Unveiling the Complex Temperature Structure of the CGM

Manami Roy
CCAPP Fellow, The Ohio State University

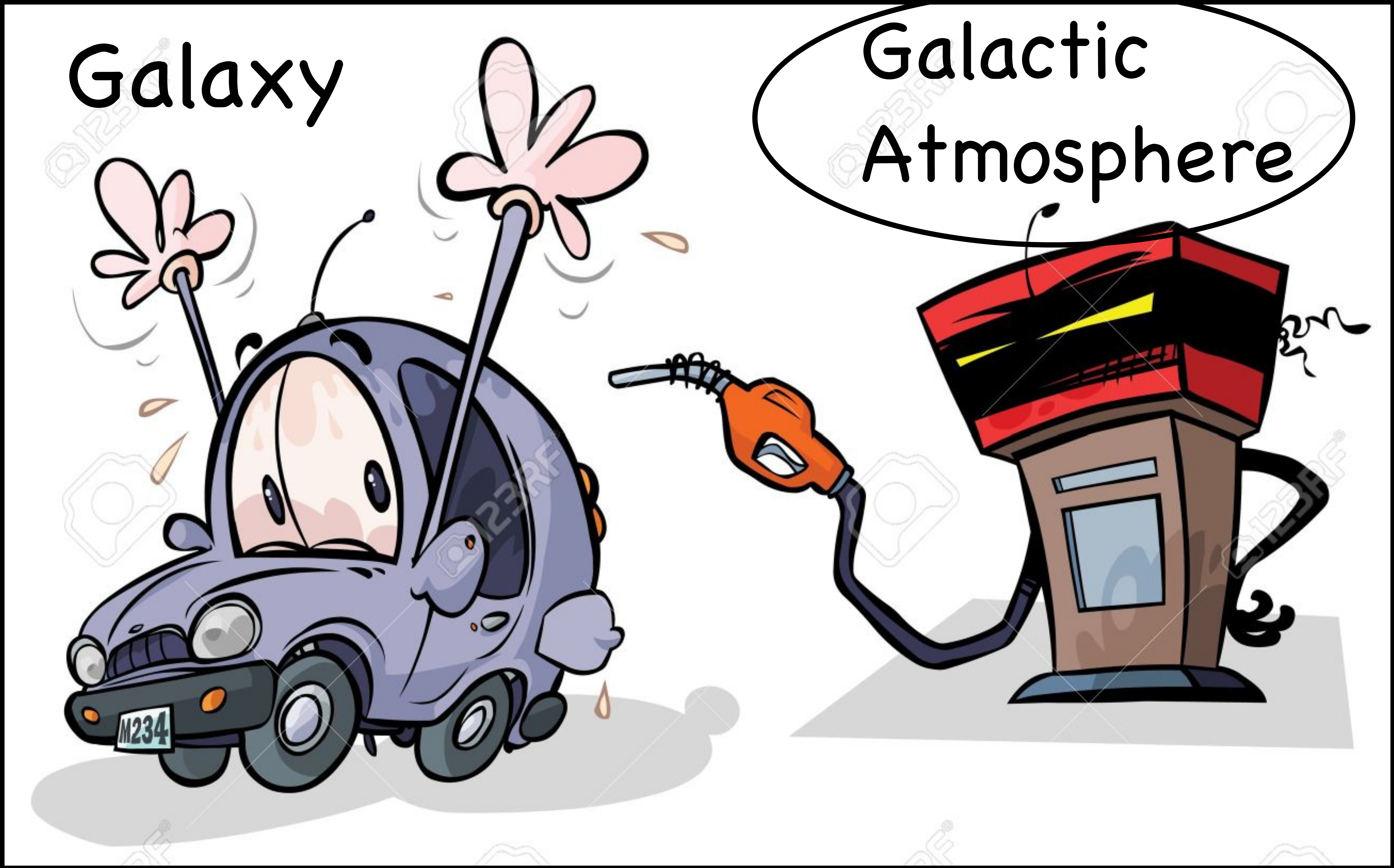
Kung-Yi Su, Smita Mathur, Jonathan Stern, Stephanie Tonnesen, Drummond Fielding

Intergalactic Medium
(IGM)
Density < 10^{-1} /cc
Virial Radius
Star-forming optically
Visible part
Invisible Dark Matter
"Invisible" Circumgalactic Medium
(CGM)
For Milky Way ~ 200 Kpc


Quasar
Brightness
Color (Wavelength)
Hubble Space Telescope
Credit : NASA; ESA; A. Feild, STScI

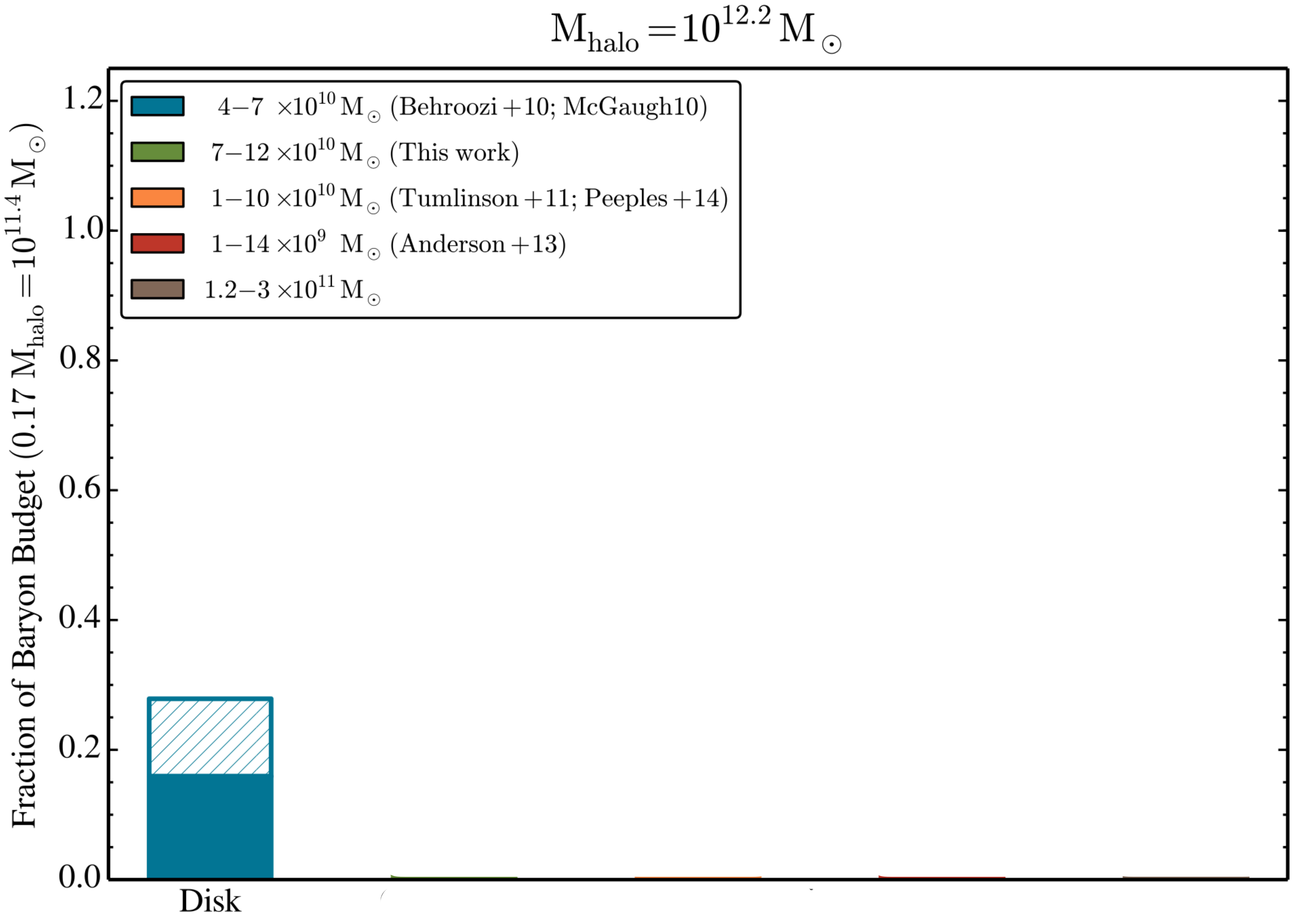
Intergalactic Medium
(IGM)
Galactic
Outflow
Virial Radius
Recycle
CGM Outflow
Star-forming optically
Visible part
CGM Inflow
Galactic Inflow
Circumgalactic Medium
(CGM)

Where Does Galaxy get Star-formation Fuel??



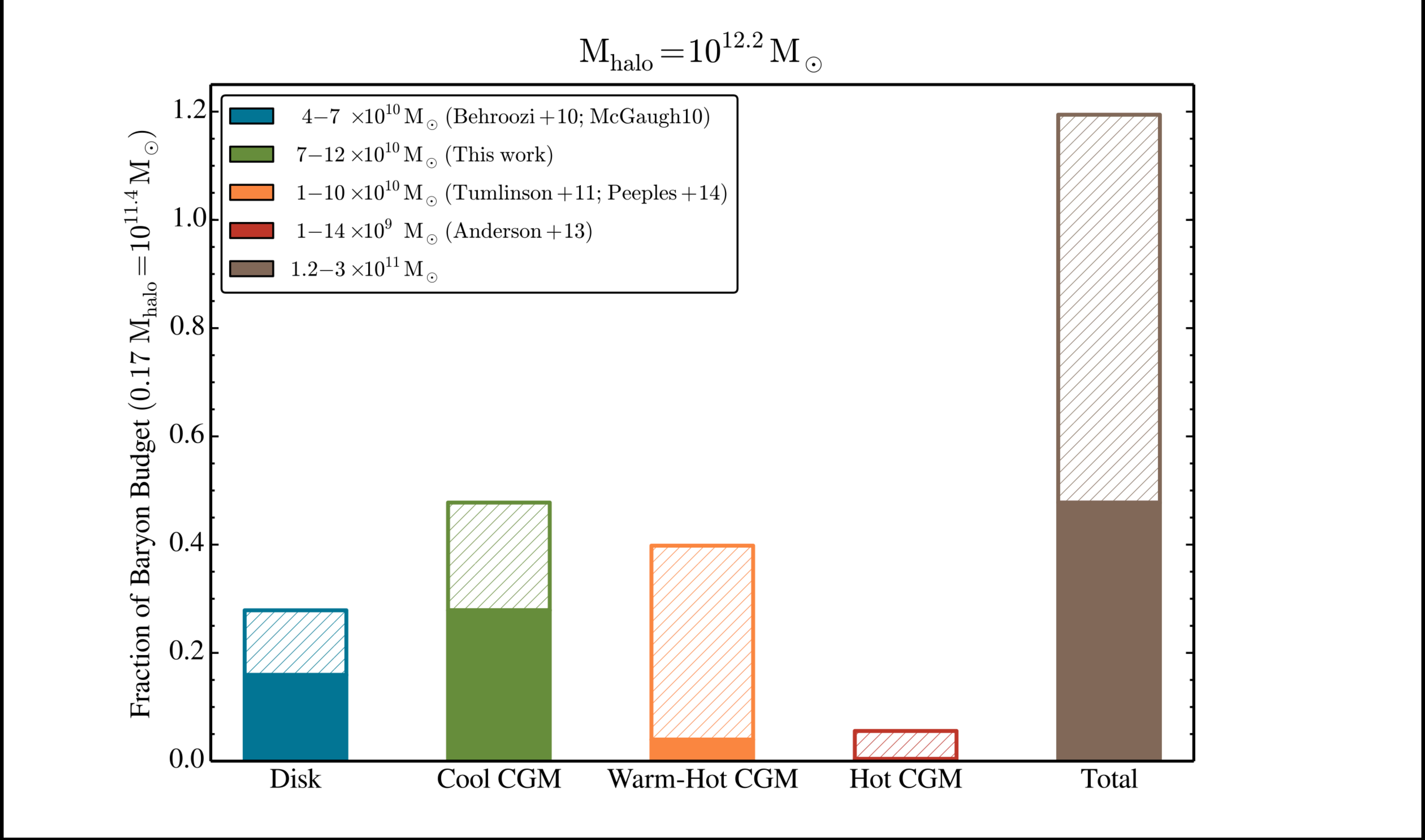
https://www.123rf.com/photo_14125374_cartoon-gas-pump-and-car.html


Intergalactic Medium
(IGM)
Density < 10-1 /cc
Temperature
Virial Radius
Hot phase > 1-2x106 K
Warm phase = 105-6 K
Cool phase < 104.5 K
Star-forming optically
Visible part
Circumgalactic Medium
(CGM)
Dark Matter



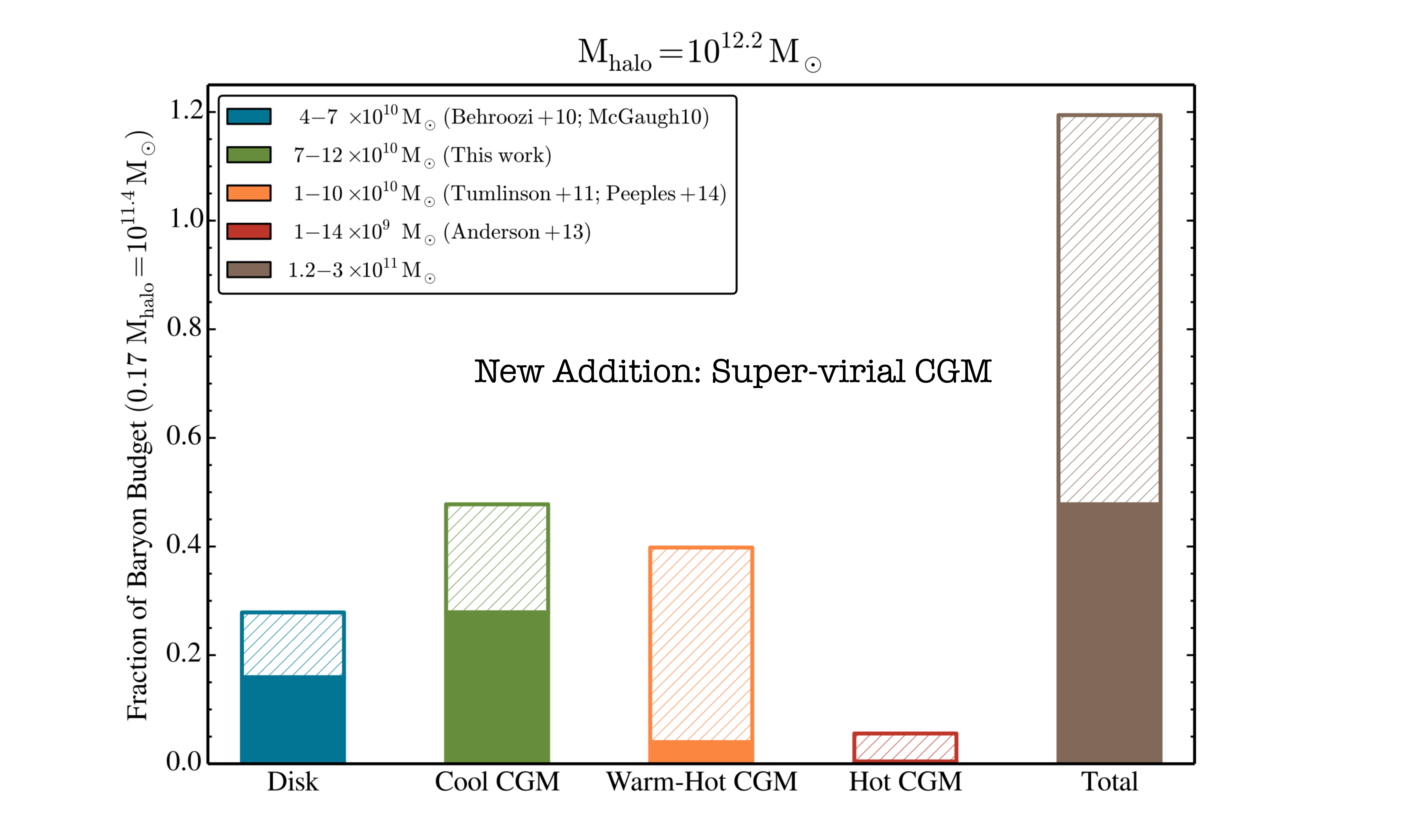
$M_{halo} = 10^{12.2} M_\odot$
Fraction of Baryon Budget ($0.17 M_{halo} = 10^{11.4} M_\odot$)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
$4-7 \times 10^{10} M_\odot$ (Behroozi+10; McGaugh10)
$7-12 \times 10^{10} M_\odot$ (This work)
$1-10 \times 10^{10} M_\odot$ (Tumlinson+11; Peeples+14)
$1-14 \times 10^{9} M_\odot$ (Anderson+13)
$1.2-3 \times 10^{11} M_\odot$
Disk

Werk+2014



$M_{halo} = 10^{12.2} M_\odot$
4–7 $\times 10^{10} M_\odot$ (Behroozi +10; McGaugh10)
7–12 $\times 10^{10} M_\odot$ (This work)
1–10 $\times 10^{10} M_\odot$ (Tumlinson +11; Peeples +14)
1–14 $\times 10^{9} M_\odot$ (Anderson +13)
1.2–3 $\times 10^{11} M_\odot$
Fraction of Baryon Budget (0.17 $M_{halo} = 10^{11.4} M_\odot$)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Disk
Cool CGM
Warm-Hot CGM
Hot CGM
Total

Werk+2014



$M_{halo} = 10^{12.2} M_\odot$
$4-7 \times 10^{10} M_\odot$ (Behroozi+10; McGaugh10)
$7-12 \times 10^{10} M_\odot$ (This work)
$1-10 \times 10^{10} M_\odot$ (Tumlinson+11; Peeples+14)
$1-14 \times 10^{9} M_\odot$ (Anderson+13)
$1.2-3 \times 10^{11} M_\odot$
New Addition: Super-virial CGM
Fraction of Baryon Budget ($0.17\ M_{halo} = 10^{11.4} M_\odot$)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Disk
Cool CGM
Warm-Hot CGM
Hot CGM
Total

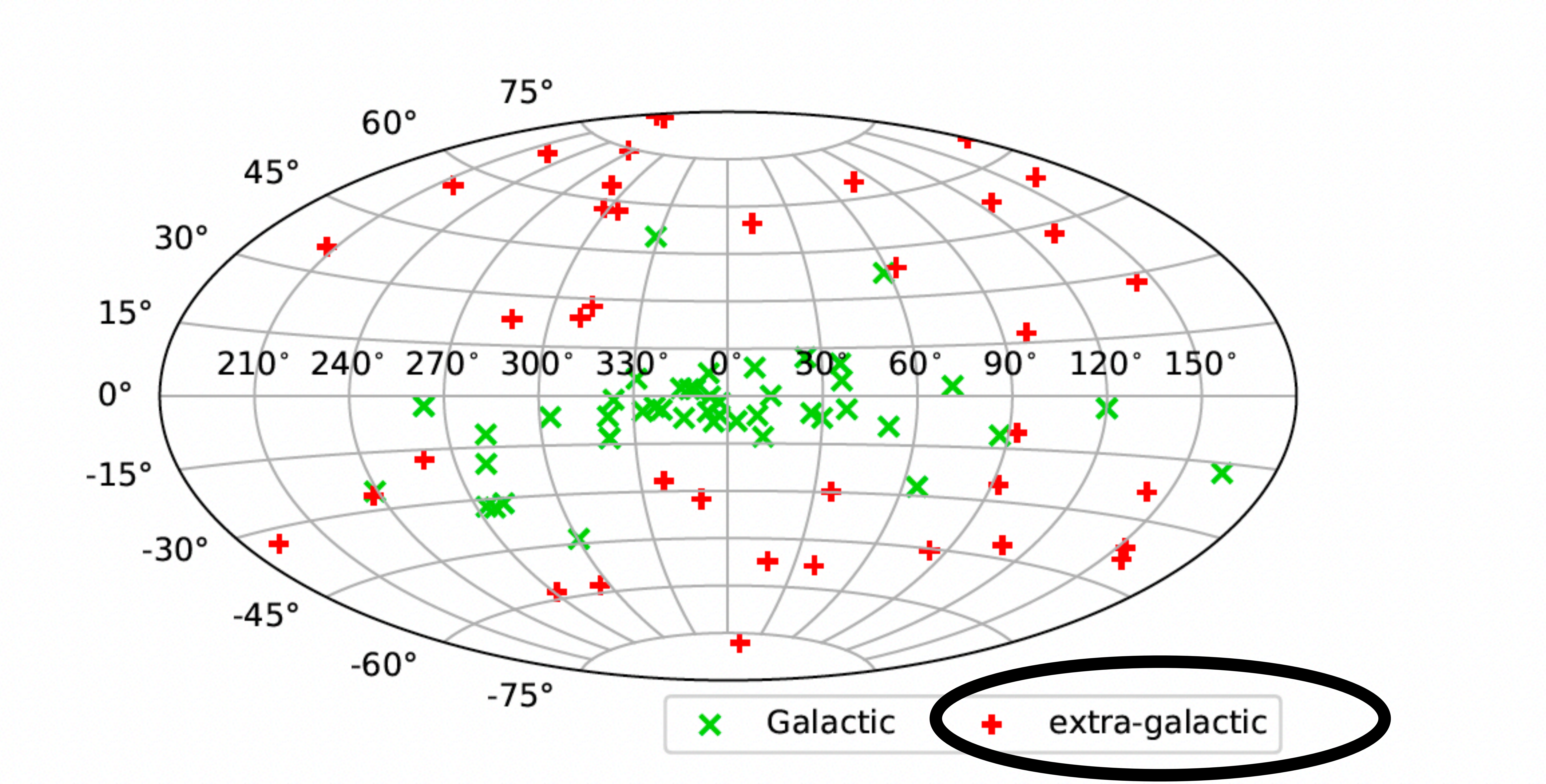
Werk+2014

Where is Super-Virial hot phase?

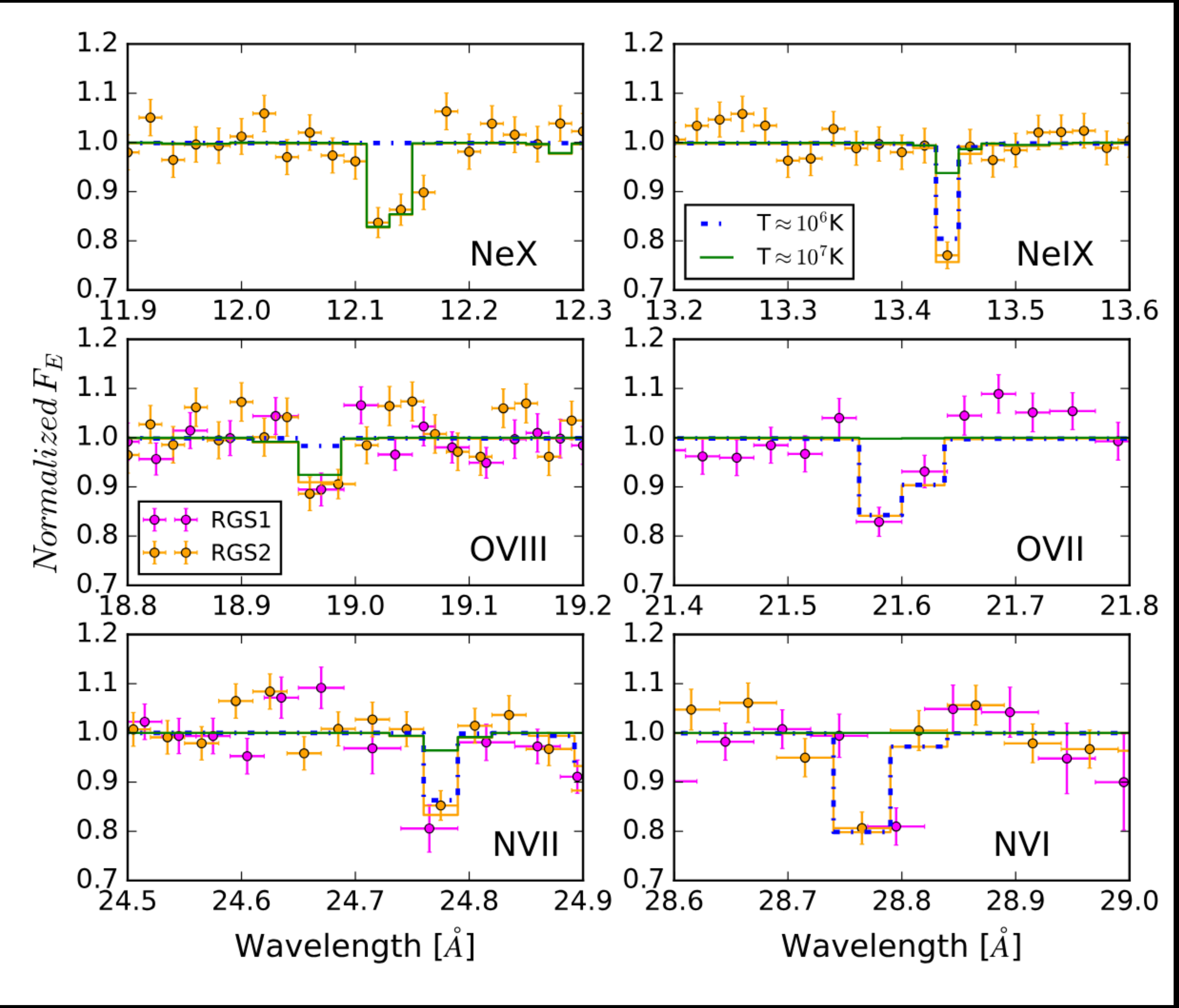
Virial Temperature ~2 x 10^6 K

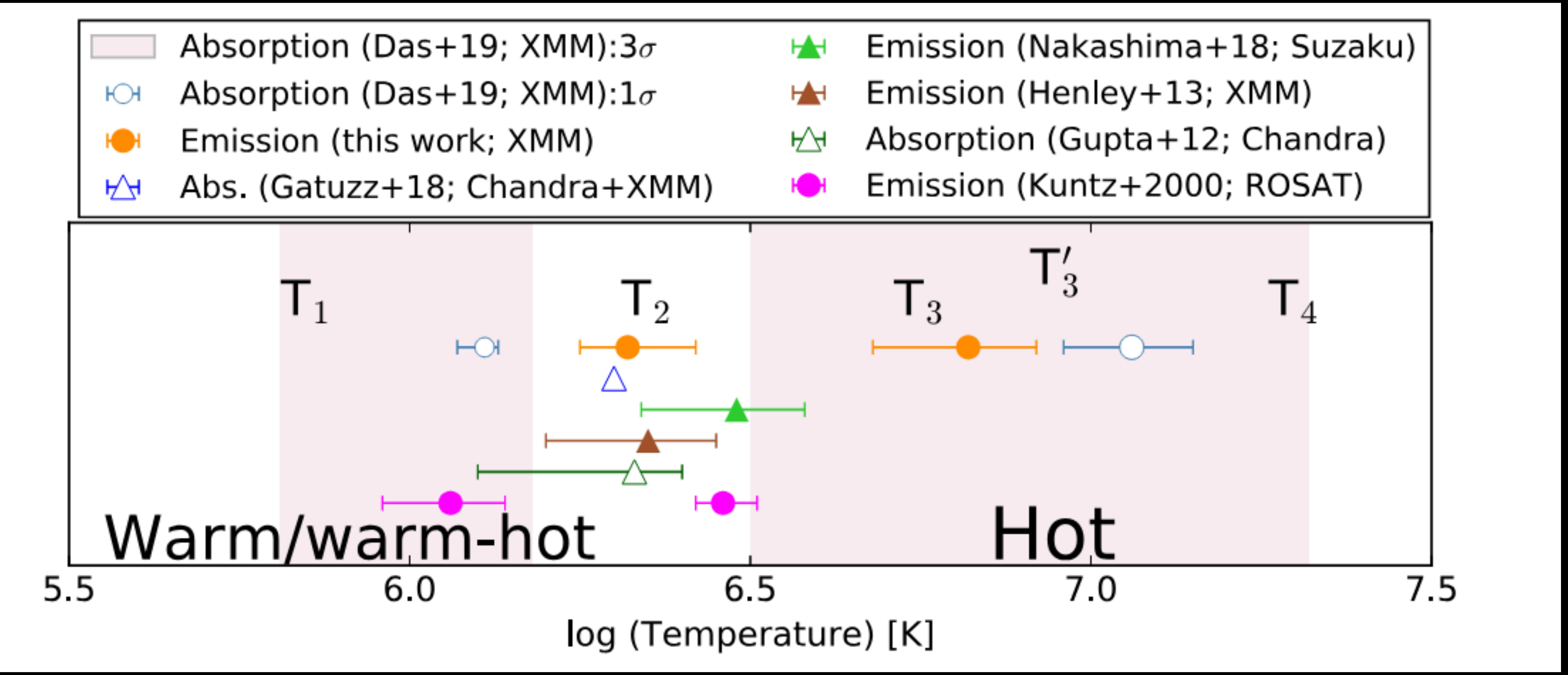
Super Virial Temperature > 6 x 10^6 K

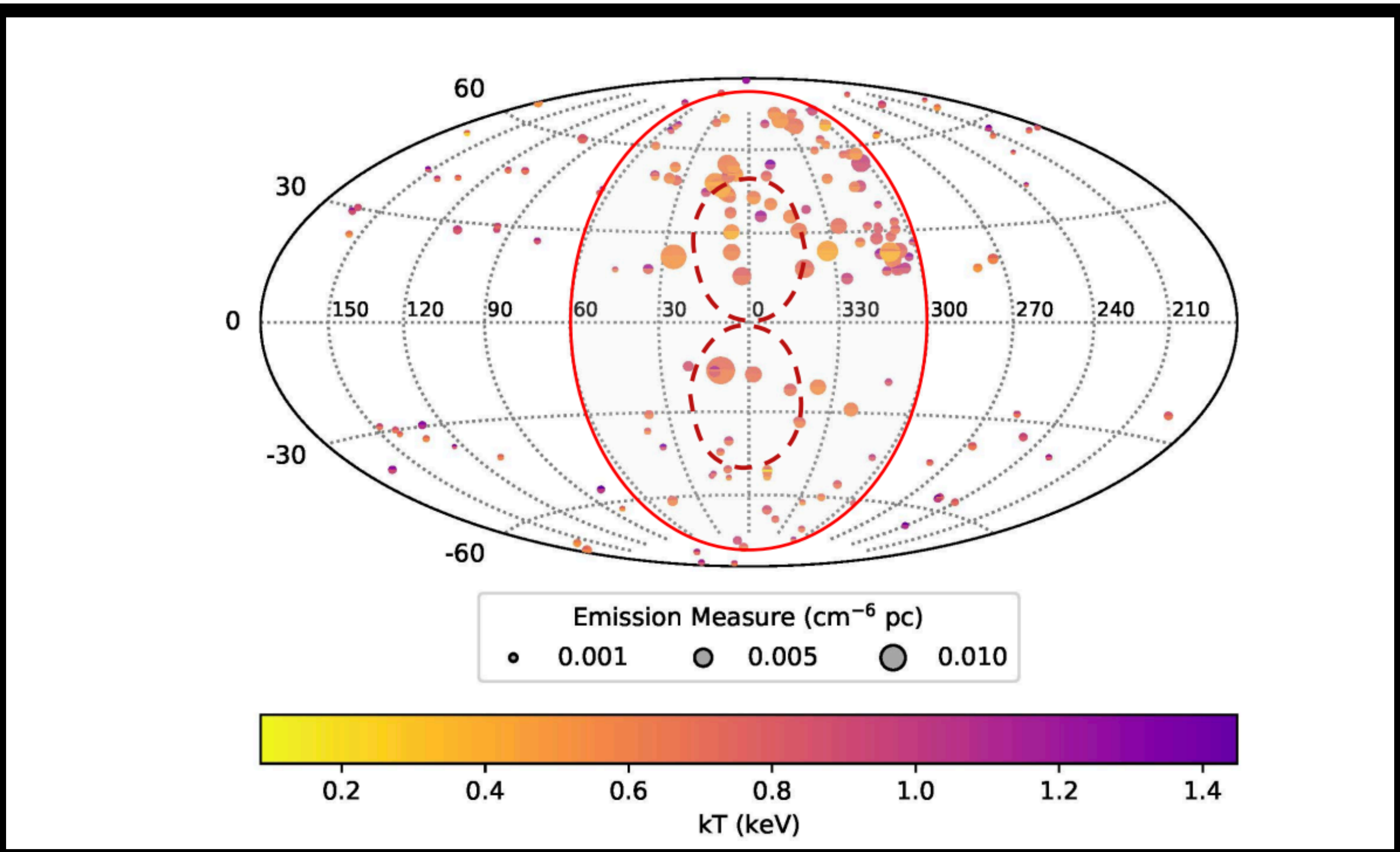
Our Galactic and Extra-galactic Sources :



Recently Discovered Super Virial Gas Phase

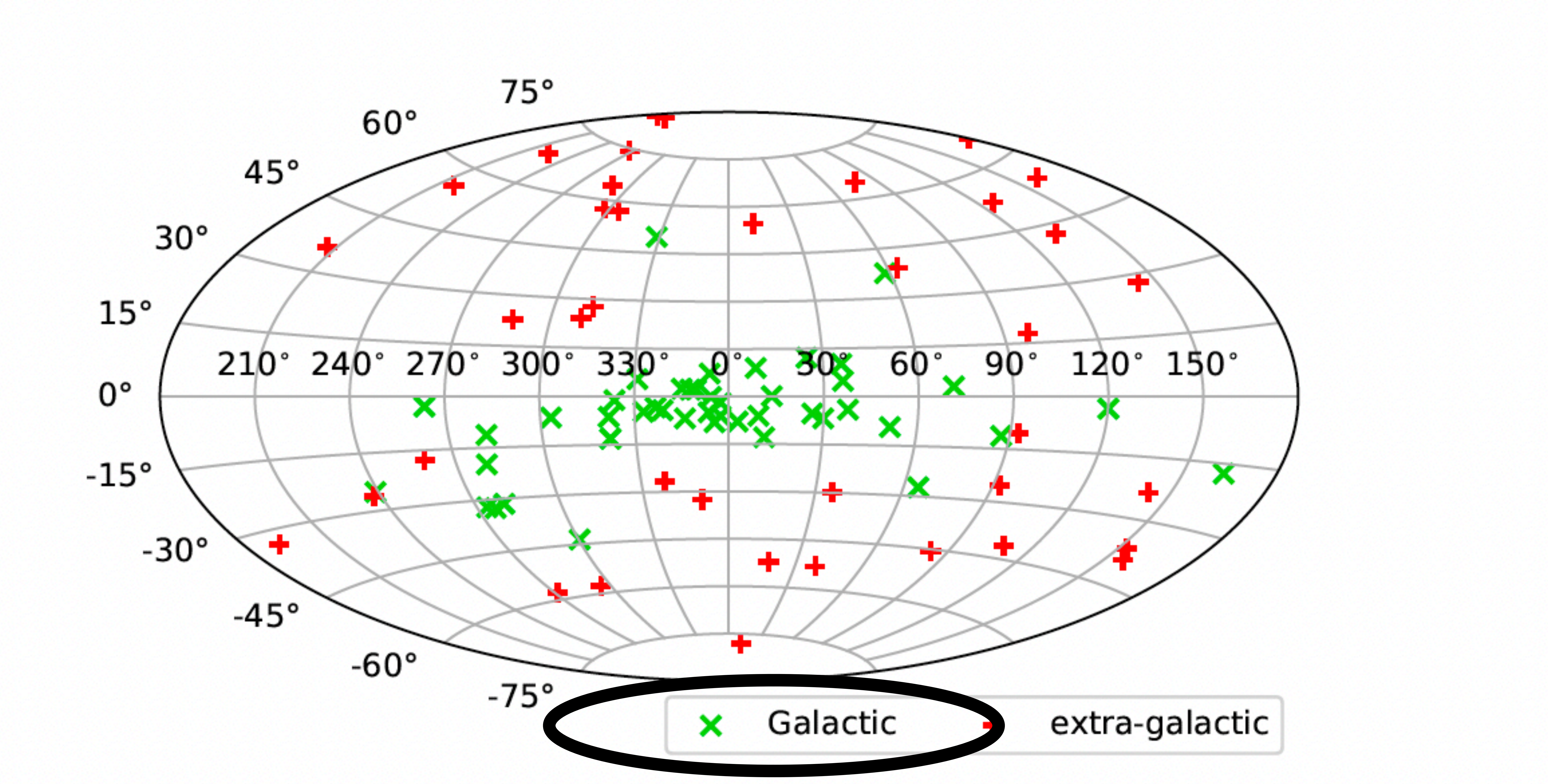






Das+2019a,b Gupta+2023

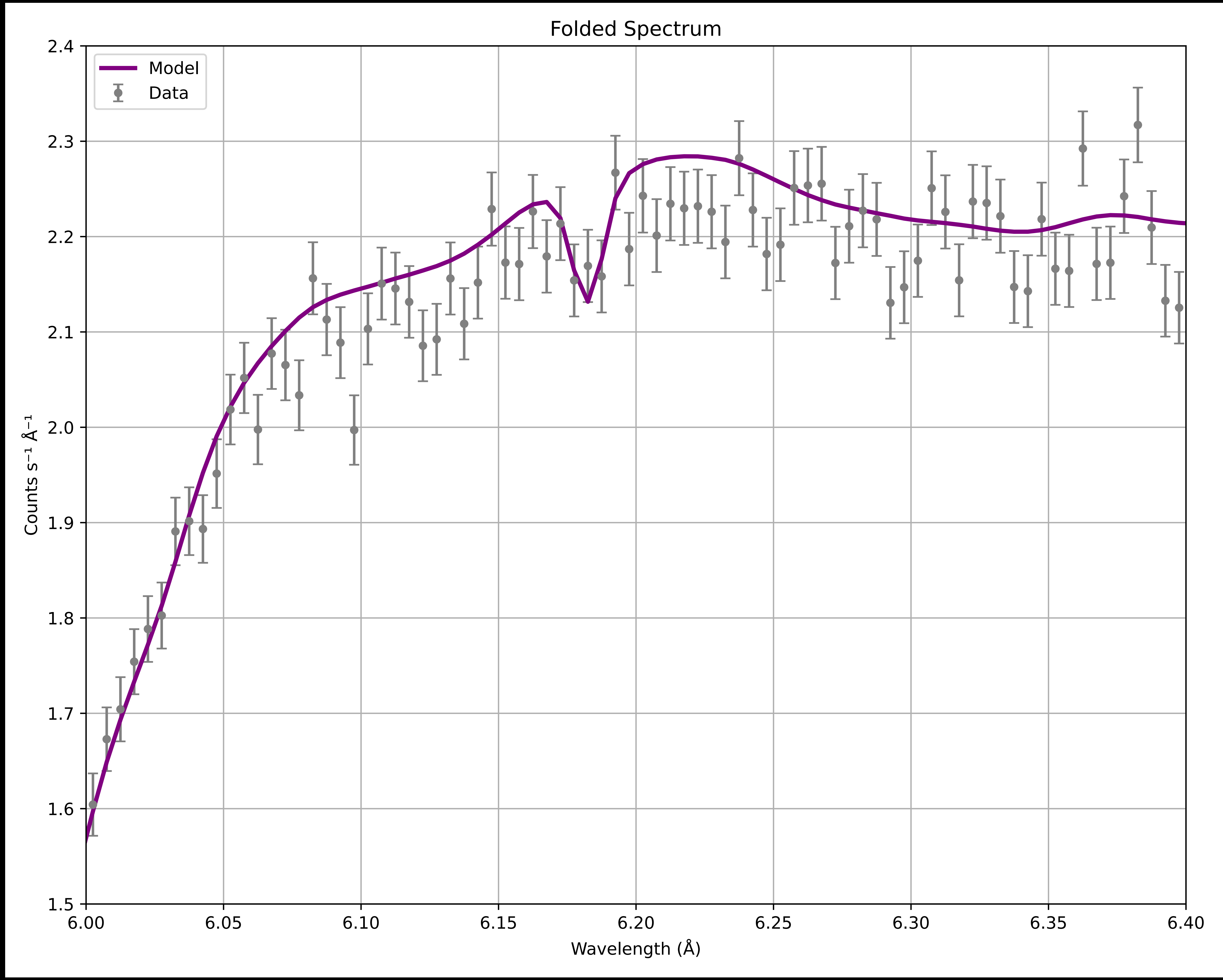
Our Galactic and Extra-galactic Sources :



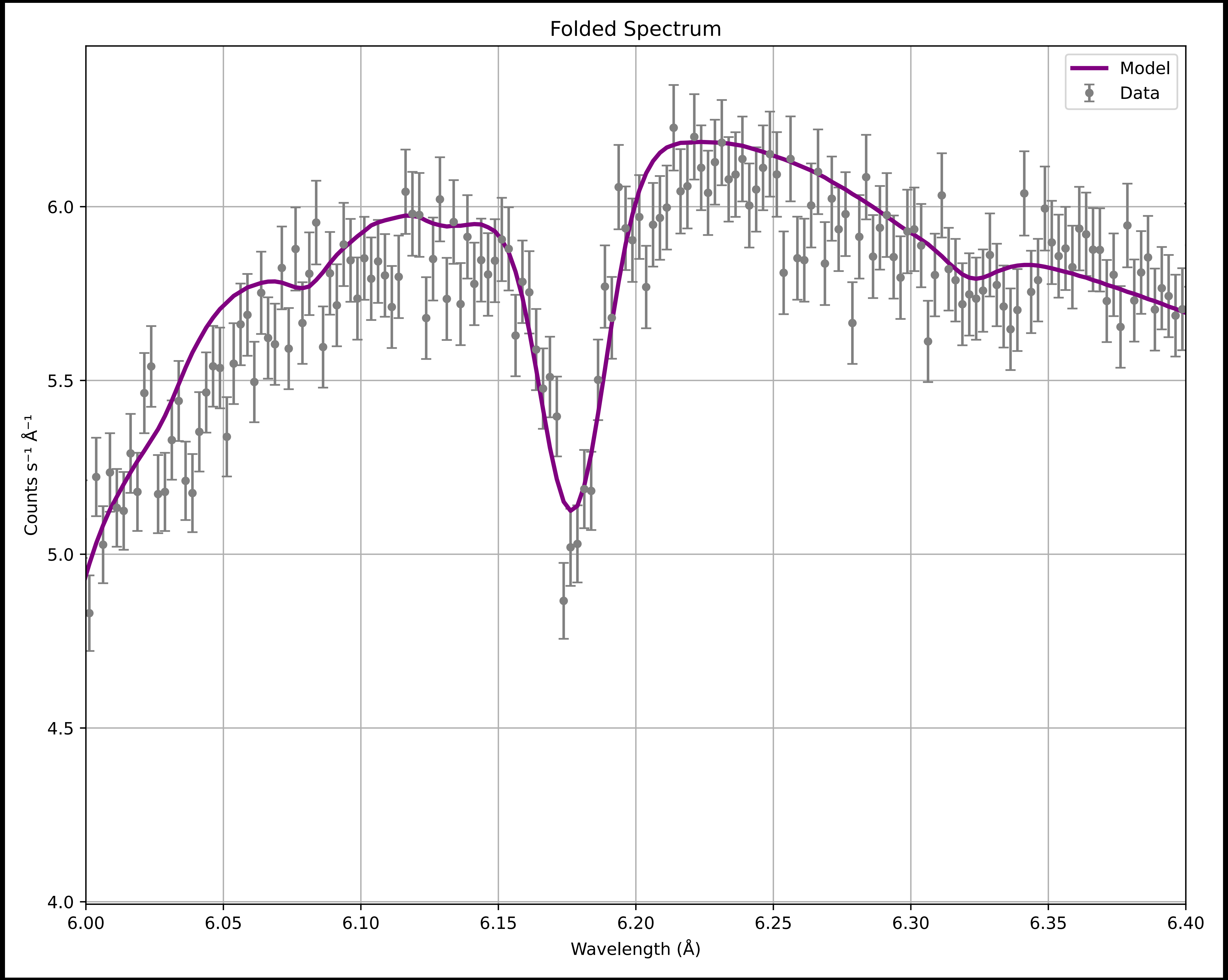
28 XRBs from Chandra Archive

Ref: Roy+ in Prep

Narrow line SiXIV : 4U1636-53



Broad line SiXIV : Cygnus X1



Best-fit parameter value : **pow+agauss**

Table 2: Best-fit parameter value

Source	Exp. Mode	Grating	Equivalent Width (mA)* Ne X (12.132 A)	Si XIV (6.181 A)	S XVI (4.728 A)
4U1636-53	CC	HEG	-2.11	-0.63	-0.32
		MEG	-1.26	-0.28	-0.19
	TE	HEG	-1.92	-0.06	-0.4
		MEG	-0.44	$\mathbf{-1.04}^{+0.2}_{-0.2}$	$-0.33^{+0.28}_{-0.28}$
EXO0748-676	TE	HEG	$-5.17^{+4.14}_{-4.14}$	$\mathbf{-5.11}^{+0.7}_{-0.7}$	$\mathbf{-3.19}^{+0.95}_{-0.95}$
		MEG	-4.34	$\mathbf{-6.43}^{+0.68}_{-0.68}$	$-1.52^{+1.0}_{-1.0}$
PSRB0833-45	CC	HEG	-4.55	$-4.28^{+2.68}_{-2.68}$	-3.89
		MEG	-5.15	-4.46	-7.75
SAXJ1808.4-3658	CC	HEG	$-2.21^{+2.21}_{-2.21}$	-0.35	-3.01
		MEG	-1.7	-0.2	-2.59
SwiftJ1753.5-0127	CC	HEG	-0.46	$0.83^{+0.63}_{-0.63}$	$-1.99^{+1.16}_{-1.16}$
		MEG	-0.97	-0.15	-1.92
SwiftJ1910.2-0546	CC	HEG	-0.66	-0.11	-0.29
		MEG	$-0.52^{+0.41}_{-0.41}$	$-0.43^{+0.24}_{-0.24}$	-0.62
4U1728-16 (GX9+9)	TE	HEG	-0.74	-0.17	$-0.26^{+0.23}_{-0.23}$
		MEG	$-0.51^{+0.46}_{-0.46}$	$\mathbf{-0.73}^{+0.18}_{-0.18}$	-0.42
V*V821Ara (GX 339-4)	CC	HEG	$-0.56^{+0.31}_{-0.31}$	-0.02	-0.17
		MEG	-0.2	-0.01	-0.03
	TE	HEG	-1.46	-0.27	-0.14
		MEG	-0.34	$\mathbf{-0.84}^{+0.23}_{-0.23}$	-0.22
GS1826-238	TE	HEG	-7.94	-0.5	-0.83
		MEG	-1.54	$-0.59^{+0.55}_{-0.55}$	-1.34
4U2129+12	TE	HEG	-2.09	-0.24	-0.63
		MEG	-0.65	-0.15	-0.70
4U1543-624	TE	HEG	-3.43	-1.73	-2.02
		MEG	-0.96	-0.33	-0.5
XTEJ1650-500	CC	HEG	-0.03 (c)	$-0.16^{+0.15}_{-0.15}$	-0.06
		MEG	0.22	$-0.13^{+0.12}_{-0.12}$	-0.17
XTEJ1650-500	TE	HEG	NE	NE	NE
		MEG	NE	NE	NE
4U 1254-69	TE	HEG	-3.85	-1.23	$-2.17^{+1.11}_{-1.11}$
		MEG	-1.63	$-1.1^{+0.58}_{-0.58}$	-0.77
4U 1957+11	CC	HEG	-6.29	-0.6	-0.79
		MEG	-2.08	$-0.96^{+0.81}_{-0.81}$	-0.54
	TE	HEG	-1.13	-0.74	$-0.76^{+0.51}_{-0.51}$
		MEG	-0.26	-0.69	-0.66
4U 0614+091	TE	HEG	-0.43	-0.36	-0.51
		MEG	-0.13	$-0.58^{+0.23}_{-0.23}$ (2)	-0.16
4U 1705-44	CC	HEG	-35.05	-0.62	-0.36
		MEG	$-13.44^{+10.24}_{-11.54}$	-0.21	-0.40
	TE	HEG	-18.6	-0.11	-0.1
		MEG	-2.17	-0.1	$-0.39^{+0.28}_{-0.28}$
4U 1728-34	CC	HEG	-3.8	-0.37	-0.31
		MEG	-1.96	$-0.25^{+0.21}_{-0.21}$	$-0.66^{+0.23}_{-0.23}$
	TE	HEG	-736.24	-0.74	-0.36
		MEG	-131.7	-0.43	-0.69
4U 1735-44	CC	HEG	-2.05	-0.07	$-0.48^{+0.43}_{-0.43}$
		MEG	$-0.89^{+0.81}_{-0.81}$	-0.31	-0.68
	TE	HEG	-2.11	-0.31	-0.13
		MEG	$-1.06^{+1.05}_{-1.05}$	$-0.59^{+0.44}_{-0.44}$	$-0.87^{+0.61}_{-0.61}$
4U 1820-30	CC	HEG	$1.09^{+0.41}_{-0.41}$	-0.05	-0.36
		MEG	-0.07	-0.14	-0.4
	TE	HEG	$-1.41^{+1.11}_{-1.11}$	-0.42	-0.57
		MEG	-0.33	$\mathbf{-1.61}^{+0.42}_{-0.42}$	-0.39
4U 1626-67	TE	HEG	-0.21 (-2.01)	-0.46	-0.65
		MEG	-0.06 ($-0.91^{+0.87}_{-0.87}$)	-0.34	-0.22
Serpens X-1	CC	HEG	-1.13	-0.02	-0.03
		MEG	-0.28	-0.01	-0.07
	TE	HEG	1.18	-0.05	-0.07
		MEG	-0.29	$-0.18^{+0.16}_{-0.16}$	-0.06
Cygnus X-1	CC	HEG	$\mathbf{-2.52}^{+0.2}_{-0.19}$ **	$\mathbf{-4.59}^{+0.15}_{-0.13}$ **	$\mathbf{-2.69}^{+0.24}_{-0.23}$ **
		MEG	$\mathbf{-1.74}^{+0.36}_{-0.22}$ **	$\mathbf{-6.07}^{+0.12}_{-0.12}$ **	$\mathbf{-2.85}^{+0.34}_{-0.21}$ **
	TE	HEG	-0.31 (em)	$\mathbf{-5.47}^{+0.19}_{-0.46}$ **	$\mathbf{-3.19}^{+0.34}_{-0.34}$ **
		MEG	-1.07	$\mathbf{-4.63}^{+0.25}_{-0.25}$ **	$\mathbf{-2.21}^{+0.25}_{-0.29}$ **
GX 349+2	CC	HEG	-1.27	-0.14 (em)	-0.18 (em)
		MEG	-0.79	-0.13(em)	-0.11
	TE	HEG	-1.2	-0.17(em)	$-0.22^{+0.2}_{-0.2}$
		MEG	-0.98	-0.6	-0.15
GX 340+00	CC	HEG	-18.74	-0.89	-0.49
		MEG	-11.27	-0.32	-0.12
	TE	HEG	-1806	-0.26	-0.32 (em)
		MEG	-640	-0.09 (em)	-0.21
GX 5-1	CC	HEG	-13.75	-0.12	$-0.42^{+0.2}_{-0.2}$
		MEG	-11.22	-0.23	-0.37
	TE	HEG	-358.16	-0.19	-0.10
		MEG	-89.94	-0.15	$-0.25^{+0.13}_{-0.13}$
GX 3+1	CC	HEG	-24.2	-0.19	-0.57
		MEG	$-12.97^{+8.38}_{-9.33}$	-1.15	-0.33
	TE	HEG	-1134.6	-0.13(em)	-0.17
		MEG	-3.91	-0.25	-0.11
GX 13+1	CC	HEG	-19.15	$\mathbf{-6.38}^{+0.75}_{-0.75}$ **	$\mathbf{-2.8}^{+0.5}_{-0.38}$ (dis)
		MEG	-19.14	$\mathbf{-5.47}^{+0.58}_{-0.44}$ **	$\mathbf{-2.99}^{+0.41}_{-0.41}$ (dis)
	TE	HEG	-2968.09	$\mathbf{-7.15}^{+0.3}_{-0.27}$ **	$\mathbf{-4.75}^{+0.27}_{-0.26}$ **
		MEG	$-11.98^{+10.47}_{-8.52}$	$\mathbf{-7.01}^{+0.17}_{-0.21}$ **	$\mathbf{-4.52}^{+0.28}_{-0.12}$ **

25 detections

Out of 112 Observations

Ref: Roy+ in Prep

Most of them likely intrinsic to XRB source; not from ISM

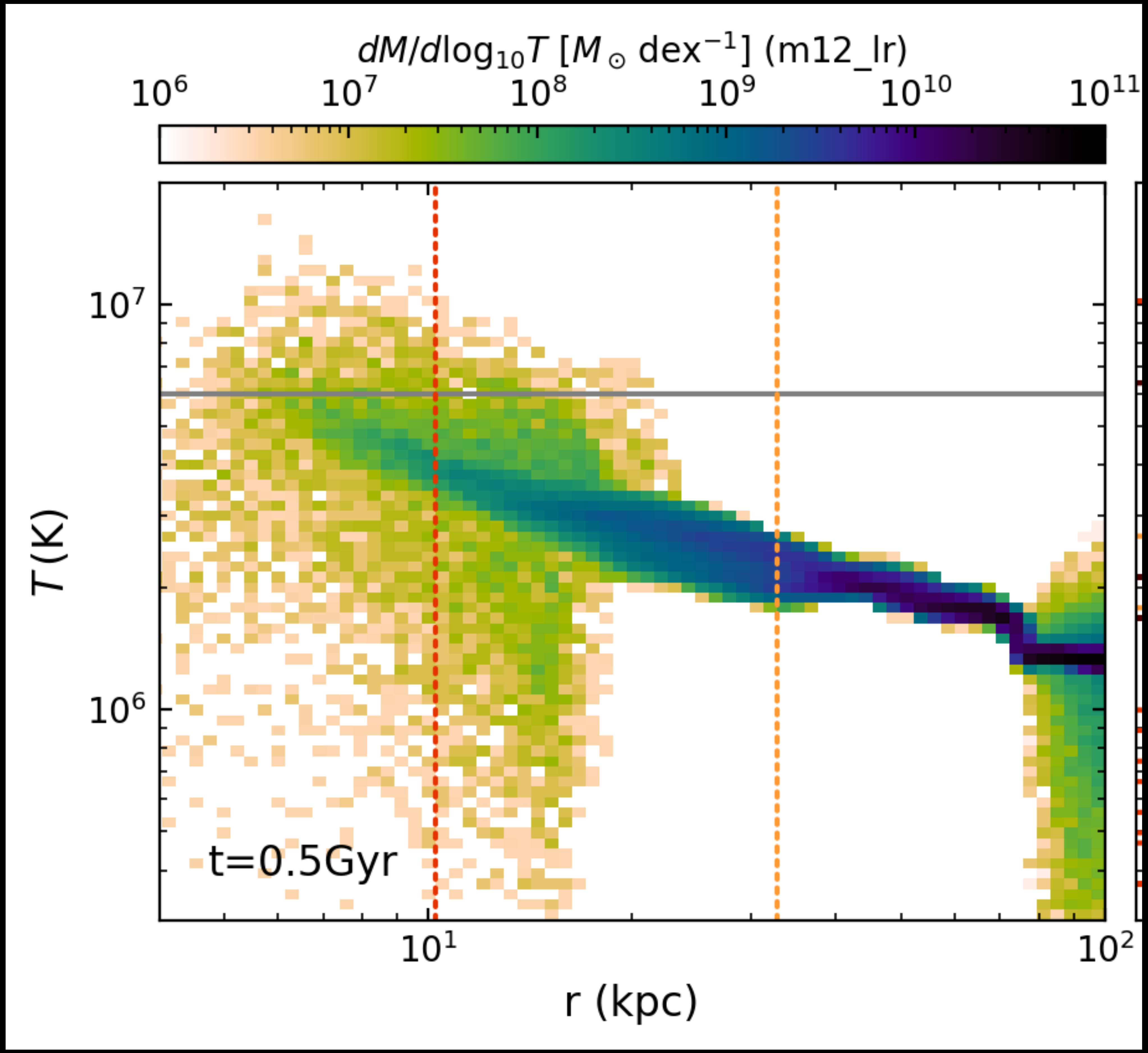
This Gas is either Extraplanar or extended CGM

Where is the hot gas?
Extraplanar or extended CGM?

Simulations can give us insight

Super Virial Gas are within 20kpc, extra planer.

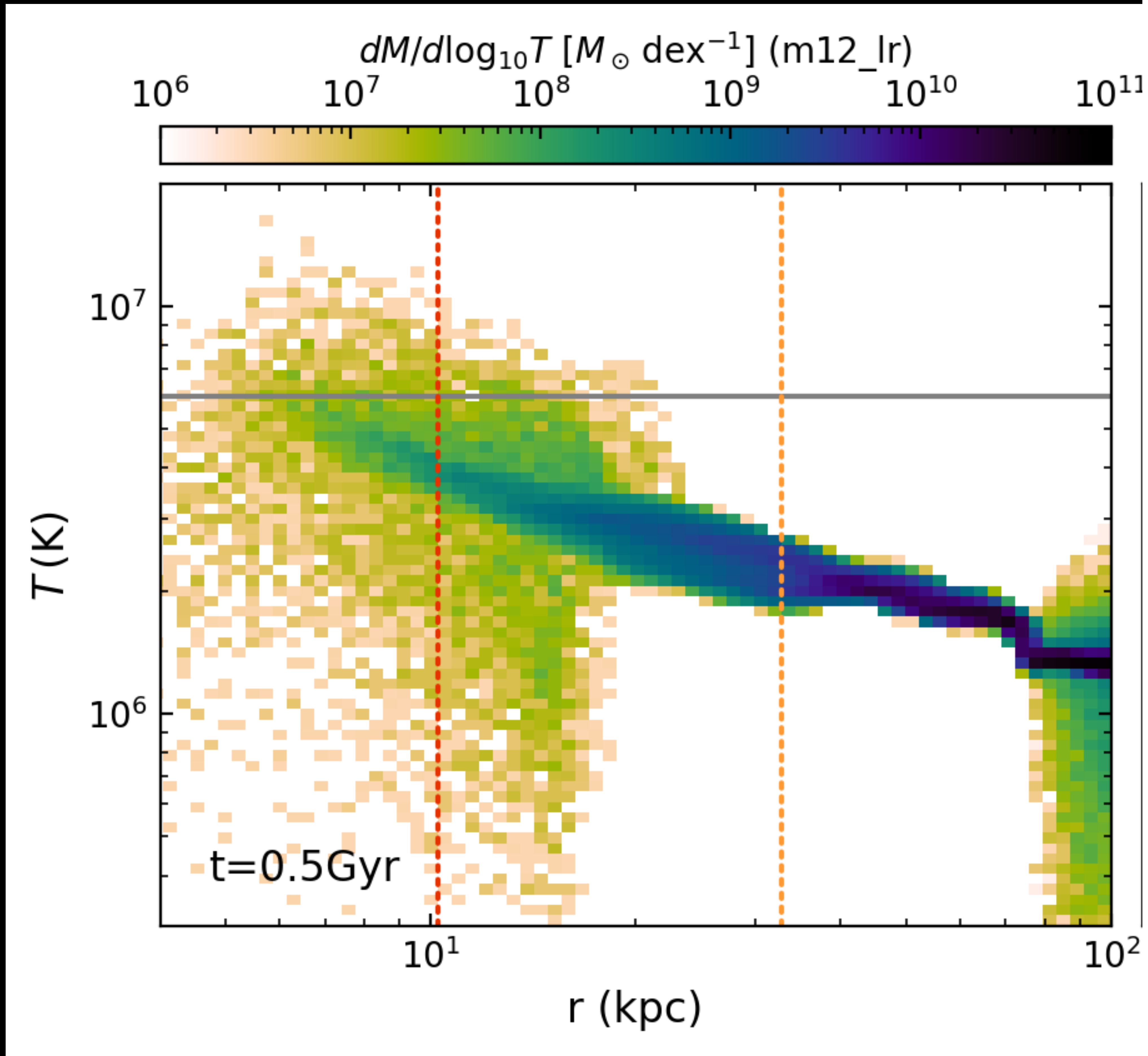
GIZMO (FIRE2)

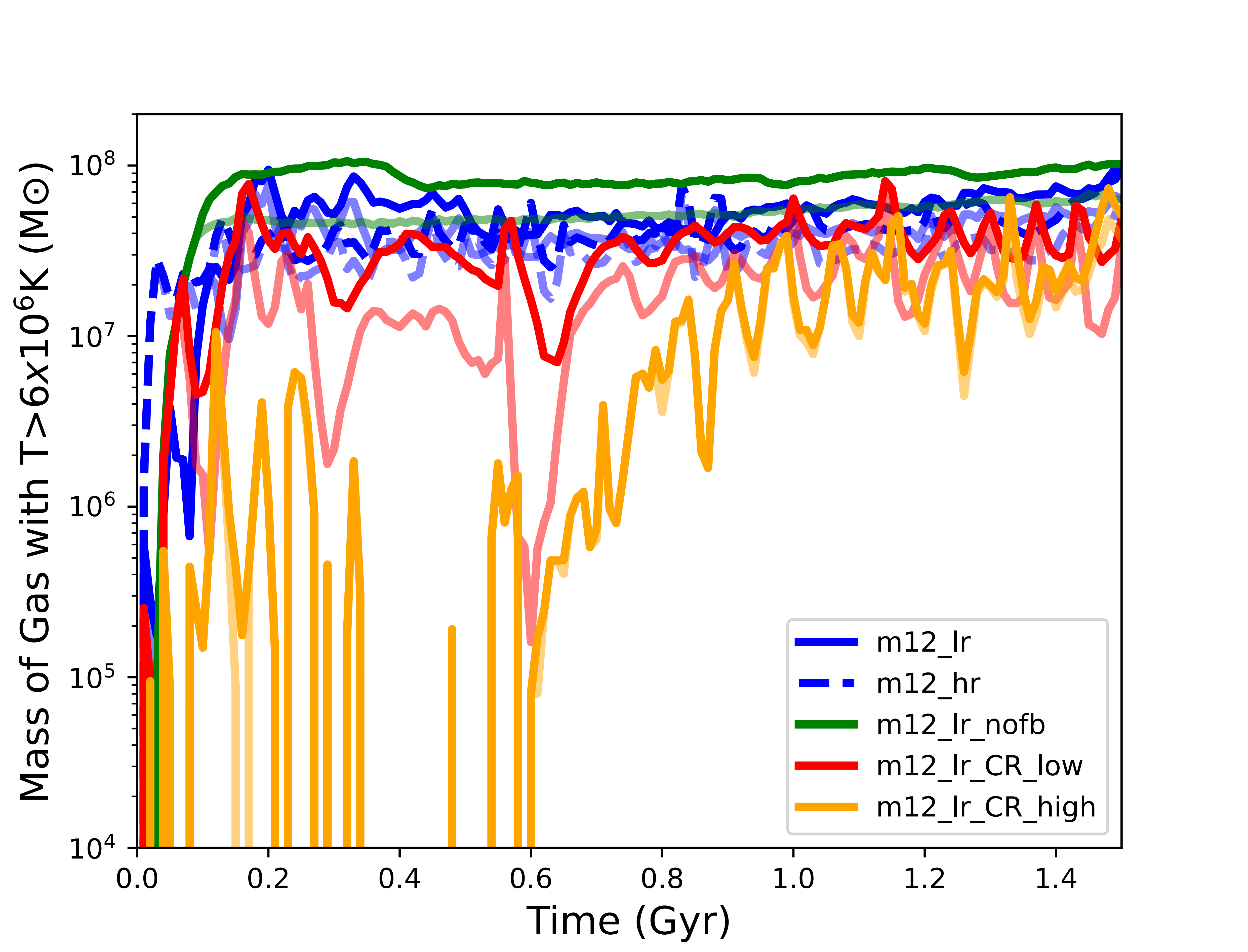


Ref: Roy+ in Prep

Super Virial Gas are within 20kpc, extra planer.

GIZMO (FIRE2)

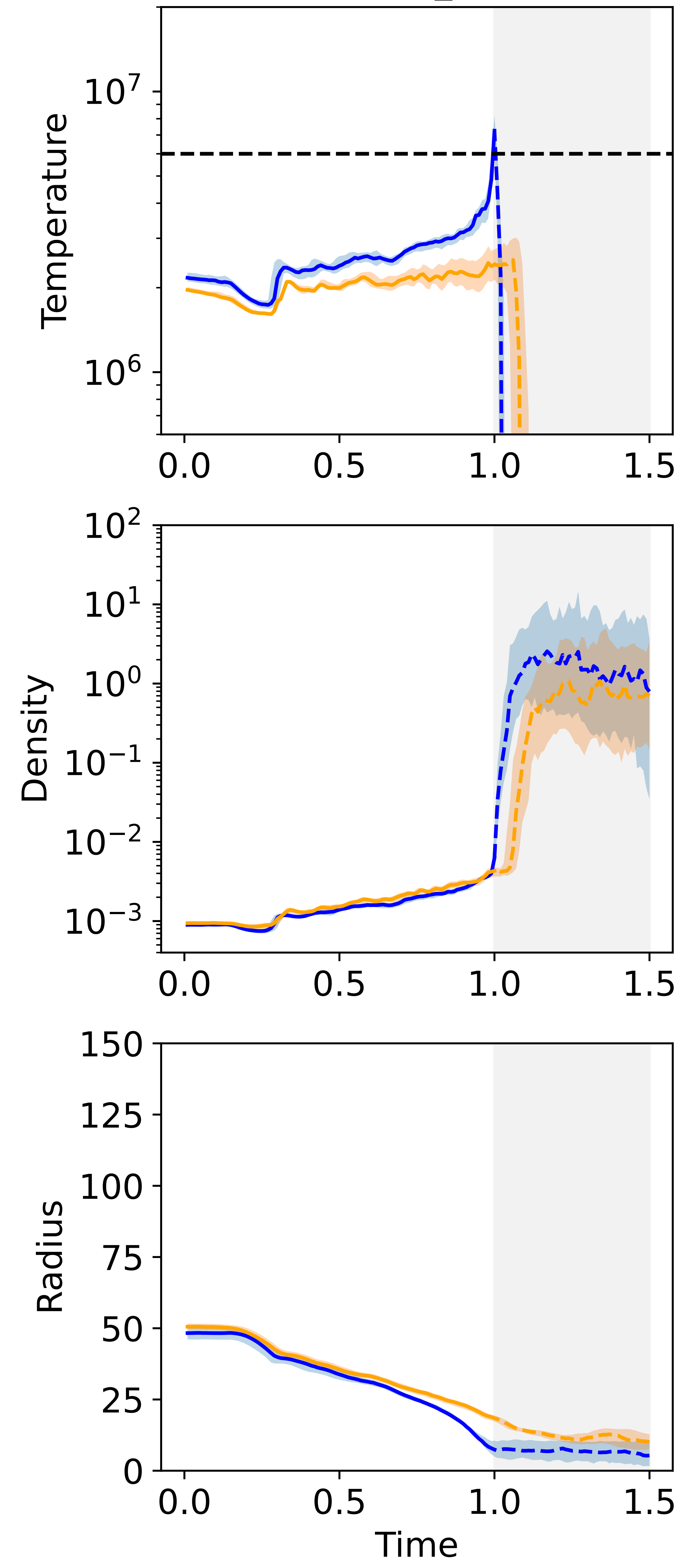




Ref: Roy+ in Prep

Even W/O feedback Super virial Phase is there.....

How is Super-Virial hot phase formed?

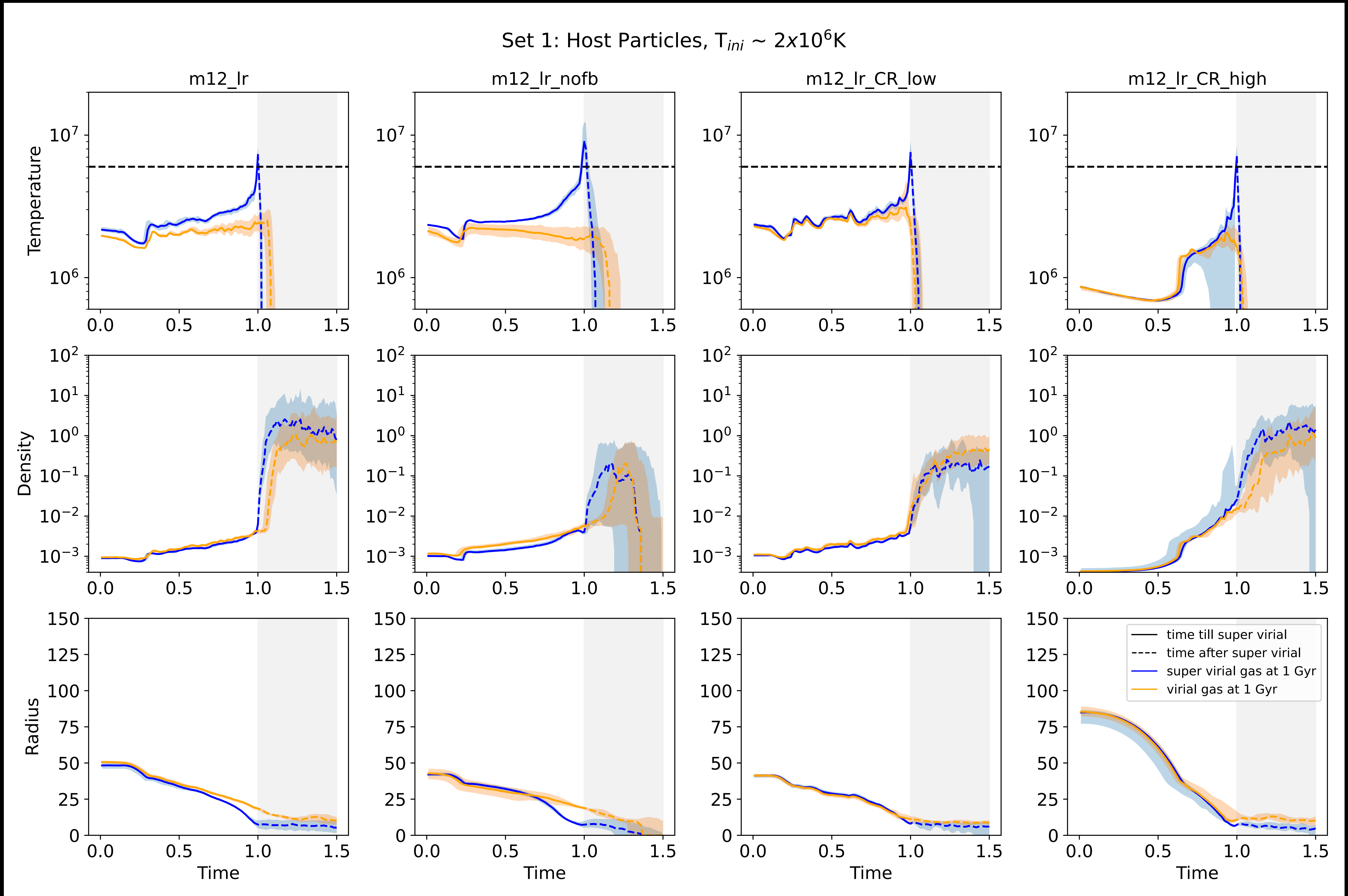


Infalling Gas Heated up

Compressed before

Joining the disc

Ref: Roy+ in Prep

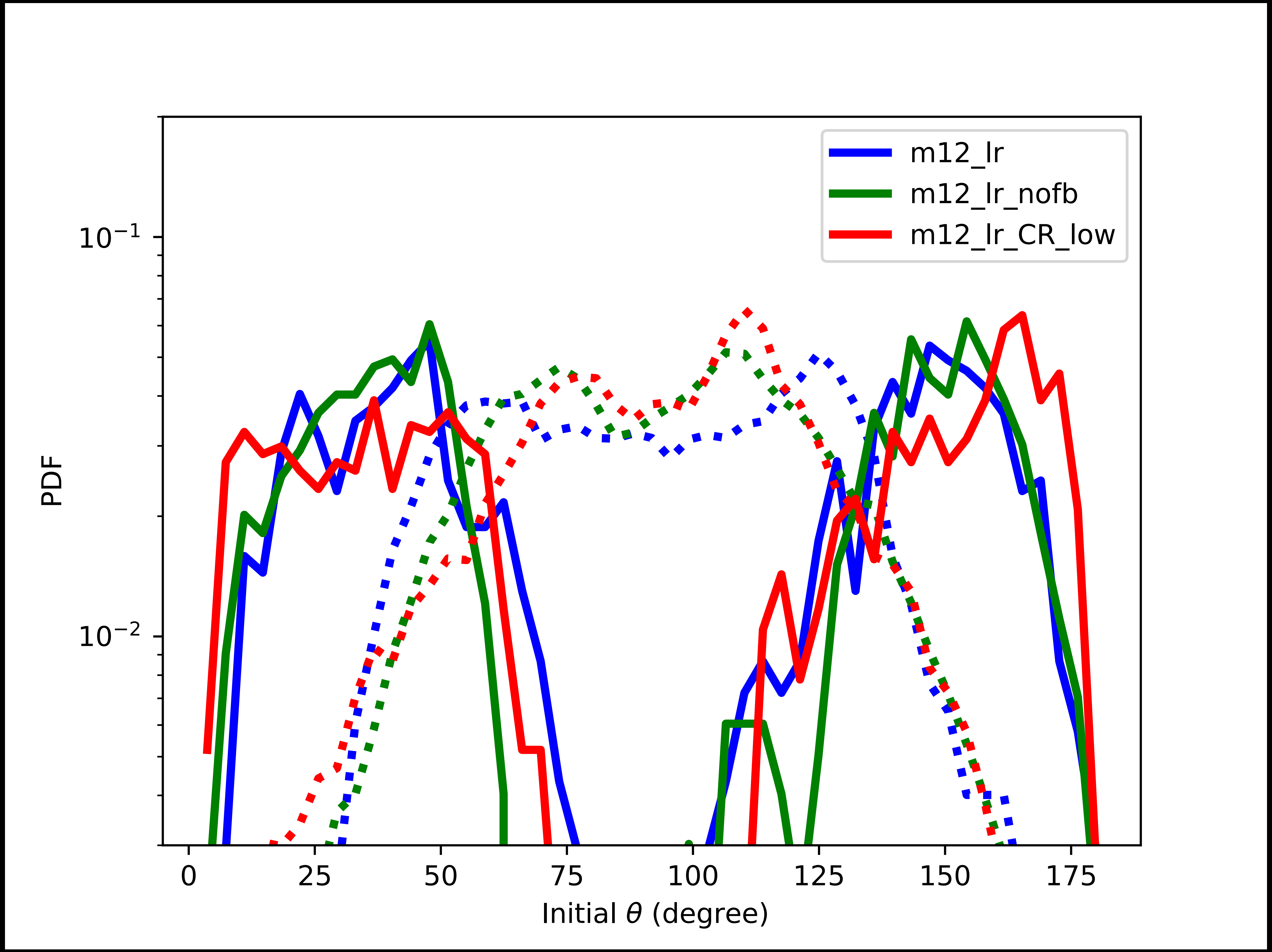


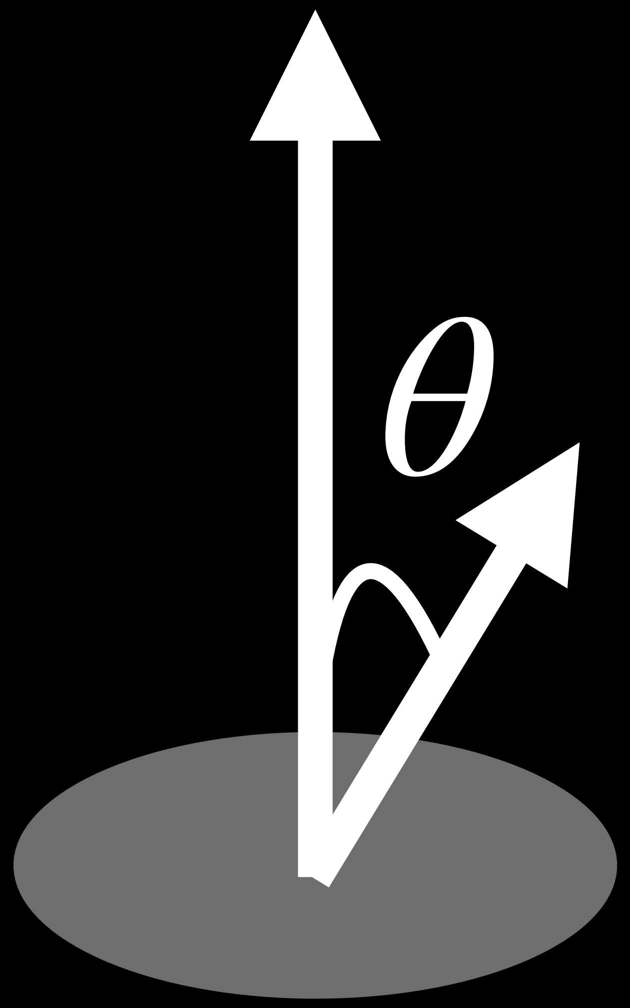
Infalling Gas Heated up

Compressed before

Joining the disc

Ref: Roy+ in Prep

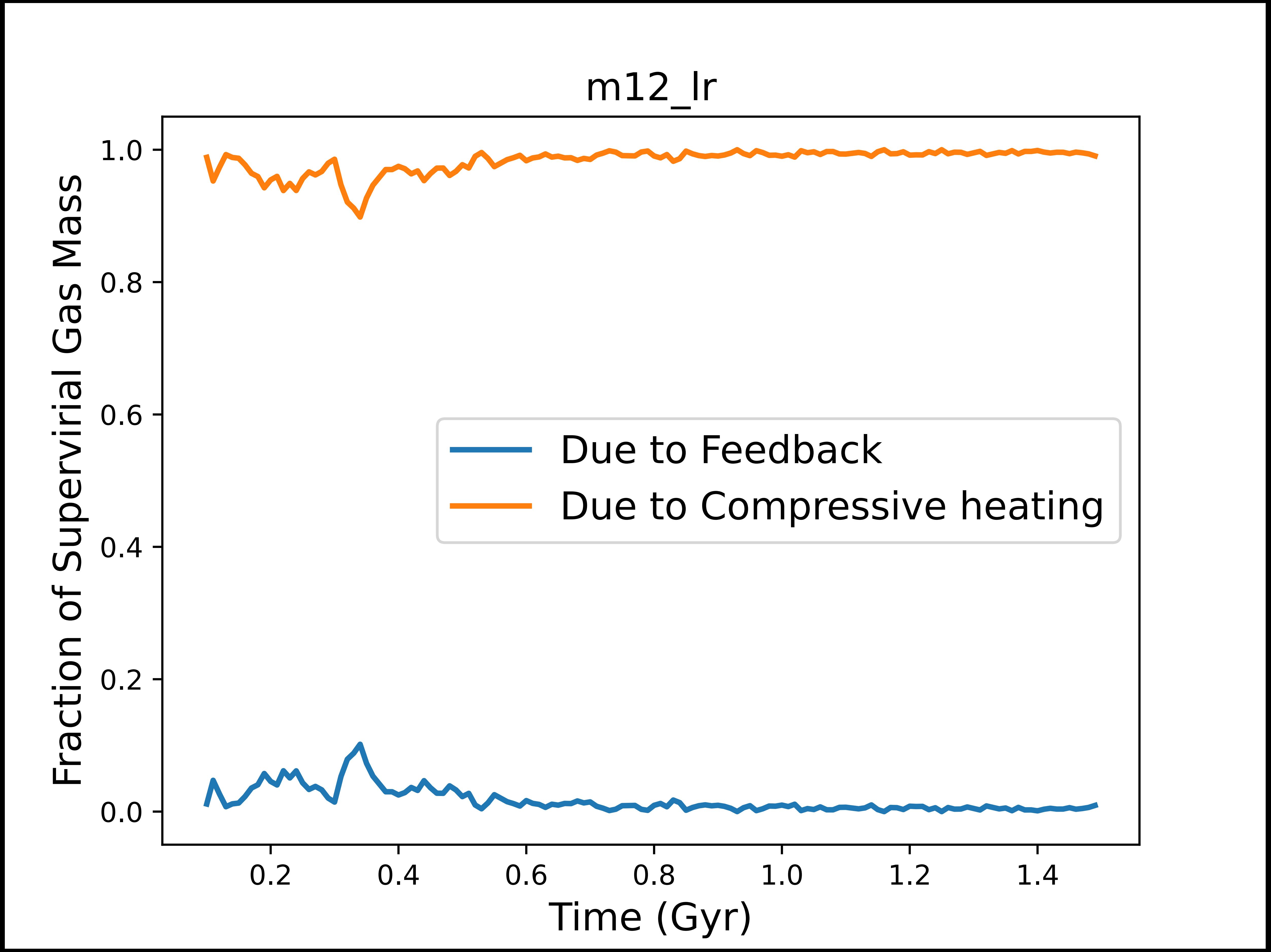




1. Infalling gas closer to the rotation axis heats up more

2. Gives rise to super virial gas

Ref: Roy+ in Prep



1% of Super-virial gas is coming from stellar feedback

Take Home Points

1. Super Virial gas is in extraplaner disc (both from observations and simulation).
2. It is coming from infalling virial gas near the rotation axis.
3. Stellar Feedback contributes ~1% of this gas.

Thank You Furry Much!!!