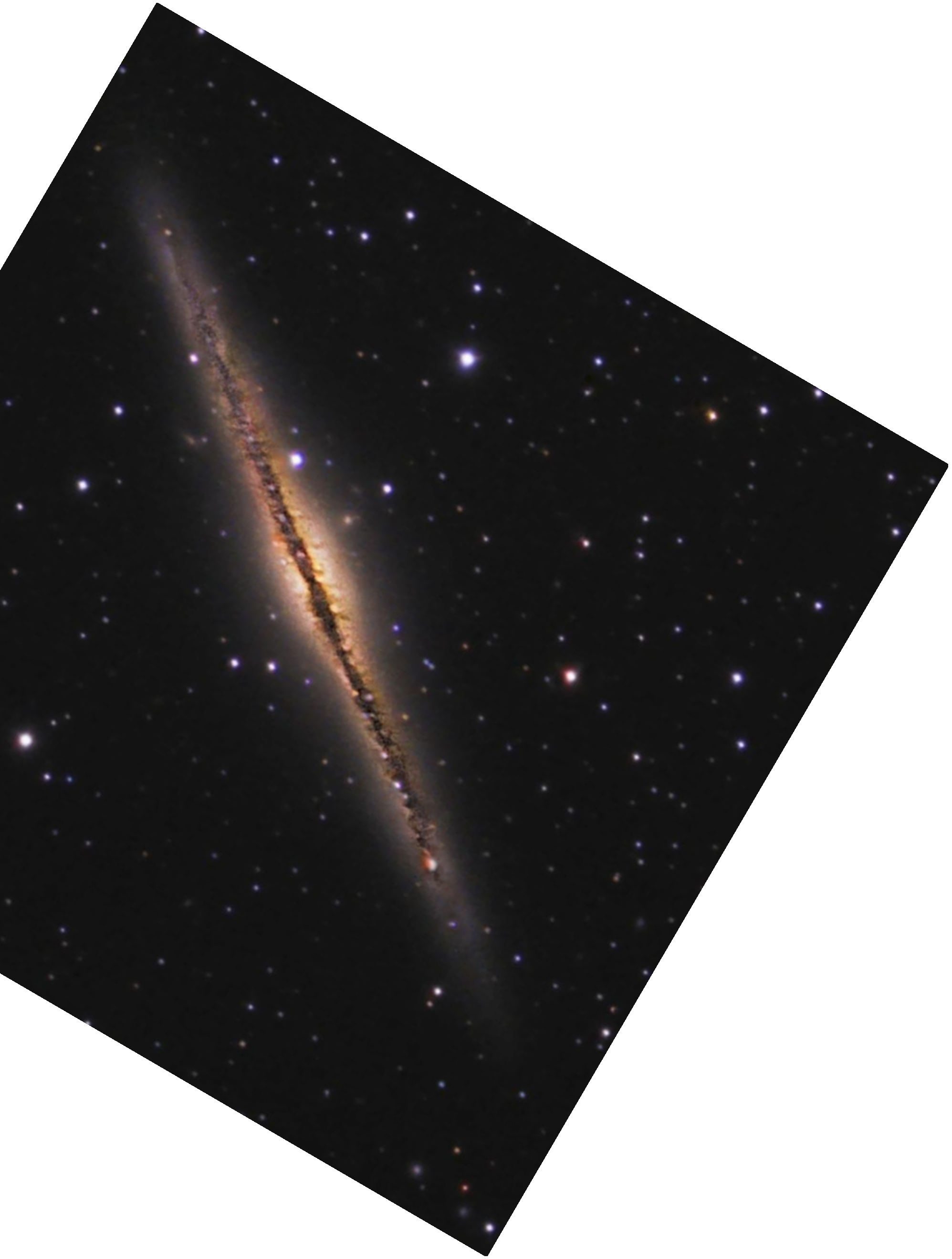

The Gaseous Halo of NGC 891

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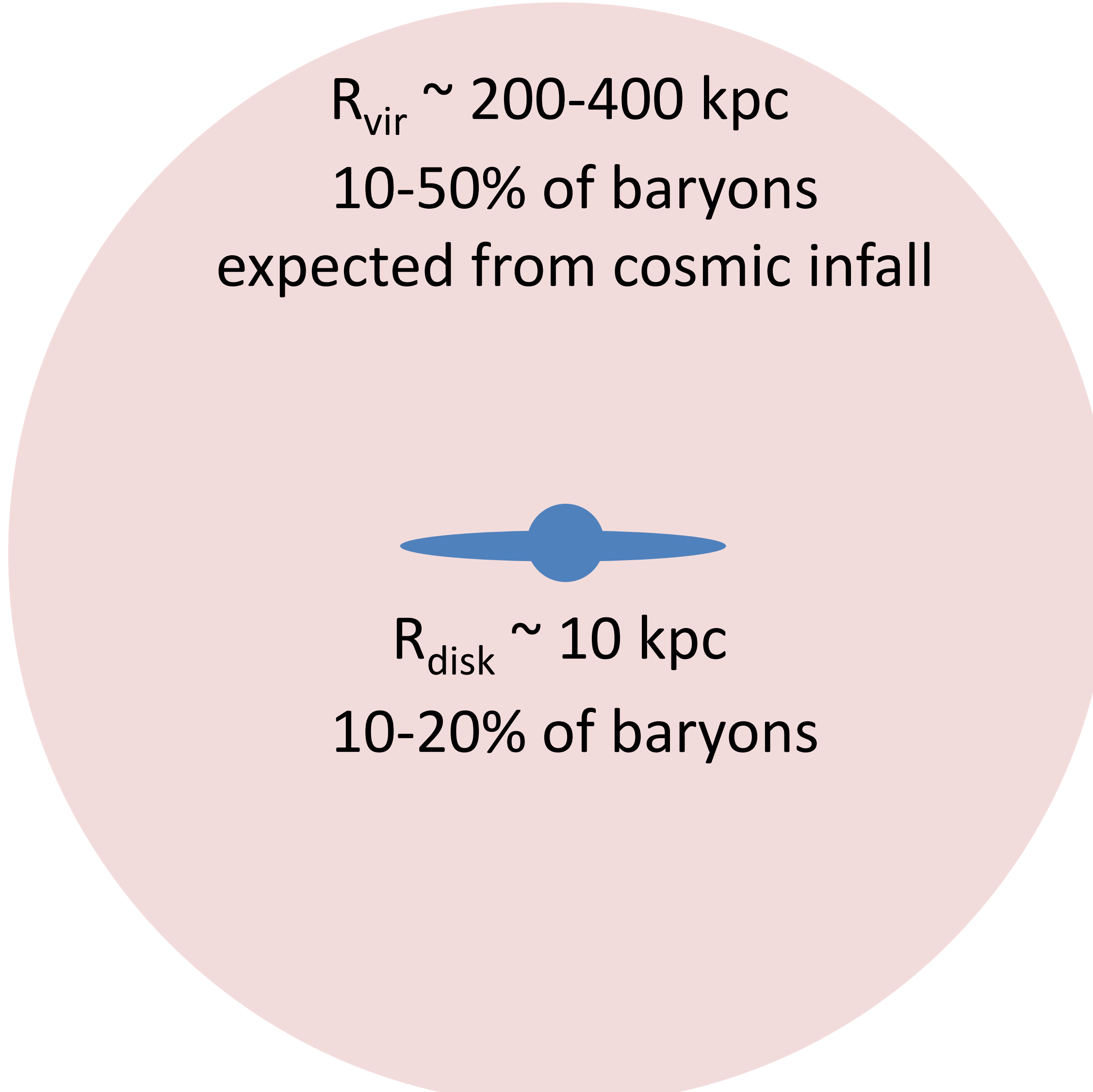
Joel Bregman
University of Michigan

Agenda

- Galaxy Halos
- NGC 891 as an interesting case
- Halo Metallicity
  - X-ray Measurements
  - Metallicity in the cool gas
  - (Possible) Interpretation

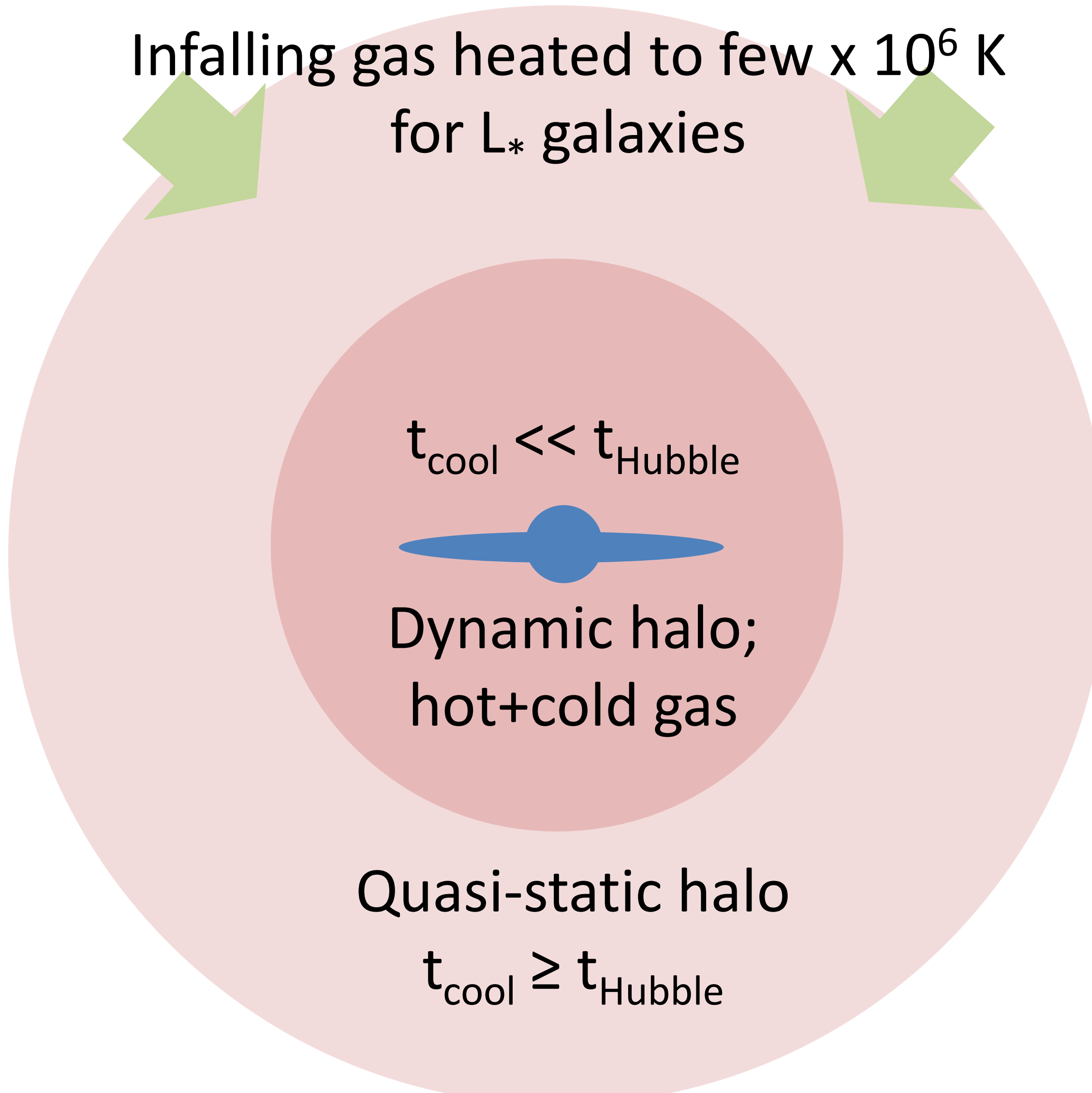
Galaxy Halos

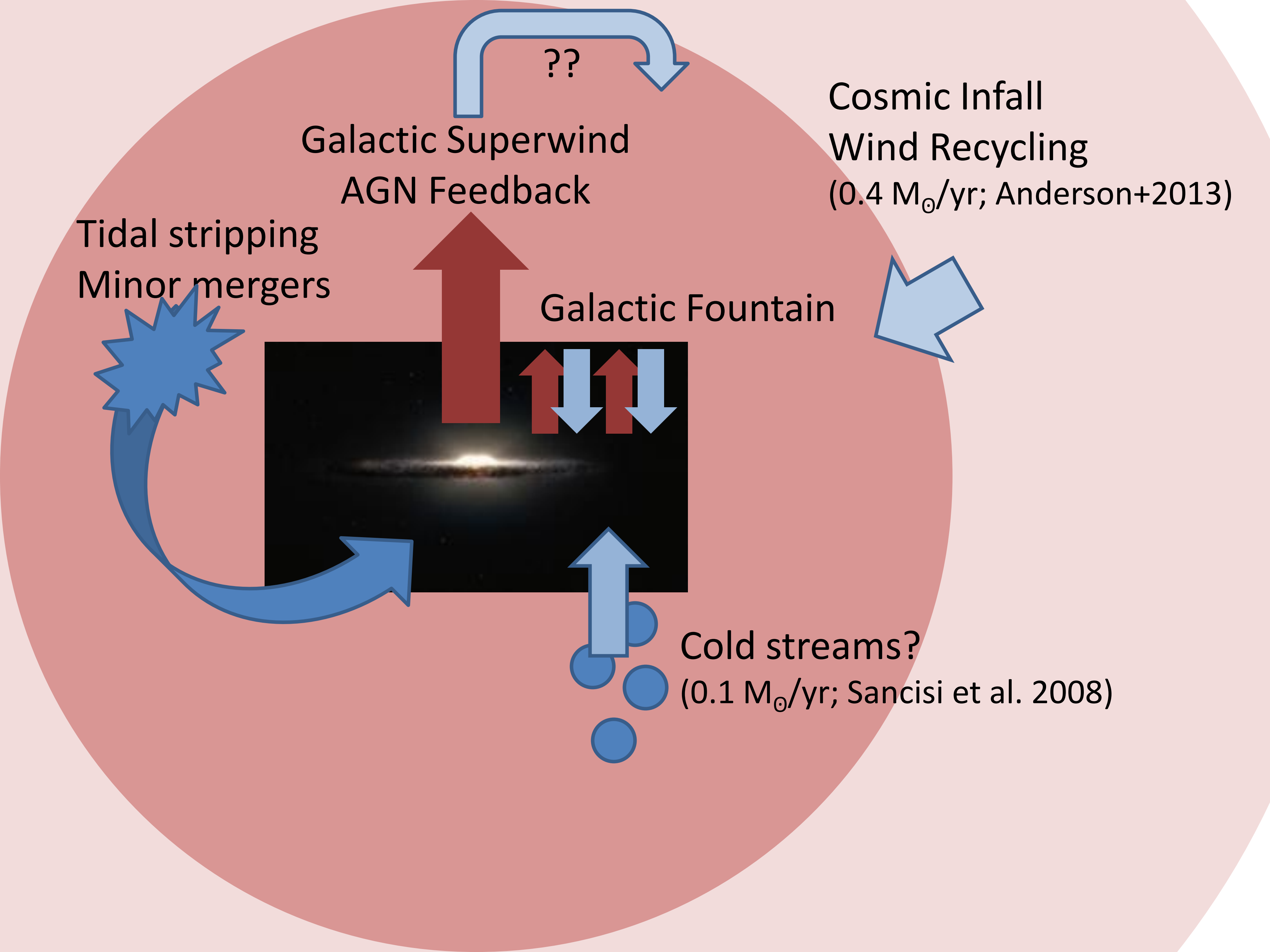
Halos are a reservoir of baryons



Galaxy Halos

Why?




??
Galactic Superwind
AGN Feedback
Cosmic Infall
Wind Recycling
(0.4 $M_\odot$/yr; Anderson+2013)
Tidal stripping
Minor mergers
Galactic Fountain
Cold streams?
(0.1 $M_\odot$/yr; Sancisi et al. 2008)

Galaxy Halos

What is the halo composition?

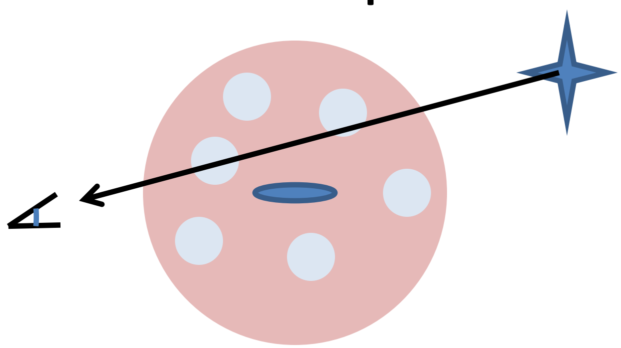
- Inflowing/outflowing material has similar n, T
- Metallicity (Z) distinguishes the two
- But, halo is very tenuous ($n \sim 10^{-2}$—10^{-3} cm^{-3}) and hard to see

- Is most of the hot material outflow or inflow?
- What is the connection, if any, between the hot and cool components?

Galaxy Halos

What is the halo composition?

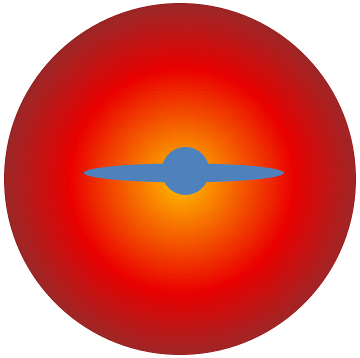
- QSO absorption lines



Metal mass from W_{eq}

  - Probes warm/cool gas
  - Few quasars near galaxy
  - Few galaxies with multiple quasars

- Hot halo emission

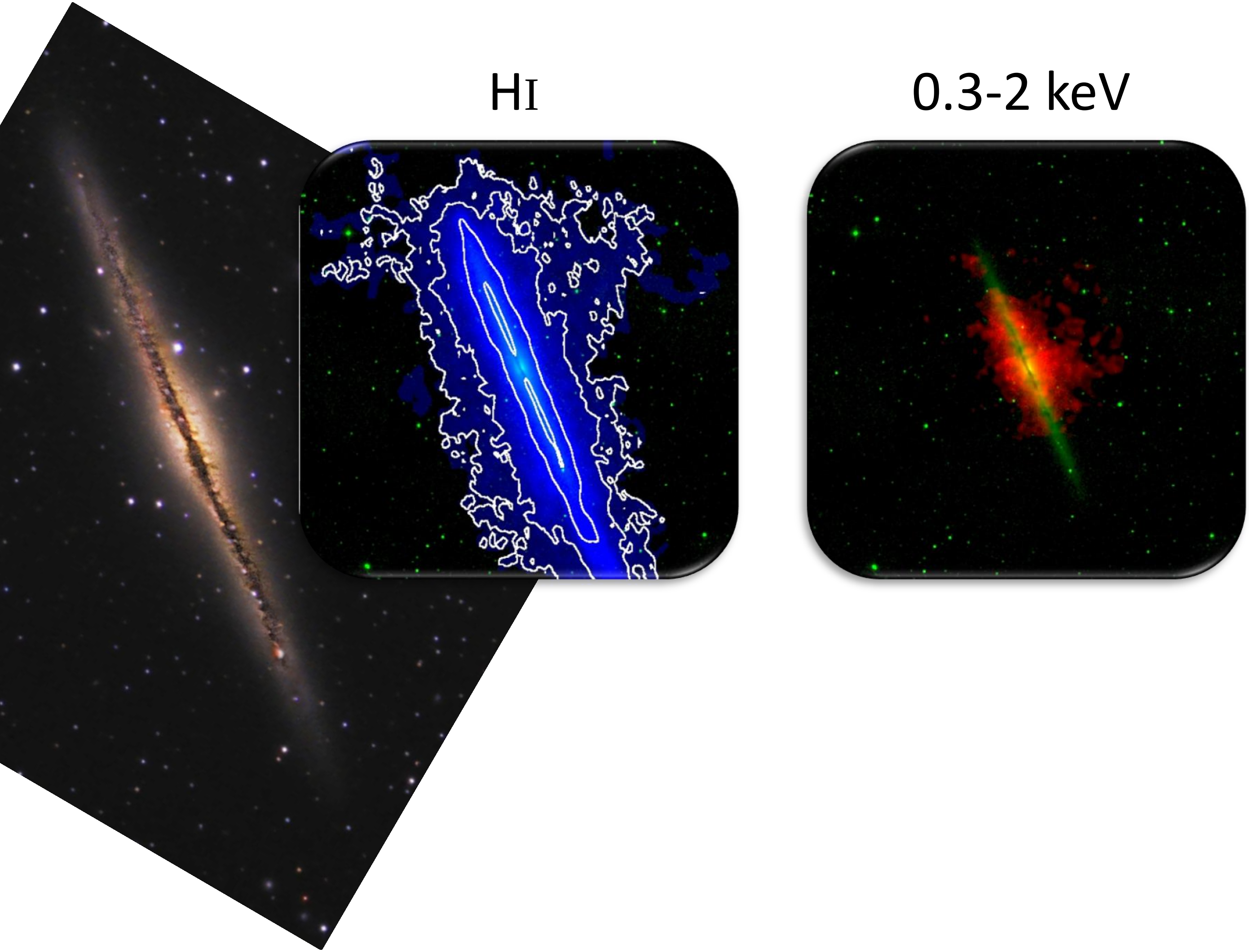


Metallicity from CIE model

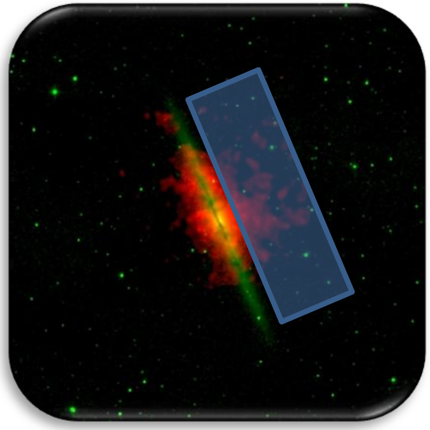
  - EM $\propto n_e n_H$ (small)
  - Few normal galaxies with X-ray halos
  - Probes densest regions

NGC 891

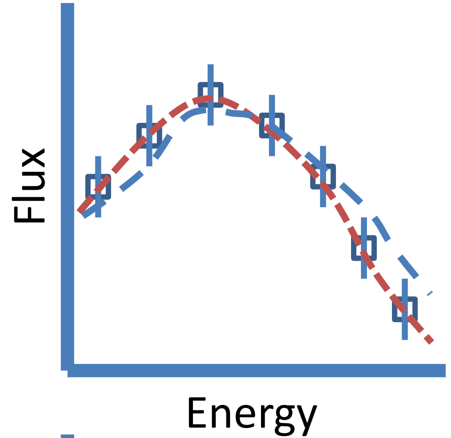
- One of the best objects to study disk-halo cycle:
  - Nearby (10 Mpc), edge-on MW analog
  - X-ray brightest halo of nearby, normal galaxies (Bregman & Pildis 1994)
  - Giant HI halo ($10^9\ M_\odot$)
  - Halo has exceptional data sets at multiple wavelengths
  - Active star formation ($4\ M_\odot$/yr; Popescu 2004)


HI
0.3-2 keV

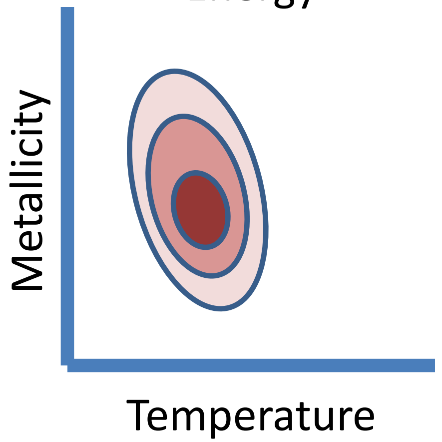
Hot Halo Metallicity



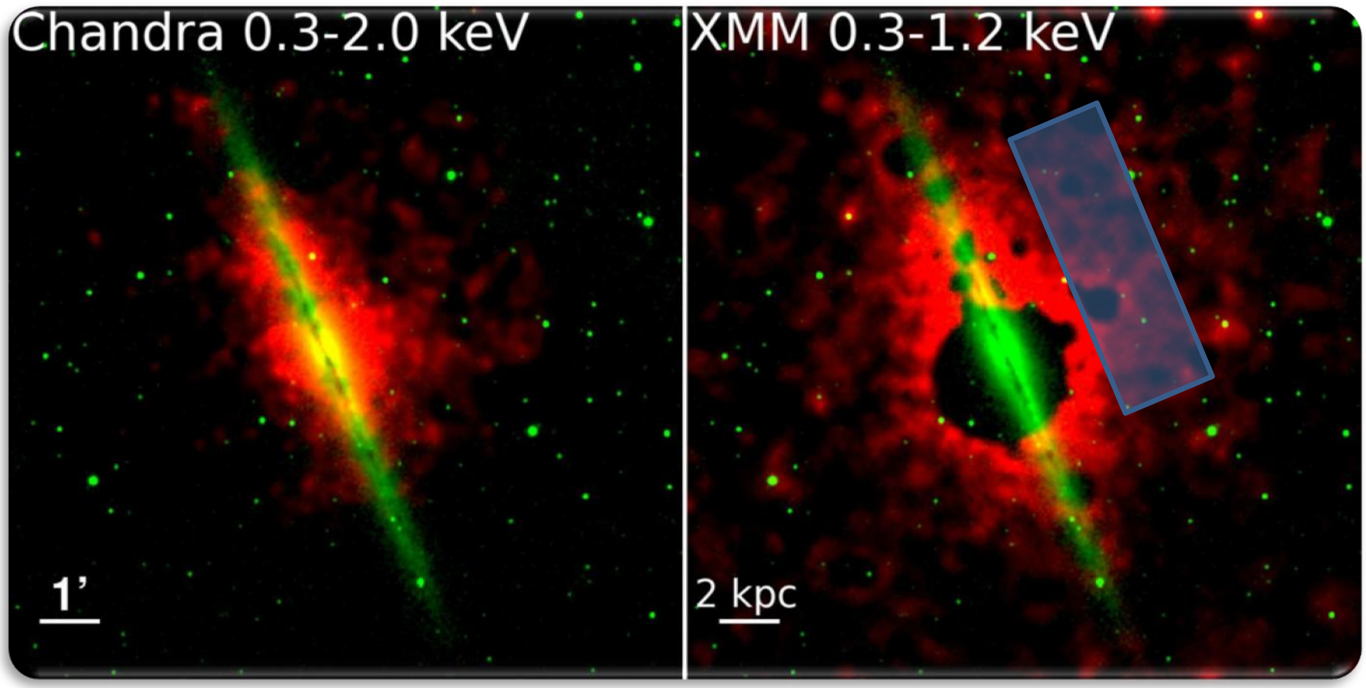
1. Extract halo spectrum



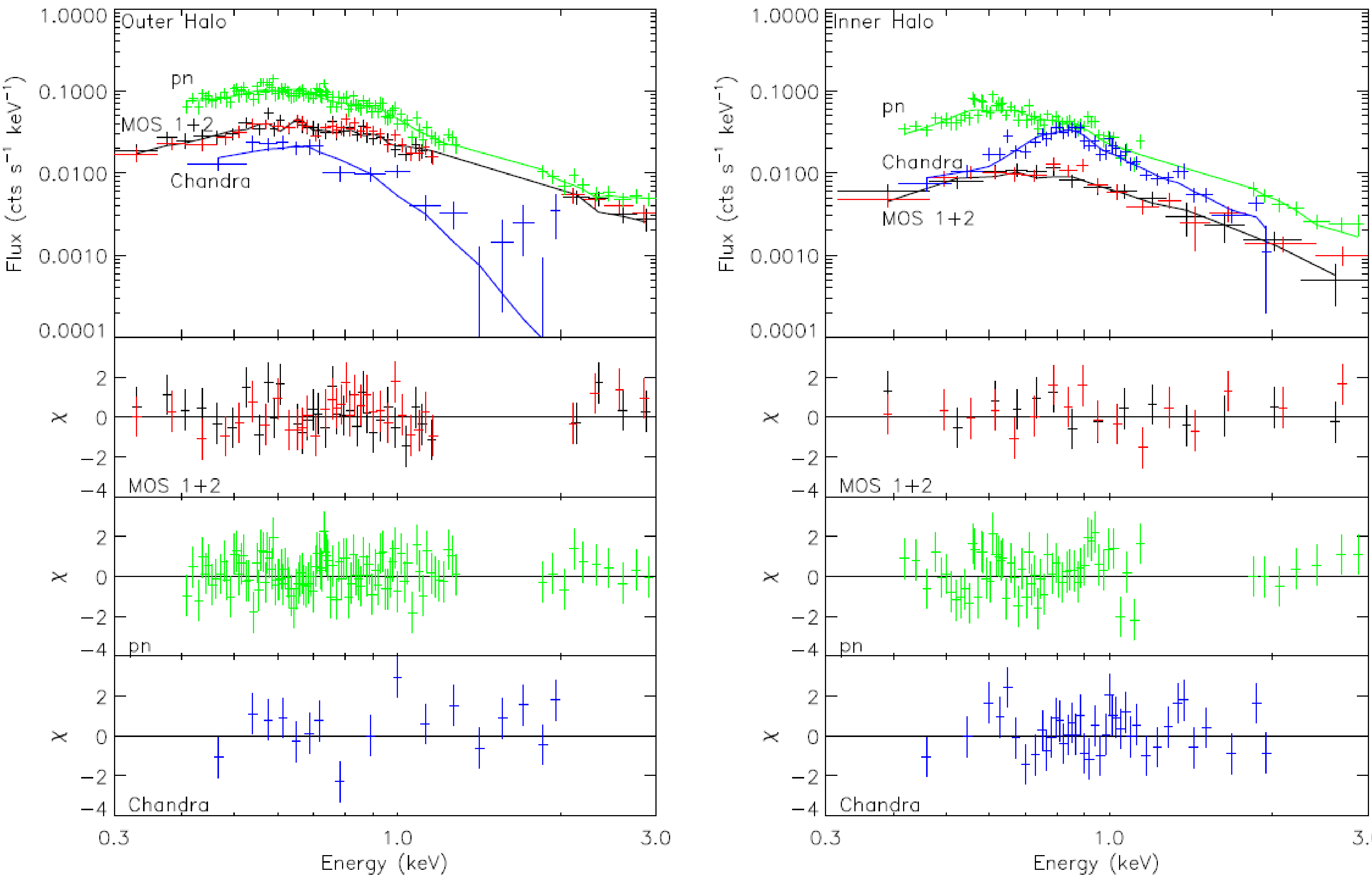
2. Fit with thermal model



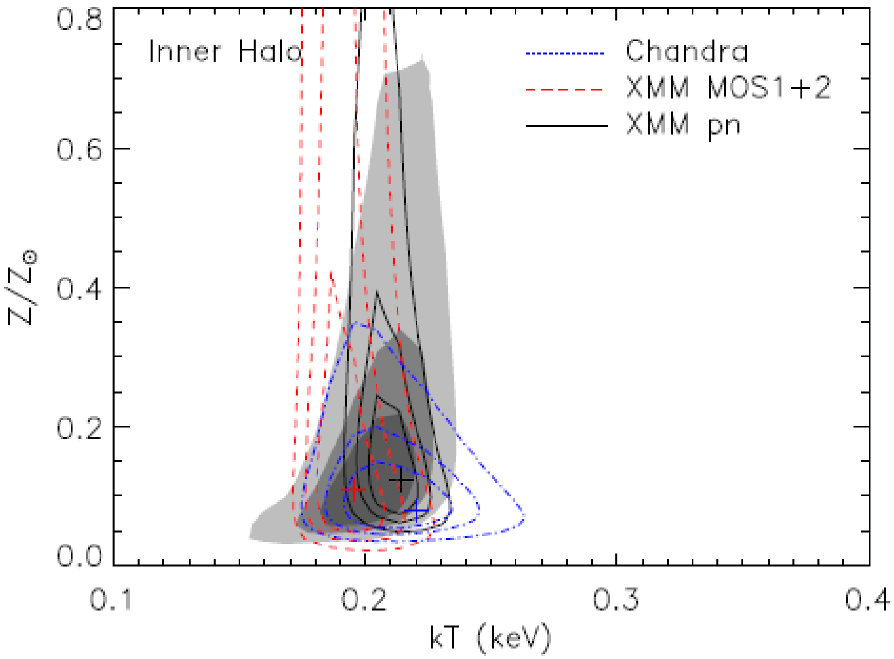
3. Assess fit/ Constrain Z

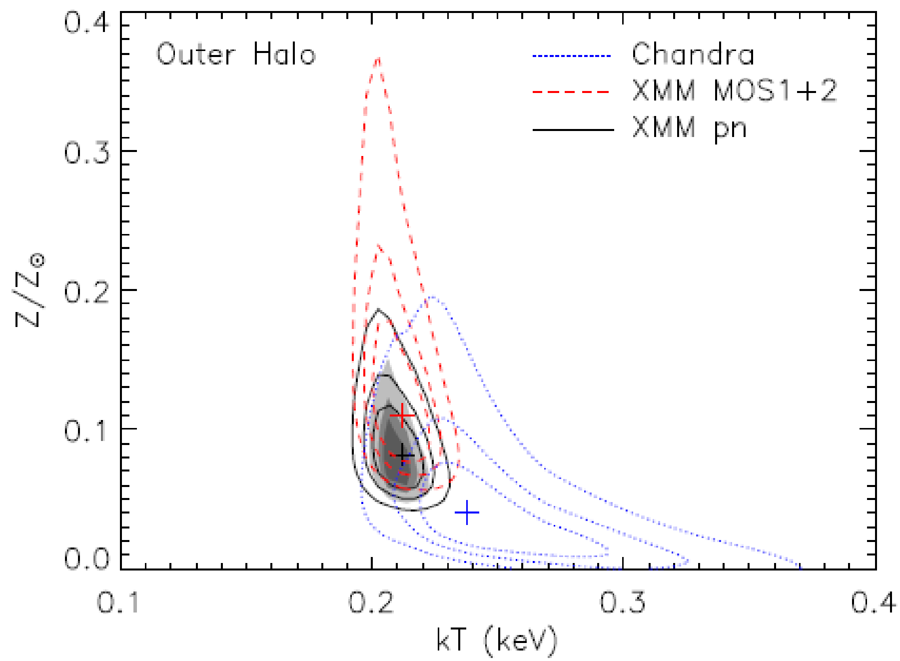


- Brighter, inner X-rays associated with bulge and star forming regions, also have high N_H
- A cleaner test obtained in the "outer halo" seen by *XMM-Newton*



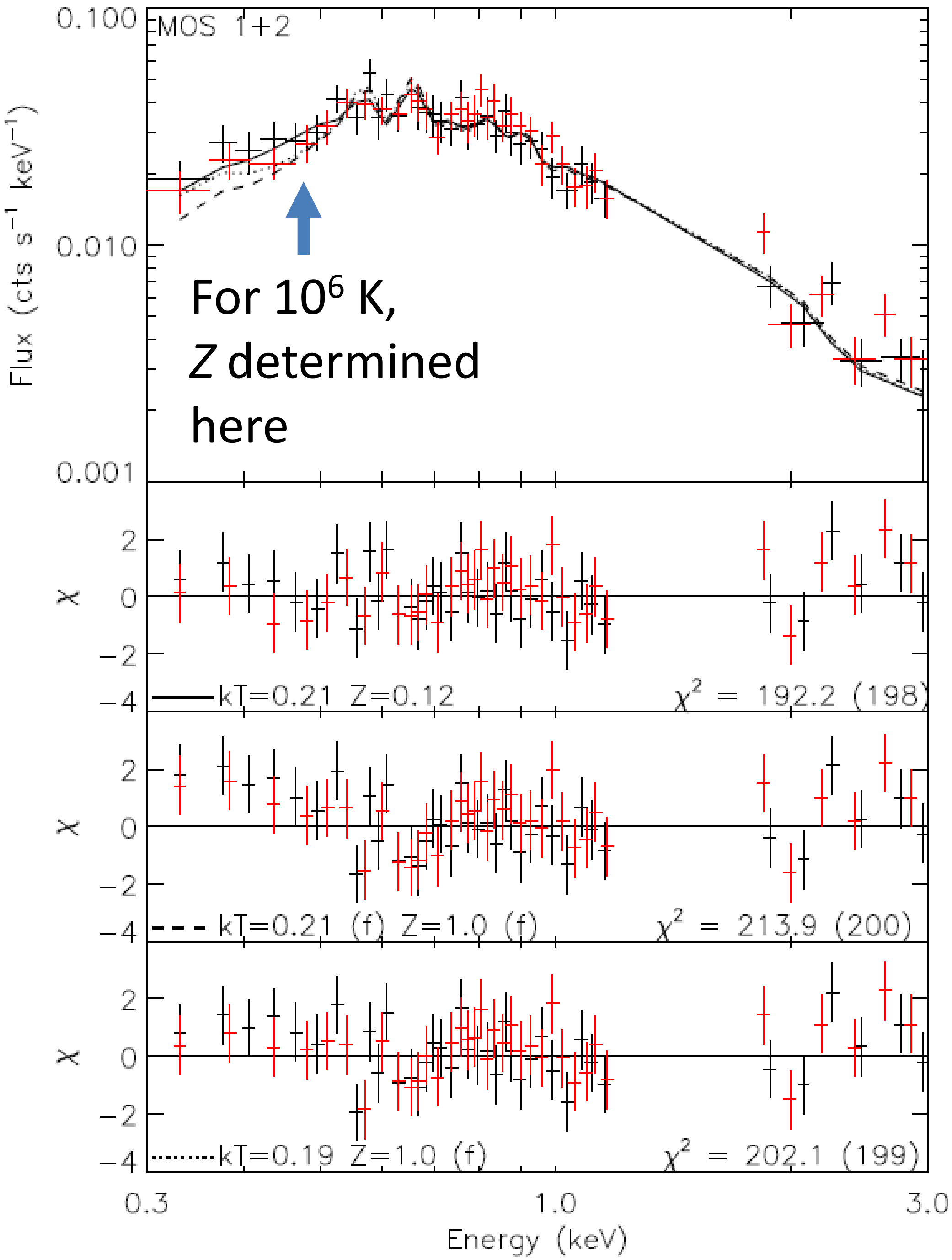
Outer Halo
pn
MOS 1+2
Chandra
Flux (cts s^{-1} keV^{-1})
1.0000
0.1000
0.0100
0.0010
0.0001
χ
2
0
−2
−4
MOS 1+2
pn
Chandra
0.3
1.0
3.0
Energy (keV)
Inner Halo
pn
Chandra
MOS 1+2
Flux (cts s^{-1} keV^{-1})
MOS 1+2
pn
Chandra
Energy (keV)





1T fits to XMM+CXO spectra prefer $Z < Z_\odot$ to 3σ (5σ joint fit)

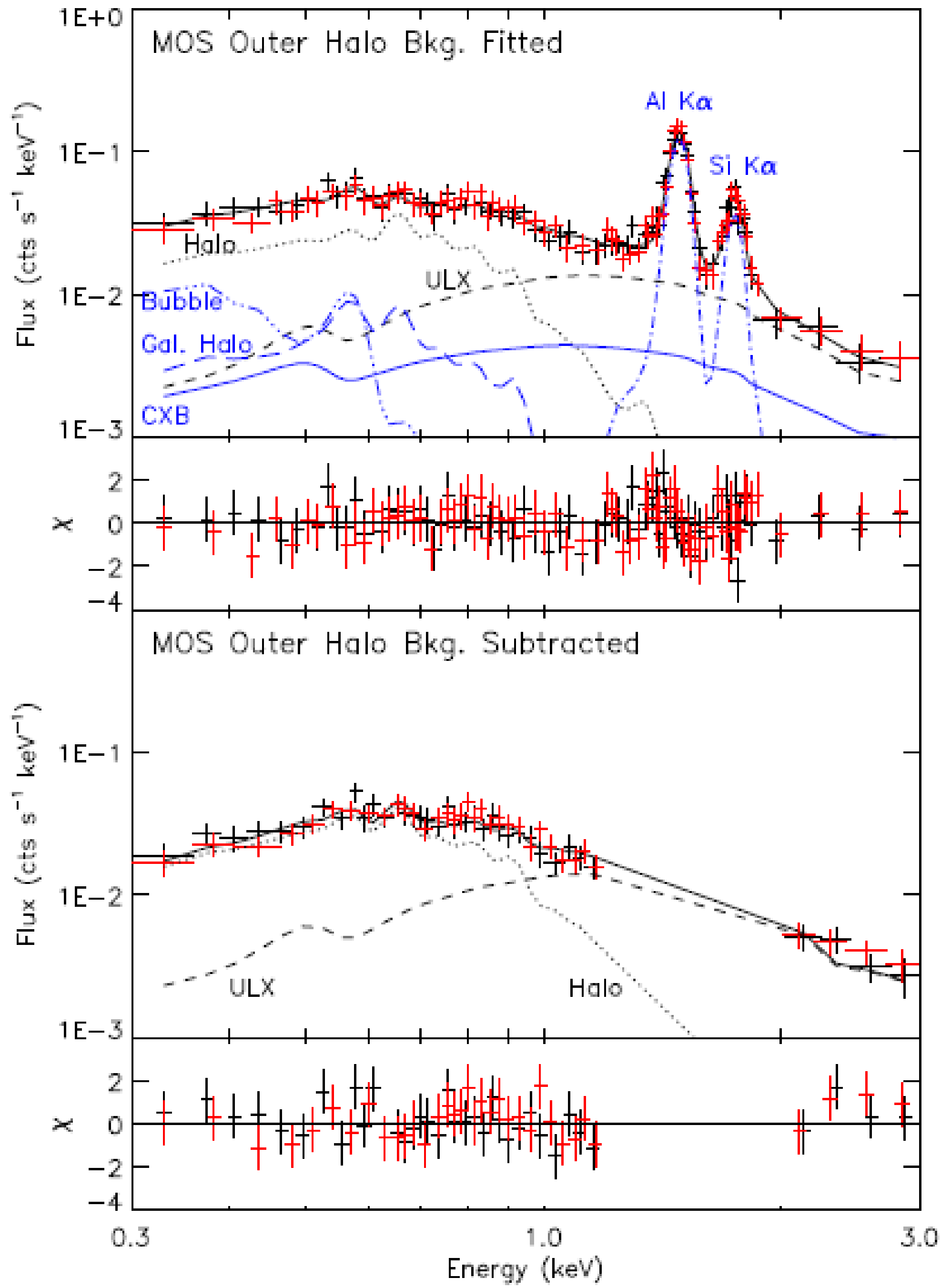
Hot Halo Metallicity



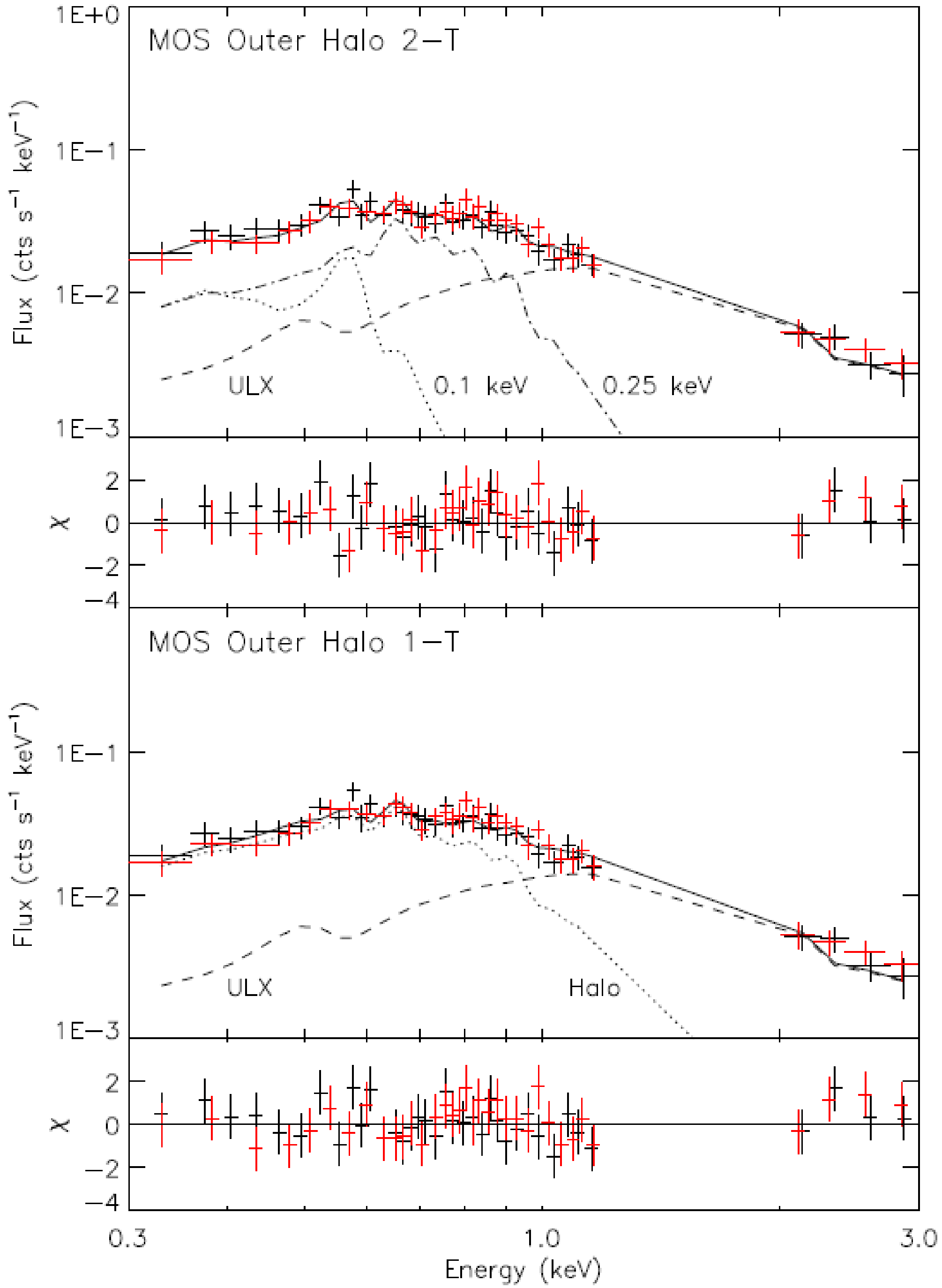
Apparent low Z not likely caused by these systematics:

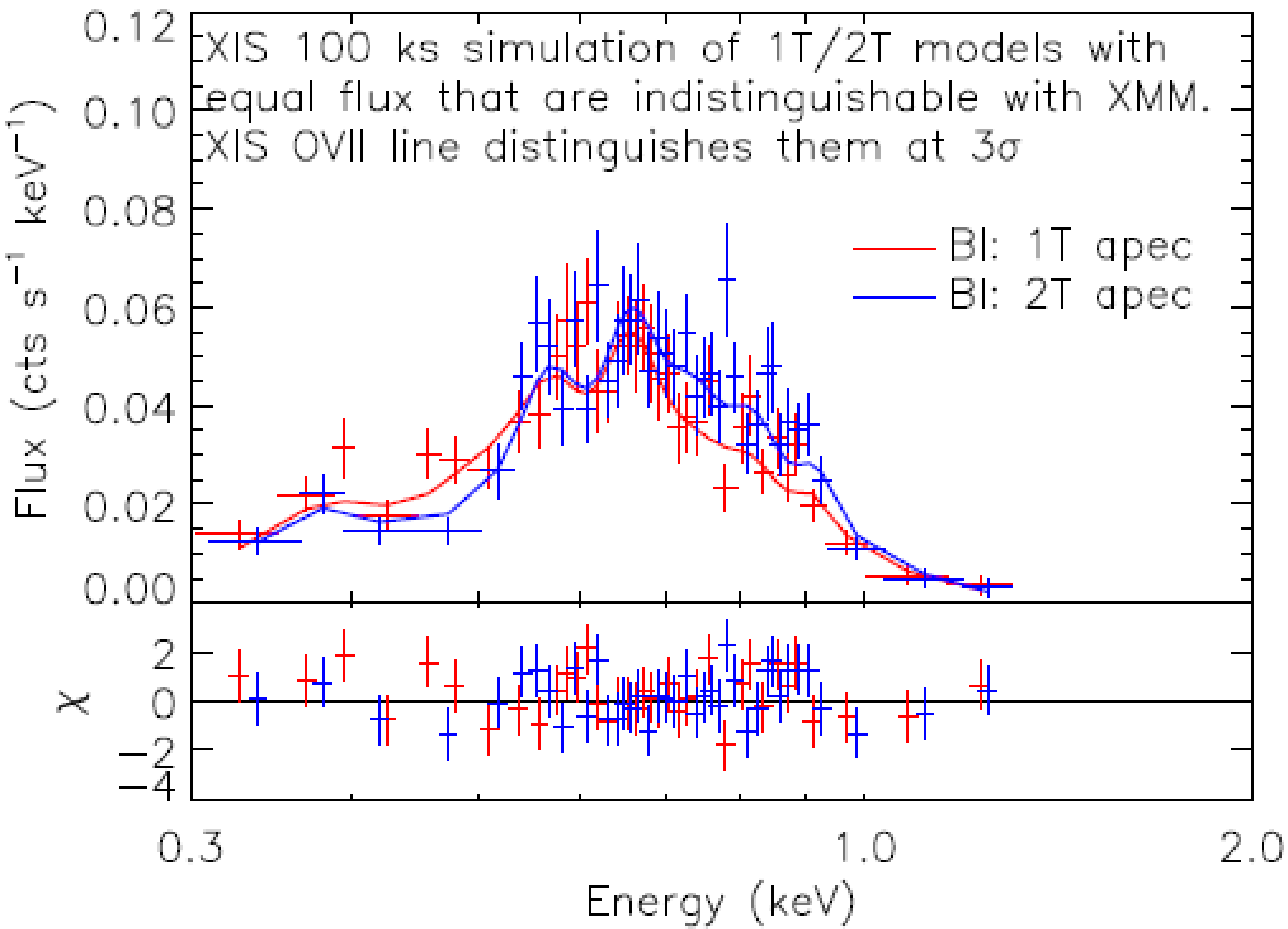
- Unaccounted bkg
- Abundance table
- Absorption model
- Calibration issues
- Energy resolution

- But, we have a *Suzaku* program to confirm



Hot Halo Metallicity




XIS 100 ks simulation of 1T/2T models with
equal flux that are indistinguishable with XMM.
XIS OVII line distinguishes them at 3σ
BI: 1T apec
BI: 2T apec
Flux (cts s^{-1} keV^{-1})
0.12
0.10
0.08
0.06
0.04
0.02
0.00
χ
2
0
−2
−4
0.3
1.0
2.0
Energy (keV)

Hot Halo Metallicity

"Reality checks" favor 1T model

- Limit on cooling rate from UV
  —O VI from Otte et al. 2003 indicates < 2-3 $M_{\odot}$/yr (2T model expects >3)
- Observed vs. expected scale height
  —H_{obs} (4-5 kpc) measured assuming hydrostatic equilibrium
  —H_{exp} from cooling time (3 kpc for 2T)
- Are we really hiding most of the emission behind Galactic HI column??

Model	kT (keV)	$\dot{M}$ ($M_{\odot}\,\mathrm{yr}^{-1}$)	$0.01 - 3.0\,\mathrm{keV}\ L_X$ ($\mathrm{erg\,s^{-1}}$)	H (kpc)	M_{tot} ($M_{\odot}$)
1-T	0.2	0.4	6×10^{39}	5 ± 2	3×10^{8}
2-T	0.1	3	4×10^{40}	3 ± 1	1×10^{8}
2-T	0.25	< 0.05	$< 2 \times 10^{39}$	6 ± 2	$< 10^{8}$

Cool Halo Metallicity

But… UV indicators suggest solar metallicity in *cool* gas

- Bregman+2013 find $\sim Z_{\odot}$ in quasar absorption lines with an impact parameter of 5 kpc
- We also developed a new method to constrain *Z* in an imaging sense using dust-scattered light
- Halos are dusty (Menard+2010); dust visible in:
  - Emission (mid-IR; sky is bright; stars)
  - Extinction (optical; Ménard+2010)
  - Scattering (σ_{scat} high in UV; sky is dark)

Cool Halo Metallicity

Galaxy Spectrum + Dust Type = Observed Spectrum

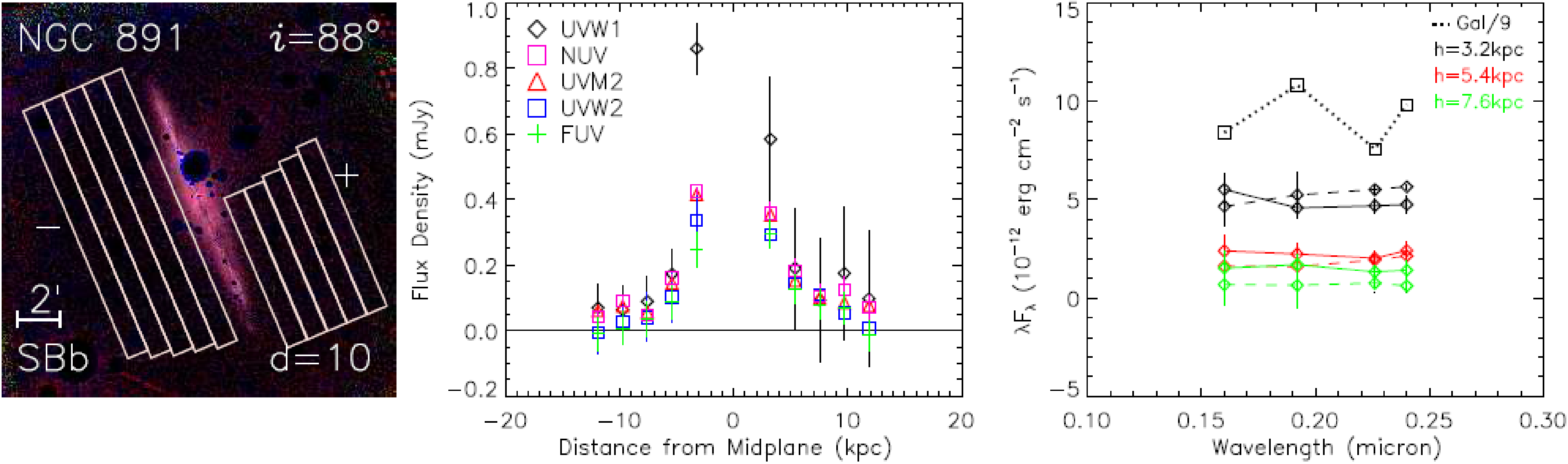
$$L_{halo}(\lambda) = L_{gal}(\lambda)(1 - e^{-\tau(\lambda)})$$

$$\approx L_{gal}(\lambda)\tau(\lambda)$$

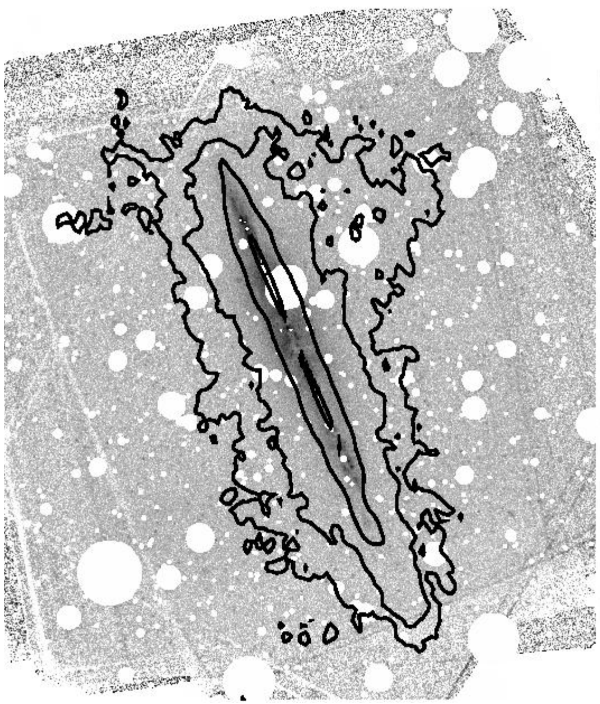
$$= L_{gal}(\lambda)\sigma_{scat}(\lambda)N_H \frac{M_{dust}}{M_{gas}}$$

Fit model SED to data (galaxy template+dust model) ↑

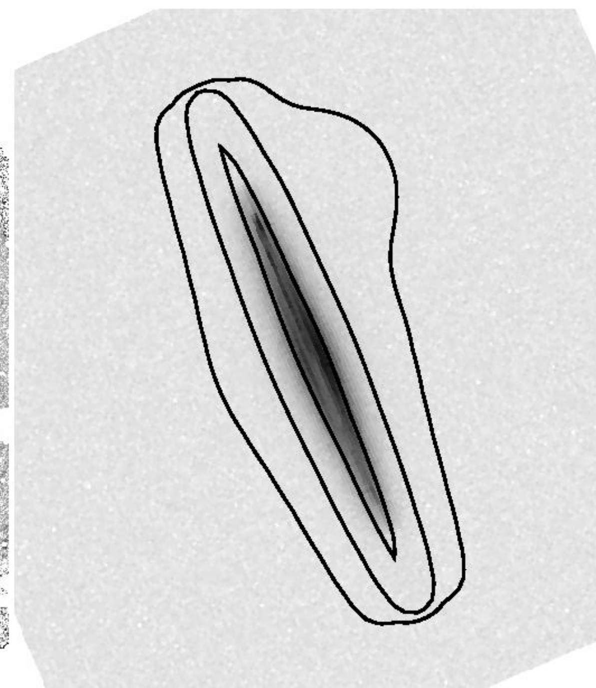
MCRT model/infer intrinsic L_{gal} ↑



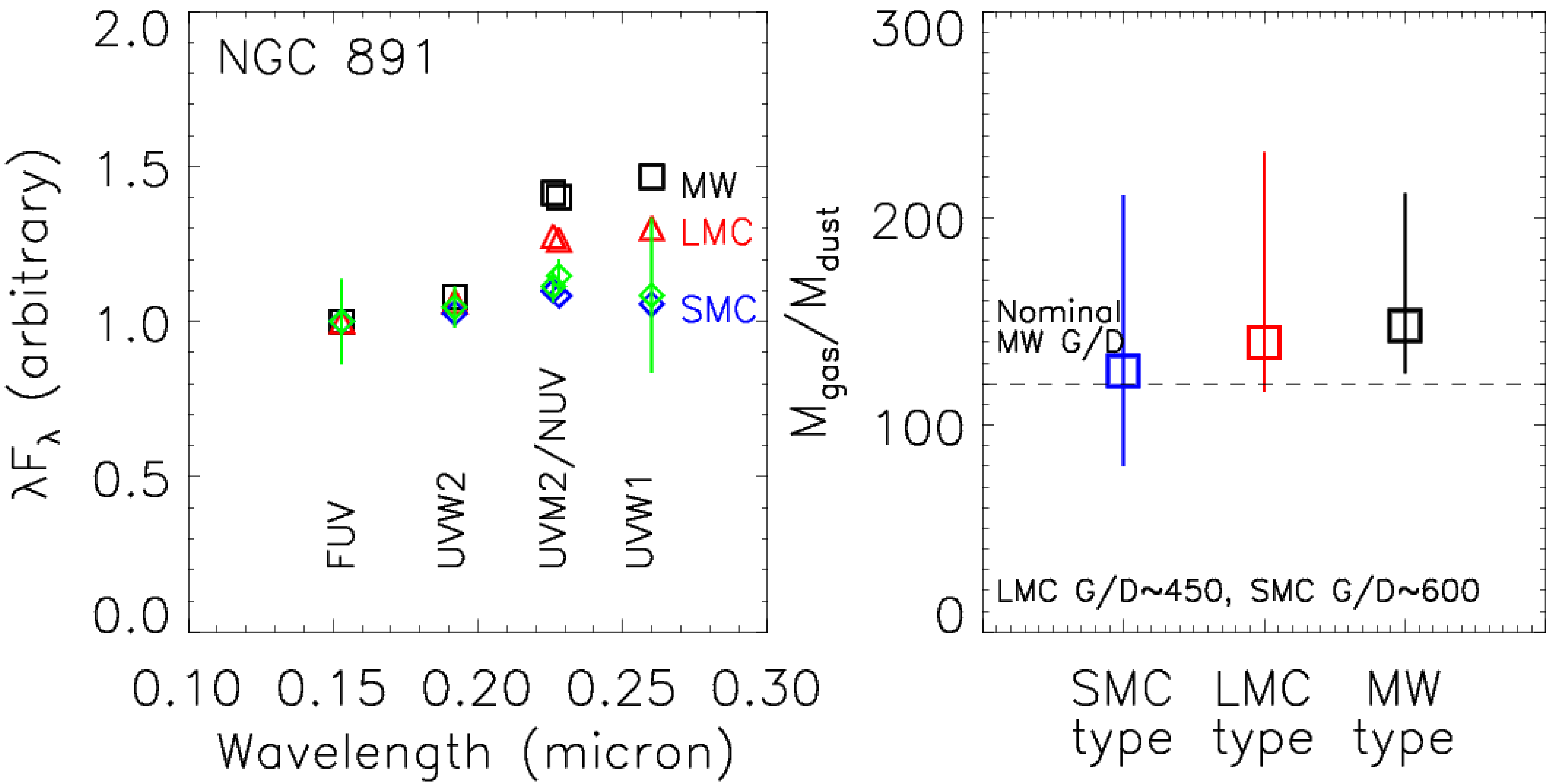
UVM2 + HI



MCRT UVM2 + HI

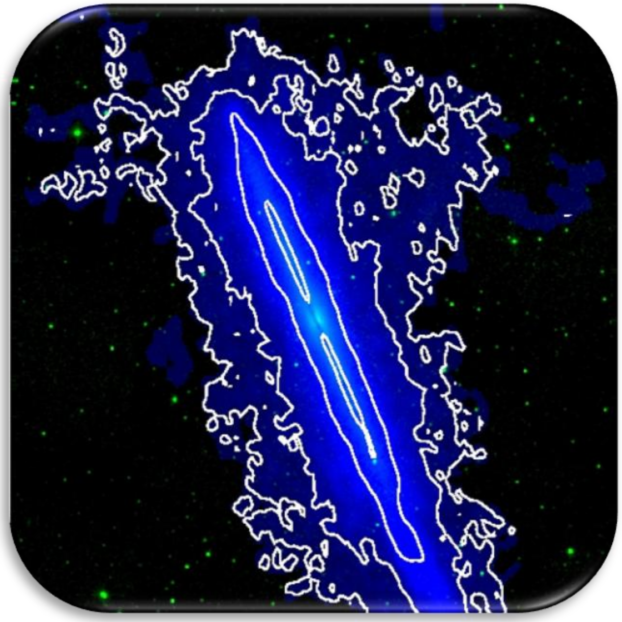


Contours:
10^{19}, 10^{20},
10^{21}, 10^{22} cm^{-2}



NGC 891
MW
LMC
SMC
FUV
UVW2
UVM2/NUV
UVW1
λF_λ (arbitrary)
Wavelength (micron)
2.0
1.5
1.0
0.5
0.0
0.10
0.15
0.20
0.25
0.30
M_gas/M_dust
300
200
100
0
Nominal MW G/D
LMC G/D~450, SMC G/D~600
SMC type
LMC type
MW type

If the cool gas originated in the galaxy, where is the hot gas that put it into the halo?

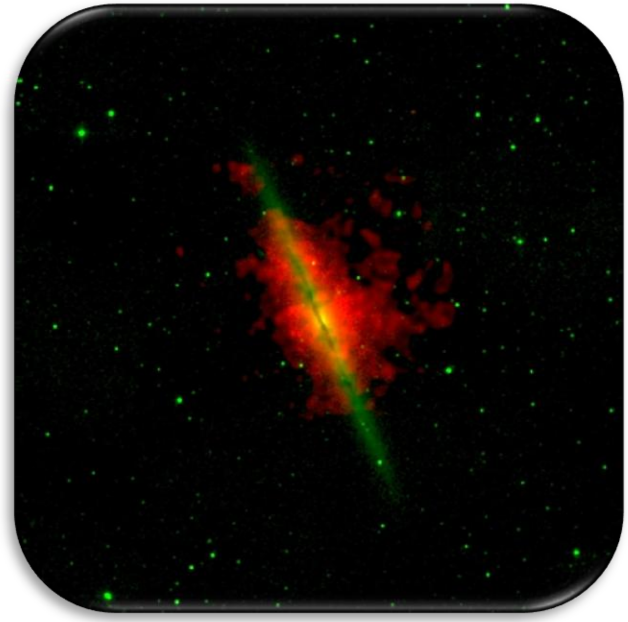


Cold Halo

$$M \approx 1.2\times10^{9} M_{Sun}$$

$$\frac{dM}{dt} \approx 30 M_{Sun} / yr$$

$$Z \approx Z_{Sun}$$



Hot Halo

$$M \approx 3\times10^{8} M_{Sun}$$

$$\frac{dM}{dt} \approx 0.4 M_{Sun} / yr$$

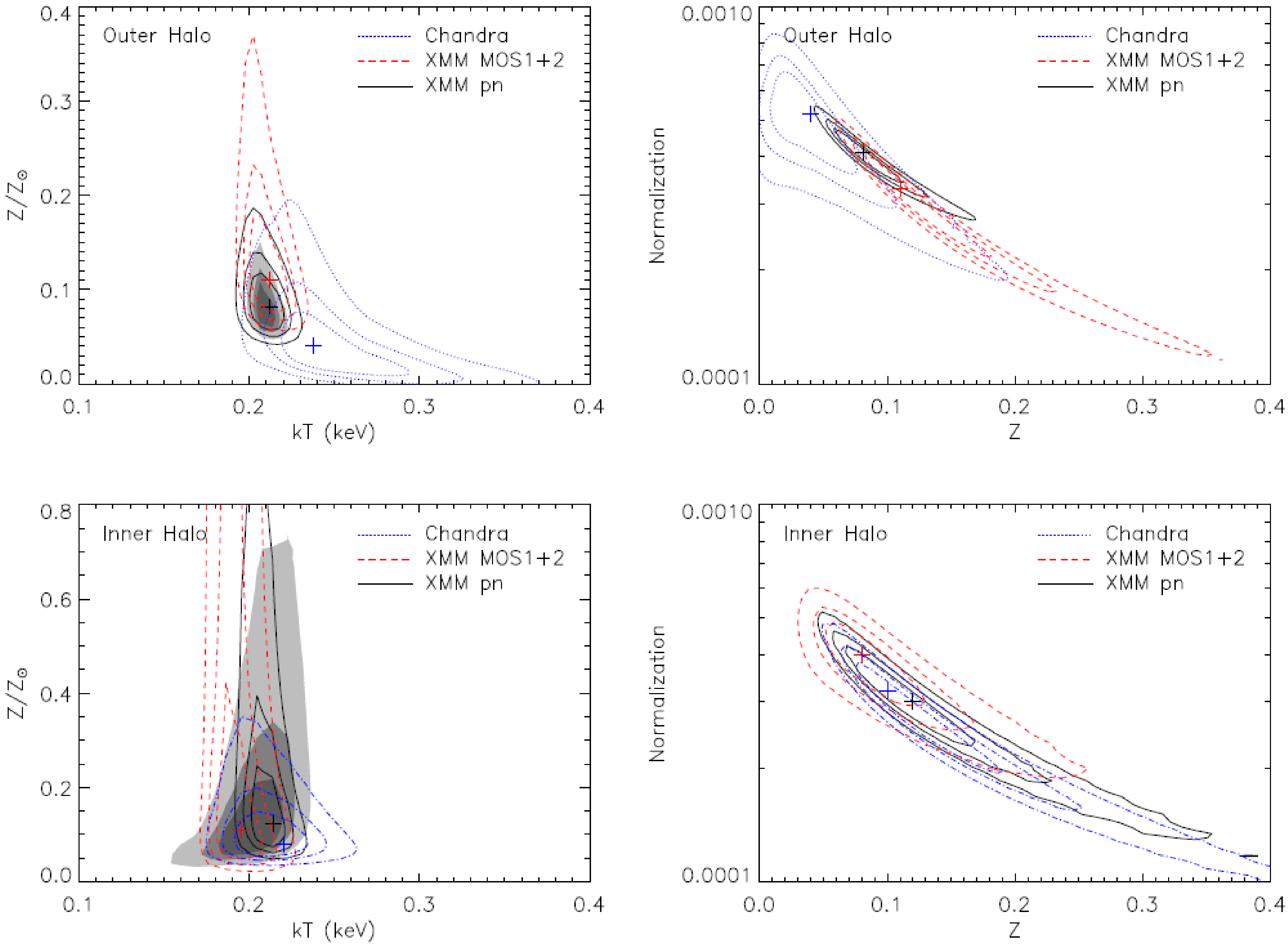
$$Z \approx 0.1 Z_{Sun}$$

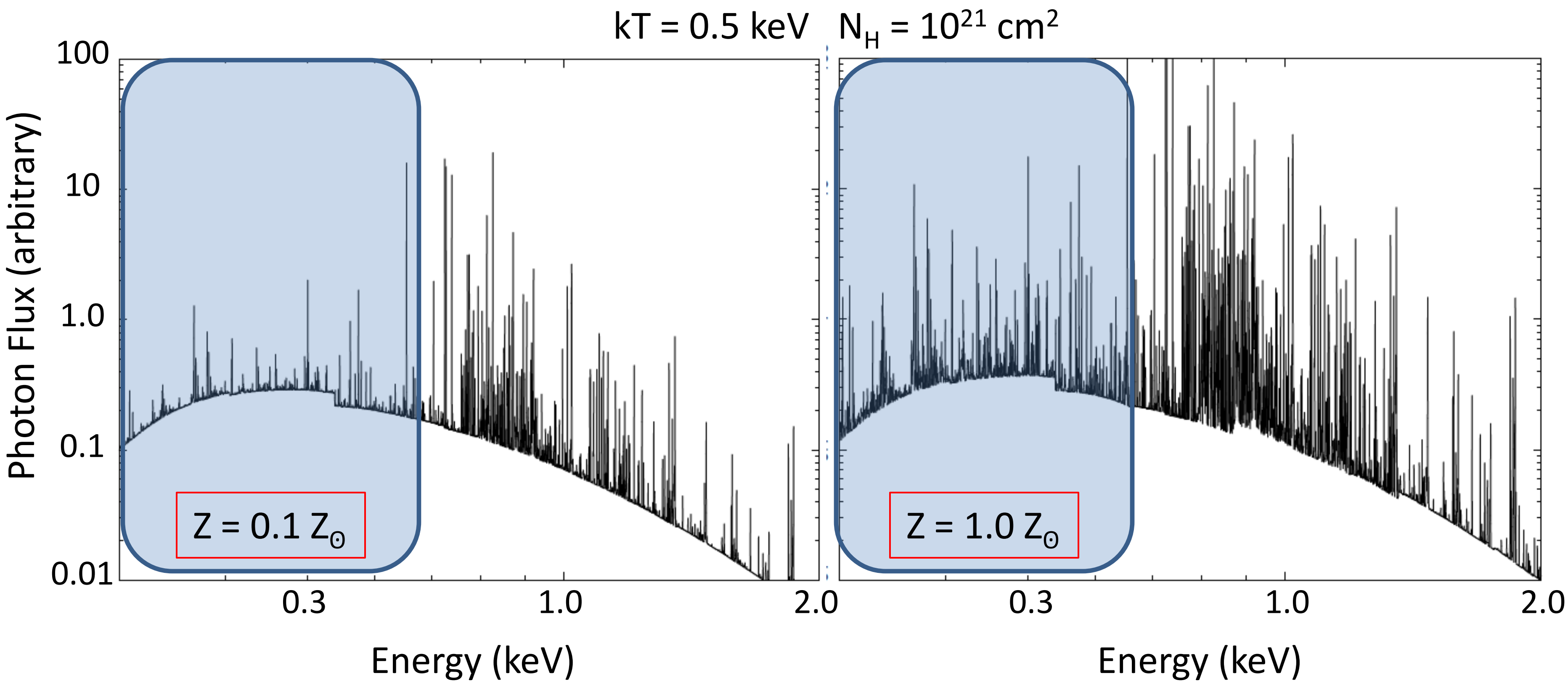
How are hot and cold halos related?

- Is the X-ray metallicity wrong (cf. Li & Wang 2013)?
- Are metals in the hot gas depleted onto dust?
- Did a small amount of accretion trigger a large amount of star formation (halo may not be in a steady state)?
- … are they unrelated?

Summary

- NGC 891 is a Milky Way analog with a giant HI halo and bright X-ray halo
- The hot halo appears to be accreted material (calorimeter could settle debate)
- If so, the hot halo out to 200+ kpc is likely accreted
- The cold halo is not accreted, and it is not clear how the gas got there
- NGC 891 is an important object, but the disk—halo cycle is messy


Outer Halo
Chandra
XMM MOS1+2
XMM pn
Z/Z⊙
kT (keV)
0.0
0.1
0.2
0.3
0.4
Normalization
Z
0.0010
0.0001
Inner Halo
0.8
0.6

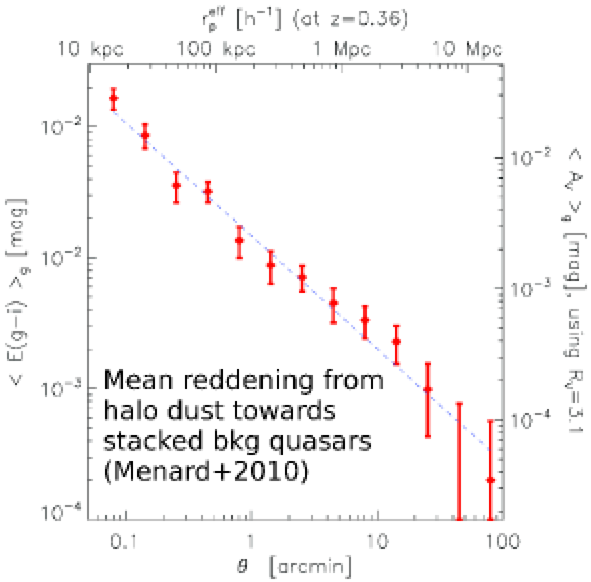


- Metallicity is a key indicator that is directly measurable in the X-rays
- At CCD resolution, good S/N needed to distinguish spectral *shape*

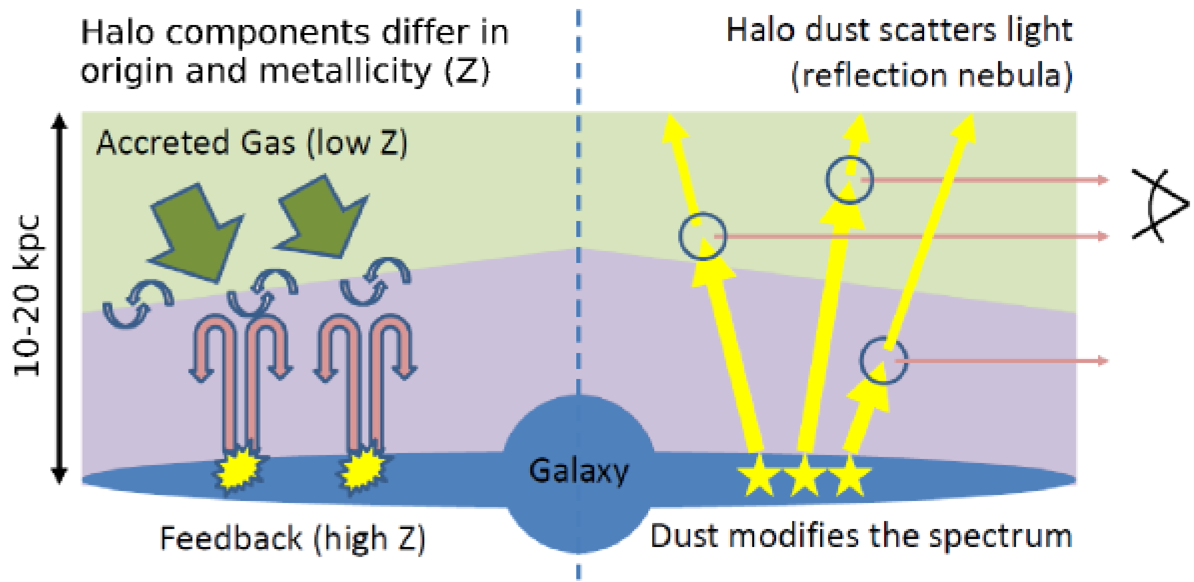
TABLE 3
1-T HALO MODEL FITS

Spectrum	$N_{H,1}$ (10^{20} cm^{-2})	kT_1 (keV)	Z_1 ($Z_\odot$)	$N_{H,2}$ (10^{20} cm^{-2})	kT_2 (keV)	Z_2 ($Z_\odot$)	χ^2
OUTER HALO ($z > 2.8$ KPC)							
Chandra	6.5(f)	$0.24^{+0.07}_{-0.03}$	$0.04^{+0.05}_{-0.02}$	-	-	-	102.6 (105)
MOS 1+2	6.5(f)	0.21 ± 0.02	$0.11^{+0.05}_{-0.04}$	-	-	-	164.5 (180)
pn	6.5(f)	$0.21^{+0.03}_{-0.02}$	$0.08^{+0.05}_{-0.03}$	-	-	-	166.1 (175)
Joint	6.5(f)	0.21 ± 0.02	0.08 ± 0.03	-	-	-	426.2 (460)
INNER HALO ($0.6 < z < 2.8$ KPC)							
Chandra	10^{+20}_{-4}	0.22 ± 0.02	$0.12^{+0.10}_{-0.06}$	77^{+12}_{-10}	$0.58^{+0.06}_{-0.03}$	1.0(f)	74.0 (79)
MOS 1+2	24^{+27}_{-18}	0.19 ± 0.05	$0.10^{+0.08}_{-0.07}$	77(f)	0.58 (f)	1.0(f)	155.5 (152)
pn	18^{+22}_{-12}	0.19 ± 0.04	$0.11^{+0.40}_{-0.07}$	77(f)	0.58 (f)	1.0(f)	117.2 (97)
Joint	16^{+16}_{-7}	0.21 ± 0.02	$0.11^{+0.11}_{-0.06}$	78^{+11}_{-10}	0.58 ± 0.05	1.0(f)	342.15 (328)

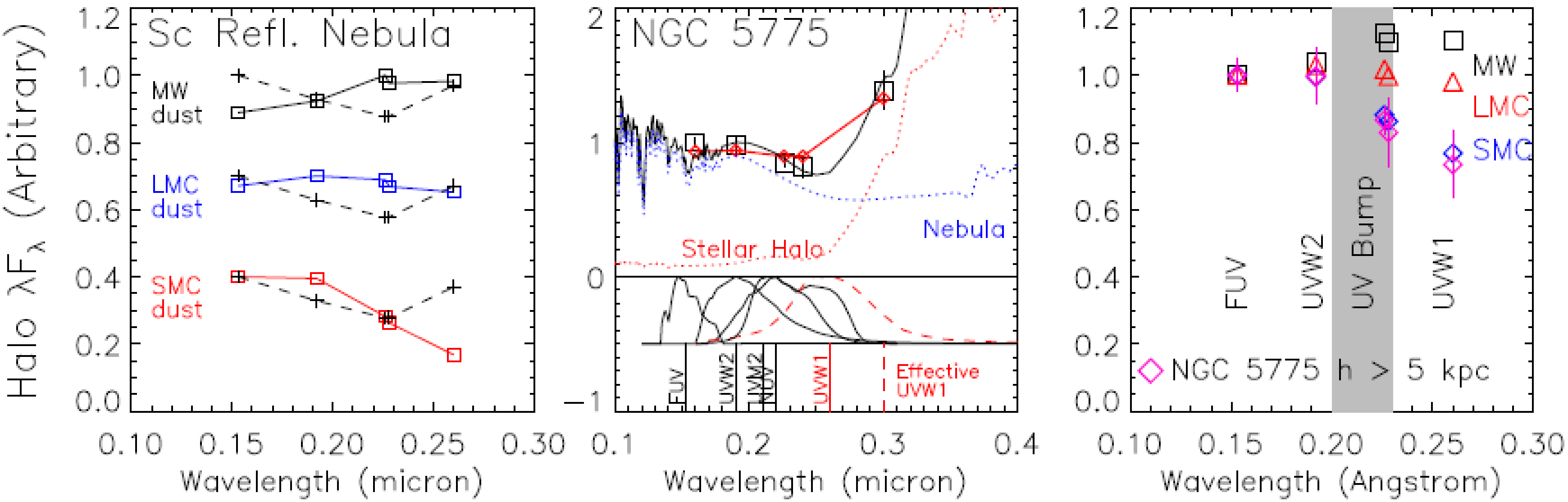
NOTE. — The MOS and pn fits include a TBABS*DISKPBB component with all parameters except flux frozen as described in the text. The fits corresponding to these models are shown in Figure 6. Errors are quoted at the 90% confidence interval based on the *Xspec* task *steppar*, and (f) designates a frozen parameter.



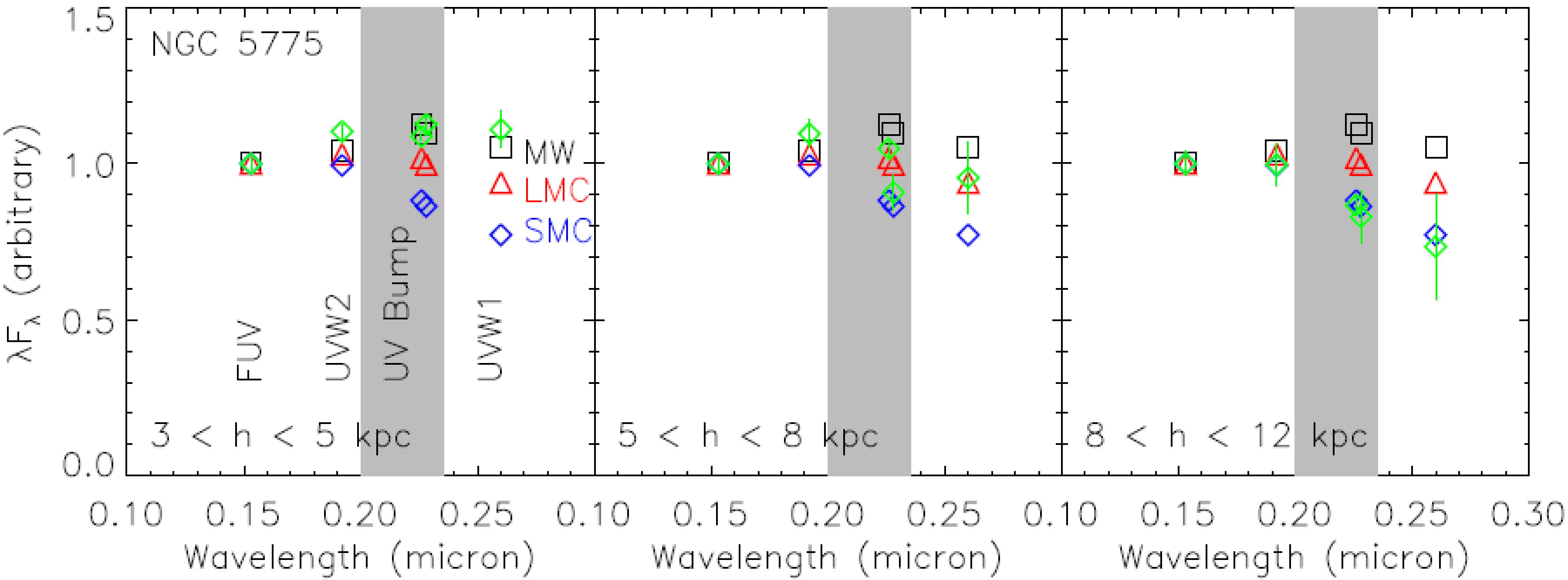
r_p^{eff} [h^{-1}] (at z=0.36)
10 kpc
100 kpc
1 Mpc
10 Mpc
10^{-2}
10^{-2}
10^{-3}
10^{-4}
< E(g−i) >$_g$ [mag]
10^{-2}
10^{-3}
10^{-4}
< A_V >$_g$ [mag], using R_V=3.1
0.1
1
10
100
θ [arcmin]
Mean reddening from
halo dust towards
stacked bkg quasars
(Menard+2010)



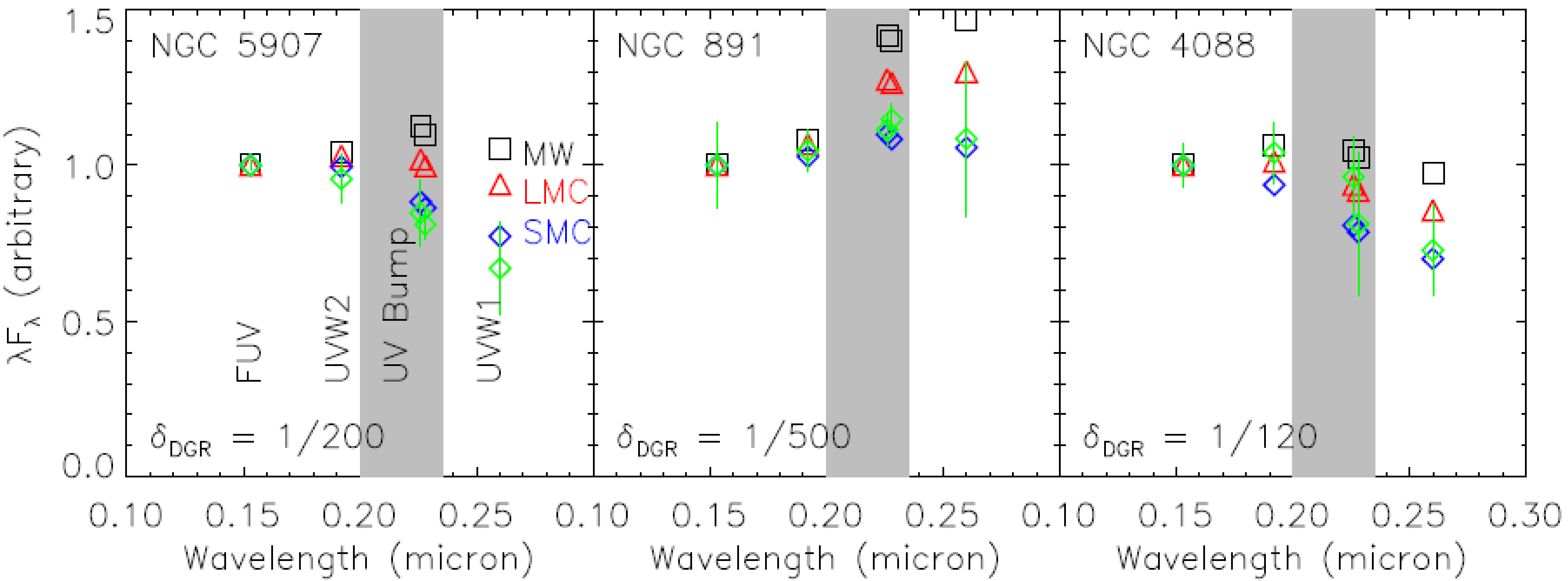
Halo components differ in
origin and metallicity (Z)
Halo dust scatters light
(reflection nebula)
10-20 kpc
Accreted Gas (low Z)
Galaxy
Feedback (high Z)
Dust modifies the spectrum



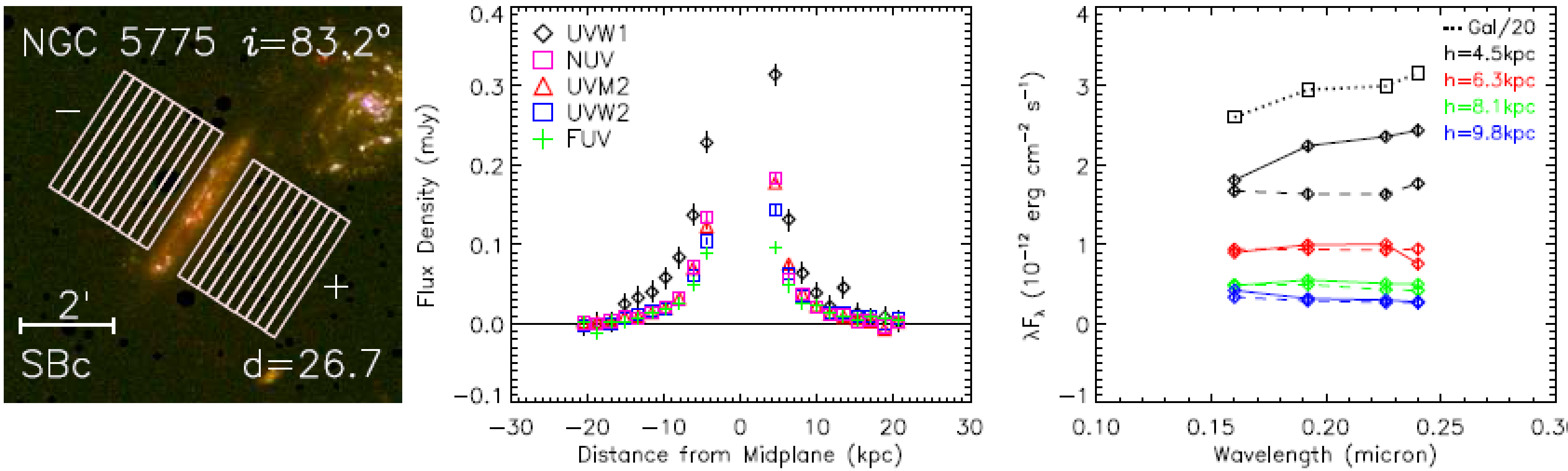
Halo λFλ (Arbitrary)
Sc Refl. Nebula
MW dust
LMC dust
SMC dust
Wavelength (micron)
NGC 5775
Stellar Halo
Nebula
FUV
UVW2
UVM2
NUV
UVW1
Effective UVW1
Wavelength (micron)
MW
LMC
SMC
FUV
UVW2
UV Bump
UVW1
NGC 5775 h > 5 kpc
Wavelength (Angstrom)

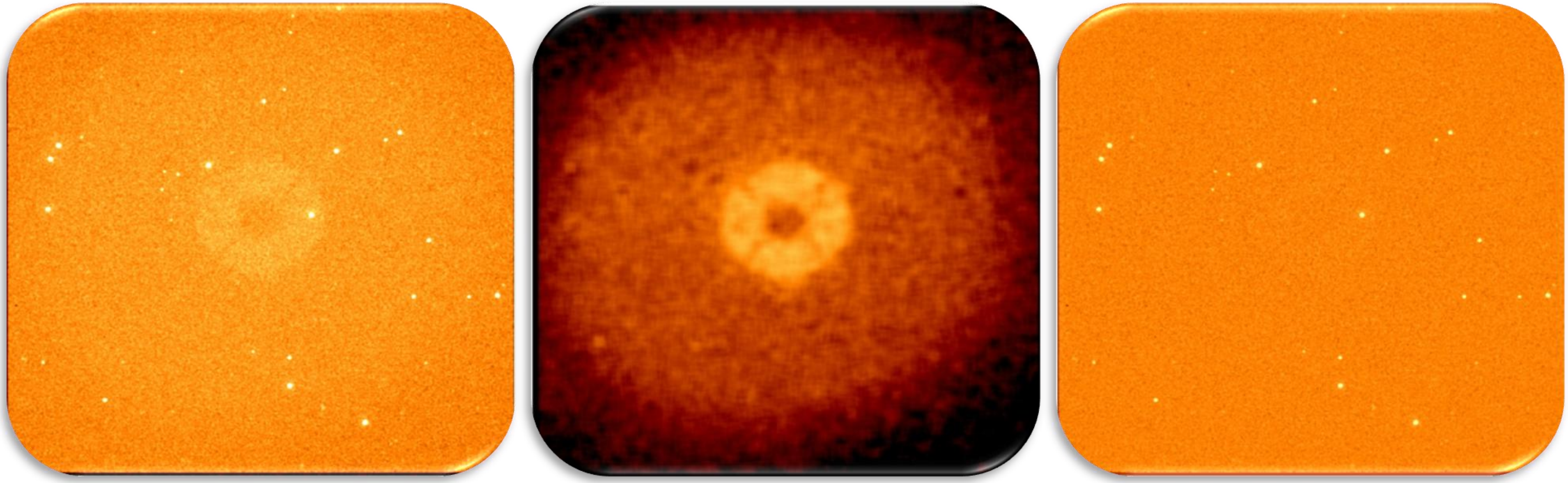


NGC 5775
MW
LMC
SMC
FUV
UVW2
UV Bump
UVW1
3 < h < 5 kpc
5 < h < 8 kpc
8 < h < 12 kpc
λF_λ (arbitrary)
Wavelength (micron)
1.5
1.0
0.5
0.0
0.10
0.15
0.20
0.25
0.30

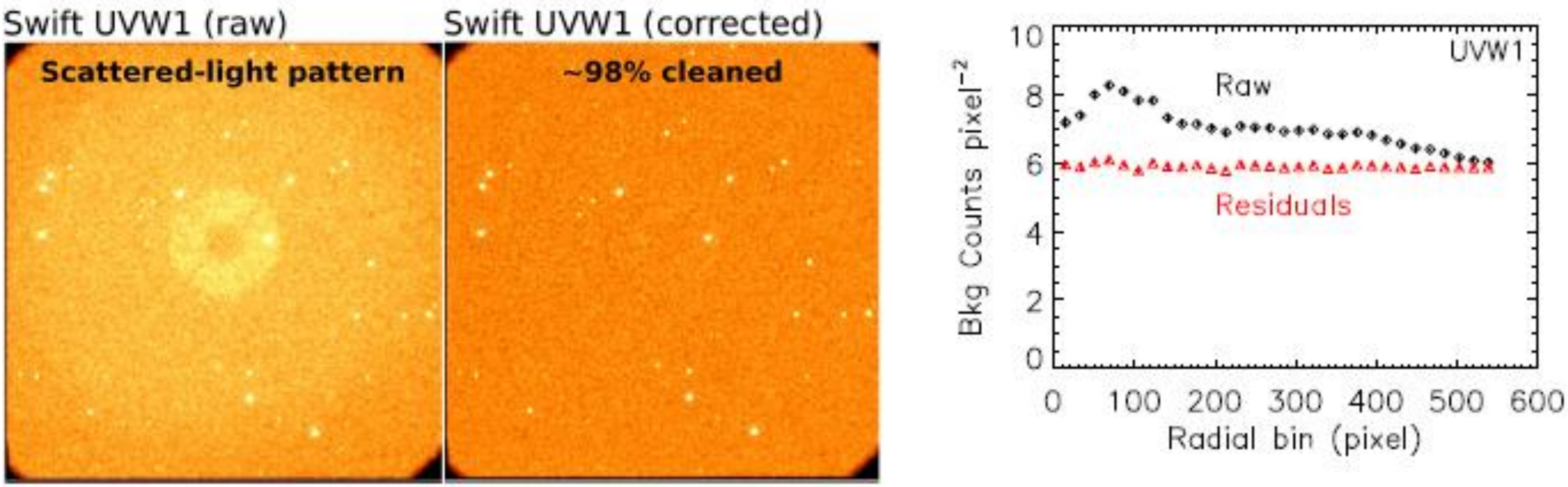


NGC 5907
NGC 891
NGC 4088
MW
LMC
SMC
FUV
UVW2
UV Bump
UVW1
δDGR = 1/200
δDGR = 1/500
δDGR = 1/120
λFλ (arbitrary)
Wavelength (micron)
1.5
1.0
0.5
0.0
0.10
0.15
0.20
0.25
0.30

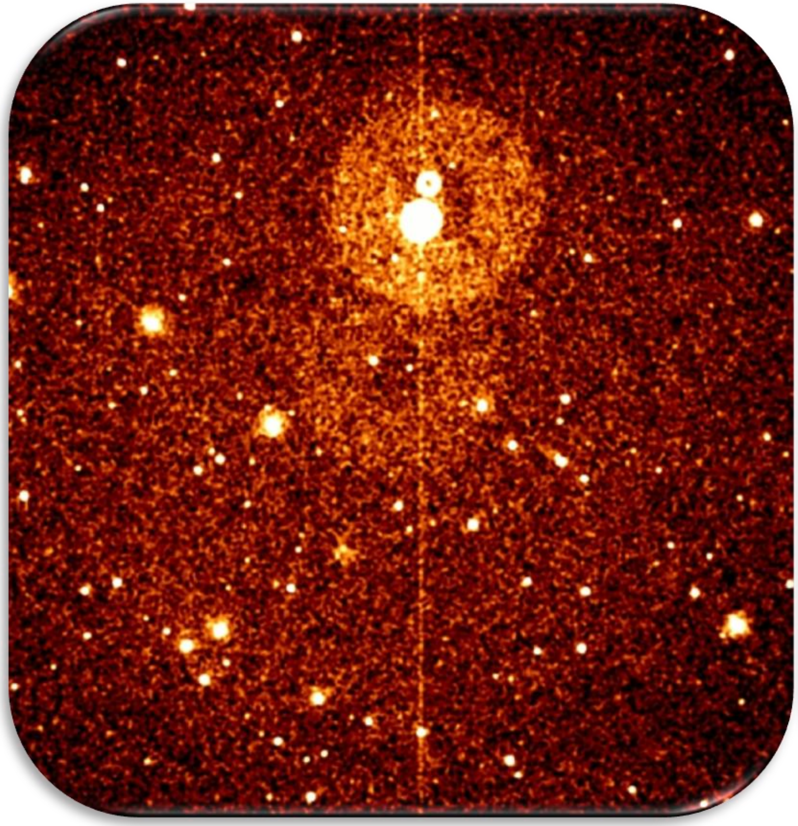

NGC 5775 i=83.2°
−
+
2'
SBc
d=26.7
UVW1
NUV
UVM2
UVW2
FUV
Flux Density (mJy)
Distance from Midplane (kpc)
Gal/20
h=4.5kpc
h=6.3kpc
h=8.1kpc
h=9.8kpc
λF_λ (10^{-12} erg cm^{-2} s^{-1})
Wavelength (micron)

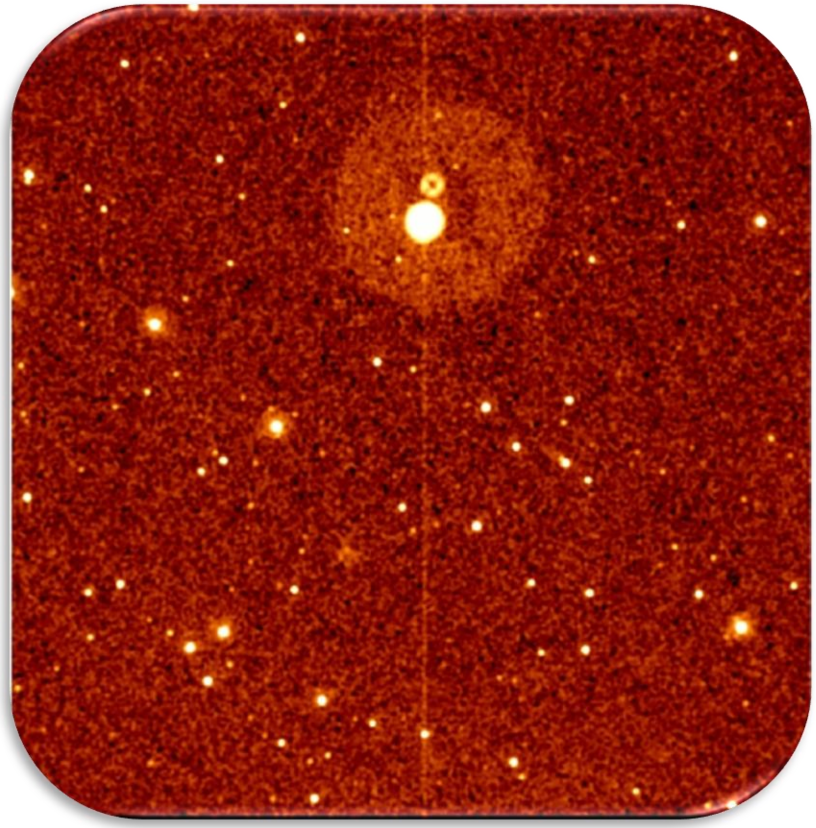


- Galex and Swift UVOT sensitivity limited by cirrus, foreground fluctuations
- Swift UVOT has persistent scattered-light artifacts, but these can be corrected by subtracting scaled templates in each filter



Swift UVW1 (raw)
Scattered-light pattern
Swift UVW1 (corrected)
~98% cleaned
UVW1
Raw
Residuals
Bkg Counts pixel^{-2}
Radial bin (pixel)
0
2
4
6
8
10
0
100
200
300
400
500
600





- Bright sources also produce their own rings (ghost images) that must be removed separately