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Turbulence Drivers in Quasar Halos

Mandy Chen

Carnegie Observatories & Caltech

18 July 2025, 18th Potsdam Thinkshop

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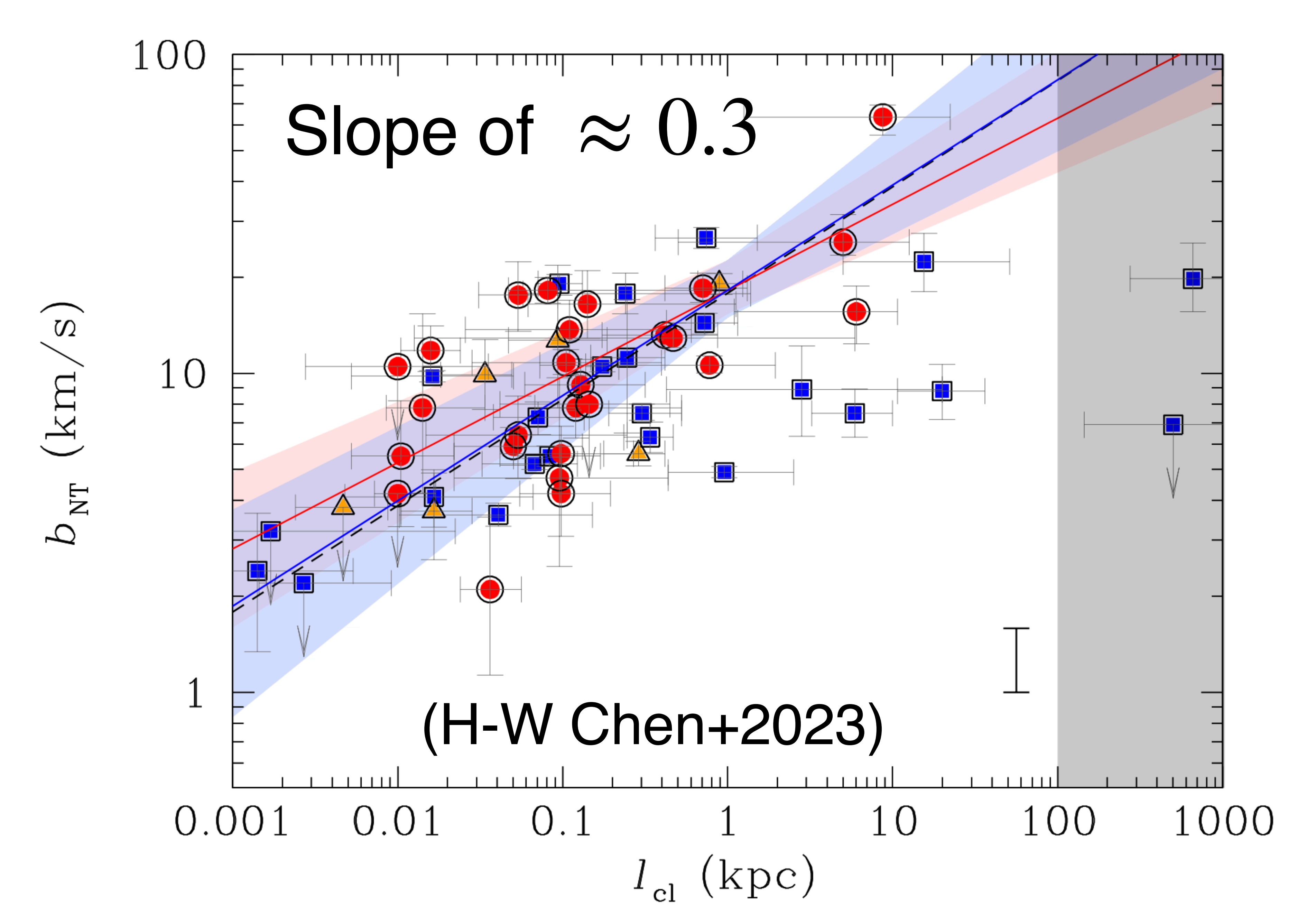
How to measure turbulence?

$b_{\rm non-thermal}$

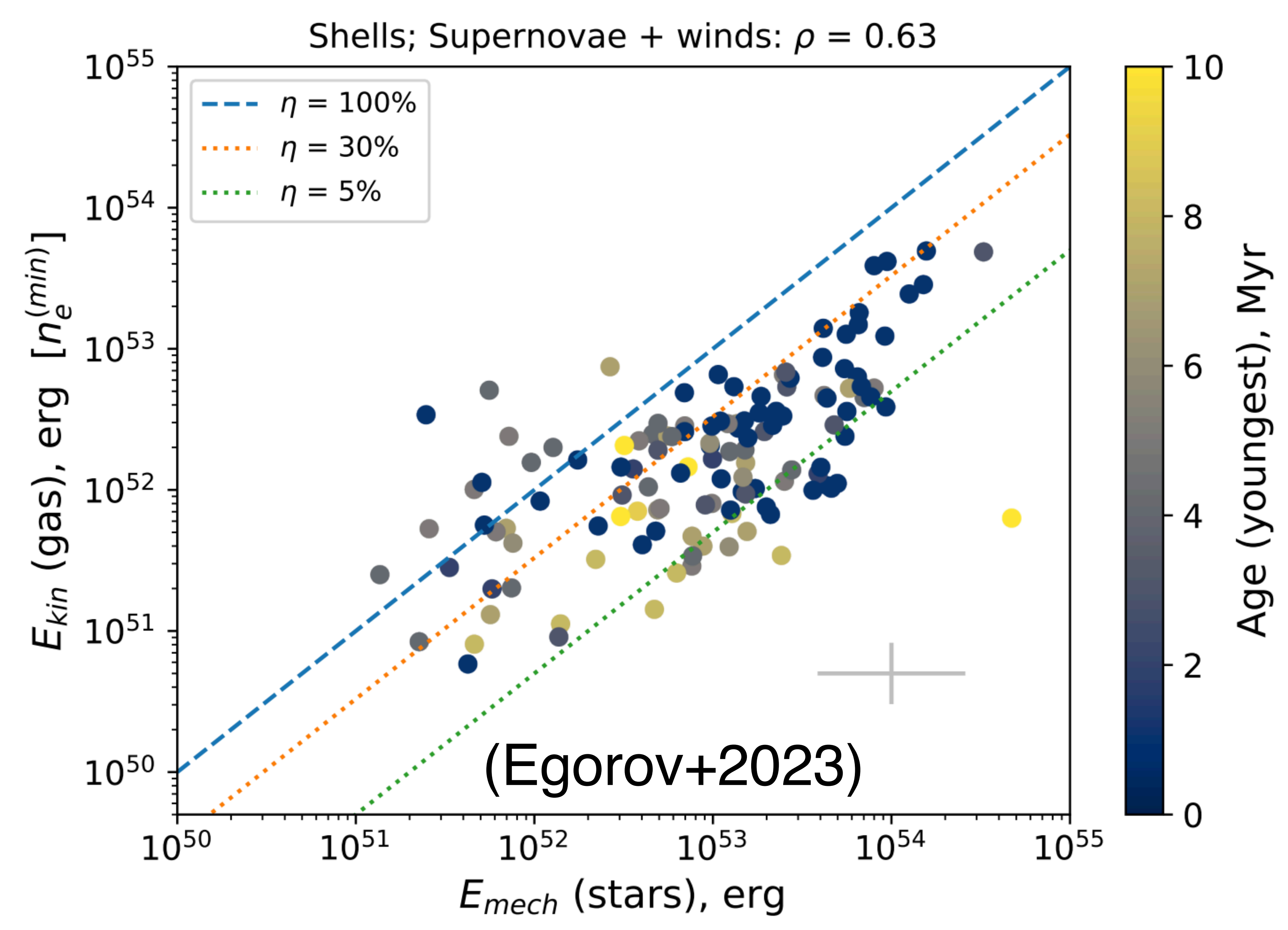
(QSO absorption line+ionization modeling)



Hsiao-Wen Chen's talk on Tuesday

$\sigma_{\rm H\alpha}$

(In expanding superbubbles)

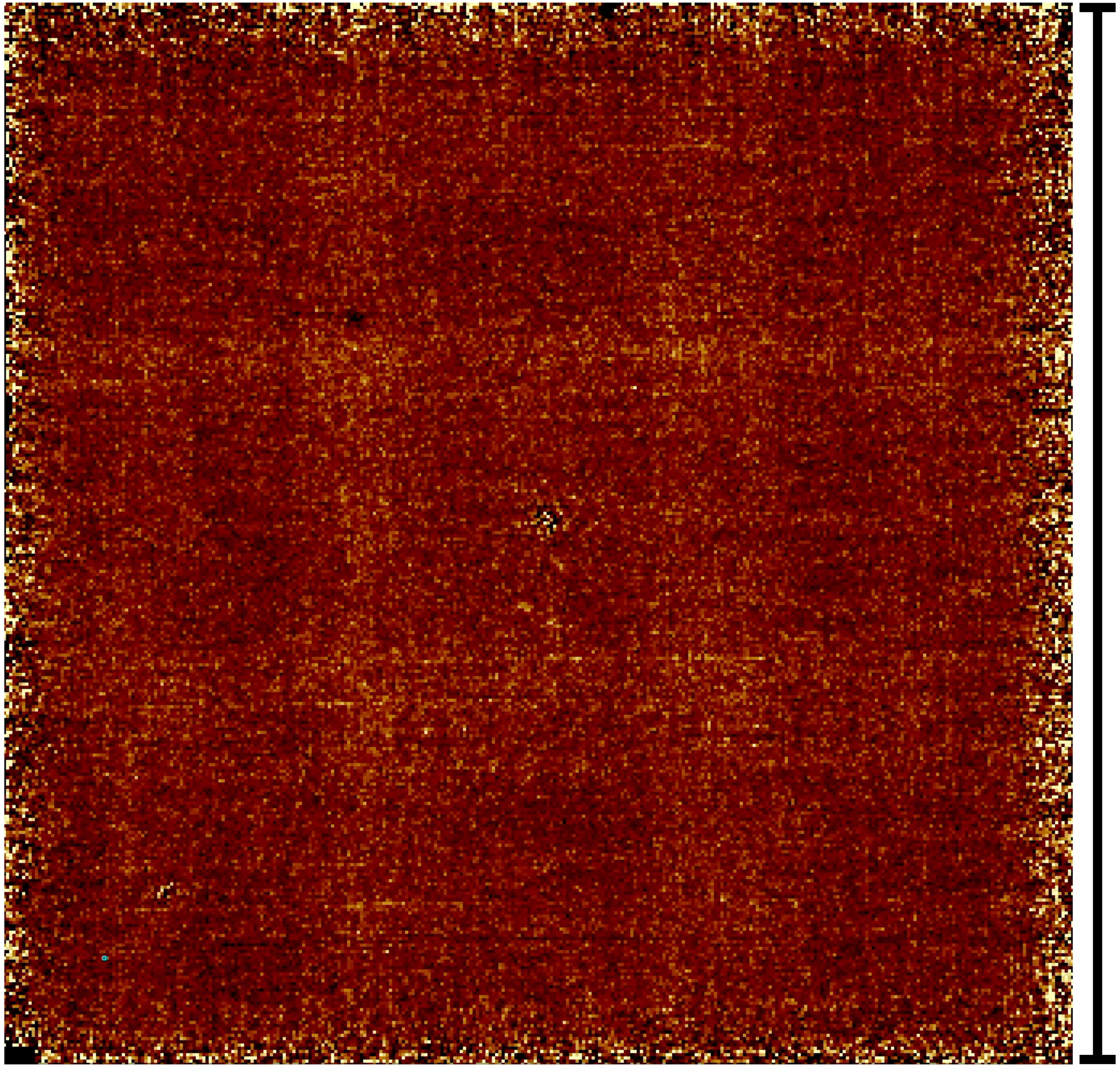


Oleg Egorov's talk on Tuesday

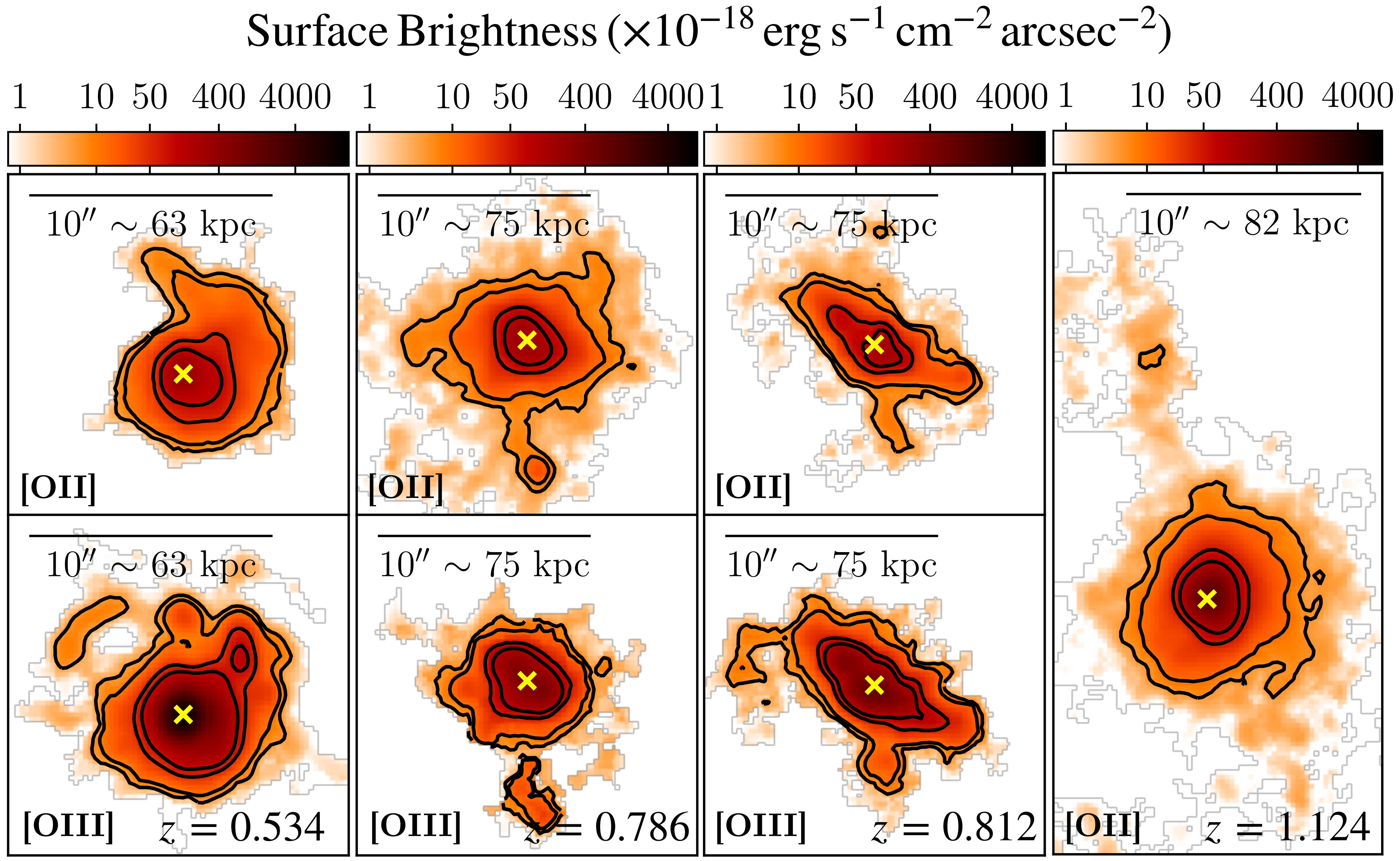
How to measure turbulence in spatially-resolved, individual sources?

→ Kinetic energy budget, turbulence cascade, driving mechanism, stellar/AGN feedback, etc.

QSO halo at z=0.57, [OIII] emission seen in VLT/MUSE data



$1' \approx 400\,\mathrm{kpc}\,@\,z = 0.57$



(MC+2023)

MUSE: [OII] and [OIII] emission at $z \approx 0.5$—1.1

Sample compiled from:

Independent program by PI Celine Péroux

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PI Hsiao-Wen Chen

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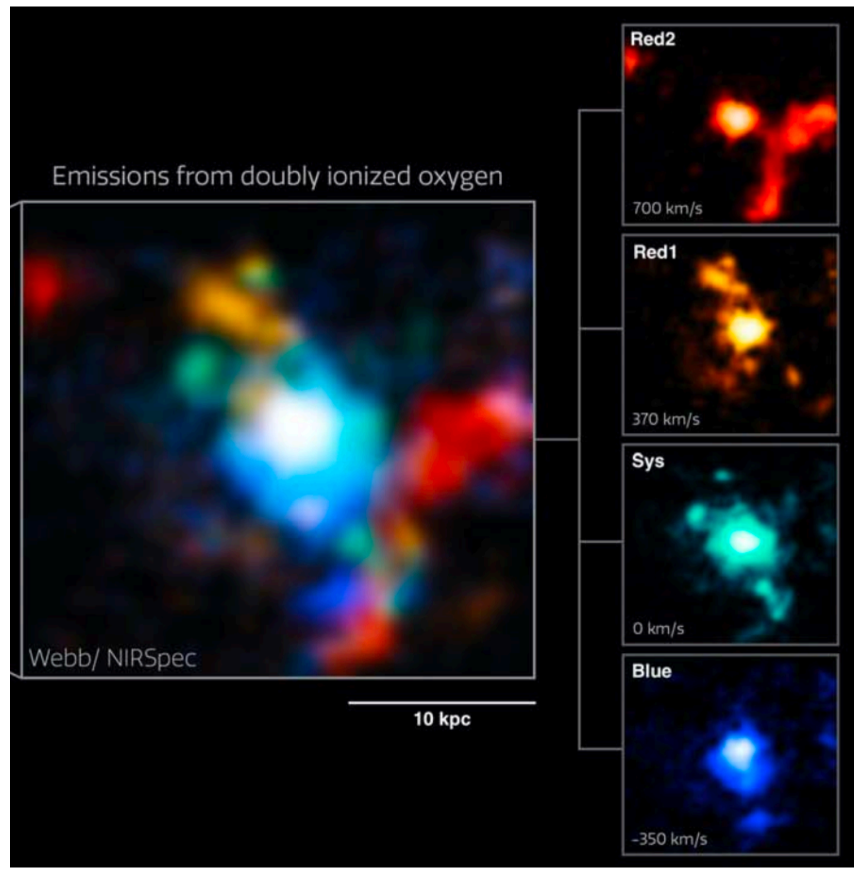
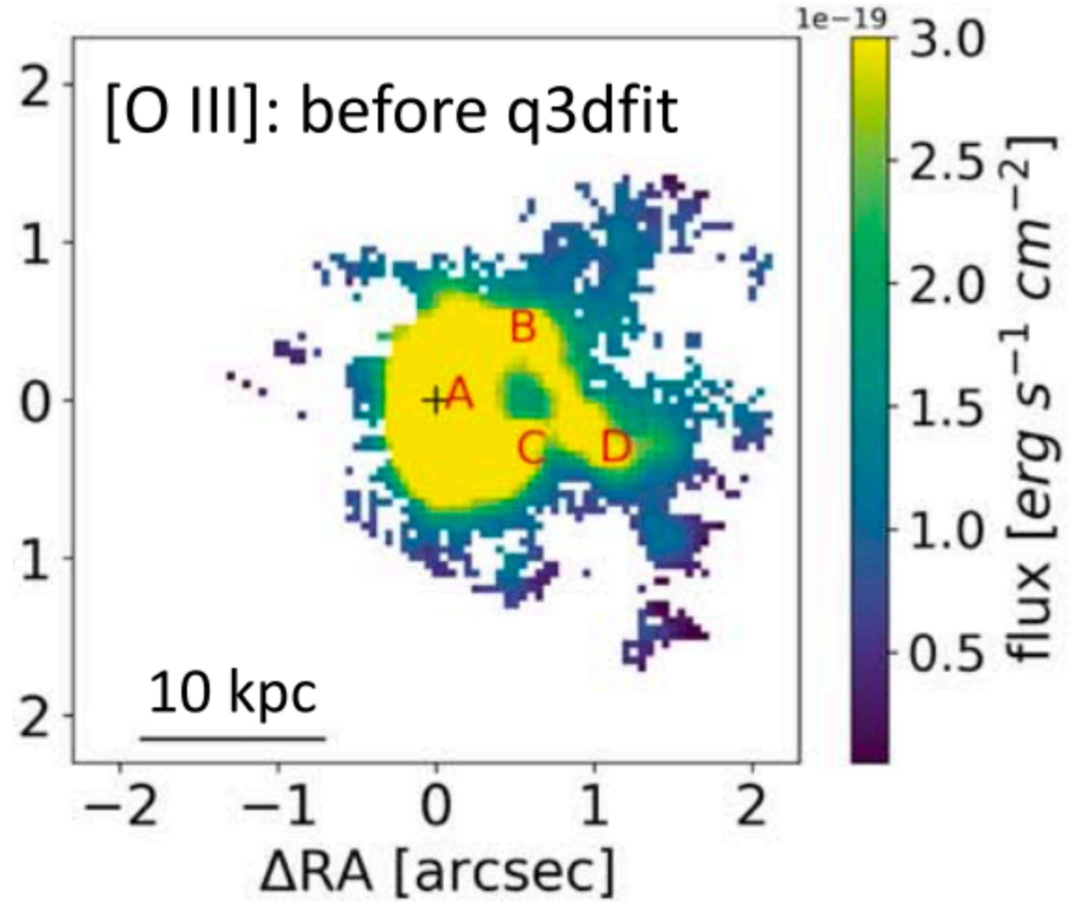


(Wylezalek+2022)



(Veilleux+2023)

JWST/NIRSpec IFU: [OIII] emission at $z \approx 1.6$—3

Q3D JWST ERS Program
PI Dominika Wylezalek

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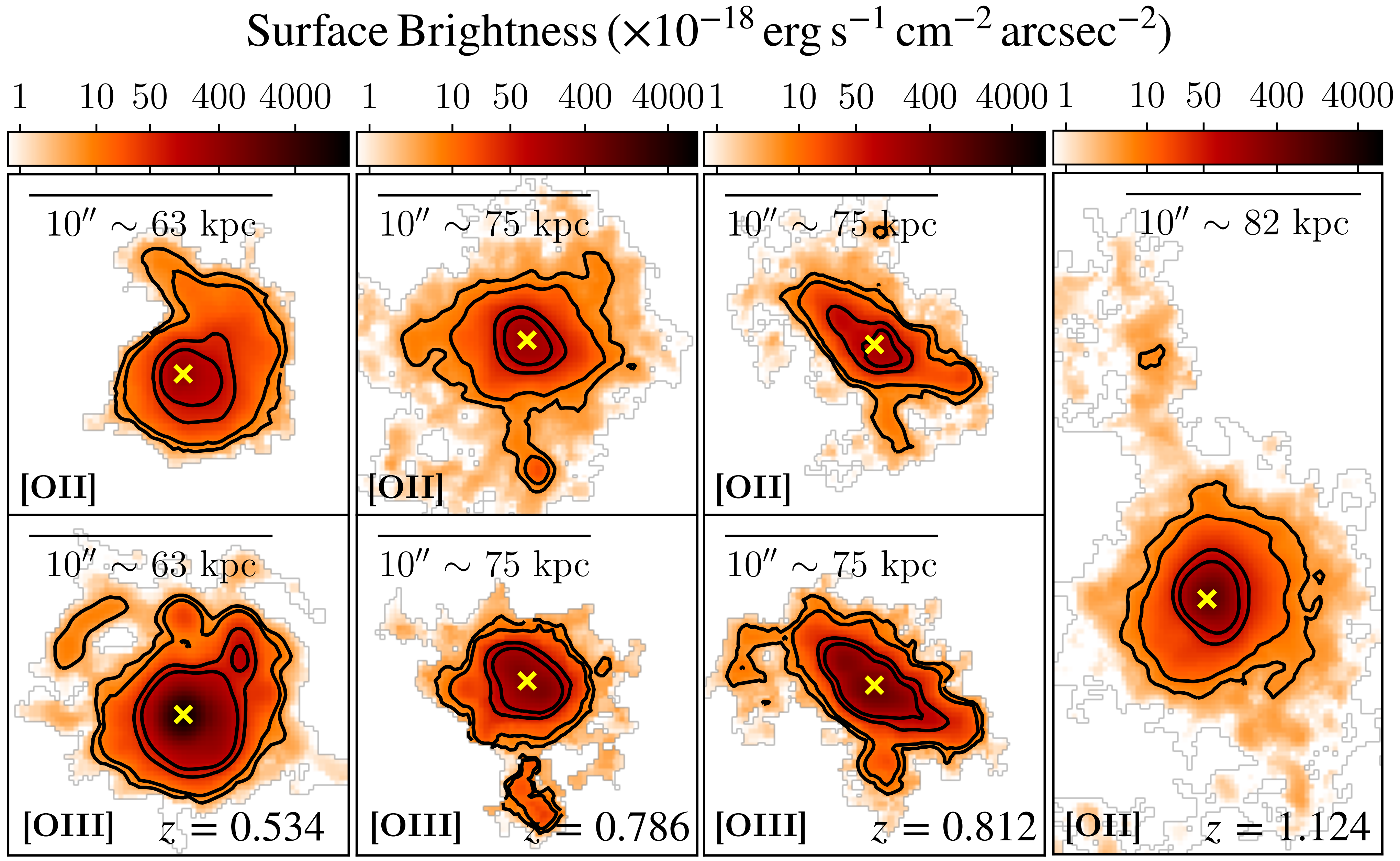

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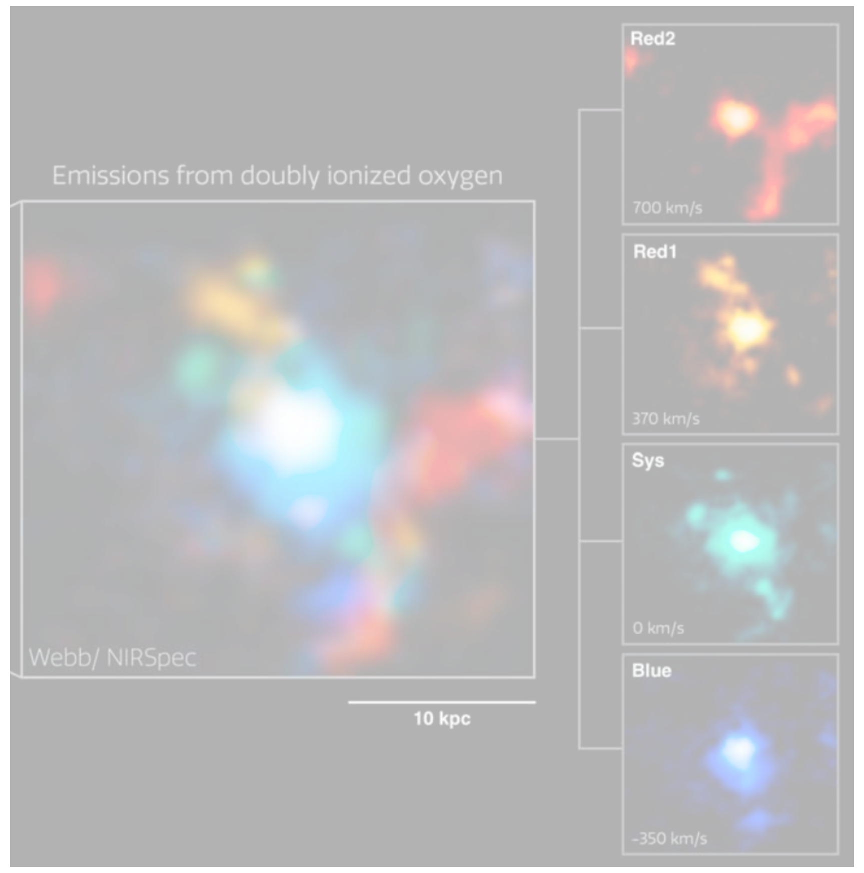

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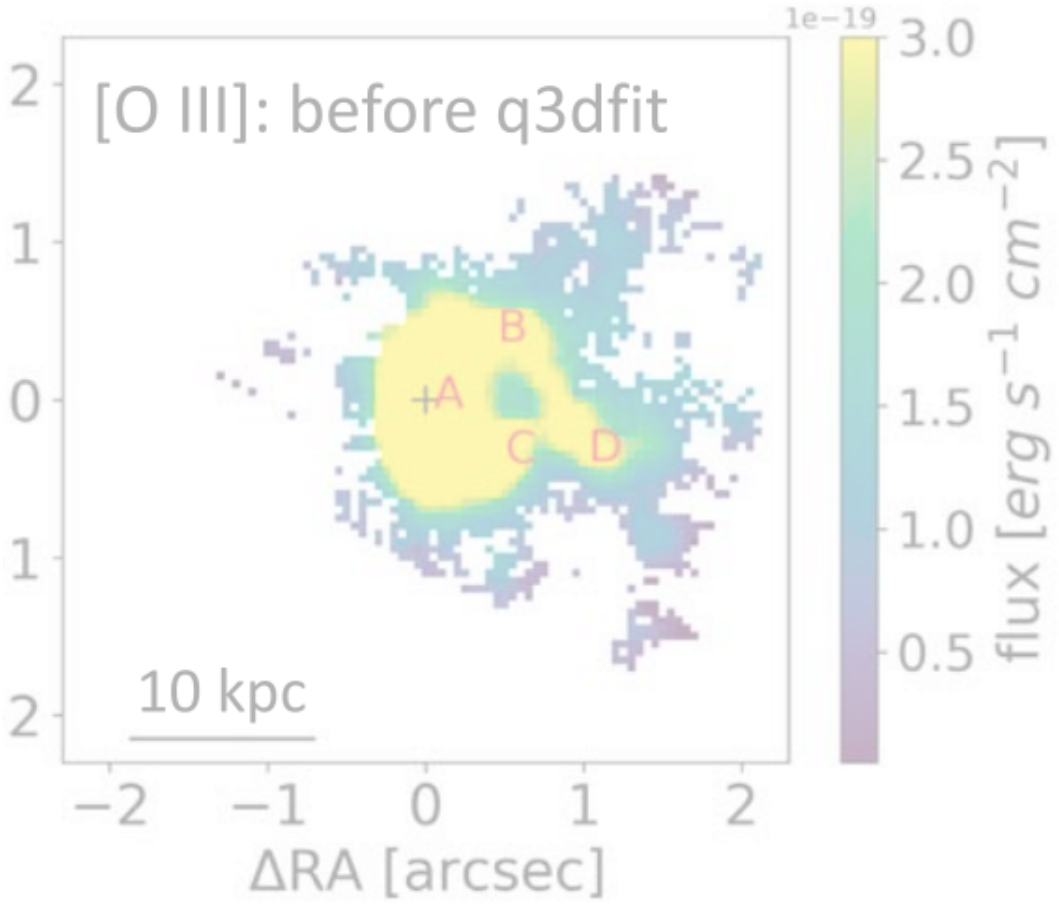

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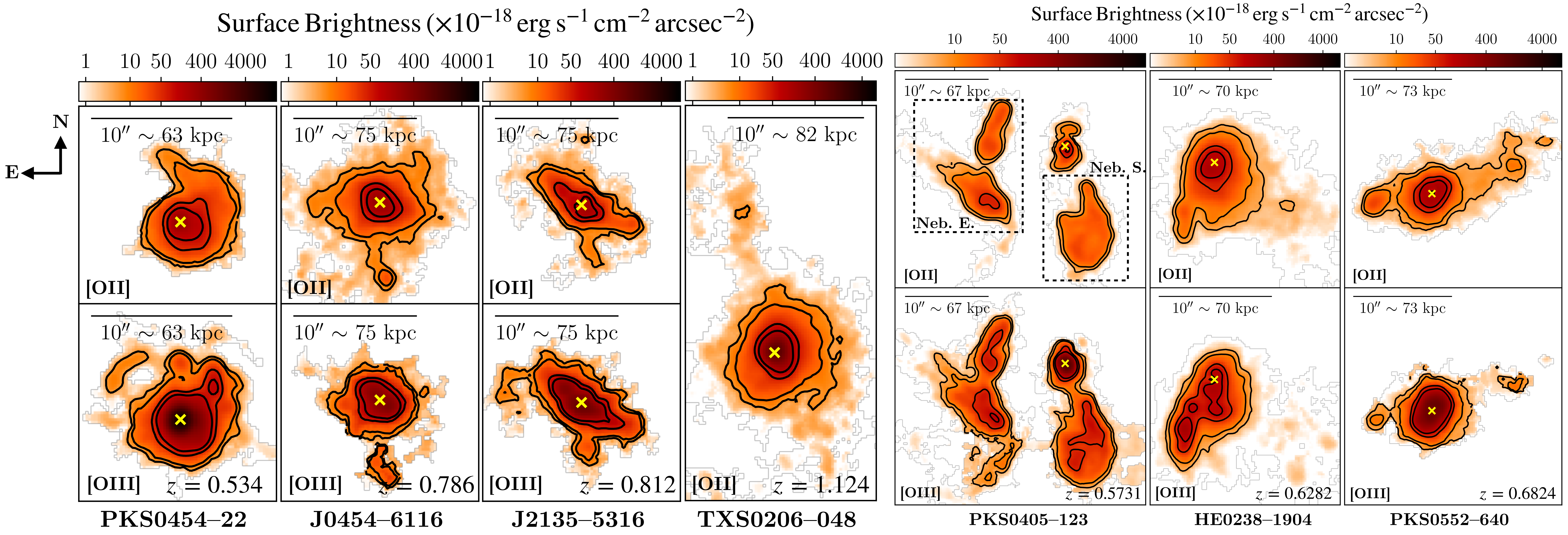
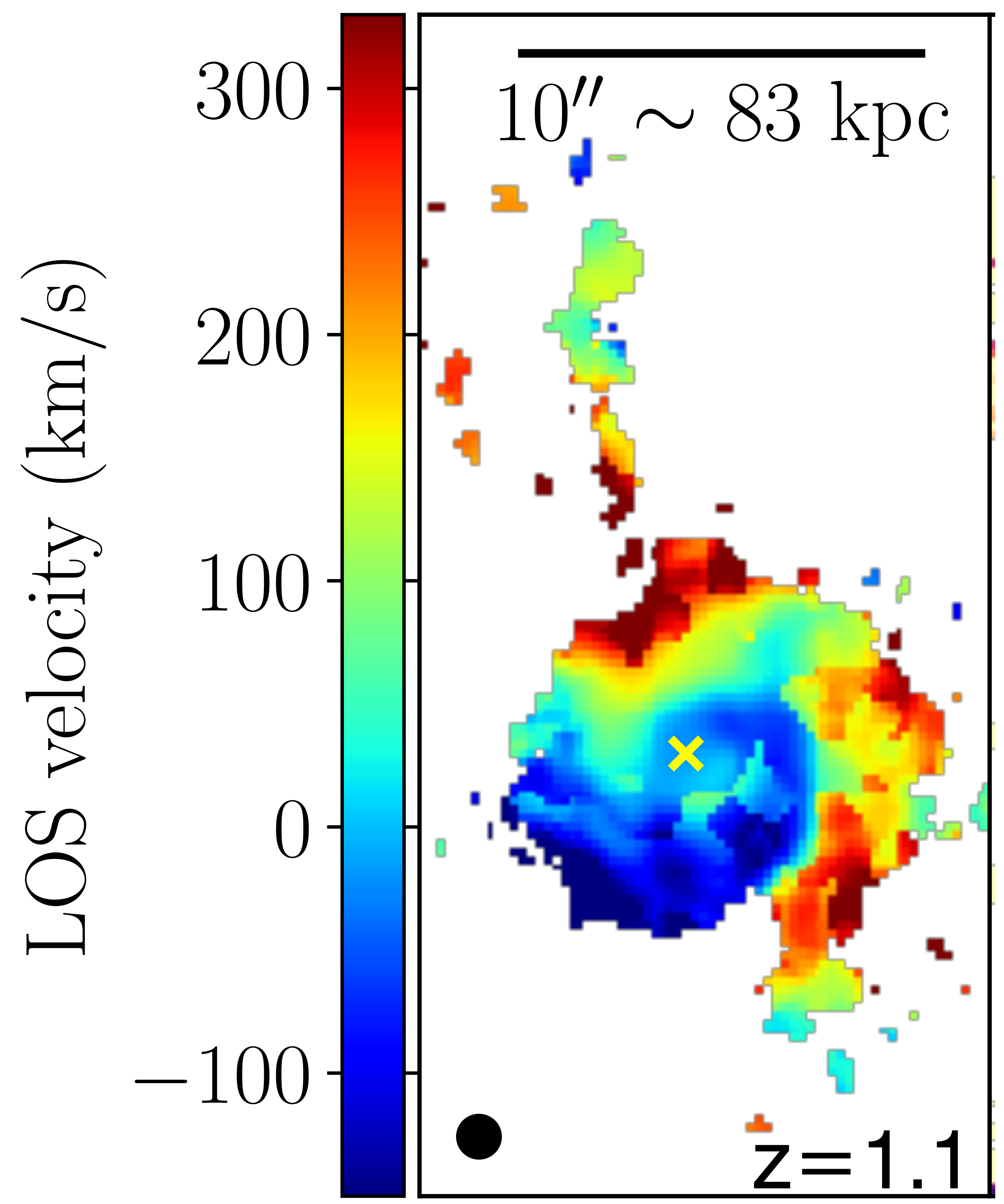
Using MUSE to trace the cool ($T \sim 10^4\,\mathrm{K}$) gas up to ≈100 kpc around QSOs at *z*≈0.5—1.1



Data from: PI: C. Péroux | CUBS, PI: H.-W. Chen | MUSEQuBES, PI: J. Schaye

(MC+2023, 2024)



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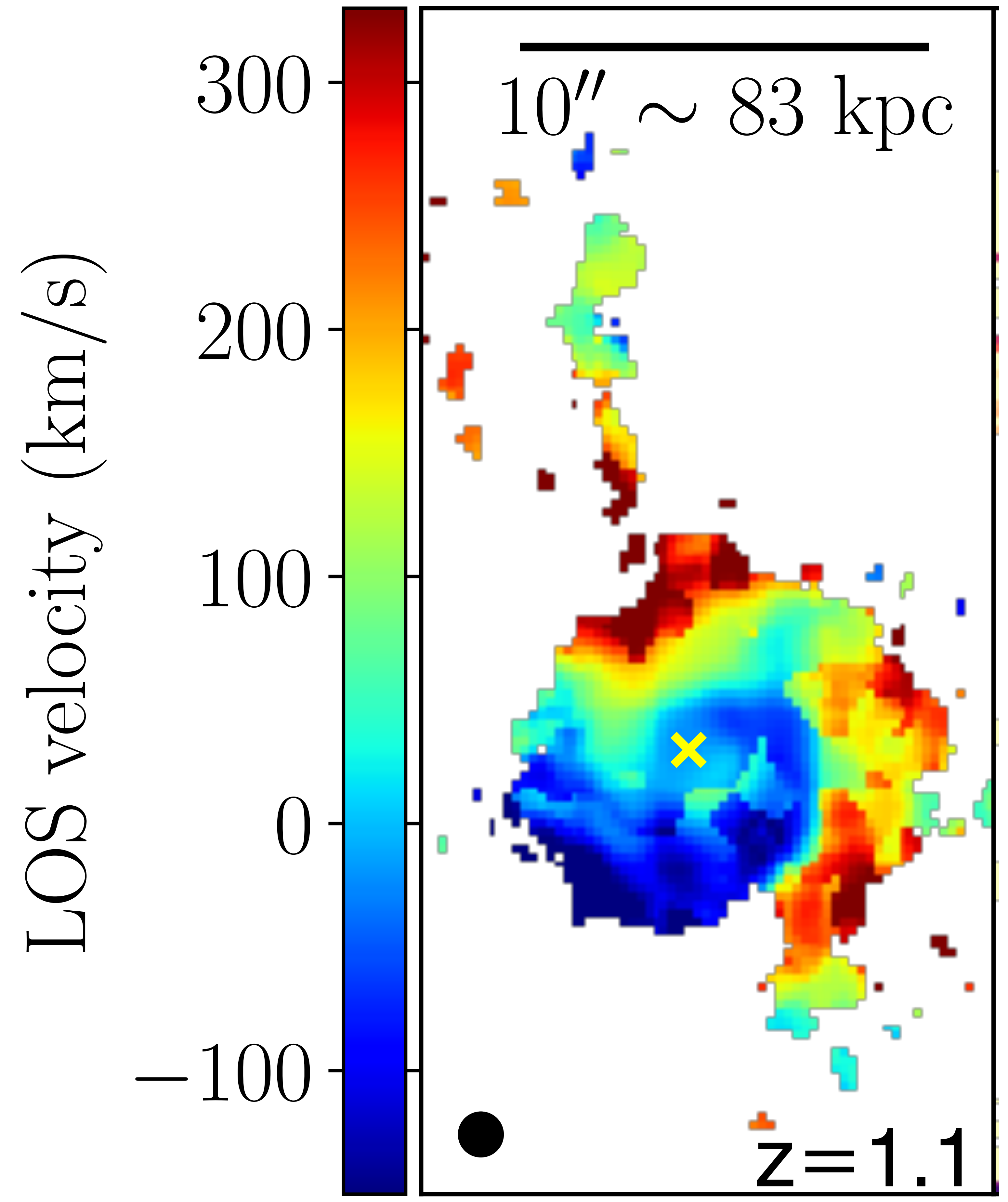
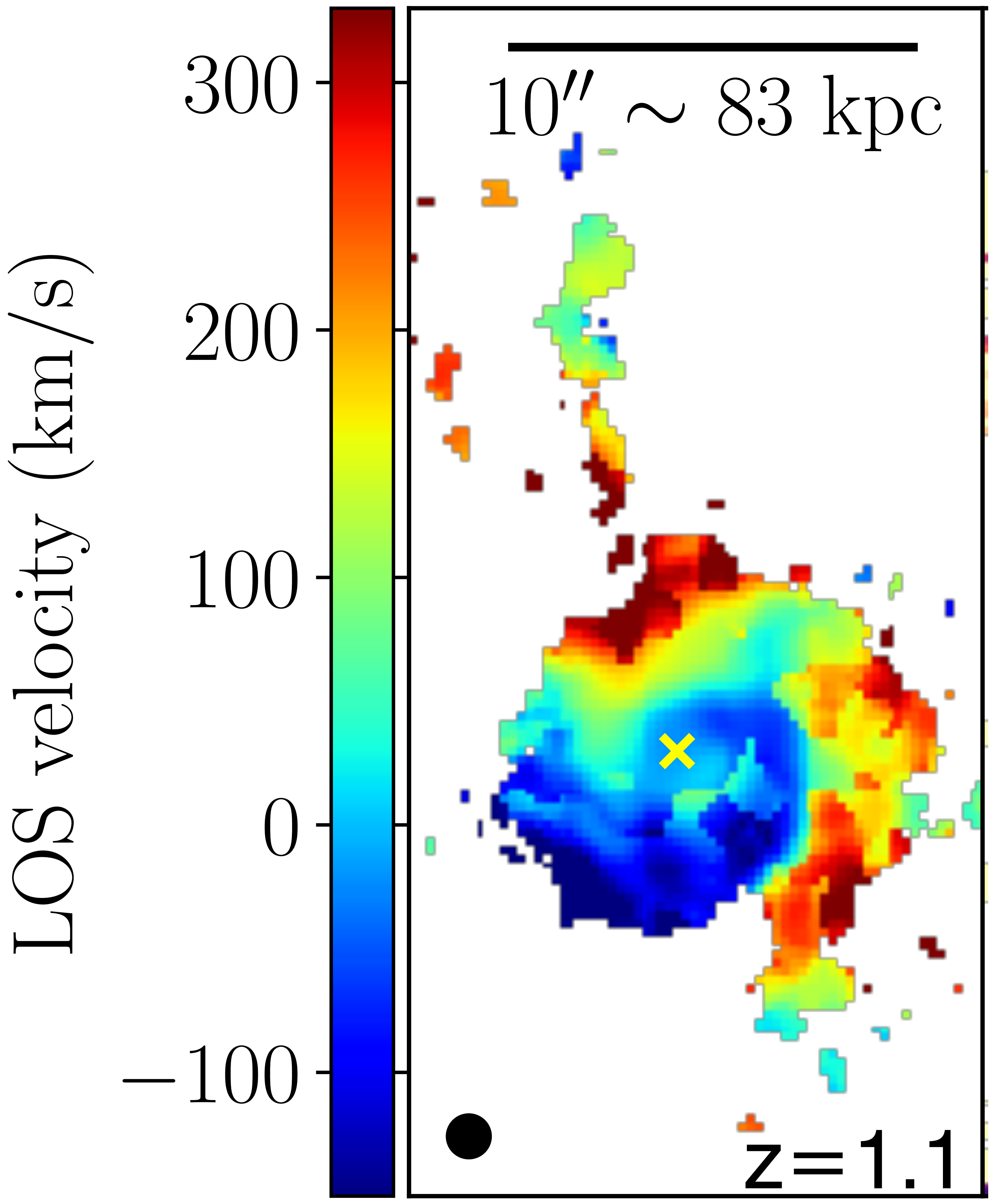


(MC+2023)

Use velocity structure function (VSF) to probe gas dynamics

VSF: $S_p(r) = \langle \, | \vec{v}(x) - \vec{v}(x + r) \, |^p \, \rangle, p = 1, 2, 3...$



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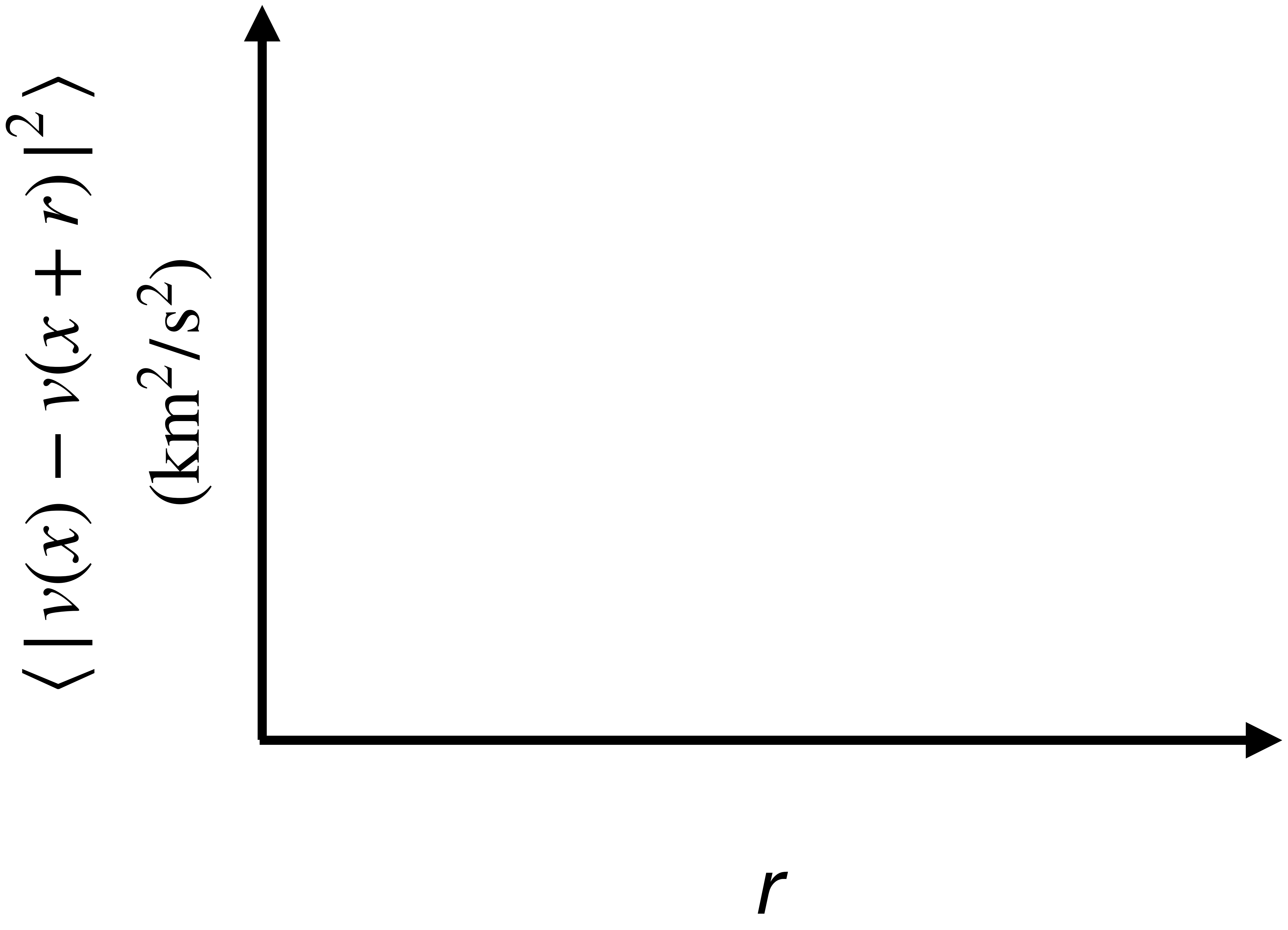

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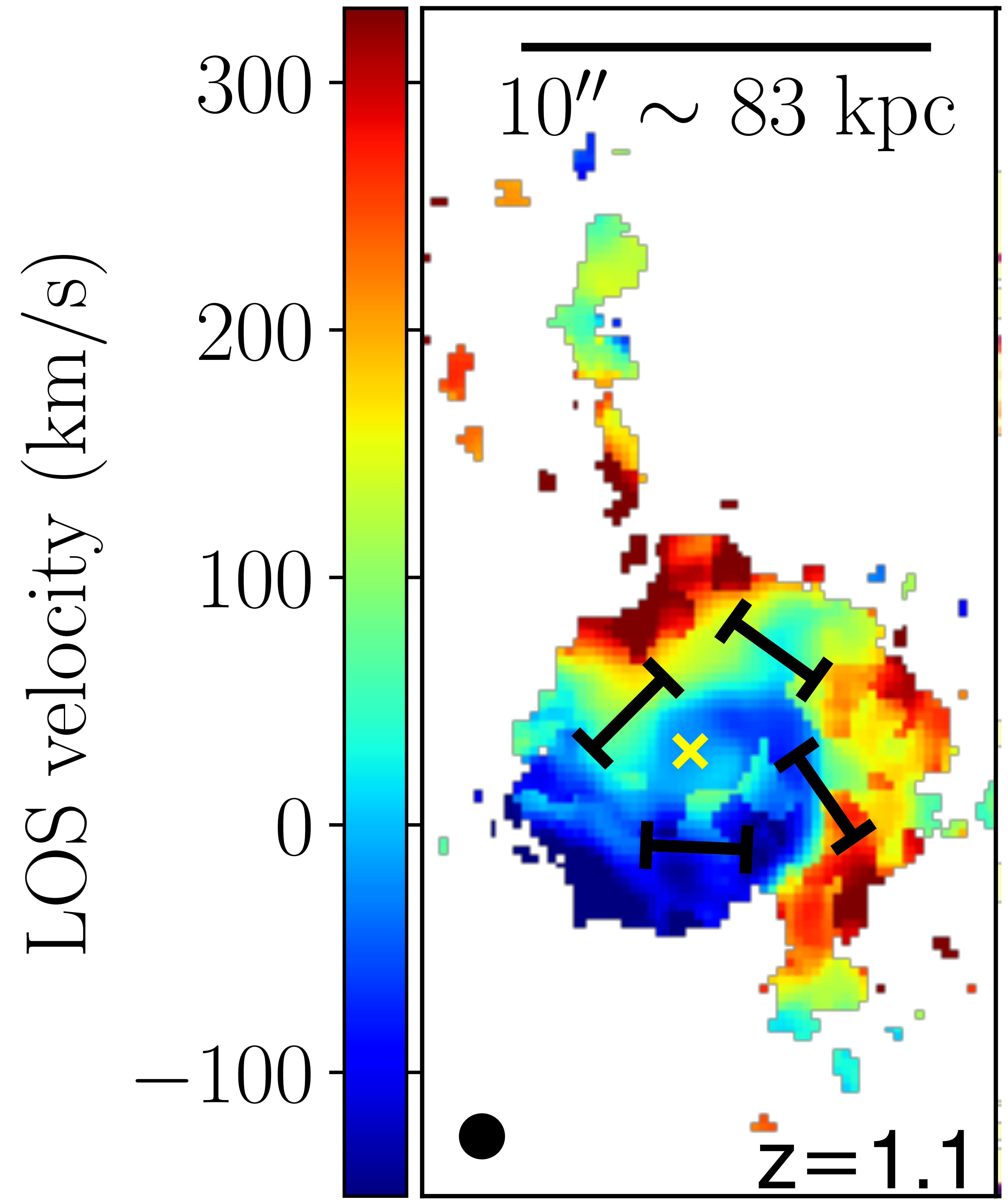

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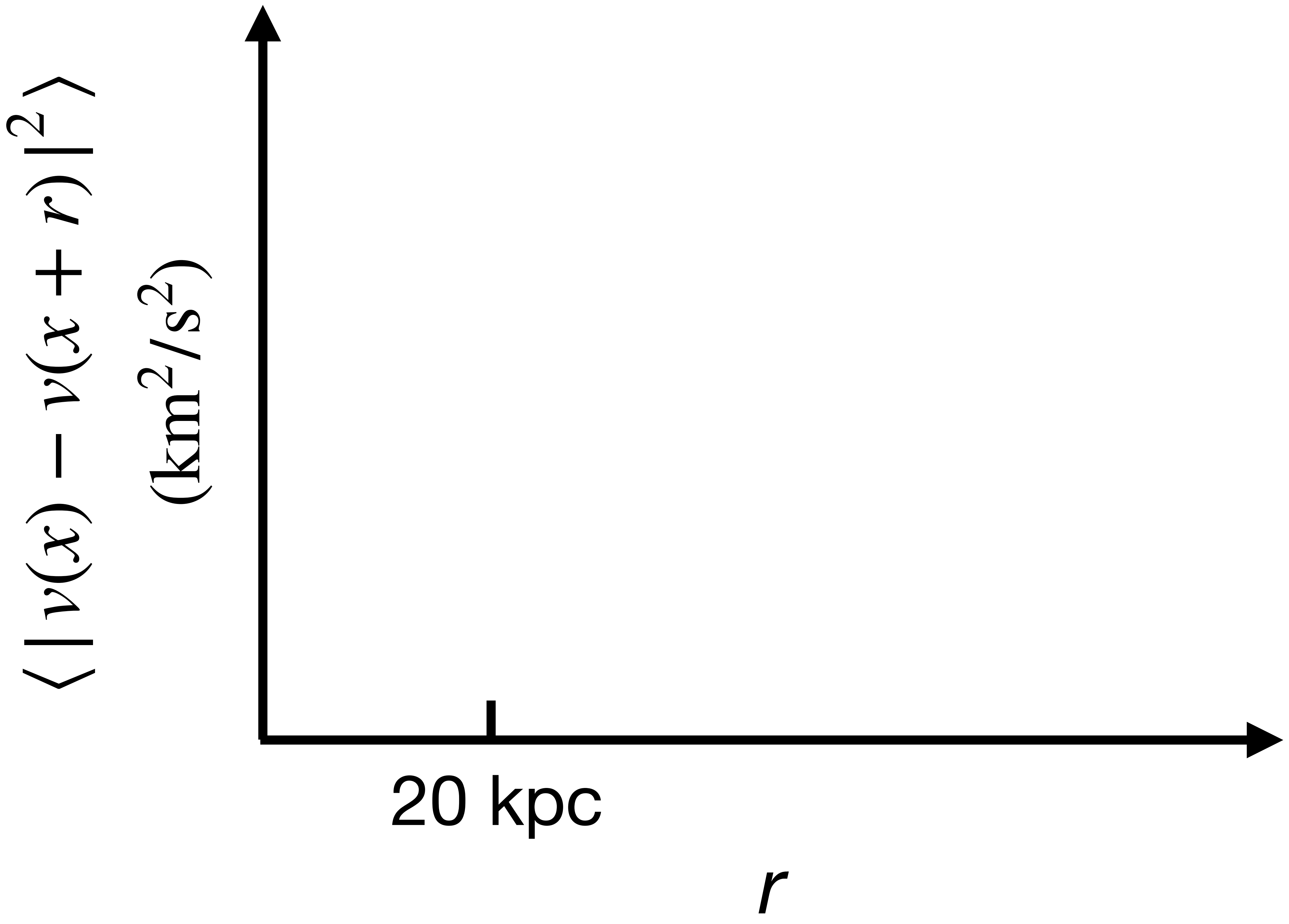

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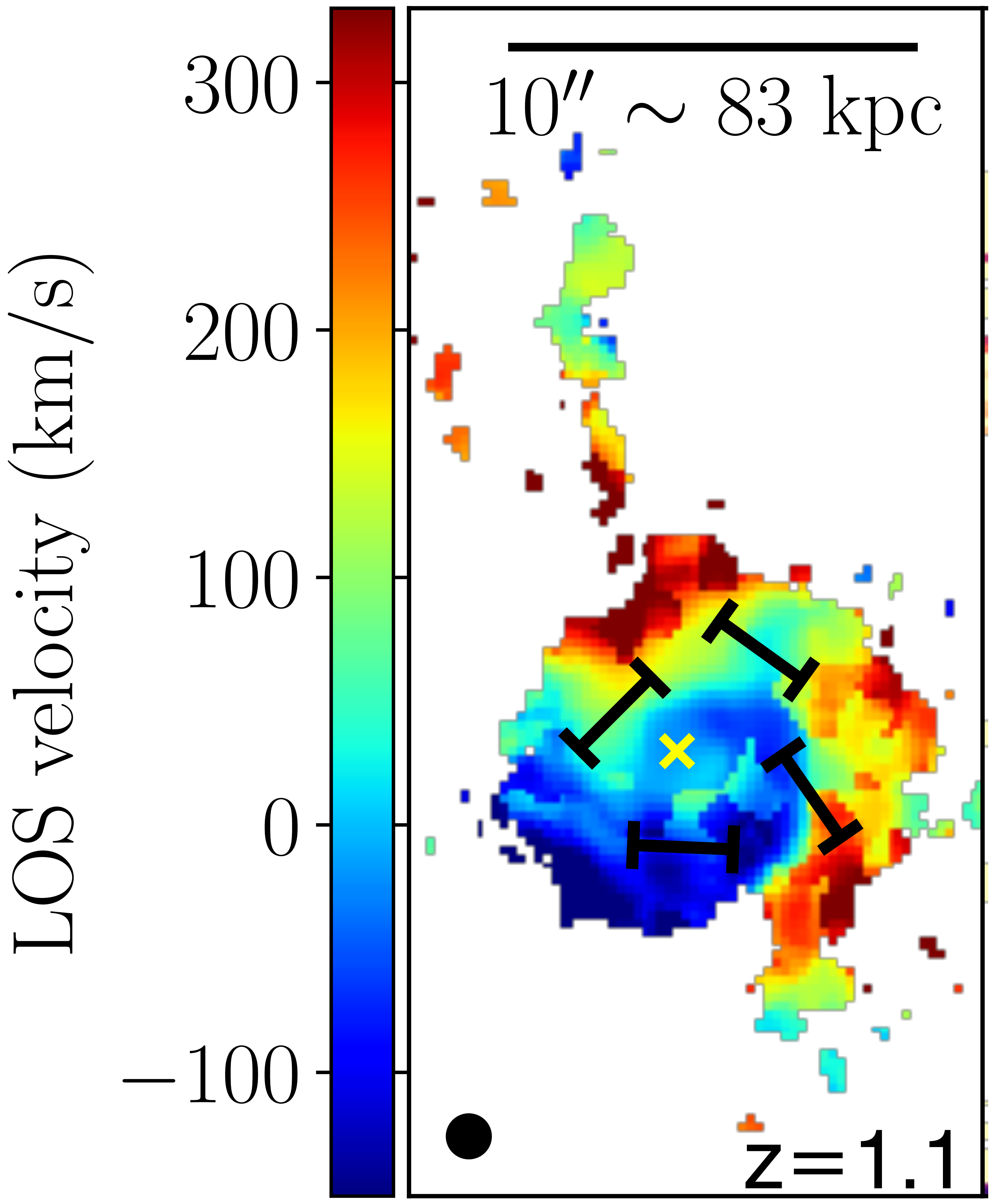

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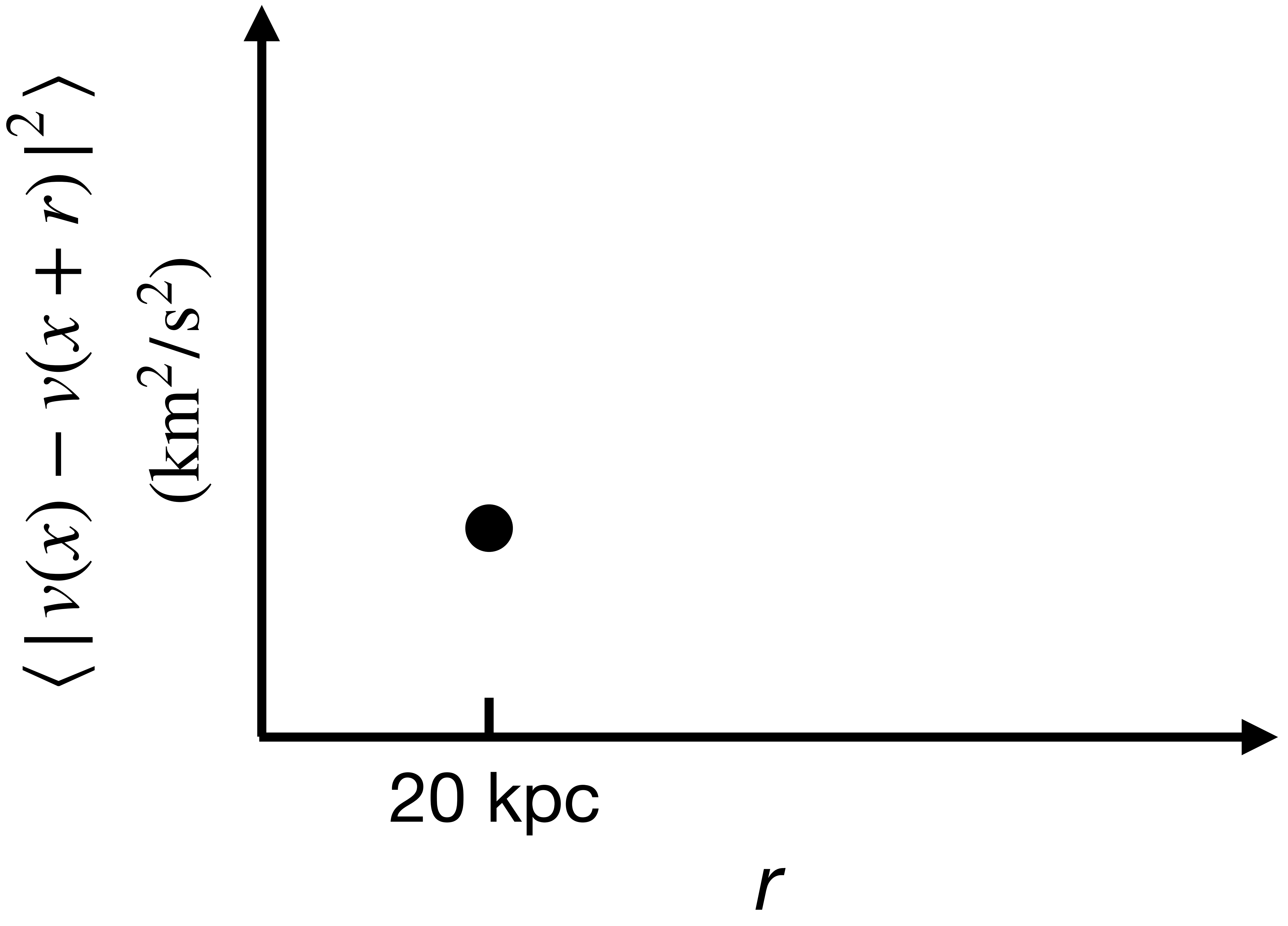

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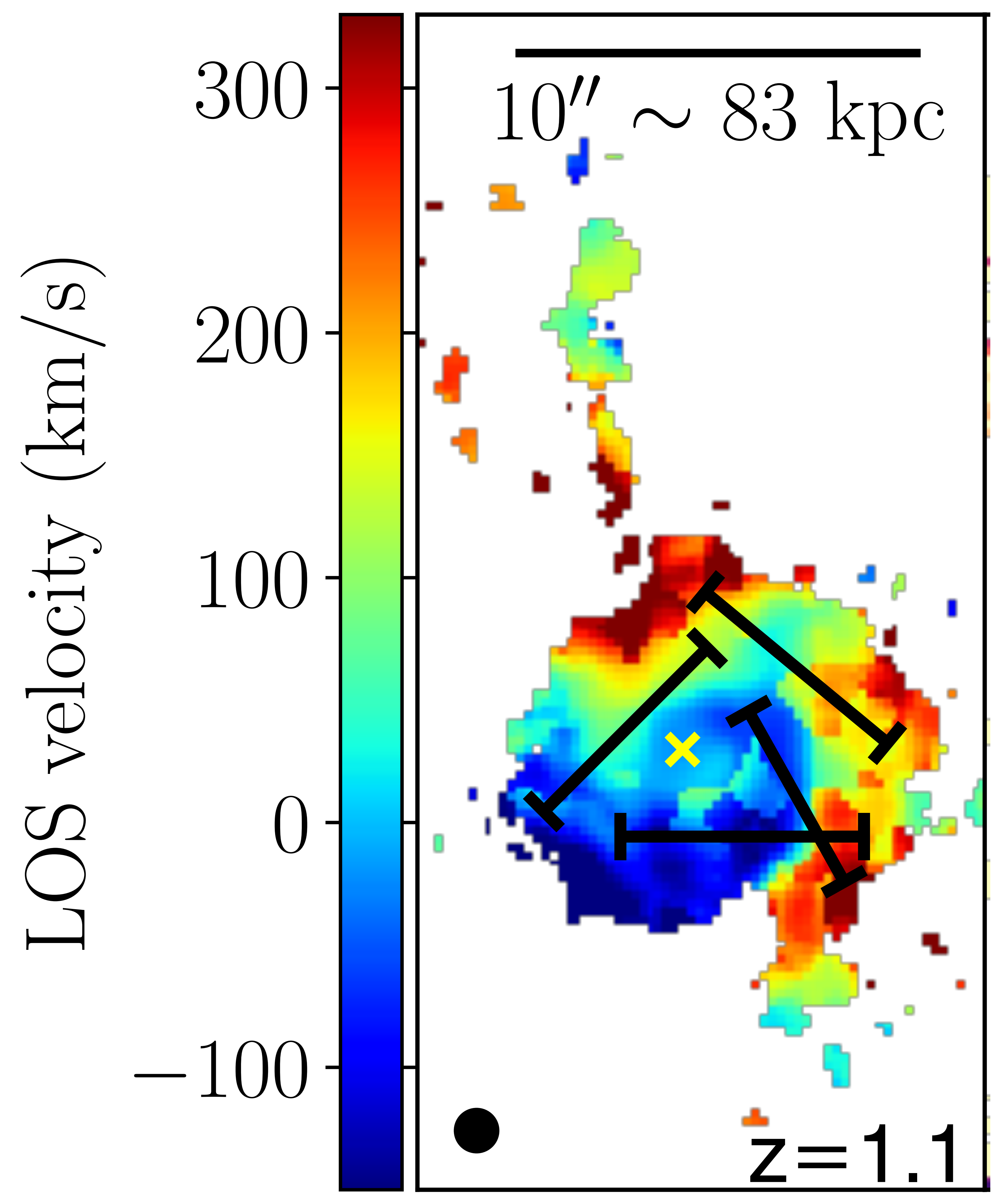

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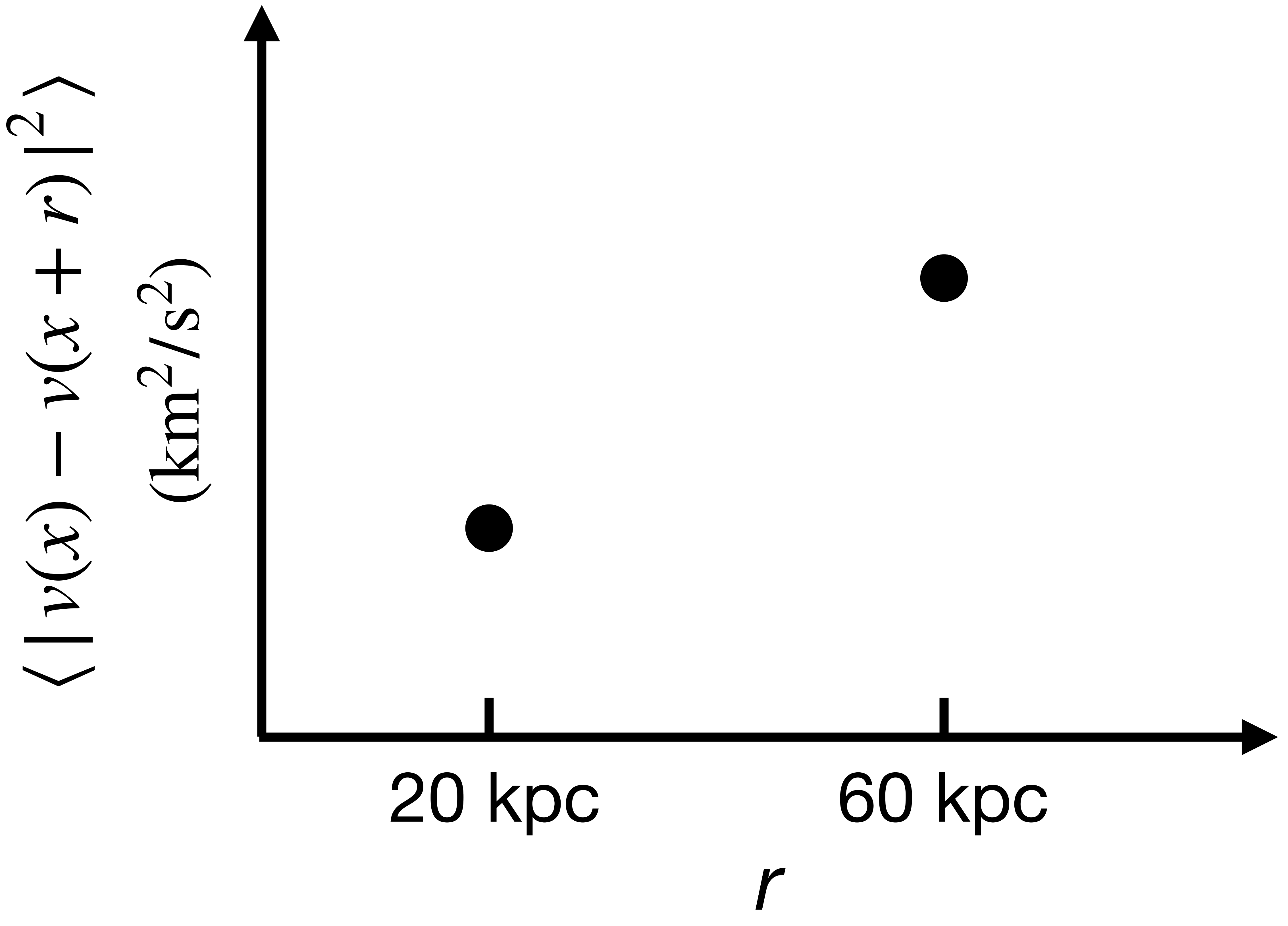

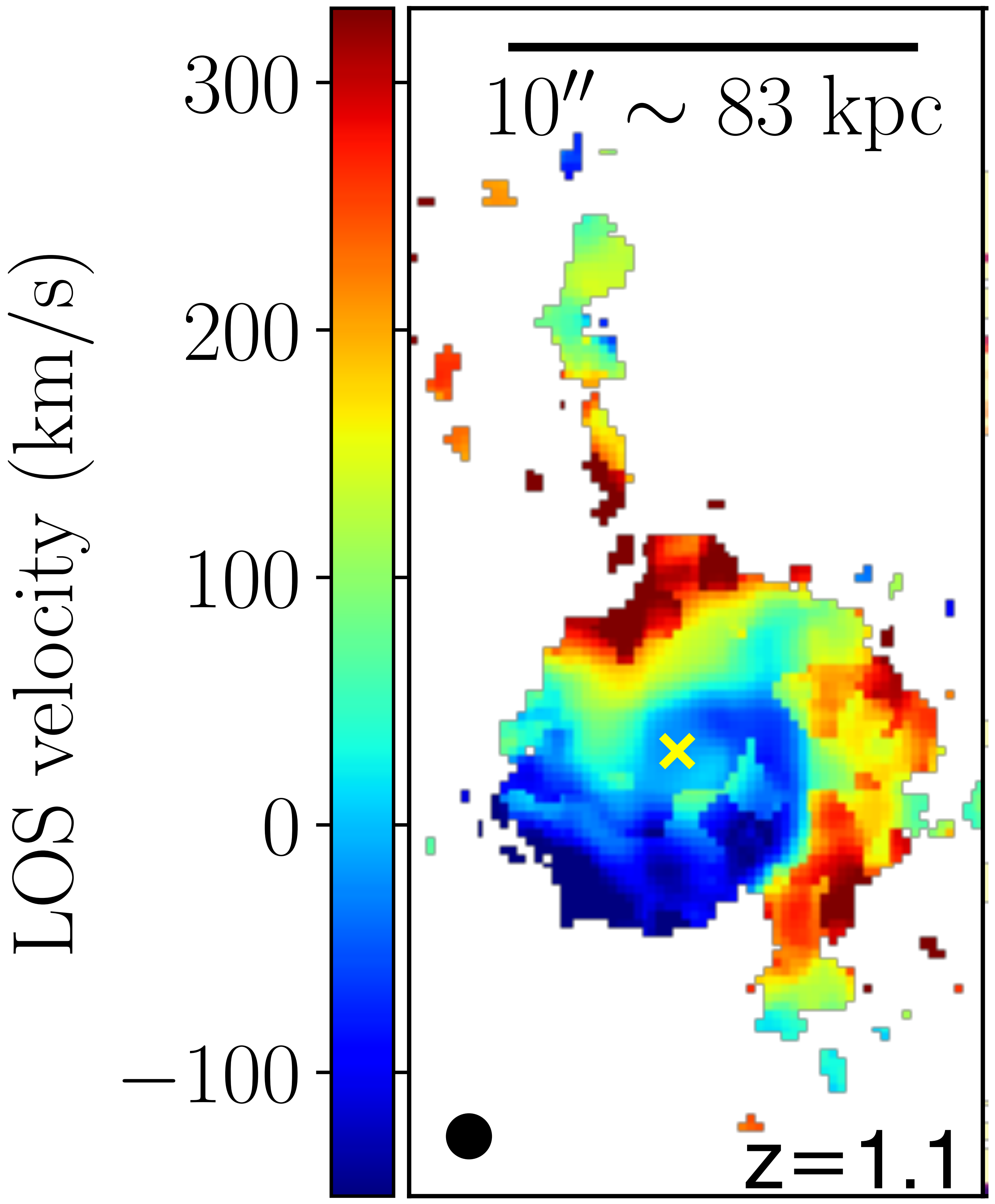

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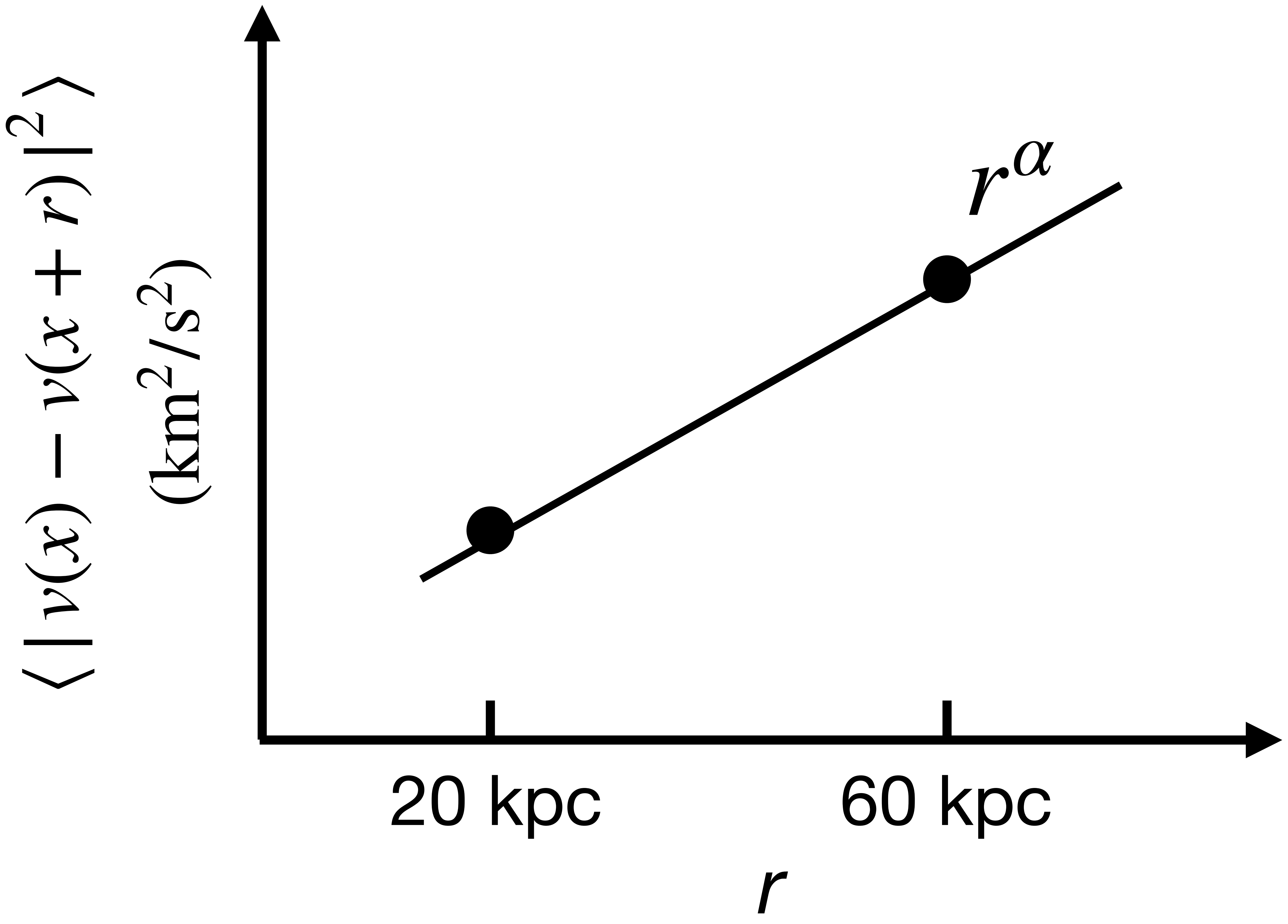

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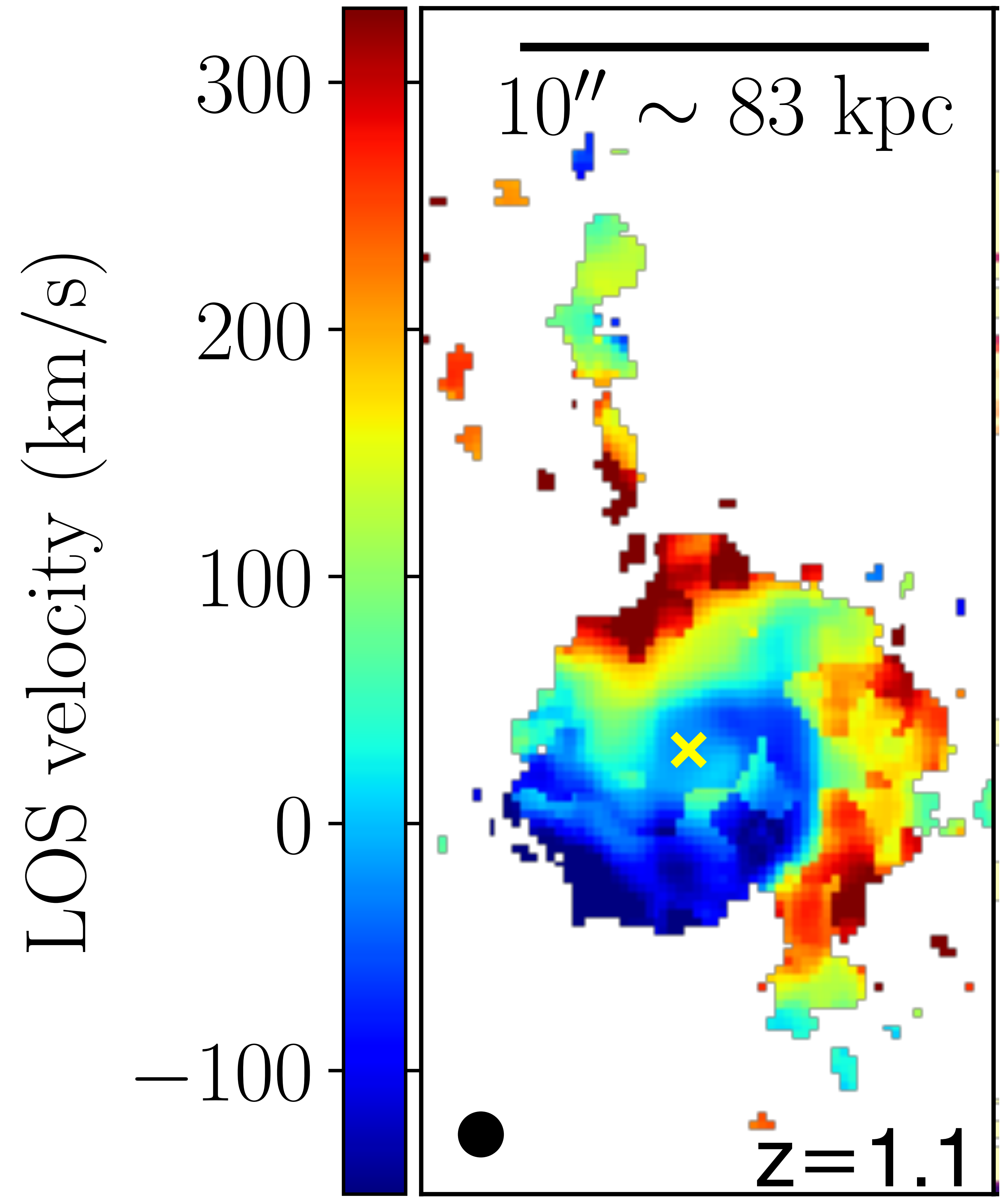

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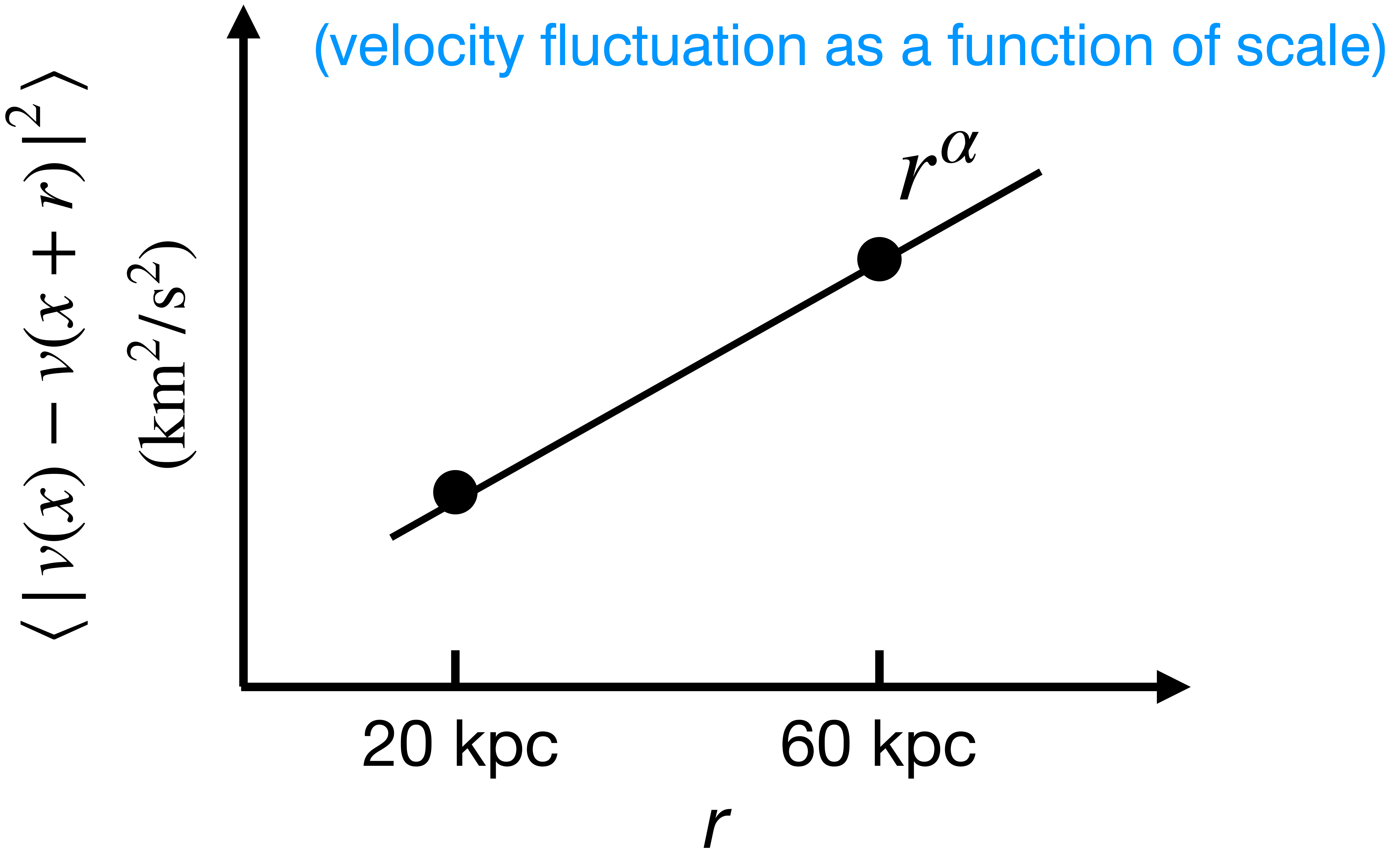

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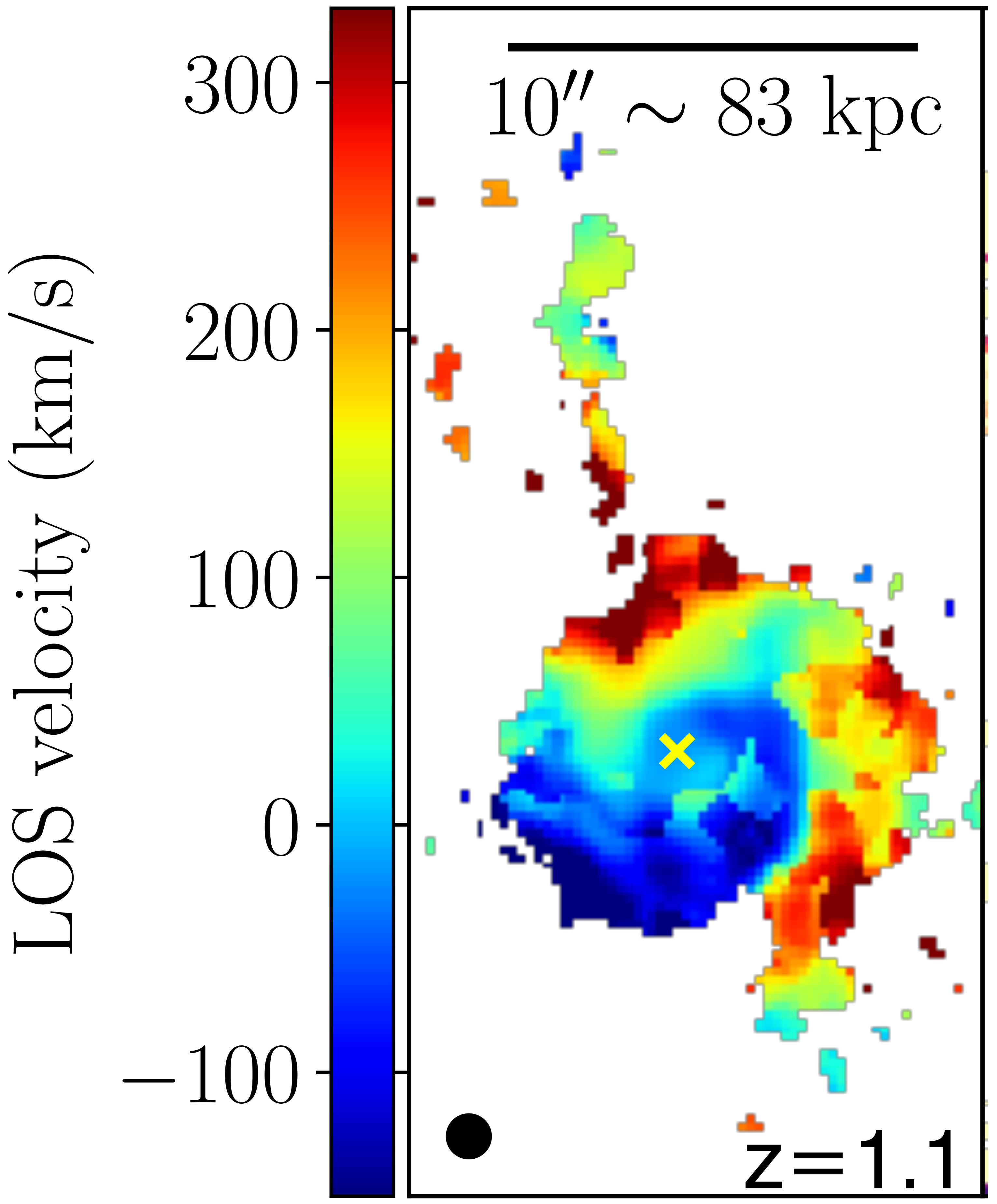

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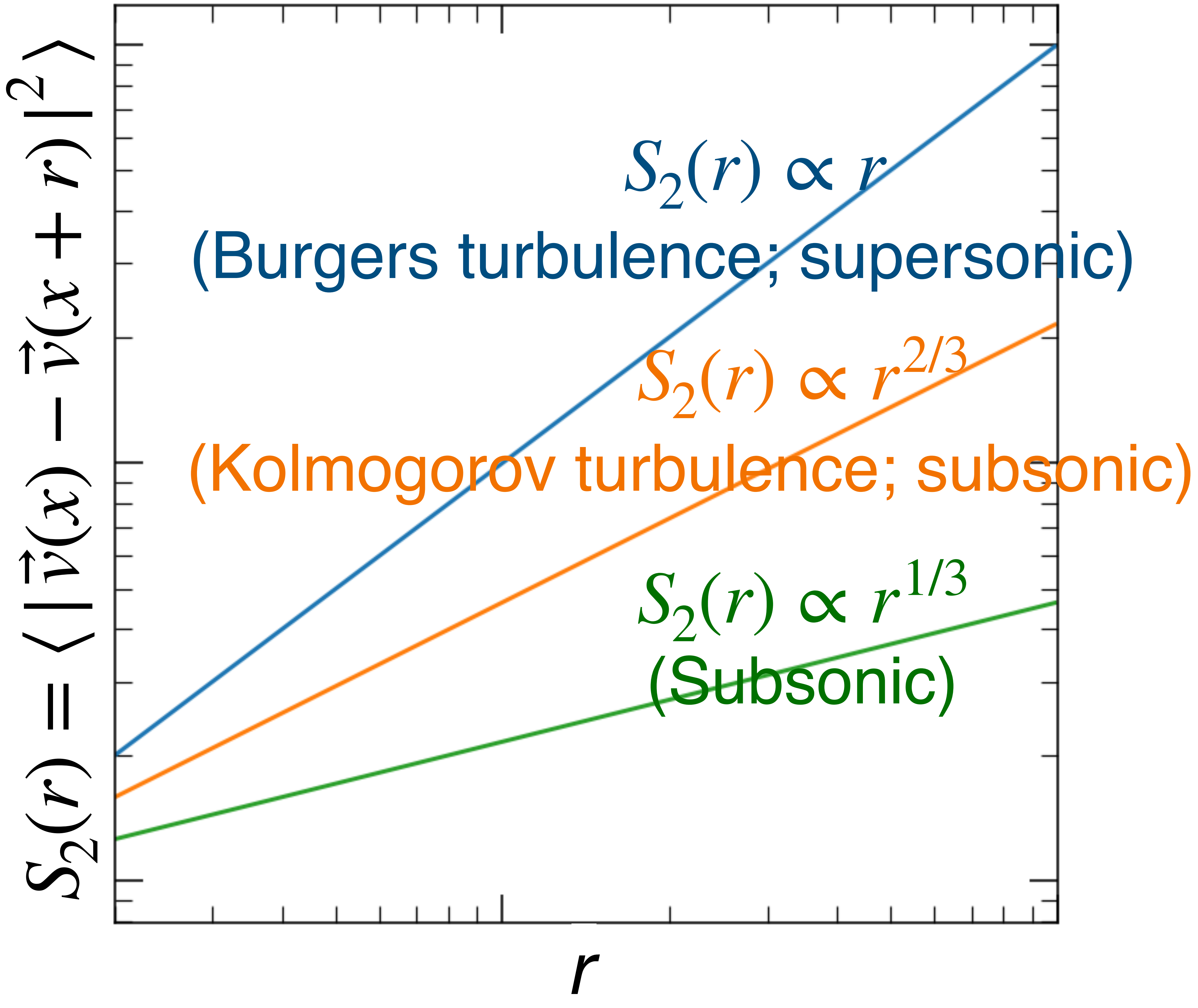

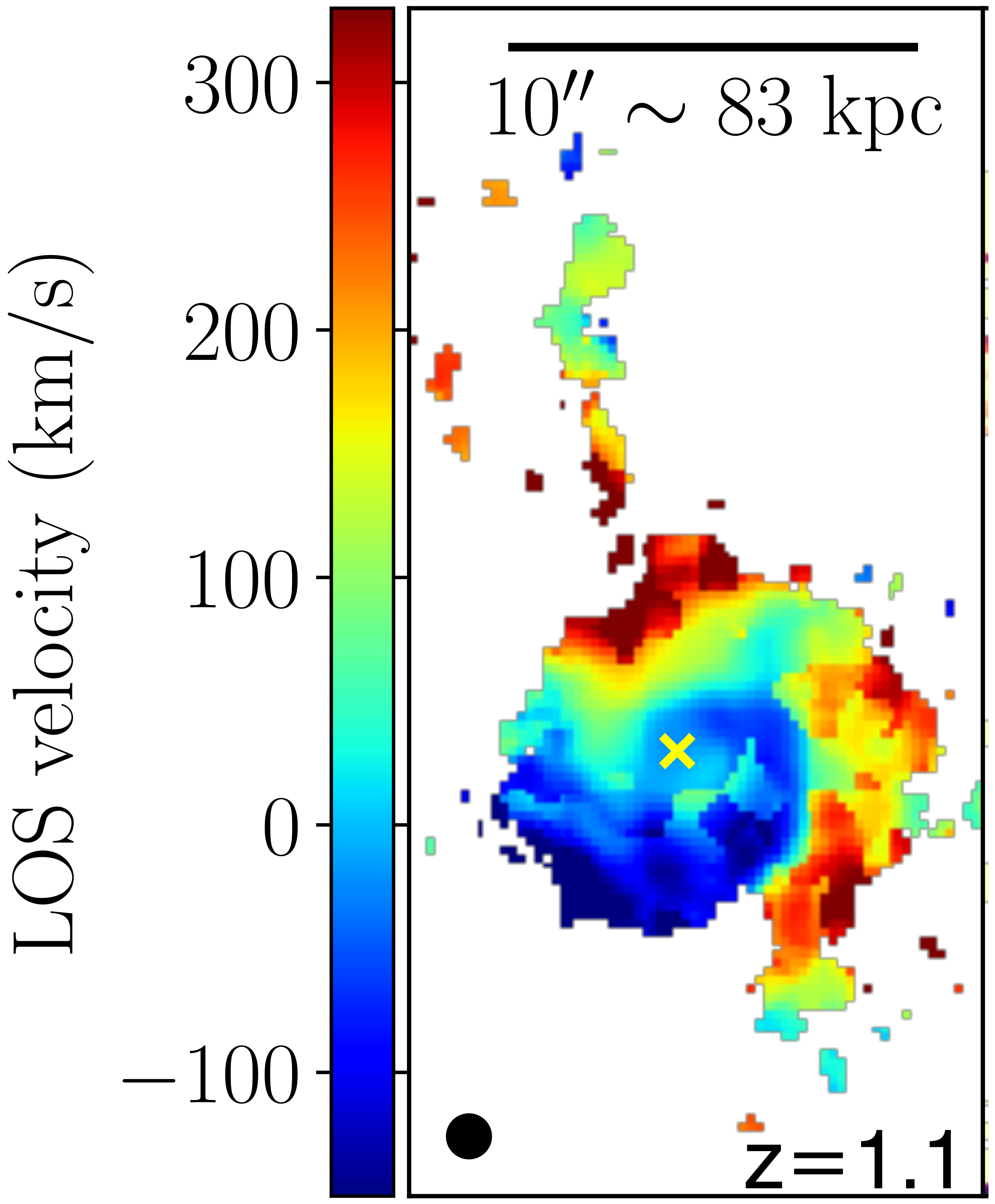

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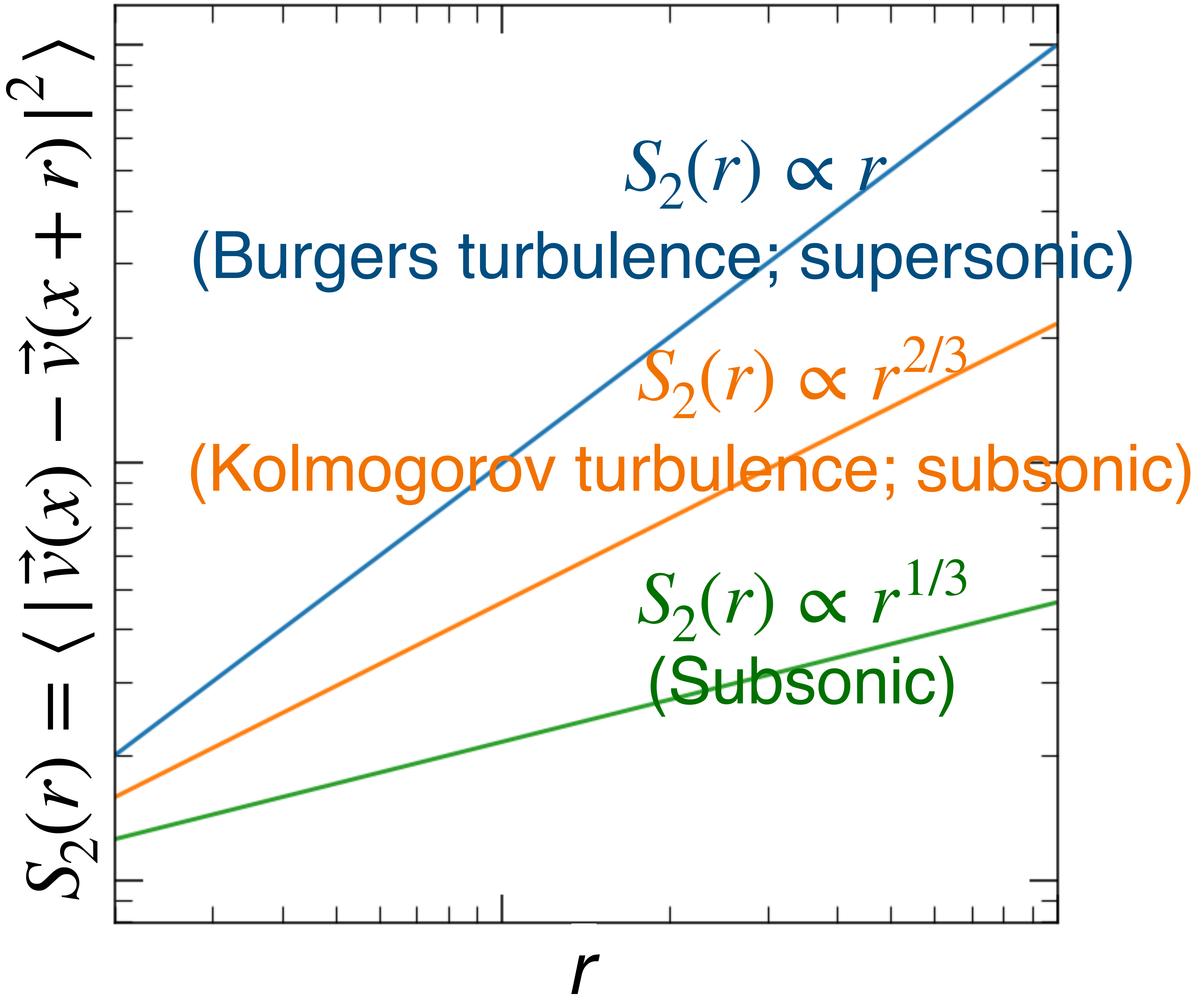

Turbulent energy per unit mass:

$$\epsilon \approx \frac{S_3}{r}$$

Eddy turnover time/dissipation timescale:

$$\tau \approx \frac{S_2}{\epsilon}$$

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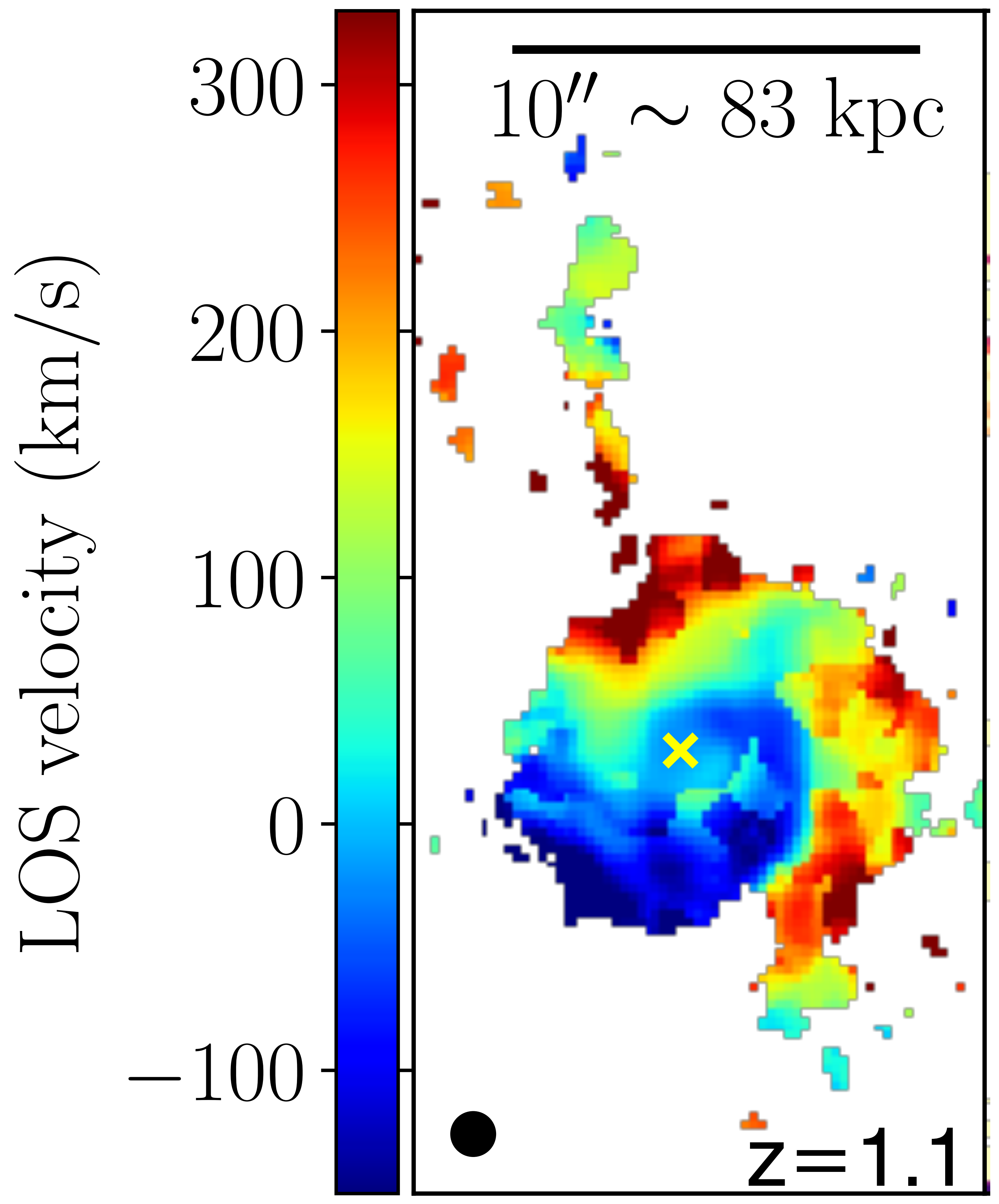

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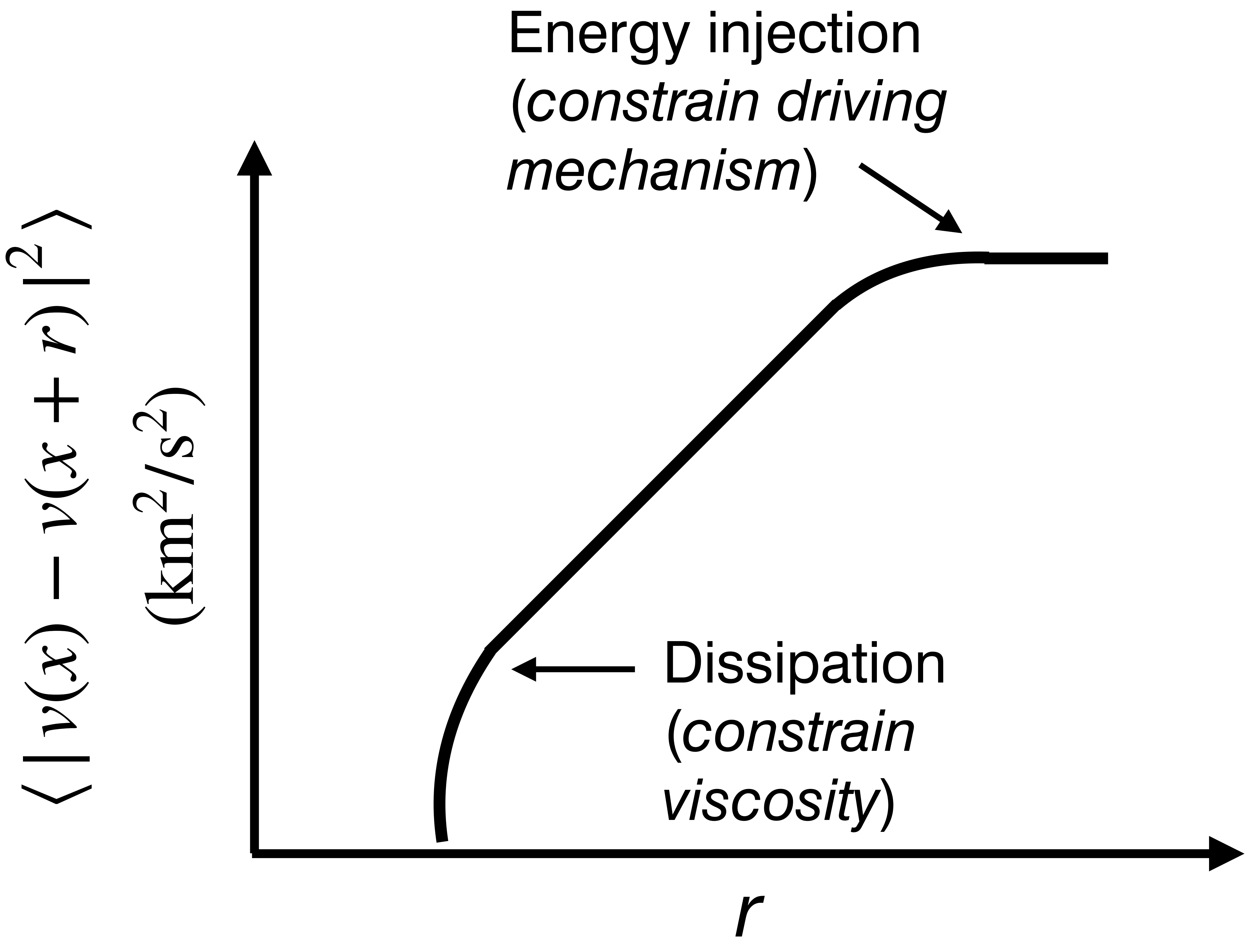

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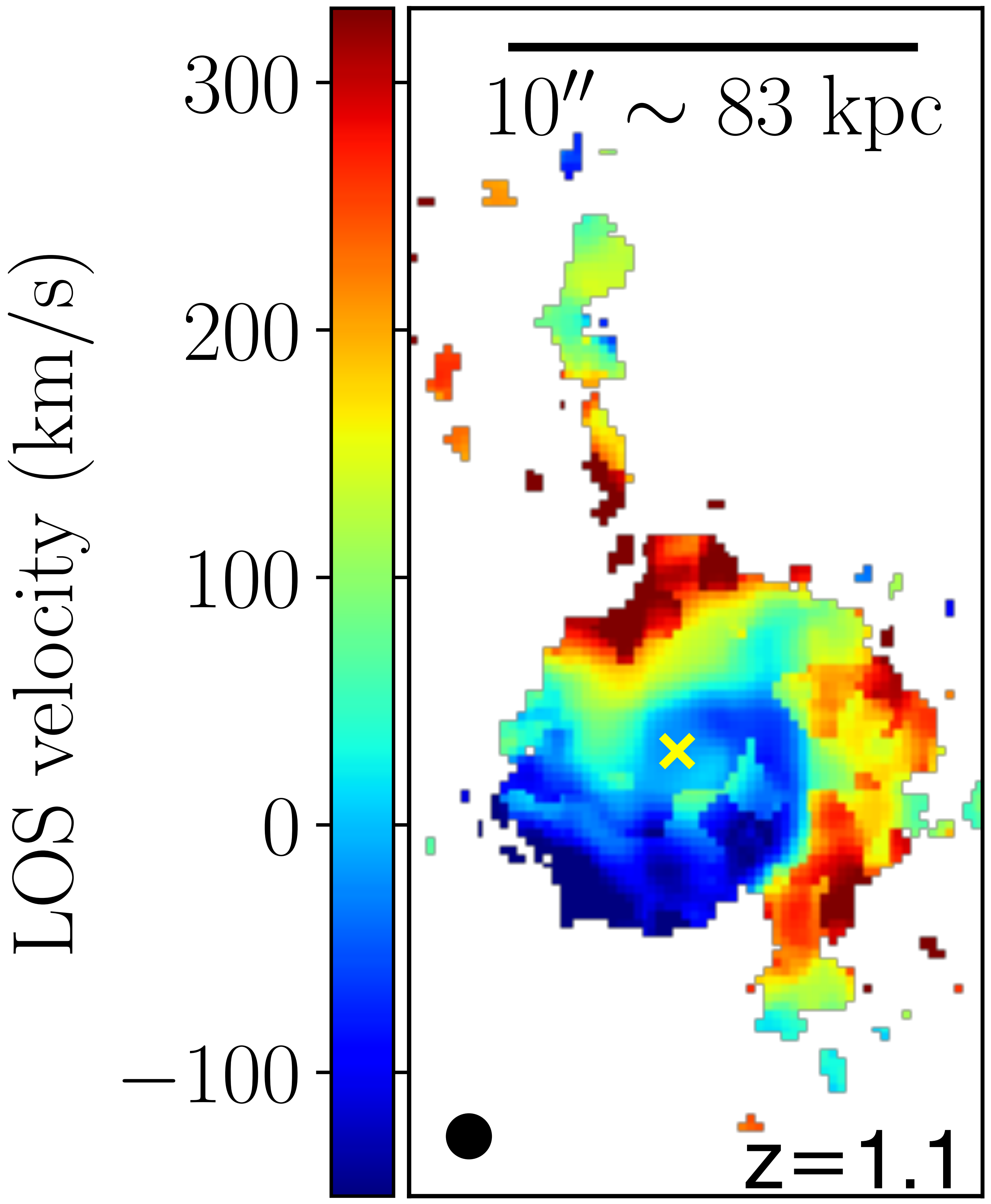
A system with Kolmogorov slope



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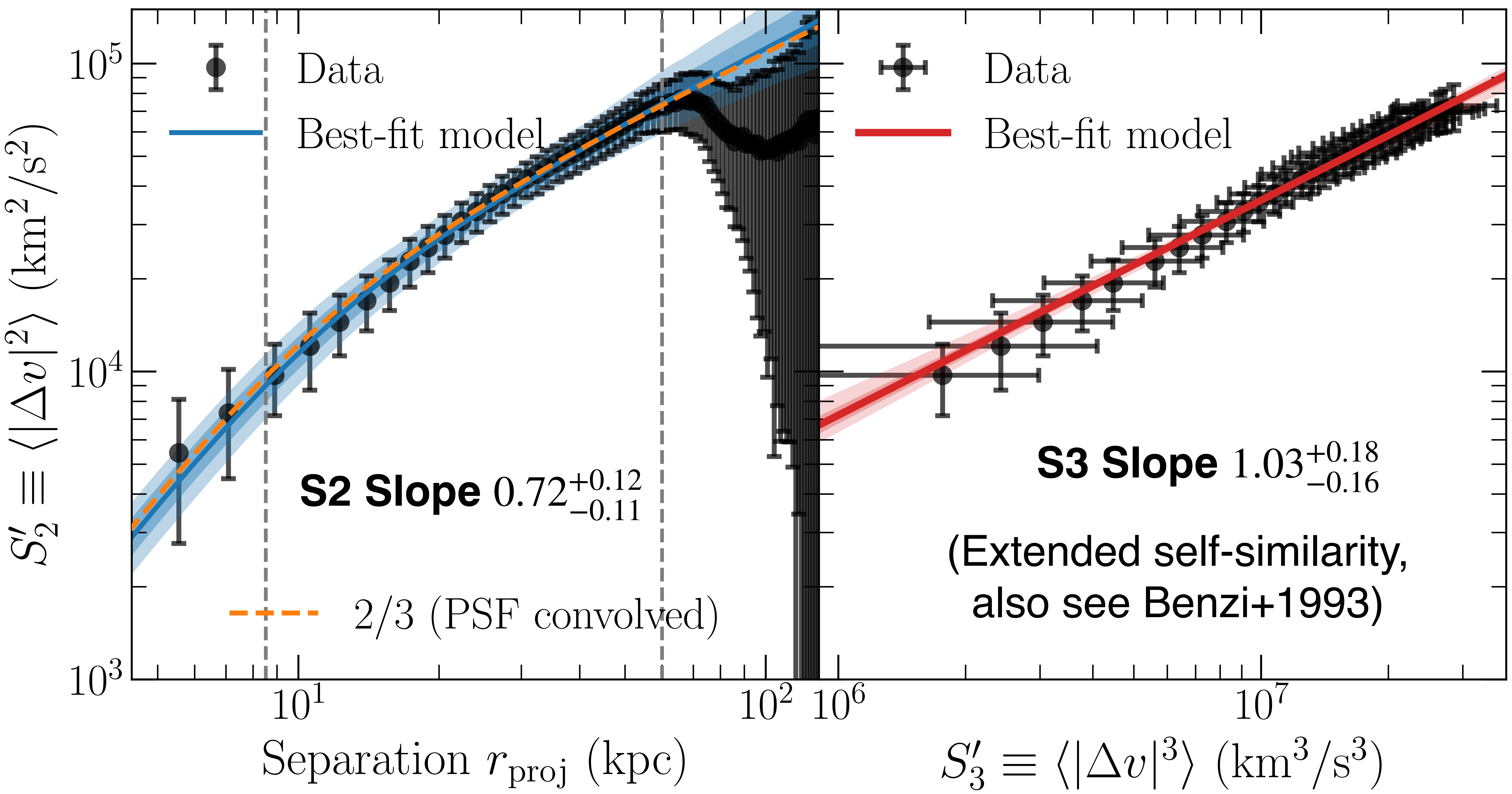

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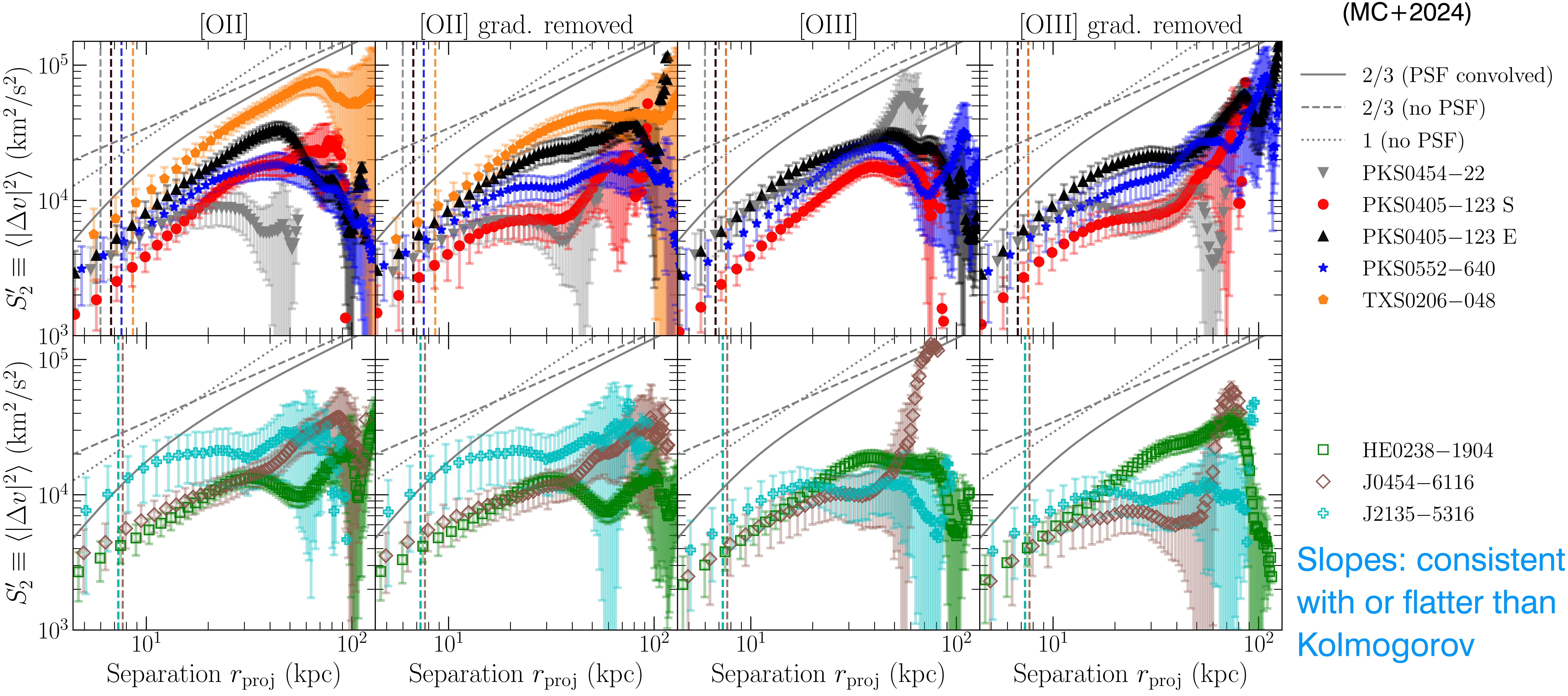
2nd-order VSF consistent with subsonic motions

(MC+2024)



Slopes: consistent with or flatter than Kolmogorov

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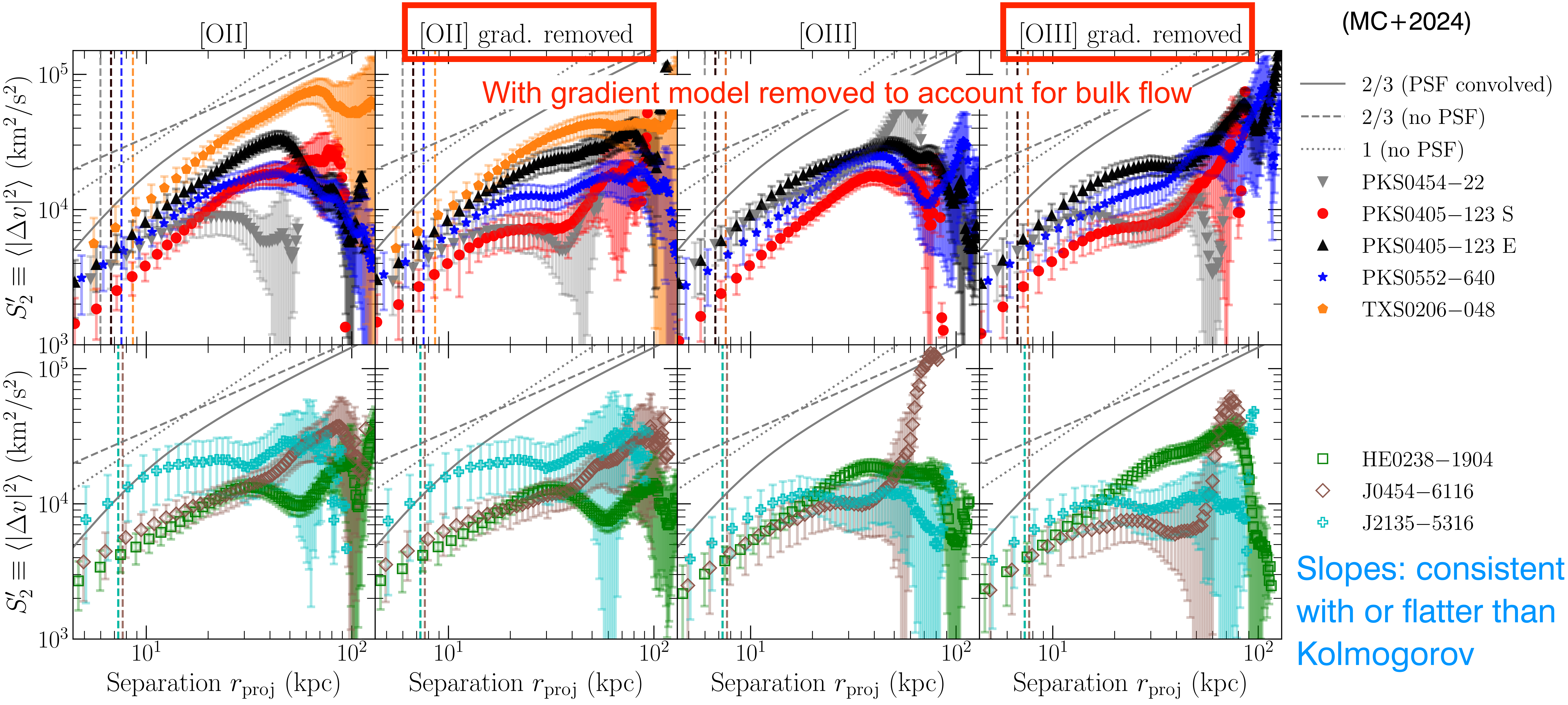

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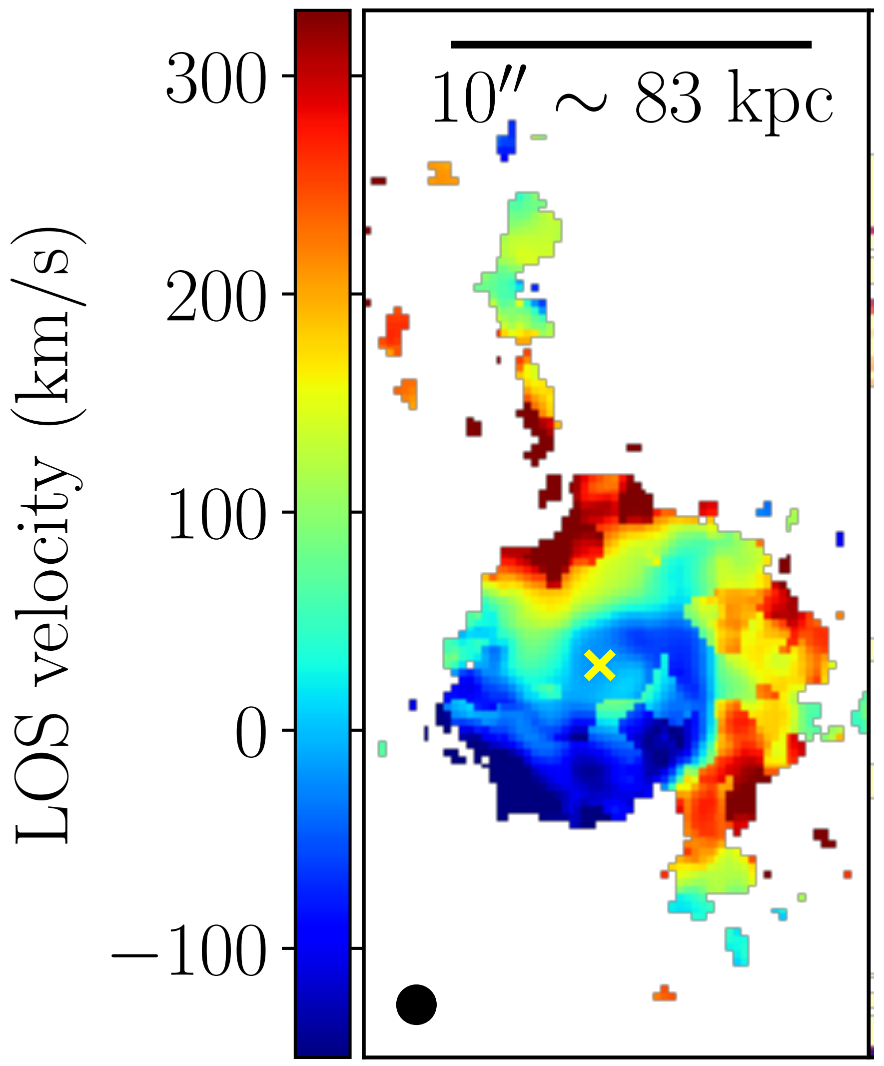
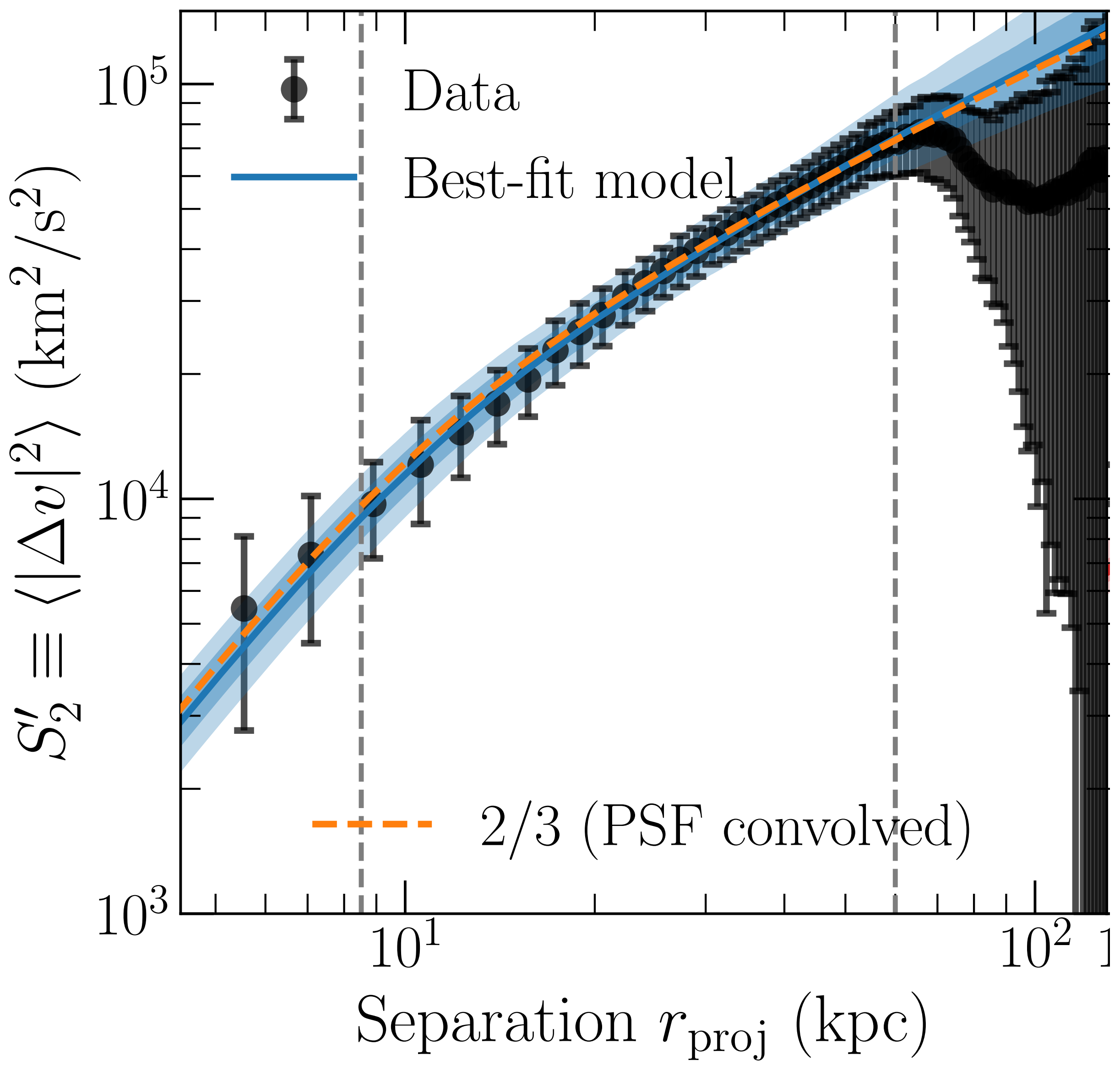
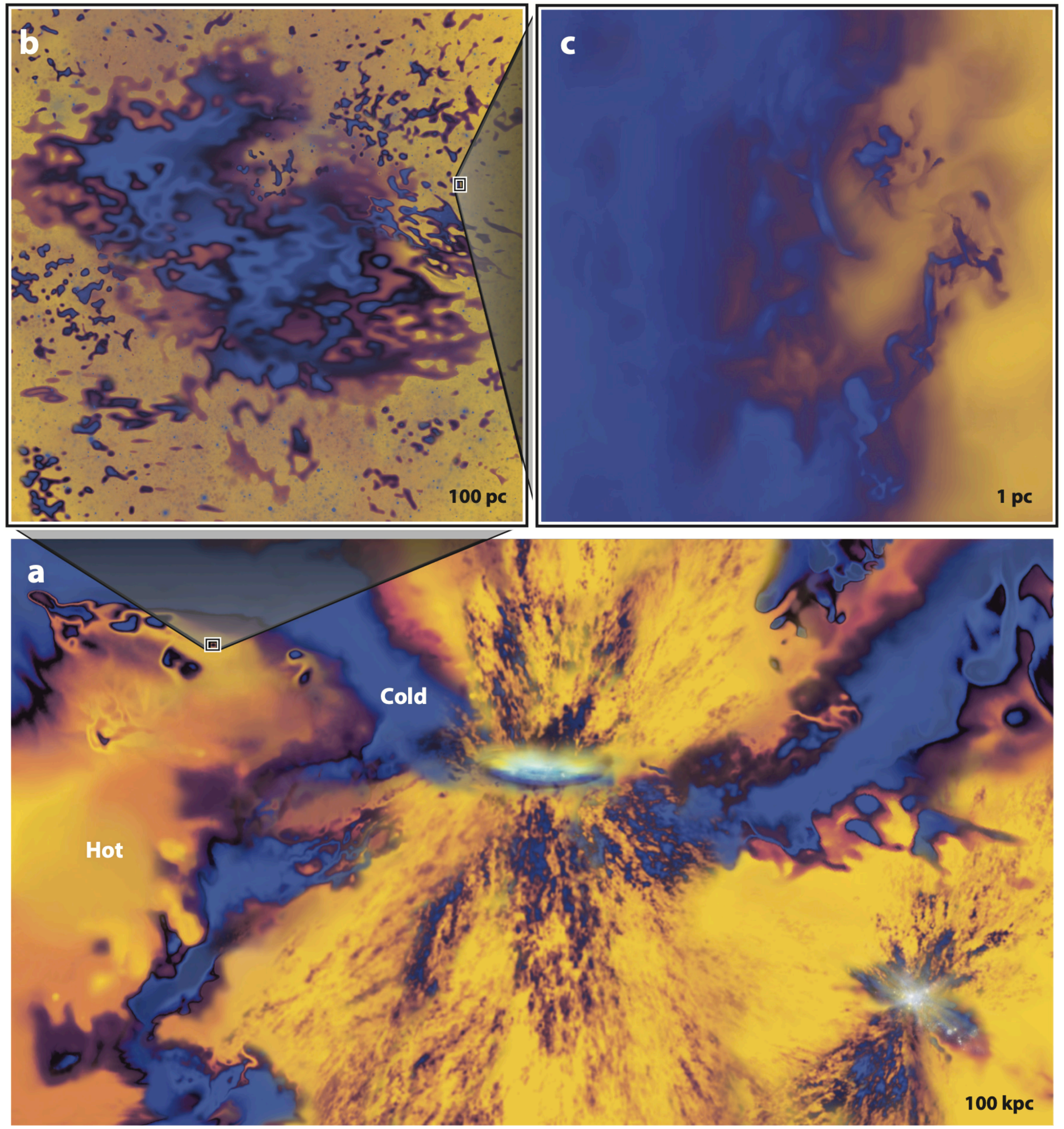
Cool gas is dynamically coupled to the hot phase





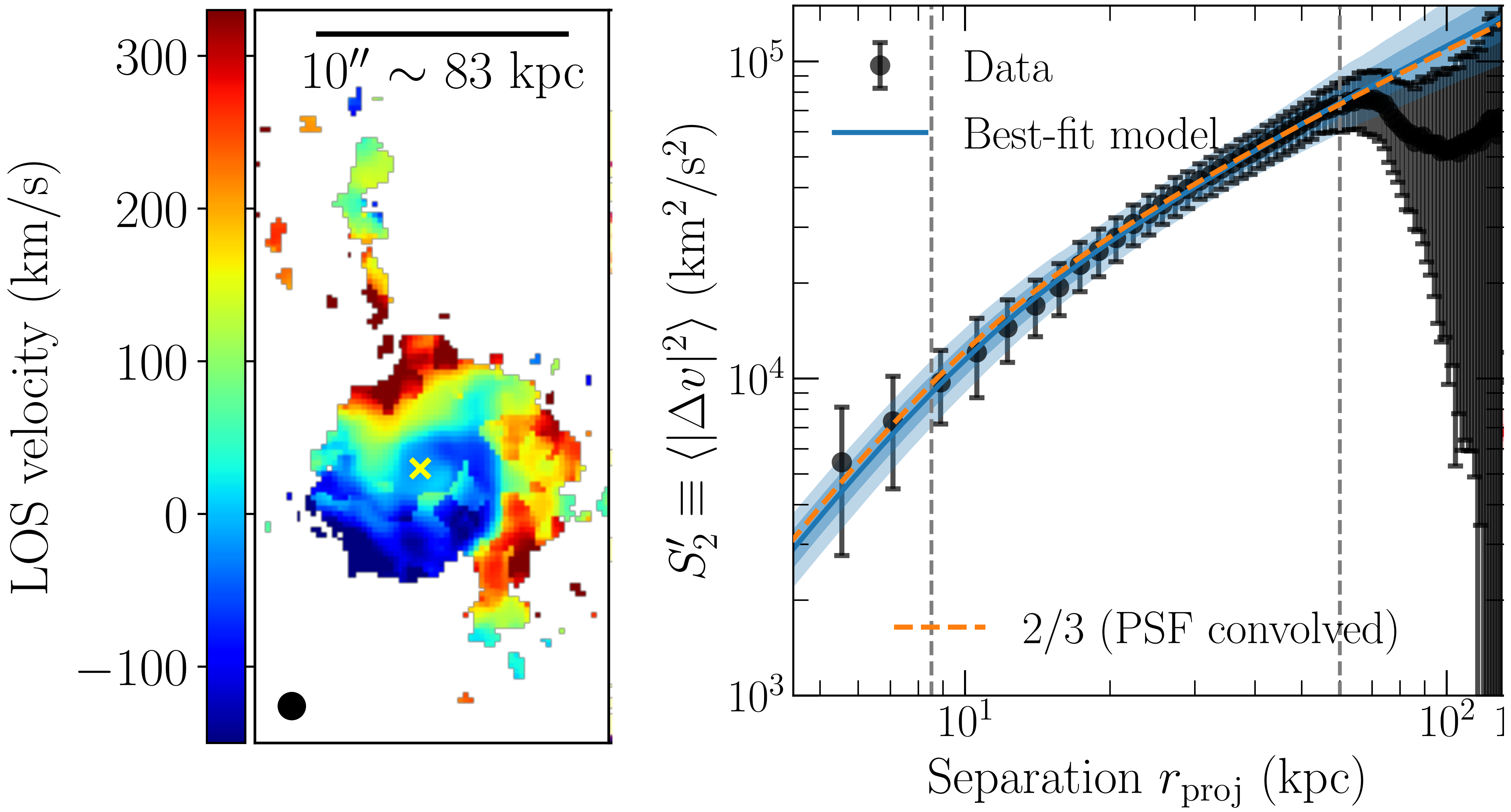


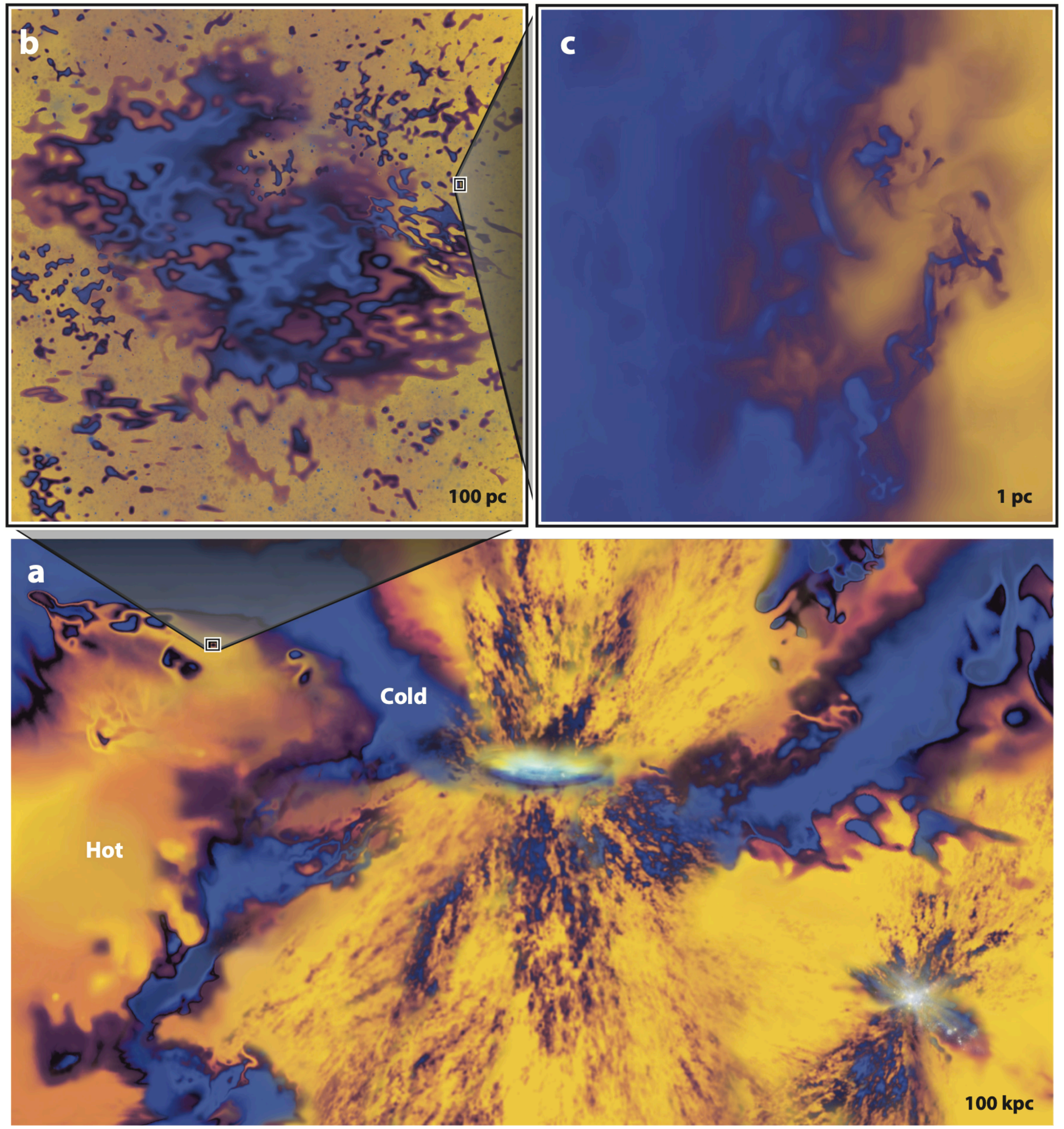
(Faucher-Giguère & Oh, 2023)

- With halo masses $\approx 10^{13} - 10^{14}\, M_\odot$, sound speed $\approx 150 - 500\,\mathrm{km/s}$ for hot phase (in contrast, sound speed $\approx 15\,\mathrm{km/s}$ for cool phase)
  $\mathrm{Mach_{cool}} \approx 7 - 18$ vs $\mathrm{Mach_{hot}} \approx 0.2 - 1.8$

(e.g., Gaspari+2018; Fielding+2020; Gronke+2022;
Talks by e.g., Max Gronke, Hitesh Kishore Das;
Posters by e.g., Fernando Hidalgo Pineda, Alankar Dutta, Ritali Ghosh)

Turbulent energy is a small fraction of $L_{\rm QSO}$





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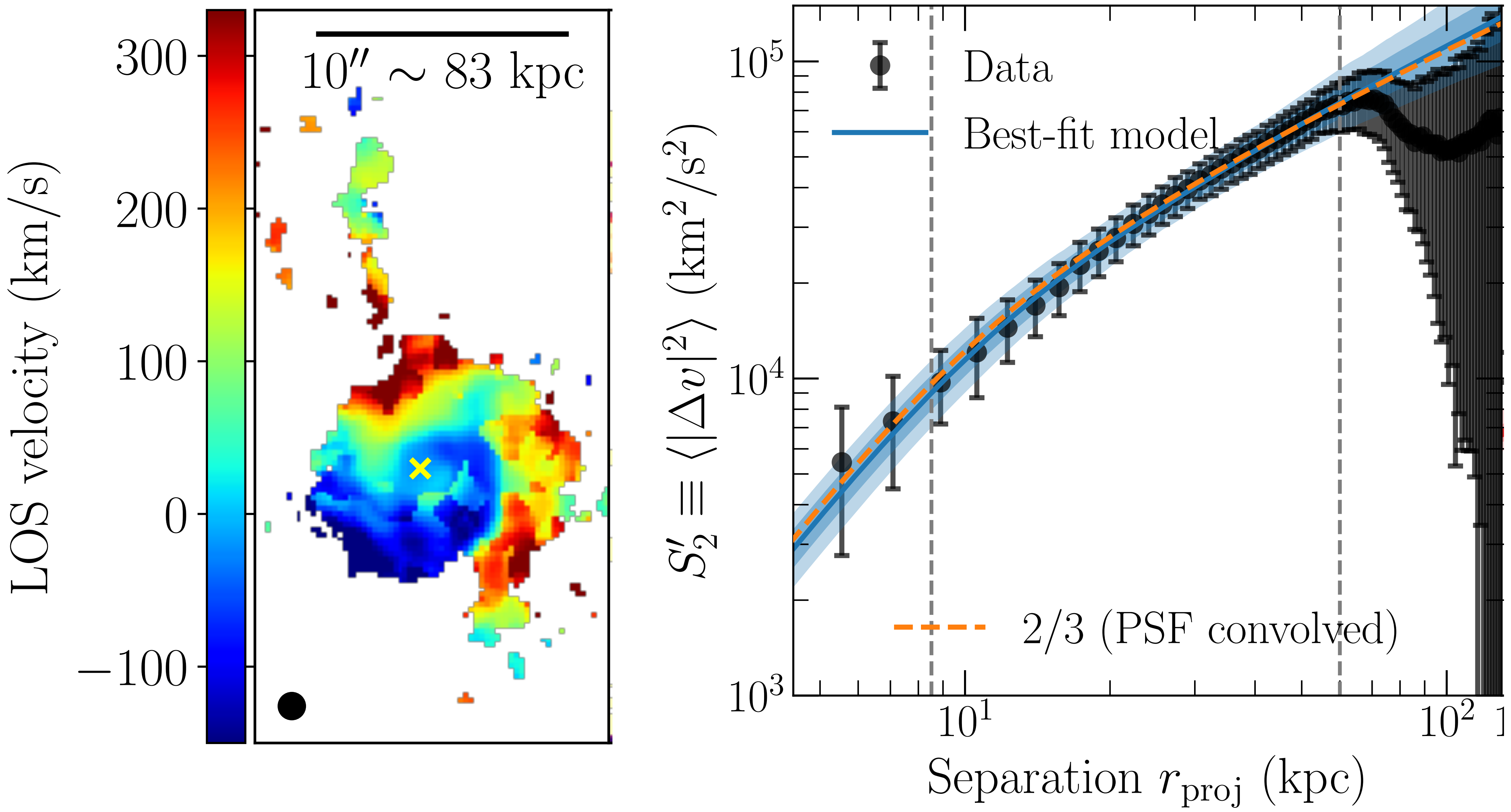
- $\dot{E} \sim 10^{44}\,\mathrm{erg\,s^{-1}}$ within 50 kpc, $\sim 0.05\,\%\,L_{\rm bol,QSO}$

Turbulence is likely driven by large-scale interactions



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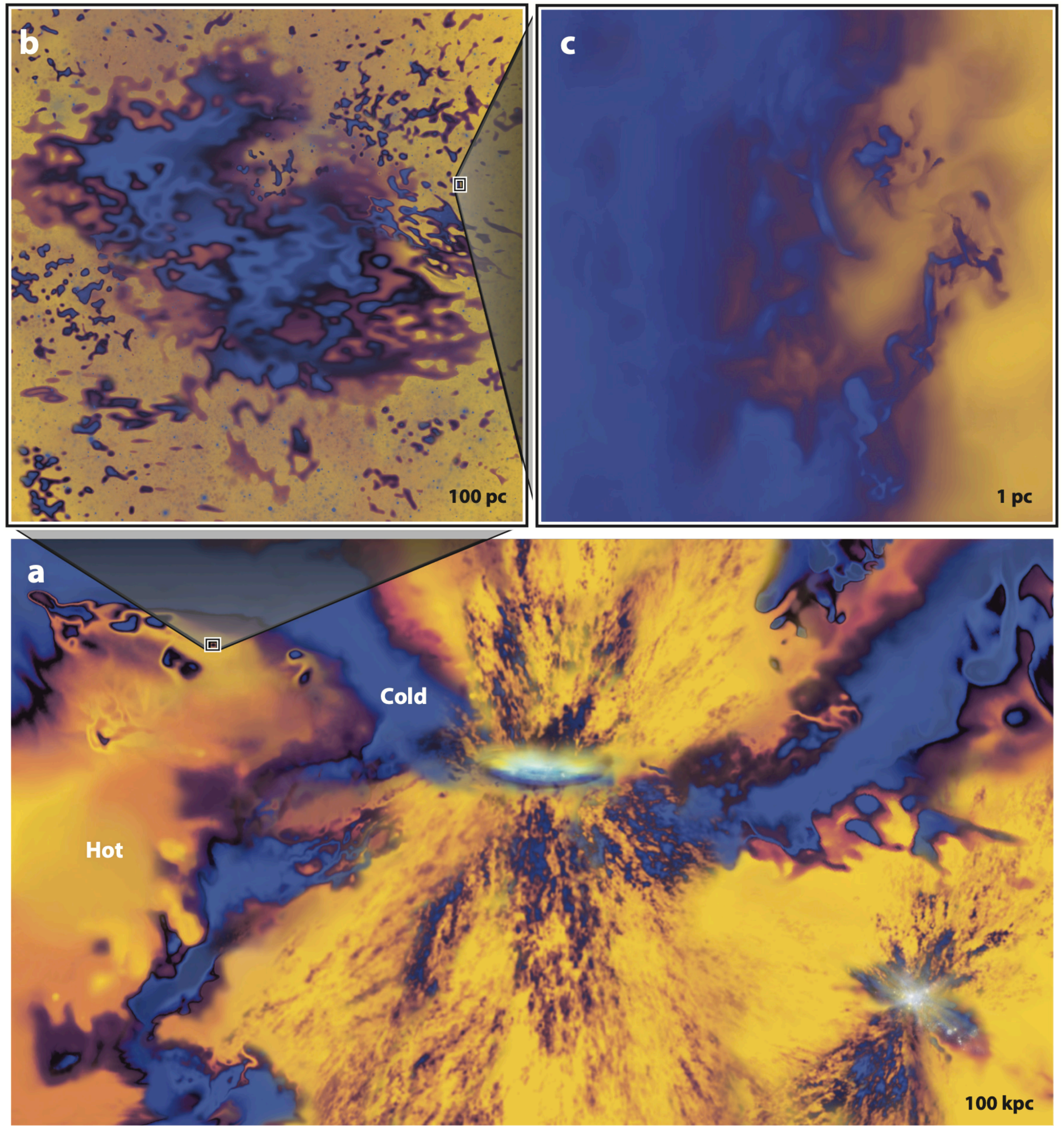
- $\dot{E} \sim 10^{44}\,\mathrm{erg\,s^{-1}}$ within 50 kpc, $\sim 0.05\,\%\,L_{\rm bol,QSO}$

- No clear detection of flattening at large scales (i.e., energy injection); turbulence is likely driven by large-scale interactions (e.g., galaxy mergers)



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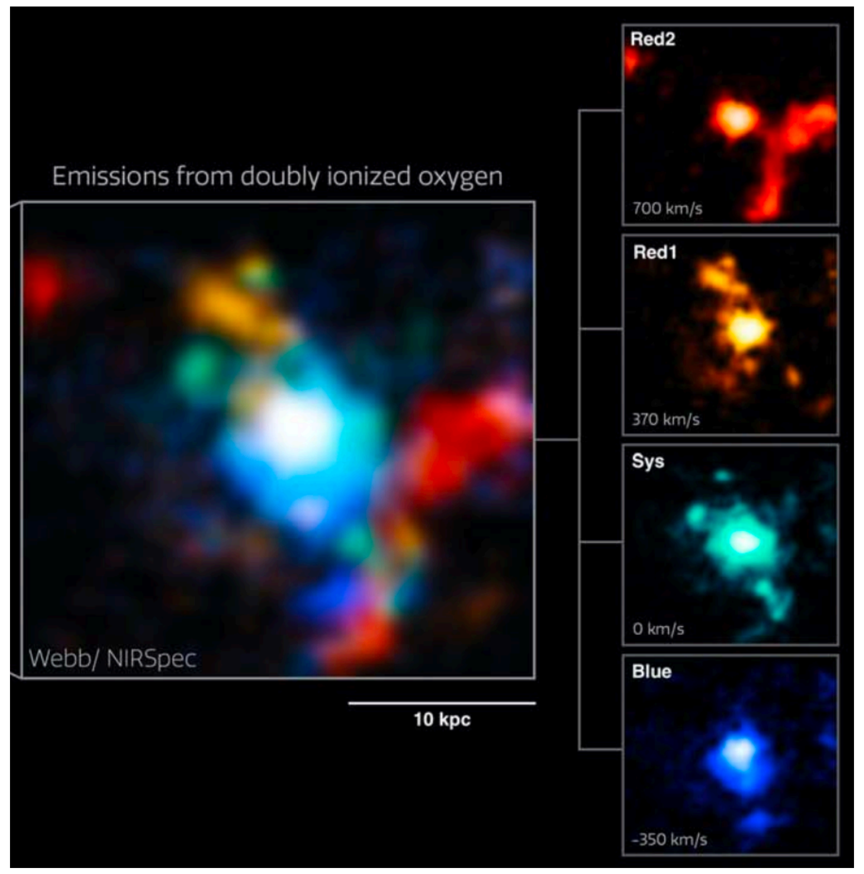

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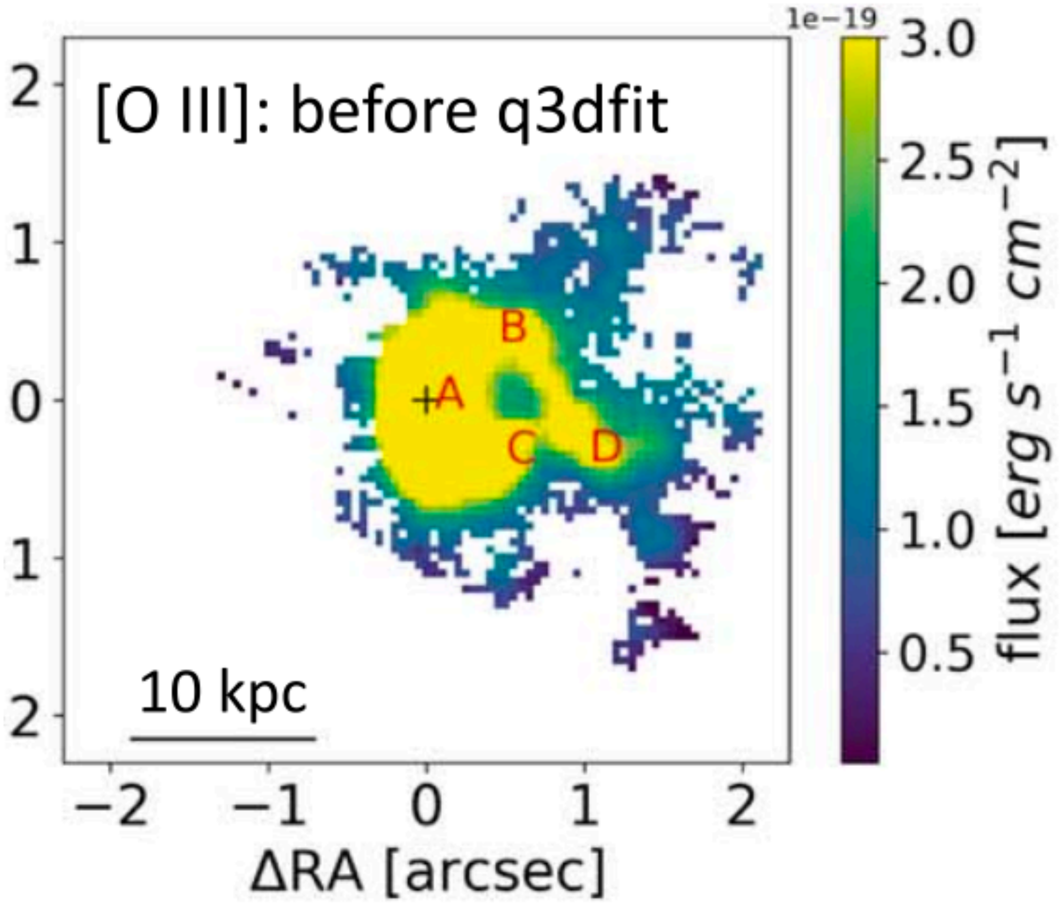

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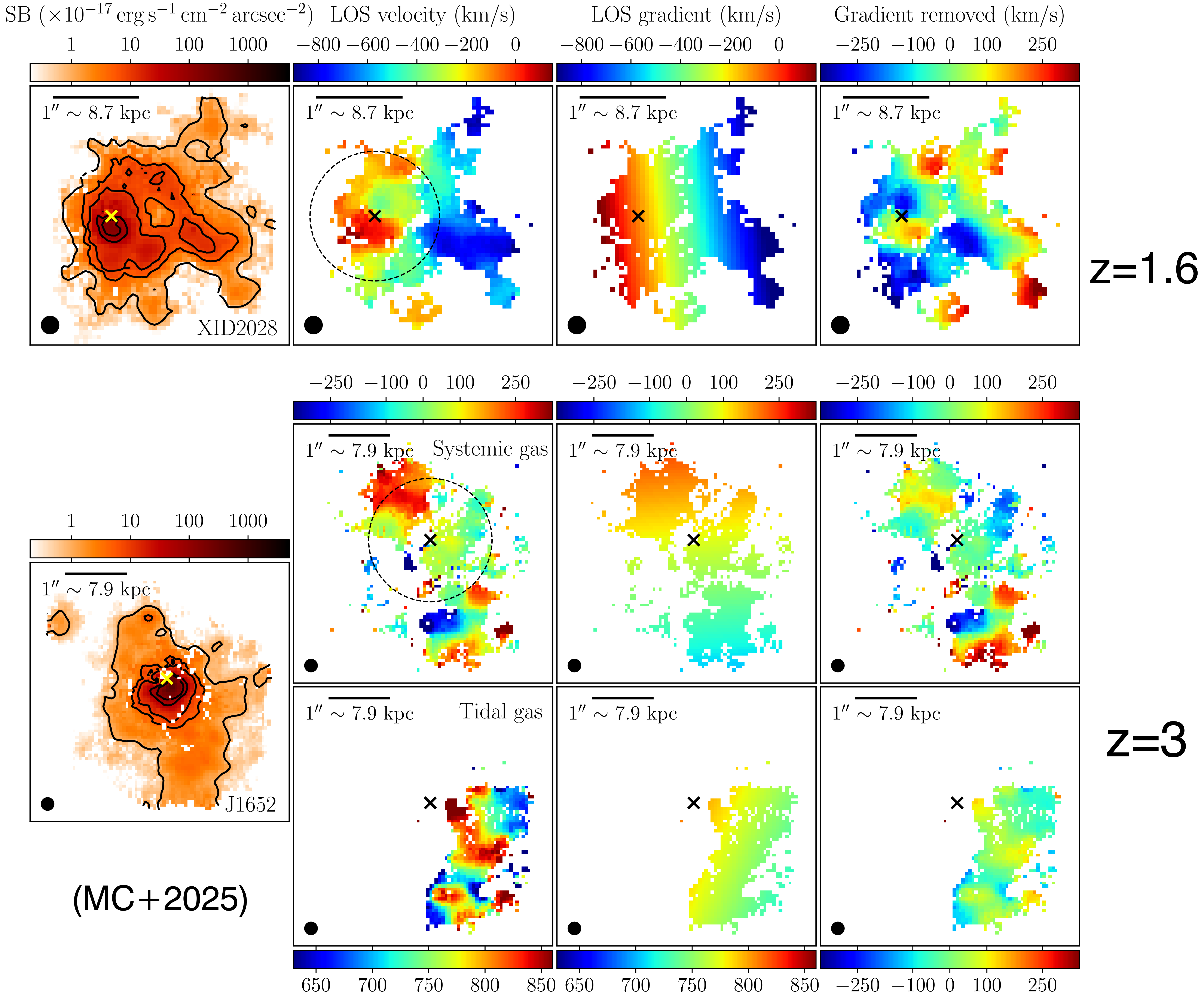
Q3D JWST ERS Program
PI Dominika Wylezalek

[OIII] emission detected by JWST/NIRSpec IFU

Q3D JWST Early Release Science Project (Wylezalek+2022, Vayner+2023, Veilleux+2023, Vayner+2024)



(MC+2025)

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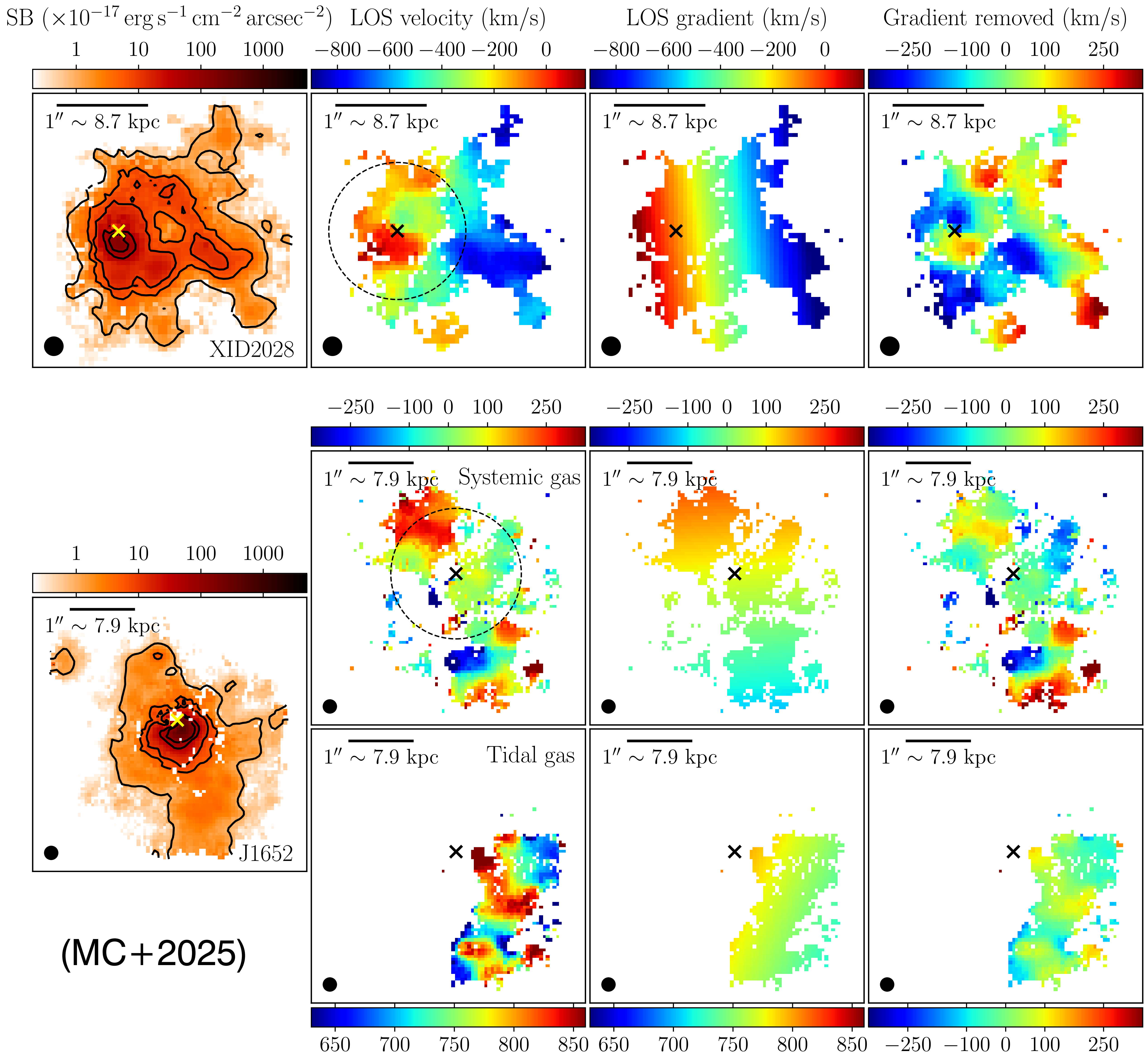

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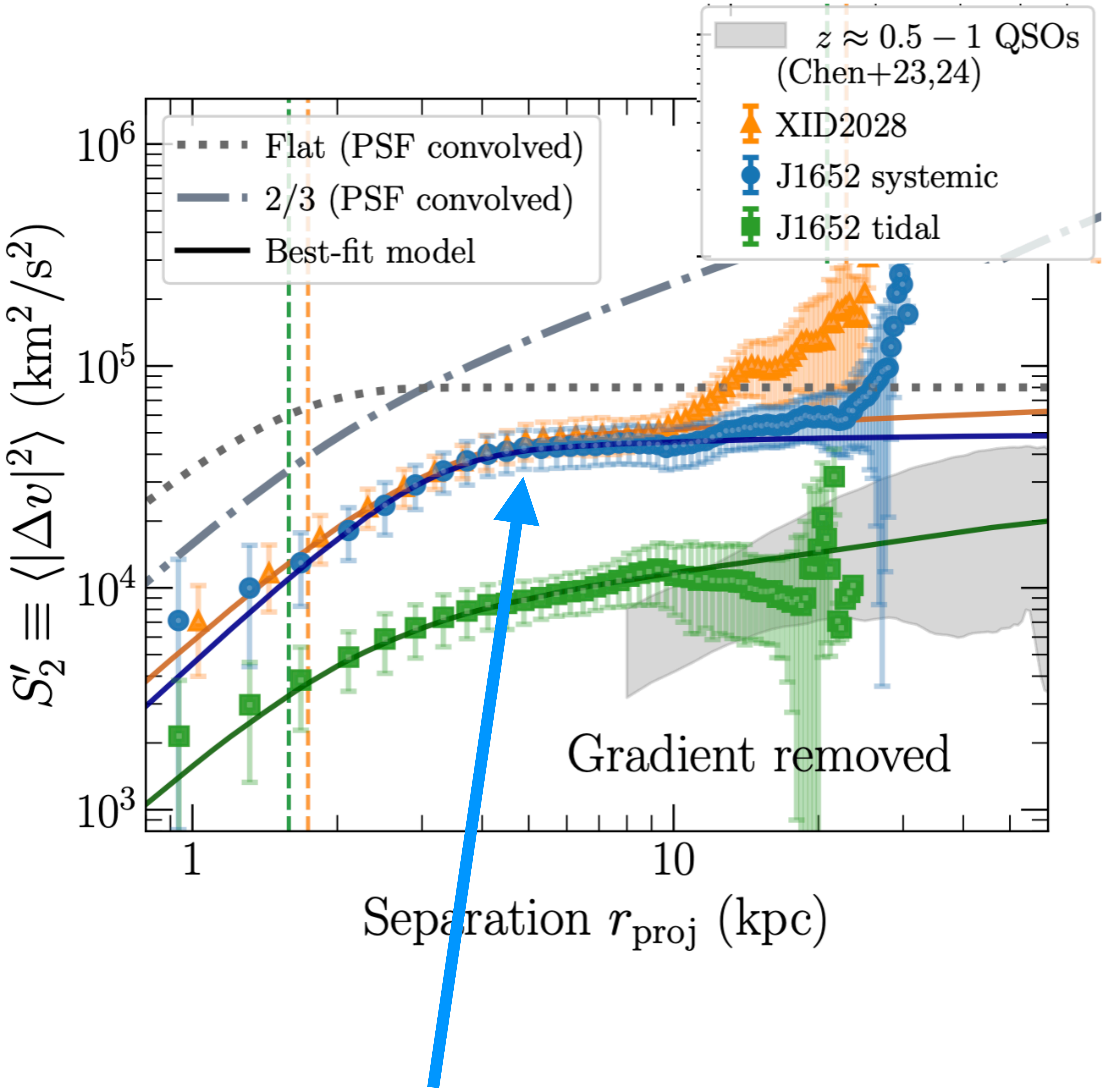

Flat slope: energy injection at <10 kpc scales, driven by AGN winds and bubbles

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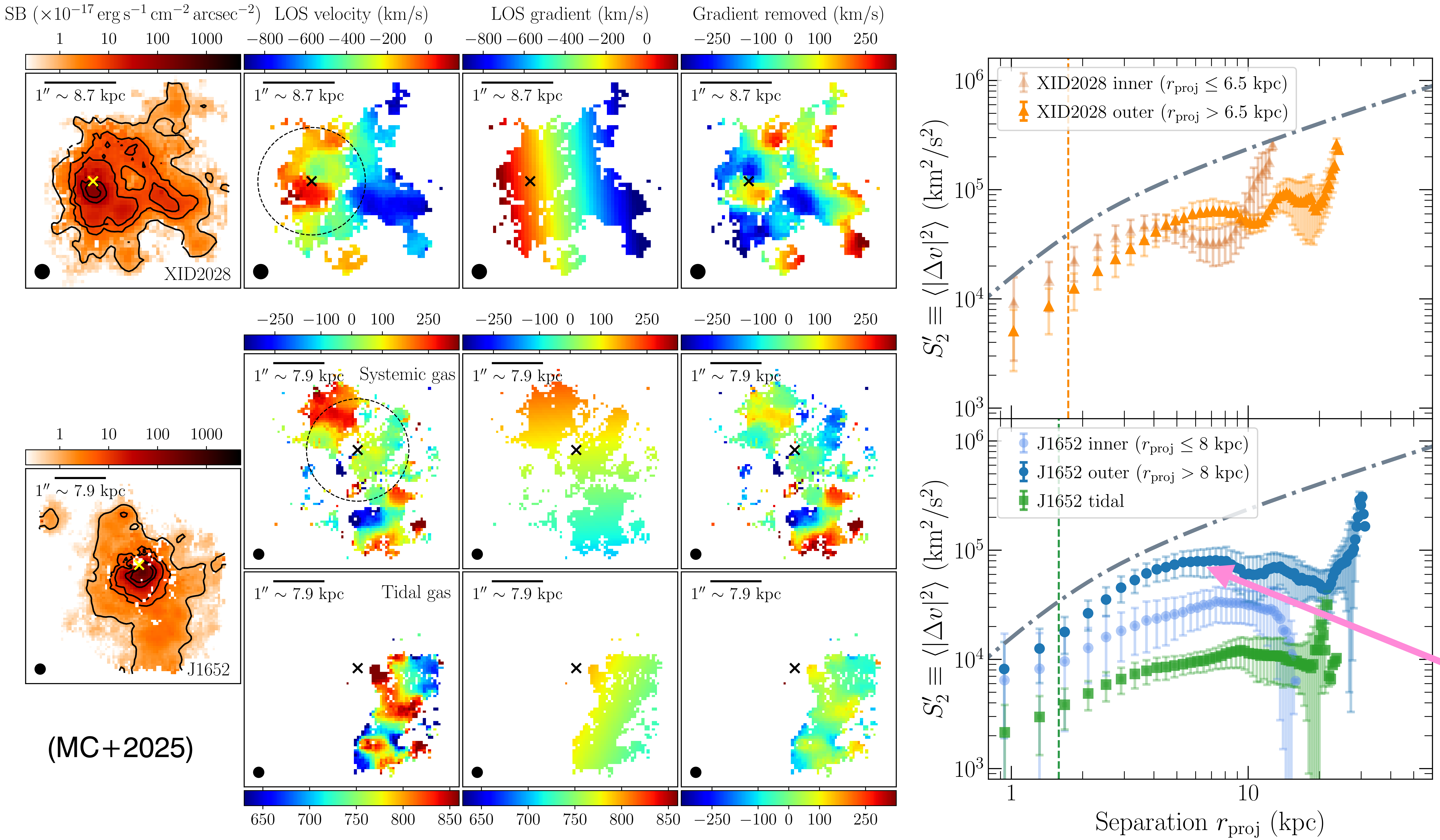
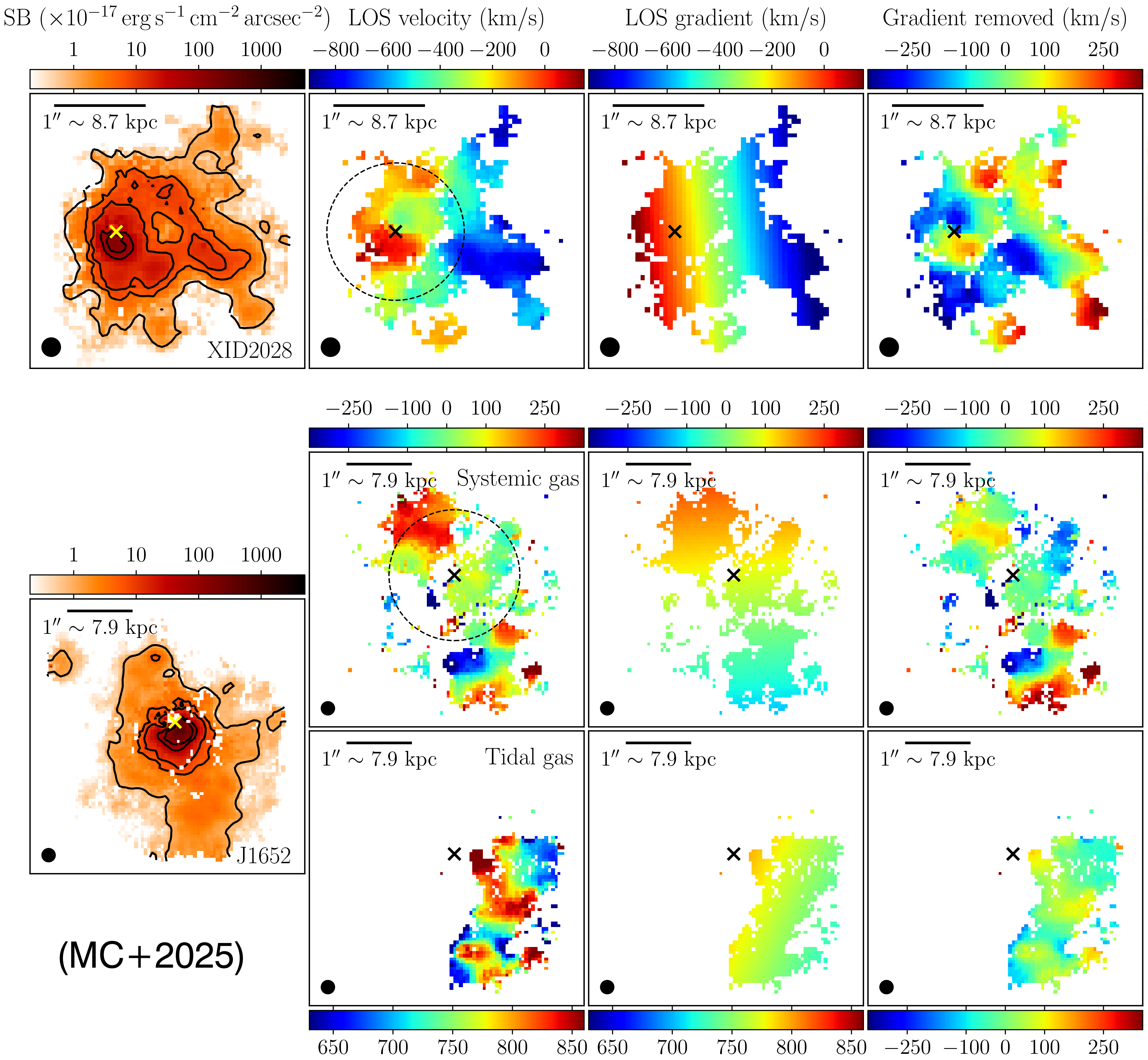


(MC+2025)

Outside-in energy injection through mergers



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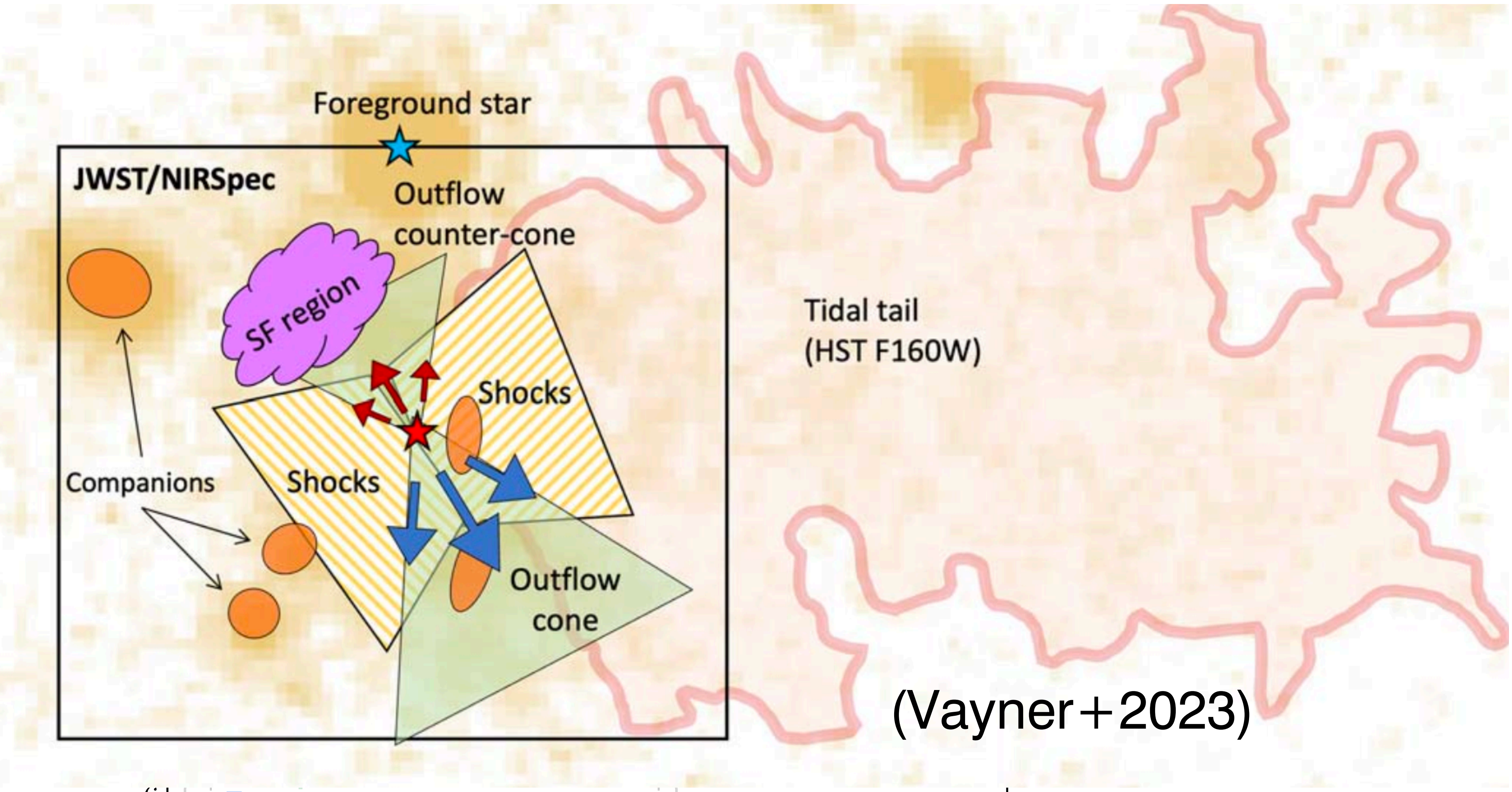
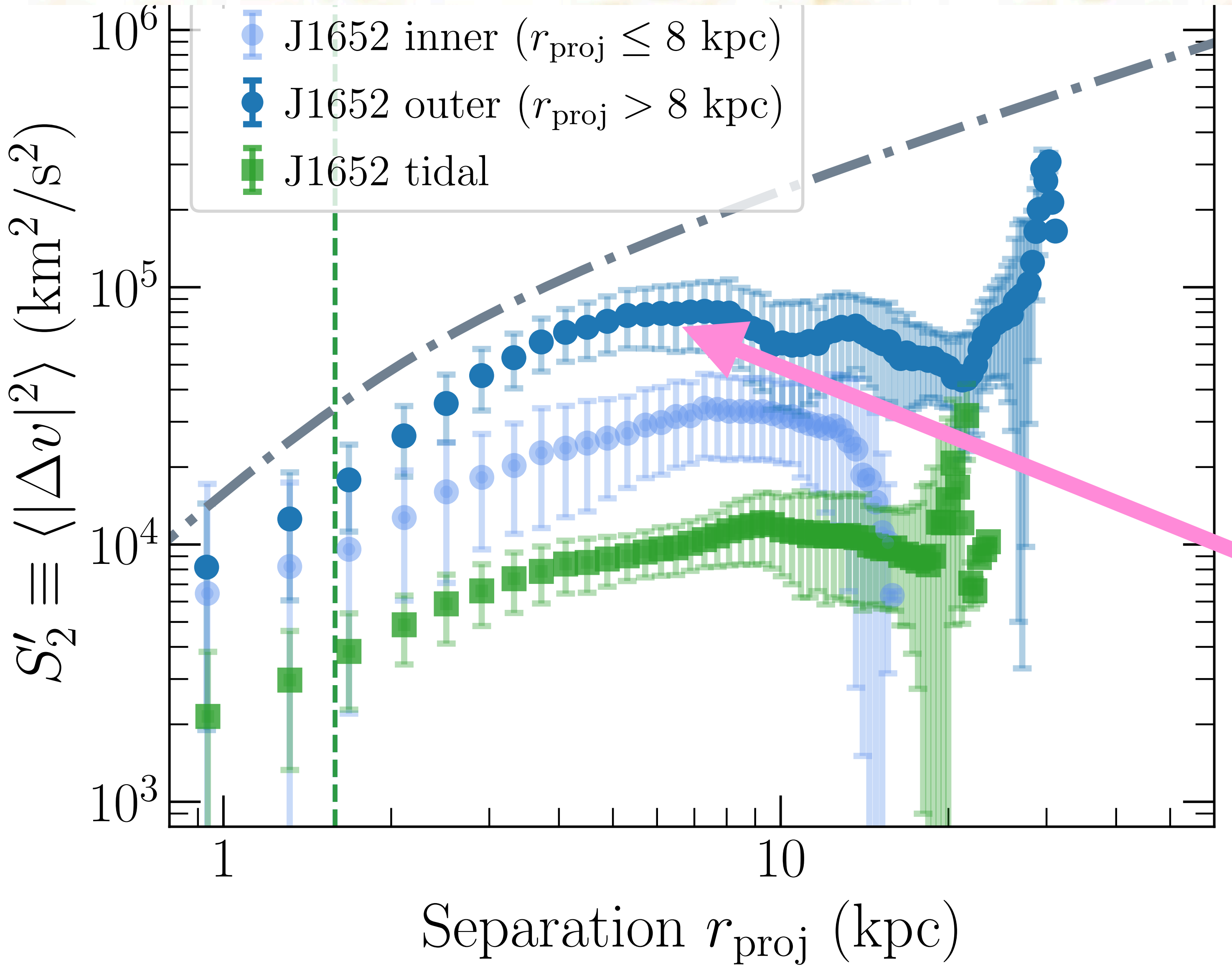


(Vayner+2023)



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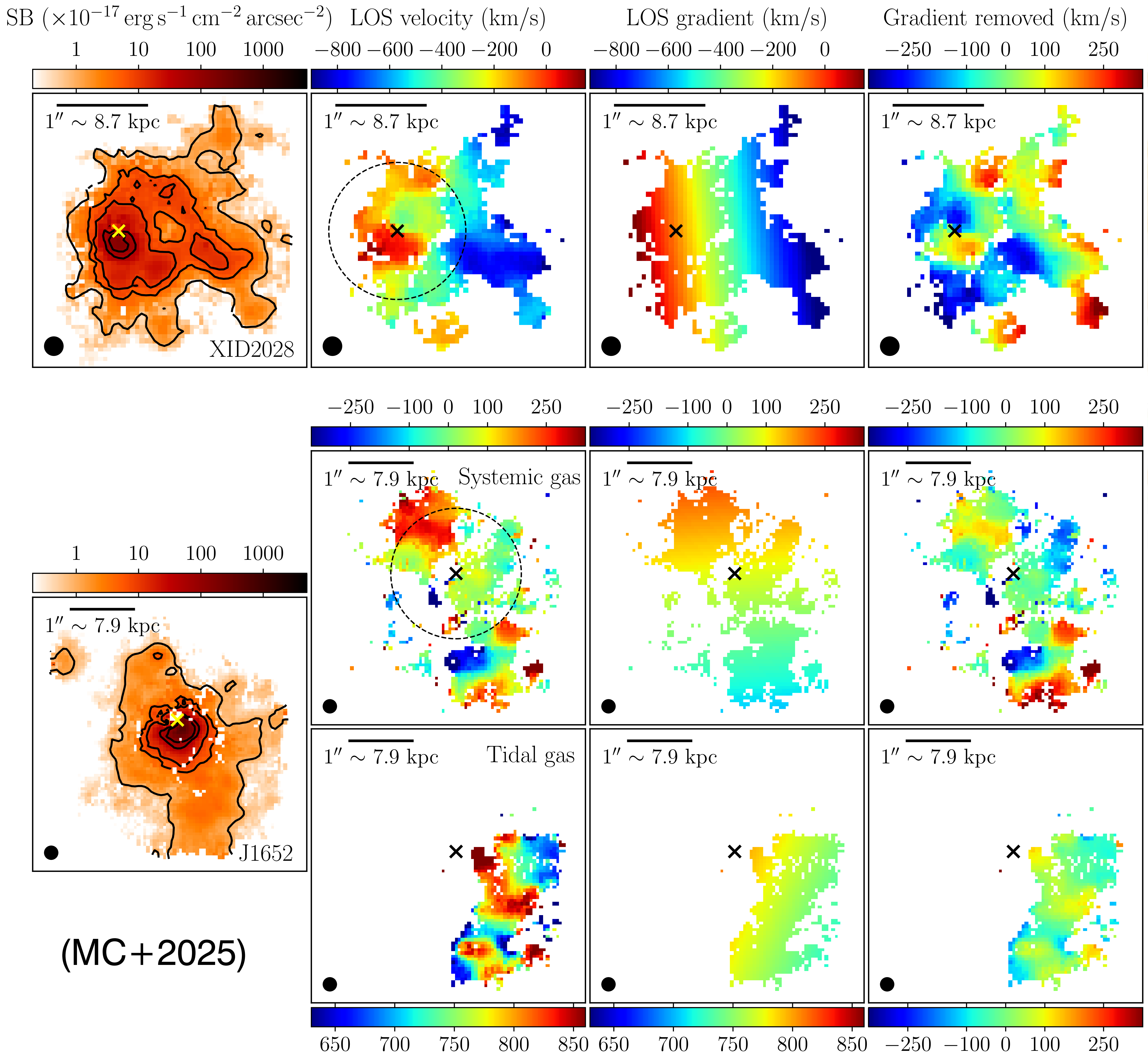

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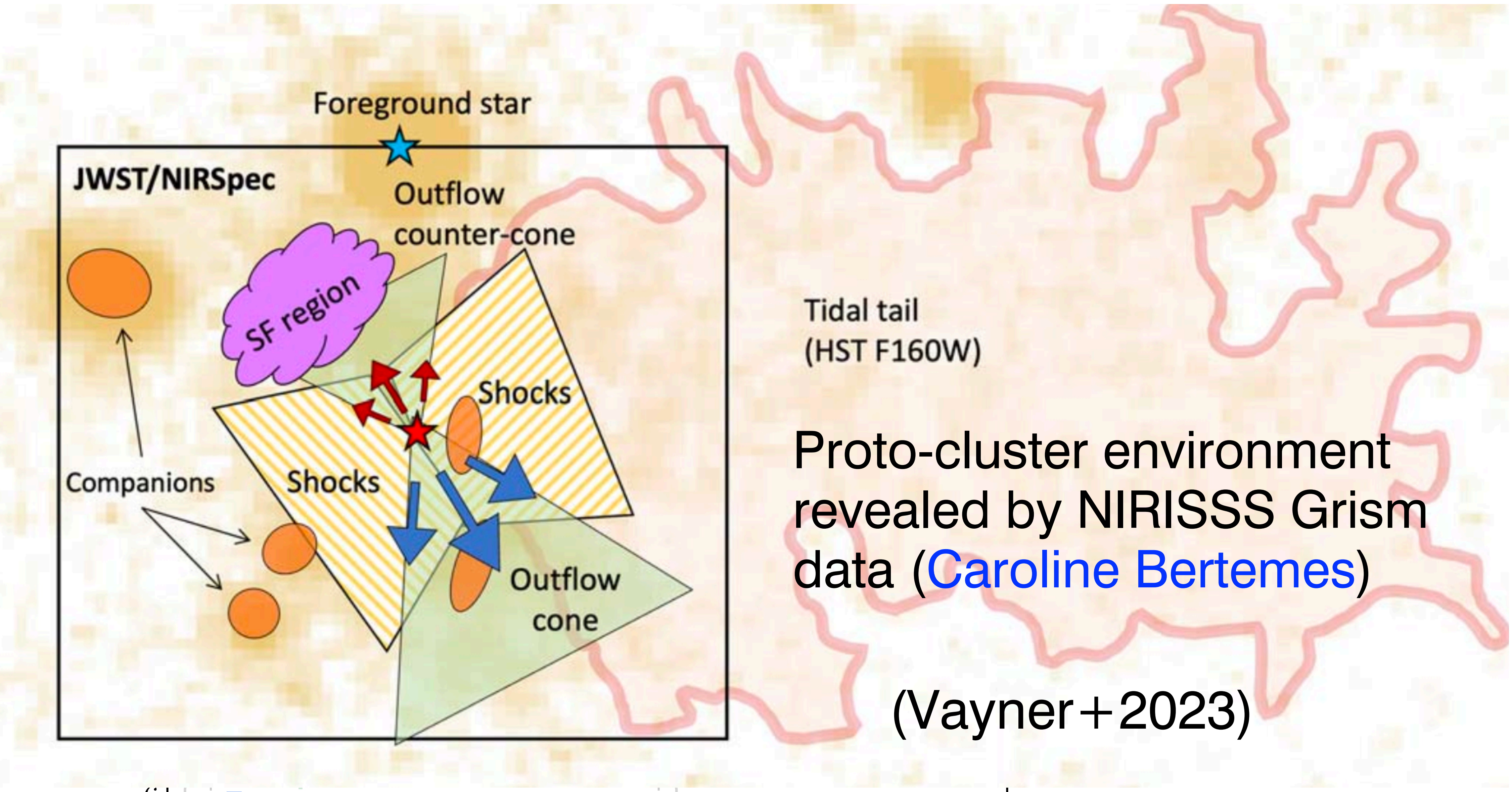
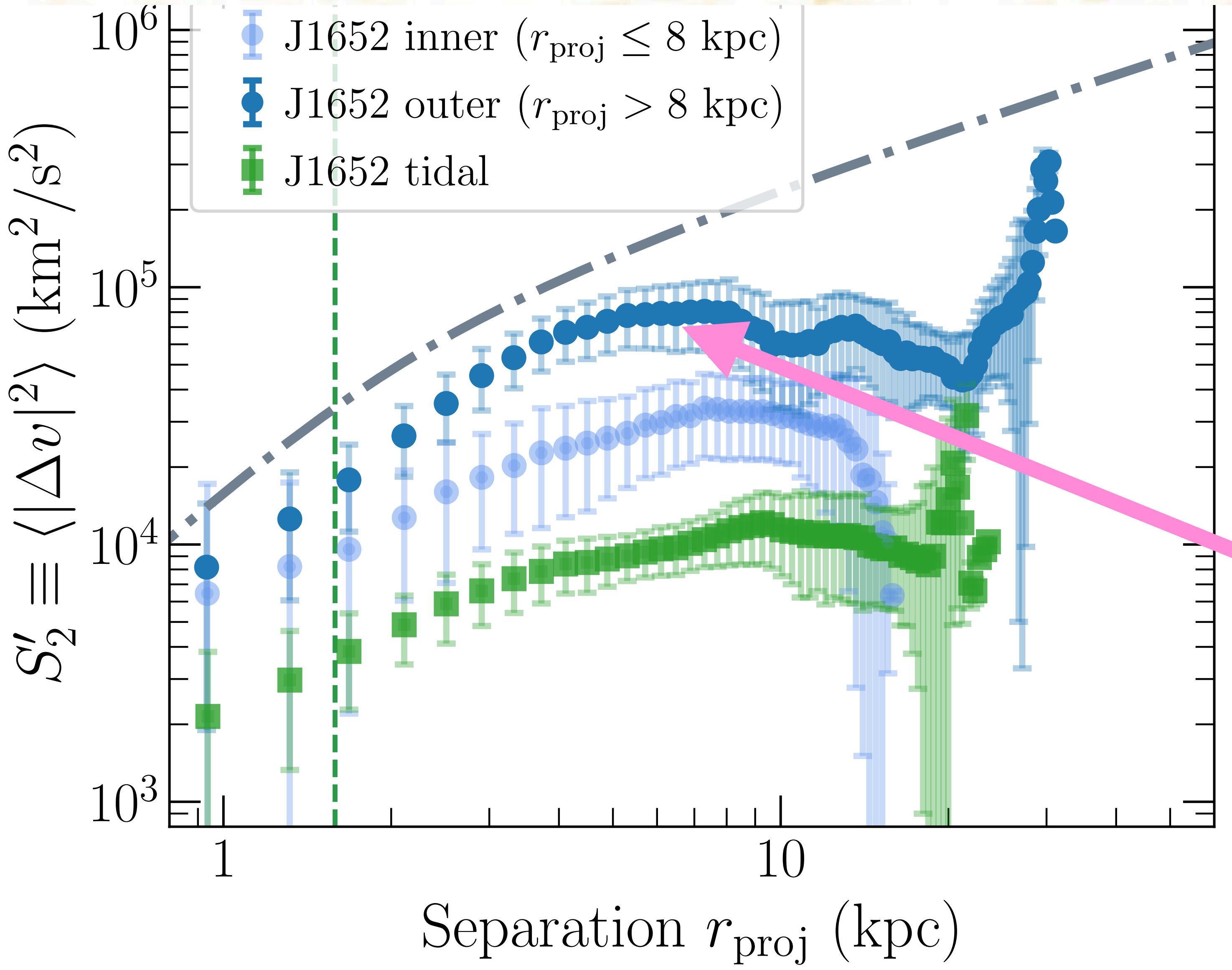


Proto-cluster environment revealed by NIRISSS Grism data (Caroline Bertemes)

(Vayner+2023)



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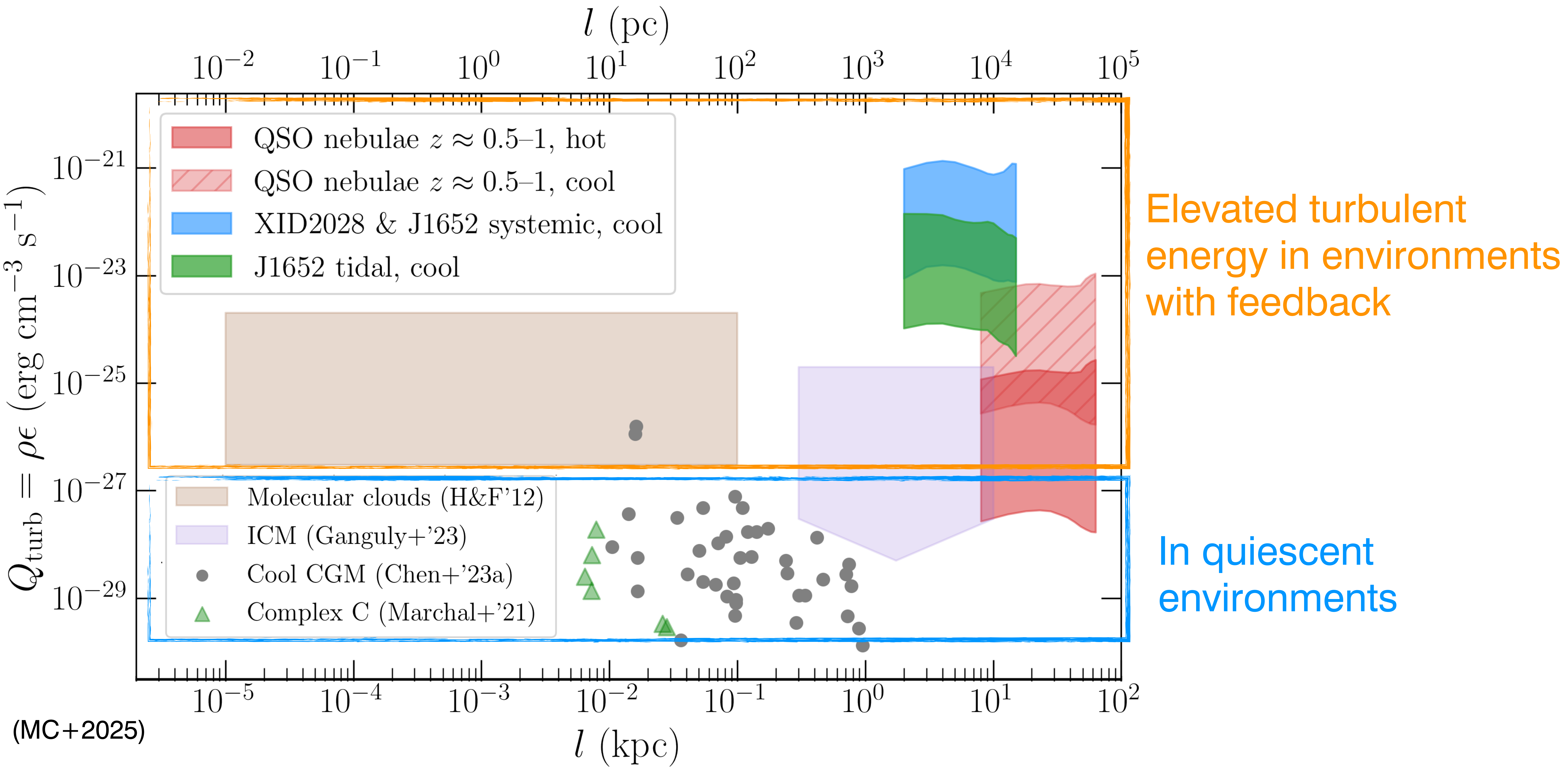

l (pc)
10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5}
QSO nebulae $z \approx 0.5$–1, hot
QSO nebulae $z \approx 0.5$–1, cool
XID2028 & J1652 systemic, cool
J1652 tidal, cool
Molecular clouds (H&F'12)
ICM (Ganguly+'23)
Cool CGM (Chen+'23a)
Complex C (Marchal+'21)
$Q_{\rm turb} = \rho\epsilon$ (erg cm^{-3} s^{-1})
10^{-21} 10^{-23} 10^{-25} 10^{-27} 10^{-29}
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2}
l (kpc)
Elevated turbulent energy in environments with feedback
In quiescent environments

(MC+2025)

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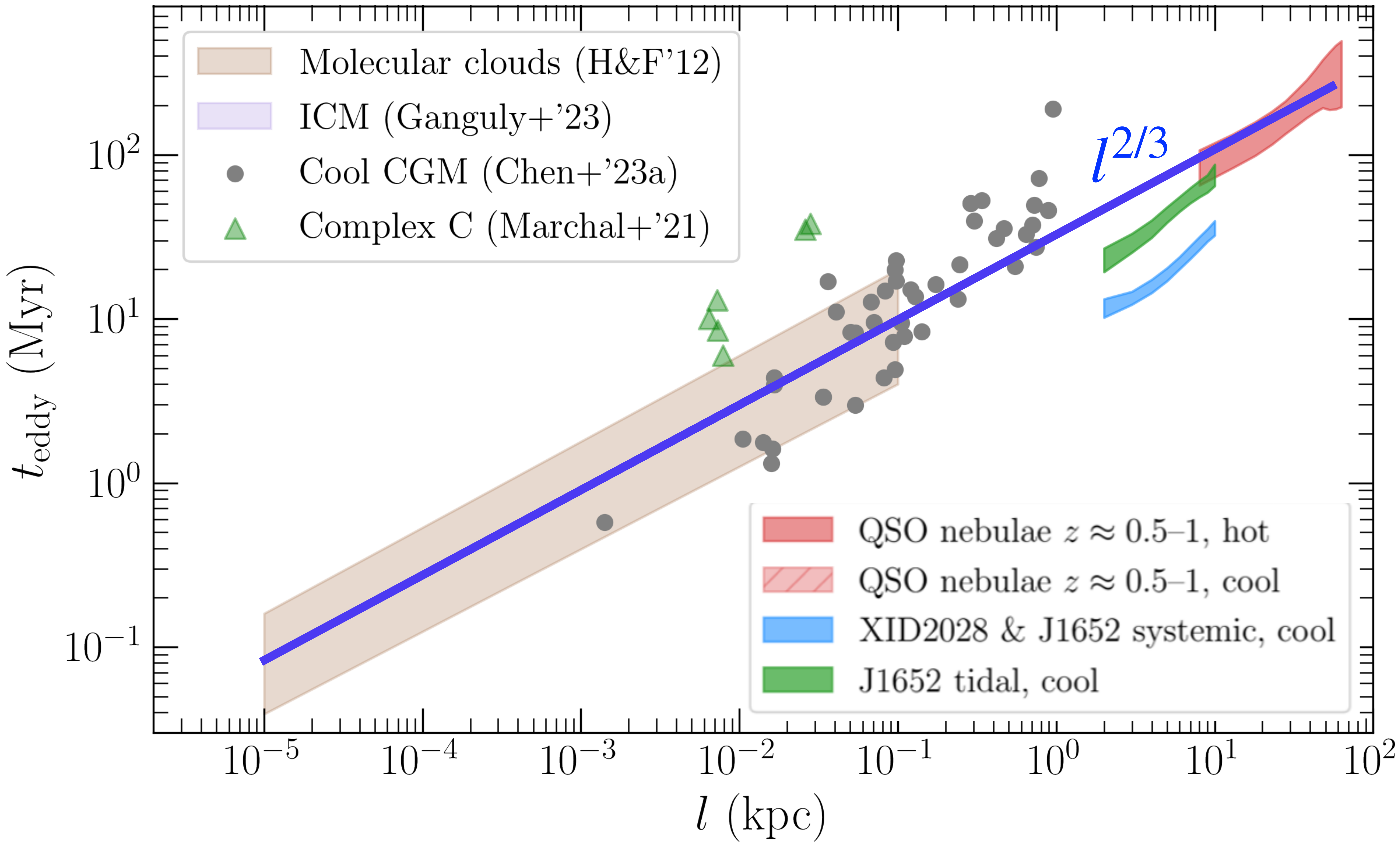
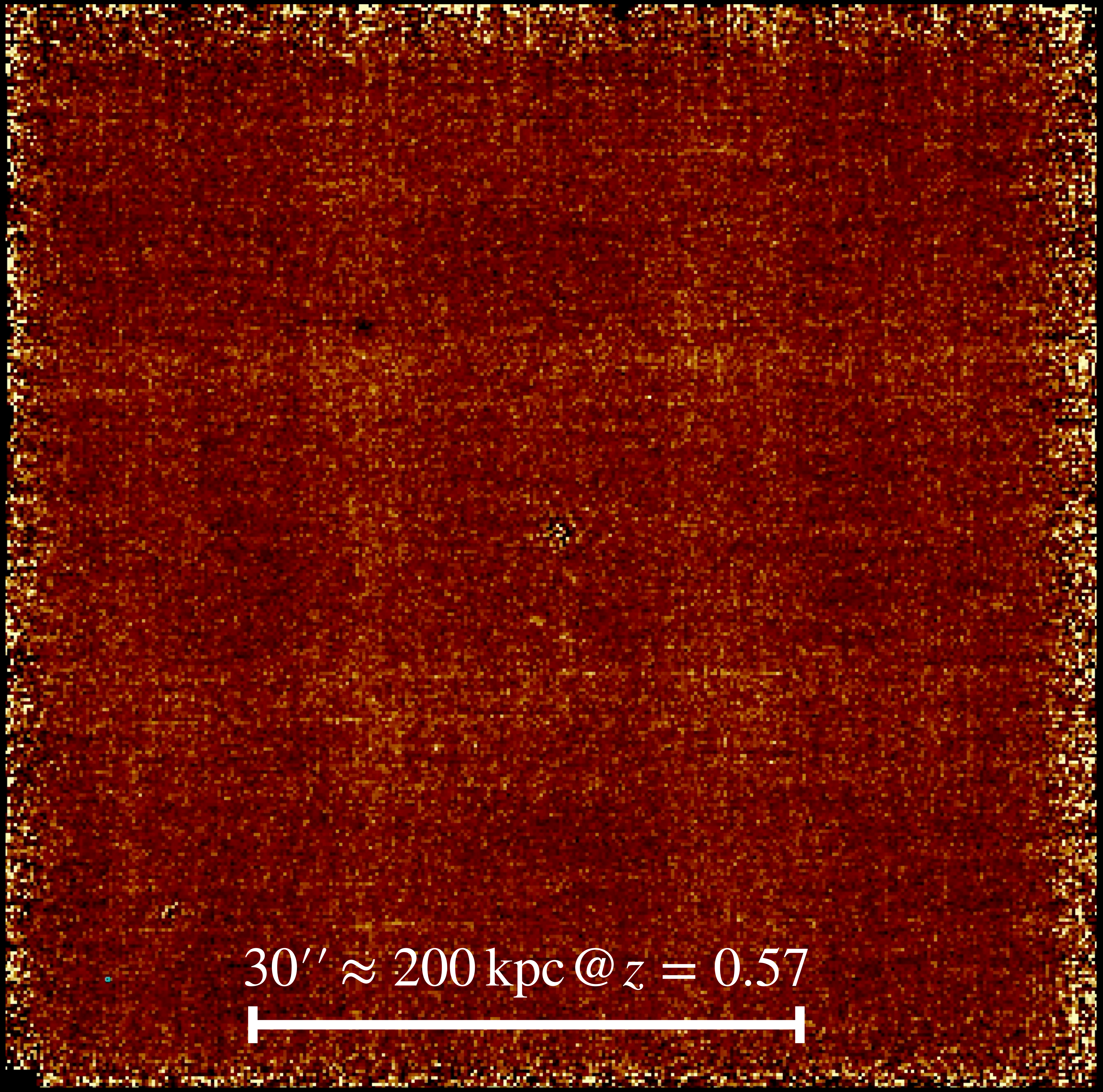


(MC+2025)

- VSF is a powerful tool in providing direct, scale-dependent constraints on turbulence
- At the current moment, there remains systematics to be further investigated



- VSFs' interpretive power increases significantly when paired with:
  - Simulations and forward modeling
  - Other diagnostics for shocks/density/ionization