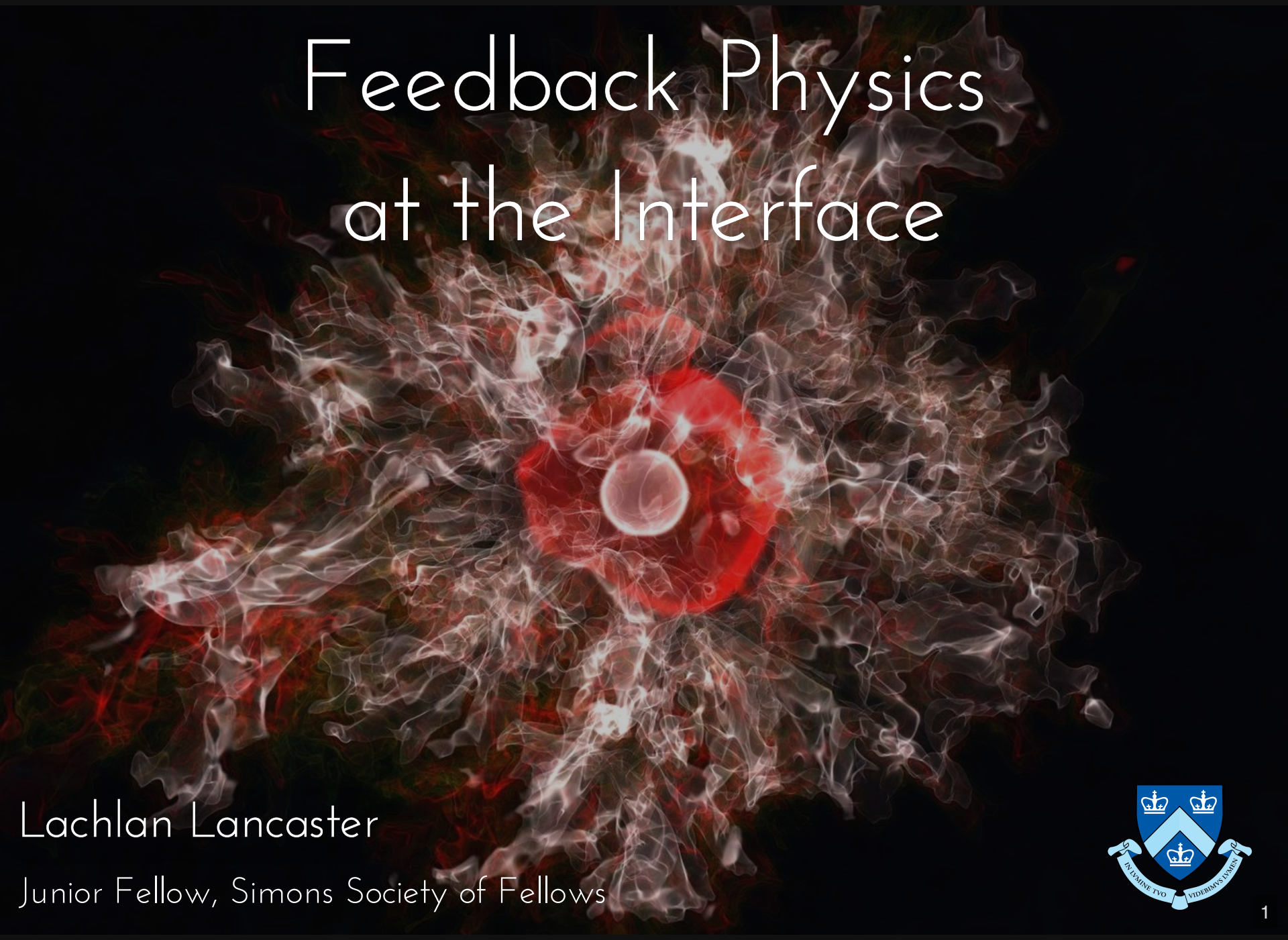
Feedback Physics at the Interface



Lachlan Lancaster

Junior Fellow, Simons Society of Fellows

Outline

- Why winds could matter

- Results suggesting they don't...

- How this is all very tied up in numerics

- The Future...

Classical Picture

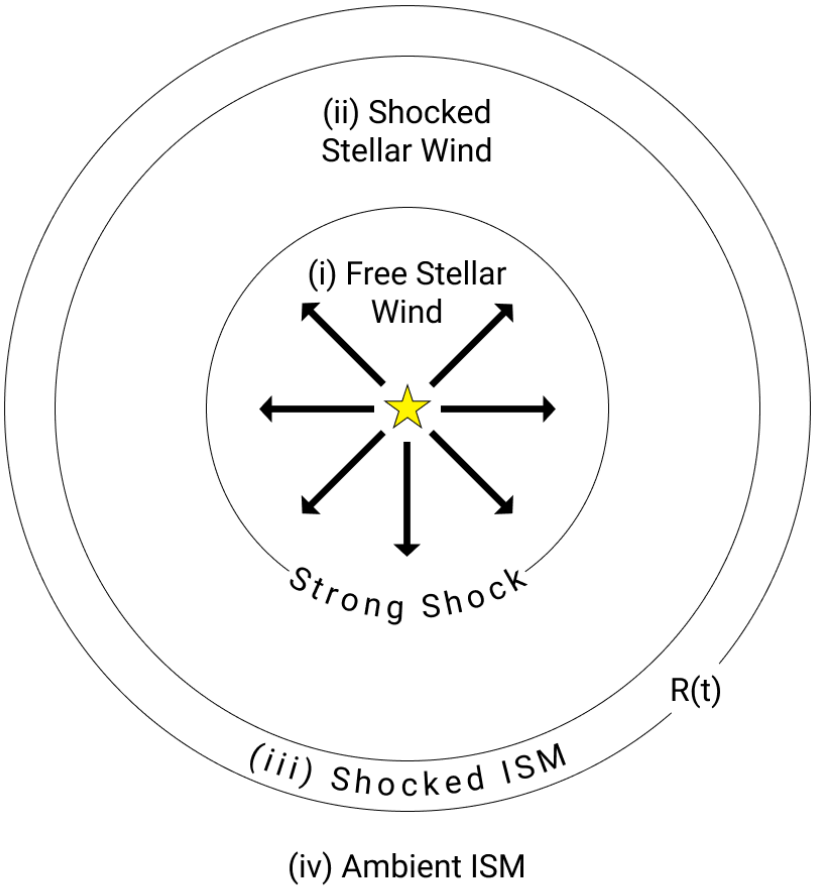
"Energy Driven"

Important Parameters:

$$\mathcal{L}_w,\ \overline{\rho},\ t$$

$$R_{\rm bub} \propto \left(\frac{\mathcal{L}_w t^3}{\overline{\rho}}\right)^{1/5}$$

$$P_{\rm hot} \propto \overline{\rho}\dot{R}_{\rm bub}^2$$



Weaver et al. 1977

"Over-Cooled" Picture

"Momentum Driven"

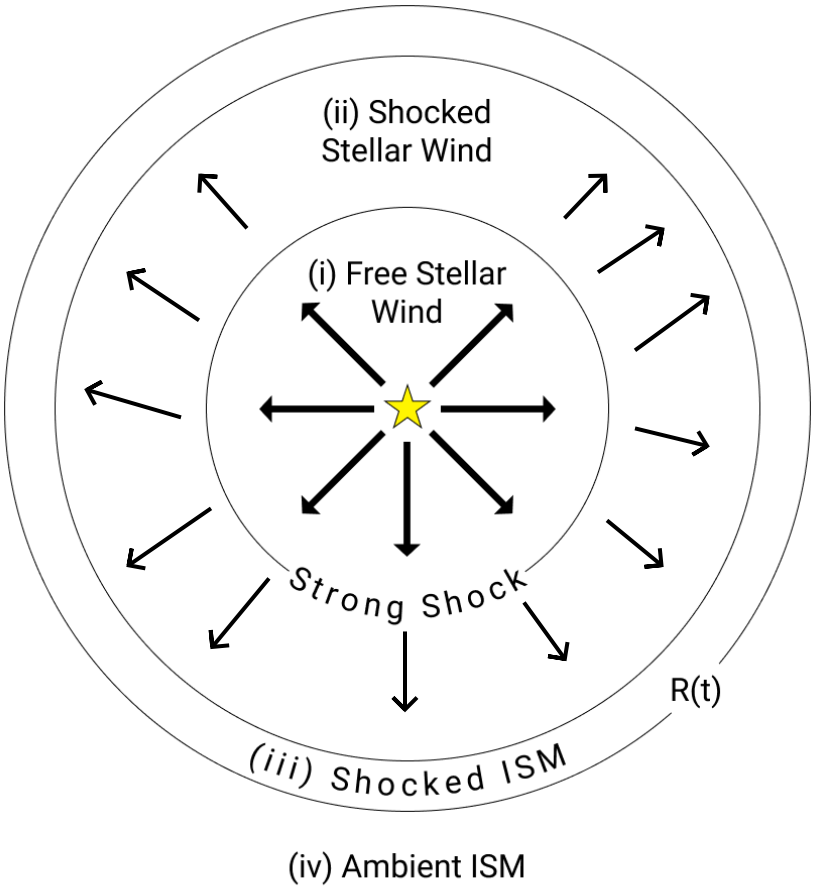
Important Parameters:

$$\dot{p}_w,\ \overline{\rho},\ t$$

$$R_{\rm bub} \propto \left(\frac{\dot{p}_w t^2}{\overline{\rho}} \right)^{1/4}$$

Unimportant:

$$P_{\rm hot} \propto \frac{3\dot{p}_w}{16\pi R_{\rm bub}^2}$$



Mac Low & McCray 1988, Silich & Tenorio-Tagle 2013

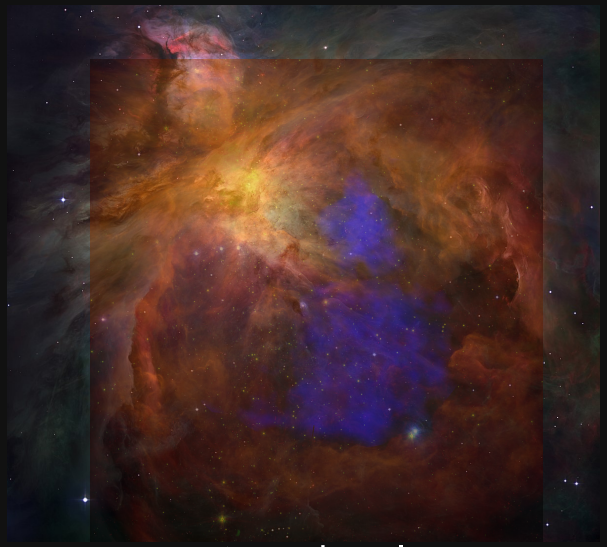
Why Winds Could Matter

- Wind- Blown Bubble's (WBB) are everywhere!
  Stellar Winds, AGN, Super-bubbles...

- Stellar Wind Effects 'should' (according to Weaver '77) dominate "early feedback"

- Observations show that this isn't the case
  Lopez+11, Rosen+14, Olivier+20, Tiwari+21

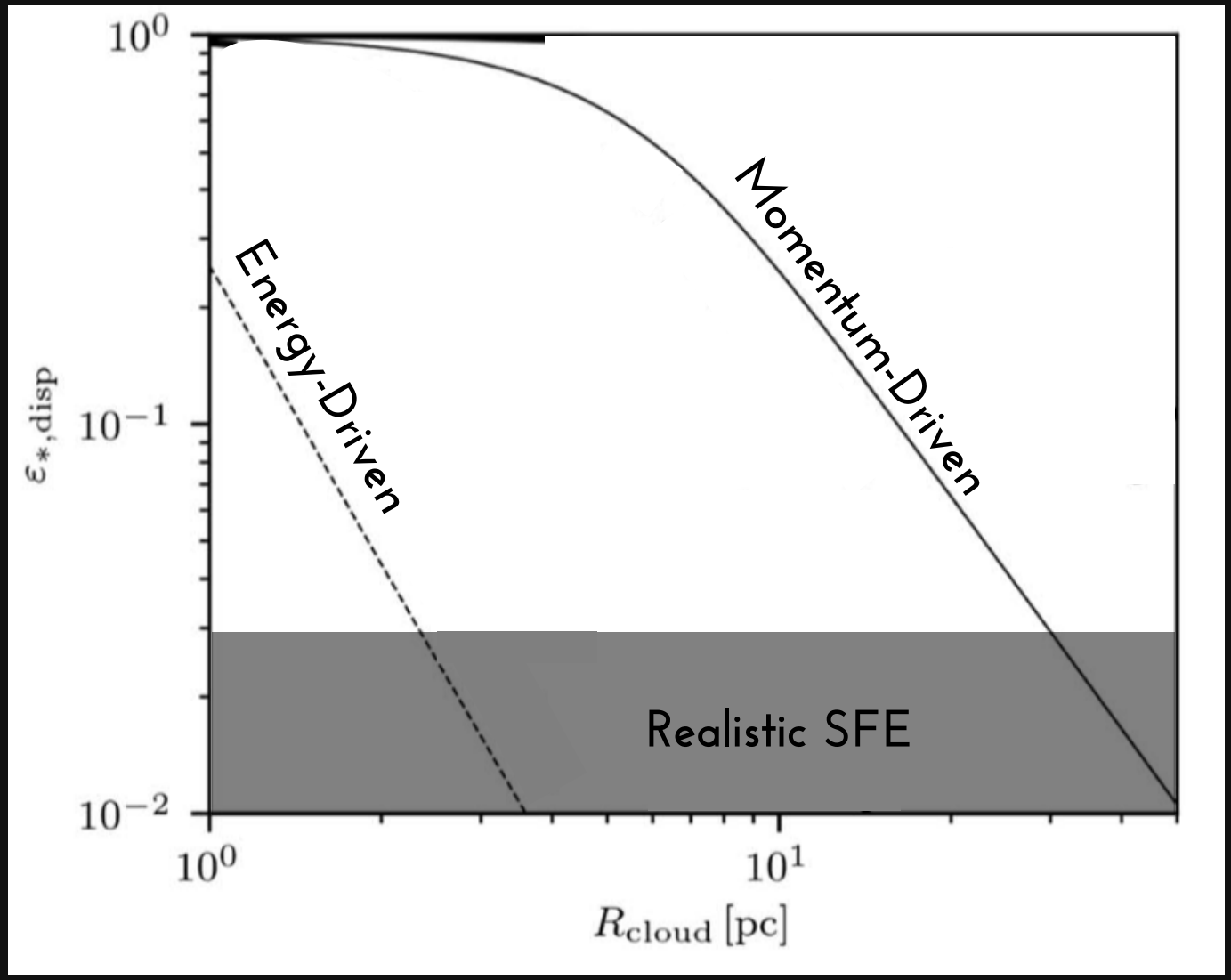
Messier 82



Orion Nebula

Why Winds Matter

Energy-driven winds should disperse clouds easily



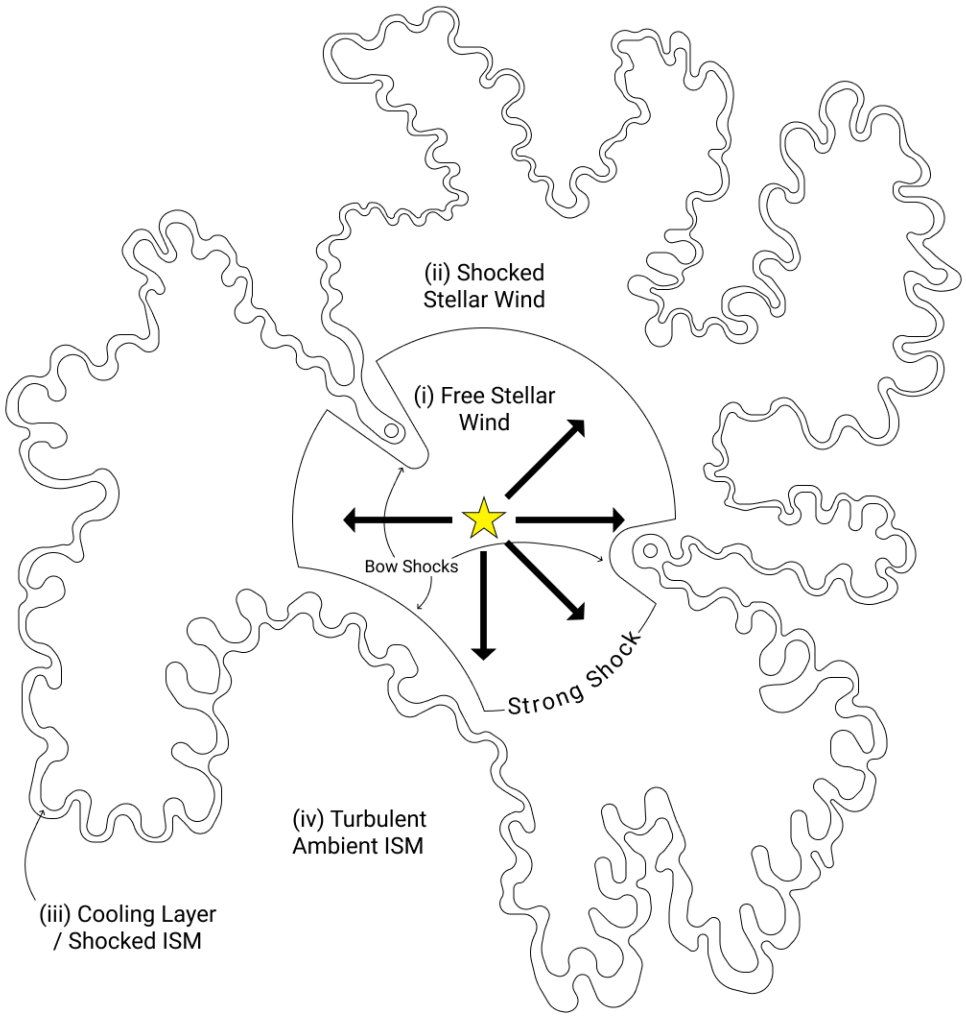
Lancaster+21a

Turbulent Picture

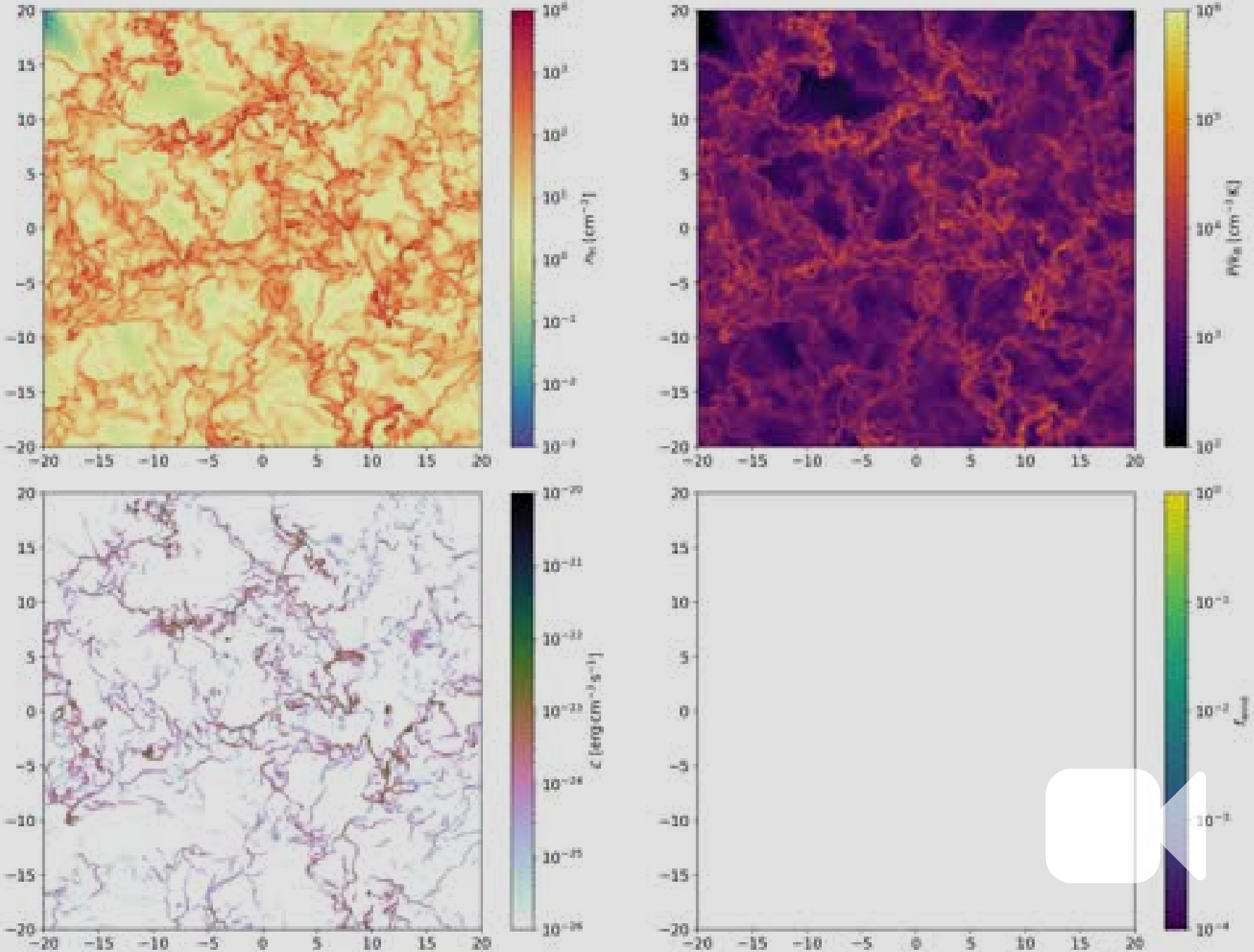
- Mixing/Dissipation at Interface enhanced by Turbulence

- Interior pressure (therefore dynamics) set by boundary conditions at surface

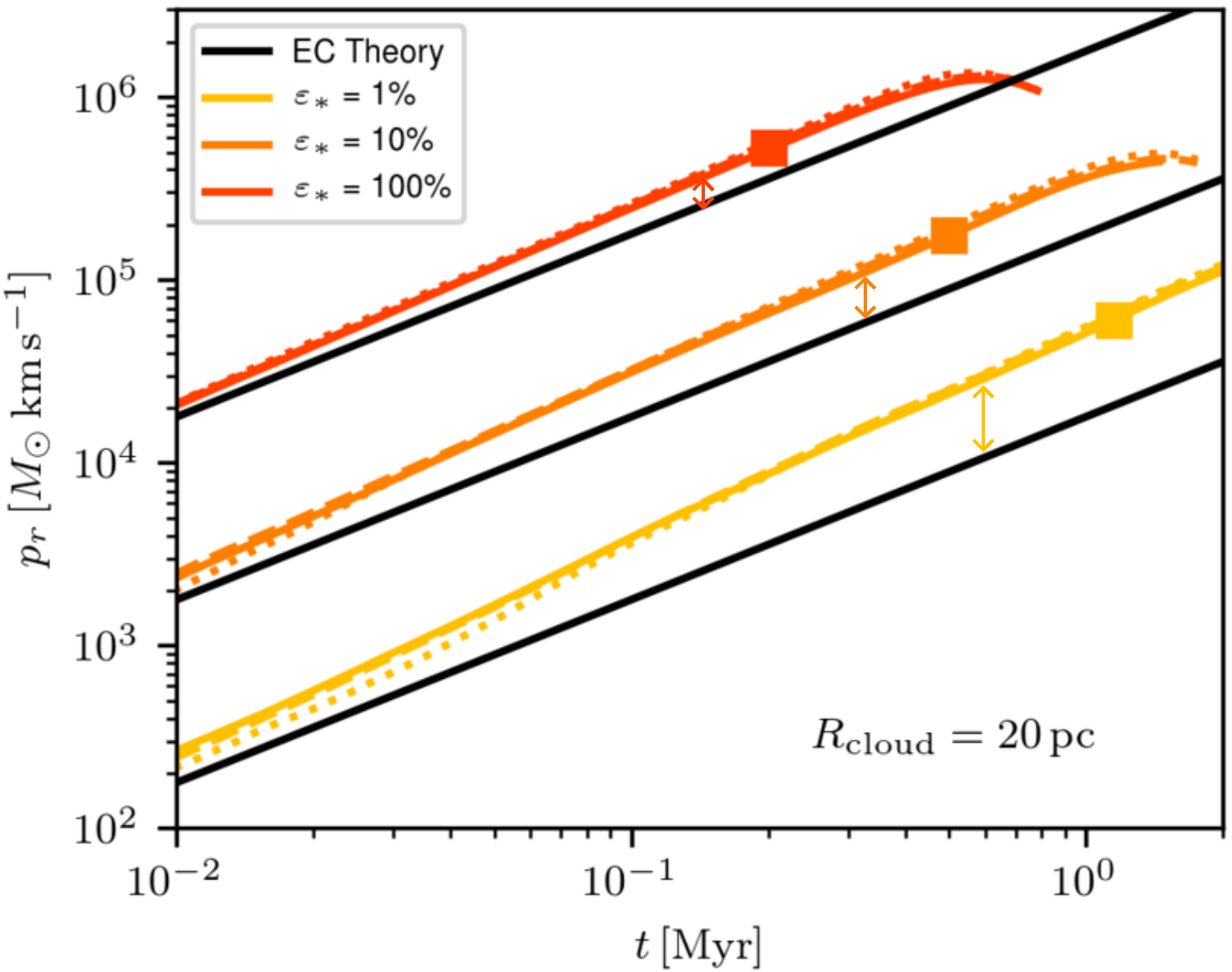
- Efficient enough to make Momentum Driven?

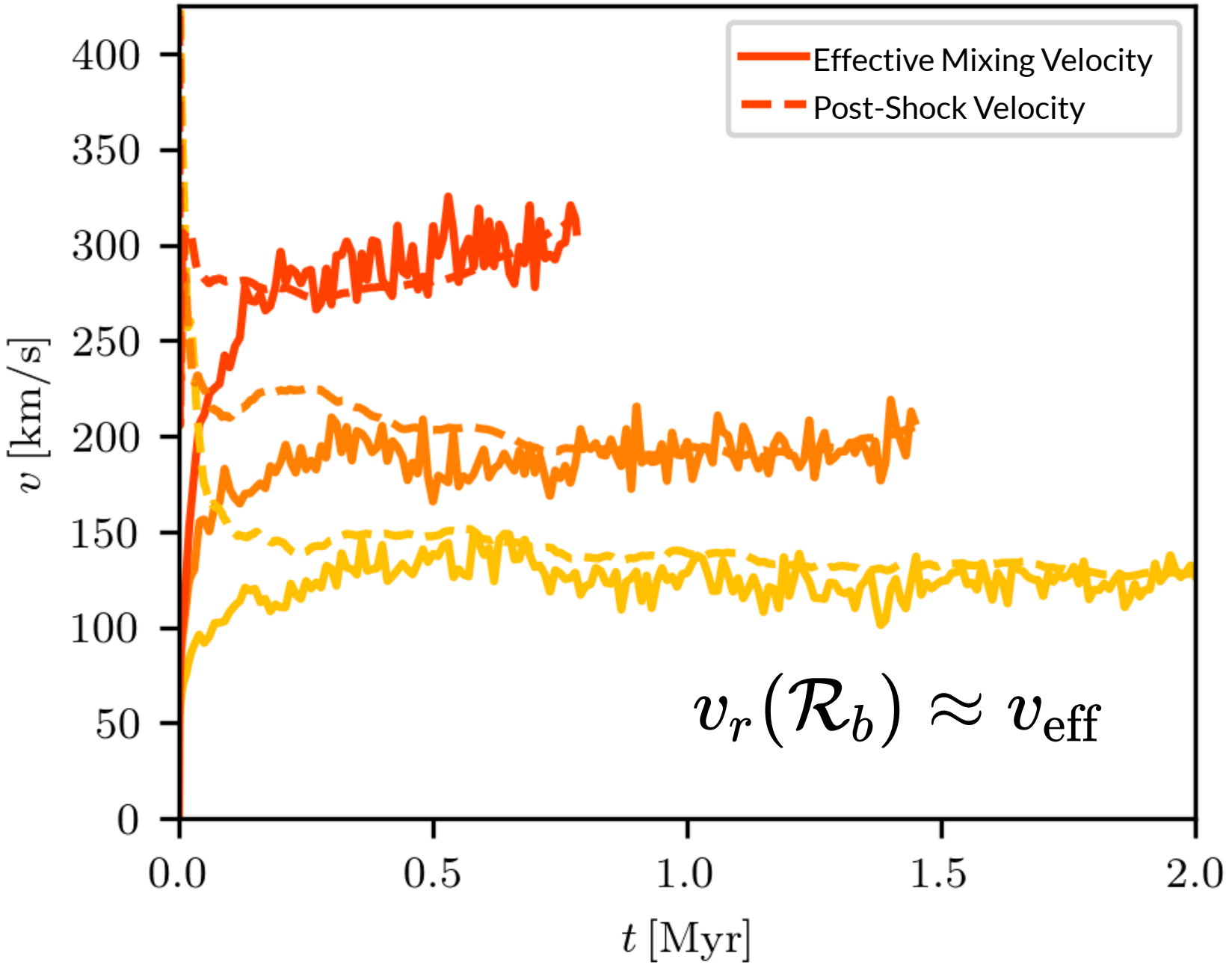


Lancaster et al. 2021a,b,c

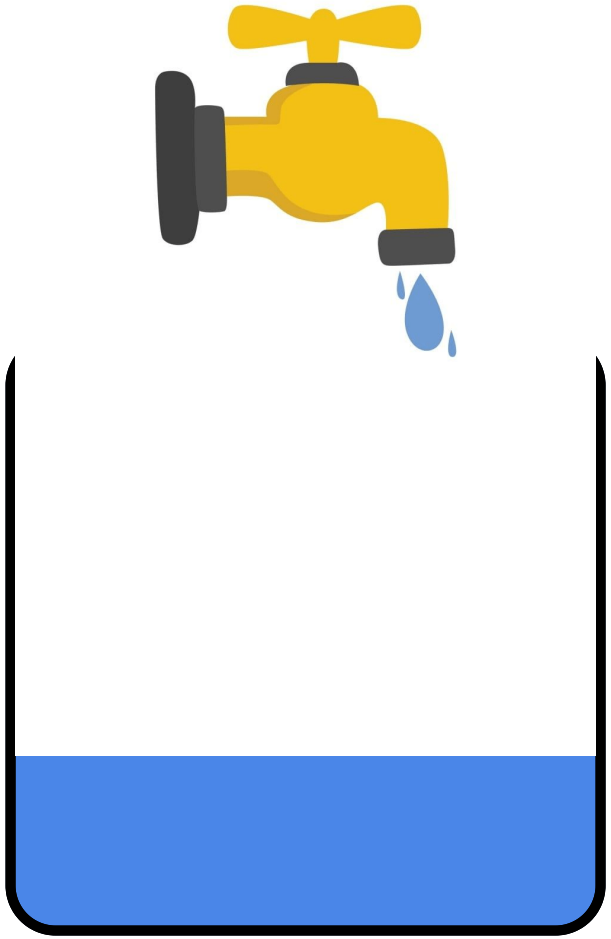


$$p_r = \alpha_p \dot{p}_w t$$



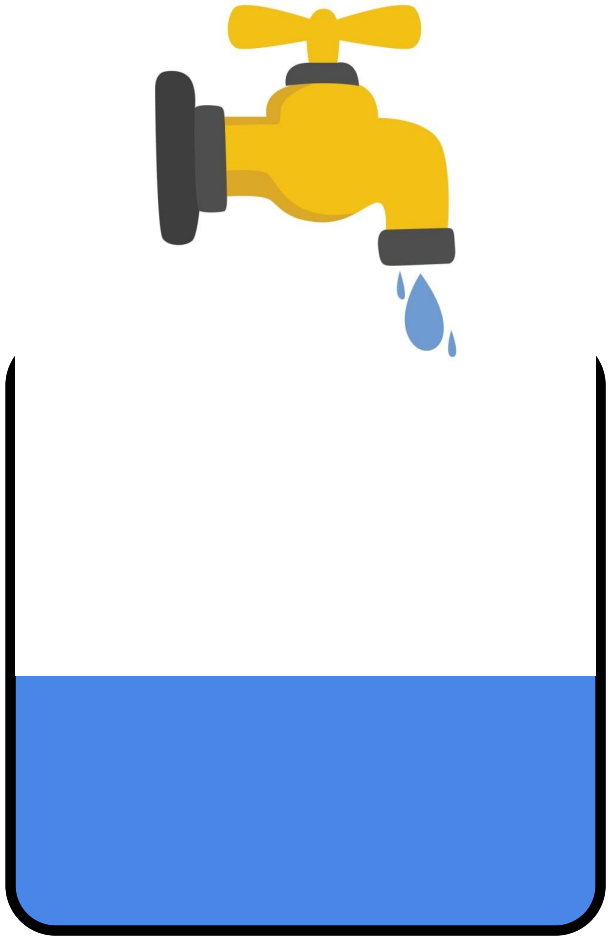

Effective Mixing Velocity
Post-Shock Velocity
$v_r(\mathcal{R}_b) \approx v_{\rm eff}$
v [km/s]
t [Myr]
0
50
100
150
200
250
300
350
400
0.0
0.5
1.0
1.5
2.0

An Analogy for Wind Bubble Cooling



An Analogy for Wind Bubble Cooling

Fills Up



An Analogy for Wind Bubble Cooling

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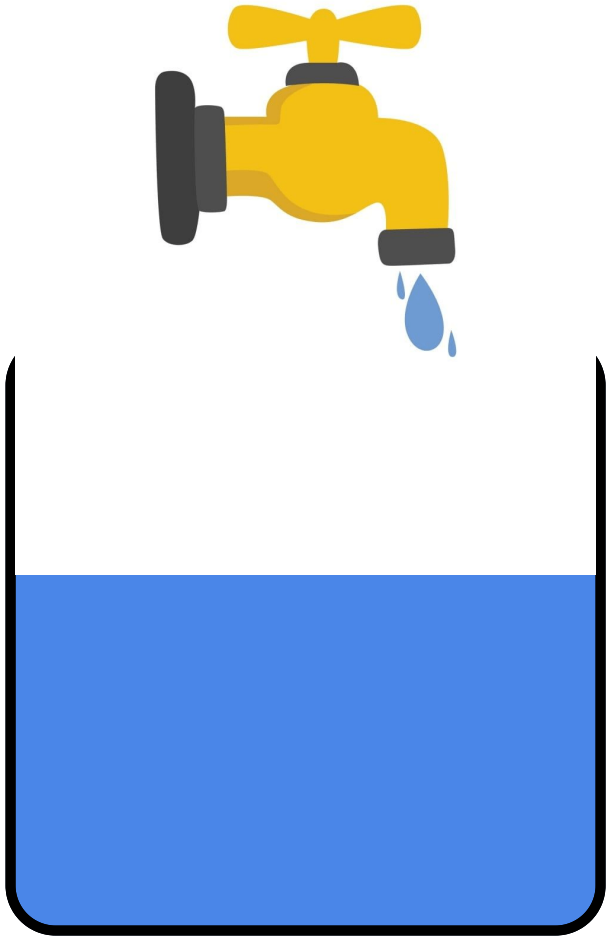
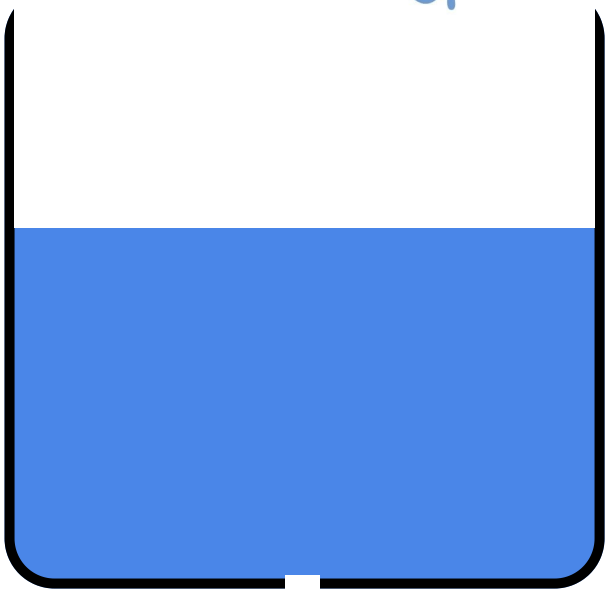


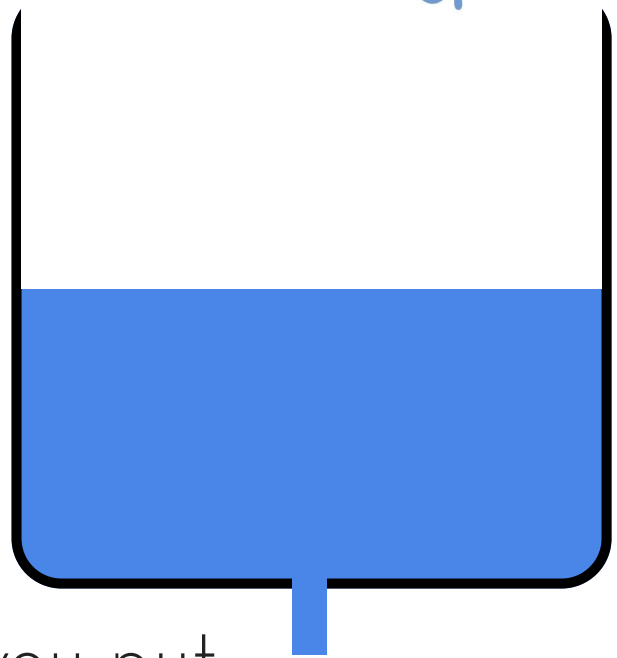
An Analogy for Wind Bubble Cooling



Fills Up

Unless you put a hole in it

An Analogy for Wind Bubble Cooling



Fills Up

Unless you put a hole in it

Initially Drains Faster than it fills

An Analogy for Wind Bubble Cooling

Fills Up

Unless you put a hole in it

Initially Drains Faster than it fills

An Analogy for Wind Bubble Cooling

Fills Up

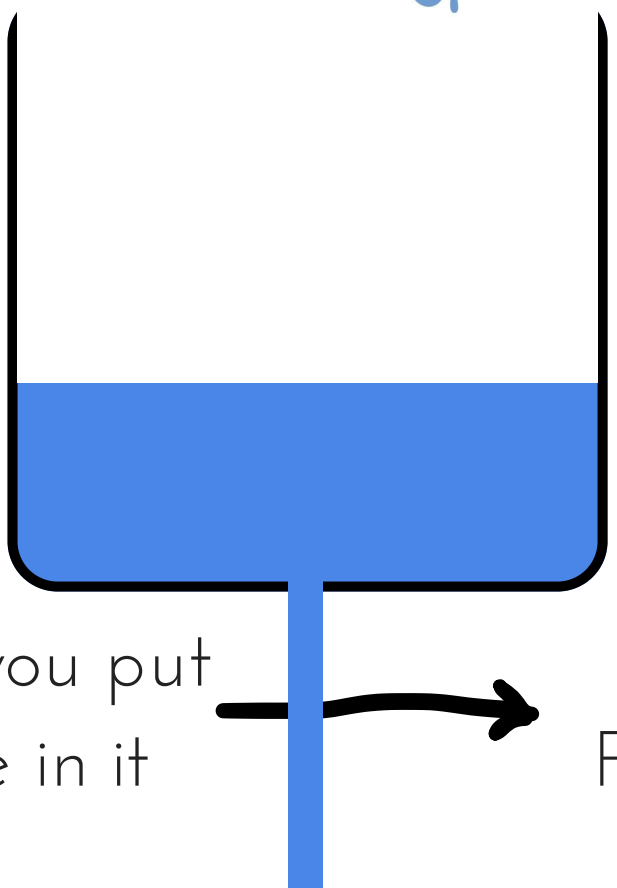
Unless you put a hole in it

Initially Drains Faster than it fills

Reaches a Steady State

An Analogy for Wind Bubble Cooling

Why am I explaining this??



Fills Up

Unless you put a hole in it

Initially Drains Faster than it fills

Reaches a Steady State

An Analogy for Wind Bubble Cooling

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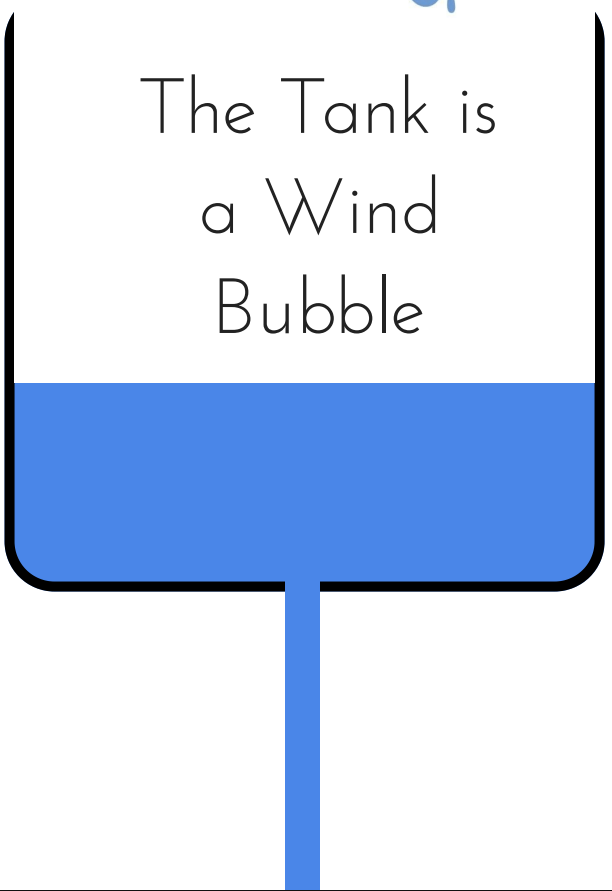

An Analogy for Wind Bubble Cooling

The Faucet is the Wind Source (stars)

Why am I explaining this??

The Tank is a Wind Bubble

An Analogy for Wind Bubble Cooling

The Faucet is the Wind Source (stars)

Why am I explaining this??

The Tank is a Wind Bubble

Water is Energy

An Analogy for Wind Bubble Cooling

The Faucet is the Wind Source (stars)

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The hole is the cooling/mixing layer

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The Faucet is the Wind Source (stars)

Why am I explaining this??

Energy goes up in bubble

Wind Bubble

Water is Energy

The hole is the cooling/mixing layer

An Analogy for Wind Bubble Cooling

The Faucet is the Wind Source (stars)

Why am I explaining this??

Energy goes up in bubble

↓

Pressure Increases

Wind Bubble

Water is Energy

The hole is the cooling/mixing layer

An Analogy for Wind Bubble Cooling

The Faucet is the Wind Source (stars)

Why am I explaining this??

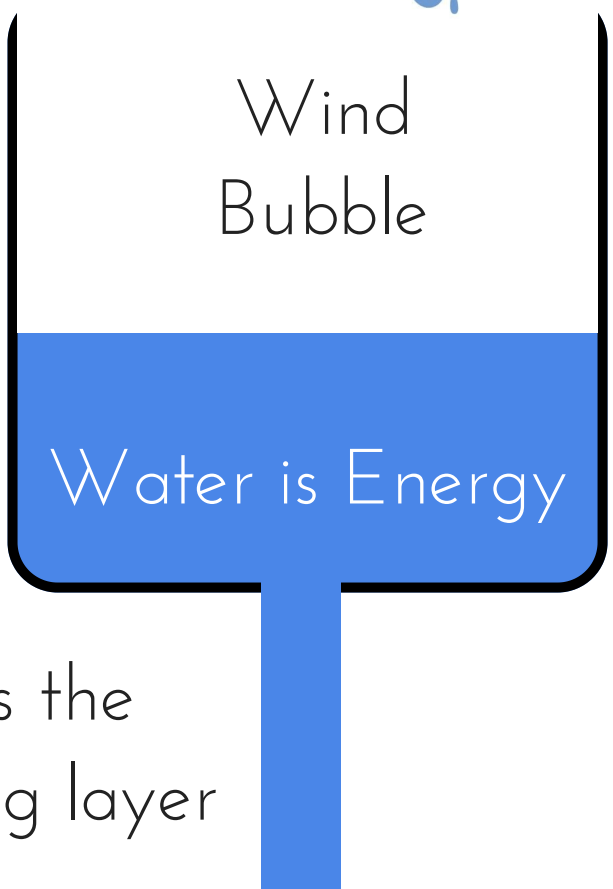
Energy goes up in bubble

↓

Pressure Increases

↓

Cooling becomes more Efficient



The hole is the cooling/mixing layer

Relation to Momentum Enhancement

$\langle v_{\rm out} \rangle \equiv$ Average velocity into the Bubble's Surface

$$v_{\rm eff} = v_t(\ell_{\rm cool}) \left(\frac{\mathcal{R}_b}{\ell_{\rm cool}} \right)^d \rightarrow \langle v_{\rm out} \rangle \, \frac{A_{\rm bub}}{4\pi \mathcal{R}_b^2}$$

$$\alpha_p \approx \frac{3}{4} \frac{V_w/4}{\langle v_{\rm out} \rangle} \frac{4\pi \mathcal{R}_{\rm bub}^2}{A_{\rm bub}}$$

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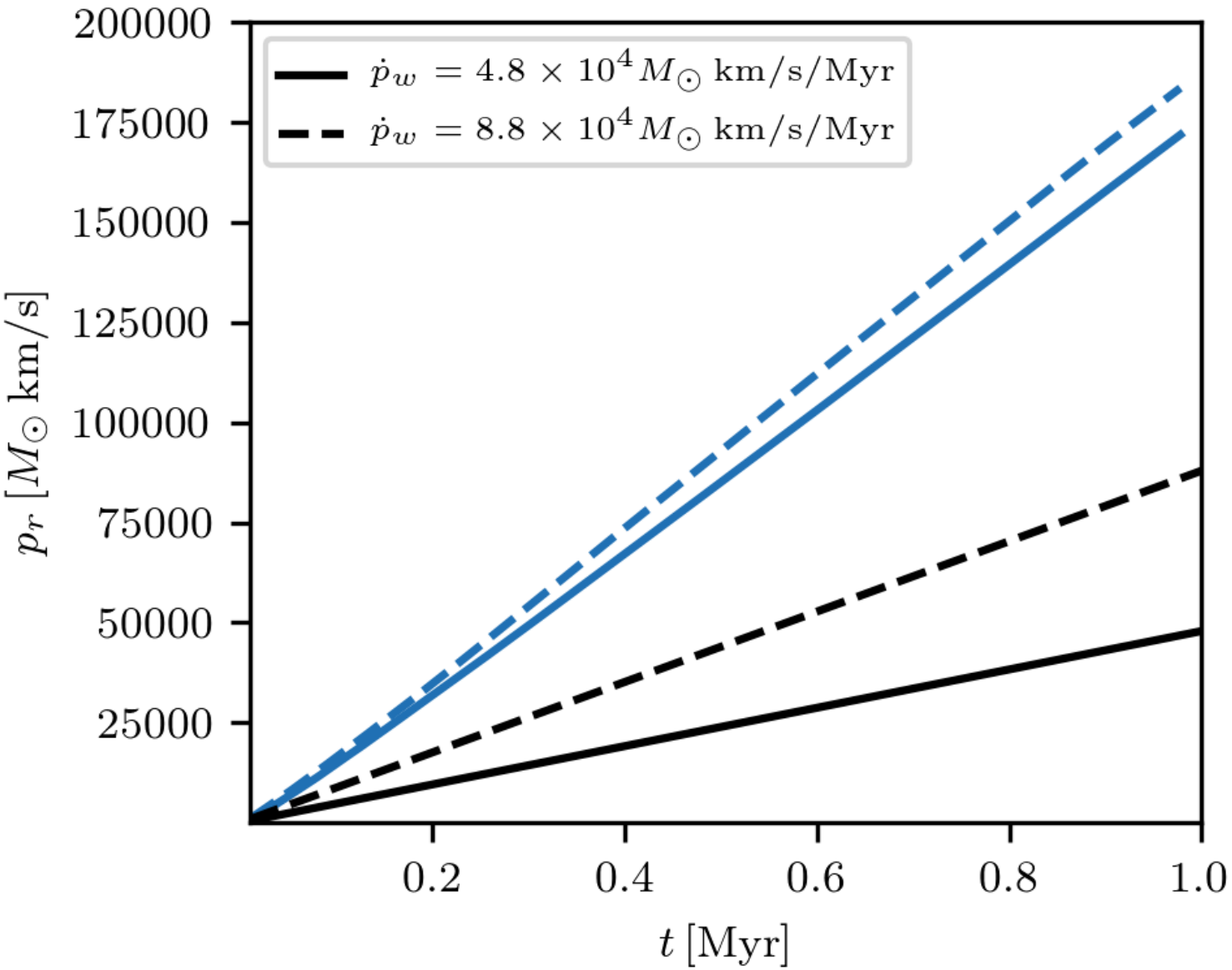
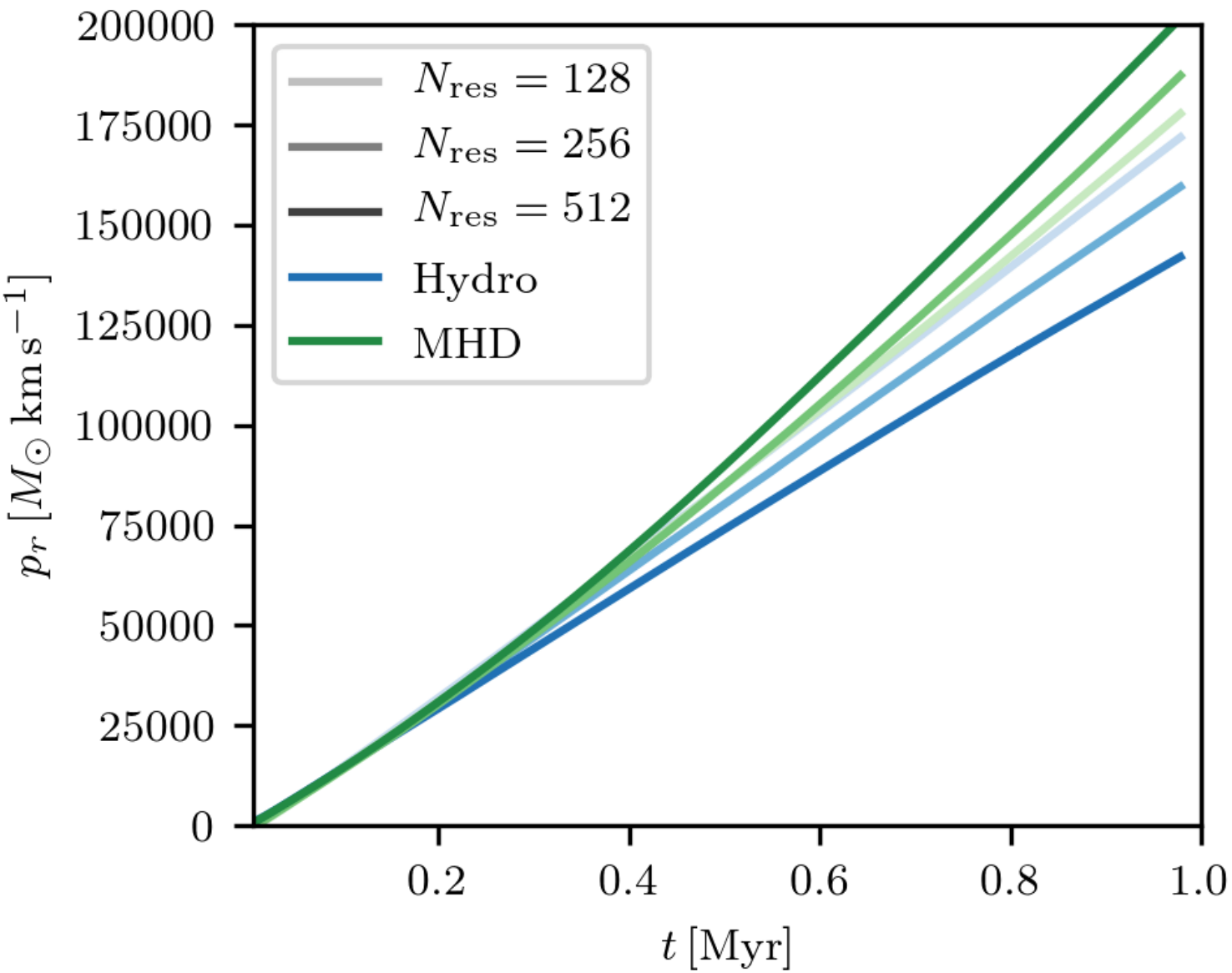
NOT MOMENTUM DRIVEN

Not Momentum Driven



Lancaster+24

Resolution Dependence



Lancaster+24

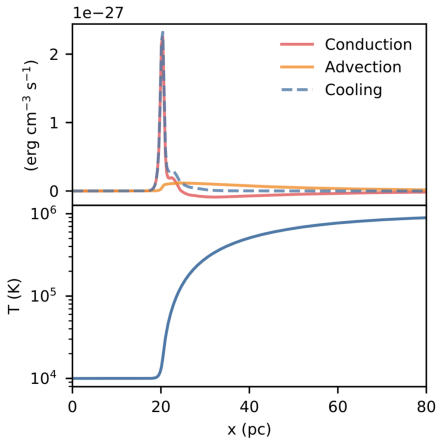
Geometry and Dissipation

$$\alpha_p = \frac{3}{16} \frac{V_w}{\langle v_{\rm out} \rangle} \frac{4\pi \mathcal{R}_{\rm bub}^2}{A_{\rm bub}}$$

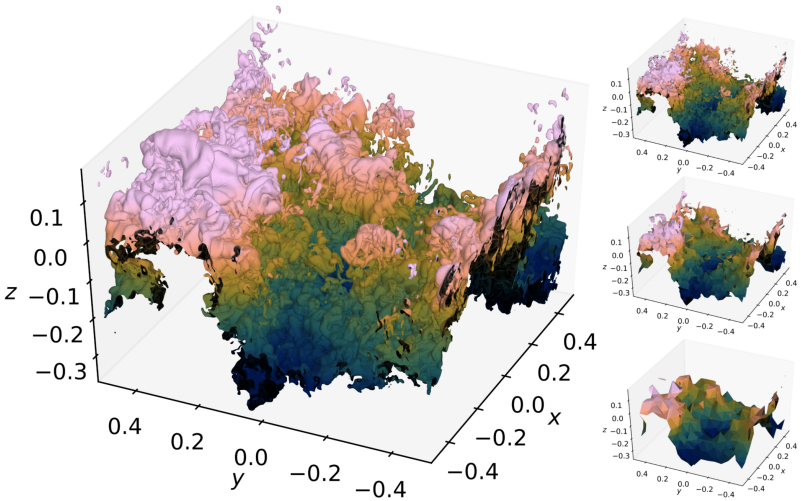
Dissipation

Geometry

$$j_x = \frac{Q}{c_p(T_2 - T_1)}; \quad Q = -\int_{-\infty}^{\infty} \rho \mathcal{L} \mathrm{d}x.$$

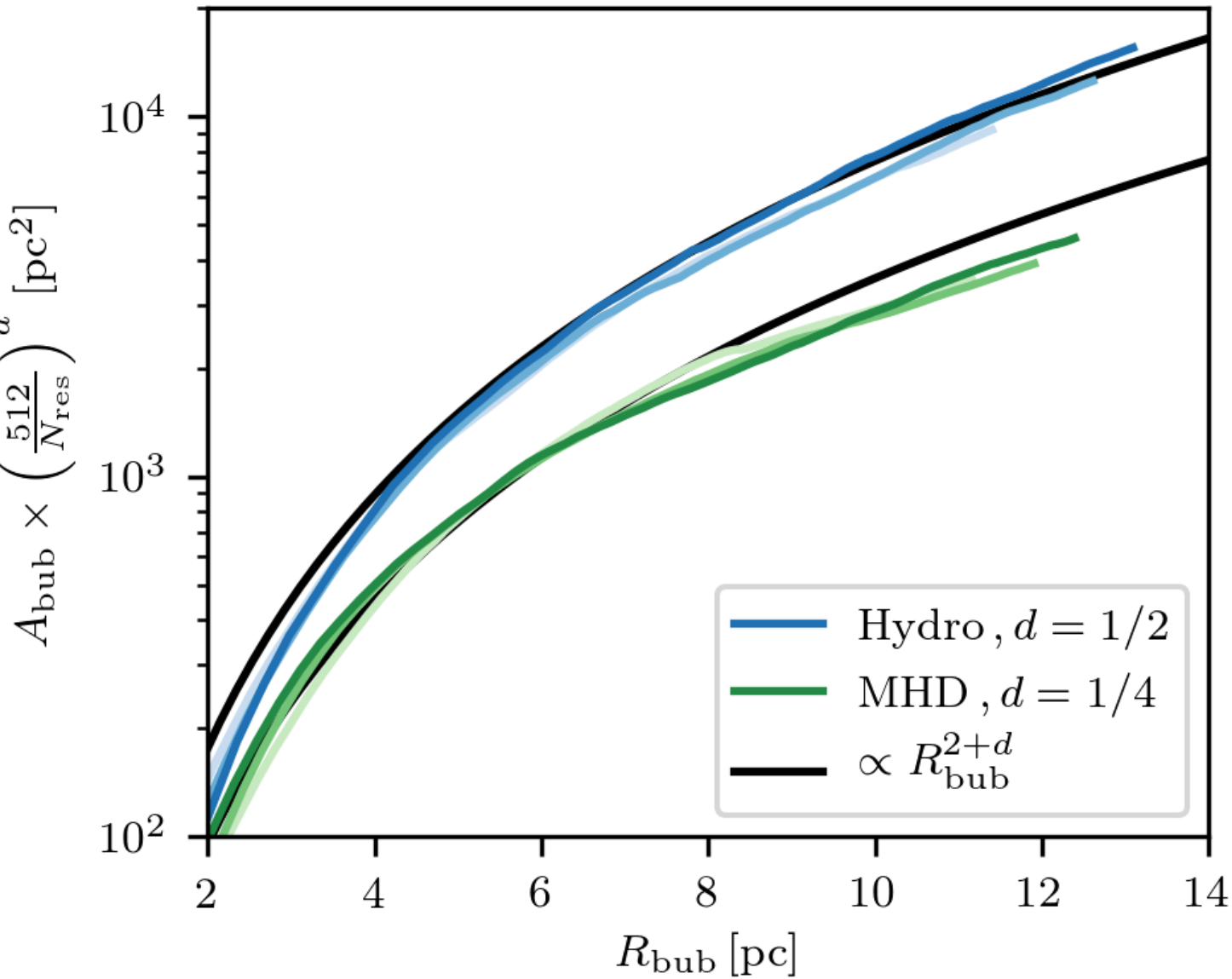


Tan, Oh, & Gronke 2021



Fielding et al. 2020

Scaling of A_{bub} - Fractals



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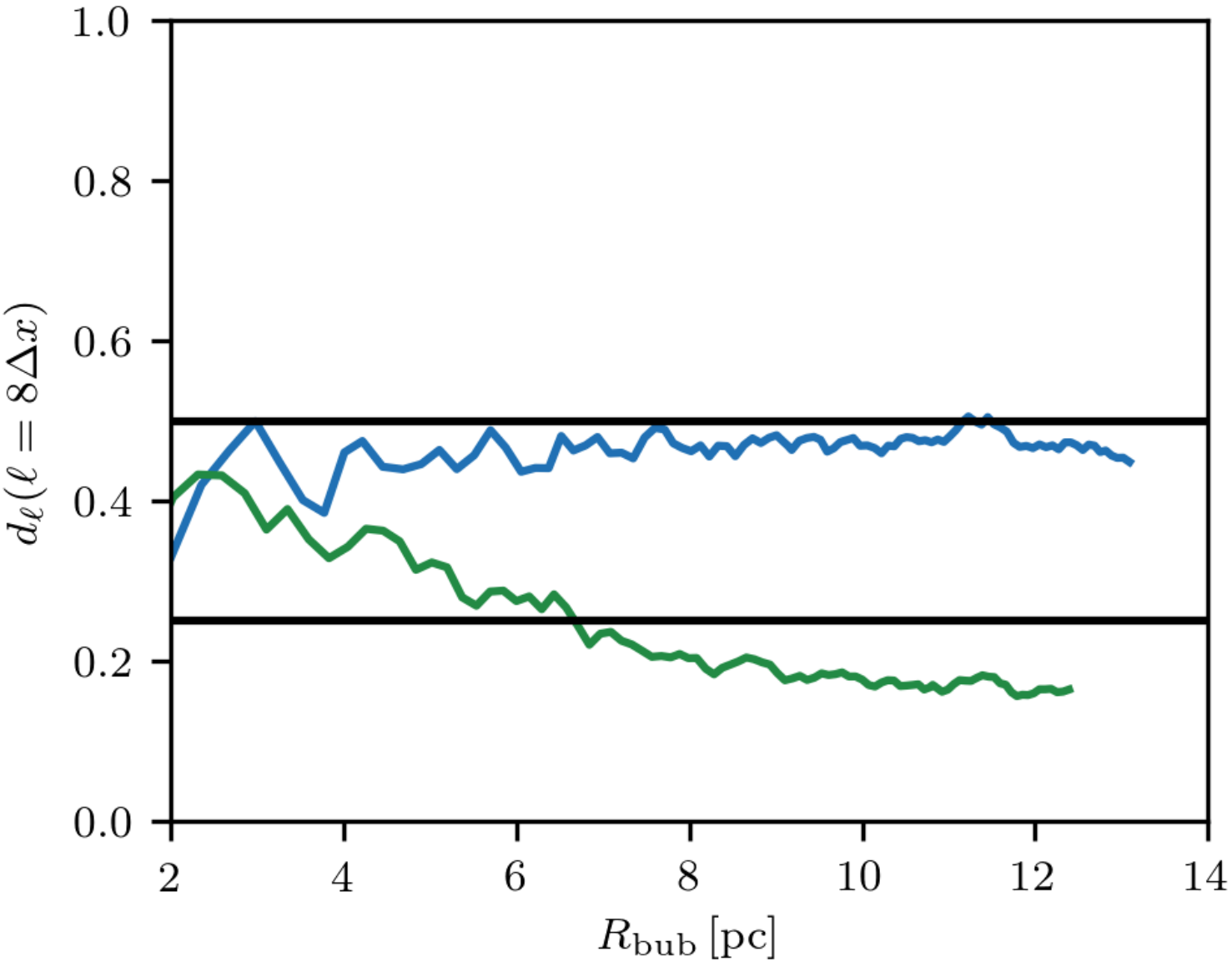
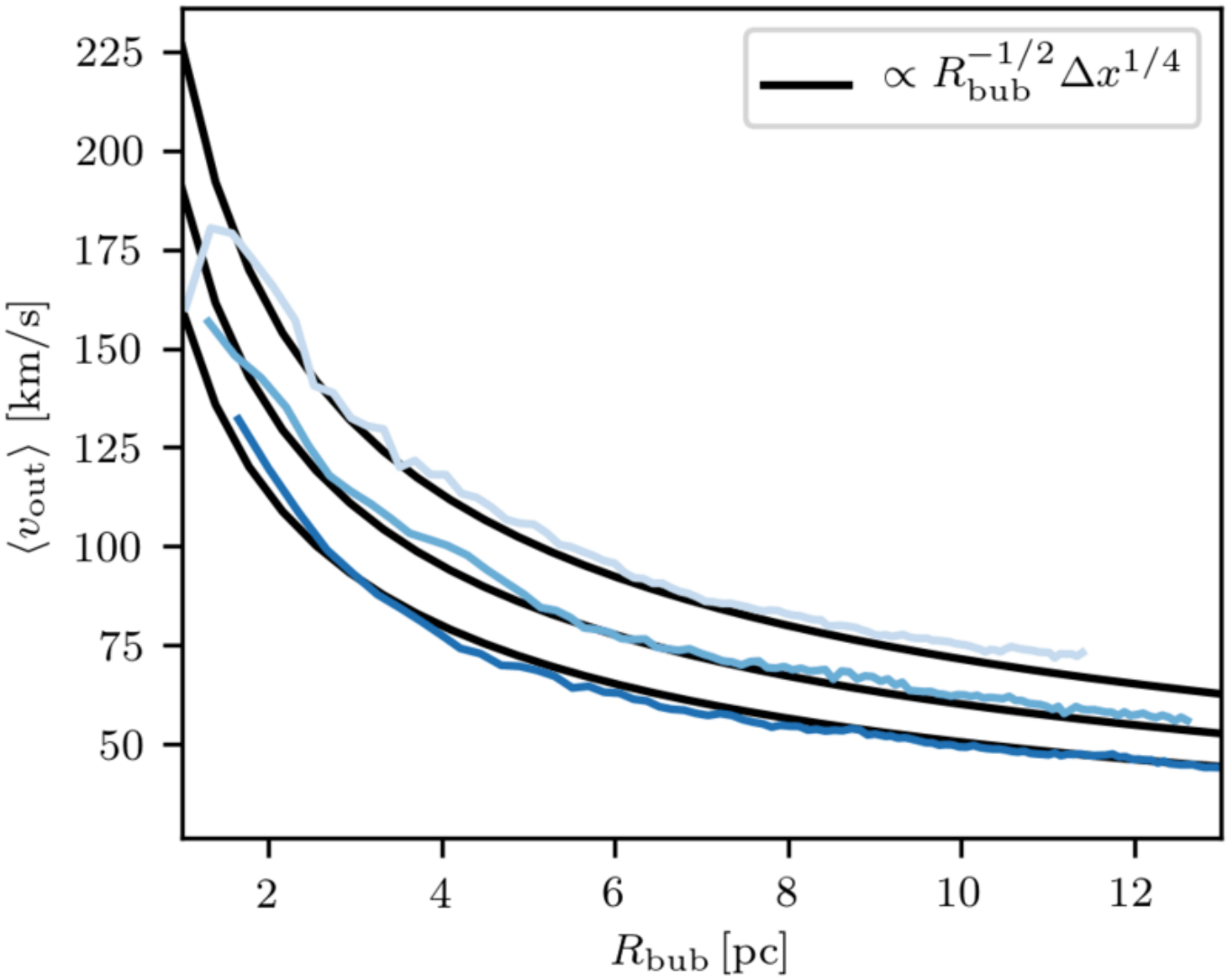
Scaling of A_{bub} - Fractals



Lancaster+24

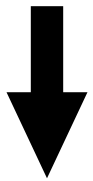
Scaling of $\langle v_{\rm out} \rangle$ - Numerics



Lancaster+24

Scalings Together

$$\alpha_p = \frac{3}{16}\frac{V_w}{\langle v_{\rm out}\rangle}\frac{4\pi\mathcal{R}_{\rm bub}^2}{A_{\rm bub}}$$

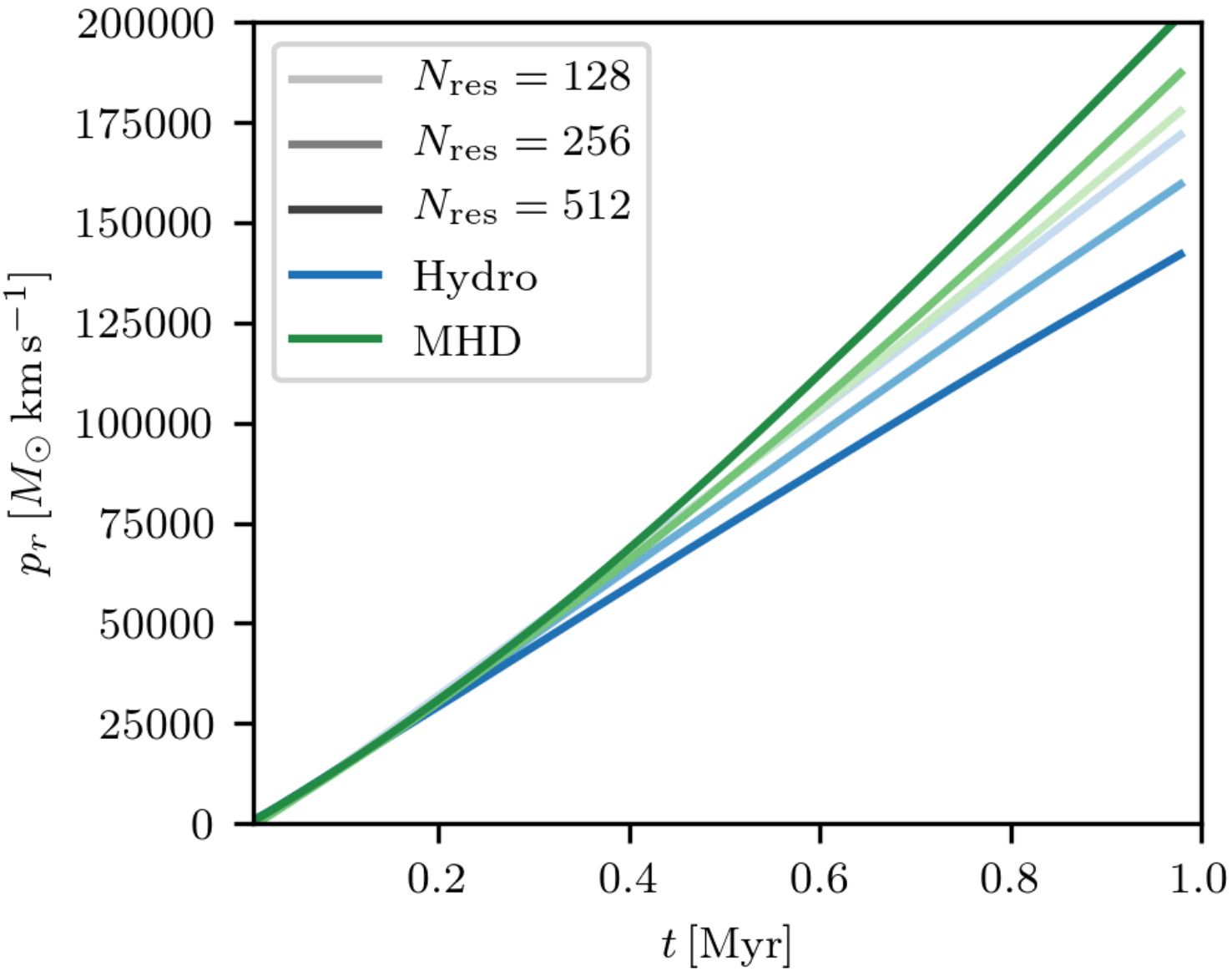


$$\alpha_p \propto V_w R_{\rm bub}^{1/2-d}\Delta x^{d-1/4}$$

$$\alpha_{p,\rm HD} \propto V_w \Delta x^{1/4}$$

$$\alpha_{p,\rm MHD} \propto V_w R_{\rm bub}^{3/10}\Delta x^{-1/20}$$

Resolution Dependence



Lancaster+24

How Does it Actually Evolve?

$$\alpha_p = \frac{3}{16}\frac{V_w}{\langle v_{\rm out}\rangle}\frac{4\pi\mathcal{R}_{\rm bub}^2}{A_{\rm bub}}$$

Turbulent Diffusivity:

$$\langle v_{\rm out}\rangle \to v_t(\ell_{\rm cool}) = v_t(L)\left(\frac{\ell_{\rm cool}}{L}\right)^p$$

Fractal Geometry:

$$\frac{4\pi R_{\rm bub}^2}{A_{\rm bub}} \to \left(\frac{\ell_{\rm cool}}{R_{\rm bub}}\right)^d$$

$$p = \frac{1}{3}\ ,\ d = \frac{1}{2}\ \Rightarrow\ \alpha_p \propto \textbf{const.}$$

Takeaways

- Need to resolve dissipative scale!

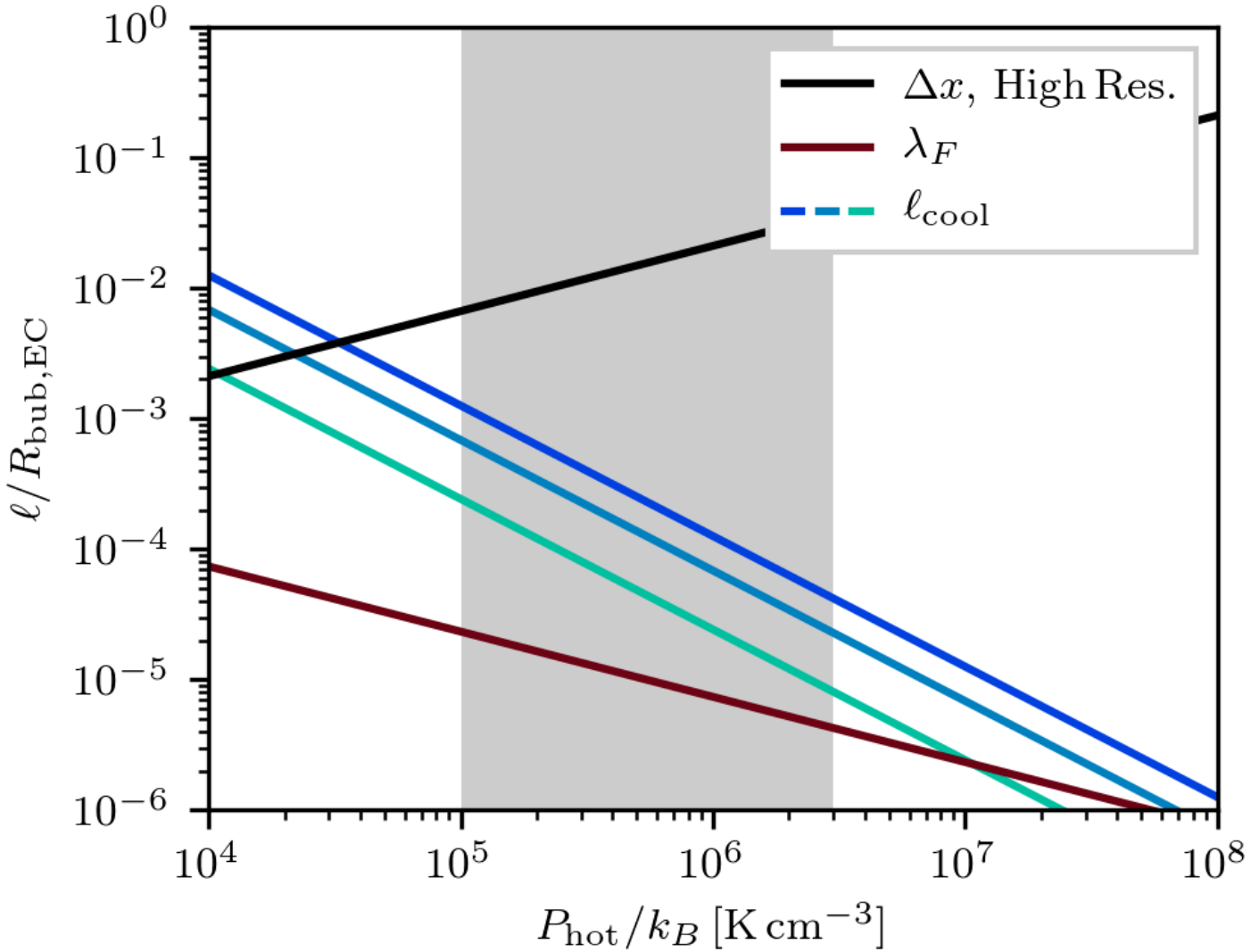
  - ℓ_{cool} / $\lambda_{F,\mathrm{turb}}$ or λ_F

- Resolves resolution scaling of both A_{bub} and $\langle v_{\mathrm{out}} \rangle$

- Likely explains "resolution independence" of mixing layer simulations

- Doesn't mean "efficient cooling" is unrealistic!

Future of Mixing Layers



Lancaster+24

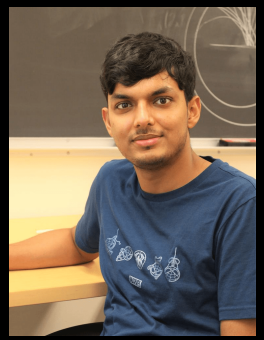
Future of Mixing Layers

- GPU Accelerated (Athena-K)

- Resolved Conduction

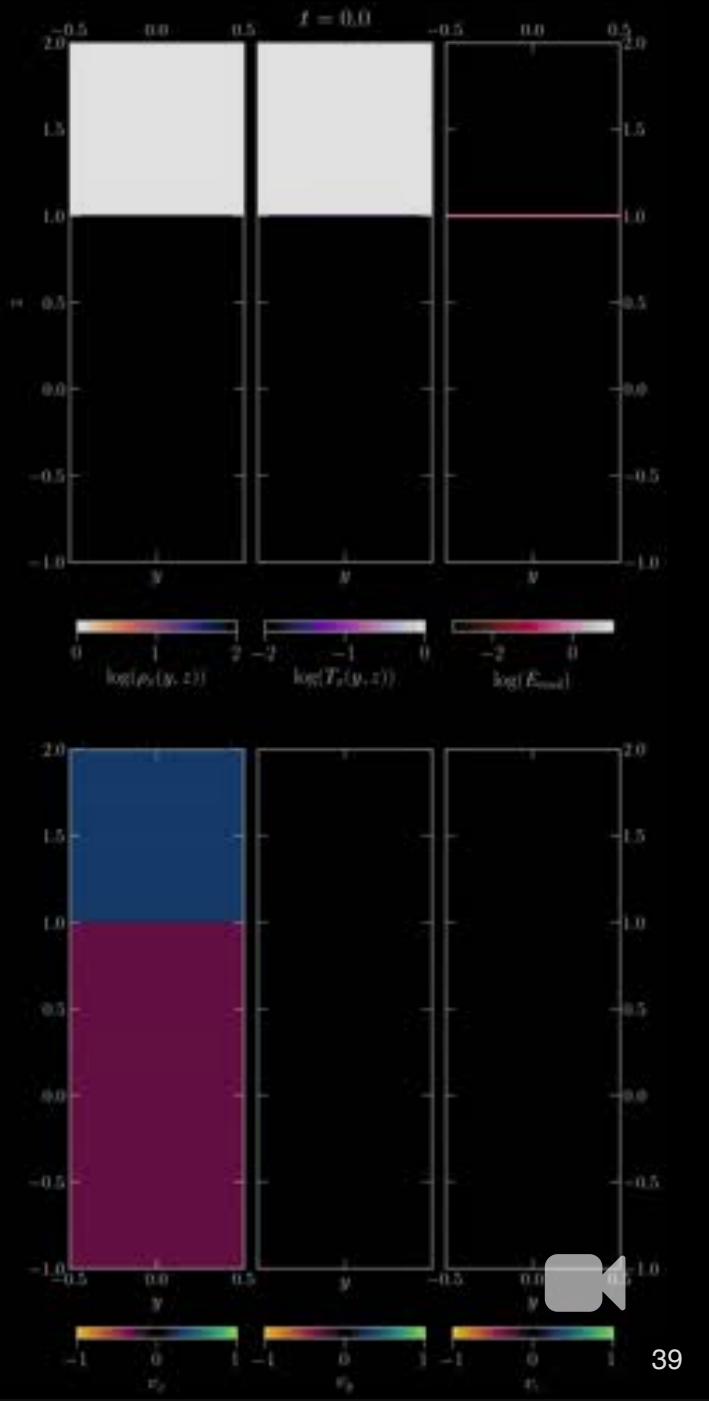
- Resolved (Hyper-) Viscosity

- Resolved Geometry & Turbulence



Rajsekhar Mohapatra

Drummond Fielding



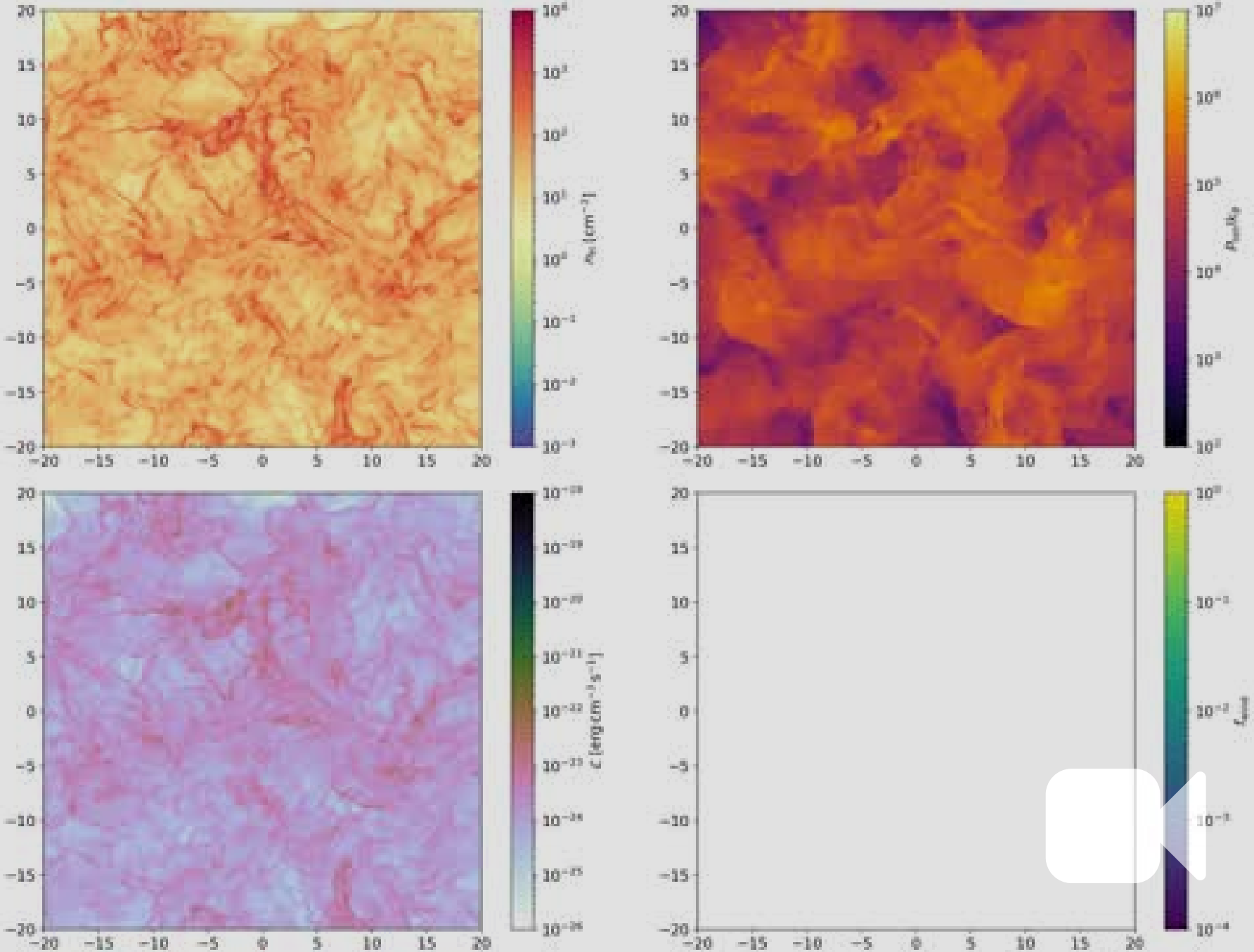
Conclusions

- Need to resolve dissipative scale!

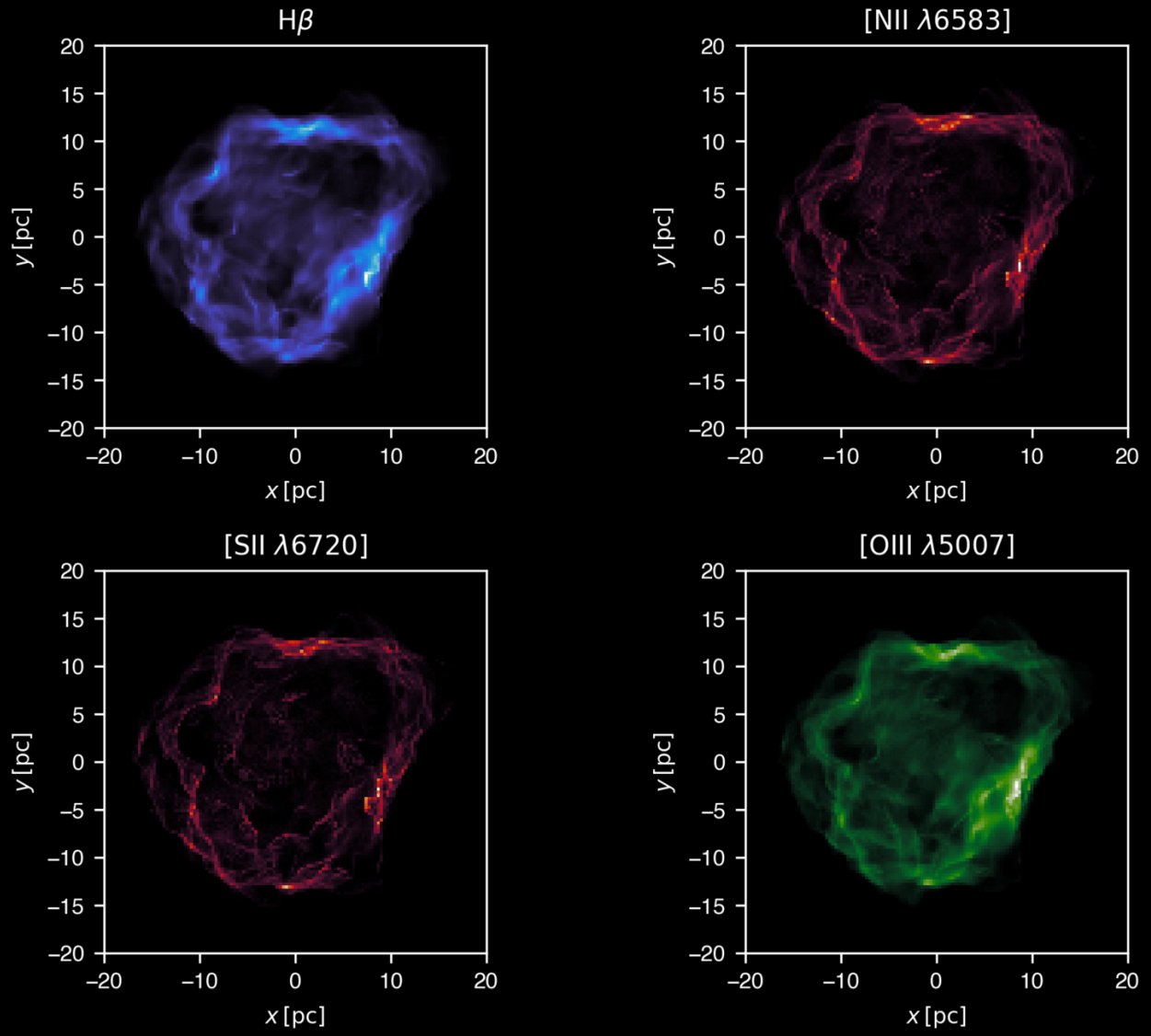
- Wind effects are still up in the air! But not for long!

- Lesson: Convergence is not always enough!

- Doesn't mean "efficient cooling" is unrealistic!



Future of Observational Comparisons



Future of Observational Comparisons