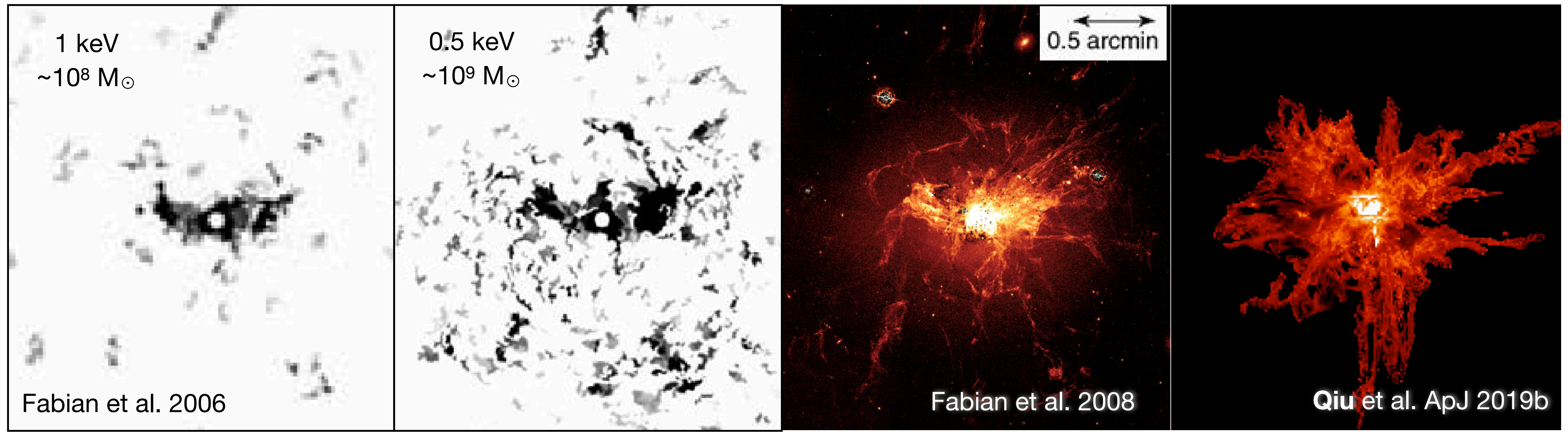
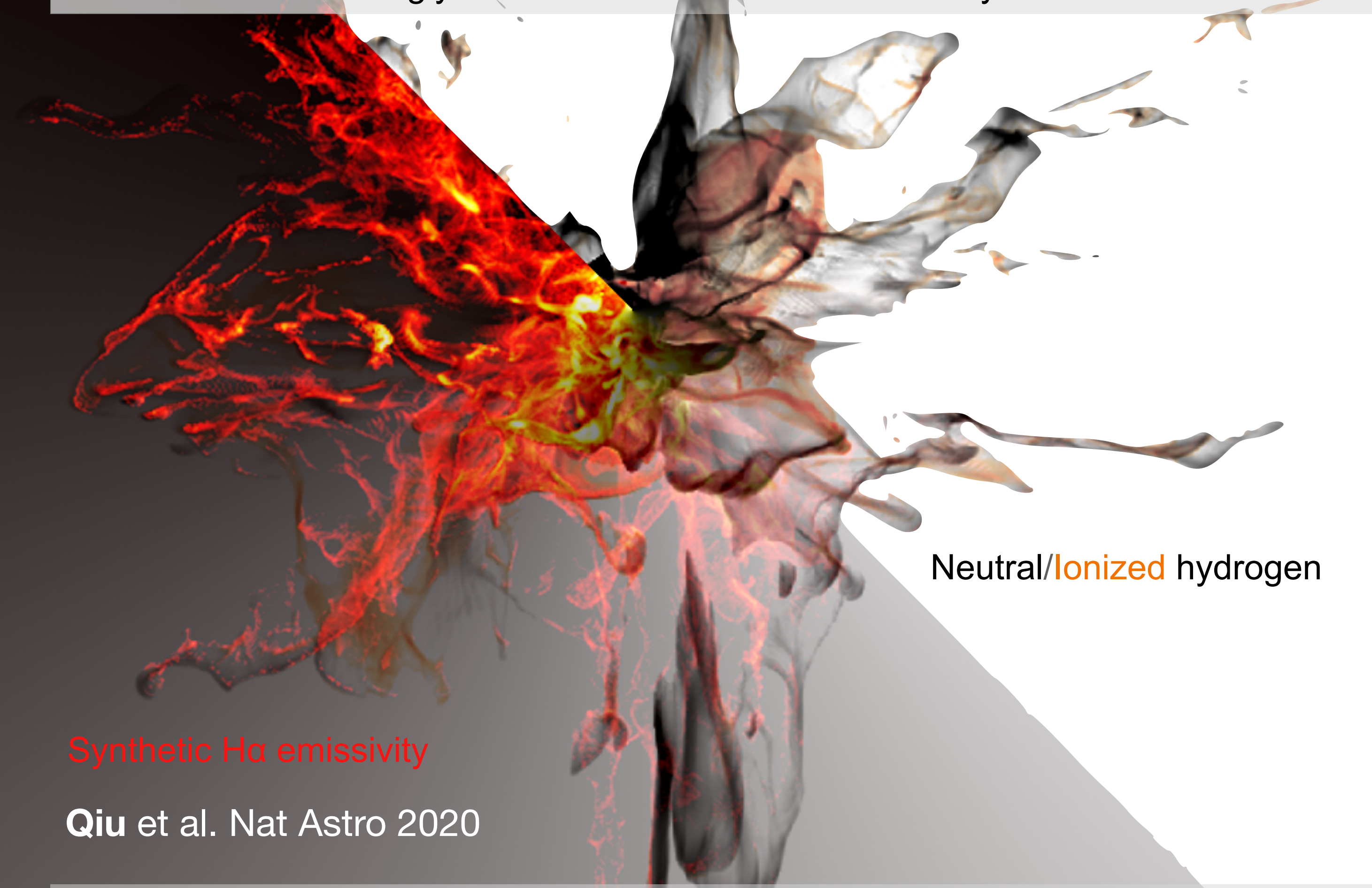
# Cold Gas in Outflow: Evidence for Delayed Positive AGN Feedback

邱宇 Qiu, Yu Kavli Institute for Astronomy and Astrophysics, Peking University Email: yuqiu@pku.edu.cn

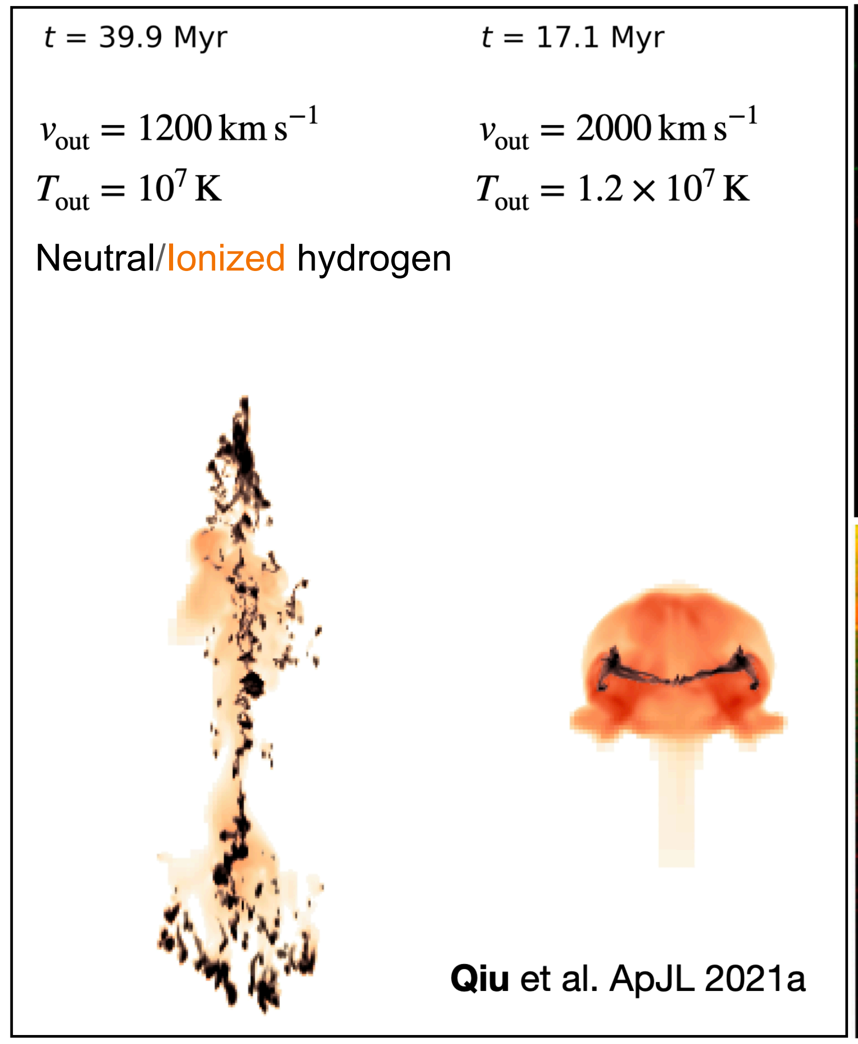
**Abstract** Multiphase outflows driven by active galactic nuclei (AGN) have a profound impact on the evolution of their host galaxies. The effects of AGN feedback are especially prominent in the brightest cluster galaxies (BCGs) of cool-core clusters, where there is a concentration of gas in all phases, ranging from cold molecular gas to hot, >10⁷ K ionized plasma. In this poster I describe recent simulation efforts to understand the formation and evolution of the 10-kpc-scale Hα-emitting filaments driven by AGN activities. Combined with observed star formation regions co-spatial with the filaments, this feedback mechanism can directly contribute to the growth of the central galaxy, albeit delayed by the characteristic radiative cooling timescale, ~10 Myr, of the outflowing plasma.

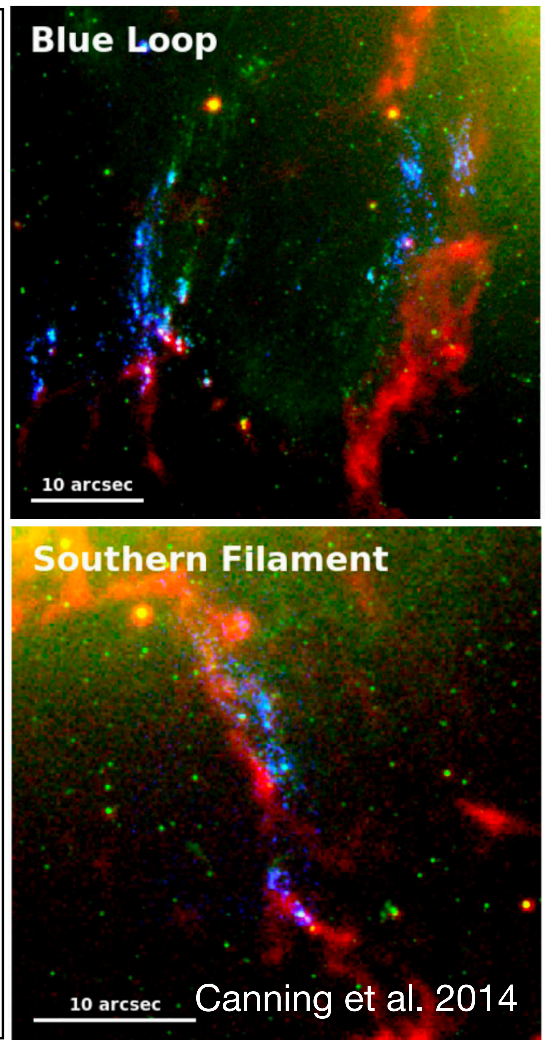



**Simulations** In order to study the impact of AGN feedback on the evolution of galaxy clusters, as well as to understand the origin of the cold filaments, in both radial and azimuthal formations, we performed a series of simulations using Enzo (Bryan et al. 2014) + Moray (Wise and Abel 2011). In the large-scale (~**Mpc**), long-duration (~**10 Gyr**) radiation-hydrodynamical simulations, we found that the AGN drives multiphase outflows that are responsible for both the X-ray cavities and the extended cold filaments in BCGs (Qiu et al. 2019b). **Positive correlations can be drawn between AGN luminosity and properties of the filaments**, such as filament mass, spatial extent, as well as Hα luminosity (Qiu et al. 2019a). The velocity dispersion of the filaments, however, depends primarily on the turbulent interactions between the ICM and the outflows, and are therefore not strongly correlated with the AGN luminosity.

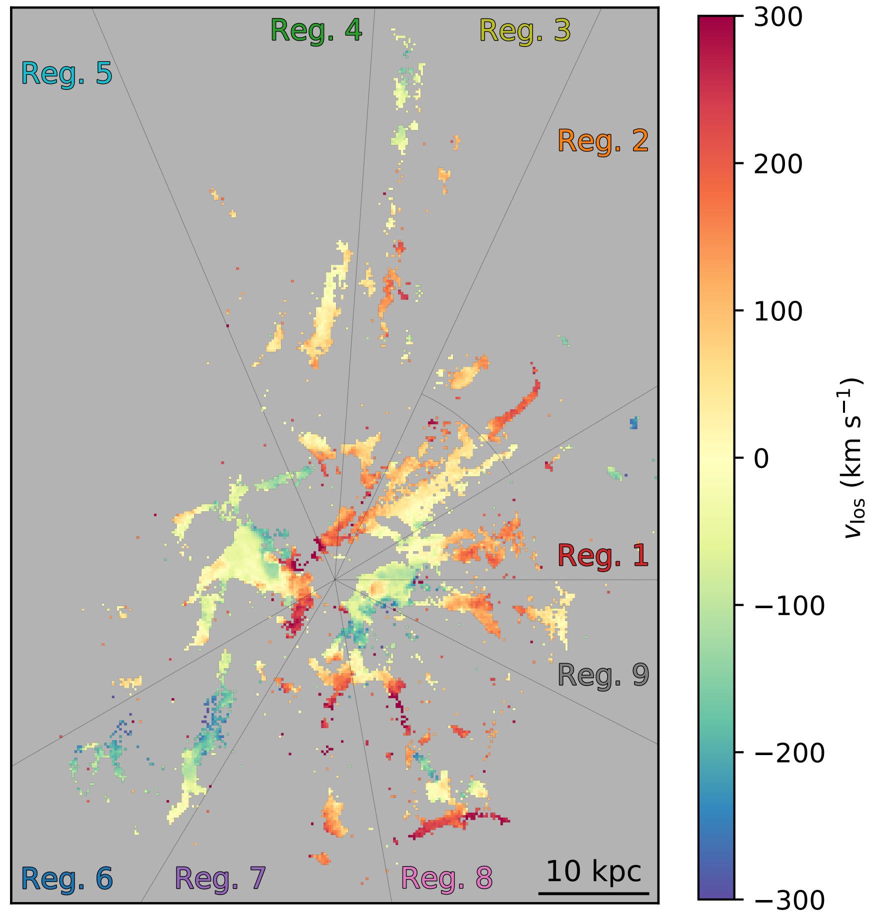


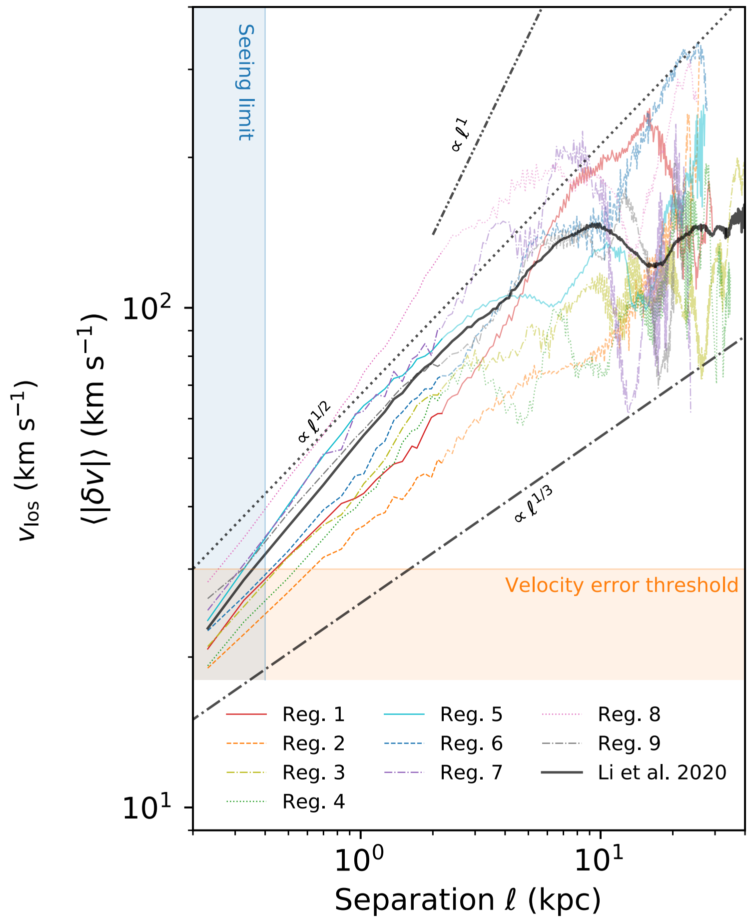

**Formation** The similarities between the simulated filamentary nebula and those in observations of the Perseus cluster motivated us to examine more closely the formation mechanism of the cold gas in a follow-up study (Qiu et al. 2020). A strong constraint from observations of the filaments is that the line-of-sight velocities are mostly below a few hundred km/s. Apart from the projection effect, if the cold gas were directly ejected from the nucleus, it requires both >1000 km/s speeds and unrealistically strong shielding from the shock heating and the hot ambient ICM to reach beyond 10 kpc. Our analysis however indicates that the **filaments form out of ionized AGN-driven outflows launched from the central 1 kpc**, with temperature <10⁷ K and characteristic cooling time below 10 Myr. Although the initial speeds are high, the ram pressure deceleration from the ICM significantly reduces the outflow velocity before cold gas forms about 10 kpc away from the nucleus.

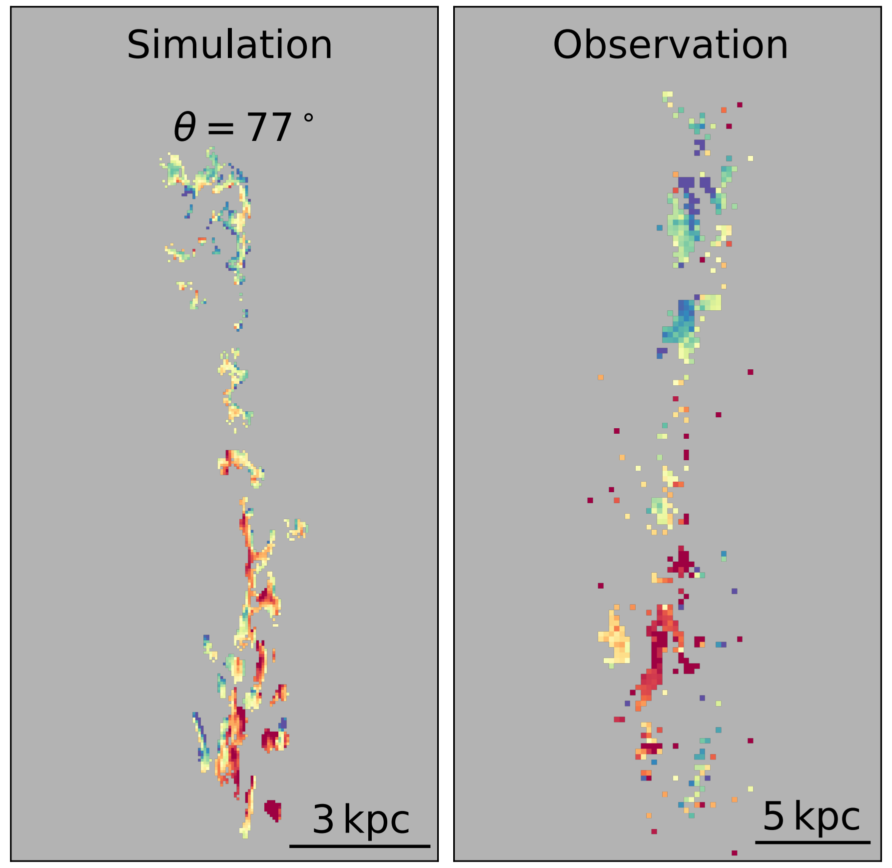



**Morphology** While the simulated filaments are visually similar to the observed filaments, the resolution required to study the filaments is much higher than those employed in cluster-scale simulations (~0.1 kpc, which is similar to or larger than the width of individual filaments). In order to characterize the filament evolution, as well as to resolve the interactions between the filament and the ambient plasma, we use high-resolution simulations (with the smallest resolution size of **~30 pc**) to further study the dynamical and morphological evolution of the cold gas in radiatively cooling AGN-driven outflows embed in the ICM (Qiu et al. 2021a). Using the parameter space found in Qiu et al. (2020) and the line-of-sight velocity constraints from observations, we vary the initial velocity and temperature of the outflowing plasma to examine the structure of the emergent cold gas. The evolution of the center of mass can be reasonably well described by a 1D model comprising radiative cooling and ICM ram pressure. In addition to longitudinal filaments parallel to the outflow direction, this study uncovered a mechanism for **transverse filaments perpendicular to the direction of motion** to form – when the outflowing plasma is marginally thermally stable between radiative cooling and heating through mixing with the ambient ICM. The ring of cold gas can potentially explain the origin of the **loop-like star formation region** in the Perseus cluster.

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**Turbulence** A follow up analysisrevealed the characteristic turbulent structure of the cold gas (Hu, Qiu et al. 2022). In this work, we compared the first order velocity structure functions (VSFs; mean velocity difference as a function of separation) of the simulated and observed filaments. The universal 1/2 slope of the VSFs is consistent with a **supersonic** origin of the cold gas, driven by the central AGN. Alternatively, if the cold gas forms due to subsonic motions of the ICM, the VSF slope is expected to be 1/3. The lack of a 1/3 slope **rules out the *in situ* formation scenario**. The dedicated high-resolution simulations also enabled a direct “deprojection” of the northern filament by examining the velocity gradient, which revealed a 77° inclination and a maximum cold gas speed of ~900 km/s.

**Summary** Using a series of simulations centered on the BCGs of cool-core clusters, we study the interplay between AGN feedback and the multiphase gas in the ICM. Our simulations indicate that the component of the outflow with characteristic cooling timescale below 10 Myr is responsible for the formation of the extended filamentary nebulae. Depending sensitively on the initial properties, both longitudinal and transverse filaments may form in the outflows. Evidently in the nearby Perseus cluster, some of the cold gas in these filaments has collapsed and formed stars in the recent few Myr. The feedback mechanisms uncovered in these works therefore demonstrate that AGN activities in gas rich environments, such as in the BCGs of galaxy clusters, can tightly control both the thermal balance of the hot gas reservoir and the scattered star formation in and around the hosts.