Galaxy-Scale AGN Outflows: Two Puzzles, Two Solutions

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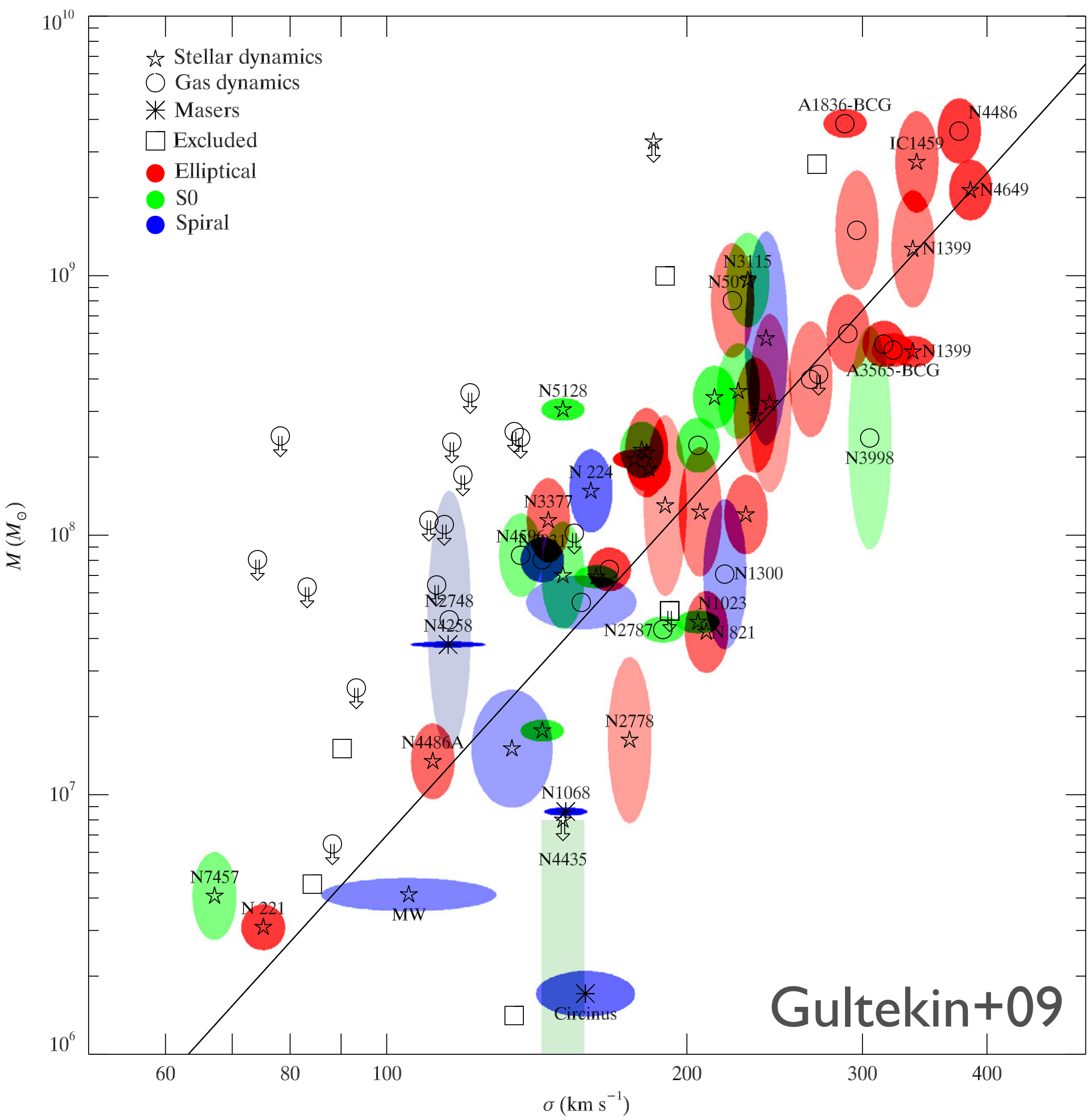
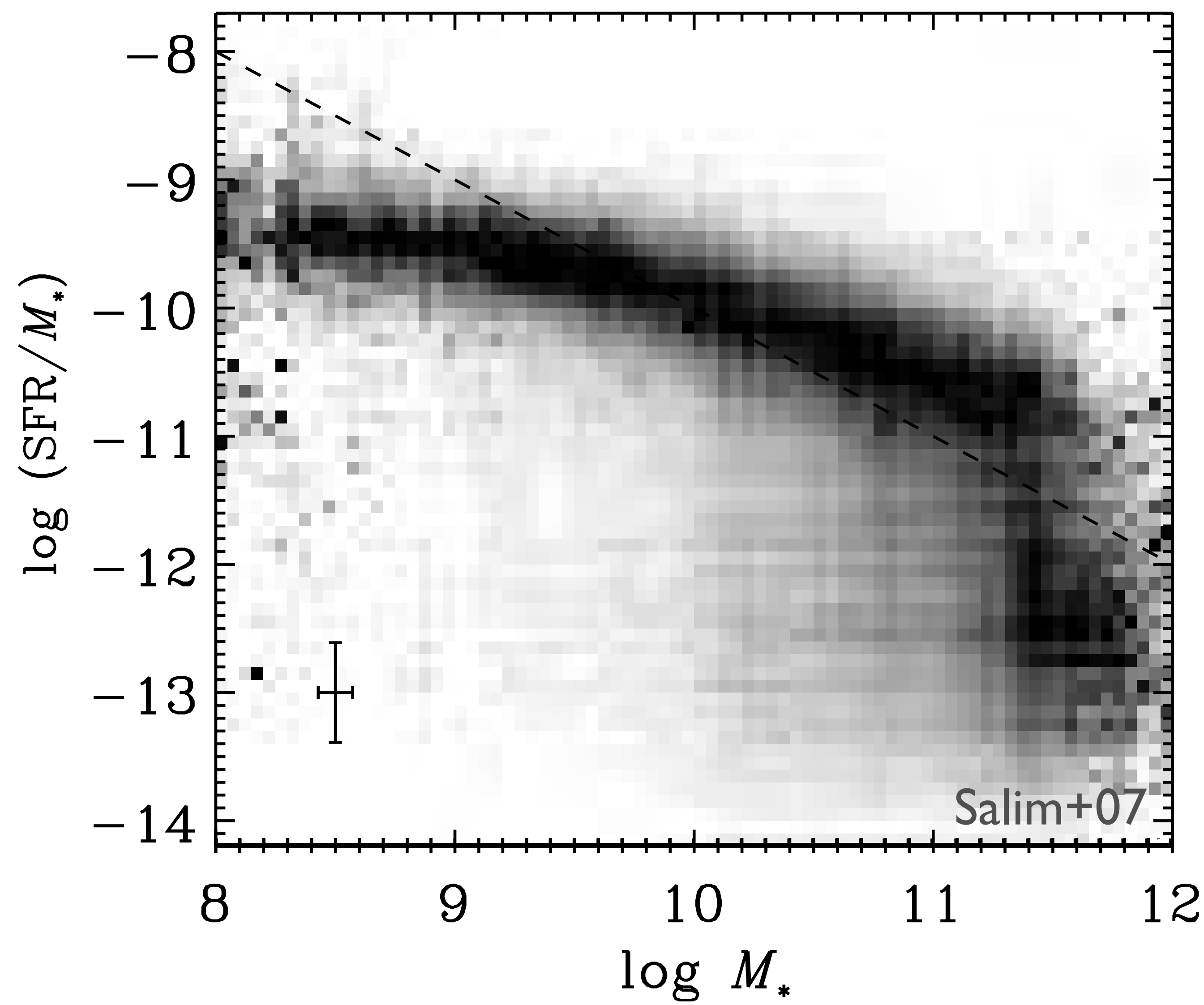
The possible roles of AGN feedback

Establish correlations between SMBH and galaxy properties



Truncate star formation



Models that assume *f*~5% *L*$_{AGN}$ couples to ISM are successful in explaining in these observations

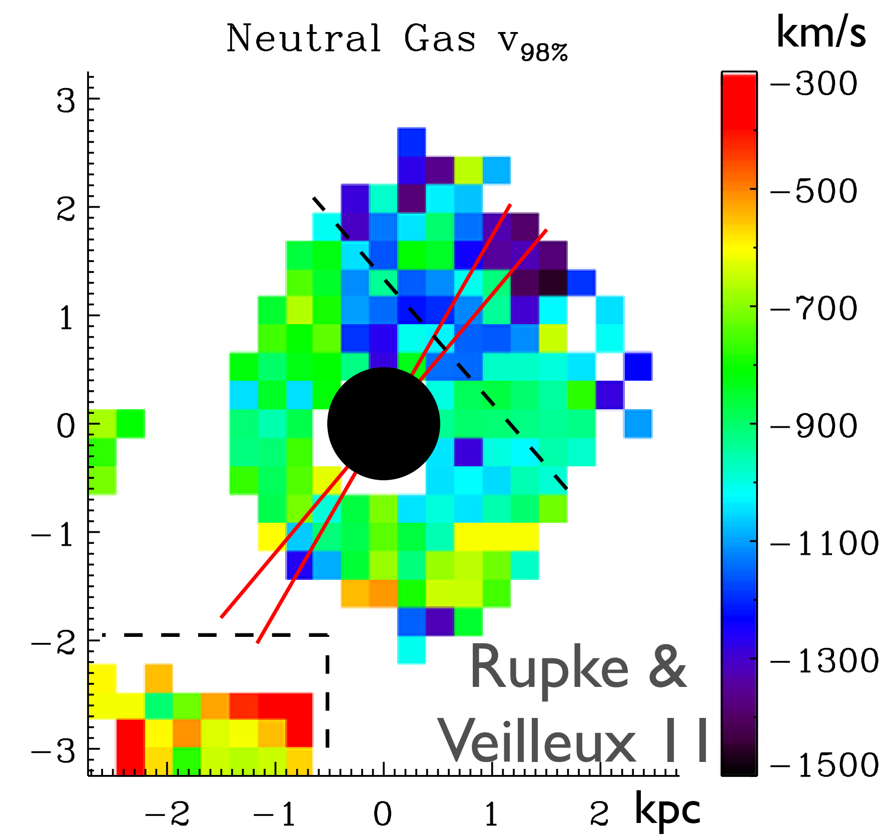
Observational breakthroughs on AGN outflows

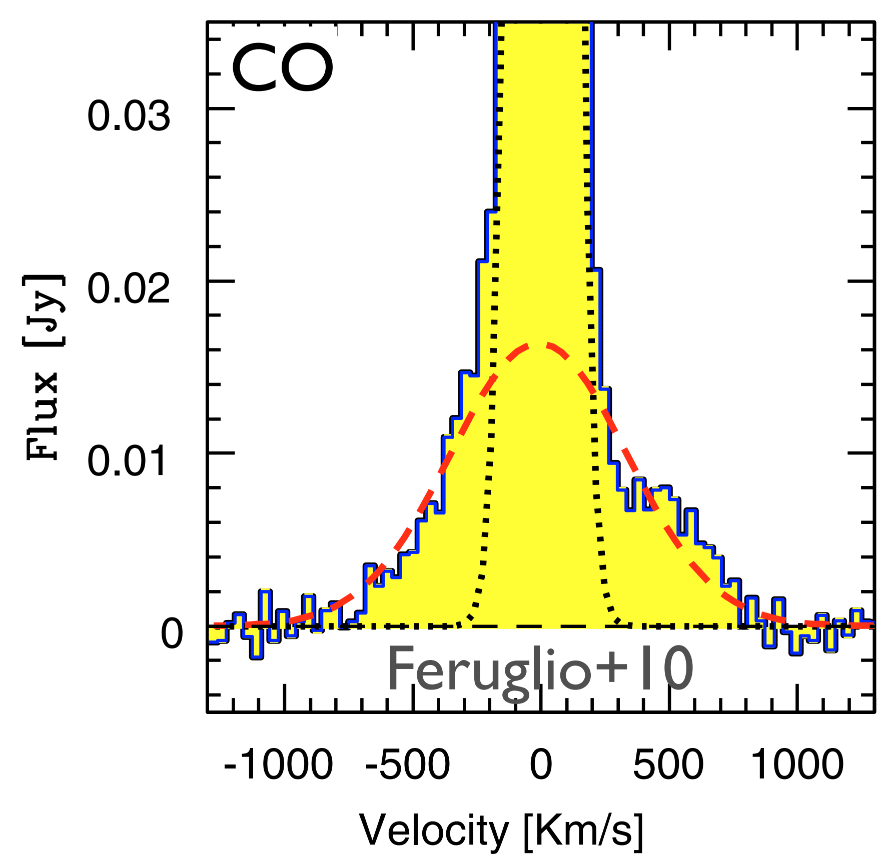
- Massive, galaxy-scale AGN outflows in local ULIRGs
  - ➡ neutral, ionized, CO, OH, HCN, ...

- Herschel, E-VLA, ALMA, ... to revolutionize this field

- Physical conditions in QSO outflows using low-ion BALs (⇒ energetics)

Mrk 231





Physical conditions in luminous QSO atomic outflows

- Photoionization modeling particularly constraining in QSOs with FeII* broad line absorption (T~10^4 K, v~5,000 km/s; FeLoBALs):

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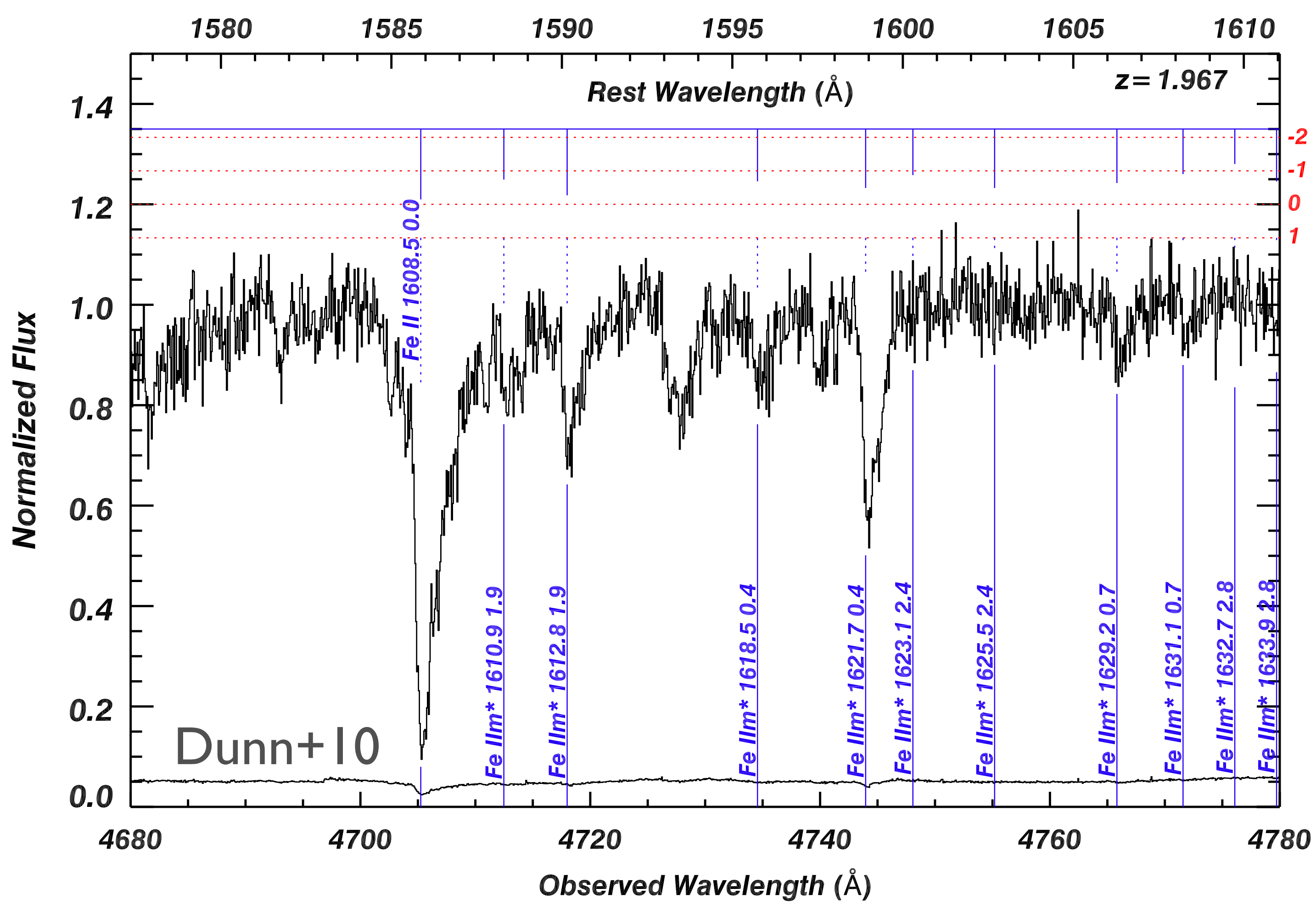

Observations from Moe+09, Dunn+10, Bautista+10, Arav 10

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n_e~10^4 cm^{-3}

N_H~$10^{20\text{-}21}$ cm^{-2}

ionization param

ΔR~0.01 pc (absorber thickness)

R~1-3 kpc (distance from SMBH)

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$\Rightarrow \Delta R/R \sim 10^{-5}$

Jupiter mass!

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1. What are these things?

2. How can we use them to measure outflow energetics?

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Compact absorbers must form *in situ*, at *R*~kpc from SMBHs

- If they traveled from the SMBH to their implied location...

$$t_{\rm flow} \approx \frac{R}{v} \approx 3 \times 10^5 \ {\rm yr} \left(\frac{R}{3 \ {\rm kpc}} \right) \left(\frac{v}{10,000 \ {\rm km \ s^{-1}}} \right)^{-1}$$

- But destroyed by hydro instabilities and thermal evaporation in

$$t_{\rm KH}, \ t_{\rm evap} \sim {\rm few} \times 10^3 \ {\rm yr}$$

Not a direct accretion disk wind!

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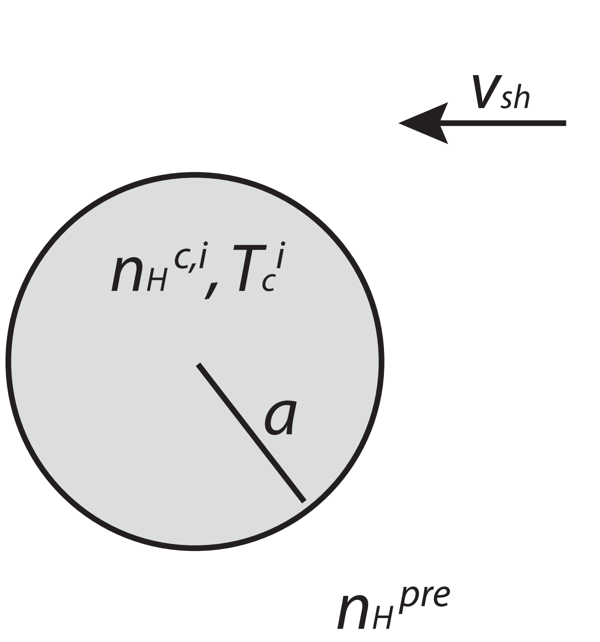
Radiative shock model

- Form in interaction of the QSO blast wave with an ISM clump:



pre-existing ISM cloud

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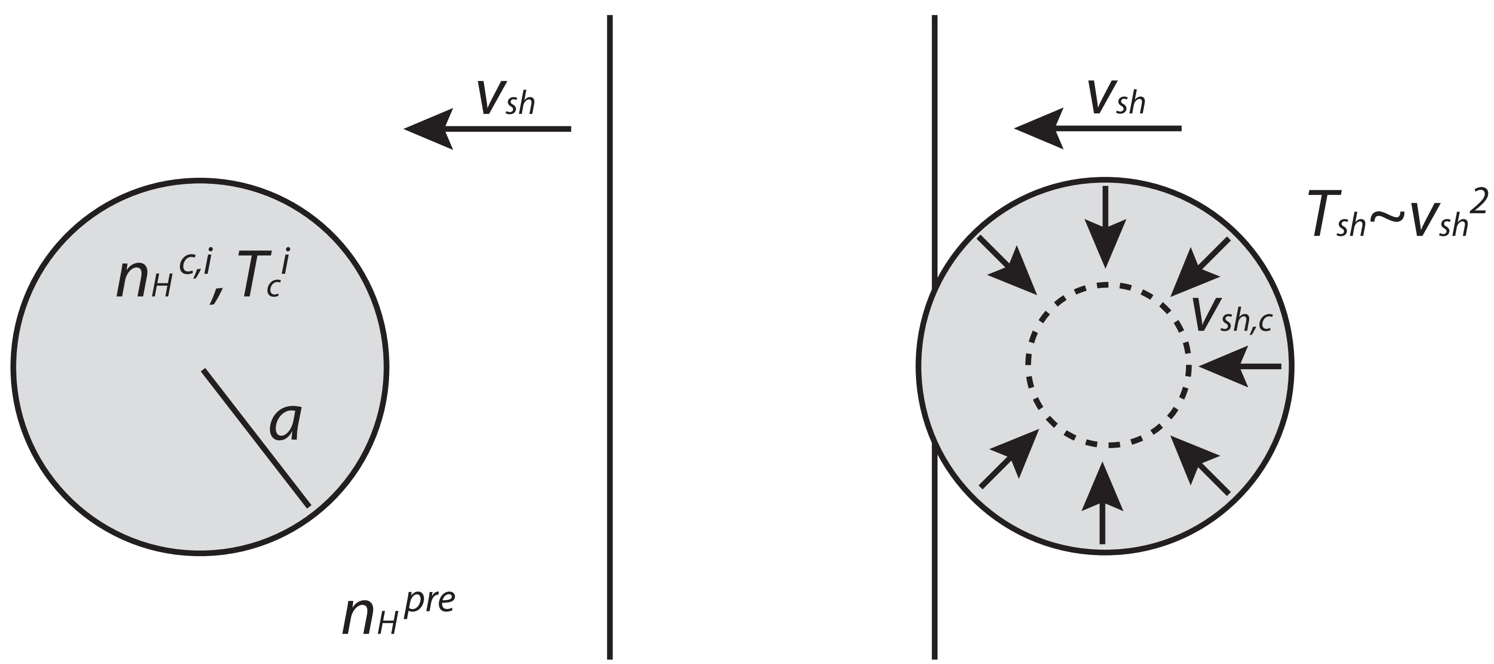

pre-existing ISM cloud

cloud crushing by QSO blast, accel by ram pressure

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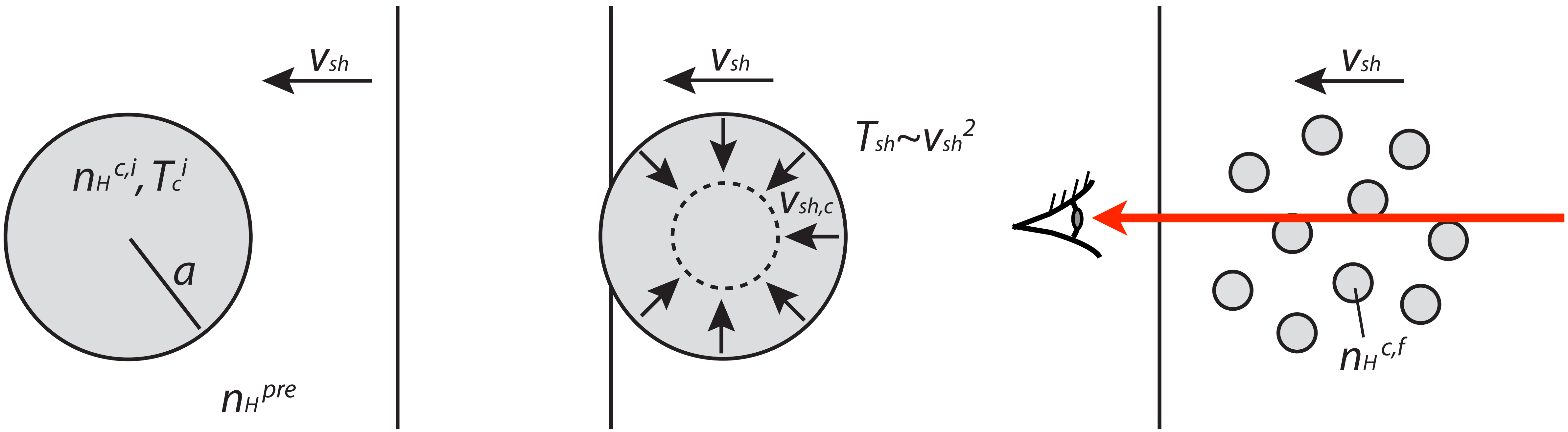

pre-existing ISM cloud

cloud crushing by QSO blast, accel by ram pressure

absorption by transient, compressed shreds

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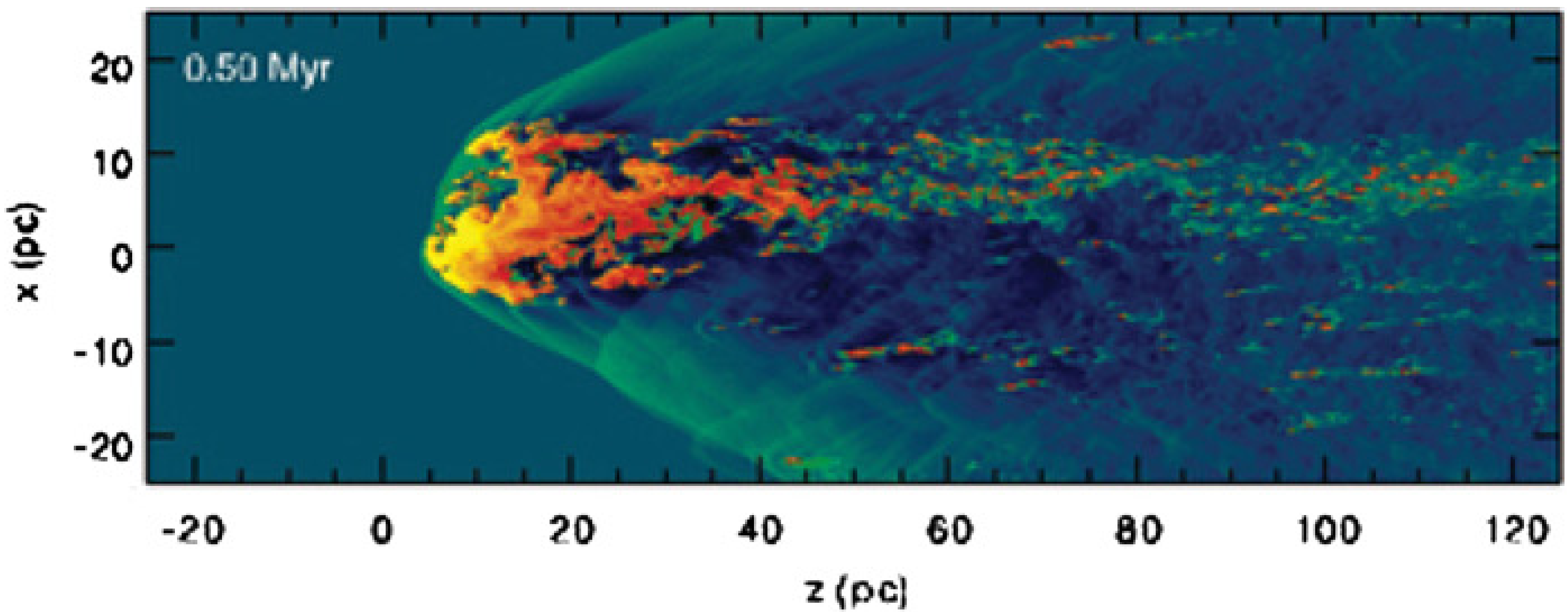
Cloud crushing by shocks, Kelvin-Helmholtz instability

- Well-studied problem for SNRs (e.g., Klein+94, Cooper+09)



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Requirements for radiative shocks explain properties of cool absorbers

- Acceleration, cold gas:

$$\begin{array}{c} t_{\rm drag} < t_{\rm KH} \\ t_{\rm cool} < t_{\rm cc} \end{array} \Rightarrow N_{\rm H} \gtrsim 10^{20}~{\rm cm}^{-2} \left(\frac{v_{\rm sh}}{5,000~{\rm km~s}^{-1}} \right)^{4.2}$$

- Post-shock compression:

$$n_{\rm H}^{\rm BAL} \approx 4 n_{\rm H}^{\rm pre} \left(\frac{T_{\rm sh}}{10^4~{\rm K}} \right) \sim 10^4~{\rm cm}^{-3}$$

$$\Rightarrow \Delta R \sim N_{\rm H}/n_{\rm H} \sim 0.01~{\rm pc}$$

- Also: super-thermal line widths, multiple *v* components, reddening, ...

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Energetics of QSO outflows

- Outflows are multiphase

- Most of kinetic power in hot flow:

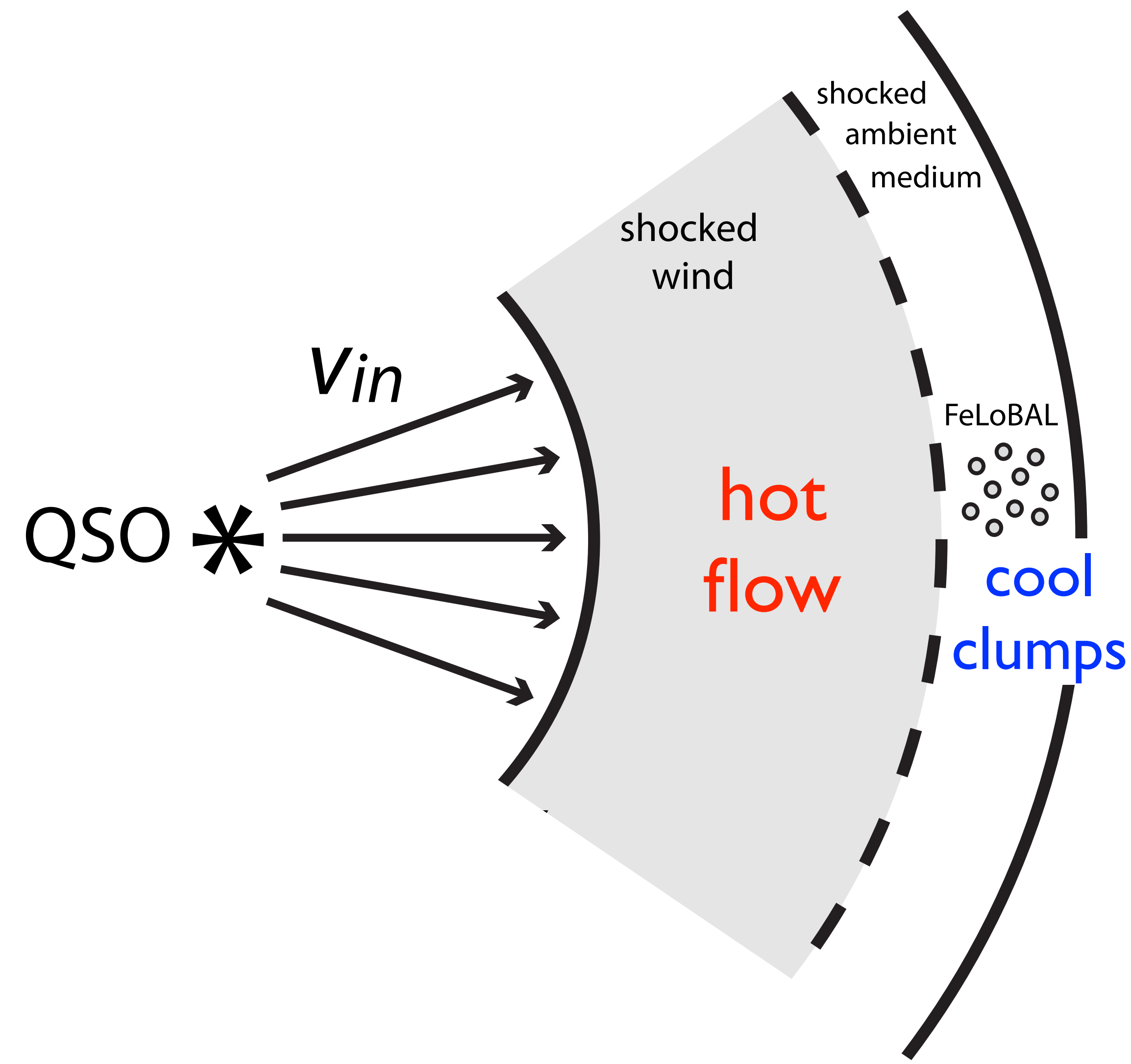
$$\dot{M}_{\rm hot} = 8\pi\Omega_{\rm hot} R N_{\rm H}^{\rm hot} \mu m_{\rm p} v_{\rm hot}$$

- Using radiative shock model:

$$\dot{E}_{\rm k} \approx 2 - 5\% \ L_{\rm AGN}$$

$$\dot{M} \approx 1,000 - 2,000 \ {\rm M}_{\odot}/{\rm yr}$$

$$\dot{P} \approx 2 - 10 \ L_{\rm AGN}/c$$



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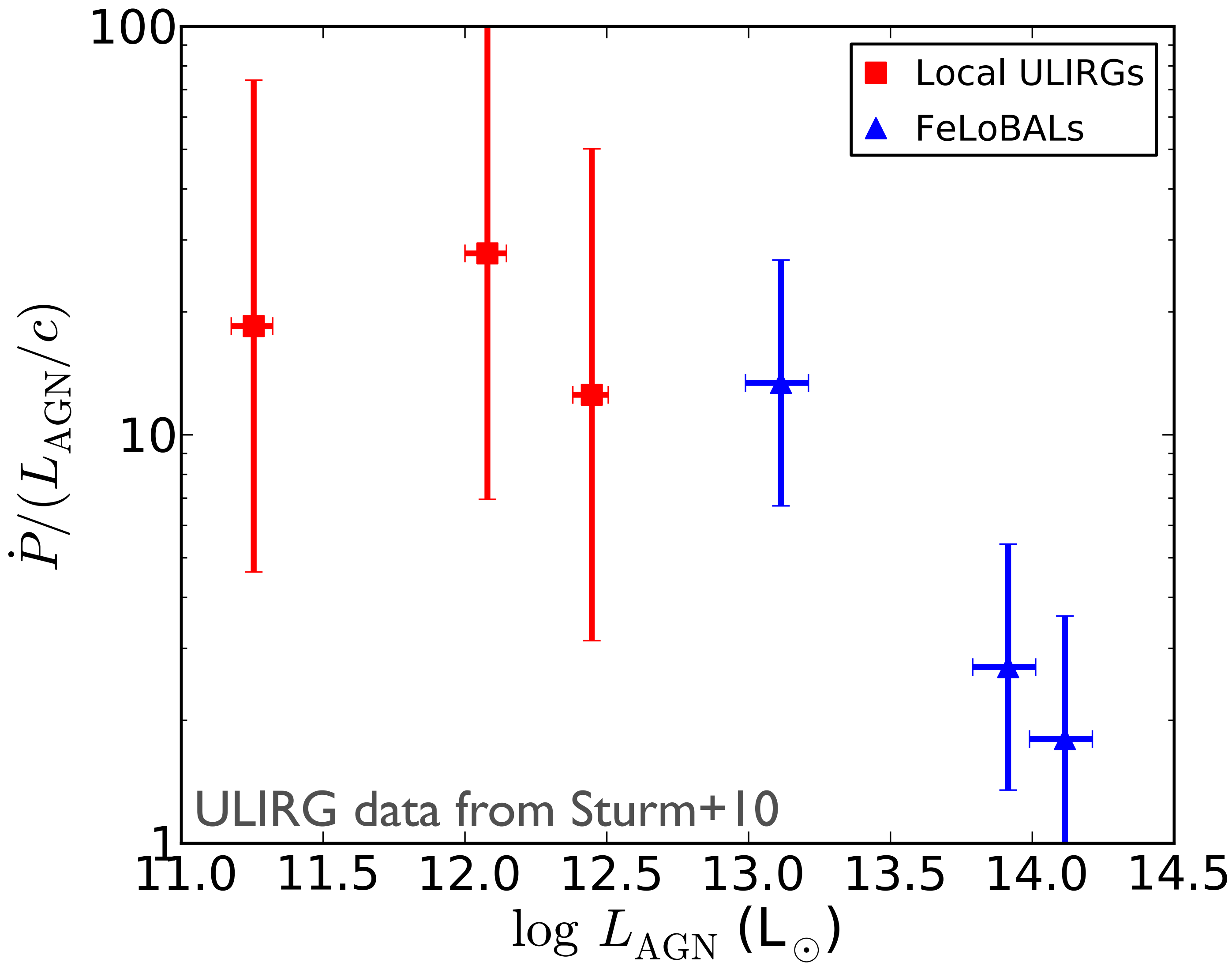
The puzzle of large momentum fluxes



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

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

- Observations indicate

$$\dot{P} \sim 10 L_{\rm AGN}/c$$

- Simulations also require

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

to reproduce $M_\bullet$-σ (DeBuhr+)

CAFG & Quataert, in prep.

Momentum driving

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

No thermal pressure

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

e.g., AGB wind

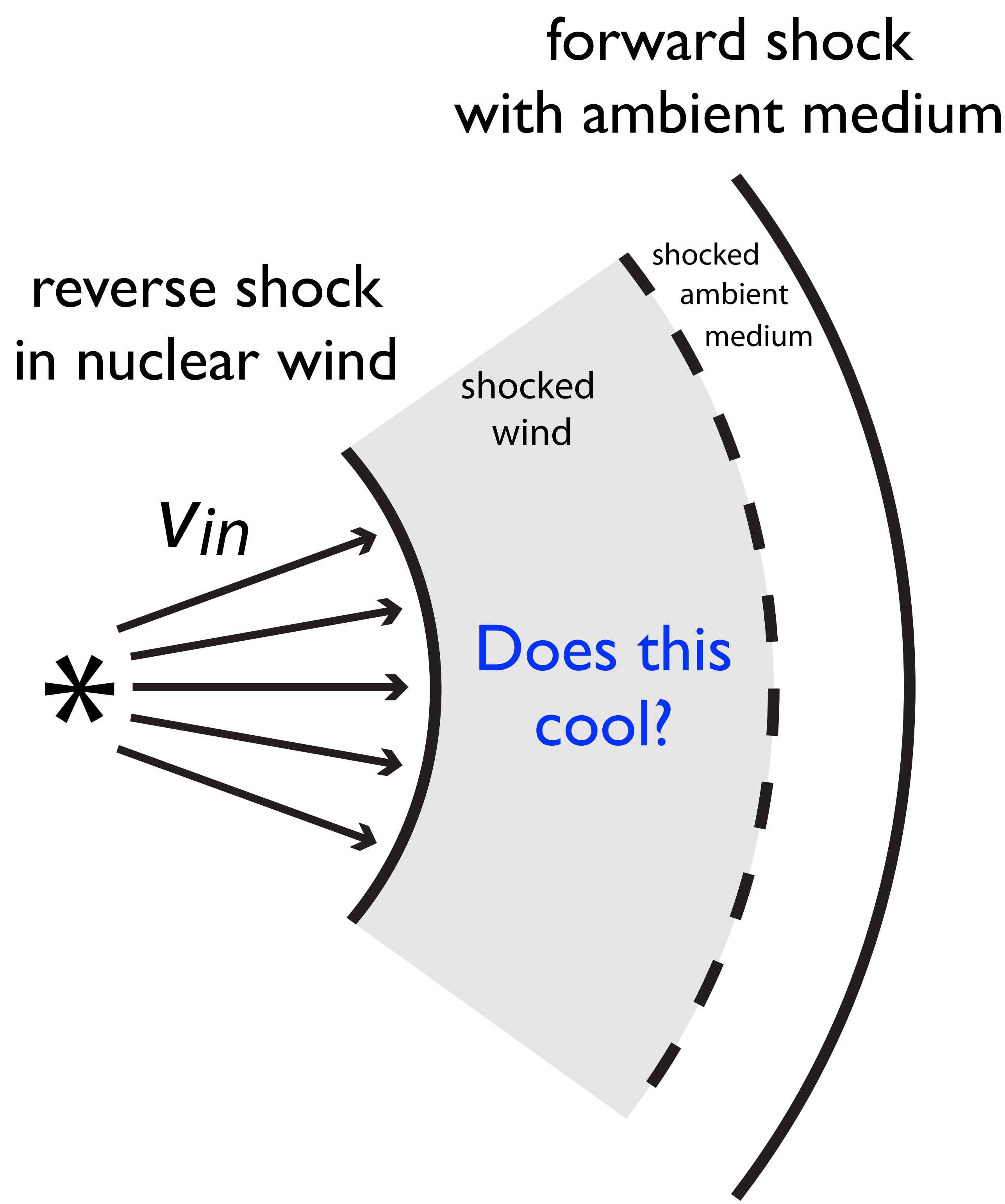
Energy driving

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

Shocked gas does work

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

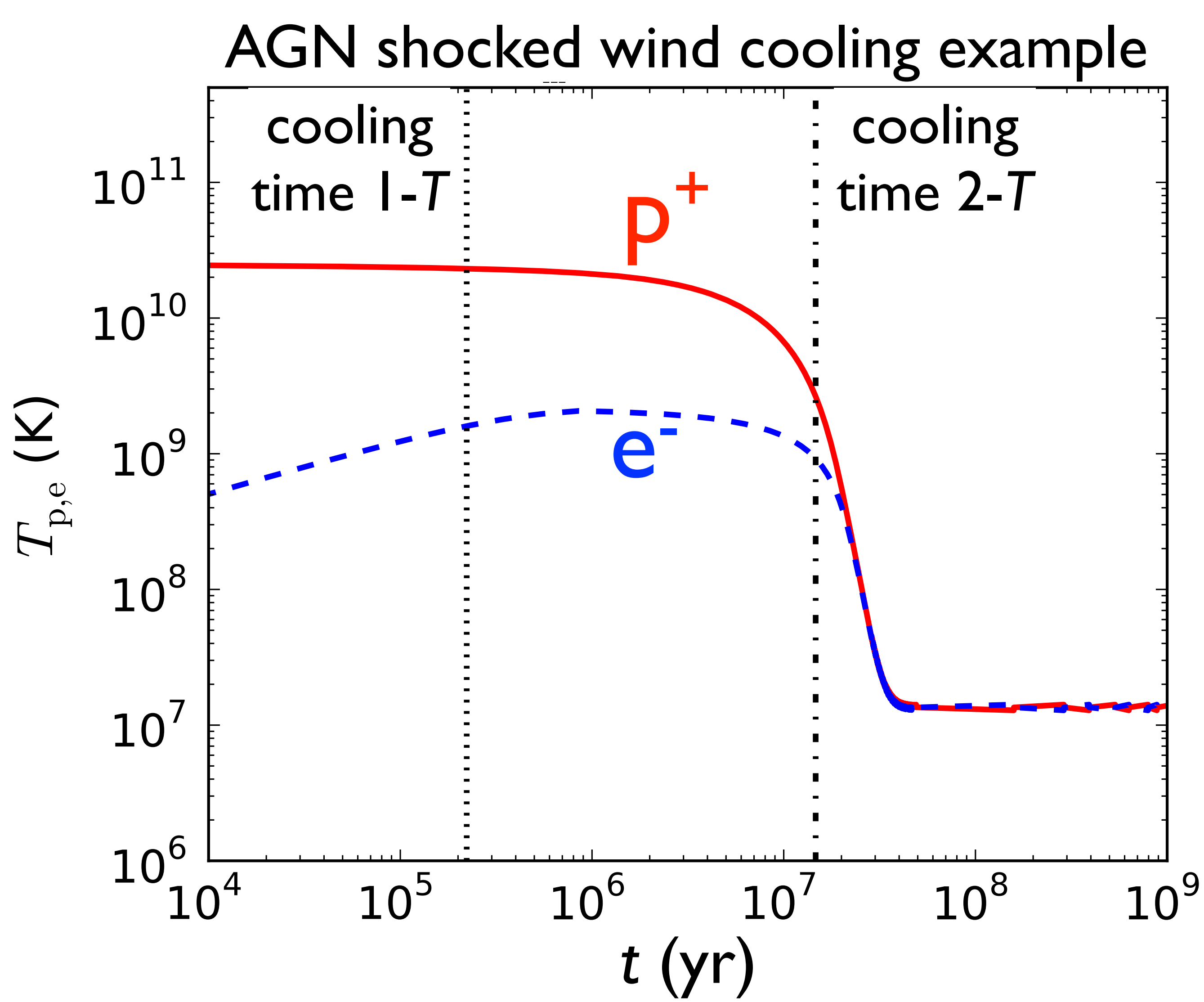
e.g., Sedov-Taylor SNR



CAFG & Quataert, in prep.

Proposal: AGN outflows are energy-driven

- Possible in ULIRGs despite extreme densities
  - ➡ relevant criterion is cooling of *reverse* shock: $T_{sw} \sim 10^{10}$ K for $v_{in} \sim 0.1c$
  - ➡ *2-T* plasma inhibits IC cooling



CAFG & Quataert, in prep.

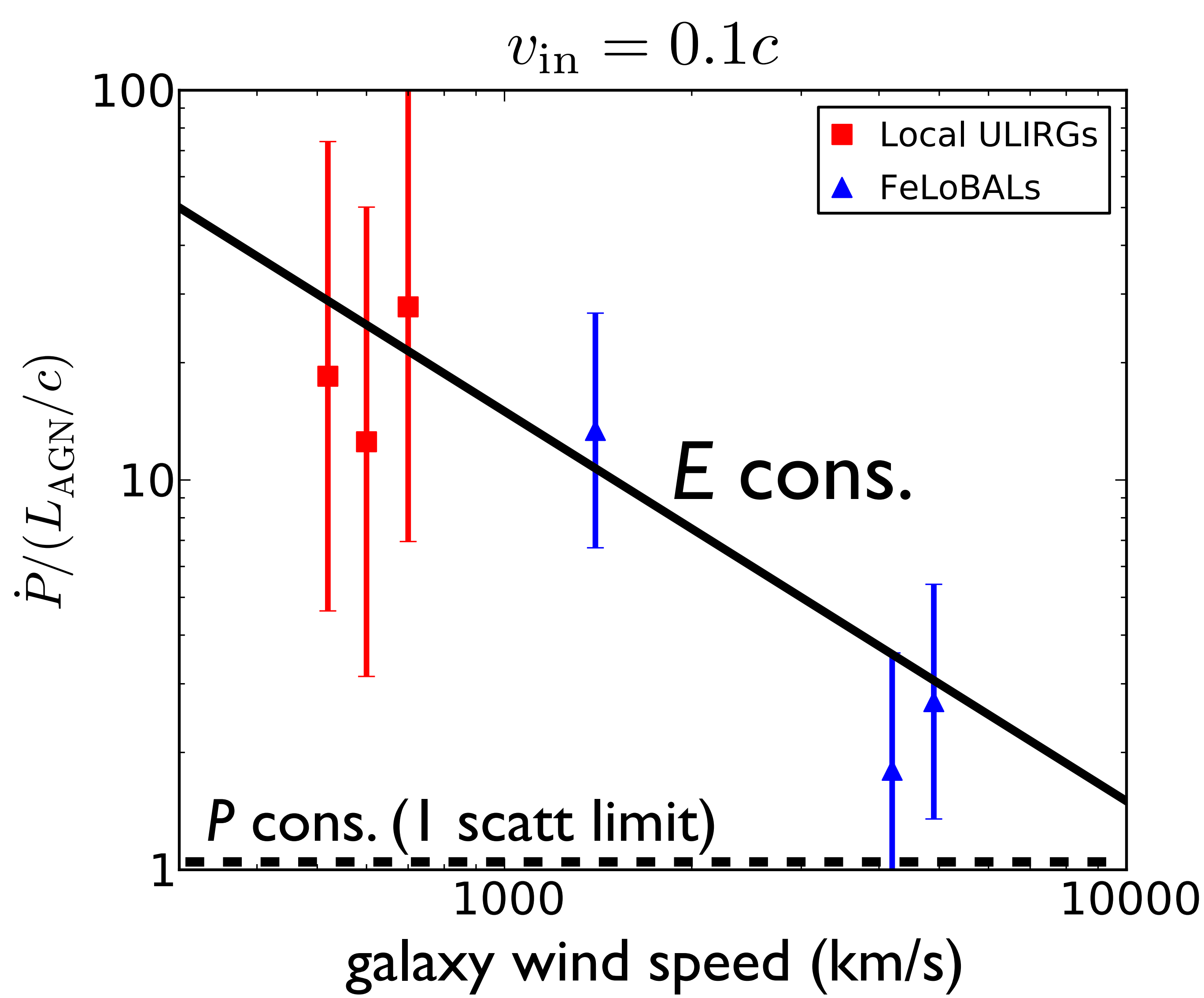
Energy conservation naturally explains measured AGN momentum boosts

- Predicts

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

- To be tested soon with Herschel, E-VLA, ALMA, ...

- Analytic model will inform numerical implementations



CAFG & Quataert, in prep.

Robust to mixing, leakage

- Stellar wind bubbles smaller & slower than in energy-conserving models (Castor)
  - ➡ cooling due to mixing (McKee+84)
  - ➡ hot gas vents out (H.-C. & Murray 09)

- AGN winds more robust
  - ➡ ~30× wind mass of cool gas before catastrophic ff cooling
  - ➡ escape along paths $<10^{-3}$ under-dense can still boost *P* by factor >10 in ULIRGs

Carina nebula

CAFG & Quataert, in prep.

Summary

- Compact, cool absorbers form in radiative shocks
- Energetics in good agreement with $M_\bullet$-σ requirements
- Observations of galaxy-scale AGN outflows suggest

$$\dot{P} \gg L_{\mathrm{AGN}}/c$$

- Proposal: outflows are energy-conserving
- Prediction:

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