Calorimeter Starburst Simulations

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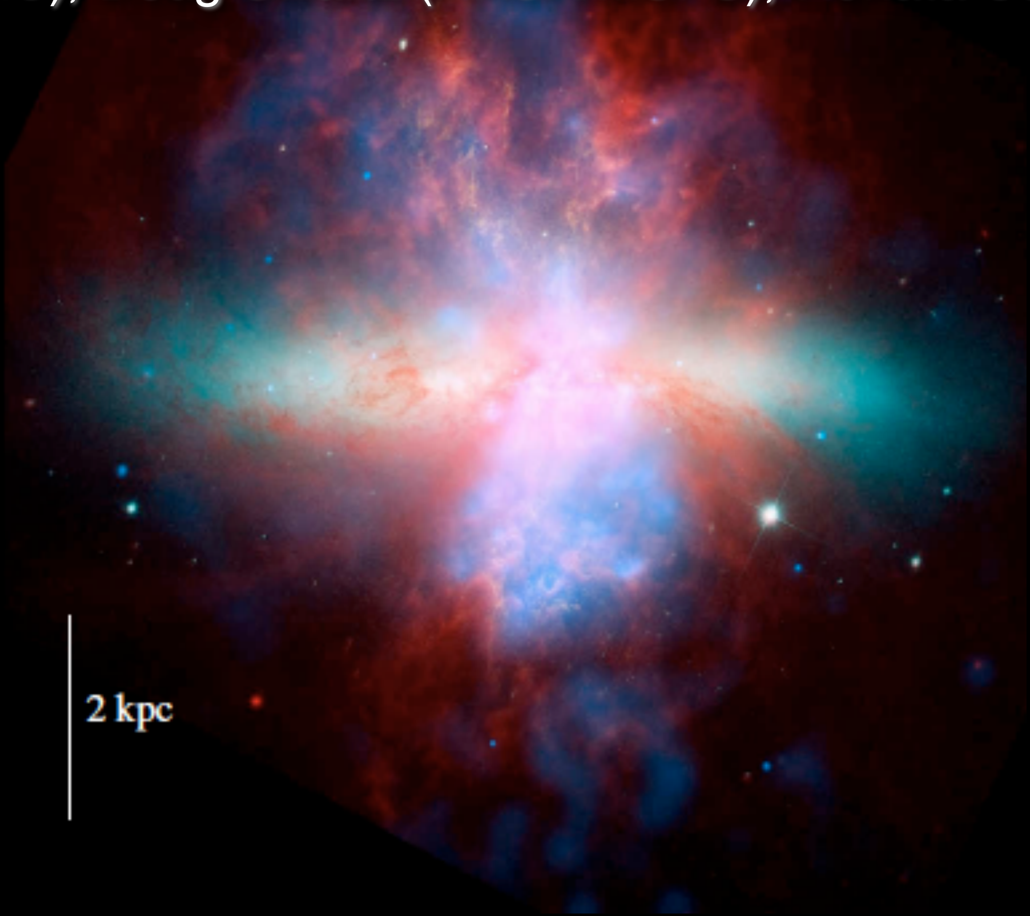
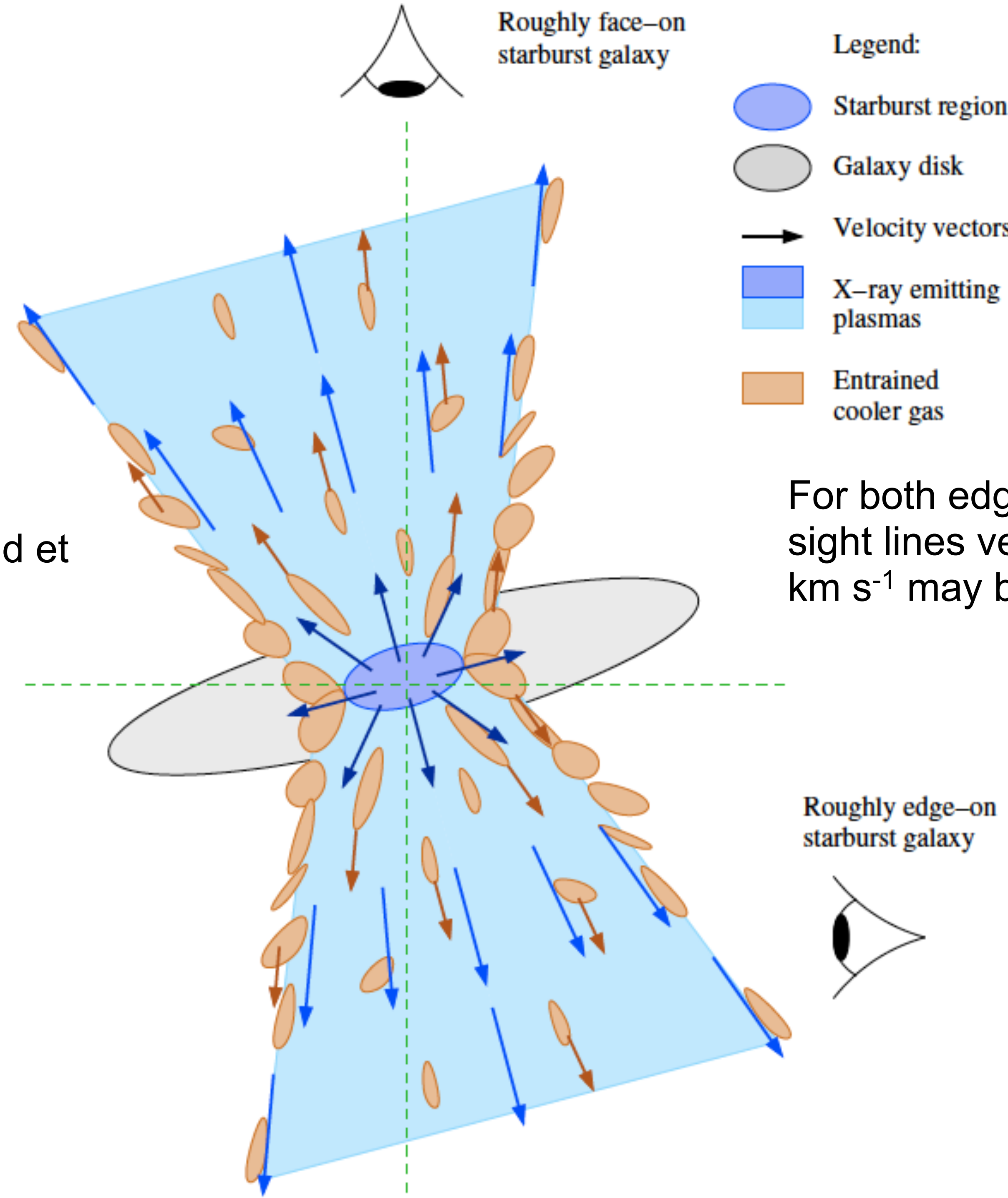


Overview

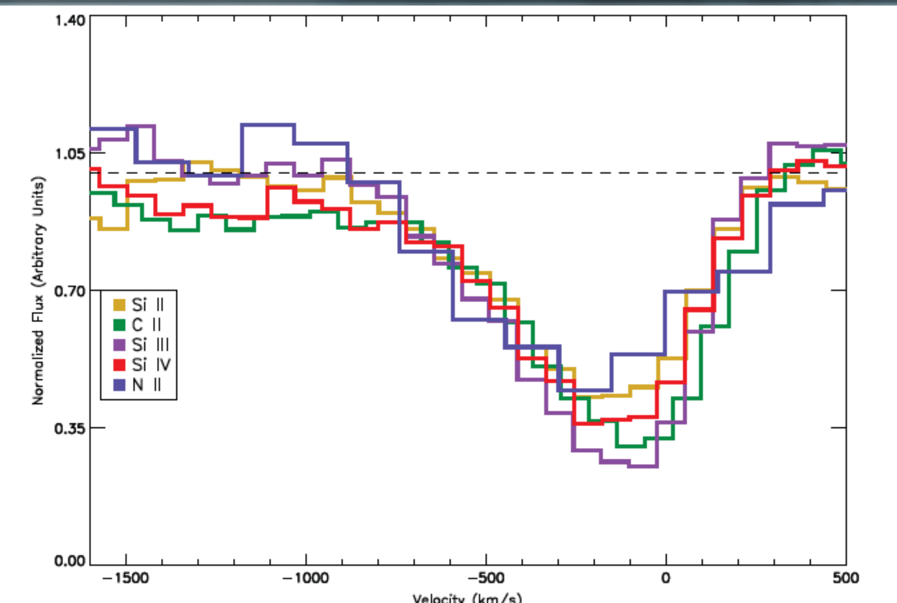
- “Feedback” in the form of starburst outflows plays an important role in galaxy evolution, particularly regulating star formation
  - How energetic are starburst winds, especially superwinds?
  - How efficiently do starburst winds transport metals to the IGM?
- Starburst outflows are directly seen in UV absorption and molecular gas studies but most energy is in the hot “fluid” which potentially stays hot out into galaxy halos

From Strickland et al. (2009)



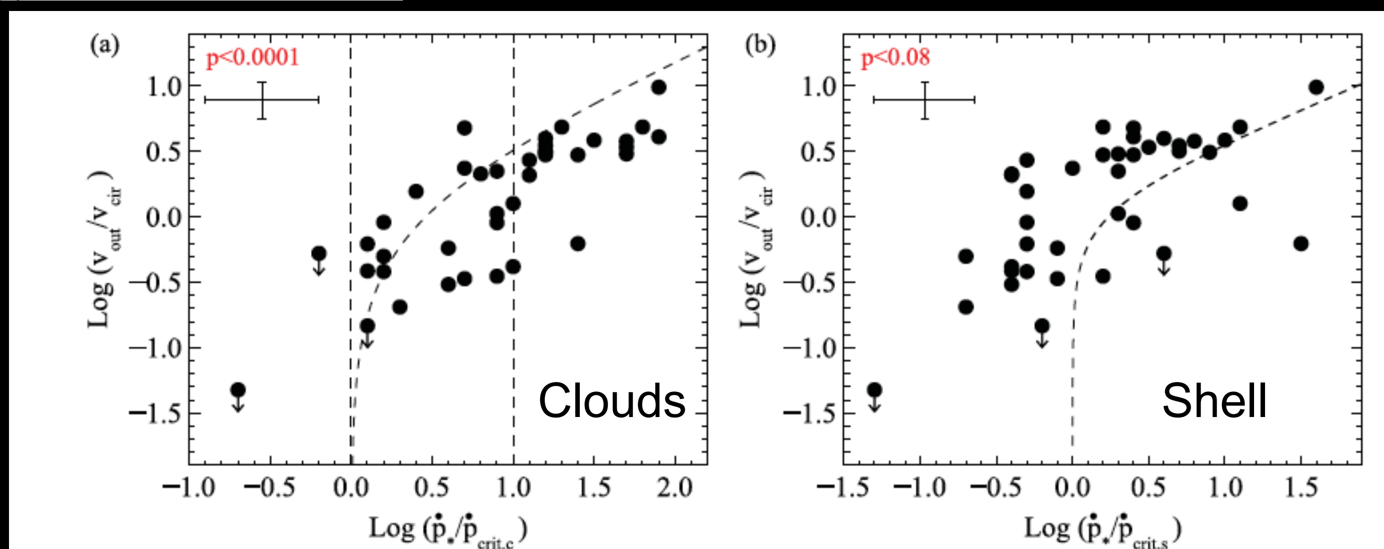
For both edge-on and face-on sight lines velocities of > 1000 km s^{-1} may be observed

UV Absorption Studies



Stacked spectra of UV absorption lines from starburst galaxies in Heckman et al. (2015). Relation between momentum flux and outflow velocity assuming an entrained cloud model is more consistent with semi-analytic starburst model expectations than a spherical shell model

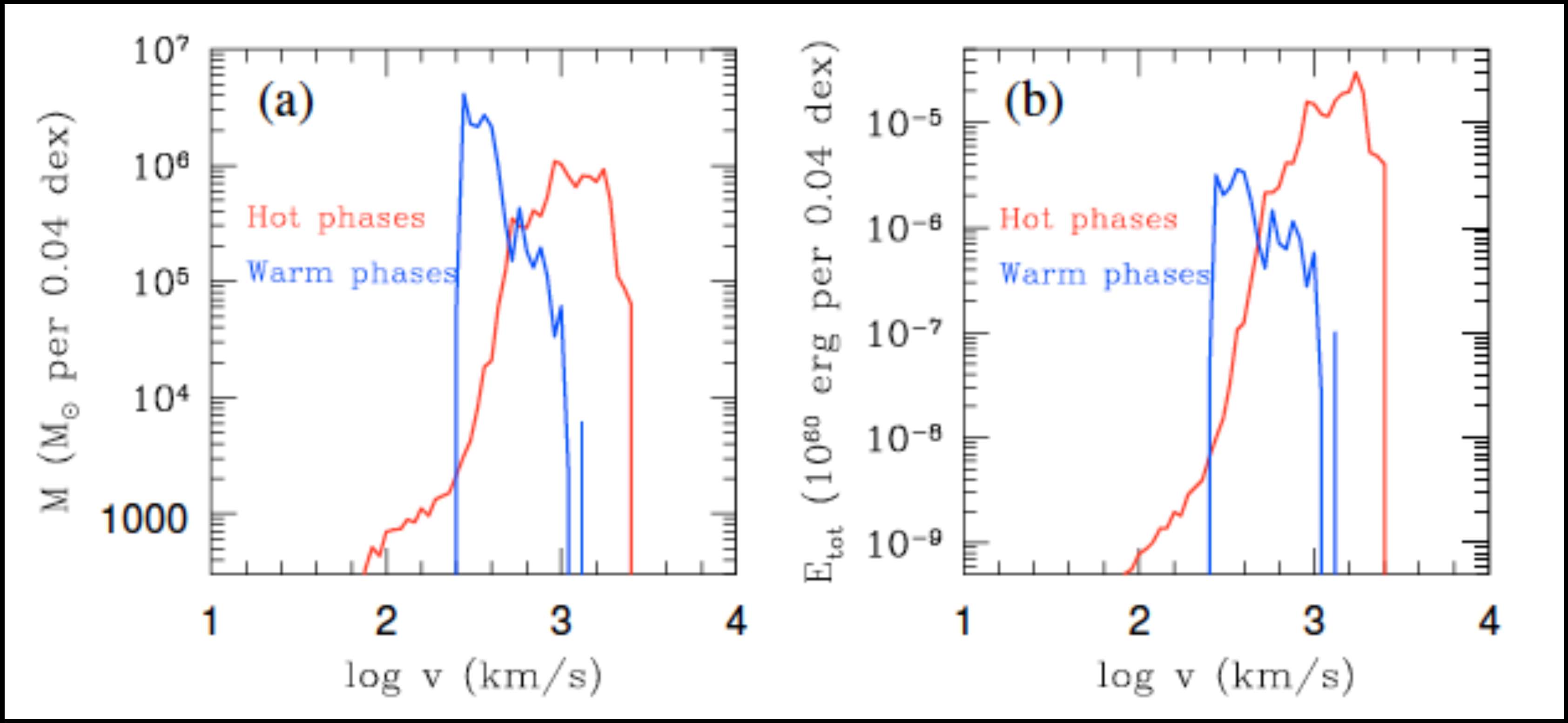
Critical momentum flux = momentum flux to overcome gravity



See recent review by Heckman & Thompson (2017)

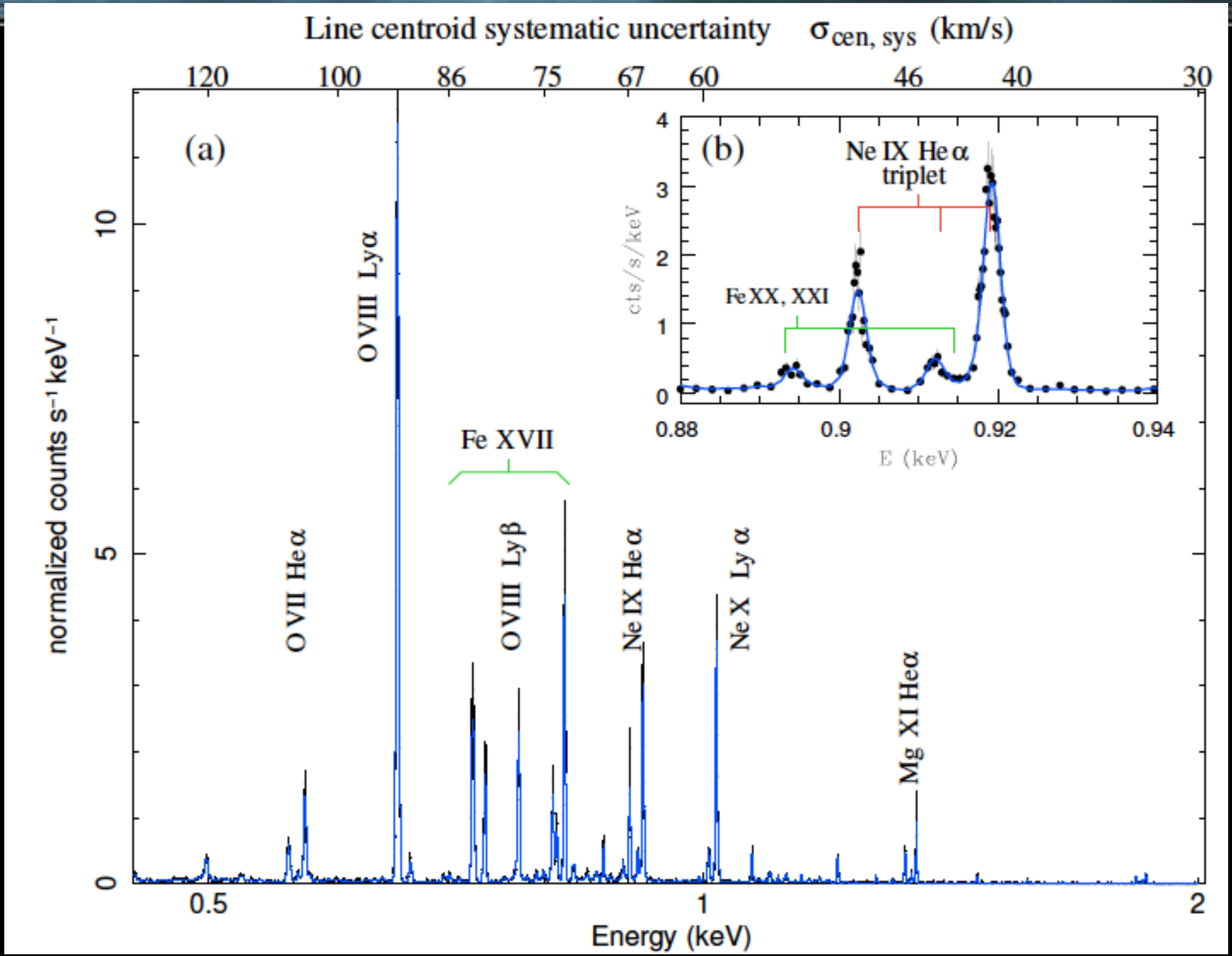
How Important is the Hot Wind Fluid?

From Strickland et al. 2009 IXO White paper
See also Melioli et al. (2013)



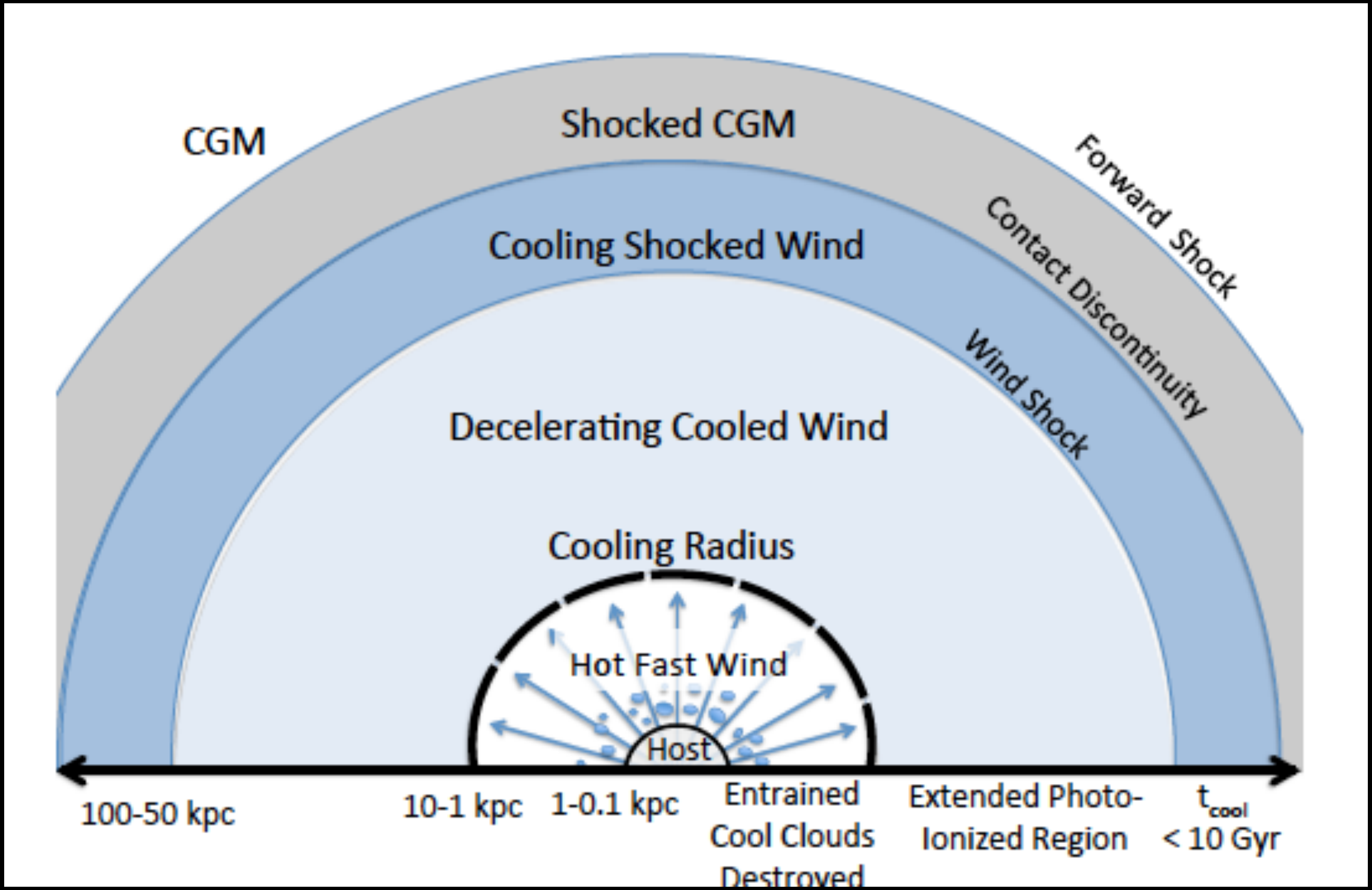
Simulating Calorimeter Observations of Superwinds

- Simulate spectra of diffuse gas
  - Simplistic approach of only assuming a single-temperature wind-dominated spectrum is straightforward
    - Initial approach by IXO team still applicable since it assumed 2.5 eV resolution and negligible background
  - More complex approach: Integrate sightlines through a starburst galaxy including wind, hot ISM, hot CSM and X-ray binaries
  - Also need to consider charge exchange and shocks
- Full end-to-end simulations
  - Would allow unresolved point sources and background to be more precisely assessed
  - Can parameters treated globally like mass loading (outflowing mass rate / SFR) be determined *locally*?



16,000 count spectrum of SN-II enhanced 0.4 keV plasma

Thompson et al. (2016) model



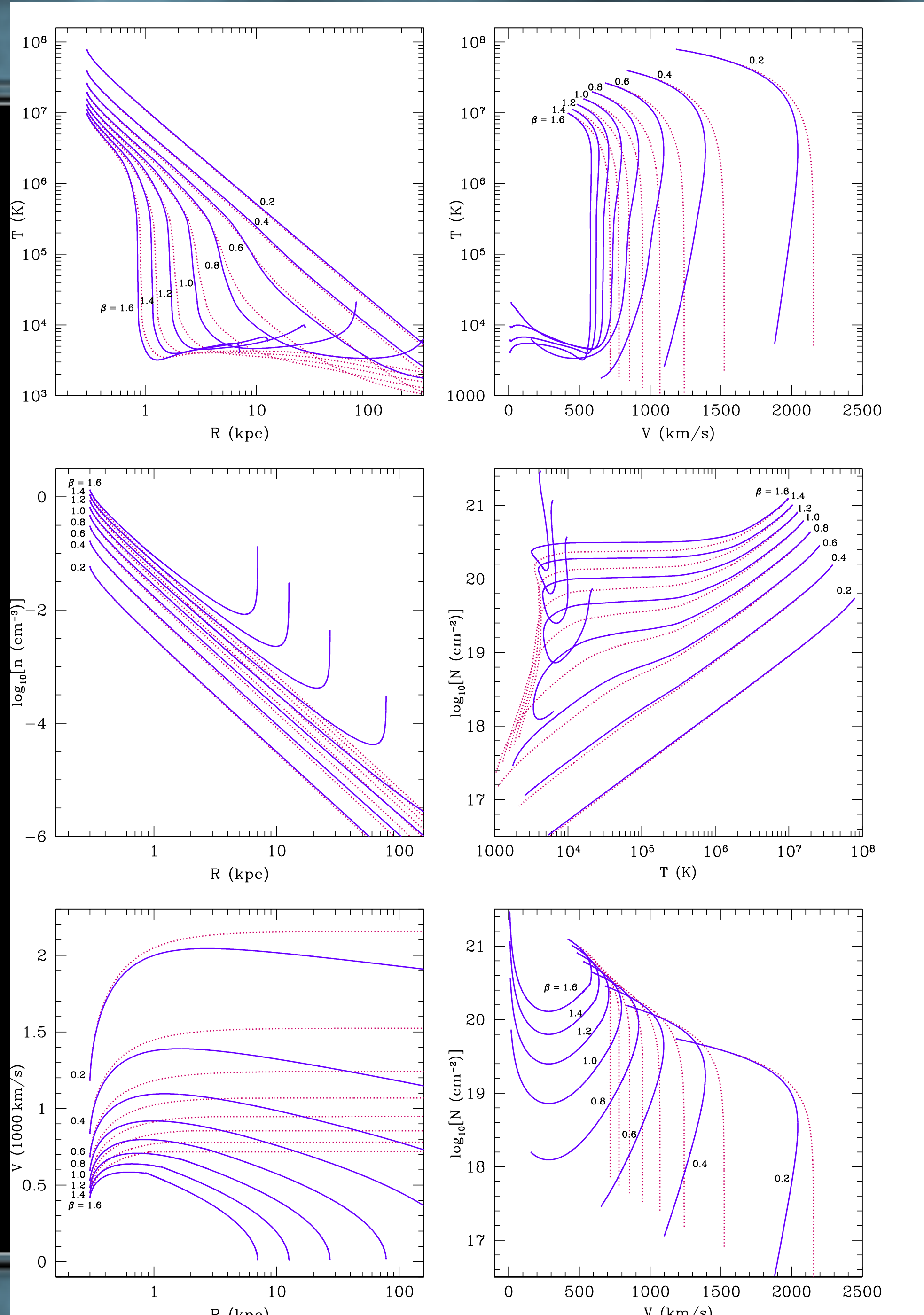
In Thompson et al. model, swept-up clouds are destroyed but then as the flow becomes increasingly mass-loaded, radiative cooling can dominate and clouds can "condense" out

Starburst wind models with different mass loading factors:

$$\beta = \frac{\dot{M}}{SFR}$$

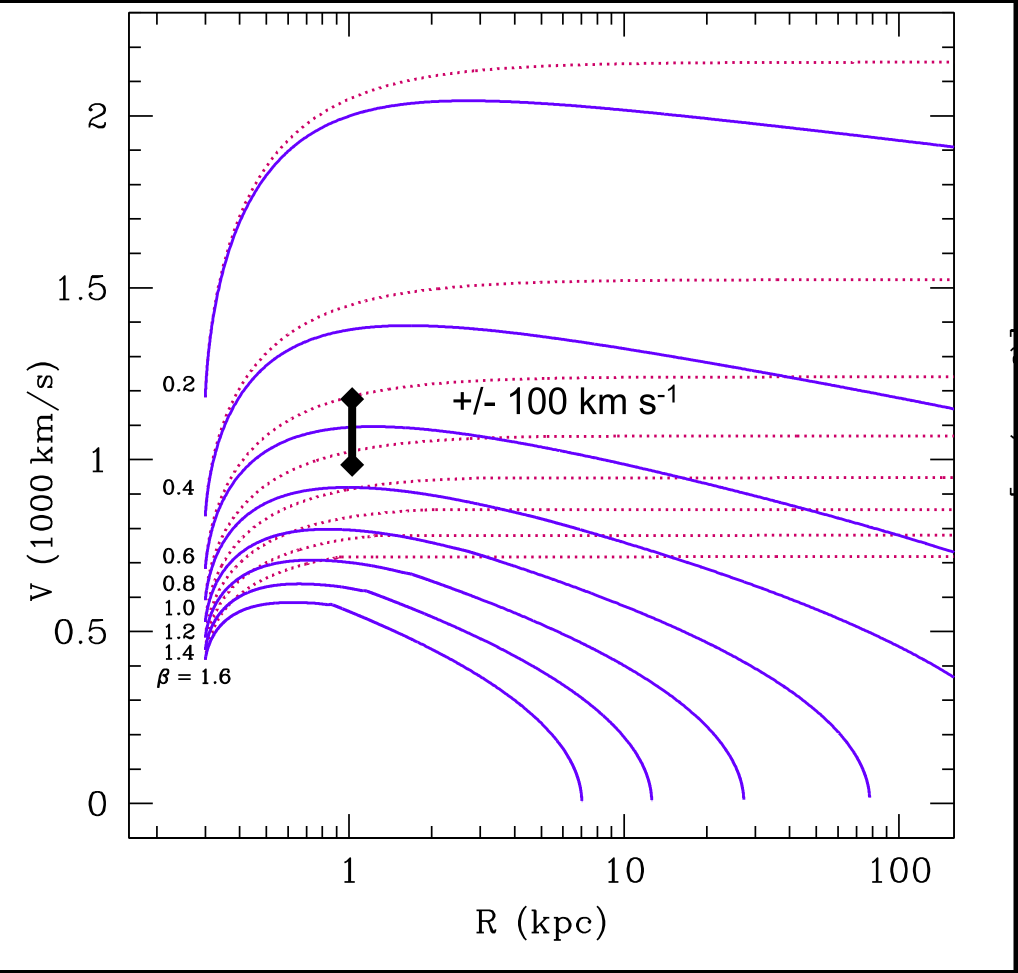
With gravity

Without gravity

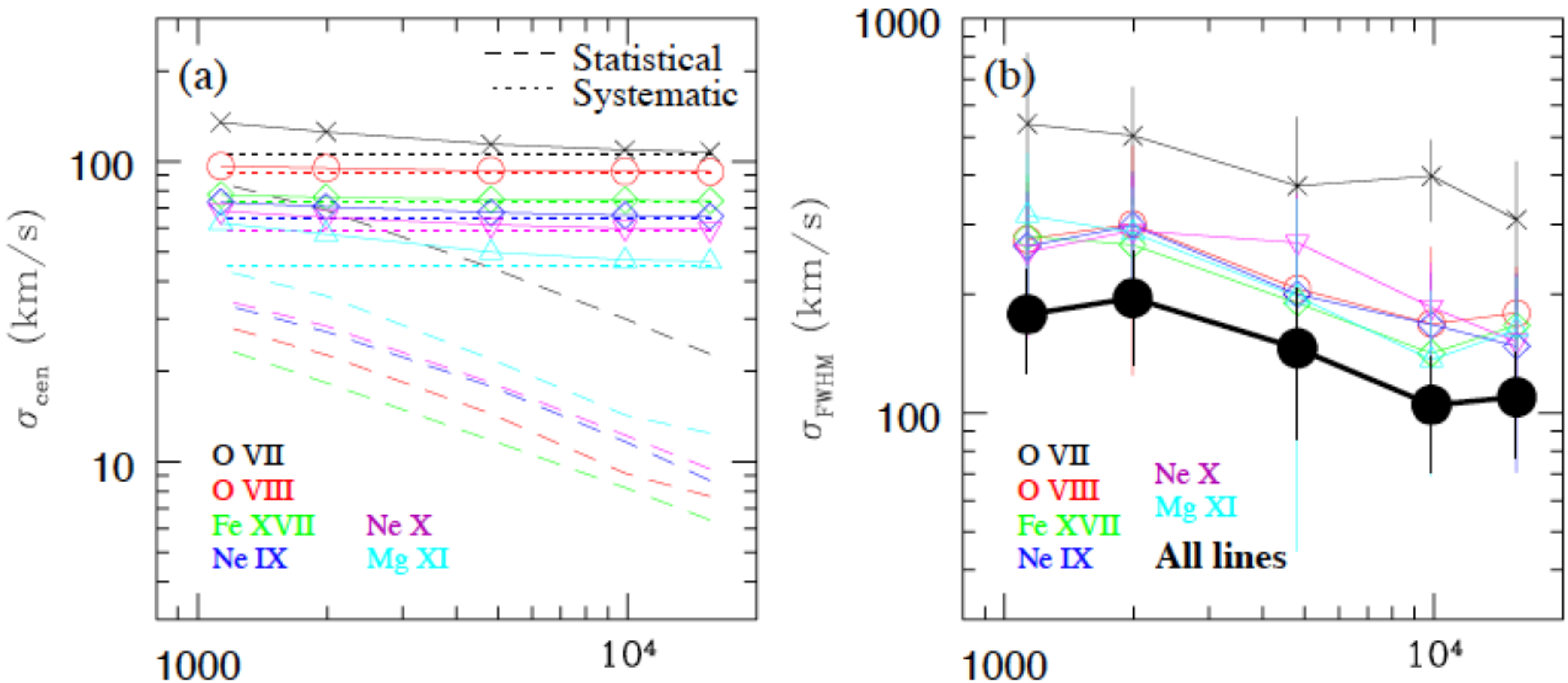


Starburst Outflow Velocities

At distance of M82 (3.5 Mpc),
1’ ~ 1 kpc



Line Velocity Diagnostics

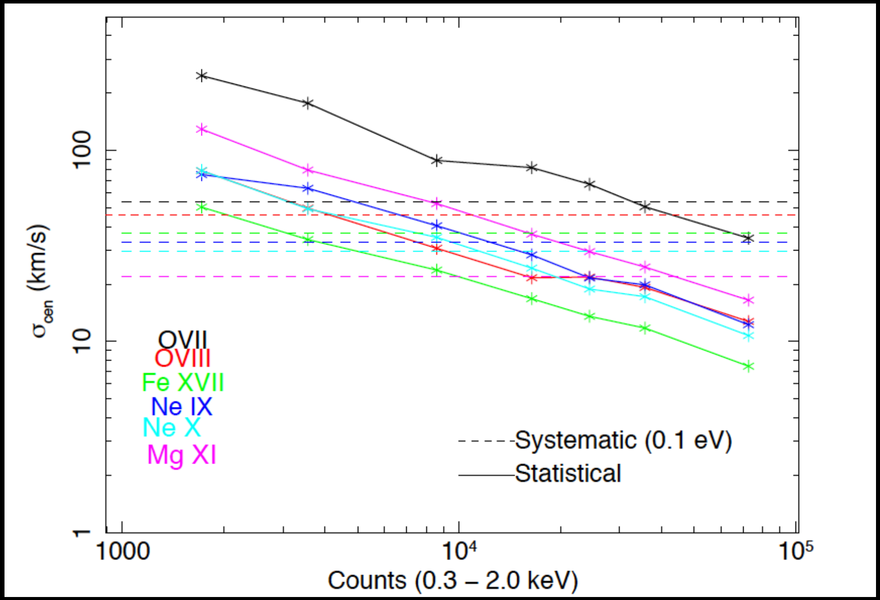


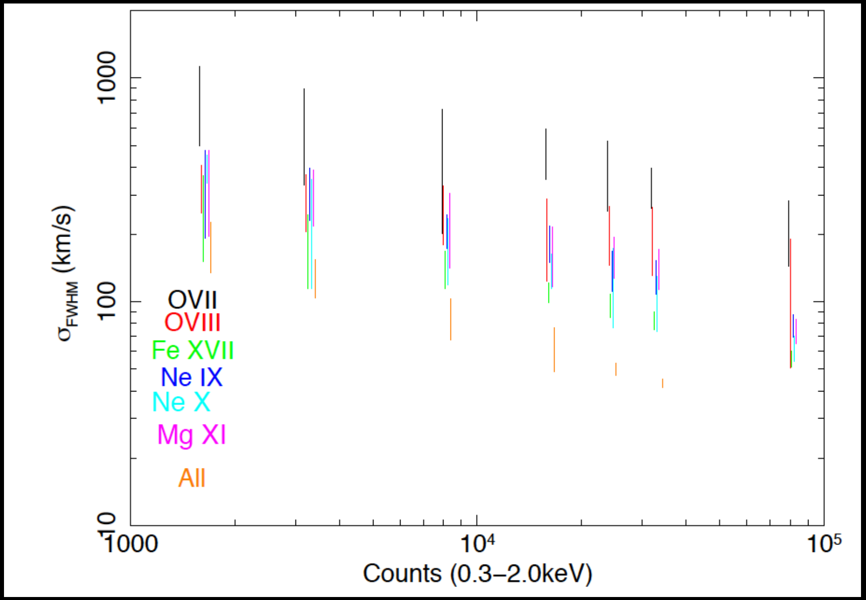
Simulations by D. Strickland, starting with narrow lines

From IXO XMS simulations, for ~ 2 eV spectral resolution, ~ 10^3 / 10^4 counts are required to constrain velocity centroid / width to within 50-100 km s^{-1}.

Centroid error likely dominated by calibration error above ~ 1000-2000 counts

Broad Line Diagnostics





Input model:
kT=0.4 keV, velocity width=500 km/s Z_{Fe}= 0.5, $Z_{\propto}$ = 1.5

Systematic error of 0.1 eV shown as dashed lines
Simulations done by M. Yukita using xrs_calorimeter.rmf, xrs_calorimeter.arf

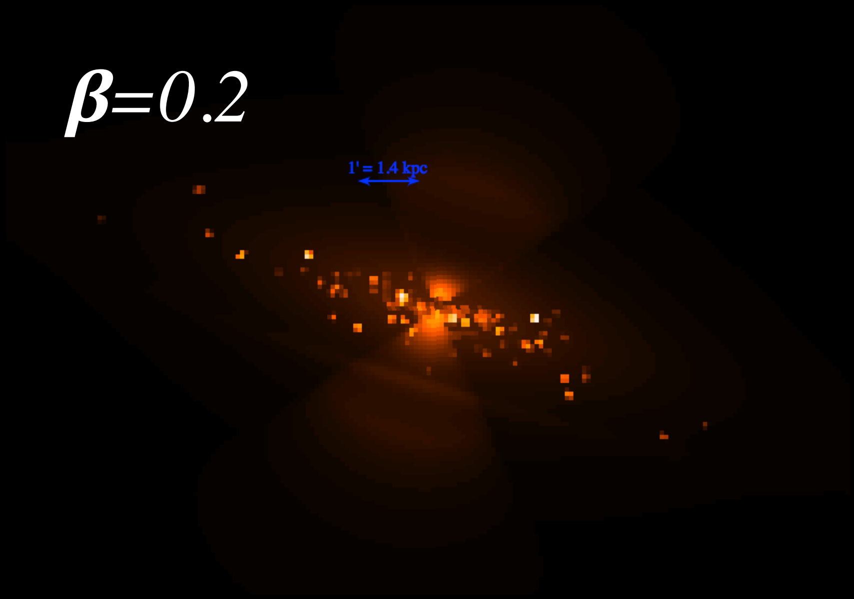
Toy Starburst Model

- Thompson et al. (2016) superwind with various **β** (mass-loading) values
- 6 kpc x 2 kpc diameter exponential hot disk ISM with kT=0.4 keV, v_{rot}=250 km/s
- Cold exponential disk absorber
- Beta-model hot halo with beta=0.5, kT=0.2, 0.3 solar, scale heights of 5 kpc x 4 kpc
- X-ray binaries distributed with power-law XLF along disk
- Soft X-ray background model from Henley & Shelton (2013)
- Simulated starbursts at 5 (and 50 Mpc)
  - generated spectral models for all components along a slice
  - Velocity structure in lines due to superposition of components, themral broadening intrinsic to APEC model

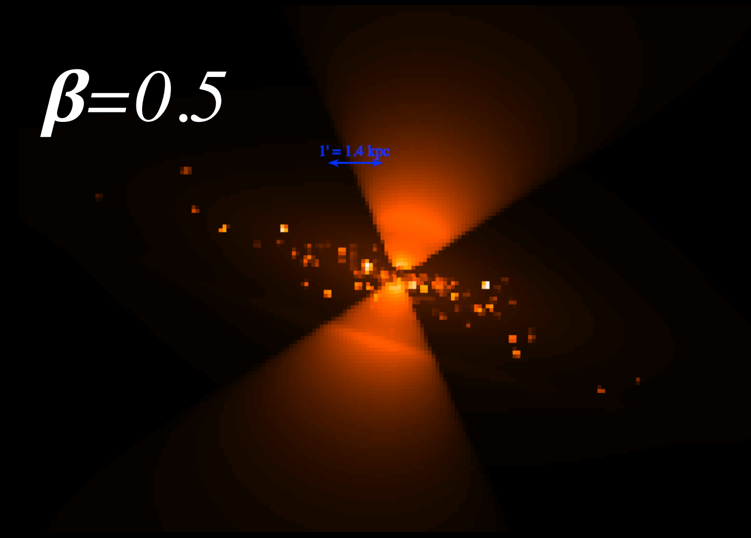
Model and simulations by Edmund Hodges-Kluck

Toy Starburst Model

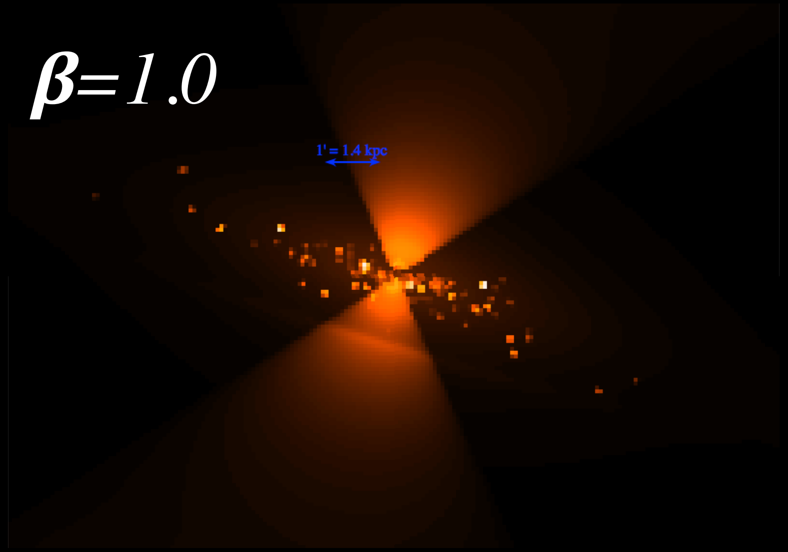
β=0.2

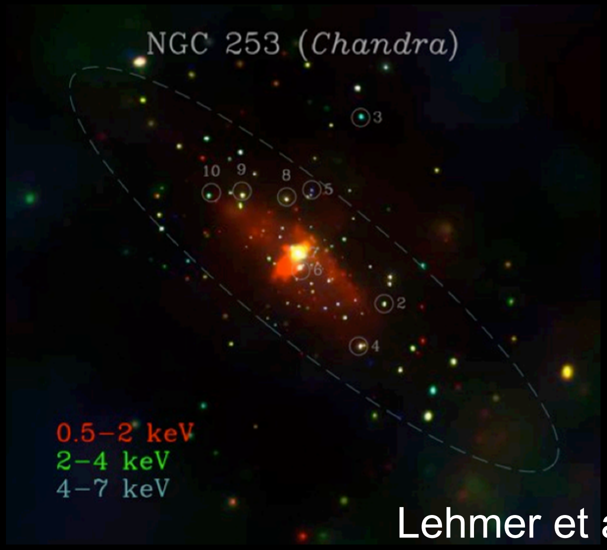


β=0.5



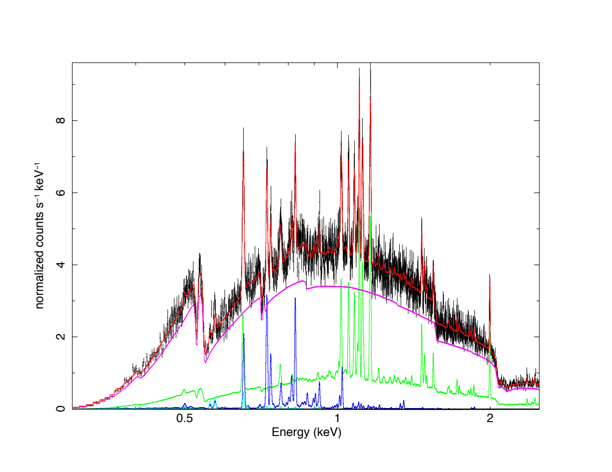
β=1.0



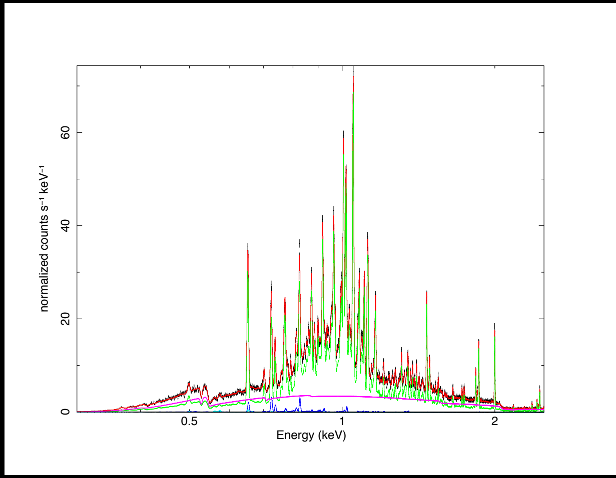


Lehmer et al. (2013)

Spectral "Slices"

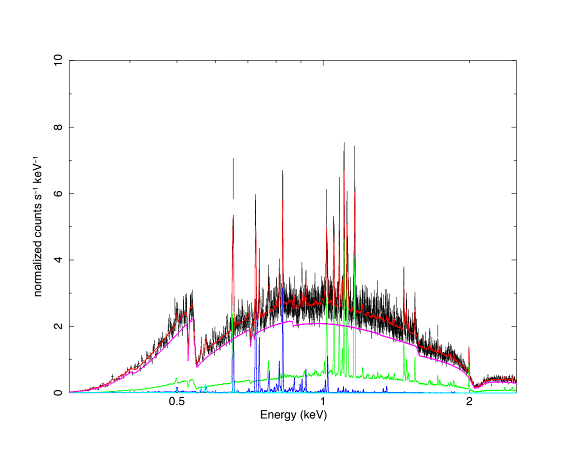


β=0.2, ΔE=5 eV



β=0.5, ΔE=5 eV

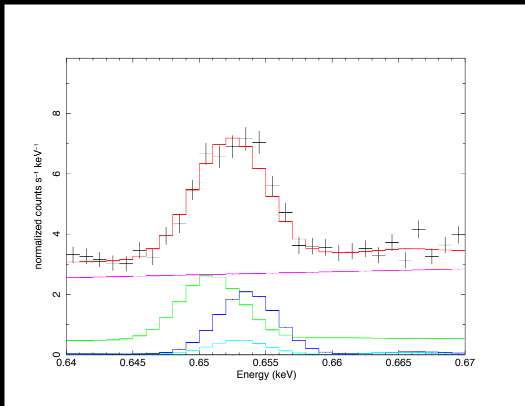
Black –Simulated data
Red – Total model
Green - Wind emission
Blue – Disk
Light Blue – Halo
Magenta - XRBs



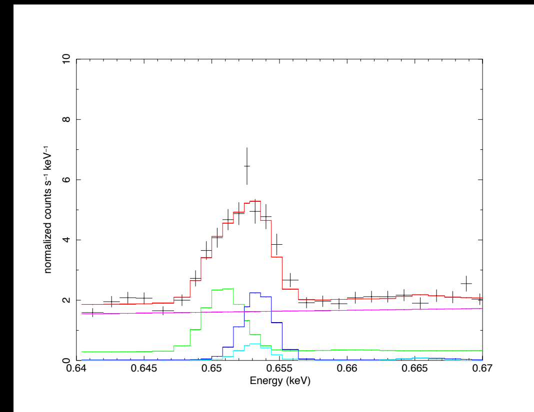
β=0.2, ΔE=2.5 eV (X-IFU)

50 ks Simulations for an M82-like starburst at 5 Mpc, 30" diameter region 1' along minor axis

O VIII



β=0.2, ΔE=5 eV



β=0.2, ΔE=2.5 eV

Black –Simulated dat
Red – Total model
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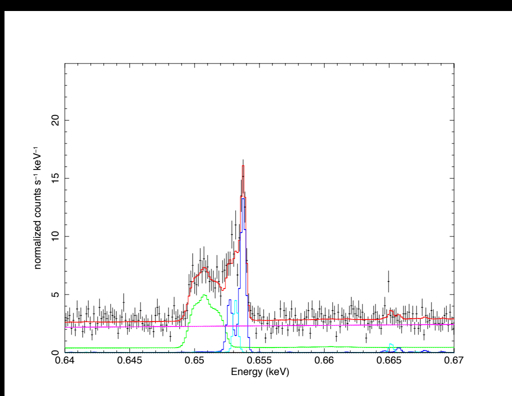
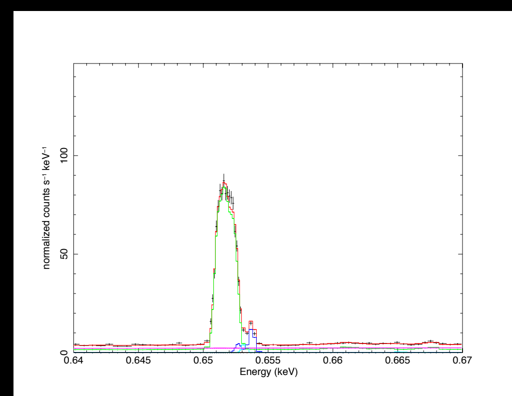


β=0.2, ΔE=0.3 eV



β=0.5, ΔE=0.3 eV

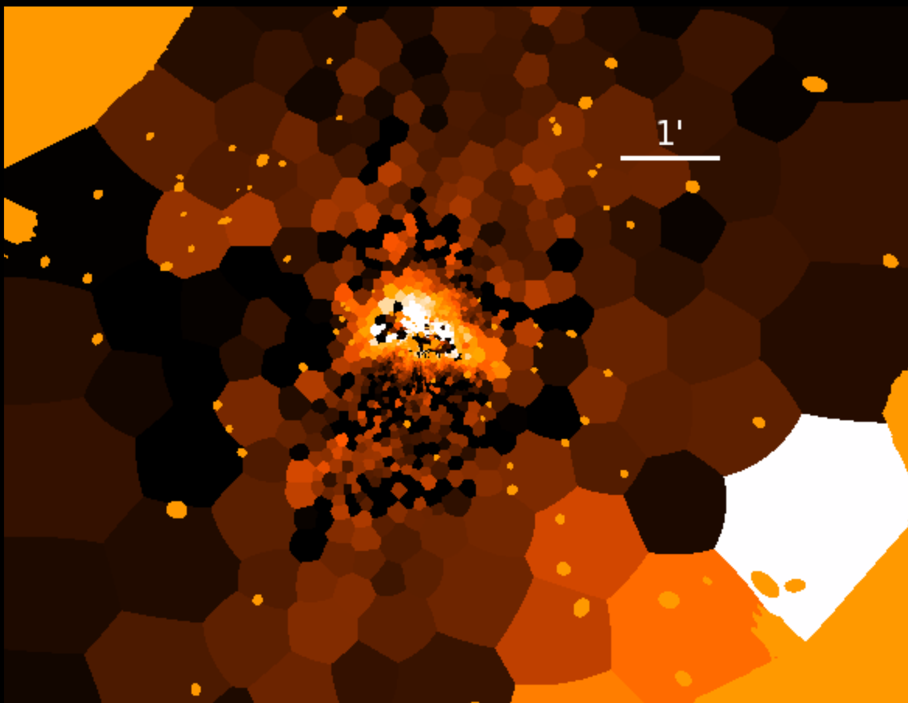
Major improvement in resolving line structure in going from ΔE= 2.5 to *ΔE = 0.3 eV*

End-to-End Simulation Strategy (Mostly Future Work)

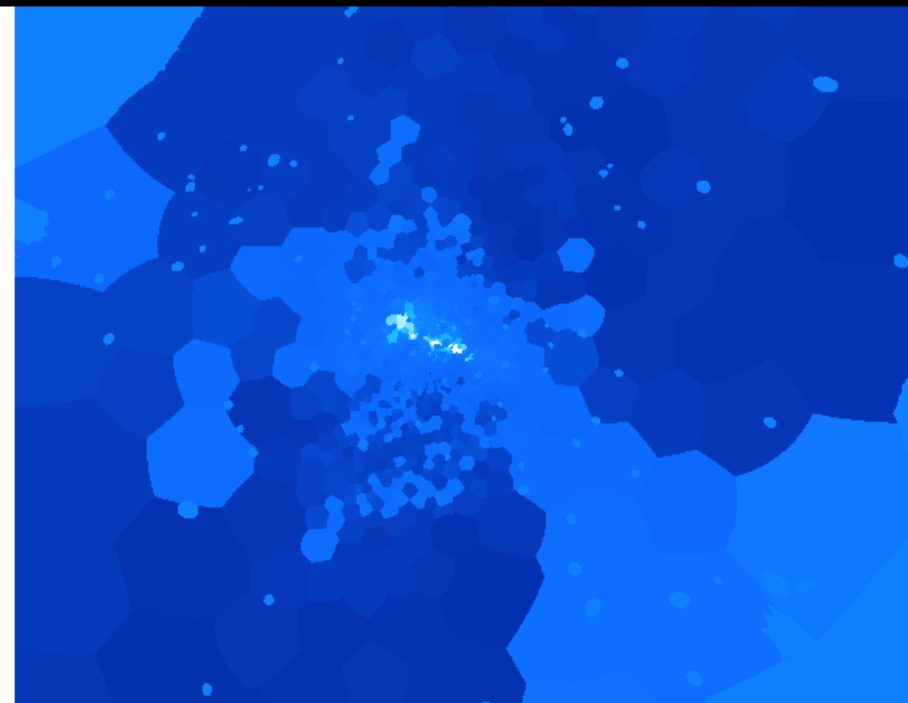
- Create diffuse-only maps of hot X-ray gas in nearby starburst galaxies
- Use adaptive region sizes to fit simple thermal models
- Use current models (e.g., Thomson et al. 2016) to model velocity distribution, or better yet “fit” toy model described previously to Chandra data to get posteriors for velocity, disk ISM flux and kT, etc.
- Simulate calorimeter observations including also XRBs
- Determine errors on temperature, (relative) abundances, velocities in outflow across starburst regions
- Also need to include shocks (non-equilibrium ionization; e.g., Wang et al. 2014) and charge exchange (additional physics due to outflow being a multi-phased medium; Zhang et al. 2014)

M82 Temperature, N_H Maps

kT

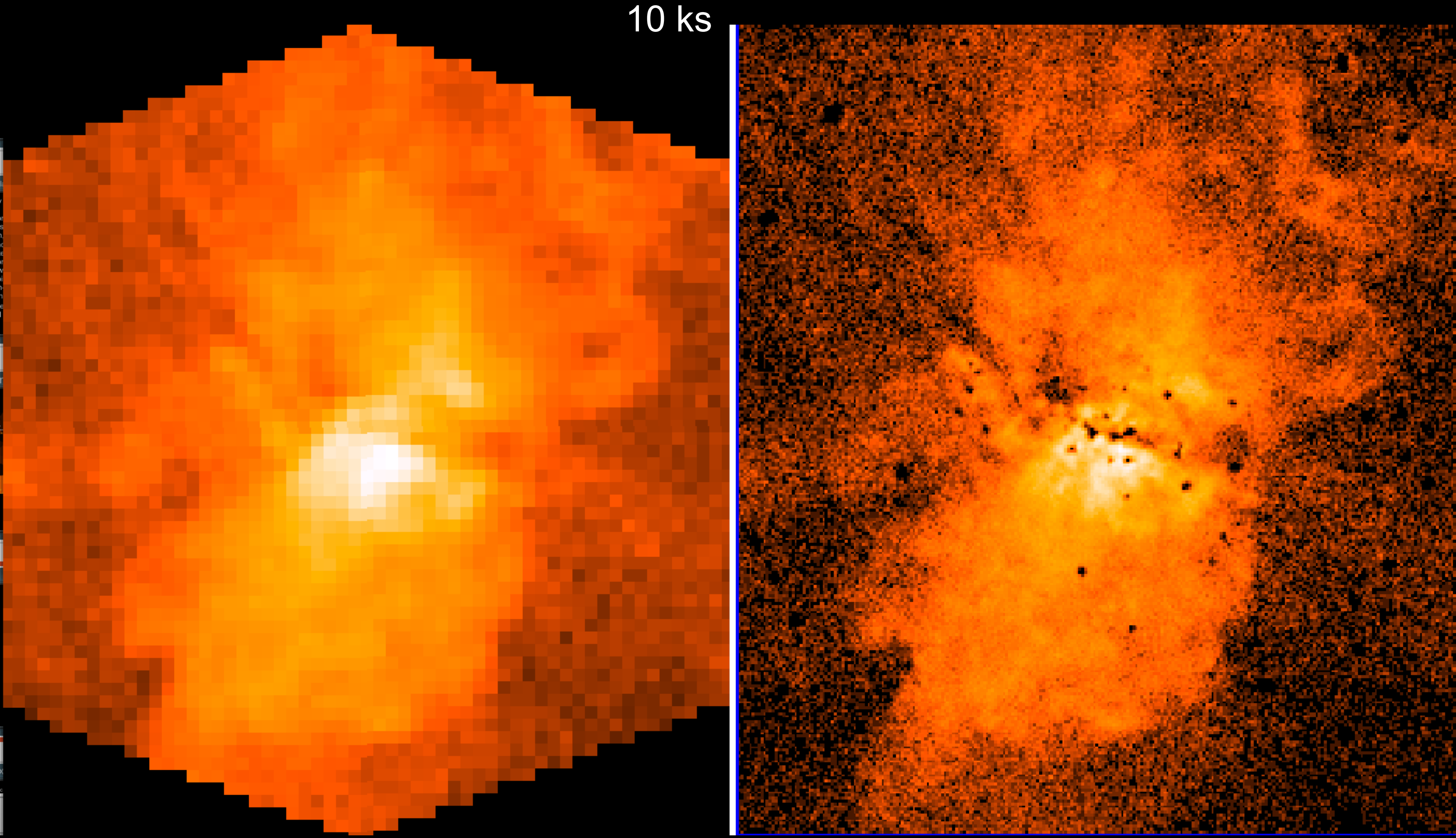


N_H



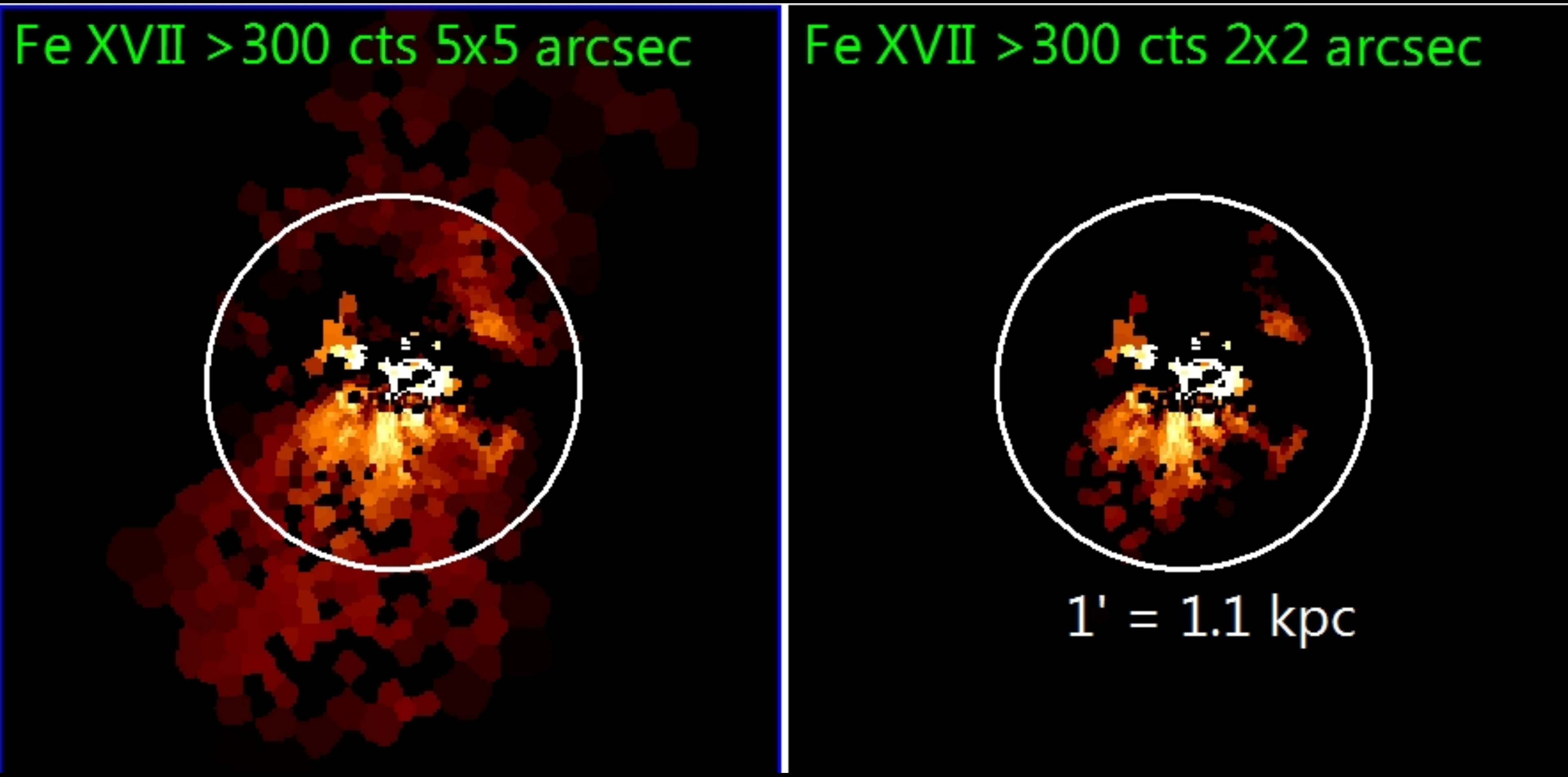
M. Yukita

Preview: M82 Diffuse-only X-IFU and Lynx Simulations



Benefits of higher spatial resolution and large FoV clearly evident

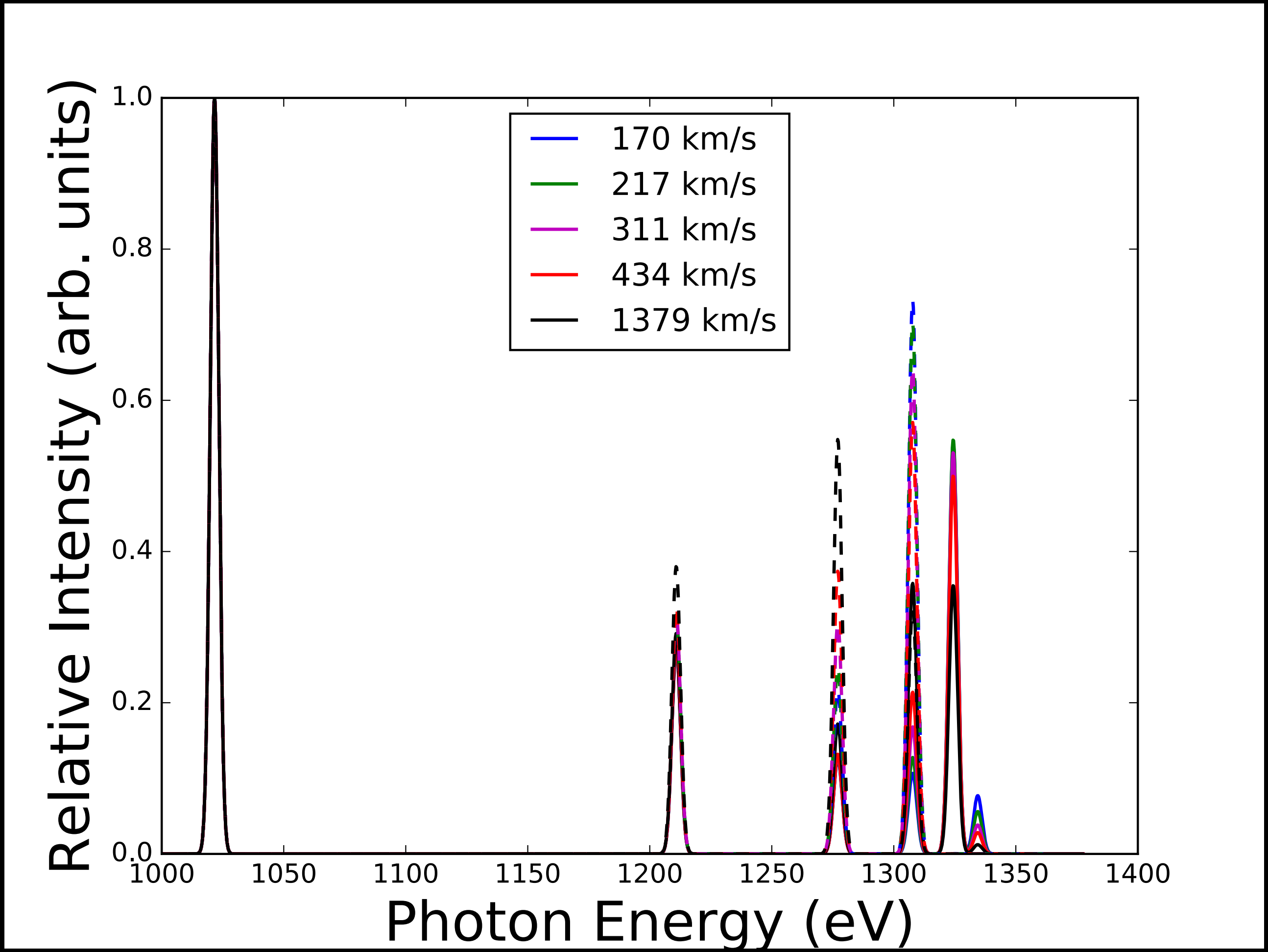
M82 Fe XVII (0.83 keV) Line Fluxes



E. Hodges-Kluck

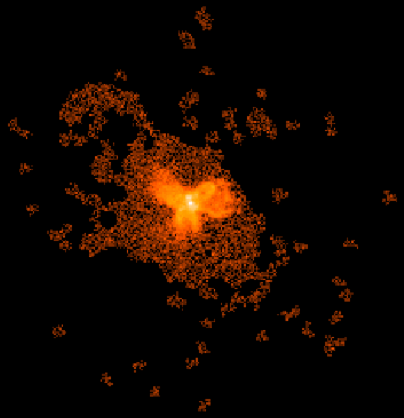
5x5” and 2x2” ”pixels” that would contain > 300 counts in the Fe VII line in 100 ks

Charge Exchange

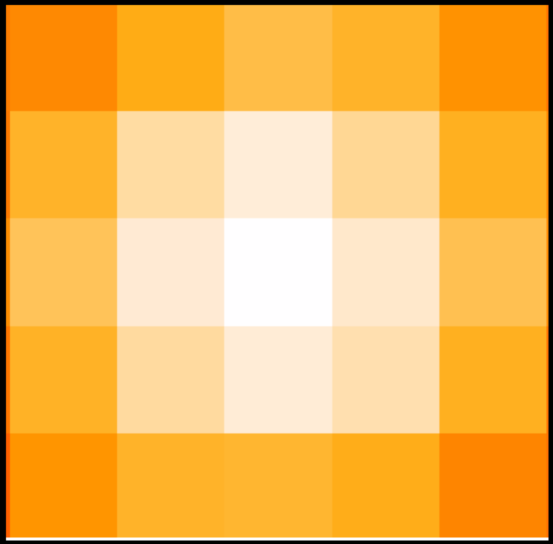


Charge exchange model being developed by **Renata Cumbee** (NPP postdoc) shown with 2.5 eV resolution will be incorporated into next iterations of Lynx starburst modeling

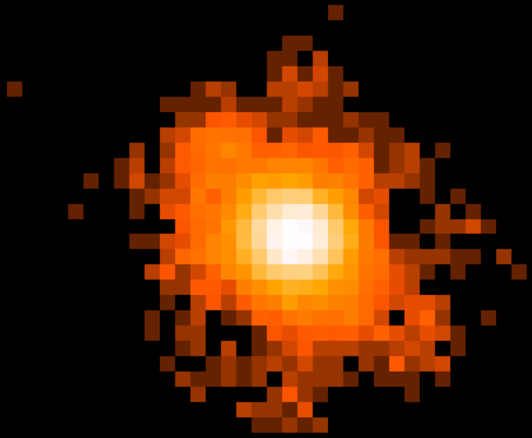
NGC 6240 at z=0.5



Chandra input image, actual distance ~ 100 Mpc



200 ks Athena WFI



200 ks Lynx HDXI

Simulation by E. Hodges-Kluck

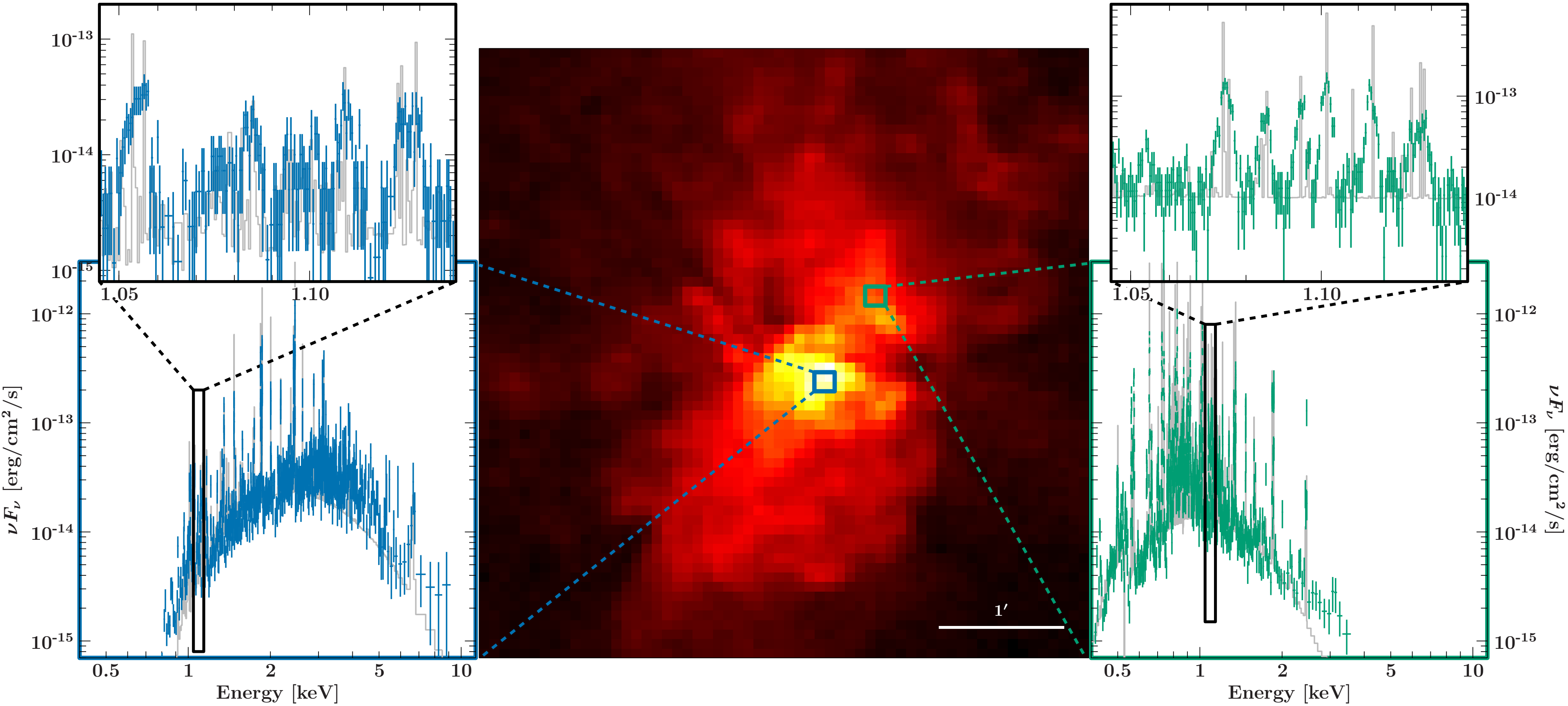
Conclusions

- Simulation and analysis of Lynx observations of starbursts is complex but preliminary results show:
  - Velocity resolutions on the order of 100 km/s are required
    - On the order of 10^{4-5} 0.5-2.0 keV counts (total) will be needed, ~ 200-300 counts in lines
  - Structure is clearly evident at subarcsecond scales, further work needed to determine required effective area / exposures to spatially and spectrally isolate filaments and importance of subtracting point sources
  - < 1 eV resolution required to resolve velocity structure in wind emission lines, may be necessary to resolve wind from disk and other components
- Resolving diffuse emission in galaxies at D>>100 Mpc clearly requires subarcsecond imaging
- Future work: end-to-end simulations using Chandra images and point source distributions, theoretical starburst models

Backup

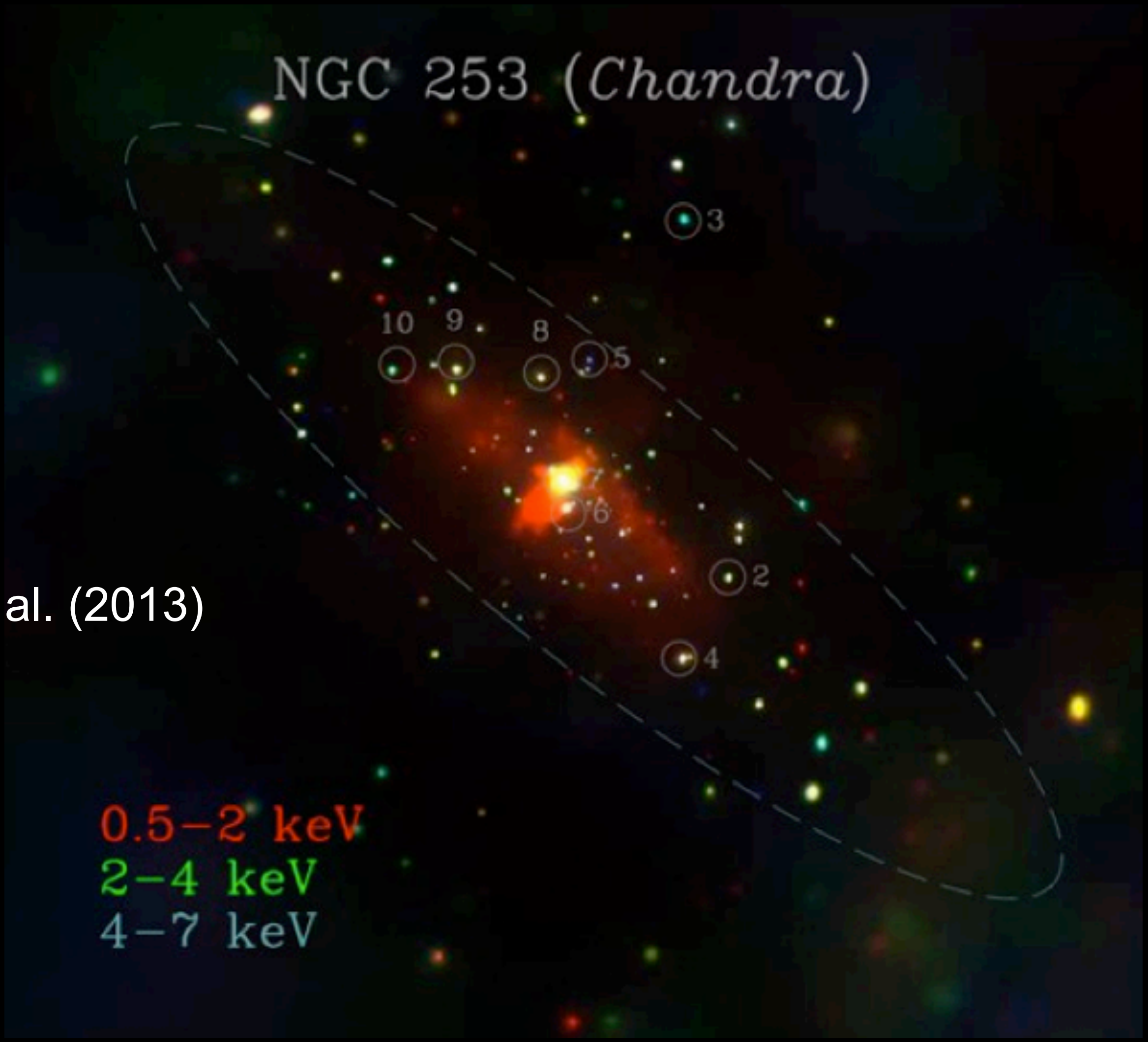
Athena WFI + X-IFU 100 ks simulation of M82

N.B. Point sources not included



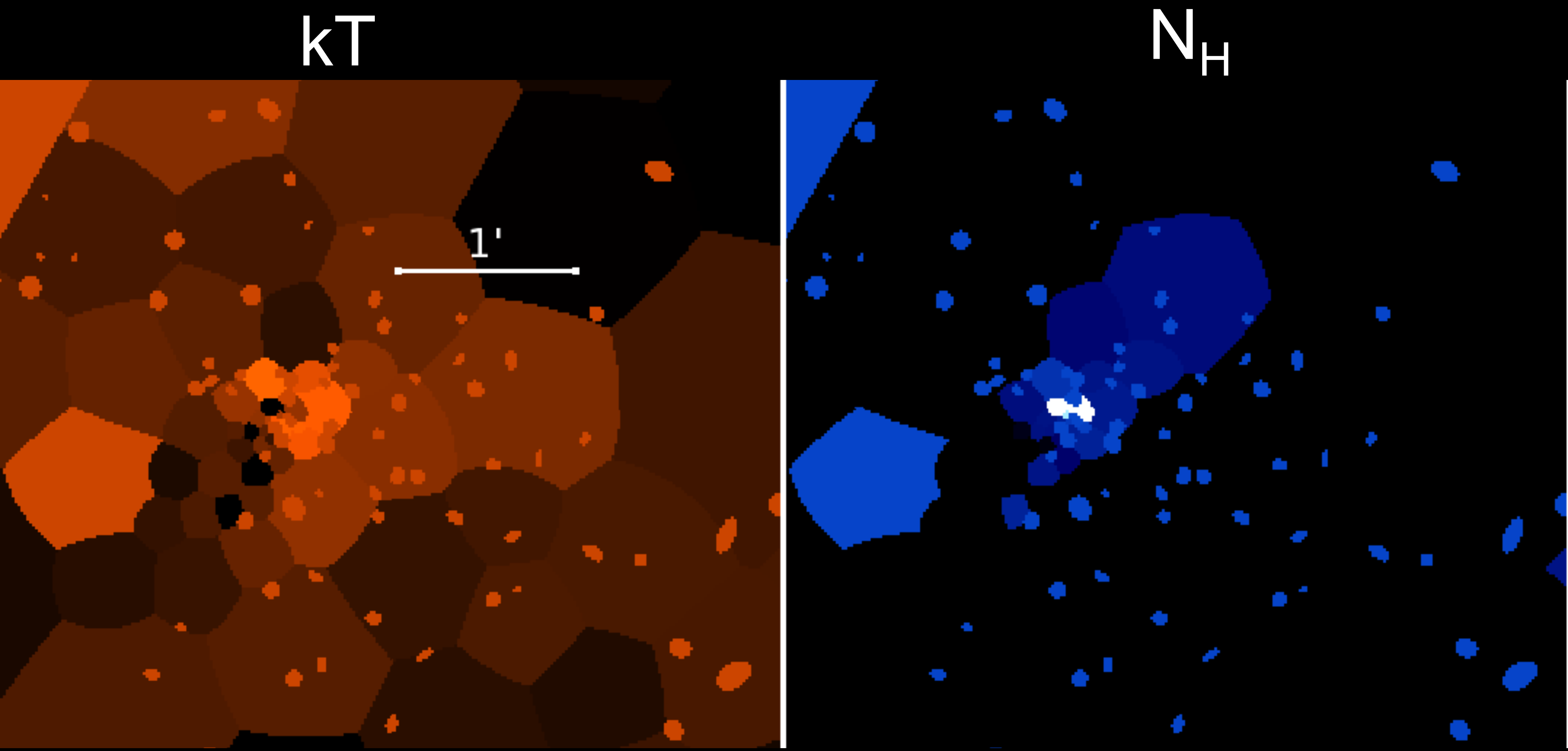
Simulation performed by Thomas Dauser

NGC 253



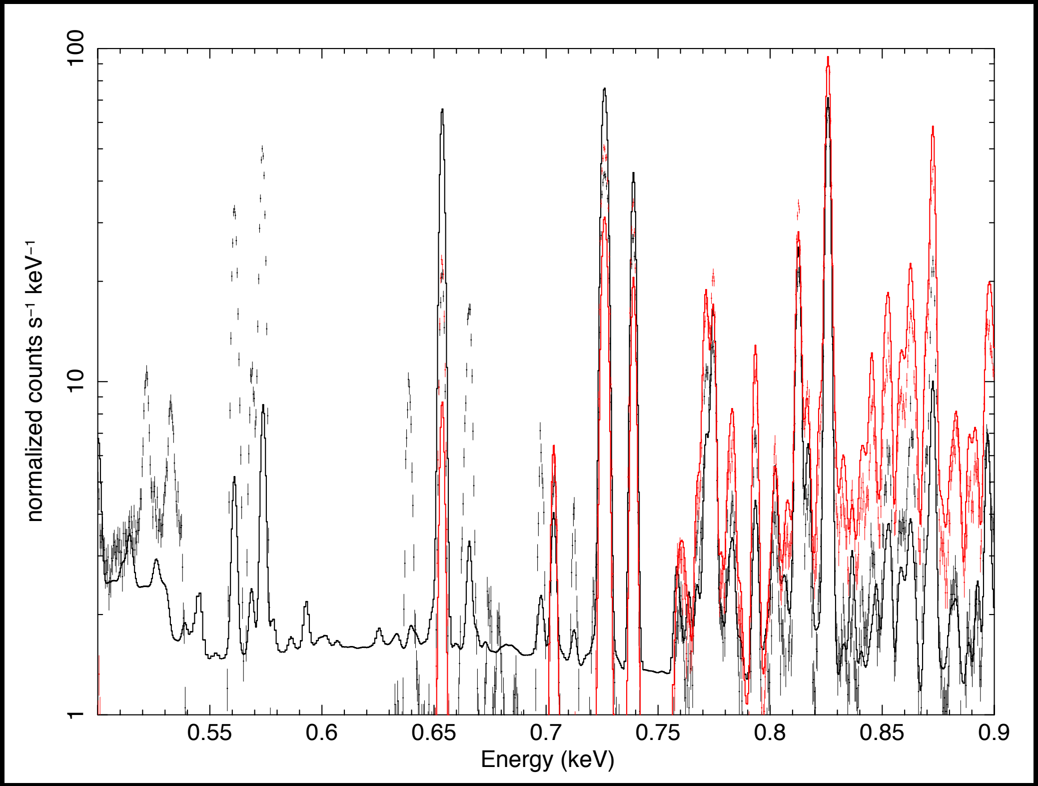
From Lehmer et al. (2013)

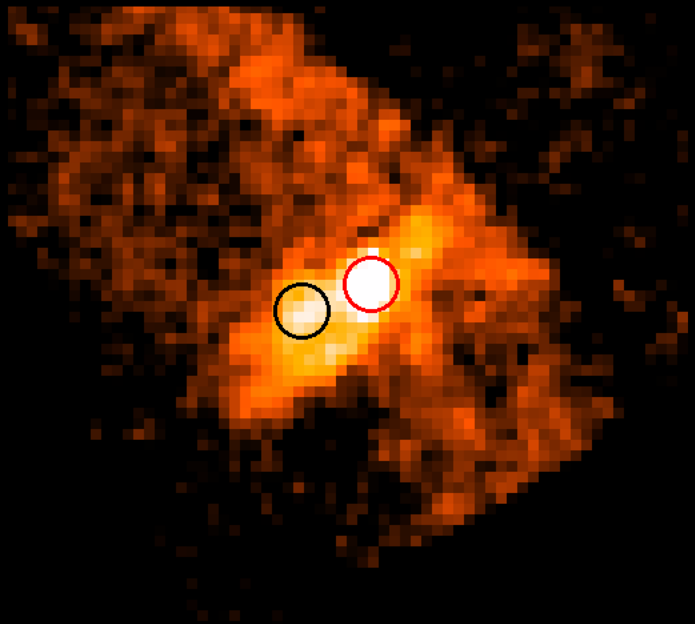
NGC 253 Temperature, N_H Maps



Courtesy of M. Yukita

NGC 253 X-IFU 100 ks Simulation





What will the Athena Starburst Sample Look Like?

	1.4 m^2 at 1 keV		2.0 m^2 at 1 keV	
Galaxy	X-IFU Surface Brightness	5σ Exp. (ks)	X-IFU Surface Brightness	5σ Exp. (ks)
NGC 3256	16.7	9.6	24.0	6.7
Henize 2-10	8.4	19.1	12.1	13.2
NGC 3310	6.4	25.3	9.1	17.5
VV 114	6.1	26.4	8.8	18.3
etc				

5σ Exposure gives exposure time to get 10,000 counts in a 15"x15" region
X-IFU Surface Brightness is in counts s^{-1} $arcmin^{-2}$ based on total diffuse X-ray luminosity and source extent. Total includes bgd. which is < 10% of counts in most cases.

For mock observing plan, also included ULIRGS to have a total of 34 galaxies requiring 15 (10) Ms for 1.5 (2.0) m^2 at 1 keV.

See also Antara Basu-Zych poster for local Lyman-break analog galaxies VV 114 and Haro 11

Conclusions

- X-IFU observations promise to directly map out the diffuse X-ray flux in a sample of ~ 30 nearby starburst and ULIRG galaxies
  - Spectral modeling needs to include background, updated estimates on achievable systematic energy calibration error
- Detailed simulation is possible with SIXTE and simx
  - Need to model X-ray binary populations
    - Interesting in their own right (see Andreas Zezas poster)
    - ULXs possibly can be used as bgd. light sources
  - Velocity model for outflowing gas and disk ISM
  - Need to include metalicity gradient, shocks (NEI) and charge exchange also