Title: Multiphase analytic CGM models

Speakers: Yakov Faerman

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

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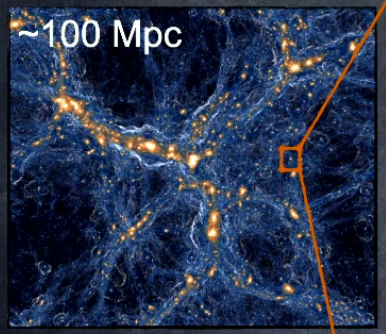
Abstract:

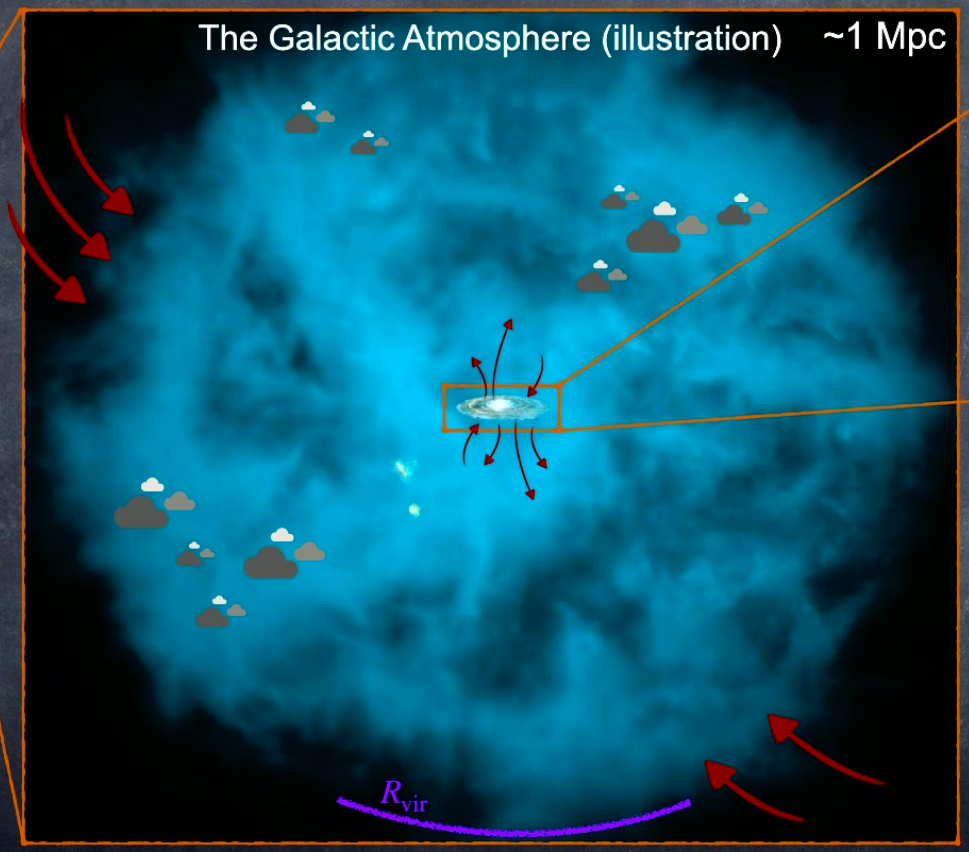
Recent observations of the CGM reveal that it is extended, multiphase, and ubiquitous, detected around star forming and quiescent galaxies. However, many questions remain open - how much gas is out there, what are its thermal properties, spatial distribution, and morphology? These are linked to the properties of gas accretion onto galaxies, star formation, and feedback processes, and are crucial to our holistic understanding of galactic ecosystems. I will present the multiphase CGM modeling framework I developed with collaborators and showcase examples of its application to a wide range of absorption measurements, constraining the CGM mass, thermodynamics, energetics, and cool gas cloud sizes. I will also demonstrate how predictions from these models can be used to test them with upcoming and future multi-wavelength observations.

Multiphase modeling of the Circumgalactic Medium

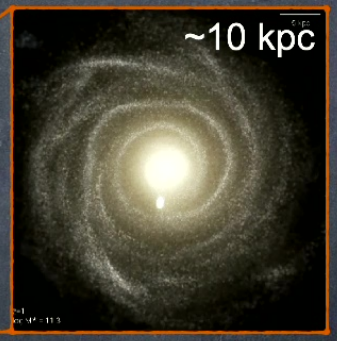
The Cosmic Web



The Galactic Atmosphere (illustration) ~1 Mpc



The Galaxy



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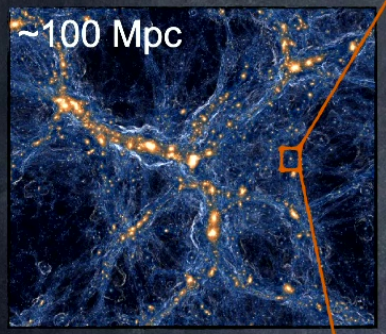

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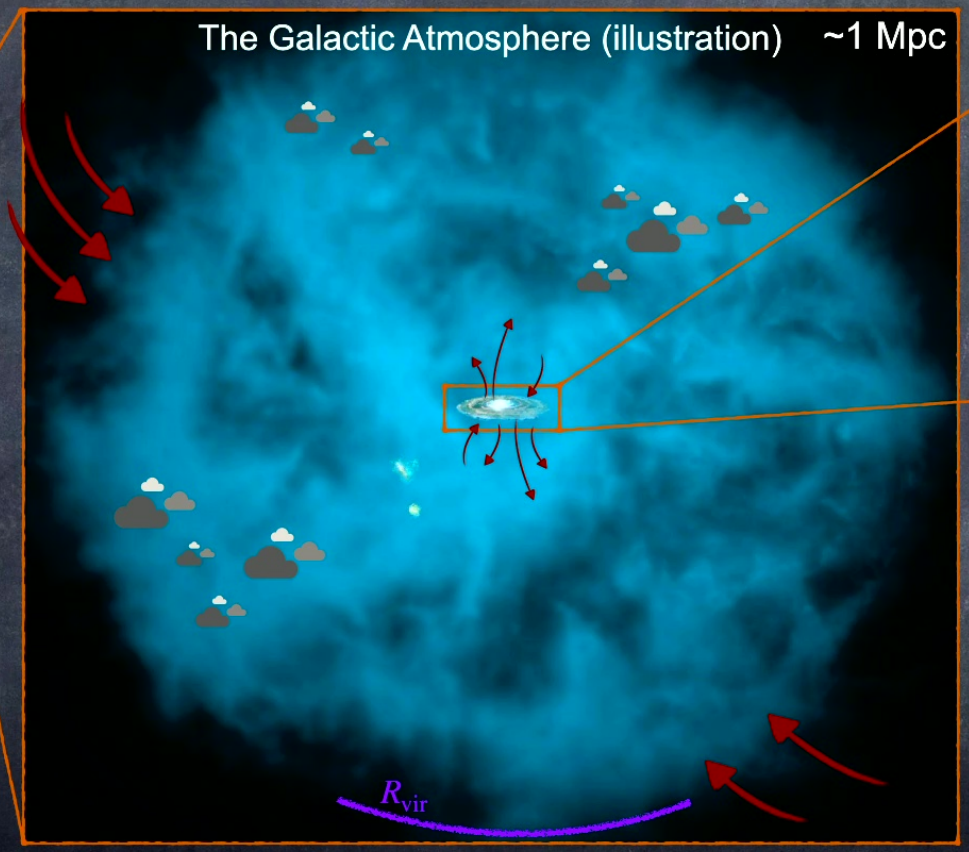

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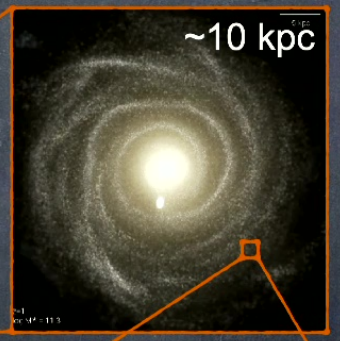

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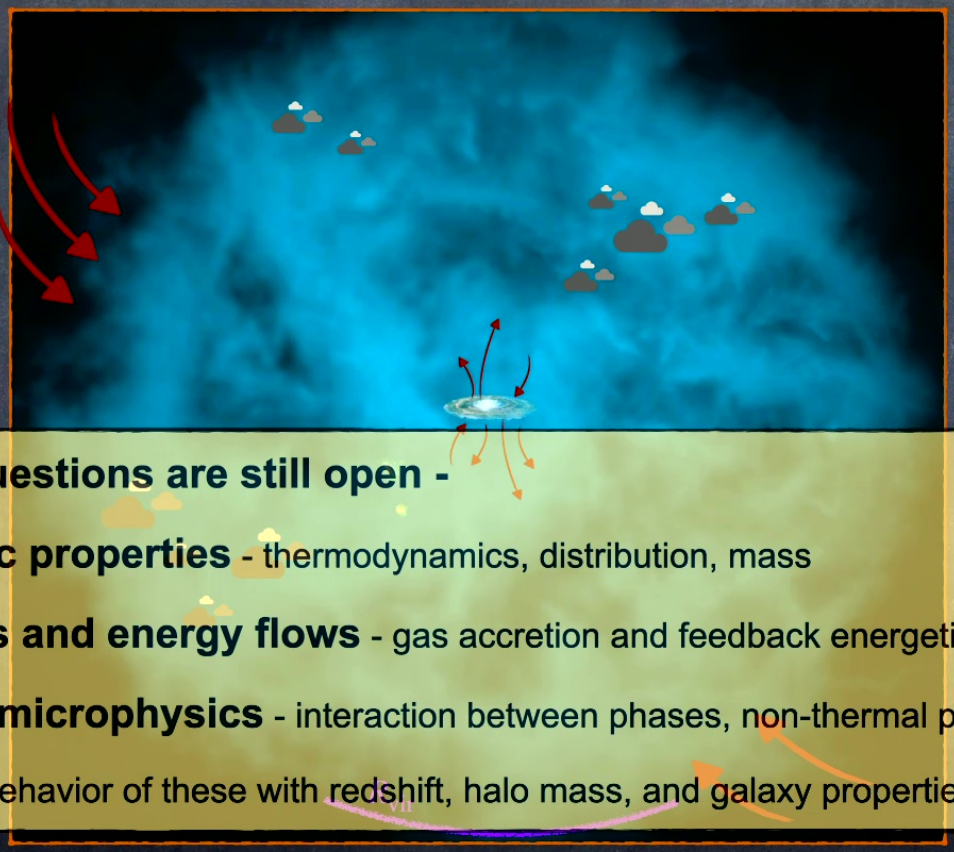
The CGM is hard to observe



Many questions are still open -

- **Basic properties** - thermodynamics, distribution, mass
- **Mass and energy flows** - gas accretion and feedback energetics
- **Gas microphysics** - interaction between phases, non-thermal processes, etc.

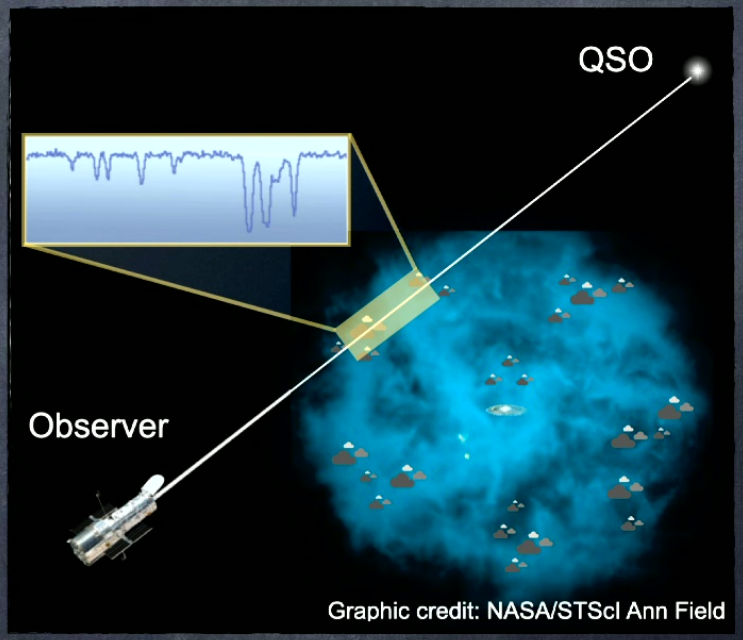
(and the behavior of these with redshift, halo mass, and galaxy properties)

Absorption is a sensitive probe of diffuse gas

X-ray absorption is detected in the Milky Way ~40-50 LoS
O VII and O VIII with Chandra and XMM-Newton
(Bregman & Lloyd Davies 2007, Gupta+ 2012, Fang+ 2015, Das+ 2021)

UV absorption - many CGM surveys at $z \lesssim 1$ ~few 100s LoS
mainly with Cosmic Origins Spectrograph (HST)
tracing cool ($T \approx 10^4$ K) to warm/hot ($T \approx 3 \times 10^5$ K) gas
(Tumlinson+ 2011, Werk+ 2012, Bordoloi+ 2014, Borthakur+ 2015,
Heckman+ 2017, Chen+ 2020, Zahedy+ 2021, Berg+ 2022, Garza+ 2025)

→ **The CGM is extended and multiphase**



Challenges -

- sparse sampling, typically 1 LoS/galaxy (no maps…)
- integrated information along the line of sight

$$N_{X,ion} = \int n_H Z A_X f_{ion} ds$$

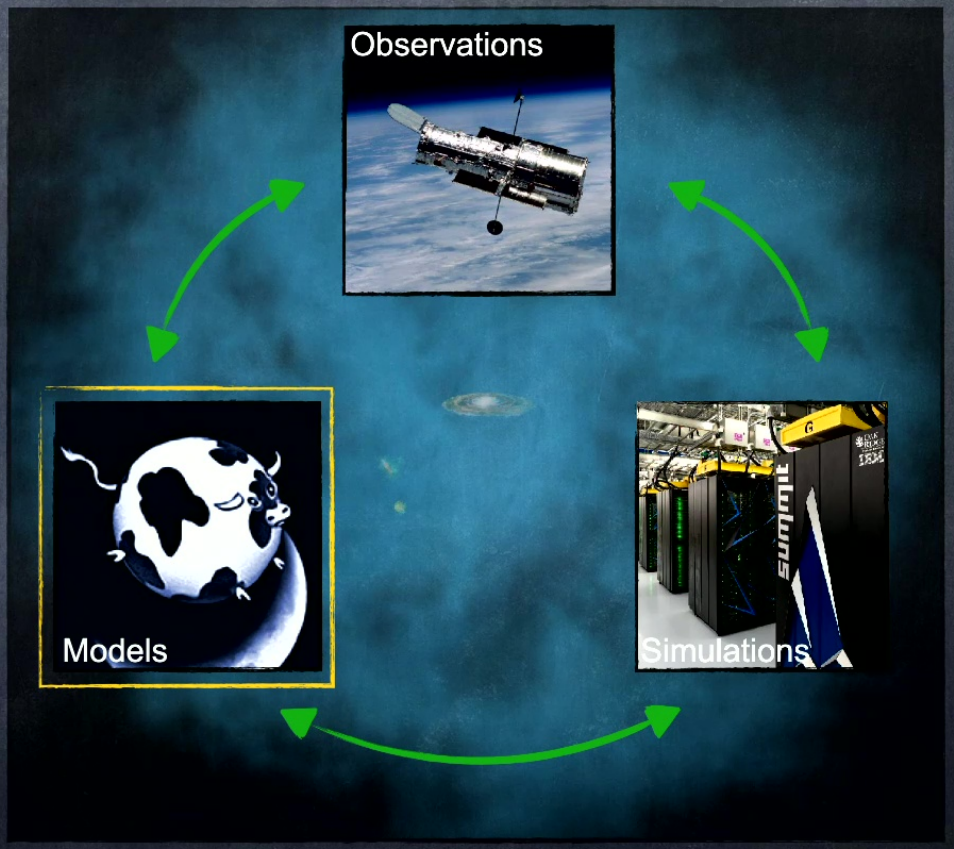
Need models to interpret observations and map to underlying gas properties

This talk - analytic CGM models

- Idealized and simplified
- Provide intuition
- Flexible and modular
- Computationally cheap
- Can be phenomenological or inspired by simulations

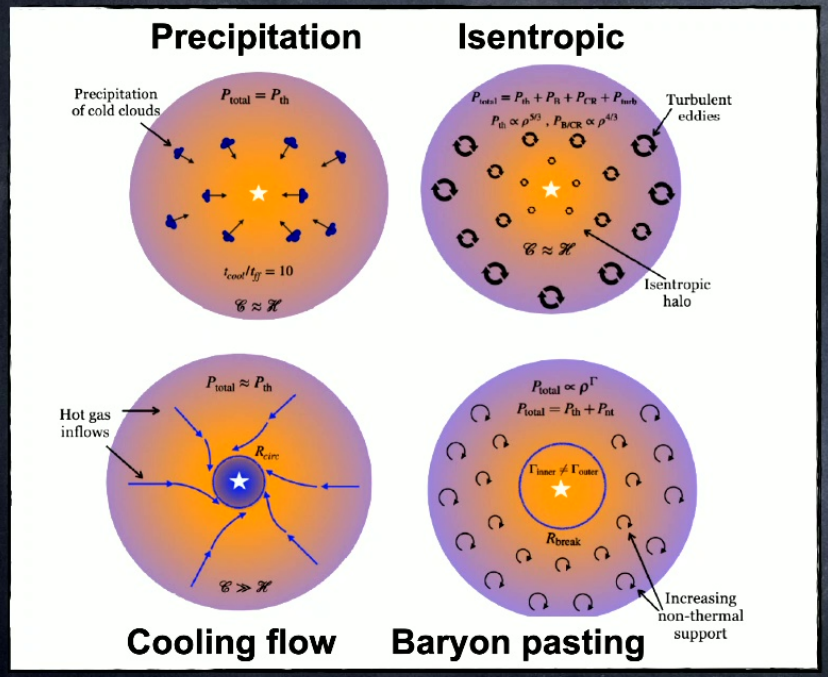
Questions to address

- **Basic CGM properties**
- **Mass and energy flows**
- **Gas microphysics**

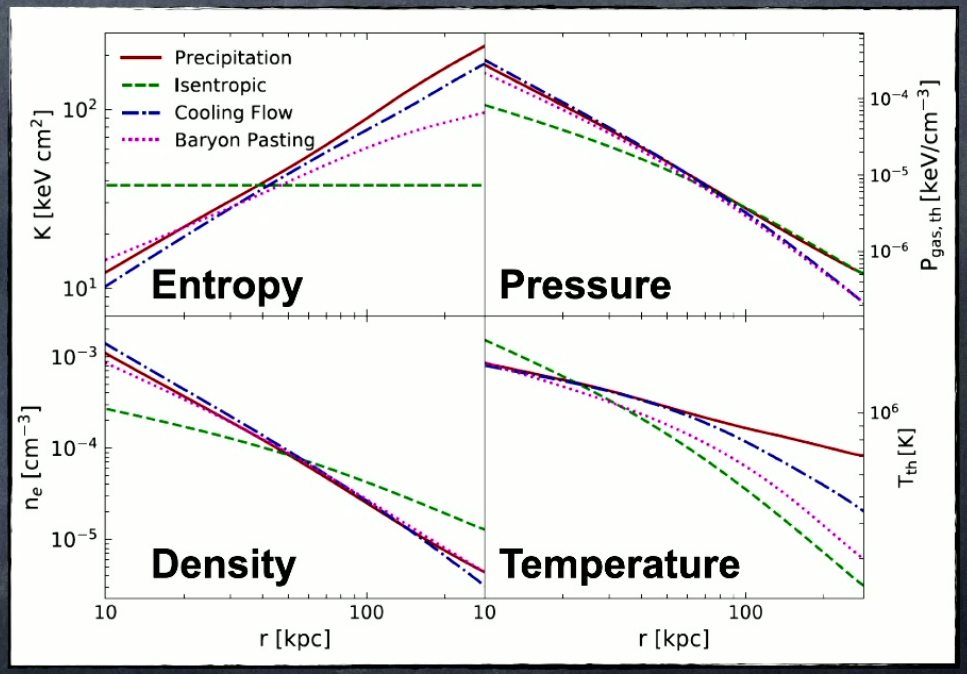


Hot gas - CGM model comparison project

Setup and main assumptions



Gas properties



Singh & Lau, YF, Stern, Nagai 2024

Code publicly available, includes calculation of observables

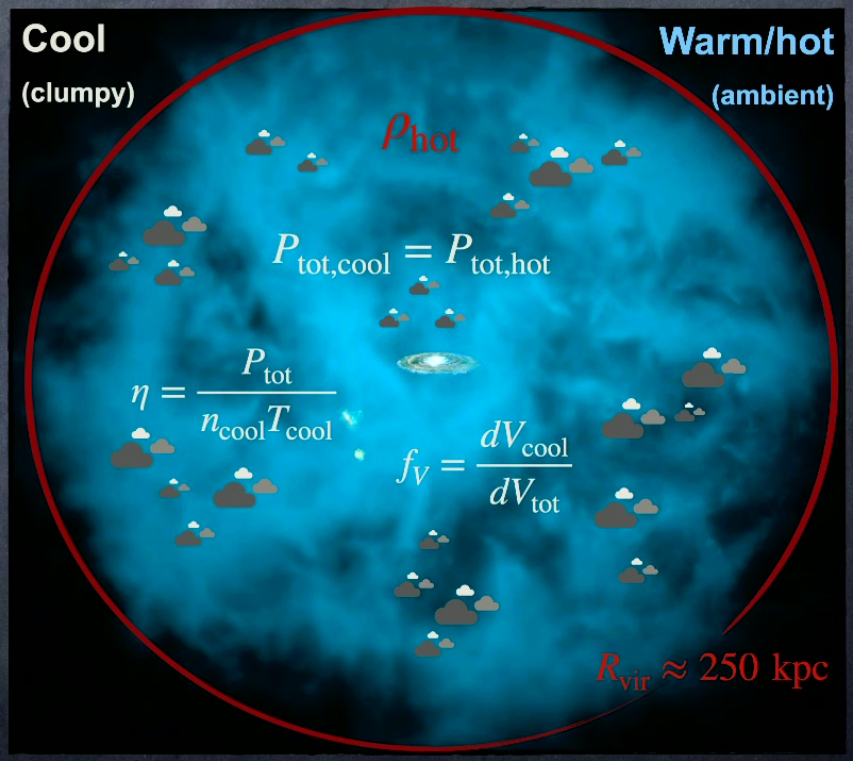
Multiphase CGM model

Part 1 - warm/hot gas (YF, Sternberg, McKee 2020, YF+ 2022)

- Hydrostatic equilibrium + spherical symmetry
  (see Nelson+ 2016, Stern+ 2021, Lochhaas+ 2023)
- Isentropic gas with polytropic EoS
- Non-thermal support allowed -
  from turbulence + B-fields and cosmic rays

Part 2 - cool gas (YF & Werk 2023)

- Total pressure equilibrium with ambient gas
  thermal pressure (density) can vary ($\eta \propto P_{\rm tot}/P_{\rm th}$)
  (contrast with Stern+ 2016)
- Heating ($T \approx 10^4$ K) and ionization by the MGRF
  (Haardt & Madau 2012, Khaire & Srianand 2019)
- Main model parameters -
  volume filling factor, hot/cool pressure contrast



(edited) Chandra press release (2012)

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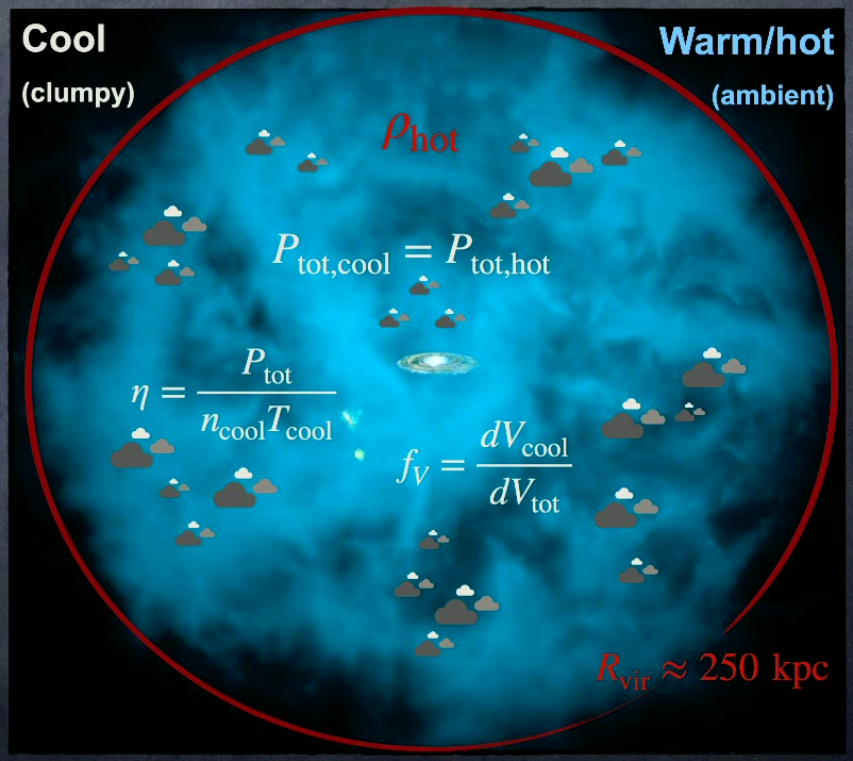
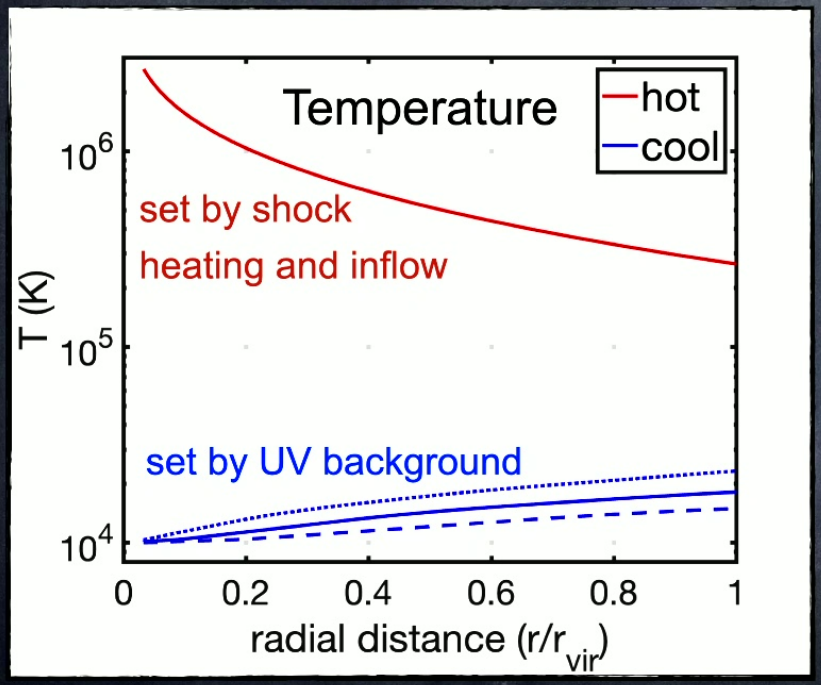
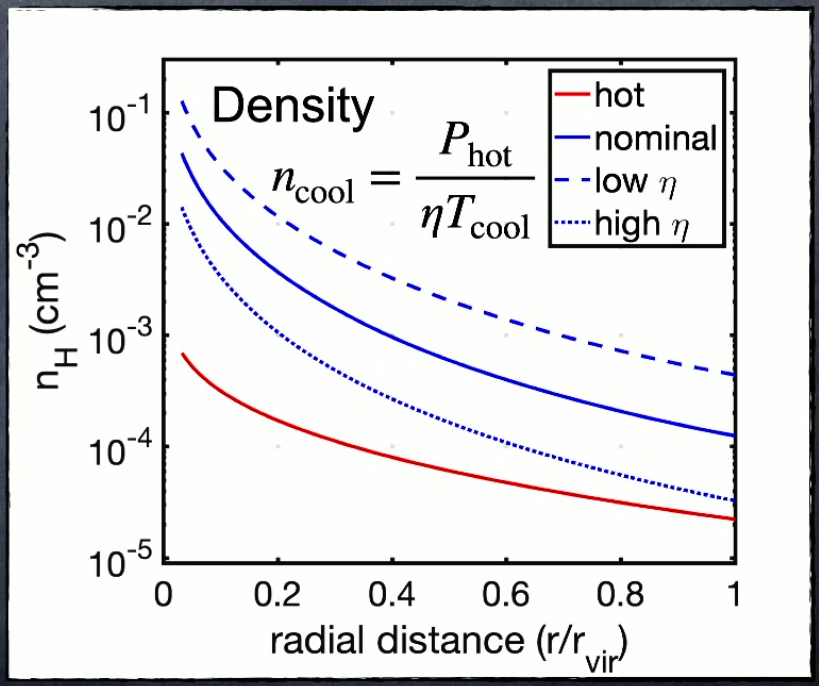


(edited) Chandra press release (2012)

Now in a single flexible code - easy forward-modeling of observations

Multiphase CGM model - thermal properties





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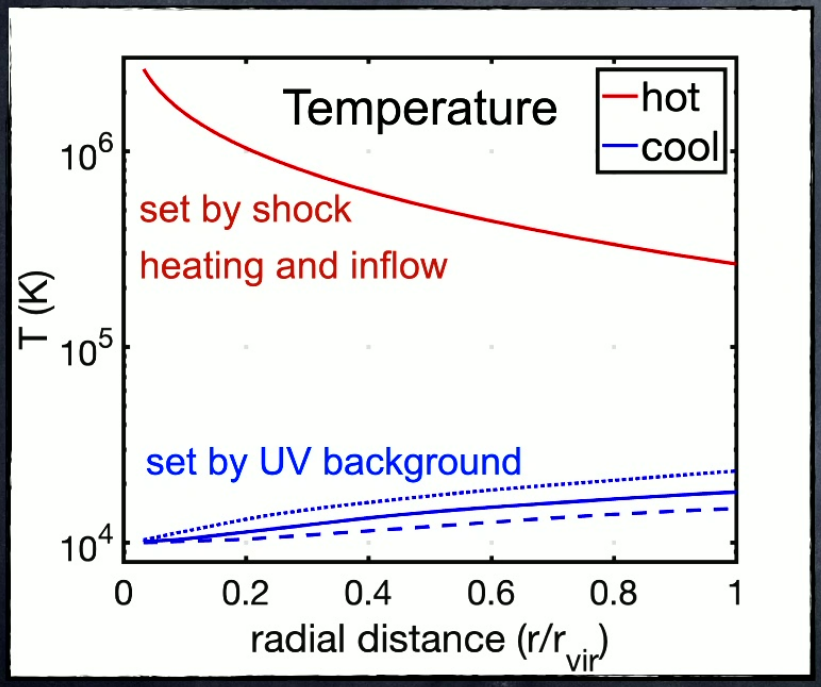
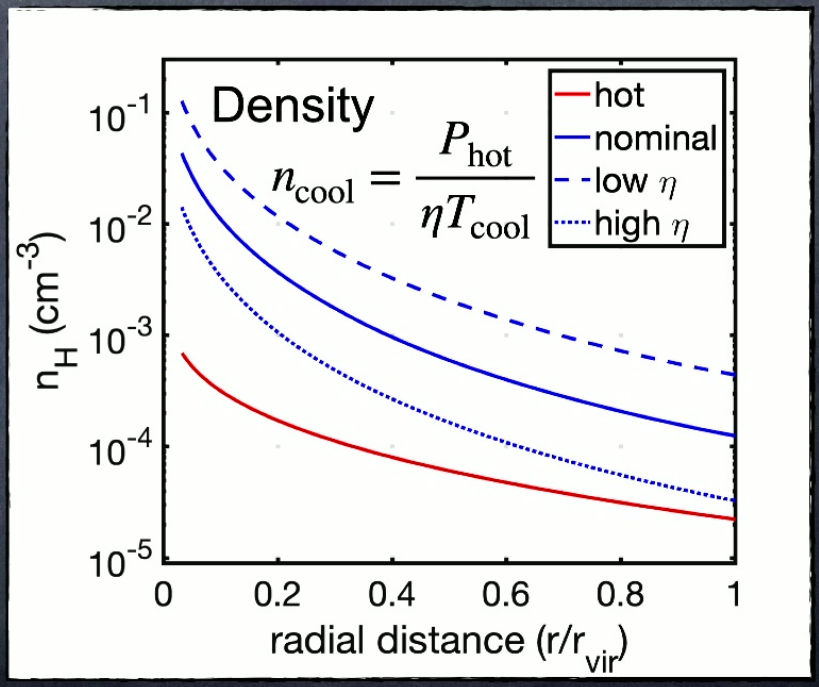
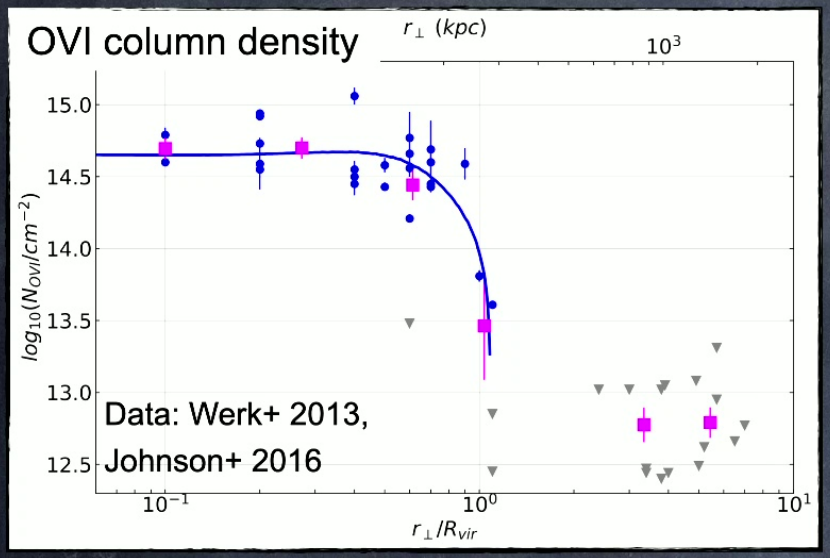




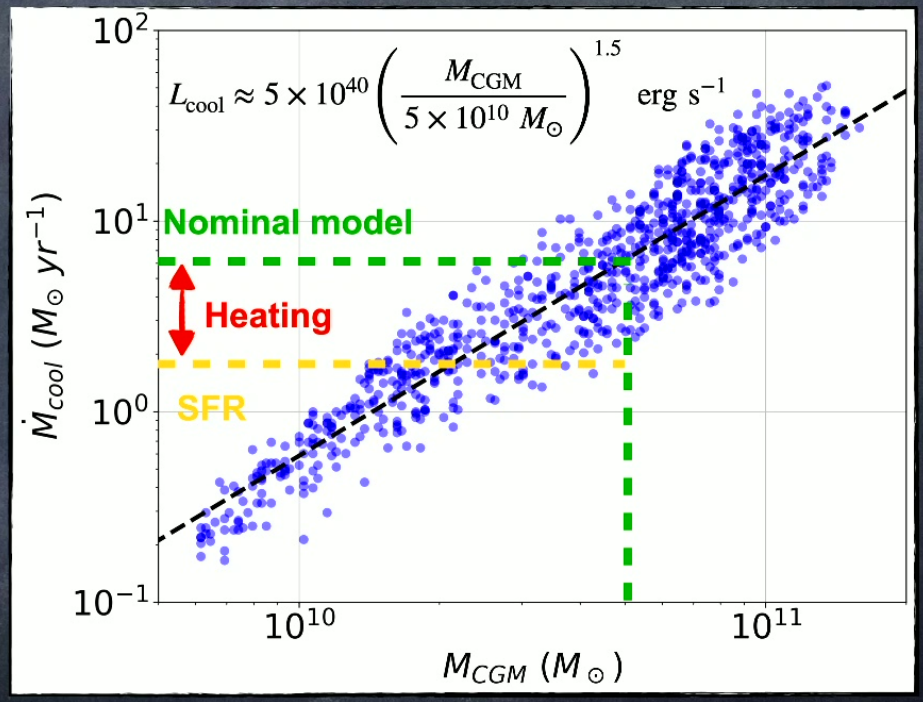
Coupled with Cloudy - detailed ionization and emission properties

Example - warm/hot gas



- Reproduces observed high oxygen columns
- Warm/hot CGM CGM - 5×10^{10} $M_\odot$
  (~30% of baryon budget, similar to stellar mass)
- Some non-thermal support needed
  Predicted magnetic field $B = 0.1 - 1\ \mu G$
  (see also Ji+ 2019, Hopkins+ 2020, Lochhaas+ 2021)

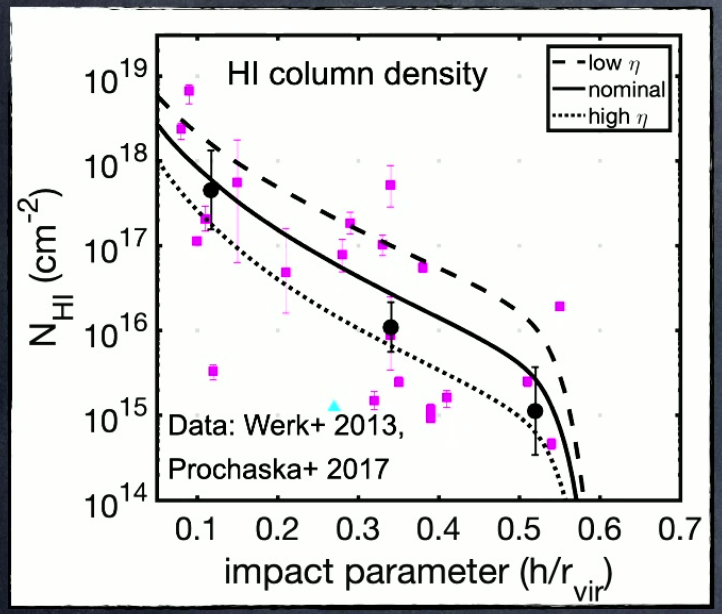
Model cooling rate → heating and feedback coupling



YF, Pandya, Somerville, Sternberg, 2022

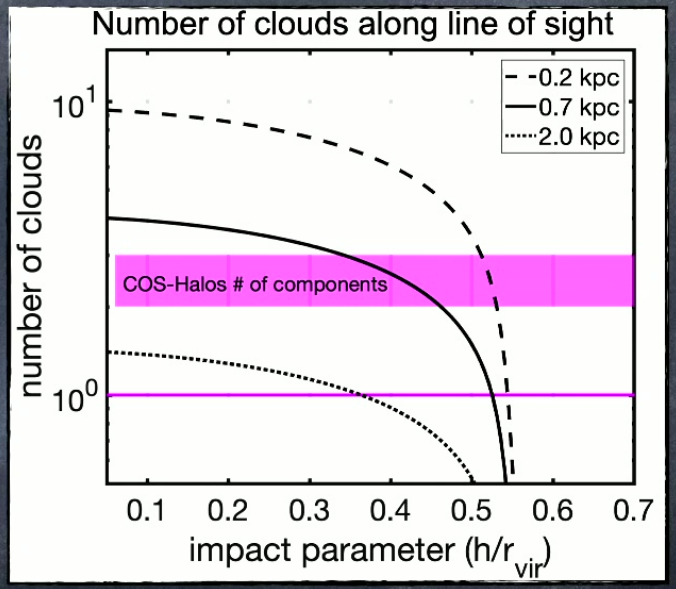
Heating by supernovae can provide enough energy to maintain a massive CGM

Example - cool photoionized gas



- Reproduces HI + metals in low-z SF galaxies
- Cool CGM mass - $10^9 - 10^{10}$ M$_\odot$ with $f_V \sim 1\,\%$
  (compare to Prochaska+ 2017 - $M_{\rm cool} \approx 10^{11}$ M$_\odot$)
- Suggests thermal pressure contrast between hot and cool phases ($\eta \sim P_{\rm tot}/P_{\rm th} \approx 3$)

What about cloud sizes, affecting their evolution?
(see also Maller & Bullock 2004, Joung+ 2012,
McCourt+ 2018, Lan & Mo 2019, Afruni+ 2022, Tan+ 2023)



YF & Werk 2023

$R_{\rm cl} \propto f_{\rm V}/N_{\rm cl}$

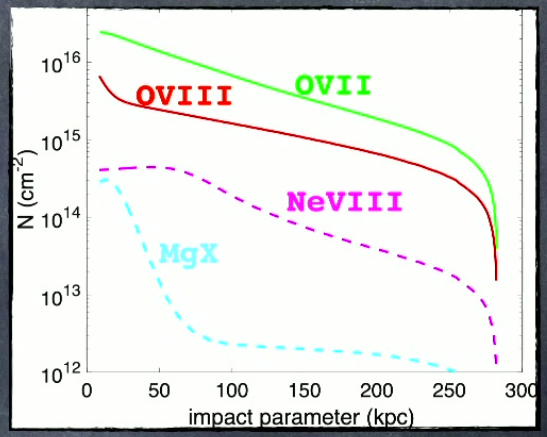
2-3 clouds/LoS
$\rightarrow R_{\rm cl} \lesssim 0.5$ kpc

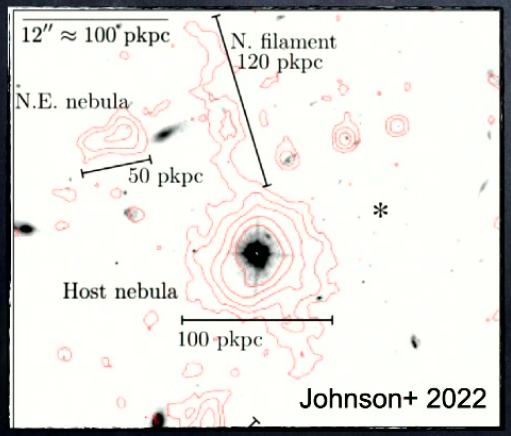
Direct limits:
$R_{\rm cloud} \approx 0.1$ kpc
(Zahedy+ 2021
also Rudie+ 2019,
Rubin+ 2015, 2018,
Augustin+ 2021)

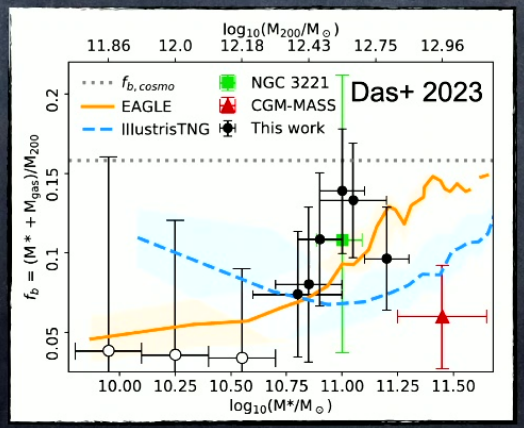
Explore cool gas mass, support, morphology
$\rightarrow$ accretion onto the galaxy and SFR

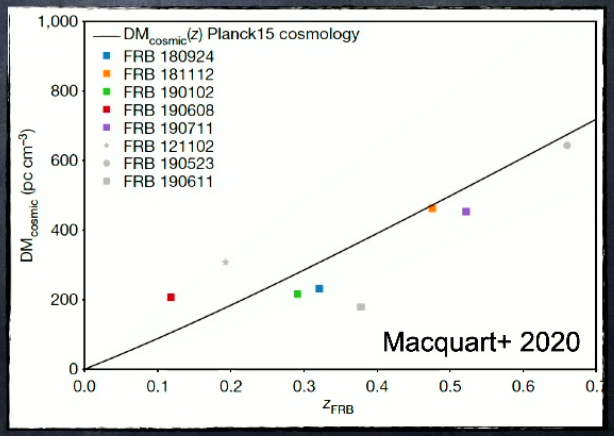
Combinations with other (CGM) probes

- Absorption from hot gas (UV+X-ray) in other galaxies - T profiles
  (Meiring+ 2013, Qu & Bregman+ 2016, Burchett+ 2019, future X-ray - LEM / Athena)
- Resolved emission - gas morphology and mass
  (Johnson+ 2022, Nielsen+ 2023, Reichardt Chu+ 2024, Piacietelli, Solhaug+ 2022)
- Sunyaev-Zeldovich effect - gas thermodynamics
  (Singh+2018, Lim+2020, Amodeo+ 2021, Bregman+ 2022, Oren+2024)
- Fast Radio Bursts - gas extent and mass + magnetic fields
  (McQuinn 2014, Prochaska & Zheng 2019, Prochaska+ 2019, Medlock+ 2024)









Summary and future work

- Analytic CGM models are crucial for understanding Cosmic Ecosystems
  connecting observations to underlying gas properties, small and to large scales
- New flexible framework for forward-modeling multiwavelength observations
  absorption, emission, tSZ, FRBs, etc. and combinations
- Future - exploring galaxy-CGM connection and gas microphysics
  gas flows to/from galaxy, individual objects vs stacks , heating and turbulence, B-fields (strength and orientation), CR (transport scenarios)