Physics of Galactic Winds Driven by AGN

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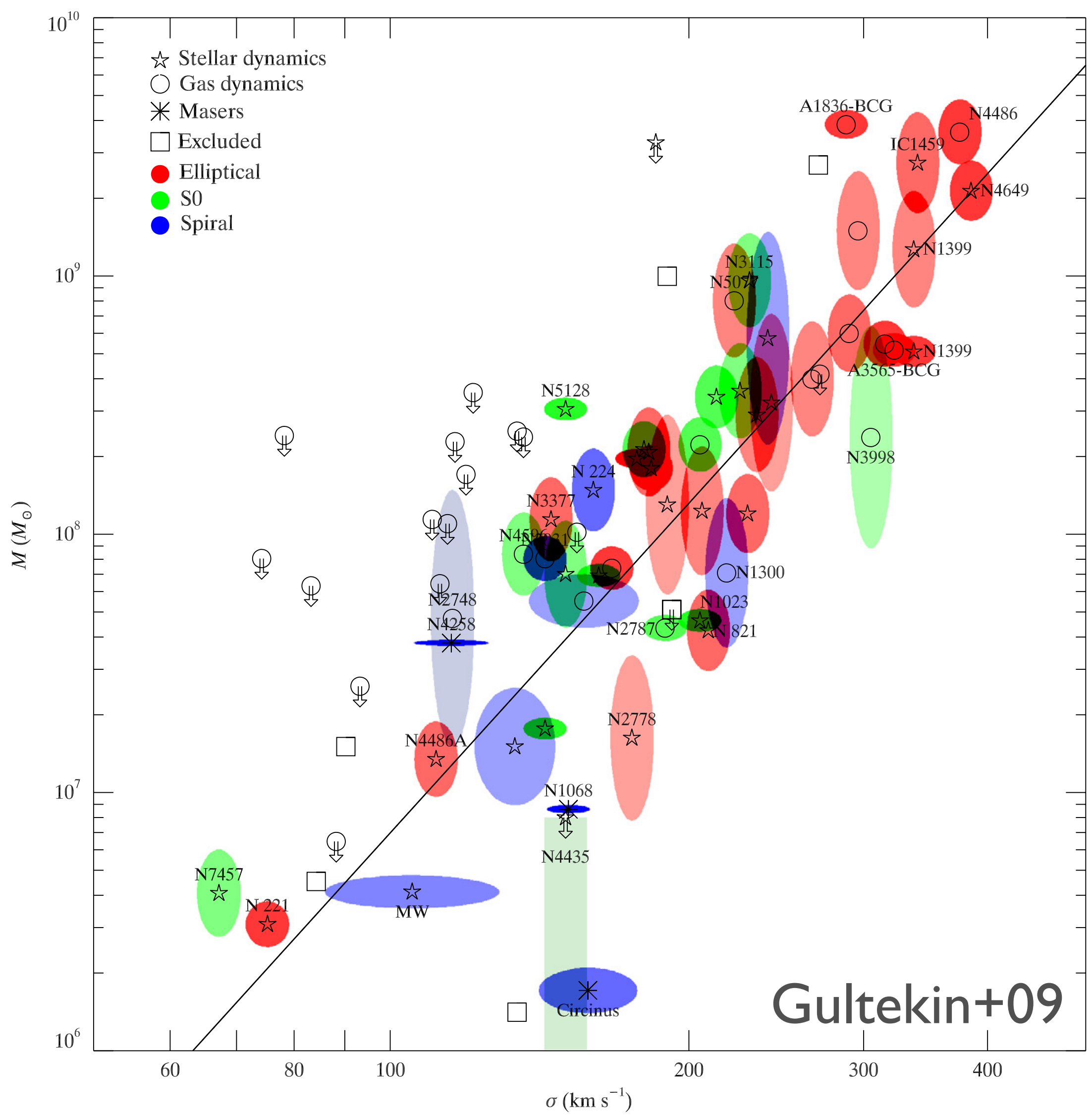
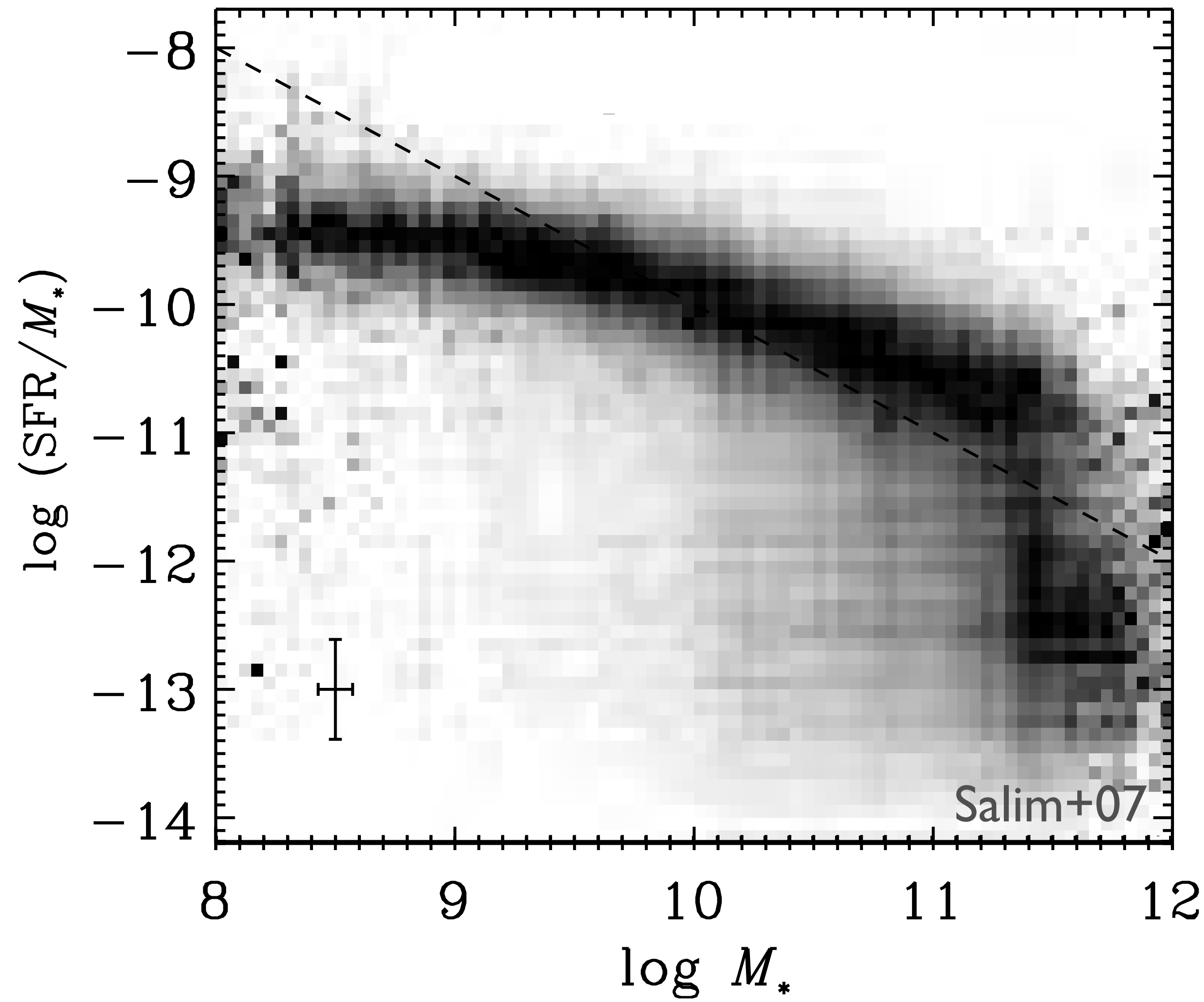
The possible roles of AGN feedback

Establish correlations between SMBH and galaxy properties



Truncate star formation

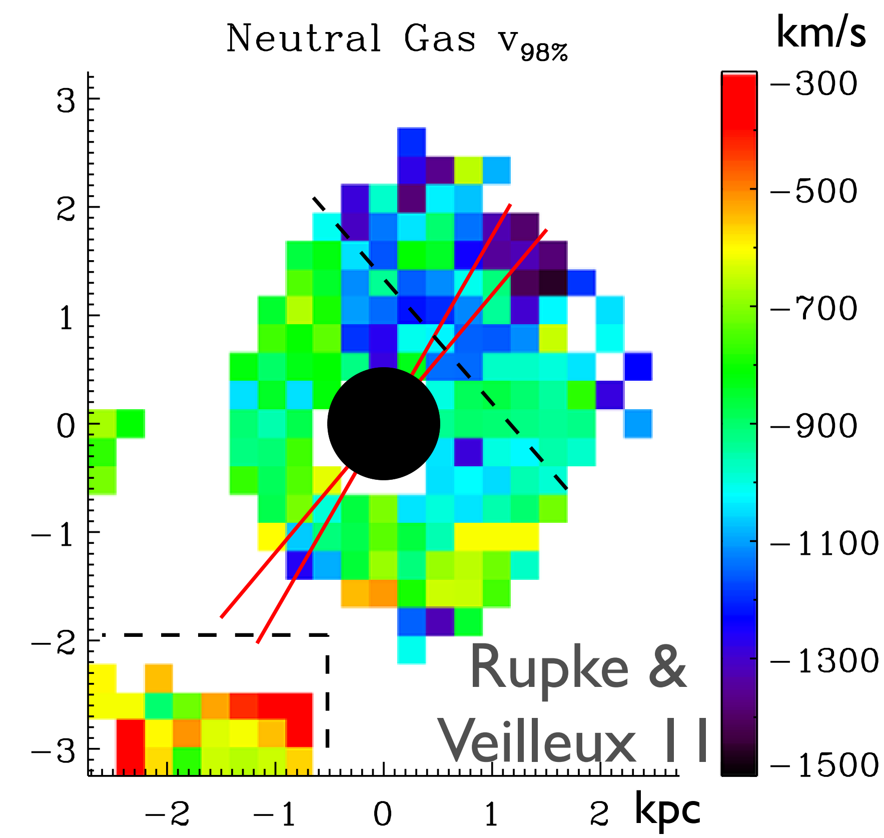


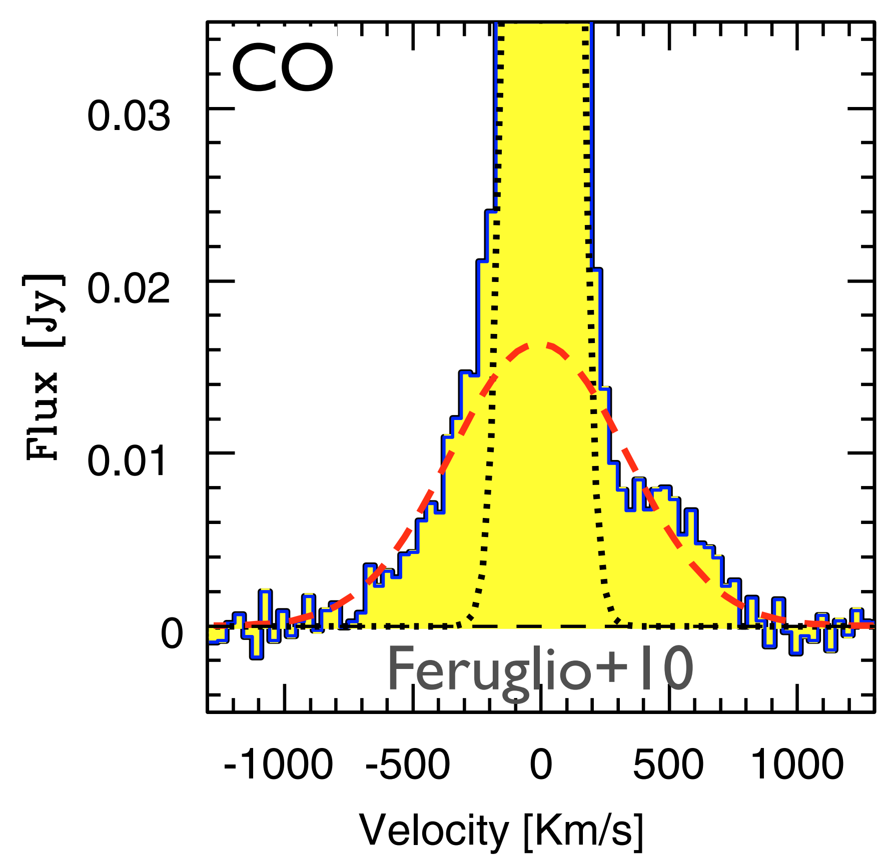
How does AGN feedback work & can it do these things?

Multi-wavelength breakthroughs on AGN outflows

- Massive galaxy-scale AGN outflows in luminous QSOs and local ULIRGs
  - ➡ neutral, ionized, CO, OH, HCN, ...
- Herschel, E-VLA, ALMA, IFS, UV spec'y to revolutionize this field

Mrk 231





The role of UV spectroscopy

- Physical conditions (⇒ energetics) in atomic gas of winds

- From *redshifted near UV*:
  - ➡ ~kpc: Arav+ measurements of low-ions in luminous QSOs
  - ➡ ~100 kpc: Prochaska & Hennawi (2009) possible wind absorber

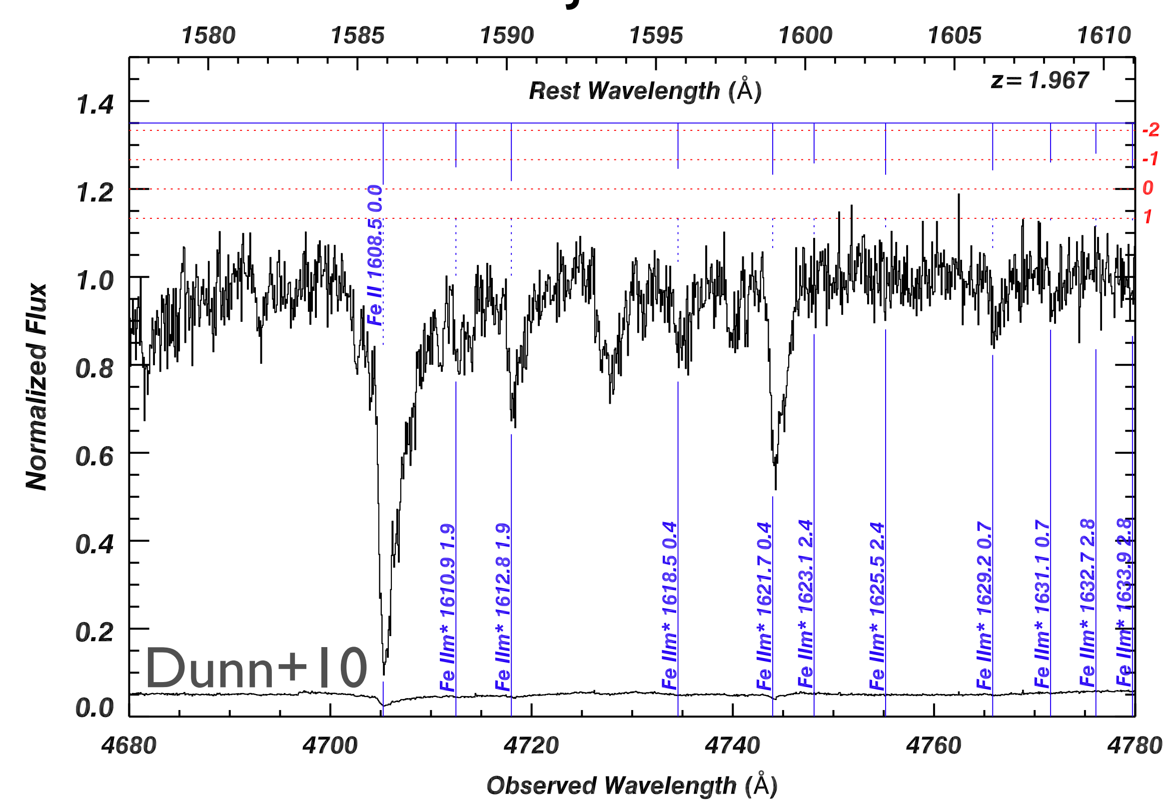
- From *far UV*: Tripp+ post-starburst wind with hidden mass reservoir (warm-hot ~10-150× cold)

Energetics of kpc-scale outflows from low-ions

- Photoionization modeling of FeLoBALs: v~1,000-5,000 km/s, R~1-3 kpc
  (Moe+09, Dunn+10, Bautista+10, Arav+11)

- CAFG+12 model:
  - ➡ interaction of QSO blast with ISM
  - ➡ *not* accretion disk wind
  - ➡ multiphase: generally, cool ≪ hot

SDSS J0318-0600

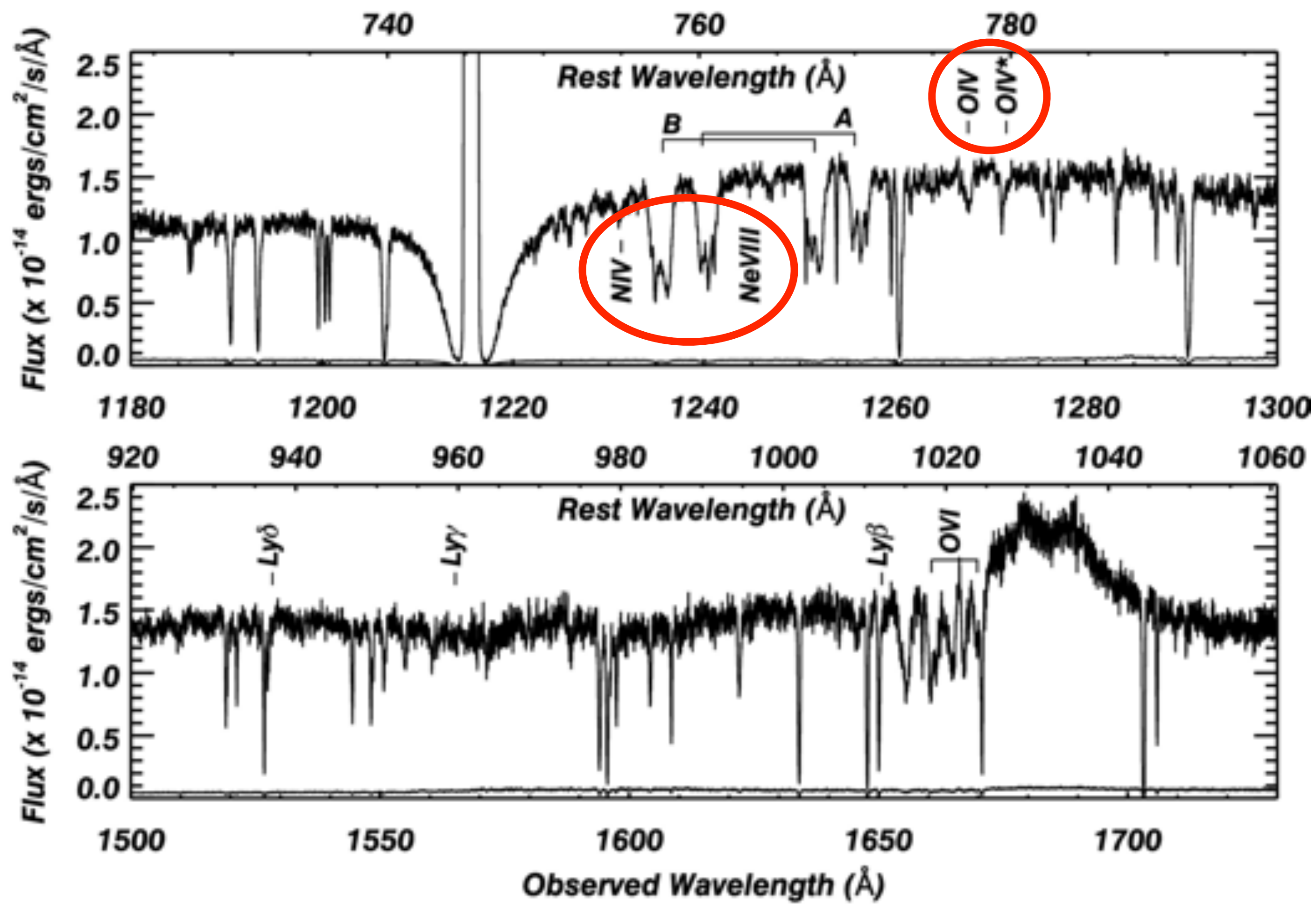


- ~1/2 of QSO outflows with reliable energetics estimates

Future: extend to high-ions with UV spectra

- Many more atomic transitions

e.g., He 0238-1904



- More representative of observed QSO outflows

- Sensitive to warm-hot gas

- Currently limited to bright QSOs, but future UV telescope could make such studies commonplace (Kriss talk)

Modeling AGN-driven galactic winds

- Focus on explosive "quasar mode" feedback, $L_{AGN} \sim L_{Edd}$
- Numerical simulations & semi-analytic models that *assume* ~5% L_{AGN} couples to the galaxy lead to BH-galaxy co-evolution

  (e.g., Silk & Rees 1998, Wyithe & Loeb 2003, Di Matteo+2005)

- Complementary: study basic physical processes through which BHs interact with the interstellar medium in the host galaxy

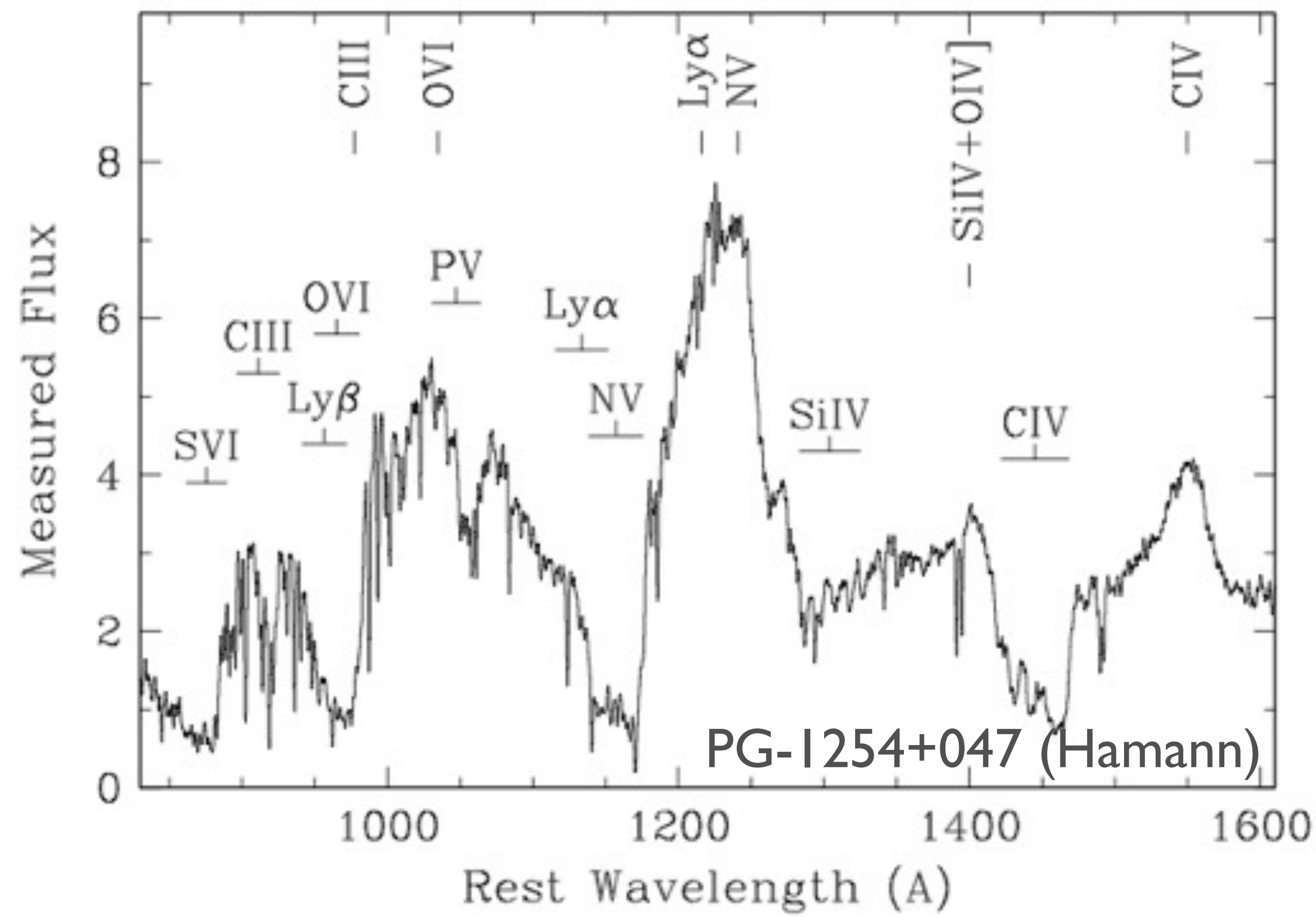
  ➡ crucial for effectiveness of feedback, how to include in sims

- Show BAL winds produce *energy-conserving* outflows

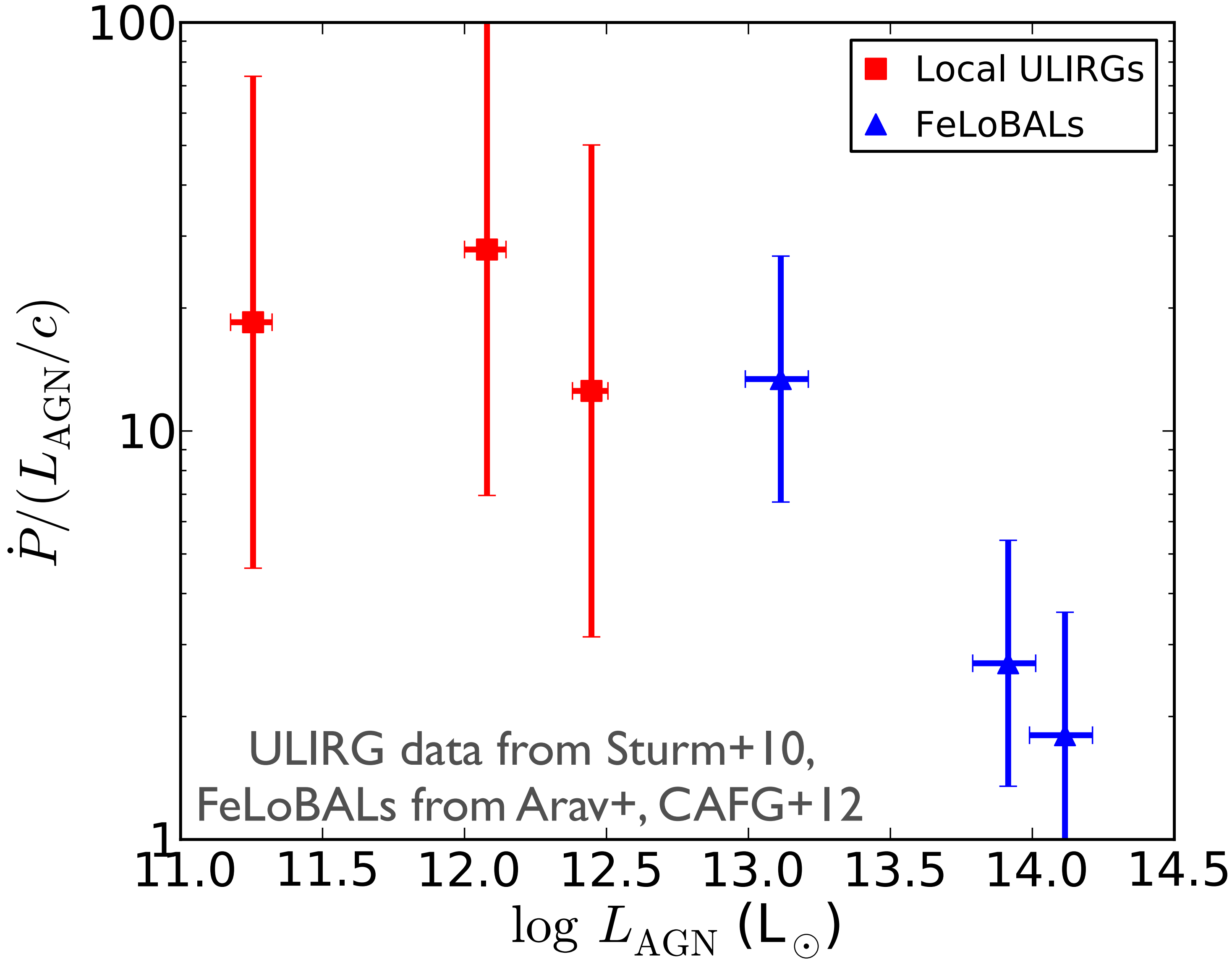
  ➡ explain large momentum fluxes observed

Broad absorption line (BAL) winds

- Observed in rest-UV of up to ~40% of QSOs
- *v*~few×1,000-30,000 km/s
- Possible x-ray counterparts (warm absorbers, UFOs)
- Modeled as accretion disk winds (Murray+95, Proga+)



Large $\dot{P}$ (=force) of galaxy-scale AGN outflows



- If all photons scatter once & P is conserved,

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

- Observations indicate

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

- Simulations also require

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

to reproduce $M_\bullet$-σ (DeBuhr+)

CAFG & Quataert, arXiv:1204.2547

Momentum-conserving

$t_{cool}/t_{flow} \ll 1$

No thermal pressure

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

e.g., AGB wind

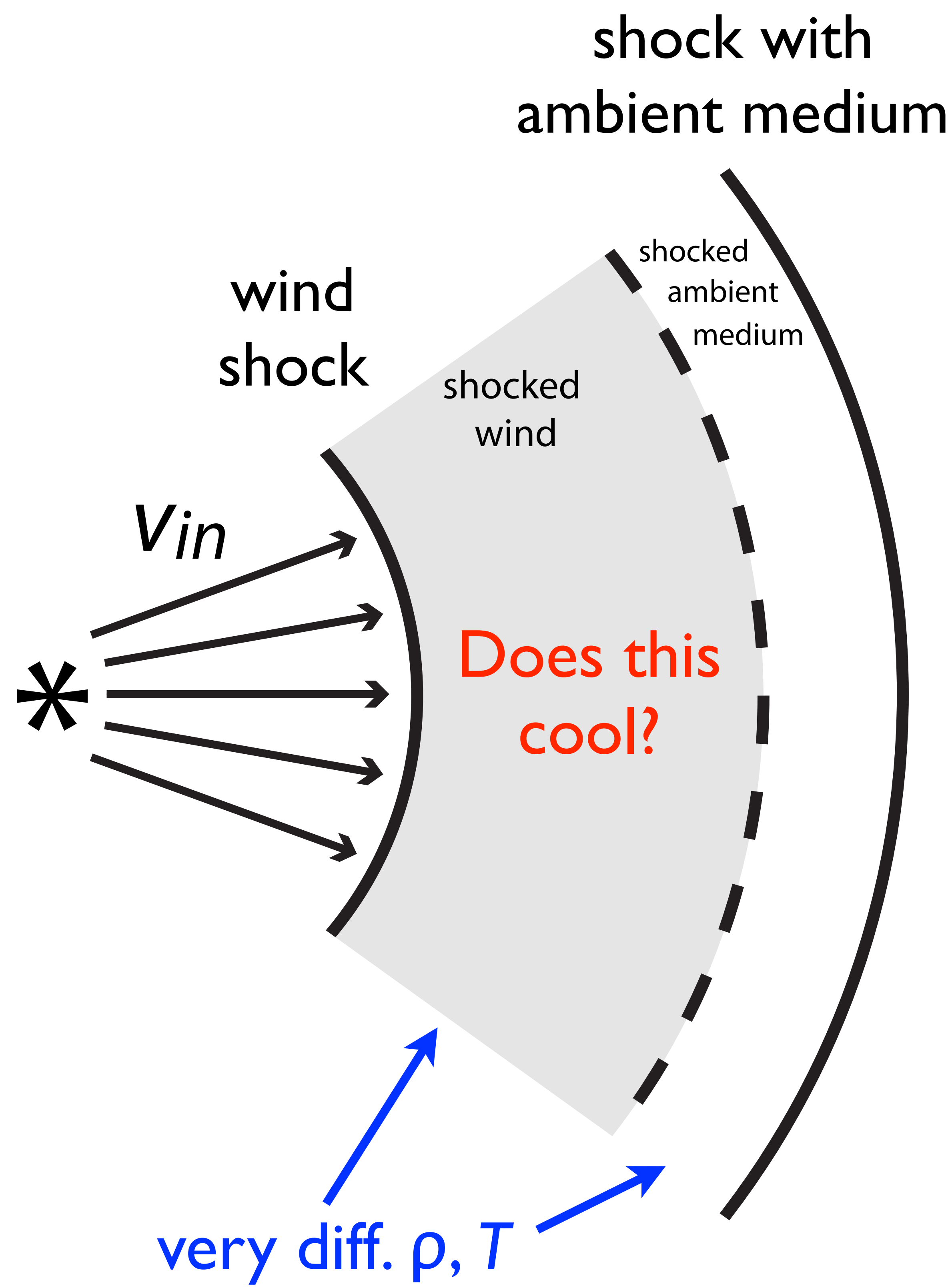
Energy-conserving

$t_{cool}/t_{flow} \gg 1$

Hot gas does work

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

e.g., Sedov-Taylor SNR



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Proposal: AGN outflows are *E*-conserving

Two-stage

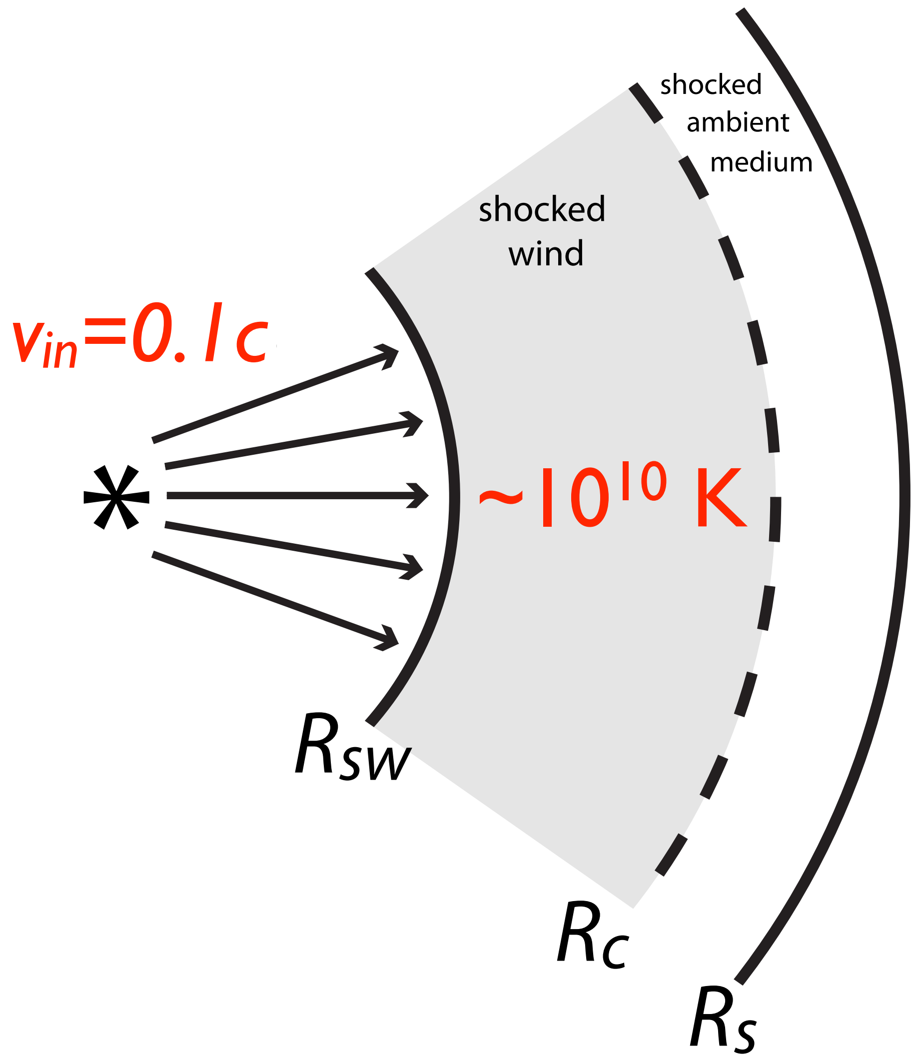
- Radiation pressure accelerates BAL wind with $\dot{P} \sim L_{\rm AGN}/c$ (assume)
- Energy-conserving wind bubble boosts by factor ~10-15 (show)

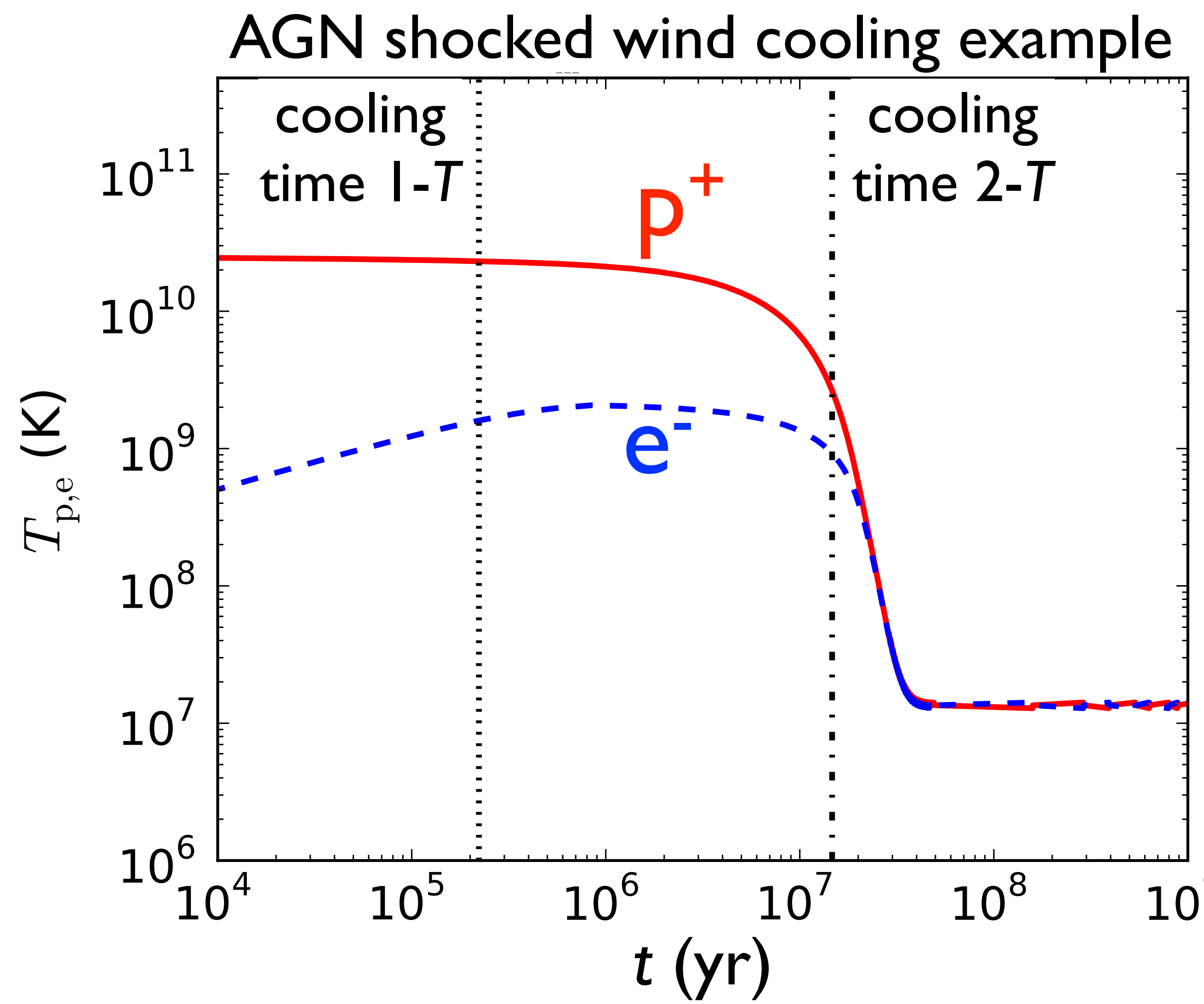
- Non-trivial because of high ambient gas densities and intense radiation fields in ULIRG nuclei, suggestive of short cooling times

(c.f., King 2003, Silk & Nusser 2010)

- Possible because shocked BAL winds T_{sw}~10^9-10^{10} K: hard to cool

Cooling of BAL shocked wind

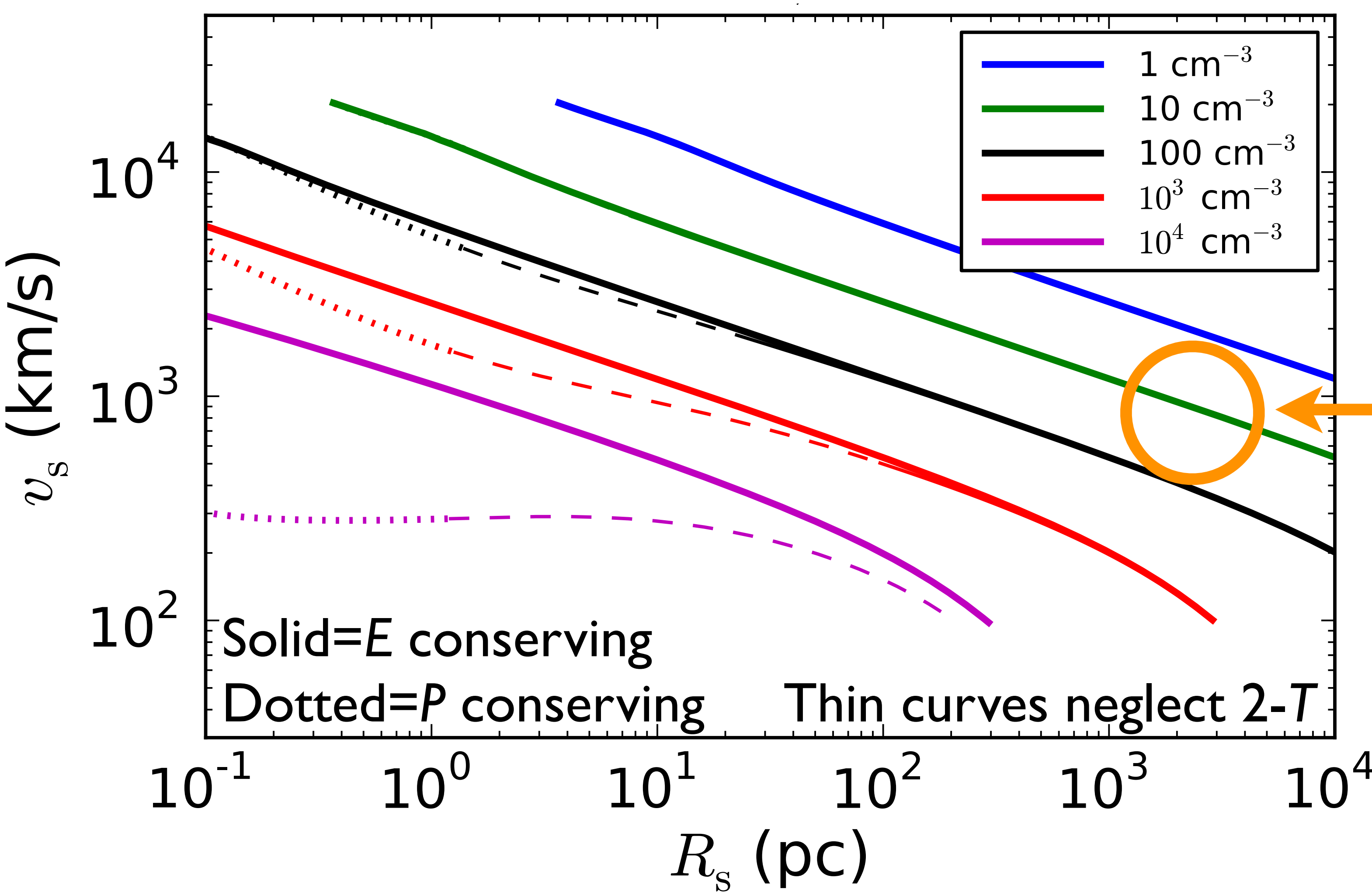


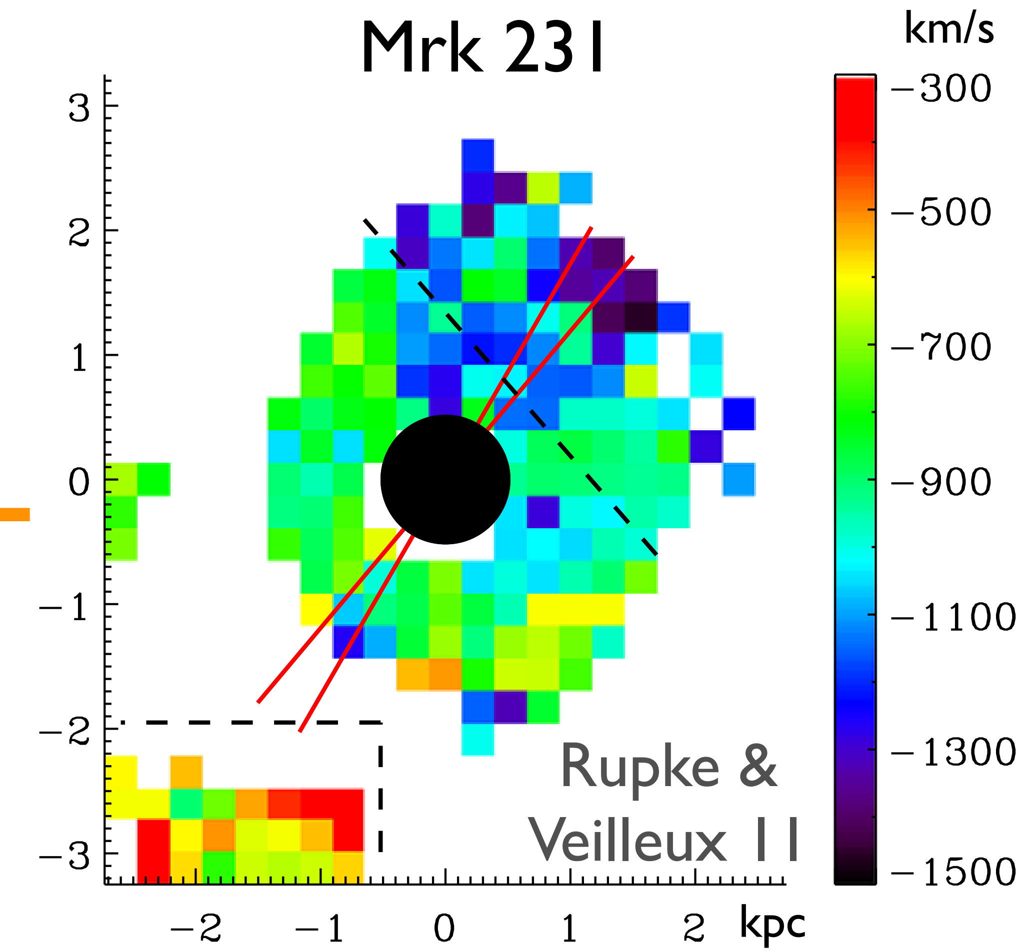


- e^- cool via inverse Compton (free free, line negligible), p^+ provide pressure
- Coulomb collisions limit p^+ cooling (robust to collisionless proc.)

CAFG & Quataert, arXiv:1204.2547

Spherically symmetric models





- Observed AGN-driven molecular outflows are in *E*-conserving limit
- Even so ignoring 2-*T* effects (2-*T* ⇒ *E*-cons. in more extreme conds)

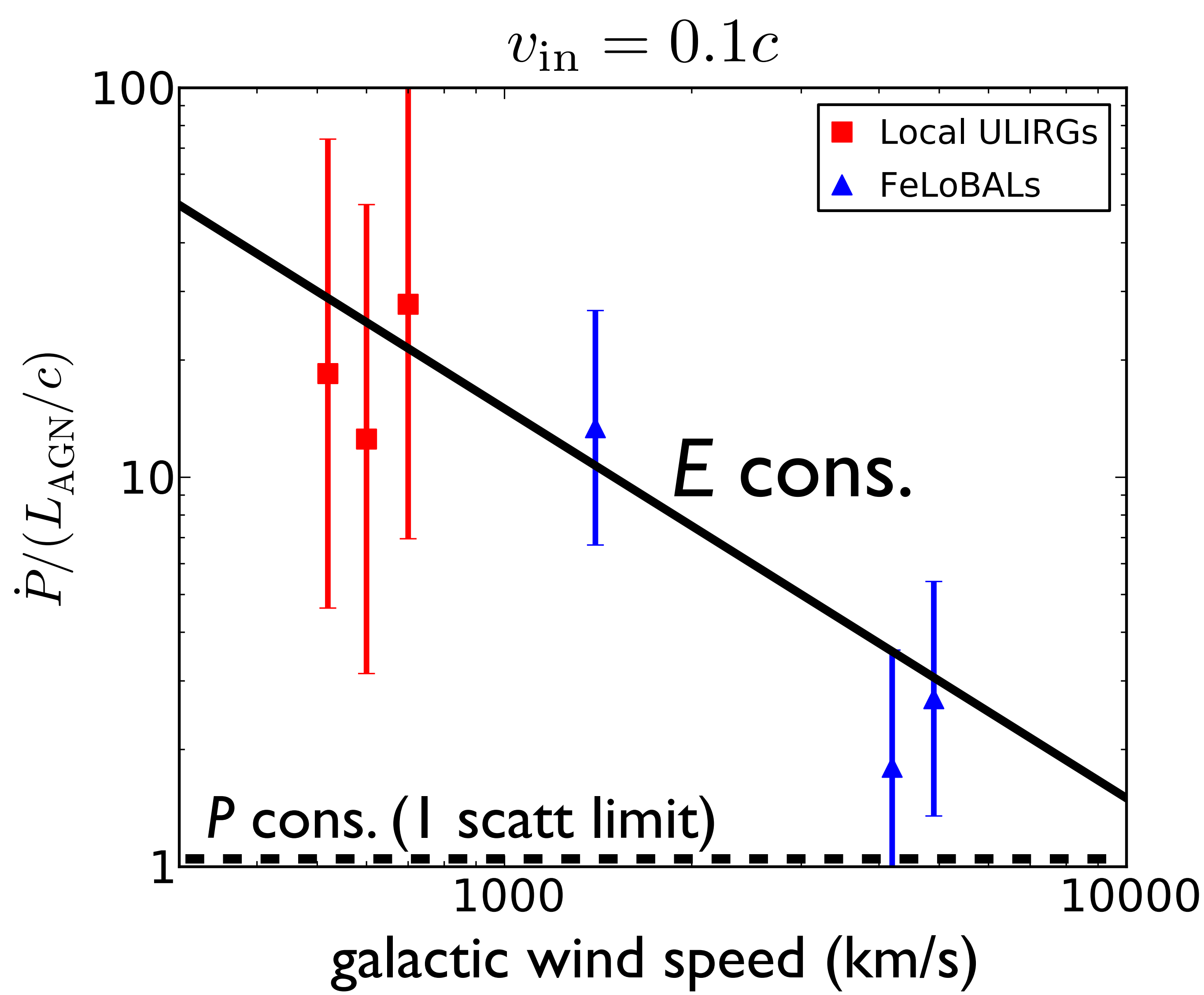
CAFG & Quataert, arXiv:1204.2547

Energy conservation naturally explains measured AGN momentum boosts

- Predicts

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

- To be tested with radio, FIR, optical, and UV spectroscopy



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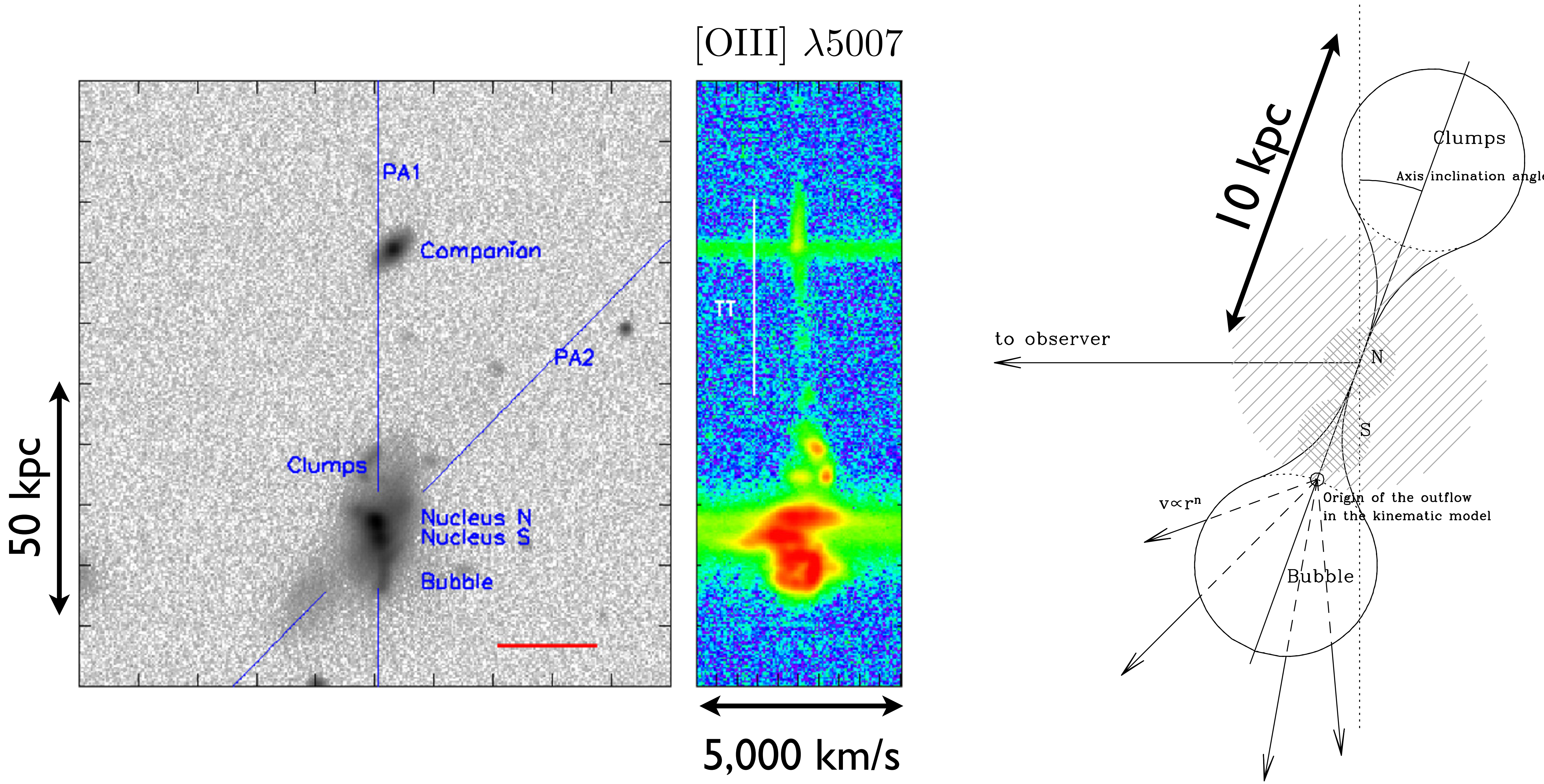
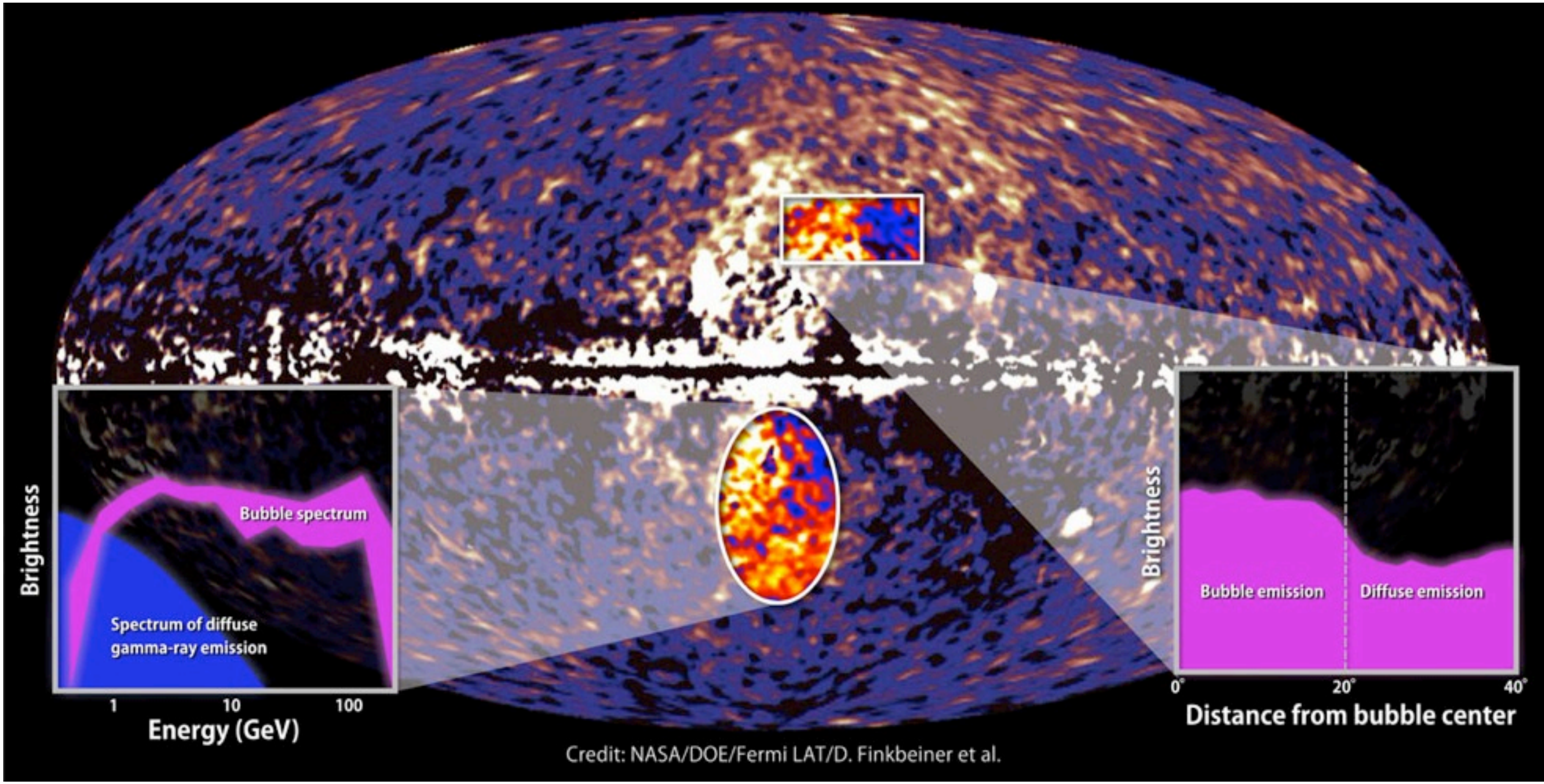
Shocked wind bubbles in Type II QSOs



Zakamska+ in prep.: 30-50 kpc ionized nebulae with outflow kinematics around every L_{AGN}~10^{46}-10^{47} erg/s Type II QSO?

Greene+12

Shocked wind bubbles in the Milky Way



Su & Finkbeiner (2012): evidence for a γ-ray jet

Summary

- Observations of galaxy-scale AGN outflows indicate

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

- Proposal: galaxy-scale outflows are energy-conserving

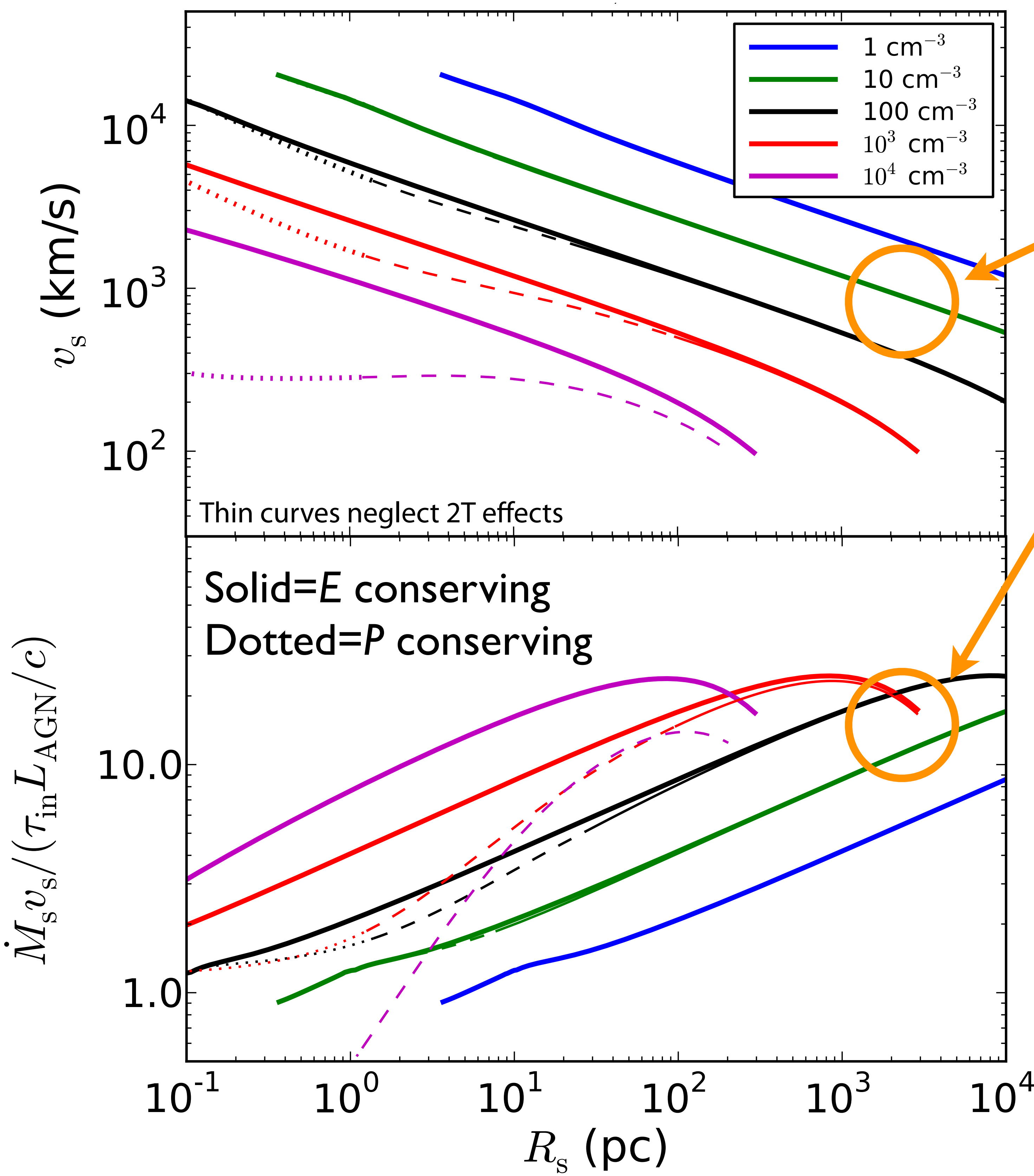
- Prediction: $$\frac{\dot{P}}{L_{\rm AGN}/c} \sim \frac{1}{2}\left(\frac{\text{nuclear wind speed}}{\text{galactic wind speed}}\right)$$

- Physics to inform numerical simulations

- UV spectroscopy probes atomic outflows, can test model

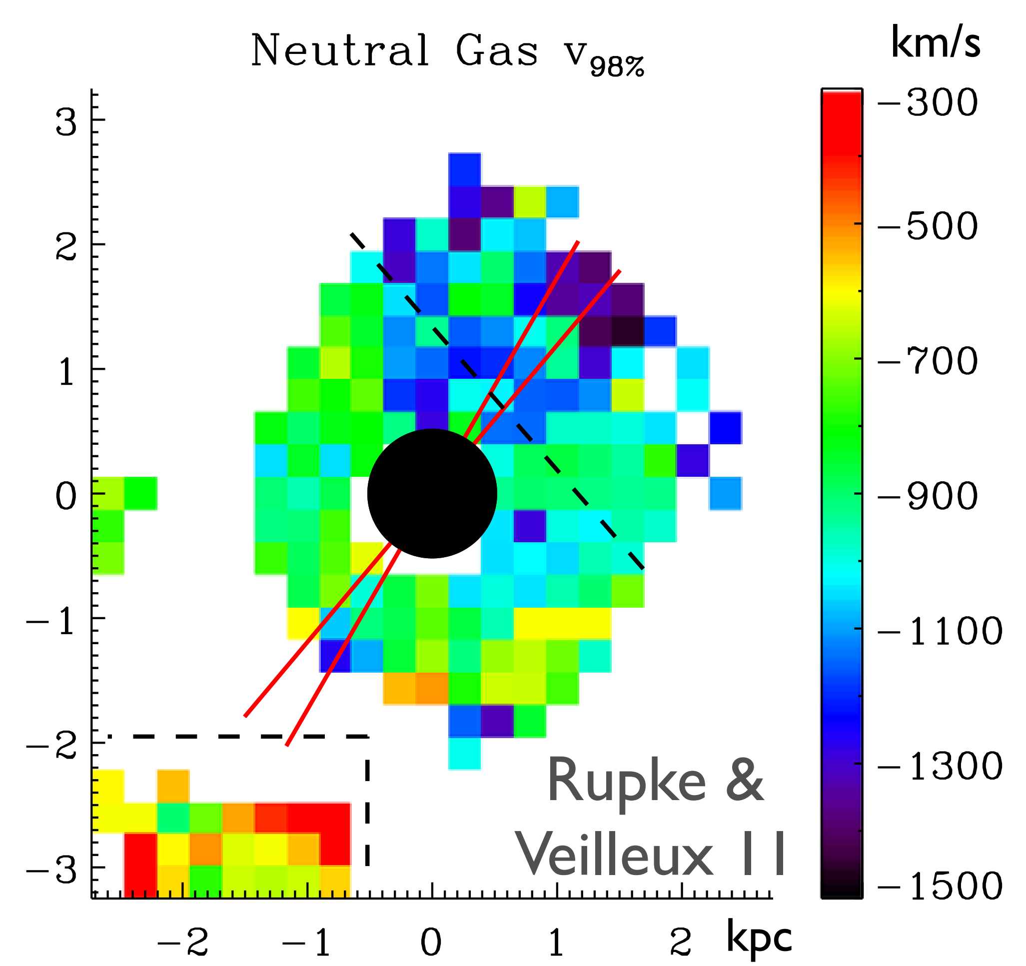
Extra Slides

Spherically symmetric models



observed galaxy-scale outflows, e.g.

Mrk 231



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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 ff cooling takes over
  - ➡ escape along paths $<10^{-3}$ under-dense can still boost *P* by factor >10 in ULIRGs

Carina nebula

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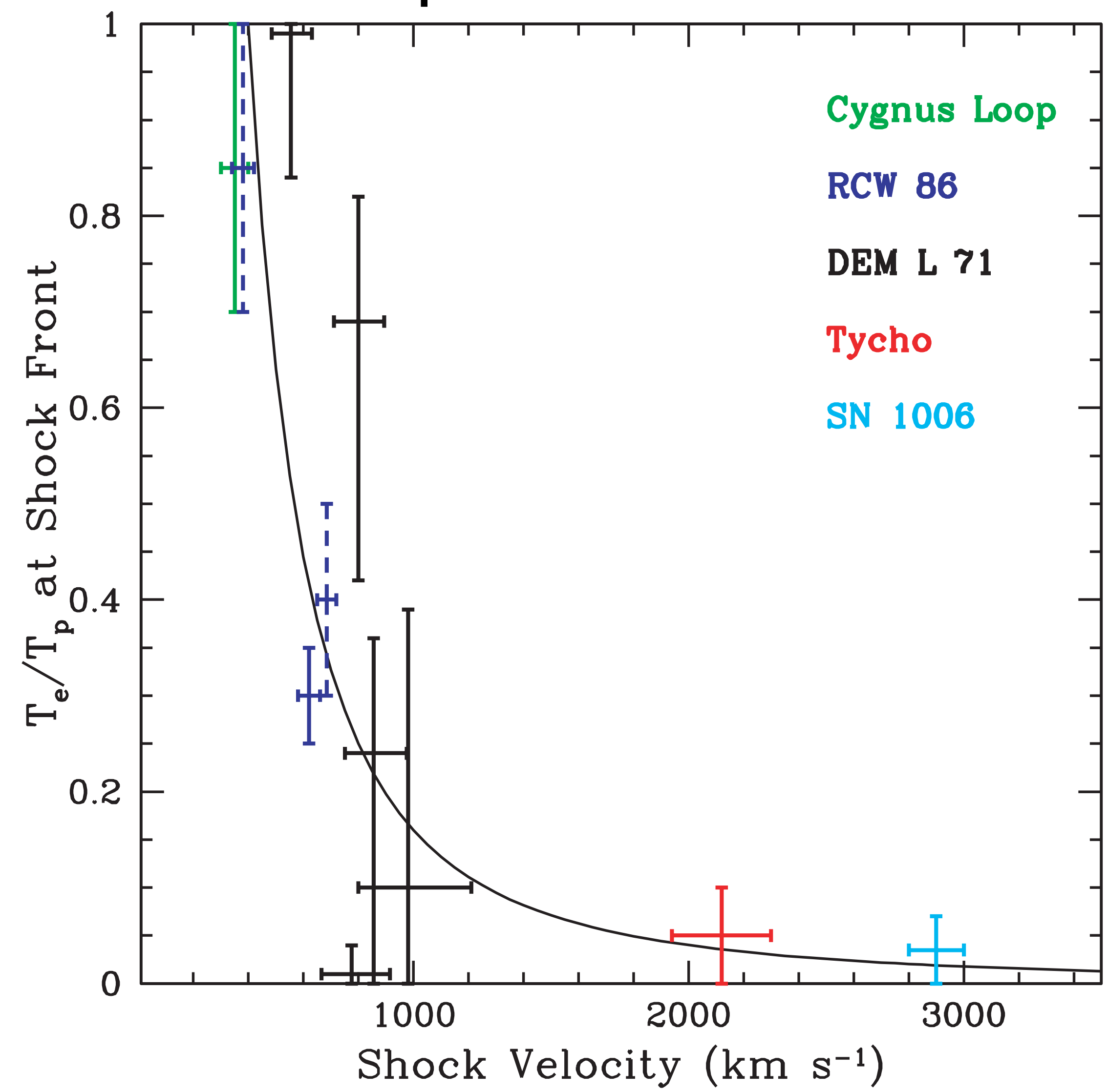
Robust to collisionless effects

- Collective E&M processes can heat electrons faster than Coulomb collisions

- May be effective at the shock, but likely damped on time scale ≪ relevant for wind cooling (Chang+08)

- Only need T_p/T_e~10: observed in SNRs & solar wind, invoked in ADAFs

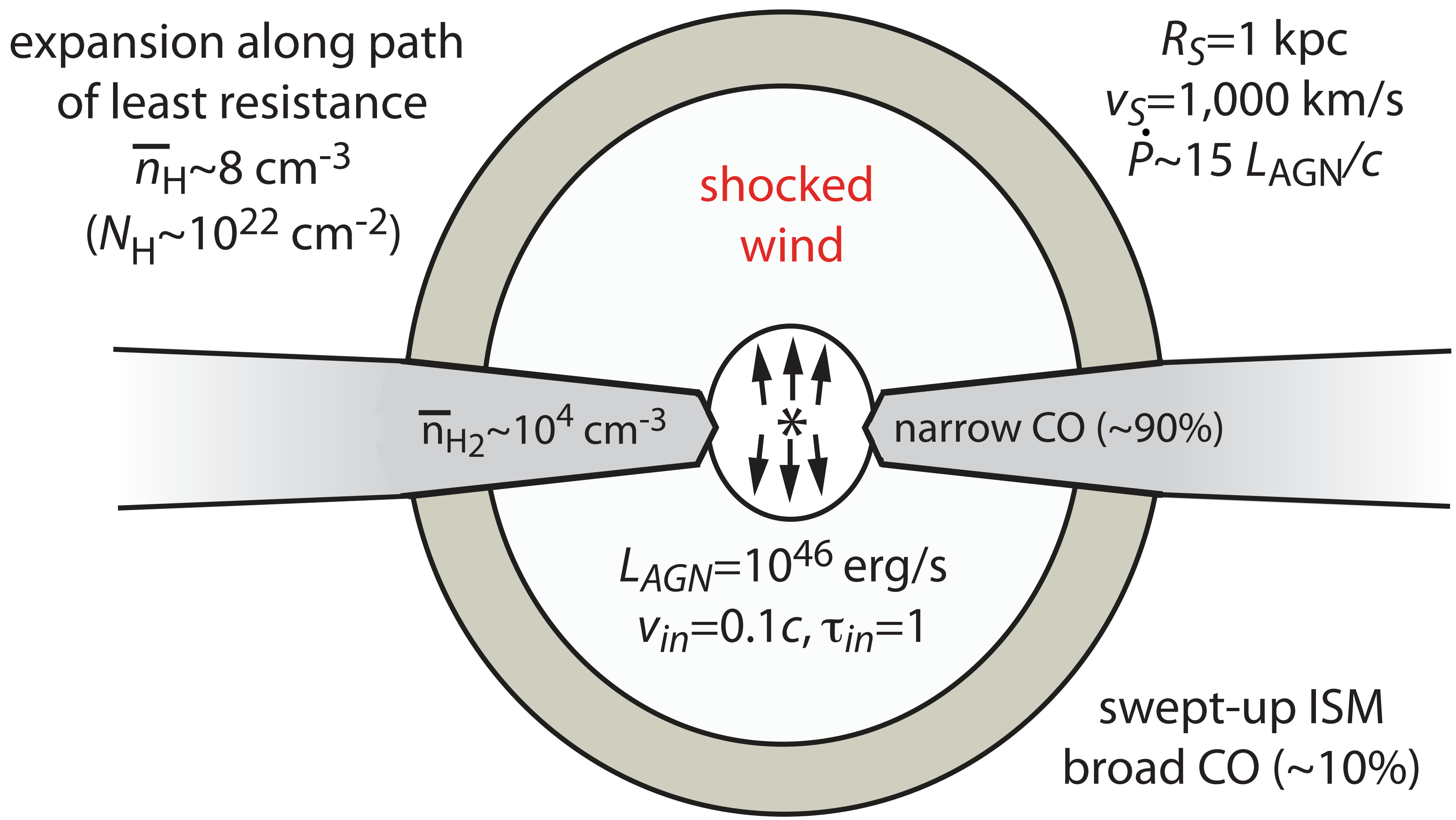
Electron/proton *T* ratio in SNRs



Ghavamian+07

Hot bubbles

- Galactic disks are thin (h/R~0.1 in ULIRGs)



- Wind bubbles expand preferentially ⊥ disk

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