The X-Ray View of AGN Ionized Outflows

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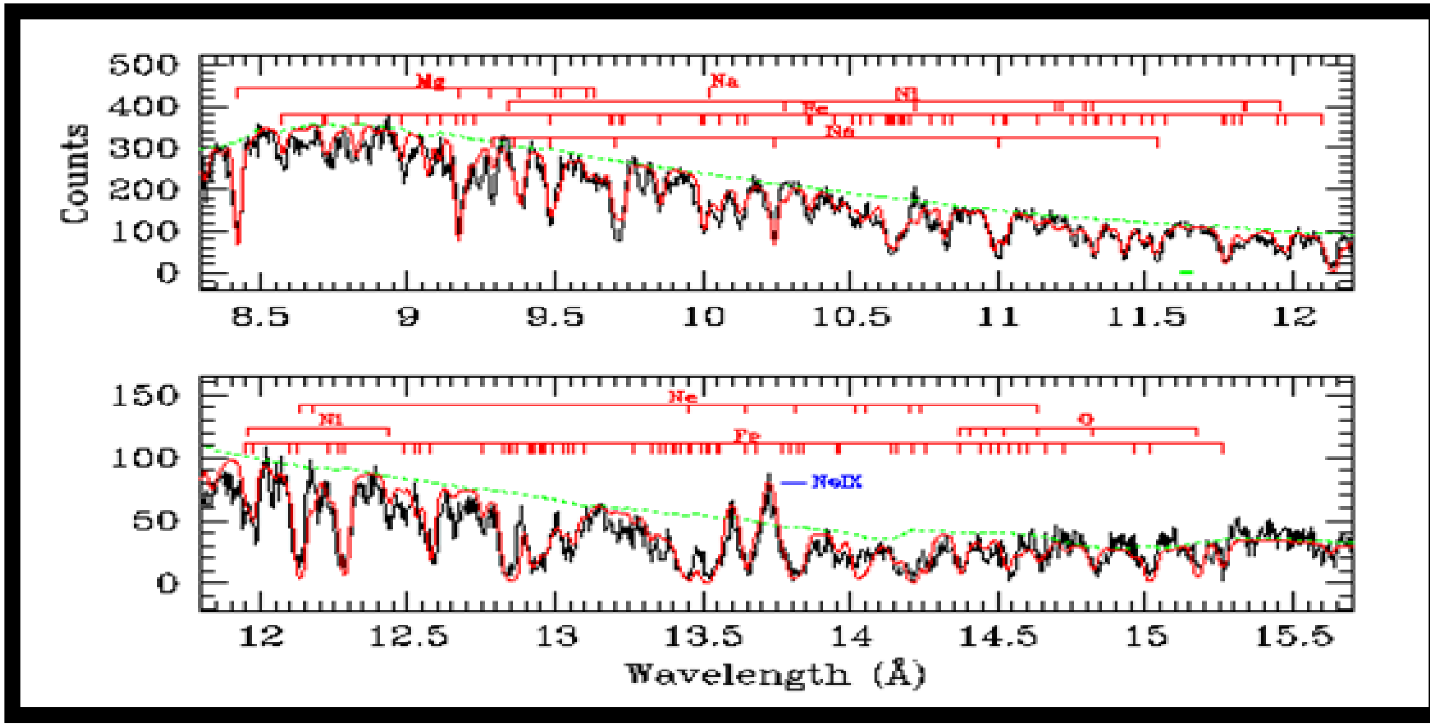
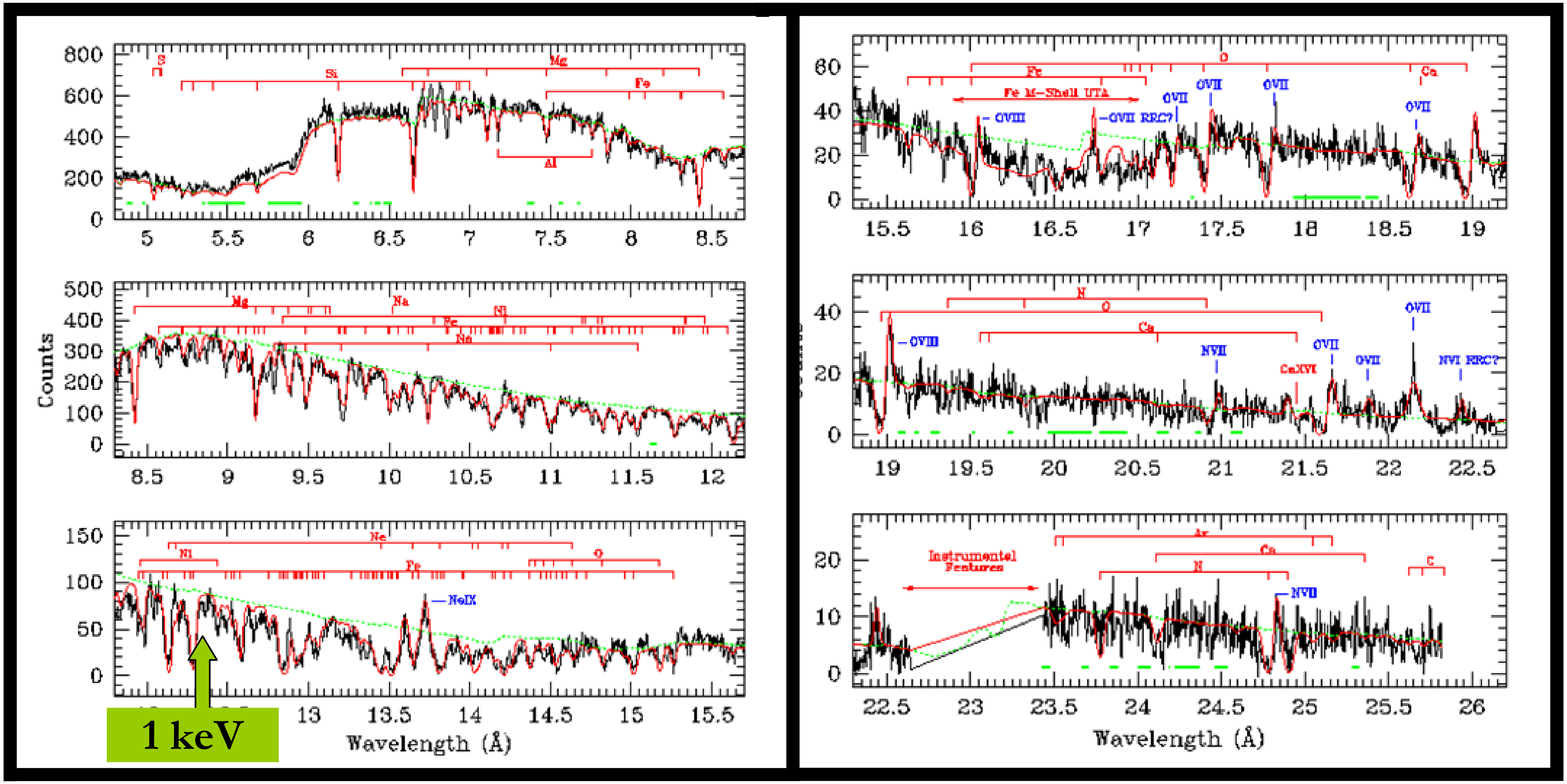
Warm Absorbers = AGN Winds



- ***Winds with velocity = 500-3000 km s^{-1}*** ***~1lt-day/yr***
- ***Found in 50% of Seyfert 1s, PG Quasars*** ***(Reynolds, 1997; George+98, Piconcelli+05)***
- ***Related to UV 'narrow absorption lines' - NALs***
- ***Possibly Ubiquitous in AGNs***

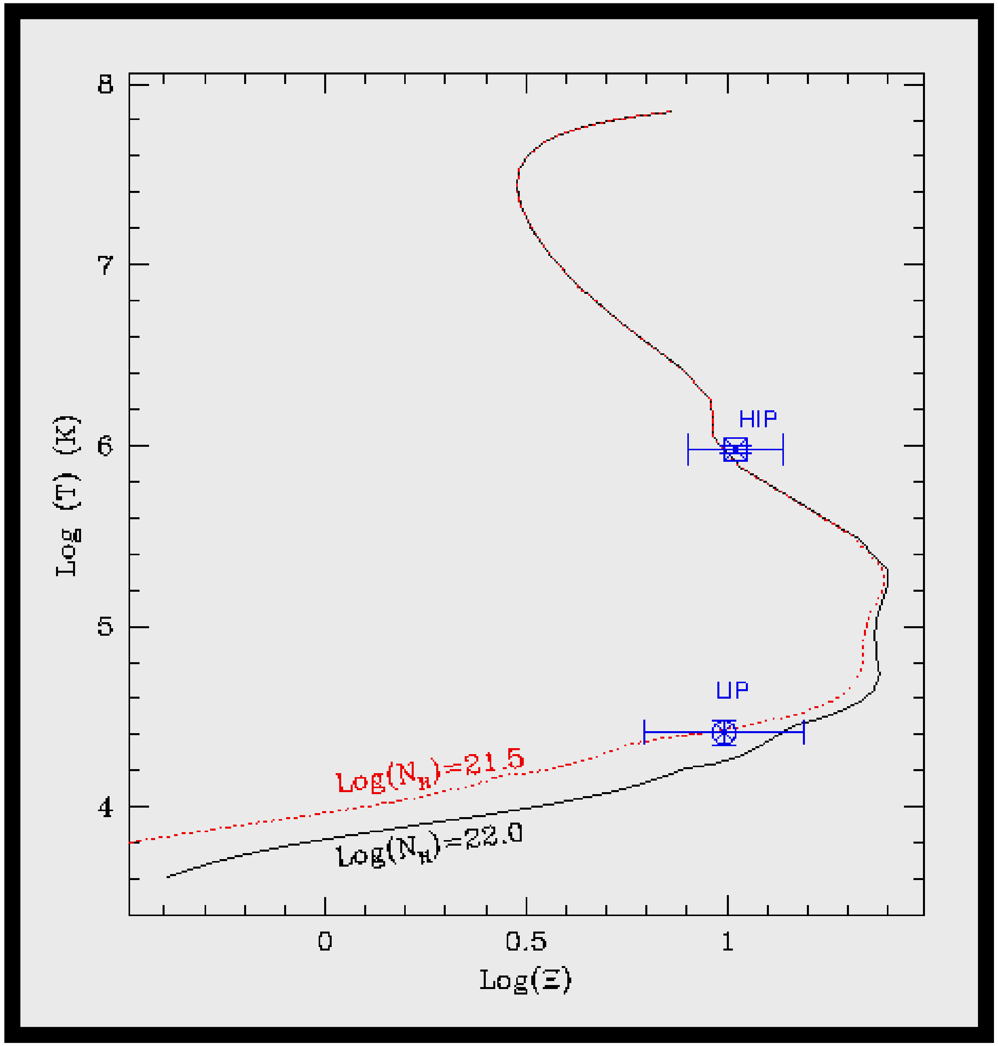
Simple solution: 2-3 components



NGC 3783 *Chandra* **MEG** **900 ksec exposure** (Krongold+03)

AGN X-Ray Outflows:
2-3 phases in pressure equilibrium?

- Similar kinematical properties
- No drag forces
- NGC 3783, NGC 985, IRAS 13349, NGC4051
- Also NGC 5548 when each Vel. Comp. is modeled independently



WA Open Questions

- Where do they arise? **10^6 in r**! - Disk wind/torus/NELR
- What is the geometry? Spherical/Bi-Conical/funnel
- *Relation with other AGN components?* BELR, BALs, Torus
- What are their Physical Properties?
  - Mass and KE outflow rates depends critically on *wind* location (0.01-1000 M_{accr})
- *Cosmologically important? Feedback, Co-evolution*

Time Evolving Photoionization provides insights

Problem Arises from:

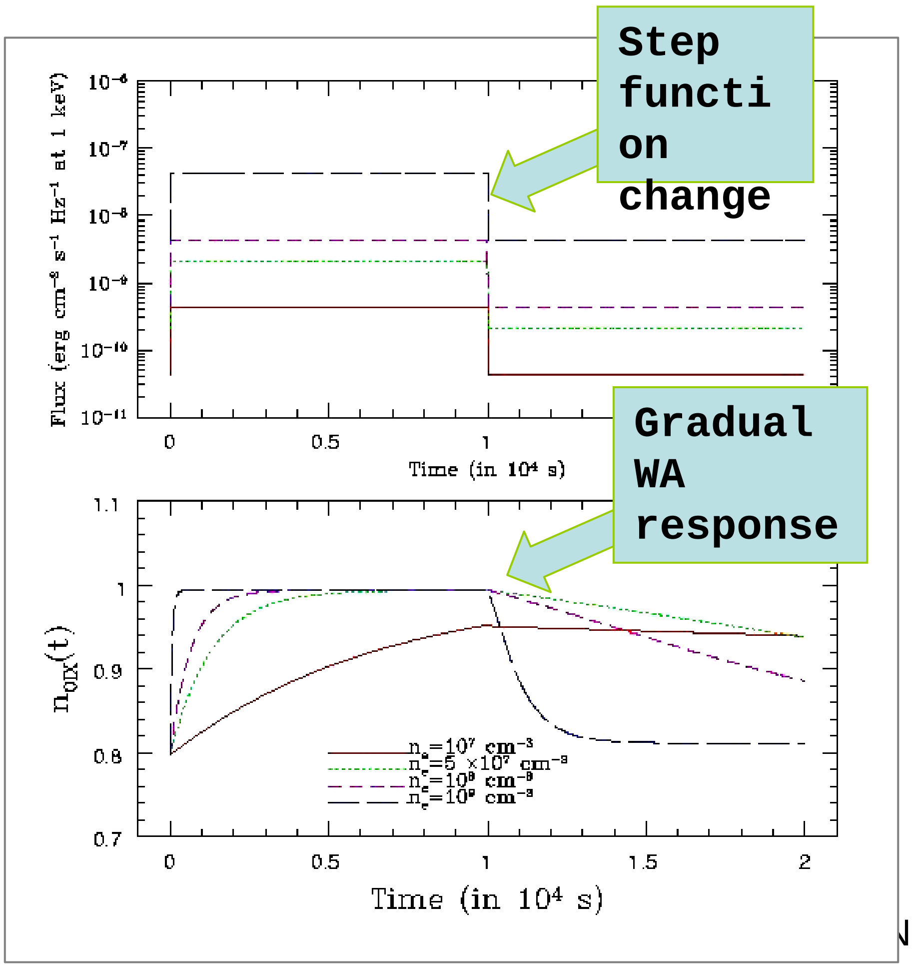
Observables

$$U = \frac{n_{ph}}{n_{gas}} = \frac{Q}{4\pi R^2 n c}$$

Un-Observables

Solution: Time Evolving Photoionization

Constrains $\mathbf{n_e}$ independently on **U**, and so constrains **R**



Response is not instantaneous: 'Ionization time' and 'Recombination time'

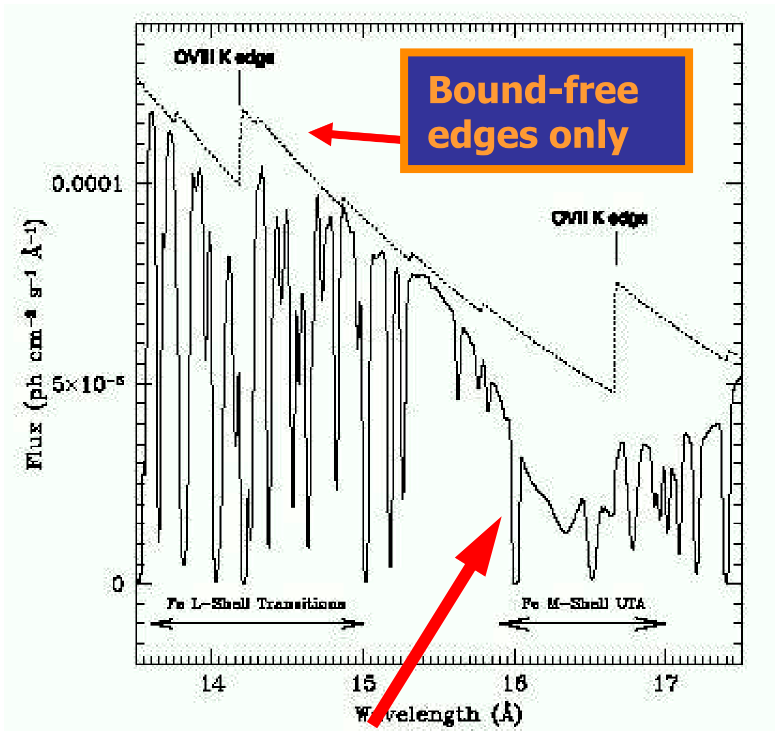
$$t_{\rm eq}^{X^i,X^{i+1}}(t \rightarrow t+dt) \sim \left[\frac{1}{\alpha_{\rm rec}(X^i, T_e)_{\rm eq}\, n_e}\right] \times \left\{\frac{1}{[\alpha_{\rm rec}(X^{i-1}, T_e)/\alpha_{\rm rec}(X^i, T_e)]_{\rm eq} + (n_{X^{i+1}}/n_{X^i})_{\rm eq}}\right\}_{t+dt}, \quad (5)$$

Following the Opacity of the WA in NGC 4051

XMM-*Newton* Observation

- **103 ksec**
- **>10x flux changes**
- **EPIC + RGS**
- **High S/N + R**

Modelled with PHASE (Krongold+03)



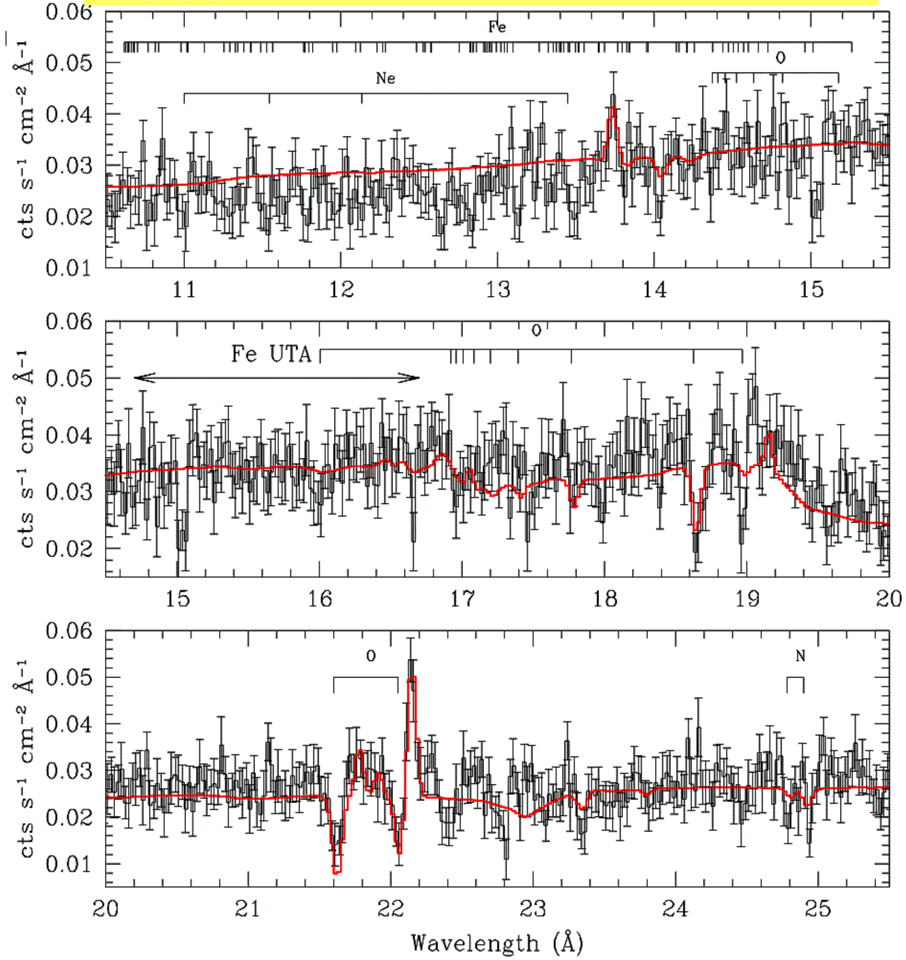
NGC 4051 RGS Data

- **Simple solution**
- **only 2 absorbing components (LIP and HIP)**

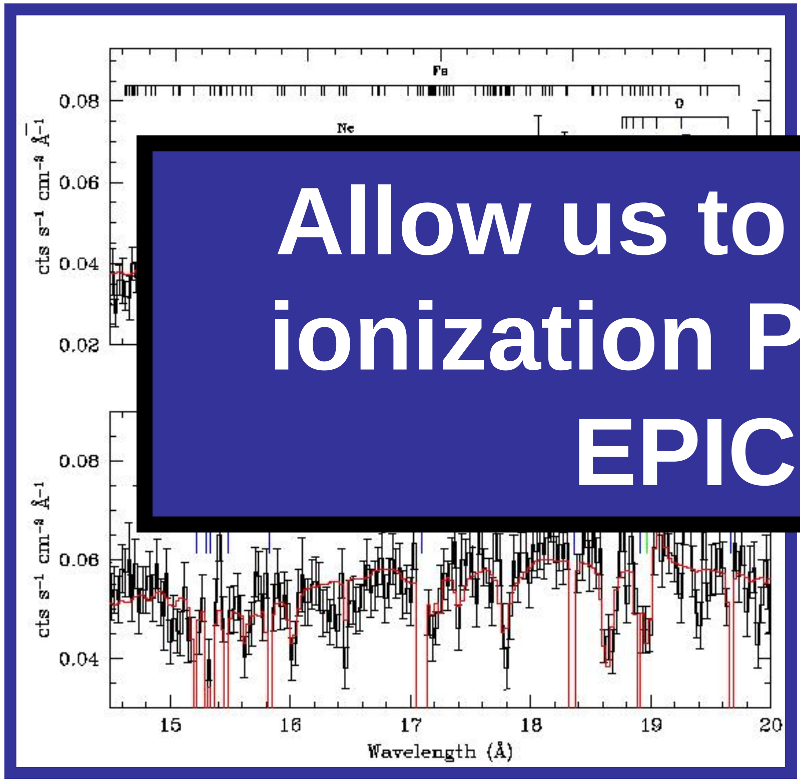
F_{6-35}=4.4x10^{-11} *cgs ~ XMM*

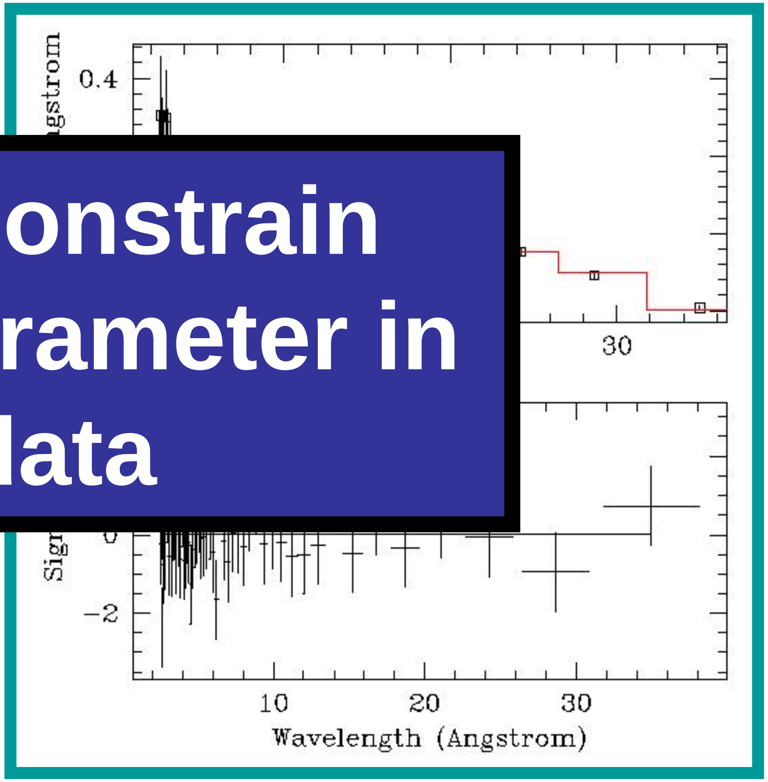
HIP

LIP



Similar Solutions RGS and EPIC





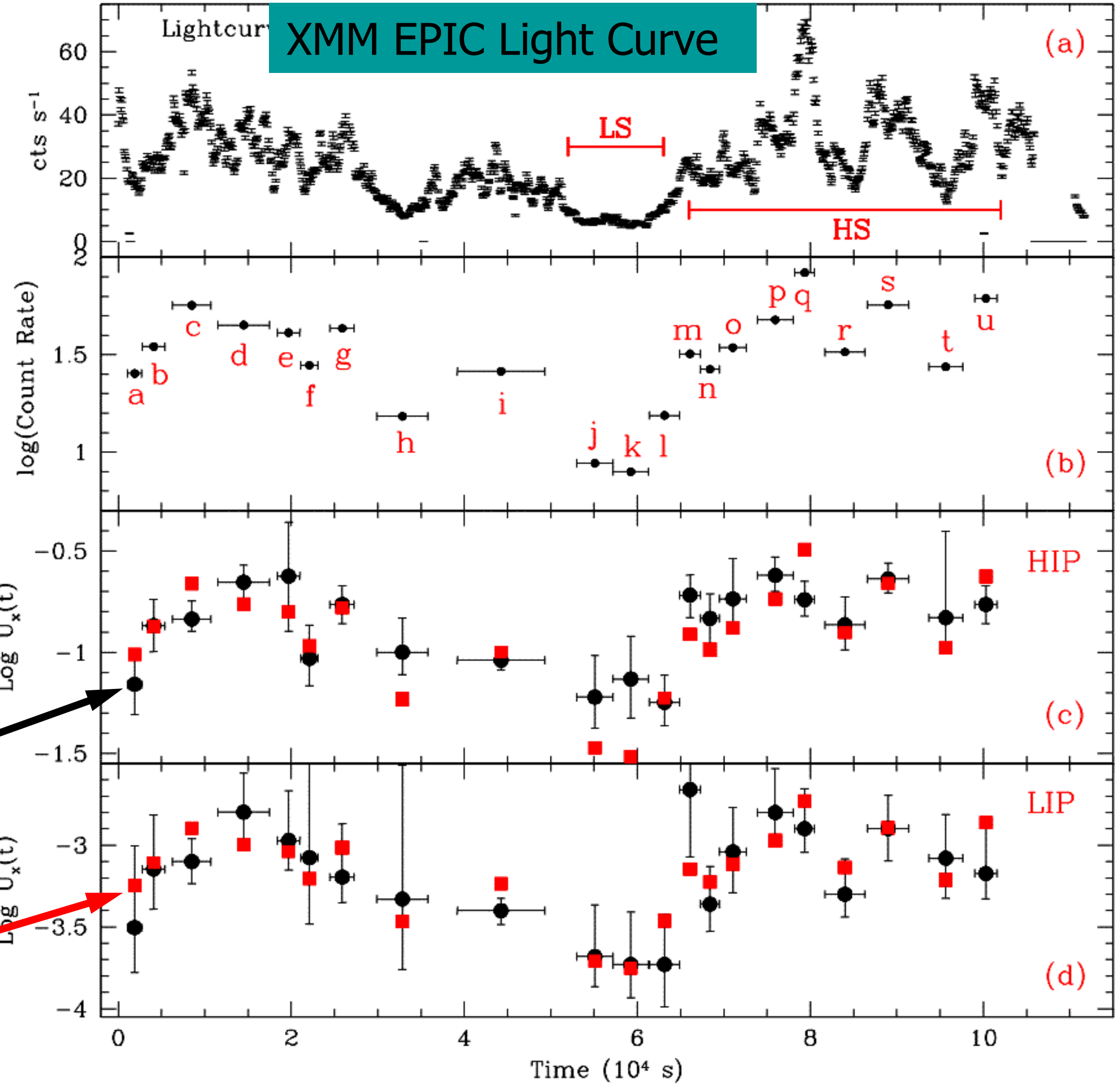
Allow us to constrain ionization Parameter in EPIC data

Abs.	EPIC (HS)	RGS (HS)
HIP $\log(U_x)$	$-0.68^{+.09}_{-.04}$	$-0.72^{+.03}_{-.06}$
LIP $\log(U_x)$	$-2.98^{+.15}_{-.10}$	$-2.93^{+.10}_{-.11}$

NGC 4051:

2 WA components in photoionization equilibrium

(Krongold et al. 2007)



log $U_x(t)$, measured

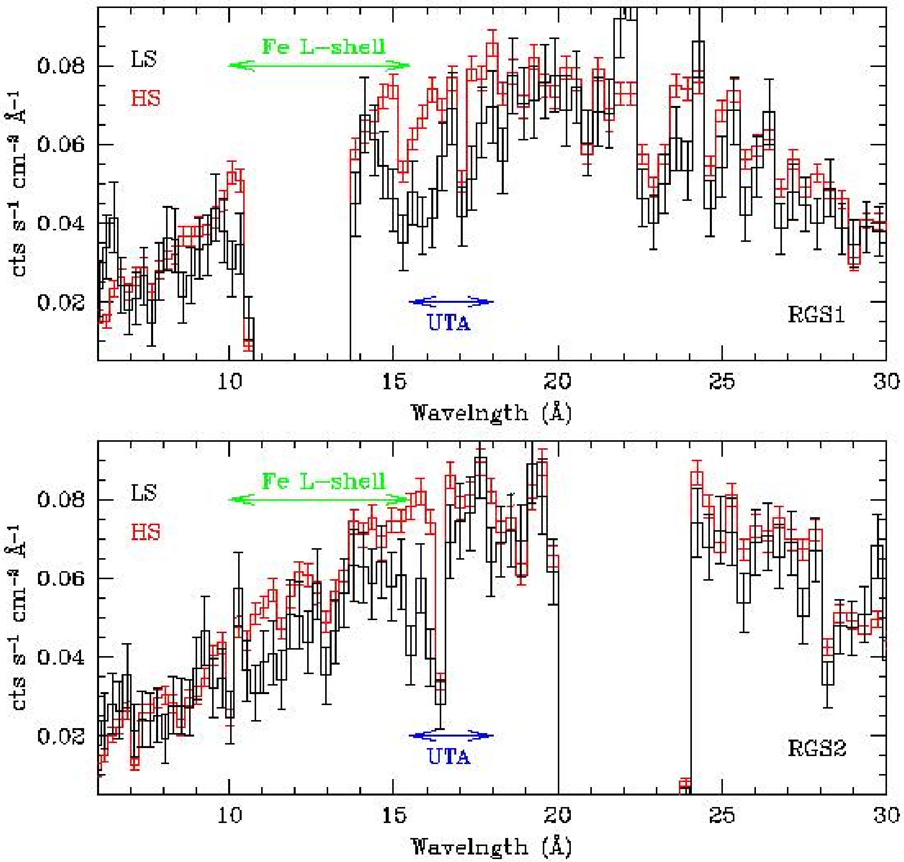
log $U_x(t)$, predicted from photoionization equilibrium

Both WA components are DENSE and COMPACT

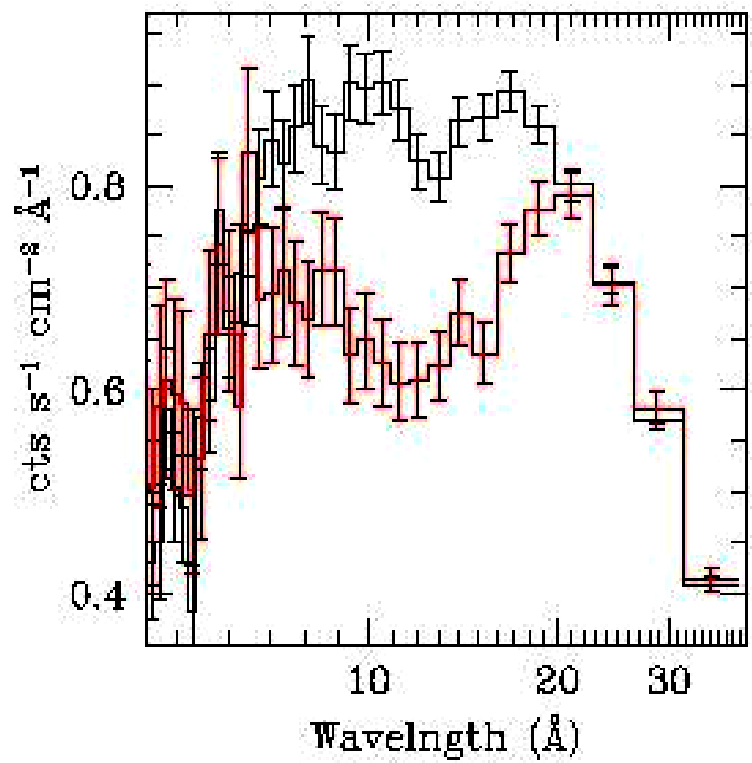
Comparing HS and LS data

4X flux increase

RGS Data



EPIC Data



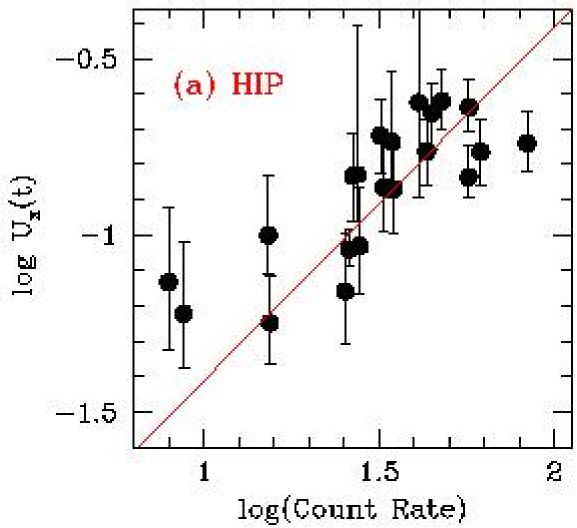
First Noted by Ogle et al. 2004

Robust Estimate of $(n_e R^2)$

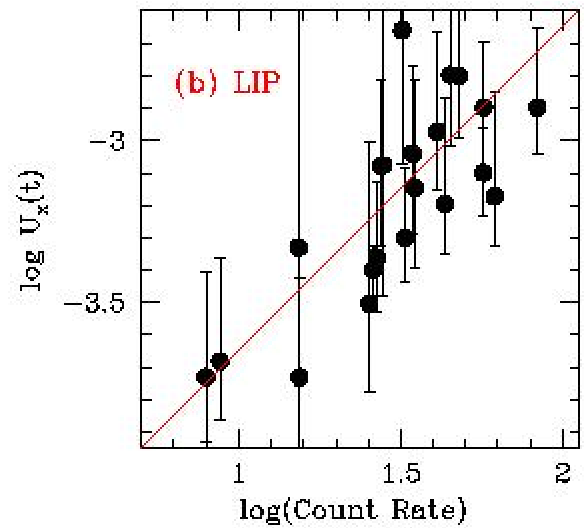
$$\log U_X(t) = \log Q_X(t) - \log(4\pi c n_e R^2) =$$

$$= \log[(Ctr(t)/S_{eff}) \times (4\pi D^2)] - \log(4\pi c n_e R^2)$$

$(n_e R^2)_{LIP} = 6.6\ 10^{39}\ cm^{-1}$



$(n_e R^2)_{HIP} = 3.8\ 10^{37}\ cm^{-1}$



Continuous Flow Model Ruled Out

→ **The Winds must be Compact**

Lower limit on LIP n_e and R

- Low Ionization Phase (LIP):

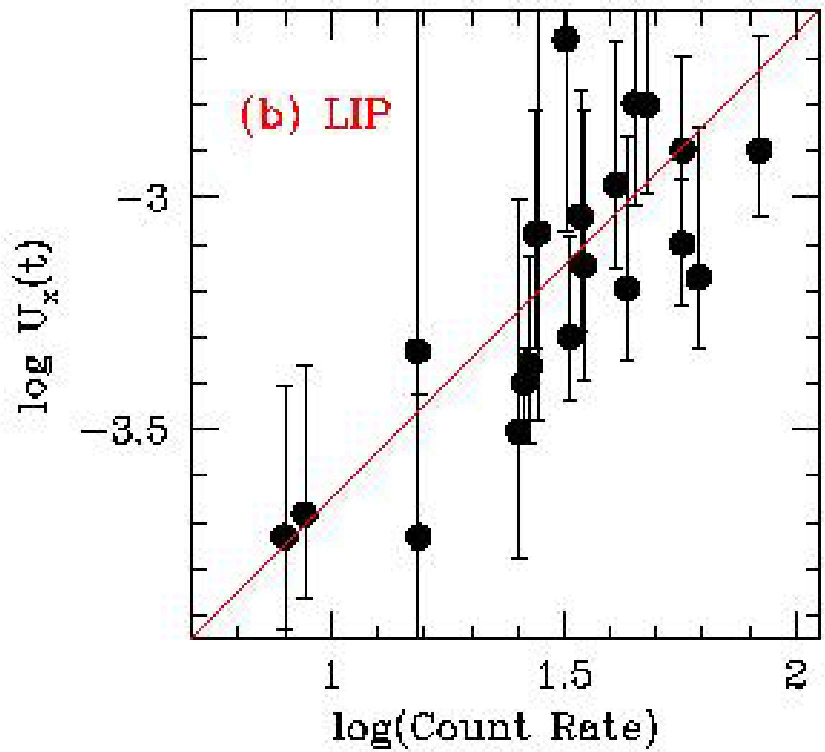
in equilibrium at all times

⇨ $t_{eq}(LIP) < \Delta t^{l,m} < 3$ ks

⇨ $n_e(LIP) > 8.1\ 10^7$ cm^{-3}

But $(n_e R^2)_{LIP} = 6.6\ 10^{39}$ cm^{-1}

⇨ **R(LIP)** $< 8.9 \times 10^{15}$cm
< 0.0029 pc



R(LIP) < 3.5 light days

HIP n_e and R

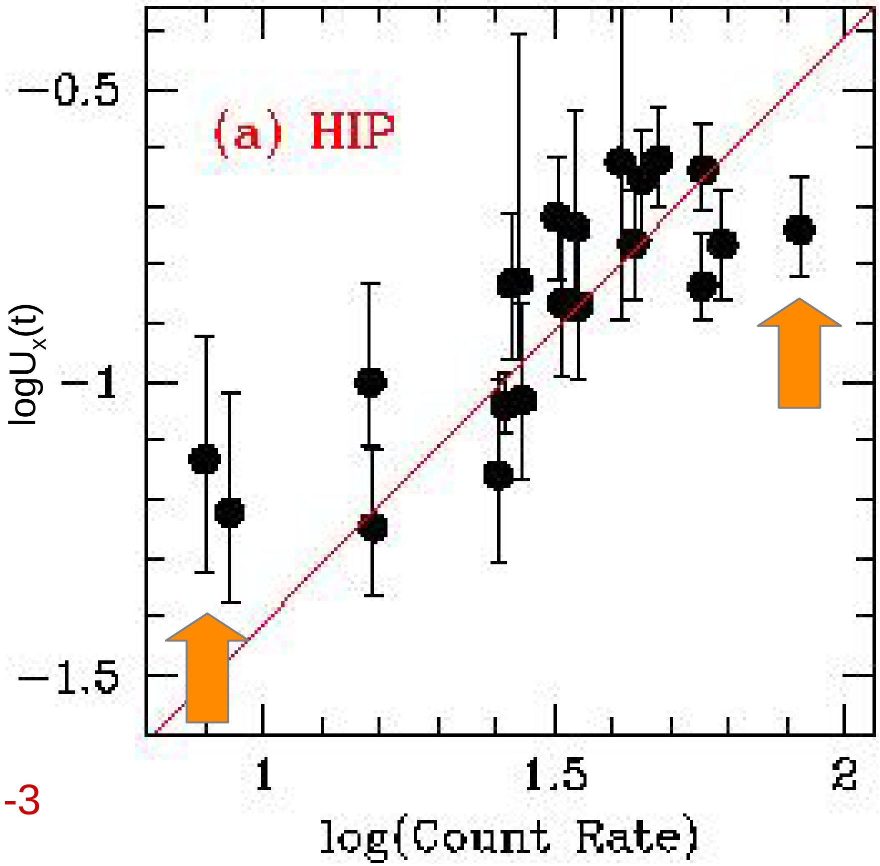
- High Ionization Phase (HIP):

  out of equilibrium at extreme fluxes (high and low)

  ⇨ $t_{eq}^{i,j+k}$(HIP) > Δt^{j+k} > 10 ks (recombining)

  HIP in eq. at moderate fluxes

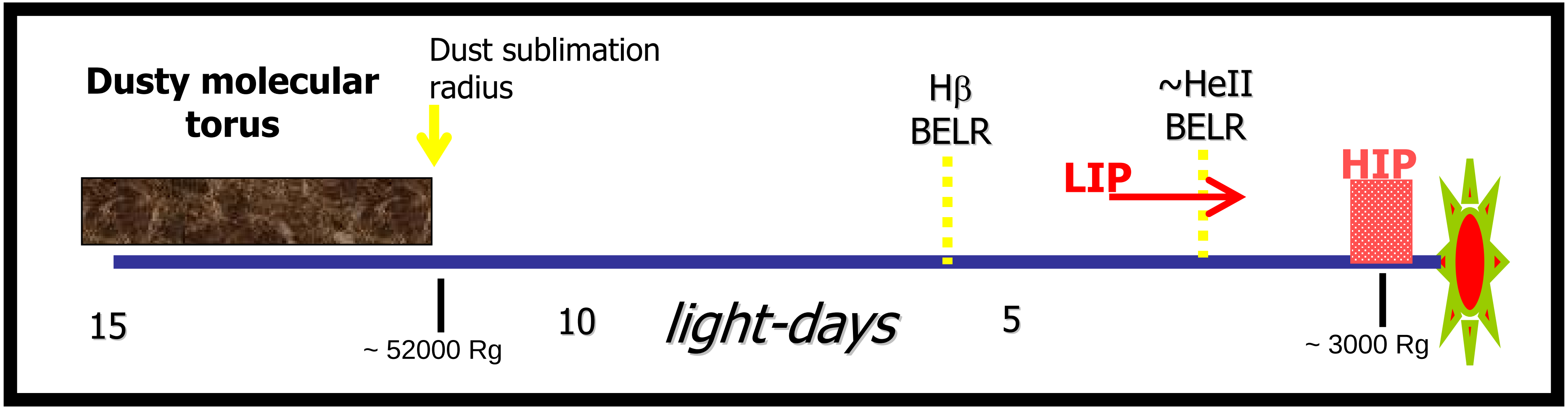
  ⇨ $t_{eq}^{l,m}$(HIP) < $\Delta t^{l,m}$ < 3 ks



➡ n_e(HIP)=(0.6-2.1)x 10^7 cm^{-3}

➡ **R(HIP) = (1.3- 2.6)x 10^{15} cm = (0.5-1.0) light days**

Warm Absorber (wind) Location



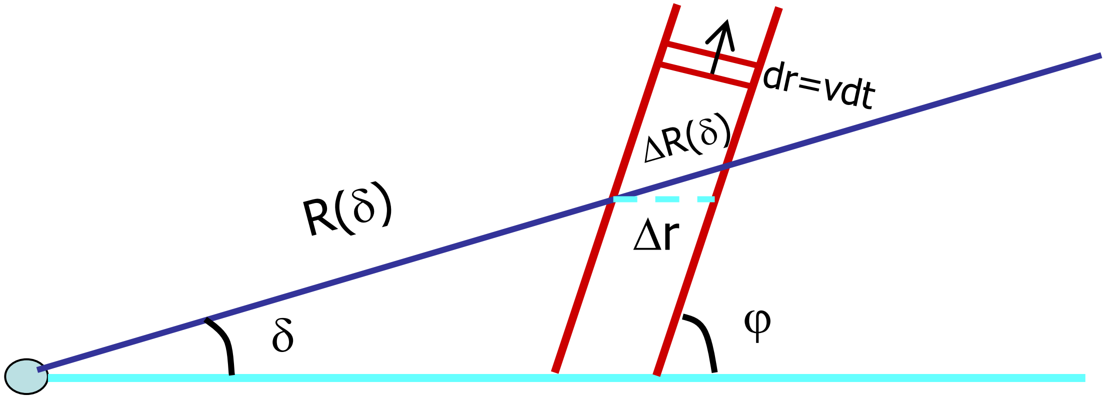
- Rules out Obscuring molecular torus
  - Minimum dust radius, r_{subl}(NGC4051) ~ 12-170 light-days
- R_{LIP} < 3.5 ld; R_{HIP}~0.5-1 ld: consistent

  ➡ Spatially co-located ?

➡ Disk winds, on BELR scale

Cylindrical/Conical Geometry

- All Spherical configuration related to known structures are ruled out.
- Thin spherical shells are still possible, but implausible (need fine-tuning not to degenerate into a continuous flow: which is ruled out): testable by re-observing NGC 4051
- Next simpler symmetry: cylindrical (or bi-conical): consistent with all our findings



$$\Rightarrow \quad \dot{M}_{out} = (0.02\text{-}0.05)\ \dot{M}_{accr}$$

Mass Outflow Rates vs Mass Accretion Rate for NGC 4051

$$\dot{M}_{out} = 0.8\pi m_p (n_e R^2)[v_r / \cos(\varphi - \delta)] \times$$
$$\times [(\Delta R / R)^2 + 2(\Delta R / R)] \cos^2 \delta \sin \varphi$$

For $\varphi = 90^0$ and $\delta = 30^0$ we measure:

$\dot{M}_{LIP} < 0.9 \times 10^{-4} M_\odot \, yr^{-1} = 0.02 \, \dot{M}_{accr}$

$\dot{M}_{HIP} = (0.7\text{-}1.4) \times 10^{-4} M_\odot \, yr^{-1} = (0.02\text{-}0.03) \, \dot{M}_{accr}$

$\dot{M}_{out} = (0.02\text{-}0.05) \, \dot{M}_{accr}$

KP = $(3\text{-}8) \times 10^{37}$ erg s^{-1}

(assuming $v = 2v_r = 1000$ km s^{-1})

AGN-Feedback from NGC 4051

Assuming $M_{BH}^{NGC4051} \sim 2\times10^6\ M_\odot$ all accreted

$M_{out} = (0.02\text{-}0.05)M_{BH} = (0.4\text{-}1) \times 10^5\ M_\odot$

→ Unimportant for IGM metal-feeding

$KE_{aval} \approx (0.4\text{-}1) \times 10^{53}$ ergs

$\lesssim 10^{55}$ ergs required to unbound hot ISM and inhibit large-scale star formation (e.g. Hopkins+06)

→ May control star-formation

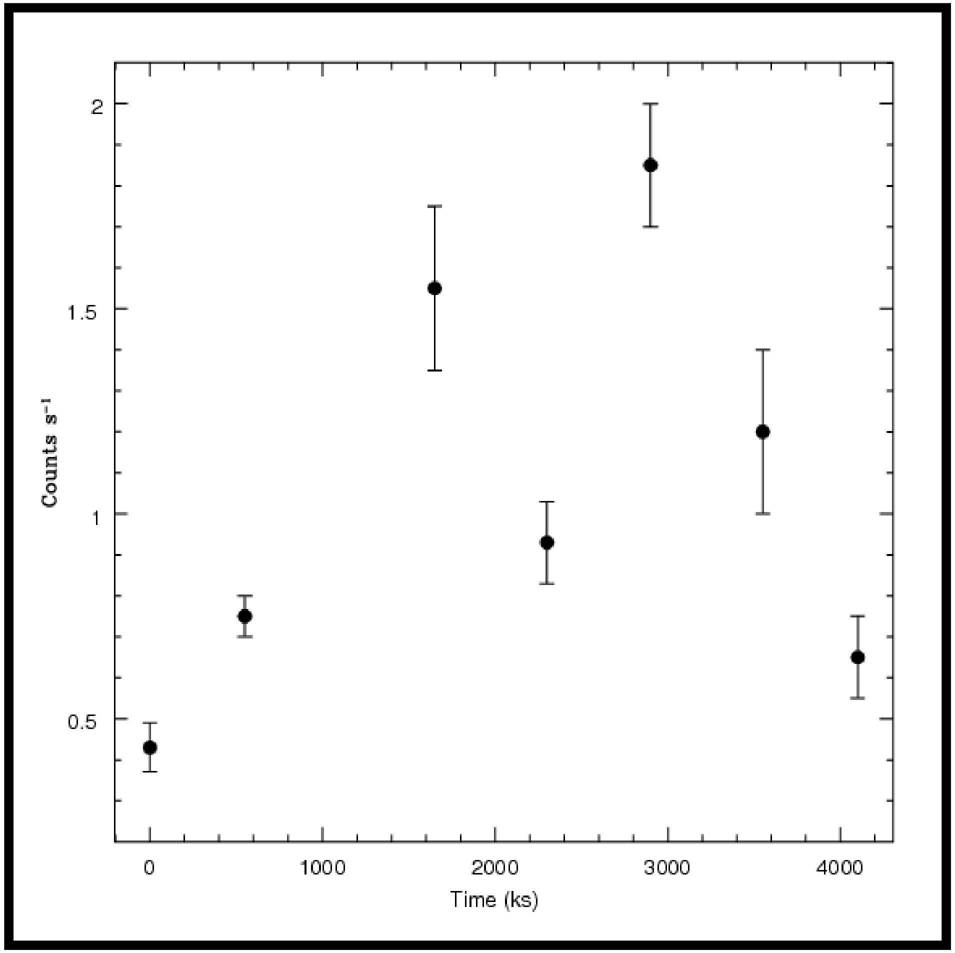
<< $\sim10^{60}$ ergs required to control host-galaxy and surrounding-IGM evolution (e.g. Natarajan+06)

→ Unimportant for M_{BH}-σ

But NGC 4051 LOW M_{BH} and L_{BOL}

SUZAKU Monitoring Campaign of NGC 5548

- **2 Month Monitoring**
- **227 ksec**
- **1 Visit every week**
- **High S/N**
- ***x*4 flux variation**



WA properties constrained through **Chandra HR data**

2 Velocity Components

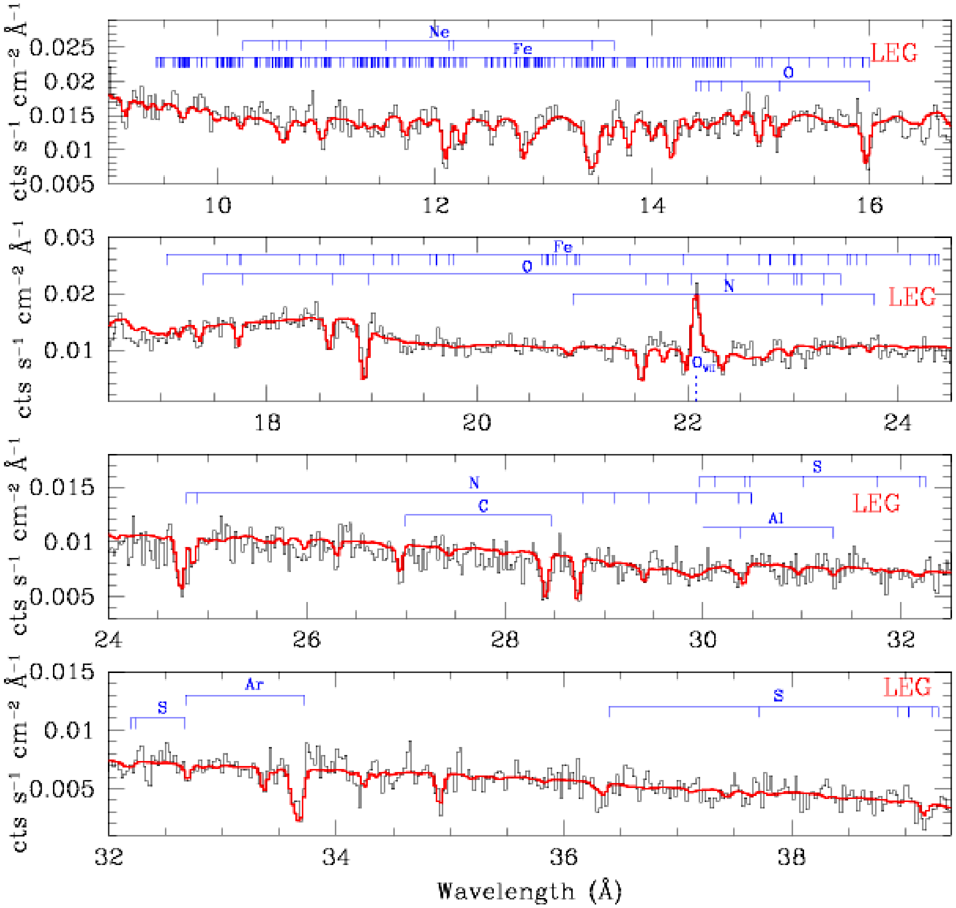
Each modeled with 2 absorbers

HV: V~1100 km/s

SHIP & HIP

LV: V~500 km/s

HIP & LIP



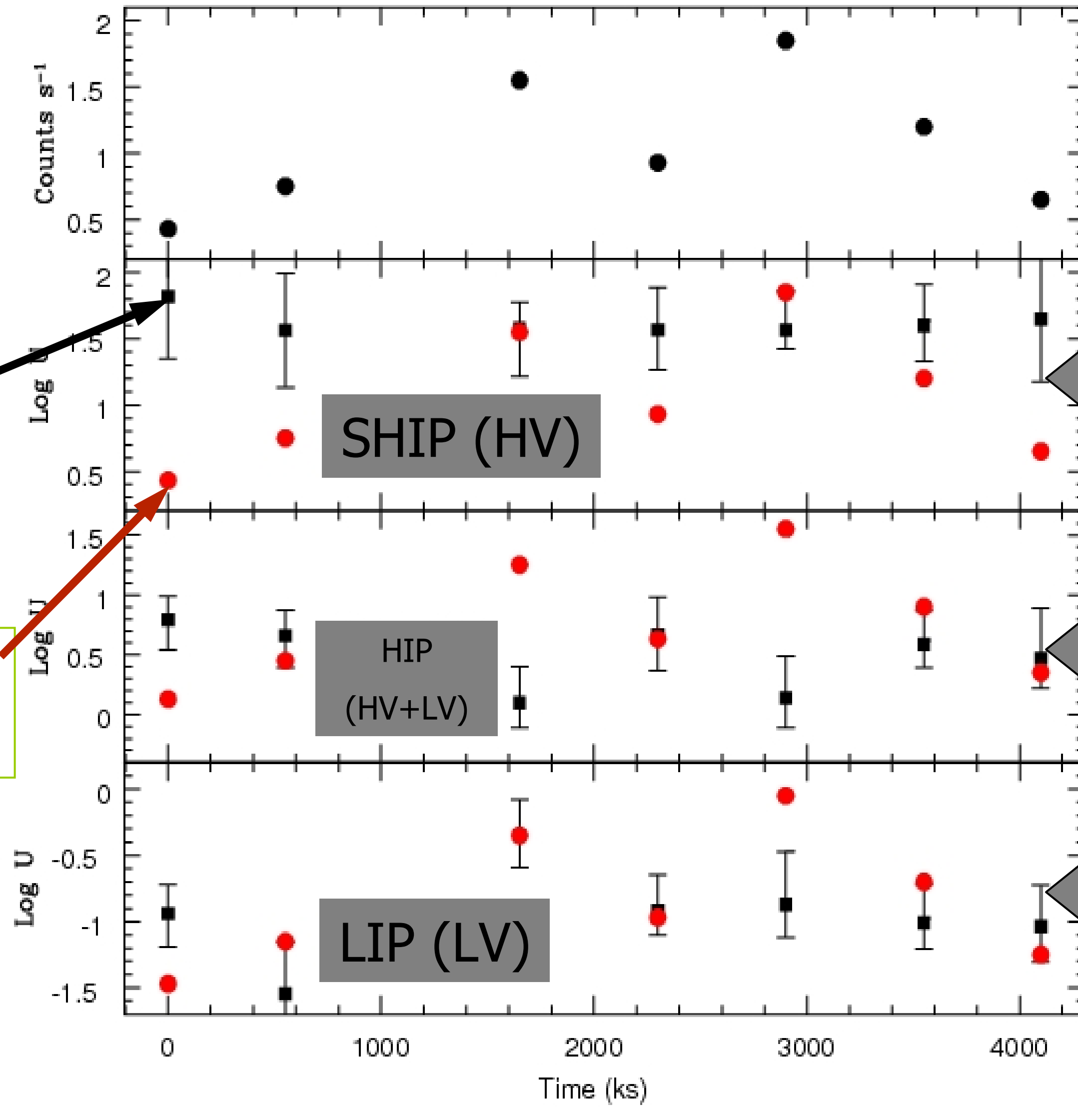
800 ksec MEG & LEG exposure (Andrade-Velazquez+08: SEE POSTER)

NGC 5548 Absorbing Components

Suzaku Light Curve

log $U_x(t)$ measured

log $U_x(t)$ predicted at PE



SHIP does not respond

HIP in PE only in average flux

LIP in PE Always

Wind Locations and Mass Rates

(Assuming NGC 4051 empty bi-conical geometry)

SHIP (HV)	HIP(HV+LV)	LIP (LV)
t_{eq} > 2 Msec	t_{eq} ~ 0.5-1 Msec	t_{eq} < 0.6 Msec
$n_e < 5.4 \times 10^5$ cm^{-3}	$n_e <$ 0.8-2.6 10^5 cm^{-3}	$n_e > 1.0 \times 10^5$ cm^{-3}
R > 0.2 pc ~ 30000 R_G	**R ~ 0.7 – 1.6 pc**	**R(LIP) < 3.1 pc**

$\dot{M}_{out} > 2.5\ \dot{M}_{accr}$ (0.2 $M_\odot$ yr^{-1}**)**

KP > 1.2 x 10^{41} ergs s^{-1} (assuming v = 2v_r = 1000 km s^{-1})

Much more massive & energetic than NGC 4051

AGN-Feedback from NGC 5548

Assuming $M_{BH}^{NGC5548} = 7 \times 10^7\ M_{\odot}$, all accreted

$M_{out} = \sim 2.5\ M_{BH} = 1.8 \times 10^8\ M_{\odot}$

→ Metal-feeds the IGM

$KE_{aval} \approx\ 3.3 \times 10^{57}$ ergs

>> 10^{55} ergs required to unbound hot ISM and inhibit large-scale star formation (e.g. Hopkins+06)

→ Unbinds hot ISM and stop star-formation

<< $\sim 10^{60}$ ergs required to control host-galaxy and surrounding-IGM evolution (e.g. Natarajan+06)

→ Unimportant for M_{BH}-σ

NGC 5548 still LOW M_{BH} and L_{BOL}

Extrapolating to Massive QSOs

($M_{BH} \approx$ *few* x 10^9 $M_\odot$, $L_{bol} \approx 10^{47}$ ergs s^{-1}
=> $\dot{M}_{accr} \approx 15$ $M_\odot$ yr^{-1}, for η=0.1)

$M_{out} \geq 2.5\ M_{BH} \approx 10^9$-$10^{10}$ $M_\odot$!!! (neglecting ISM mass entraining)

Comparable with ULRIGS (+ QSO Envs are Metal-rich)

Important for IGM metal-feeding

$KE_{aval} \approx$ *few* x 10^{59} ergs !!! (neglecting wind acceleration)

Comparable to E_{bound}(Bulge) and

E from simulations

Controls star-formation + Regulates M_{BH}-σ

Speculative !!! More data needed!

Conclusions

- **AGN X-ray Outflows are:**
  - **Disk winds** (NGC 4051 + NGC 5548)
  - **Dense, compact**, and **multi-phase** (possibly in **pressure balance)**
- **Location & Geometry:**
  - **NELR and Torus are ruled out** as *Originating* locations (too far)
  - **Continuous Flow is ruled out** (WA are seen varying)
  - **Spherical geometry is** (almost) **ruled out**
  - **Conical** (cylindrical) geometry works:
    - N_H down cone > 10 x N_H observed, possibility NALs=BALs (Krongold et al., 2007)
    - *Consistent with transverse motion evidence* (*UV data: REF.)*
- **Feedback:** NGC 4051 + NGC 5584 results imply (speculative!!!):
  - **Large Mass and Energy** deposited into Bulge/IGM, if scales with L_{bol}
  - Important for **IGM Metal-feeding**
  - **Control Start-Formation**
  - **Regulate MBH-σ**
- More Objects needed