STRAWBERRY

Binding particles to haloes using the full potential field

Tamara R. G. Richardson

Haloes in brief

In theory, haloes are:

> Overdense peaks

> Gravitationally bound

Why are they relevant?

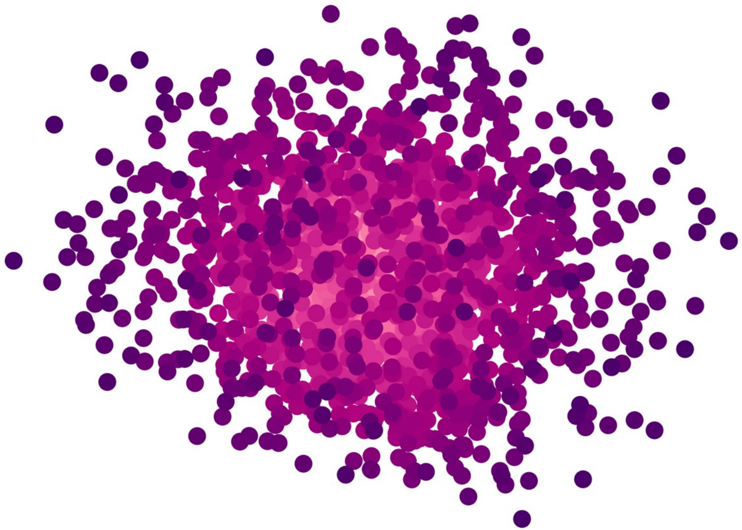
> Halo Mass Function

> Galaxy-Halo connection

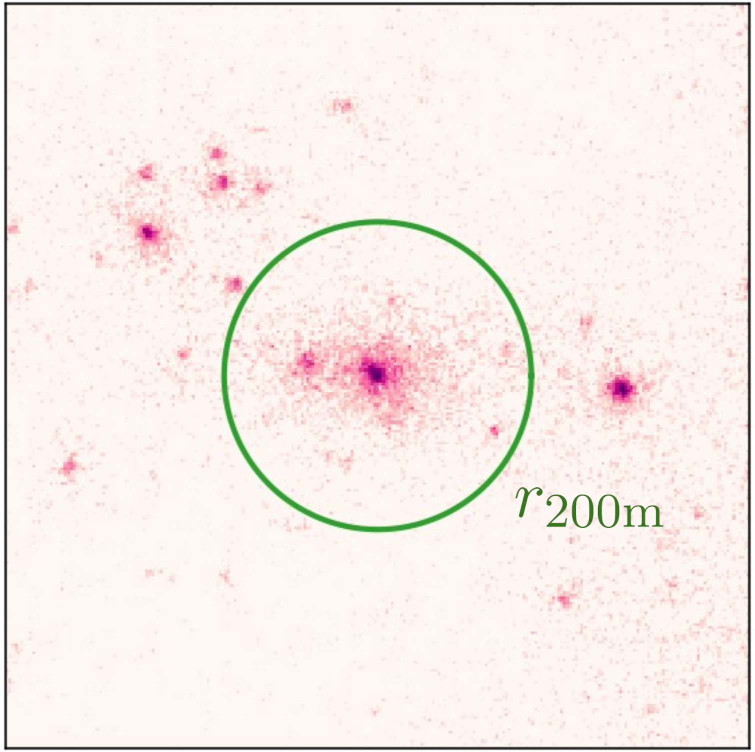
> Halo Model for non-linear P(k)

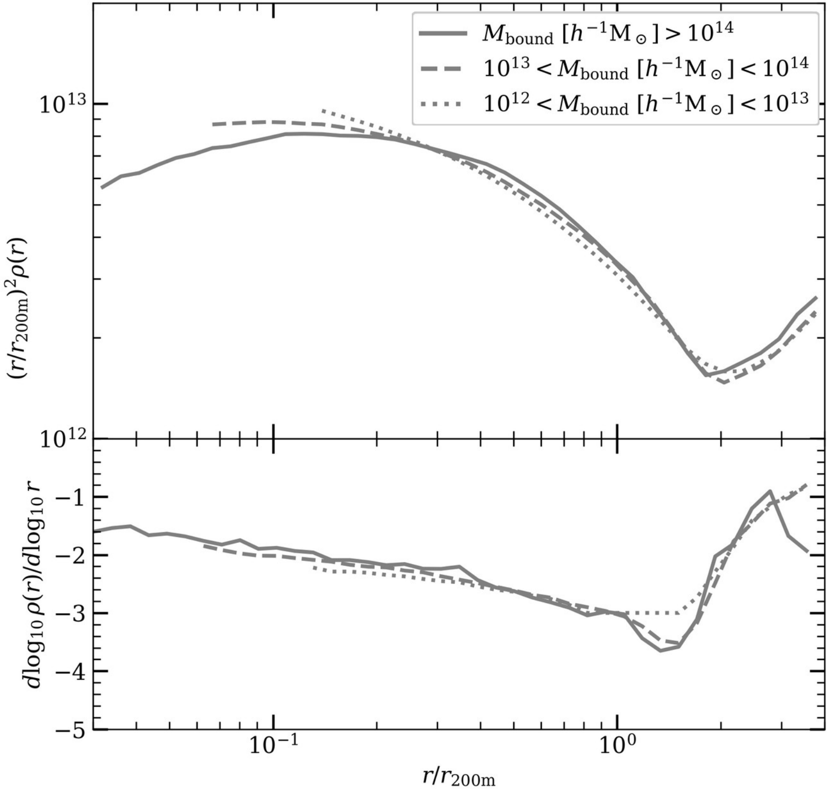
> Mass modeling / Scaling relations

Detailed studies require **simulations**

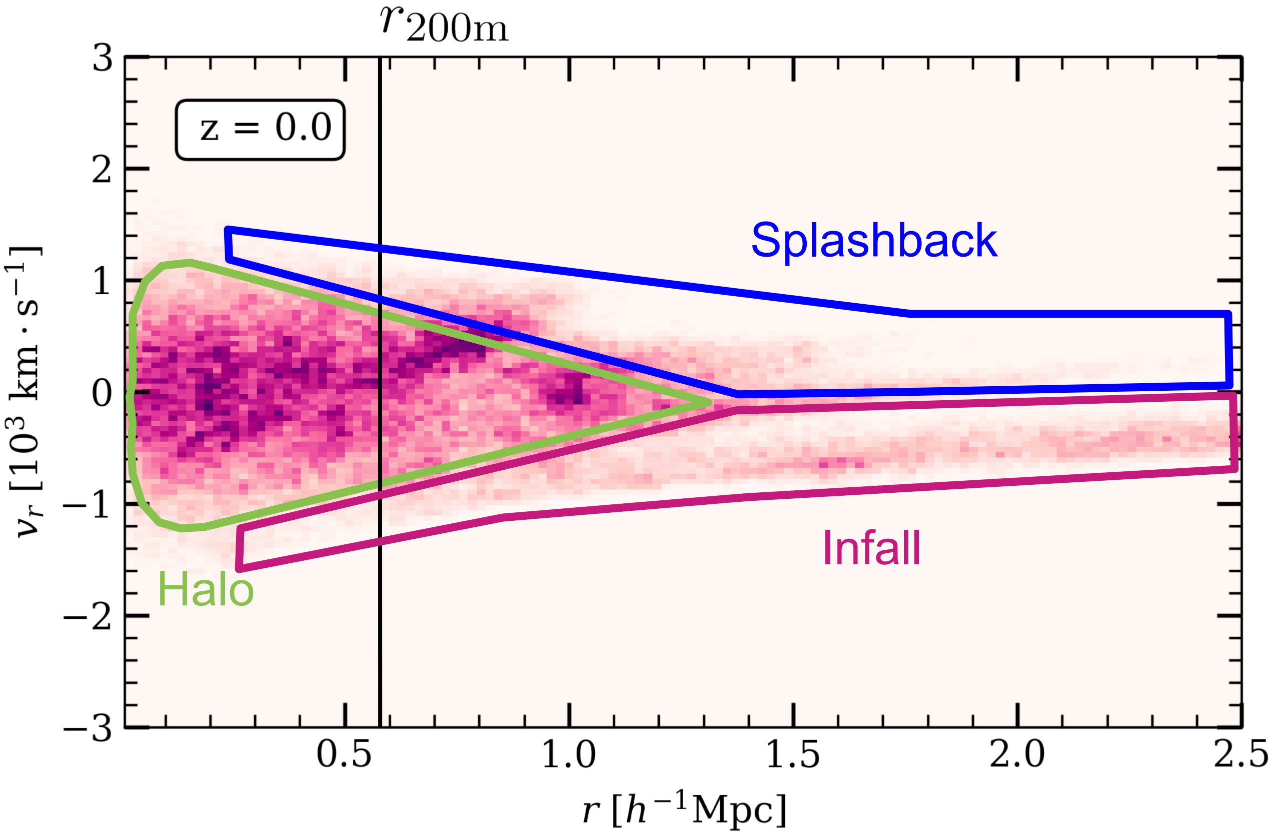


Haloes in simulations: Weird and Wonderful

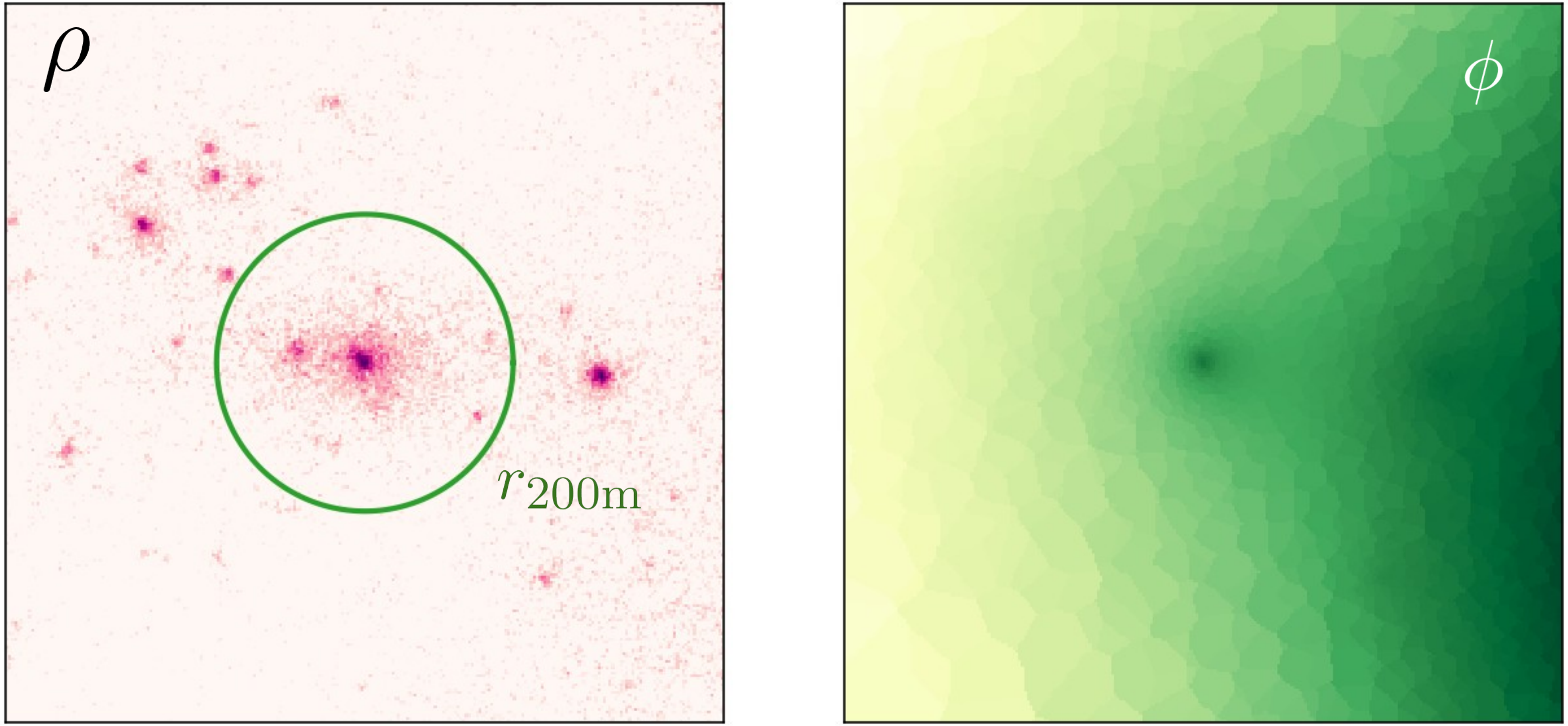




Haloes in radial phase space



But why not use the potential??



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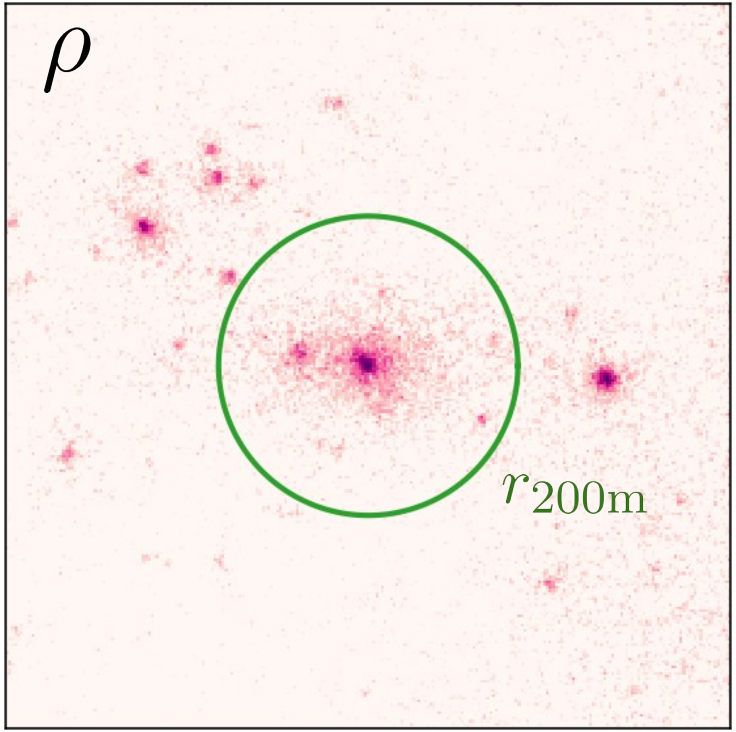

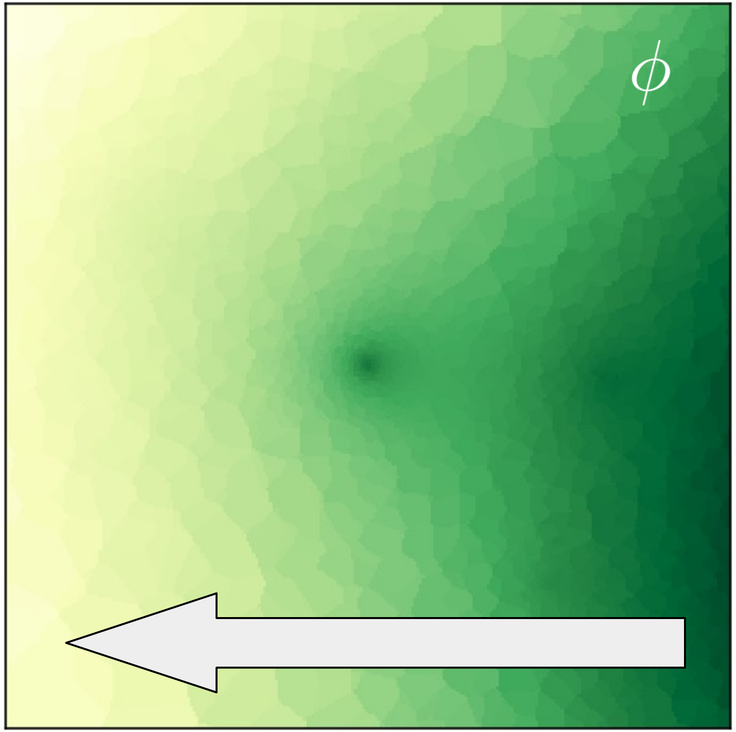

Large scale gradients!

Cleaning the Gradients

$$\phi = \phi_{\mathrm{int}} + \phi_{\mathrm{ext}}$$

(Stücker et al. 2021)

Cleaning the Gradients

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$$\phi = \phi_{\mathrm{self}} + \phi_{\mathrm{ext}}(\mathbf{x}_{\mathrm{h}}) + \Delta x_i \partial_i \phi_{\mathrm{ext}}(\mathbf{x}_{\mathrm{h}}) + \frac{1}{2} \Delta x_i \Delta x_j \partial_i \partial_j \phi_{\mathrm{ext}}(\mathbf{x}_{\mathrm{h}}) + \cdots$$

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Absolute value of the potential

Uniform acceleration

No influence
(in GR)

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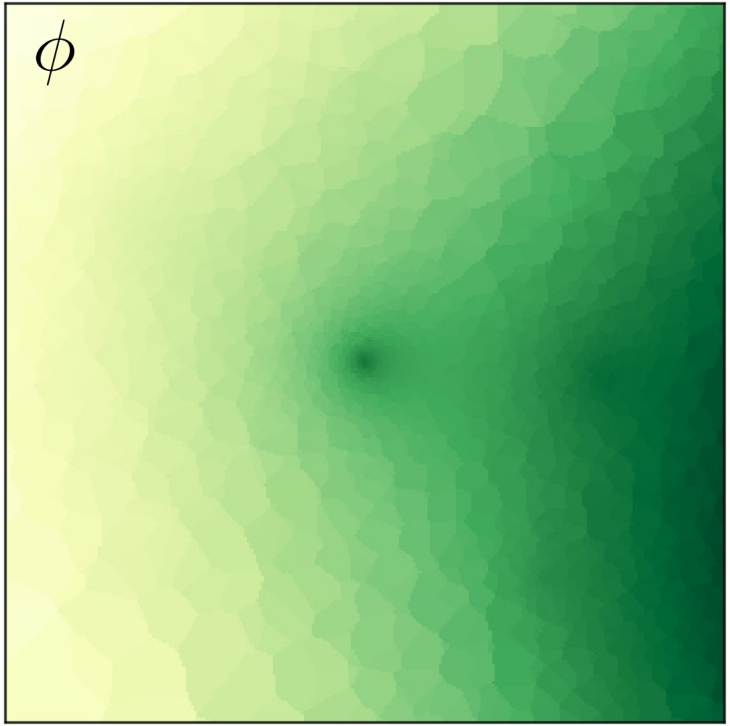
$$\phi_{\text{boost}} = \phi_{\text{self}} + \phi_{\text{ext}} - (\mathbf{x} - \mathbf{x}_{\text{h}}) \cdot \nabla \phi_{\text{ext}}$$

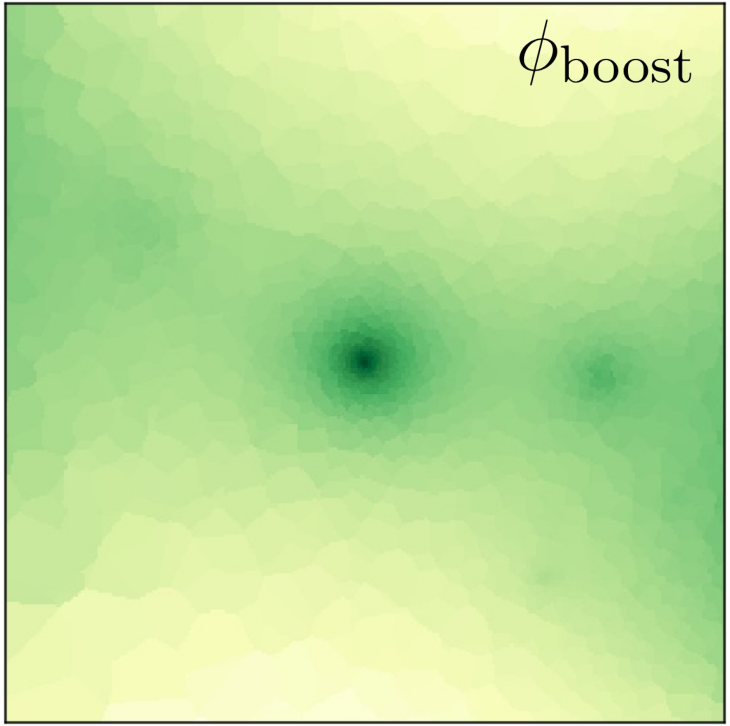
$$\phi_{\text{boost}} = \phi + (\mathbf{x} - \mathbf{x}_{\text{h}}) \cdot \mathbf{a}_{\text{ext}}$$

Internal dynamics are completely equivalent!

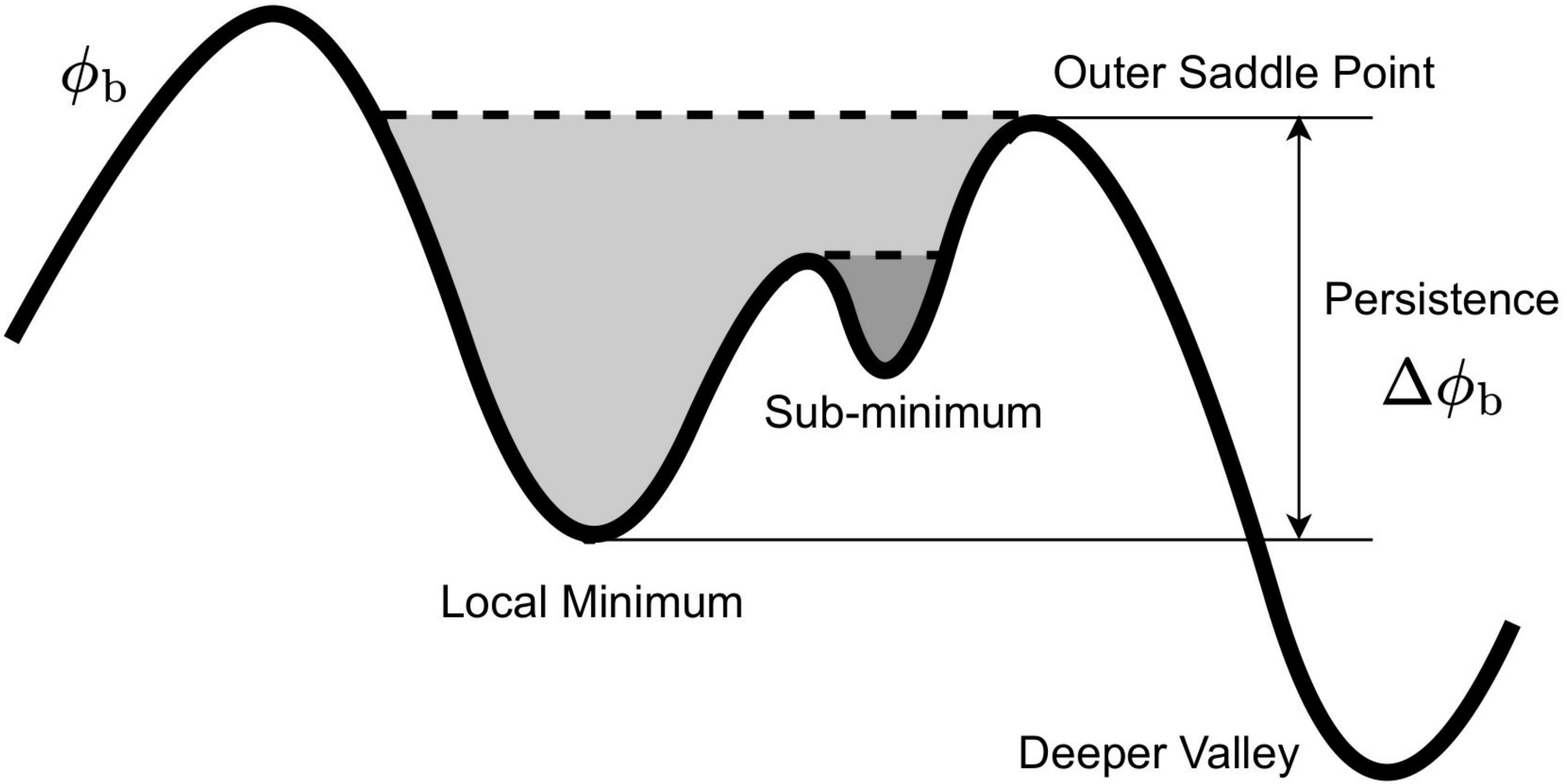
(Stücker et al. 2021)

Bang! And the gradient is gone!





Defining haloes as potential wells



Goal: Turn this into a ‘halo finder’

STRAWBERRY

STRucture **A**ssignment **W**ith **B**oost**E**d **R**efe**R**ence frame in c**Y**thon

Goal: Turn this into a ~~'halo finder'~~
binding check

STRAWBERRY

STRucture **A**ssignment **W**ith **B**oost**E**d Refe**R**ence frame in c**Y**thon

To find a halo

$$\phi_{\mathrm{boost}} = \phi + (\mathbf{x} - \mathbf{x}_{\mathrm{h}}) \cdot \mathbf{a}_{\mathrm{ext}}$$

Advantages:

> Physically motivated binding check

> Accounts for environment (Tides, Torques, etc…)

Disadvantages:

> Internal-External split -> Ill defined

> Local quantity -> Need an inital seed to start

Need to rely on a **seed catalogue**

Four-step roadmap

$$\phi_{\mathrm{boost}} = \phi + (\mathbf{x} - \mathbf{x}_{\mathrm{h}}) \cdot \mathbf{a}_{\mathrm{ext}}$$

1. First guess (FoF Halo)
2. Switch to accelerated frame
3. Fill potential well
4. Unbind particles

Visualising 1 halo

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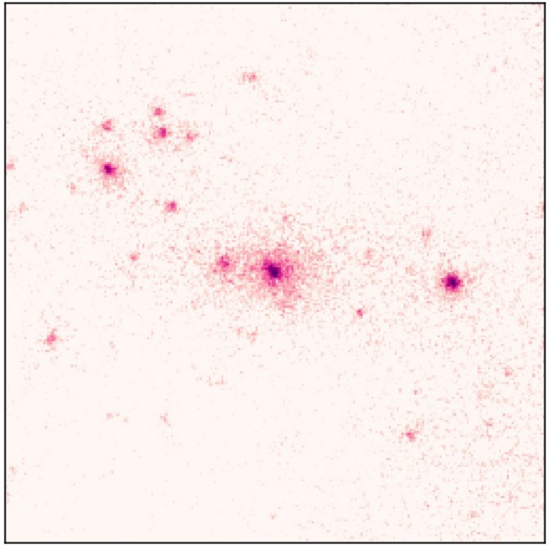
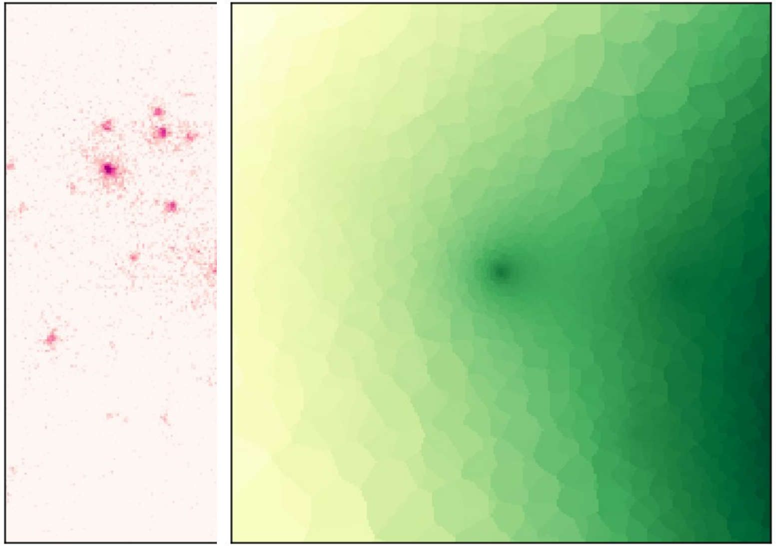


Visualising 1 halo



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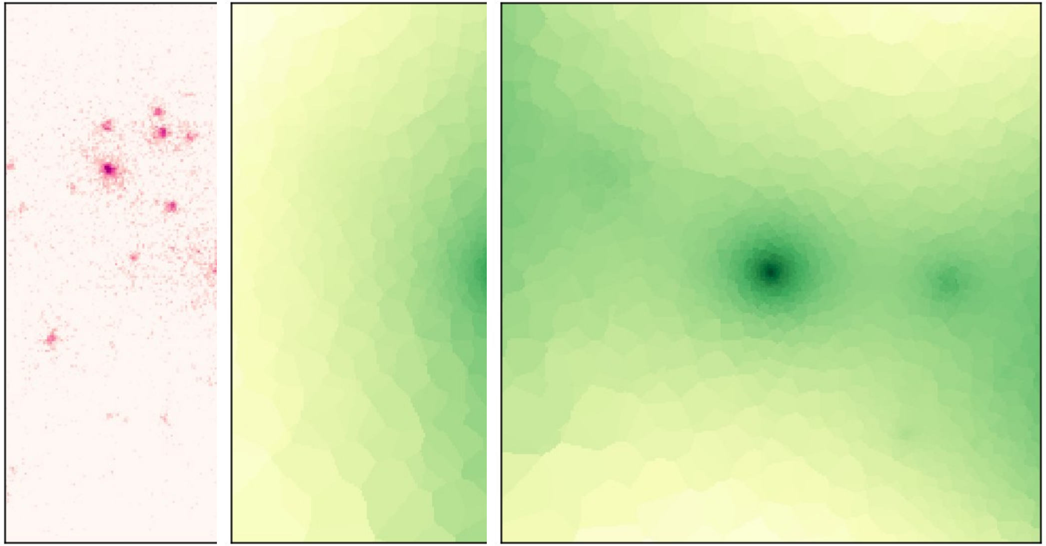

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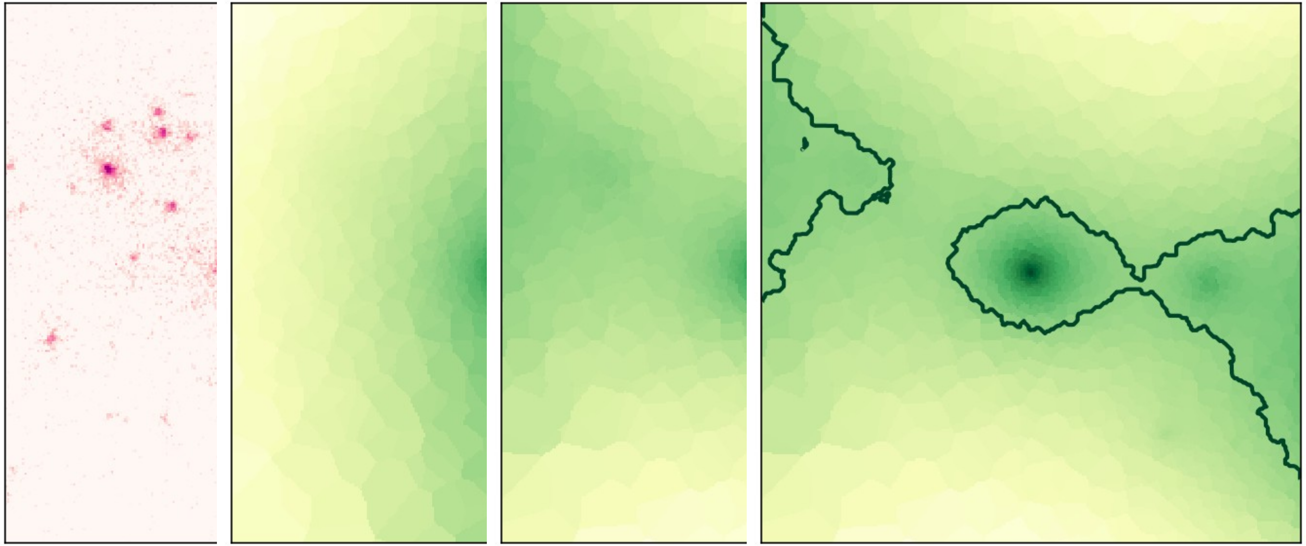

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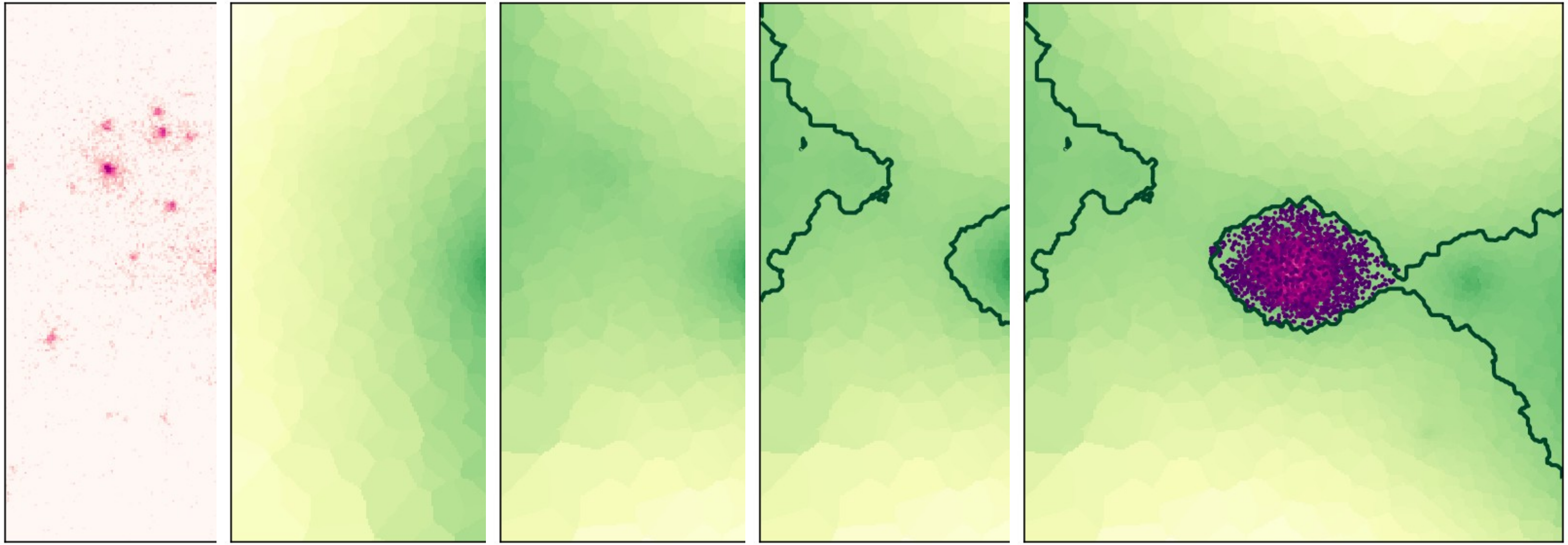

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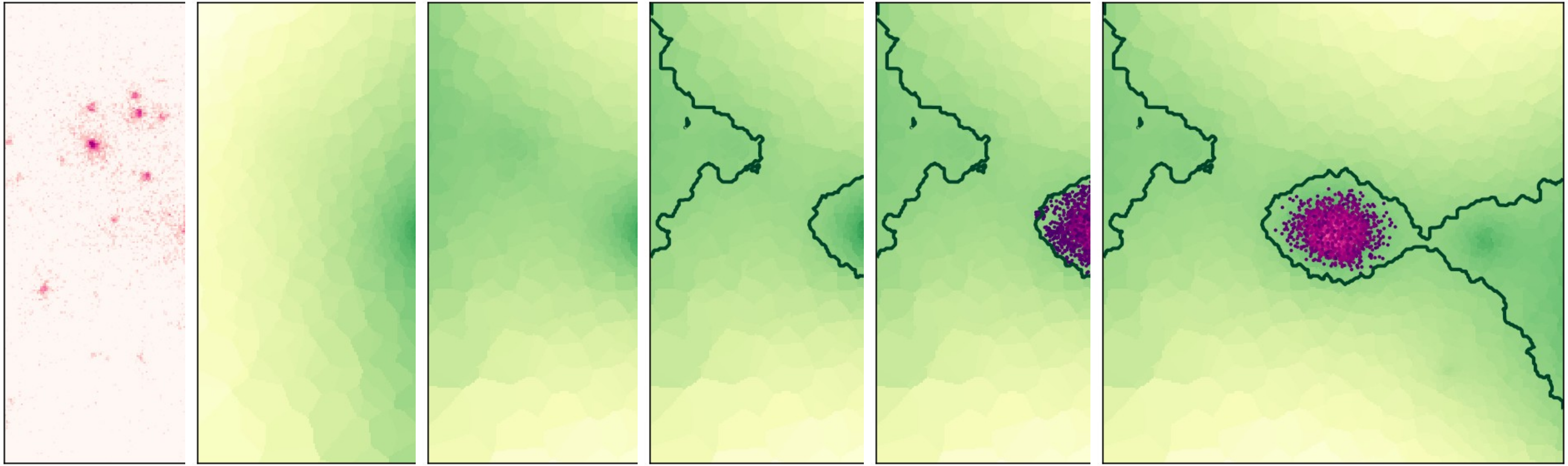
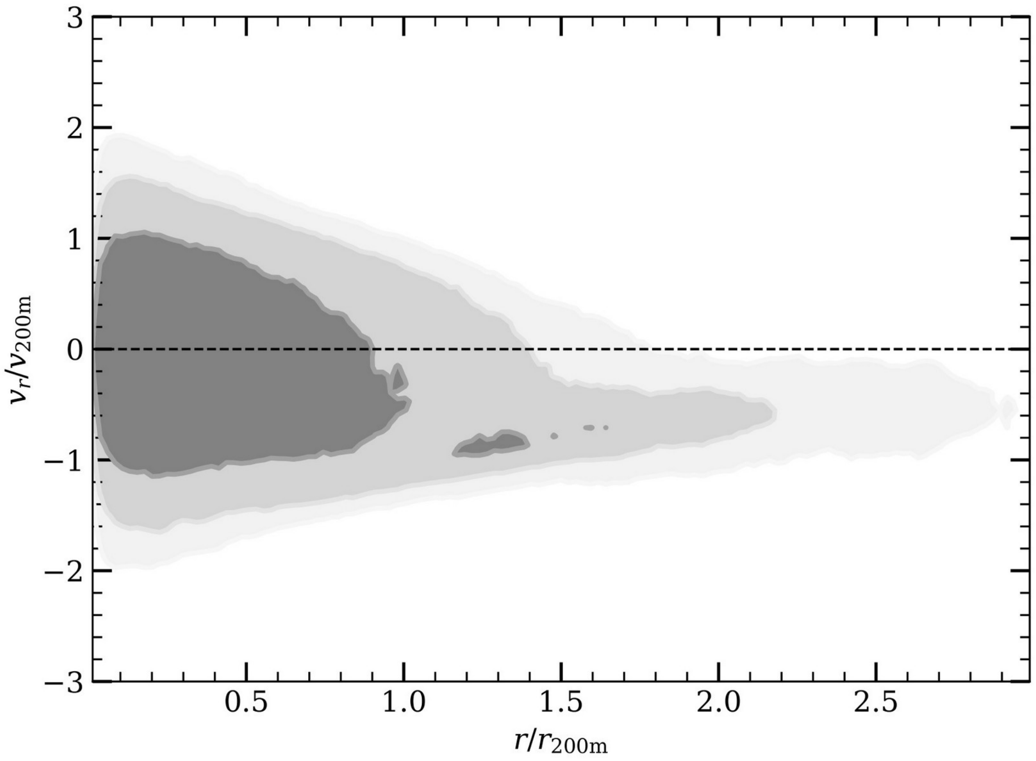


(Almost) Perfect Preening



Selection using the potential:

Leaves us with **bound** population.

Removes **infalling** and **splashback** particles.

← Stack of 100 haloes $M_{\mathrm{bound}} \sim 10^{14}\,h^{-1}\mathrm{M}_\odot$

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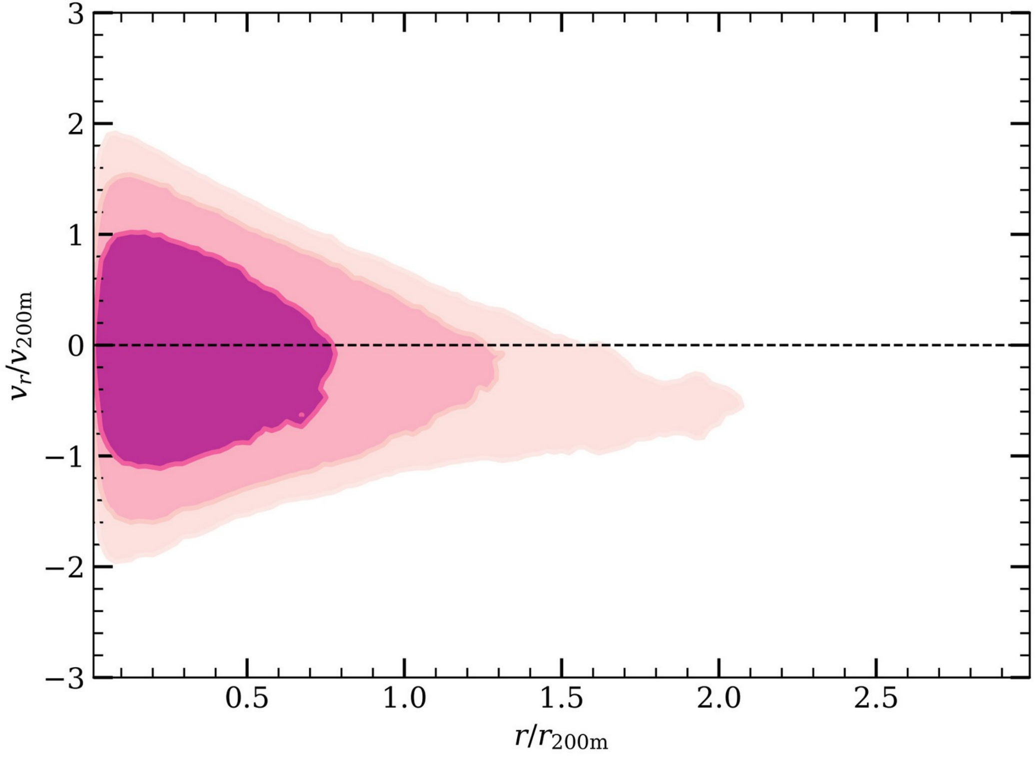

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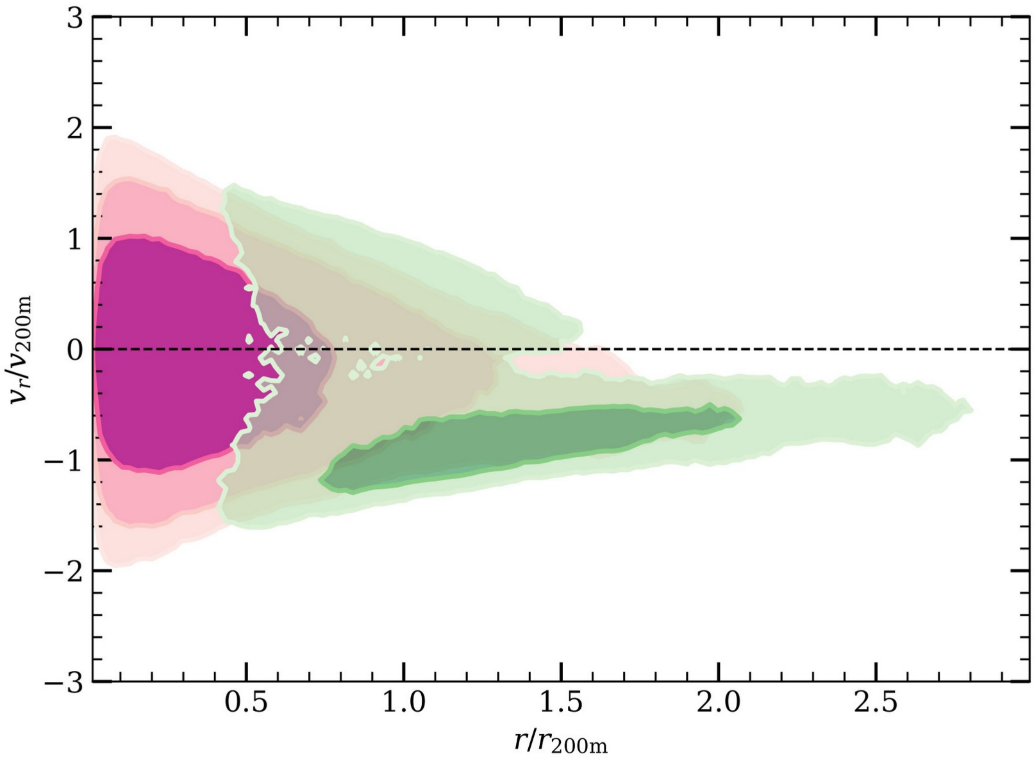

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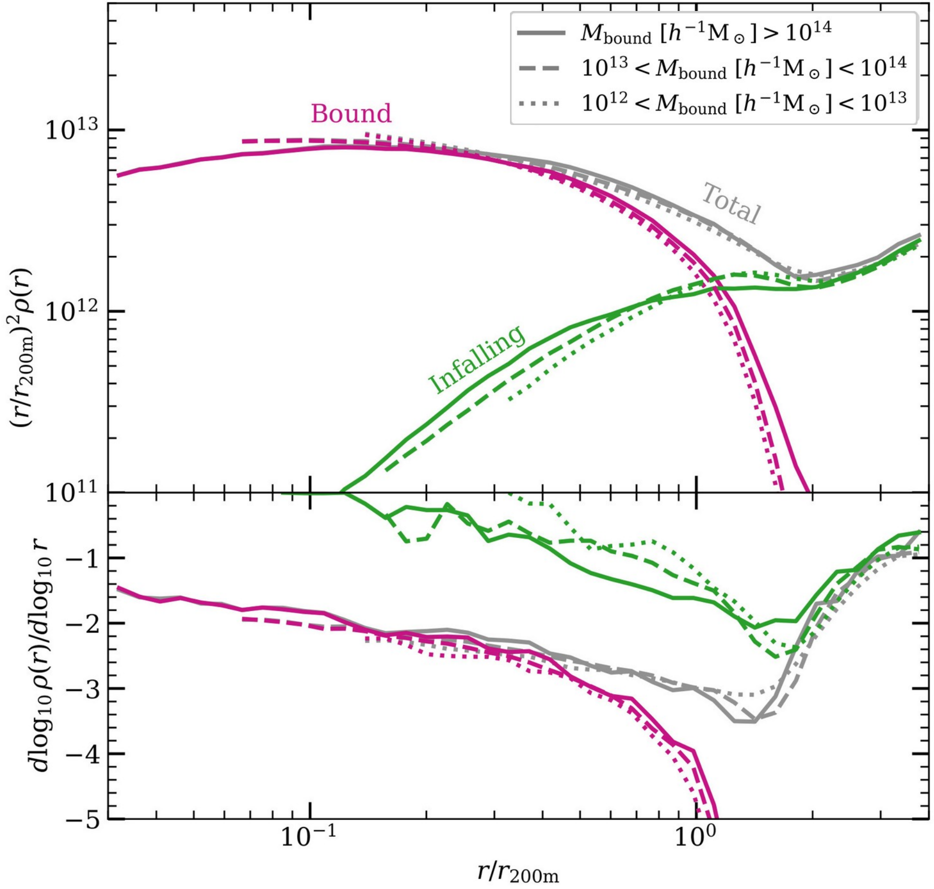
Finally, an edge

The selection create an exponential cut-off in the halo profile beyond the virial radius.

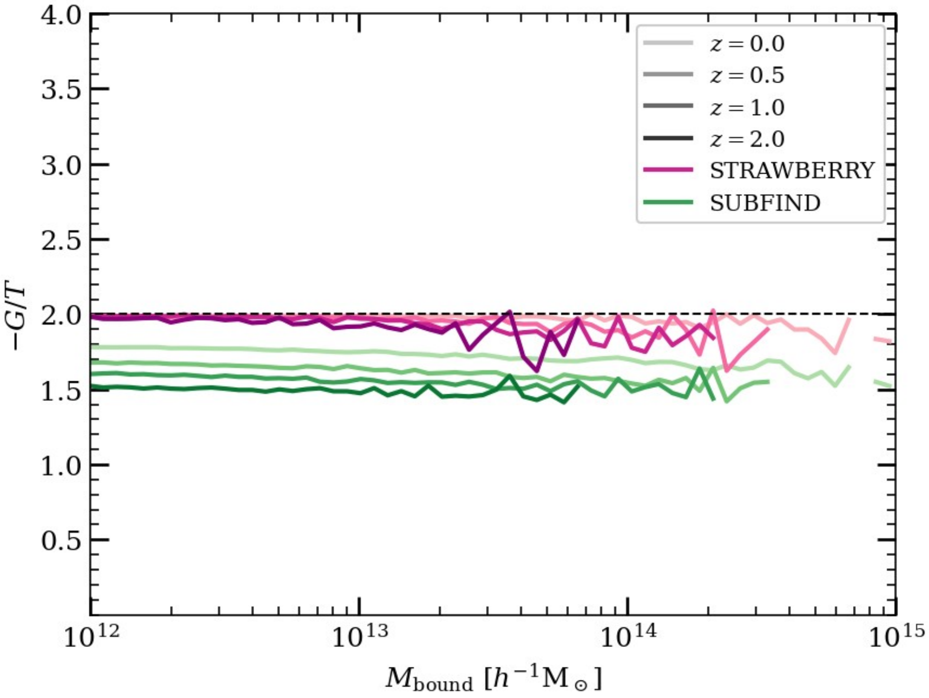
Consistent with:

- Adhikari et al. 2014
- Diemer et al. 20XX
- Garcia et al. 2023
- Salazar et al. 2024

And a bunch of other cool things discussed this week some of which I didn't know about before!!!



Boosted Haloes are Virialised!



$$\frac{-G}{T} = \frac{-\langle \mathbf{x} \cdot \mathbf{a} \rangle}{0.5\langle \mathbf{v} \cdot \mathbf{v} \rangle} \sim 2$$

Discrepancy attributed to "external pressure"

Removing bound particles

Including unbound particles

(e.g. Shaw et al. 2006, Poole et al. 2006, and Davis et al. 2011)

Summary

The boosted potential framework provides a **physically motivated framework** to perform a **binding check**.

Boosted haloes are virialised and have edges.

Questions we can already answer.

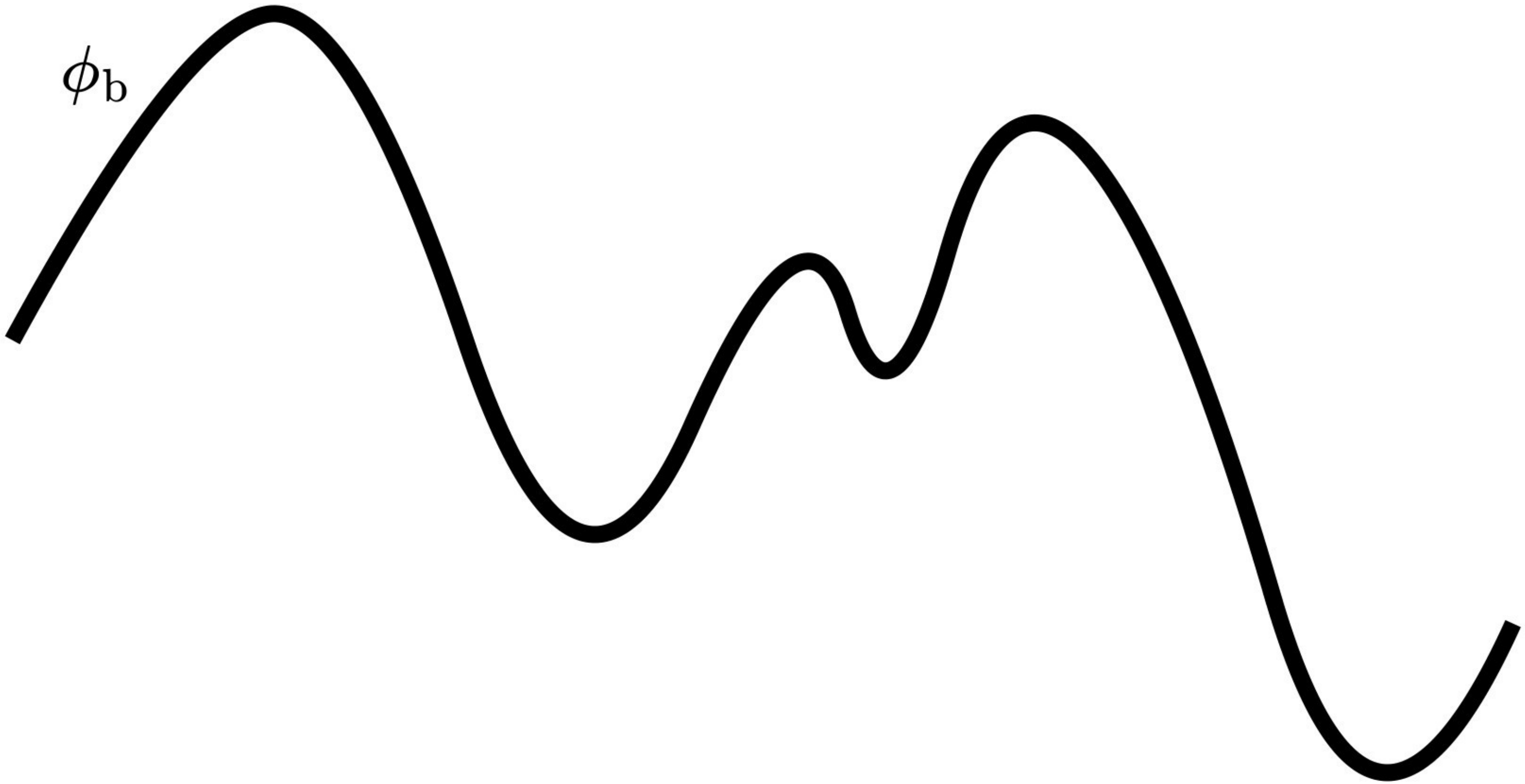
When does infalling matter virialise?

How do the profiles change with redshift?

How does $M_{\rm boost}$ *relate to other masses?*

Look out for **STRAWBERRY** in the near future!

Introducing Strawberry



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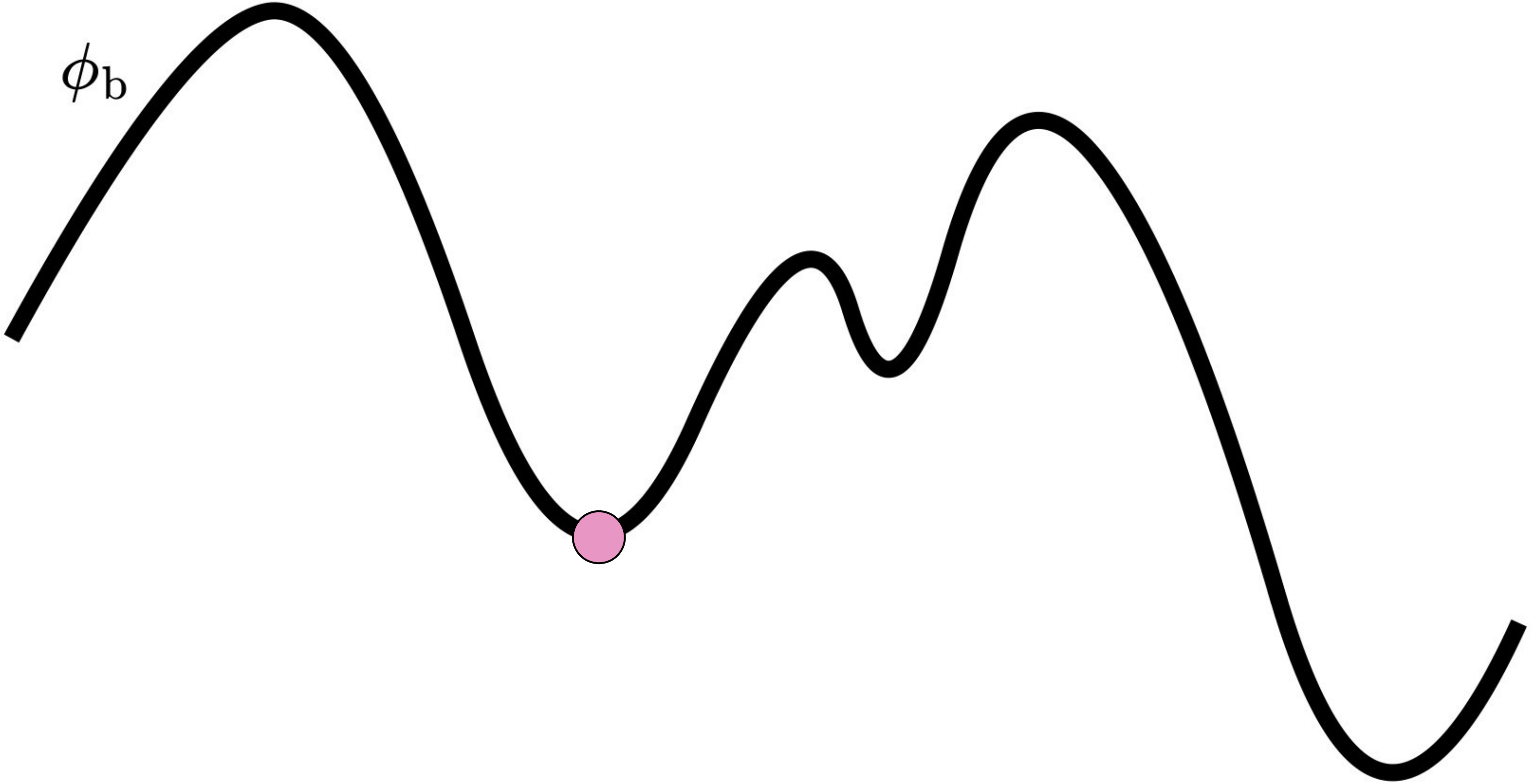

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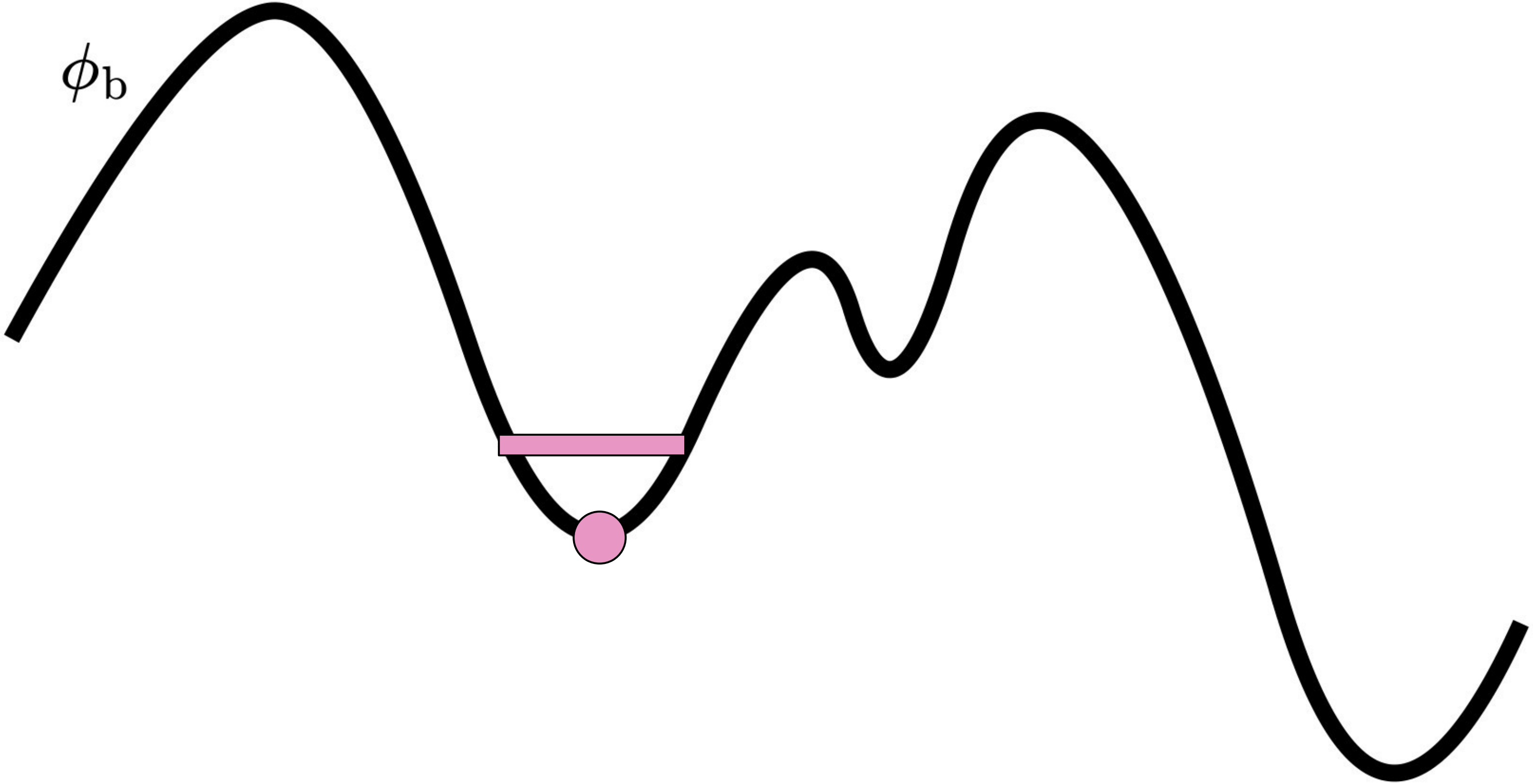

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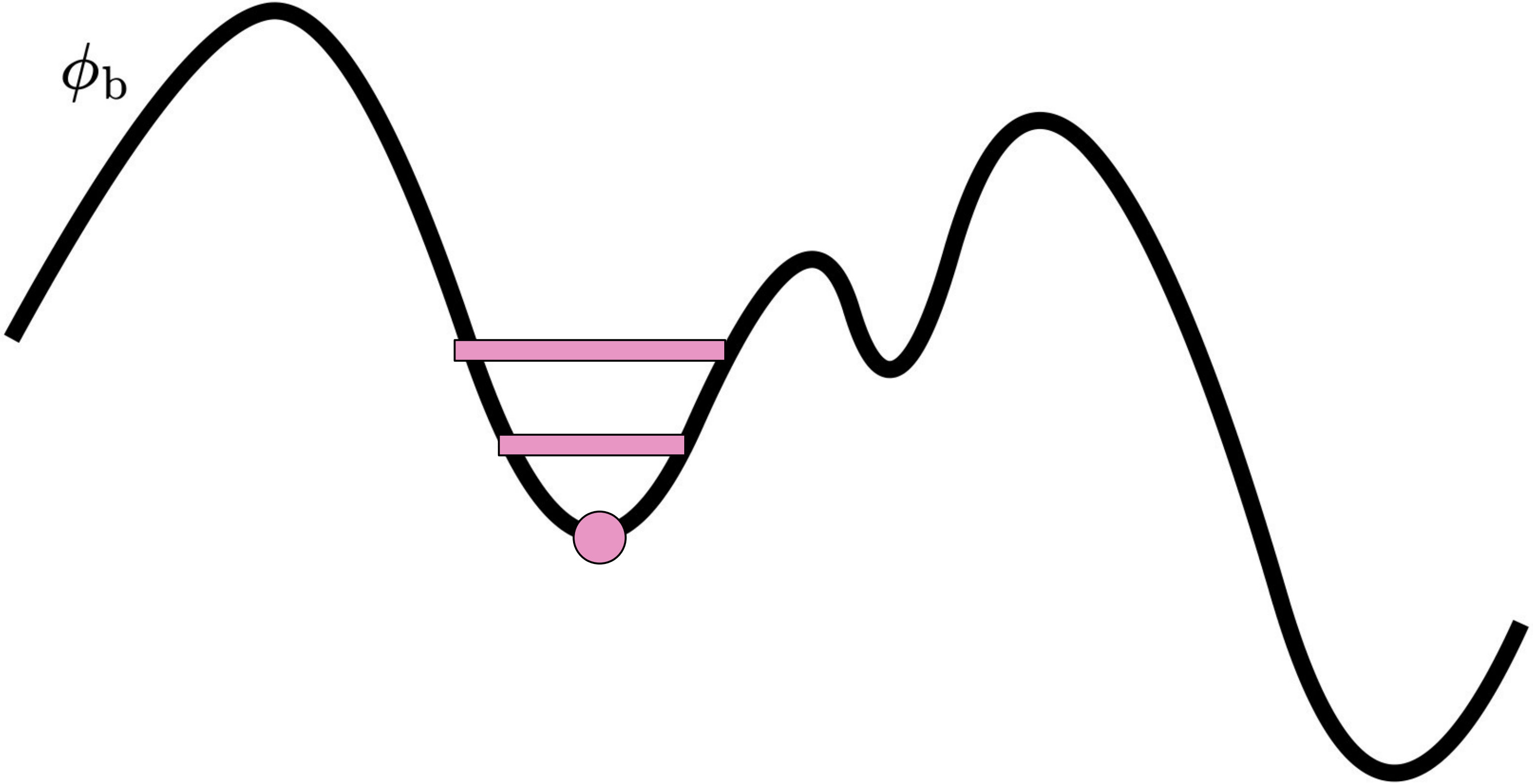

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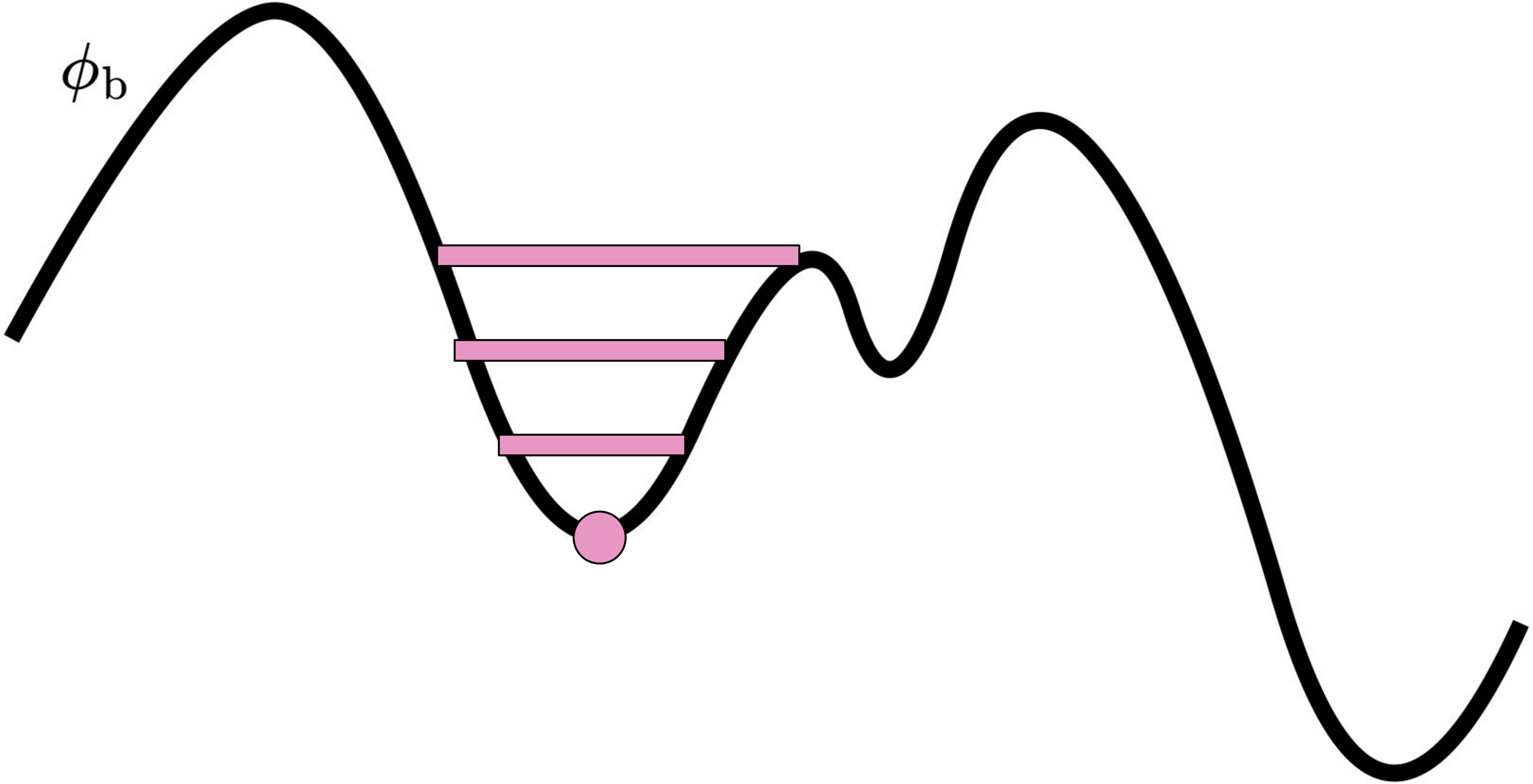

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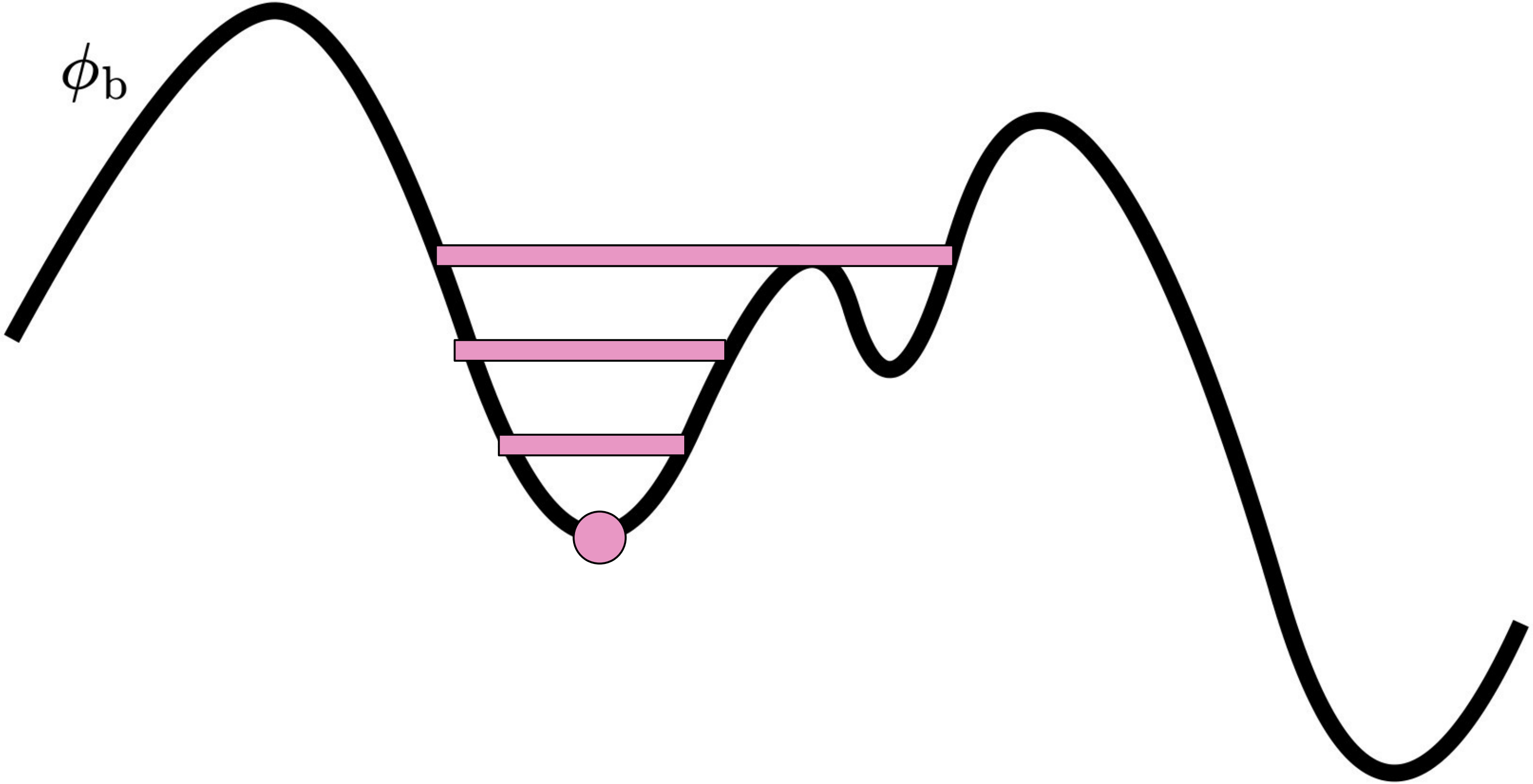

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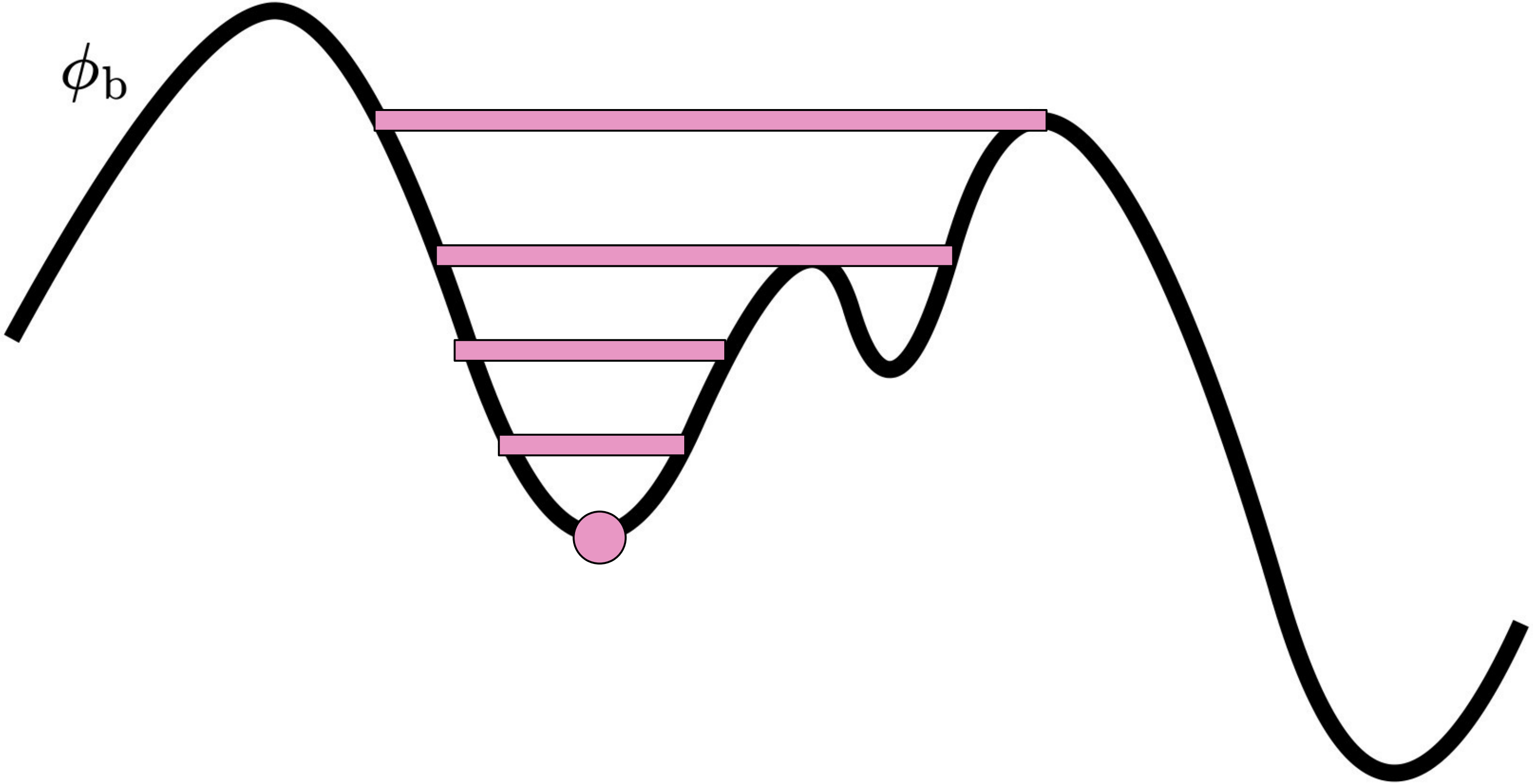

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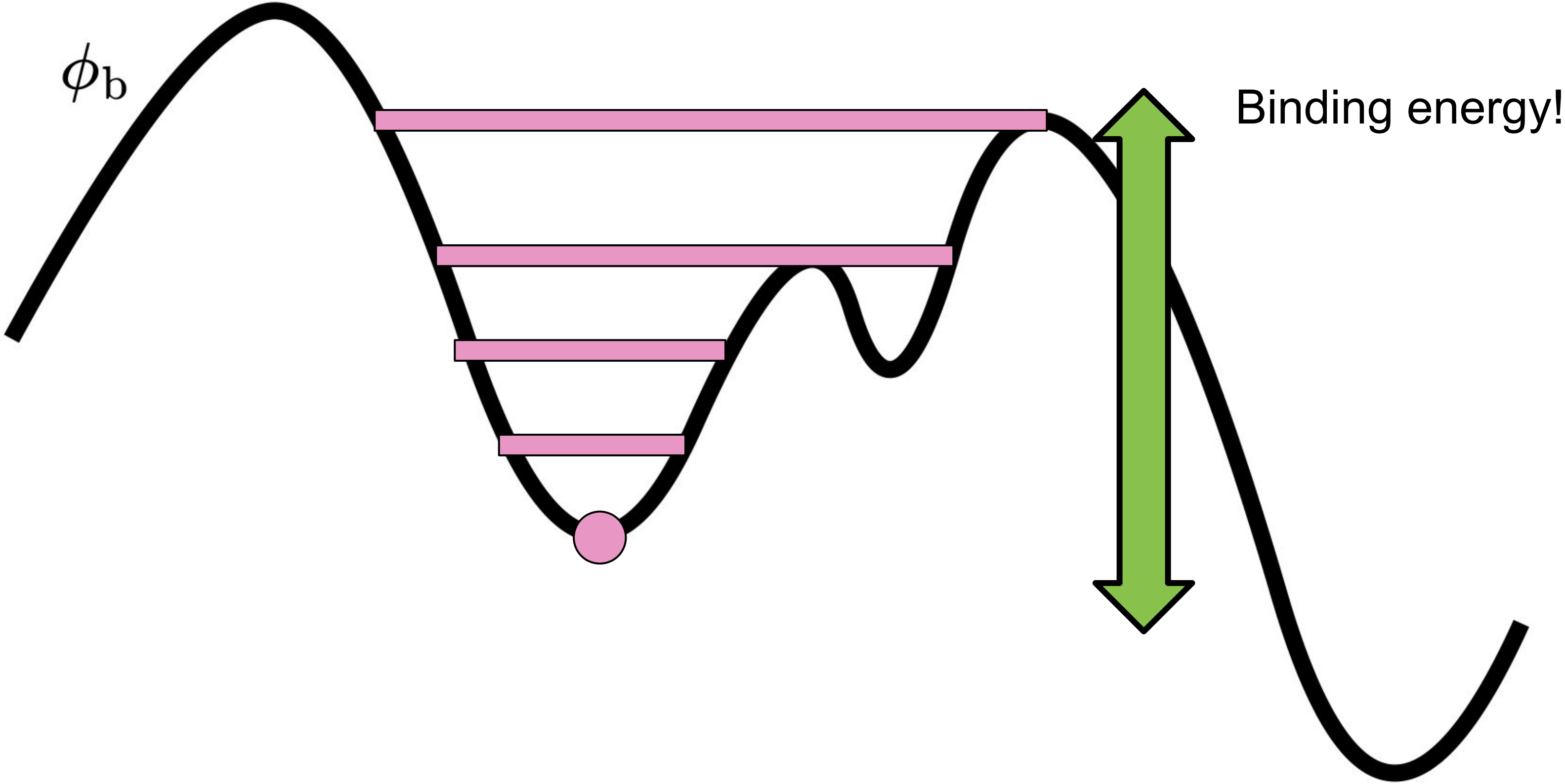
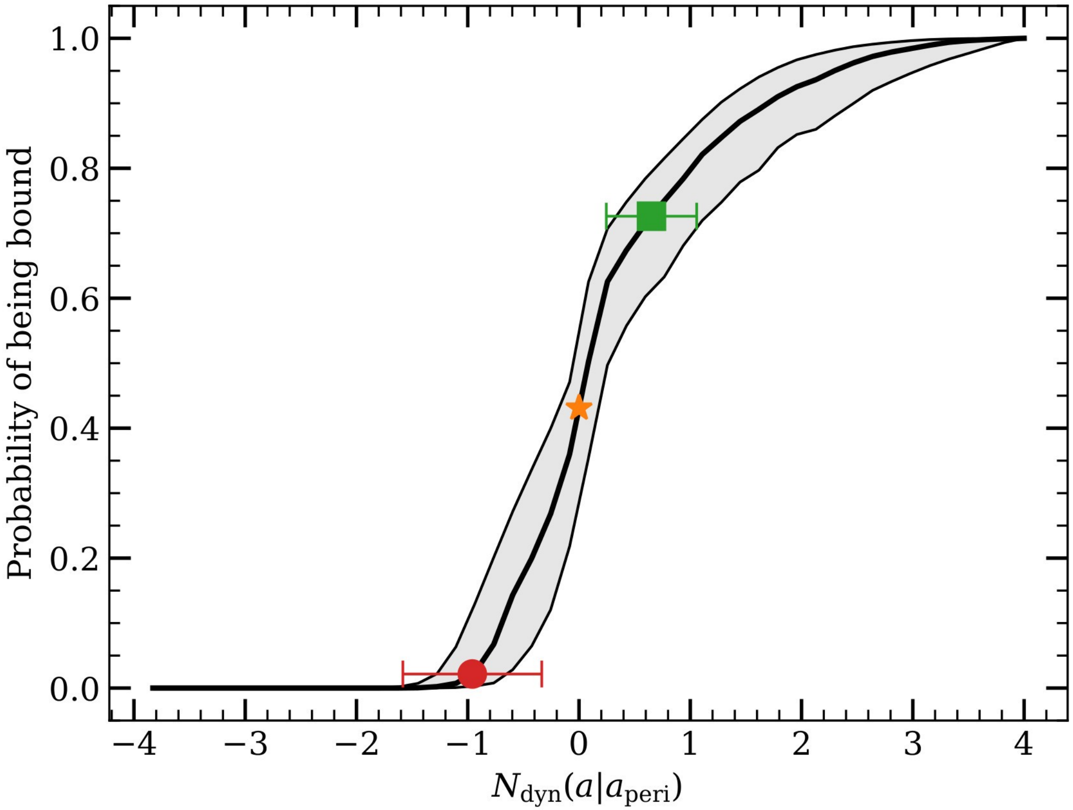


When do you bind?



$$N_{\rm dyn}(a|a_{\rm peri}) = \frac{\sqrt{2}}{\pi}\int_{a_{\rm peri}}^{a} \frac{1}{a}\sqrt{\frac{\bar{\rho}}{\rho_{\rm c}}}\,{\rm d}a,$$

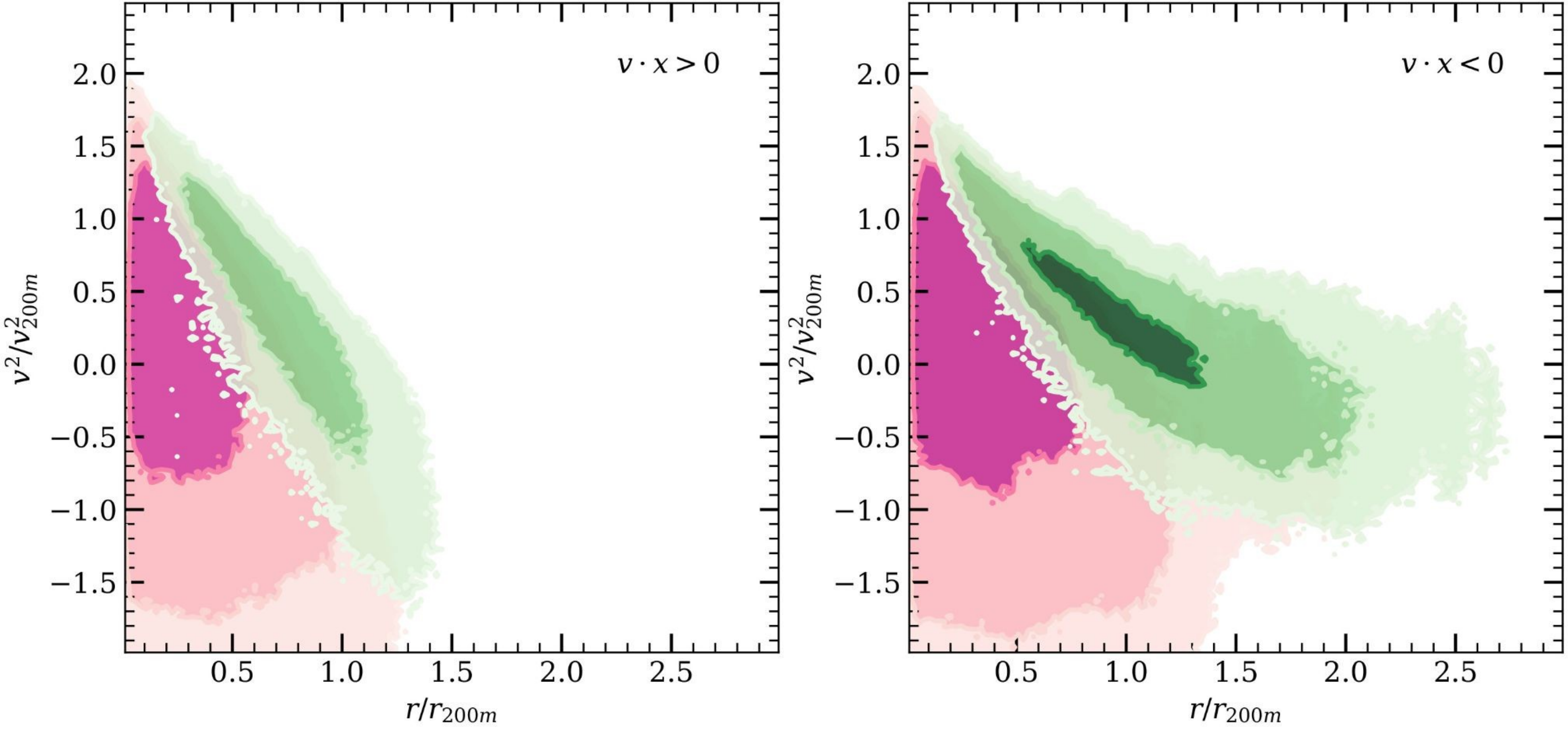
Jiang et al. 2016

Median binding time is the first pericentric passage.

After 1st **apocentre**, ~80% of particles are bound.

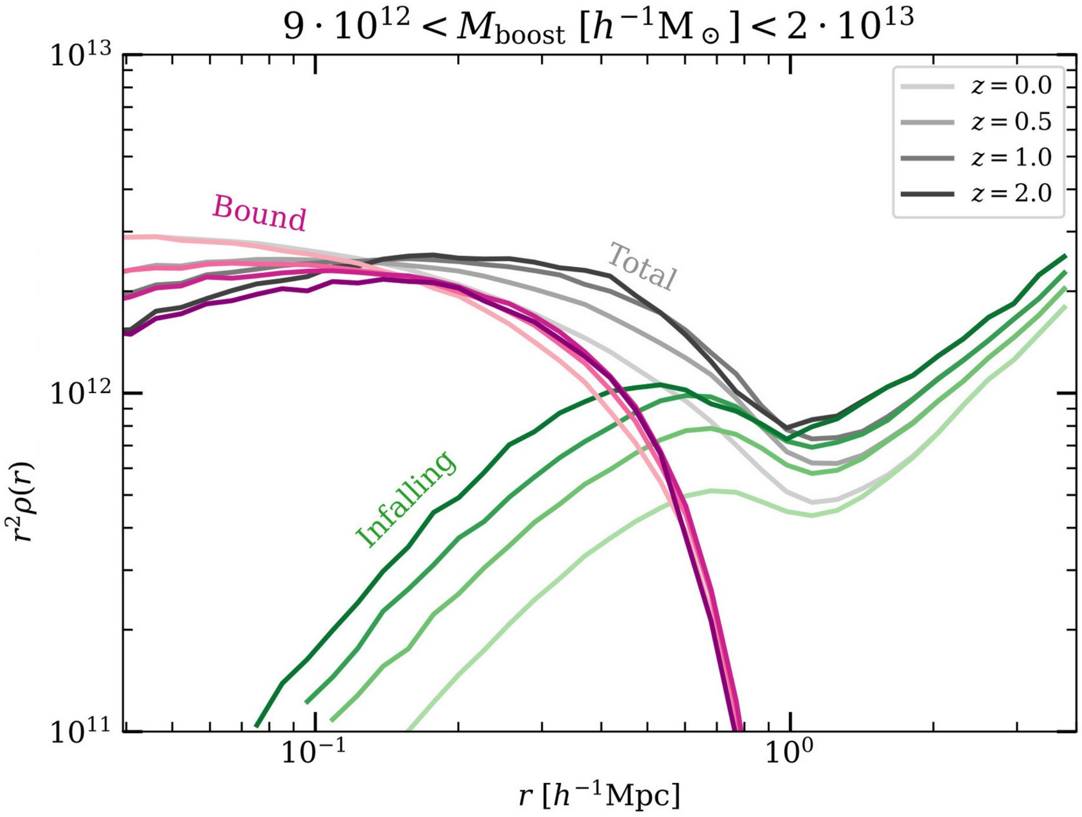
~ Orbit based mass definitions

Where do you bind?

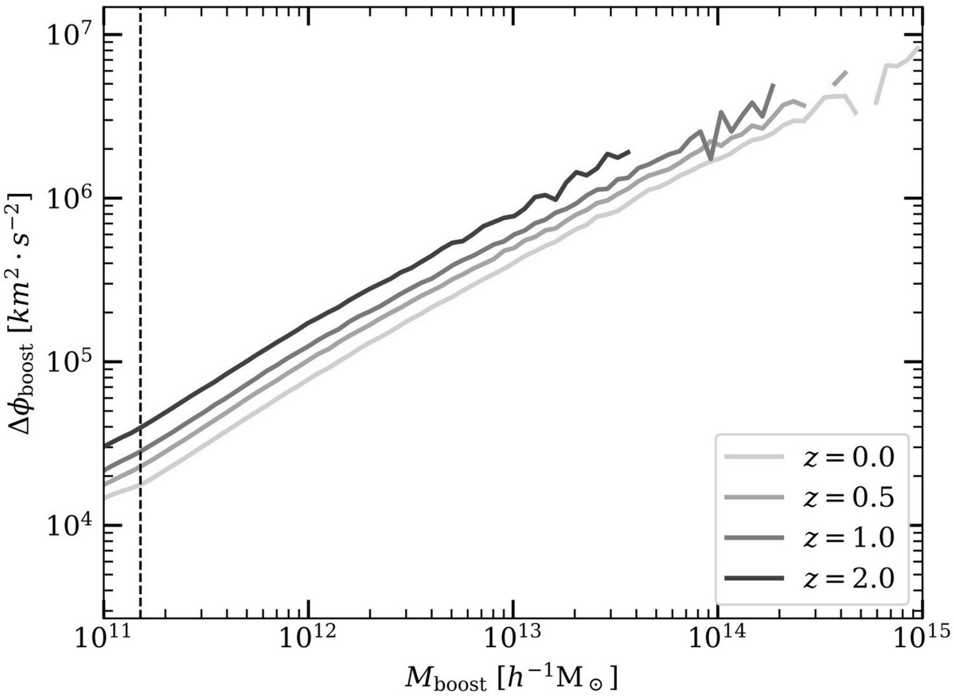


~ K-r Mass definition (Garcia et al. 2023, Salazar et al. 2024)

Profile evolution



Tight scaling relation



Tight relation

$$M_{\rm boost} \Leftrightarrow \Delta\phi_{\rm boost}$$

More unbound material surrounds haloes at **higher redshift, deepening the potential.**

Possible implications for known scaling relations.

Time scaling

Quasi-Linear

Single snapshot