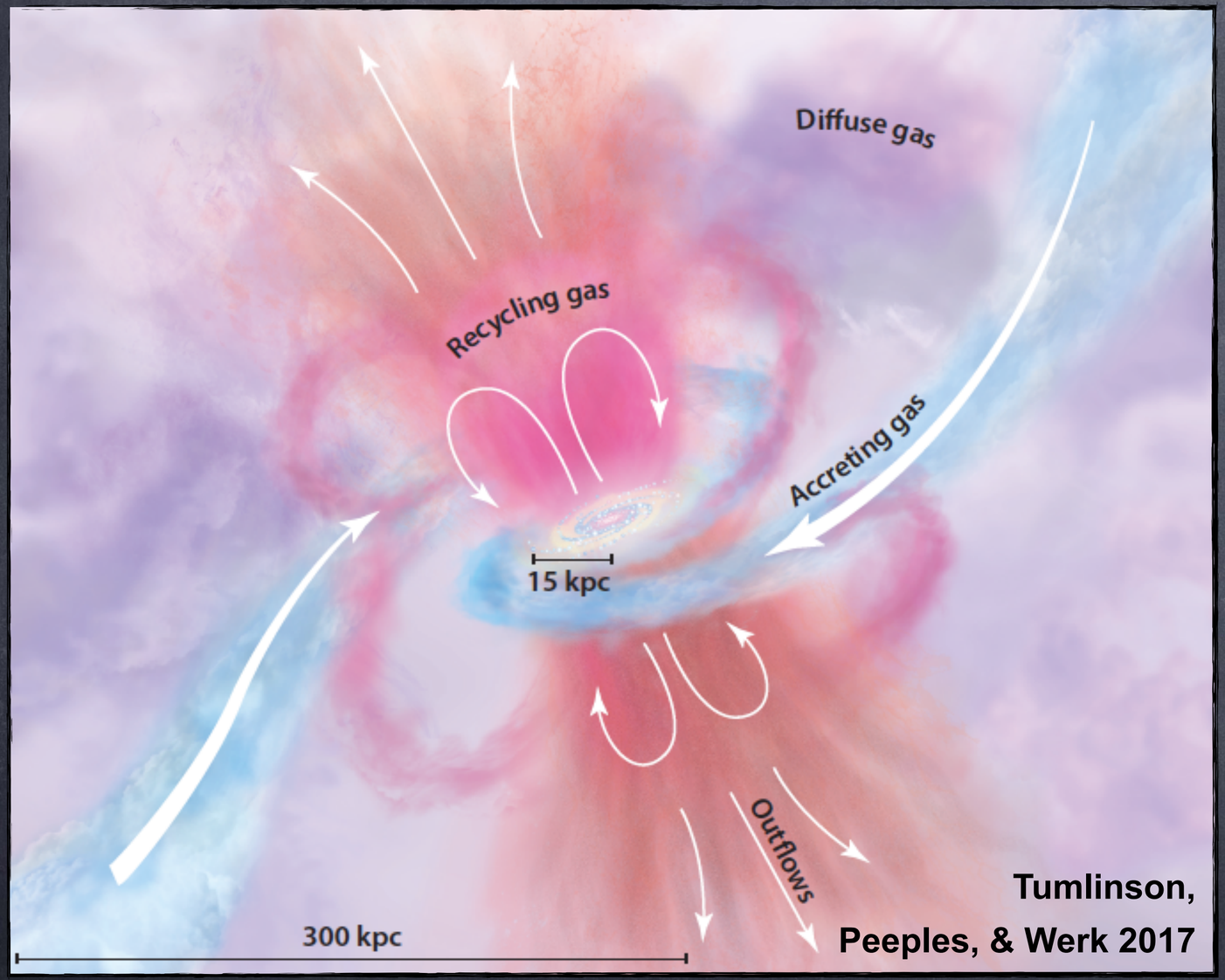
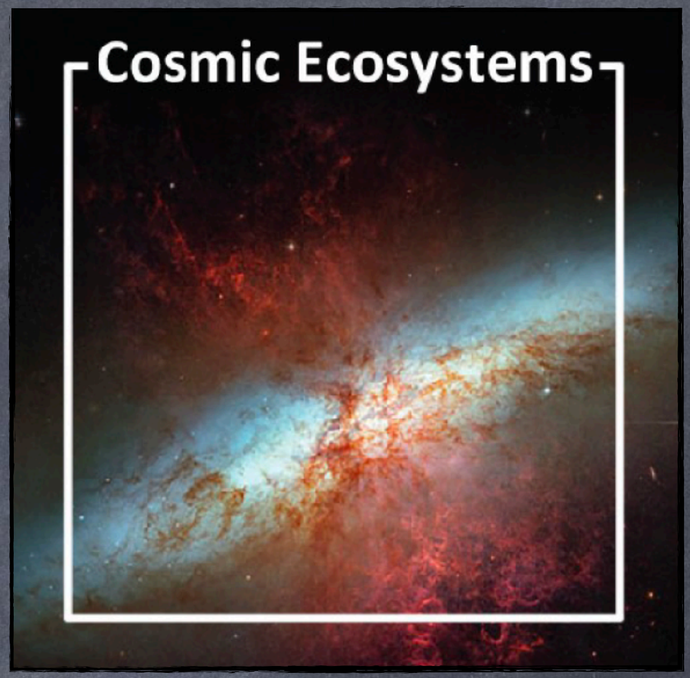
The multiphase CGM through UV-colored glasses





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The (pre-) Historical CGM

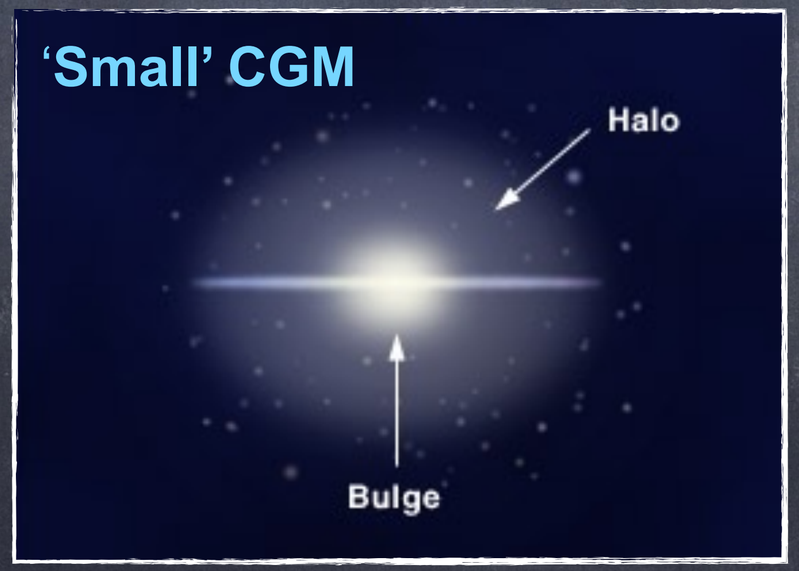
ON A POSSIBLE INTERSTELLAR GALACTIC CORONA*

LYMAN SPITZER, JR.
Princeton University Observatory
Received March 24, 1956

ABSTRACT

The physical conditions in a possible interstellar galactic corona are analyzed Pressure equilibrium between such a rarefied, high-temperature gas and normal interstellar clouds would account for the existence of such clouds far from the galactic plane and would facilitate the equilibrium of spiral arms in the presence of strong magnetic fields. Observations of radio noise also suggest such a corona.

Such a corona is apparently not observable optically except by absorption measures shortward of 2000 A.

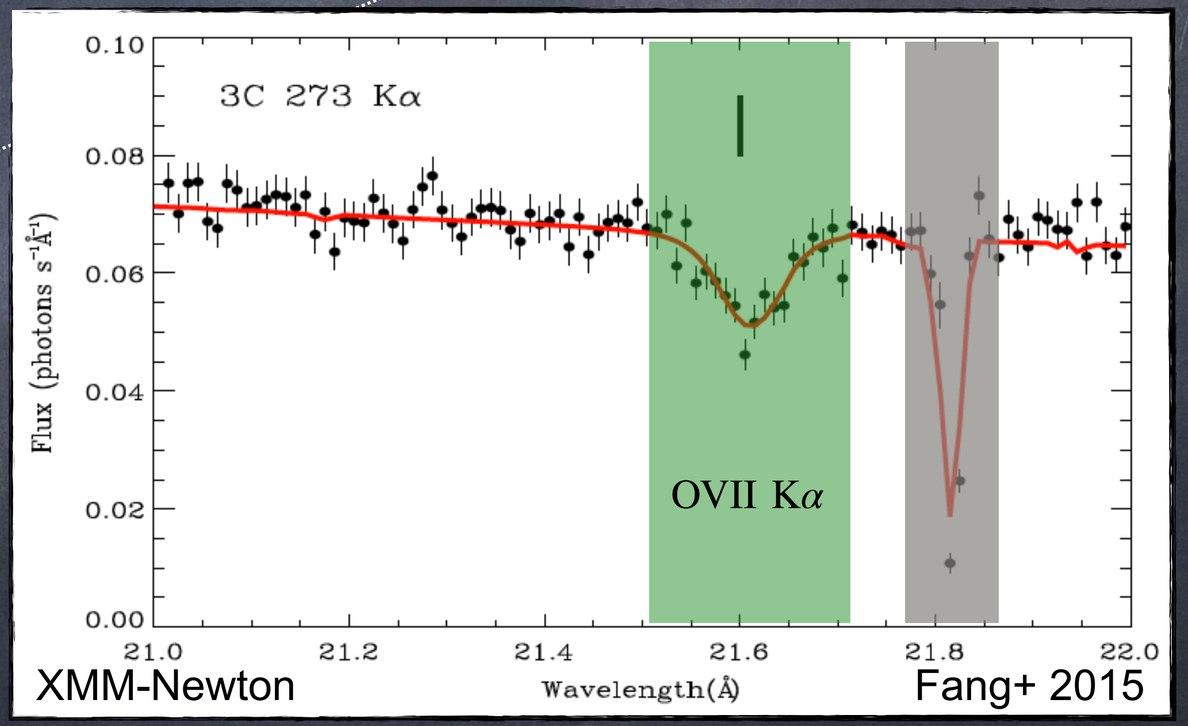


The Classical CGM

- Motivated by structure formation theory, extended structure
- Accretion shock forms hot gas, cold gas is short lived, fueling SF
  (Maller & Bullock 2004, Dekel & Birnboim 2006)
- Hot phase ($T \sim 10^6$ K) traced by X-ray absorption, observed in the MW
  (Bregman & Lloyd-Davies 2007, Gupta+ 2012, Fang+ 2015)

X-ray is the way to go!

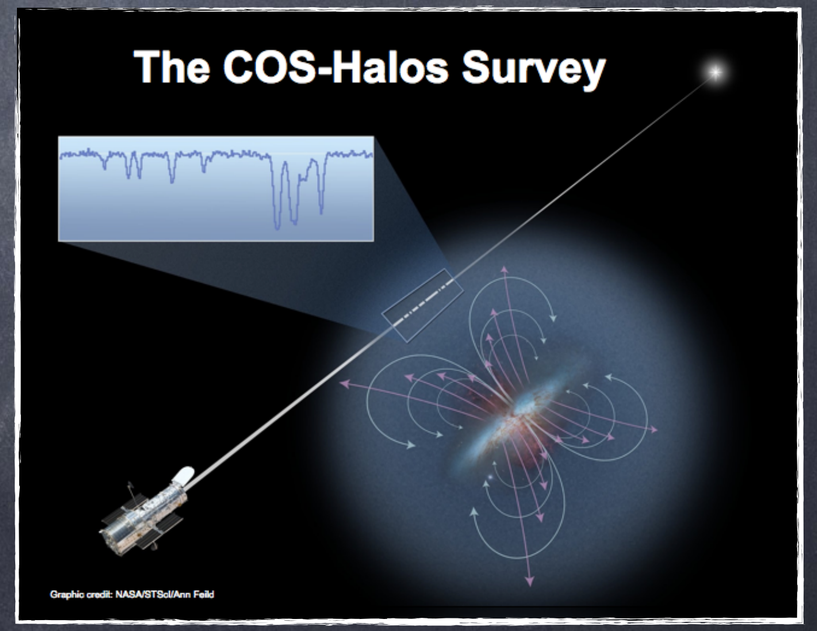
(Wait…)



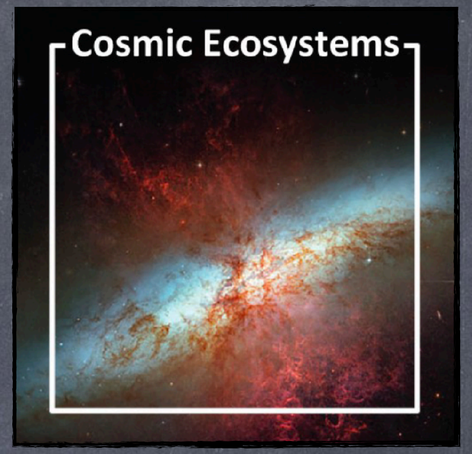
Today - the Multiphase CGM

- The Cosmic Origins Spectrograph (COS/HST, ~2010)
  FUV ~ $100 - 200$ nm, NUV ~ $200 - 300$ nm
- 100s CGM lines of sight, metal lines tracing gas across phases, from the cool ($T \sim 10^4$ K) to the warm/hot ($\sim 10^5 - 10^6$ K)
- Cool gas is abundant in the CGM of both SF and Q galaxies
- CGM surveys at low redshifts ($z \lesssim 1$)
  - **COS-Halos** - L* galaxies (Tumlinson+ 2011, Werk+ 2012)
  - **COS-Dwarfs** - low mass galaxies (Bordoloi+ 2014)
  - **COS-GASS** - CGM-ISM connection (Borthakur+ 2015)
  - **COS-burst** - starburst galaxies (Heckman+ 2017)
  - **CUBS** - QSO-selected sample (Hsiao-Wen+ 2020)
  - **CIViL** - CIV in L* galaxies (Berg+ 2022, in progress)
  - and more! (mostly absorption studies)

UV is crucial to observing and characterizing the CGM



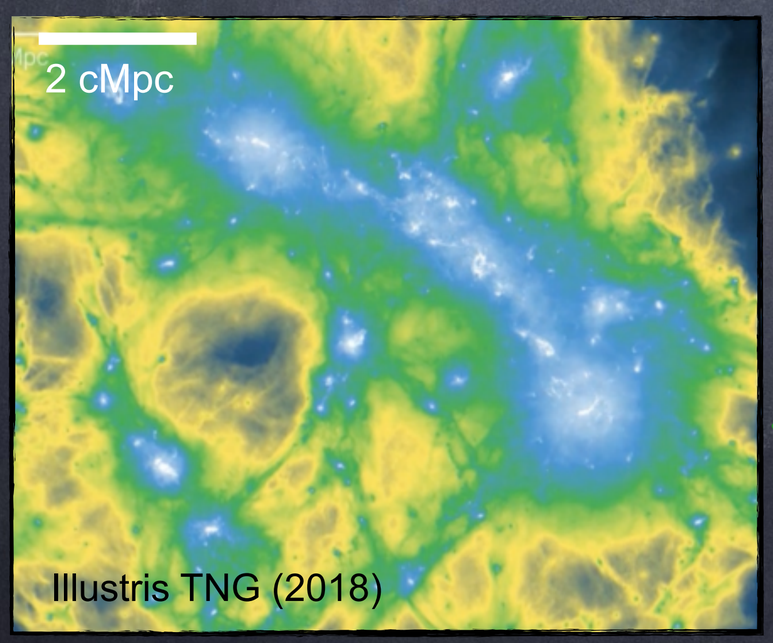
Studying the CGM - why and how?



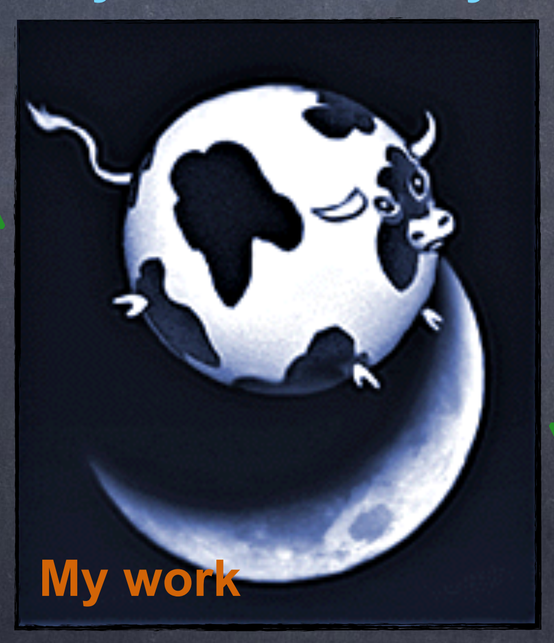
Many open questions

- Gas properties - morphology, mass, metallicity
- Baryon cycle - cosmological accretion, AGN and SNe feedback, galaxy mergers
- Small scale physics - mixing, turbulence, magnetic fields, cosmic rays, etc.

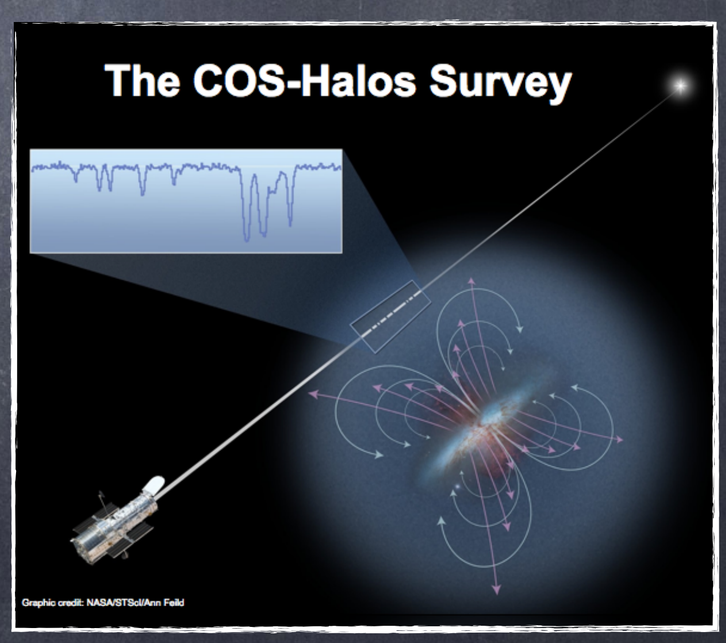
Simulations (cosmological / idealized)



Modeling (analytic / semi-analytic)

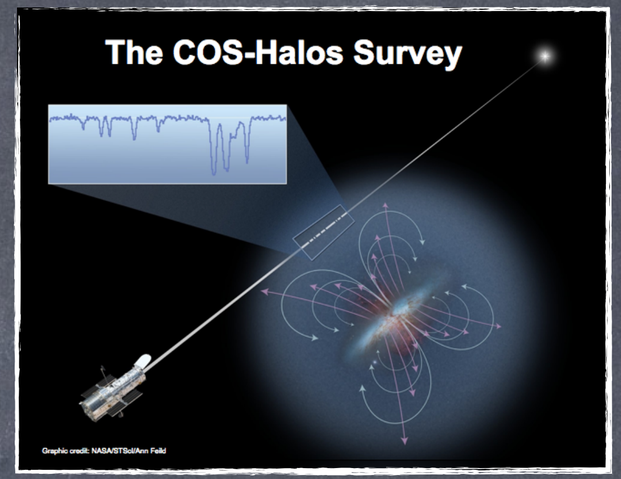


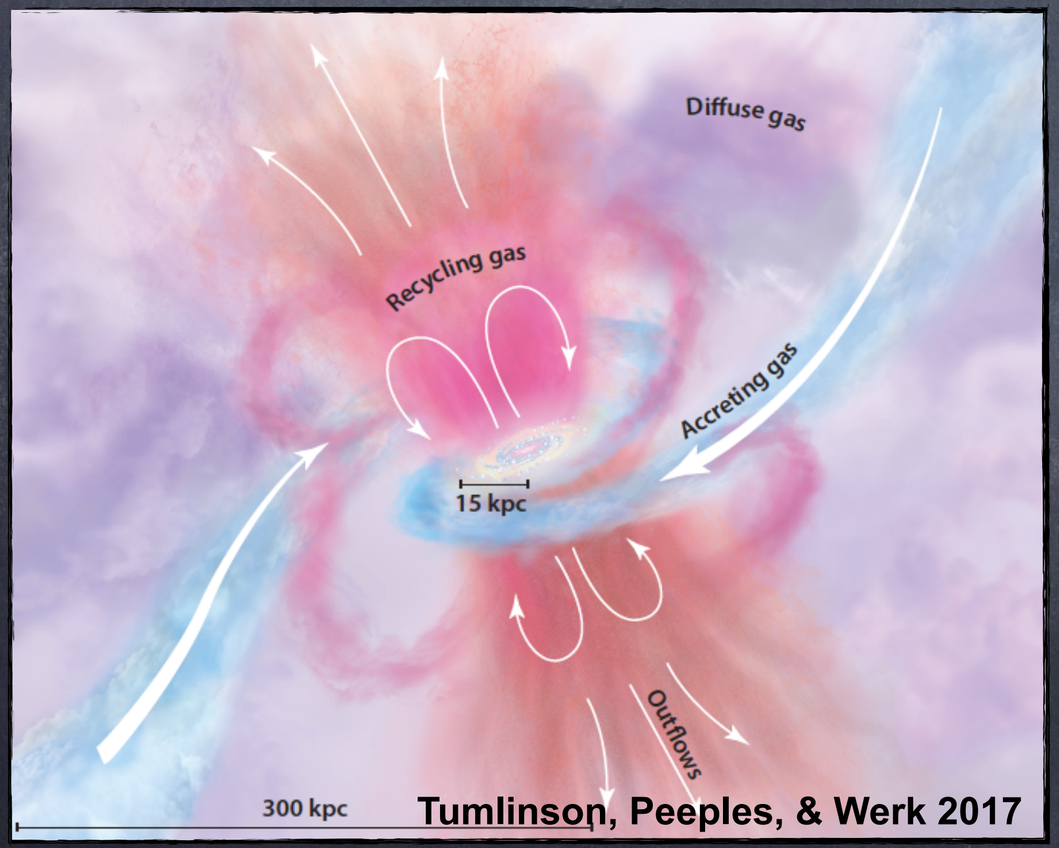
Observations and instrumentation



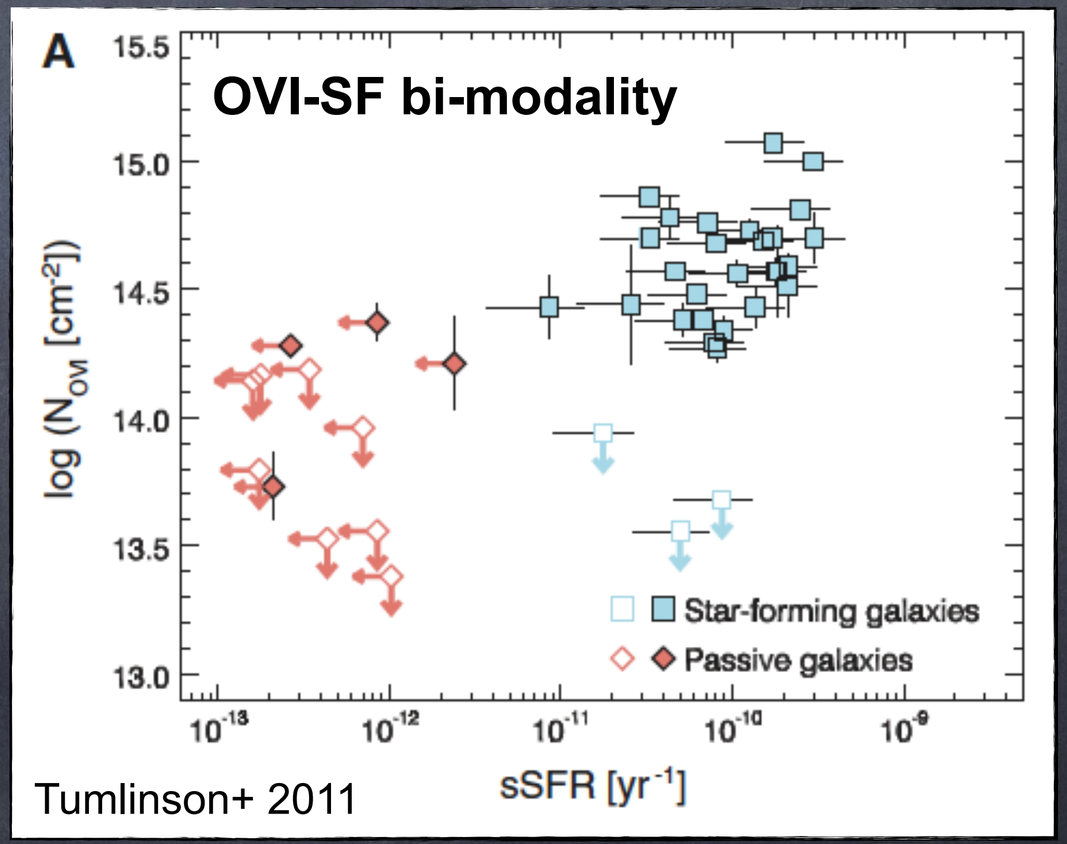
Example - OVI in the CGM

- OVI - $1032/1038$ Å doublet, tracing warm ($T \approx 10^5$ K) or (very) diffuse gas
- High column densities - suggesting high oxygen and gas masses
- Abundant around SF galaxies - virial temperature or stellar feedback?
- Uncertainty in gas distribution, thermal and ionization properties





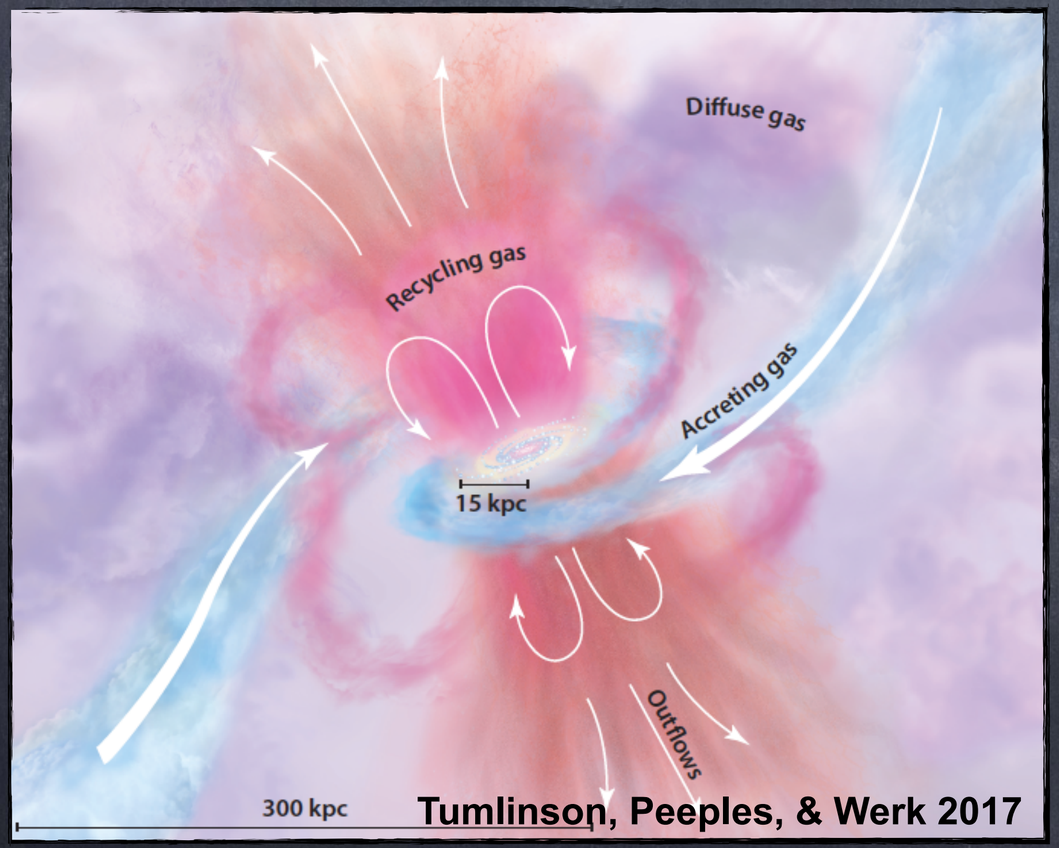
Tumlinson, Peeples, & Werk 2017



Tumlinson+ 2011

Models for OVI in the CGM

- Photoionized (low pressure) gas at halo outskirts (Stern+ 2018) } no SFR connection
- Precipitation-limited CGM with large density fluctuations (Voit+ 2019) } low CGM mass
- Ambient CGM with non-thermal pressure (YF, Sternberg, McKee 2020) } high CGM mass
- Mixing interfaces of cool clouds or streams (Strawn+ 2021) } ‘clumpy’ morphology



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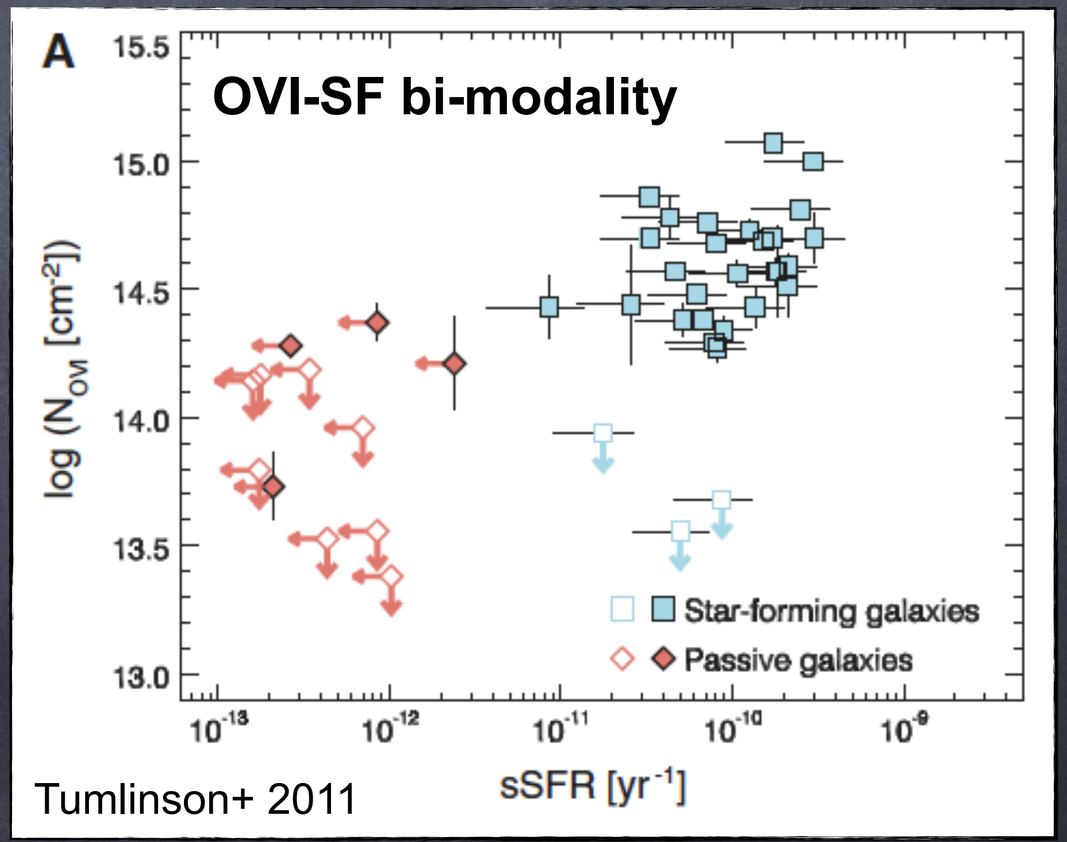
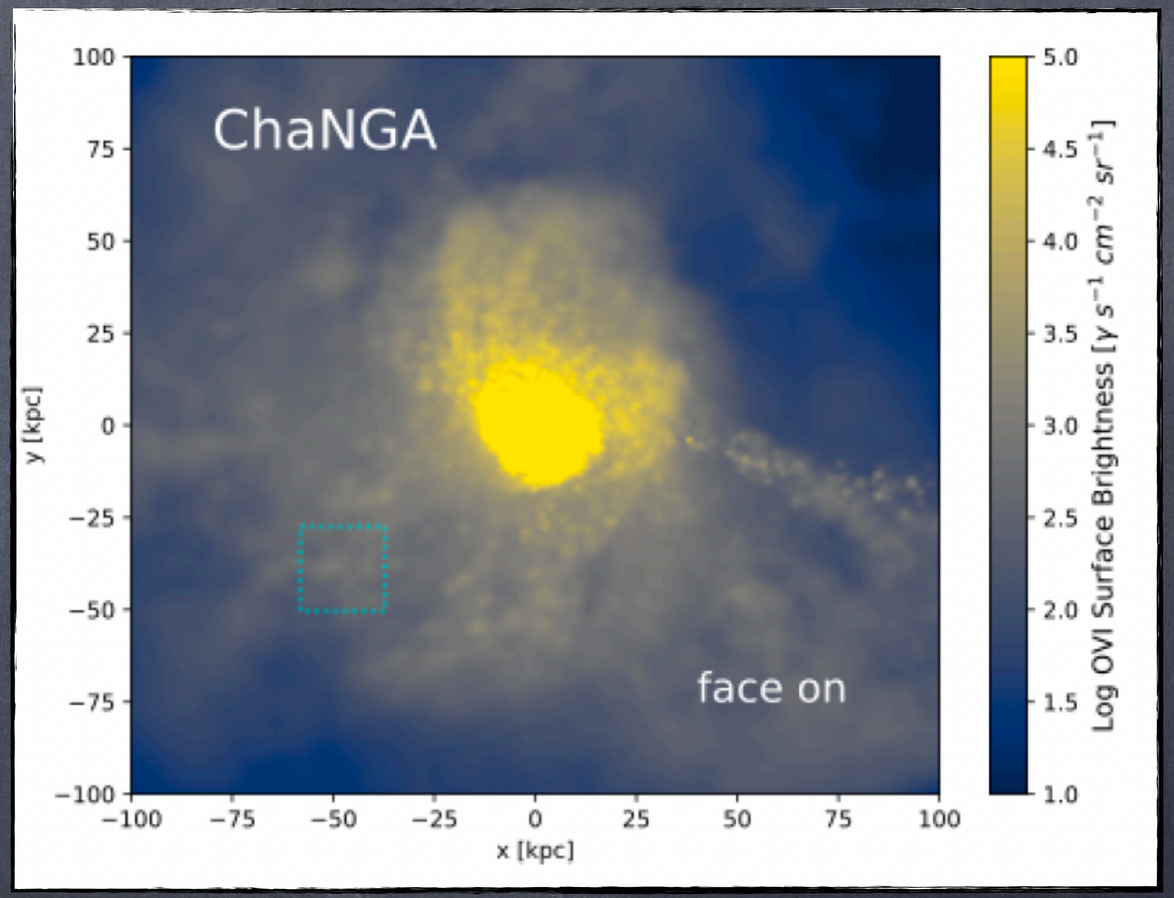


Tumlinson+ 2011

Testing the models with more UV

- **OVI in emission** - Aspera! Maratus!
  (Piacitelli+ 2022 - absorption-based emission predictions)
- **Absorption** - additional metal ions
  - CIV (1548/1550 Å)
    (CIViL - PI: Trystin Berg, with Sam Garza, Jess Werk+)
  - NeVIII (770/780 Å), MgX (610/625 Å)
    (Meiring+ 2013, Qu & Bregman 2016, Burchett+ 2019)

OVI emission in simulations



Tuttle+ (Maratus), see also Corlies+ 2020, Chung+ 2021

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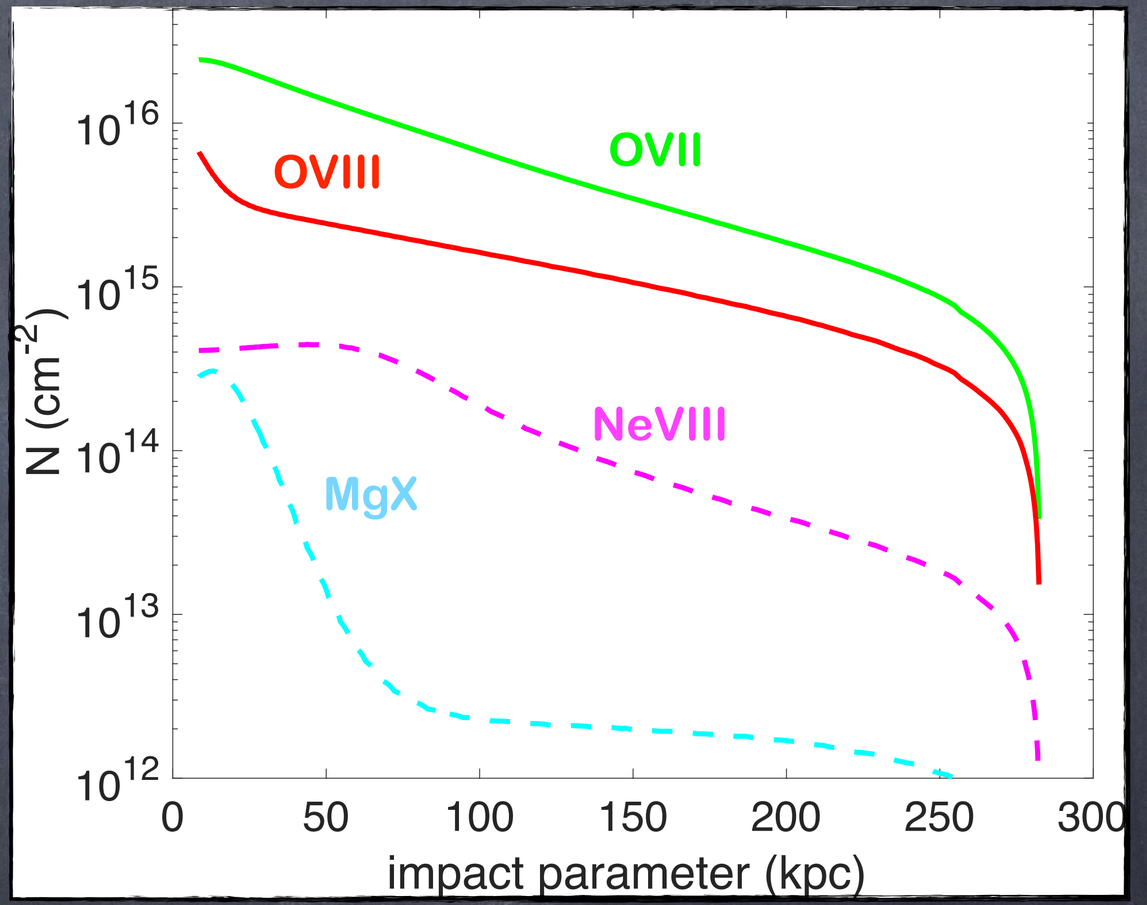
Columns for an external observer



YF, Sternberg & McKee, 2020

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What else do we need?

- Sensitivity (more LoS overall and per galaxy)
- Spectral resolution (non-thermal physics)
- Spatially resolved imaging (gas morphology)

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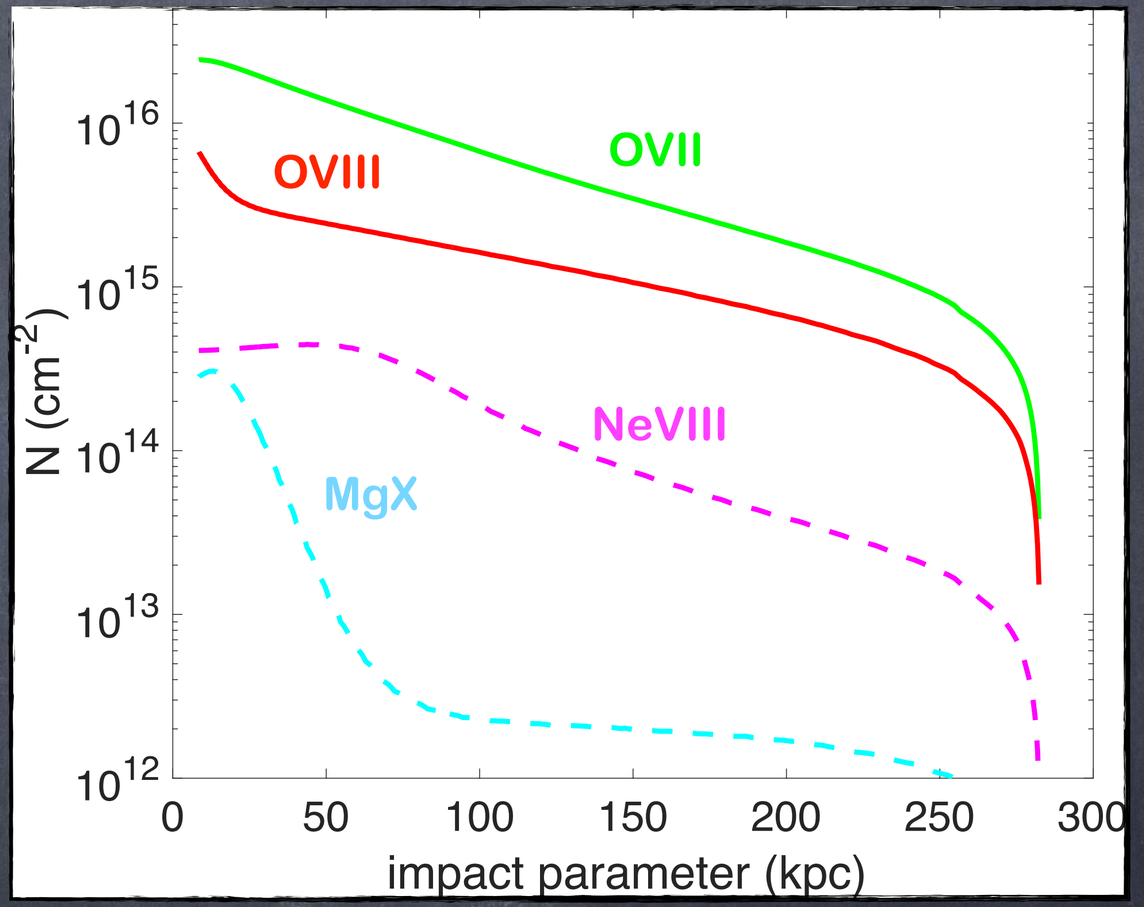
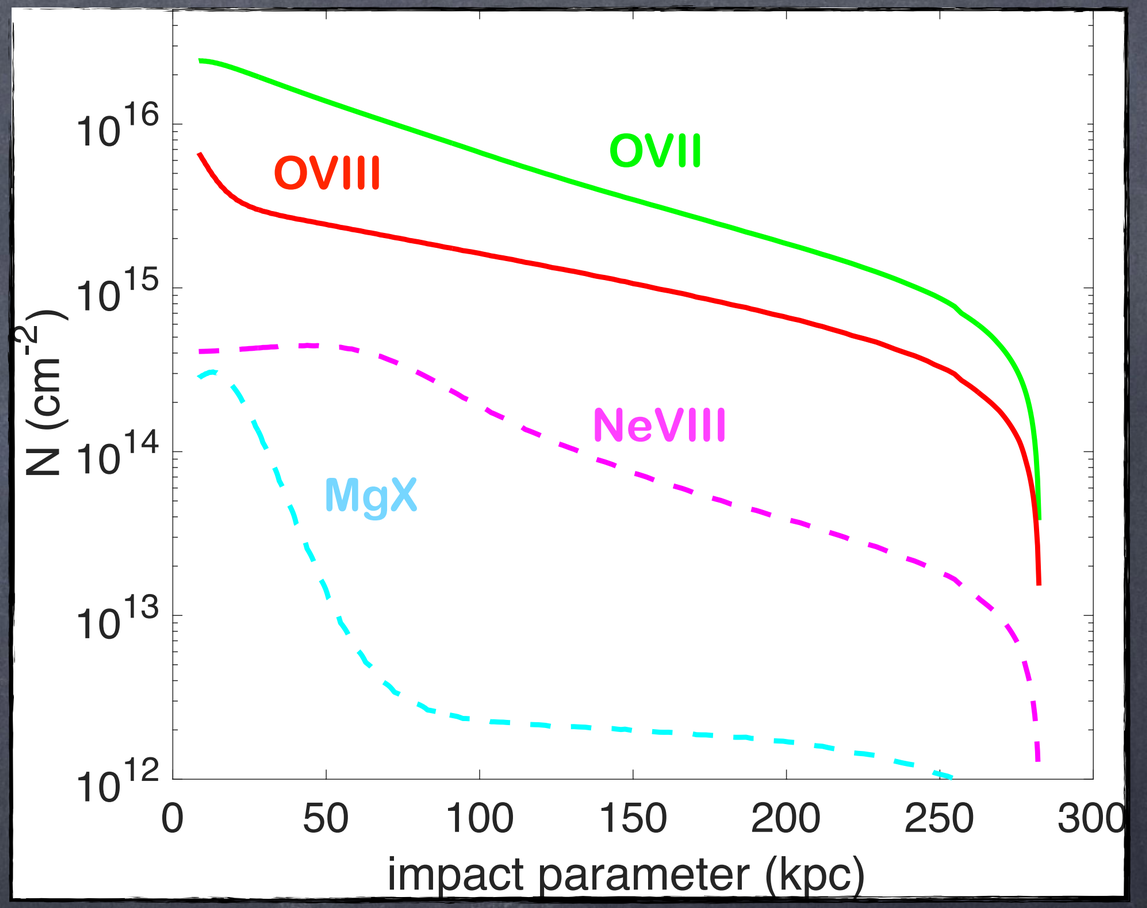


YF, Sternberg & McKee, 2020

But we also need other probes

- **X-ray -** extended OVII/OVIII in <u>other</u> galaxies
  (HUBS, LEM, Arcus, Lynx, Athena)
- **Optical -** OII and NII, tracing $T \approx 10^4$ K gas
  (Johnson+2022, Nielsen+ 2023, Reichardt Chu+ 2024)
- **CMB/mm -** Sunyaev-Zeldovich effect
  (Singh+ 2018, Lim+ 2020, Amodeo+ 2021, Bregman+ 2022)
- **Fast Radio Bursts** - dispersion and rotation measure
  (McQuinn 2014, Prochaska & Zheng 2019, Prochaska+ 2019)
- **Resolved galaxy properties -**
  kinematics, morphology, star formation history - connection to the baryon cycle

Columns for an external observer



YF, Sternberg & McKee, 2020

Combinations are only available at low redshifts

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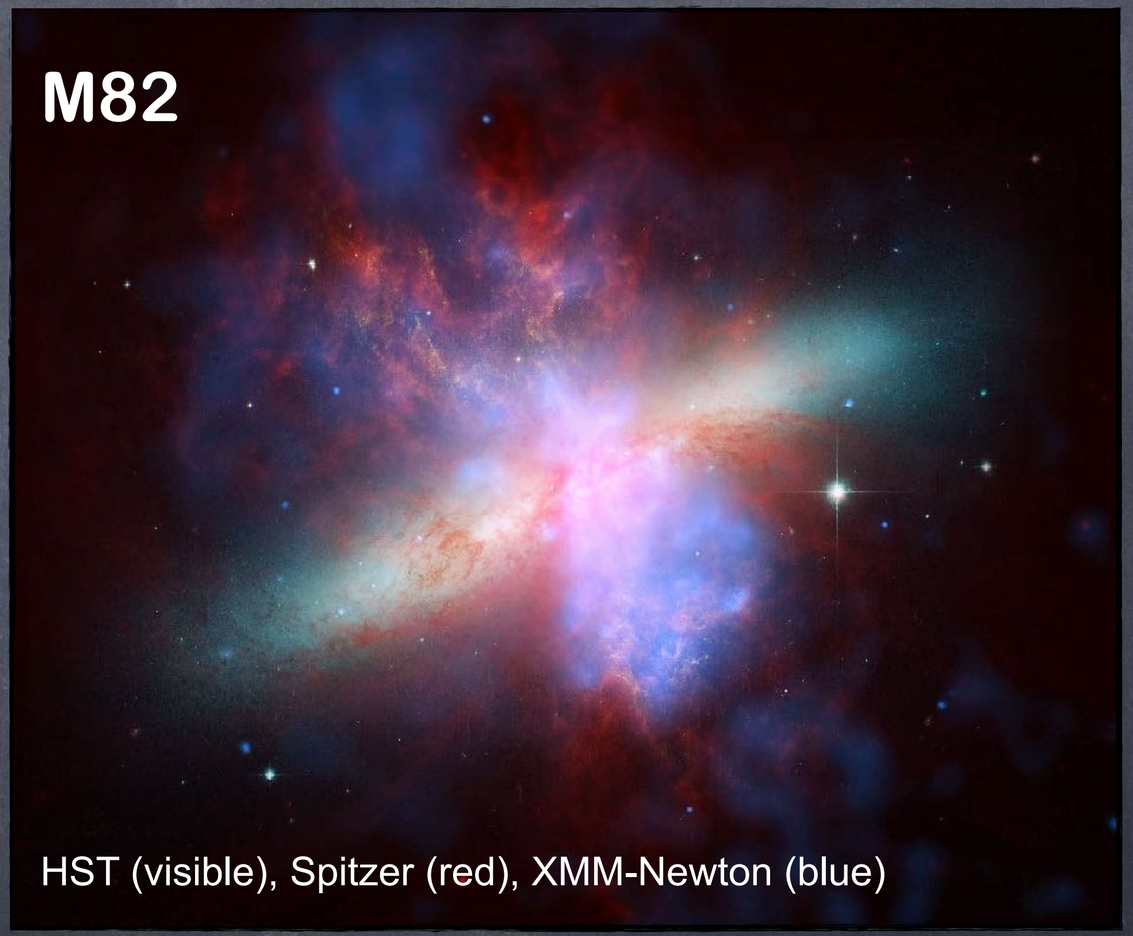
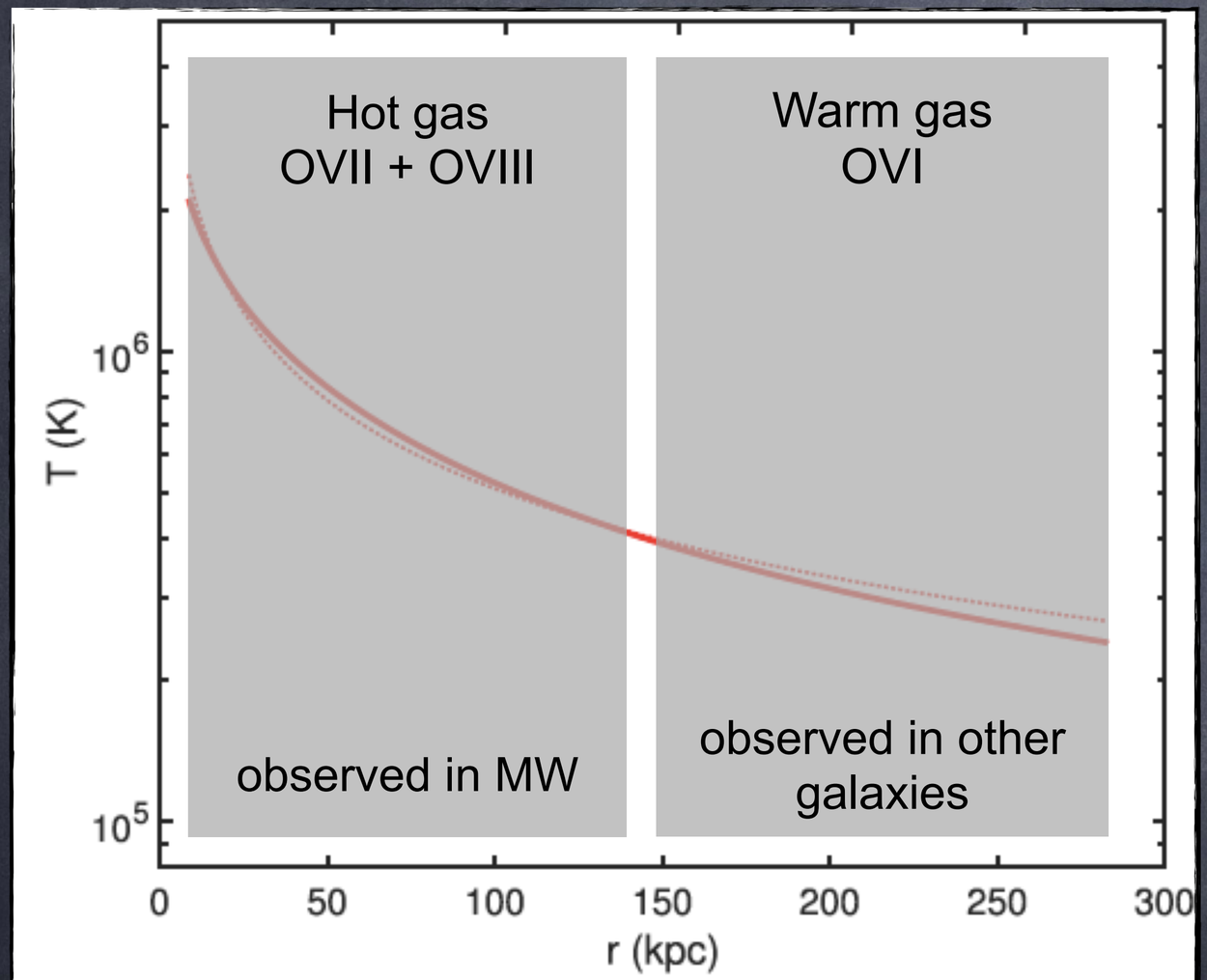


HST (visible), Spitzer (red), XMM-Newton (blue)

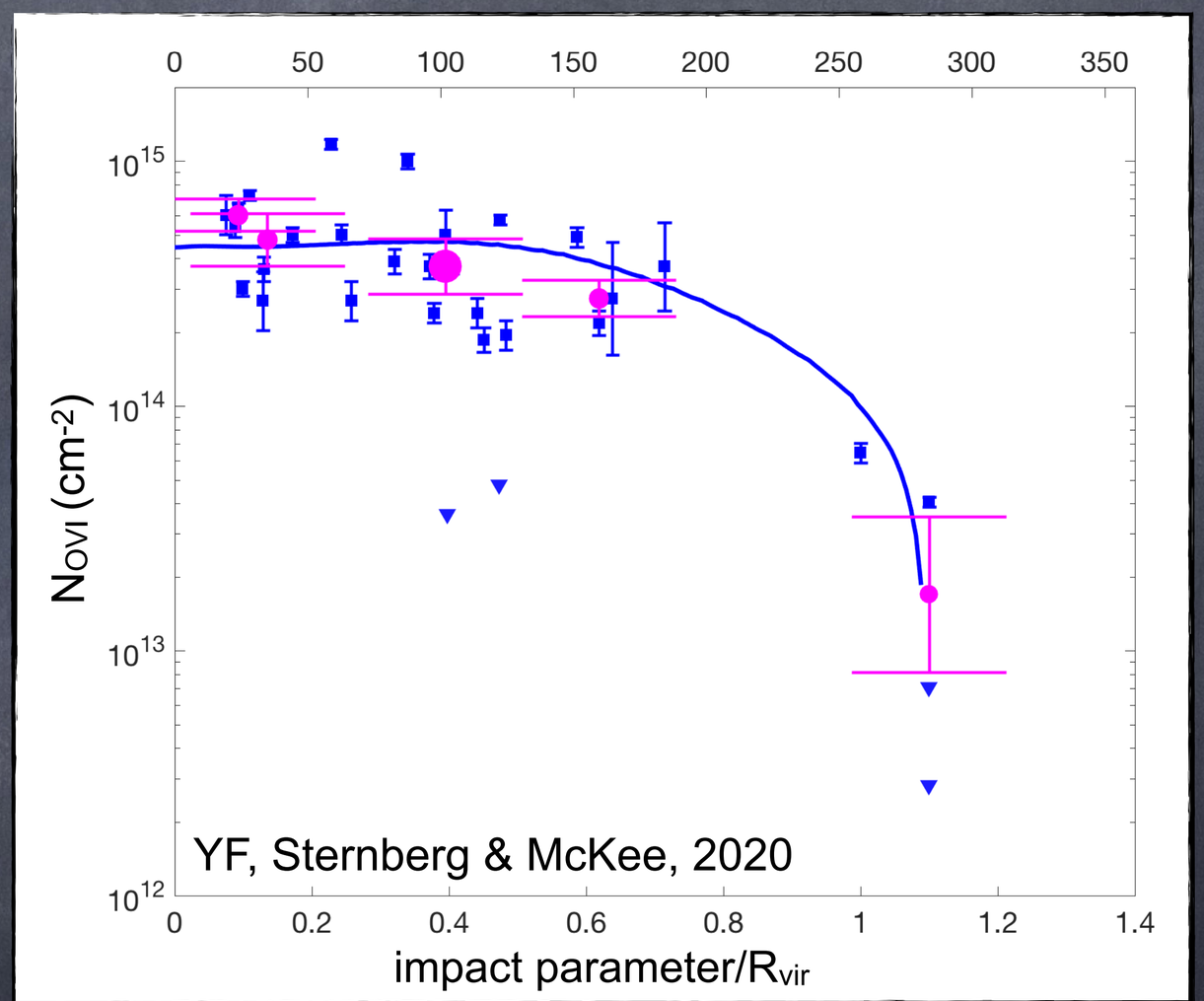
Combinations are only available at low redshifts

Modeling the multiphase CGM

Temperature (isentropic model)



OVI column density



Can we have these for the same galaxies?

Summary

- The CGM is extended, metal-enriched, and multiphase
- Many interesting questions are still open
  galaxy evolution (feedback, SF quenching) and gas physics
- Sensitivity, spectral resolution, and imaging are all important
  for larger samples, constraints on gas morphology and kinematics
- Synergy with other probes will be transformational
  multi-wavelength data (radio to X-ray) challenges and motivates theory

The (F)UV is crucial for understanding
the physics of the CGM and its role in galaxy evolution