How to get virialised haloes? Add STRAWBERRY!

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Haloes in brief

In theory, haloes are:

> Gravitationally bound

> Collapsed peaks in the initial density fields

Why are they relevant?

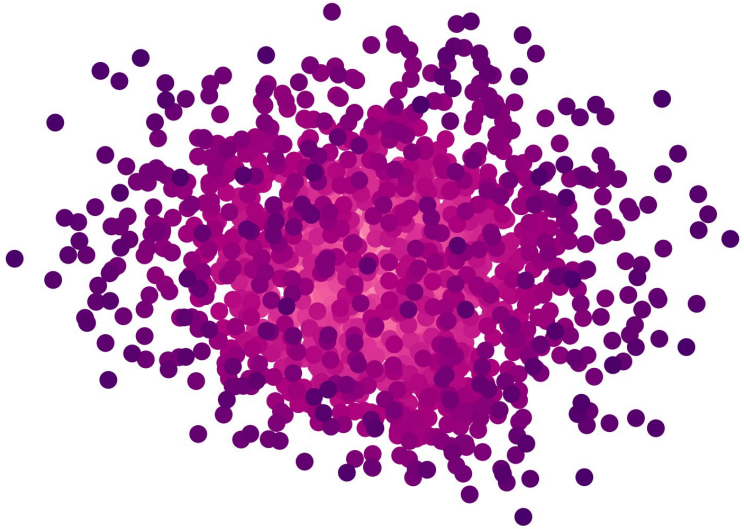
> Halo Mass Function

> Galaxy-Halo connection

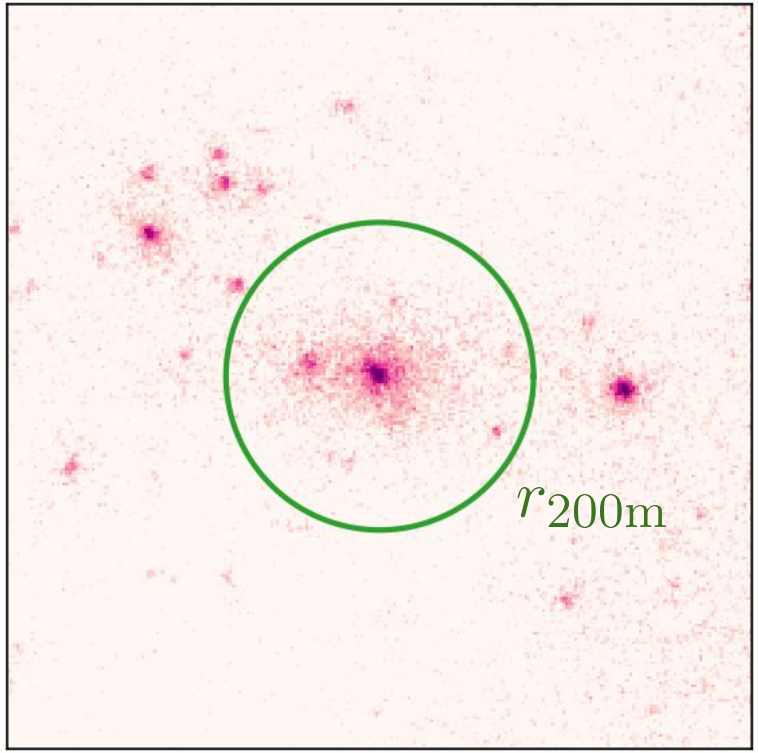
> Halo Model for non-linear P(k)

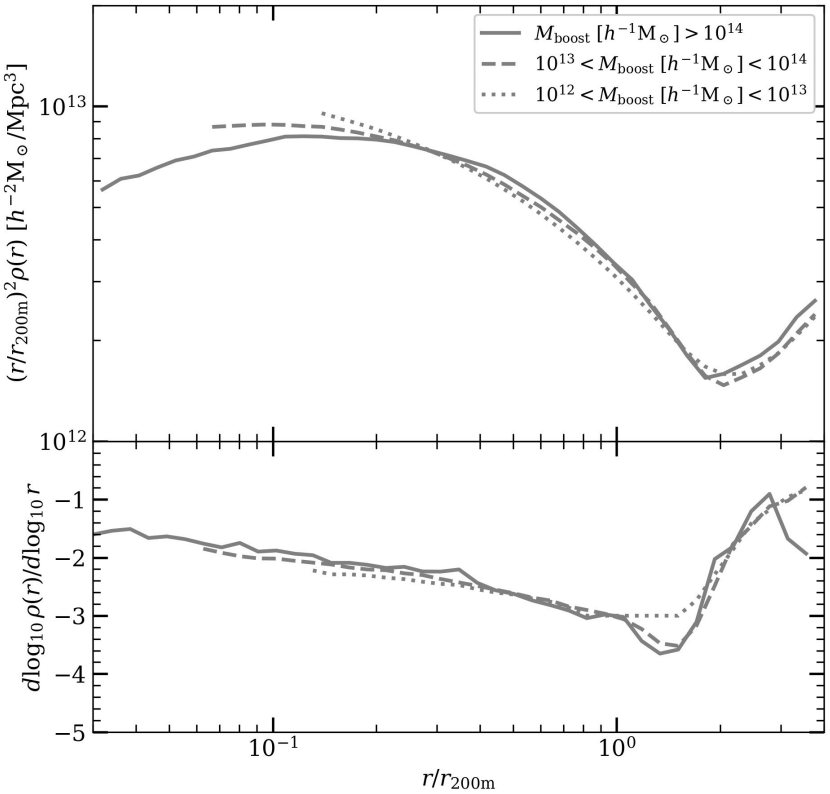
> Mass modeling / Scaling relations

Detailed studies require **simulations**

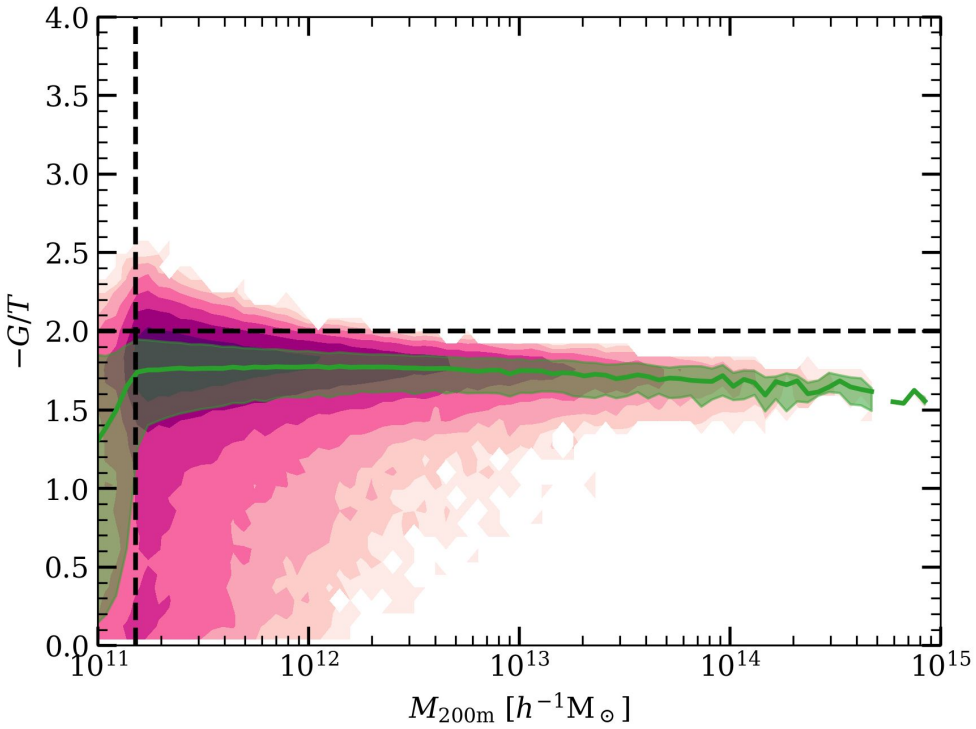


Haloes in simulations: Weird and Wonderful





But a bit broken too



Even with classical binding checks

The particle distributions are **NOT virialised!**

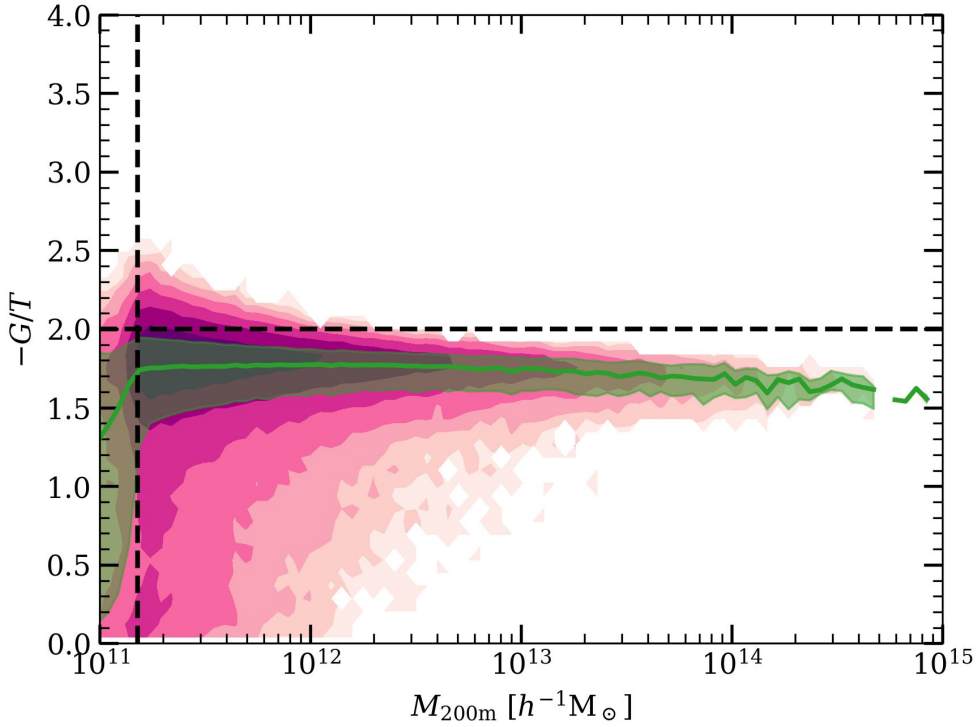
For virialised systems:

$$-G/T \sim 2$$

The discrepancy attributed to “External Pressure”

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

Sounds like a Selection Issue



The “External Pressure” is not a pressure at all.

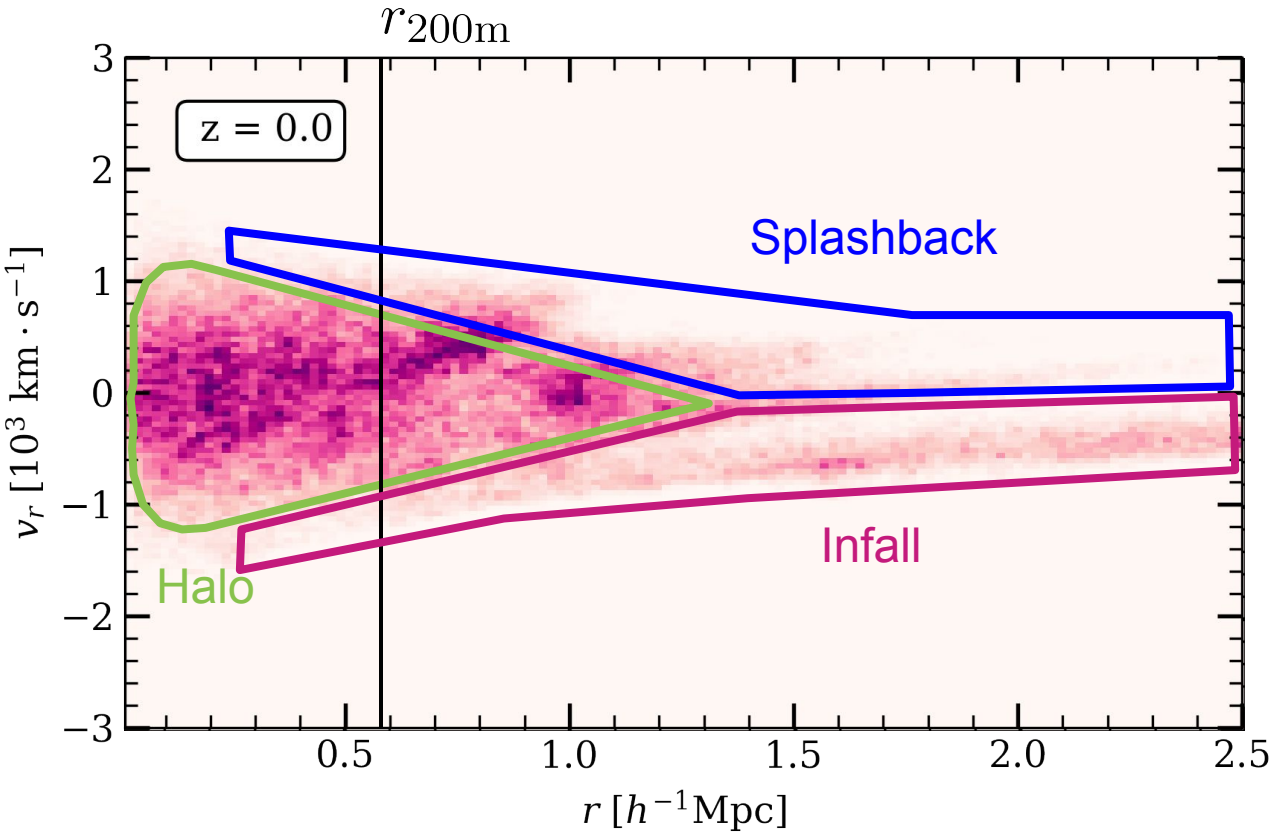
Mismatch comes from two places:

Removing bound particles

Adding unbound particles

Shaw et al. 2006,
Poole et al. 2006,
Davis et al. 2011

Haloes in radial phase space



But what about binding checks?

Most halo finders first select particles, then apply a binding check.

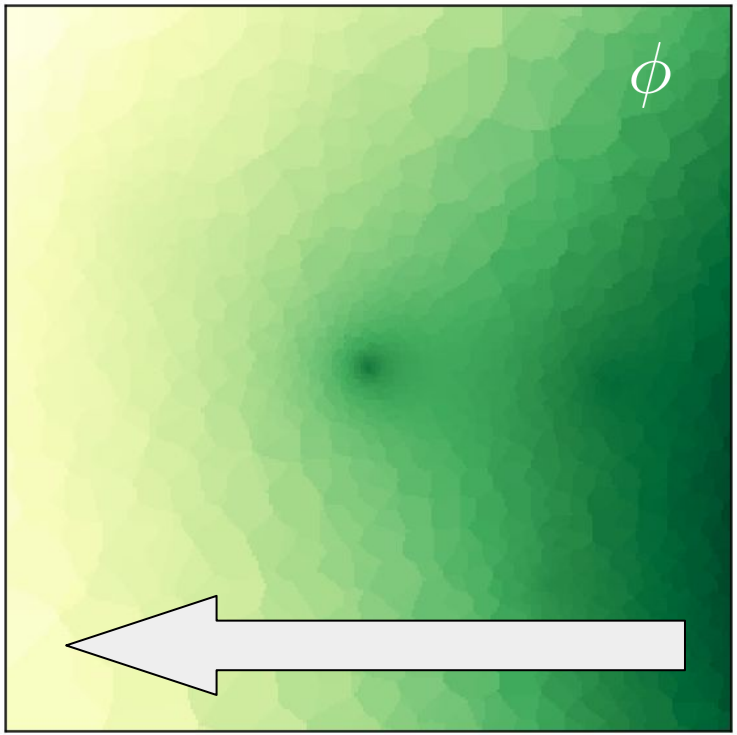
Most checks:

> Neglect large scale contributions

> Don’t check for virialisation

> Are missing particles to start out

Why not use the potential? ϕ



Large scale gradients!

Cleaning the Gradients

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

Absolute value of the potential

Uniform acceleration

No influence (in GR)

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

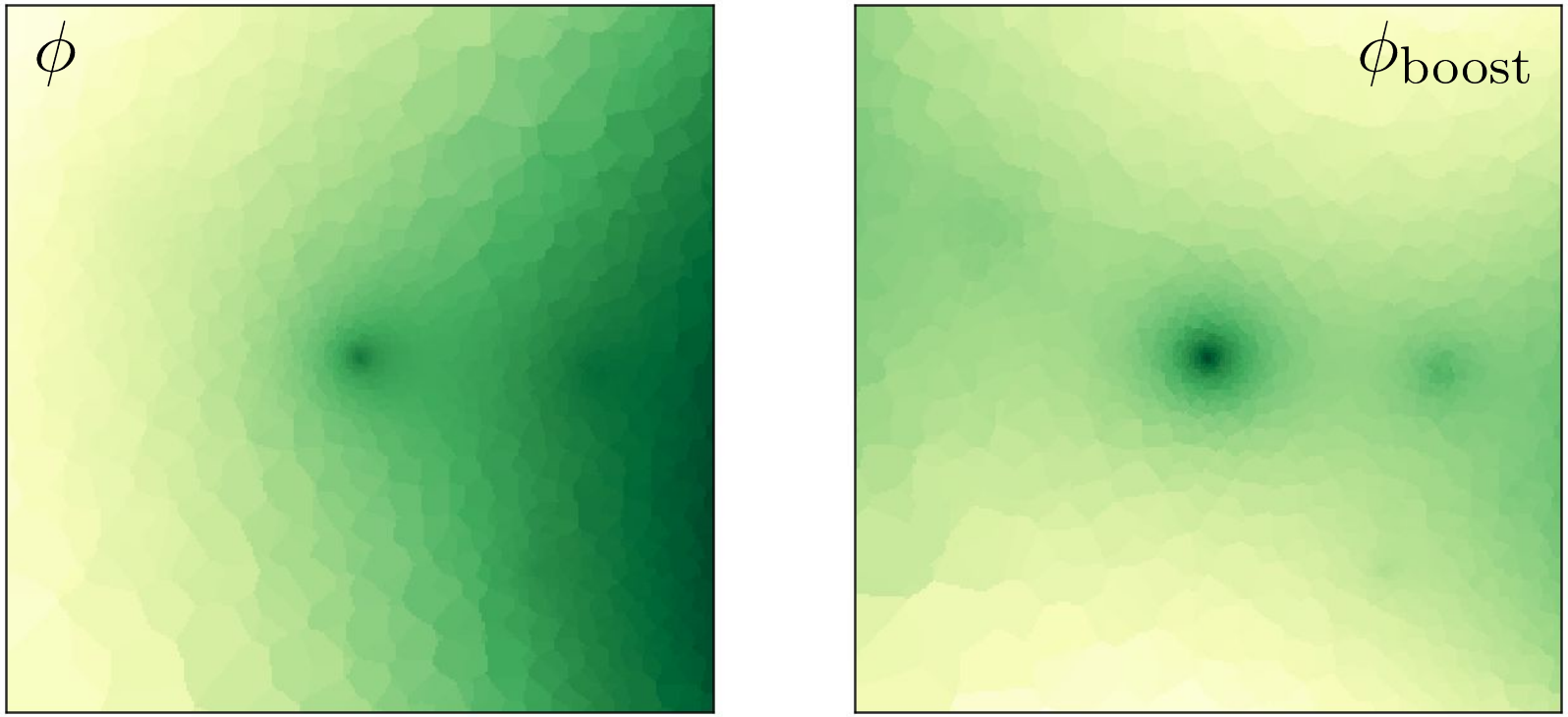
$$\phi_{\mathrm{boost}} = \phi_{\mathrm{self}} + \phi_{\mathrm{ext}} - (\mathbf{x} - \mathbf{x}_{\mathrm{h}}) \cdot \nabla \phi_{\mathrm{ext}}$$

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

Internal dynamics are completely equivalent!

(Stücker et al. 2021)

Bang! And the gradient is gone!



Goal: Turn this into a ~~‘halo finder’~~ binding check

STRAWBERRY

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

To find a halo

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

Advantages:

> Physically motivated binding check

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

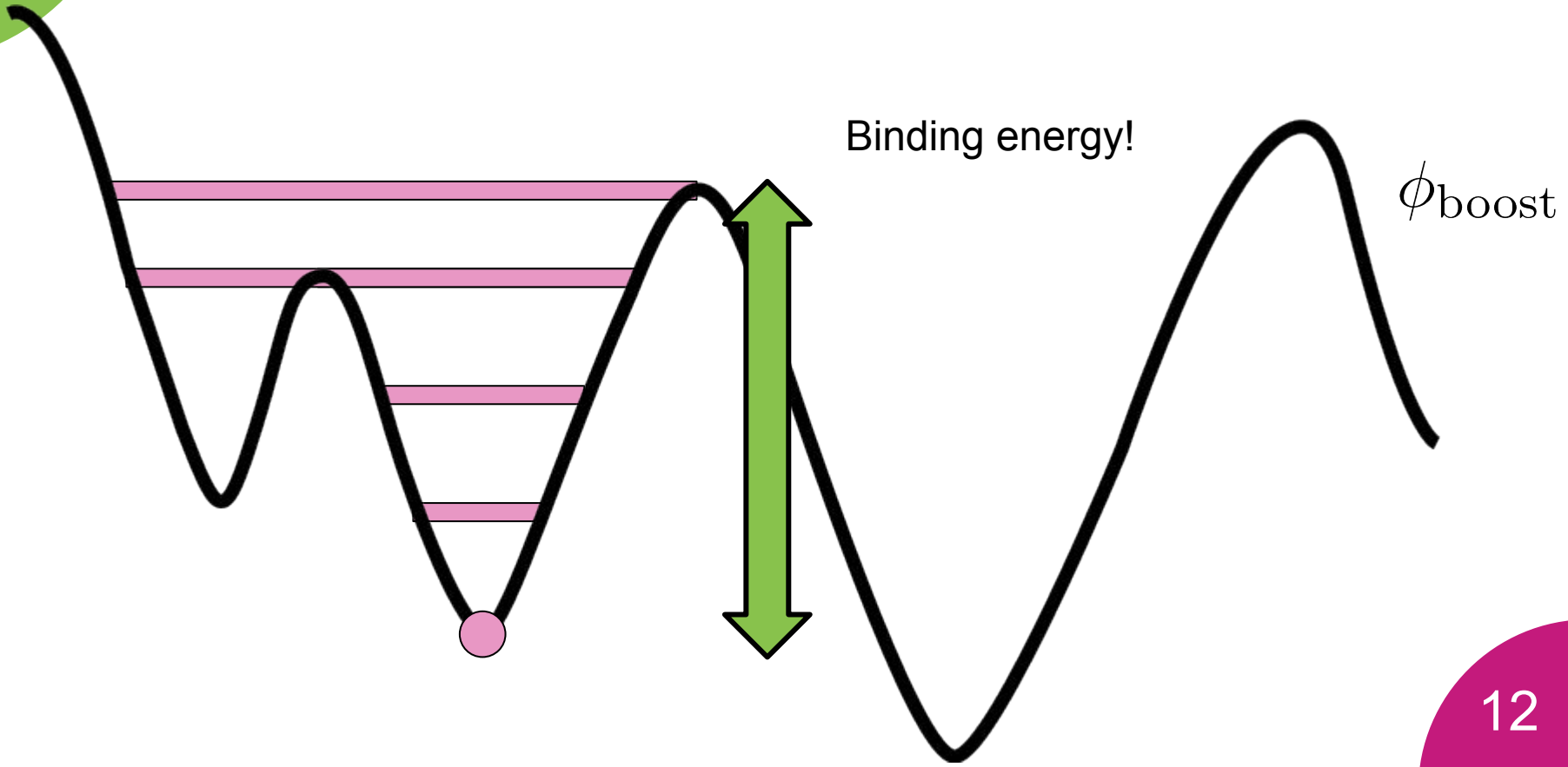
Disadvantages:

> Internal-External split -> Ill defined

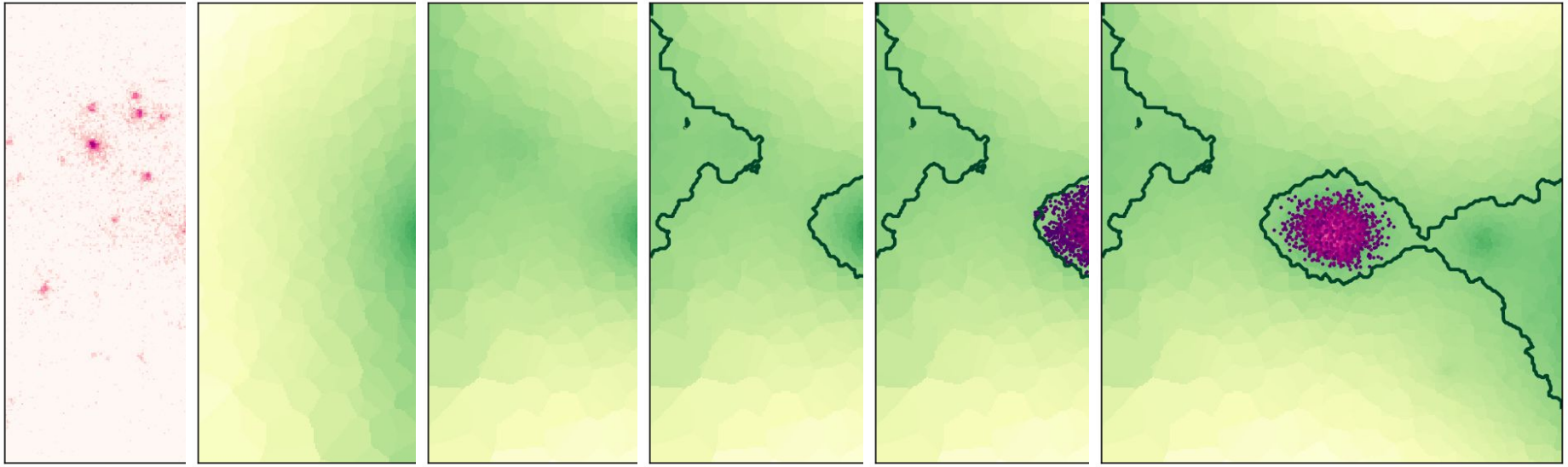
> Local quantity -> Need an inital seed to start

Need to rely on a **seed catalogue**

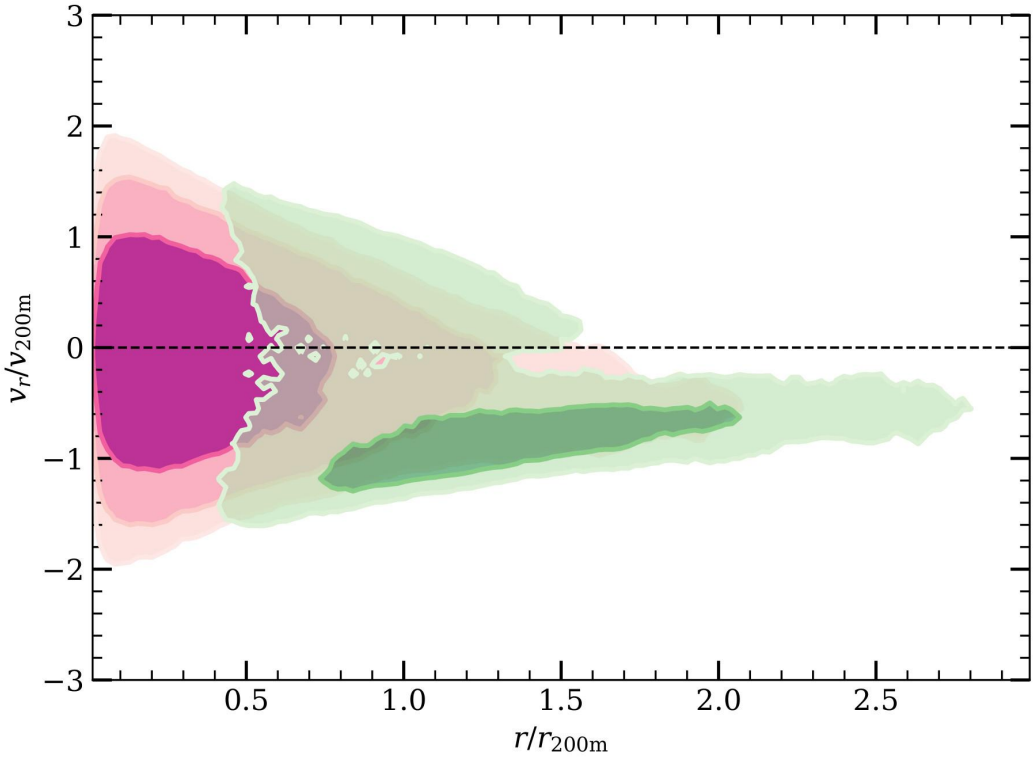
Introducing Strawberry



Visualising 1 halo



(Almost) Perfect Preening

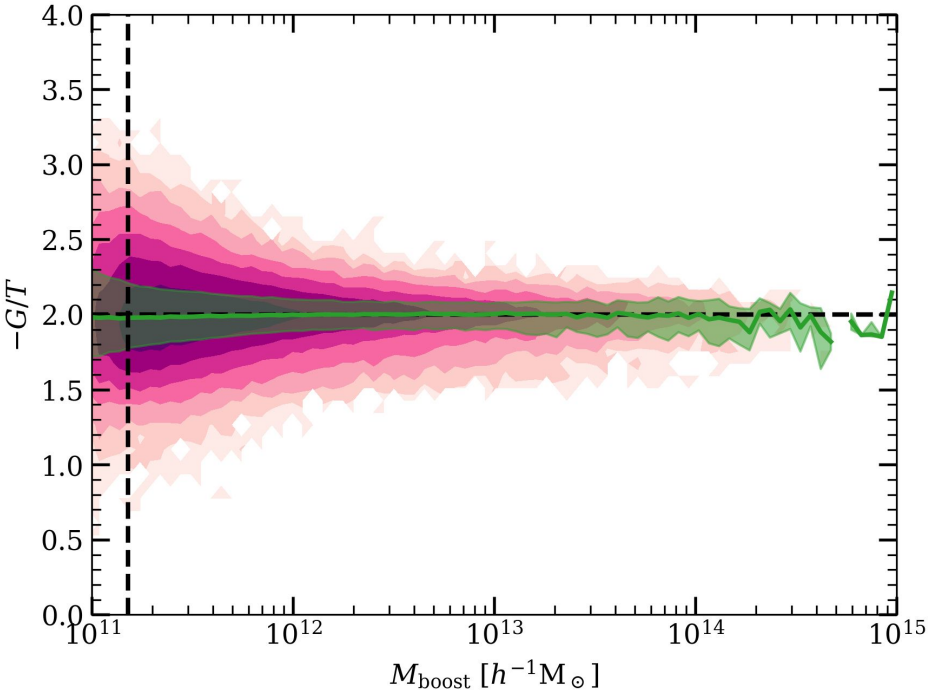


Selection using the potential:

Leaves us with **bound** population.

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

Boosted Haloes are Virialised!



On average, boosted haloes **do not need** external pressure

They also verify virial theorem to second order.

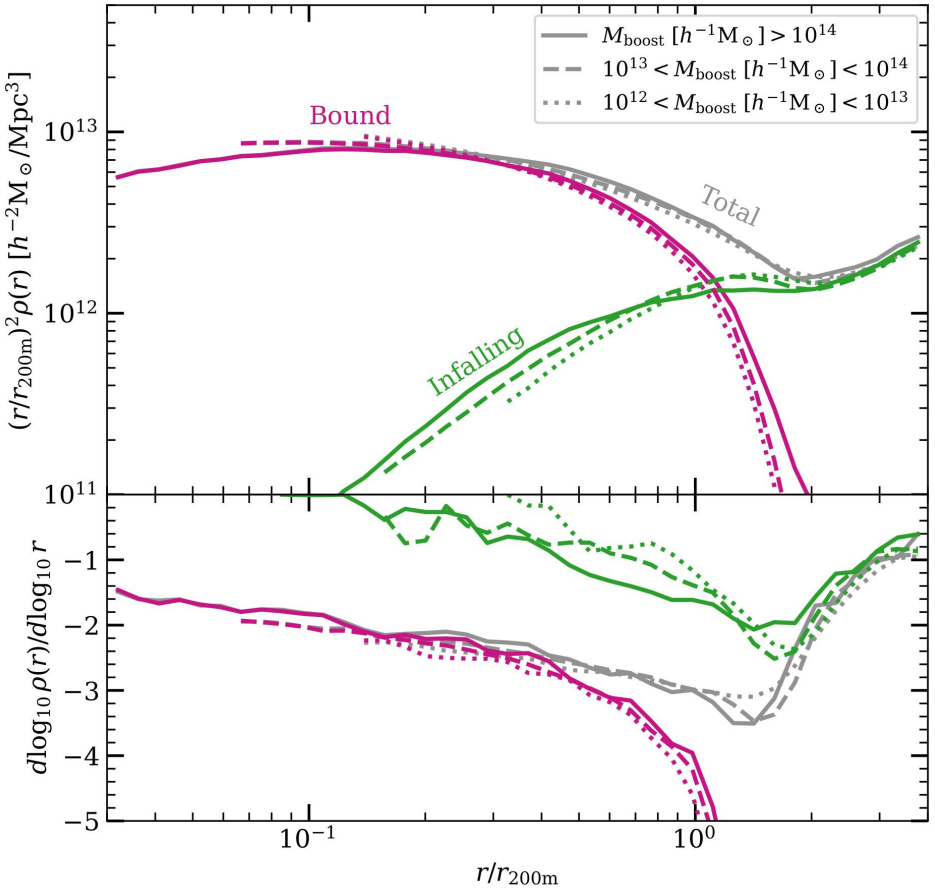
Bound particle distributions are **stable ellipsoids**!

Finally, an edge

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

Consistent with:

Diemer et al. 2022
Garcia et al. 2023
Salazar et al. 2024



Summary

The boosted potential framework provides an **ideal 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!