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AGN-Driven Outflow Scaling Relations: Robust Mass Outflow Rate Measurements from Simulations

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Motivation

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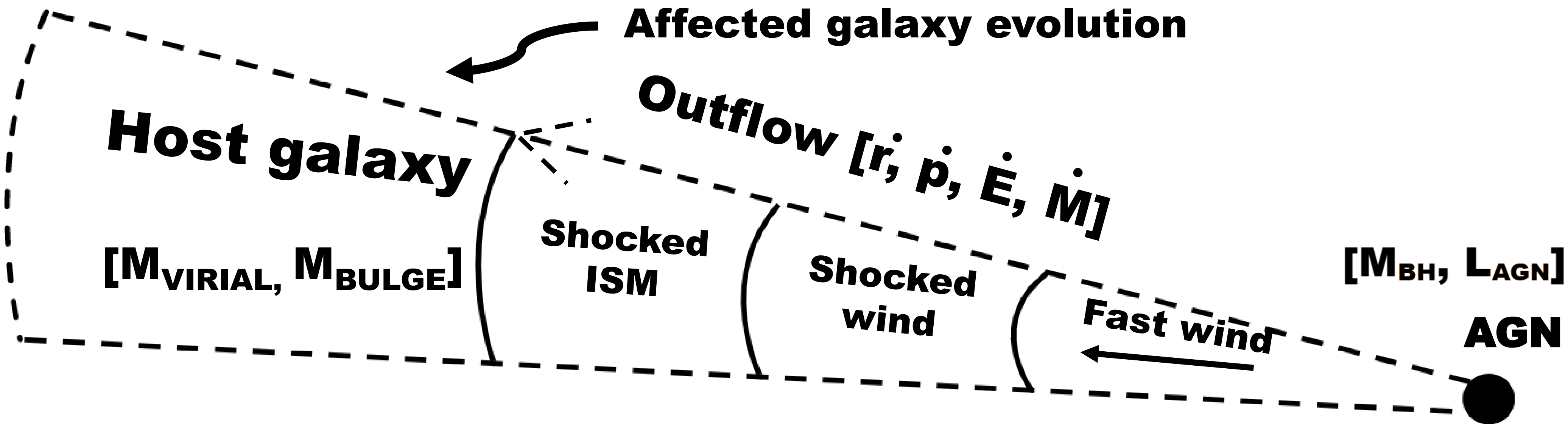
Mass outflow rate $\dot{M}$ is a **key tracer** of feedback and galaxy evolution. It **links feedback** processes (e.g. AGN activity) to galaxy-scale properties (such as SFR).

By combining **idealized simulations** and the cosmological **IllustrisTNG50** model, we test how outflow-rate measurements depend on both physical drivers and measurement methodology.



Simulation data: IllustrisTNG

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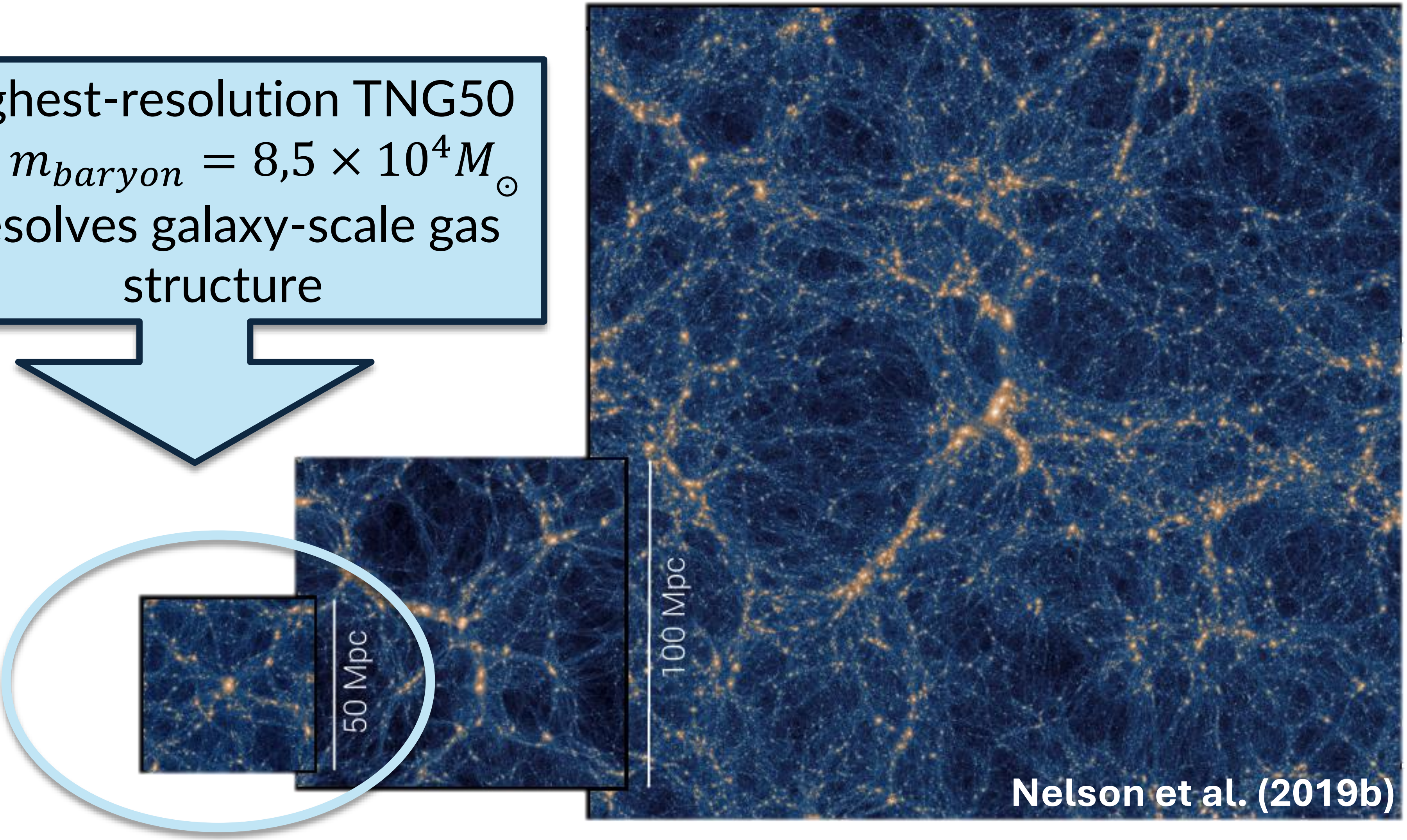
- Highest-resolution TNG50 run $m_{baryon} = 8{,}5 \times 10^4 M_{\odot}$
- Resolves galaxy-scale gas structure



What defines an outflow?

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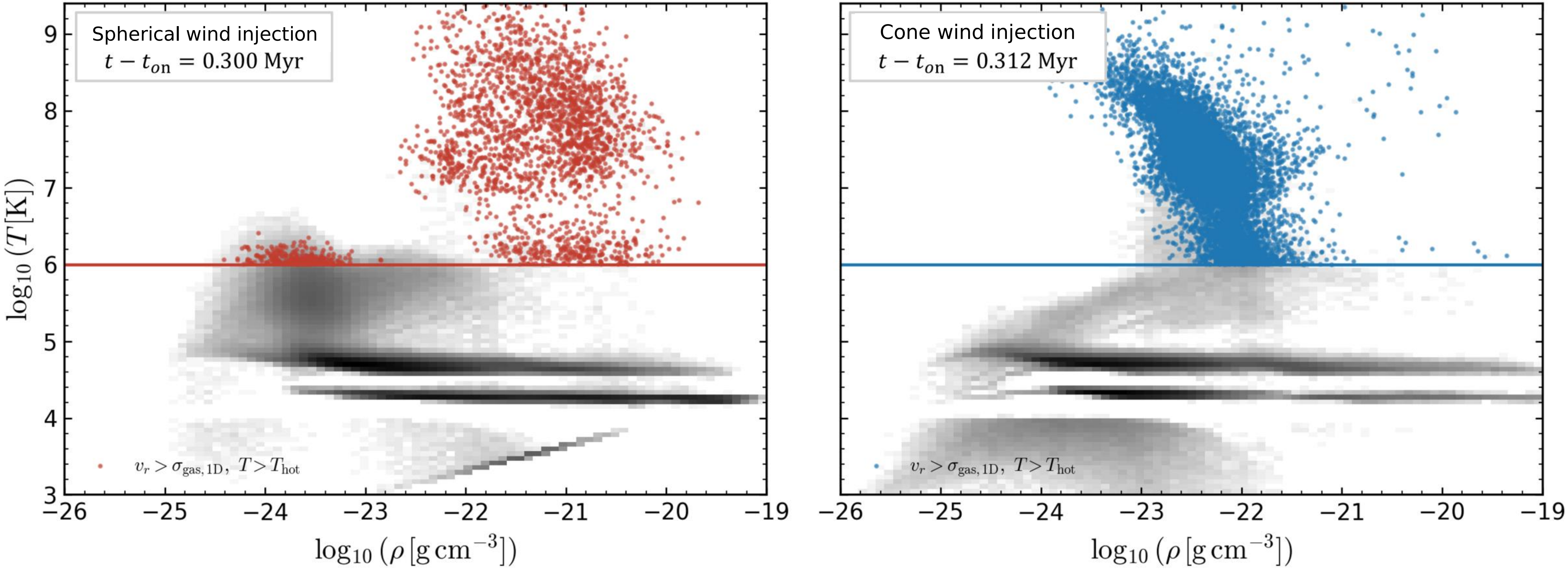
Two SPH simulations with different geometries were used to test outflow selection criteria.

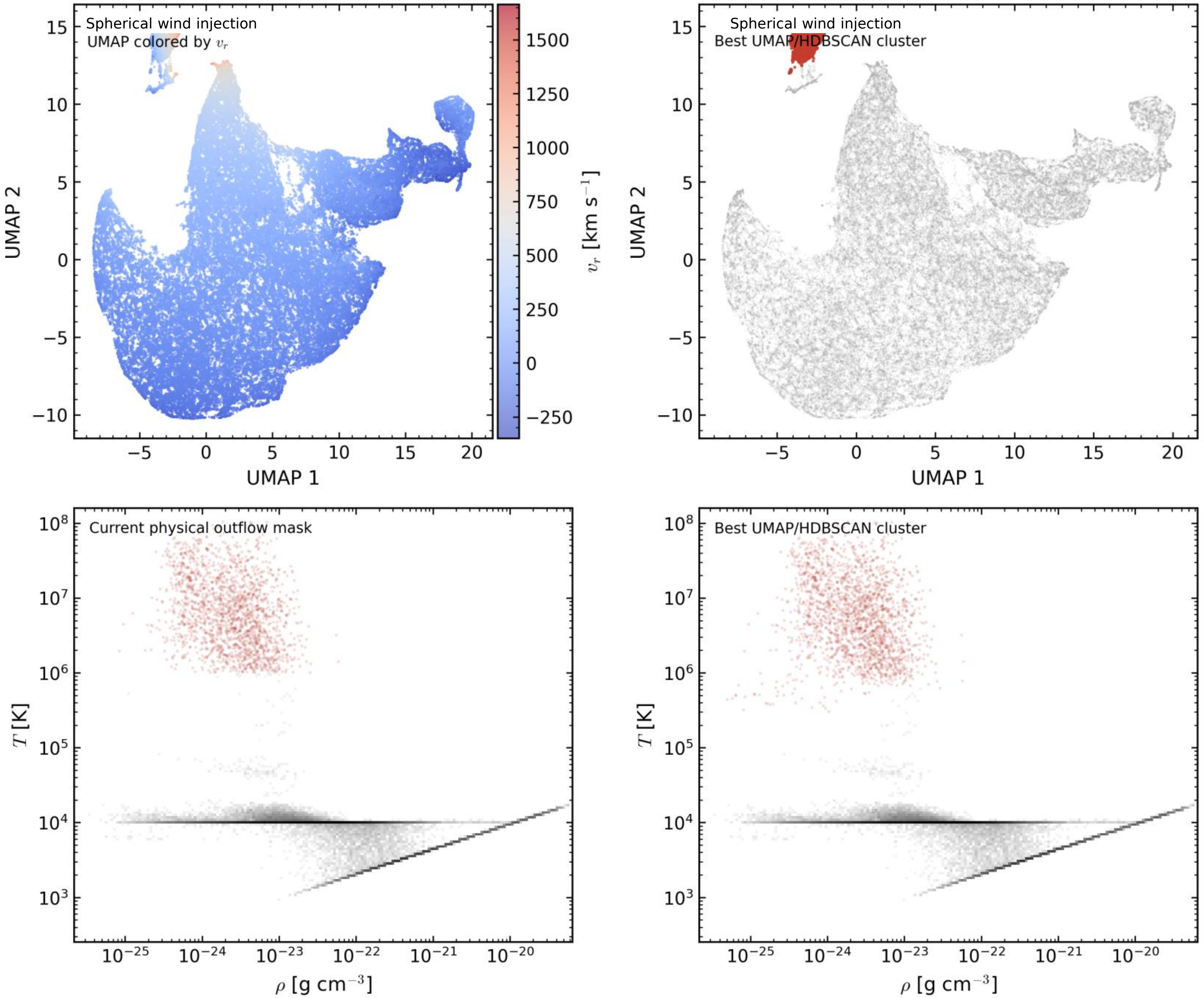
Low-density, high-temperature gas is identified as the hot AGN-driven outflow phase.



Testing UMAP for outflow identification

UMAP + HDBSCAN identifies a cluster that almost fully overlaps with the previously selected hot outflow.

Main limitation: computationally too expensive for large-scale application.



Mass outflow rate measurements

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In simulations, mass outflow rate can be estimated as:

$$\dot{M}_{\mathrm{Eulerian}}(r) \equiv \frac{1}{\Delta r} \sum_{i \in \mathrm{shell}} m_i \, v_{r,i}$$

Nelson et al. (2019b)

$$\dot{M}_{\mathrm{Lag}}(r) \approx \frac{1}{\Delta t} \sum_{j \in \mathrm{crossed}} m_j$$

Observers most commonly estimate:

$$\dot{M}_{\mathrm{out}} = C \frac{M_{\mathrm{gas}} \, v_{\mathrm{out}}}{r_{\mathrm{out}}}$$

Fluetsch et al. (2019); Bischetti et al. (2019), Herrera-Camus et al. (2019)

However, estimates of $\dot{M}$ **vary by orders of magnitude** depending on definition and assumptions used.

Mass outflow rate definitions

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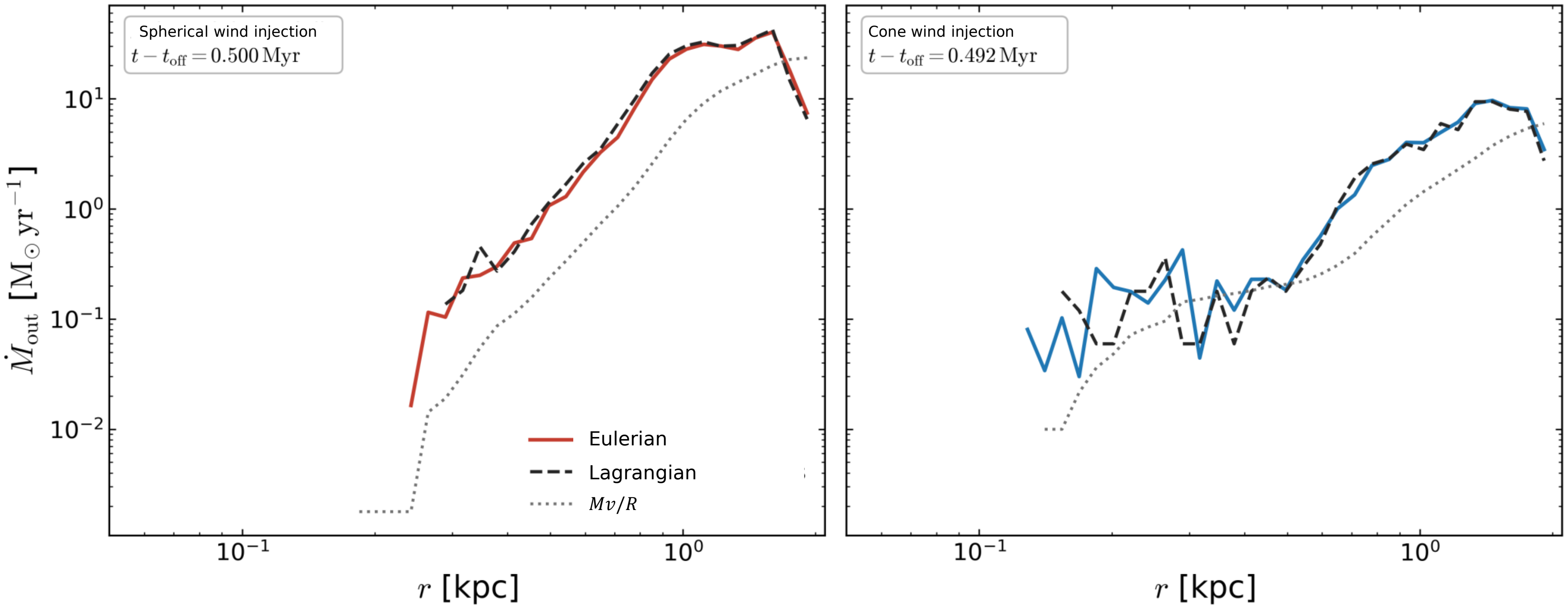
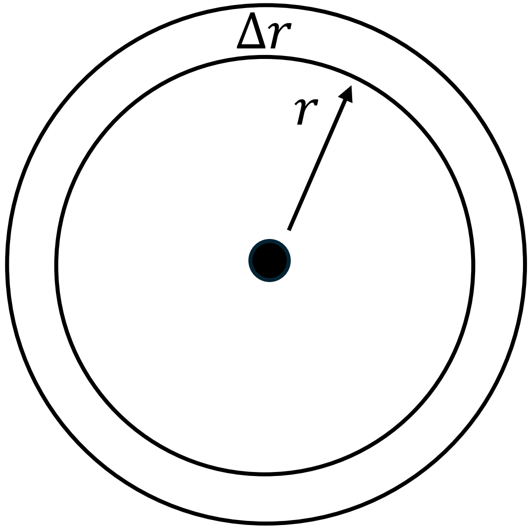
Eulerian and Lagrangian estimates agree well, but the Mv/R estimate is systematically lower.

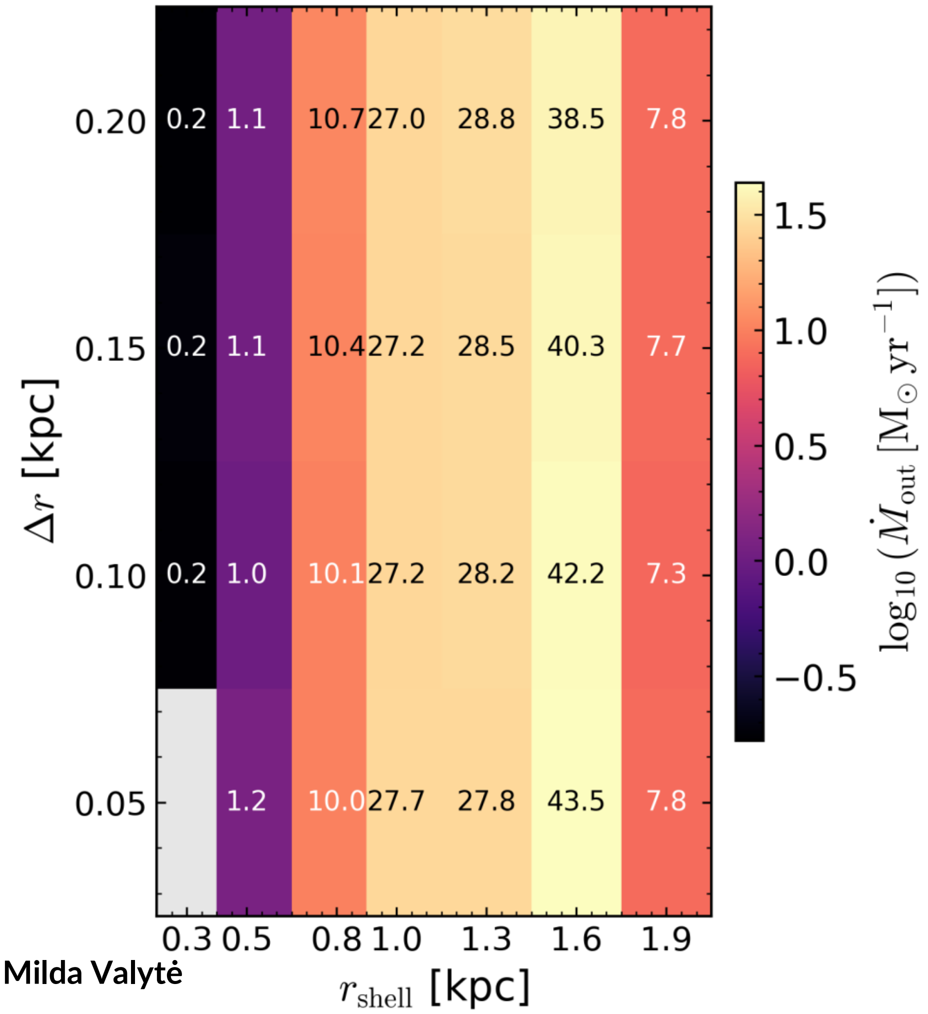


Eulerian method: sensitivity to hyperparameters

The main source of variation is not the shell thickness (Δr), but the chosen shell radius (r_{shell}).

$$\dot{M}_{\text{Eulerian}}(r) \equiv \frac{1}{\Delta r} \sum_{i \in \text{shell}} m_i \, v_{r,i}$$

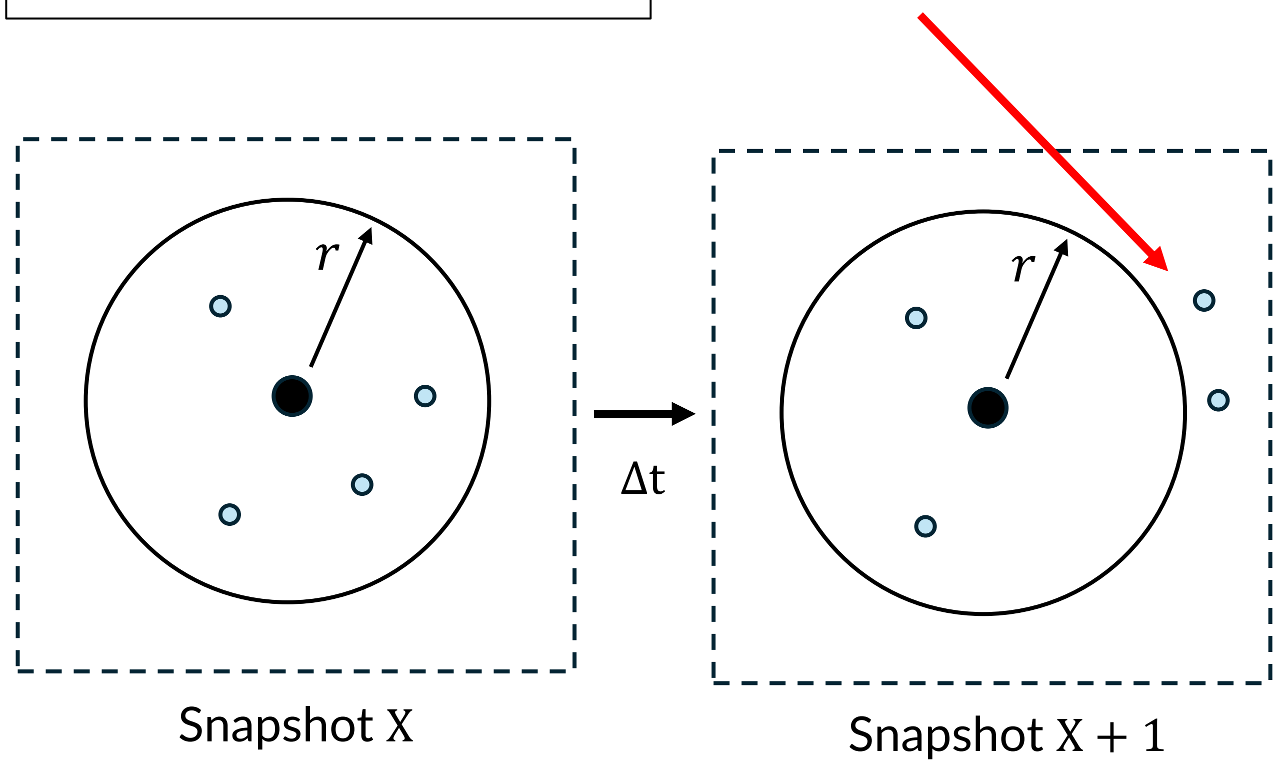


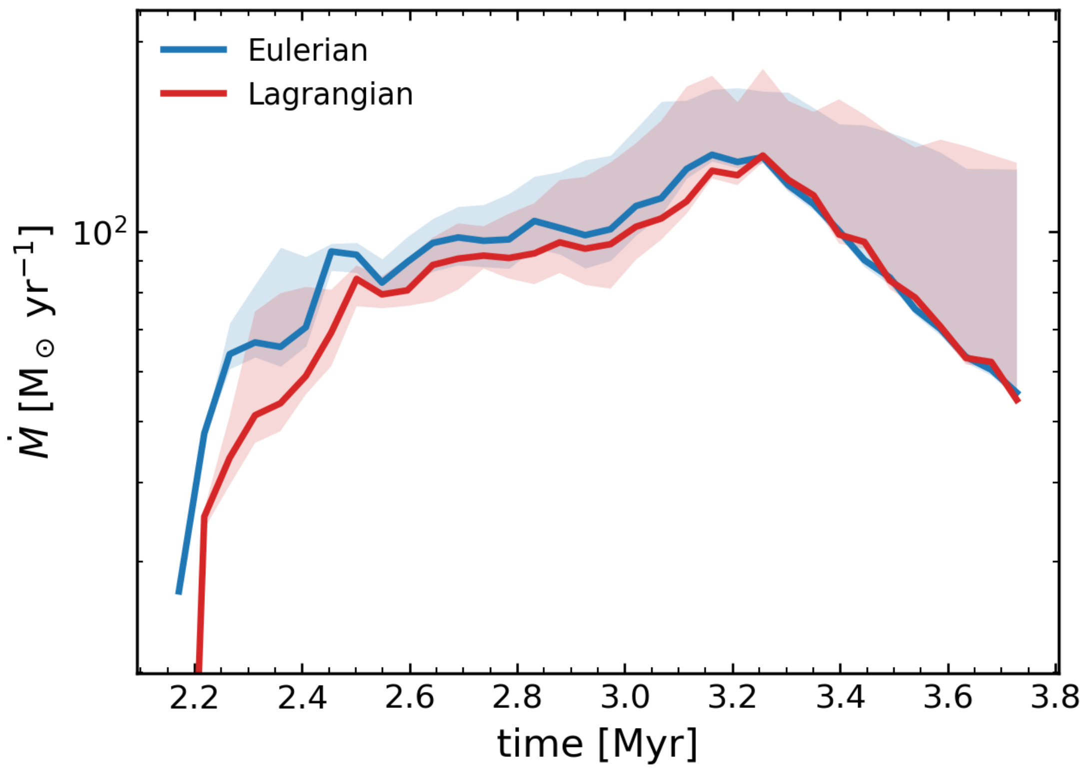


Lagrangian estimator: time-step sensitivity

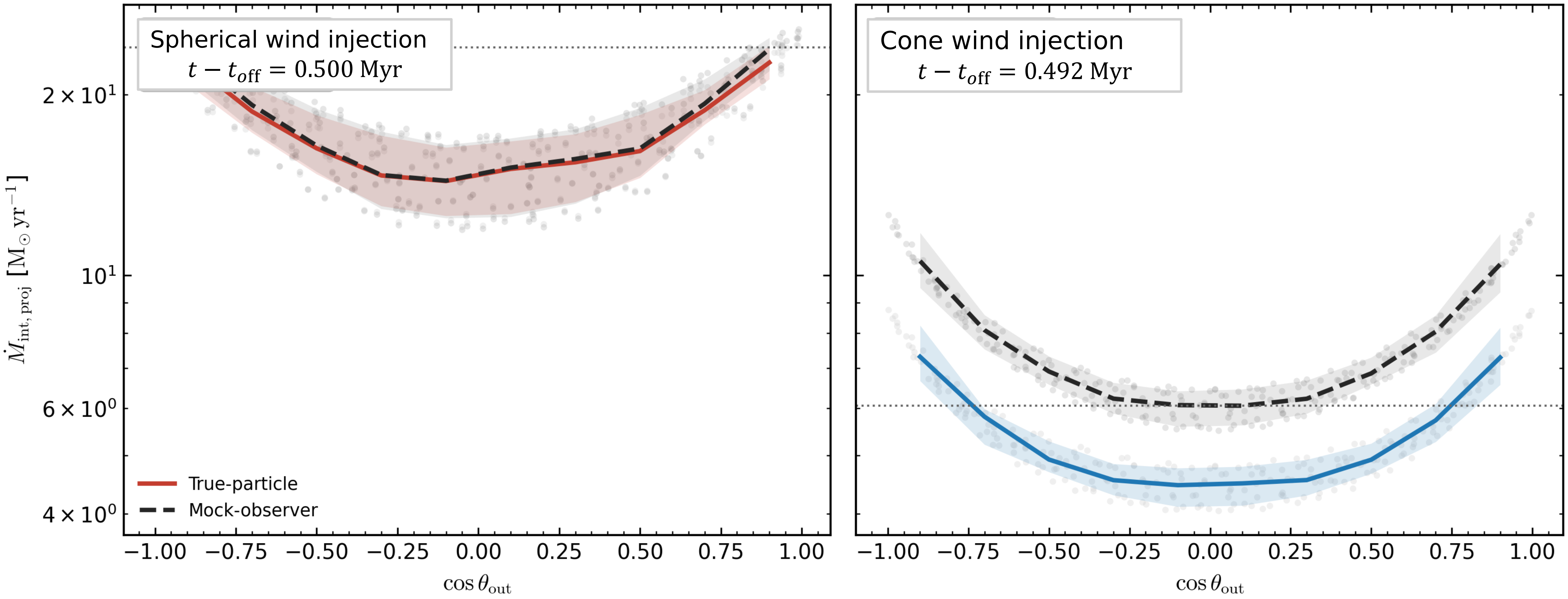
$$\dot{M}_{\mathrm{Lag}}(r) \approx \frac{1}{\Delta t} \sum_{j \in \mathrm{crossed}} m_j$$

crossing particles





The number of crossing particles depends on Δt, leading to statistical fluctuations.



$$\sigma_{\rm var} = \frac{P_{84}(\log_{10}\dot{M}) - P_{16}(\log_{10}\dot{M})}{2}$$

Model	$\sigma_{\rm hyp}$ [dex]	$\sigma_{\rm ang}$ [dex]	$\sigma_{\rm tot,ind}$ [dex]	$f_{\rm tot,ind}$
Spherical wind injection	0,593	0,100	0,60	4,0
Cone wind injection	0,480	0,097	0,49	3,1

AGN selection in TNG50

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Cosmic epochs: $z \sim 0, z \sim 2$ ir $z \sim 6$.

Group catalogs

$M_\star > 10^8 M_\odot$

Sample reduced by $10^3 - 10^4$ times.

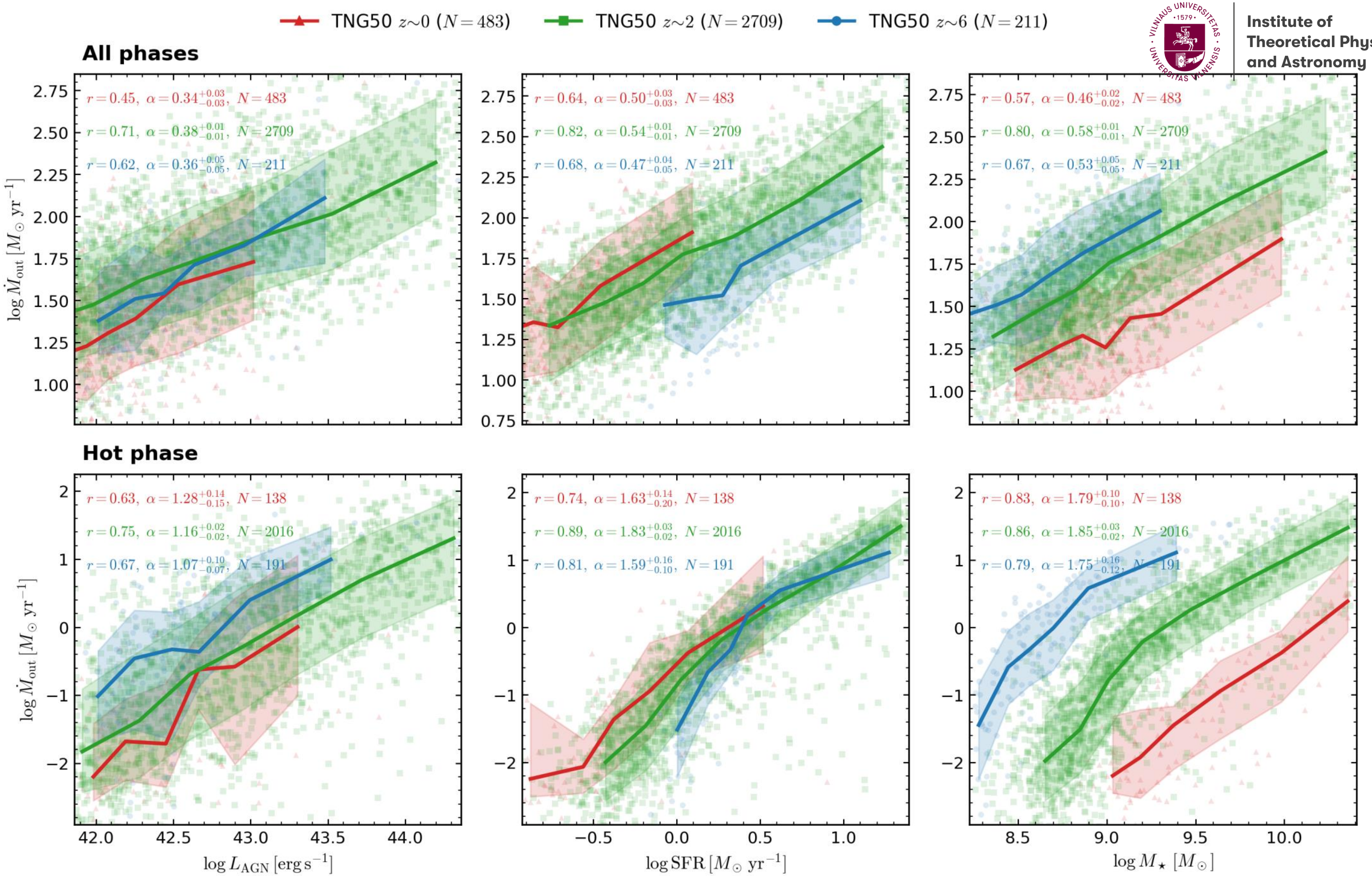
Initial data volume:
6.7 TB

Snapshot

$v_{\rm rad} > 1.0\ \sigma_{\rm gas}$
$L_{\rm bol} > 10^{37}\ {\rm erg\ s^{-1}}$
$f_{\rm Edd} > 0.01$

483 outflows at $z \sim 0$ (13.8 Gyr)
2705 outflows at $z \sim 2$ (3.1 Gyr)
211 outflows at $z \sim 6$ (0.9 Gyr)

Final outflow sample



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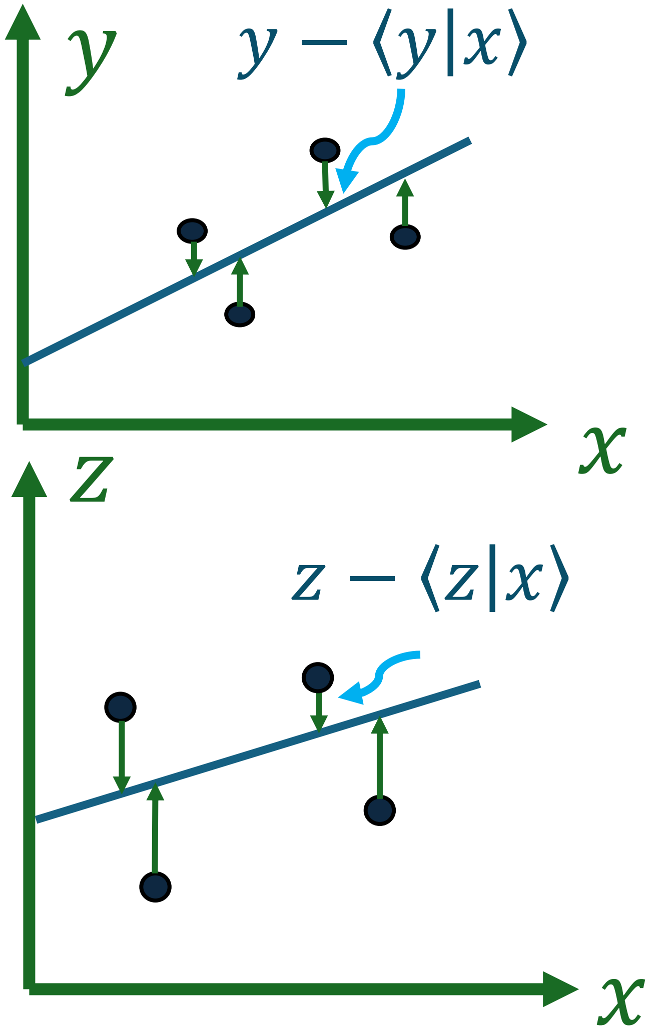
Among the tested parameters, SFR shows the strongest connection with the mass outflow rate.

Residual analysis

Bernardi et al. (2005), Shankar et al. (2016)



what is the dominant parameter?

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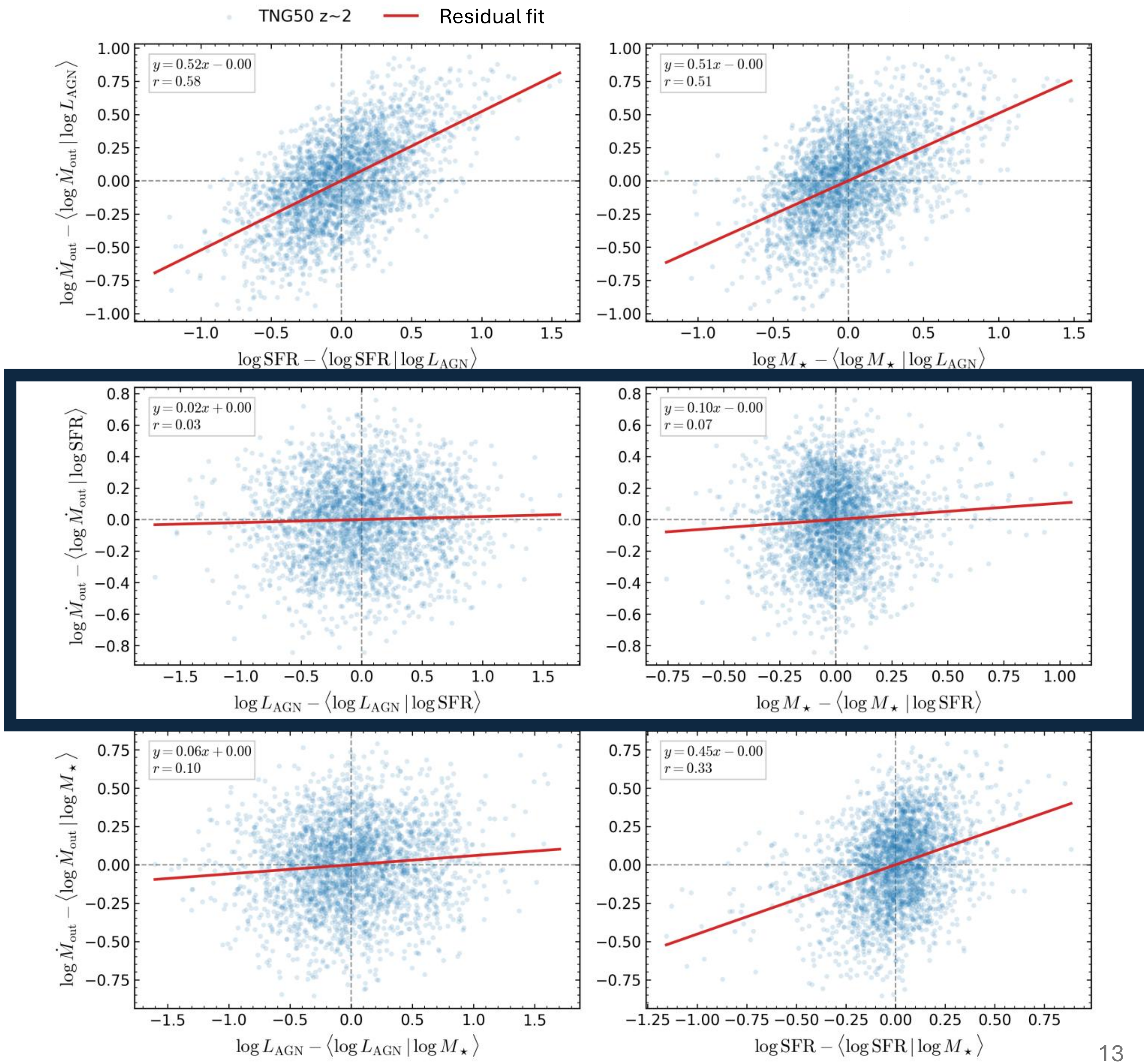
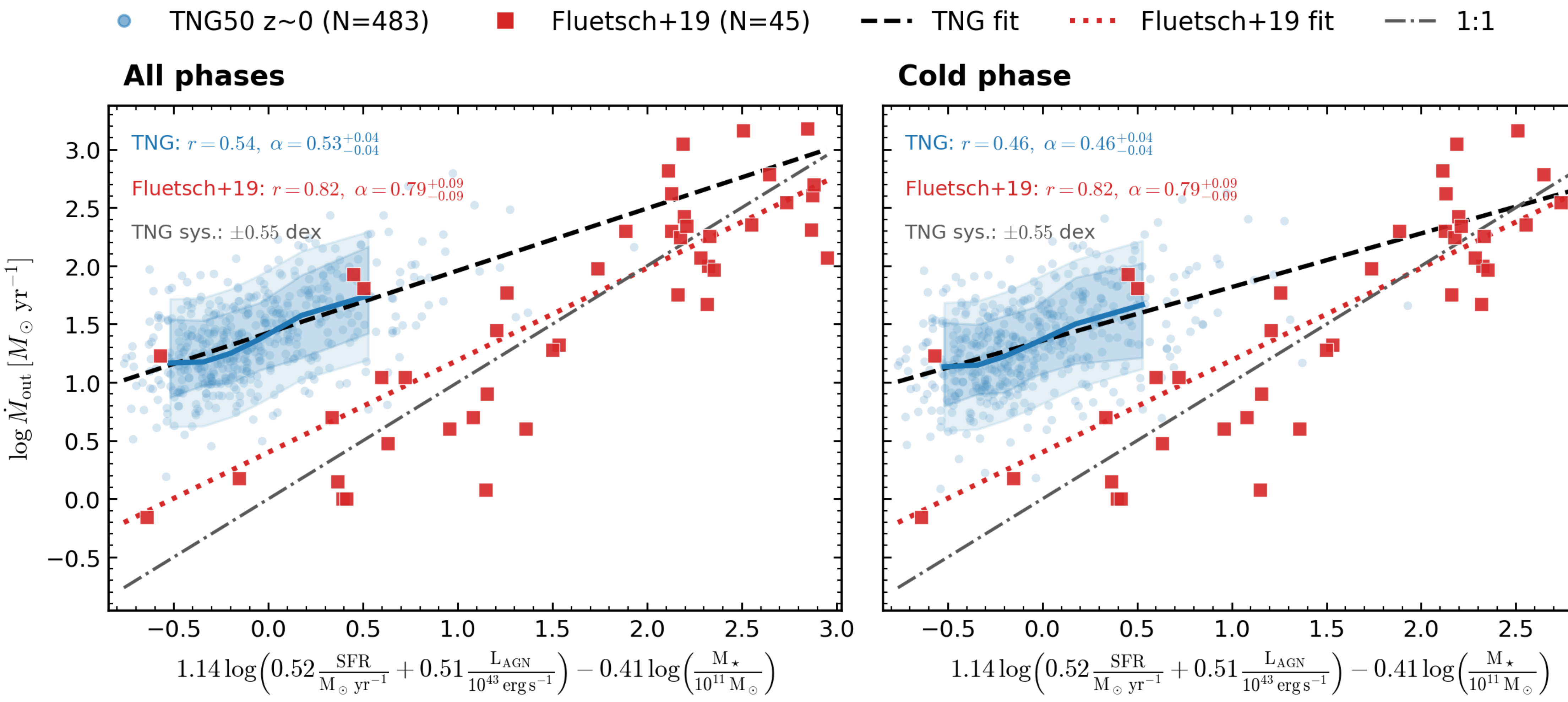


Observed vs simulated combined outflow relation



Re-fitting the combined relation

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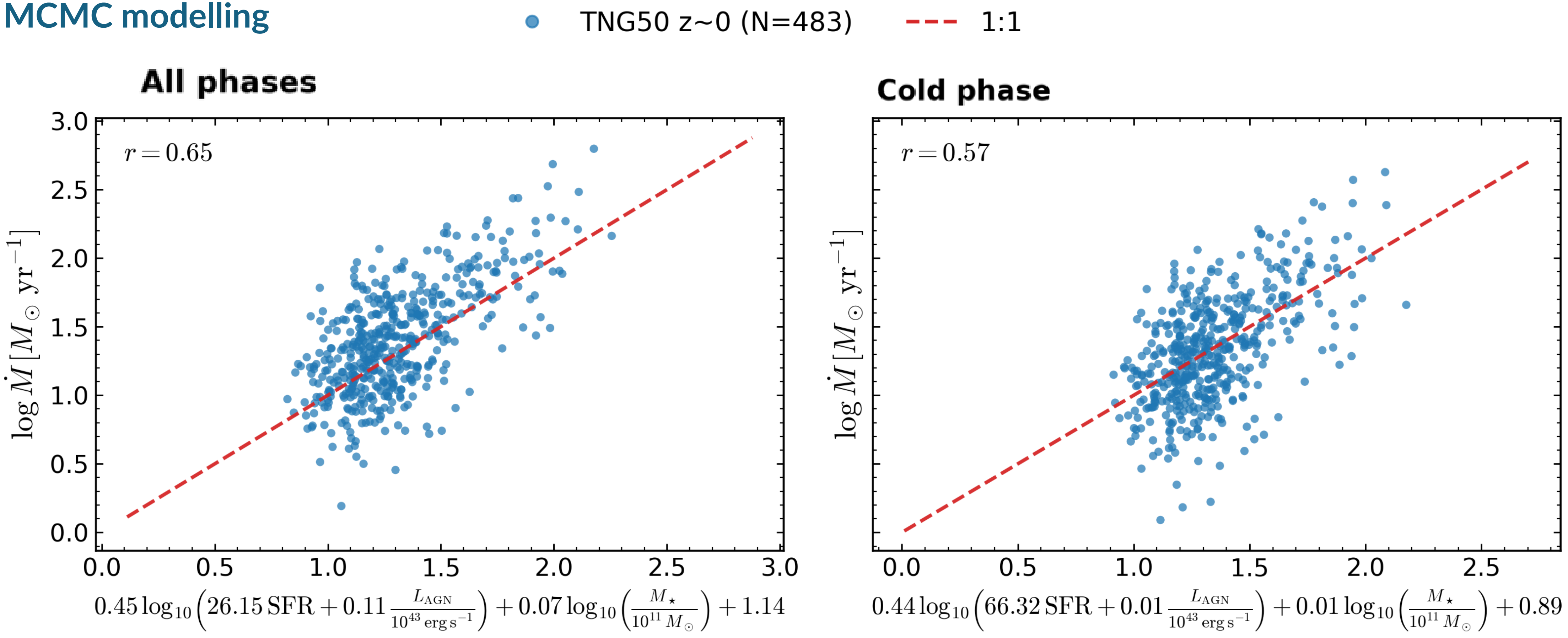
Fluetsch et al. (2019)
$$\log\left(\frac{\dot{M}_{\rm out}}{M_\odot\,{\rm yr}^{-1}}\right) = x\log\left(\alpha\frac{\rm SFR}{M_\odot\,{\rm yr}^{-1}} + \beta\frac{L_{\rm AGN}}{10^{43}\,{\rm erg\,s}^{-1}}\right) + y\log\left(\frac{M_\star}{10^{11}M_\odot}\right)$$

MCMC modelling



Re-fitting the combined relation

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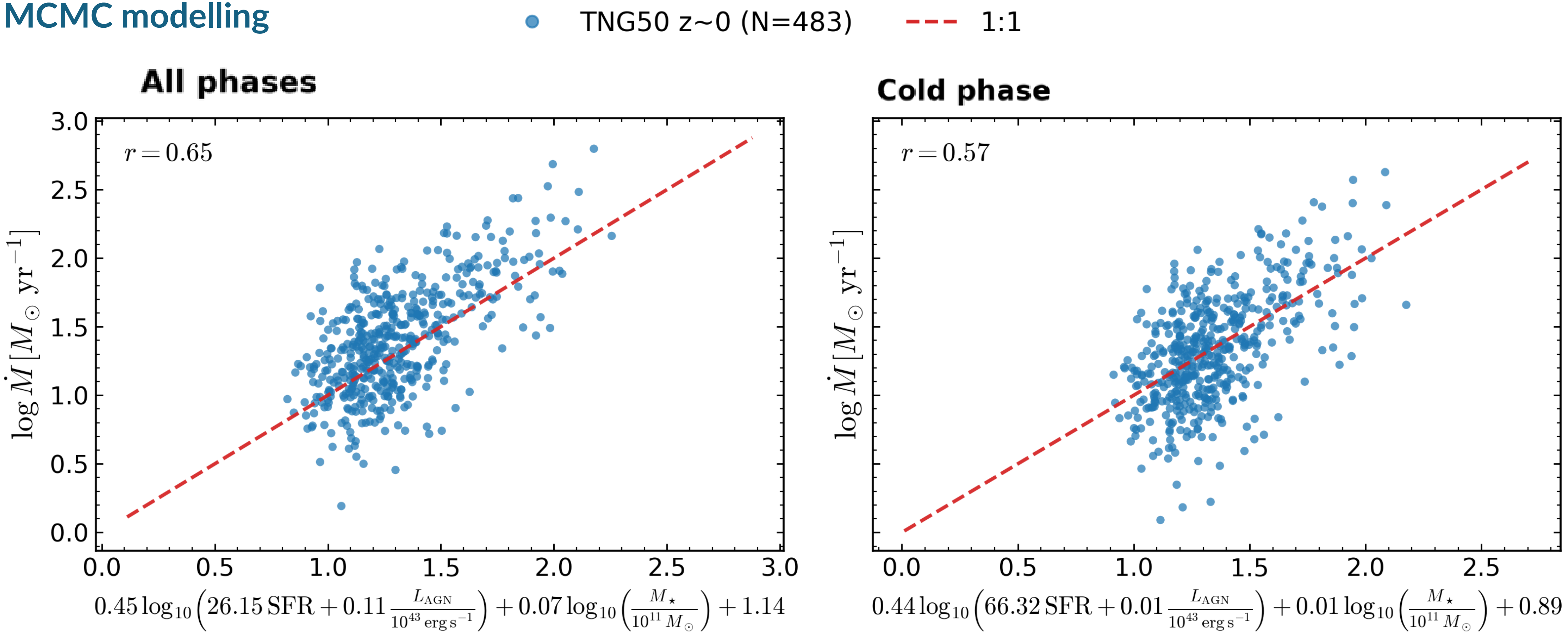
SFR is the dominant parameter driving TNG50 outflows

MCMC modelling



Conclusions

1. Mass outflow rate measurements are strongly method-dependent. The largest uncertainty comes not from the formal definition itself, but from its geometrical implementation and parameter choices.
2. In TNG50-1, the mass outflow rate correlates most strongly with SFR, especially at z ~ 2.
3. Both residual analysis and Fluetsch-type re-fitting identify SFR as the dominant driver of TNG50 outflows.
4. TNG50-1 reproduces the $\dot{\mathrm{M}}_{\mathrm{out}} - L_{\mathrm{AGN}}$ slope reasonably well, but less successfully matches the relations with SFR and especially $M_{\star}$.