Complex outflows, simple relations

how $M - \sigma$ emerges in a turbulent environment
(A&A, submitted)

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$M - \sigma$ relation

- A fundamental connection between the mass of the SMBH and the velocity dispersion of its host galaxy spheroid:

$$M_{\rm BH} \simeq 3 \times 10^8 \left(\sigma_* / 200 {\rm km/s}\right)^{\alpha} \, M_{\odot}; \quad \alpha \sim 4 - 5 \qquad (1)$$

- Established as early as $z \sim 6$, hardly any evolution with redshift
- Cannot be explained by gravity, because SMBH gravitational influence reaches ~ 20 pc $\ll R_{\rm spheroid}$
- Most likely evidence of energetic feedback from SMBH growth during luminous accretion

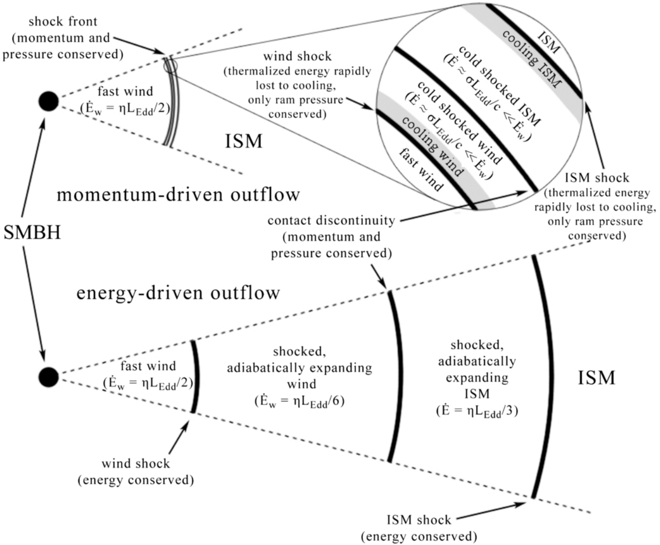
AGN wind-driven feedback

- Ultra-fast (quasi-relativistic) wide-angle winds in AGN discovered in 2003 (Pounds et al. 2003)
- Common in AGN (Tombesi et al. 2013)
- Velocity $v_{\rm w} \sim 0.1c$, kinetic power $\sim 0.05 L_{\rm AGN}$
- Freely streams for tens to hundreds pc (Costa et al. 2020), then shocks against relatively static ISM
- Shock temperature $T_{\rm sh} \sim 10^{10}$ K, can only cool by inverse Compton scattering (King 2003)

Momentum versus energy driving

- If cooling is efficient ($t_{\rm cool} < t_{\rm expansion}$), only wind momentum rate $\dot{p}_{\rm w} \sim L_{\rm AGN}/c$ is transferred to the surrounding ISM
- Momentum-driven outflow can only expand to large distances if $L_{\rm AGN} > L_{\rm crit}$ (Murray et al. 2005)
- Equating $L_{\rm AGN}$ with $L_{\rm Edd}$ gives a condition on $M_{\rm BH}$ which is remarkably close to the observed $M - \sigma$ relation: $M_\sigma \simeq 3 \times 10^8 \left(\sigma/200{\rm km/s}\right)^4\ M_\odot$ (King 2003, 2010)
- Conversely, inefficient cooling leads to much more powerful outflows with properties comparable to many observed large-scale outflows (Zubovas & King 2012)
- How do we get both momentum- and energy-driven outflows?

Momentum versus energy driving

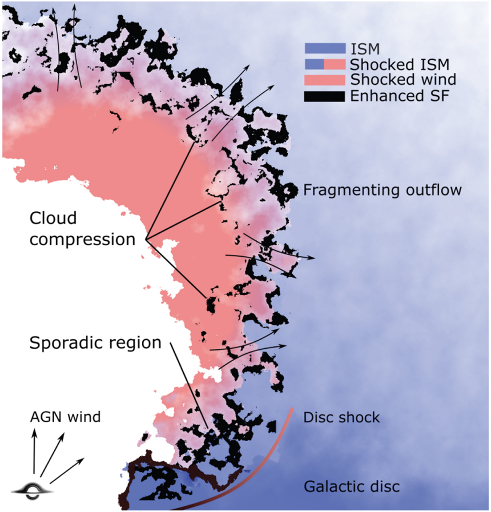


KZ+King (2012)

Cooling vs turbulence

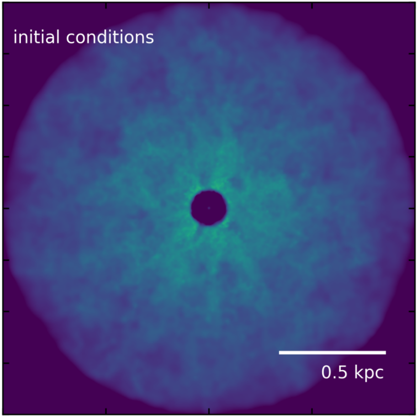
- Original idea: cooling efficient within some radius $R_C \sim 500$ pc, so only momentum-driven outflows exist inside; when they reach this radius, they transition to energy-driven (King 2003)
- Two problems:
  - Massive powerful outflows detected at smaller radii
  - Shocked wind plasma is two-temperature, cools very inefficiently, $R_C \ll 1$ pc (Faucher-Giguère & Quataert 2012)
- Alternate idea: in a turbulent ISM, energy-driven outflow expands through low-density channels, leaving dense clumps behind; they are exposed to wind momentum only (Zubovas & Nayakshin 2014)

Outflow in a turbulent medium



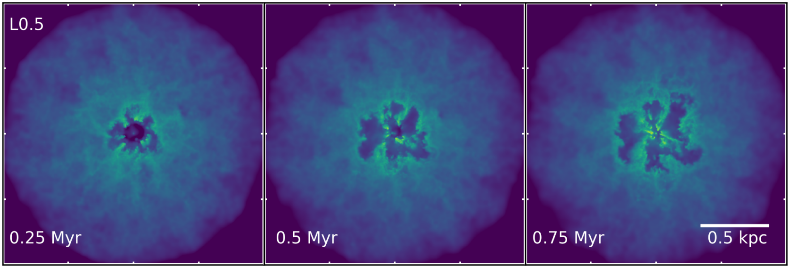
Laužikas+KZ (2024)

Simulation setup

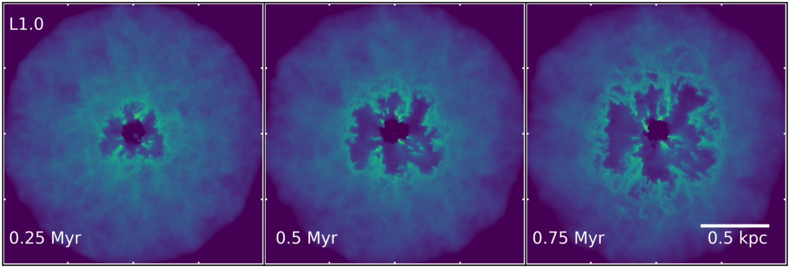


- SMBH, $M_{\mathrm{BH}} = 10^8\, M_\odot = M_\sigma$
- Background isothermal gravitational potential with $\sigma = 142$ km s^{-1}
- Turbulent gas shell between $R_{\mathrm{in}} = 0.1$ kpc and $R_{\mathrm{out}} = 1$ kpc, total mass $M = 9.4 \times 10^8\, M_\odot$ ($f_{\mathrm{g}} = 0.1$)
- AGN luminosity $L = \{0.1 - 2.5\} L_{\mathrm{Edd}}\, (M_\sigma)$

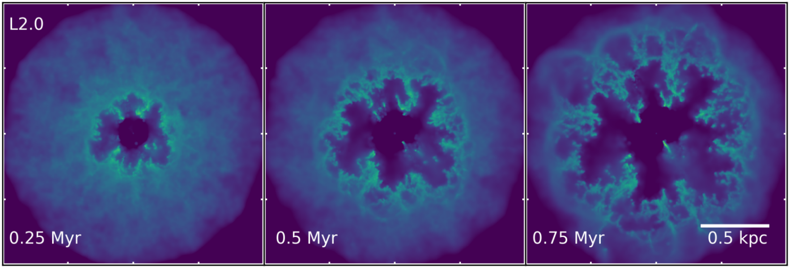
Density evolution



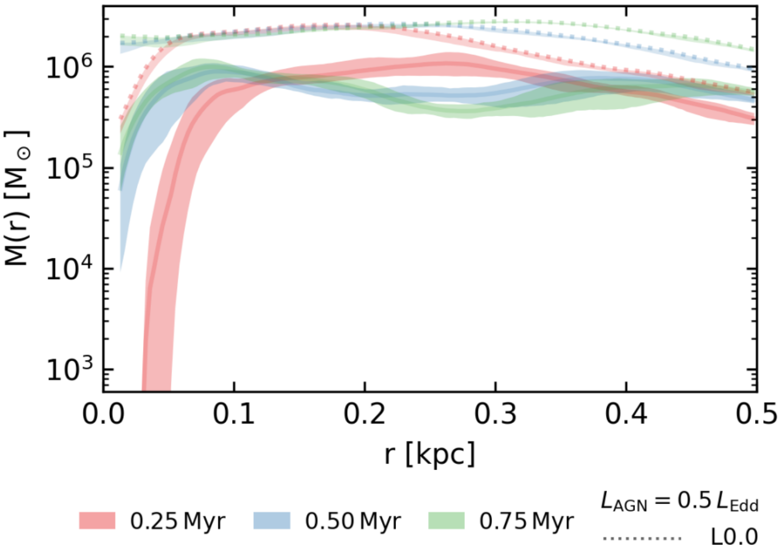
Density evolution



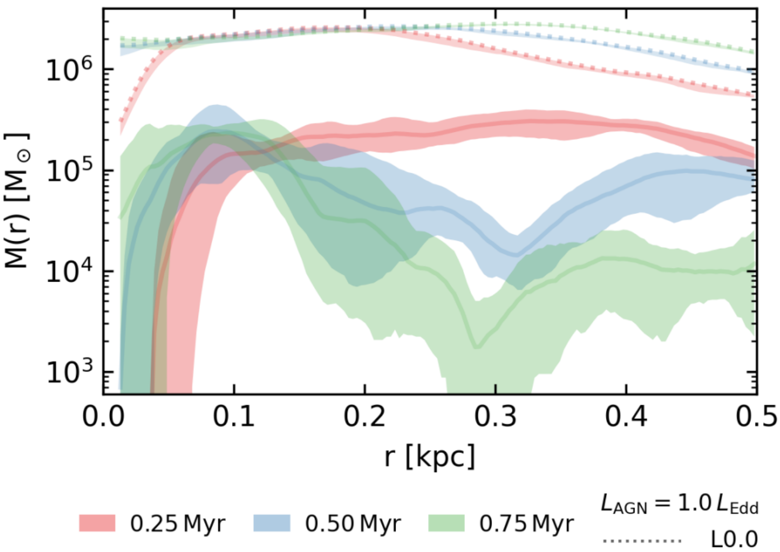
Density evolution



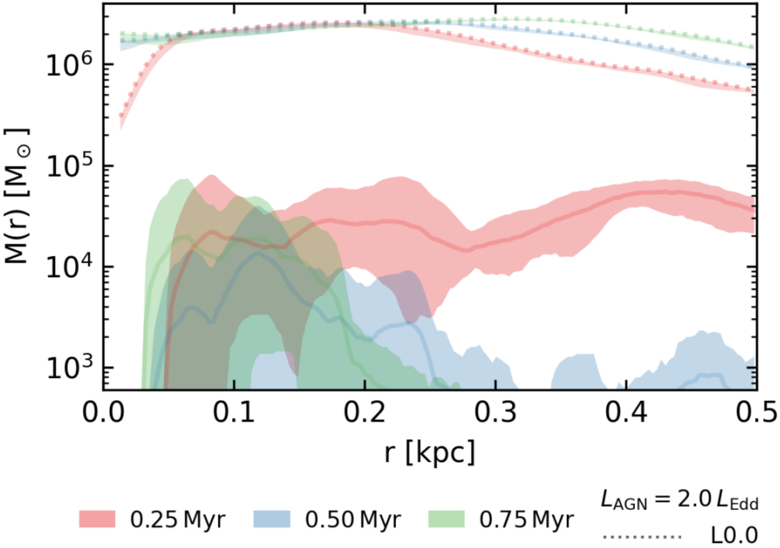
Mass profiles - L0.5



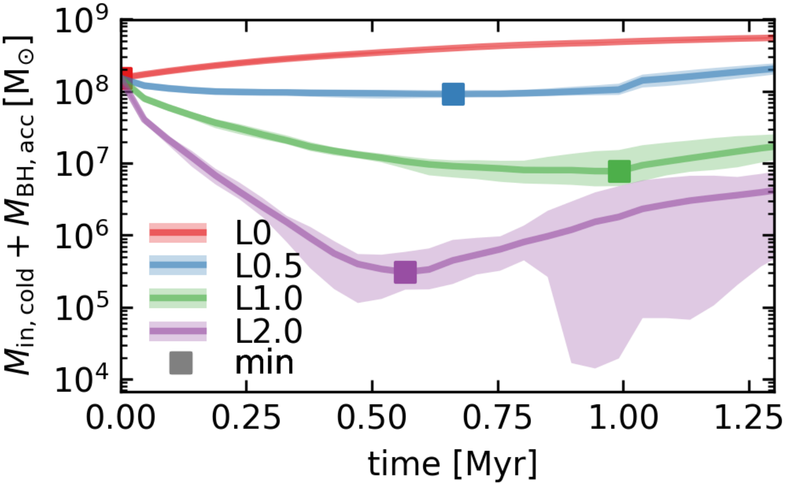
Mass profiles - L1.0



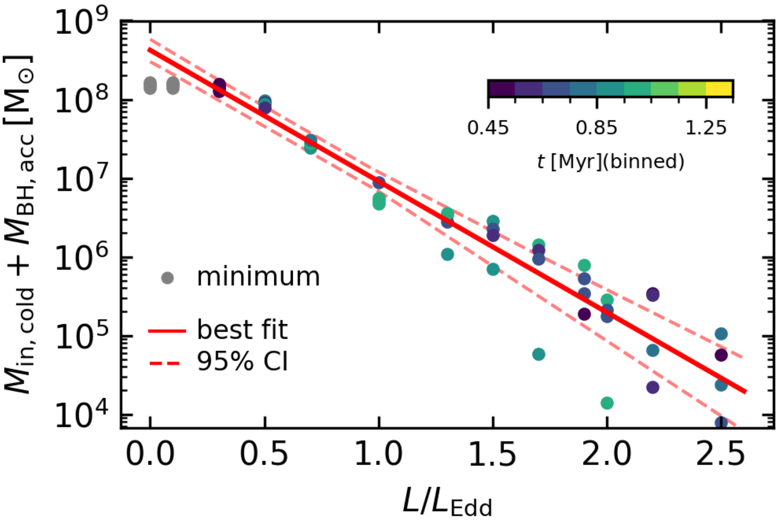
Mass profiles - L2.0



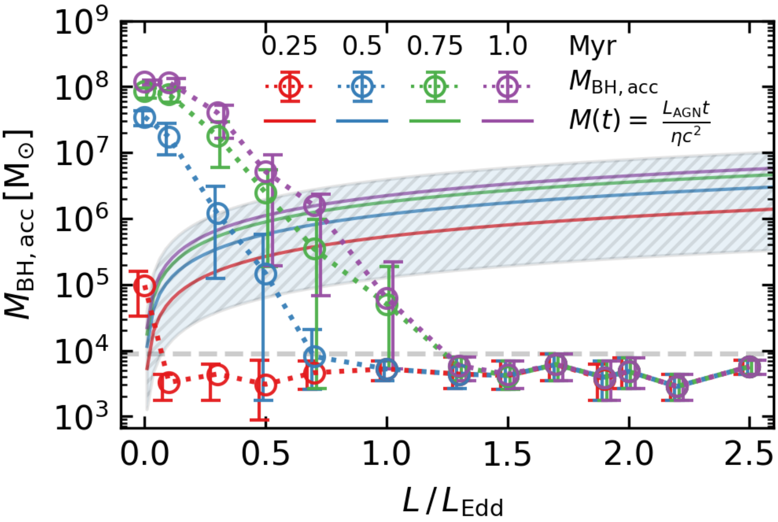
Cold gas mass evolution



Cold gas mass



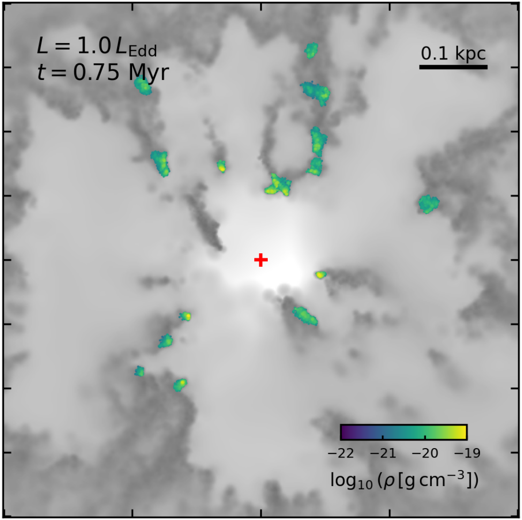
SMBH growth


0.25
0.5
0.75
1.0
Myr
$M_{\mathrm{BH,\,acc}}$
$M(t) = \frac{L_{\mathrm{AGN}} t}{\eta c^2}$
10^9
10^8
10^7
10^6
10^5
10^4
10^3
$M_{\mathrm{BH,\,acc}}\,[\mathrm{M}_\odot]$
0.0
0.5
1.0
1.5
2.0
2.5
$L\,/\,L_{\mathrm{Edd}}$

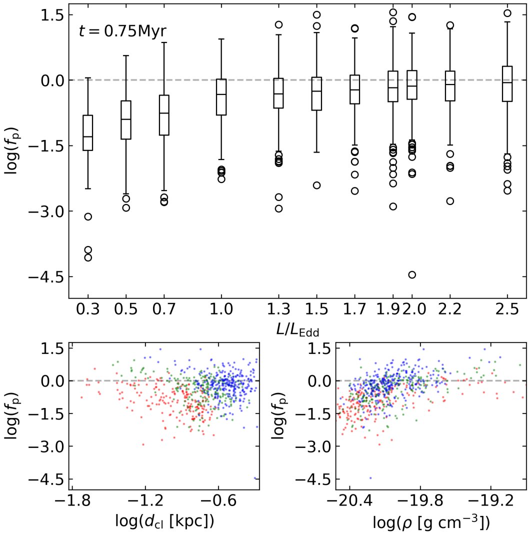
Global gas response to outflow

- AGN with $L_{\rm AGN} \lesssim 0.7 L_{\rm Edd}$ inflate outflows, but do not stop cold gas infall
- AGN with $L_{\rm AGN} \simeq L_{\rm Edd}$ stall cold gas infall and remove cold diffuse gas, but cannot prevent cold dense filament accretion
- An AGN needs $L_{\rm AGN} \gtrsim 1.7 L_{\rm Edd}$ to quench further SMBH growth, even when the shocked wind energy is not radiated away

Effect on clusters



Effect on clusters

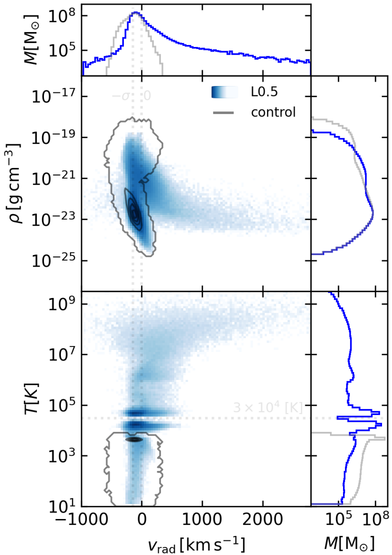


Summary

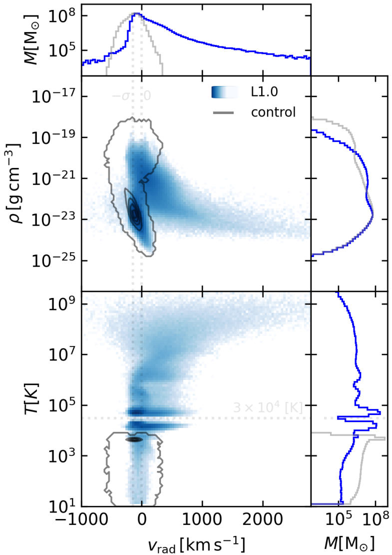
- An outflow driven by AGN wind energy input, carrying a total of $\sim 0.02 L_{\rm Edd}$ kinetic power, deposits most of this power into diffuse gas and inflates large bubbles, while dense gas clouds and filaments remain exposed primarily to the wind momentum
- This result allows both energy-driven and momentum-driven outflows to coexist in the same object, the first leading to massive observed gas flows, the second providing a condition for establishing the $M - \sigma$ relation
- Rather idealised tests so far, many steps needed to create self-consistent simulations following the whole feedback loop; we're working on it!

Bonus slides

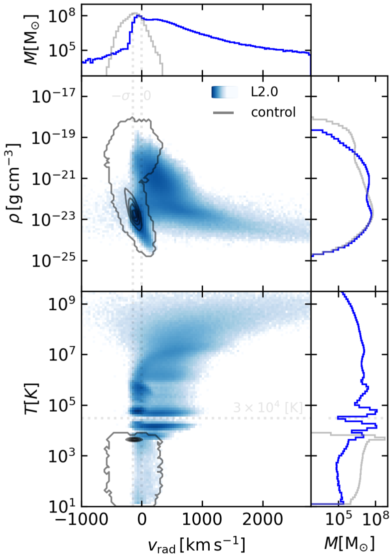
Phase plots - L0.5



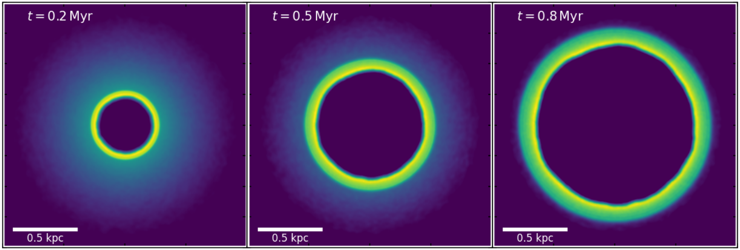
Phase plots - L1.0



Phase plots - L2.0

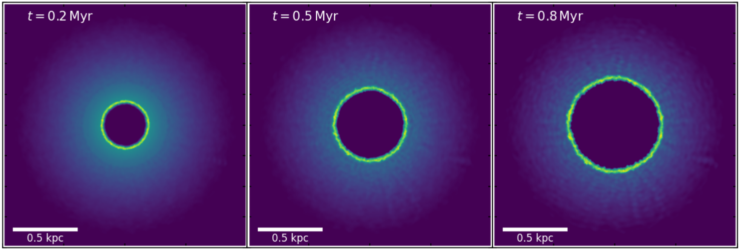


Simpler outflows - smooth, adiabatic



KZ, Tartėnas, Bourne (2024)

Simpler outflows - smooth, cooling



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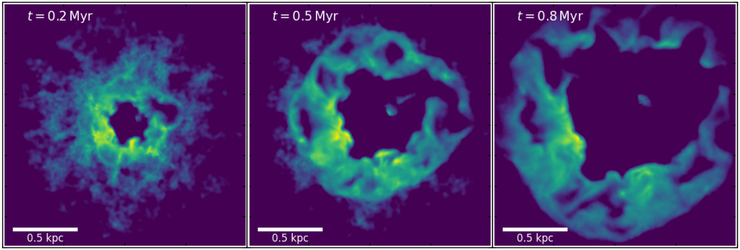
Simpler outflows - turbulent, adiabatic



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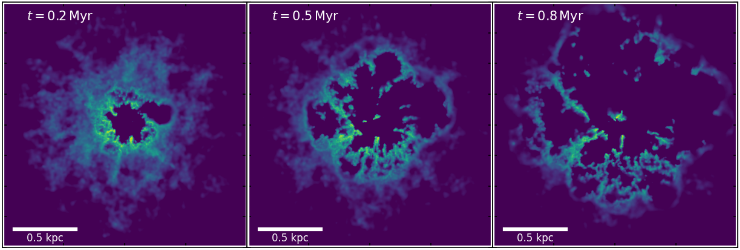
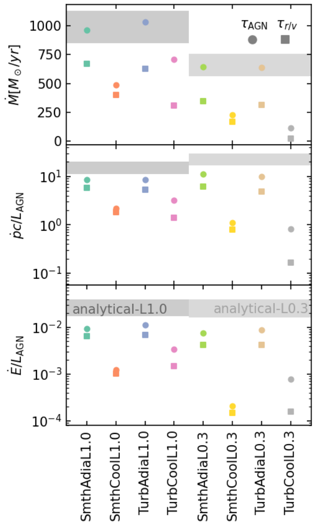
Simpler outflows - turbulent, cooling



KZ, Tartėnas, Bourne (2024)

Simpler outflows - coupling efficiencies



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