A Physical Model of FeLoBALs:

Implications for Quasar Feedback

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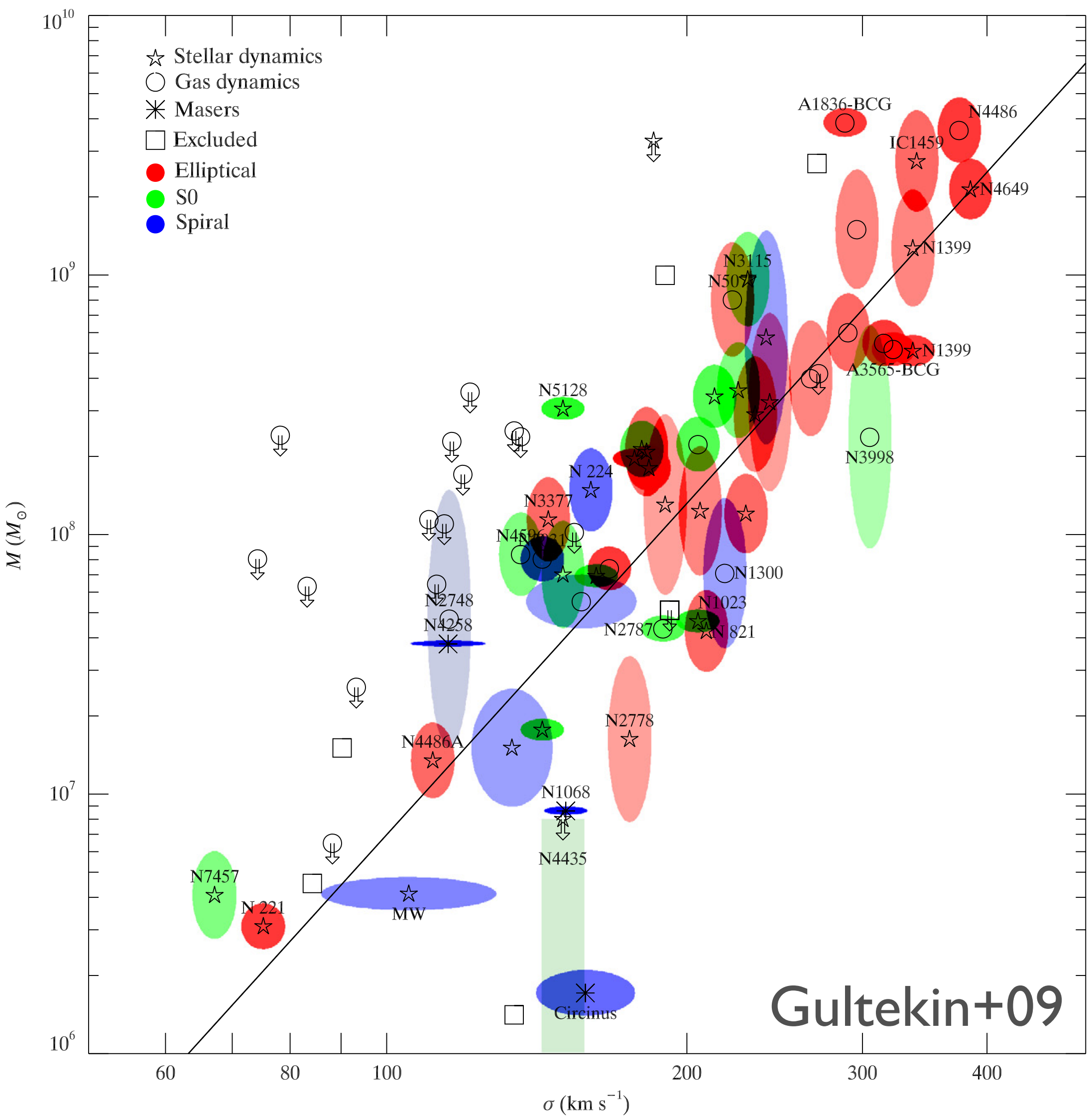
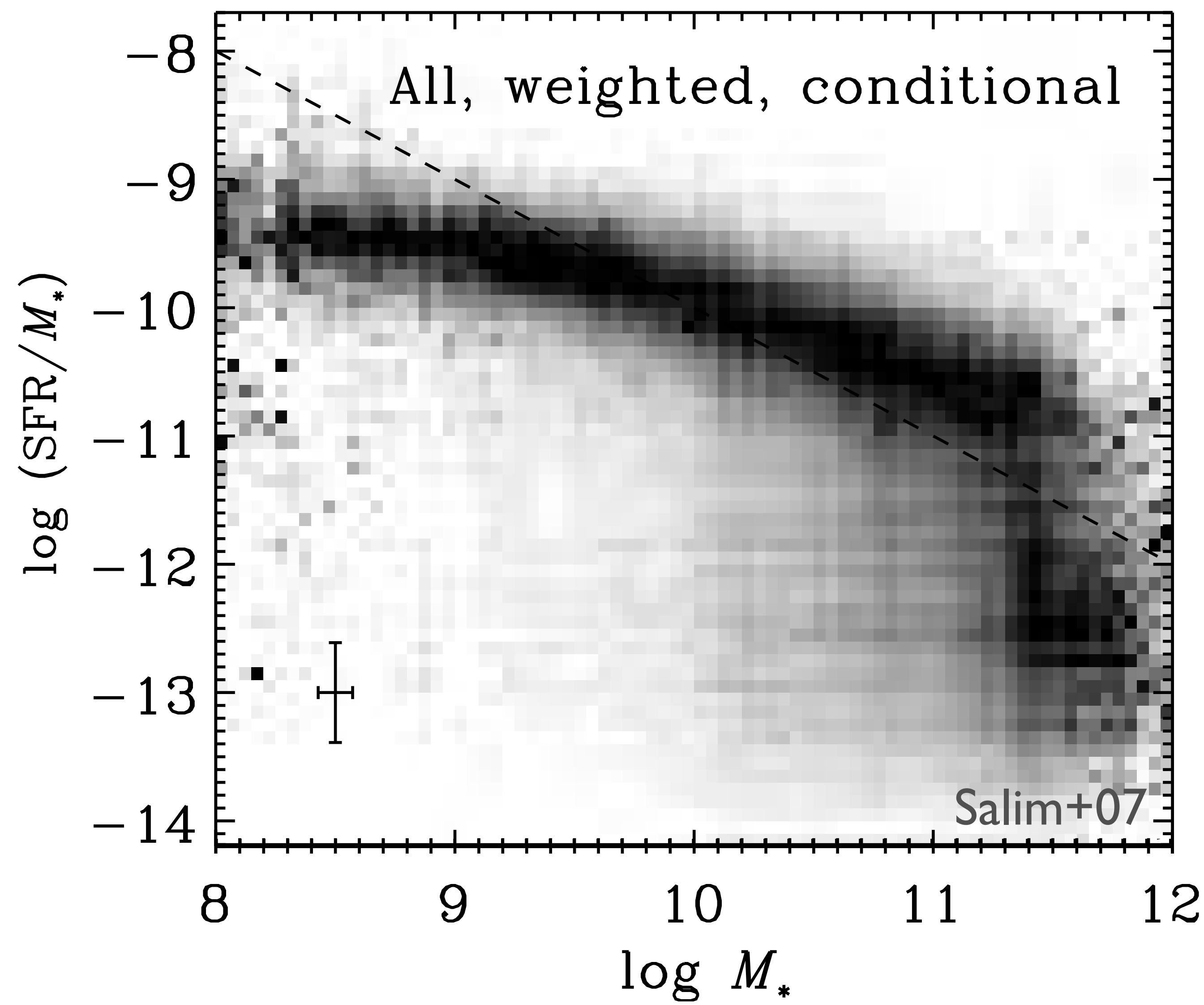
The possible roles of AGN feedback

Establish correlations between SMBH and galaxy properties



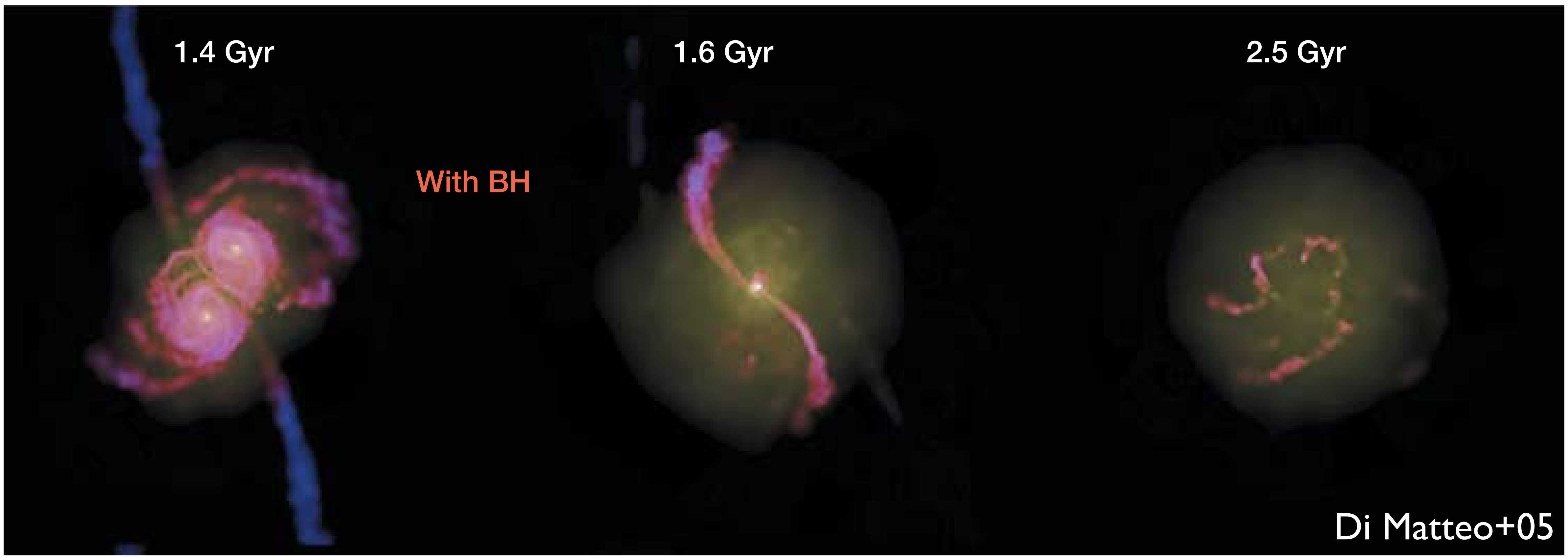
Truncate star formation



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

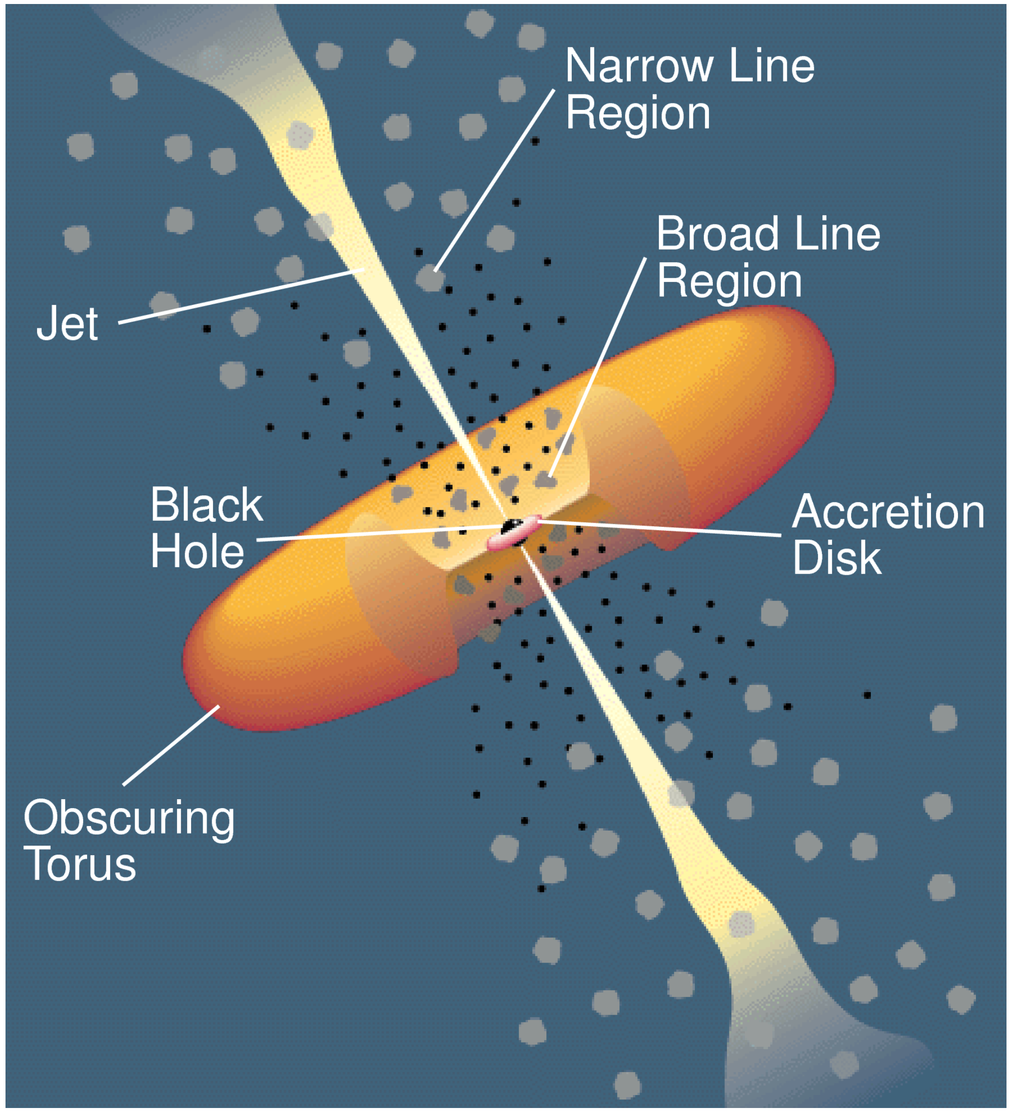


- But, poor understanding of coupling mechanisms & scarce observational constraints

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

Outline

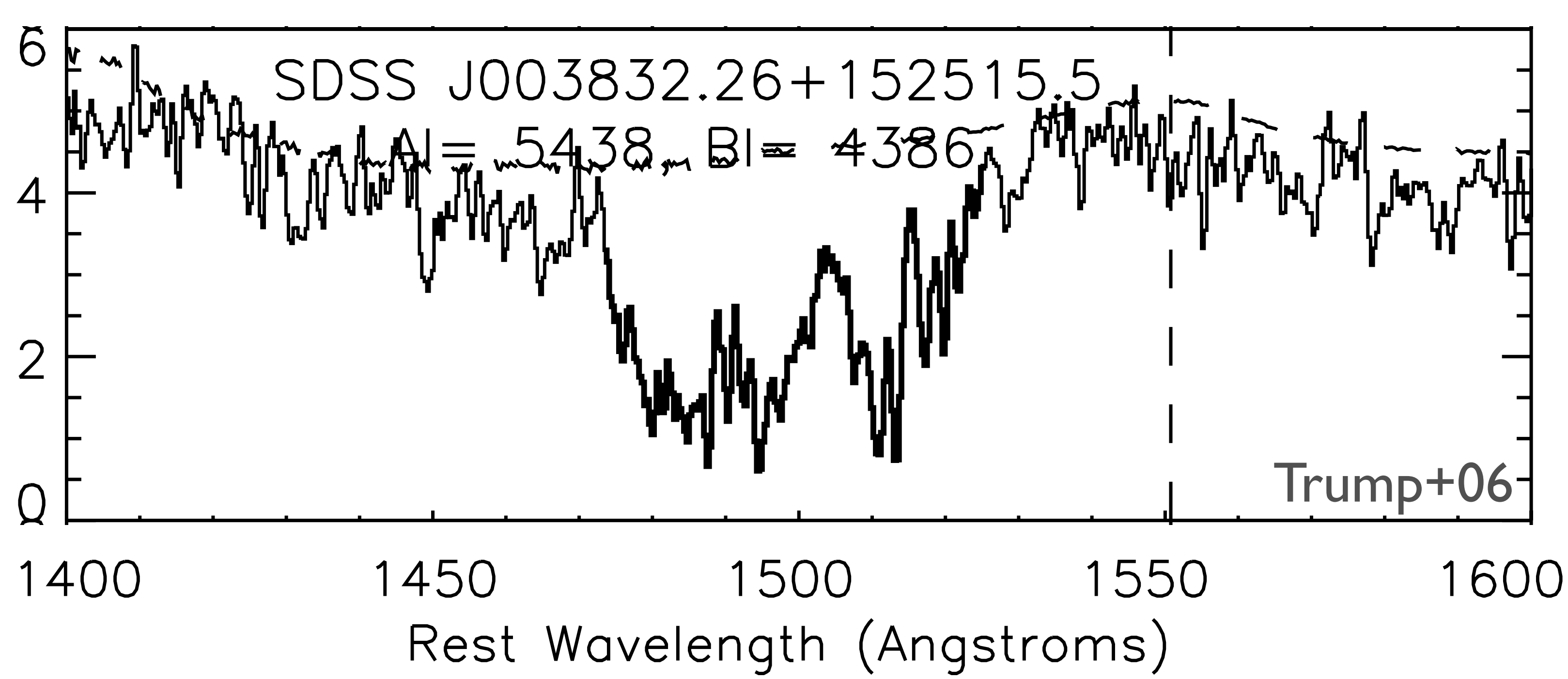
- What are FeLoBALs?
- A physical model of FeLoBALs:
  - ➡ formation *in situ* at R~kpc
    (physically distinct from most, high-ionization BALs)
  - ➡ radiative shocks in cloud crushing
- Implications for QSO feedback



Urry & Padovani 95

What are BALs?

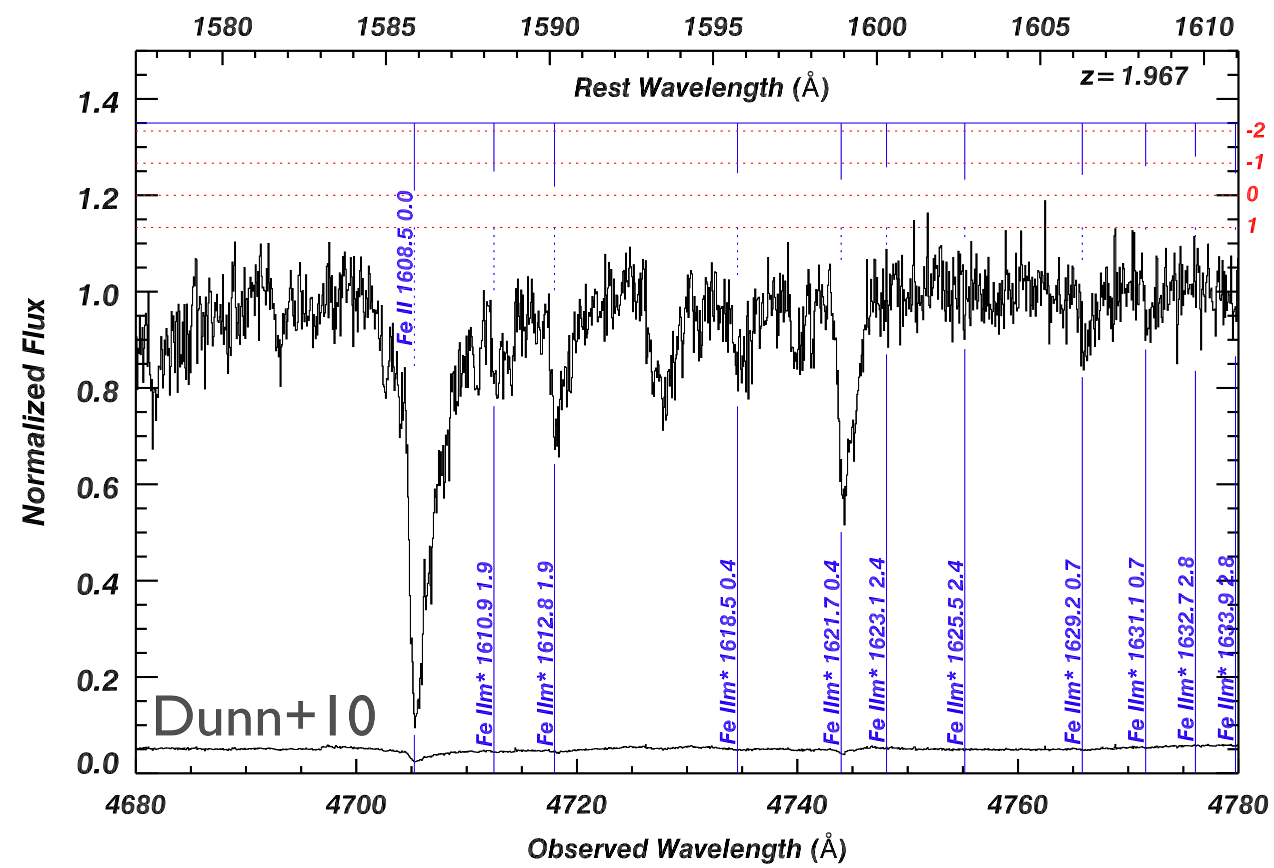
- Broad absorption lines in QSOs:
  - ➡ usually high-ionization SiIV, CIV
  - ➡ blue shifted v~10,000 km/s, Δv~1,000s km/s ⇒ AGN outflows
  - ➡ $R \lesssim 1$ pc (variability) ⇒ accretion disk winds (Murray+95)
- Seen in ~20% of QSOs (up to 40% in IR-selected samples)



What are FeLoBALs?

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

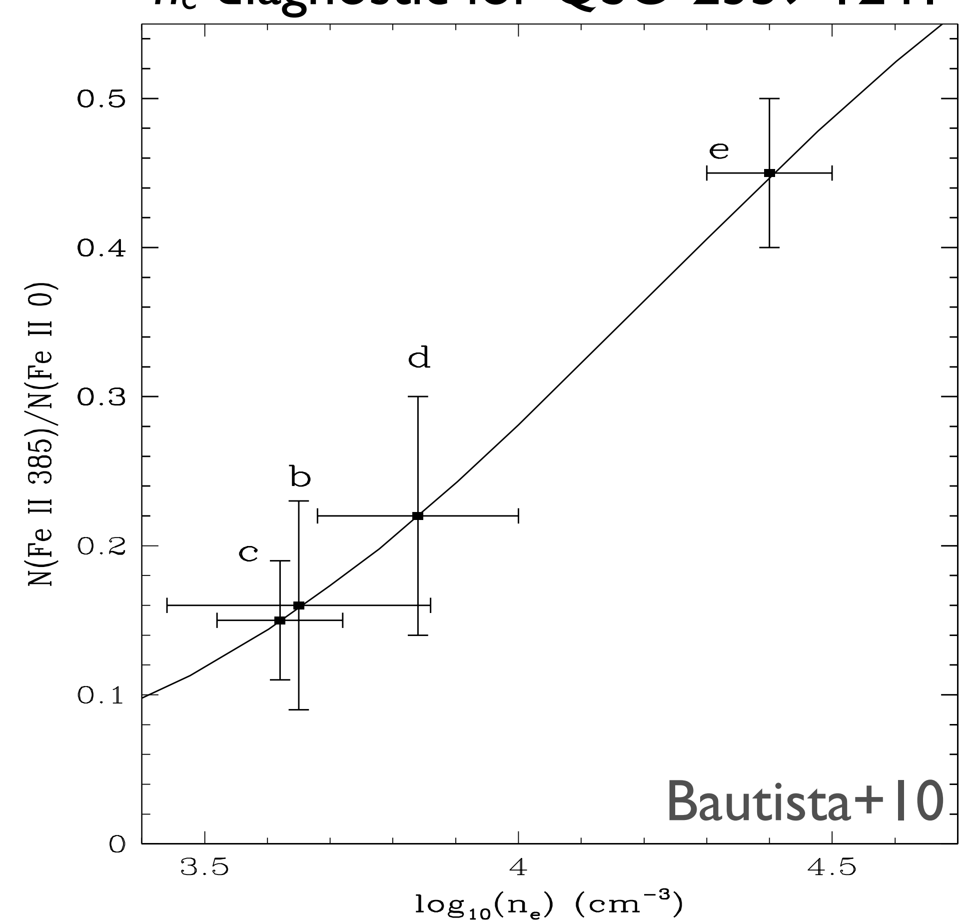
SDSS J0318-0600



FeLoBALs are particularly well-suited for photoionization modeling

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

n_e diagnostic for QSO 2359-1241



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  - ➡ R~1-3 kpc
  - ➡ ΔR~0.01 pc

⇒ $\Delta R/R$~10^{-5} !!!

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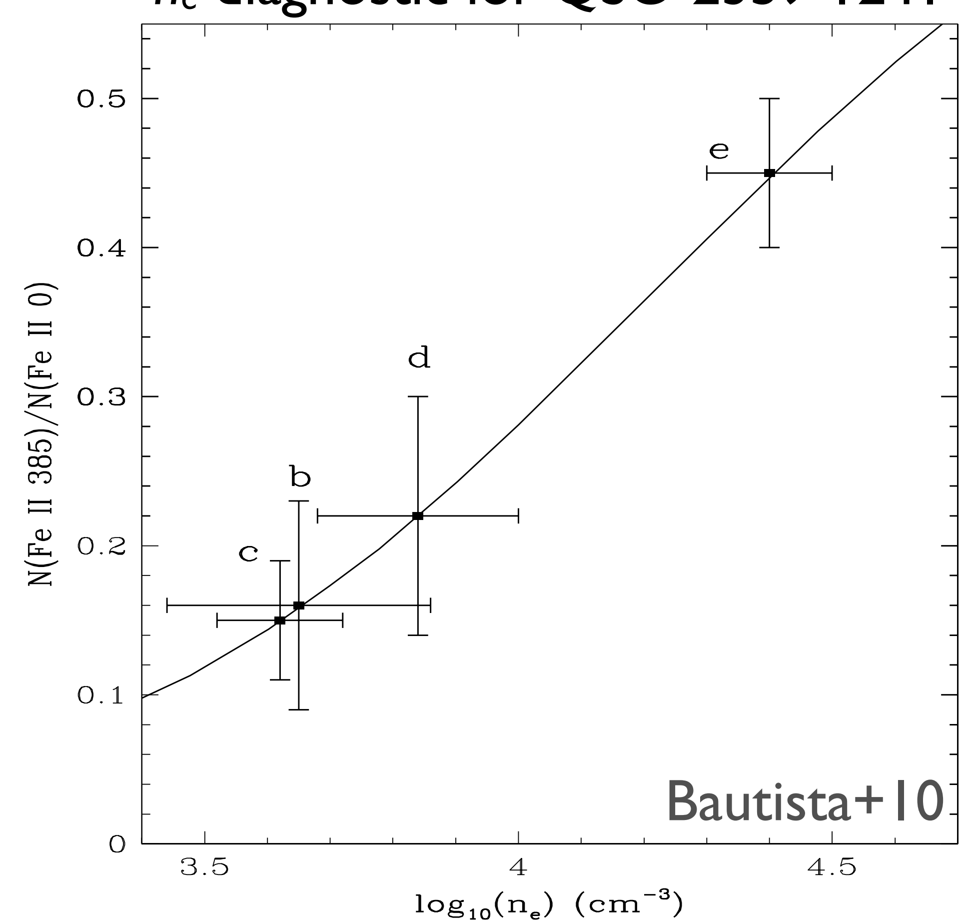


In principle, can derive mechanical properties of the QSO wind

- 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?

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

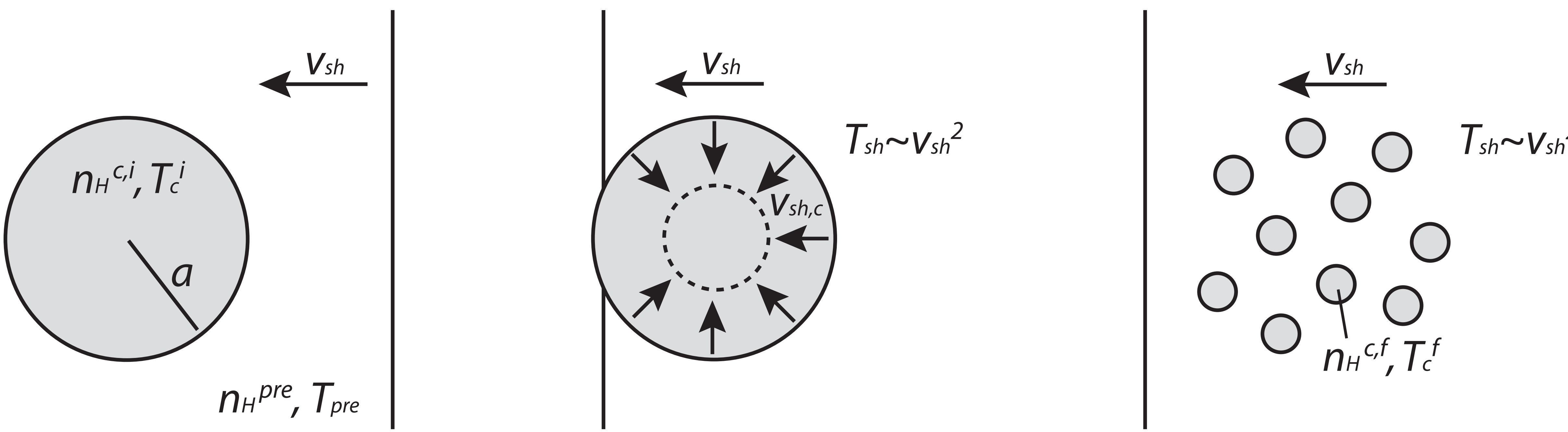
$$t_{\rm KH} \approx 630 \kappa \ {\rm yr}$$

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

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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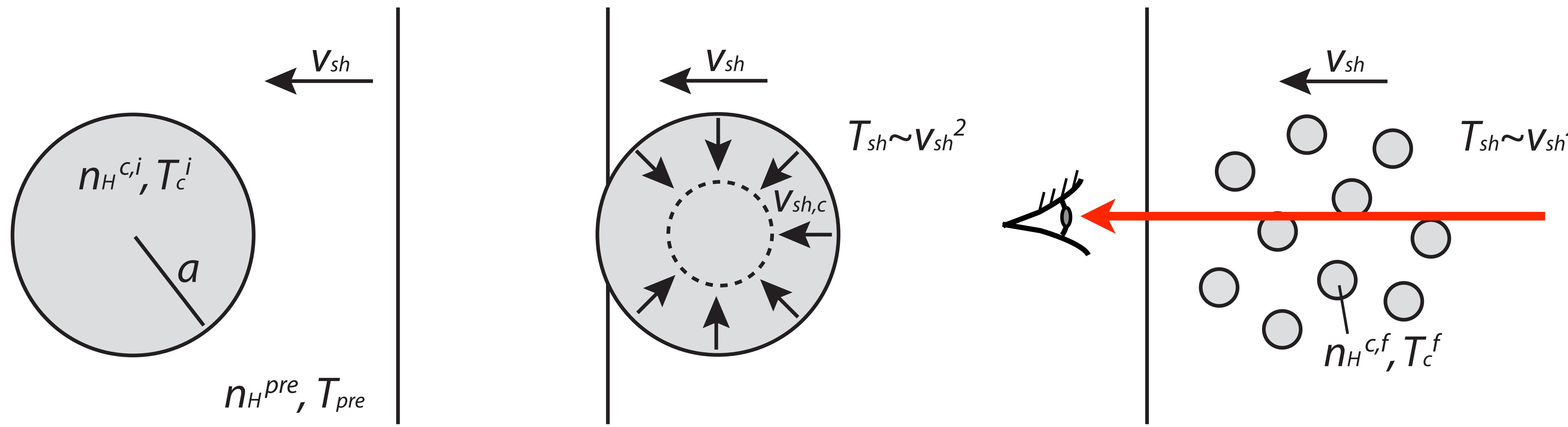

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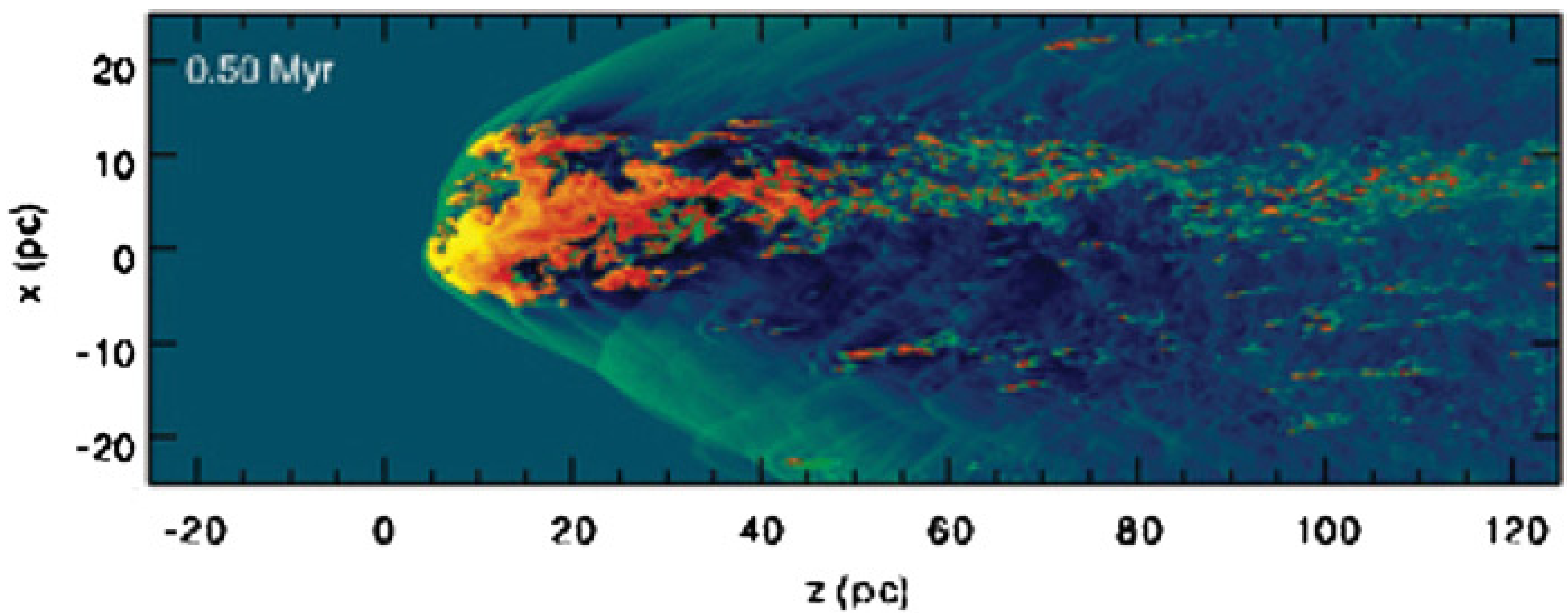
Cloud crushing by shocks, Kelvin-Helmholtz instability

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



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

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Requirements for producing FeLoBALs in radiative shocks explain observed

- Acceleration, cold gas:

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

- 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 FeLoBAL model successes

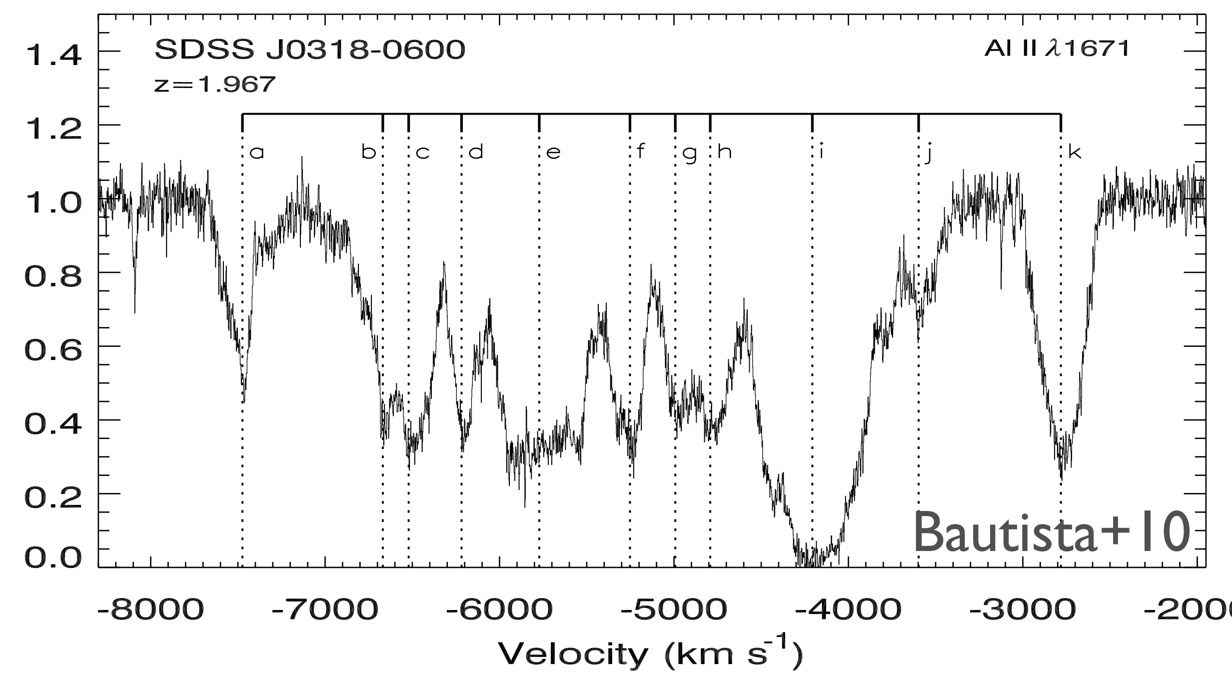
- FeII selects $U_{\rm H} \propto L_{\rm bol}/R^2 n_{\rm H}^{\rm BAL} \sim 10^{-3} - 10^{-2}$

  ⇒ 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!

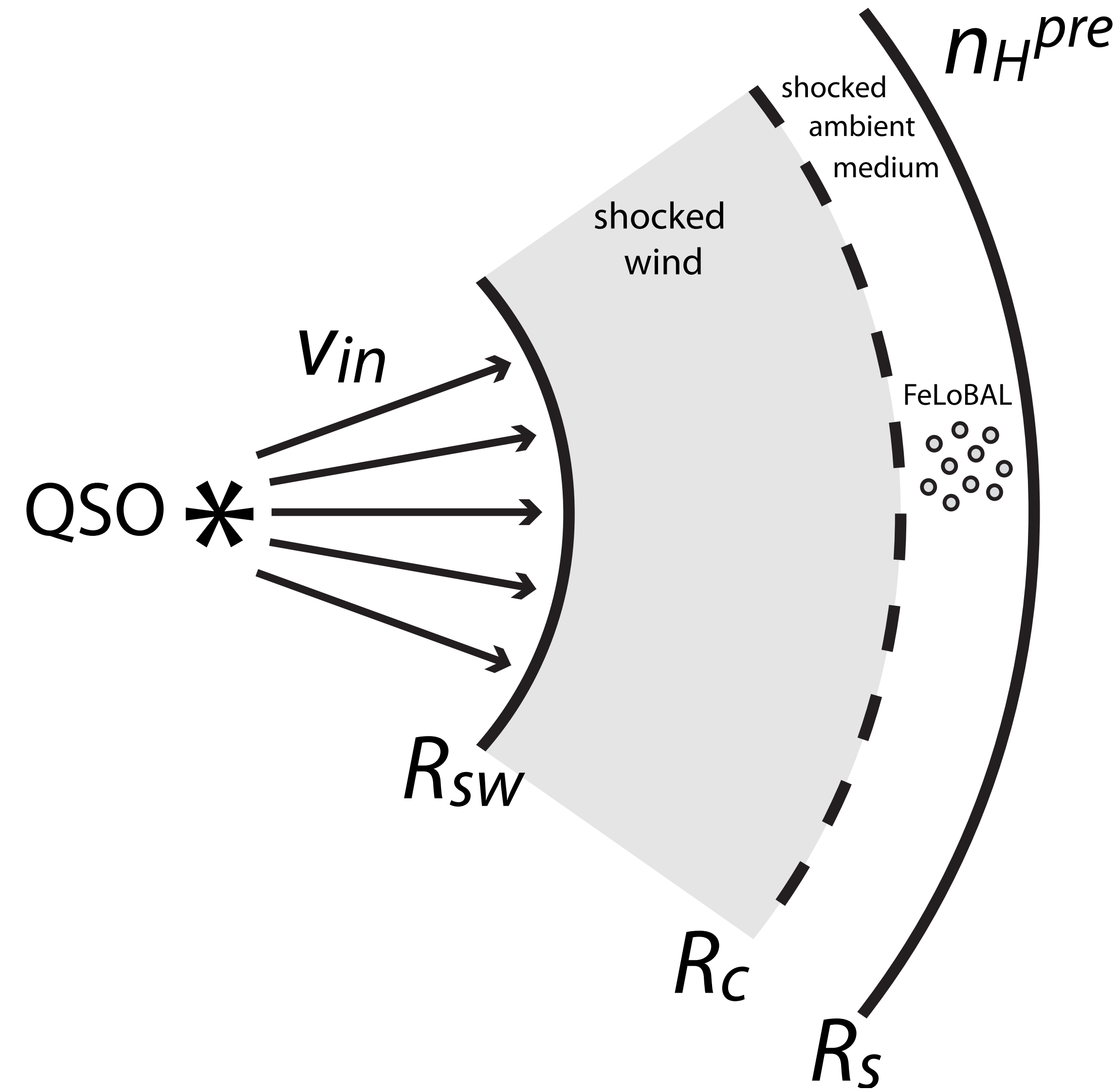
- Most of kinetic power in hot flow:

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

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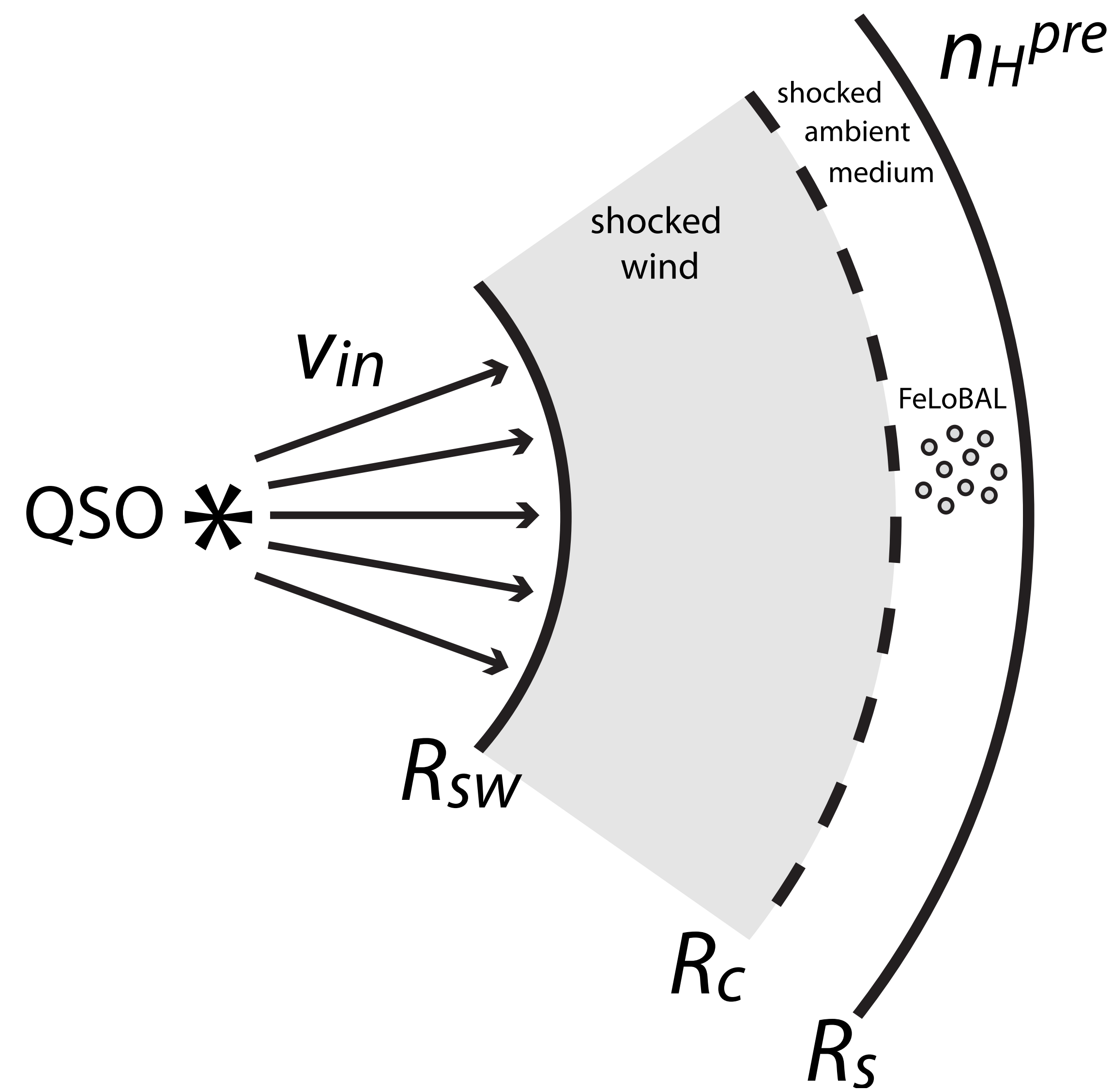
$$\Rightarrow \dot{E}_{\rm k} \approx 2-5\%\ L_{\rm bol}$$
$$\dot{P} \approx 2-10\ L_{\rm bol}/c$$
$$\dot{M} \approx 1,000-2,000\ {\rm M}_\odot\ {\rm yr}^{-1}$$



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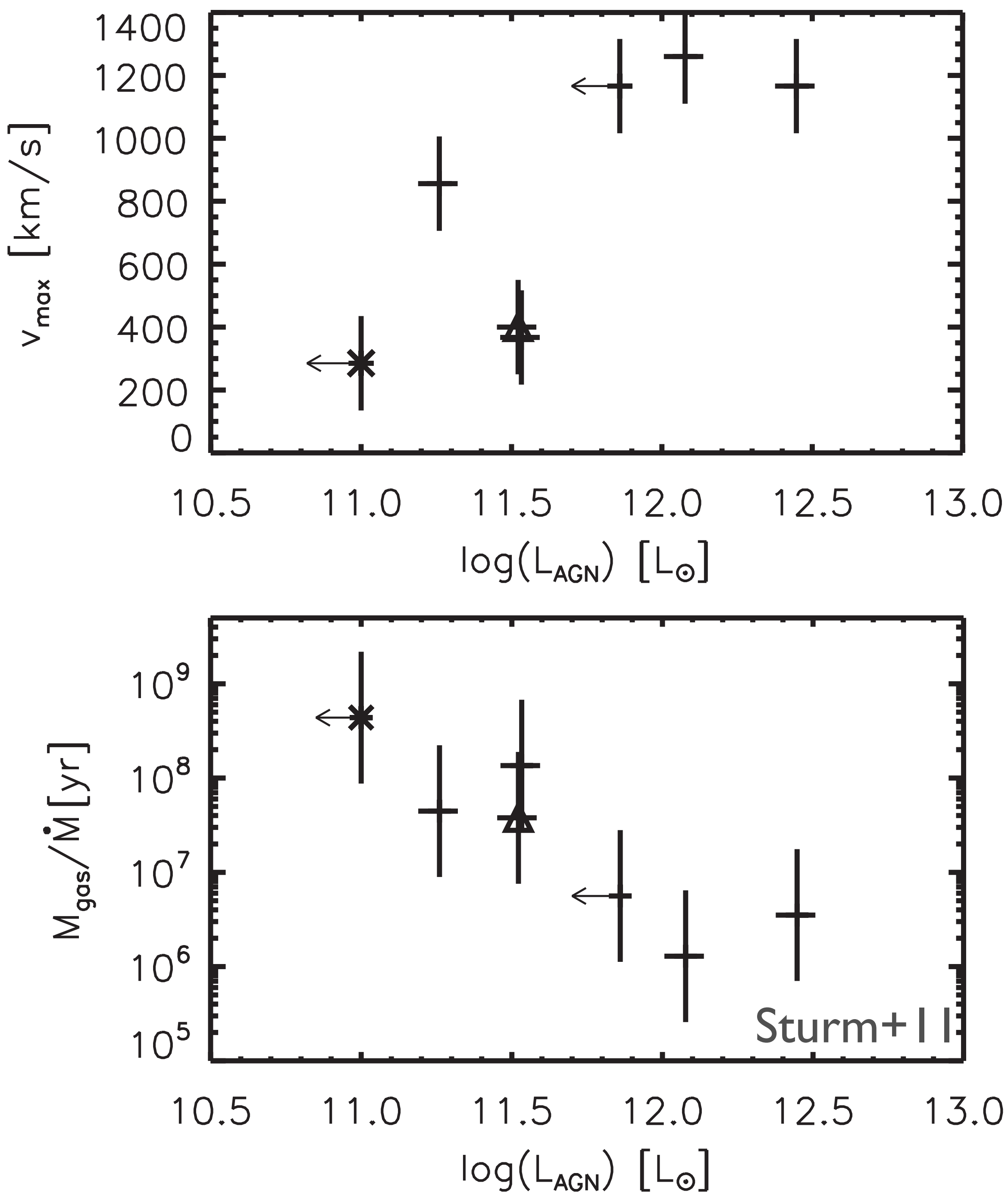
FeLoBAL outflow properties agree well with ULIRGs

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

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

- But, debate over whether powered by AGN or SF (Chung+10)

- FeLoBALs demonstrate that AGN can couple to ISM & drive the observed galaxy-scale outflows



Summary

- FeLoBALs probe QSO outflows
- Radiative shock, cloud crushing model explains all the observed FeLoBAL properties (not regular BALs / disk winds!)
- Model + observations $\Rightarrow \dot{E}_{\rm k} \approx 2 - 5\% \; L_{\rm bol}$
- Provides support for (sub-resolution) *M*-σ models
- Energetics consistent with ULIRG molecular winds