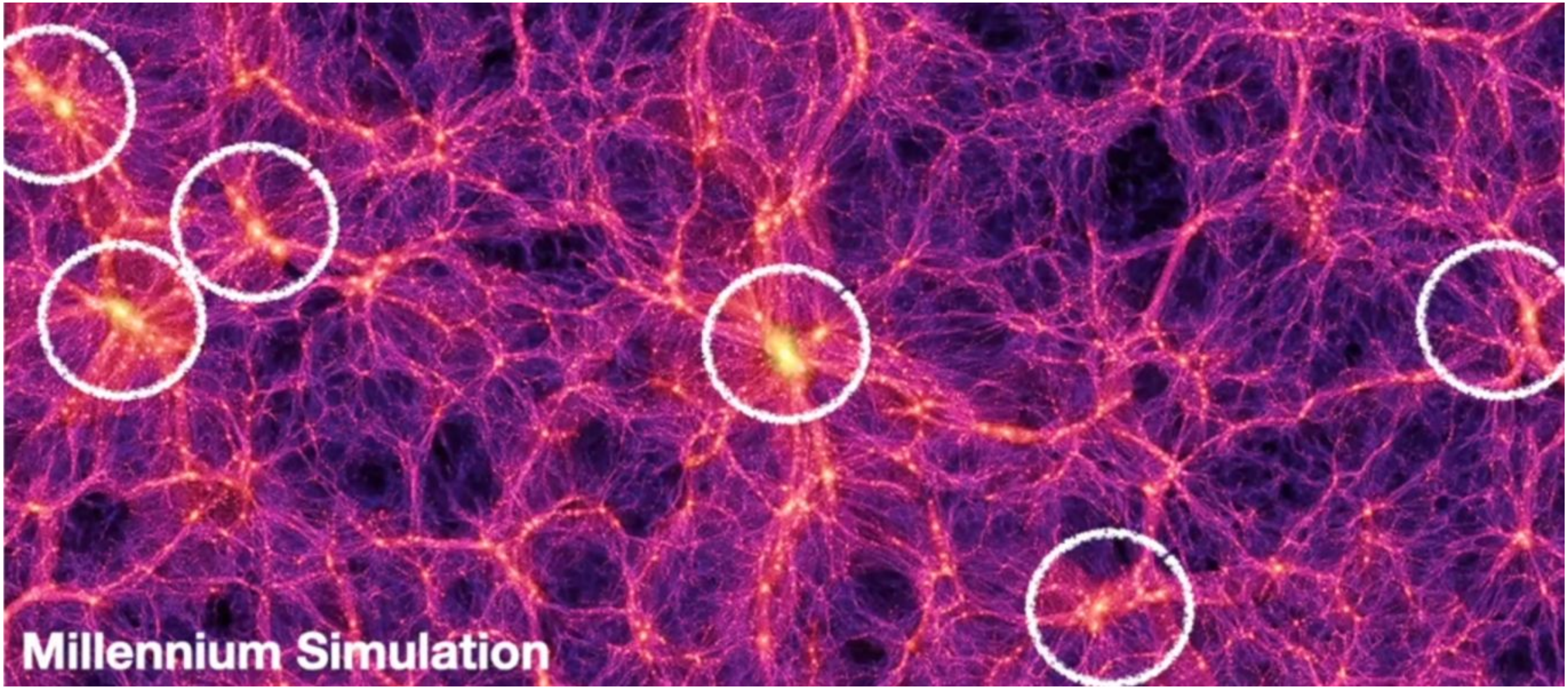
GW-CMB 2025

Dark Matter and Baryons beyond Equilibrium: Cluster Outskirts and Infall

Keiichi Umetsu (ASIAA)

Cosmology and astrophysics with galaxy clusters

Galaxy clusters are massive cosmic-web nodes still growing under gravity



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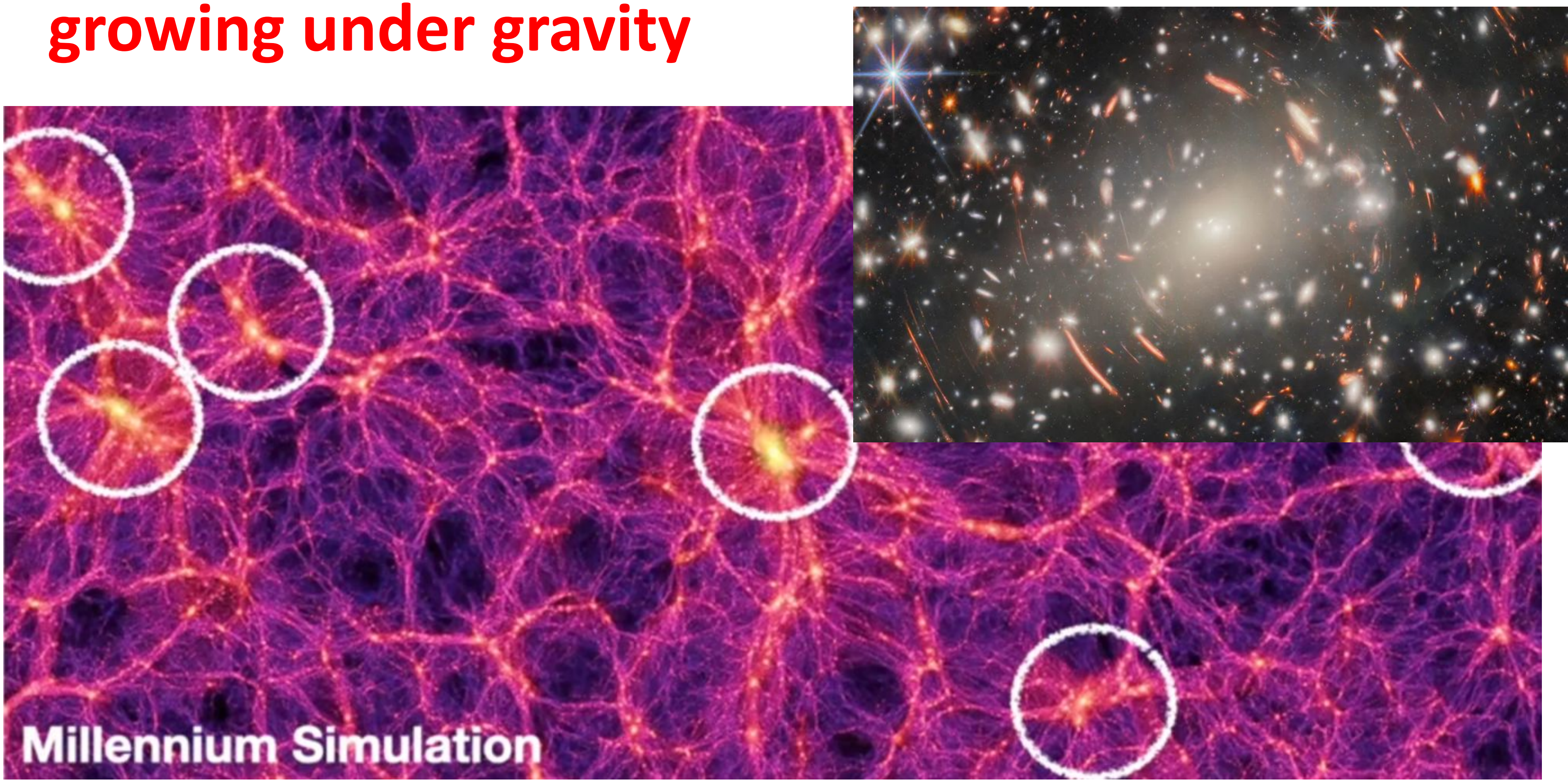
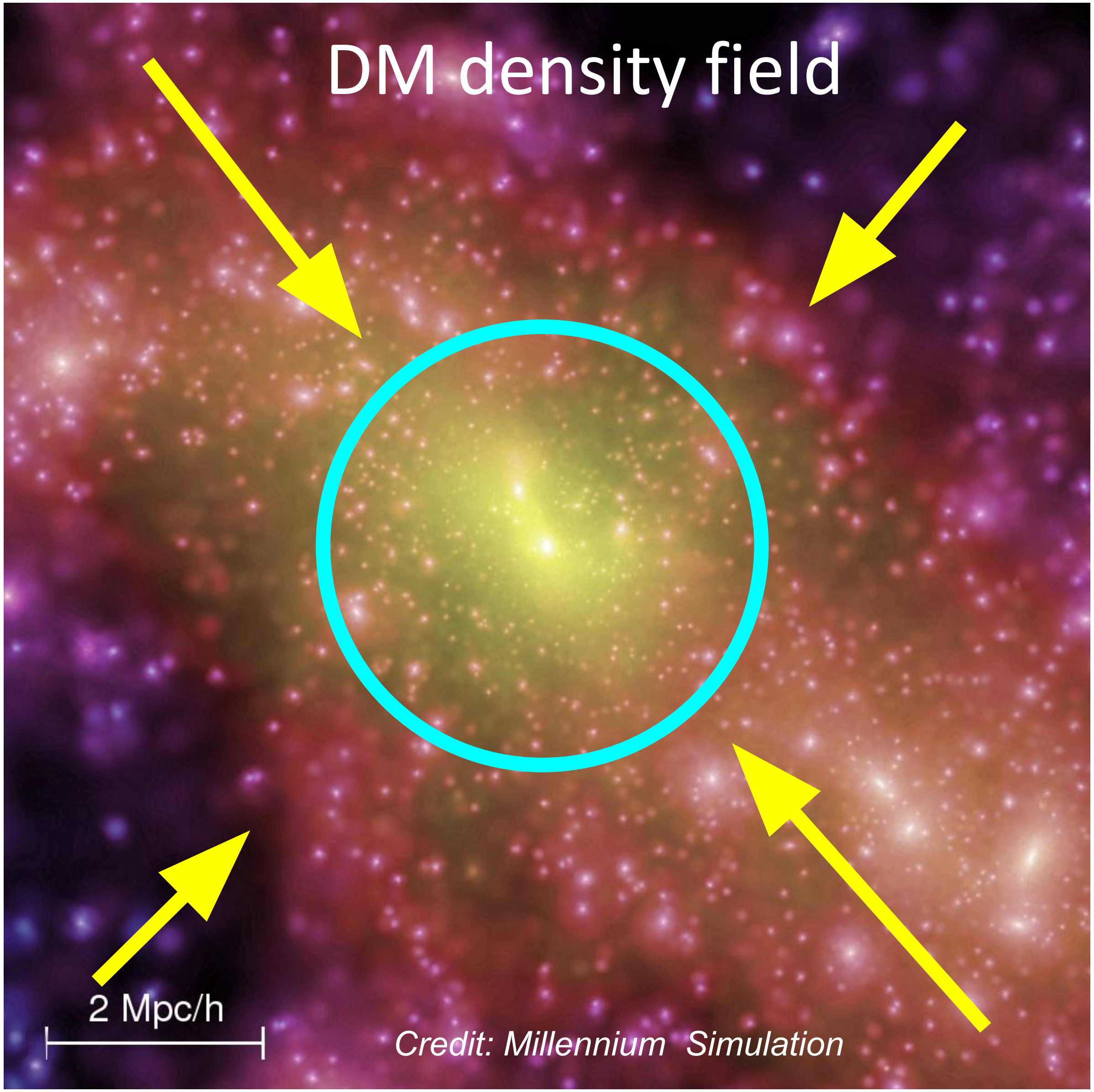


Cluster halo at a cosmic-web node

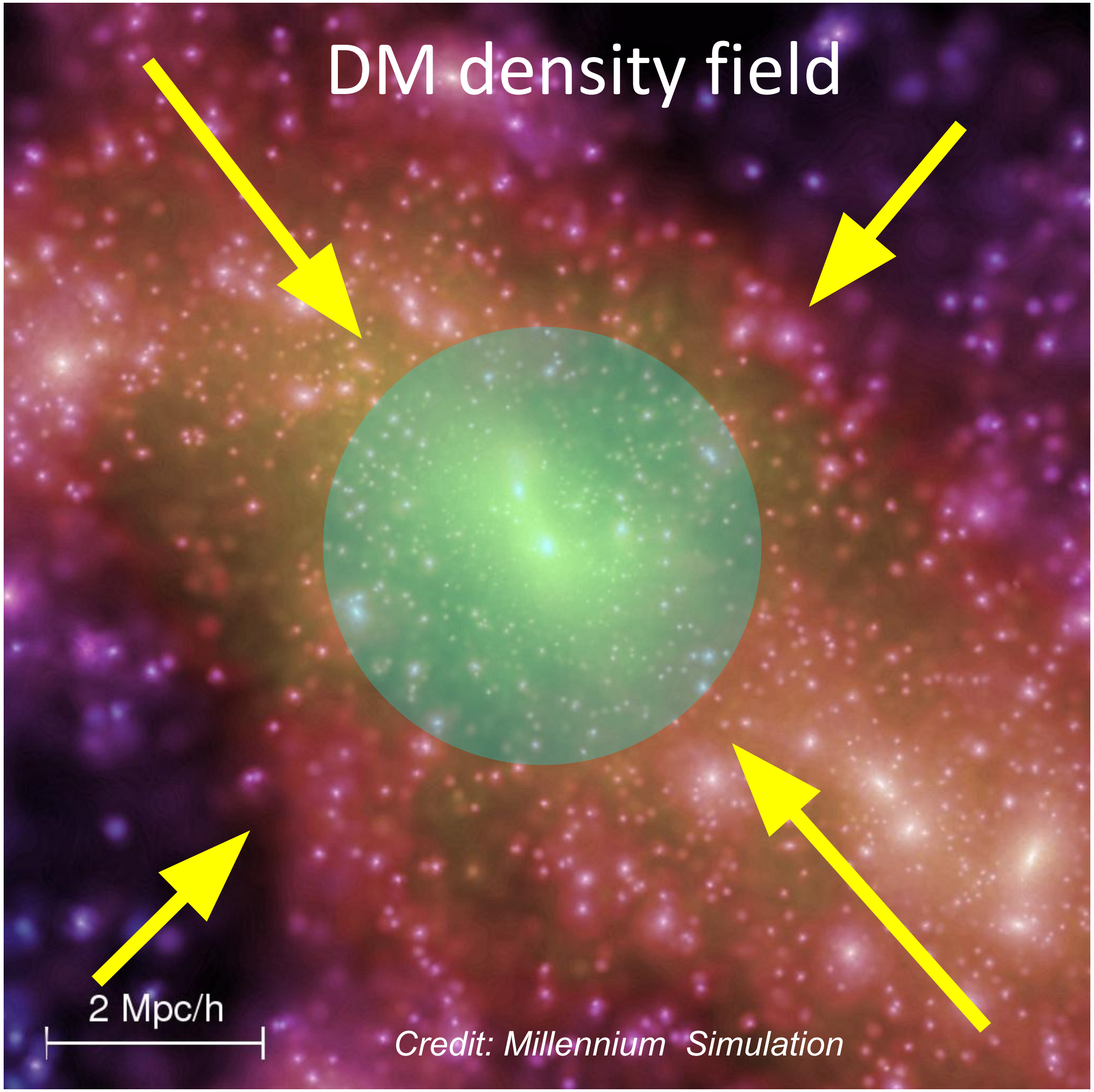


Halo's dynamical boundary @
$R\_sp \approx 2$ Mpc/h

Interior
= quasi-equilibrium

Exterior
= infall regions

Multi-tracers of the cluster potential



Kinematic / thermodynamic tracers (galaxies, gas)

$$U + 2T + \cancel{S} \simeq 0$$

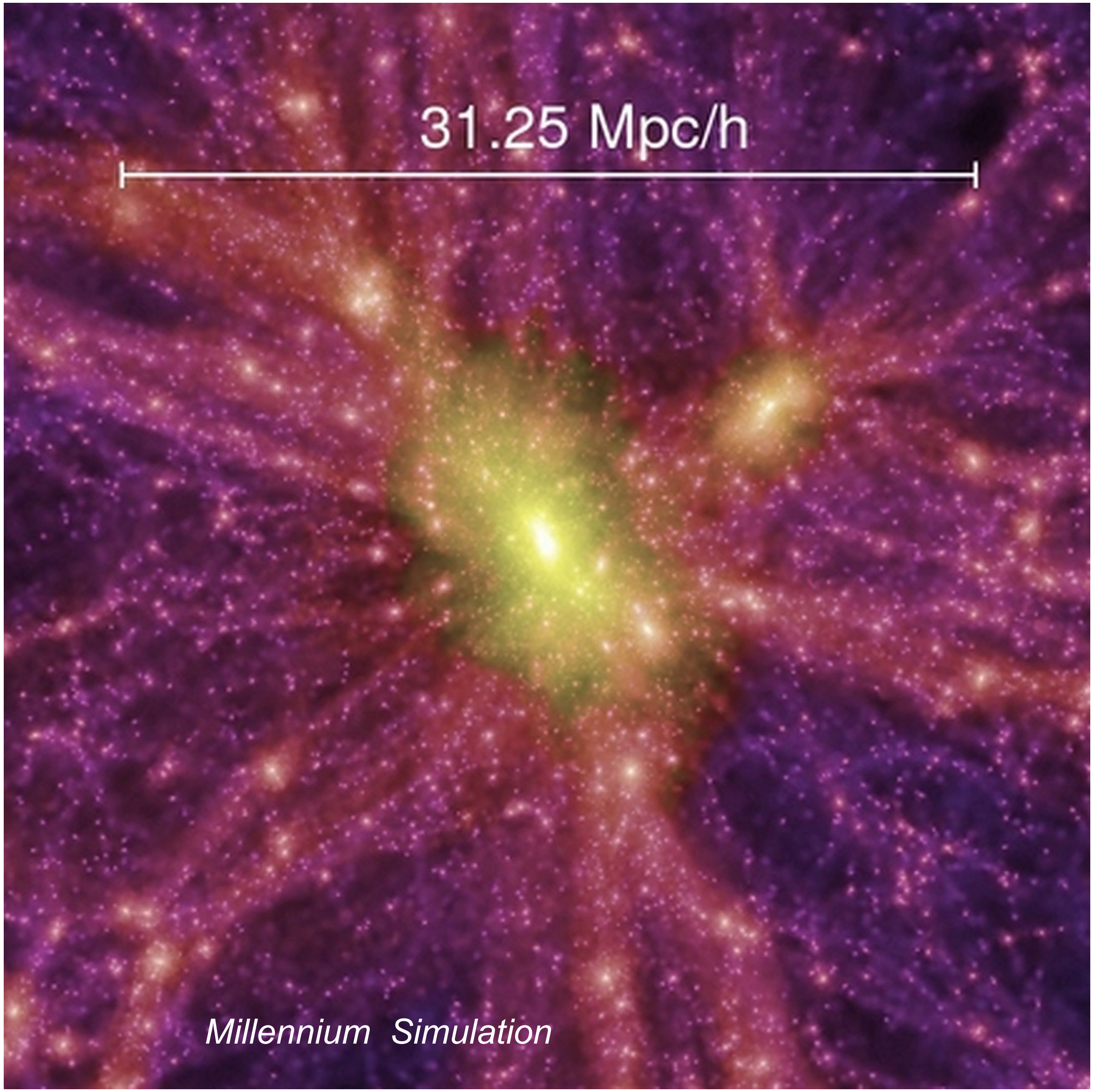
$$U = \sum_i m_i \Phi(\boldsymbol{r}_i)$$

Geometric tracers (weak lensing)

$$\nabla_i \nabla_j \psi = \kappa \delta_{ij} + \gamma_{ij}$$

$$\psi \propto \int \Phi_W(\boldsymbol{r})\, dl$$

Cluster outskirts and infall: the nonlinear, non-equilibrium frontier



Outskirts are dynamically young and far from equilibrium.

Maximum turnaround radius: $r_{eq} \approx 10$ Mpc/h at $z = 0$

Weak lensing

$$\nabla_i \nabla_j \psi = \kappa \delta_{ij} + \gamma_{ij}$$

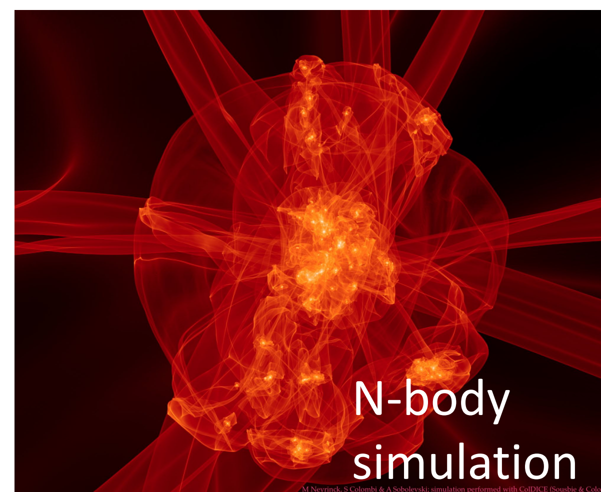
Phase-space kinematics

$$v_{\rm esc}^2 = -2\left[\Phi(r) - \Phi(r_{\rm eq})\right] - qH^2(r^2 - r_{\rm eq}^2)$$

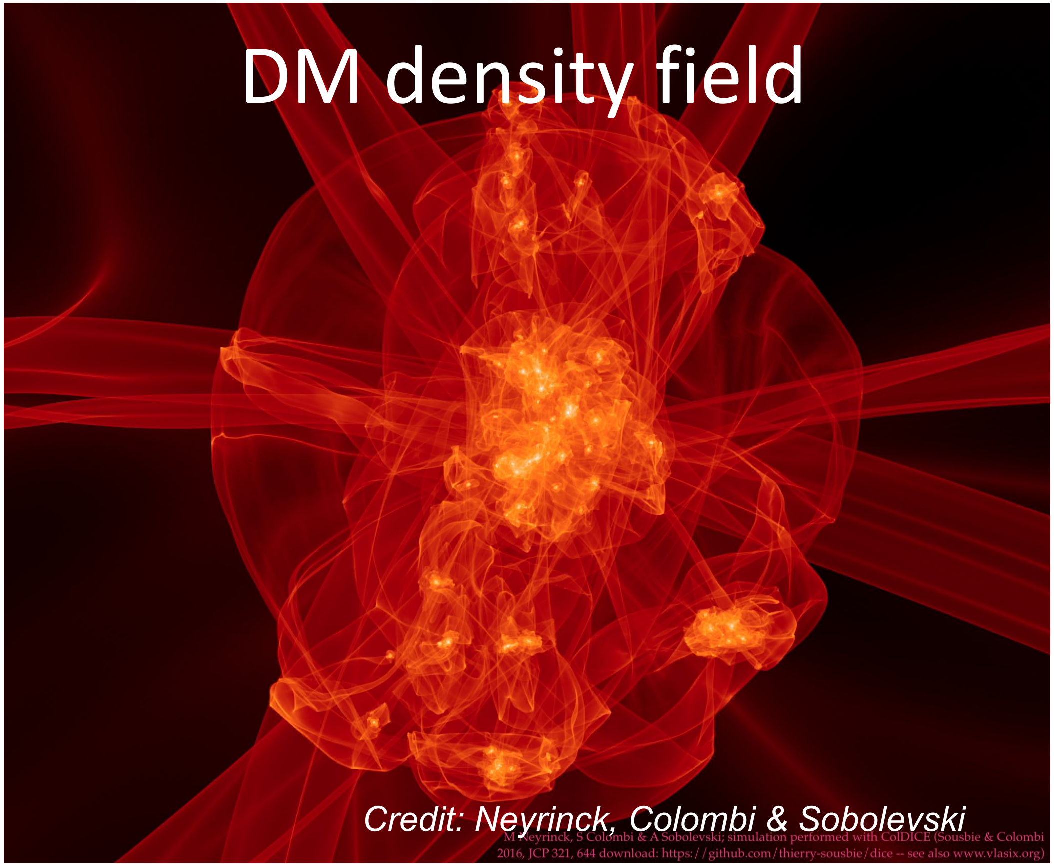
Key questions:
DM and baryons beyond equilibrium

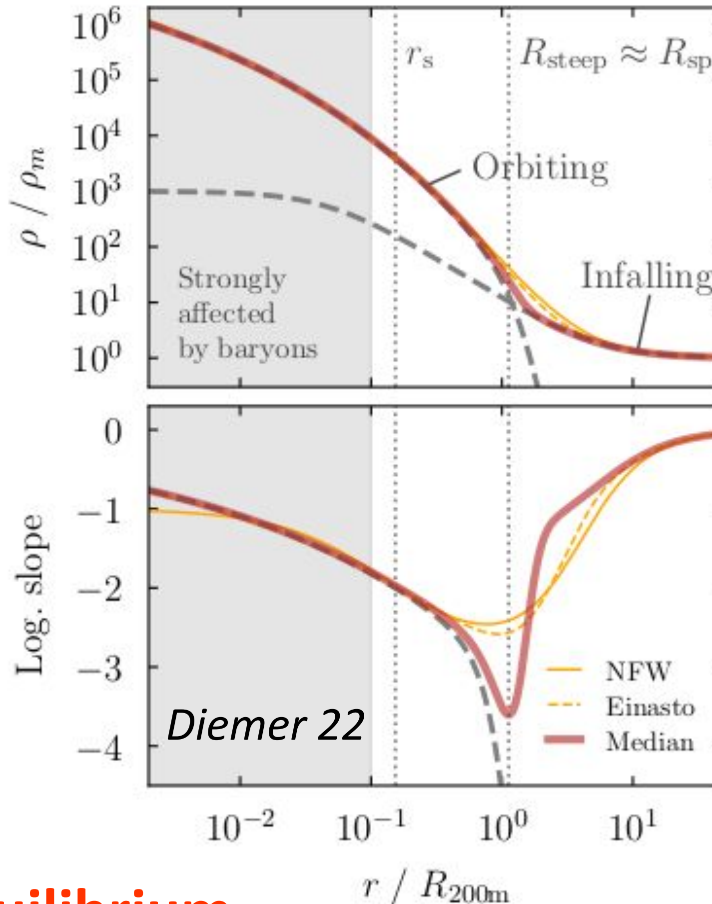
- **How does matter flow from the cosmic web into massive halos?**
  - Reveals how halos grow and evolve in the nonlinear regime.
- **How do dark matter and diffuse baryons respond differently to gravity?**
  - Their mass and velocity structure is key to probing the nature of DM and gravity.
- **Where do the boundaries of collisionless and collisional matter emerge?**
  - Identifies the dynamical (splashback) and hydrodynamic (accretion shock) edges of halos.

Non-equilibrium structure formation on megaparsec scales



Dynamical halo boundary: splashback radius

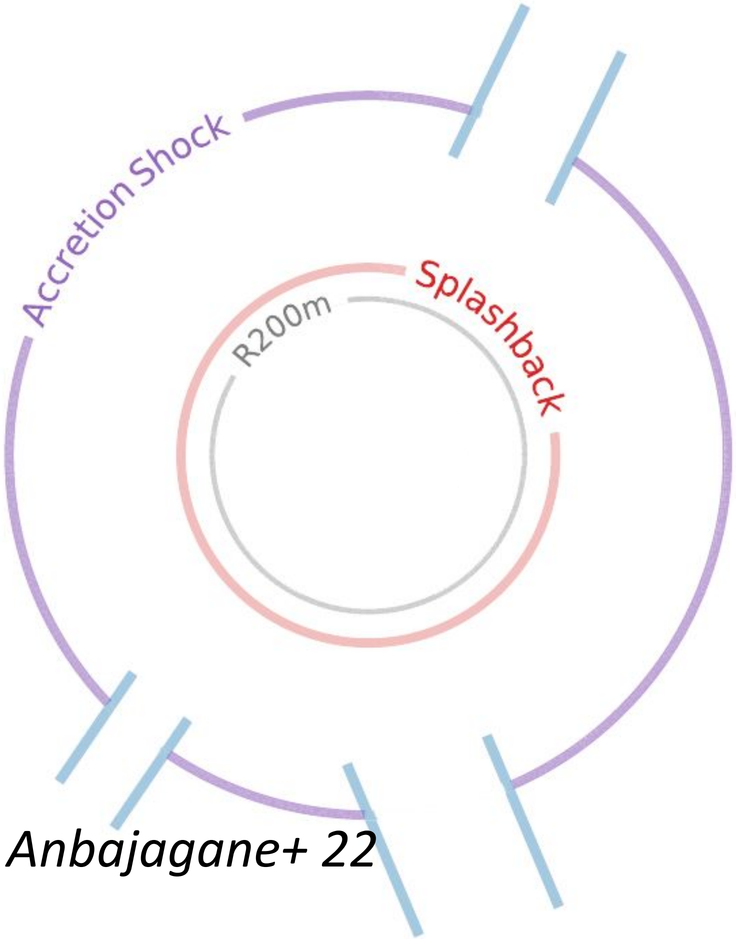




Gravitational potential tracers beyond equilibrium

- **Gravitational lensing** (e.g., Umetsu & Diemer 2017)
- **Escape velocity** from phase-space galaxy kinematics (Pizzardo+ 2024)
- **CLUMI+**: joint weak lensing + escape velocity (Umetsu, Pizzardo+ 2025)

Hydrodynamic halo boundary: accretion shock radius



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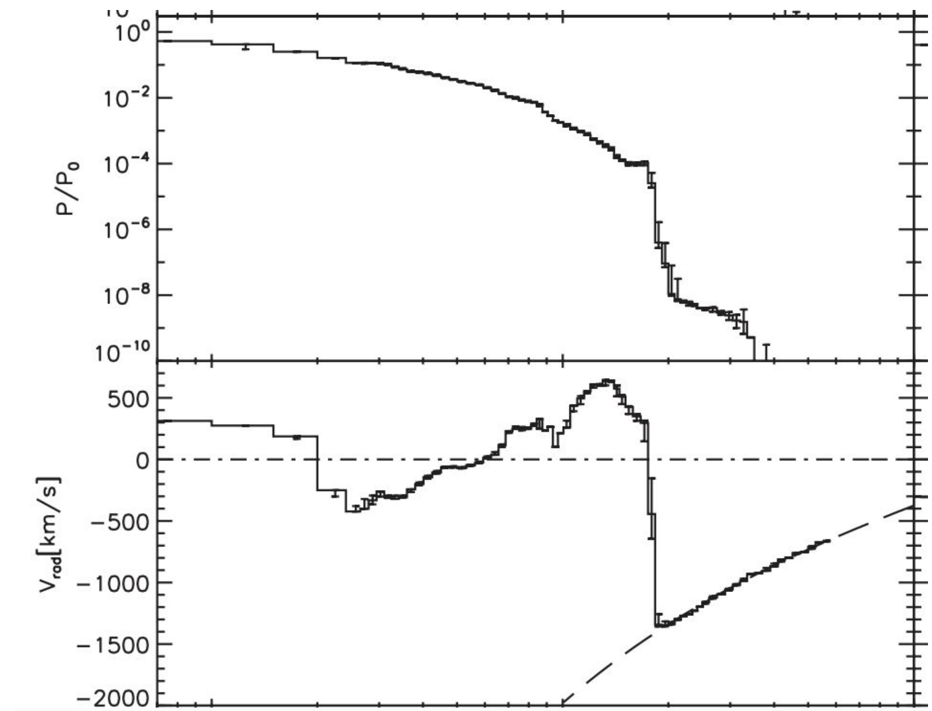
Pressure & velocity jumps at $r \approx 2\ R$_sp
(Molnar+10, Lau+15, Avestruz+15, Shi 16)

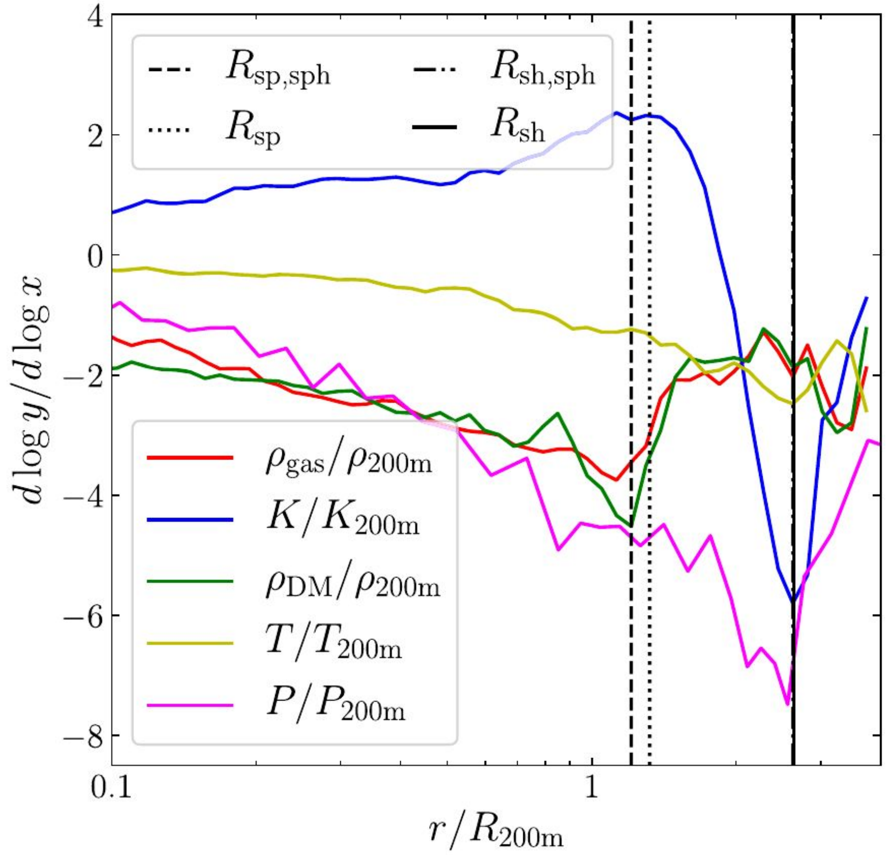


tSZ + kSZ → pressure & momentum diagnostics across the shock

Cosmological hydro simulations (off-filament directions) by Molnar+10

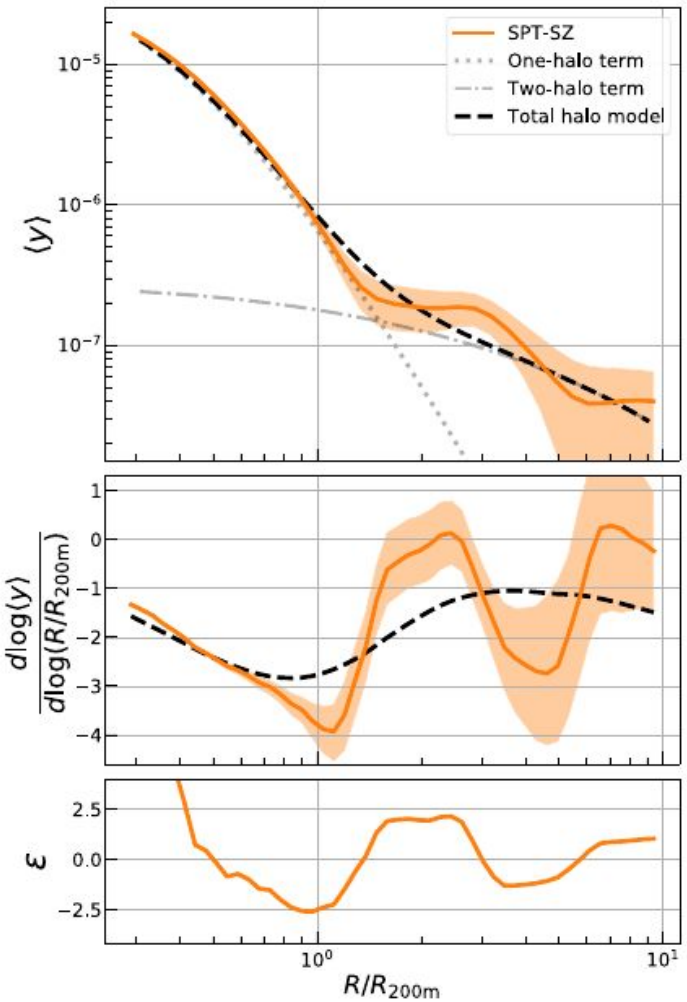
Simulations vs. current measurements

Zoom-in cosmological hydro simulations (65 clusters)



Aung, Nagai, & Lau 21

SPT + Planck tSZ (516 clusters)



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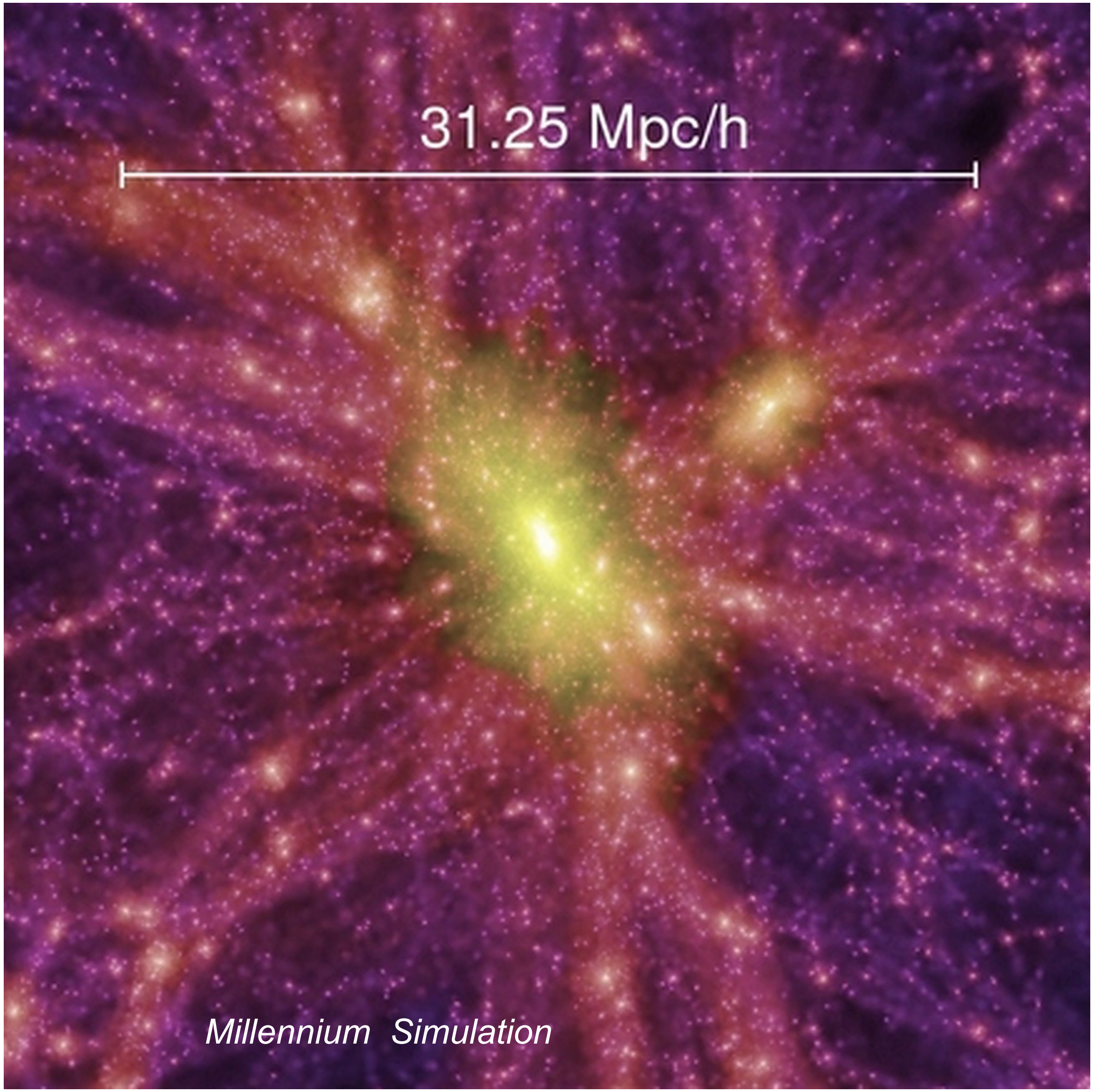
Non-equilibrium cluster outskirts with SO+



Weak lensing + phase-space to anchor the underlying potential

$$\nabla_i \nabla_j \psi = \kappa \delta_{ij} + \gamma_{ij}$$

$$v_{\rm esc}^2 = -2\left[\Phi(r) - \Phi(r_{\rm eq}) - qH^2(r^2 - r_{\rm eq}^2)\right]$$

Thermal and kinetic SZ signals in the CMB

$$y \propto \int P_e \, dl$$

$$\frac{\Delta T_{\rm kSZ}}{T_{\rm CMB}} = -\int \frac{v_\parallel}{c} \, d\tau_e$$

Key objectives with SO+ (initial ideas)

Case A: Dark matter vs. gas boundaries

- WL + redshifts (CLUMI+) measures the collisionless boundary (splashback).
- SO’s tSZ (thermal pressure) + kSZ (LOS momentum) measures the collisional boundary (accretion shock).
- Combining tSZ and kSZ + redshifts yields the radial entropy profile, whose jump is a robust signature of the shock.

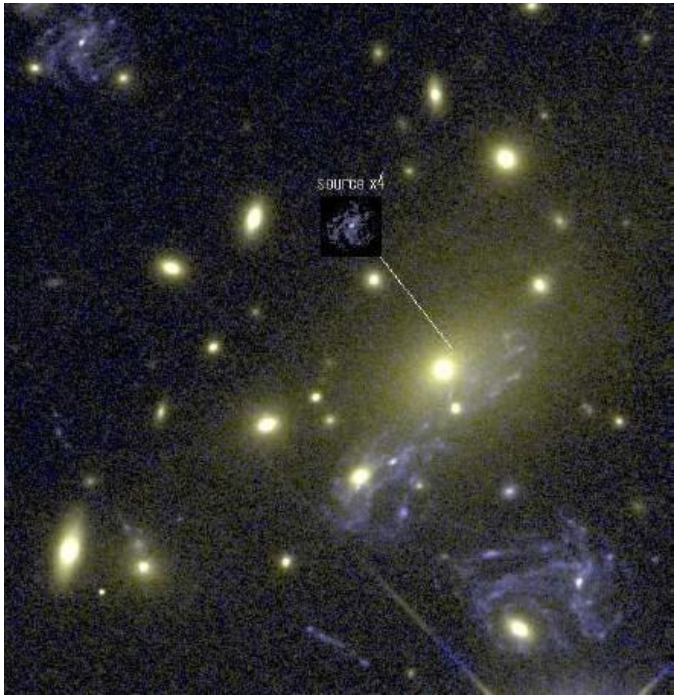
Case B: Infall kinematics in the transition region

- Compare collisionless infall velocities (from CLUMI+) with LOS electron momentum (from velocity-weighted cluster–satellite kSZ) to study where and how gas slows relative to the collisionless infall flow.

Weak lensing in galaxy clusters

Shape distortions (shear)

Magnification



- **Gravitational shear**
  - ✔ Shape distortion: $\delta e \sim \gamma$
- **Magnification bias**
  - ✔ Flux amplification: μF
  - ✔ Area distortion: $\mu \Delta\Omega$

Sensitive to "excess" mass density

$$\Sigma_{\rm cr}\gamma_+ = \Delta\Sigma(r_\perp) \equiv \Sigma(< r_\perp) - \Sigma(r_\perp)$$

Sensitive to "total" matter density

$$\mu \simeq 1 + 2\kappa; \quad \Sigma_{\rm cr}\kappa = \Sigma(r_\perp)$$