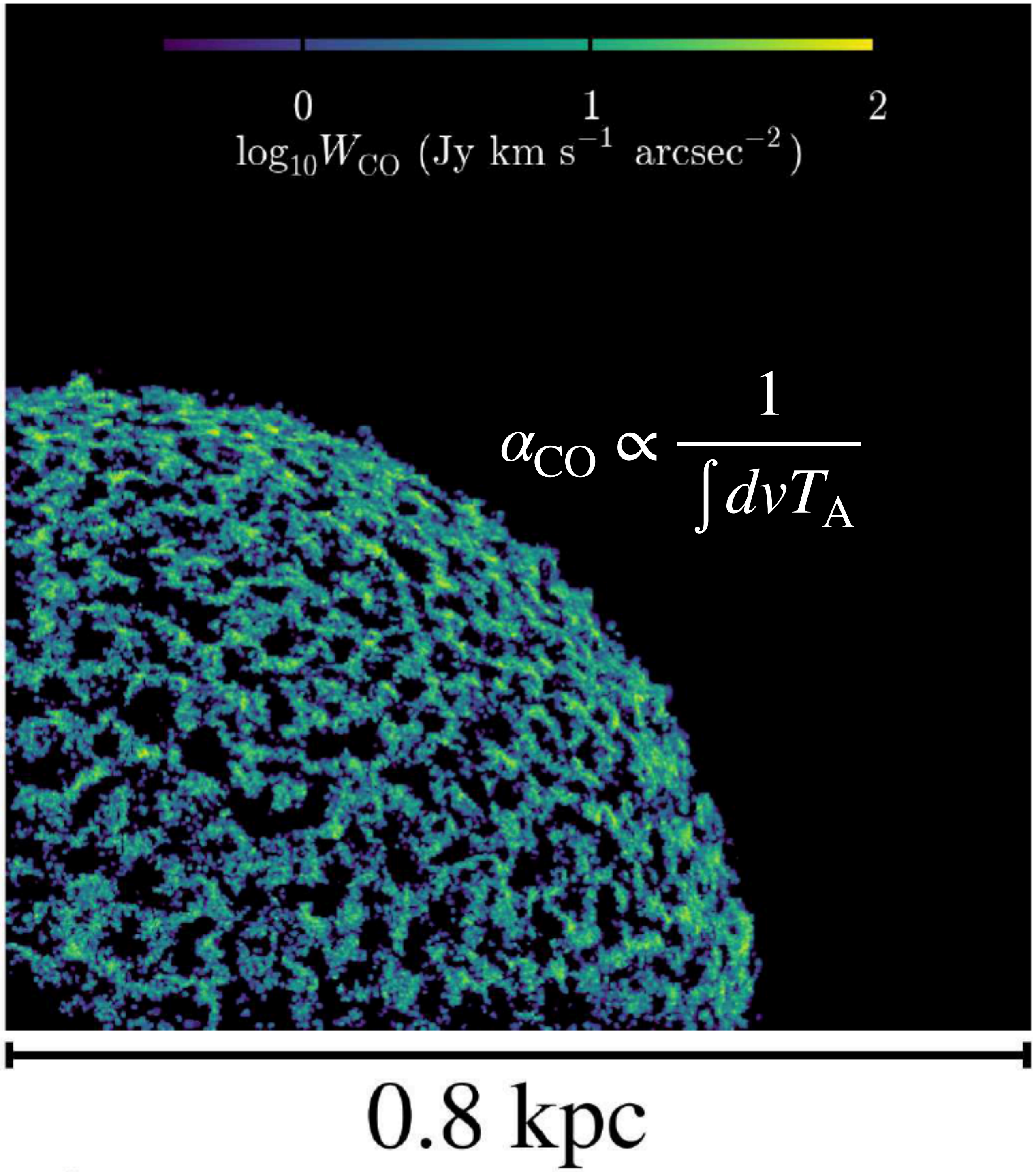
- Radiative transfer with RADMC-3D



Simulation	$\alpha_{\mathrm{CO}} = M_{\mathrm{H_2}}/L_{\mathrm{CO}}$ [a] (1–0)	(2–1)	(3–2)
L=10^{46}, $Z_\odot$	0.13	0.08	0.06
10^{45}, $Z_\odot$	0.15	0.09	0.07
10^{46}, $0.1 Z_\odot$	1.77	0.82	0.80

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

- Standard ULIRG value: $\alpha_{CO(1-0)}$=0.8
  - observationally-inferred molecular outflow rates could be biased high by ~5× at solar metallicity
  - but since f_{H2}~20%, implied *total* gas outflow rates not as affected



$$\alpha_{\mathrm{CO}} \propto \frac{1}{\int dv T_{\mathrm{A}}}$$

Richings & FG 18a

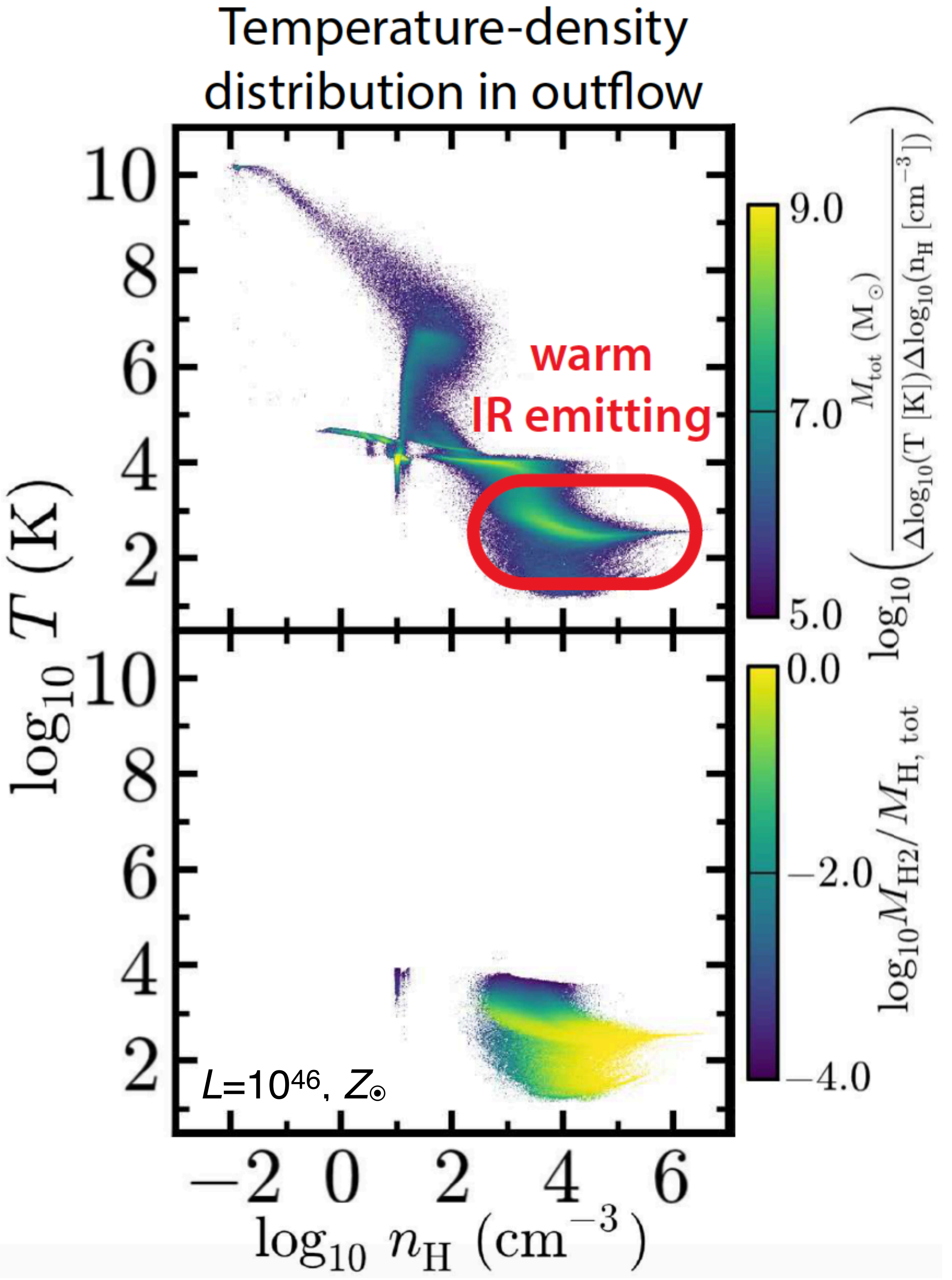
Warm H_2 in outflows

- >99% molecular mass is H_2, but

  $T_{\mathrm{min}} = E_{\mathrm{rot}}/k_{\mathrm{B}} = 510\ \mathrm{K} \gg T_{\mathrm{GMC}}$

- In outflow simulations, most H_2 is warm and observable in IR rotational lines
  - may explain "warm H_2 excess" found by Spitzer in ULIRGs

    (e.g. Zakamska 10)



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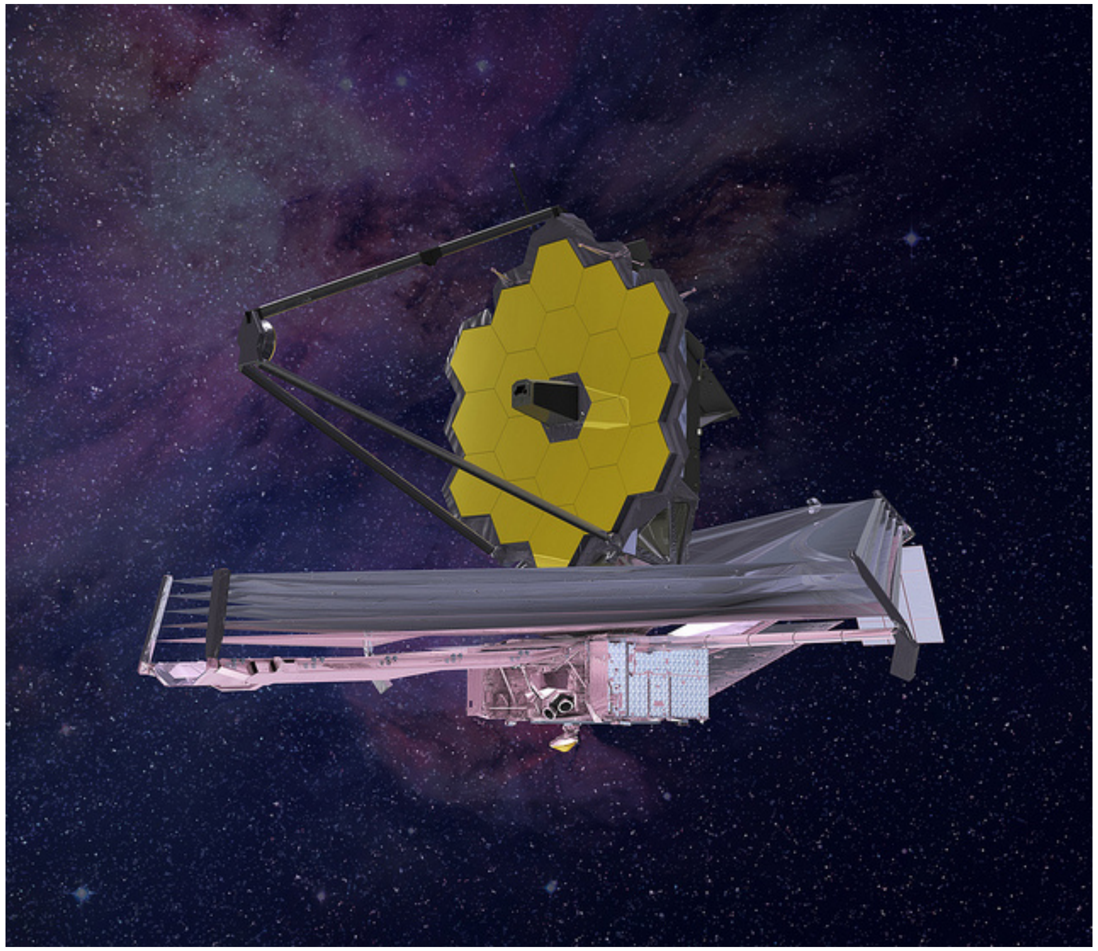
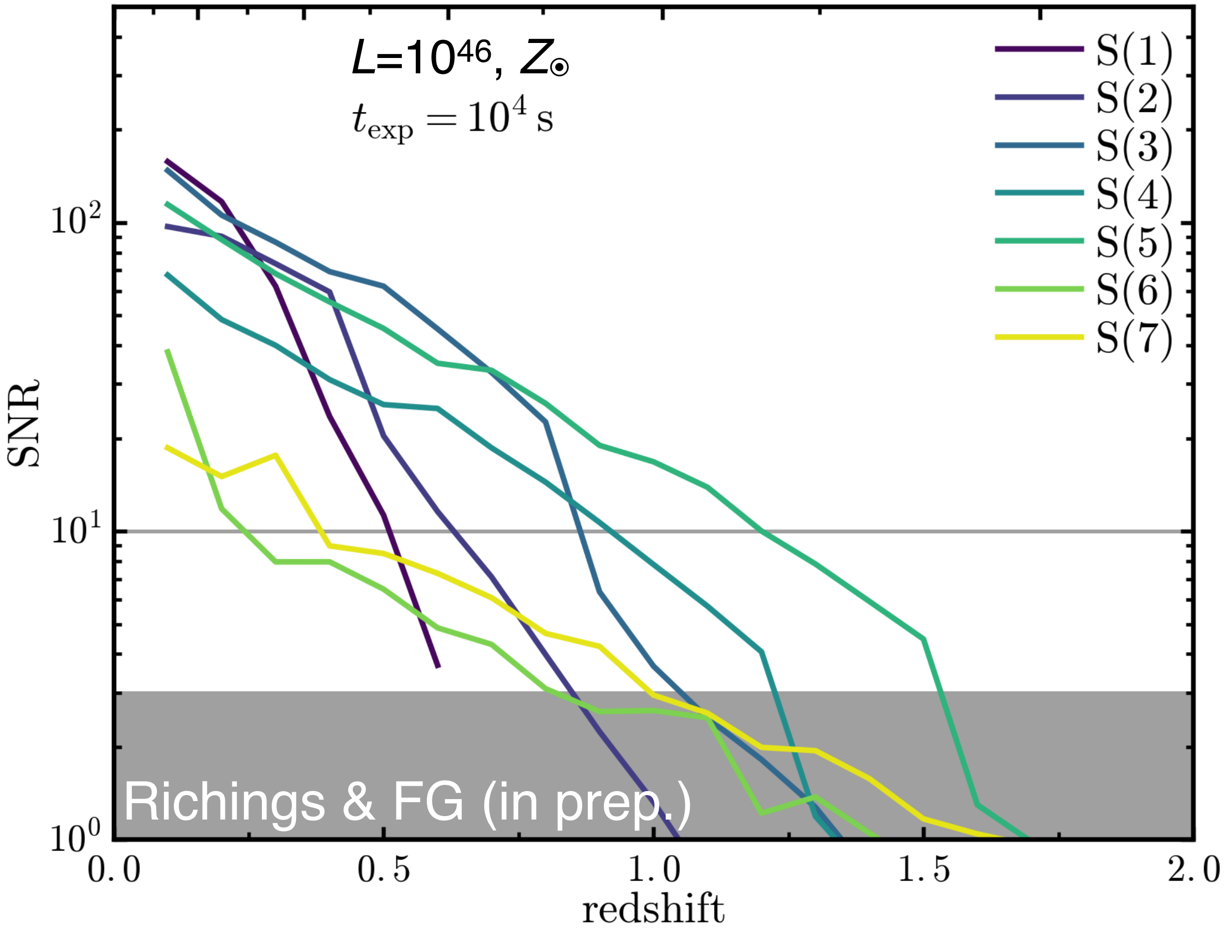
Warm H_2: JWST predictions



- Multiple IR rotational H_2 lines will be spectrally and spatially resolvable by JWST/MIRI (IFU)

JWST SNRs from outflow simulation



- JWST SNRs include realistic galaxy+QSO continuum and noise using Exposure Time Calculator

Summary

- Energy-conserving AGN outflows ⇒ momentum fluxes $\gg L_{\mathrm{AGN}}/c$
- Shocks with the ambient medium can cool and form new molecules (H_2, CO, OH, HCO^+, …), for a wide range of galaxy and AGN properties
- α_{CO} in outflows could be ~5× lower than standard ULIRG value
- Most H_2 is predicted to be warm, consistent with IR line luminosities and excitation temperatures observed by Spitzer
- JWST will spatially and spectrally resolve warm H_2 at high SNR

Extra Slides

What about dust?

- Needed to catalyze molecule formation

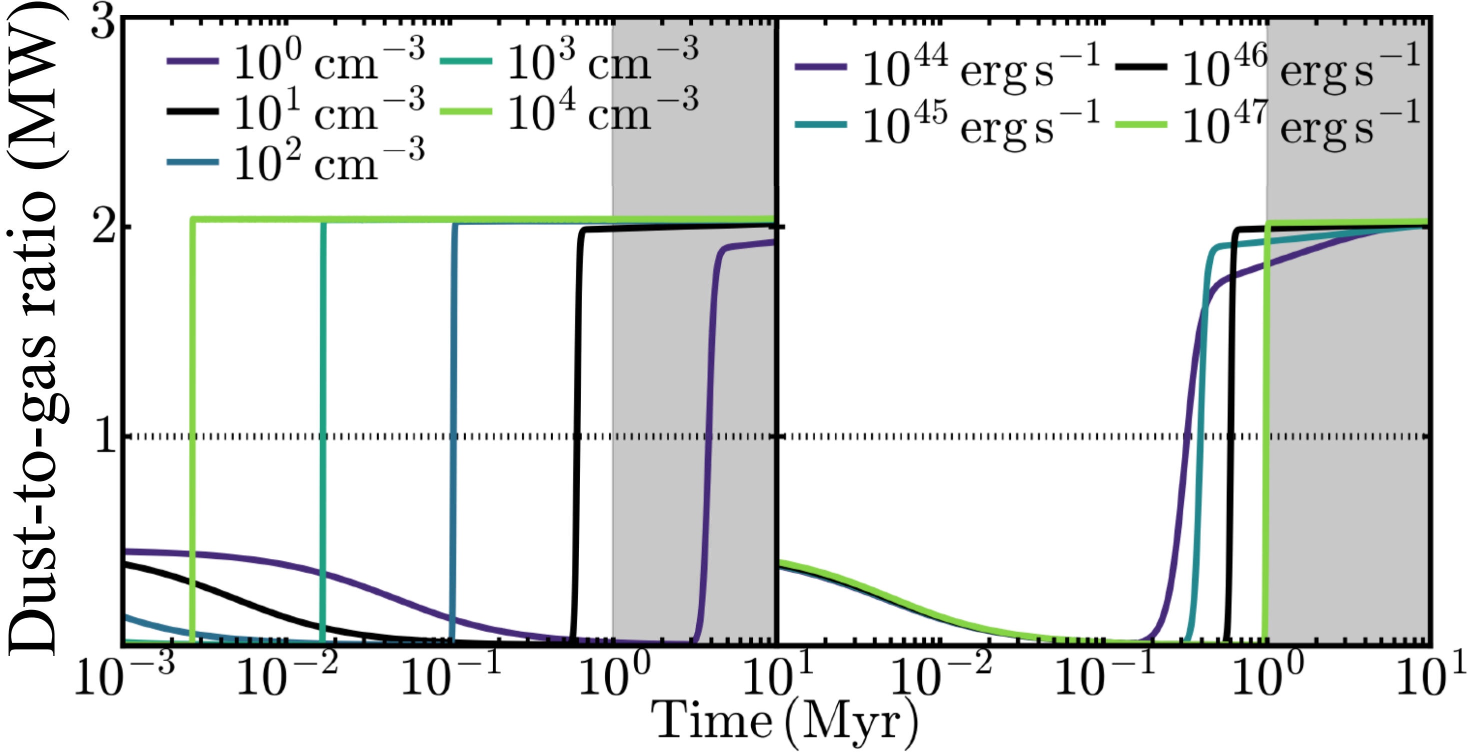
- Even if most dust destroyed, can (probably) regrow from tiny seed abundance

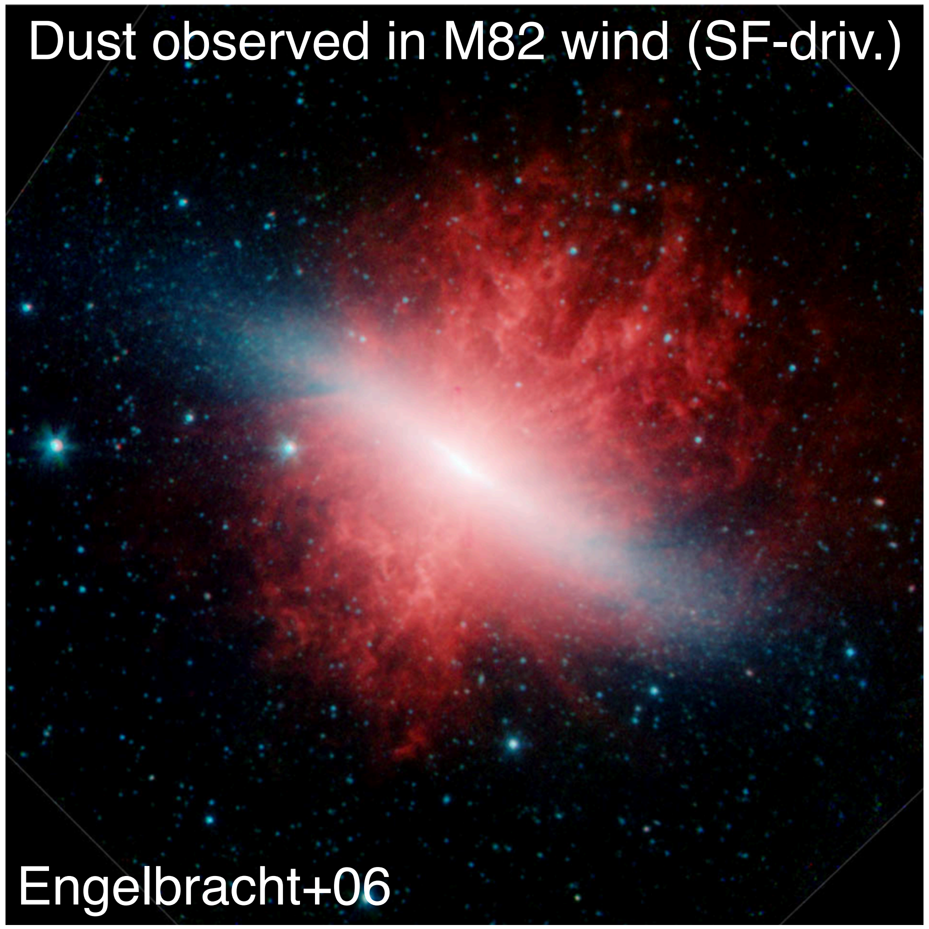
- Since nominal metals accretion timescale $\tau_{acc} \ll t_{flow}$:

$$\tau_{\rm acc} = 2.2 \times 10^4 \left(\frac{a}{0.1\,\mu{\rm m}} \right) \left(\frac{n_{\rm H}}{10^4\,{\rm cm}^{-3}} \right)^{-1} \times \left(\frac{T}{10^4\,{\rm K}} \right)^{-1/2} \left(\frac{Z}{0.0129} \right)^{-1} {\rm yr}$$

(e.g., Asano+13)

Dust re-growth in swept-up gas for survival fraction 10^{-6}





Dust observed in M82 wind (SF-driv.)

Engelbracht+06

Richings & FG 18b

Theoretical vs. observational momentum fluxes

- Models predict *instantaneous rate of change* of outflow momentum

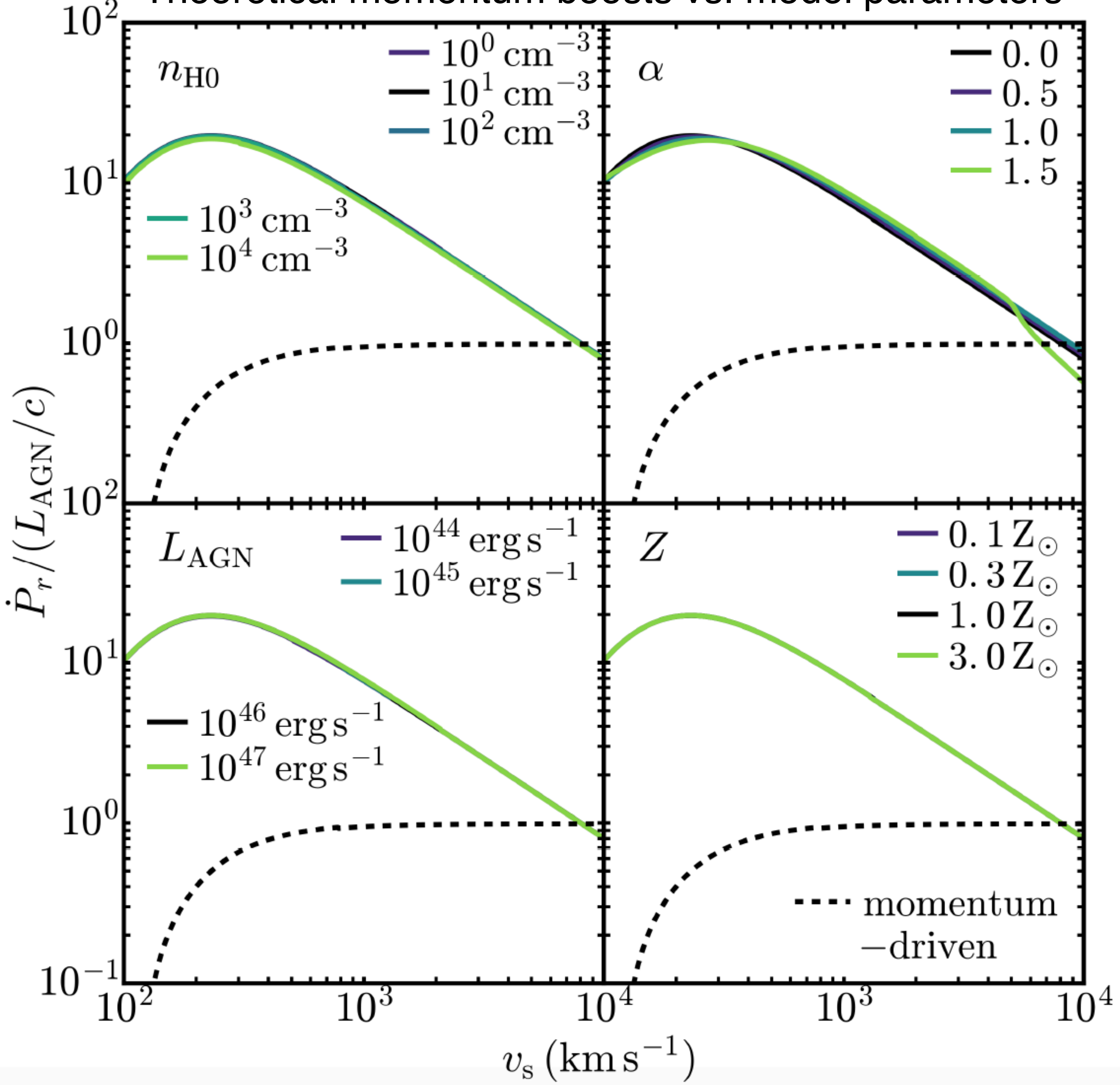
$$\dot{P}_{\rm r} = \frac{d(M_{\rm s} v_{\rm s})}{dt}$$

$$\approx \dot{M}_{\rm s} v_{\rm s}$$

- In energy-conserving models with initial momentum *L*AGN/*c*, neglecting gravity,

$$\frac{\dot{P}_{\rm r}}{L_{\rm AGN}/c} \propto \frac{v_{\rm in}}{v_{\rm s}} \gtrsim 10$$

Theoretical momentum boosts vs. model parameters



FG & Quataert 12; Richings & FG 18b

Theoretical vs. observational momentum fluxes

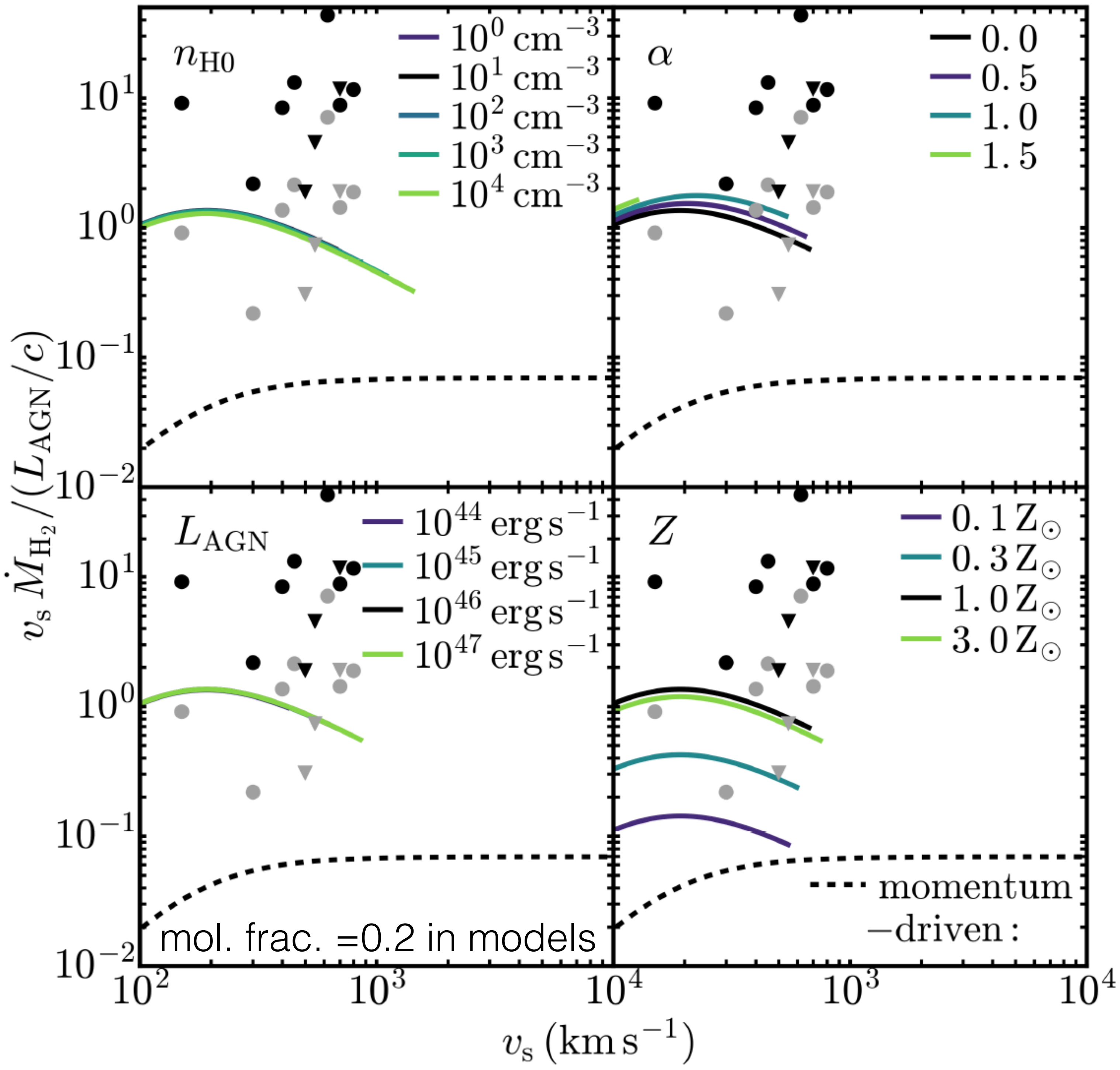
- <u>Observations</u> estimate *time-averaged* momentum change

$$\dot{P}_{\rm r}^{\rm obs} = \frac{M_{\rm s} v_{\rm s}}{R_{\rm s}/v_{\rm s}}$$

and often only probe one phase, e.g. molecular

- Can produce observationally-inferred momentum boosts ~1 even for energy-conserving outflows (expect ≪1 for momentum-conserving)

Observationally-inferred molecular momentum boosts



Data points from Cicone+14, for different $\alpha_{\rm CO}$ assumptions

Richings & FG 18b