Modeling AGN Outflows:

Implications for Feedback

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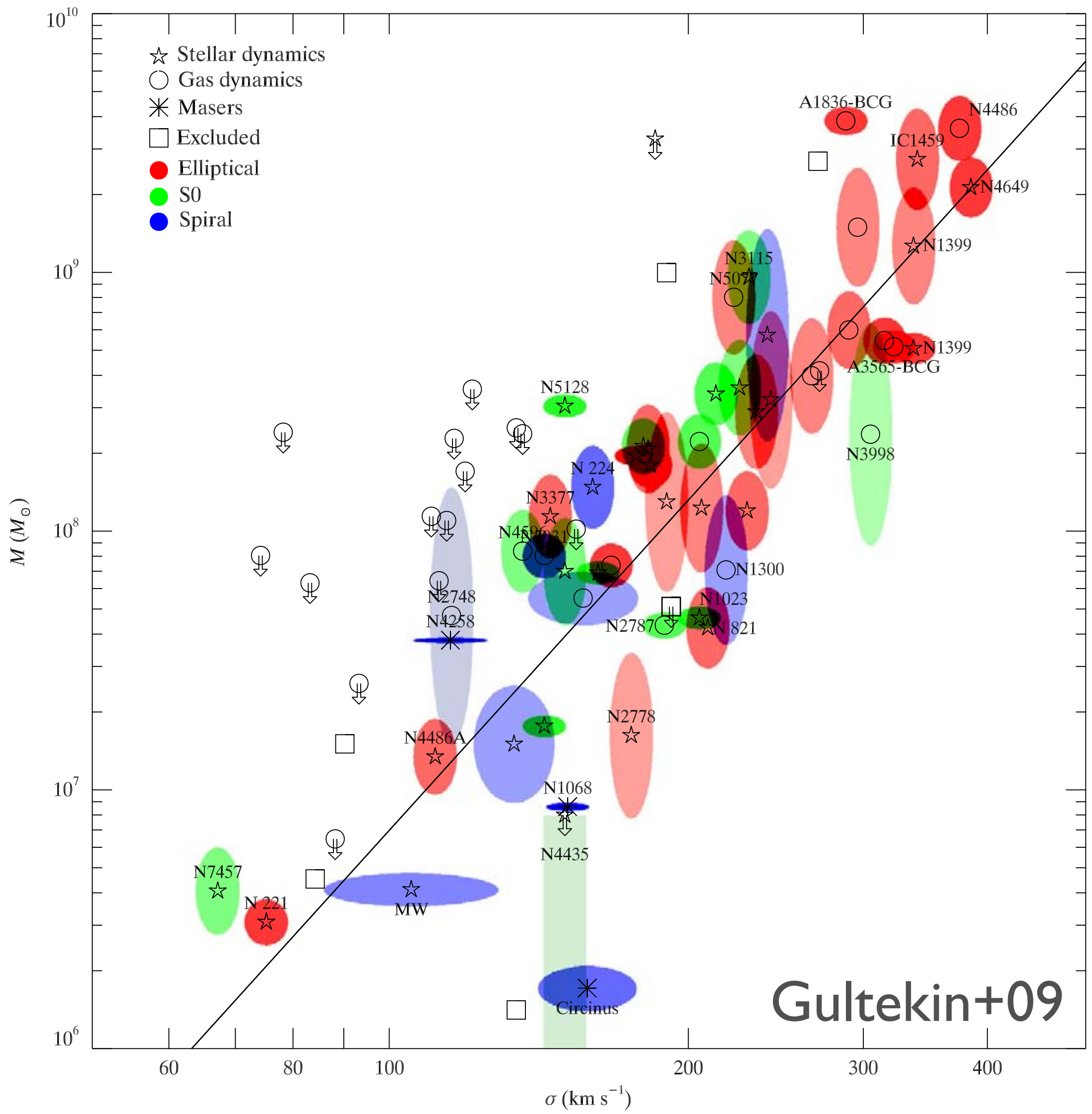
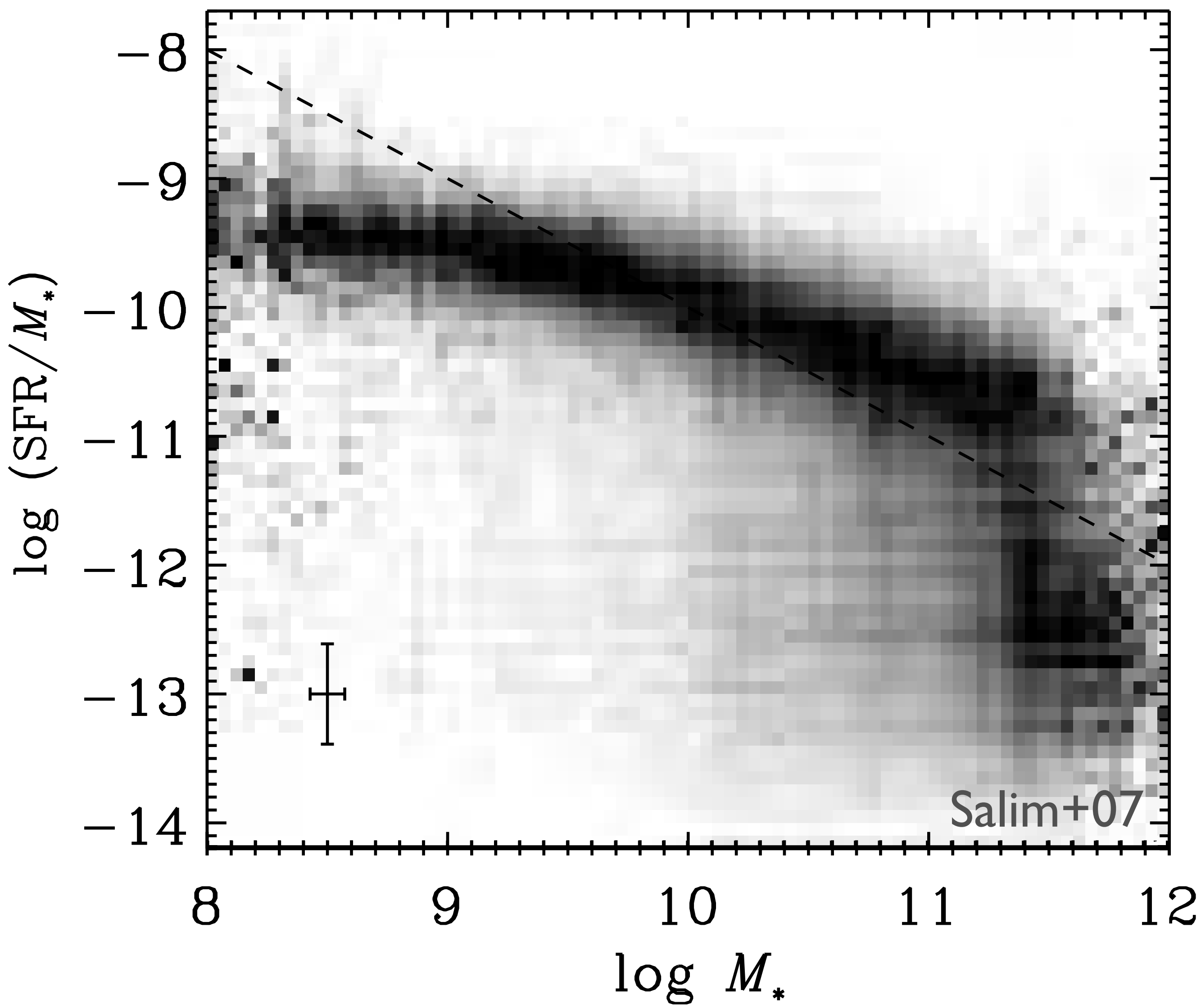
The possible roles of AGN feedback

Establish correlations between SMBH and galaxy properties



Truncate star formation



Models that assume f~5% L_{bol} couples to ISM are successful in explaining in these observations

Outline

- A physical model of FeLoBALs:
  - ➡ formation in radiative shocks
  - ➡ observed outflow energetics
- Molecular outflows in ULIRGs

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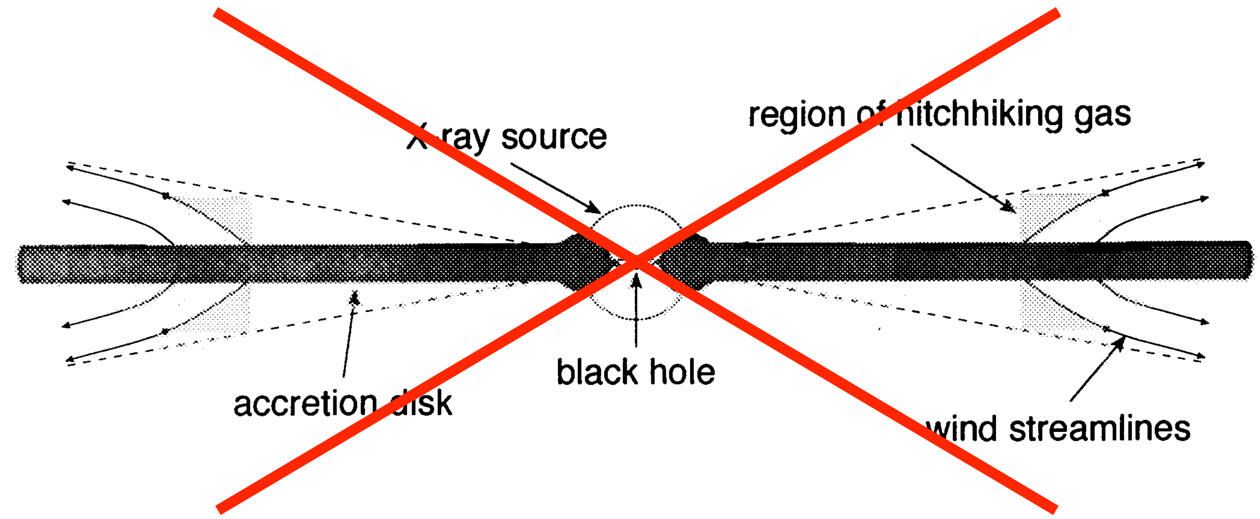


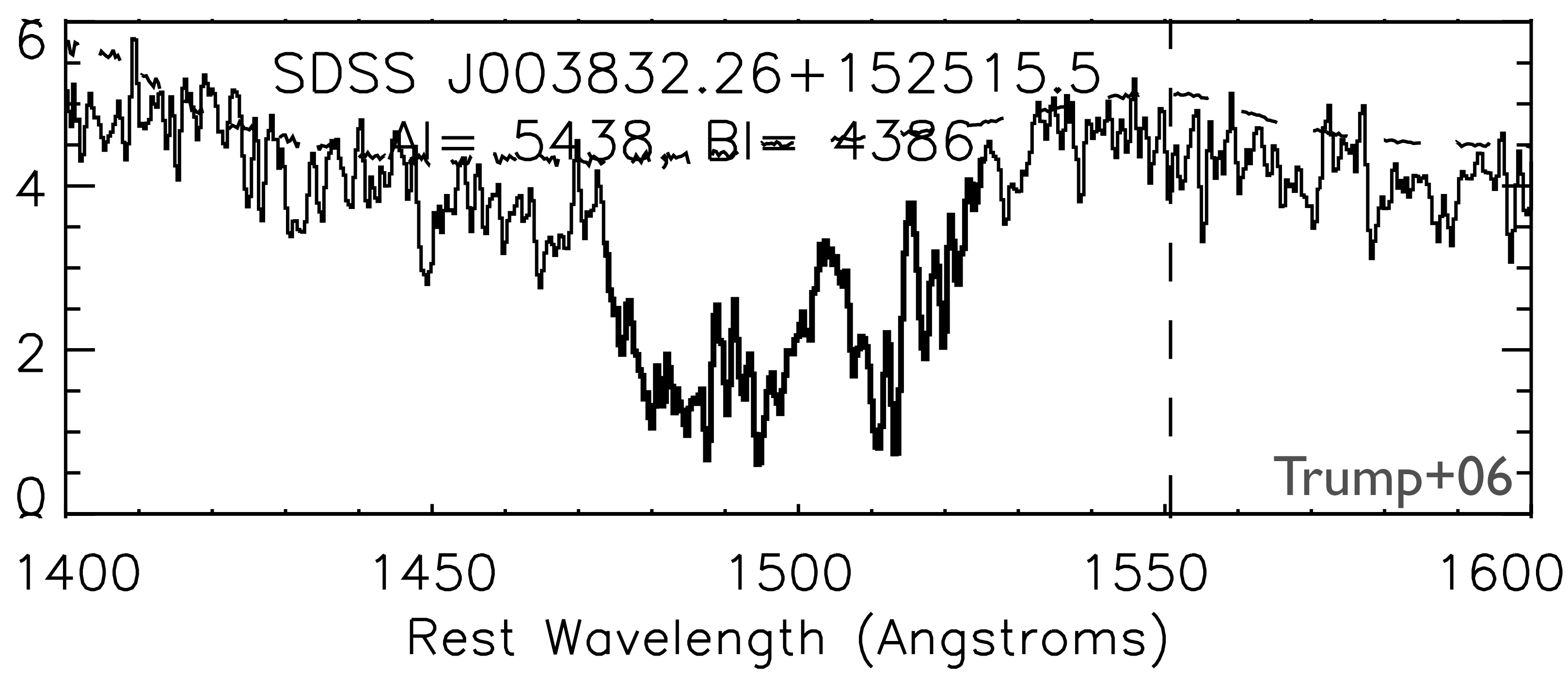
not accretion disk wind

(strictly, applies to handful of FeLoBALs studied in detail, but could also be relevant for other galaxy-scale absorbers, NALs?)

- Molecular outflows in ULIRGs

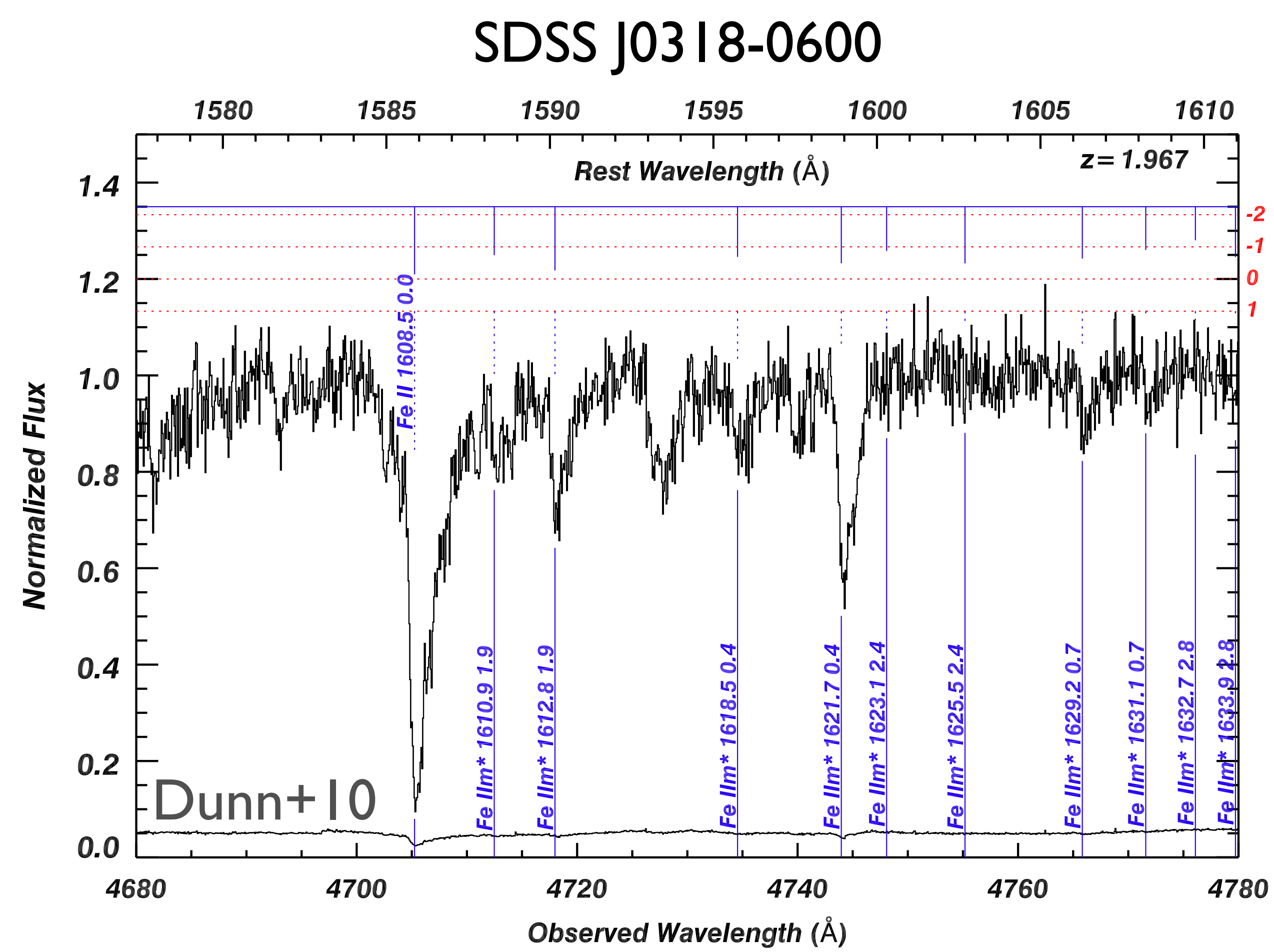
What are BALs?

- Broad absorption lines in QSOs:
  - ➡ usually high-ionization SiIV, CIV
  - ➡ blue shifted v~10,000 km/s, Δv~1,000s km/s ⇒ AGN outflows
  - ➡ often $R \lesssim 1$ pc (variability) ⇒ accretion disk wind (Murray+95, Proga+)
- Seen in ~20% of QSOs (up to 40% in IR-selected samples)



What are FeLoBALs?

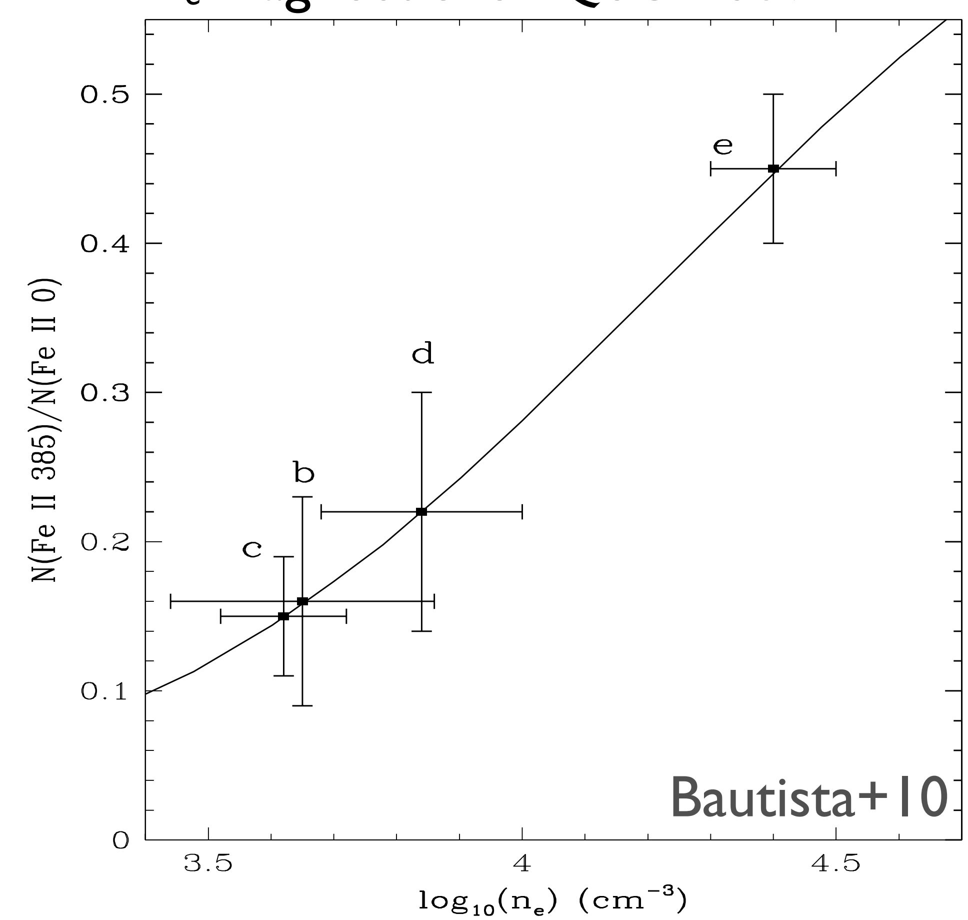
- Subset of QSO BALs
  - ➡ absorption by low-ionization species, including FeII
  - ➡ lower v~1,000-10,000 km/s, Δv~100s km/s
- Rare:
  - ➡ only ~1/500 of optical QSOs have FeLoBALs
- No real theory



FeLoBALs are particularly well-suited for photoionization modeling

- Fine structure lines of FeII and HeI have orthogonal dependences on n_e and T
- Observations (L_{bol}=$10^{46.7-47.7}$ erg s^{-1}) + photoionization modeling (Cloudy) have revealed (Moe+09, Dunn+10, Bautista+10):
  - ➡ n_e~10^4 cm^{-3}
  - ➡ T~10^4 K
  - ➡ N_H~10^{20-21} cm^{-2}
  - ➡ R~1-3 kpc (distance from SMBH)
  - ➡ ΔR~0.01 pc (absorber thickness)

n_e diagnostic for QSO 2359-1241



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  - ➡ $n_e \sim 10^4$ cm^{-3}
  - ➡ $T \sim 10^4$ K
  - ➡ $N_H \sim 10^{20\text{-}21}$ cm^{-2}
  - ➡ $R \sim 1\text{-}3$ kpc
  - ➡ $\Delta R \sim 0.01$ pc

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

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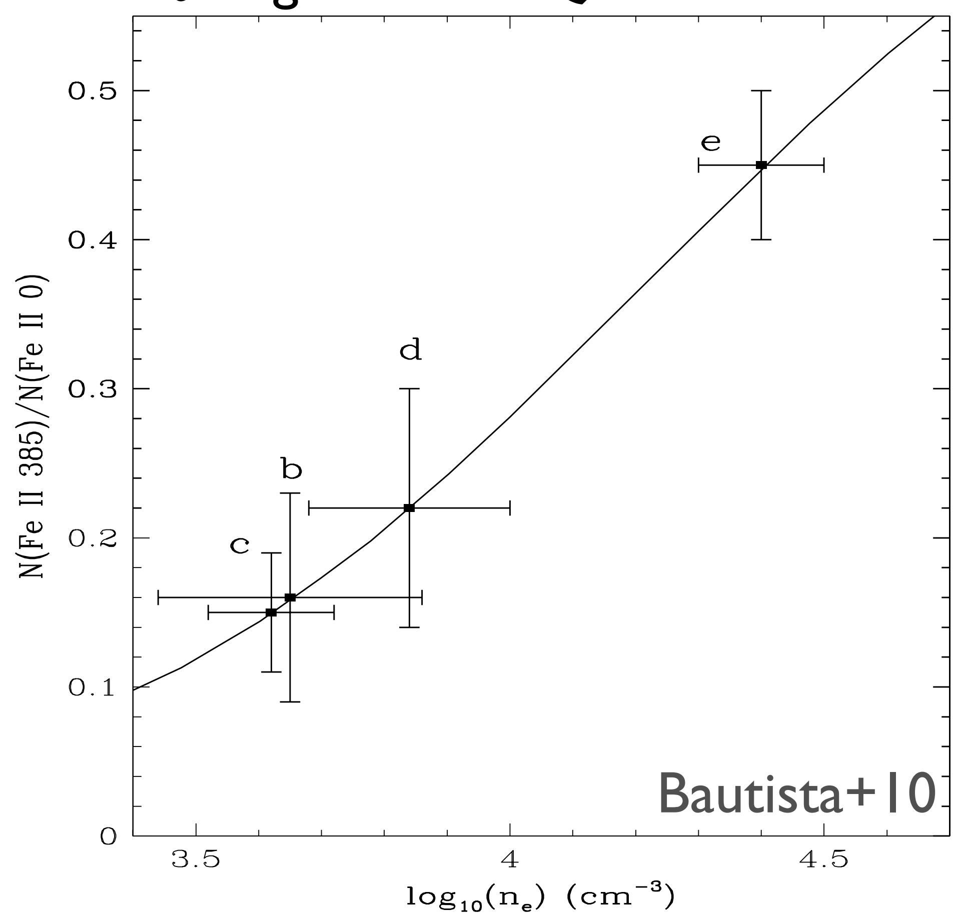


FeLoBAL must form *in situ*, at *R*~kpc from SMBHs

- If FeLoBALs 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

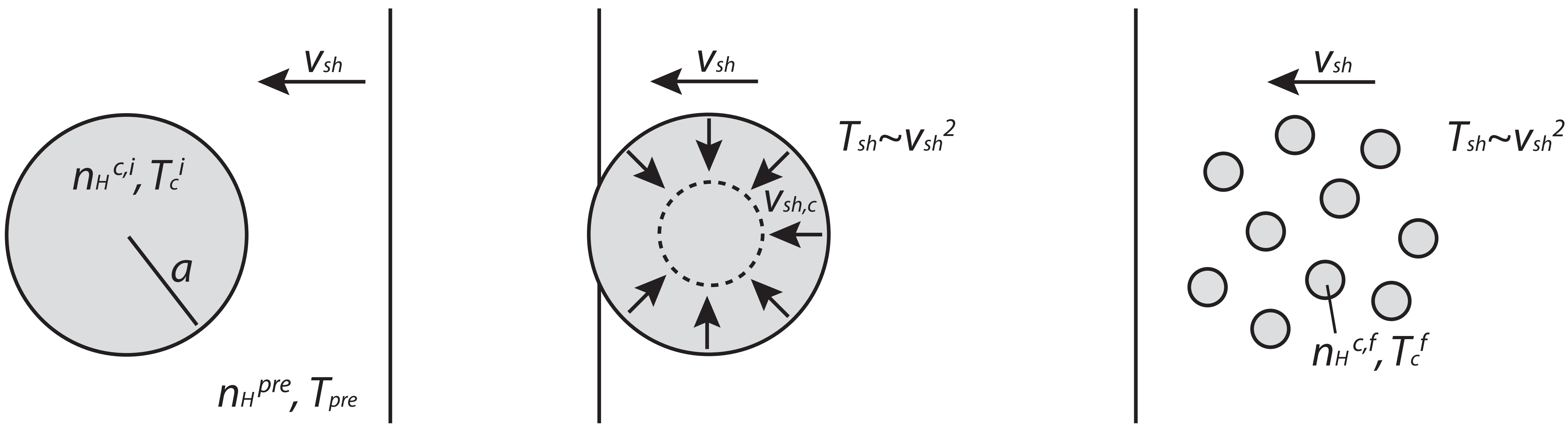
$$t_{\rm KH} \approx 630\kappa \ {\rm yr}$$

$$t_{\rm evap} \approx 6 \times 10^3 \ {\rm yr}$$

CAFG, Quataert, & Murray, submitted

Radiative shock model outline

- FeLoBALs can form *in situ* via interaction of a quasar blast wave with an interstellar gas clump



QSO blast wave encounters moderately dense ISM cloud.

Shock wave propagates in cloud on crushing time t_{cc}, cloud is destroyed by K-H in $t_{KH} \sim 20 t_{cc}$, and is accelerated to $\sim v_{sh}$ in t_{drag}.

At $t > t_{KH}$, t_{drag}, original cloud is shredded into cloudlets traveling at $\sim v_{sh}$ and compressed by hot post-shock gas.

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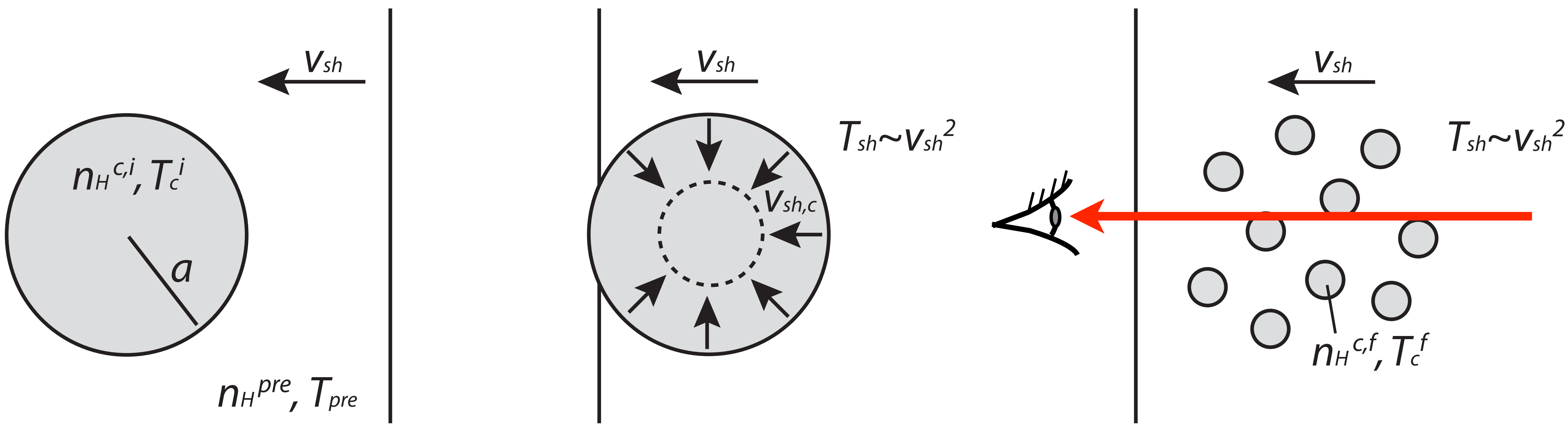

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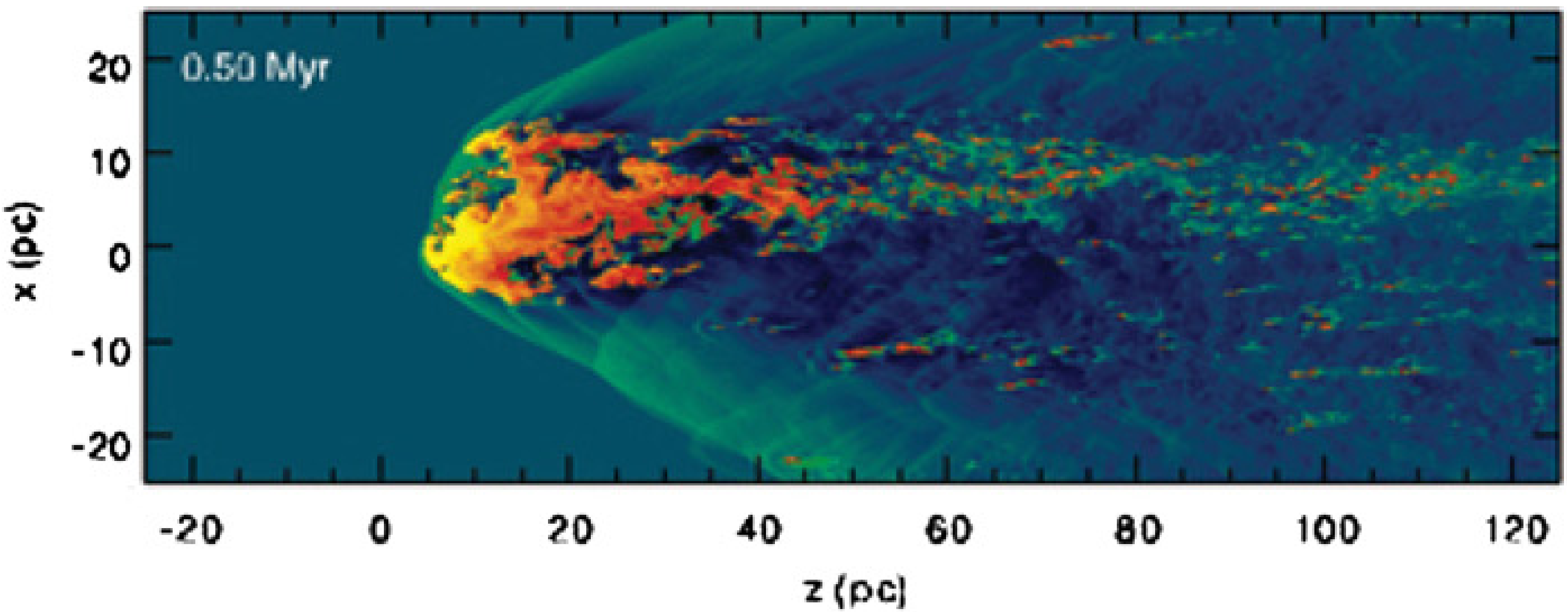
Cloud crushing by shocks, Kelvin-Helmholtz instability

- Well-studied problem for SNRs (e.g., Klein+94, Mellema+02, Cooper+09)



$$v_{\rm sh,c} \approx v_{\rm sh}\sqrt{\frac{n_{\rm H}^{\rm ext}}{n_{\rm H}^{\rm c}}} \qquad t_{\rm cc} \approx \frac{\Delta R}{2 v_{\rm sh,c}} \qquad t_{\rm KH} \sim \kappa t_{\rm cc}$$

CAFG, Quataert, & Murray, submitted

Requirements for producing FeLoBALs in radiative shocks explain observed properties

- Acceleration, cold gas:

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

- Post-shock compression:

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

$$\Rightarrow \Delta R \sim 0.01\ {\rm pc}$$

CAFG, Quataert, & Murray, submitted

Other radiative shock model successes

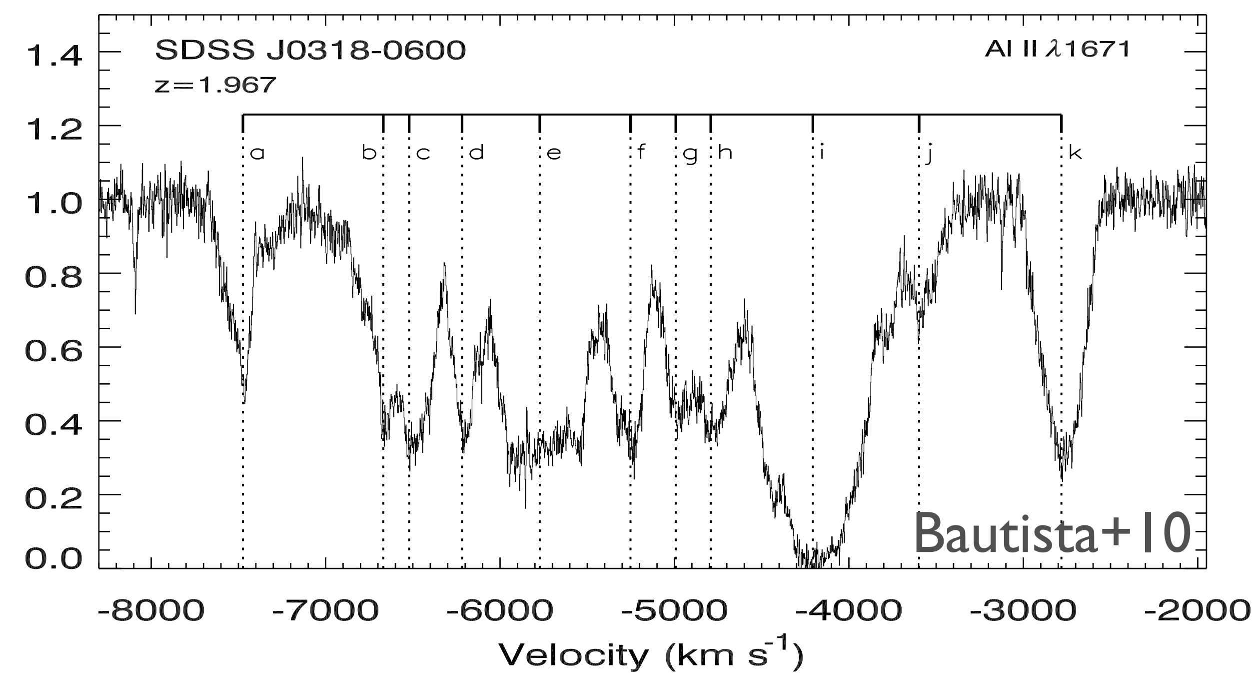
- Fell selects $U_{\rm H} \propto L_{\rm bol}/R^2 n_{\rm H}^{\rm BAL} \sim 10^{-3} - 10^{-2}$

  ⇒ R~kpc in bright L_{bol}=$10^{46.7\text{-}47.7}$ erg s^{-1} QSOs analyzed

- Shredding of ISM clump

  ⇒ multiple components at same *R*, but different *v*

  ⇒ supra-thermal line widths



- Dust in clump ⇒ FeLoBAL QSOs are redder than average

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Implications for QSO feedback

- Not a cold, thin shell outflow!

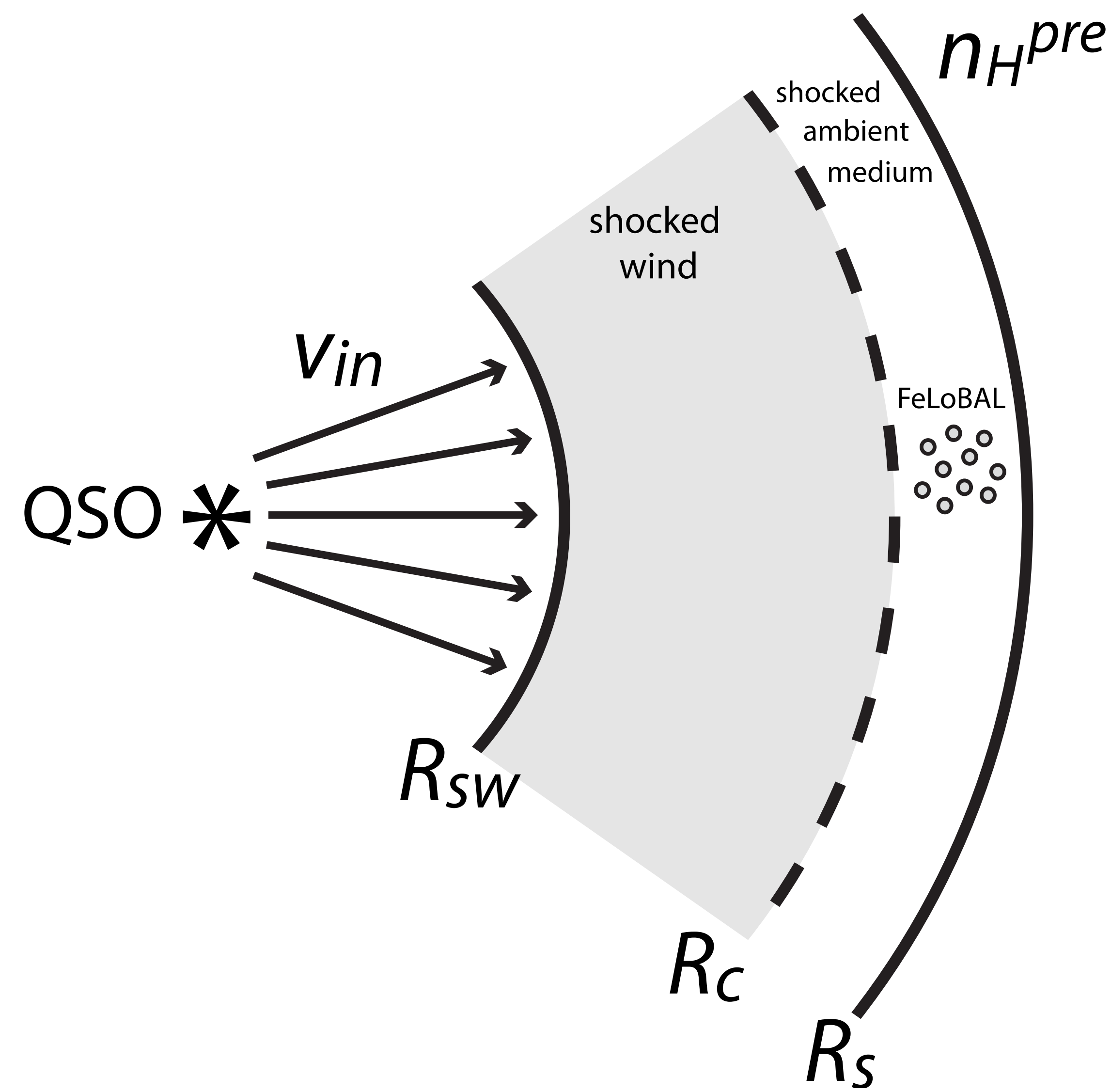
- Most of kinetic power in hot flow:

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

- Can be estimated from FeLoBALs assuming v_{hot}~v and pressure eq.

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

(vs. ~0.05-1% for shell approx; Moe+09, Dunn+10, Bautista+10)



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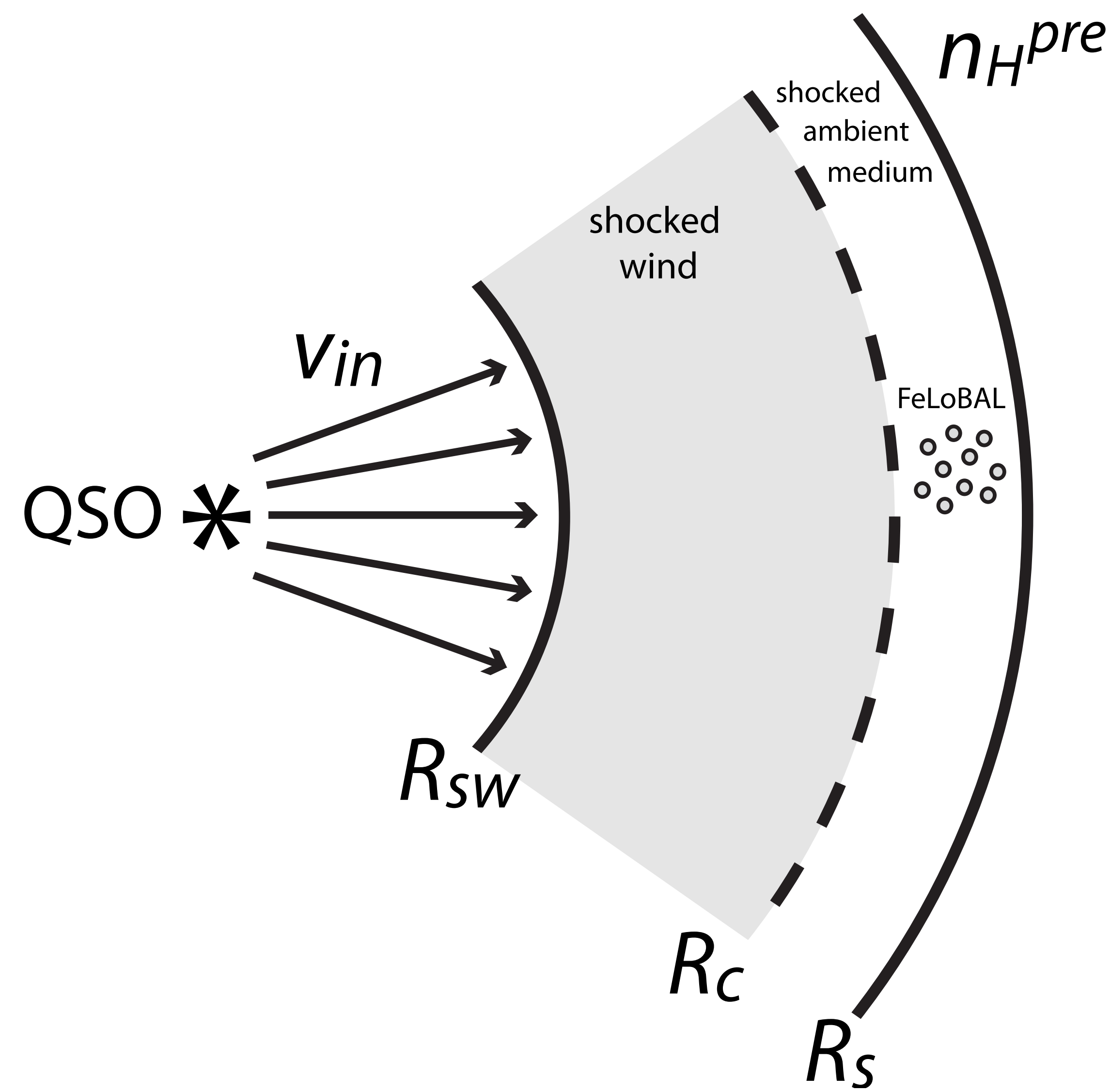
$$\Rightarrow \dot{E}_{\rm k} \approx 2 - 5\%\ L_{\rm bol}$$
$$\dot{P} \approx 2 - 10\ L_{\rm bol}/c$$
$$\dot{M} \approx 1,000 - 2,000\ {\rm M}_\odot\ {\rm yr}^{-1}$$



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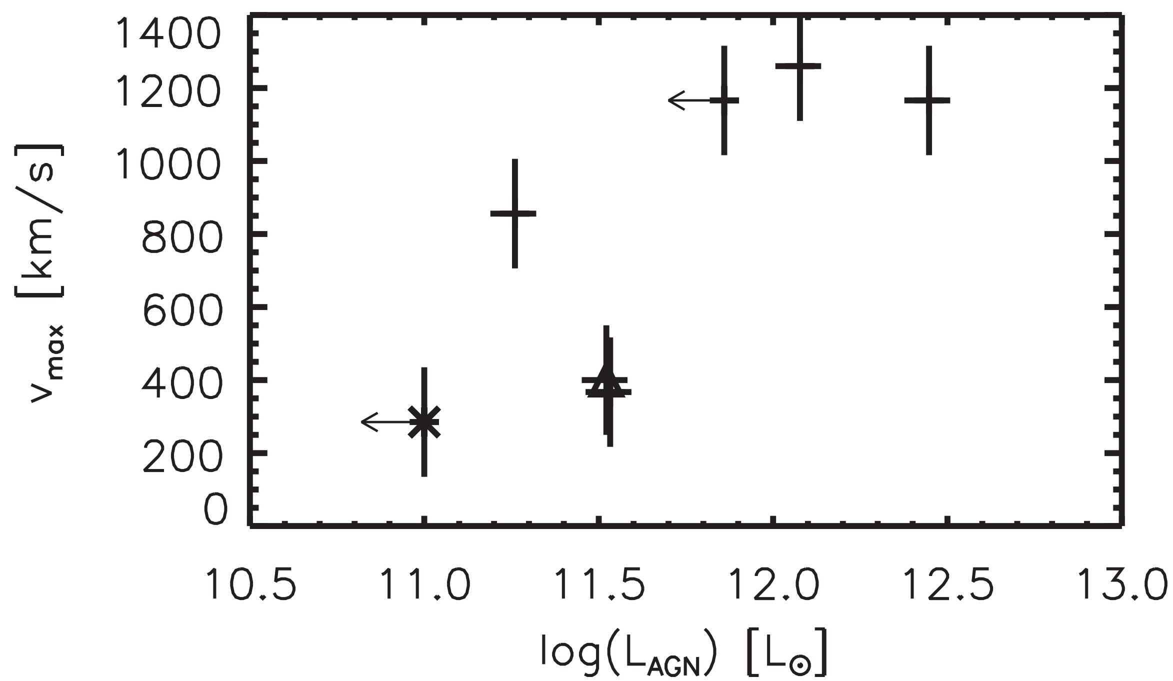
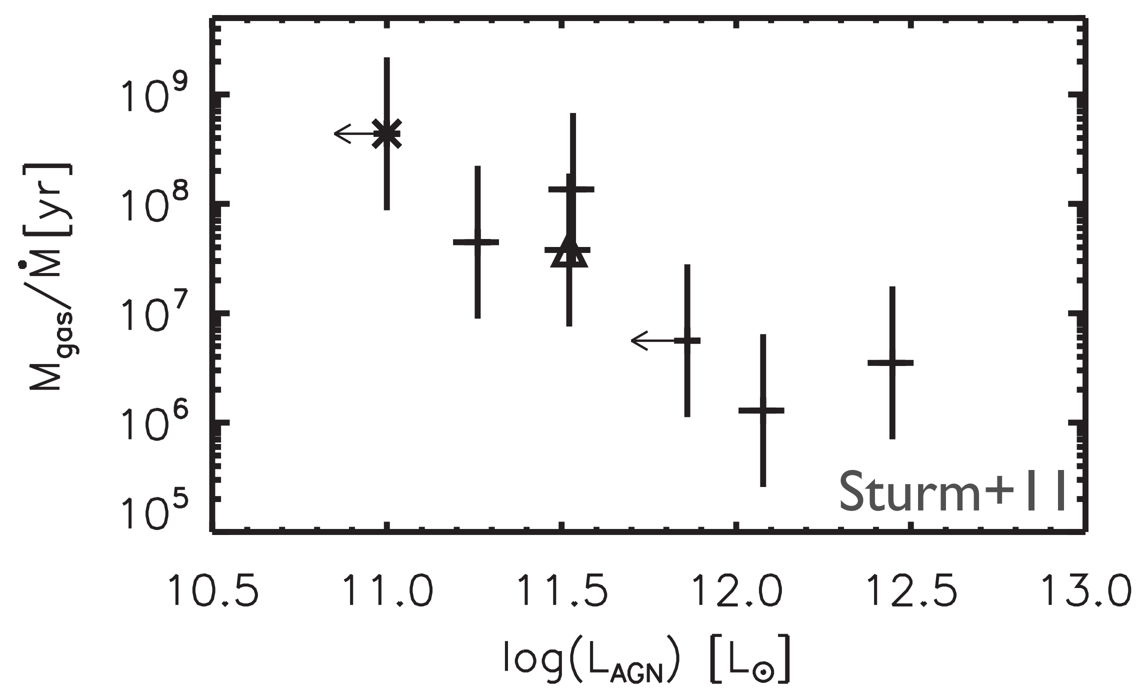
FeLoBAL energetics agree well with molecular outflows in ULIRGs

- Recent observations of outflows in local ULIRGs also indicate $\dot{E}_{\rm K} \sim \text{few}\ \%\ L_{\rm bol}(\text{AGN})$

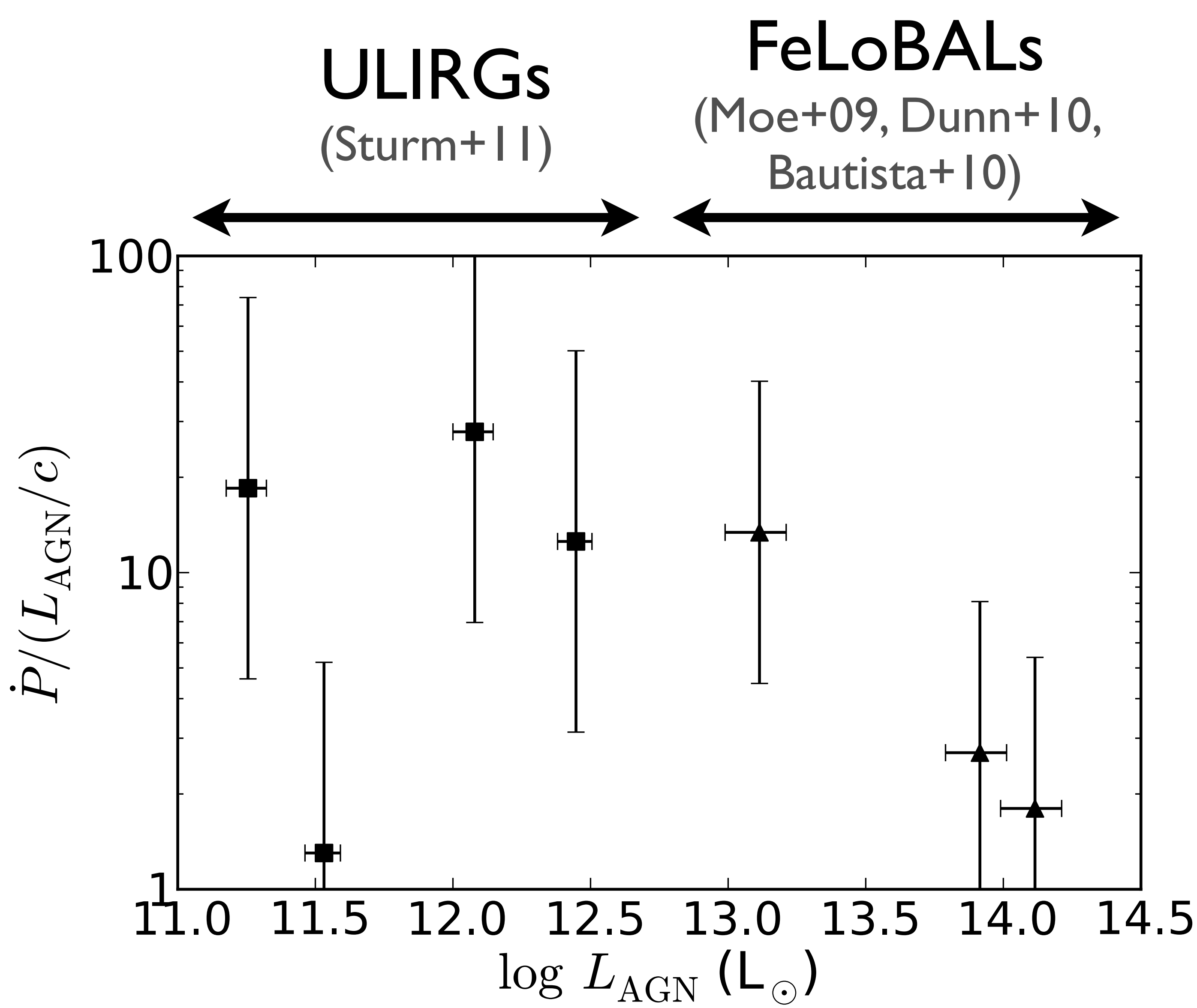
  (Feruglio+10, Fischer+10, Sturm+11, Rupke & Veilleux 11)



- FeLoBALs may be analogous galaxy-scale AGN outflows in later ('blow out') evolutionary stage



Momentum Flux of AGN Outflows



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

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

- Observations indicate

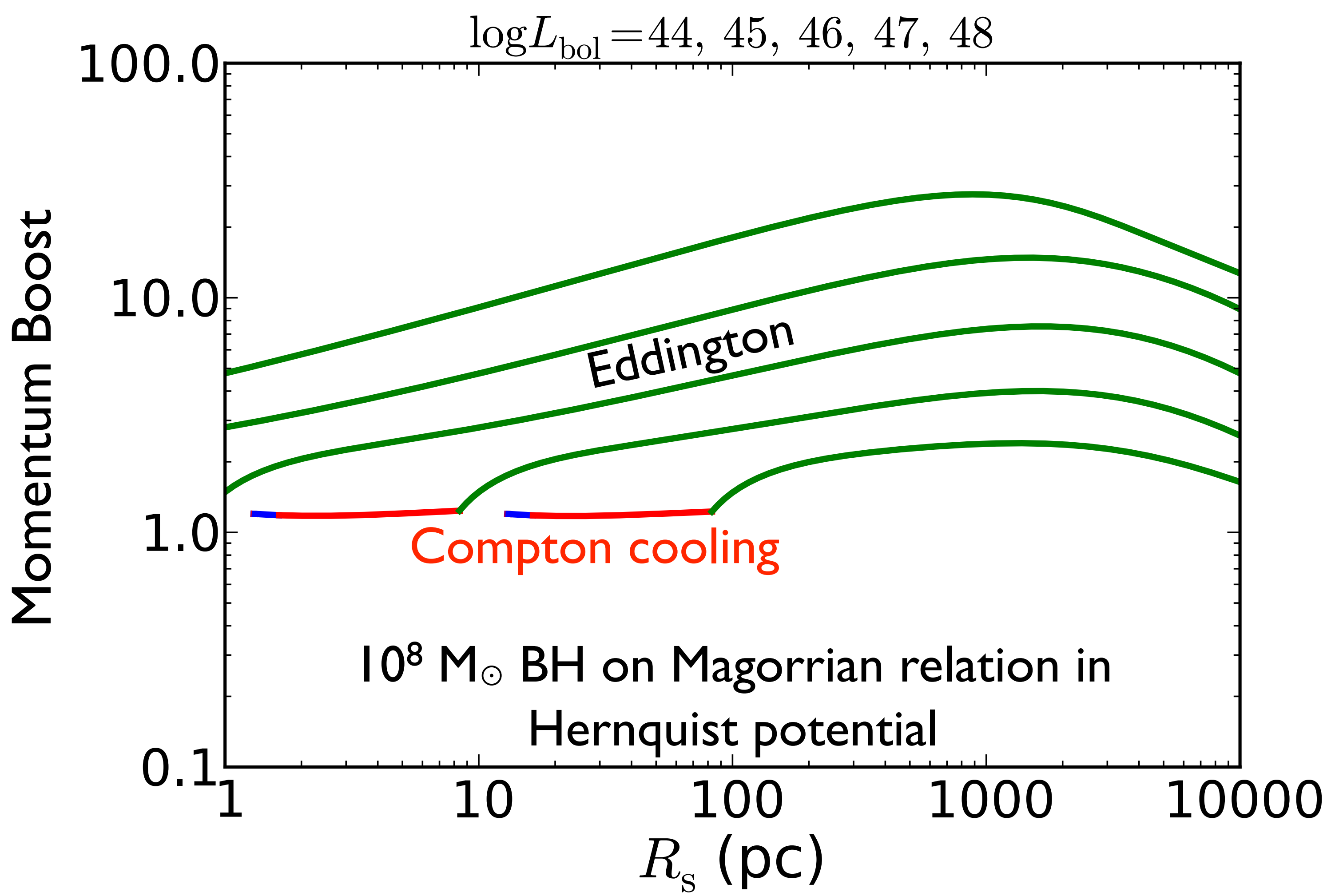
$$\dot{P} \sim 10 L_{\rm AGN}/c$$

- Either:
  1) photons are trapped (see Roth talk)
  2) *P* boost from *E* conserv.

CAFG+, in prep.

Energy vs. Momentum-Conserving Expansion

- If post-shock gas does not cool (*E* conserved), work boosts $\dot{P}$
  - ➡ e.g., Sedov-Taylor phase of SNRs
- In AGN, must consider Compton cooling (e.g., King, Ostriker)
- In spherically symmetric models, can still boost $\dot{P}$ by ~10x



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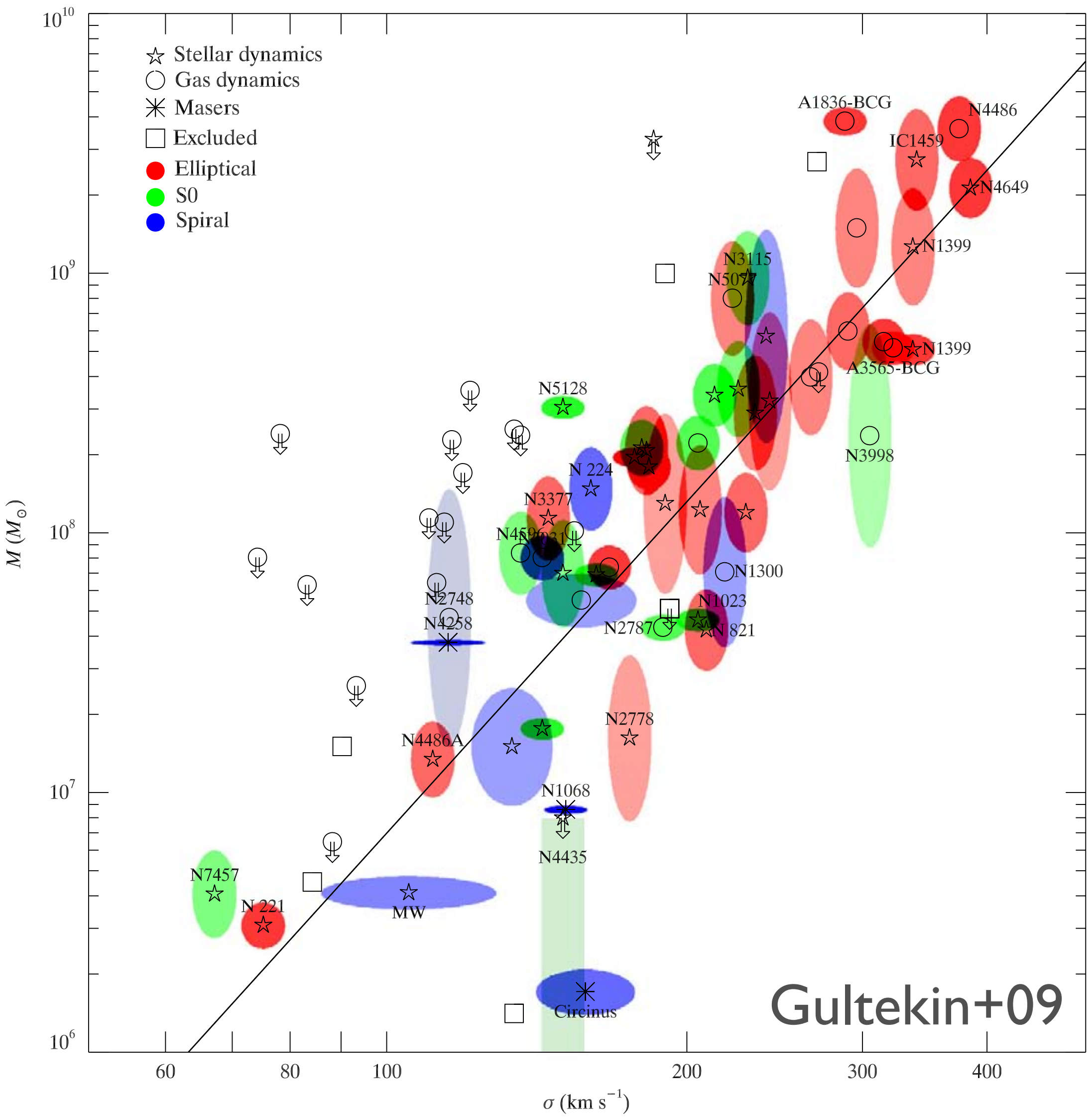
Summary

- FeLoBALs probe galaxy-scale QSO outflows
- Radiative shock model explains the observed FeLoBALs
- Model + observations $\Rightarrow \dot{E}_{\mathrm{k}} \approx 2 - 5\% \; L_{\mathrm{bol}}$
- Provides support for (sub-resolution) *M*-σ models
- Energetics consistent with ULIRG molecular outflows
- Evidence for energy-conserving phase?

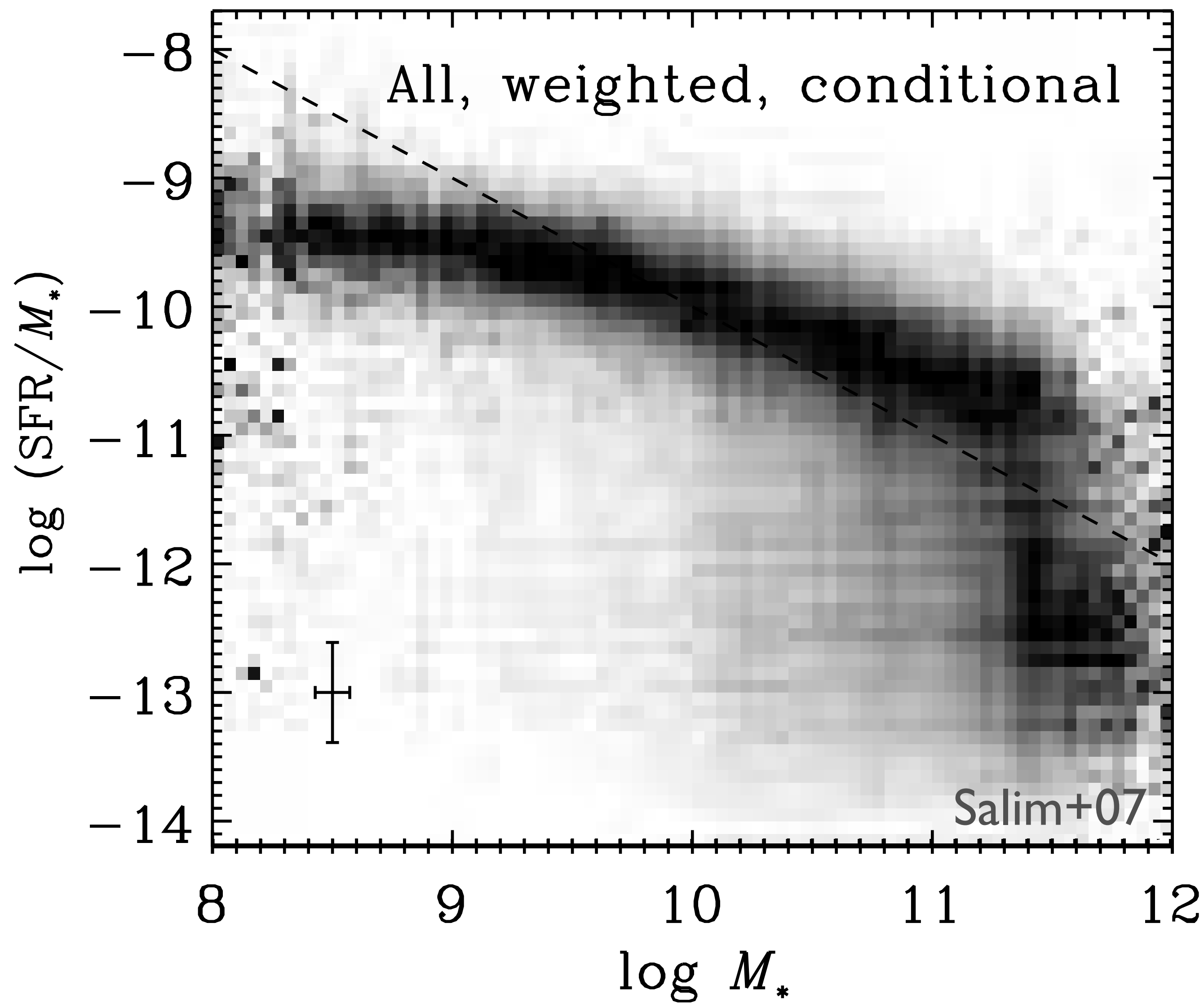
Extra Slides

The possible roles of AGN feedback

Establish correlations between SMBH and galaxy properties



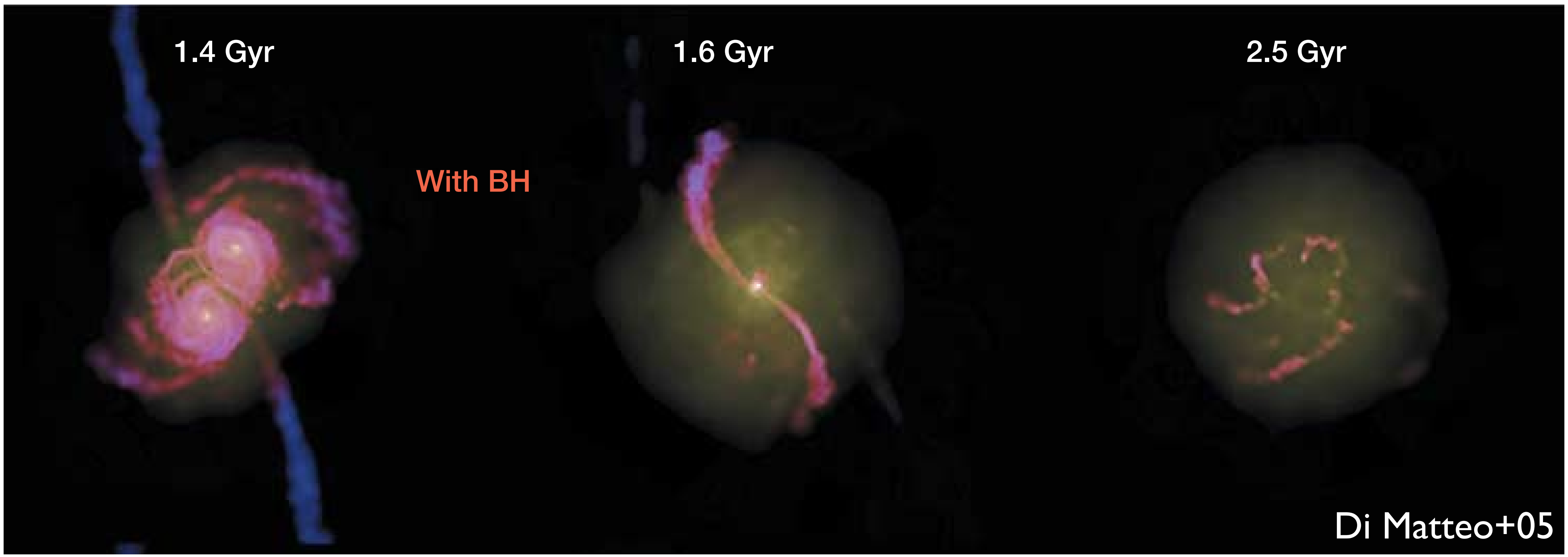
Truncate star formation



Also, prevent gas cooling in massive halos ("radio mode")

Prescription-based model successes

- If f~5% of L_{bol} couples to the ISM, then simulations can reproduce the M-σ relation and truncate star formation



- But, poor understanding of coupling mechanisms & scarce observational constraints

Silk, Rees, Springel, Di Matteo, Hernquist, Hopkins, Wyithe, Loeb, ...

In principle, can derive mechanical properties of the QSO wind

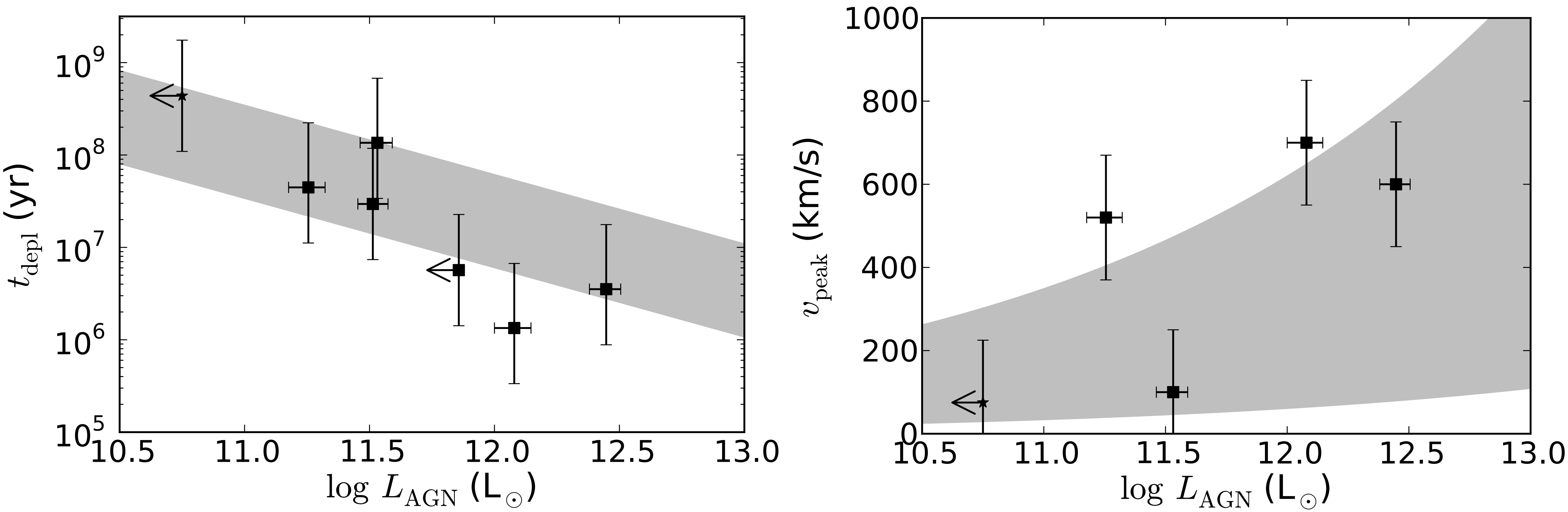
- Common assumption of partial, cold thin shell (e.g., Arav 10)

$$\dot{M}_{\rm shell} = 8\pi\Omega R N_{\rm H}^{\rm BAL}\mu m_{\rm p} v \qquad \dot{E}_{\rm k} = \frac{1}{2}\dot{M}_{\rm shell} v^2$$

$\Rightarrow \dot{E}_{\rm K} \sim 0.05 - 1\%\ L_{\rm bol}$ for Ω=0.2 (Moe+09, Dunn+10, Bautista+10)

- But:
  - ➡ can we understand the implied FeLoBAL properties (esp., $\Delta R/R \sim 10^{-5}$)?
  - ➡ what is the proper way of relating the observations to the underlying quasar outflows?

Origin of correlations with L_{AGN} in ULIRGs



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