Self-regulated AGN feedback of light jets in cool-core galaxy clusters

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in collaboration with

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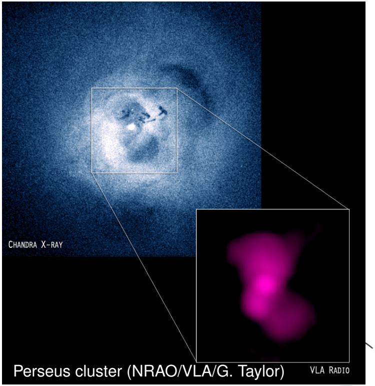
Outline

1. Observational clues and modeling
   - Basic facts
   - SZ effect of AGN bubbles
   - Modeling accretion and AGN jet
2. Simulating AGN jet feedback
   - Time evolution of global quantities
   - Morphology of AGN bubbles and cold gas
   - Conclusions

Feedback by AGN jets

Paradigm: accreting AGNs at the centers of cool core clusters launch relativistic jets, which self-regulate the cooling ICM $\Rightarrow$ **but how?**

- energy source: release of non-gravitational energy due to accretion on a black hole and its spin



Perseus cluster (NRAO/VLA/G. Taylor)

AIP

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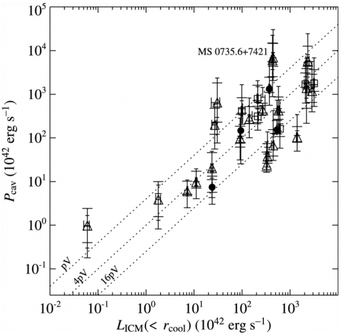
- correlation of AGN cavity power P_{cav} and X-ray luminosity $L_{\mathrm{ICM}}(< r_{\mathrm{cool}})$



Rafferty+ 2006

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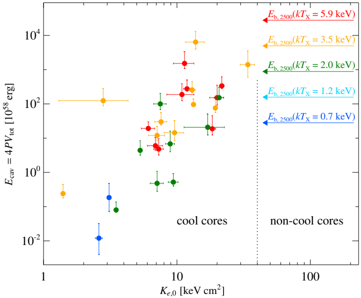
- AGN feedback heats slowly and does not transform a CC to a NCC: weak correlation of P_{cav} and entropy K_0



Pfrommer+ 2012

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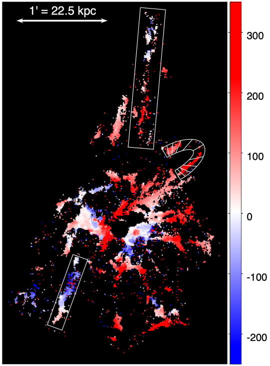
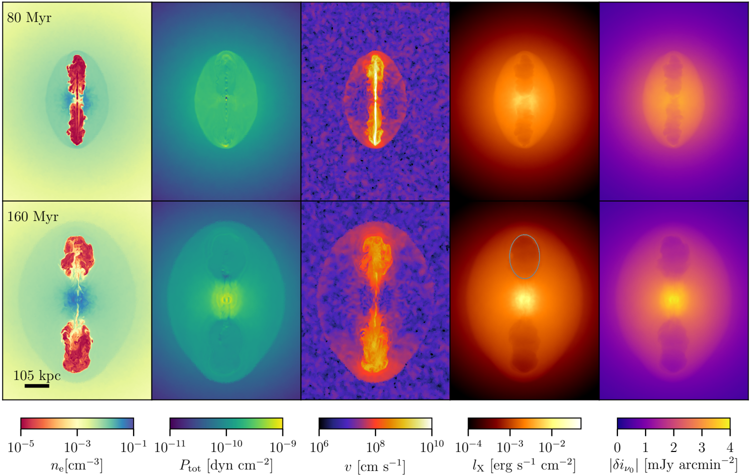
- AGN feedback heats slowly and does not transform a CC to a NCC: weak correlation of $P_{\rm cav}$ and entropy K_0
- elongated Hα filament morphology, rich velocity structure across the entire nebula without clear rotation



Gendron-Marsolais+ 2018: v [km s^{-1}]

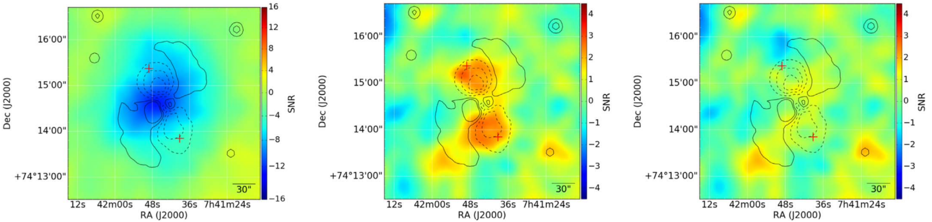
Are AGN jets heavy or light?



⇒ observe Sunyaev-Zel'dovich (SZ) effect of AGN outburst

analytical model: CP+ (2005); simulation: Ehlert, CP, Weinberger+ (2019)

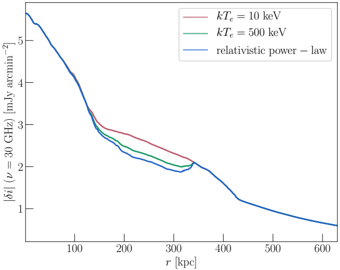
SPT observation of the major outburst in MS 0735



Abdulla+ (2019)

- *left:* point source-removed image of the total SZ signal
- *center:* the point sources and double-β model are removed: detection of the cavities
- *right:* residual image after removing point sources, double-β model and cavities: model accounts for nearly all of the observed signal

Probing AGN jet composition with the SZ effect



Ehlert, CP, Weinberger+ (2019)

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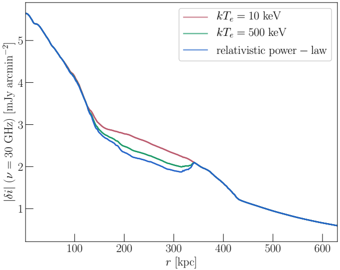

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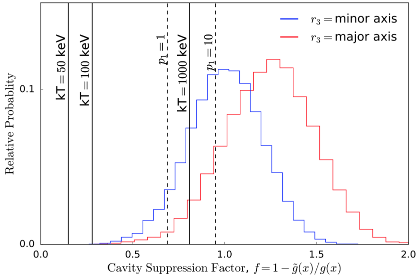

Abdulla+ (2019)

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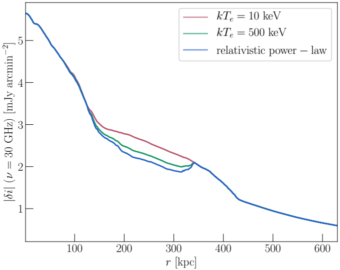
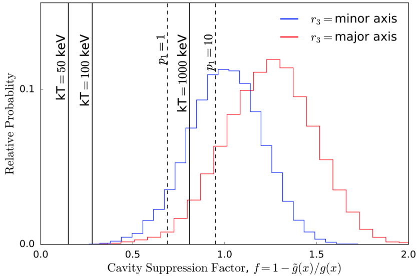


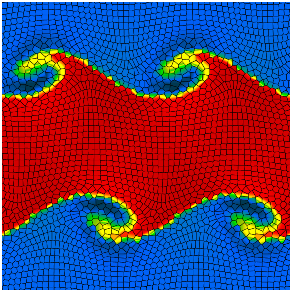
Ehlert, CP, Weinberger+ (2019)



Abdulla+ (2019)

- bubble filling must be relativistic: $T_{\mathrm{bubble}} \gtrsim 100\, T_{\mathrm{ICM}}$
- in pressure equilibrium: $n_{\mathrm{bubble}} \lesssim n_{\mathrm{ICM}}/100$
- AGN jets must be light: $n_{\mathrm{jet}} \lesssim n_{\mathrm{ICM}}/1000$
  (allowing for ICM entrainment)

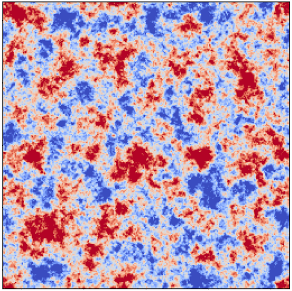
MHD jet simulations of Perseus-like cluster



AREPO: unstructured-mesh

- MHD moving-mesh code AREPO
- NFW cluster potential and isothermal central galaxy

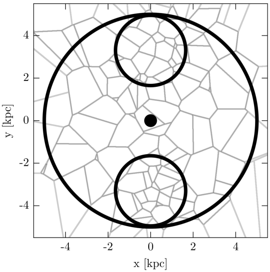
MHD jet simulations of Perseus-like cluster



initial magnetic field

- MHD moving-mesh code AREPO
- NFW cluster potential and isothermal central galaxy
- external turbulent magnetic and velocity fields (Kolmogorov)

MHD jet simulations of Perseus-like cluster



AREPO: jet injection region

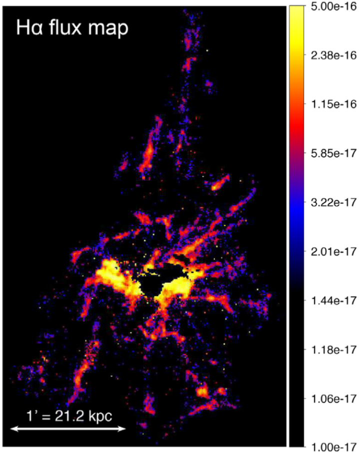
(Weinberger+ 2017)

- MHD moving-mesh code AREPO
- NFW cluster potential and isothermal central galaxy
- external turbulent magnetic and velocity fields (Kolmogorov)
- jet module
  - prepare low-density state in pressure equilibrium
  - inject kinetic energy and ***B***
  - refine to sustain density contrast

Modelling accretion onto the AGN

- Bondi accretion model:

$$\dot{M}_{\rm bondi} = \frac{4\pi G^2 M^2 \rho}{c_s^3}$$



Gendron-Marsolais+ (2018)

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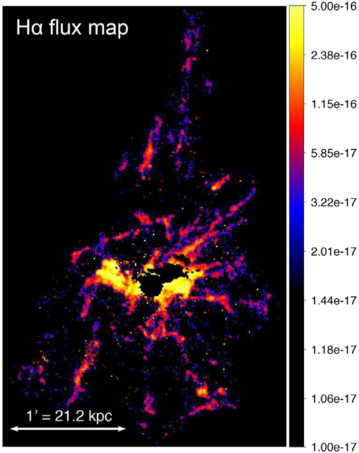
- cold accretion model (`Fiducial`):

$$\dot{M}_{\rm cold} = \epsilon \frac{M_{\rm cold}}{t_{\rm ff}}$$



Gendron-Marsolais+ (2018)

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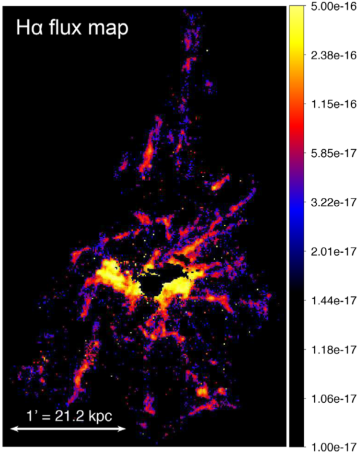
- jet power:

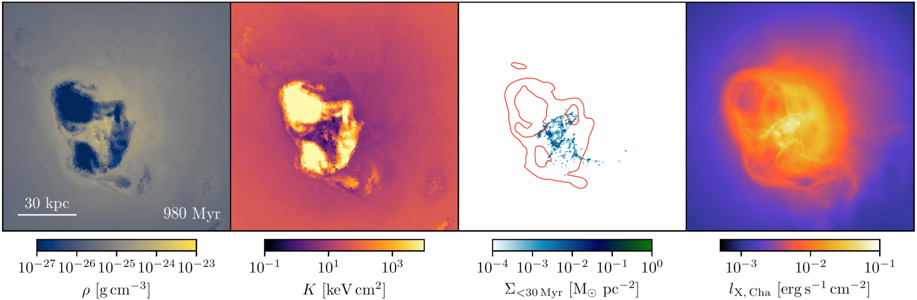
$$L_{\text{jet}} = \eta \dot{M} c^2$$



Gendron-Marsolais+ (2018)

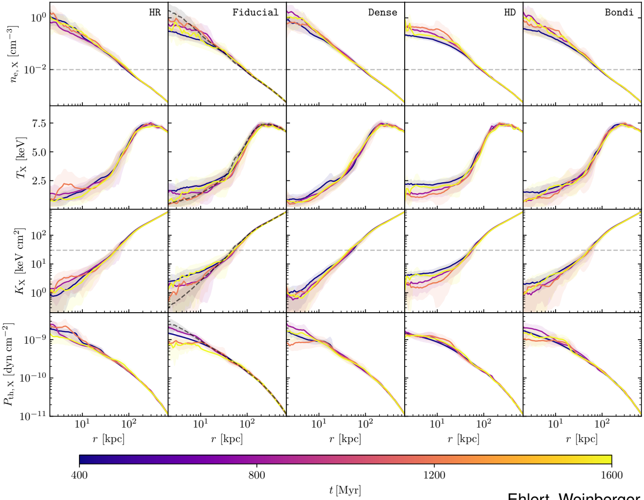
Cold accretion powering low momentum-density jets

Jet simulation: gas density, entropy, cold gas ($t_{\rm cool} < 30$ Myr), X-ray surface brightness



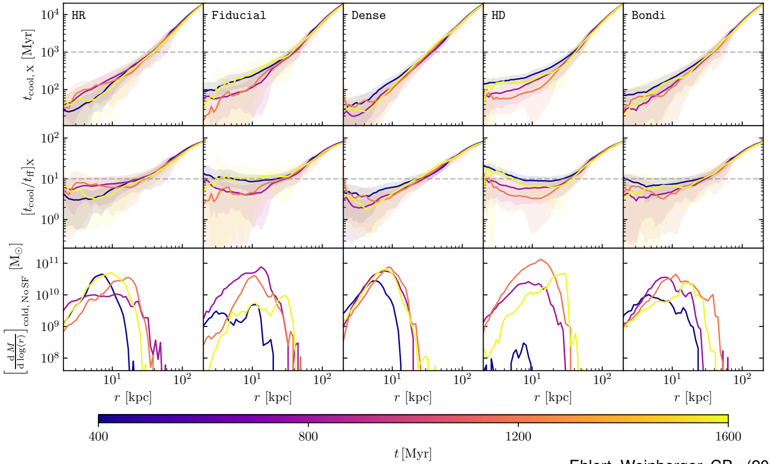
Ehlert, Weinberger, CP+ (2022), movie by Jlassi

Jet models all self-regulate ICM in a cool core state



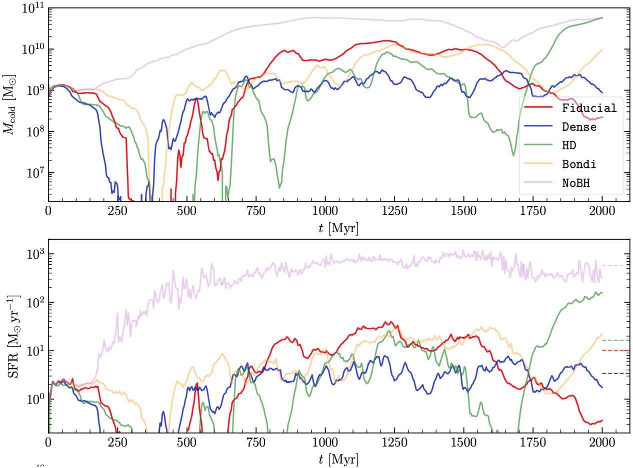
Ehlert, Weinberger, CP+ (2022)

Cooling times and cold gas distribution ($t_{\rm cool} < 100$ Myr)



Ehlert, Weinberger, CP+ (2022)

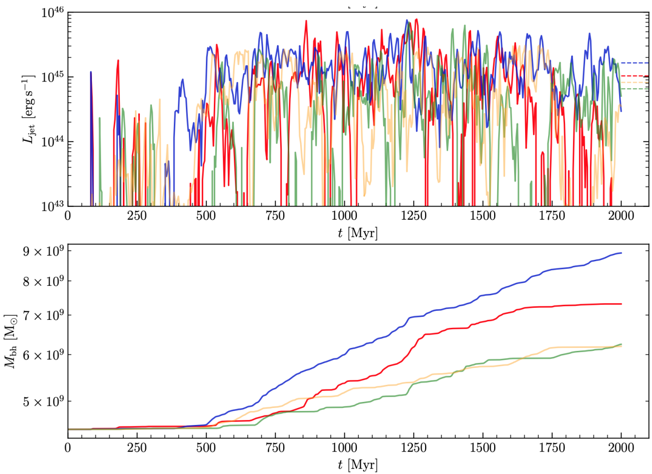
Cold gas mass and star formation rates



Fiducial, Dense, HD, Bondi

(Ehlert, Weinberger, CP+ 2022)

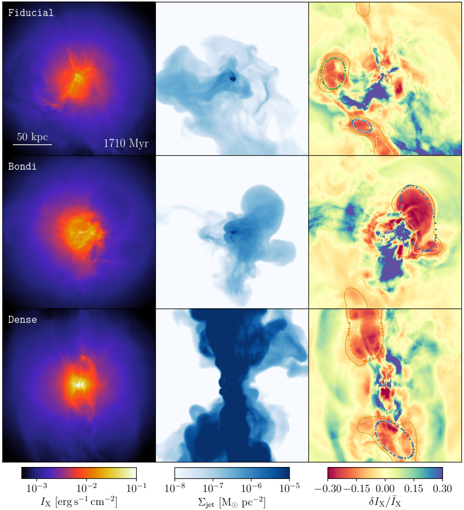
Jet luminosity and black hole growth



Fiducial, Dense, HD, Bondi

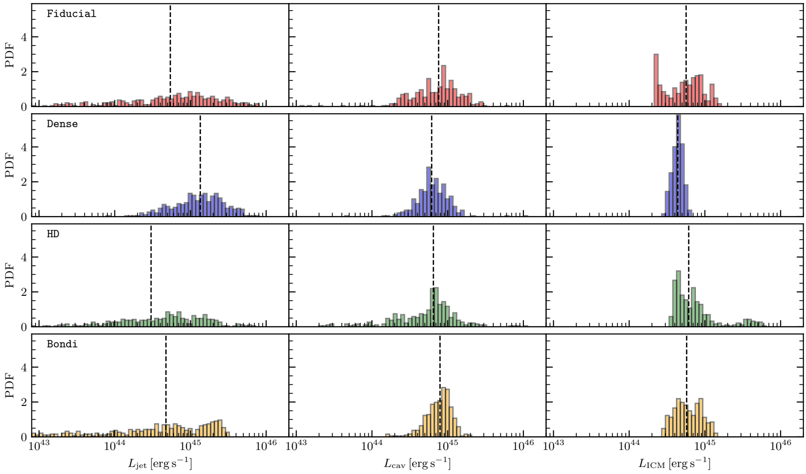
(Ehlert, Weinberger, CP+ 2022)

X-ray emissivity, jet material and bubble morphologies



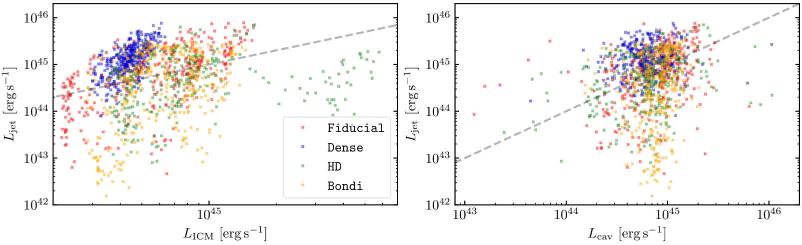
Ehlert, Weinberger, CP+ (2022)

Distributions of jet, cavity, and ICM cooling power



Ehlert, Weinberger, CP+ (2022)

Correlating jet, cavity, and ICM cooling power



Ehlert, Weinberger, CP+ (2022)

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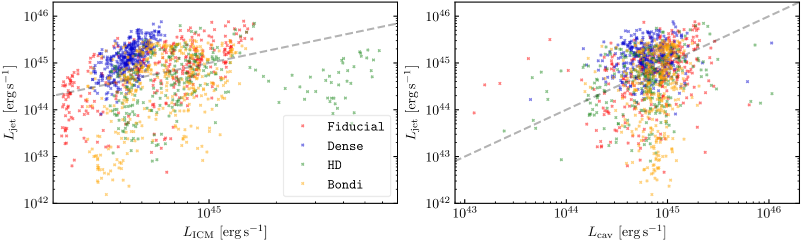
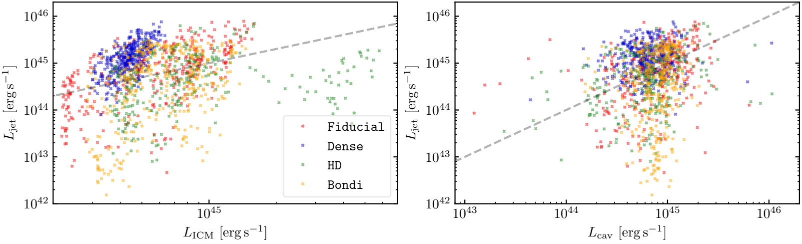


Ehlert, Weinberger, CP+ (2022)

- jet powers do not always match the current cooling luminosity
  ⇒ self-regulation is achieved on average on longer timescales
- the hydrodynamical run (HD) shows a phase of stronger cooling, which corresponds to a forming disk

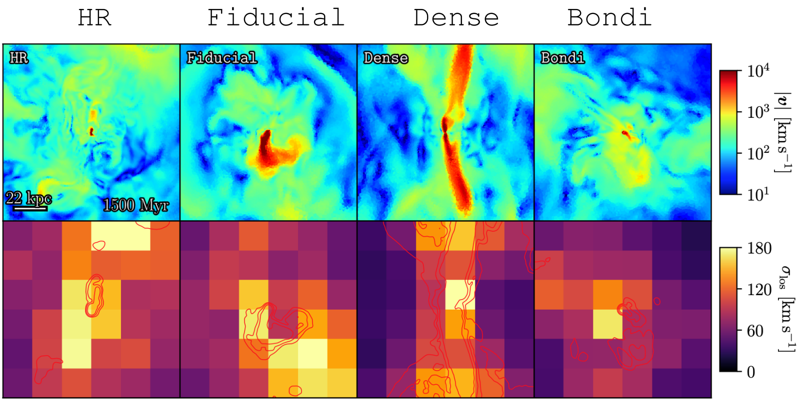
Correlating jet, cavity, and ICM cooling power



Ehlert, Weinberger, CP+ (2022)

- jet powers do not always match the current cooling luminosity
  $\Rightarrow$ self-regulation is achieved on average on longer timescales
- the hydrodynamical run (HD) shows a phase of stronger cooling, which corresponds to a forming disk
- observationally we can only recover two orders of magnitude of cavity powers while jet powers span four orders of magnitude

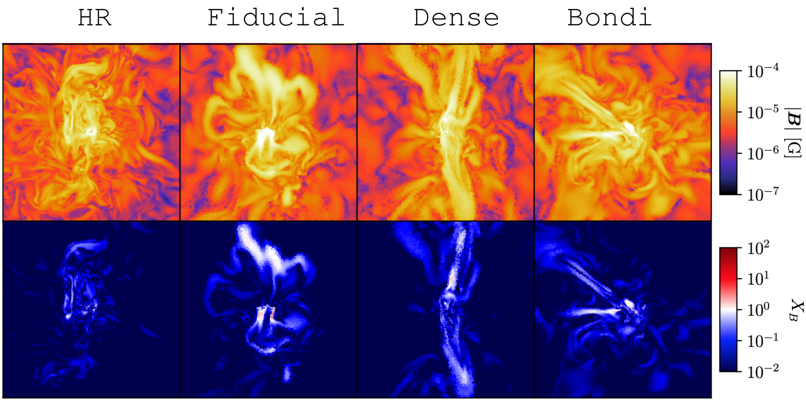
Velocity distributions: magnitude and dispersion



Ehlert, Weinberger, CP+ (2022)

- ***low-density jets are isotropizing ICM velocities,*** high-density jets cause bimodal outflows

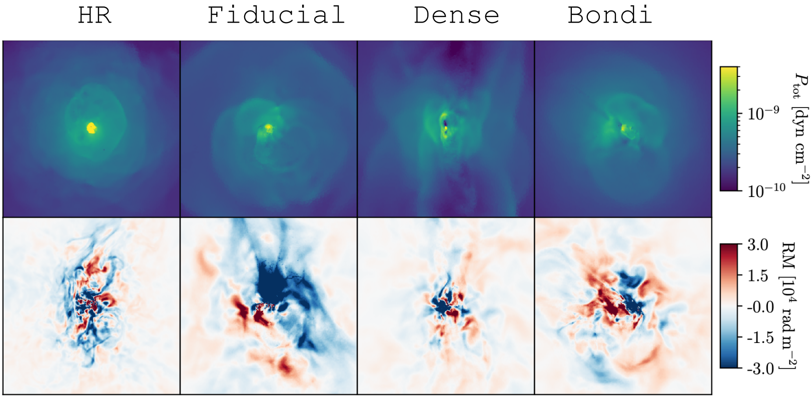
Magnetic fields



Ehlert, Weinberger, CP+ (2022)

- ***converging flows in bubble wake amplify magnetic fields*** so that the magnetic-to-thermal pressure ratio X_B approaches unity

Shocks and Faraday rotation measure (RM)

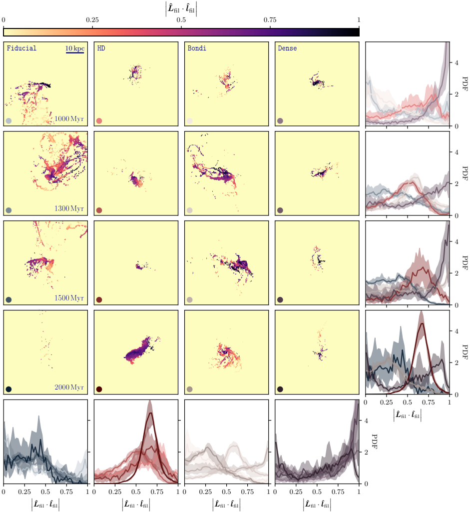


Ehlert, Weinberger, CP+ (2022)

- ***AGN jets drive shocks into the ICM,***
  high-resolution necessary to generate small-scale RM structure

Angular momentum distribution of cold gas

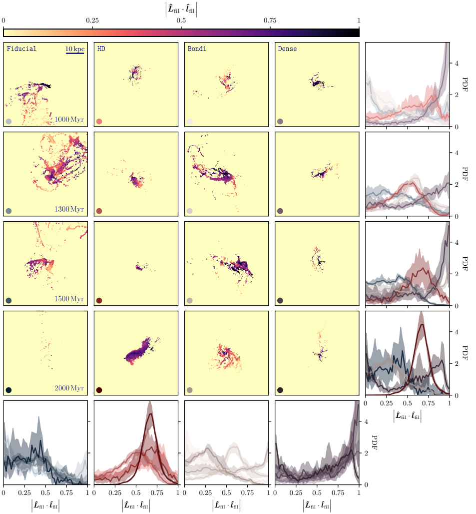
- columns show different models, rows different times
- magnetic fields cause elongated cold gaseous filaments



Ehlert, Weinberger, CP+ (2022)

Angular momentum distribution of cold gas

- columns show different models, rows different times
- magnetic fields cause elongated cold gaseous filaments
- HD and Dense models have rotationally supported cold gas, i.e., large alignment of the total angular momentum with that of computational cells



Ehlert, Weinberger, CP+ (2022)

Conclusions

AGN jet simulations of idealized Perseus cluster:

- SZ observation of AGN outburst suggests light jet composition $\rightarrow$ cold filaments easily deflect jets $\rightarrow$ isotropic bubble distributions and more efficient ICM heating

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AIP

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- cluster core self-regulates with central entropies and cooling times consistent with observations independent of the probed accretion model, accretion efficiency, jet density and resolution
- simulated cavity luminosities reflect ICM cooling luminosities and averaged jet powers; insensitive to short periods of low-luminosity jet injection

Literature for the talk

AGN jet feedback in galaxy clusters:

- Ehlert, Weinberger, Pfrommer, Pakmor, Springel, *Self-regulated AGN feedback of light jets in cool-core galaxy clusters,* 2022, subm.
- Weinberger, Su, Ehlert, Pfrommer, Hernquist, Bryan, Springel, Li, Burkhart, Choi *Active galactic nucleus jet feedback in hydrostatic halos,* in prep.
- Ehlert, Pfrommer, Weinberger, Pakmor, Springel, *The Sunyaev-Zel'dovich effect of simulated jet-inflated bubbles in clusters,* 2019, ApJL, 872, L8.

PICOGAL: From Plasma KInetics to COsmological GALaxy Formation

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