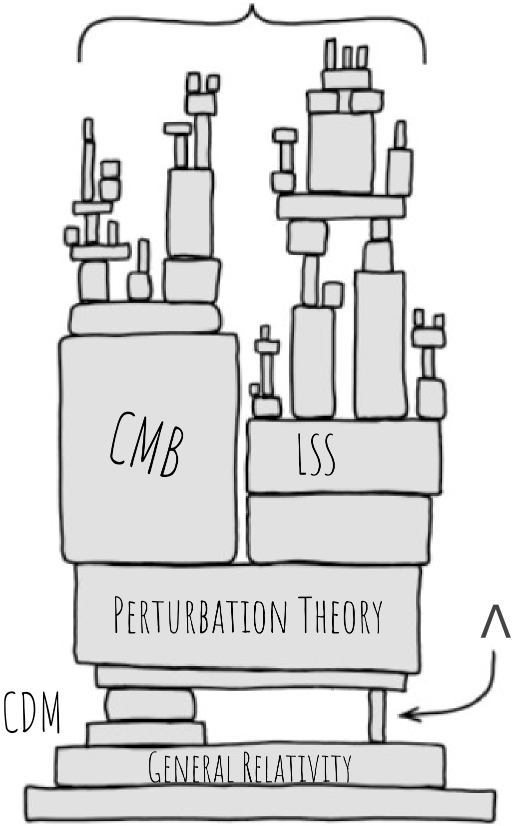
STRAWBERRY

Binding particles to haloes using the full potential field

Tamara R. G. Richardson

Everything we've been talking about this week



This is only a simplified view of the current state of the field

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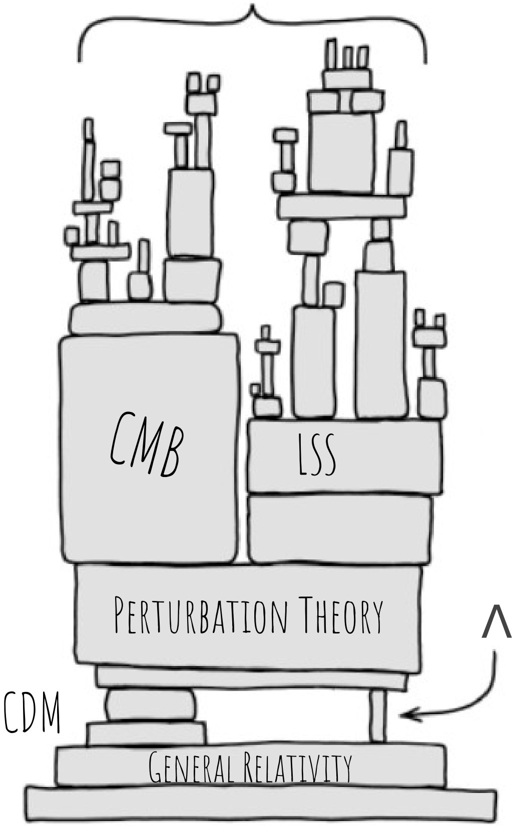

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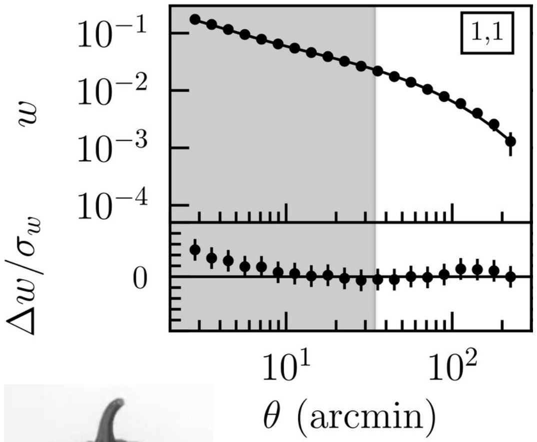
What we keep brushing away
Small Scales



DES Y3 Results (2021)

What's the issue?

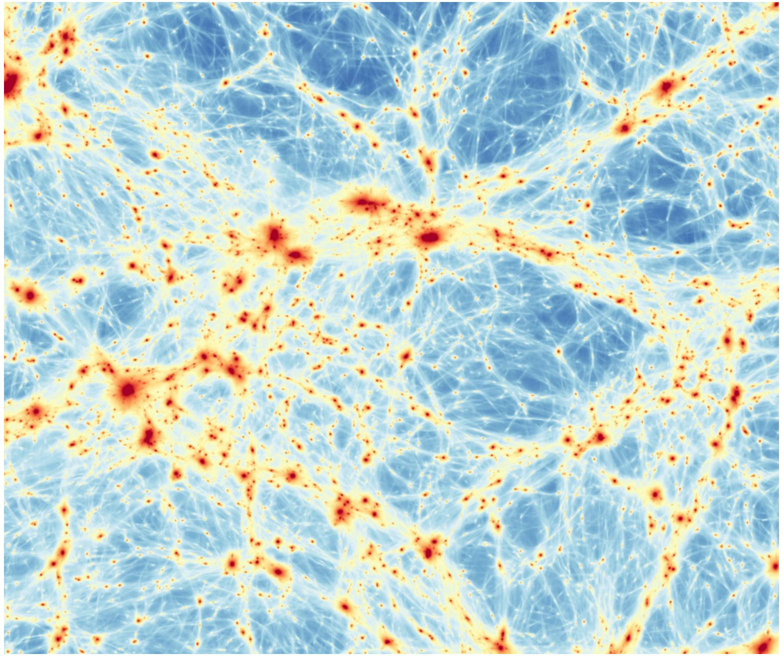
Perturbation theory breaks down

Highly non-linear

- Shell-crossing
- Virialisation

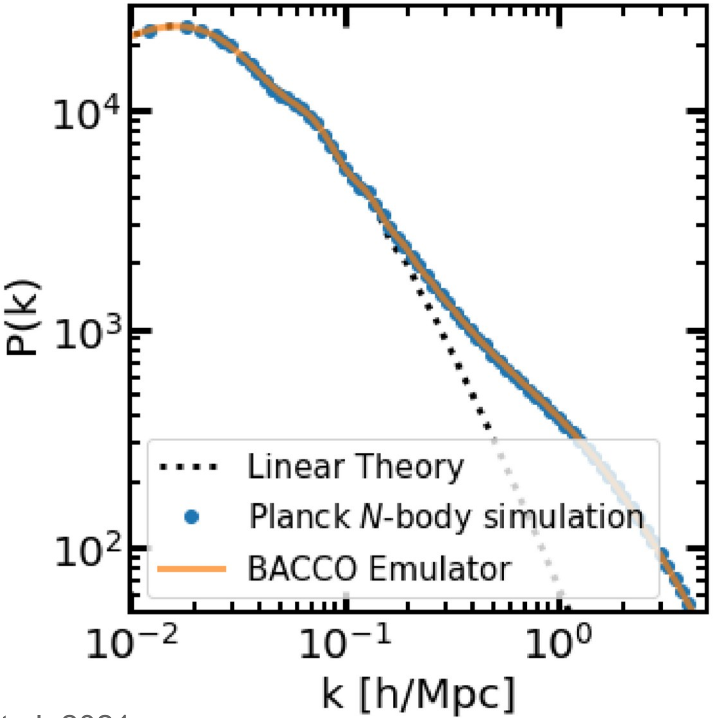
Too scary for this presentation

- Baryonic Feedback

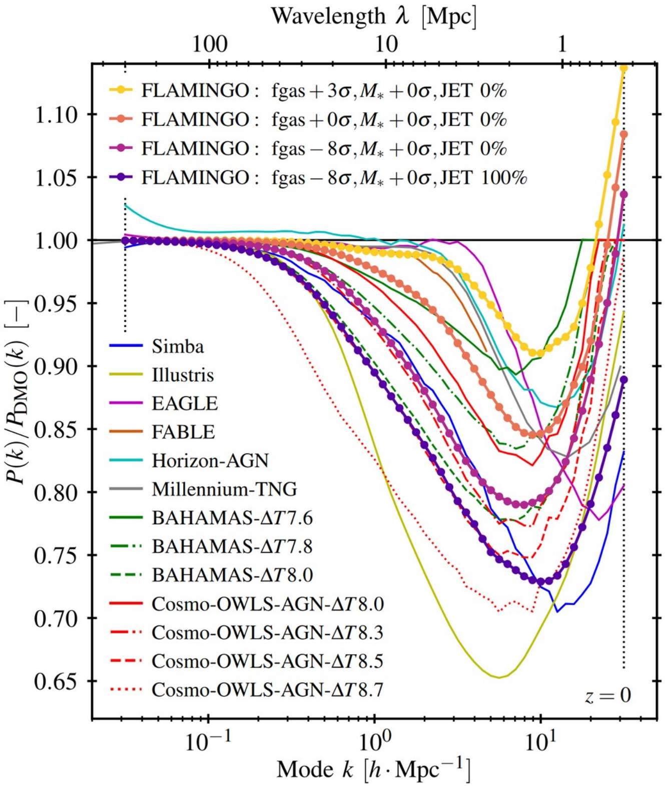


BACCO simulation project (Angulo et al. 2021)

What that looks like for P(k)



Angulo et al. 2021



Schaller et al. 2025

How can we reach small scales

Emulators

Benefits:
- Fast
- Proven method
- Ready for use

Downsides:
- Limited by training sample
- You make the climate crisis worse

Main hurdle:
- Numerical design
- CPU/GPU time

Modelling non-linearity

Benefits:
- You get to do physics

Downsides:
- Slower
- Needs additional steps

Main hurdle:
- Theory

Haloes in brief

In theory, haloes are:

> Overdense peaks

> Gravitationally bound

Why are they relevant?

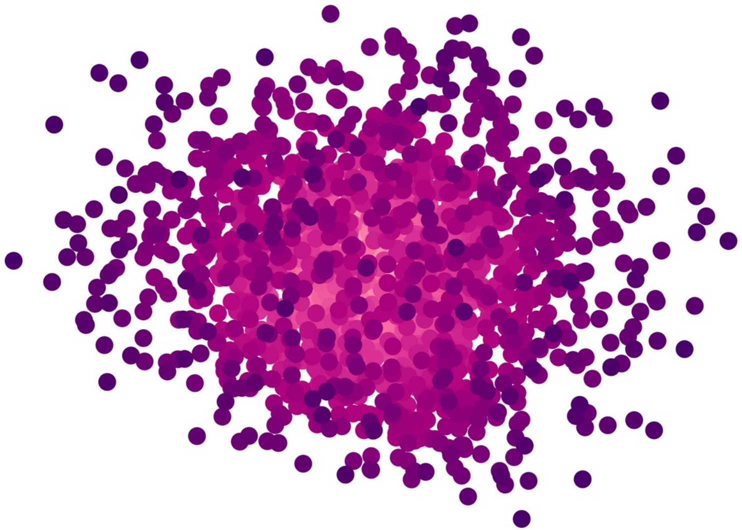
> Halo Mass Function

> Galaxy-Halo connection

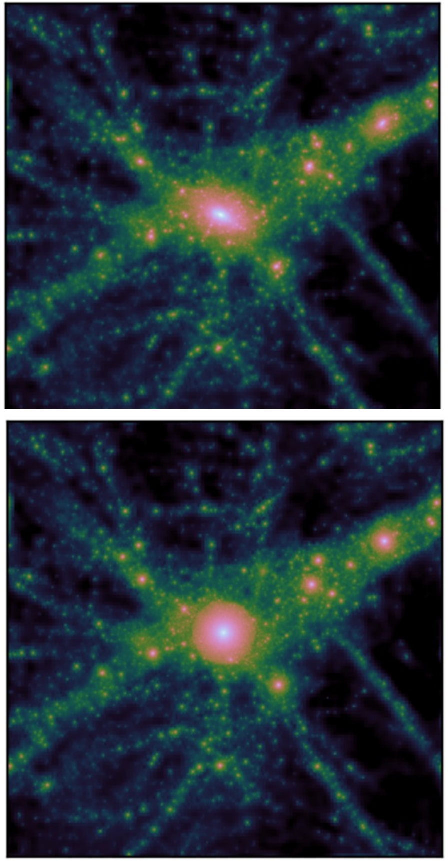
> Halo Model for non-linear P(k)

> Mass modeling / Scaling relations

Detailed studies require **simulations**



Example: The halo model



$$P_{\mathrm{nl}}(k) = P_{\mathrm{1h}}(k) + P_{\mathrm{2h}}(k)$$

$$P_{\mathrm{1h}}(k) = \int_0^\infty W^2(M,k)n(M)\mathrm{d}M$$

$$W(M,k) = \frac{1}{\rho_{\mathrm{m}}}\int_0^{r_{\mathrm{v}}} 4\pi r^2 \frac{\sin(kr)}{kr}\rho(M,r)\mathrm{d}r$$

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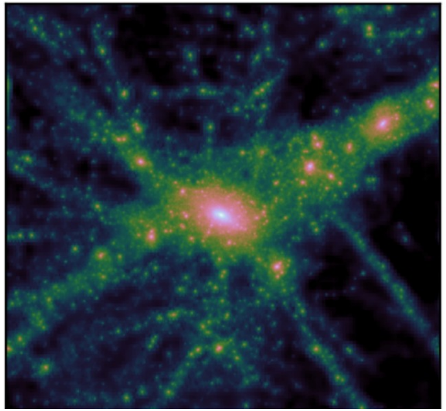

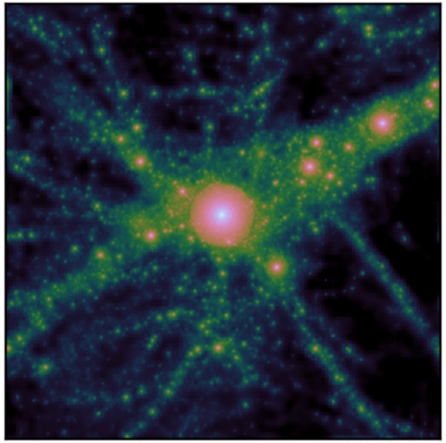

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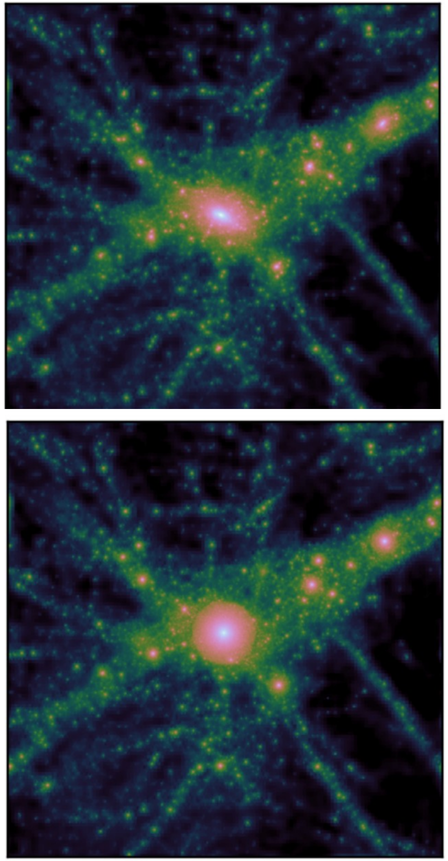
Not an attack on HMCode just an example

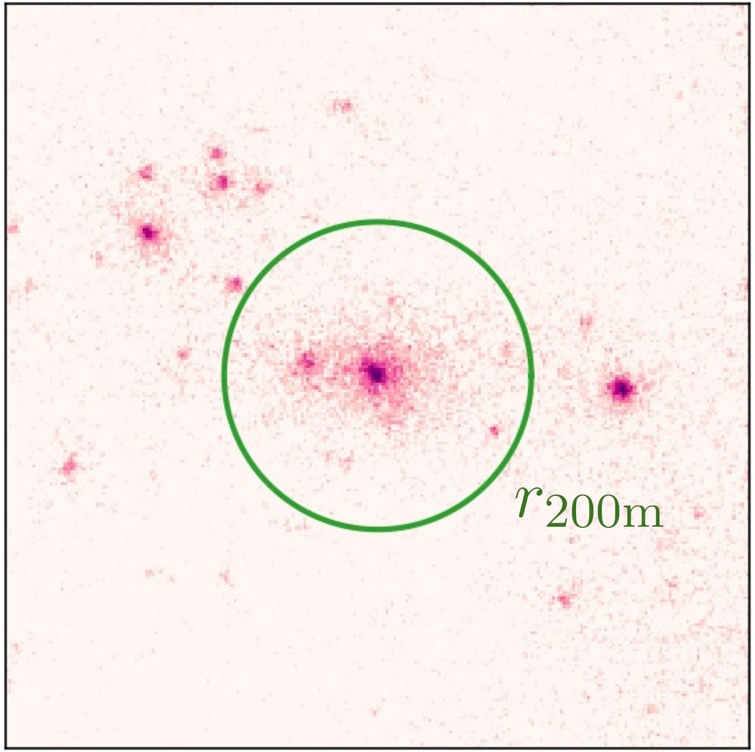


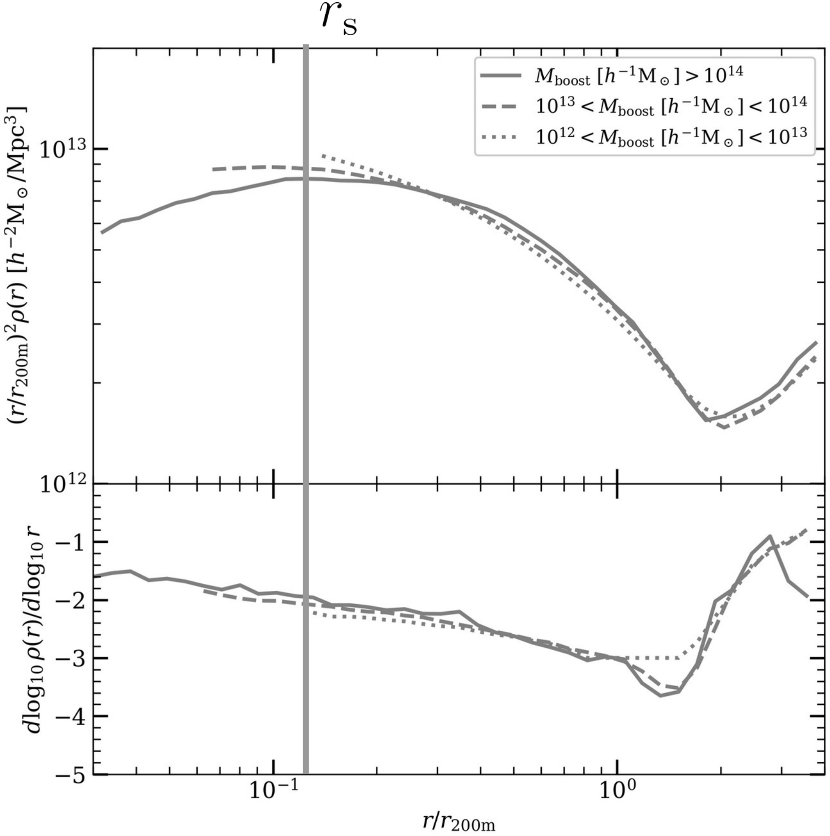
HMCode 2020 (Mead et al. 2020)

Halo model Requires:

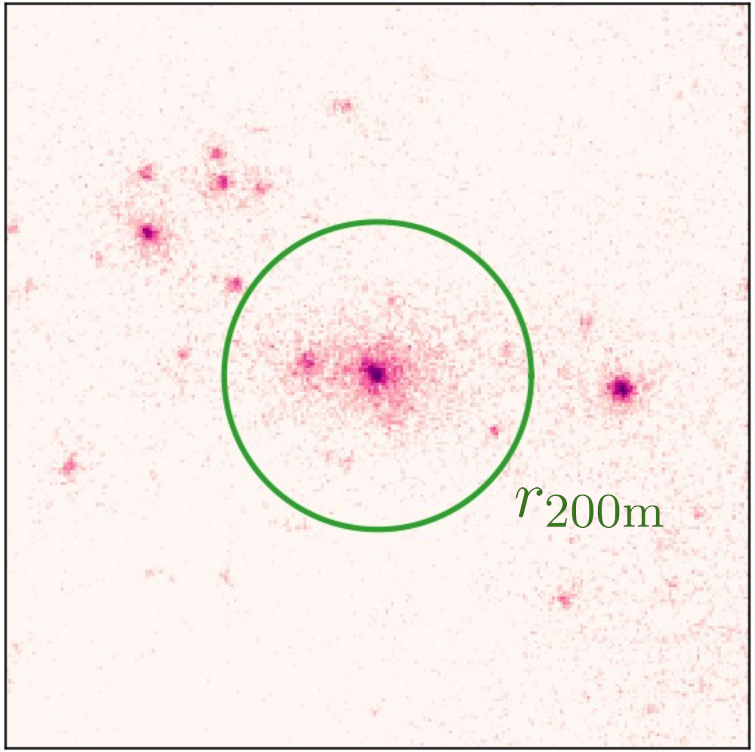
- Linear P(k) => CAMB
- Halo mass function => Sheth & Tormen (1999)
- Halo bias => Sheth & Tormen (1999)
- Halo profile => NFW (1997)
- c-M_{vir} relation => Duffy et al. (2008)

Haloes as two numbers





Detection of haloes



Usually, choose a boundary (SO)

$$r_{\Delta\mathrm{m}}$$

$$\langle \rho(< r_{\Delta\mathrm{m}}) \rangle = \Delta \rho_{\mathrm{m}}$$

or some numerical parameter (FoF)

$$b = 0.2$$

to define the edge of haloes.

Other density based methods are available

Beyond Density

In phase space and in energy space, haloes are more distinct from their environment.

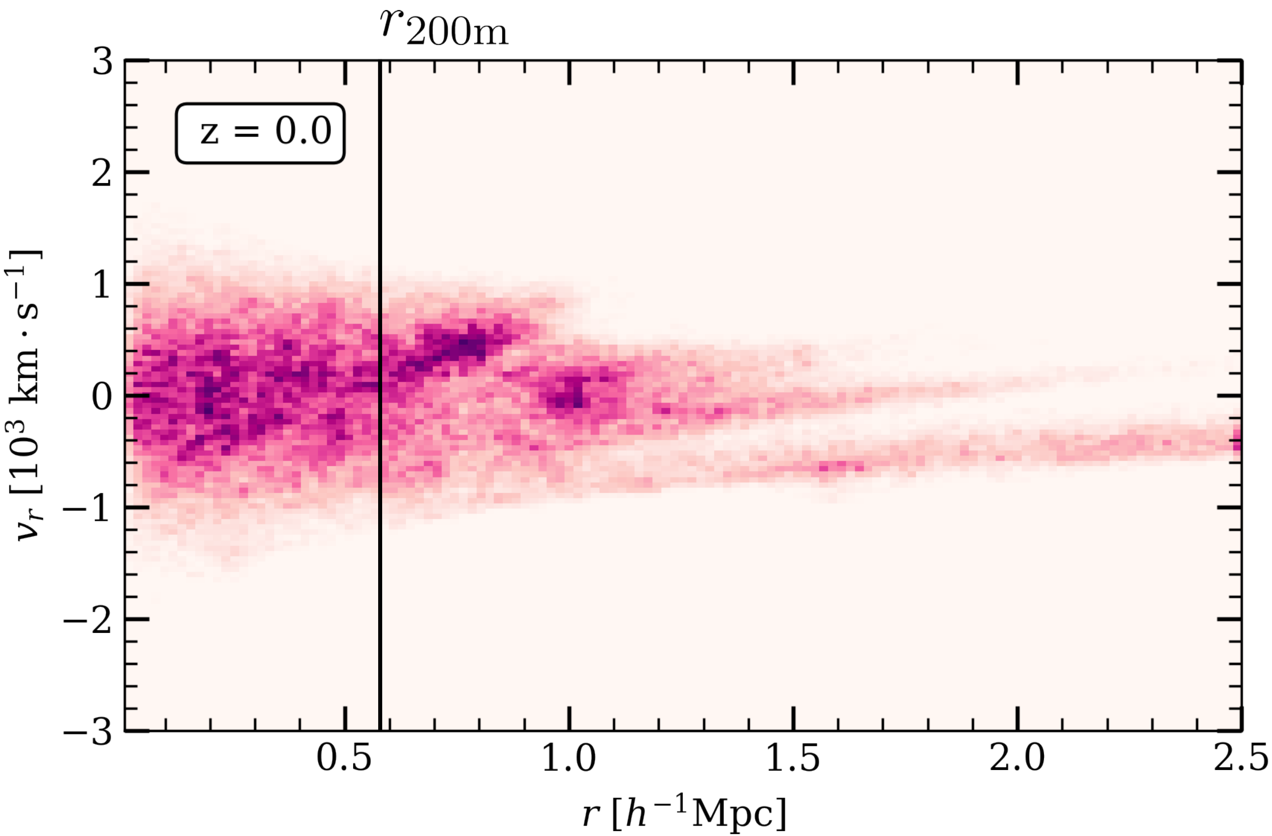
They can be extracted using these features

Halo ‘finders’ (characterisers) that do not use density to detect haloes

- ORIGAMI (Falck et al. 2012)
- SPARTA (Diemer 2017-2020)
- OASIS (García et al. 2023, Salazar et al. 2025, Shields et al. 2025)
- STRAWBERRY (Stücker et al. 2021, Richardson et al. 2025)

Other examples are available

Haloes in radial phase space



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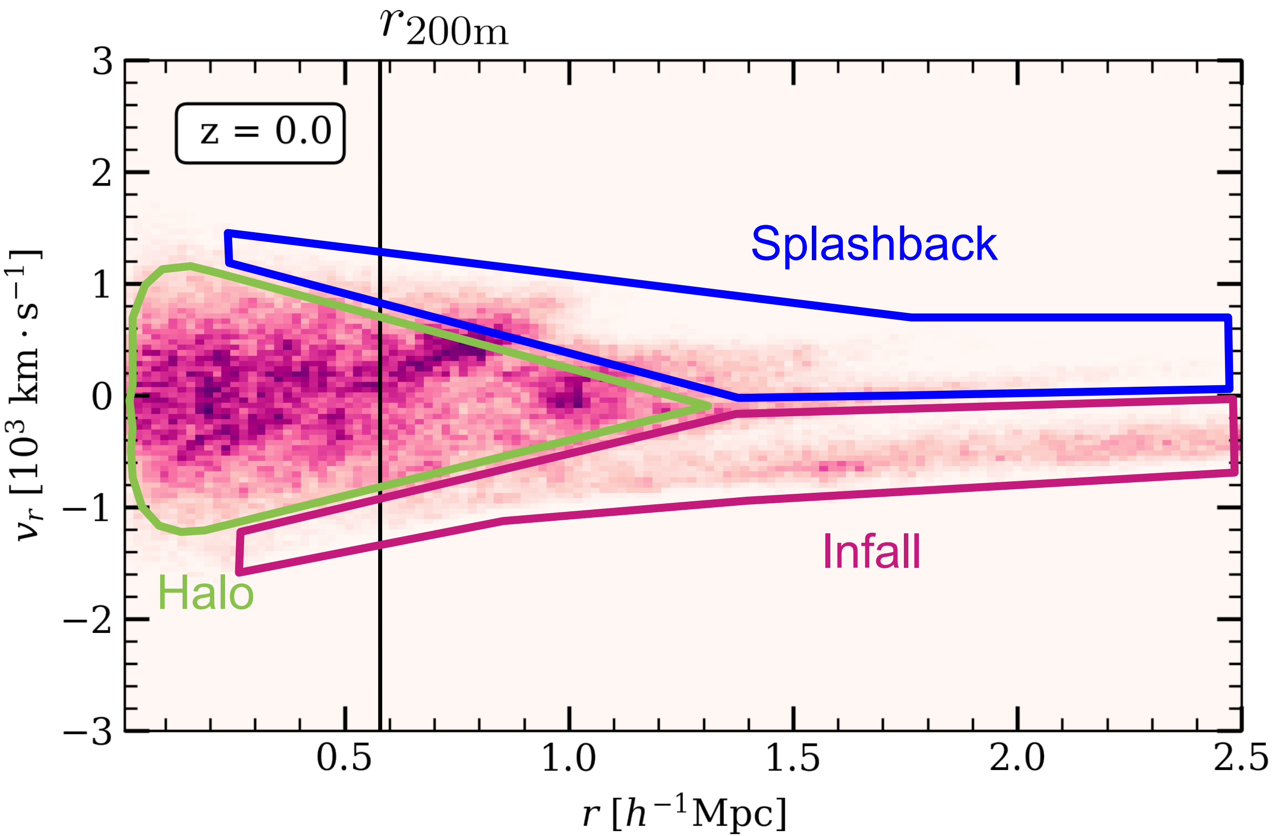
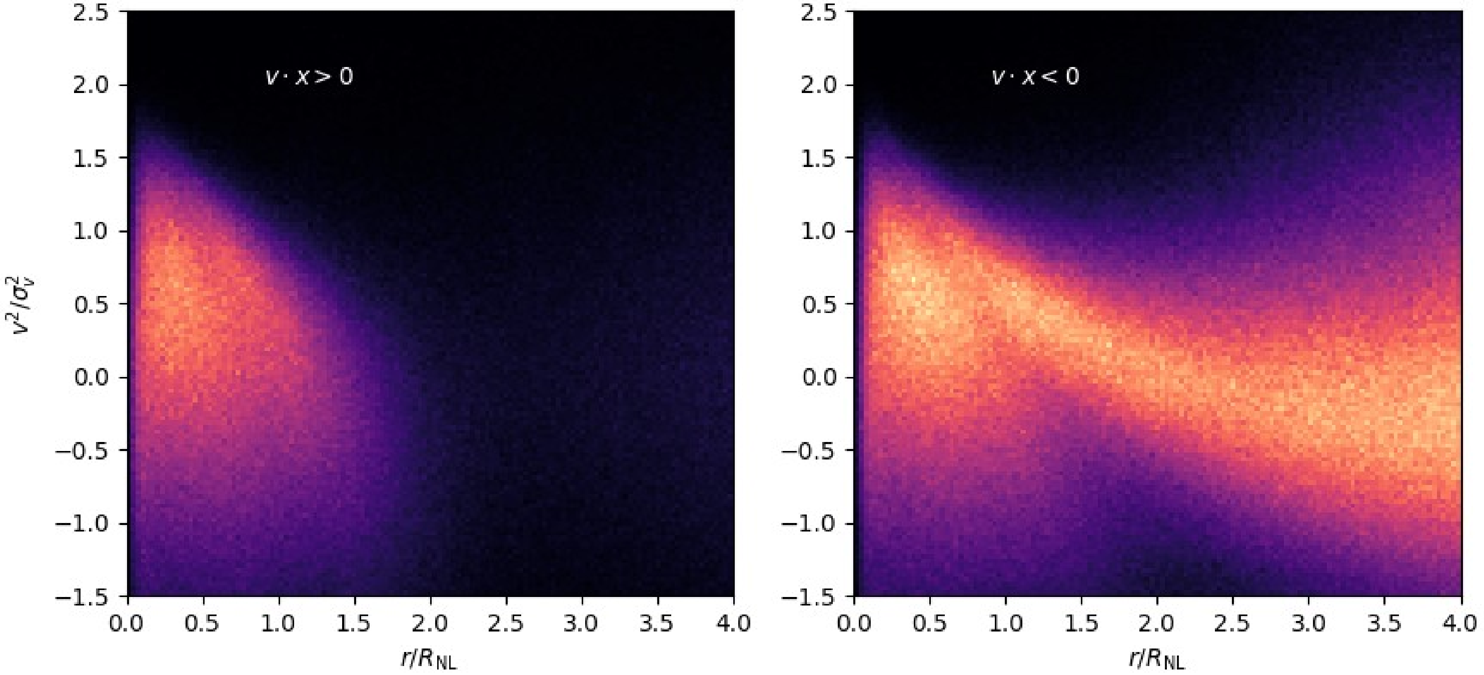
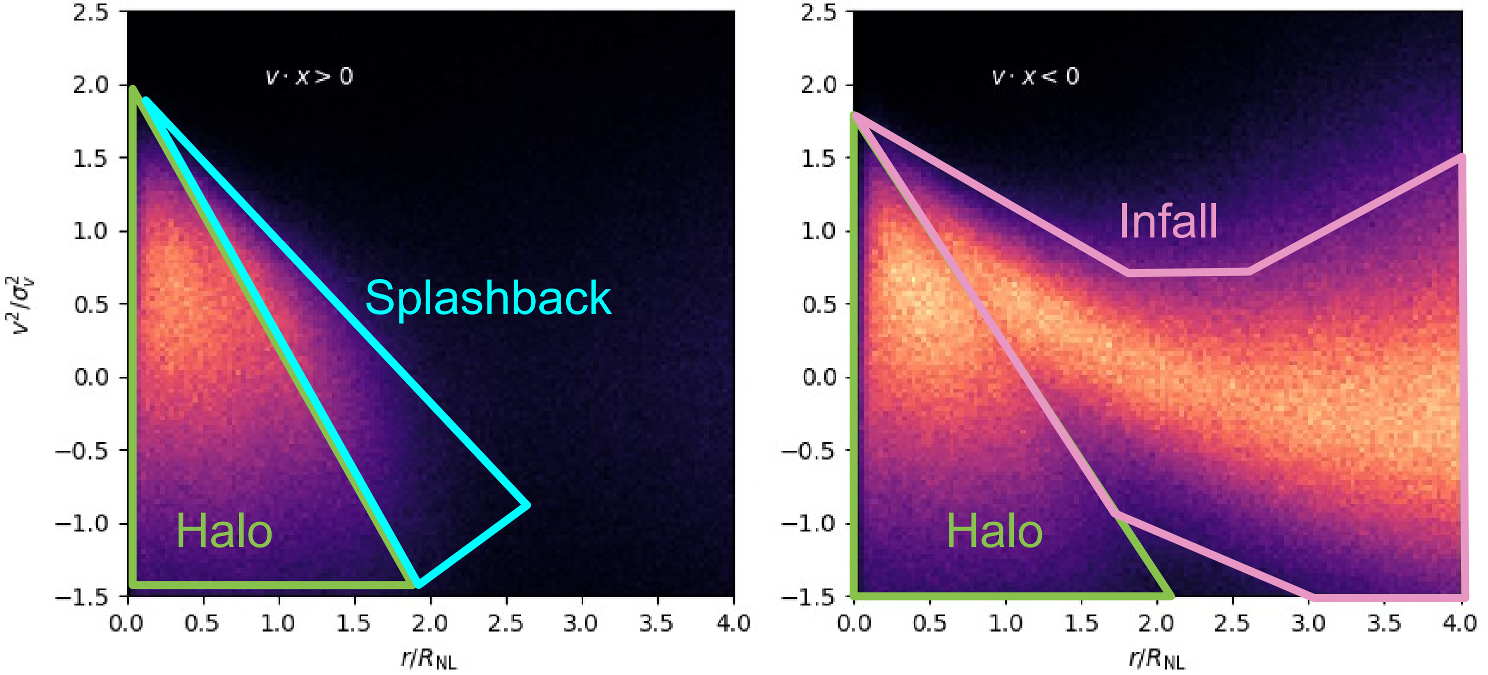


Haloes in Energy space



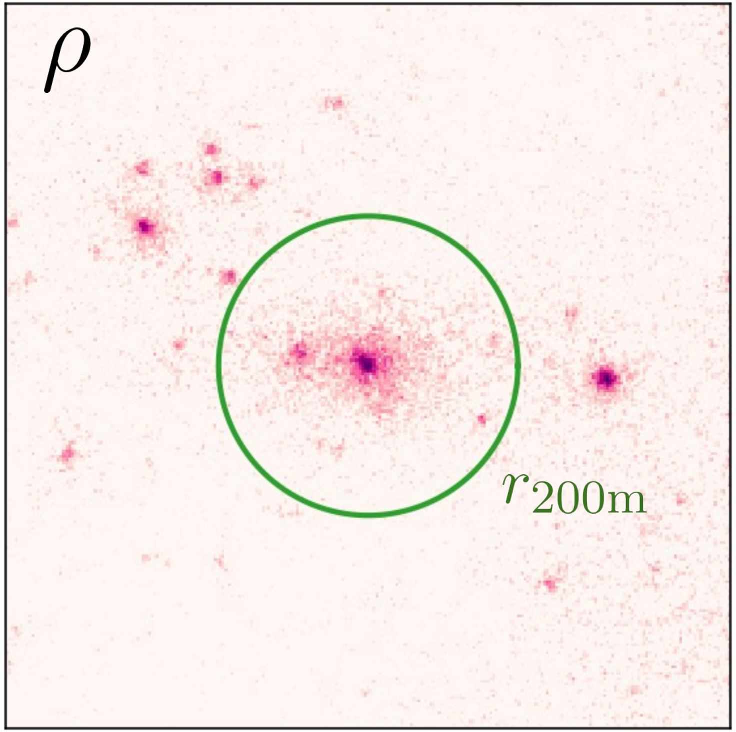
Example from a scale-free simulation

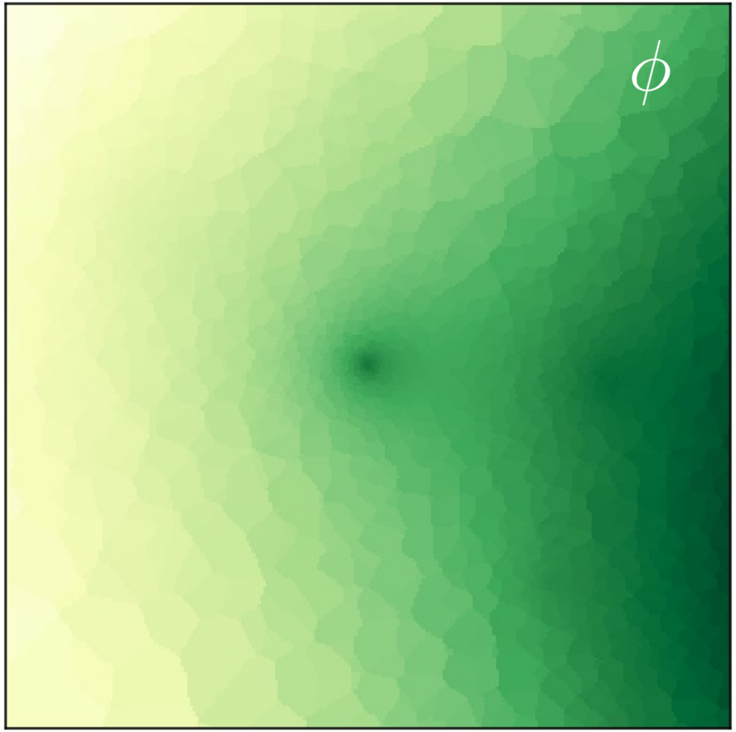
Haloes in Energy space



Example from a scale-free simulation

Lets use the potential??





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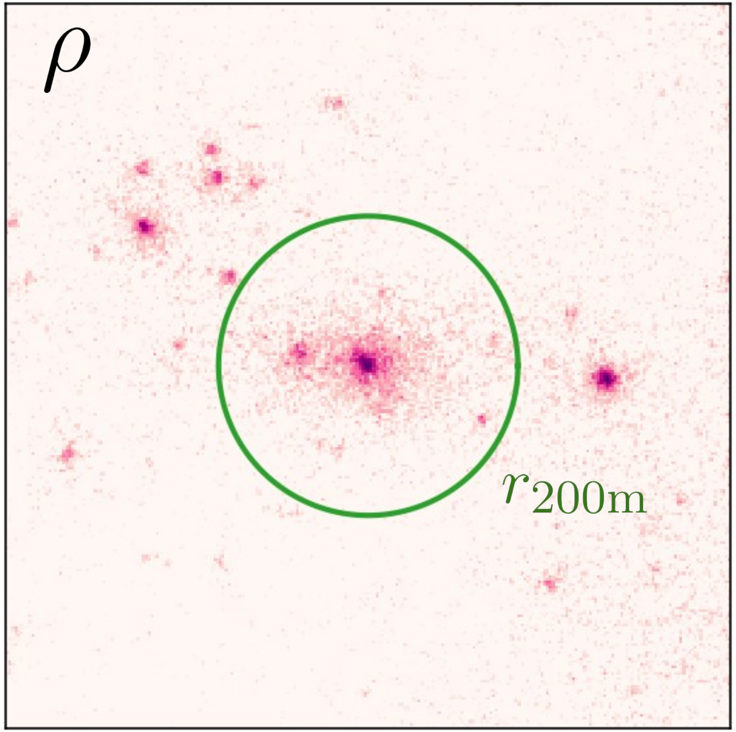

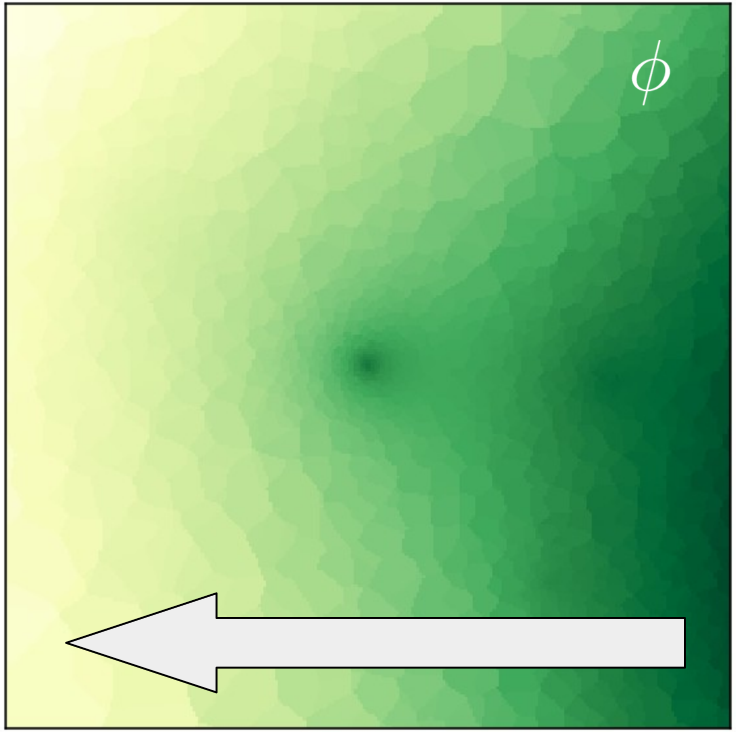

Large scale gradients!

Cleaning the Gradients

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

(Stücker et al. 2021)

Cleaning the Gradients

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

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

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Cleaning the Gradients

Absolute value of the potential

Uniform acceleration

No influence (in GR)

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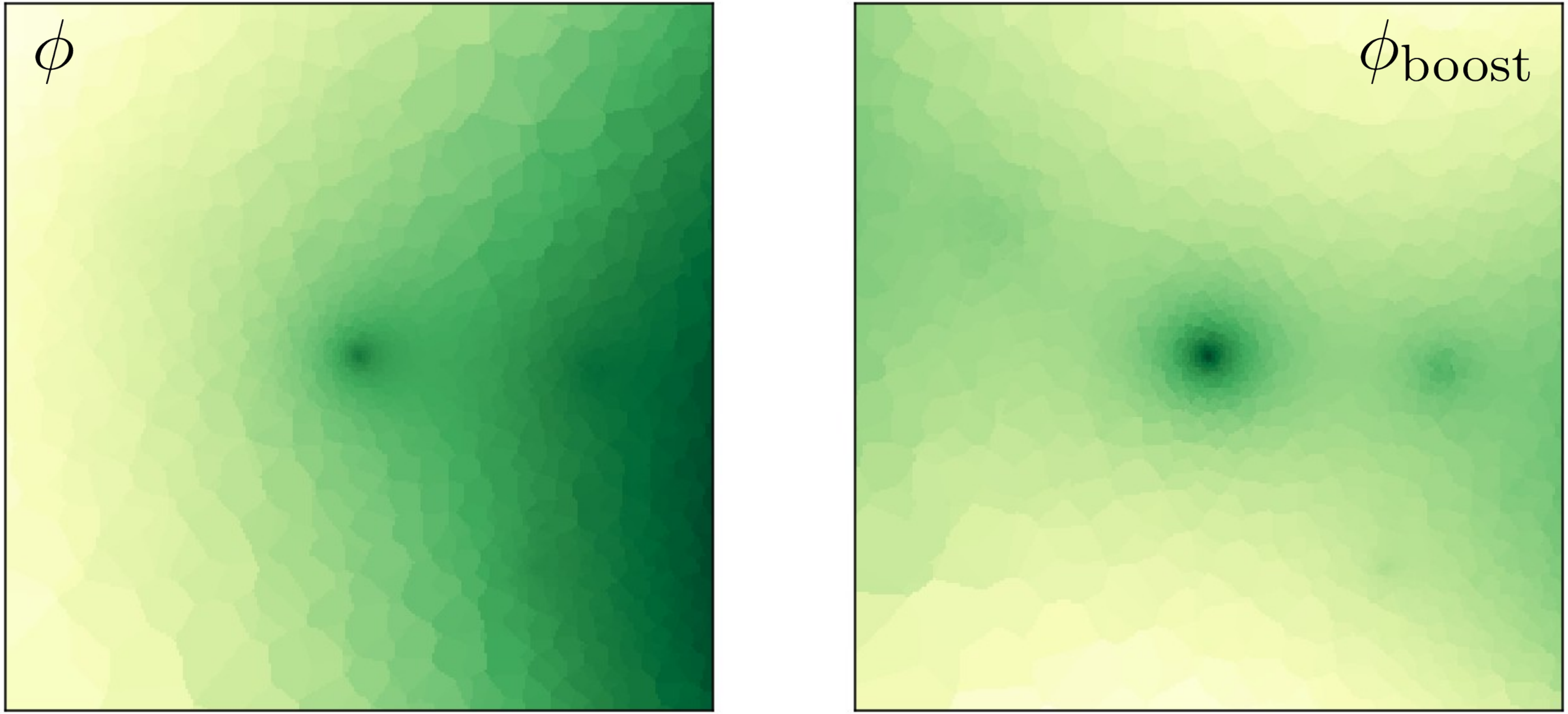
$$\phi_{\rm boost} = \phi_{\rm self} + \phi_{\rm ext} - (\mathbf{x} - \mathbf{x}_{\rm h}) \cdot \nabla \phi_{\rm ext}$$

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

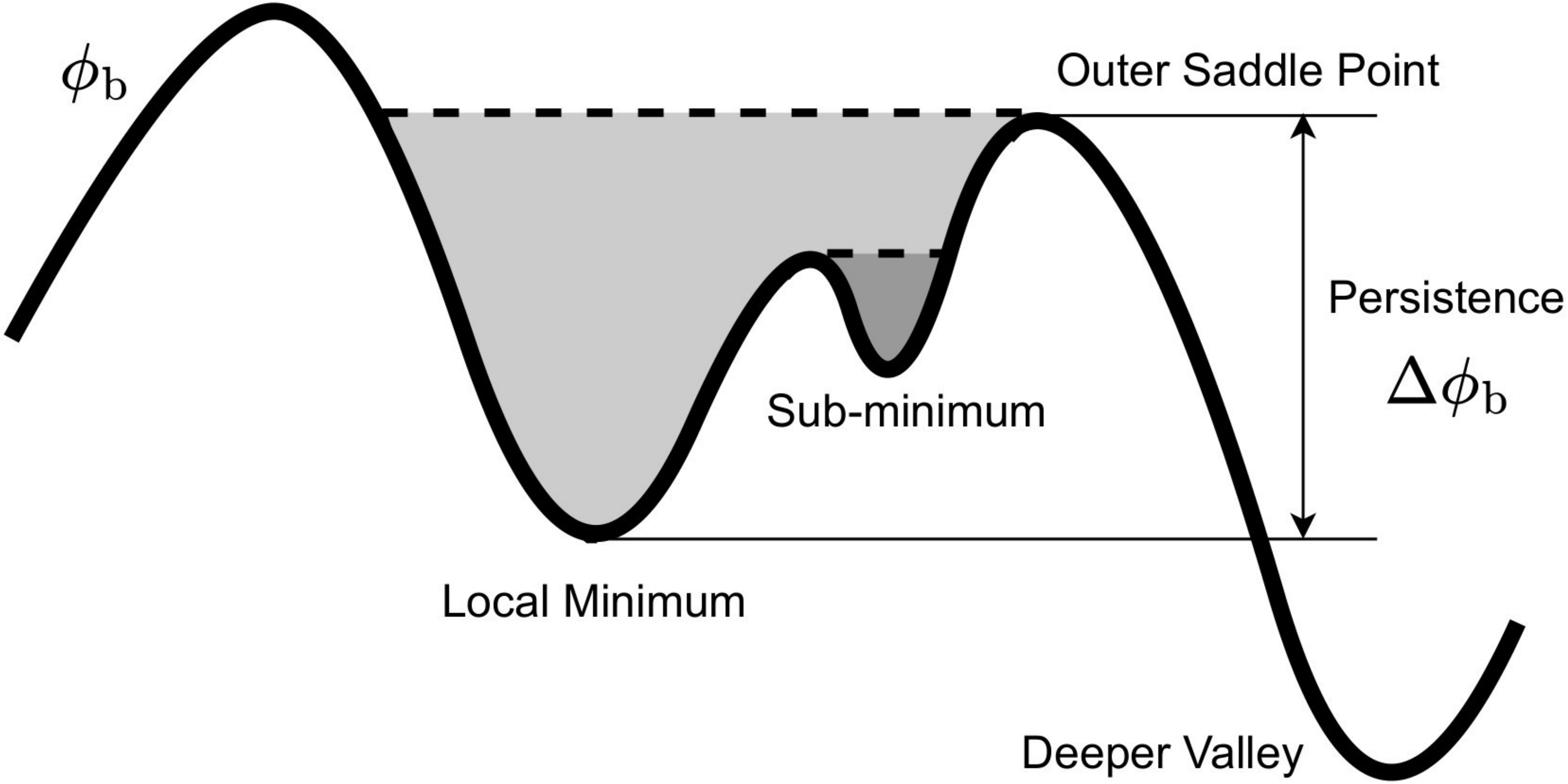
Internal dynamics are completely equivalent!

(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 **R**efe**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

}

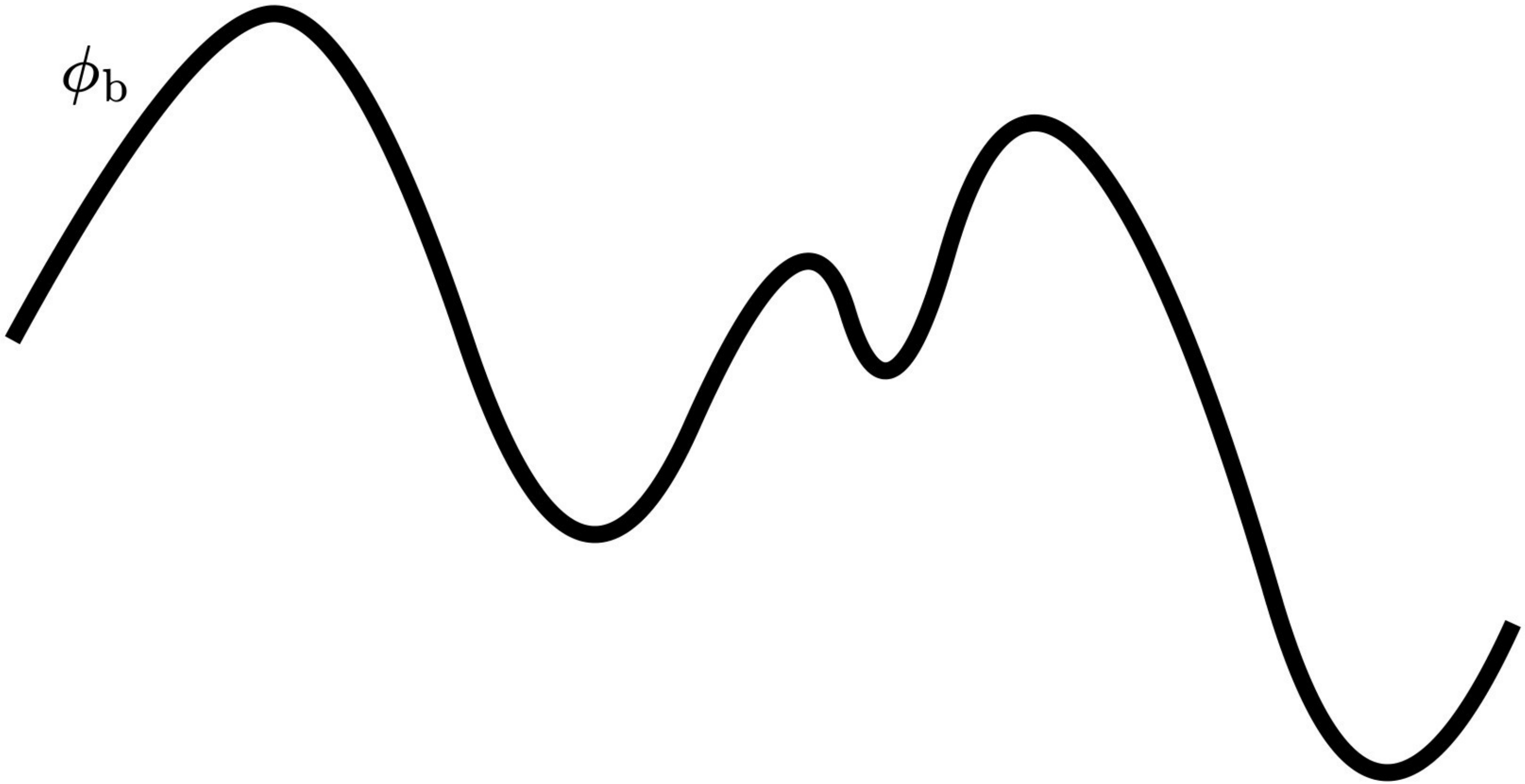
Need to rely on a **seed catalogue**

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

Introducing Strawberry



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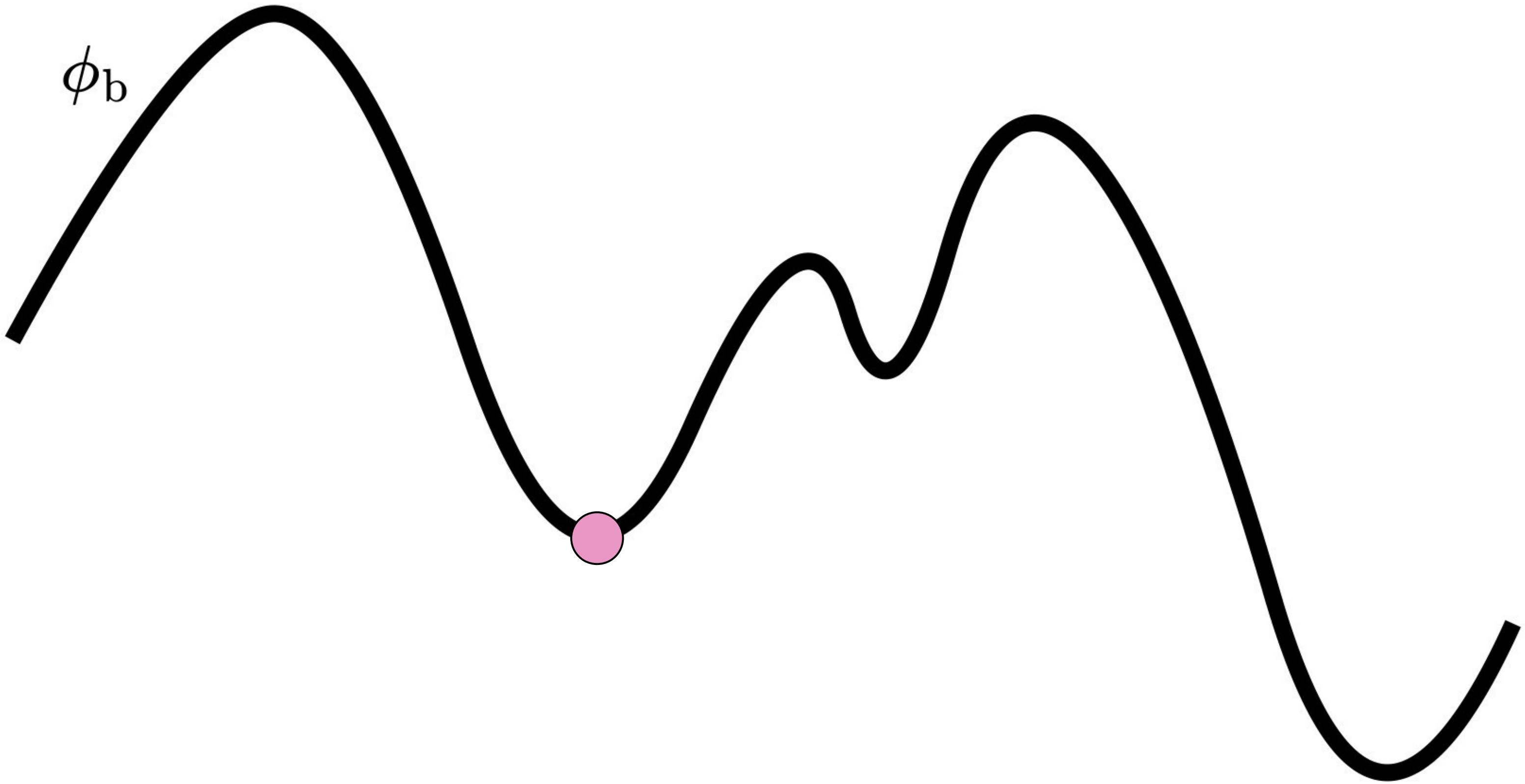

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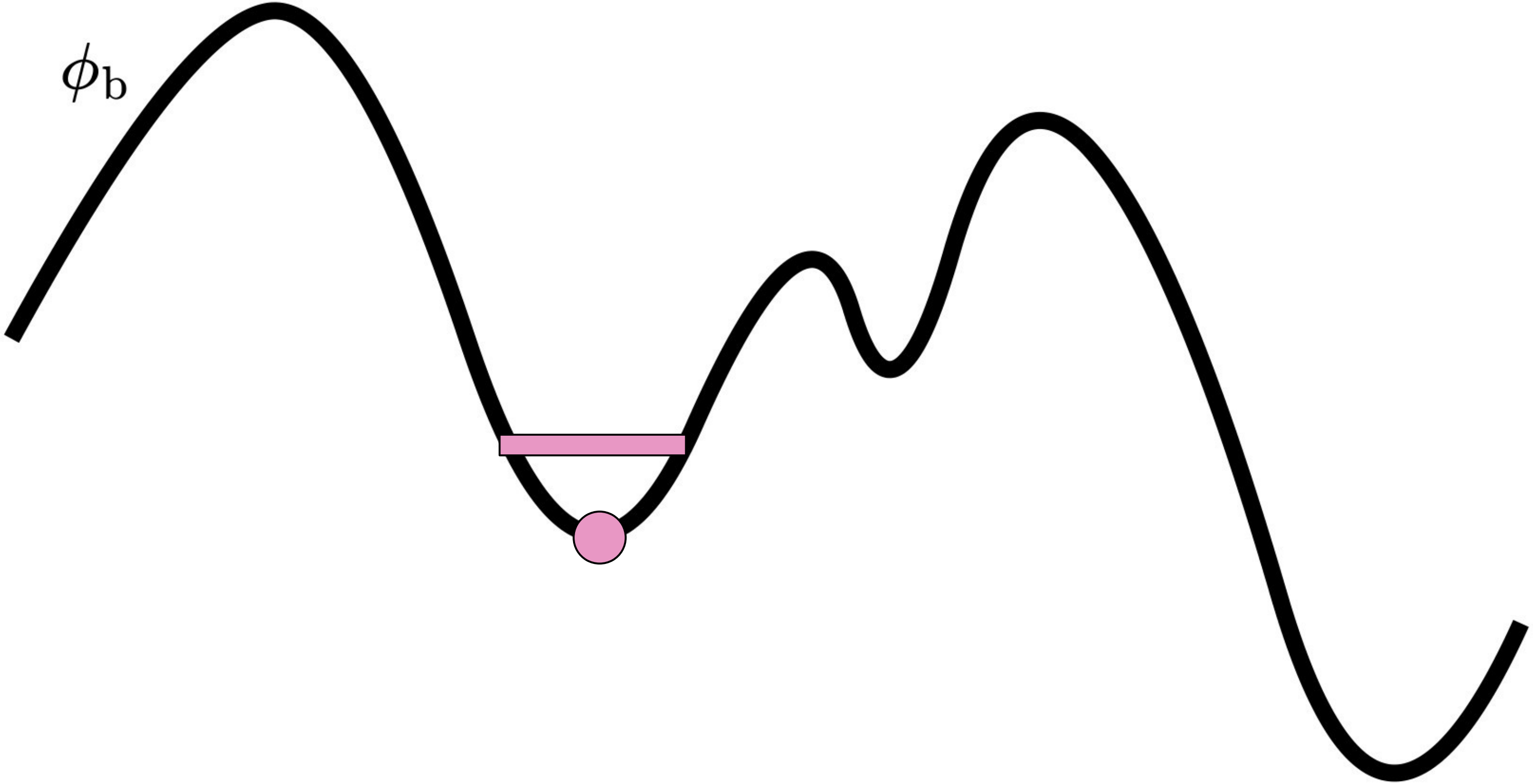

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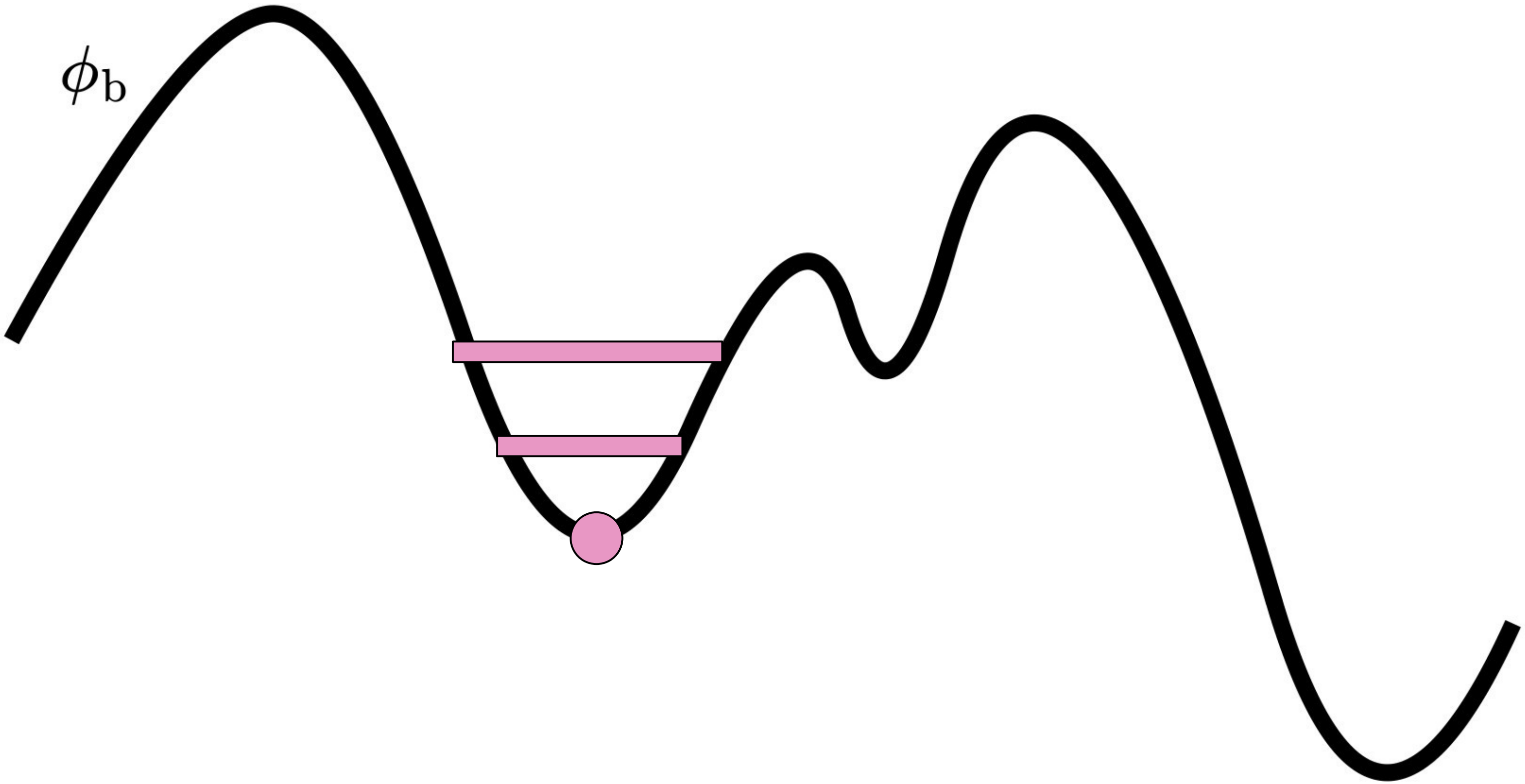

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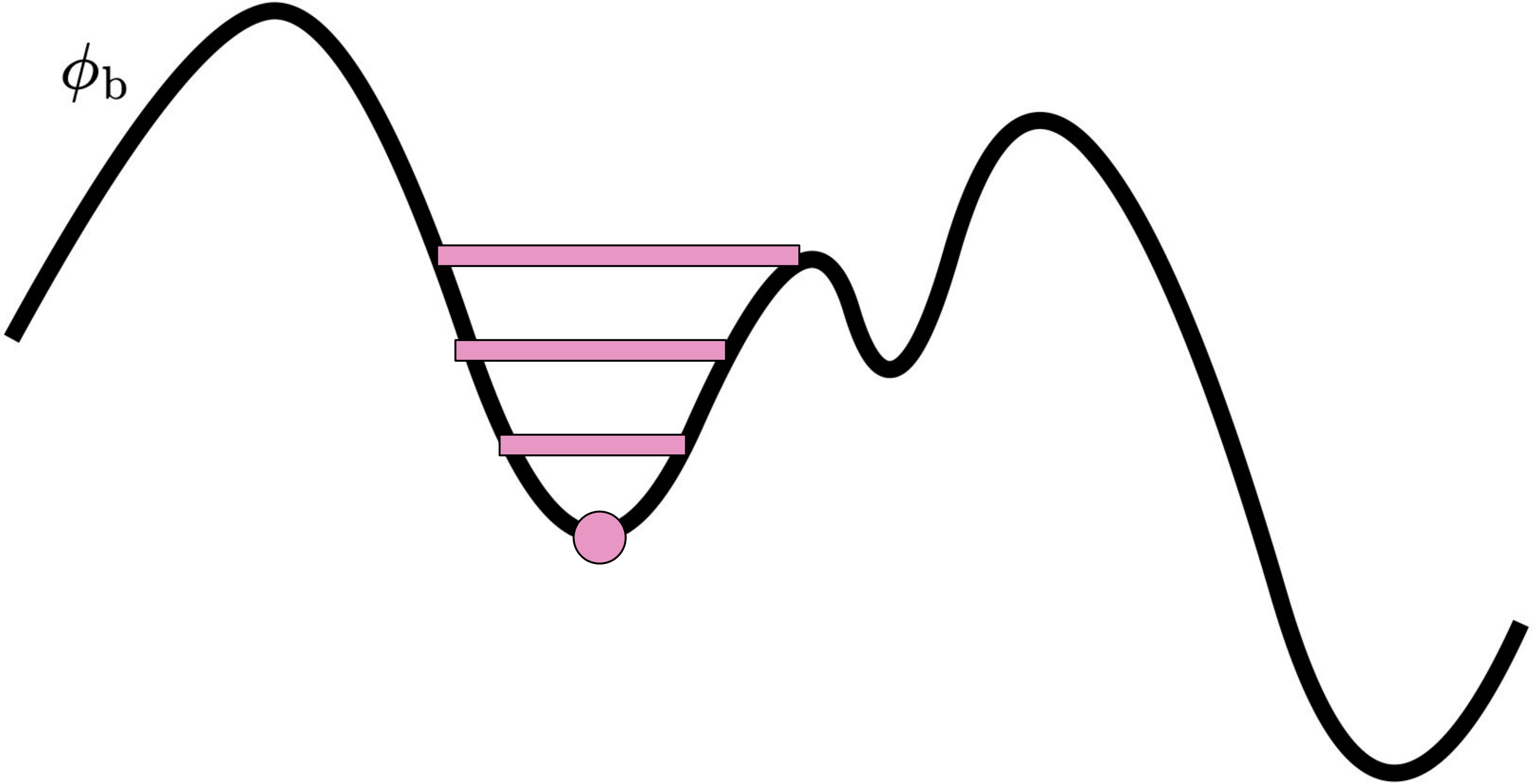

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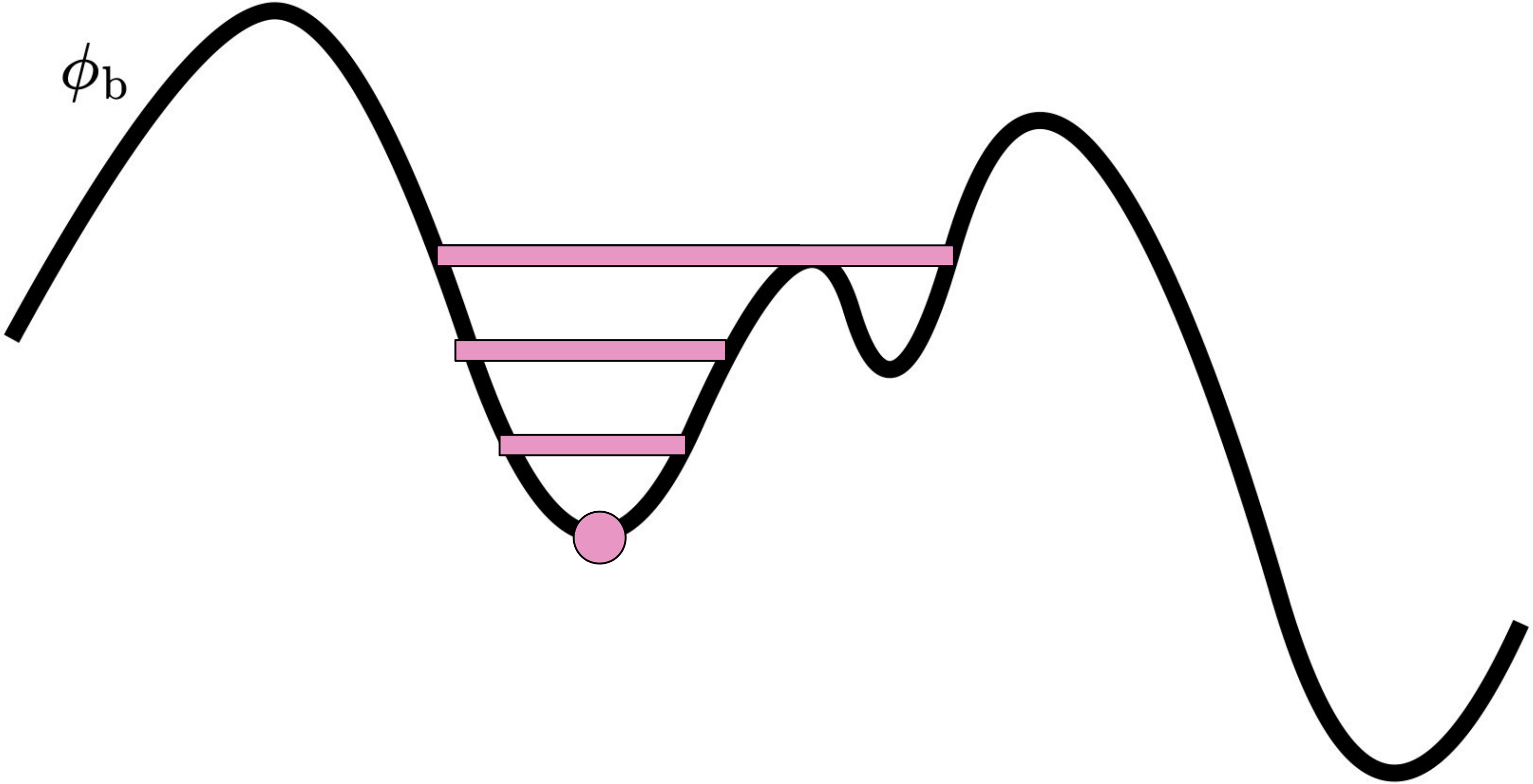

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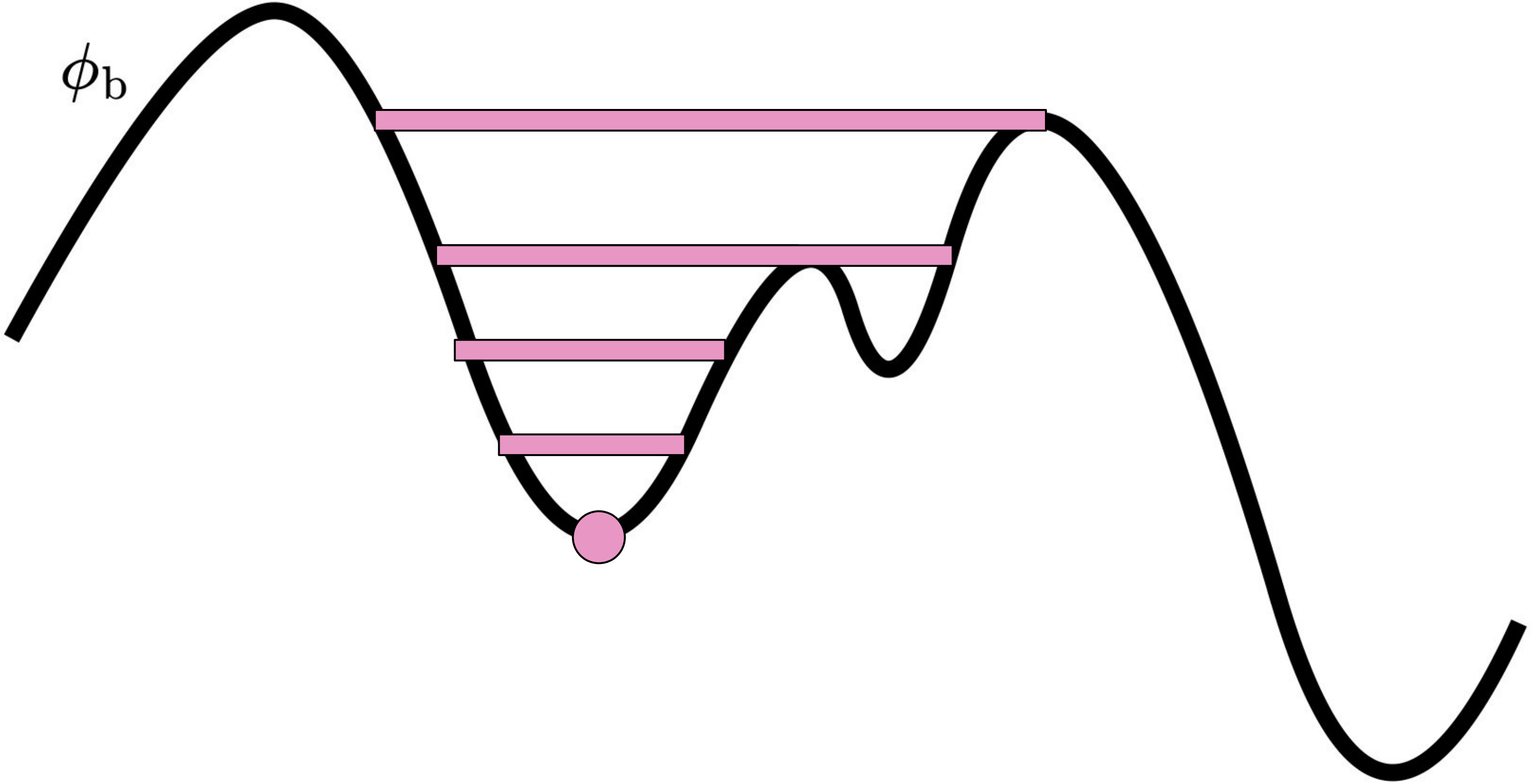

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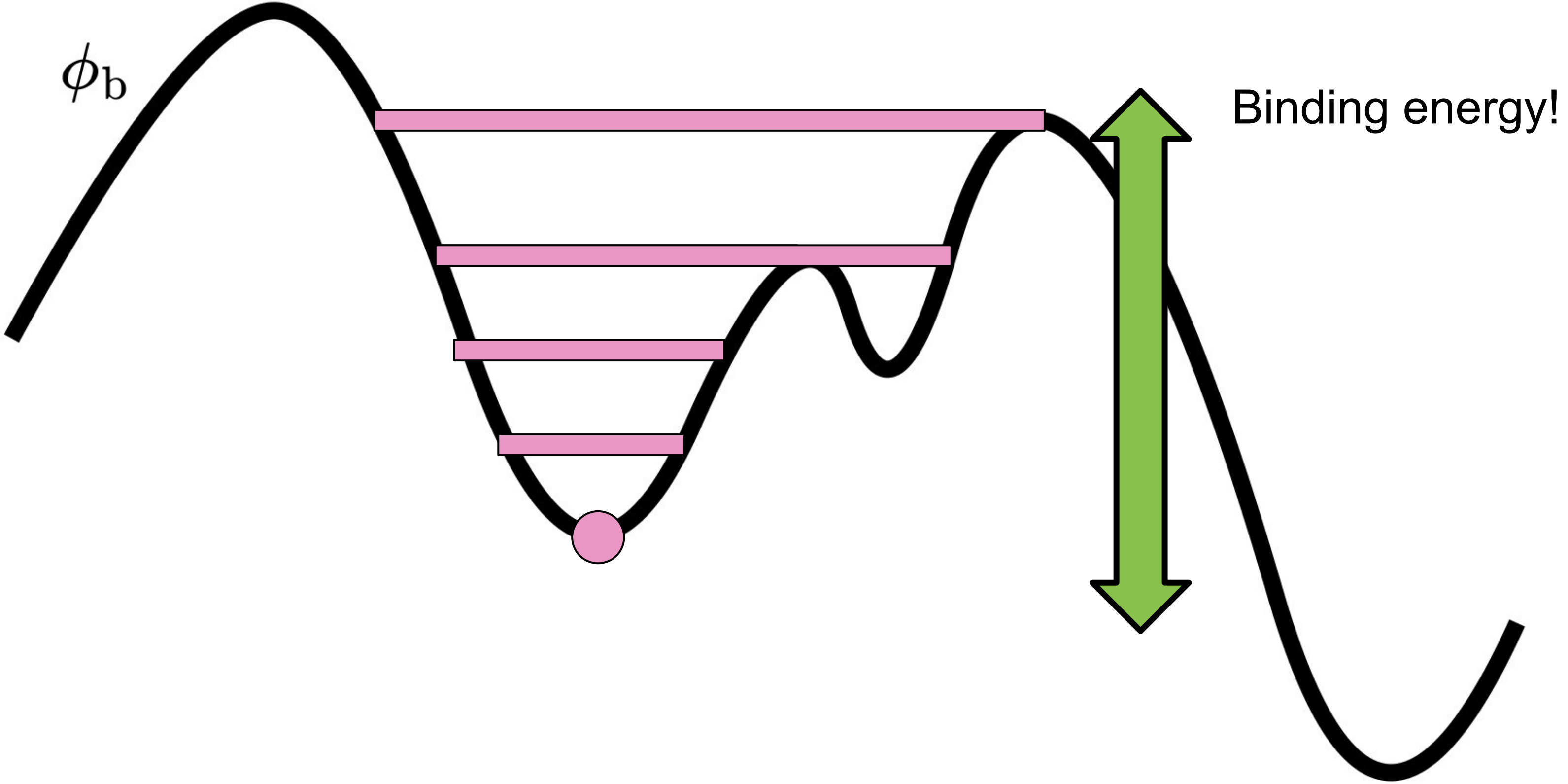

Visualising 1 halo

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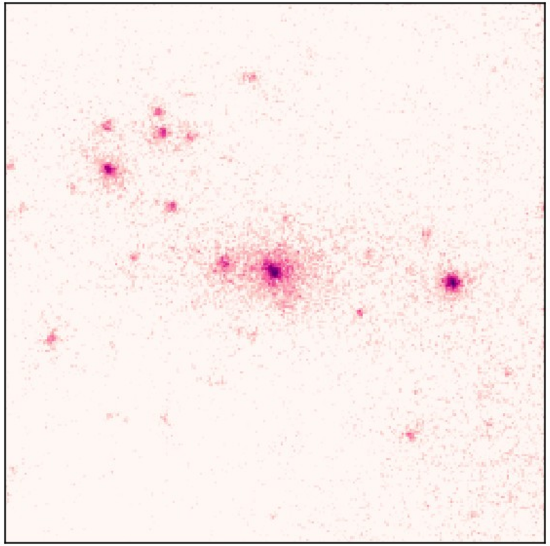

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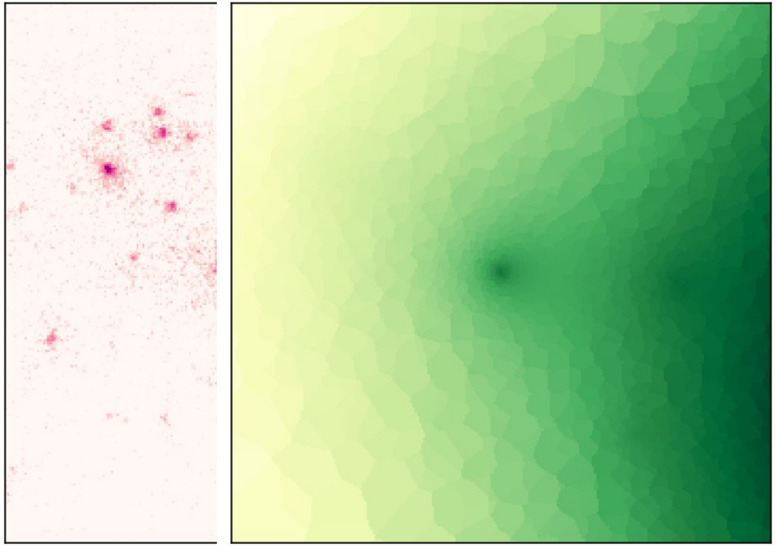

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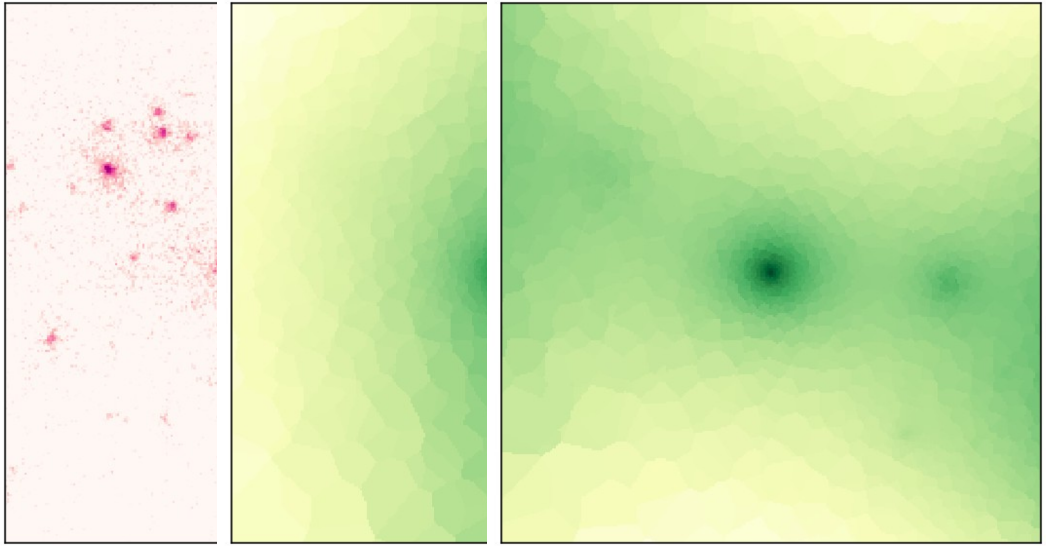

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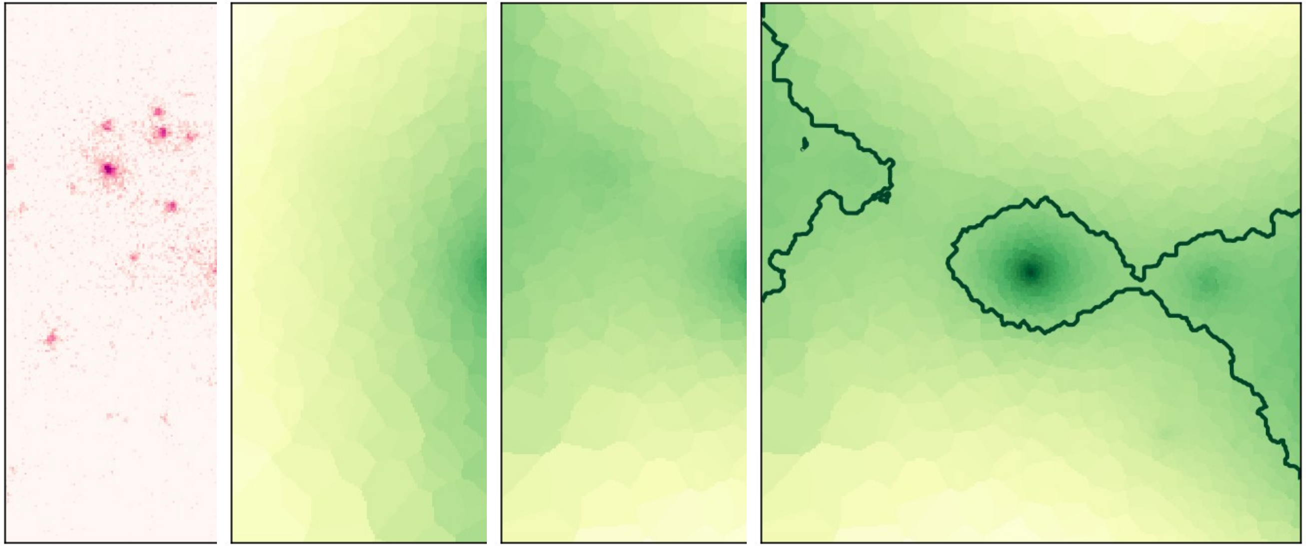

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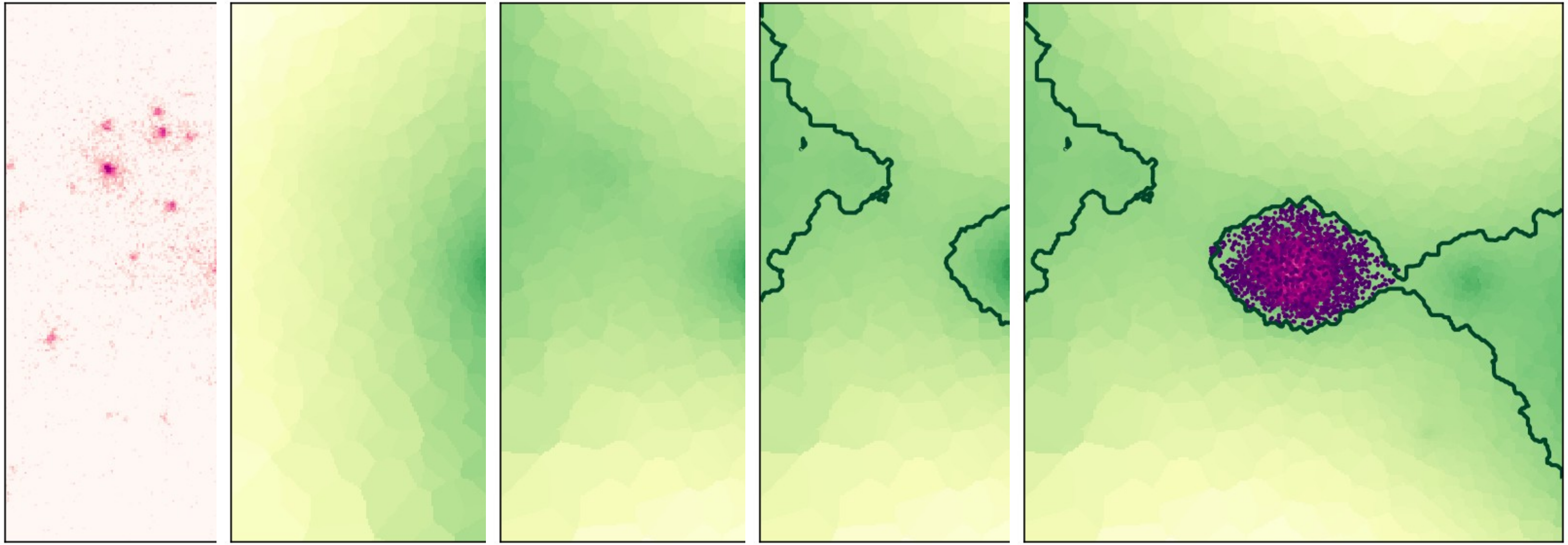

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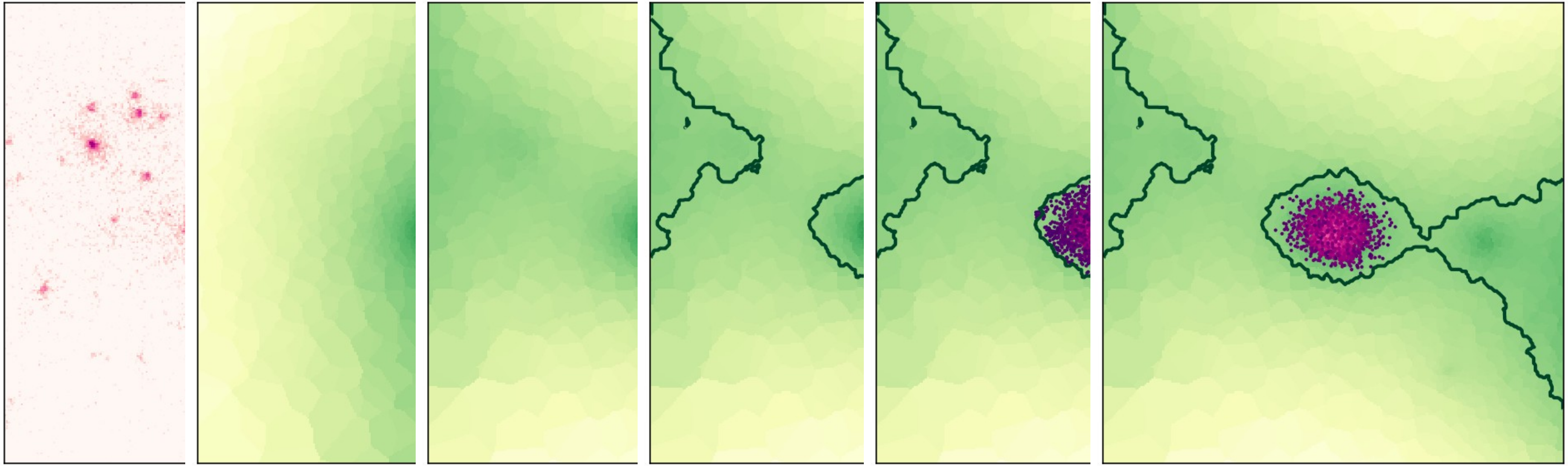
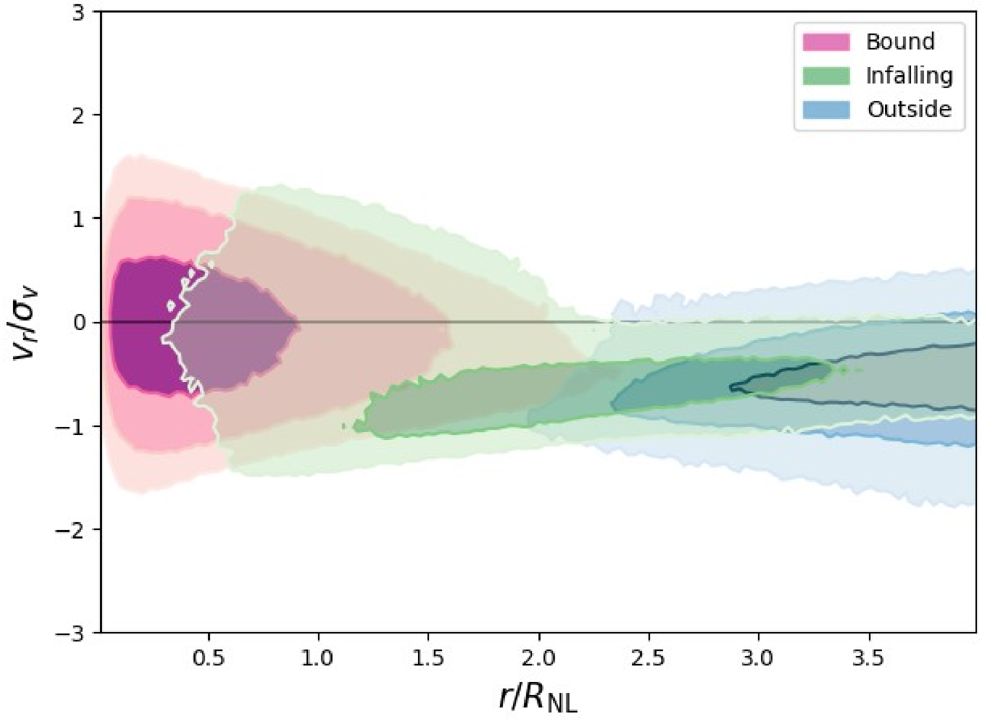


(Almost) Perfect Preening



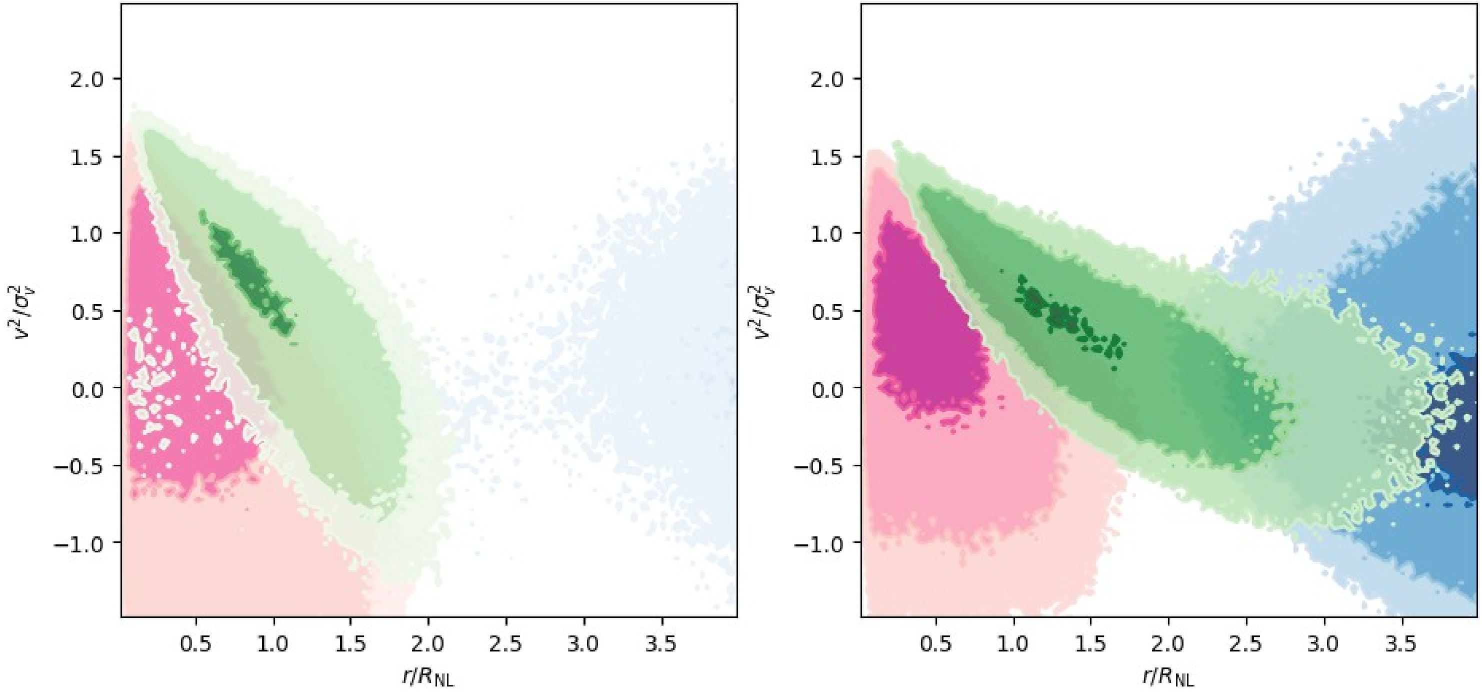
Selection using the potential:

Leaves us with **bound** population.

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

Separates particles **outside** of the potential

Where do you bind?



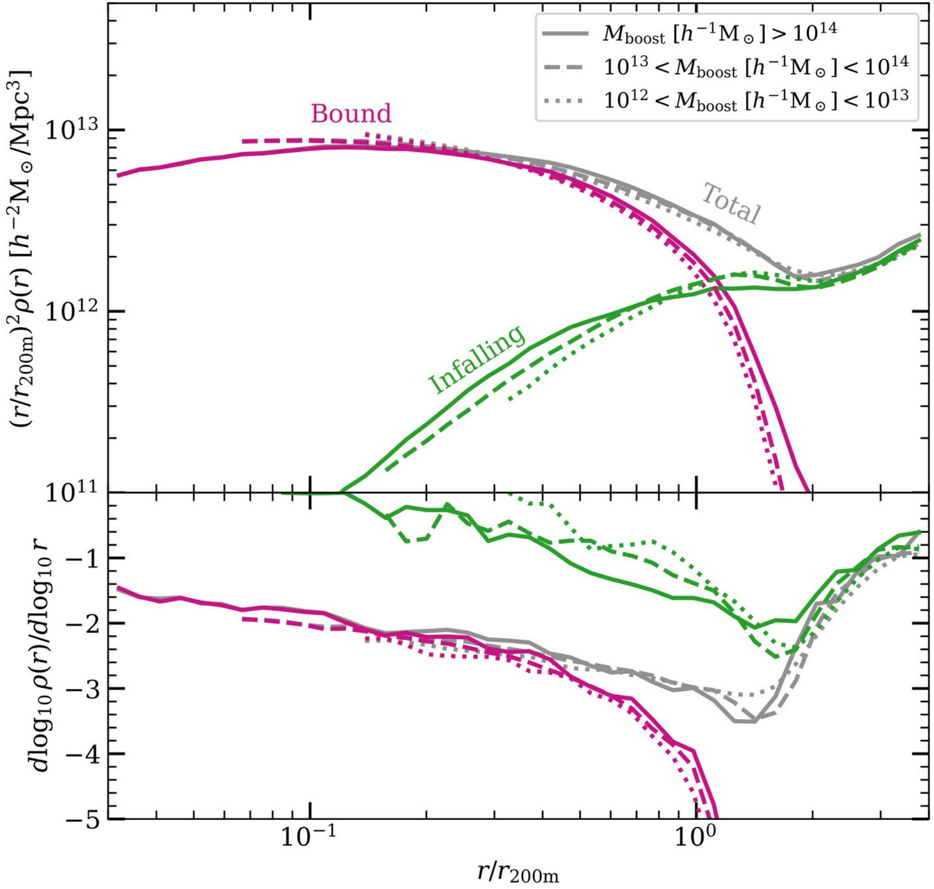
~ K-r Mass definition (Garcia et al. 2023, Salazar et al. 2024)

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 a **physically motivated framework** to perform a **binding check**.

Boosted haloes are **virialised and have edges**.

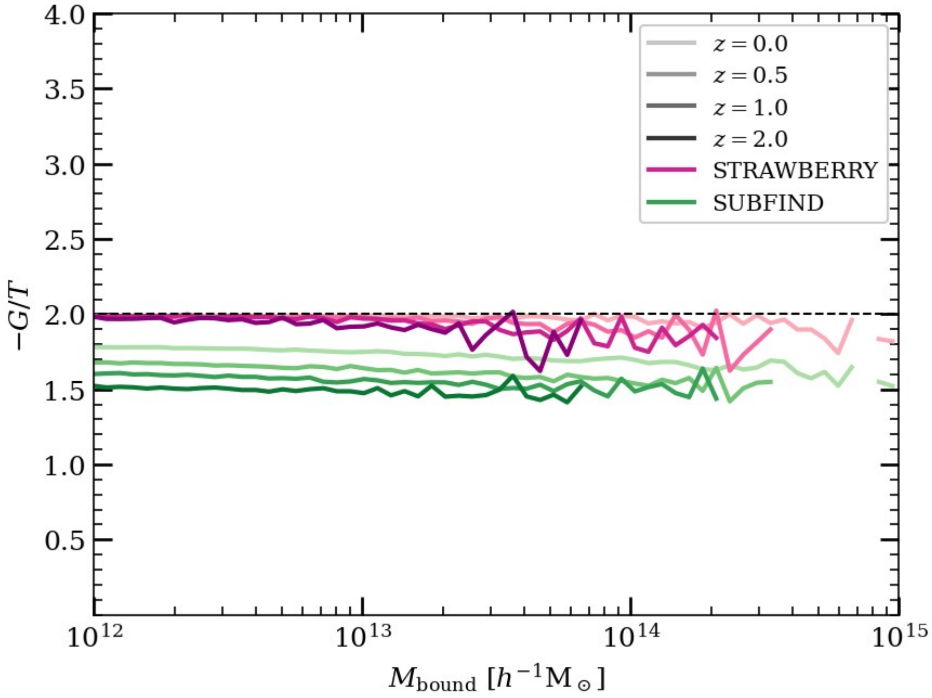
Future prospects:

- Characterisation of halo properties (in progress)
- Link to observation (still needs work)

STRAWBERRY test version is out now!
github.com/trg-richardson/strawberry

arXiv:2509.11993

Boosted Haloes are Virialised!



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

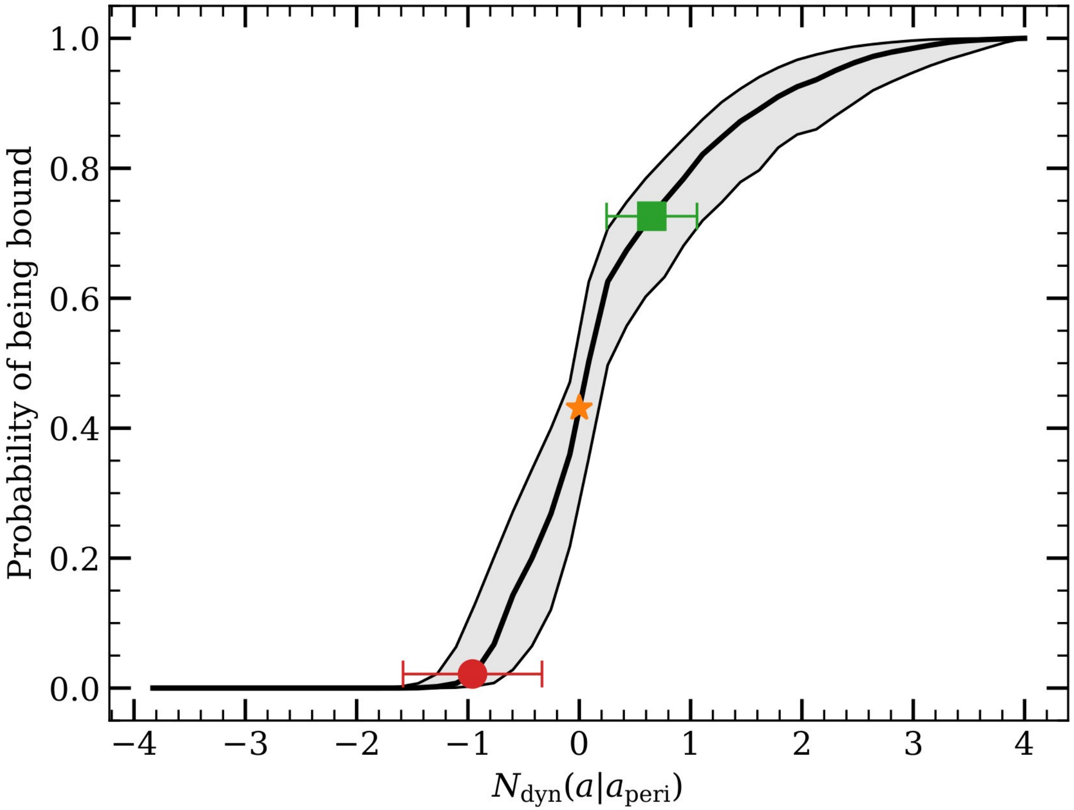
Discrepancy attributed to “external pressure”

Removing bound particles

Including unbound particles

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

When do you bind?



$$T(z|z_{\rm LMM}) = \frac{\sqrt{2}}{\pi}\int_{z_{\rm LMM}}^{z} \frac{\sqrt{\Delta_{\rm vir}(z)}}{z+1}dz$$

Jiang et al. 2016

Median binding time is the first pericentric passage.

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

~ Orbit based mass definitions

Time scaling