

# Starburst Galaxies: Outflows of Metals and Energy into the IGM

A White Paper for the Astro2010 Decadal Survey

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# Starburst Galaxies: Outflows of Metals and Energy into the IGM

**Key Question:** What is the contribution of mass, metals and energy from starburst galaxies to the Intergalactic Medium?

**Summary of Present Knowledge:** Starburst galaxies drive galactic-scale outflows or “superwinds” that may be responsible for removing metals from galaxies and polluting the Intergalactic Medium (IGM). Superwinds are powered by massive star winds and by core collapse supernovae which collectively create  $T \lesssim 10^8$  K bubbles of metal-enriched plasma within star forming regions. These over-pressured bubbles expand, sweep up cooler ambient gas, and eventually blow out of the disk into the halo. In the last decade tremendous progress was made in mapping *cool* entrained gas in outflows through UV/optical imaging and absorption line spectroscopy. These studies demonstrated that superwinds are ubiquitous in galaxies forming stars at high surface densities and that the most powerful starbursts can drive outflows near escape velocity. Theoretical models of galaxy evolution have begun to incorporate superwinds, using various ad-hoc prescriptions based on our knowledge of the cool gas. However, these efforts are fundamentally impeded by our lack of information about the *hot* phase of these outflows. *The hot phase X-ray emitting phase of a superwind contains the majority of its energy and newly-synthesized metals, and given its high specific energy and inefficient cooling it is also the component most likely escape from the galaxy’s gravitational potential well. Knowledge of the chemical composition and velocity of the hot gas are crucial to assess the energy and chemical feedback from a starburst.* A high priority for the next decade is to enable direct measurements to be made of the rates at which starburst galaxies of all masses eject gas, metals, and energy into the IGM.

**Experimental Requirement Necessary to Answer Key Question:** A high sensitivity X-ray imaging spectrometer capable of measuring velocities in faint diffuse X-ray emission from plasmas in the temperature range  $10^6 \lesssim T(K) \lesssim 10^8$ , with a velocity accuracy of  $\lesssim 100$  km/s. Such spectral resolution automatically allows detailed line-based plasma diagnostics, and thus composition, energetics and flow rates can be derived.

## 1 Feedback between Stars, Galaxies and the IGM

We now know that galaxies and the IGM are intimately connected by flows of matter and energy. Both accretion onto galaxies and outflows from galaxies or their central black holes link galaxies to the IGM in what has been termed “Cosmic Feedback.” To obtain a deeper physical understanding of either galaxy formation and evolution or the IGM requires that we better understand the physical processes that link them.

In many respects Cosmic Feedback is analogous to Stellar Feedback within galaxies. Stars return both energy and matter back into the interstellar medium (ISM) from which they formed: either mechanically via metal-enriched stellar winds (primarily from massive stars) and supernovae (SNe), or via ionizing photons from hot massive stars. This combination of energetic and chemical “feedback” also plays an important, but currently poorly understood, role in galaxy formation and evolution (see e.g. Kauffmann et al. 1999; Cen et al. 2005; Scannapieco et al. 2008).

Mechanical feedback (stellar winds and SNe) is the primary physical mechanism creating the hot phases of the ISM in star-forming galaxies (spiral, irregular and merging galaxies). The plasmas making up the hot phases of the ISM have temperatures in the range  $T = 10^6$

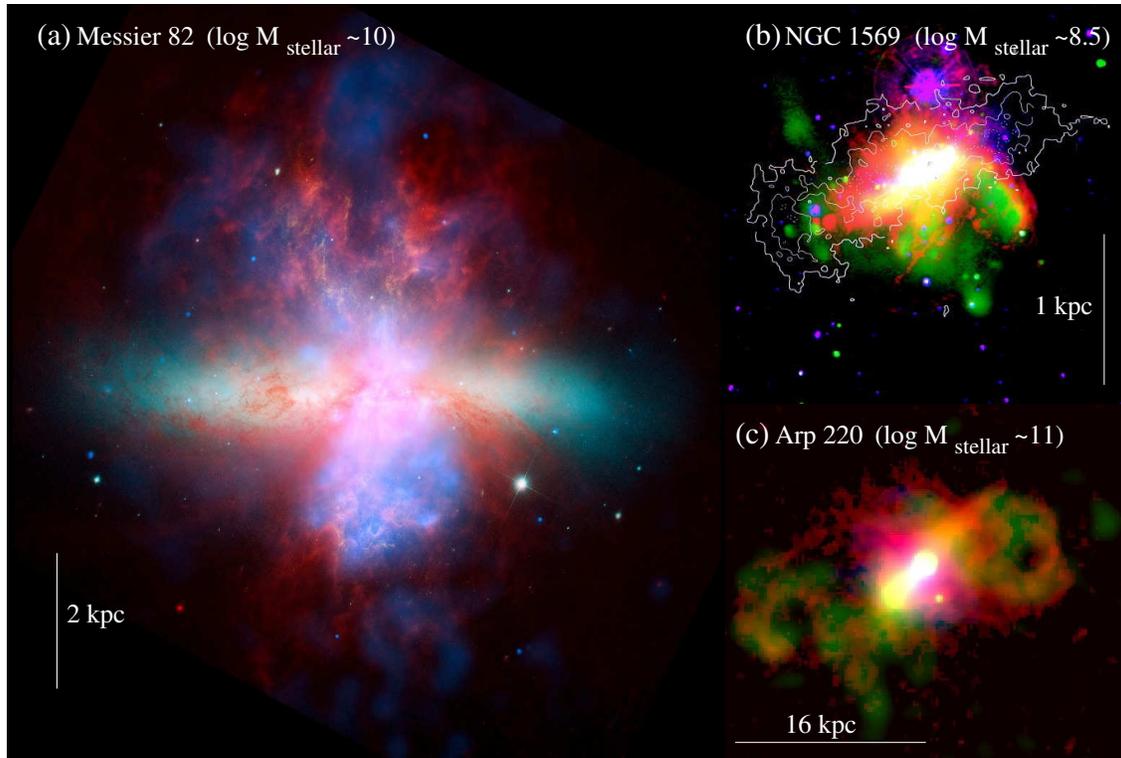


Fig. 1: Superwinds in nearby starburst galaxies of different mass. (a) Messier 82: The archetype of a starburst-driven superwind, as seen by the three NASA Great Observatories. Diffuse thermal X-ray emission as seen by *Chandra* is shown in blue. Hydrocarbon emission at  $8\mu\text{m}$  from *Spitzer* is shown in red. Optical starlight (cyan) and  $\text{H}\alpha + [\text{NII}]$  emission (yellow) are from *HST ACS* observations. (b) The dwarf starburst NGC 1569. X-ray emission is shown in green,  $\text{H}\alpha$  emission in red, optical starlight in blue, and HI column density as white contours (Martin et al. 2002). (c) The Ultra-luminous IR galaxy and merger-driven starburst Arp 220. X-ray emission is shown in green,  $\text{H}\alpha$  emission in red, and J-band starlight in blue.

–  $10^8$  K and predominantly emit and absorb photons in the X-ray energy band from  $E \sim 0.1$  – 10 keV. Line emission (from highly-ionized ions of the astrophysically important elements O, Ne, Mg, Si, S, and Fe) dominates the total emissivity of plasmas with temperatures  $T \lesssim 10^7$  K, and at higher temperatures Ar, Ca and in particular Fe also produce strong lines. Although the hot phases probably do not dominate the total mass of the ISM in normal spiral galaxies (observationally the properties of the hot phases are uncertain and remain a subject of vigorous ongoing research) they dominate the energetics of the ISM and strongly influence its phase structure (Efstathiou 2000). X-ray observations are a natural and powerful probe of the composition and thermodynamic state of hot phases of the ISM in and around galaxies, and thus are also a powerful tool for exploring the physics of feedback.

This White Paper focuses on the intersection of Cosmic and Stellar Feedback. The intense star formation occurring in starburst galaxies leads to the creation of energetic metal-enriched outflows or superwinds that may pollute the IGM with metals and energy. A high priority for the next decade is to enable direct measurements to be made of the rates at which starburst galaxies of all masses eject gas, metals, and energy into the IGM.

## 2 Starburst-Driven Superwinds

Superwinds are large-angle (opening angles  $\gtrsim 30^\circ$ ), multi-phase, galactic-scale ( $R \gtrsim 5 - 20$  kpc) outflows that have been observed in starbursting galaxies of all masses and environments. Indeed, starburst galaxies with superwinds account for  $\sim 20\%$  of the high mass star formation in the local Universe, having been observed in all galaxies where the average star formation rate per unit area exceeds  $\Sigma_{\text{SF}} \gtrsim 10^{-1} M_\odot \text{yr}^{-1} \text{kpc}^{-2}$  (Heckman et al. 1990; Lehnert & Heckman 1996; Veilleux et al. 2005, see Fig. 1). The UV-selected star-forming galaxies at  $z \sim 2 - 4$  that may dominate the total star formation density at these redshifts are known to drive powerful winds that appear to be physically identical to local superwinds (see e.g. Pettini et al. 2001; Shapley et al. 2003). Thus superwinds are a fundamental aspect of the Universe as we know it.

Superwinds are the strongest candidate for the cause of a number of current astrophysical puzzles: the origin of the galaxy mass-metallicity relationship ( $M - Z$ ), and more specifically the galaxy mass versus effective yield relationship,  $M - y_{\text{eff}}$ , which suggest that lower mass galaxies have lost significant fractions of all the heavy elements ever created by their stars (Tremonti et al. 2004); the source of the metal enrichment of the IGM (e.g. Songaila 1997; Simcoe et al. 2006); and the creation of  $\sim 100$ -kpc-scale holes in the IGM at redshift  $z \sim 3$  (Adelberger et al. 2003).

Although we have good reasons to suspect that superwinds are solely or partly responsible for these phenomena we have yet to robustly quantify their role. We do not know the rates at which even local starbursts eject gas, metals and energy, in particular because these are dominated by the hottest and most tenuous gaseous phases. Even if winds are significant contributors to IGM enrichment we do not know what type of galaxy dominates ejection (Which masses? What level of star formation? Is galaxy environment important?), and over what range of epochs this process is significant. There is still much we don't know about the IGM baryon and metal budget. The galaxy  $M - y_{\text{eff}}$  relationship is not a measure of the instantaneous metal ejection efficiency for starbursts of a given mass, and is potentially misleading because  $y_{\text{eff}}$  is only a sensitive barometer of metal loss in gas rich systems with little star formation subsequent to the burst (Dalcanton 2007). For example, some authors argue that only winds from the lowest mass galaxies can reach the IGM (Ferrara & Tolstoy 2000; Keeney et al. 2006), while others argue that winds can indeed escape from powerful starbursts in more massive galaxies (Strickland et al. 2004b).

Solving these problems requires the capability to directly measure the pollution rate of the IGM with gas, metals, energy and momentum by superwinds in galaxies covering a broad range of galaxy mass and star formation activity.

### 2.1 What We Currently Know About Superwinds

Superwinds are driven by merged core-collapse SN ejecta and stellar winds, which initially create a  $T \sim 10^8$  K metal-enriched plasma within the starburst region. This over-pressured gas expands and breaks out of the disk of the host galaxy, converting thermal energy into kinetic energy in a bi-polar outflow, which can potentially reach a velocity of  $3000 \text{ km s}^{-1}$ . This tenuous wind-fluid sweeps up and accelerates cooler denser ambient disk and halo gas. Radiation pressure may also play a role in accelerating the dense entrained gas.

Theoretical models predict that the entrained cool gas is accelerated to lower velocities than the hot, metal-enriched, gas (e.g. Chevalier & Clegg 1985; Strickland & Stevens 2000,

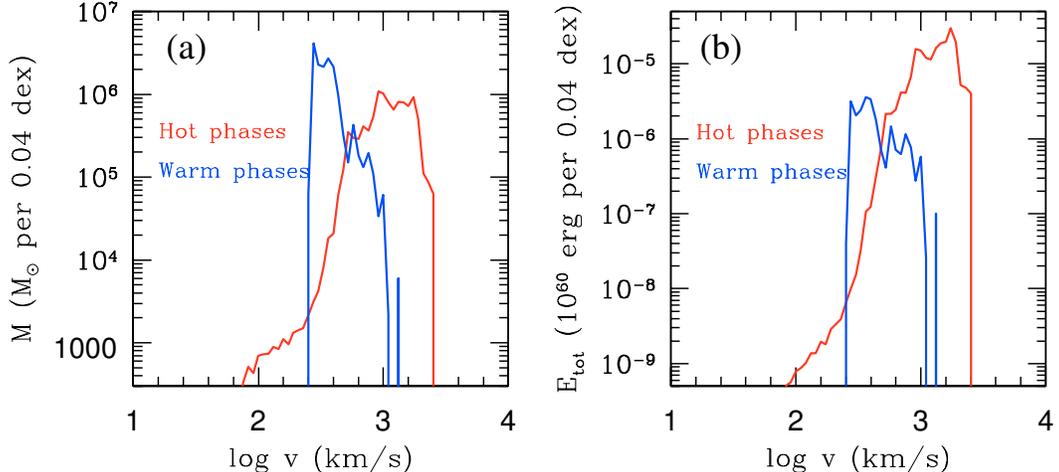


Fig. 2: Gas mass and total energy (thermal plus kinetic) as a function of velocity in a hydrodynamical simulation of a starburst-driven superwind. Current theoretical models for superwinds predict that the hot phases ( $6.3 \leq \log T \leq 8.3$ , shown in red) have systemically higher outflow velocities than the warm neutral and ionized phases ( $3.8 \leq \log T \leq 4.2$ , shown in blue) that are currently used to measure velocities in superwinds. From Strickland & Dine (in preparation).

see Figs. 2 & 3). All existing observational velocity measurements of superwinds are of the entrained cooler material, e.g. warm neutral and ionized gas with outflow velocities in the range  $200 - 1000 \text{ km s}^{-1}$  measured using UV/optical emission and/or absorption lines (see Shapley et al. 2003; Rupke et al. 2005; Martin 2005). Although this material has velocities that are near galactic escape velocity, we expect that the hot phases are indeed escaping.

The theoretical models predict that the majority of the energy (90%) and metal content in superwinds exists in the hot ( $T \geq 10^6 \text{ K}$ ) phases, with the kinetic energy of such gas being several times the thermal energy. Thus the metal-enriched phases are most likely to escape into the IGM. This material has long been observationally elusive, although we now believe we have firmly detected it in X-ray emission (Strickland & Heckman 2007; Tsuru et al. 2007).

The current generation of X-ray telescopes offer spectral-imaging with a spectral resolution of order  $\Delta E \gtrsim 100 \text{ eV}$  over the  $0.3 - 10 \text{ keV}$  energy band (Chandra ACIS, XMM-Newton EPIC and Suzaku XIS). At this resolution the emission lines are strongly blended, preventing the use of line-ratio-based spectral diagnostics. *This spectral resolution is too low to allow line shifts or broadening to be measured, preventing any direct measurement of the velocity of the hot gasses.* Nor can existing X-ray gratings be used to obtain higher spectral resolution, because the X-ray emission is both spatially extended and faint.

Nevertheless spectral imaging observations with *Chandra* and *XMM-Newton* detect thermal X-ray emission from hot gas in superwinds extending out to  $5 - 30 \text{ kpc}$  from the plane of edge-on starburst galaxies (Strickland et al. 2004a; Tüllmann et al. 2006). Forward-fitting techniques do allow certain spectral parameters such as temperature, emission integral ( $n_e^2 V$ ), and relative elemental abundances (suggestive of enrichment by core-collapse SN) to be crudely estimated under the assumption of collisional ionization equilibrium. Obtaining accurate plasma diagnostics, in particular of ionization state and elemental abundances, will require higher spectral than existing X-ray observatories can provide.

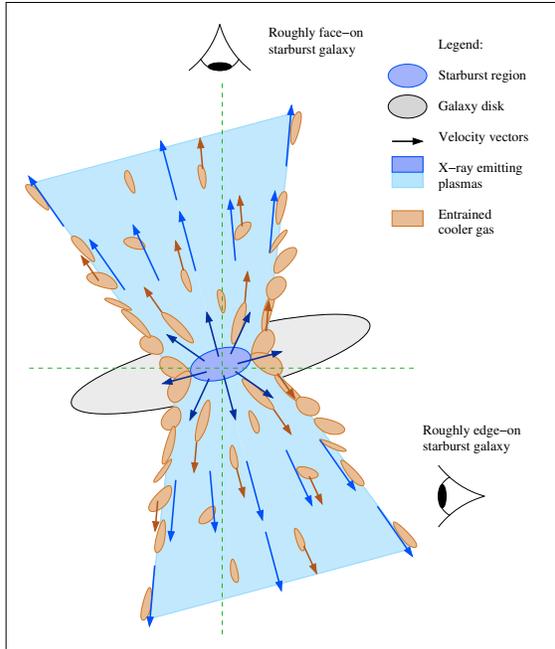


Fig. 3: Schematic diagram of a superwind viewed from different angles, with phase-dependent velocity vectors added to illustrate the line of sight velocity components expected. The combination of galaxy inclination and geometrical divergence within the wind leads to velocity shifts in the line centroids and line broadening or splitting. The resulting velocity components along the line of sight are significant fractions of the intrinsic velocity even in roughly edge-on starbursts. This diagram is simplified in that no acceleration or deceleration or change of geometry of the flow with position is shown. In practice we would look for such changes (in particular in roughly edge-on systems) using spatially-resolved X-ray spectroscopy. [Figure best viewed in color.]

Although the average galaxy with a superwind at  $z \sim 3$  has a higher net star formation rate than the average local starburst, local starbursts with superwinds cover the same range of fundamental wind parameters such as warm gas outflow velocity and mass flow rate, and star formation rate per unit area, as high redshift starbursts. There are no significant obstacles that prevent us from applying the physics of local superwinds to superwinds at the epoch of galaxy formation.

### 3 Creating A Future for Superwind Studies

Without direct measurements of the velocity of the hot gas in a superwind, which can only be obtained with a high resolution X-ray imaging spectrometer, we can not know whether the hot metals created in the starburst have sufficient energy to escape the galactic gravitational potential well and reach the IGM.

High spectral resolution would automatically allow the use of line-ratio-based temperature and ionization state diagnostics, and thus lead to more accurate elemental abundance determinations. Combined with velocity measurements we would obtain the mass, metal and energy flow rates that we require to assess the impact and influence of superwinds.

High sensitivity will allow robust spectroscopy of the very faint soft X-ray emission from the halos of starburst galaxies and the accumulation of moderately-sized samples of local galaxies covering meaningful ranges in parameter space. We require measurements of gas velocity and ejection rates in superwinds covering a range of different galaxy mass and star formation rate to assess which class of galaxies dominates the metal enrichment of IGM in the present-day Universe, and in order to relate the results to higher redshift galaxies and local galaxy properties such as the galaxy  $M - y_{\text{eff}}$  relationship.

This is not to suggest that advances in theoretical or other observational capabilities are neither welcome nor necessary. For example, UV/optical spectroscopy of the warm neutral and warm ionized phases (entrained gas) in superwinds provides the vital link that allows us to relate the properties of  $z \ll 1$  superwinds to the starburst-driven outflows at redshifts

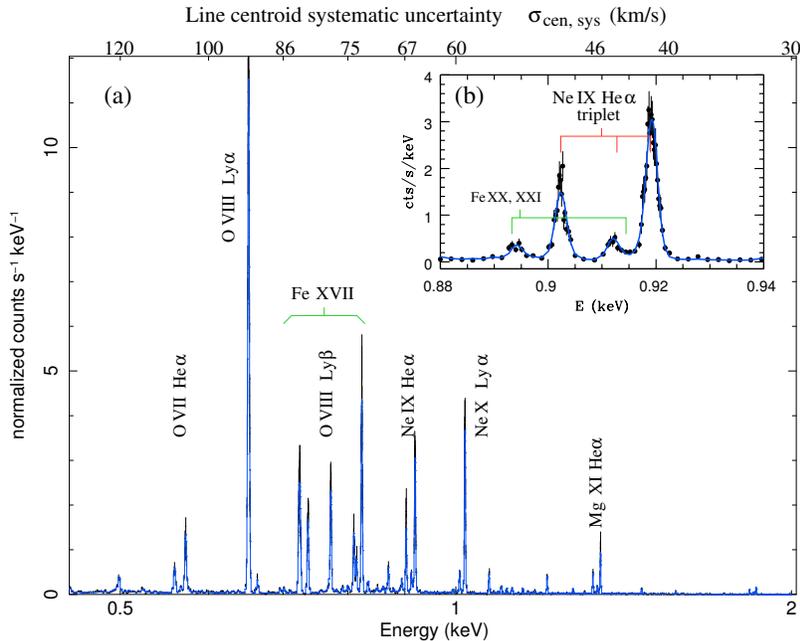


Fig. 4: (a) A simulated spectrum of a small region within a superwind based on the *IXO* XMS microcalorimeter instrument, illustrating the relative strength of the line emission. The simulation is of a supernova II-enriched  $kT = 0.4$  keV thermal plasma containing  $\sim 16000$  counts in the  $E = 0.3 - 2$  keV energy band. The uncertainty in the line centroids due to the  $\pm 0.2$  eV systematic uncertainty in the absolute XMS energy scale is shown in terms of the associated velocity uncertainty. (b) A close-up of the spectrum around the energy of the Ne IX He $\alpha$  triplet.

$z \gtrsim 2$  (Shapley et al. 2003). Radio and millimeter wavelength observations (e.g. *ALMA*) constrain the molecular gas budget of winds and the nature of the starburst regions where winds are launched. Nevertheless, without the X-ray spectroscopic capability to measure the “true” velocity of superwinds such progress would be futile.

## 4 Measuring Velocities in the X-ray-emitting Gas of a Superwind

The remainder of this White Paper discusses the experimental accuracy needed to achieve these goals, in particular velocity measurements, in comparison to the expected capabilities of the *International X-ray Observatory (IXO)*. We consider only one of the possible observational methods of measuring hot gas velocities in superwinds with *IXO*, specifically soft X-ray emission-line spectroscopy using the X-ray Microcalorimeter System (XMS). This method is most closely related in method to traditional observational studies of the soft X-ray emitting plasmas in the halos of starbursts (e.g. Grimes et al. 2005; Tüllmann et al. 2006). The results presented here are derived and described in greater detail in the Technical Supplement<sup>1</sup>, which also discusses alternative methods of measuring wind velocities in the soft and hard X-ray bands.

What velocities do we expect for the X-ray emitting plasma in superwinds?

- Gas motions must be comparable to galaxy escape velocities to be significant in ejecting metals, where  $v_{\text{esc}} \sim 2 - 3 \times v_{\text{rot}}$  (the rotational velocity of the host galaxy).
- Theoretical models of superwinds predict high velocities (up to  $3000 \text{ km s}^{-1}$ ) in gas with  $T \gtrsim 10^6$  K, and that this material moves significantly faster than the warm neutral and ionized medium in winds (e.g. see Fig. 2).
- Even if this existing theory is completely wrong, for a wind to exist the hot gas velocity must be comparable or higher than the sound speed in the X-ray emitting gas, for which

<sup>1</sup>The Technical Supplement can be accessed at <http://proteus.pha.jhu.edu/~dks/Science/DecadalWP/index.html>, or by following the links in the PDF version of this White Paper.

we have existing temperature measurements from *Chandra* and *XMM-Newton*. Thus  $v_{\text{HOT}} \gtrsim c_s \sim 360(kT_X/0.5 \text{ keV})^{0.5} \text{ km s}^{-1}$ .

- Observed line-of-sight (LOS) velocities will be lower than the intrinsic velocity, but even in the case of roughly edge-on starbursts (e.g. M82) the geometry typically only decreases the LOS velocity by a factor  $\sim 2$  from the intrinsic velocity (see Fig. 3).

Outflows alter both the mean energy (i.e. the line centroid) and width of the strong emission lines that dominate the soft thermal X-ray emission from superwinds (Fig. 4). We expect LOS line shifts and line broadening in the range several hundred to a thousand kilometers per second, hence requiring measurements accurate to  $\lesssim 100 \text{ km s}^{-1}$ .

We find that the *IXO* XMS is capable of obtaining high quality X-ray spectra ( $> 10^4$  counts) for even the faintest currently known sub-regions of superwinds in reasonable exposures ( $t_{\text{exp}} \leq 100 \text{ ks}$ ). With such spectra we can measure *individual* line centroid shifts with uncertainties  $\sigma_{\text{cen}} \sim 50 - 100 \text{ km/s}$  (68.3% confidence), and line widths with uncertainties of  $\sigma_{\text{FWHM}} \sim 100 \text{ km/s}$  (this by fitting all lines in a single spectrum). In fact it is calibration uncertainties that limit the line centroid measurement to a net accuracy of  $\sigma_{\text{cen}} \sim 50 - 100 \text{ km/s}$ . Note that both line widths and line centroids can be measured accurately to a fraction ( $\sim 10\%$ ) of the nominal instrument resolution of  $\Delta E \approx 2.5 \text{ eV}$  (FWHM).

The *IXO* XMS provides its highest spectral resolution over a 4 arcmin<sup>2</sup> field of view, with a spatial resolution  $\sim 5''$ . This would allow multiple high-quality spectra from different regions of a nearby superwind to be accumulated simultaneously. This is advantageous as it allows multiple sanity checks on the individual measurements, and the use of position-velocity diagrams to probe possible acceleration or deceleration in the wind (as done in the optical for superwinds, e.g. Shopbell & Bland-Hawthorn 1998).

**Observations using *IXO* of a sample of  $\sim 30$  local starbursts, covering a suitably broad range of galaxy mass ( $8 \lesssim \log M_{\text{stellar}}(M_{\odot}) \lesssim 11.5$ , well matched to the local galaxy  $M - y_{\text{eff}}$  relationship presented in Tremonti et al. 2004), are possible with a net exposure of 1.3 Ms. Such a project will reveal whether starburst galaxies are responsible for IGM enrichment and the galaxy mass-metallicity relationship.**

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