Title: Galaxies as Cosmic Ecosystems

Speakers: Mark Voit

Collection/Series: Cosmic Ecosystems

Subject: Cosmology

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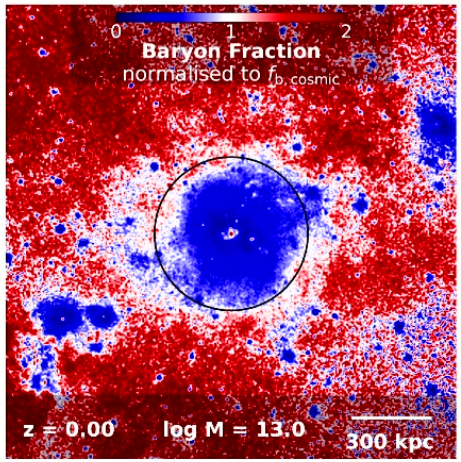
Abstract:

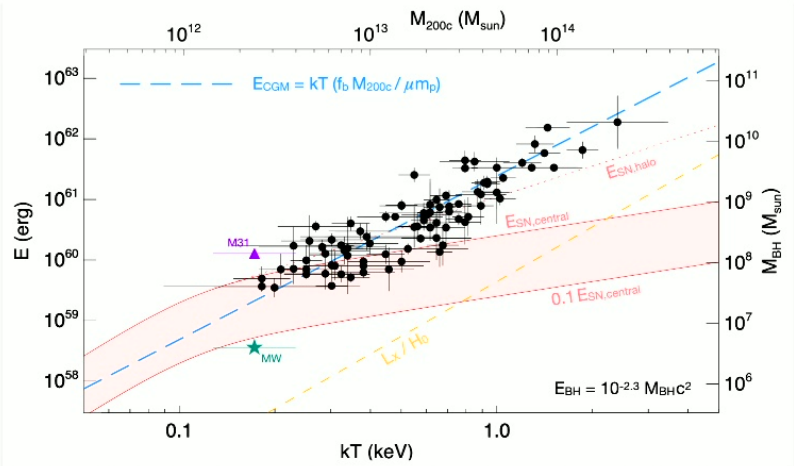
Terrestrial ecosystems exhibit ecological stability: If an ecosystem is perturbed, biological feedback drives it back toward an equilibrium state, but an ecosystem does not remain stuck in its equilibrium state because it is continually perturbed. Are galaxies really similar to biological ecosystems in that regard? My talk will consider whether the atmospheres of galaxies have feedback-regulated equilibrium states and what the observational consequences of those states might be. While considering those questions I will lay out a framework for classifying how halo-scale feedback loops operate.

Galaxies as Cosmic Ecosystems

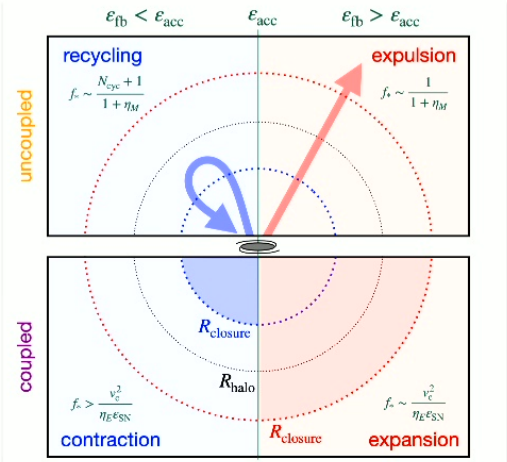
G M Voit (Michigan State U)



Baryon Lifting



Energy Requirements



Expandable CGM

Conference Themes

- Small to large scales
- Hot gas to cold gas
- Galactic to intergalactic scales
- Diffuse to dense structures
- Past feedback processes to present-day observations

Conference Metaphor

Ecosystem

113 languages

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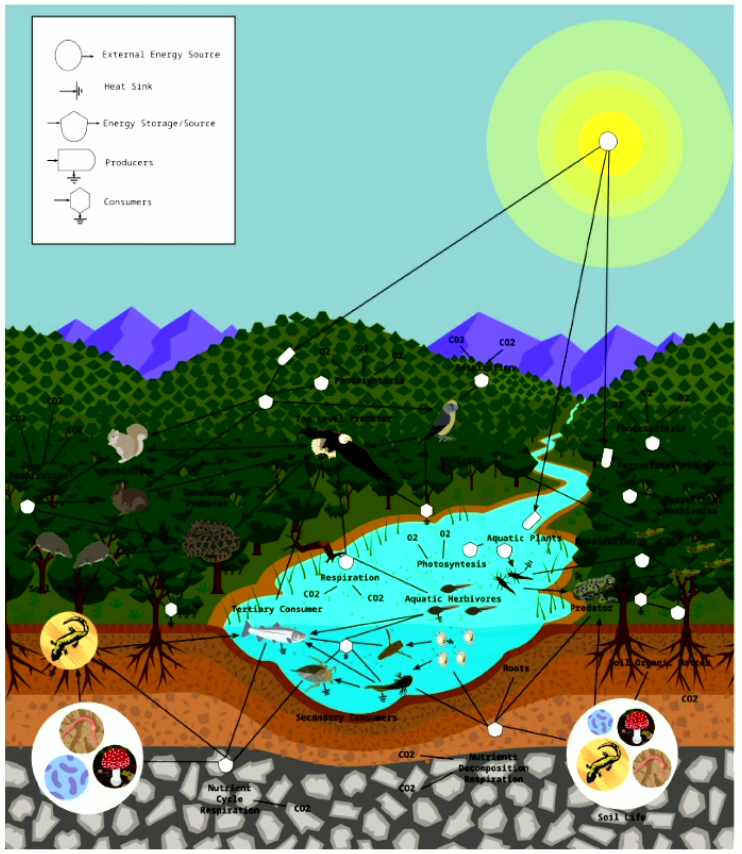
In ecology, an ecosystem is said to possess **ecological stability** (or **equilibrium**) if it is capable of returning to its equilibrium state after a perturbation (a capacity known as resilience) or does not experience unexpected large changes in its characteristics across time.[1] Although the terms **community stability** and ecological stability are sometimes used interchangeably,[2] community stability refers only to the characteristics of communities. It is possible for an ecosystem or a community to be stable in some of their properties and unstable in others. For example, a vegetation community in response to a drought might conserve biomass but lose biodiversity.[3]

An example of ecological stabilit

Stable ecological systems abound in nature, and the scientific literature has documented them to a great extent. Scientific studies mainly describe grassland plant communities and microbial communities.[4] Nevertheless, it is important to mention that not every community or ecosystem in nature is stable (for example, wolves and moose on Isle Royale). Also, noise plays an important role on biological systems and, in some scenarios, fully determine their temporal dynamics.



Conference Metaphor

Do galactic ecosystems have equilibrium states?

Are those states stable?

On what timescale do they stablize?

Ecosystem

113 languages

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Article Talk

Ecological stability

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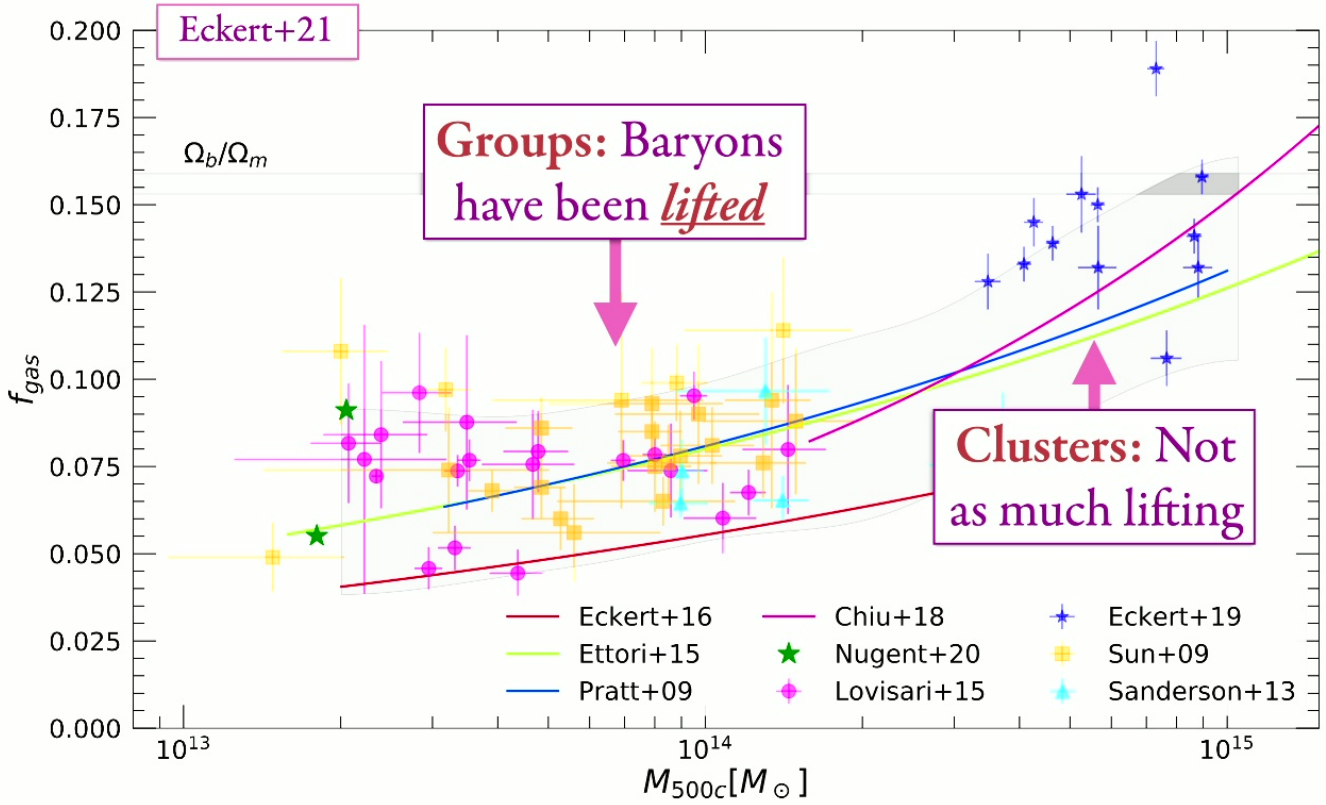
Gravitational Binding Energy

Gravitational Binding Energy



CGM binding energy:

$$E_{\rm CGM} \sim kT\left(f_{\rm b}M_{\rm halo}/\mu m_p\right)$$

For groups:

$$E_{\rm CGM} \sim 10^{60-61}\,{\rm erg}$$

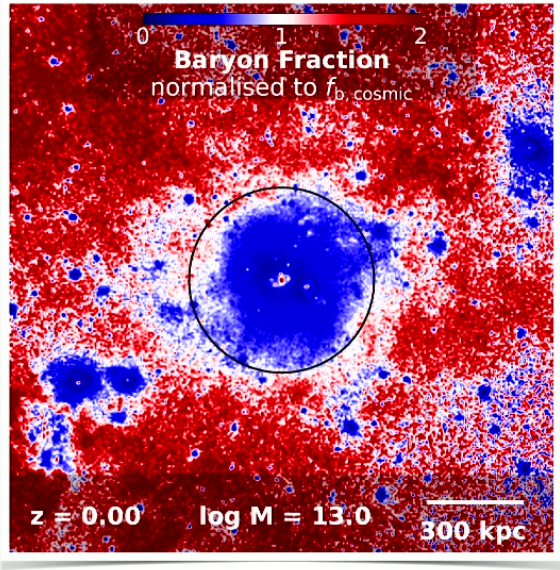
$$E_{\rm CGM}H_0 \sim 10^{43-44}\,{\rm erg\,s^{-1}}$$

$$\langle \dot{E}_{\rm lifting}\rangle \gg L_{\rm cool}$$

AGN heating has greatly exceeded cooling in groups!

Powerful feedback events have long-term consequences

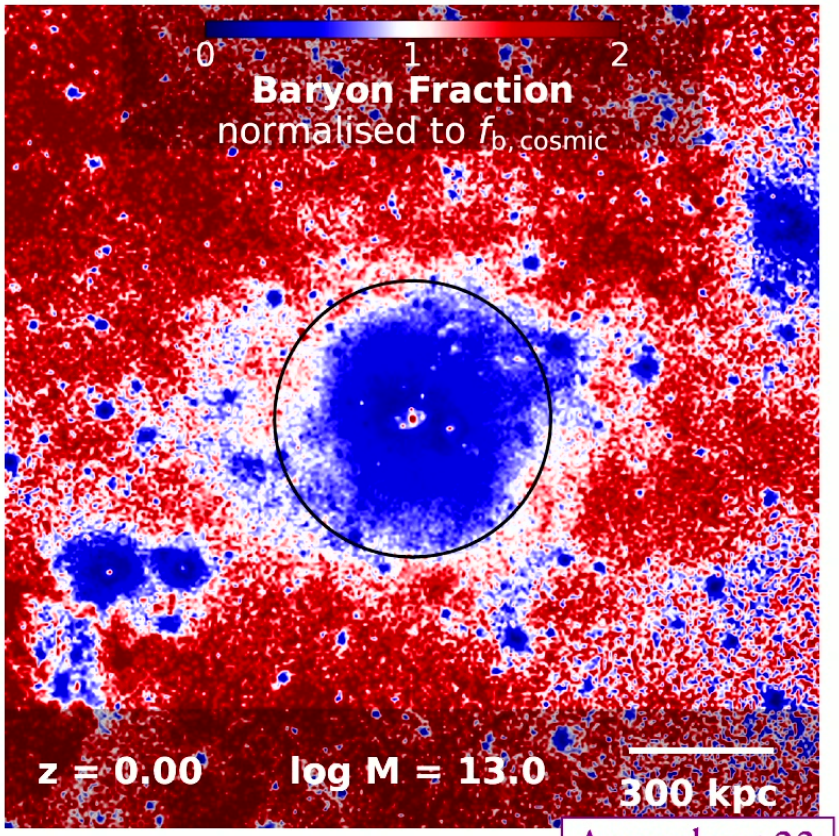
Current / Transient



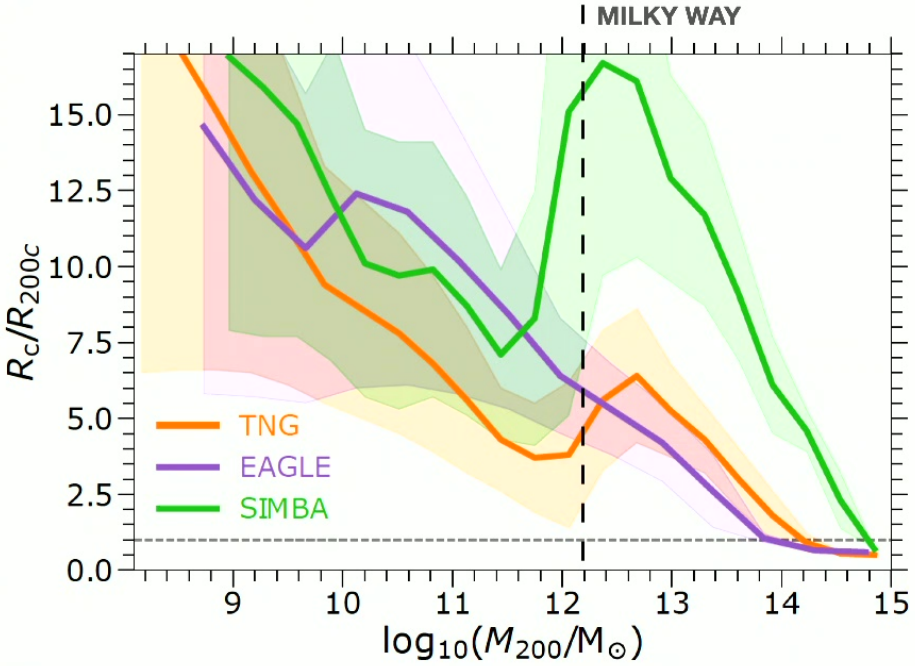
Cumulative / Permanent

The large-scale baryon distribution is a feedback bolometer!

Large-Scale Baryon Distribution

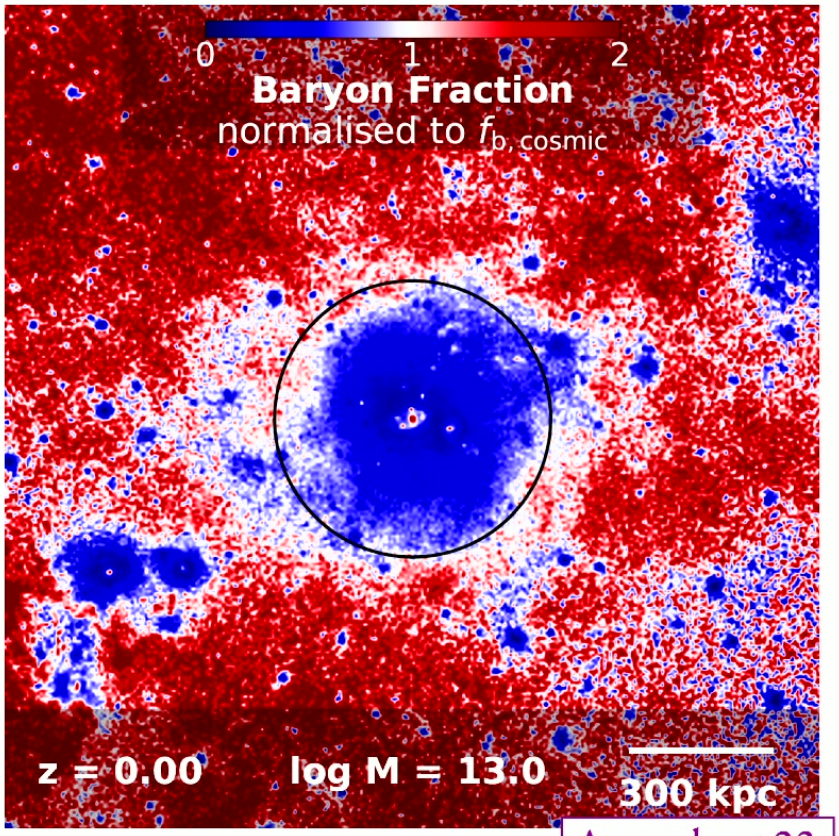


Ayromlou+23



Both galaxy evolution and large-scale baryon distribution depend on poorly understood feedback mechanisms

Large-Scale Baryon Distribution



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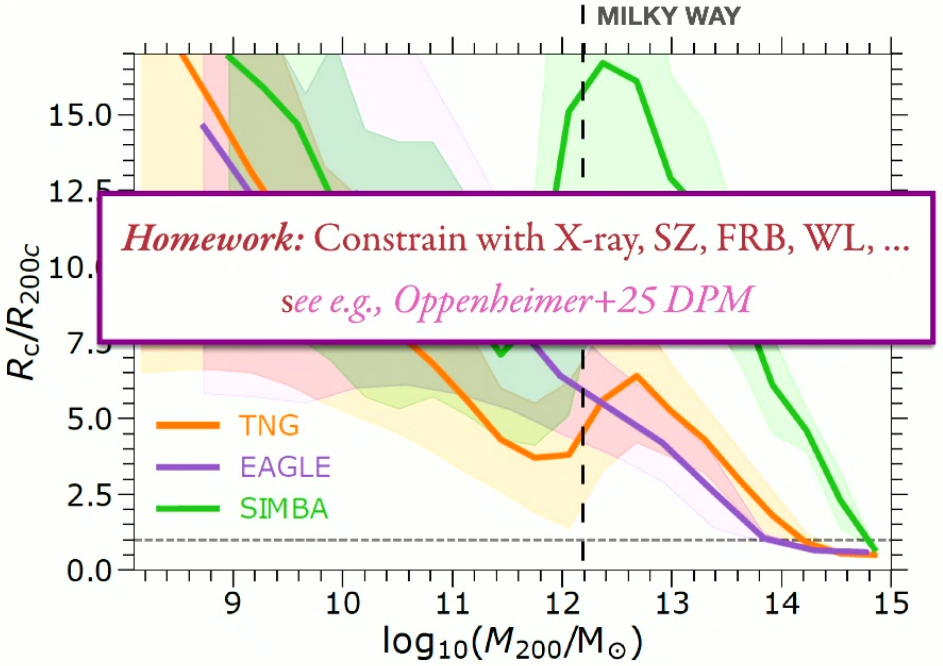


Homework: Constrain with X-ray, SZ, FRB, WL, ...

see e.g., Oppenheimer+25 DPM

Both galaxy evolution and large-scale baryon distribution depend on poorly understood feedback mechanisms

Baryon Lifting: Energy Requirements

$$\Delta E_{\rm CGM} \sim E_{\rm CGM}$$

$$\eta_E \varepsilon_{\rm SN} M_* + f_{\rm BH} M_{\rm BH} c^2 \sim f_{\rm b} M_{\rm halo} \cdot v_{\rm c}^2$$

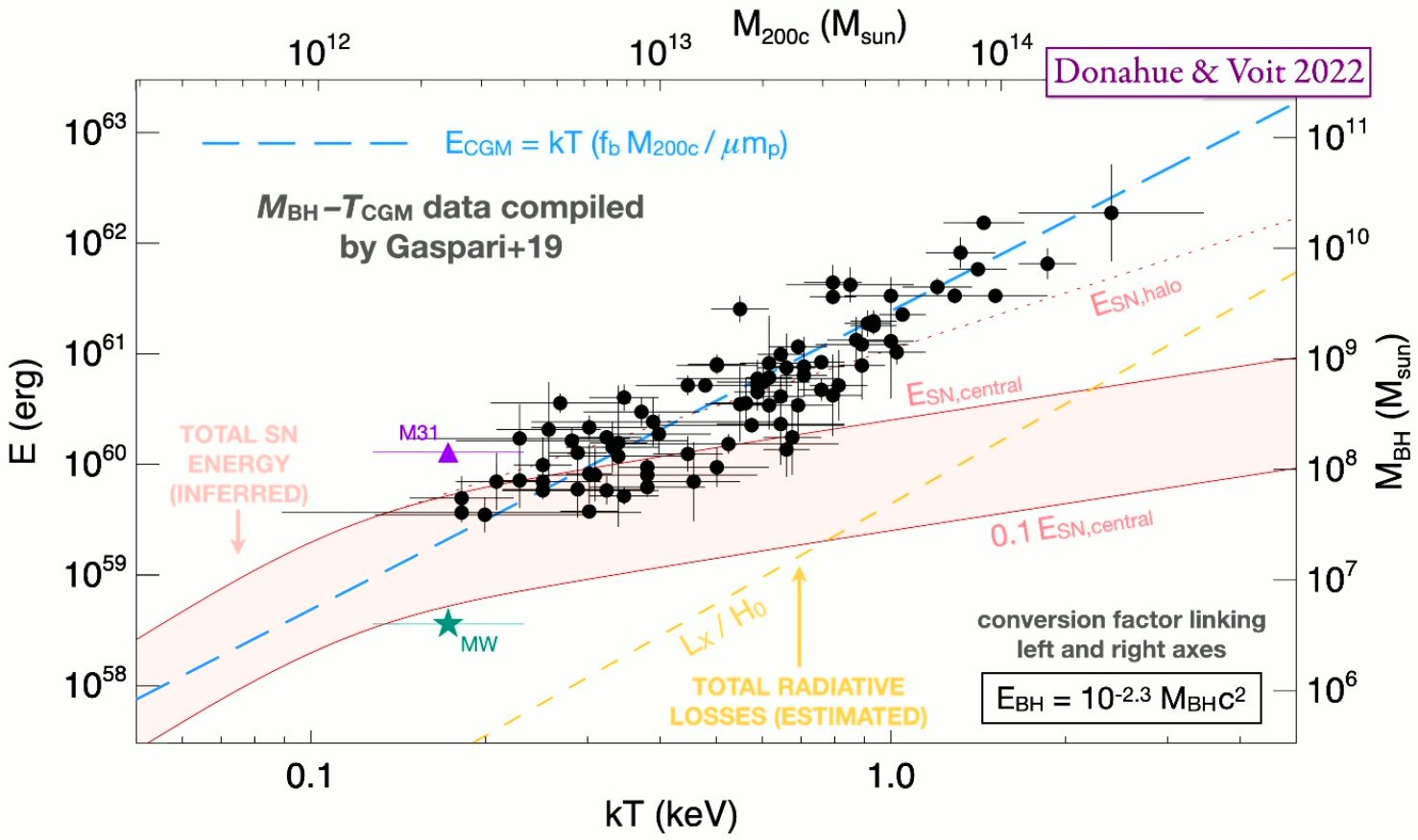
proportion of SN energy reaching the CGM

proportion of BH energy coupling with the CGM

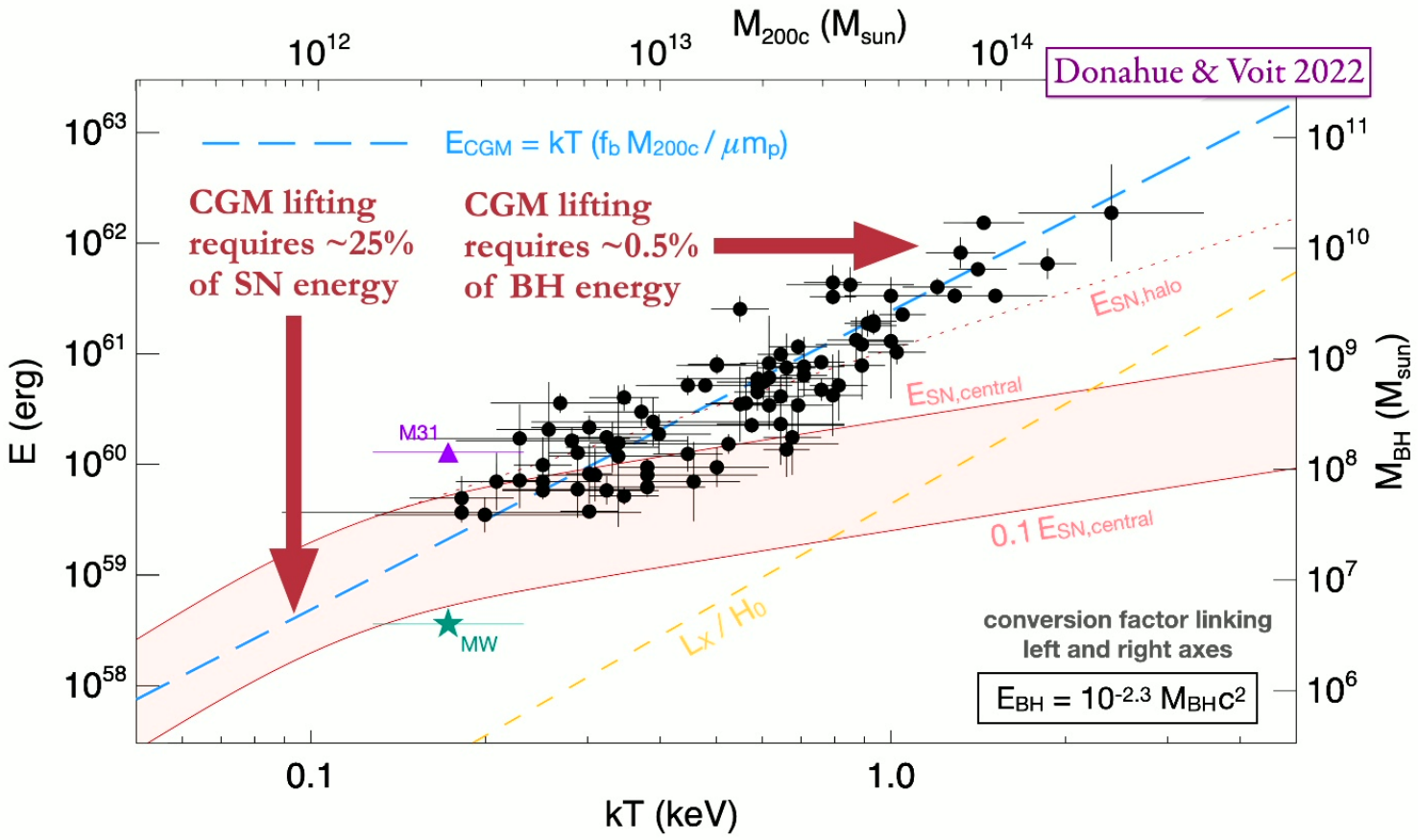
proportional to $M_{\rm halo}^{2/3}$

Expect $M_{\rm BH} \propto M_{\rm halo}^{5/3}$ in massive halos

Baryon Lifting: The Big Picture



Baryon Lifting: The Big Picture



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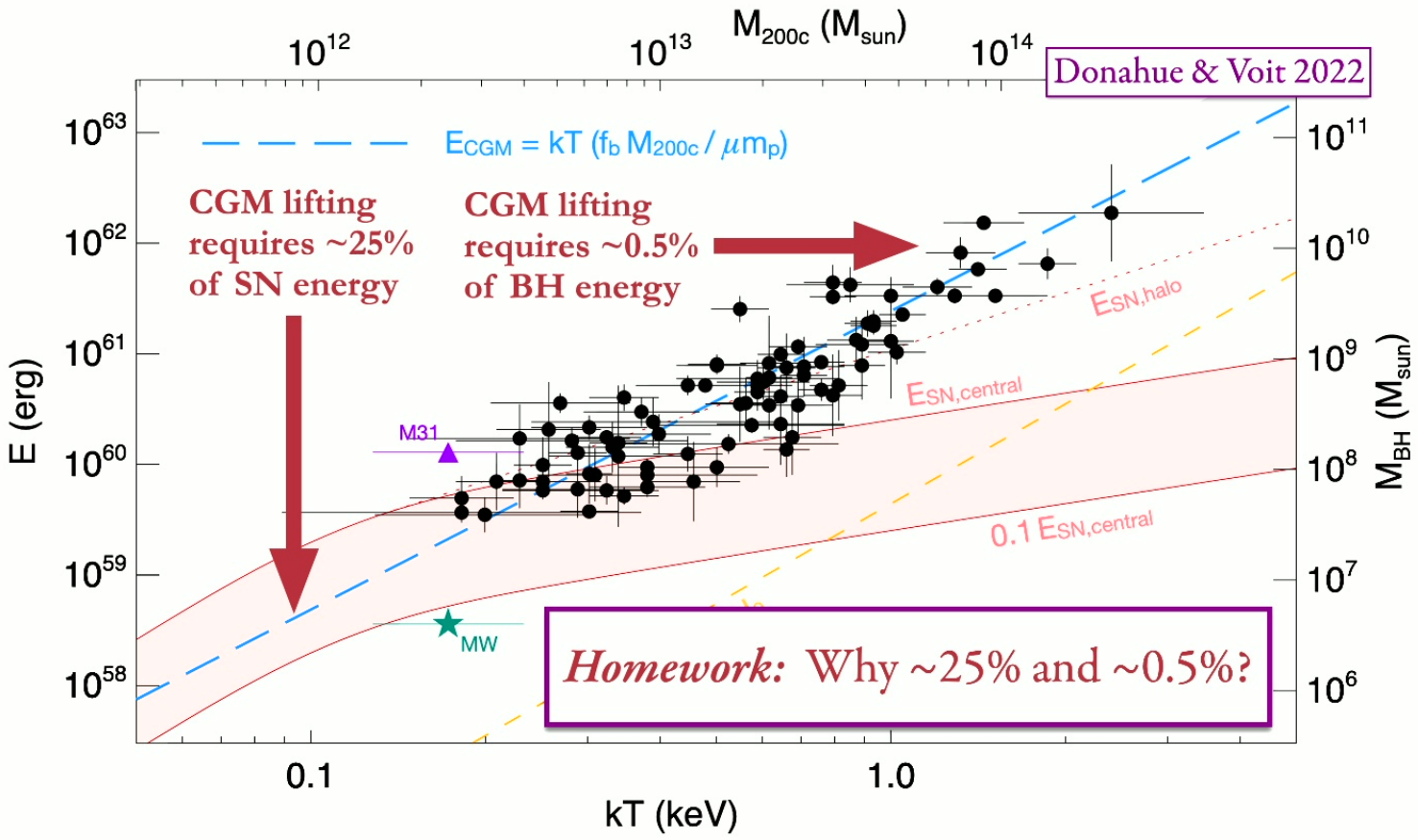
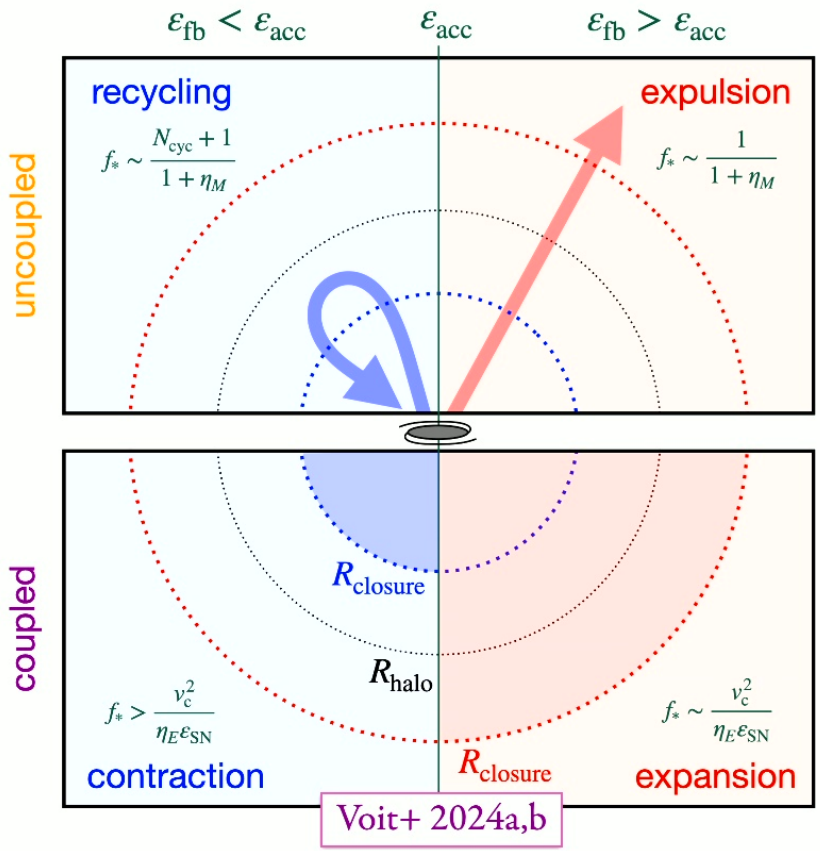


The Crucial Role of Specific Feedback Energy



ε_{acc} = specific energy of accreting gas (at R_{halo})

ε_{fb} = specific energy of outflowing gas (at R_{gal})

$$\varepsilon_{CGM} = \frac{E_\varphi + E_{th} + E_{non-th}}{M_{CGM}}$$

$$f_{CGM} = \frac{M_{CGM}}{f_b M_{halo}}$$

Equilibrium: ε_{CGM} and f_{CGM} remain constant

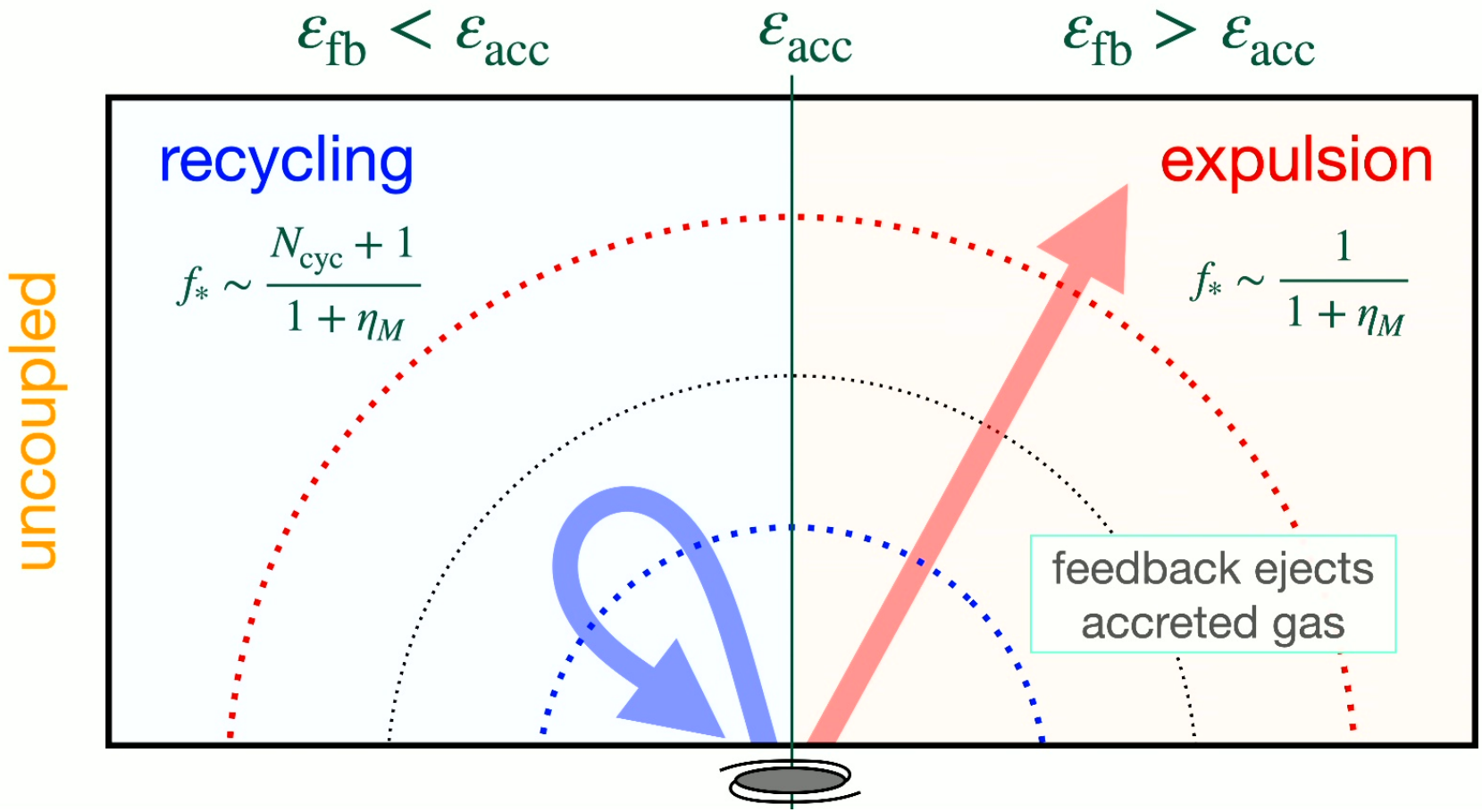
ExpCGM

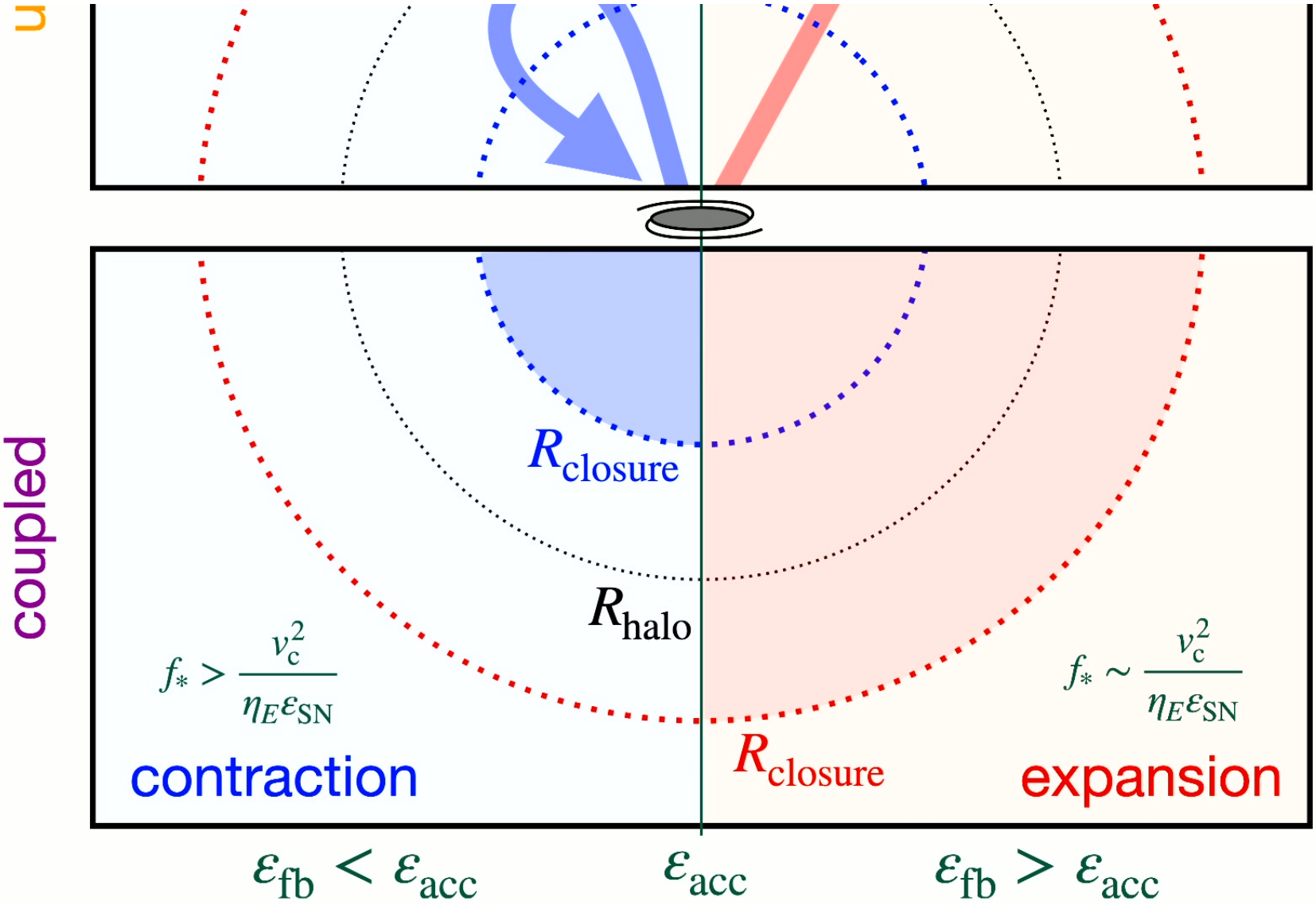
Viraj Pandya

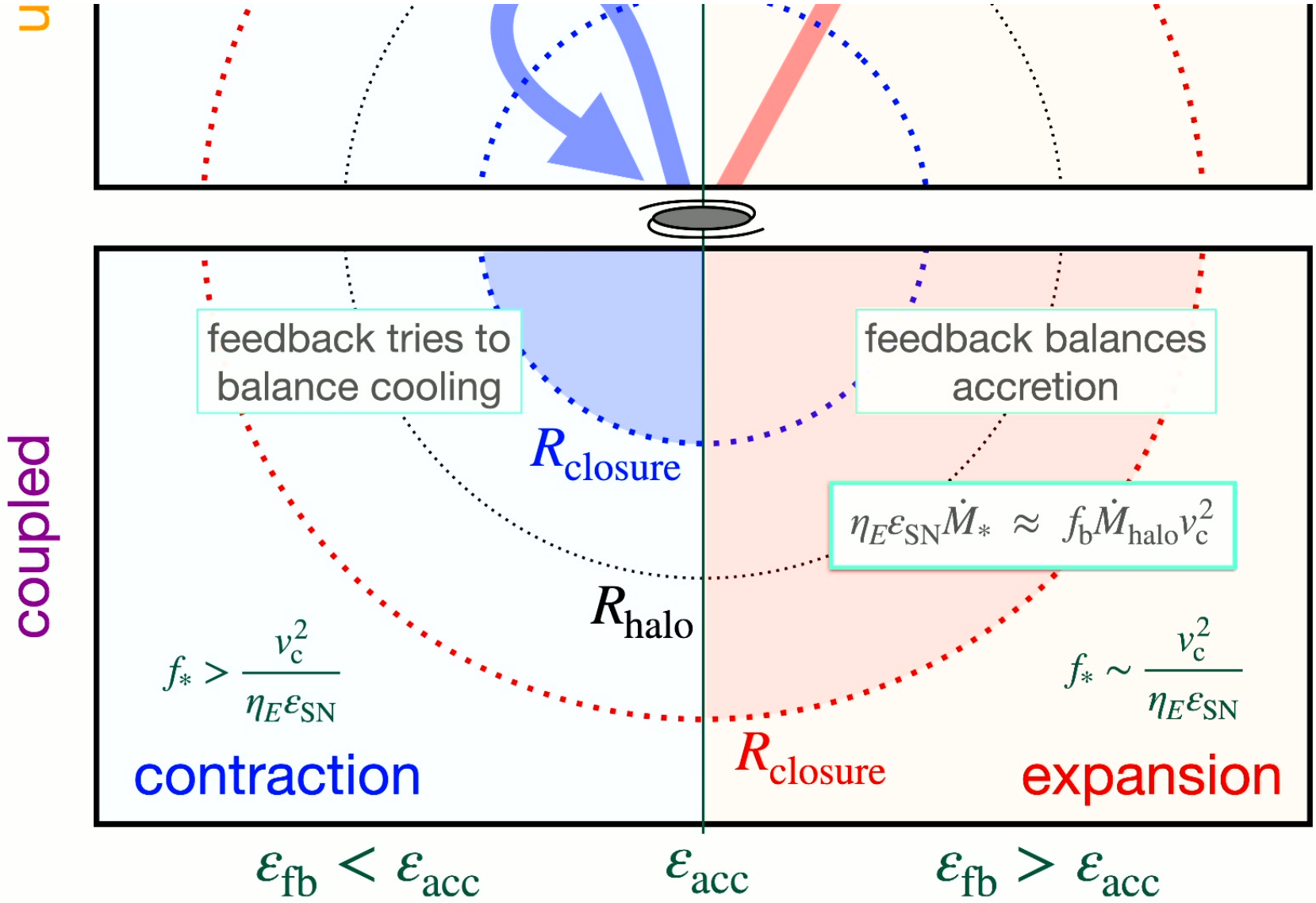
Greg Bryan
Chris Carr
Megan Donahue
Drummond Fielding
Ben Oppenheimer
Rachel Somerville

uncoupled outflows: no energy transfer to accreting gas

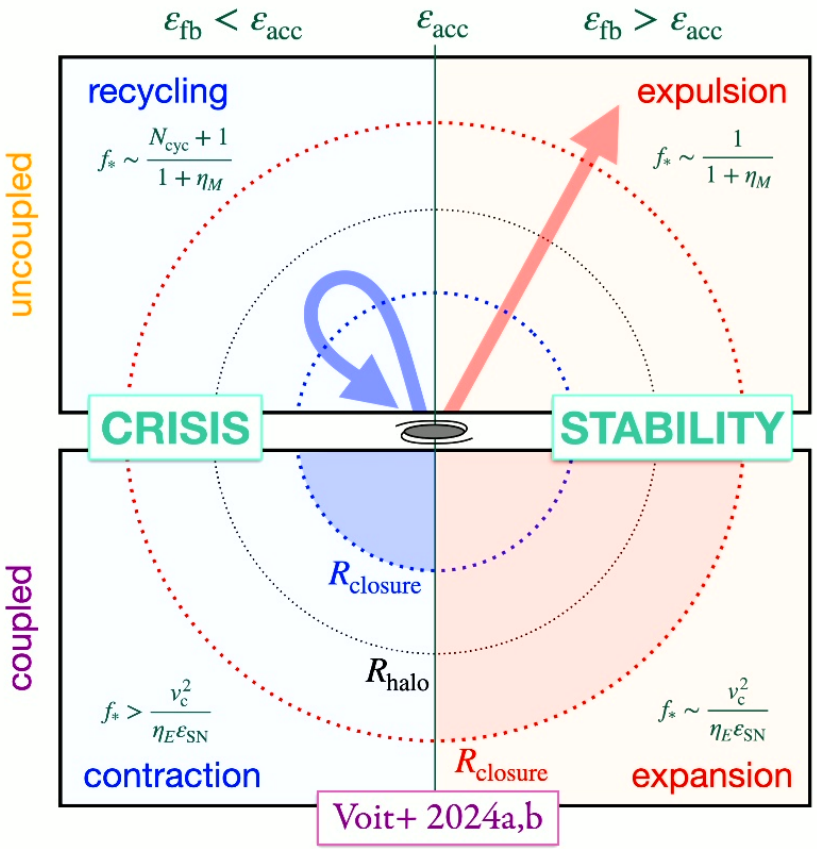
coupled outflows: energy transferred to accreting gas




un
coupled
$R_{\rm closure}$
$R_{\rm halo}$
$f_* > \frac{v_c^2}{\eta_E \varepsilon_{\rm SN}}$
$f_* \sim \frac{v_c^2}{\eta_E \varepsilon_{\rm SN}}$
contraction
$R_{\rm closure}$
expansion
$\varepsilon_{\rm fb} < \varepsilon_{\rm acc}$
$\varepsilon_{\rm acc}$
$\varepsilon_{\rm fb} > \varepsilon_{\rm acc}$


coupled
feedback tries to balance cooling
feedback balances accretion
$R_{\rm closure}$
$\eta_E \varepsilon_{\rm SN} \dot{M}_* \approx f_{\rm b} \dot{M}_{\rm halo} v_{\rm c}^2$
$R_{\rm halo}$
$f_* > \frac{v_{\rm c}^2}{\eta_E \varepsilon_{\rm SN}}$
$f_* \sim \frac{v_{\rm c}^2}{\eta_E \varepsilon_{\rm SN}}$
contraction
$R_{\rm closure}$
expansion
$\varepsilon_{\rm fb} < \varepsilon_{\rm acc}$
$\varepsilon_{\rm acc}$
$\varepsilon_{\rm fb} > \varepsilon_{\rm acc}$

How does $\varepsilon_{\rm fb}$ compare with $\varepsilon_{\rm acc}$?



$$\varepsilon_{\rm fb} = \frac{\dot{E}_{\rm fb}}{\dot{M}_{\rm out}} = \frac{\eta_E \varepsilon_{\rm SN}}{\eta_M} + \varepsilon_{\rm BH}$$

hard to compute

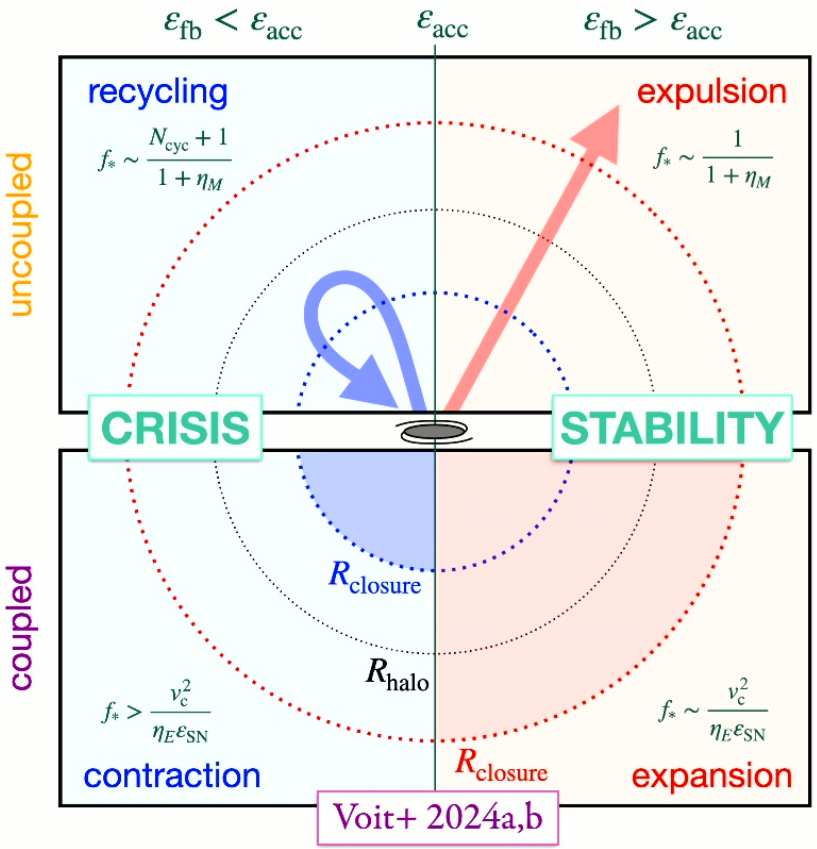
$$\frac{\varepsilon_{\rm fb}}{\varepsilon_{\rm acc}} \approx \frac{\eta_E/\eta_M}{0.2}\left(\frac{v_c^2}{300\,{\rm km\,s^{-1}}}\right)^{-2} + \frac{\varepsilon_{\rm BH}}{4v_c^2}$$

Equilibrium States

stable expansion: $\varepsilon_{\rm fb} > \varepsilon_{\rm acc}$, $\dfrac{\partial \dot{M}_{\rm in}}{\partial \varepsilon_{\rm CGM}} < 0$

volatile contraction: $\varepsilon_{\rm fb} < \varepsilon_{\rm acc}$, $\dot{E}_{\rm fb} \approx \dot{E}_{\rm rad}$

How does $\varepsilon_{\rm fb}$ compare with $\varepsilon_{\rm acc}$?



$$\varepsilon_{\rm fb} = \frac{\dot{E}_{\rm fb}}{\dot{M}_{\rm out}} = \frac{\eta_E \varepsilon_{\rm SN}}{\eta_M} + \varepsilon_{\rm BH}$$

hard to compute — not well constrained

$$\frac{\varepsilon_{\rm fb}}{\varepsilon_{\rm acc}} \approx \frac{\eta_E/\eta_M}{0.2}\left(\frac{v_c^2}{300\,{\rm km\,s^{-1}}}\right)^{-2} + \frac{\varepsilon_{\rm BH}}{4v_c^2}$$

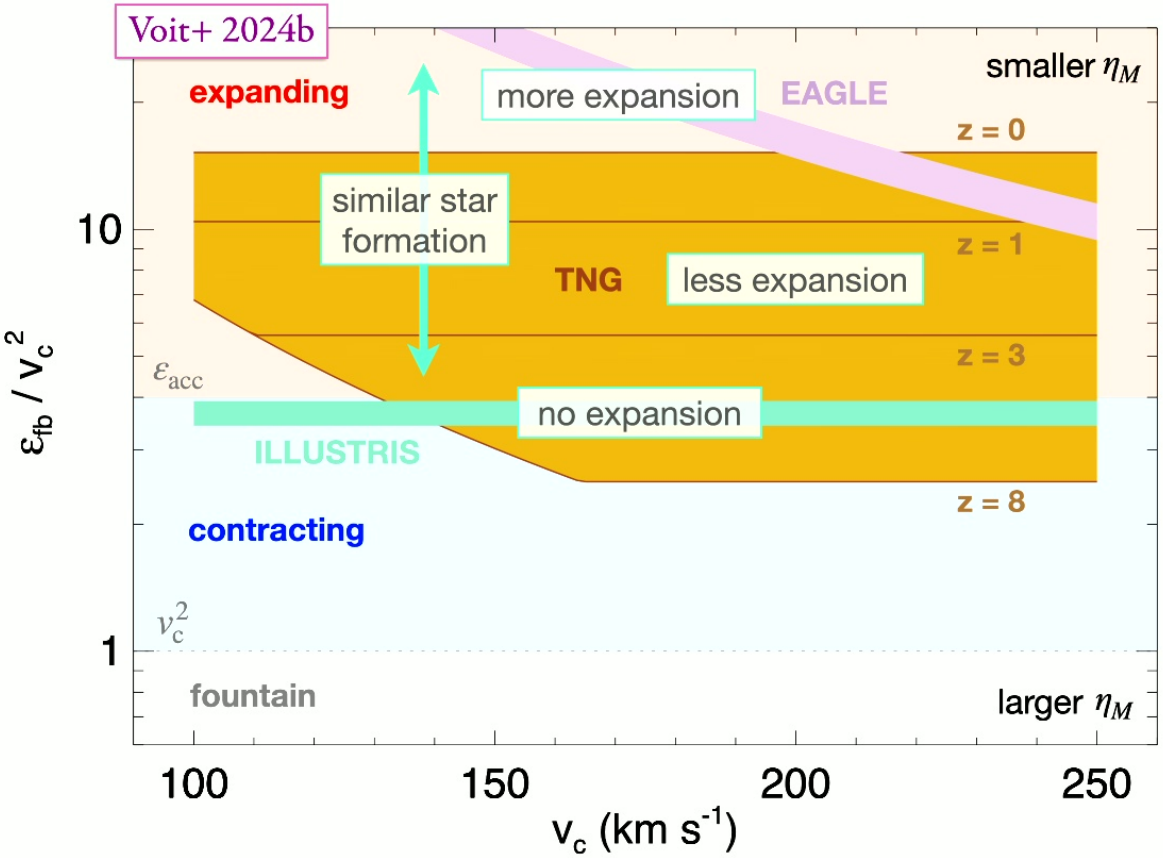
expect BH response to SN feedback crisis in massive galaxies

Equilibrium States

stable expansion: $\varepsilon_{\rm fb} > \varepsilon_{\rm acc}$, $\frac{\partial \dot{M}_{\rm in}}{\partial \varepsilon_{\rm CGM}} < 0$

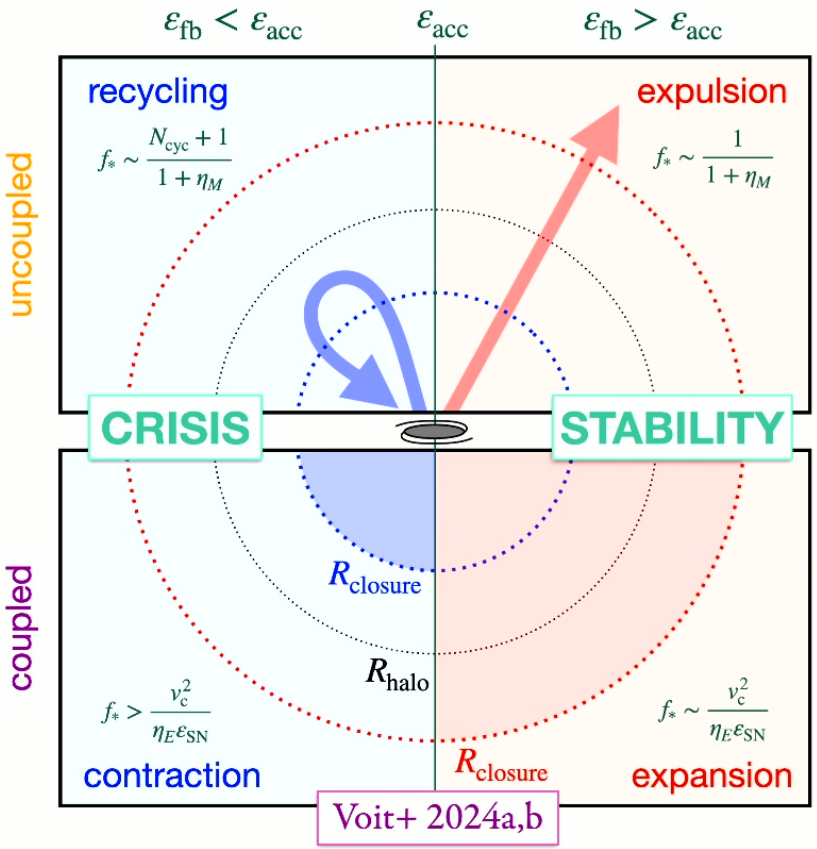
volatile contraction: $\varepsilon_{\rm fb} < \varepsilon_{\rm acc}$, $\dot{E}_{\rm fb} \approx \dot{E}_{\rm rad}$

Diversity in the Simulated CGM



The equilibrium states of coupled outflows may explain why simulations producing similar galaxy populations have differing CGM properties

How does ε_{fb} compare with ε_{acc}?

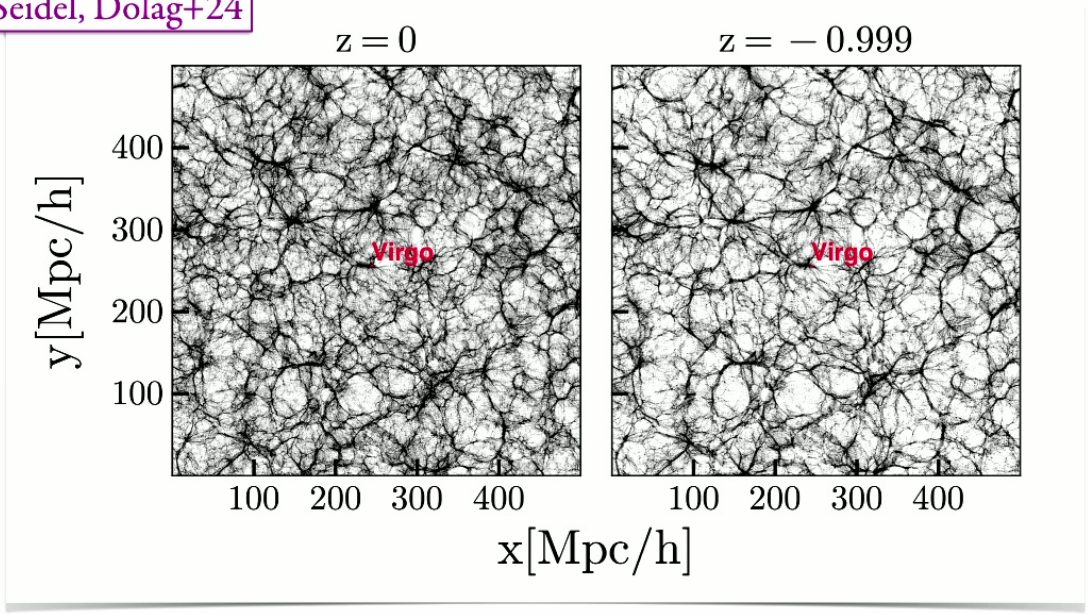


- Map radial baryon distribution
- Measure *specific* feedback energy
- Understand the SN feedback crisis
- Identify BH-CGM connections


Bound Domains

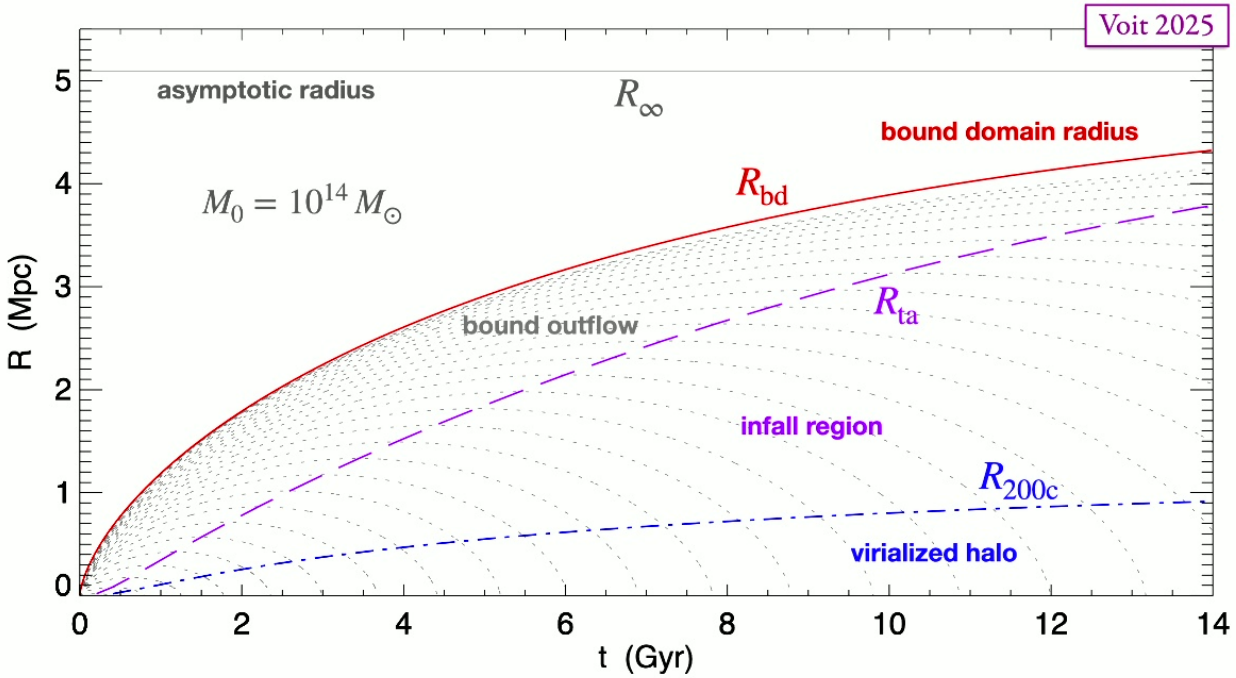
A *bound domain* is a collection of matter in a ΛCDM universe that remains gravitationally bound into the distant future

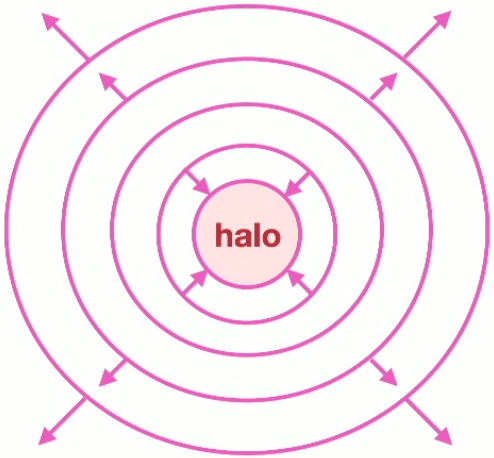
Seidel, Dolag+24



"Clairvoyant" simulation from SLOW IV

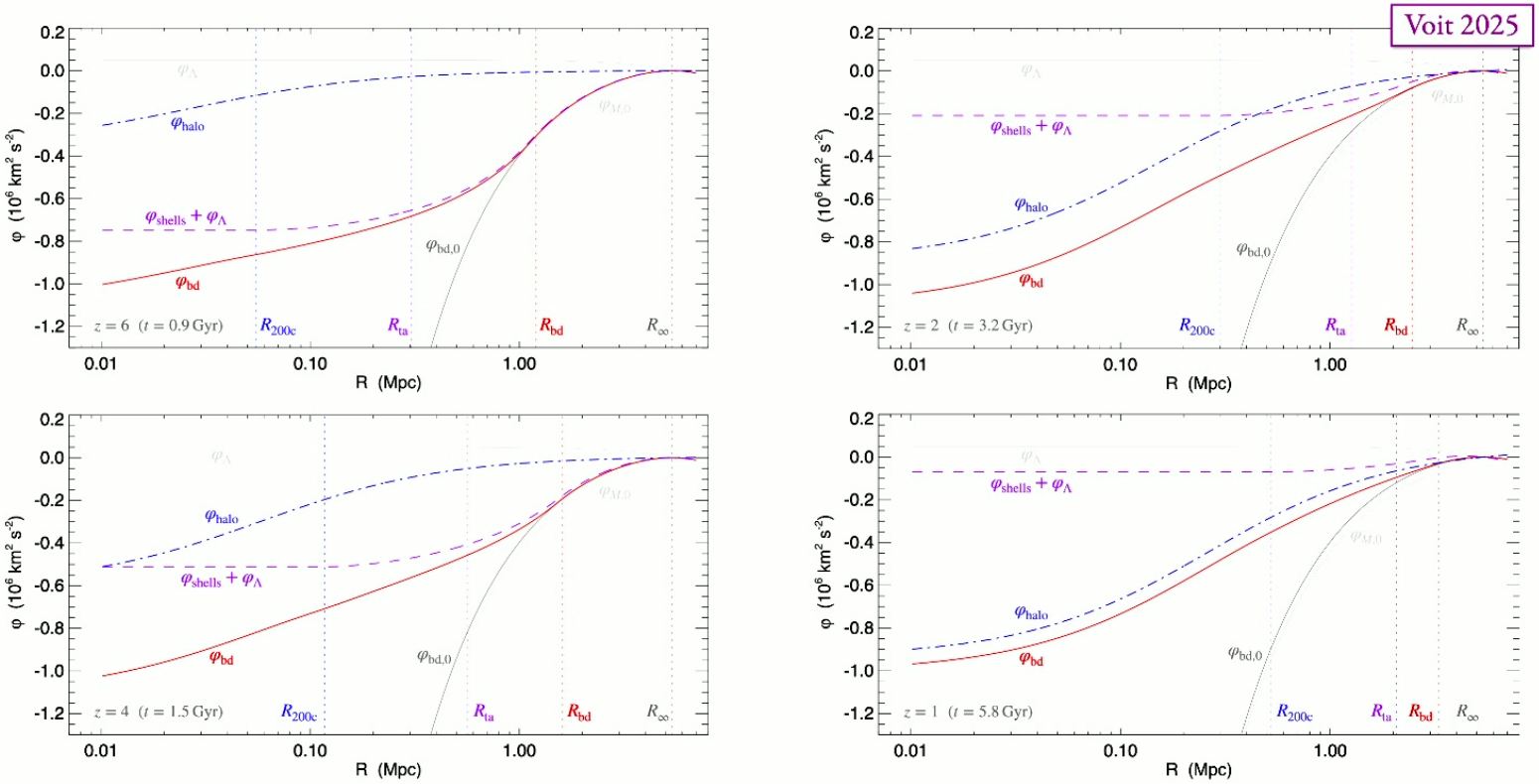
Bound Domain Evolution





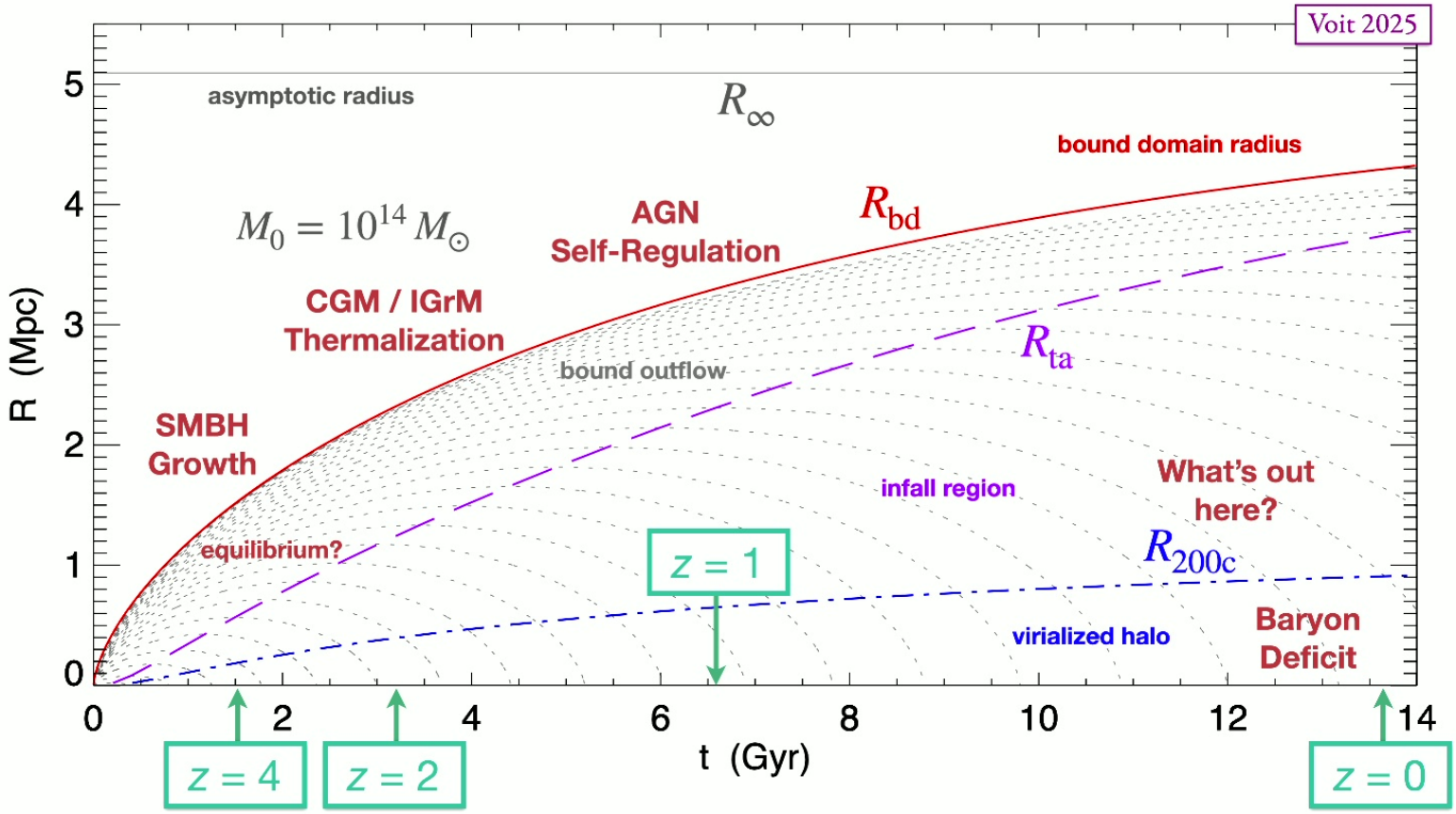
Halo mass accretion history determines dynamics of idealized shell system

Bound Domain Potential Well



A bound domain's potential well depth remains nearly invariant from z > 6 to the present!

Bound Domain Evolution



Conference Themes — Revisited

- Small to large scales → Equilibrium hinges on small/large connections
- Hot gas to cold gas → Assess total *specific* energy: $\varepsilon_\phi + \varepsilon_{\text{th}} + \varepsilon_{\text{non-th}}$
- Galactic to intergalactic scales → Adopt full baryon accounting
- Diffuse to dense structures → What are the equilibration timescales?
- Past feedback processes to present-day observations → Bound domains!