A Distant Echo of Milky Way Central Activity closes the Galaxy's Baryon Census

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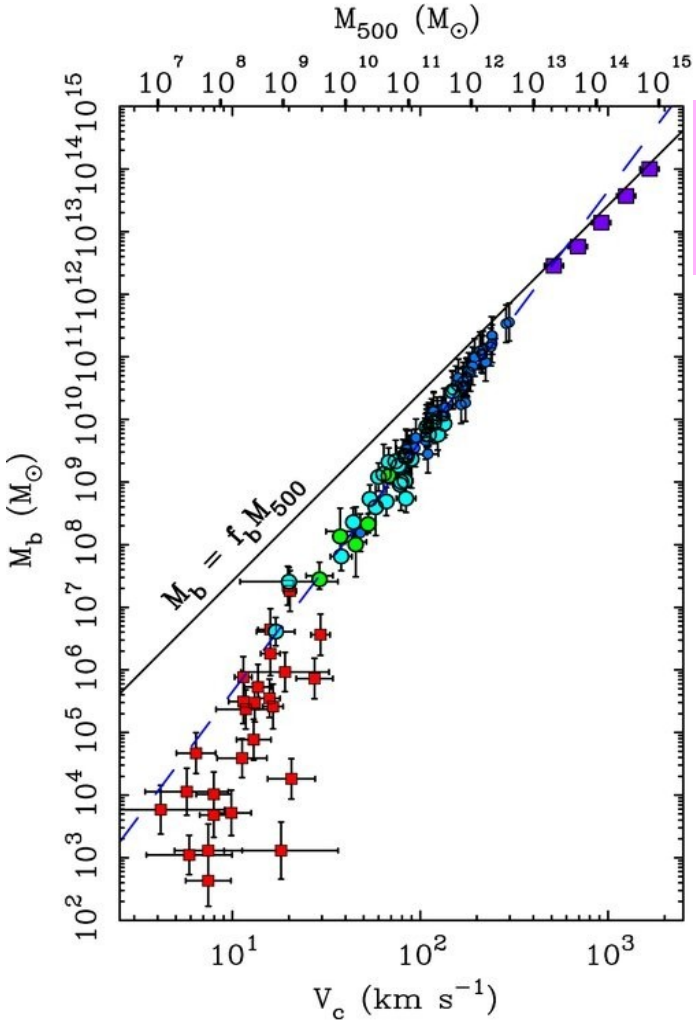
Outline

- The Galaxy roaming baryon problem
- All the Milky Way gaseous components, as seen in X-rays
- The million degree gas against Low Galactic Latitude (LGL: XRBs) and High Galactic Latitude (HGL: AGNs) lines of sight:
  - Reconstructing the Galaxy's density profiles through OVII column densities + comparison with EM
- Three main results:
  - Two components: disk + halo
  - Presence of central cavity in the halo
  - Hot gas in the halo sufficient to close the Galaxy's baryon census

The Galaxy Missing Baryons Problem



Cosmological Baryon Fraction
$f_b = 0.157$

The baryon deficit is more severe in smaller galaxies

➔ Less massive objects are unable to retain baryons (and metals?) due to feedback processes (winds)?

➔ Are these baryons in the surrounding CGM/IGM?

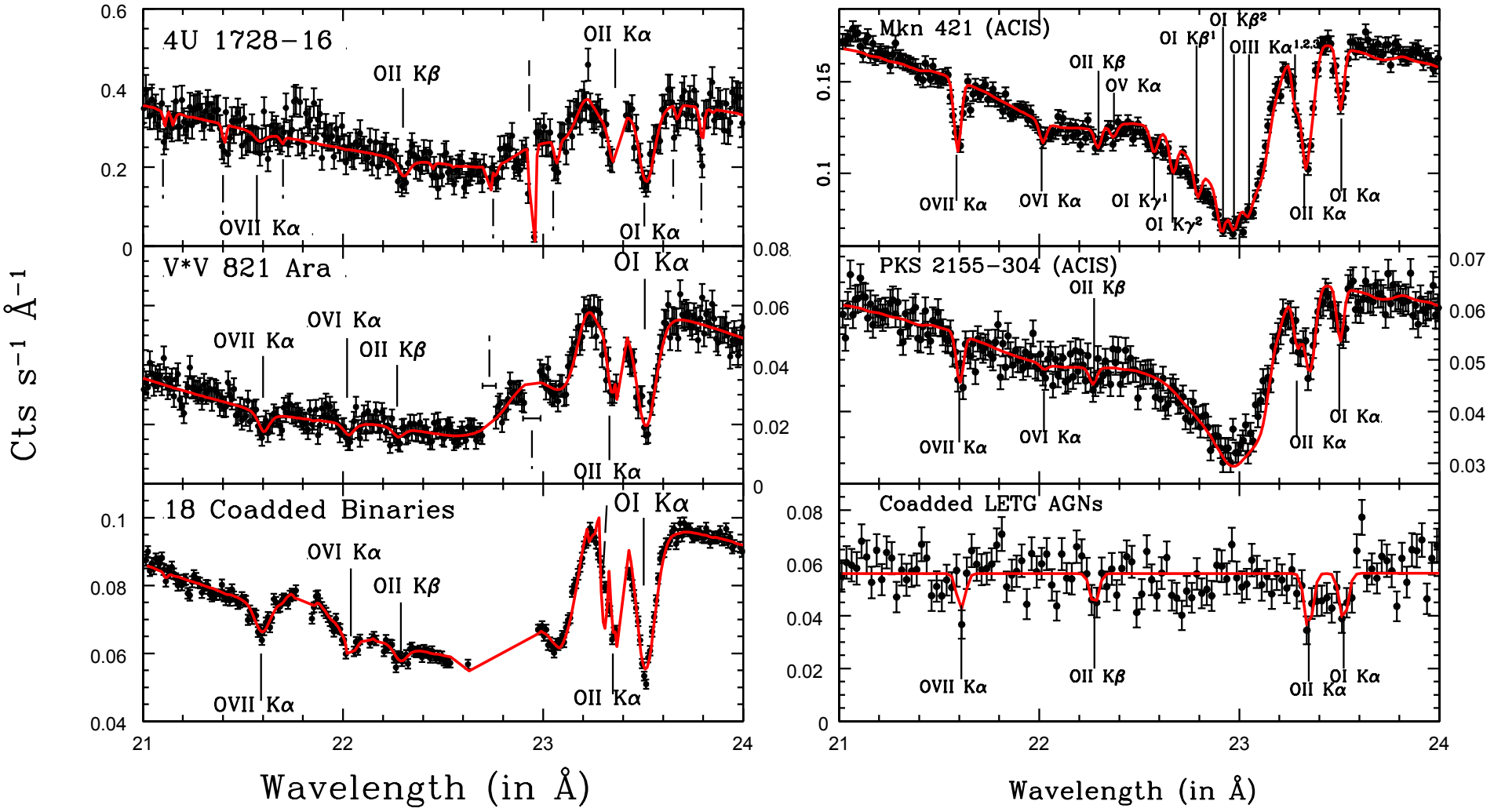
The Milky Way's Baryon Problem

- $(M_b)^{Obs} = 6.5 \times 10^{10}\ M_\odot$ (McMillian & Binney, 2012)
- $M_{DM} = (1\text{-}2) \times 10^{12}\ M_\odot$ (Boylan-Kolchin+12)
- $f_b = 0.157$ (The Plank Collaboration, 2015)

$$M_b^{Missing} \approx (1.5\text{-}3) \times 10^{11}\ M_\odot$$

All the X-ray Spectral Signatures of the Milky Way

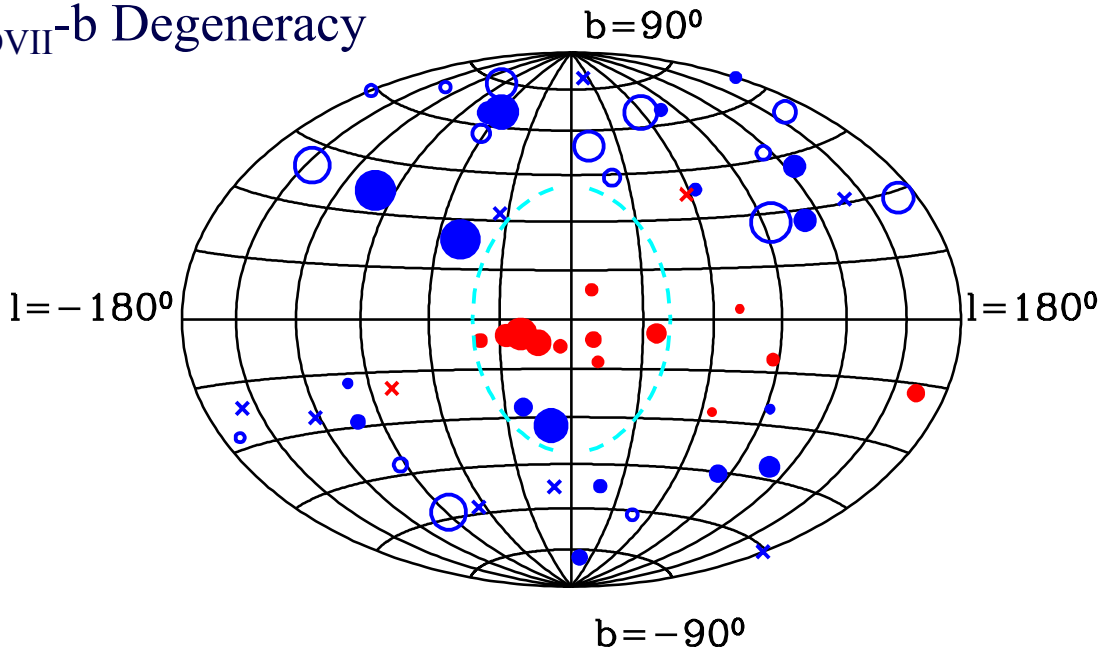
Nicastro+16a



The Optimal OVII Sample

Differs from previous (e.g. Gupta+12, Miller&Bregman13):

- HGL + LGL for the first time
- Complete to SNRE>10 at 22 Å
- Remove N_{OVII}-b Degeneracy



18/20 (90%) LGL have OVII, but only 14 known distance (1 contaminated)

51 HGL; 9 contaminated + 3 Instr.Feat.; 34/39 (87%) have OVII, but only 18 Kα & Kβ

➔ 13 LGL (XRBs) + 18 HGL (AGNs) = 31 LoS

Adopted Density Profiles

$\xi(R)$ = LoS coordinate, with $R^2 = \xi^2 + R_\odot^2 - 2\xi R_\odot \cos(b)\cos(l)$

$$n(R) = n_0 e^{-|R - R_s|/R_c}; \quad \text{(Exponential Sphere)}$$

$$n(R) = n_0 e^{-\sqrt{(\rho/\rho_c)^2 + (z - h_s)/h_c)^2}}; \quad \text{(Exponential Disk)}$$

$$n(R) = n_0 [1 + (R - R_s)^2/R_c^2]^{-3\beta/2}; \quad (\beta\text{-Sphere})$$

$$n(R) = n_0 [1 + \rho^2/\rho_c^2 + (z - h_s)^2/h_c^2]^{-3\beta/2}. \quad (\beta\text{-Cylinder})$$

R_s and h_s = Offset Radius and Height

Separate LGL & HGL N_{OVII}-(l,b) Fits

Model Name	Model Type	n_0 (10^{-2} cm^{-3})	R_c or ρ_c (kpc)	h_c (kpc)	R_s (kpc)	Halo Size (kpc)	Mass (10^9 $M_\odot$)	chi^2(dof)
HGL	Exp-SS	$4.9^{+1.1}_{-0.4}$	$3.1^{+0.3}_{-0.2}$	N/A	$5.4^{+0.6}_{-0.4}$	> 46	$3.3^{+4.1}_{-1.4}$	10.9(15)
LGL	Exp-CS	52^{+5}_{-15}	$2.4^{+0.3}_{-0.1}$	$0.16^{+0.04}_{0.03}$	N/A	N/A	$0.14^{+0.11}_{-0.06}$	12.8(10)

LGL: $\chi^2_{flat}(dof) = 12.8(10)$ vs $\chi^2_{Sph}(dof) = 22.5(11)$

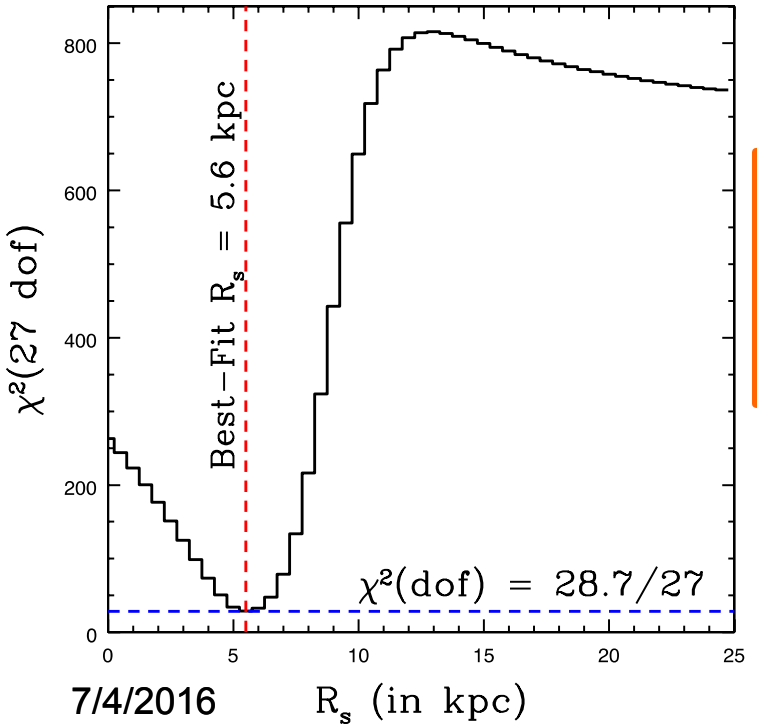
LGL to HLG: $\chi^2(dof) = 373(18)$!!!

HGL to LGL: $\chi^2(dof) = 147(13)$!!!

- LGLs trace the Galaxy's Disk: $M_{OVII}(Disk) \approx 1.4 \times 10^8\ M_\odot$
  - 2 distinct components or compromising solution

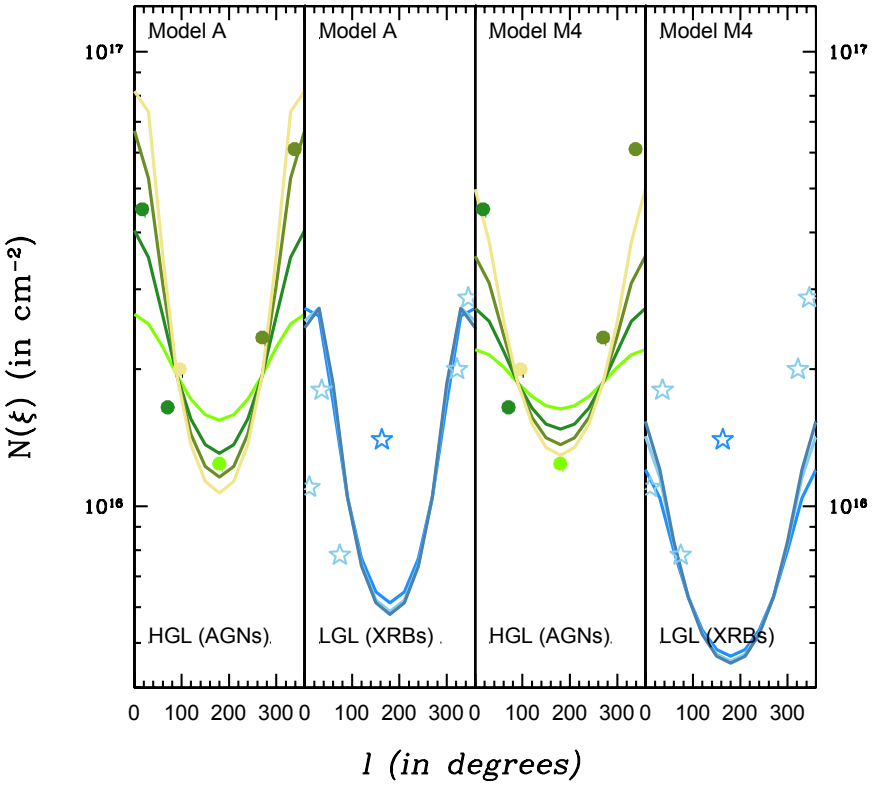
Combined LGL+HGL N_{OVII}-(l,b) Fits

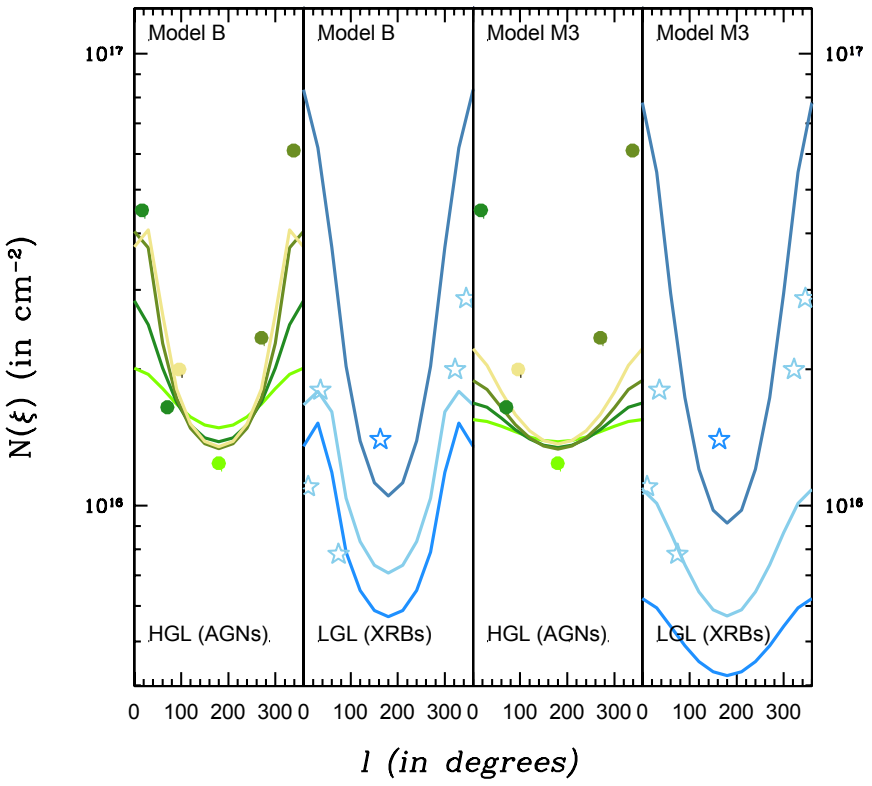
Model Name	Model Type	n_0 (10^{-2} cm^{-3})	R_c (kpc)	β	R_s (kpc)	Halo Size (kpc)	Mass (10^{11} $M_\odot$)	chi^2(dof)
A	β-SS	$2.7^{+0.3}_{-0.3}$	$2.1^{+0.3}_{-0.2}$	$0.62^{+0.04}_{-0.04}$	$5.6^{+0.6}_{-0.6}$	> 64	$0.2^{+0.3}_{-0.1}$	28.7(27)
B	M2 + β-SS	$1.3^{+0.3}_{-0.2}$	$0.7^{+0.2}_{-0.1}$	$0.33^{+0.03}_{0.03}$	$6.7^{+0.9}_{-1/8}$	> 193	$1.3^{+2.1}_{-0.7}$	30.9(27)
M3	M2 + β-SS	$0.8^{+0.1}_{-0.1}$	$1.7^{+0.2}_{-0.2}$	0.33 (frozen)	0 (frozen)	> 250	$2.0^{+0.4}_{-0.5}$	34.9(29)
M4	β-SS	$5.8^{+0.7}_{-0.9}$	$2.5^{+0.2}_{-0.2}$	0.62 (frozen)	0 (frozen)	> 94	$0.5^{+0.2}_{-0.1}$	45.6(29)



Model A: peak density at 6 kpc
Model B: empty central 6-kpc sphere
P(A;M4) = 99.8% ; P(A;M3) = 91.3%

Why an Offset Radius?





OVII Emission Measure

- In 1-sr around l=90^0, b=60^0: EM = 0.0125 cm^{-6} pc (McCammon+02)

$$\mathrm{EM(A;}|b| \geq 60^0; 30^0 < l < 150^0) = 0.013^{+0.022}_{-0.009}\ \mathrm{cm}^{-6}\ \mathrm{pc}$$
$$\mathrm{EM(B;}|b| \geq 60^0; 30^0 < l < 150^0) = 0.005^{+0.012}_{-0.003}\ \mathrm{cm}^{-6}\ \mathrm{pc}.$$

- Toward the Galactic Center at $|b|$<20^0 and across the Fermi Bubbles: EM = (0.08-0.3) cm^{-6} pc (Kataoka+15)

$$\mathrm{EM(A;}|b| \leq 20^0; 340^0 < l < 20^0) = 0.4^{+0.1}_{-0.2}\ \mathrm{cm}^{-6}\ \mathrm{pc}$$
$$\mathrm{EM(B;}|b| \leq 20^0; 340^0 < l < 20^0) = 0.03^{+0.03}_{-0.01}\ \mathrm{cm}^{-6}\ \mathrm{pc}$$

The 6-kpc Central "Cavity"
(other pieces of evidence)

- Size and shape similar to "Fermi Bubbles" (gamma-rays) and Plank Haze (microwave): Dobler+10; Su+10
- Seen in Hα and IR emission: Bland-Hawthorn+03
- Seen in modulation of X-ray EM across edges of Fermi Bubbles: Kataoka+15
- Resolved in moderate-ionization "double-peaked" (near- and far-side of the bubble) metal absorption suggesting expansion $v \approx 1000$ km/s: Fox+15

A Distant Echo of Central Activity

- A fast moving "piston" powered by a period of activity of our supermassive black hole moves outwards and compresses the ambient gas while pushing (a fraction of) it outwards (i.e. Davè+11; Faucher-Giguère & Quataert, 2012, Lapi+05)
- Nuclear energy-conserving outflows with $v_{in} \approx 10000$ km/s produce shock traveling at $v_s \approx 1000$ km/s (Faucher-Giguère & Quataert, 2012)
- At this rate it would take 6 Myrs for the OVII-traced shock to reach its current position at 6 kpc
- (6 ± 2) Myr is also the age of 2 stellar disks in the innermost 0.2 pc of the Milky Way, thought to be a relic of a gaseous accretion disk (Paumard+06; Levin, Beloborodov 03)

Checking the Energetic

For a simple isothermal sphere $\Delta M/M \approx 1/2 \Delta E/E$ (Lapi+05)

$$M_{Bubble} = 3.4^{+1.8}_{-1.3} \times 10^8 \, M_\odot \rightarrow (\Delta M/M)_{Bubble} \simeq 0.005 - 0.05$$

$$\Delta E/E \simeq 0.01 - 0.1 \quad E \simeq 2 \times 10^{61} ((kT_{Hot})/keV)^{5/2} \text{ ergs}$$

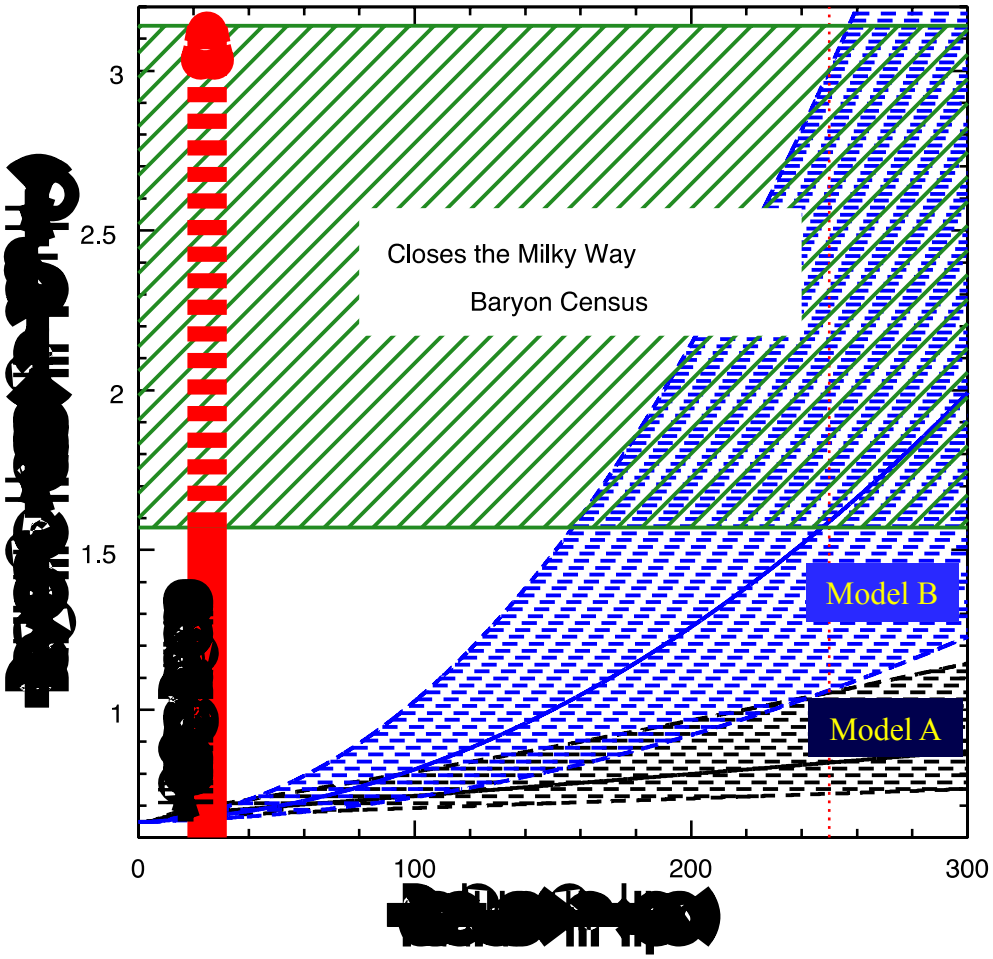
For $T_{Hot} \approx (0.6\text{-}1) \times 10^6$ K ➔ $E \approx (0.1\text{-}0.4) \times 10^{59}$ ergs

➔ $\Delta E \approx (0.1\text{-}4) \times 10^{57}$ ergs $= 1/2 \Delta M \langle v^2 \rangle$

➔ $\langle v \rangle \approx 150\text{-}1400$ km/s

$\Delta E << E_{AGN}(\Delta t = 4\text{-}8 \text{ Myr}) \approx (2.5\text{-}5) \times 10^{58}$ ergs

Closing the Galaxy's Baryon Census



Sizes:
R(A)>61 kpc
R(B)>190 kpc

Masses at R_{vir}:
$M(A)=(0.2^{+0.3}_{-0.1})x10^{11}\ M_{\odot}$
$M(A)=(1.3^{+2.1}_{-0.7})x10^{11}\ M_{\odot}$

Actual Solution probably in between

Conclusions

- Million-degree Gas permeates both the Disk and Halo of our Galaxy

- A spherically symmetric structure in the density profile of the million-degree halo gas tracks the current position of a shock-front generated 6 Million years ago by an energetic outflow powered by an AGN-like accretion episode

- The Mass of the OVII-bearing Gas may be sufficient to close the Galaxy's Baryon Census