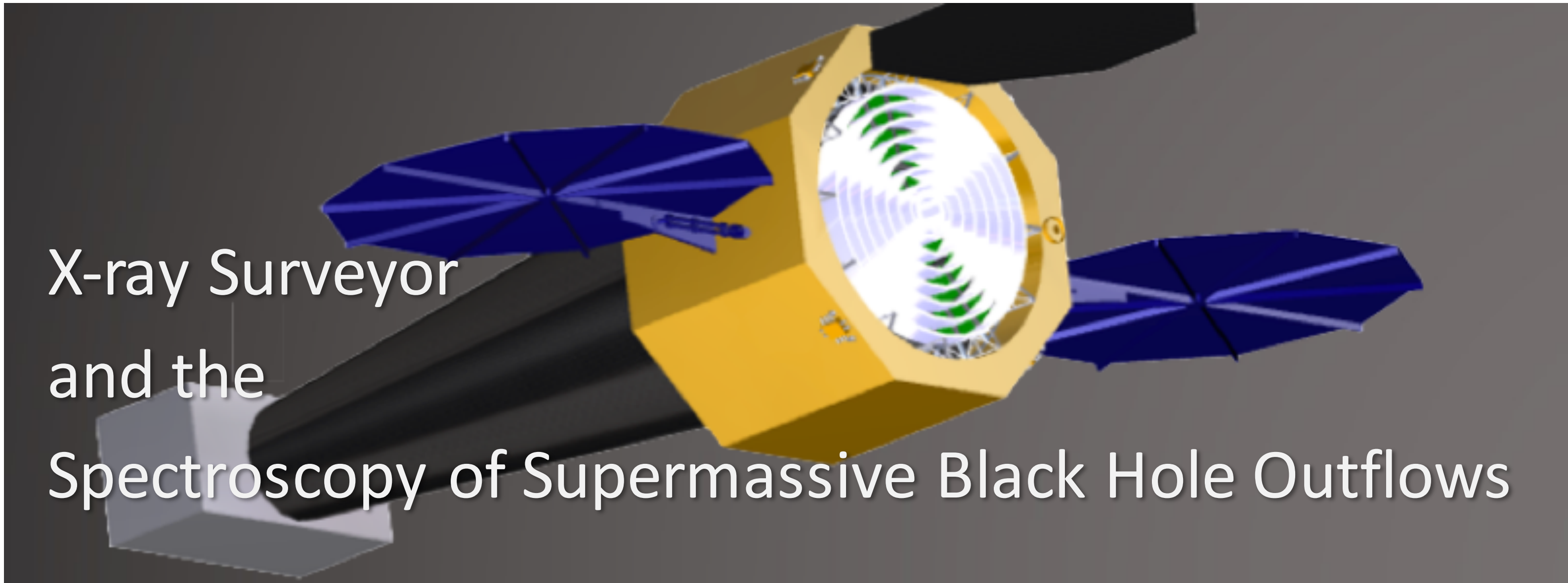
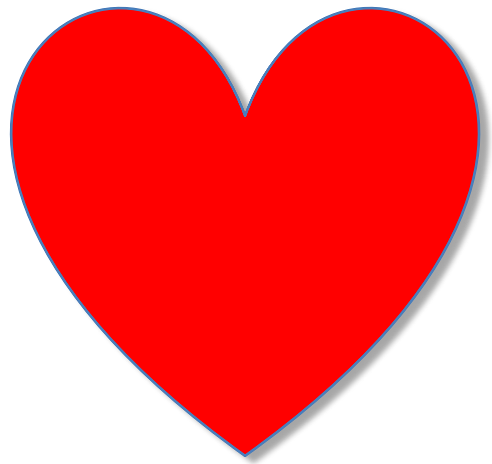


X-ray Surveyor and the Spectroscopy of Supermassive Black Hole Outflows

Martin Elvis

Harvard-Smithsonian Center for Astrophysics

I



X-ray Surveyor

The need has long been obvious

Cornell University Library

We gratef

arXiv.org > astro-ph > arXiv:astro-ph/9611178

Search or Article-id

Astrophysics

Science Driven arguments for a 10 sq.meter, 1 arcsecond X-ray Telescope

Martin Elvis, Giuseppina Fabbiano (Harvard-Smithsonian Center for Astrophysics)

(Submitted on 21 Nov 1996)

X-ray astronomy needs to set bold, science driven goals for the next decade. Only with defined science goals can we know what to work on, and a funding agency appreciate the need for significant technology developments. To be a forefront science the scale of advance must be 2 decades of sensitivity per decade of time. To be stable to new discoveries these should be general, discovery space, goals.
A detailed consideration of science goals leads us to propose that a mirror collecting area of 10 sq.meters with arcsecond resolution, good field of view (>10 arcmin), and with high spectral resolution spectroscopy (R=1000-10,000) defines the proper goal. This is about 100 times AXAF, or 30 times XMM. This workshop has shown that this goal is only a reasonable stretch from existing concepts, and may be insufficiently bold. An investment of roughly $10M/year for 5 years in X-ray optics technologies, comparable to NASA's investment in ASTRO-E or a SMEX, is needed, and would pay off hugely more than any small X-ray mission.

Comments:	20 pages, Latex, ngxo.sty file included Talk given at ``Next Generation X-ray Observatories" Workshop, Leicester, England (June 1996)
Subjects:	**Astrophysics (astro-ph)**
Cite as:	**arXiv:astro-ph/9611178**
	(or **arXiv:astro-ph/9611178v1** for this version)

Because: Diagnostics!

High Resolution X-ray Spectroscopy has also long been obviously needed

New Century of X-ray Astronomy
ASP Conference Series, Vol. 251, 2001
H. Inoue and H. Kunieda, eds.

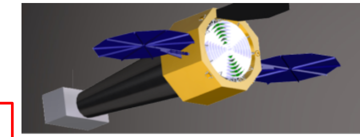
Thermal Limit Spectroscopy as a Goal for X-ray Astronomy

Martin Elvis

Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge MA 02138 USA

Abstract.
The R ~300–1000 grating spectra from XMM-Newton and *Chandra* are a radical advance, allowing spectroscopic physics techniques to be applied to X-ray astronomy, revolutionizing a wide range of research. Ten years on these spectra will be routine, and higher resolution will be needed. I propose "Thermal Limit Spectroscopy" as the next natural goal for X-ray spectroscopy. This will open up new physics: plasma physics, velocity widths, Doppler shifts, line profiles, and absorption lines in photoionized plasmas. A resolution of R=3000–10,000 is required, and the technology is within reach.

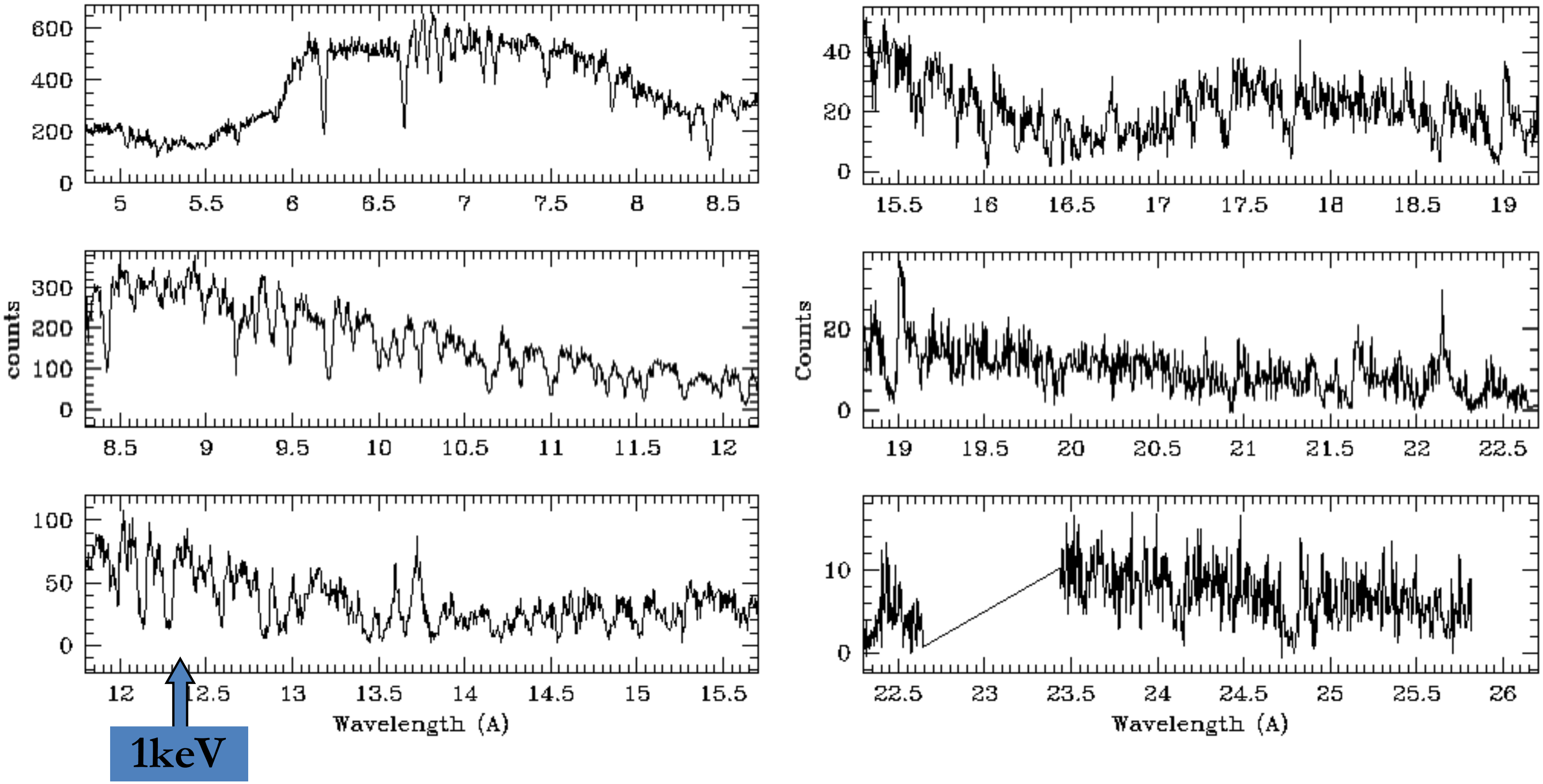
State of the Art in X-ray AGN Winds



10 days (900 ksec) with Chandra HETGS @ R~400

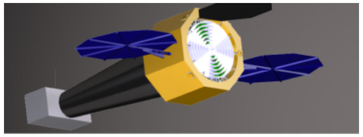
Active Galaxy NGC3783

> 100 spectral features



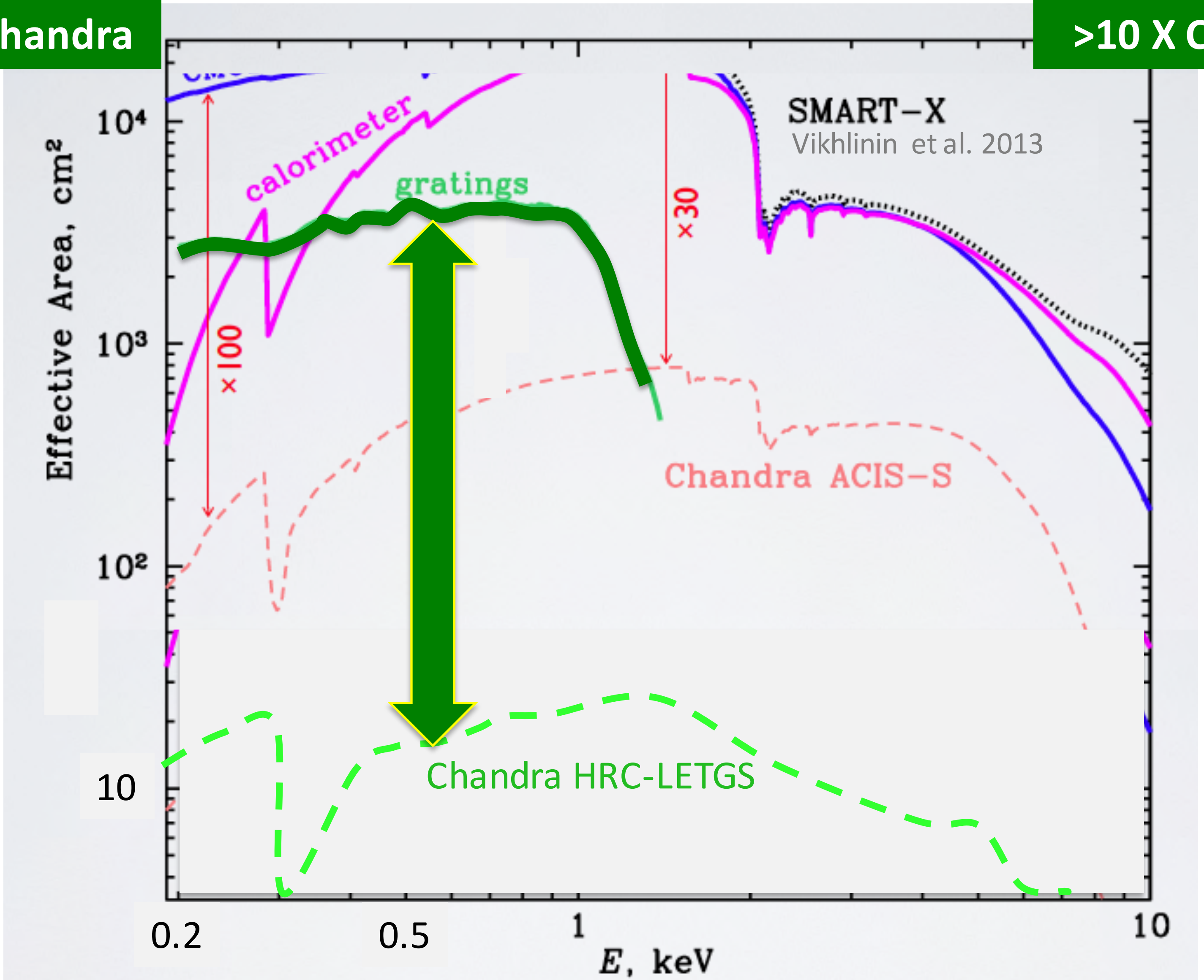
Kaspi et al. 2001
Krongold et al. 2005
…

1 hour @ R ~ 5000 with X-ray Surveyor

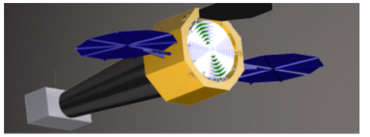


Area 4000 cm^{-2}
>250 X Chandra

***R* ~ 5000**
>10 X Chandra



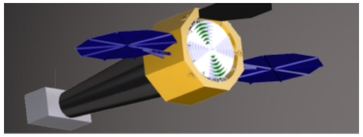
Diagnostics



RESOLUTION

- Resolves ~all blends
- Weaker lines detectable → more (n_e, T) diagnostics
- 60 km s^{-1} → thermal line widths resolved
    - in collisional X-ray plasma
- Doppler shifts
- Turbulent velocities, $T_{thermal}$ vs T_{ion}
- Curve of growth → n_{ion}
- Resolves components seen in UV
- *Needs excellent calibration*:
    - wavelength/energy to small fraction of resolution (5%?)

Diagnostics need Area



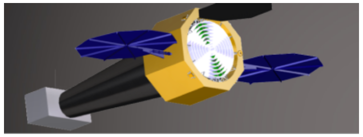
PHOTON HUNGRY

- R=5000 requires ~10× #photons as R=500

For absorption lines

- $\Delta E = 0.1$ eV @ 0.5 keV
  - $\Delta\lambda = 0.0044$A @22A
- 10^4 resolution elements/keV
- 100 counts each
- = 10^6 counts/1keV wide spectrum

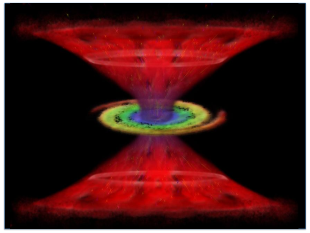
Area Enables



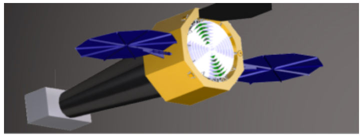
AREA ENABLES

- **Depth:**
  - 1 Msec gives to NGC3783-quality spectra at $f = 4 \times 10^{-14}$ cgs
  - → High z
    - Fe-K @ z>2 (6.4keV → 2.1 keV)
    - OVII 21.6Å → 64.80Å
  - → Low Luminosity $L \ll L_{Edd}$
  - → Weak Lines

- **Speed:**
  - → Large Surveys: $M_\bullet$, L/L_{Edd}, …
  - → 100s/year NGC3783-quality spectra of 10×fainter sources, $f = 10^{-12}$ cgs
  - → Variability on short-timescales → density, radius.
    - 1Ms on NGC3783 → 250 spectra
  - *Needs spacecraft agility: rapid slew/settle*



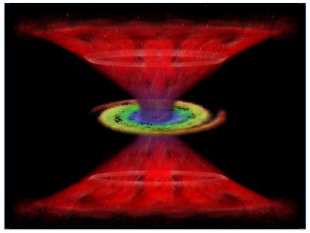
Outflows from Super-Massive Black Holes



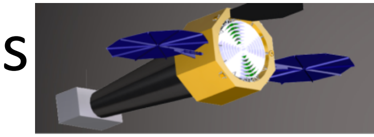
The Big Questions

- How supermassive black holes work
- How SMBH grow
- How SMBH merge
- Accretion luminosity of the universe
- Effects on galaxies, cluster growth
- "Pollution" of the primordial gas

- ➢ What is a quasar?
- ➢ Quasar evolution
- ➢ Runaway black holes
- ➢ Versus nuclear fusion (stars)
- ➢ Feedback
- ➢ Warm-Hot Intergalactic Medium



Outflows from Super-Massive Black Holes



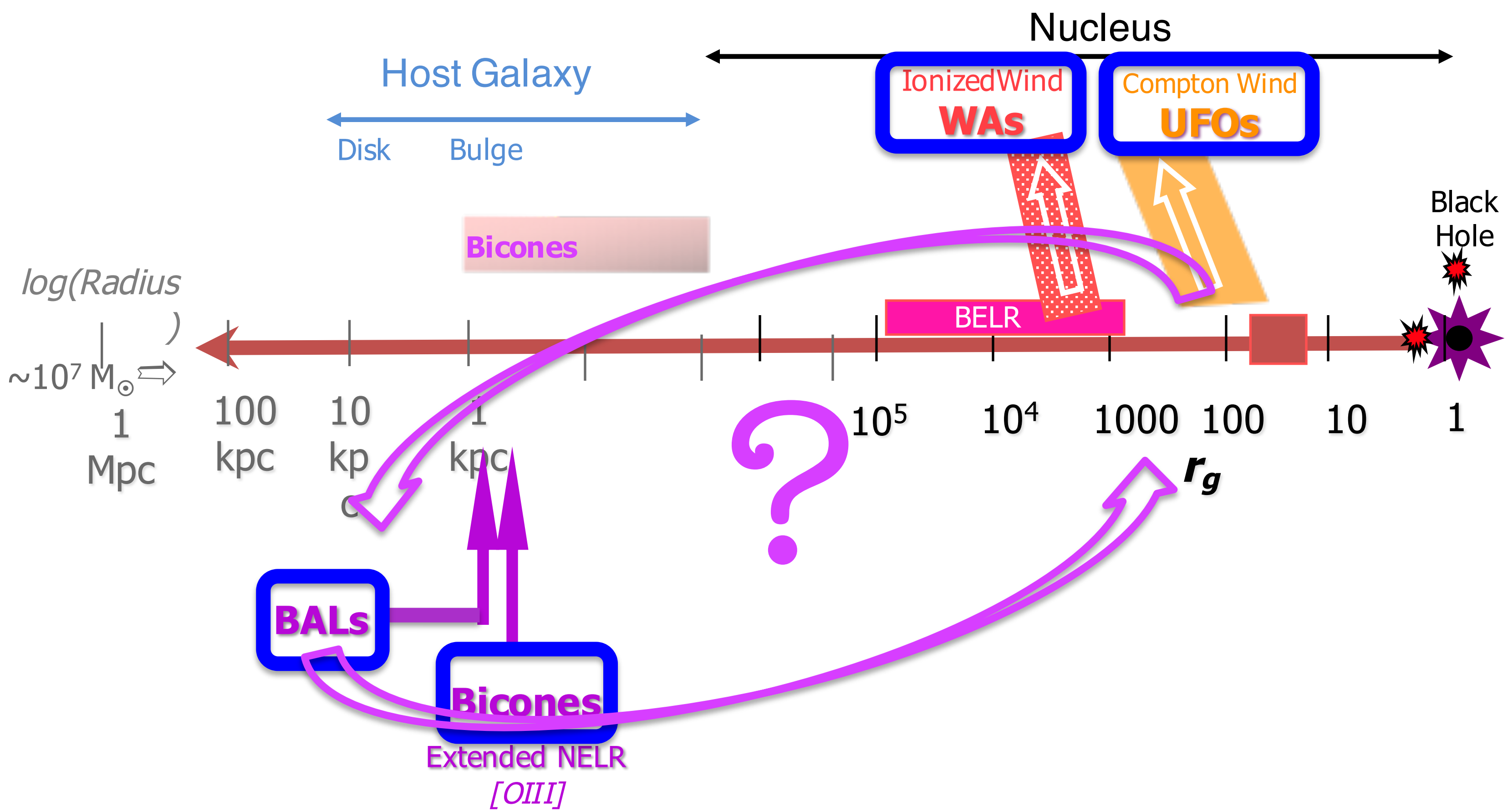
Why do we care?

- How supermassive black holes work
- How SMBH grow
- How SMBH merge
- Accretion luminosity of the universe
- Effects on galaxies, clusters
- “Pollution” of the primordial gas

- What is a quasar?
- Quasar evolution
- Runaway black holes
- Versus nuclear fusion (stars)
- Feedback
- Warm-Hot Intergalactic Medium

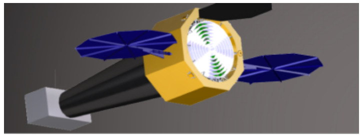
Outflows from Super-Massive Black Holes

6 ORDERS OF MAGNITUDE IN SCALE FOR AGN PHYSICS

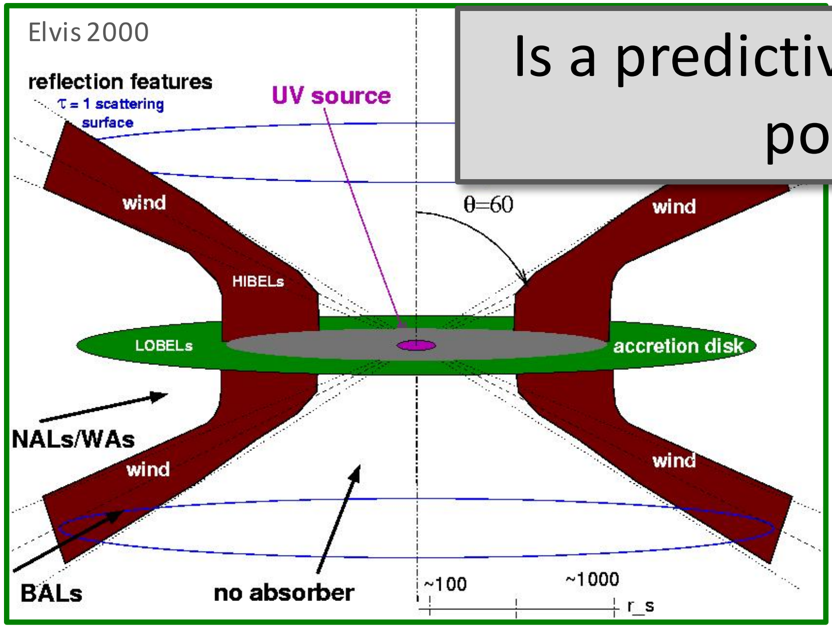


Martin Elvis, September 2007

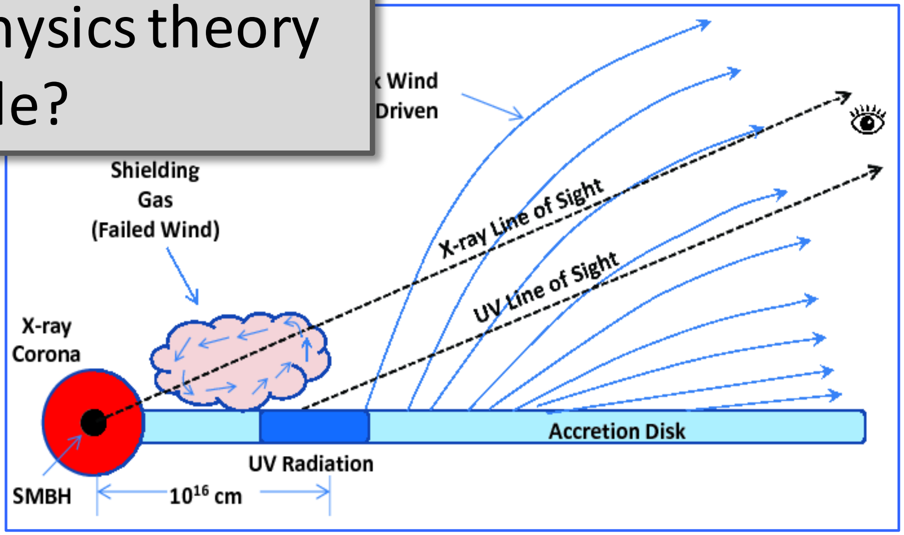
How do Supermassive Black Holes Work?



Is the physics of the **Inner Structure of Quasars** dominated by *winds*?



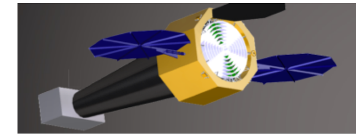
Is a predictive physics theory possible?



Just 4 Mechanisms

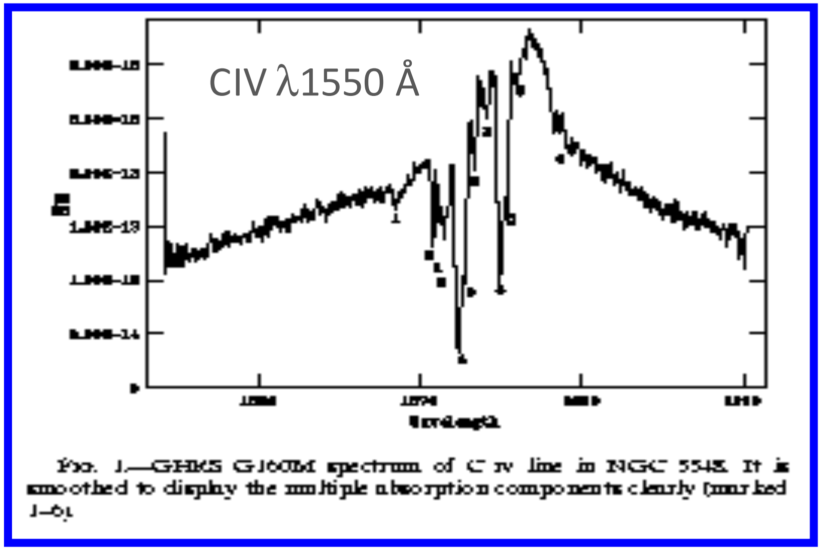
1. Compton scattering – *electrons: only at $L=L_{Edd}$*
2. Line driving – *atoms: force multiplier $L>\sim 0.05\ L_{Edd}$*
3. Dust driving – *molecules, solids*
4. Magnetic "slingshot"

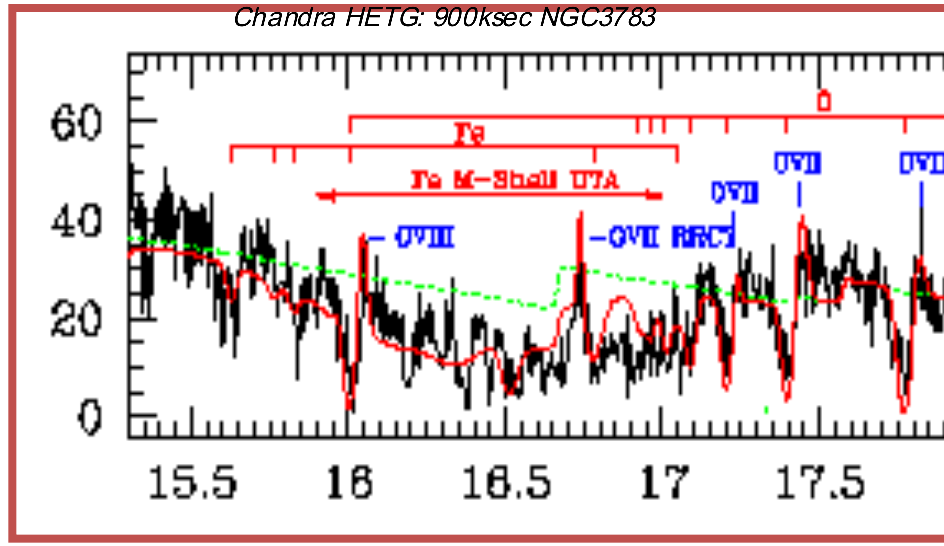
Warm Absorber outflows (WAs)



Narrow UV lines: NAL

Narrow X-ray lines: WA

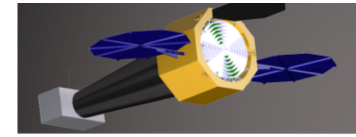




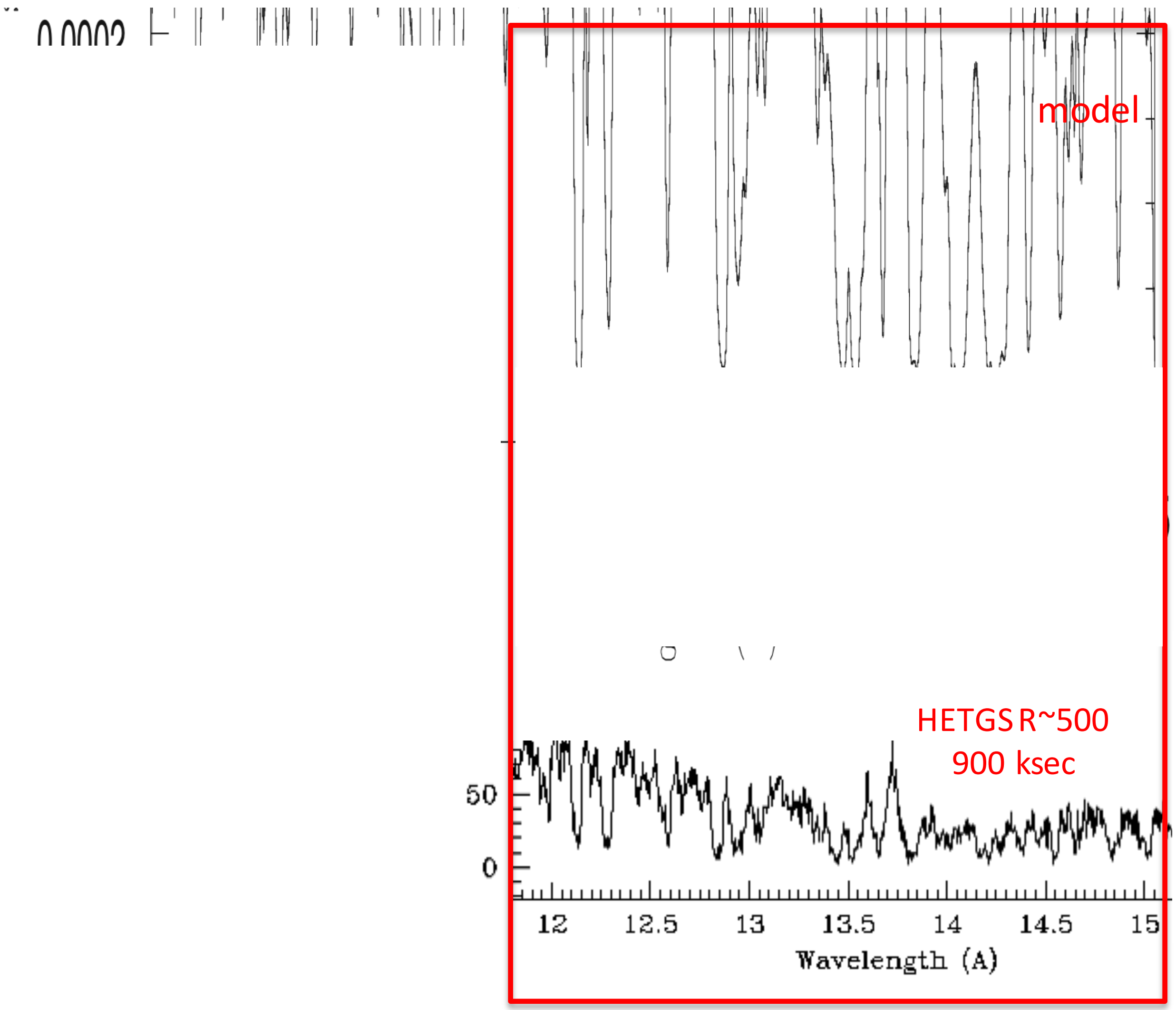
Narrow UV lines	→Same Wind:	Narrow X-ray lines
Outflow ~1000 km s^{-1}	From accretion disk?	Outflow ~1000 km s^{-1}
Seen in 50% of AGN	From "torus"?	*Same* 50% of AGN
High ionization **CIV, OVI**	Base of bi-cones on kpc scale?	High ionization **OVII, OVIII**

Use high *R* UV spectra
as a guide for
X-ray Surveyor

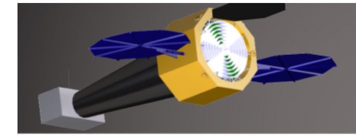
Warm Absorber outflows (WAs)



Line blending is widespread @ R=500
Virtually gone at R=5000



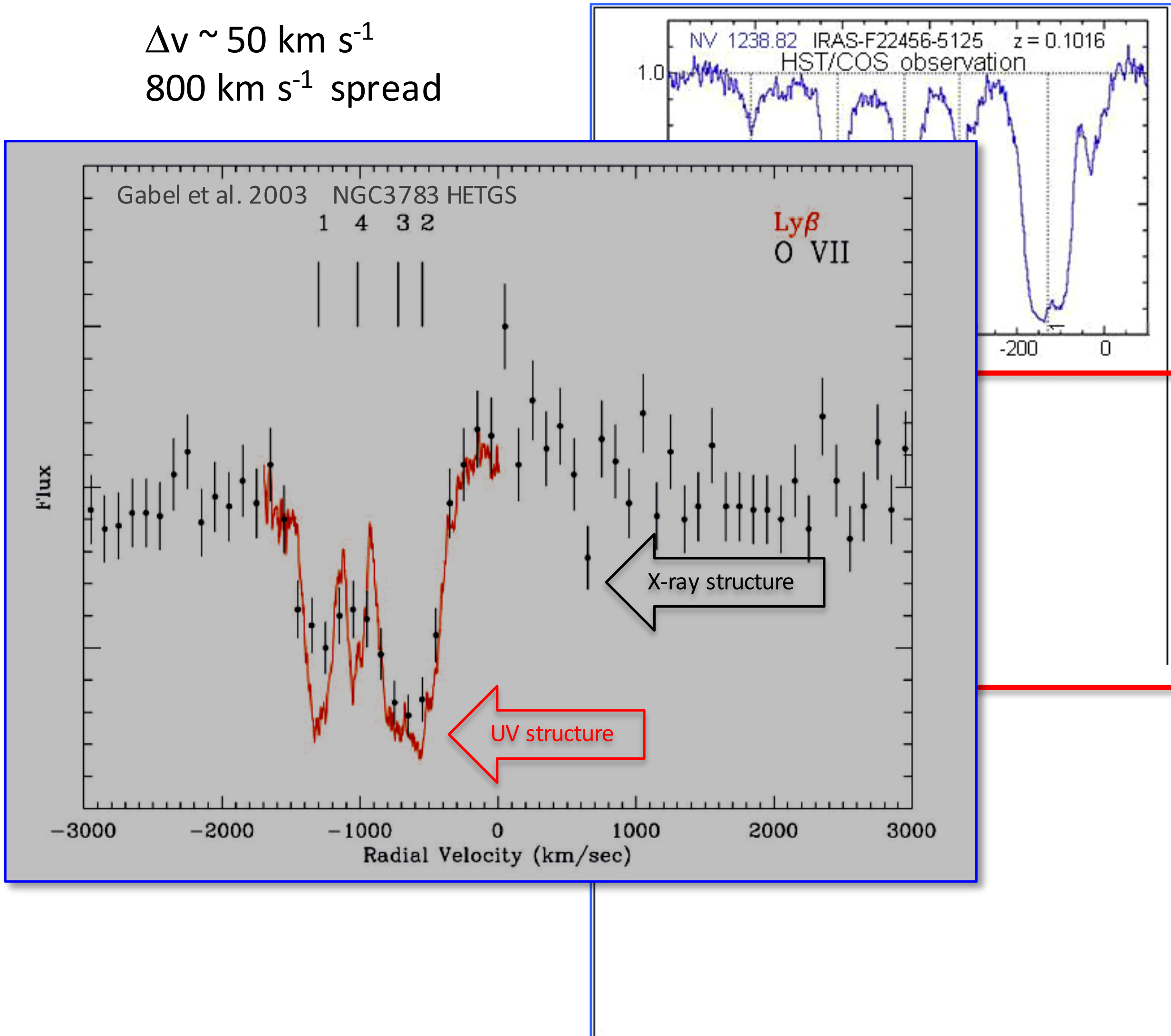
Warm Absorber outflows (WAs)



Even supersonic flows have narrow velocity structures

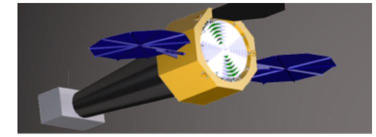
$\Delta v \sim 50$ km s^{-1}
800 km s^{-1} spread

Multiple mass ejection episodes?



adapted from Arav, WHIMEX simulation

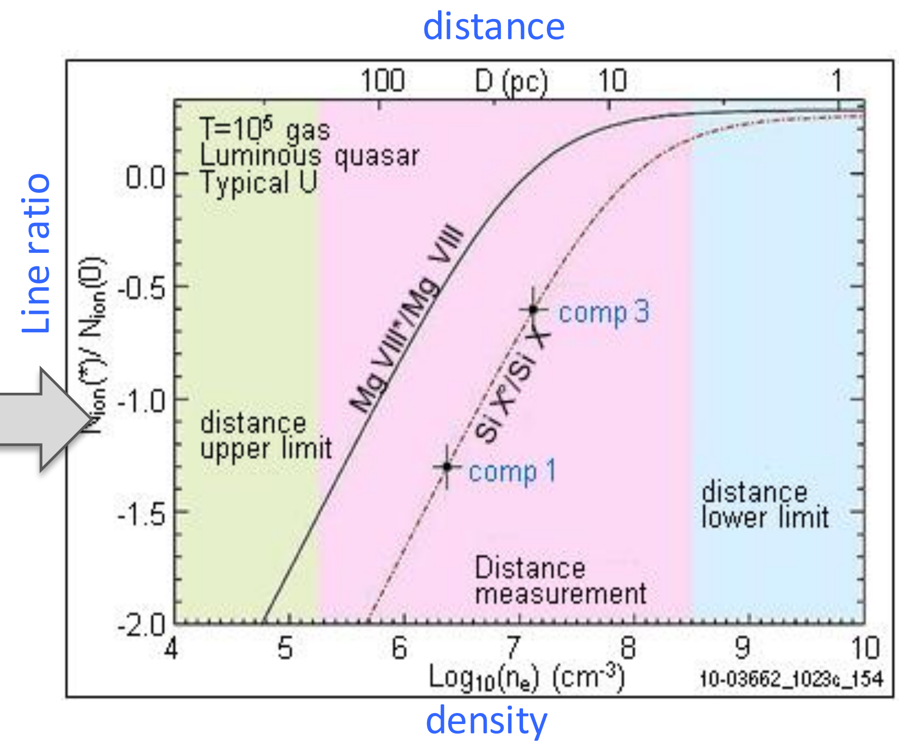
Warm Absorber outflows (WAs)



Where are they? Determines Mass/Energy outflow rates

High ~1%*c* velocities suggest
radius$_{WA}$ ~ few ×1000 r_g = disk wind
Modest energy + mass flow rates
-More subtle feedback physics?
e.g. Hopkins & Elvis (2010)

Metastable lines can give densities
densities give distances
with ionization parameters



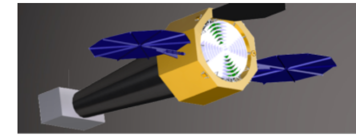
adapted from Arav, WHIMEX simulation

UV gives kiloparsec distances!
e.g. Dunn et al. 2010 –but see McGraw et al. 2015

Energy + mass flow scale with r^2
~10⁸× bigger E_{out} *:* $\mathbf{M_{out}} > \mathbf{M_{accretion}}$
ISM interaction with "dark" outflow

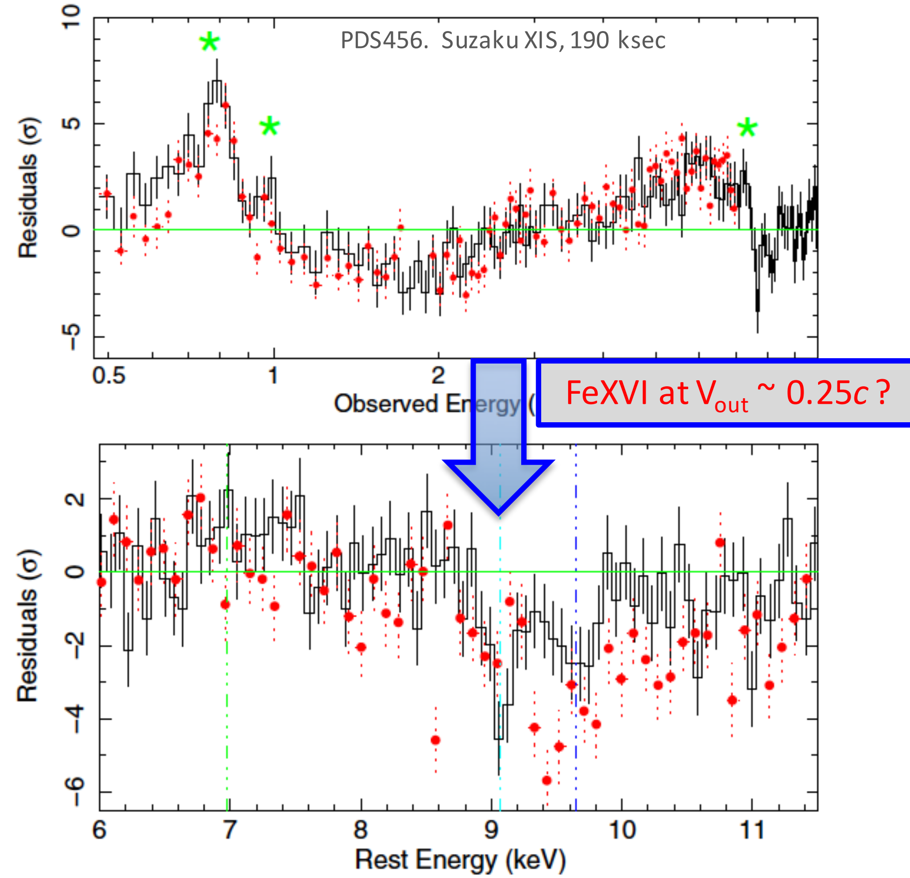
Where will X-ray WAs lie?
Sub-pc or kpc?
Minor or powerful?

Ultra-Fast Outflows (UFOs)



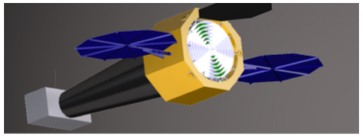
High ~0.1c velocities

- Somewhat controversial
  - E.g. Laha et al. (2014)
- v > 0.1*c* → origin at <100 r_g?
- Present location = ?
- Could they be the BAL "dark" outflows?
- X-ray Surveyor has nothing to add?
  - Highly ionized
    - → No need for lower energy spectra?
  - Features are broad
    - → No use for R=5000?



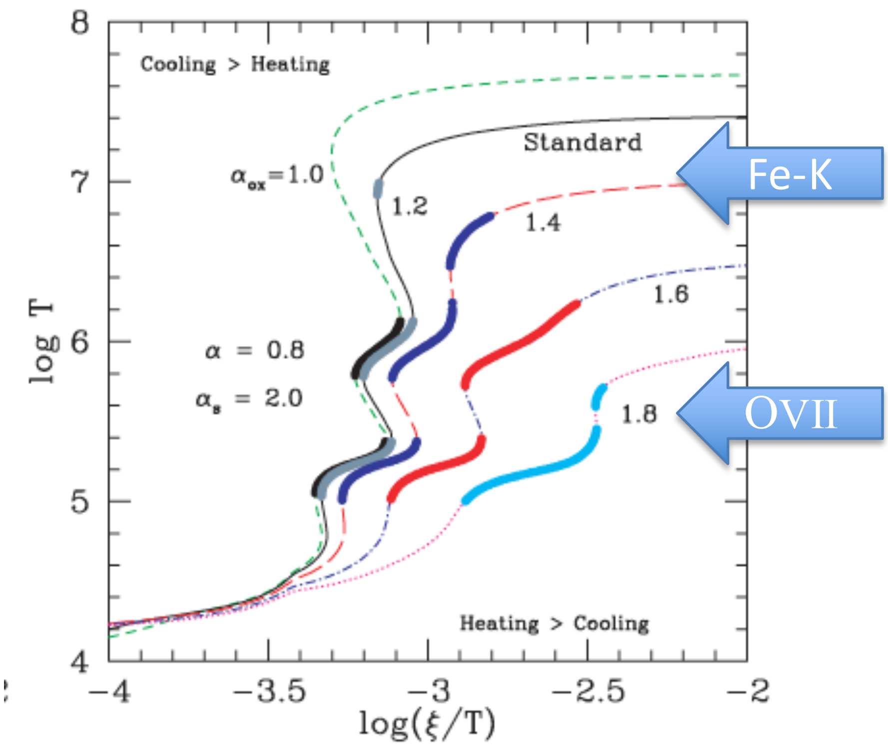
Reeves et al., 2009

Ultra-Fast Outflows (UFOs)



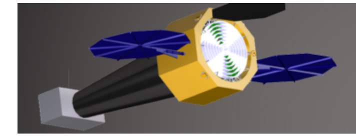
Low Ionization, Low n_{ion} phases?

- Low ionization components are found in Warm Absorbers
- 2-3 phases in pressure equilibrium?
- Why not in UFOs?
  - → R=5000 to see low n_{ion} lines
  - → Low energies for low Ξ transitions



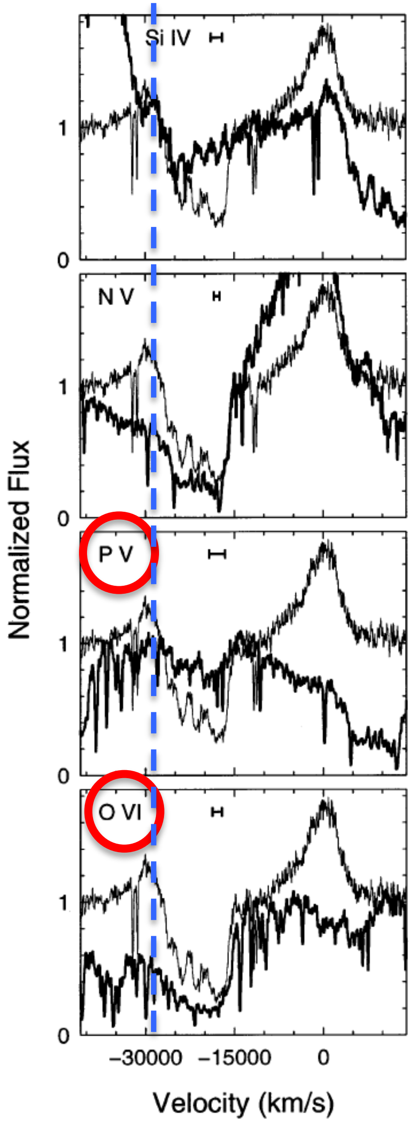
Chakravorty et al., 2009

Broad Absorption Lines (BALs)



Have 3 things in common with UFOs

1. High ~0.1c velocity outflows



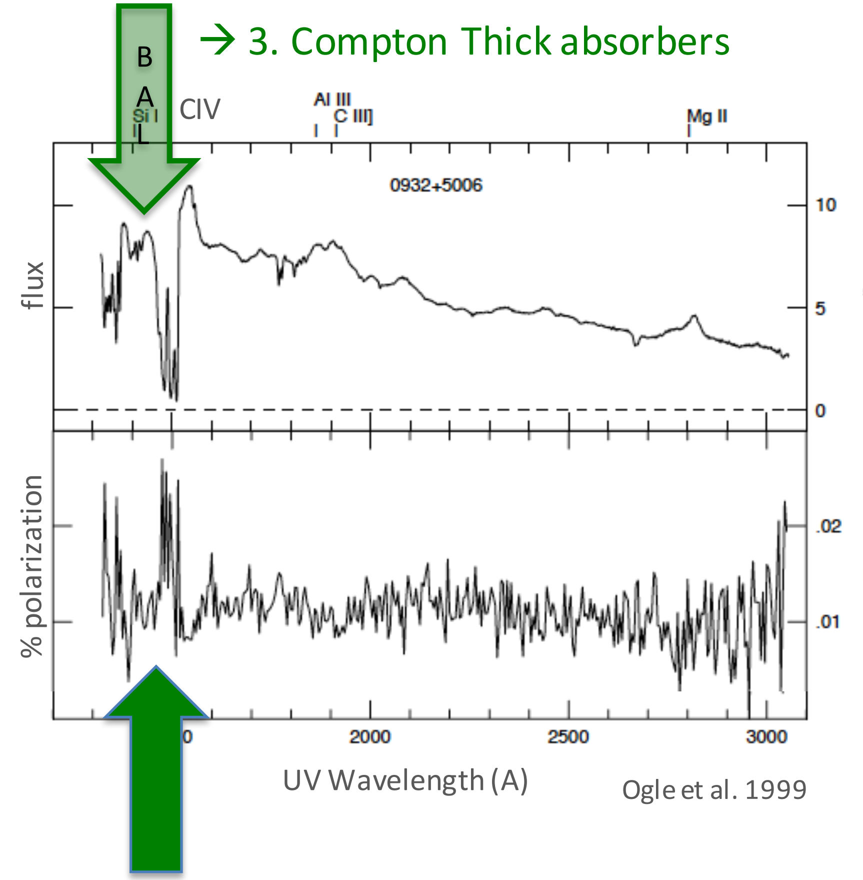
→ Same Wind ?

BUT
UFOs and BALs
Have wildly different cold N_H
$>10^{24}$ vs $<10^{22}$ cm^{-2}

2. High ionization

Hamann et al. 1998

→ 3. Compton Thick absorbers

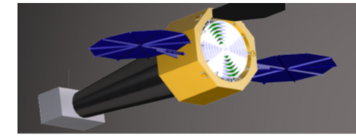


Ogle et al. 1999

Highly polarized
electron scattered flux

Are the weak X-rays polarized/scattered too?

Broad Absorption Lines (BALs)

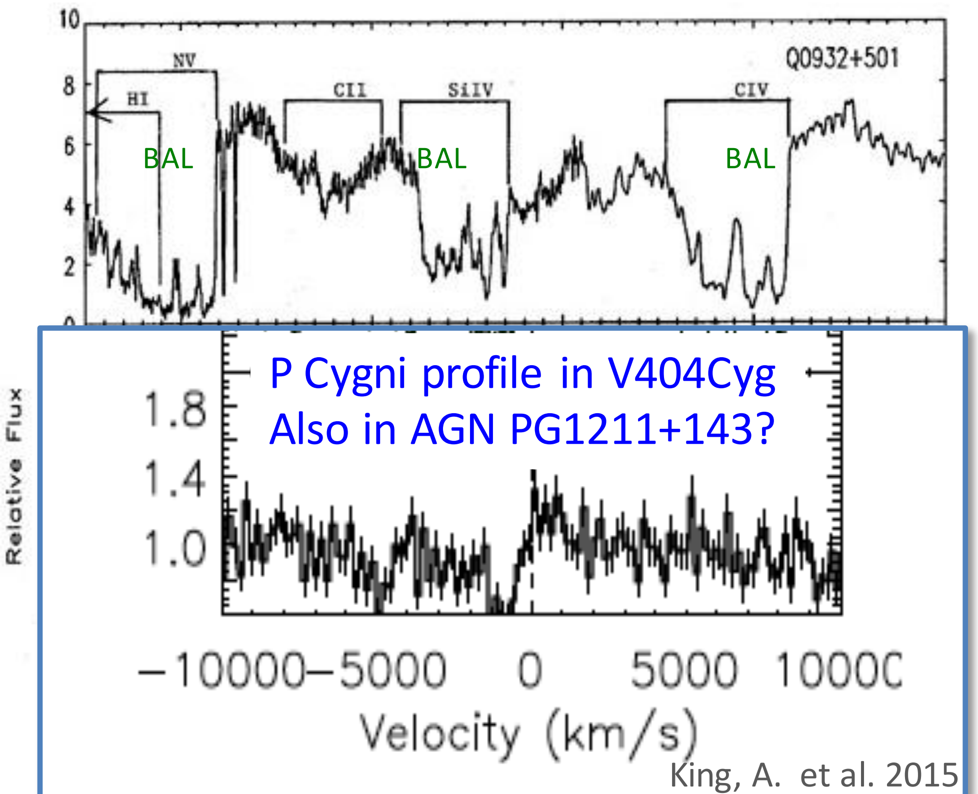


…have complex narrow velocity structure
Why not UFOs too?

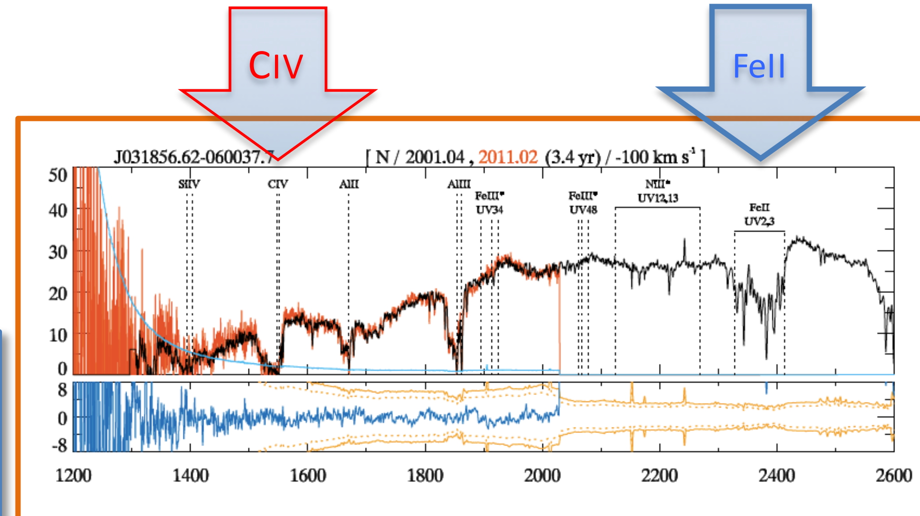
→ R=5000 to see narrow components

…& have low ionization components
Why not UFOs too?

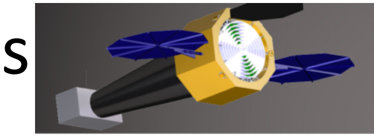
→ E<~2keV to see low ionization lines



King, A. et al. 2015



McGraw et al. 2015



Supermassive Black Holes' Effects on Galaxies = "Feedback"

Narrow Emission Line Regions (NELRs)

1st order Questions:

- How much energy, momentum deposited?
- How are they coupled to ISM?
- Where are they coupled?

Coupling Mechanisms:

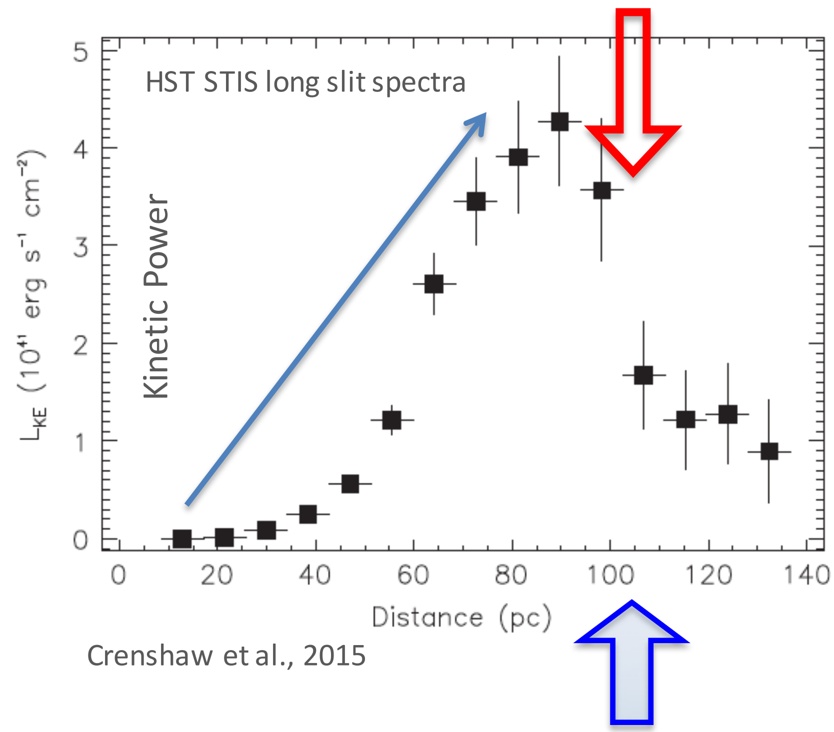
1. Winds
2. Relativistic Jets
3. Radiation

Which dominates where?

All these interactions should generate X-rays
Spectroscopy can diagnose the process

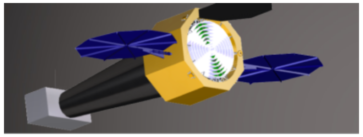
E.g. Active Galaxy NGC4151 [OIII]

Wind loses ⅔ KE in ~20 pc ~0.3"



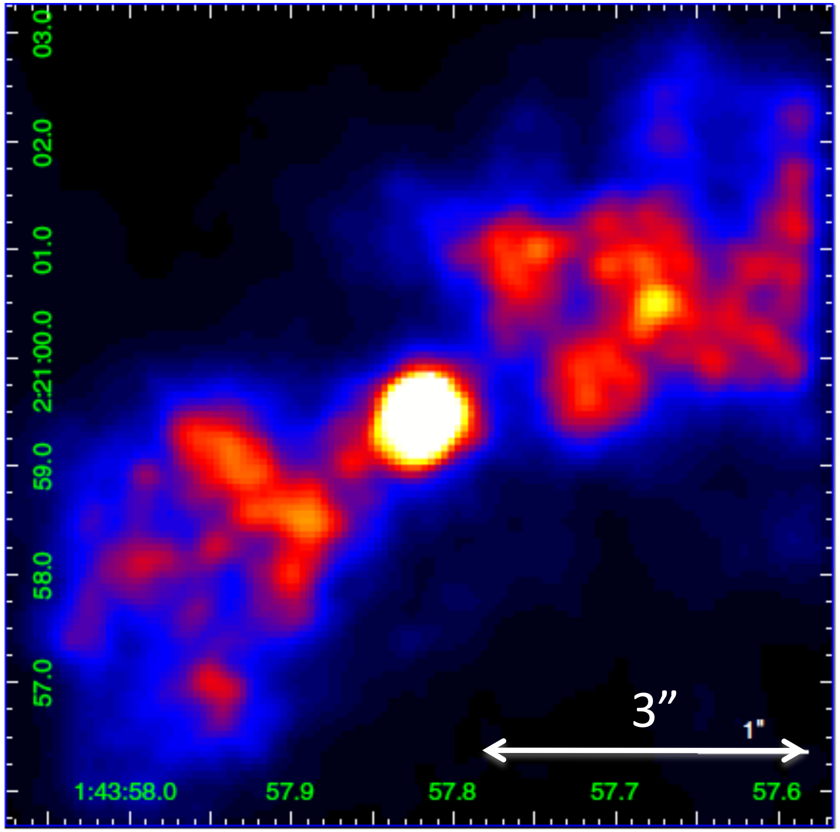
Crenshaw et al., 2015

What happens here?



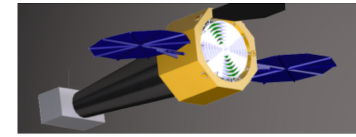
Imaging X-ray Outflows: X-ray Calorimeter

Active Galaxy MRK573.   ACIS subpixel binning



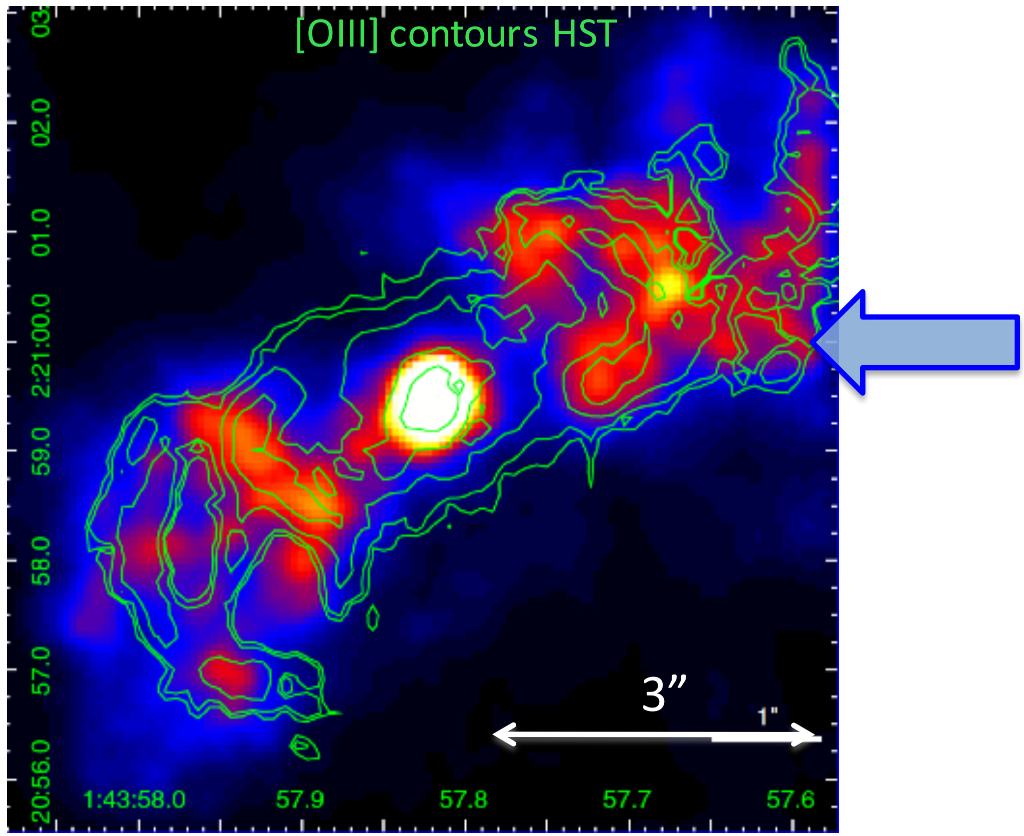
Paggi et al., 2012

Narrow Emission Line Regions (NELRs)



X-rays map interaction of wind ([OIII]), jet (radio) with Host galaxy ISM

Active Galaxy MRK573

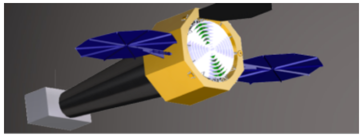


Paggi et al., 2012

<u>Thermal regions</u>:

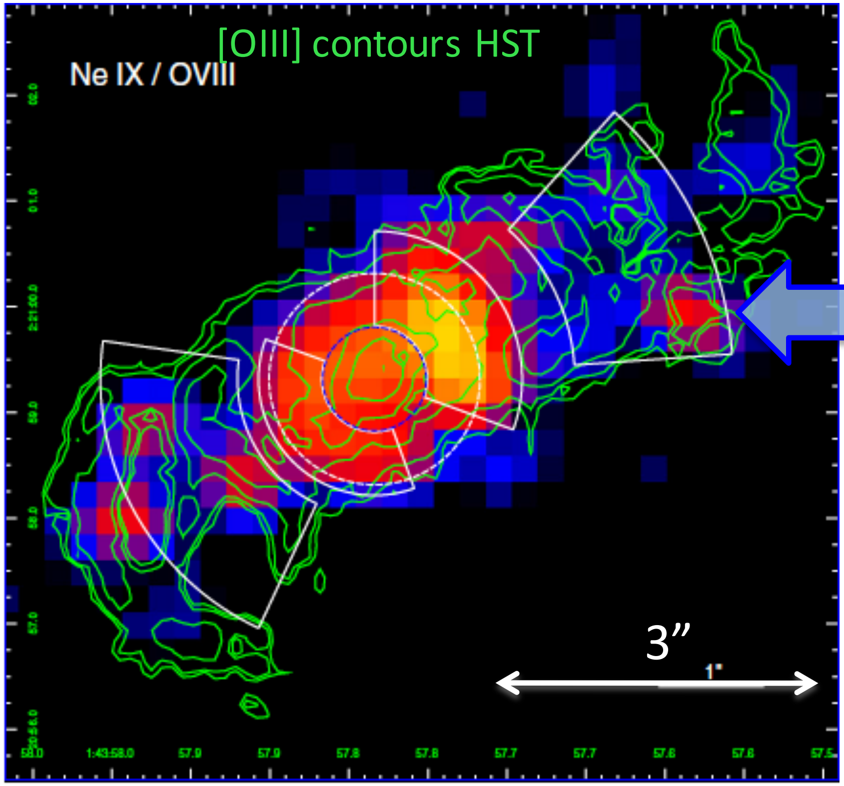
Temperature
Emission measure
Density
Pressure (cf radio)
Total energy
Cooling time
Shock speed
Crossing time
E-loss rate
Coupling efficiency
(~30% of jet power
0.05% of nucleus)

Narrow Emission Line Regions (NELRs)



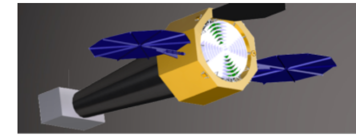
X-ray Emission Line ratios pick out different mechanisms
Photoionization (AGN). Thermal (Shocks?)

Active Galaxy MRK573



Paggi et al., 2012

Narrow Emission Line Regions (NELRs)



Calorimeter: Many more emission lines; Kinematics

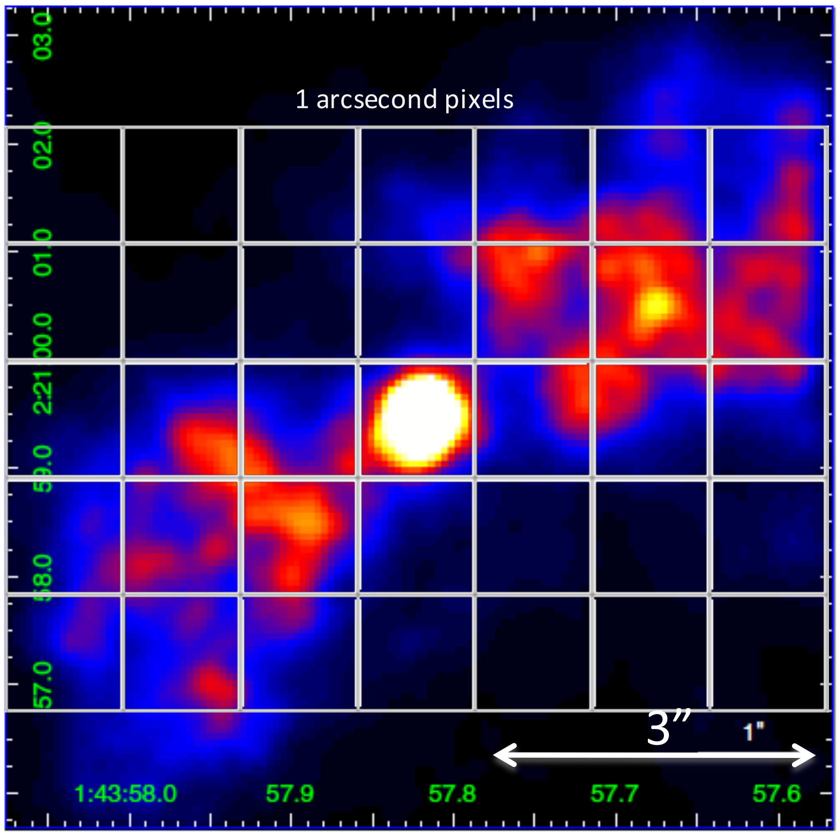
1 arcsec pixels are kinda large. Smaller pixel array at center? Good for bright sources too.

Velocities ΔE=5eV is kinda large. 3000 km s^{-1} @ 0.5keV. Centroid to 5% if good calibration.

Low Energy array with smaller ΔE ?

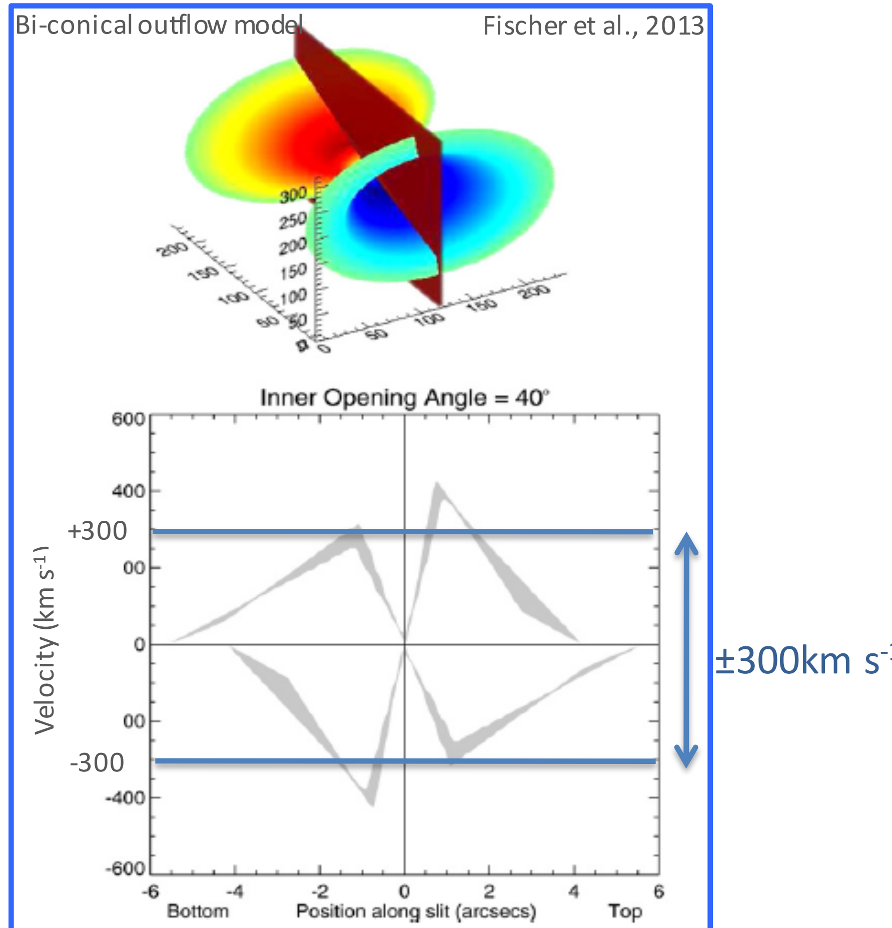
"Long Slit" grating spectra?

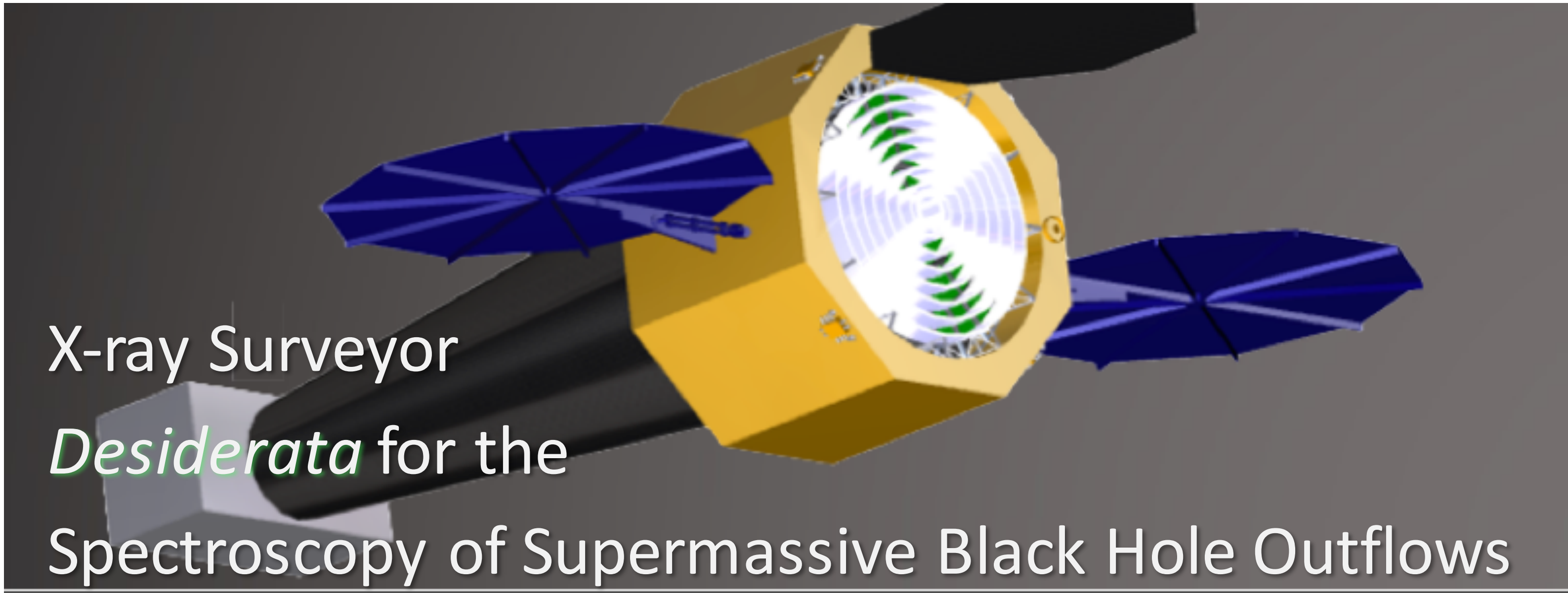
Active Galaxy MRK573



grid from art-is-fun.com

Paggi et al., 2012

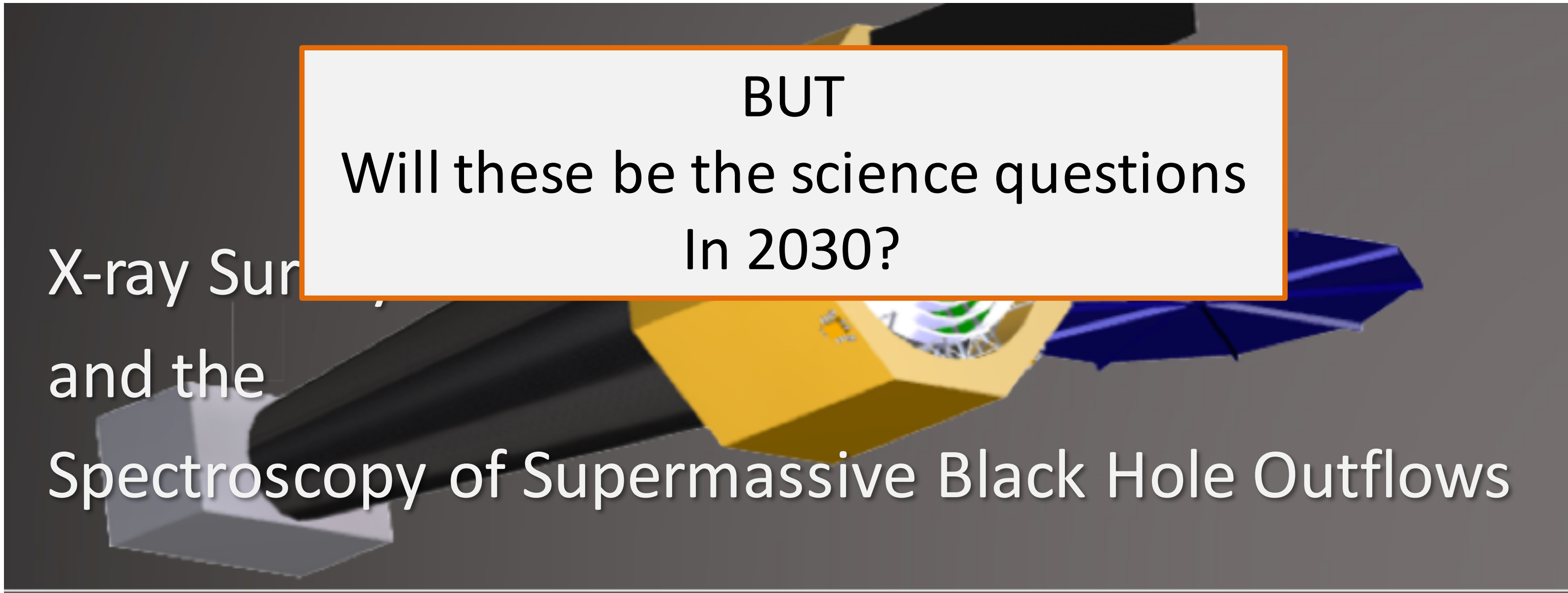




X-ray Surveyor *Desiderata* for the Spectroscopy of Supermassive Black Hole Outflows

Modest changes can make a disproportionate difference in science output

- *Calibration*: wavelength/energy to small fraction of resolution (5%?)
  - Doppler shifts
- *Agility: rapid slew/settle* – enables large surveys of types of object
  - C.f. *Swift*. Large samples little done since ROSAT
- *Calorimeter:*
  - *Angular resolution*: factor 2 gives **8× more** NELRs accessible
  - *Pixel size*: central finer pixels (~1/2 PSF) uses full power of mirror
  - *Lower particle background* is ALWAYS good – low surface brightness
- *Another instrument?* E.g. polarimeter –also photon hungry → low E.



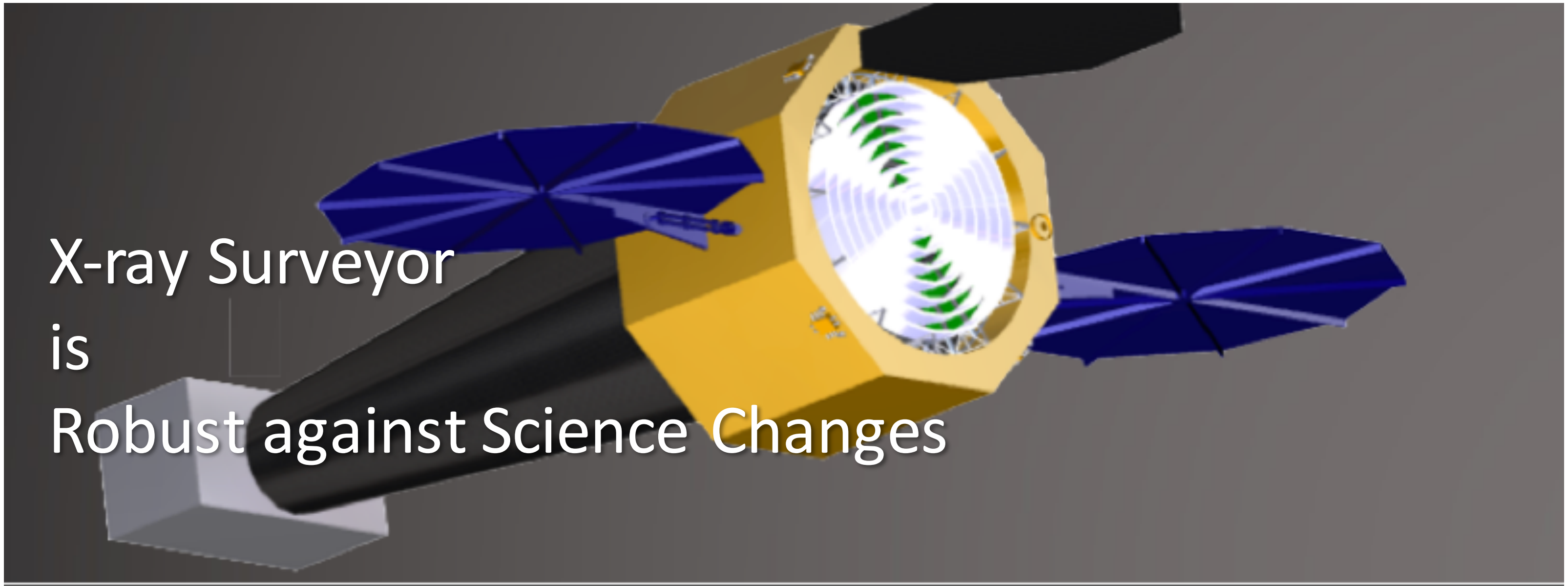
BUT
Will these be the science questions
In 2030?

X-ray Sur

and the

Spectroscopy of Supermassive Black Hole Outflows

- Grating Spectroscopy at R~5000 → **Physics of AGN Structure**
  - ultra-fast outflows/broad absorption lines, warm absorbers/narrow absorption lines
- Calorimeter Integral Field Unit → **AGN Feedback Physics**
  - bi-conical narrow emission line regions
- Modest changes can make a disproportionate difference in science output



X-ray Surveyor Opens a Large Discovery Space
"100×"

- Imaging goes ~100 × deeper
- Surveying is ~500-800 x faster
- Spectra have ~200× #photons, 10× resolution elements
    - *~150× information content*
    - new physics available

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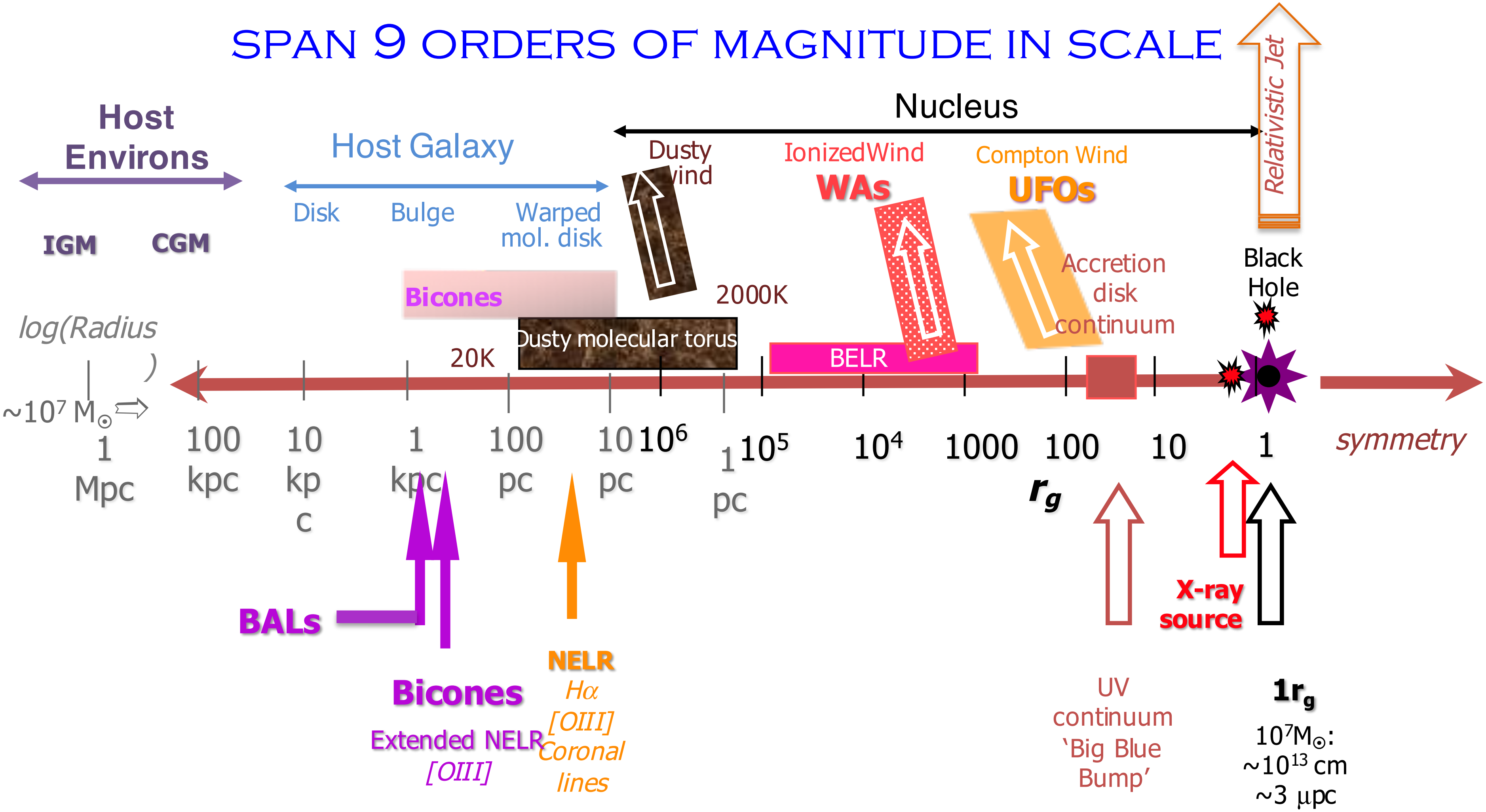
X-ray Surveyor

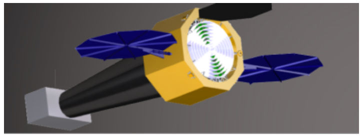
Outflows from Super-Massive Black Holes

SPAN 9 ORDERS OF MAGNITUDE IN SCALE



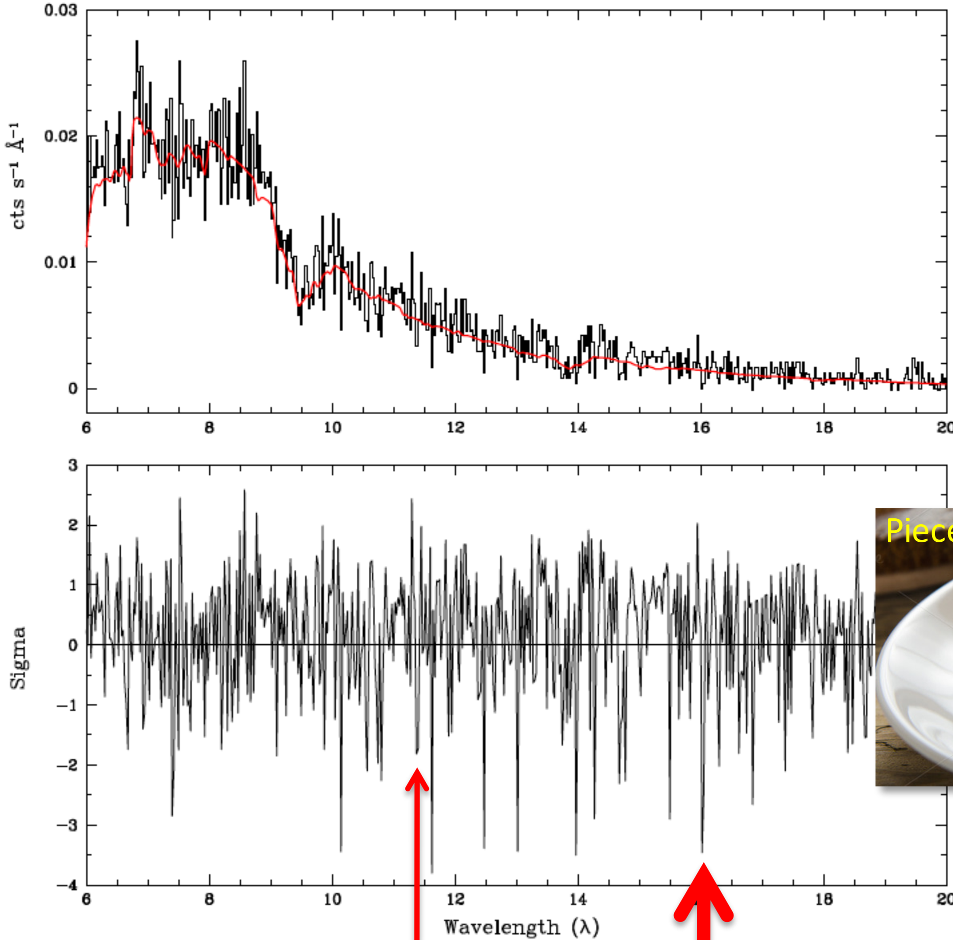
Martin Elvis, September 2007

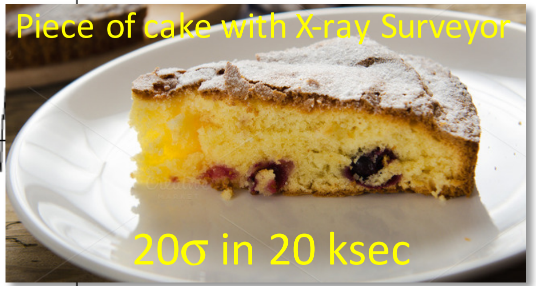
Broad Absorption Lines (BALs)



e.g. MRK590: complex narrow velocity structure in a UFO?
several low S/N lines: tantalizing

HETG 100ksec





Gupta, Mathur & Krongold, 2015

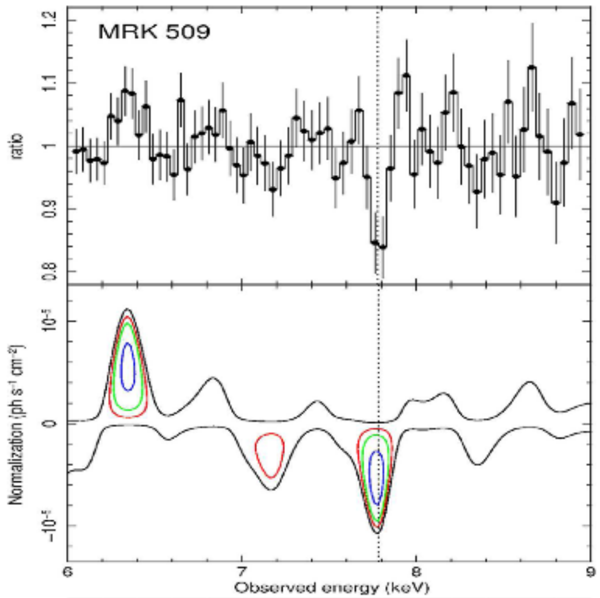
2.8σ
= NeVIII v=0.175*c*?

>3σ
= FeXVII v=0.04*c*?
= OVIII v=0.176*c*?

Clues from Intermediate Cases?

‘Not-so-Ultra-Fast Outflows’
5000 – 10000 km s^{-1} X-ray velocities

V_{out} ~ 6500 km s^{-1}

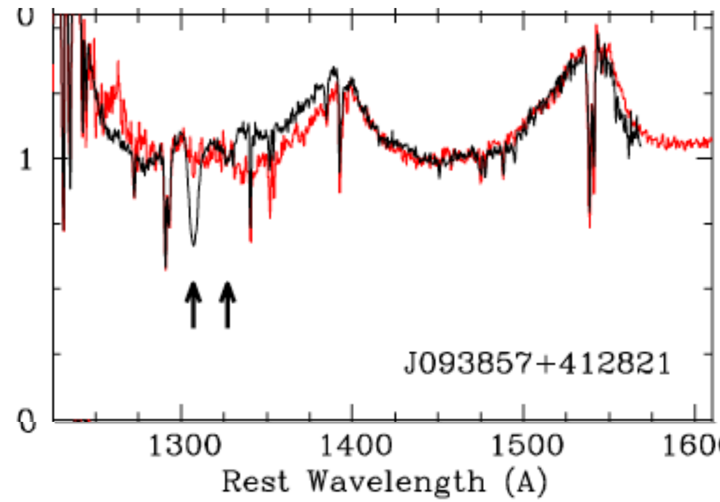


Tombesi & Cappi 2014, MNRAS, 443, L104

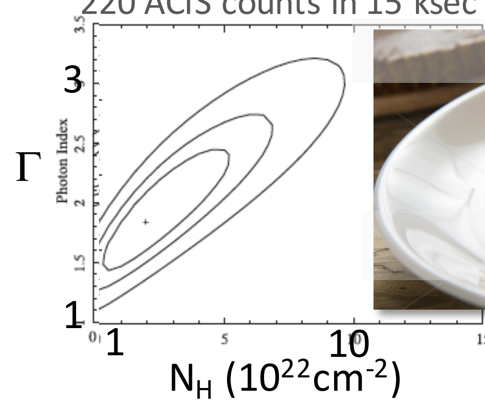
mini-BALs:
High UV v_{out}, low FWHM

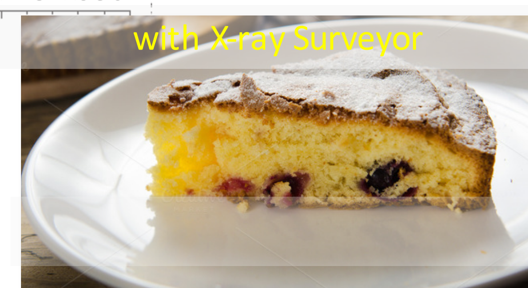
N_H ~ 10^{22} cm^{-2}

Hamann et al., 2013



220 ACIS counts in 15 ksec





Diagnostics

RESOLUTION

- Resolves blends
  - 40% of features in NGC3783 are blends
  - UTA no longer unresolved
- Weaker lines detectable → more (n_e, T) diagnostics
- 60 km s^{-1} → thermal line widths resolved in collisional X-ray plasma.
- Turbulence, $T_{thermal}$ vs T_{ion}
- Curve of growth → n(ion)
- Resolves components seen in UV

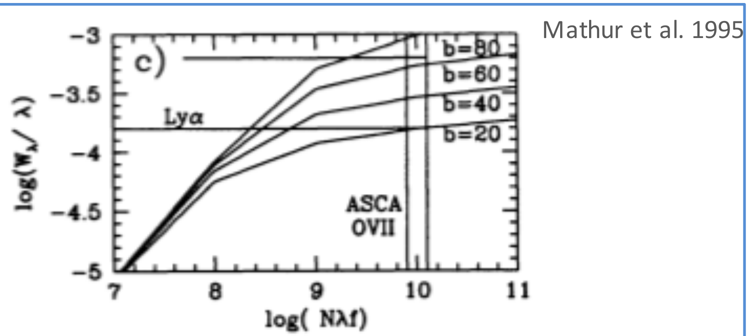


FIG. 5.—Curve of growth for *b*-values from 20 to 80 km s^{-1} in steps of 20 km s^{-1}. Horizontal lines are for the observed values of absorption lines in the mean *HST* spectrum. (*a*) C IV; (*b*) N V ; and (*c*) Lyα.

$$b_{th} = \sqrt{2kT/m_p}$$

$$N_{ion}(cm^{-2}) = 1.3 \times 10^{20}\ (EW/f\ \lambda^2)$$

Diagnostics need Area

PHOTON HUNGRY

- R=5000 requires ~10× #photons as R=500
- X-ray Surveyor has
  - Gratings: ~8× efficiency
  - Mirror: ~30× area
- → Same S/N in sources 25× fainter
- or 4% of the exposure time.

<u>For absorption lines</u>

- ΔE = 0.1 eV @ 0.5 keV
  - $\Delta\lambda$ = 0.0044A @22A
- 10^4 resolution elements/keV
- 100 counts each
- = 10^6 counts/1keV wide spectrum

- *#photons = fate/hν*
- *fate = flux × area × time × efficiency*

Outflows from Super-Massive Black Holes

Why do we care?

- How supermassive black holes work
- How SMBH grow
- How SMBH merge
- Accretion luminosity of the universe
- Effects on galaxies, clusters
- "Pollution" of the primordial gas

- What is a quasar?
- Quasar evolution
- Runaway black holes
- Versus nuclear fusion (stars)
- Feedback
- Warm-Hot Intergalactic Medium

Supermassive Black Holes' Effects on Galaxies = "Feedback"

Narrow Emission Line Regions (NELRs)

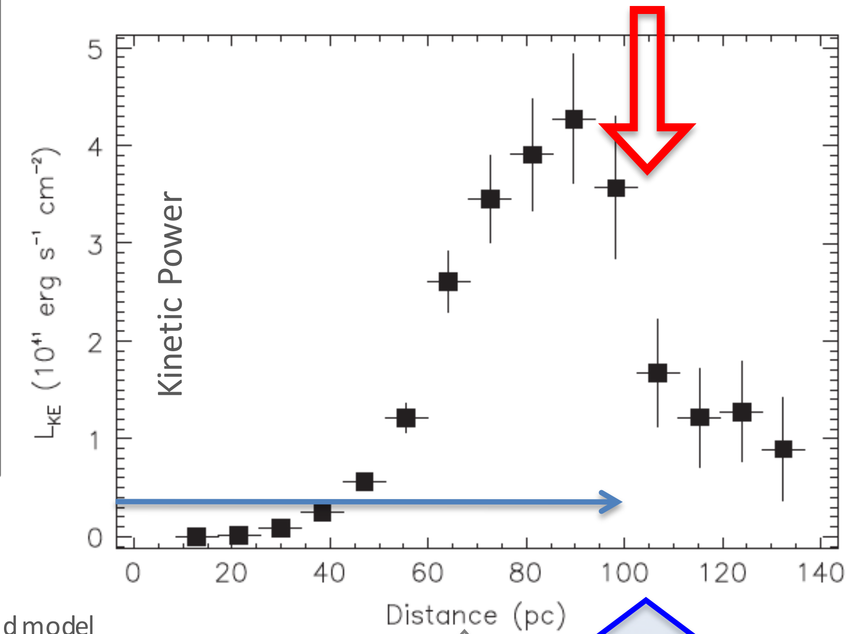
Mechanisms for interaction with the ISM:

1. Winds
2. Relativistic Jets
3. Radiation

Which dominates where?

All these interactions should generate X-rays
Spectroscopy can diagnose the process

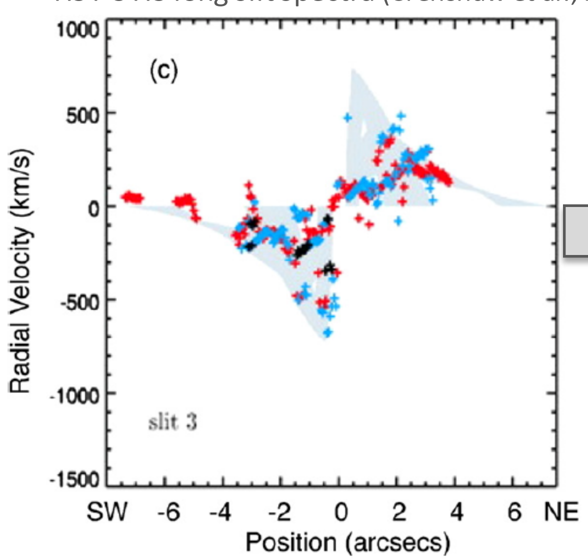
Wind loses ⅔ KE in ~20 pc ~0.3"



What happens here?

E.g. Active Galaxy NGC4151 [OIII]

HST STIS long slit spectra (Crenshaw et al., 2015)



Bi-conical wind model