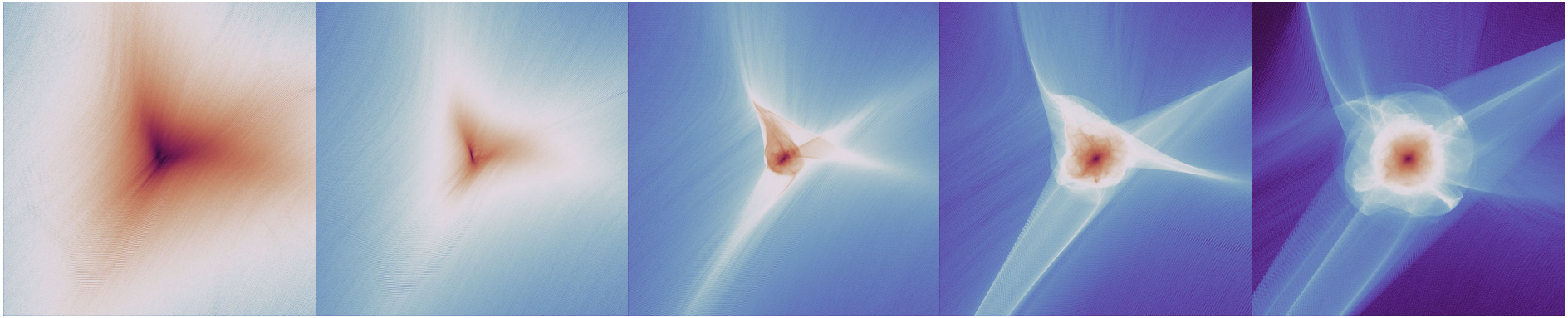


Simulating the first halos in warm dark matter cosmologies

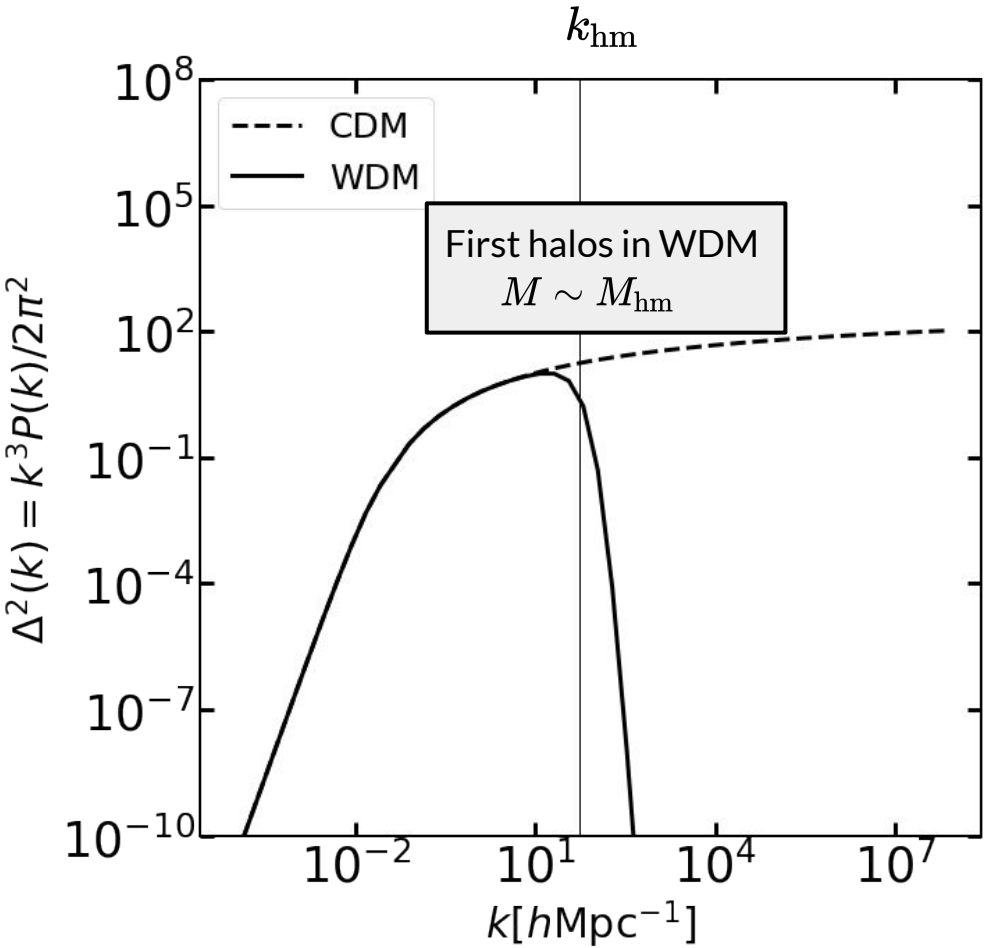
Lurdes Ondaro Mallea

with Raul Angulo, Jens Stücker, Simon White, Oliver Hahn

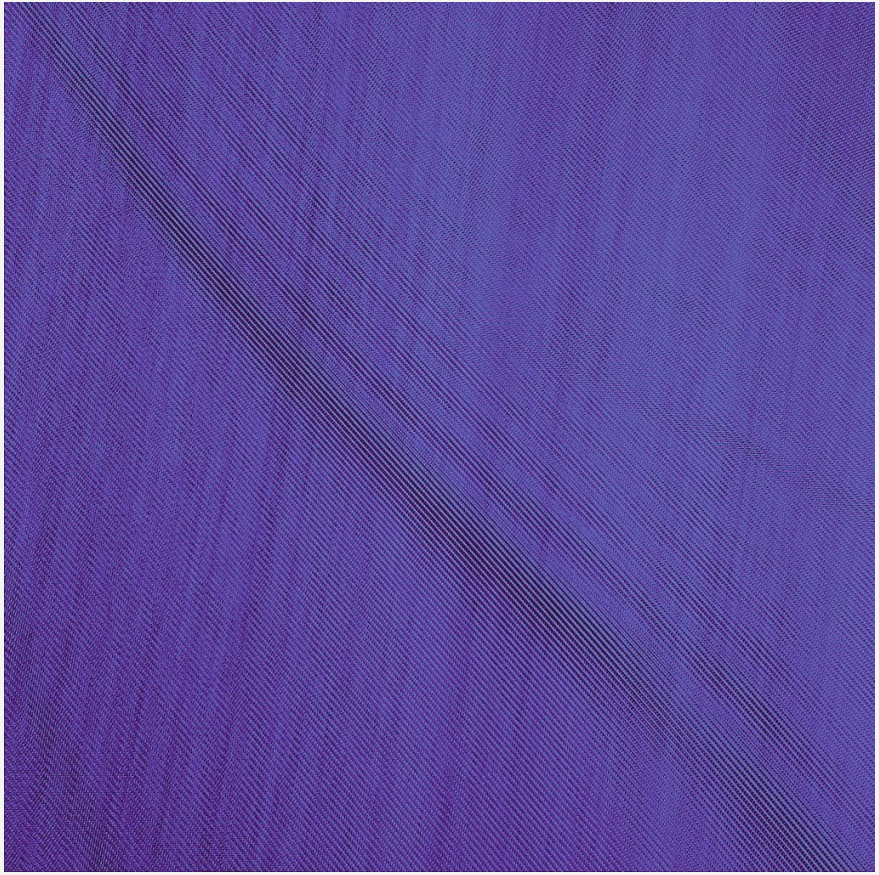
XXXIII Canary Islands Winter School of Astrophysics
November 2022

Donostia International Physics Center

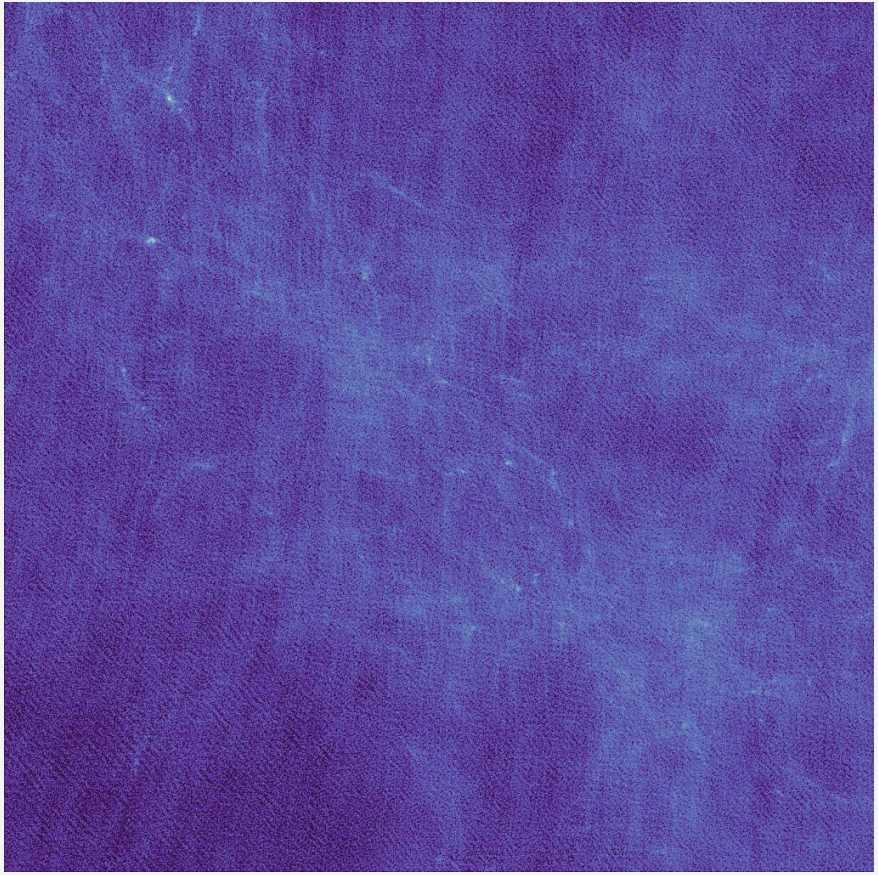
"la Caixa" Foundation


$k_{\rm hm}$
CDM
WDM
First halos in WDM
$M \sim M_{\rm hm}$
$\Delta^2(k) = k^3P(k)/2\pi^2$
10^{8}
10^{5}
10^{2}
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-2}
10^{1}
10^{4}
10^{7}
$k[h\mathrm{Mpc}^{-1}]$

WDM

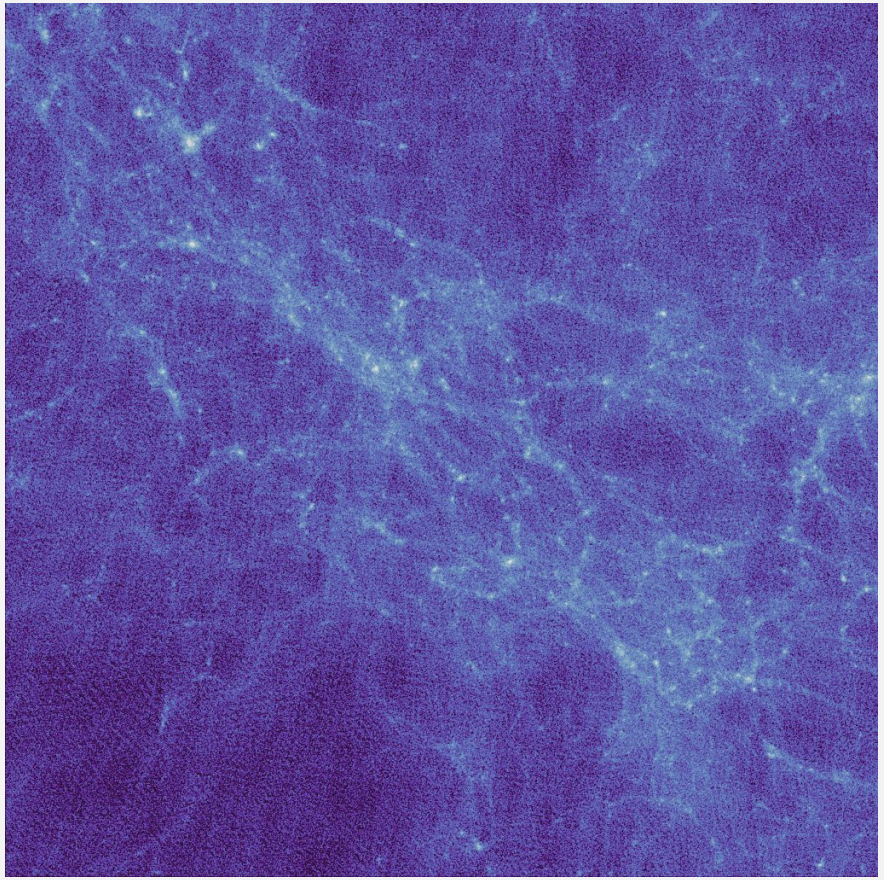


CDM



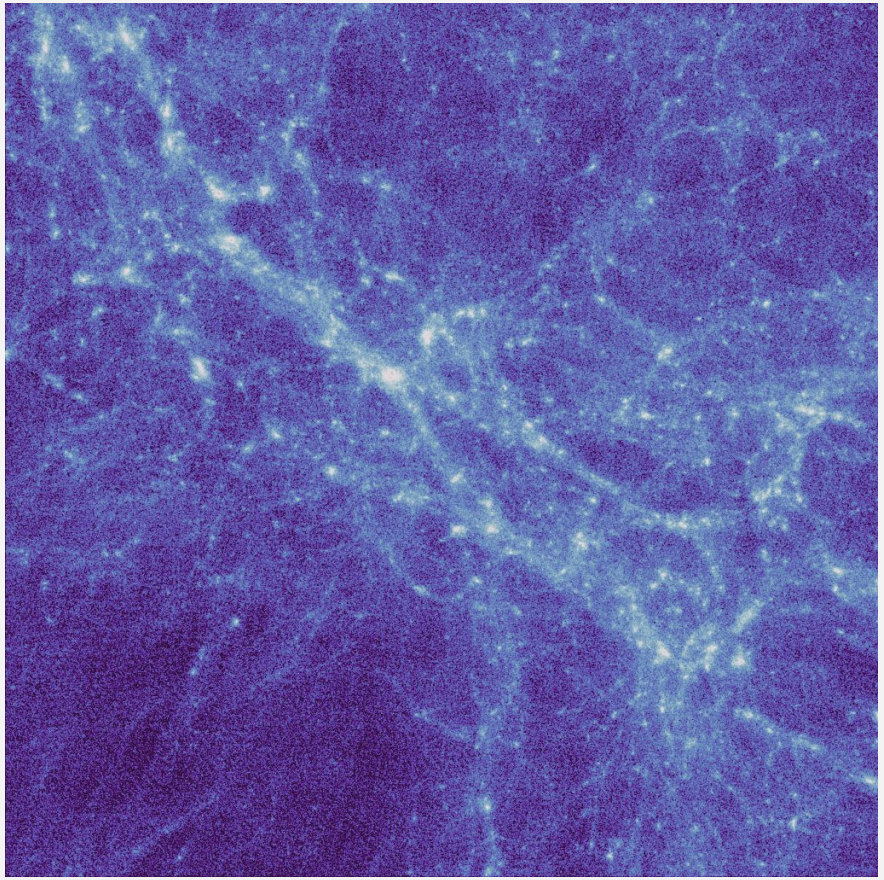
WDM

CDM

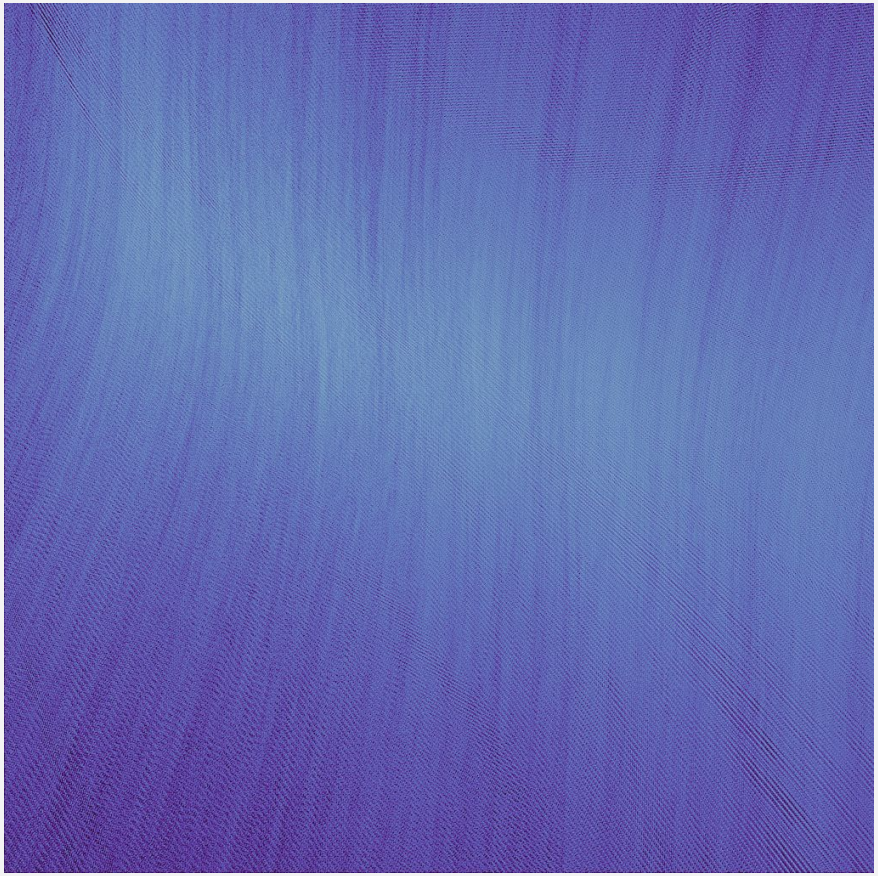


WDM

CDM



WDM



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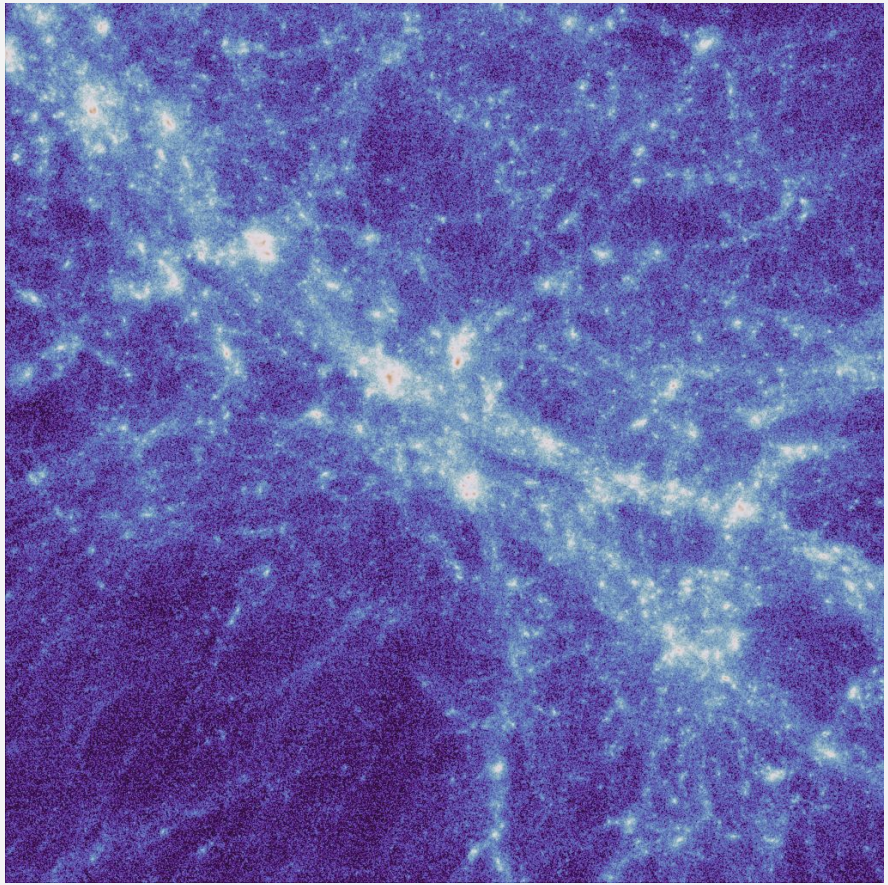
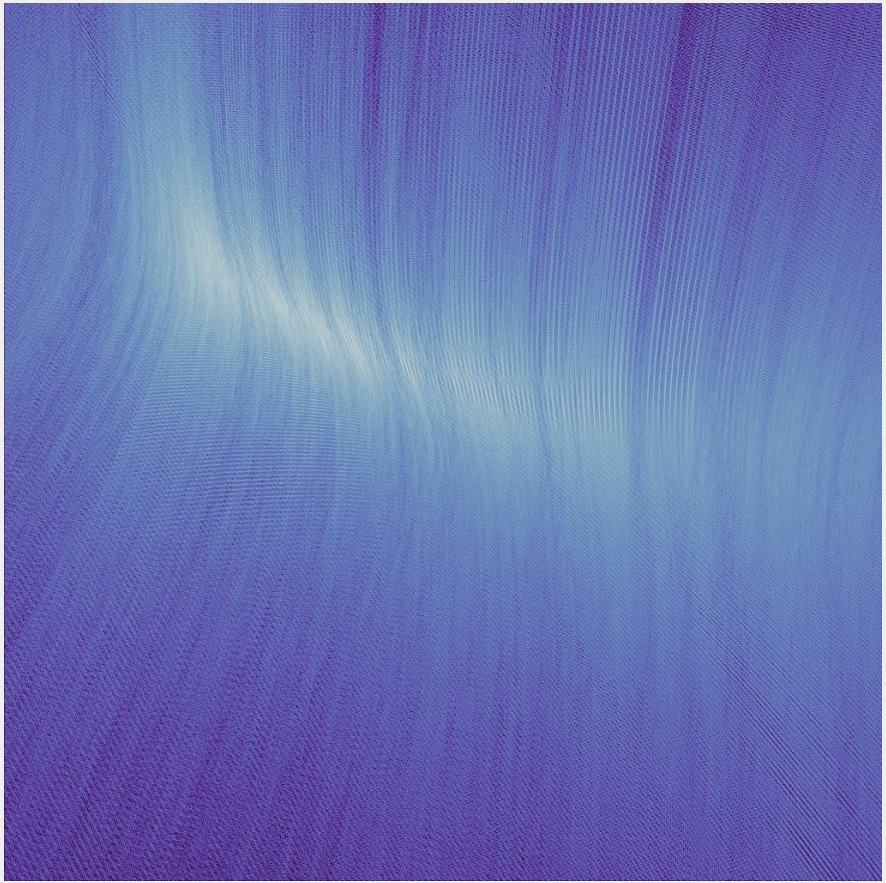


WDM



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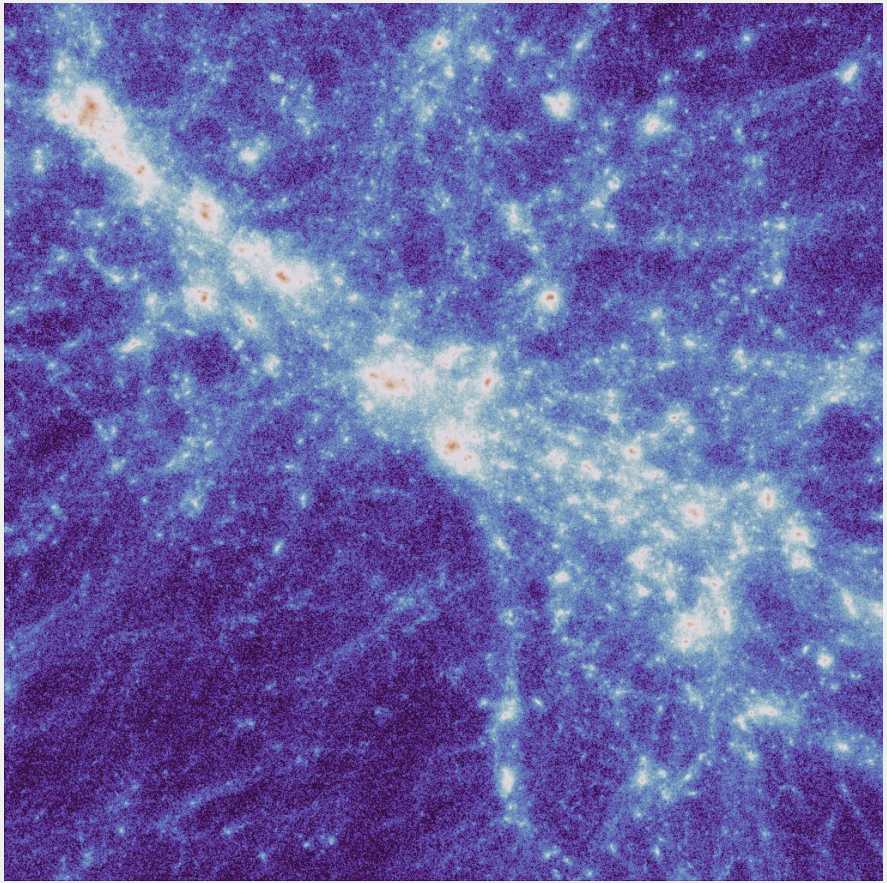
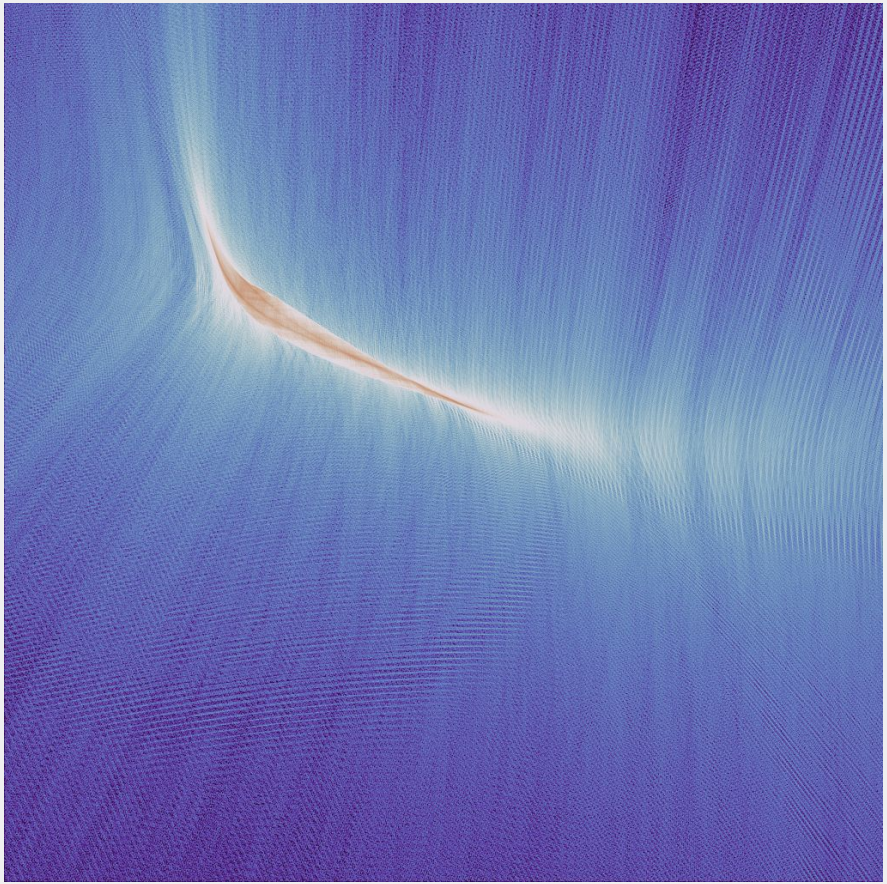
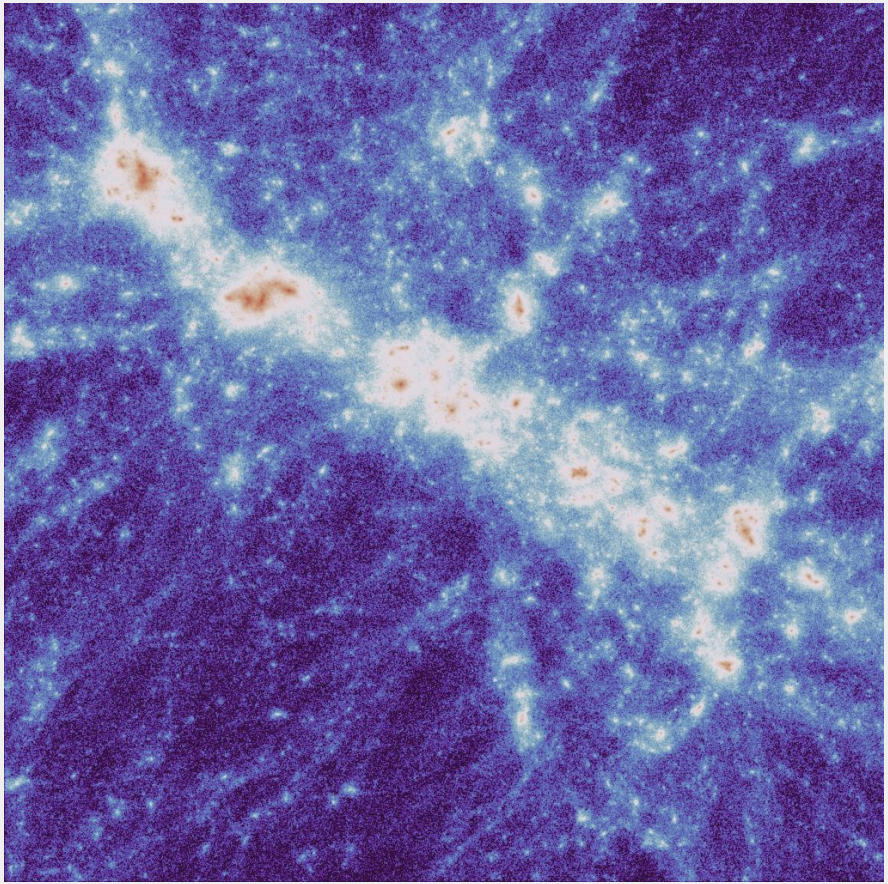


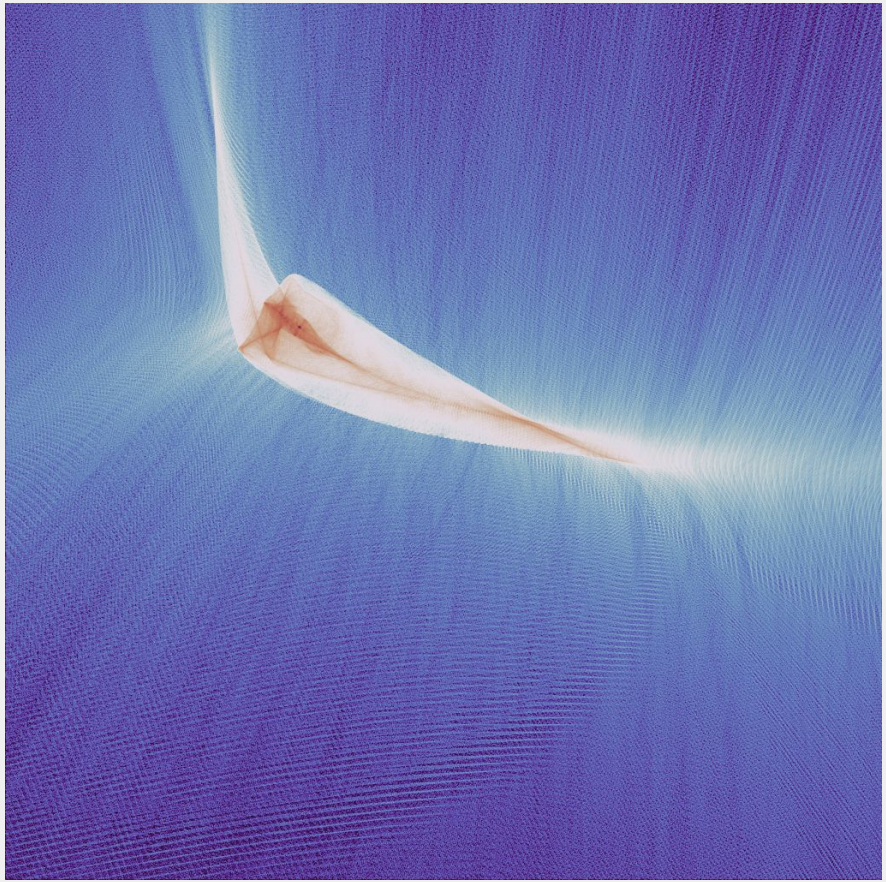
WDM



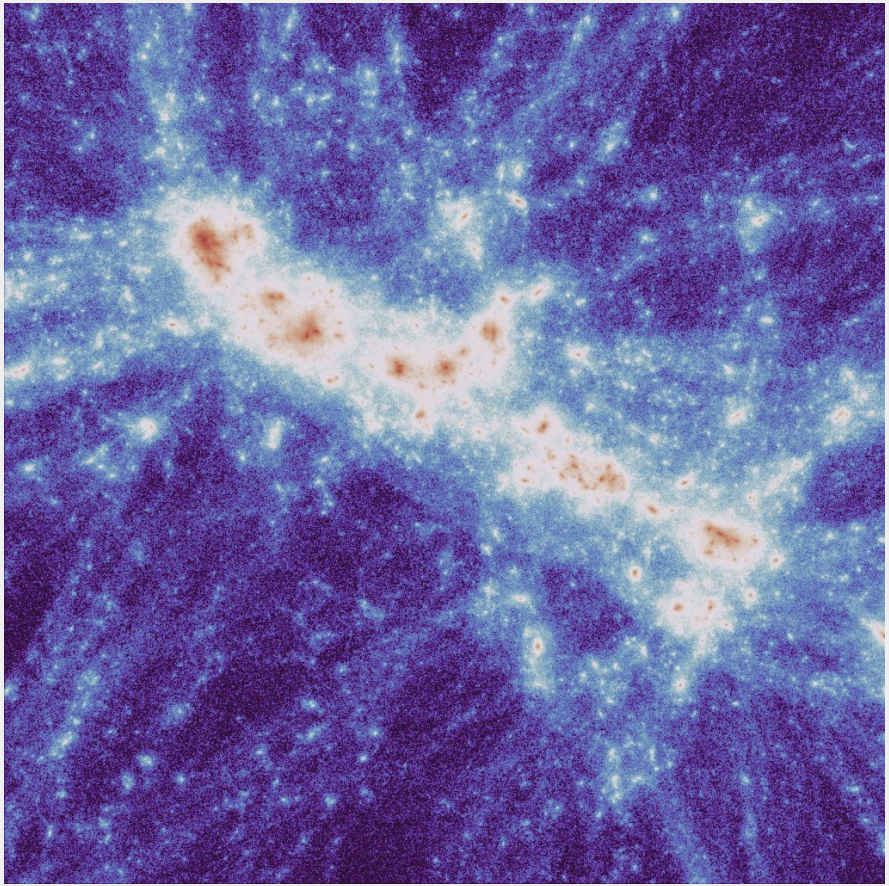
CDM



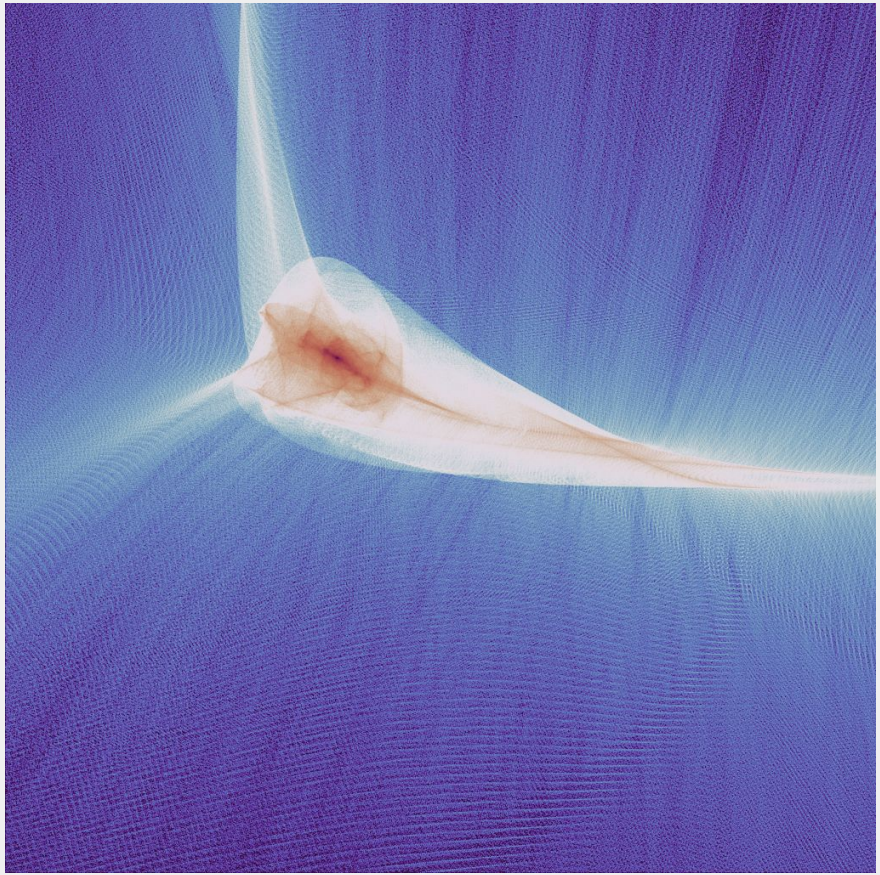
WDM



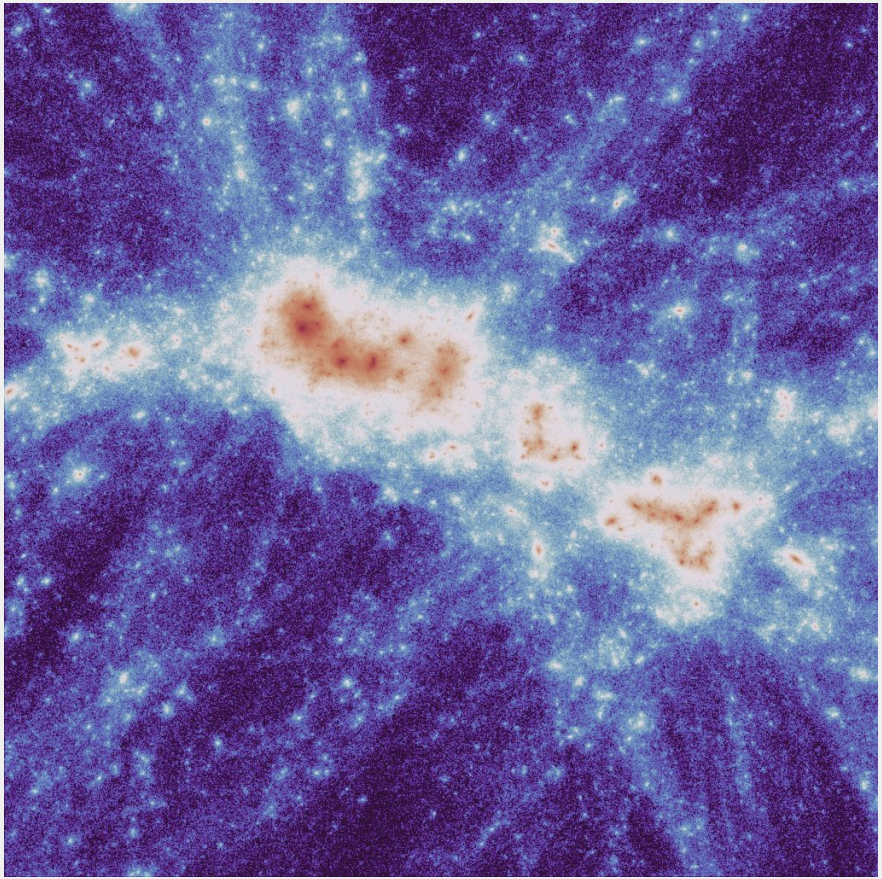
CDM



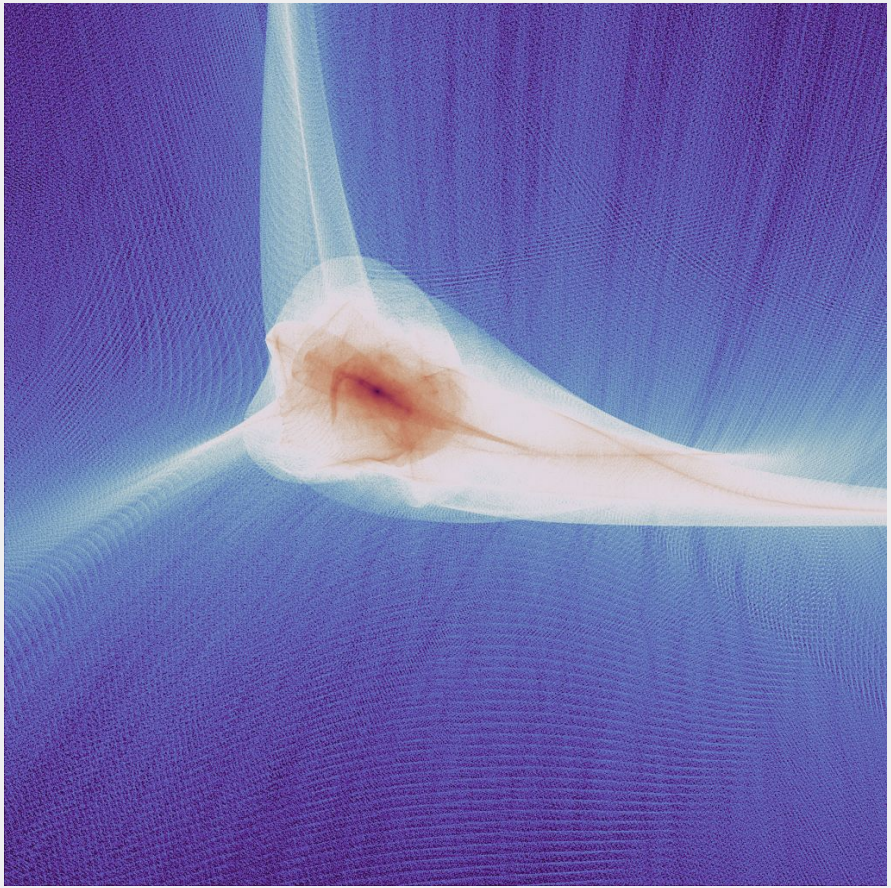
WDM



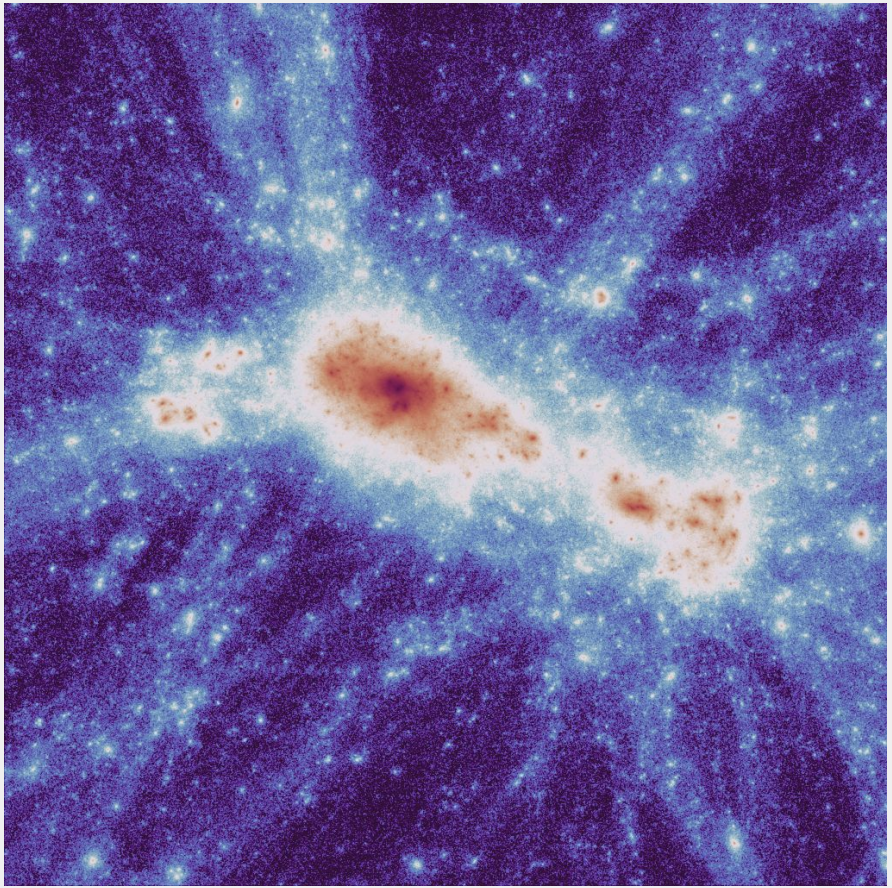
CDM



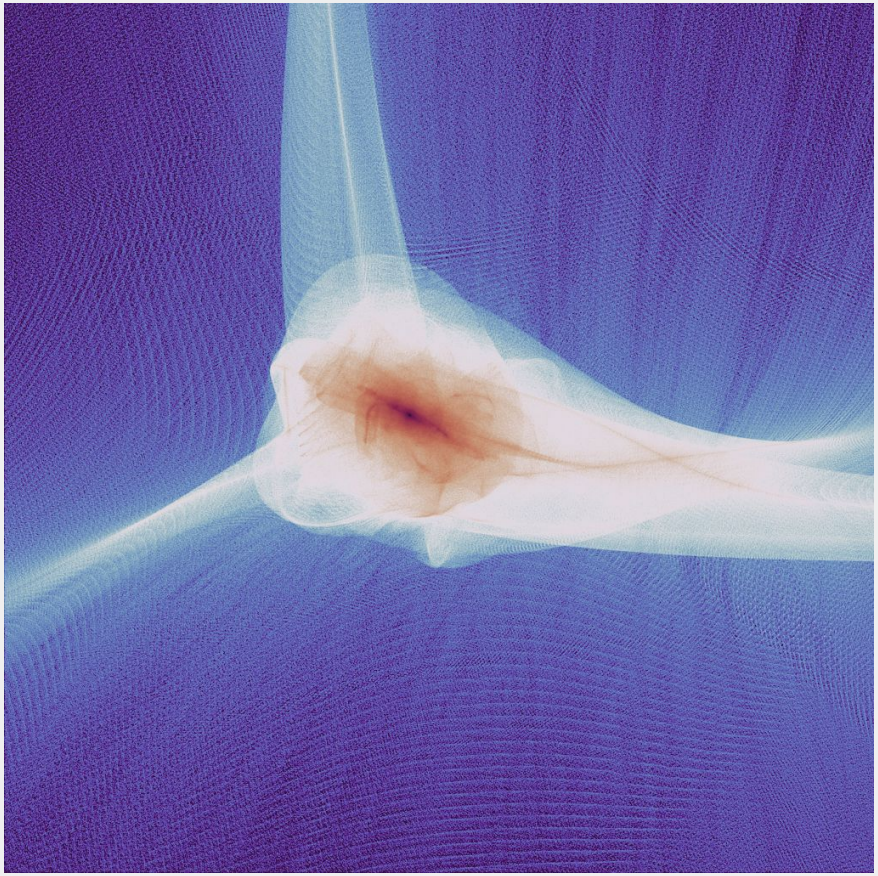
WDM



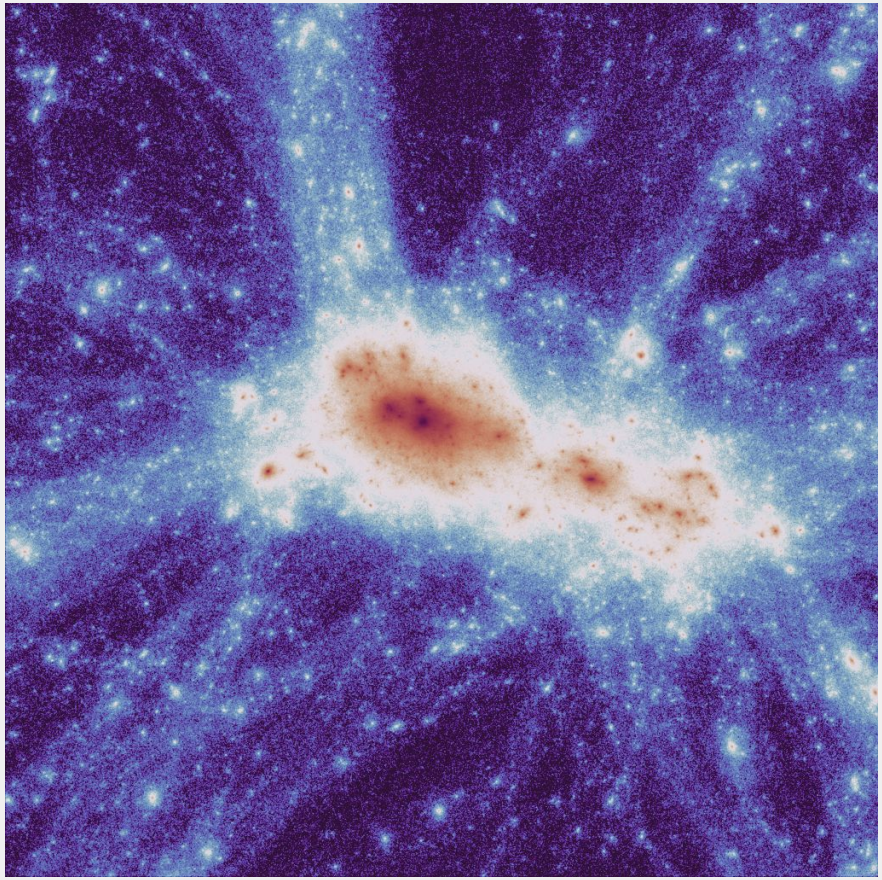
CDM



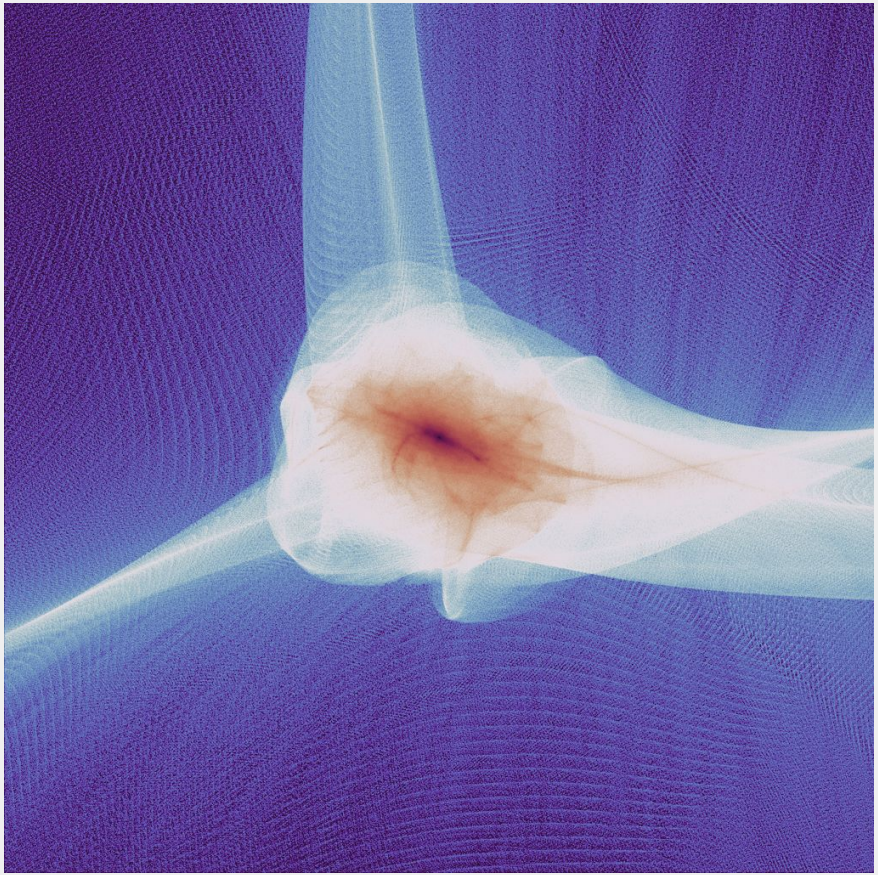
WDM



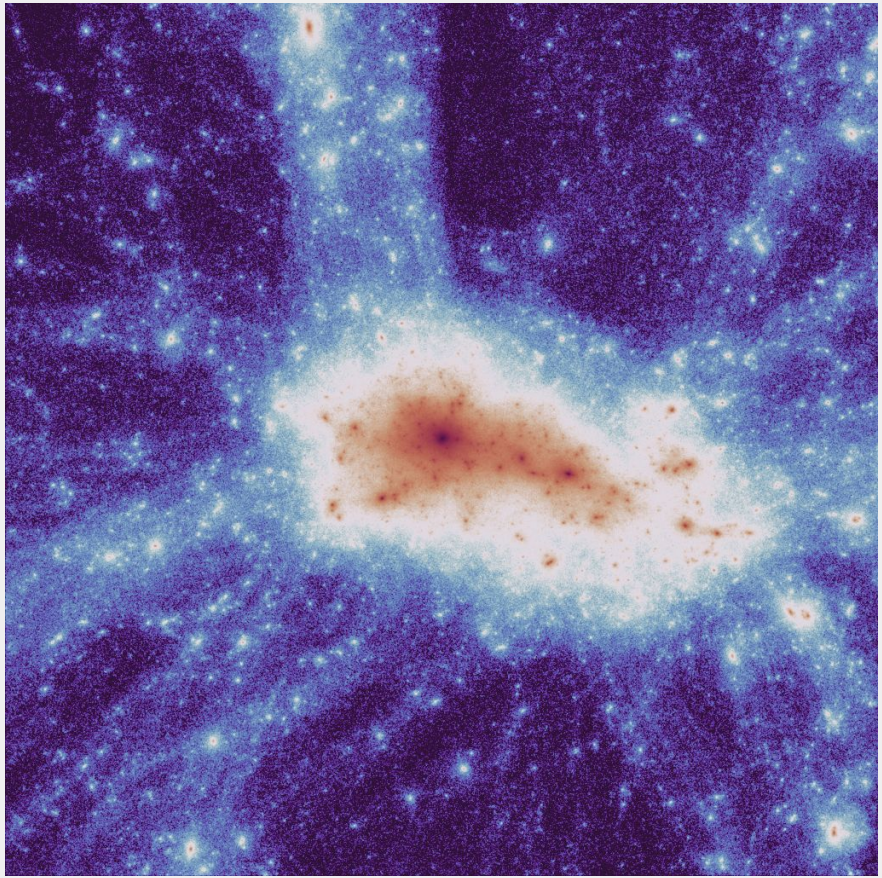
CDM

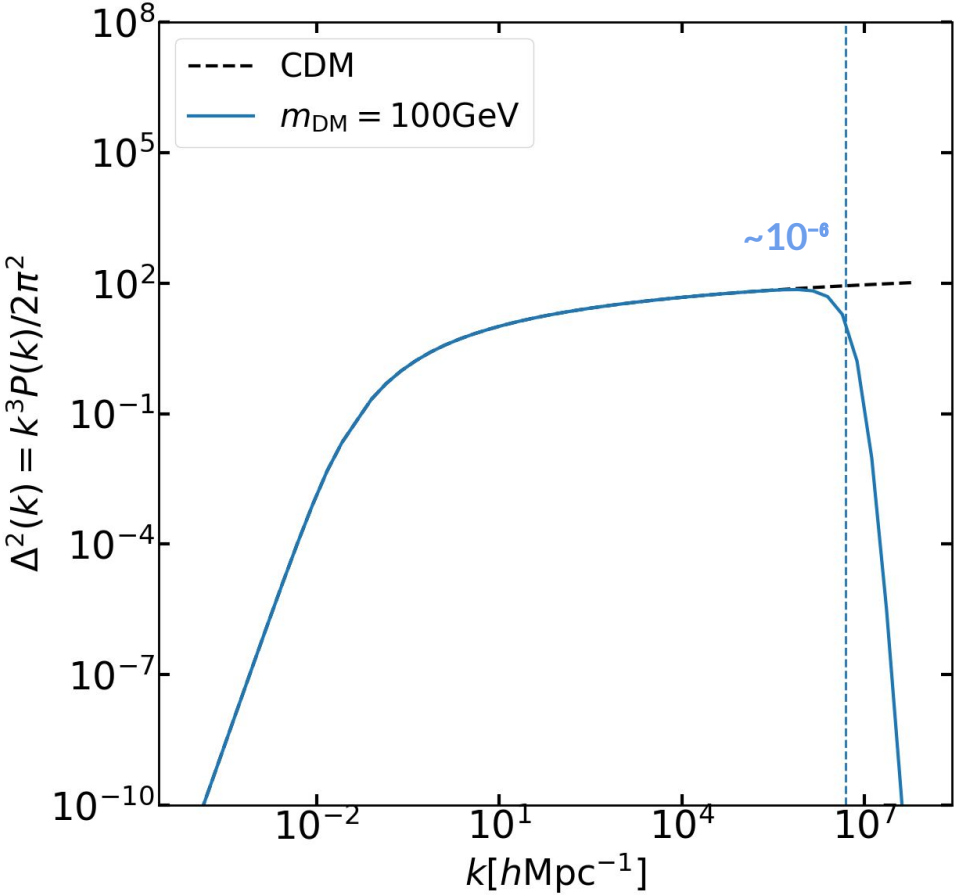


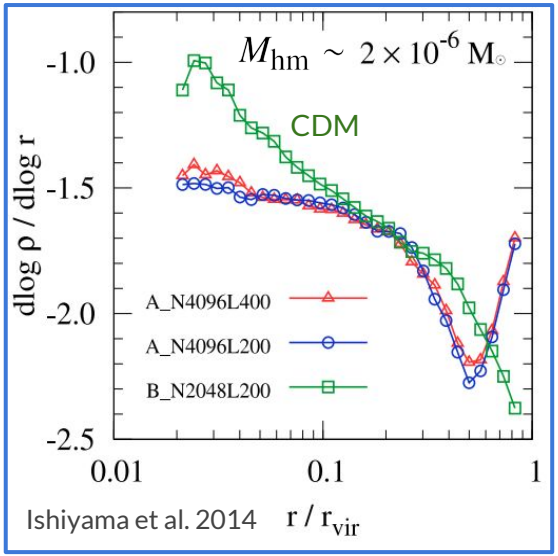
WDM

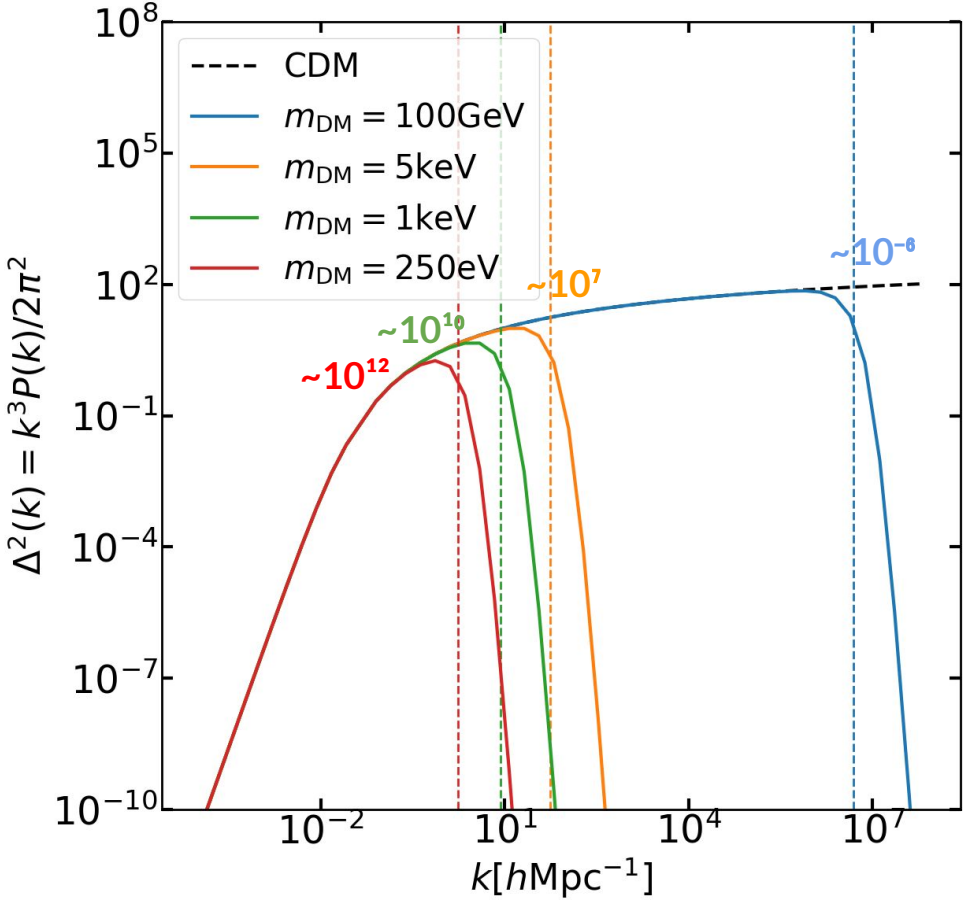


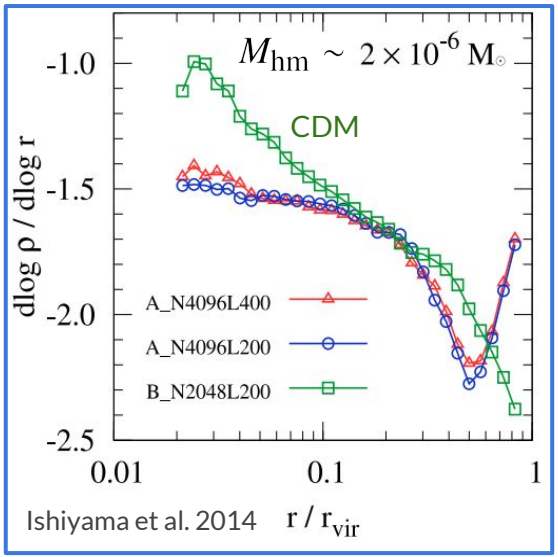
CDM




CDM
$m_{DM} = 100GeV$
~10⁻⁶
$\Delta^2(k) = k^3P(k)/2\pi^2$
$k[h\mathrm{Mpc}^{-1}]$
10^{8}
10^{5}
10^{2}
10^{-1}
10^{-4}
10^{-7}
10^{-10}
10^{-2}
10^{1}
10^{4}
10^{7}


$M_{hm} \sim 2 \times 10^{-6}$ M⊙
CDM
A_N4096L400
A_N4096L200
B_N2048L200
dlog ρ / dlog r
-1.0
-1.5
-2.0
-2.5
0.01
0.1
1
r / r_vir
Ishiyama et al. 2014


CDM
$m_{DM} = 100GeV$
$m_{DM} = 5keV$
$m_{DM} = 1keV$
$m_{DM} = 250eV$
~10¹²
~10¹⁰
~10⁷
~10⁻⁶
$\Delta^2(k) = k^3P(k)/2\pi^2$
$k[h\mathrm{Mpc}^{-1}]$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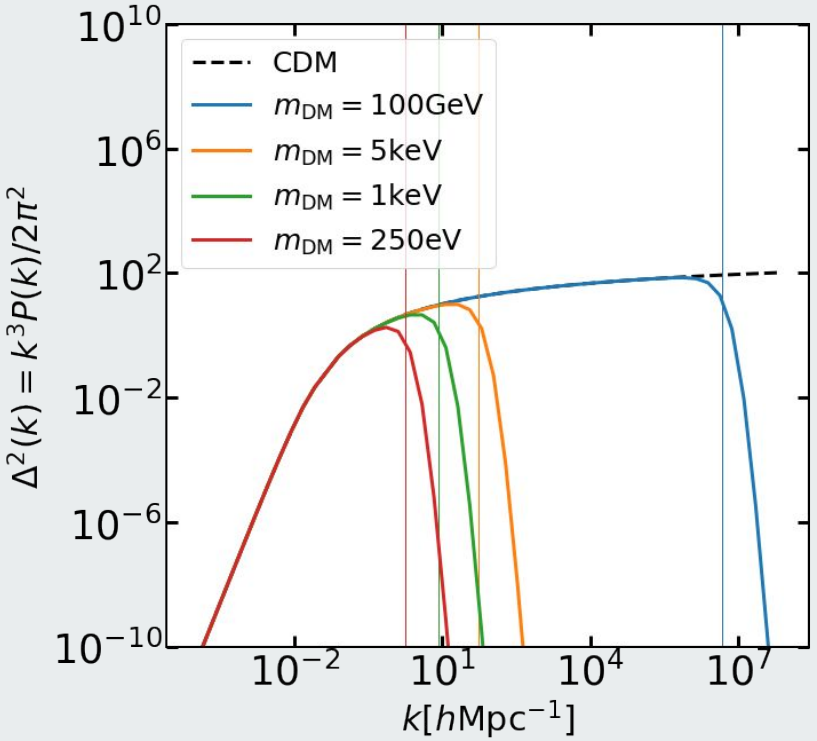
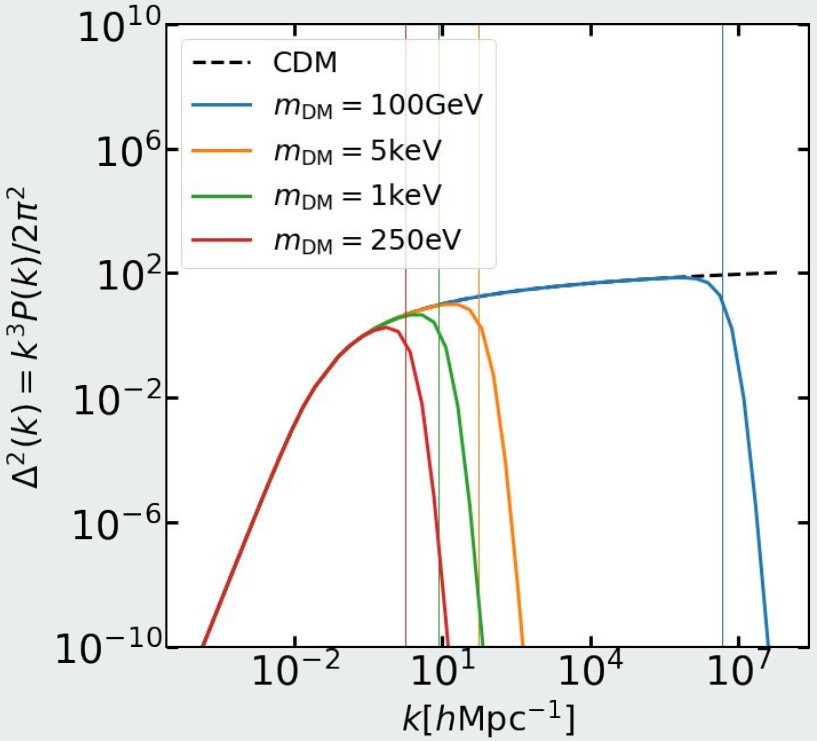
CDM
A_N4096L400
A_N4096L200
B_N2048L200
dlog ρ / dlog r
r / r_vir
Ishiyama et al. 2014

Outline



- Does the steep cusp form in any WDM cosmology?

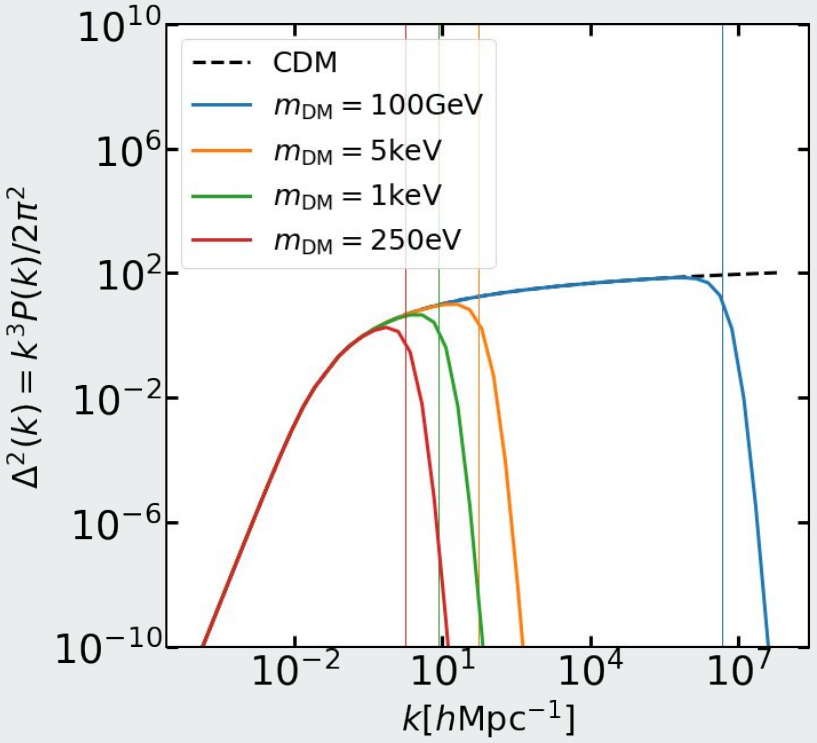
Outline



- Does the steep cusp form in any WDM cosmology?

N-body simulations

Outline

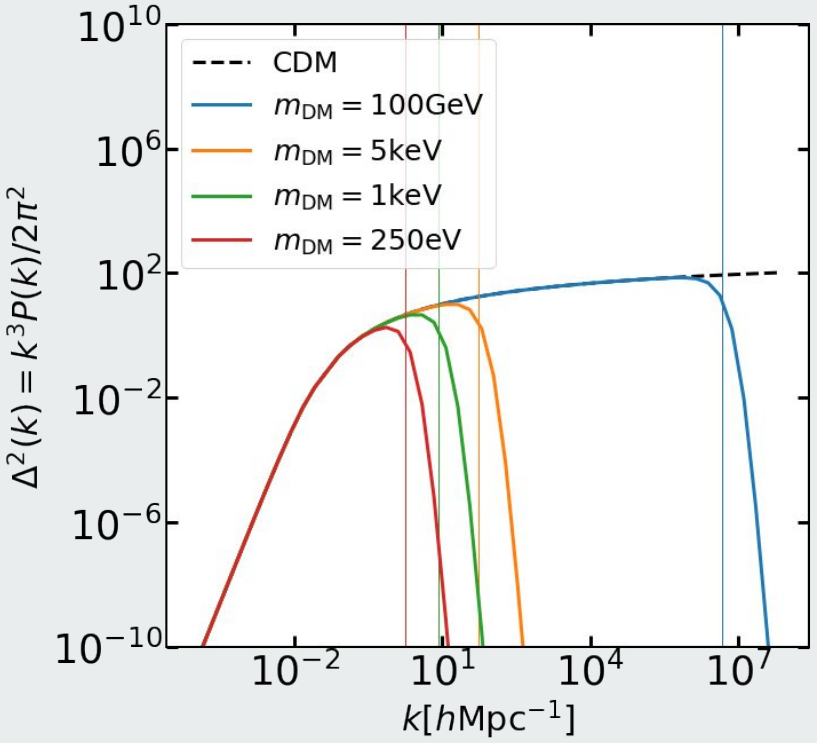


- Does the steep cusp form in any WDM cosmology?

N-body simulations

- Can we be sure about the results?

Outline

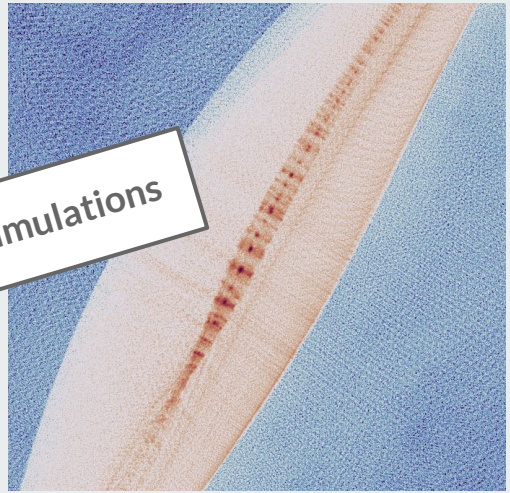


- Does the steep cusp form in any WDM cosmology?

N-body simulations

- Can we be sure about the results?

sheet+release simulations



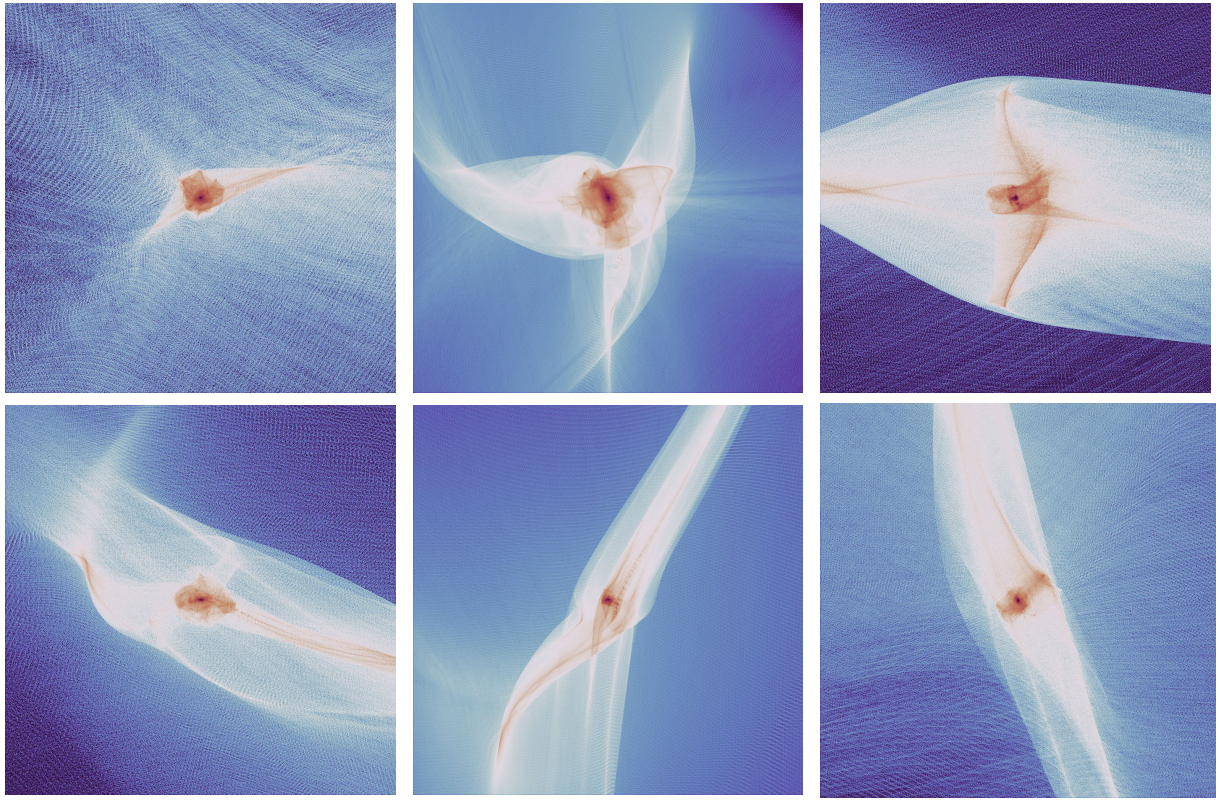
N-body zoom-in simulations

- Zoom-in setup :
  resolve %0.2-0.5 of the virial radius
- 16 halos at the half-mode mass

mDM = 250eV
Mhm ~ 10^{12} Msun/h

mDM = 1keV
Mhm ~ 10^{10} Msun/h

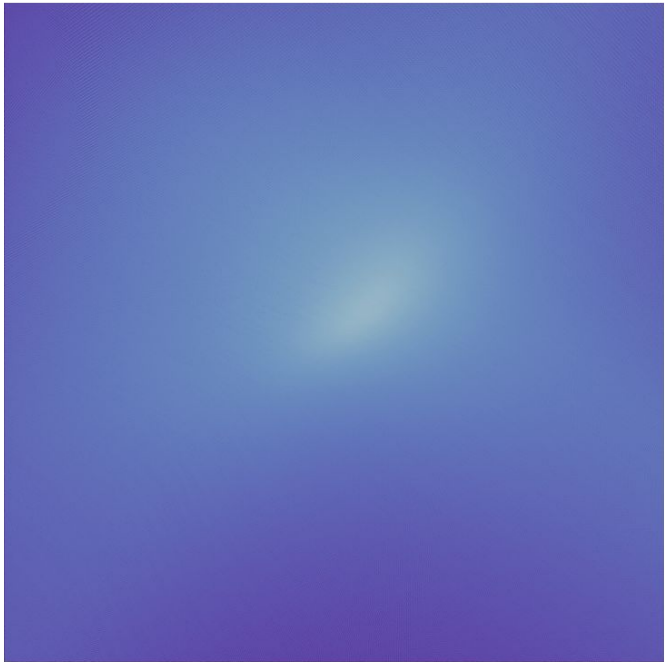
mDM = 5keV
Mhm ~ 10^{7} Msun/h



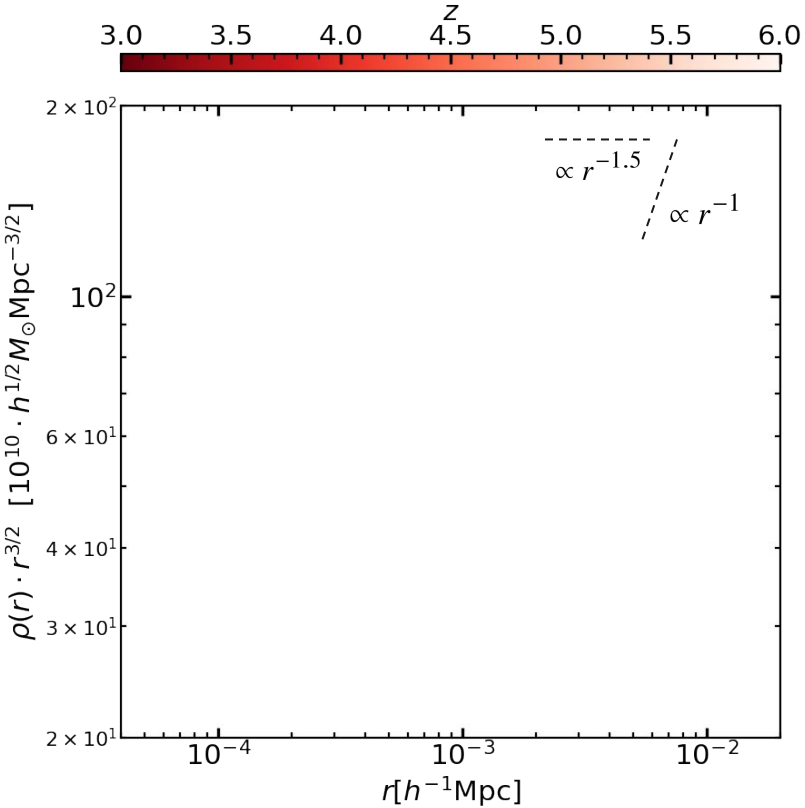
Density profiles: example

$m_{\rm DM} = 1{\rm keV}$

$M(z_{\rm fin}) = 1.55 \cdot 10^{10} h^{-1} {\rm M}_\odot$



Collapse from sheet



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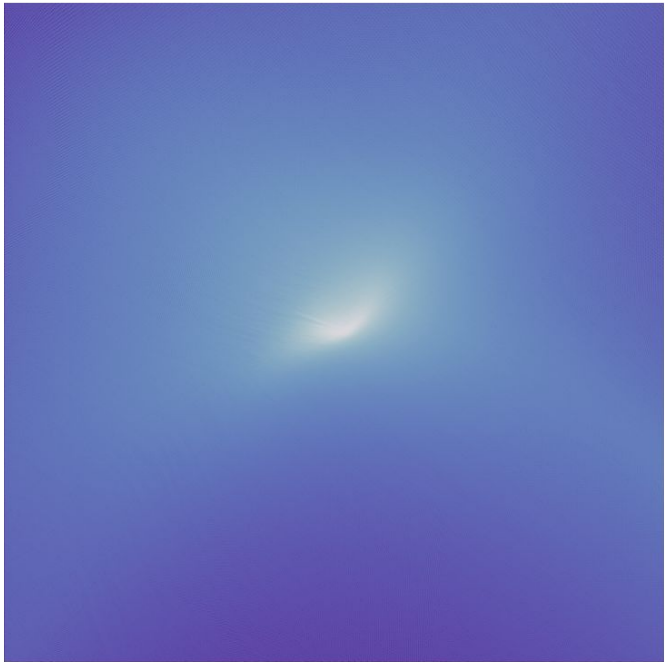

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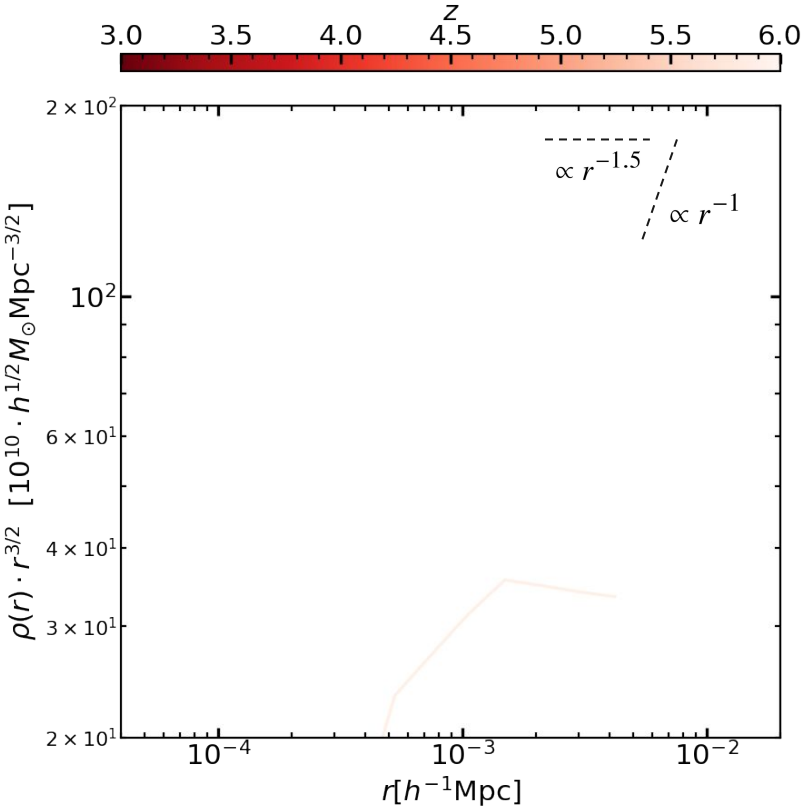

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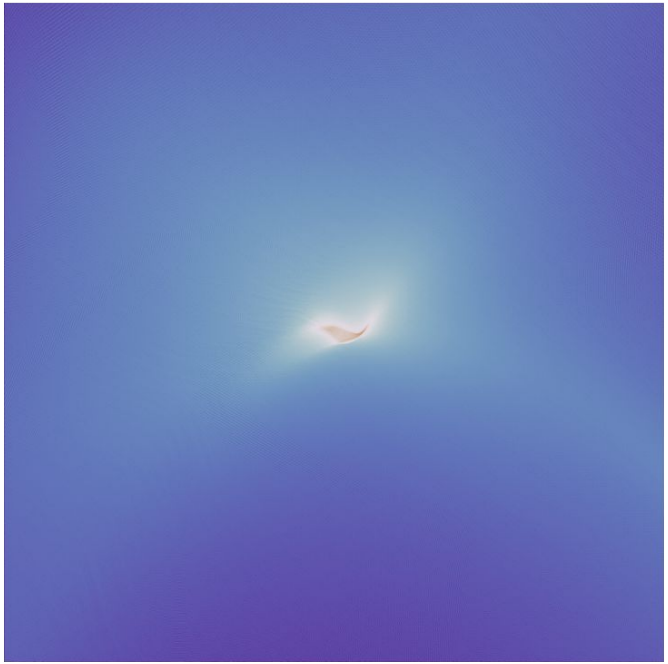

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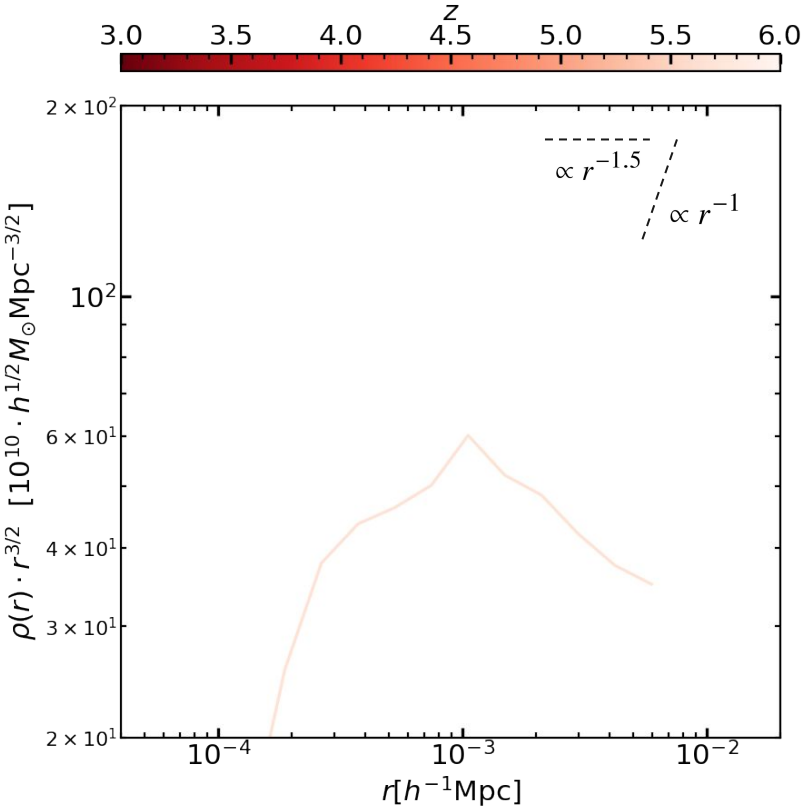

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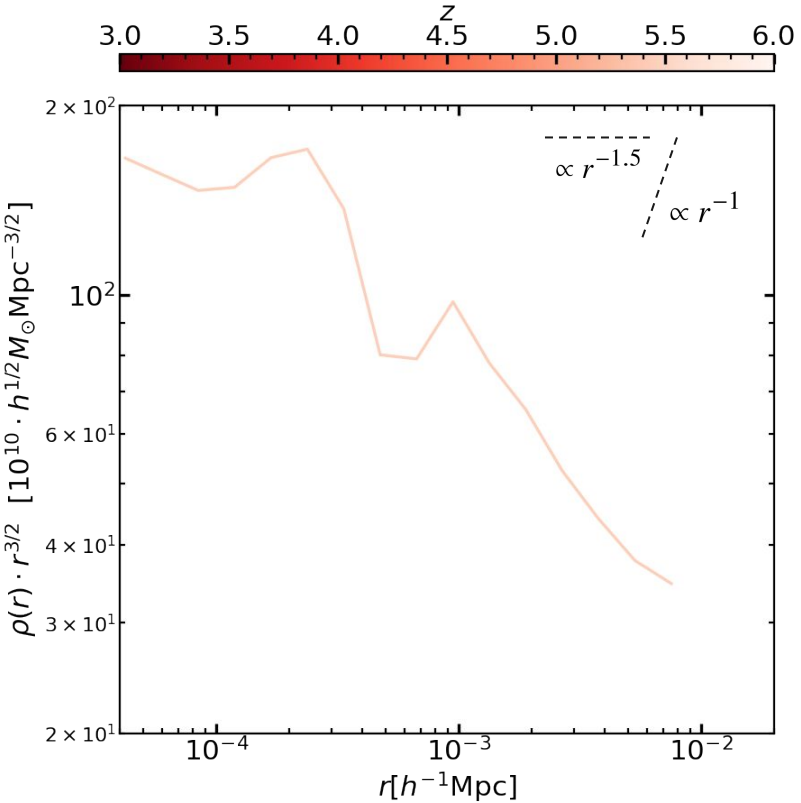
Collapse from sheet



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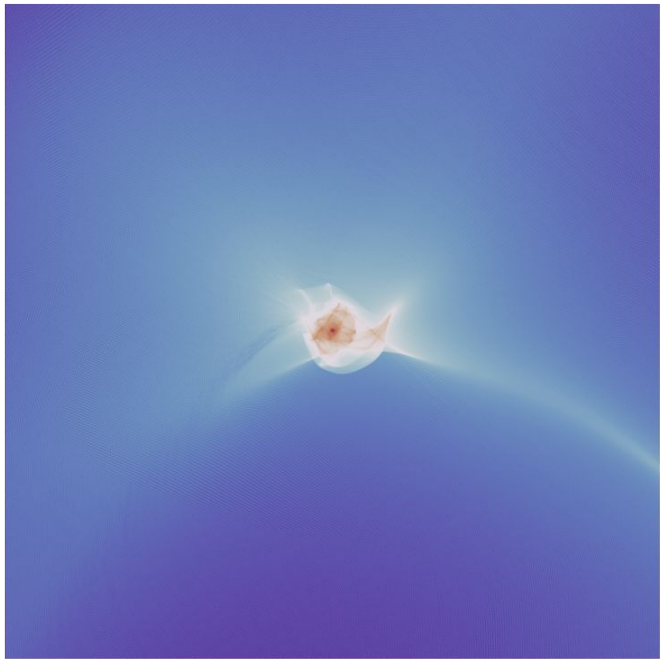
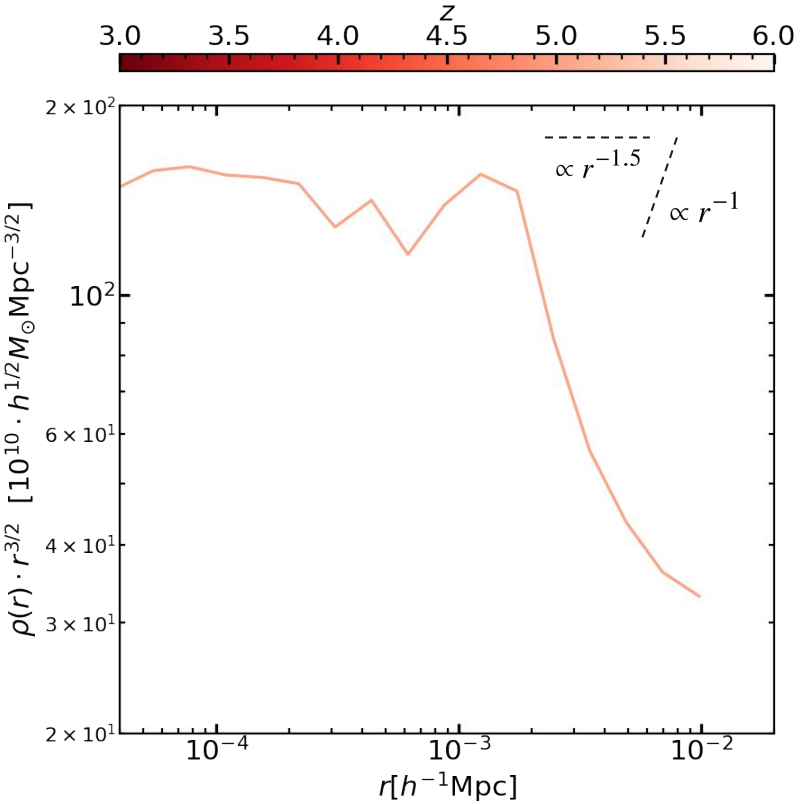


Collapse from sheet



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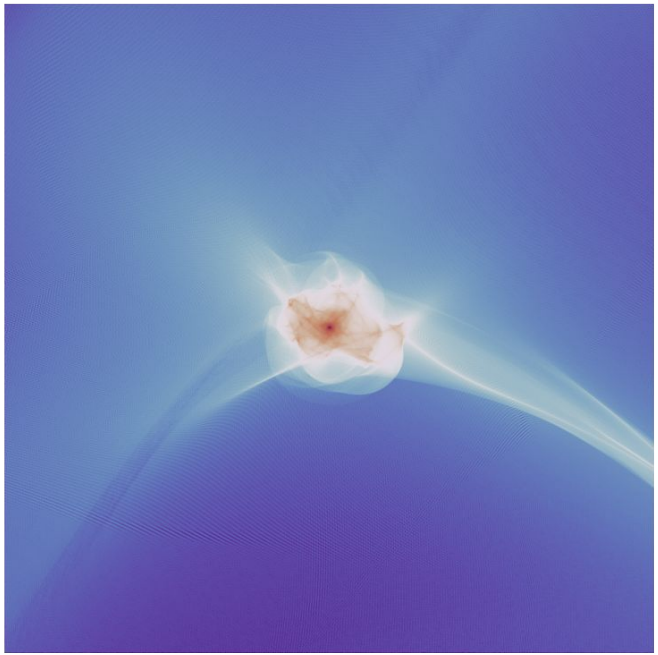

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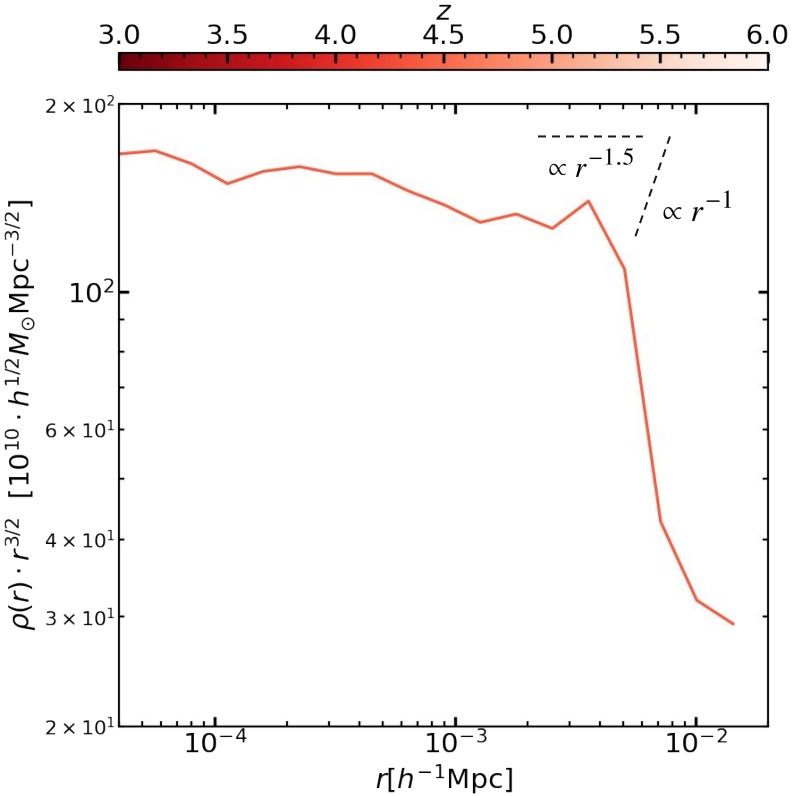

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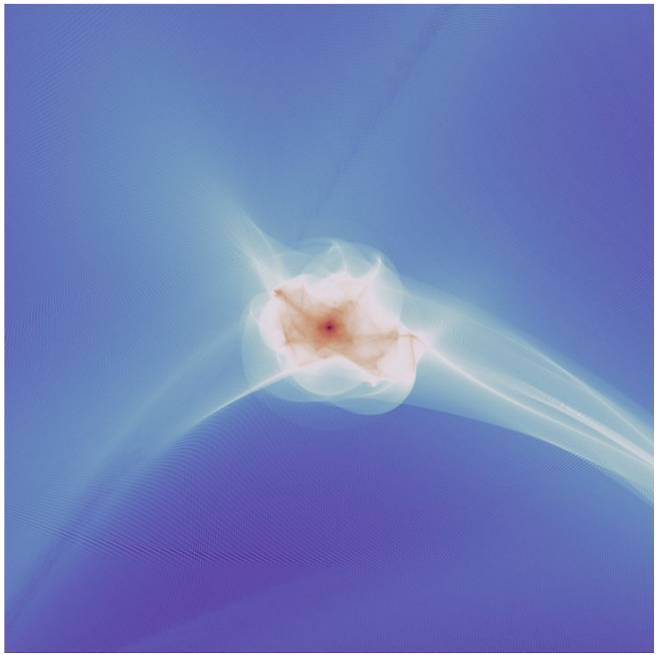

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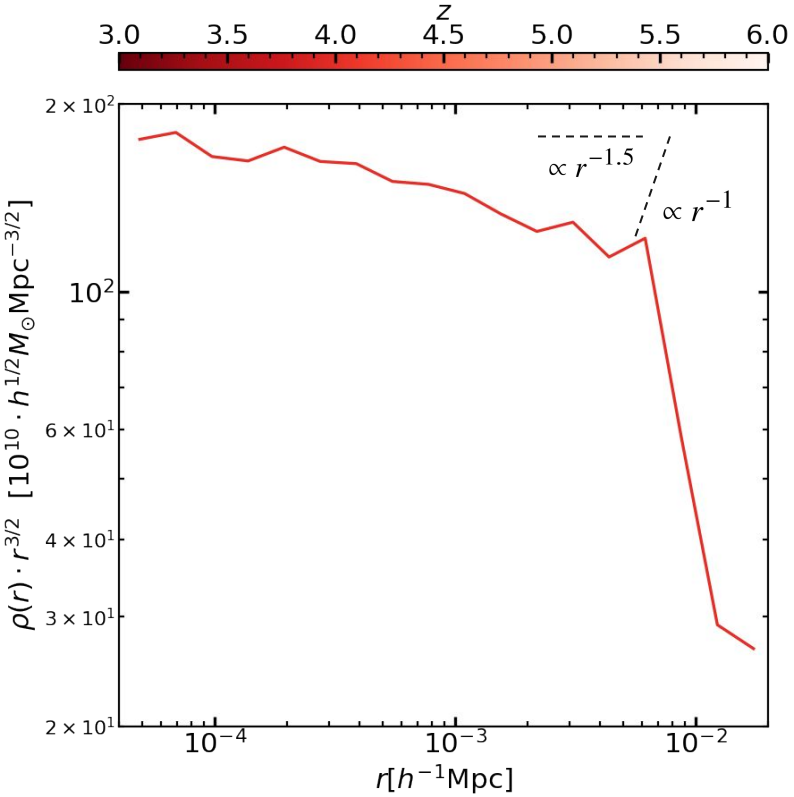

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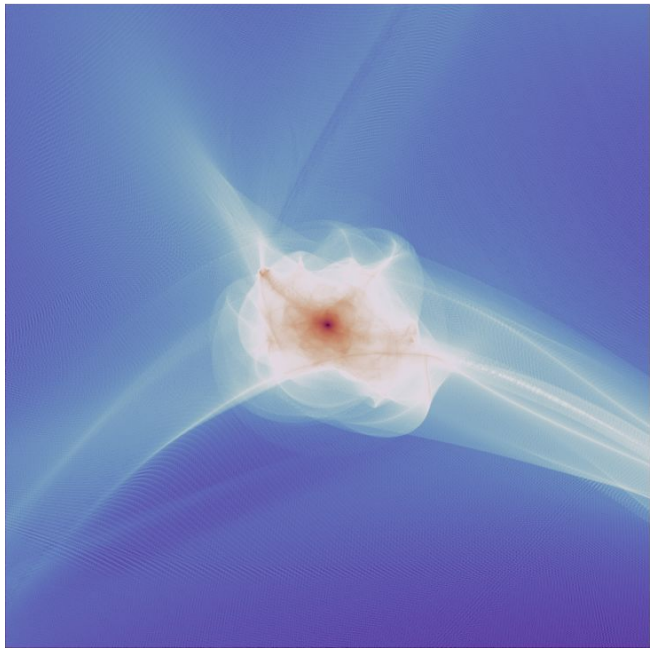
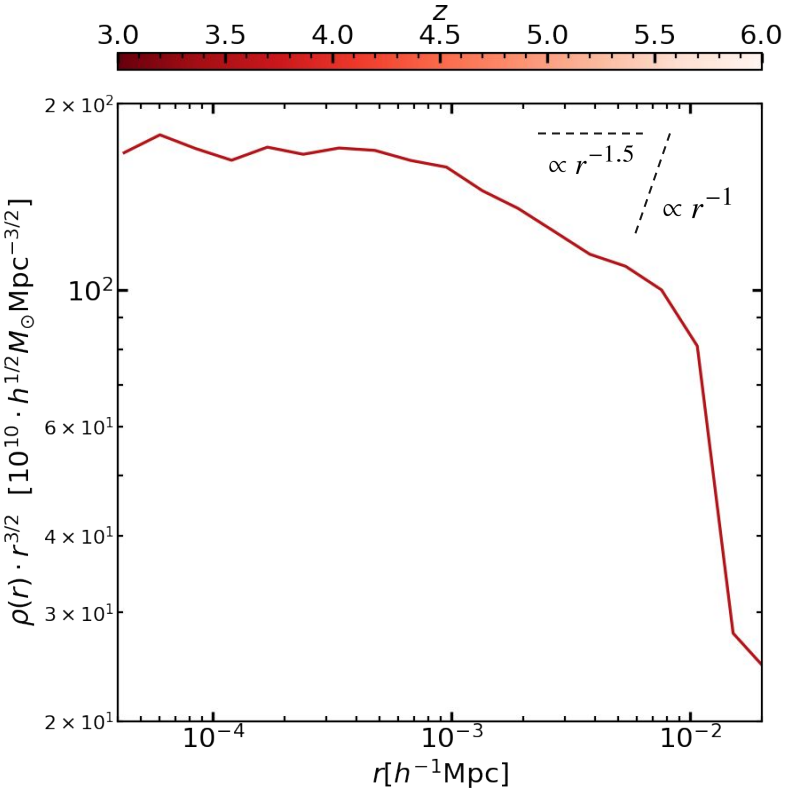


Collapse from sheet



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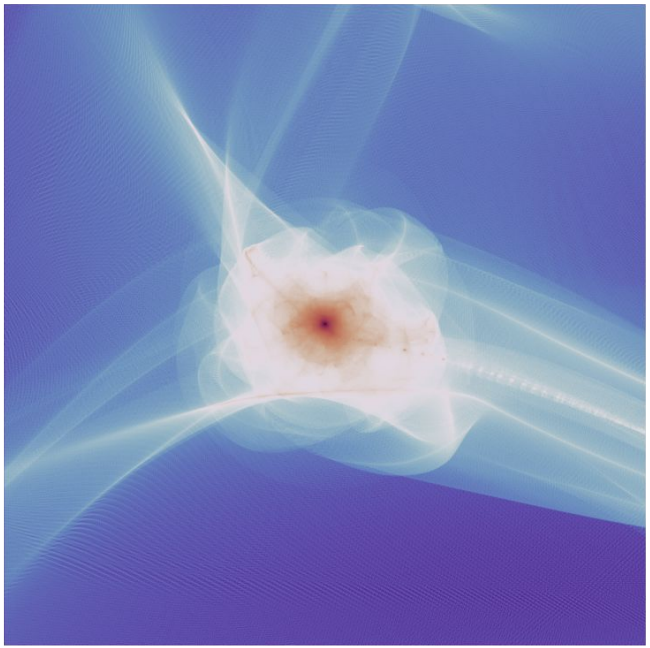
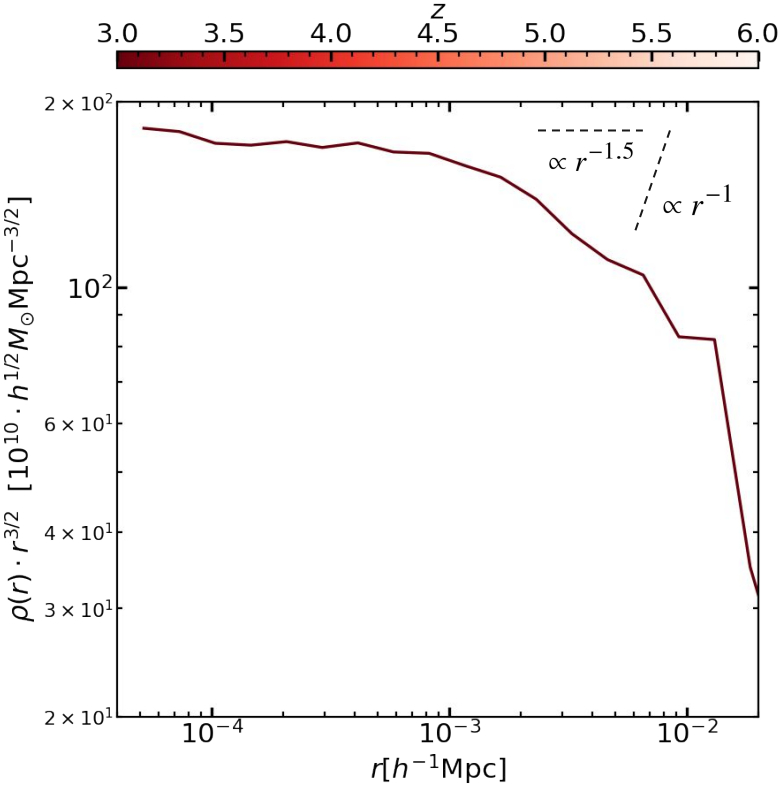
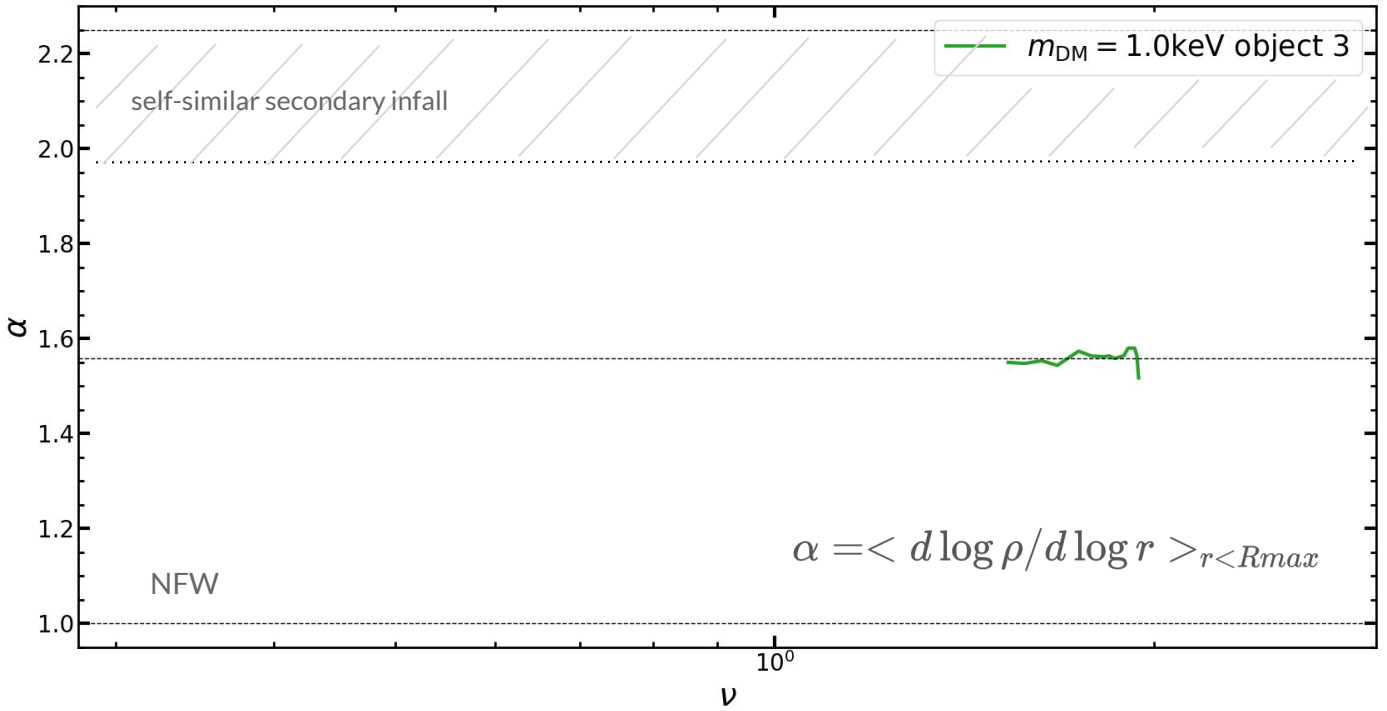


Collapse from sheet



Summary plot: inner cusp slope



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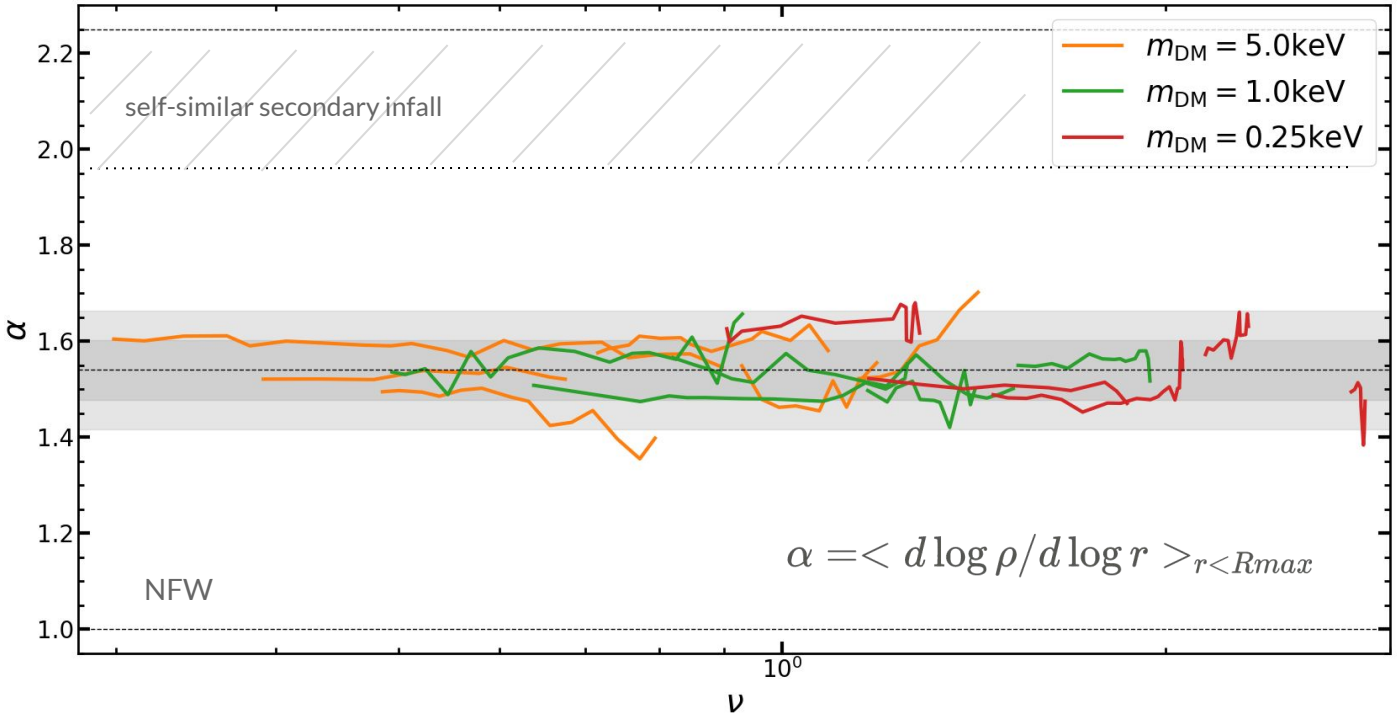


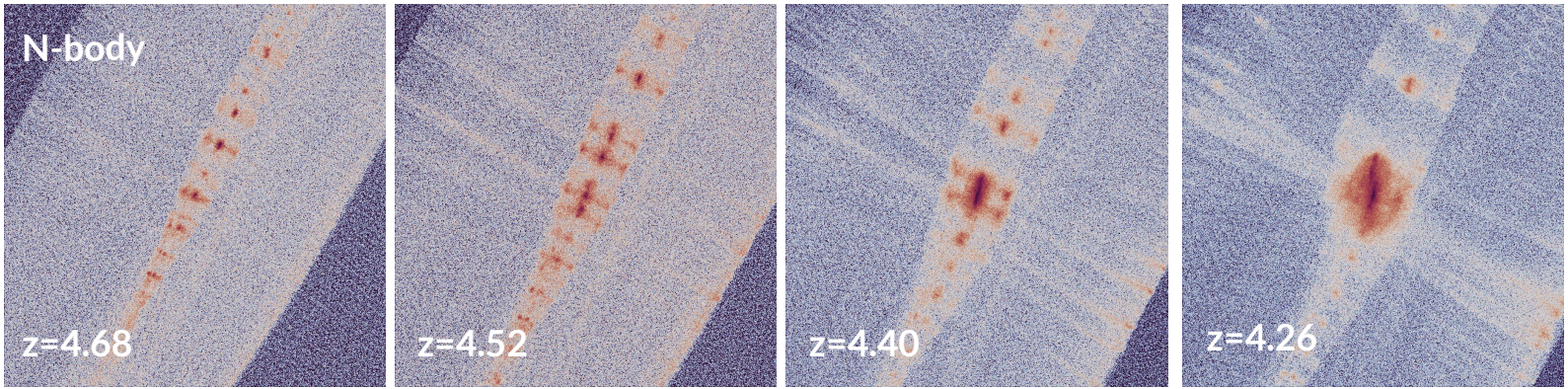
~10^7 Msun

~10^{10} Msun

~10^{12} Msun

Artificial fragmentation: N-body simulations

Does it affect the structure of the halo?



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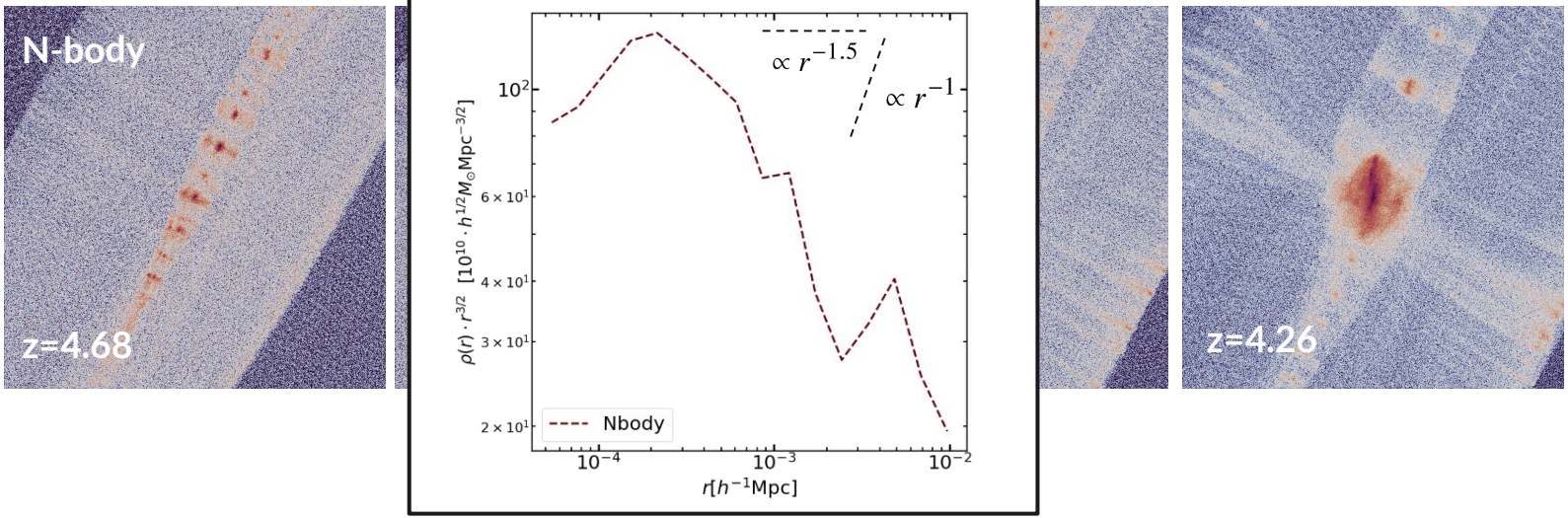
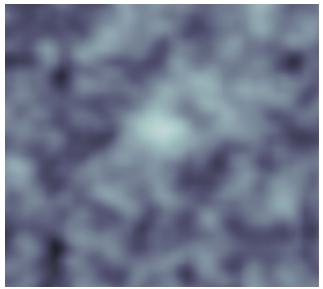
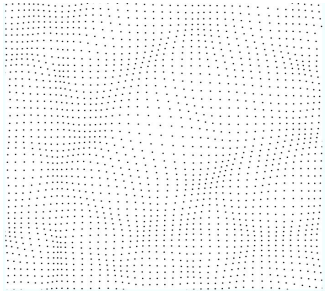


Solving the Vlasov-Poisson equation

N-body Discretize → Evolve →





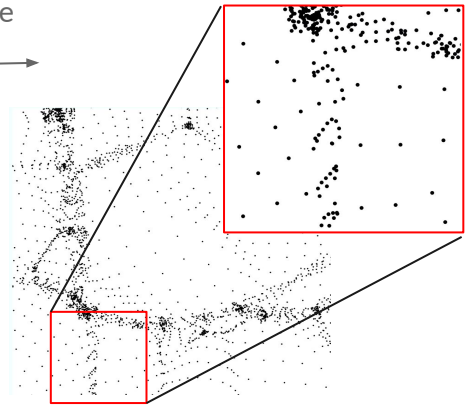
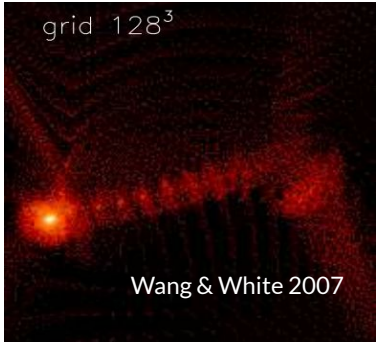


Image credit: Jens Stücker



Solving the Vlasov-Poisson equation

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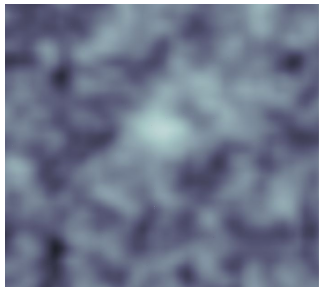
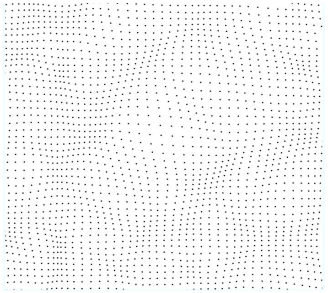




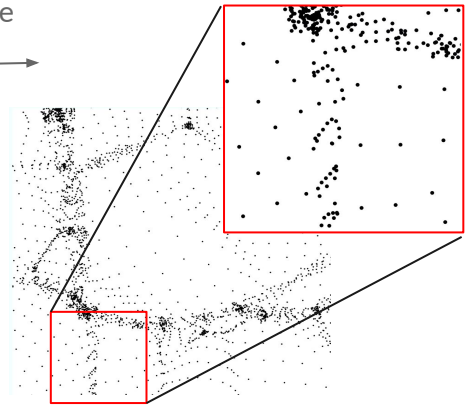
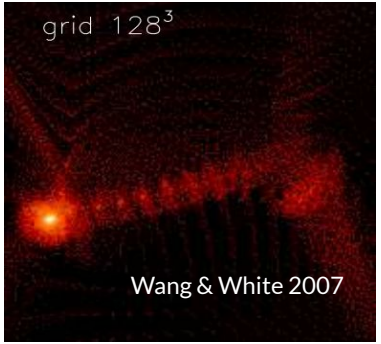


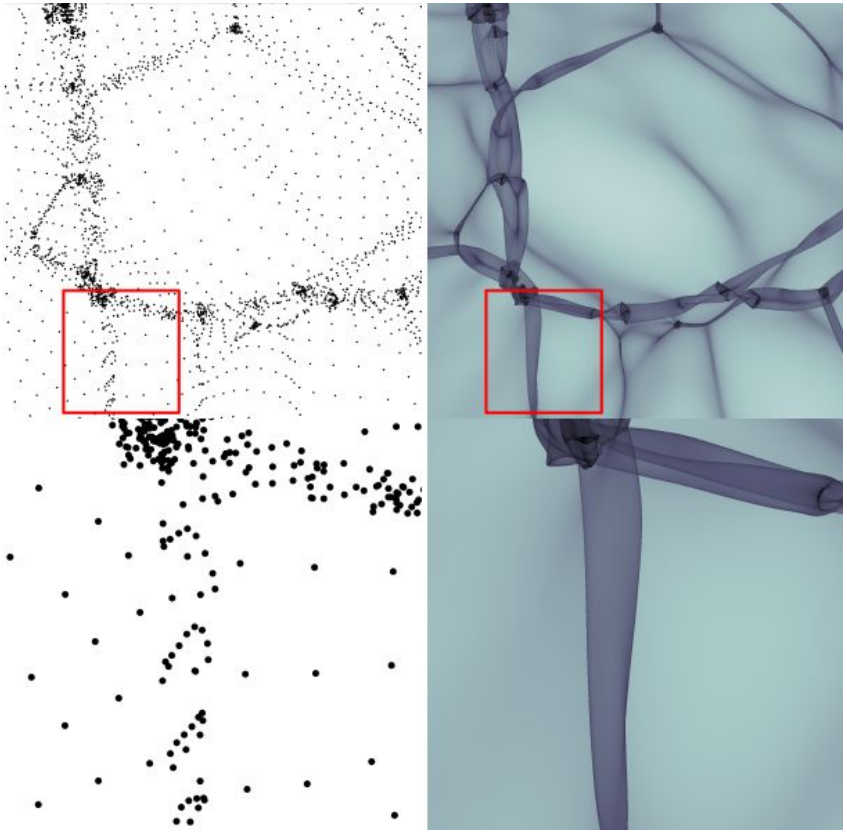
Image credit: Jens Stücker



If we used a **better density estimate** for the computation of the forces,
the numerical errors that cause the artificial fragmentation would be negligible

N-body and Phase-space density estimates

N-body density estimate



Phase-space density estimate

Solving the Vlasov-Poisson equation

Image credit: Jens Stücker

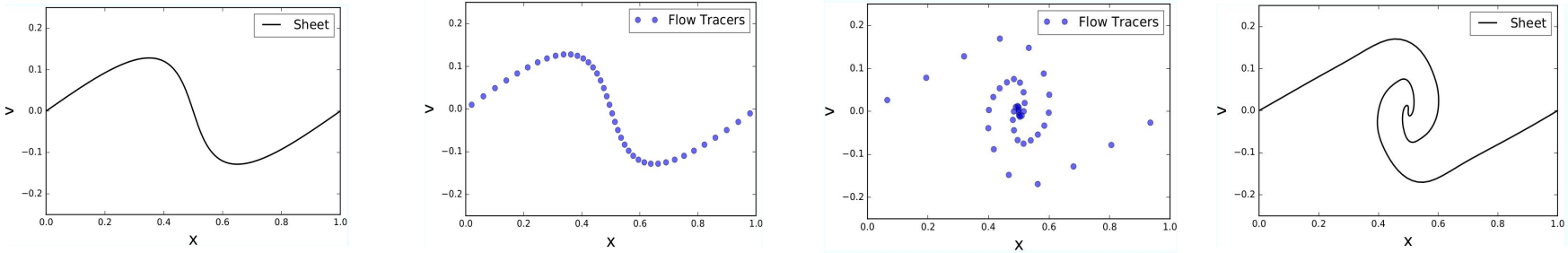
Sheet

Discretize

to compute the forces we have a great density estimate

Evolve

Interpolate back and recover the phase-space dark matter sheet



1D dark-matter phase-space sheet

Solving the Vlasov-Poisson equations

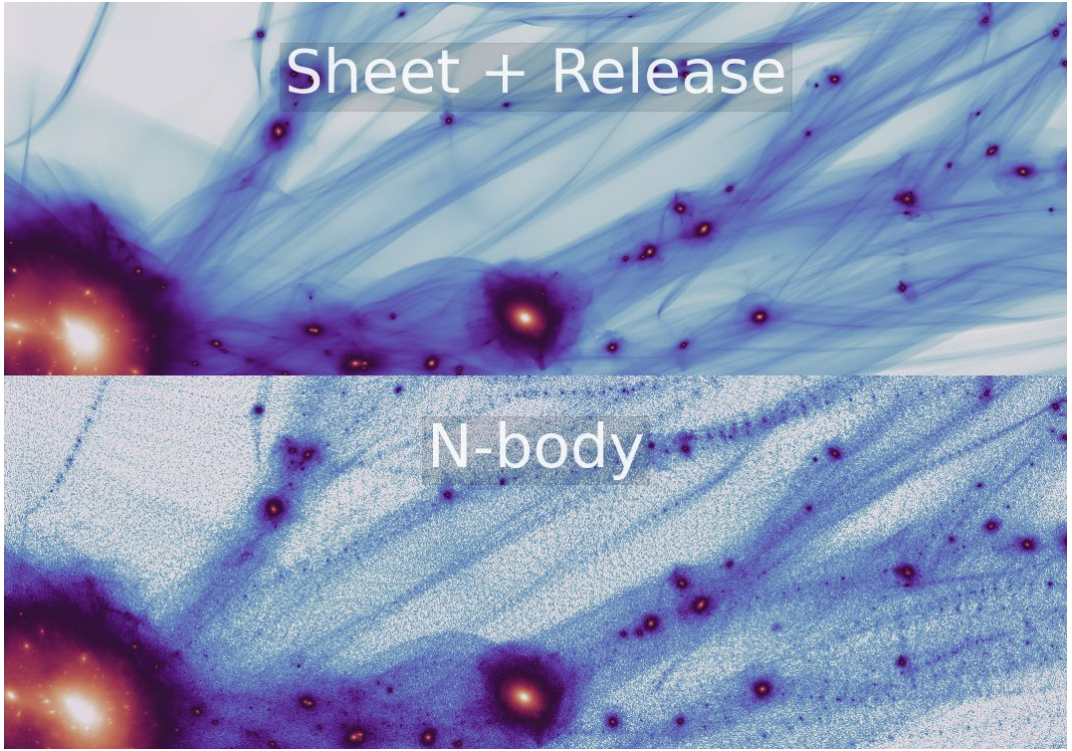
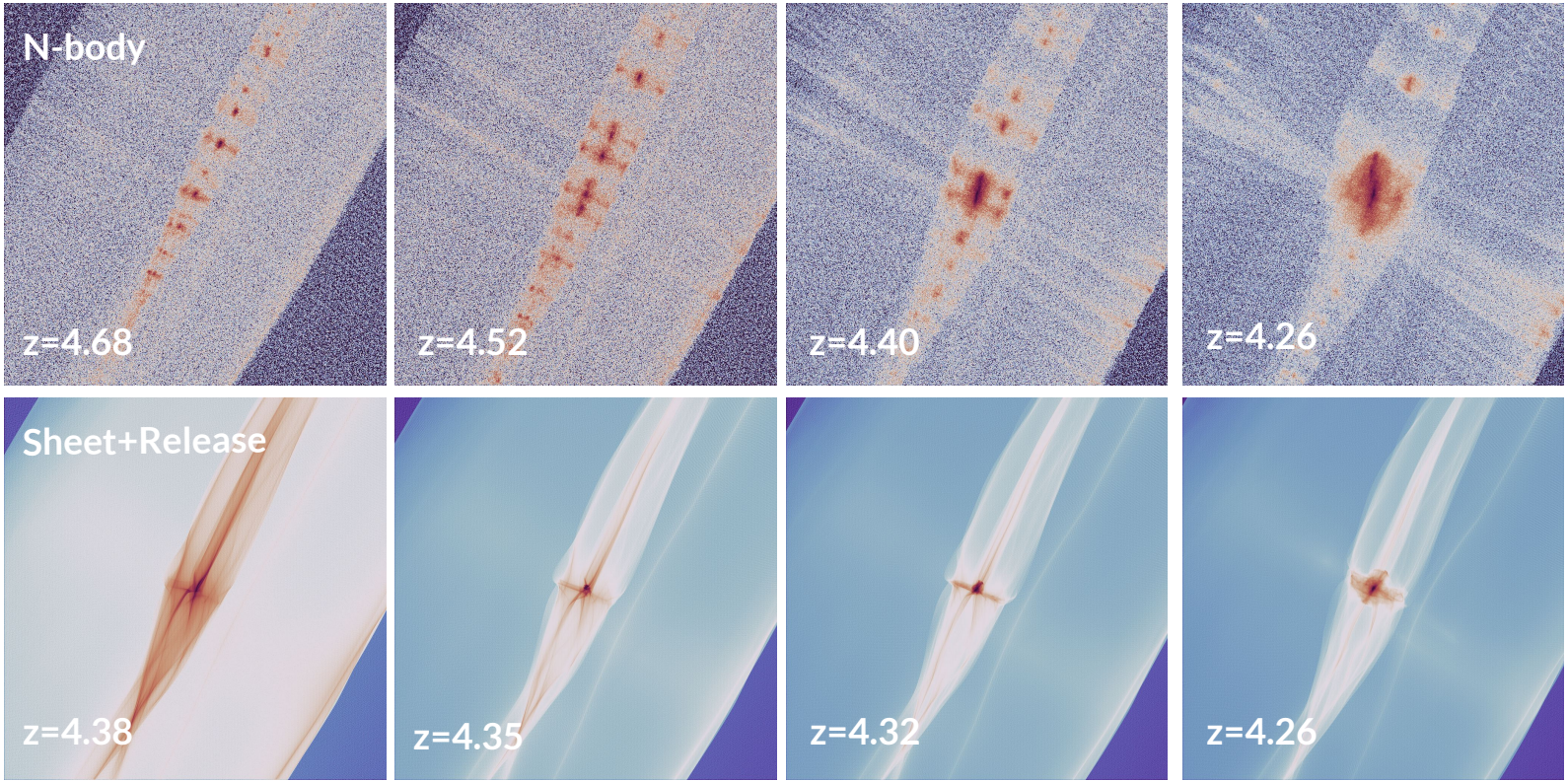


Image credit: Jens Stücker

- good density estimate (also in low density regions)
- no artificial fragmentation
- independent code to N-body

Removing the pre-collapse fragmentation



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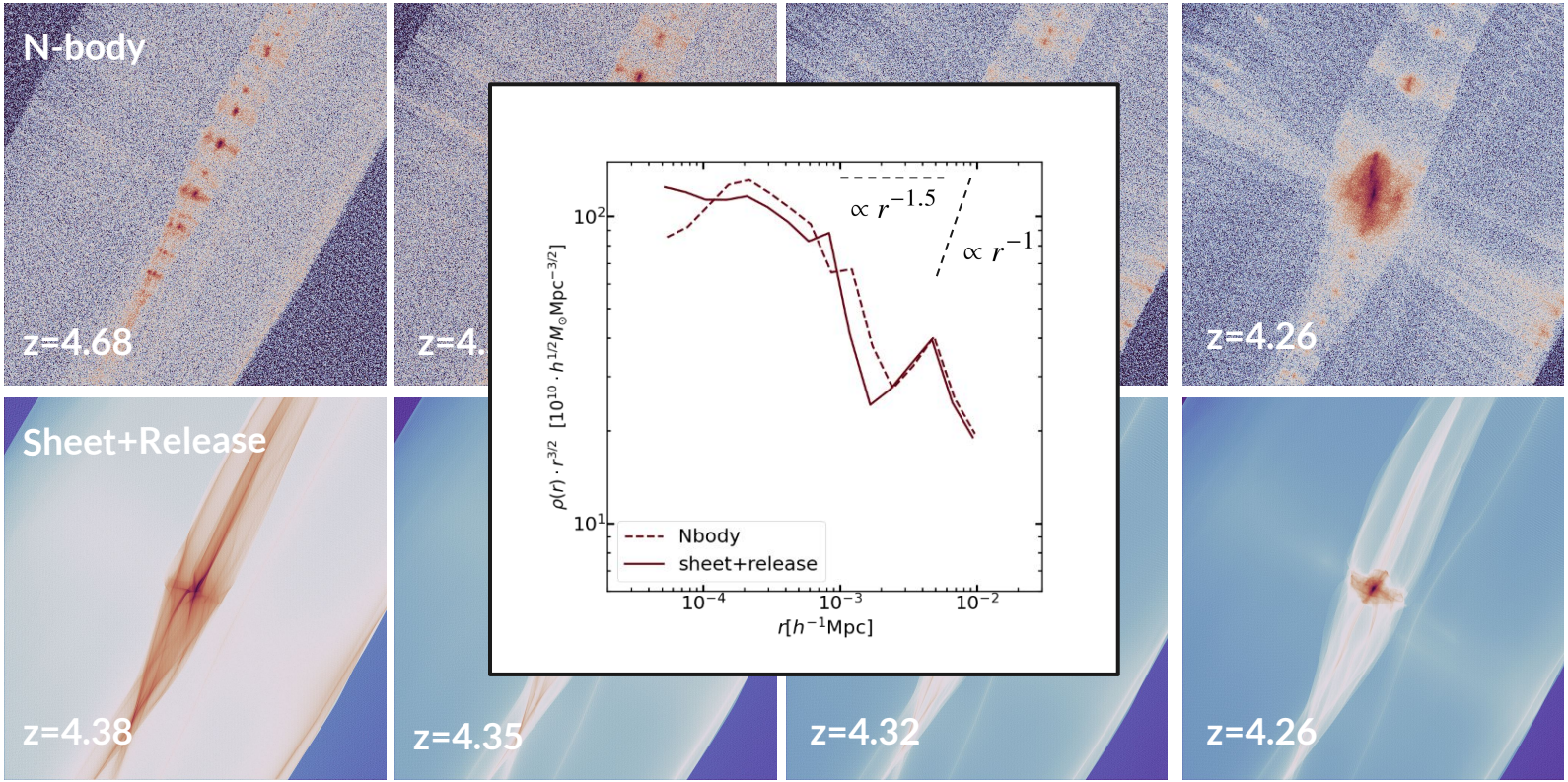


Conclusions

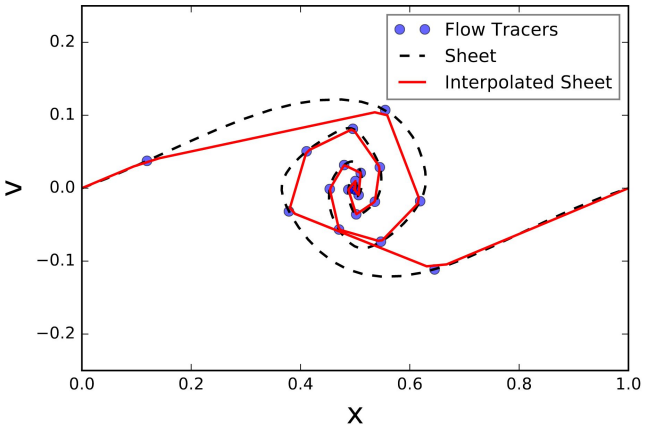
- The first halos in WDM cosmologies have steep inner cusps (at least 18 orders of magnitude in mass)
- Artificial fragmentation shallows the innermost part of the cusp.
- Getting rid of the artificial fragmentation, we recover the steep cusp.

Conclusions

- The first halos in WDM cosmologies have steep inner cusps (at least 18 orders of magnitude in mass)
- Artificial fragmentation shallows the innermost part of the cusp.
- Getting rid of the artificial fragmentation, we recover the steep cusp.

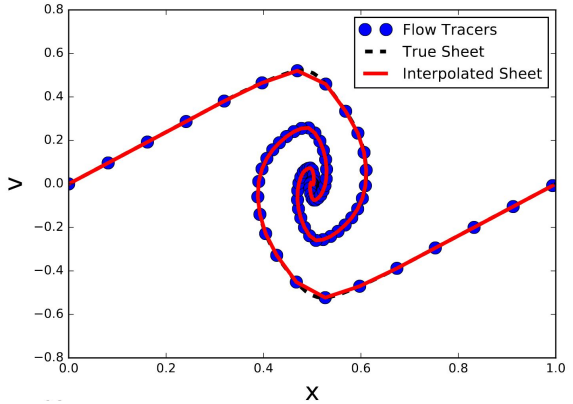
- **The inner cusp is set by the gravitational collapse from the smooth field. If there are mergers in the formation process, the inner cusp is shallowed.**

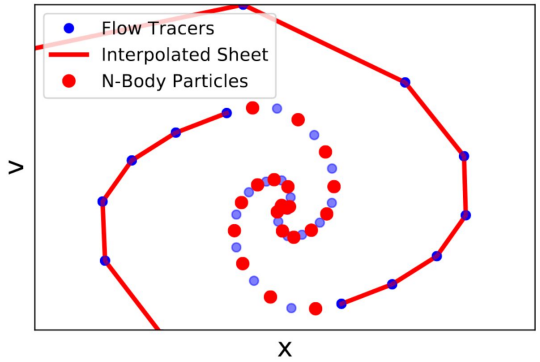
Back-up slides: Complexity of the sheet



add more flow tracers

release

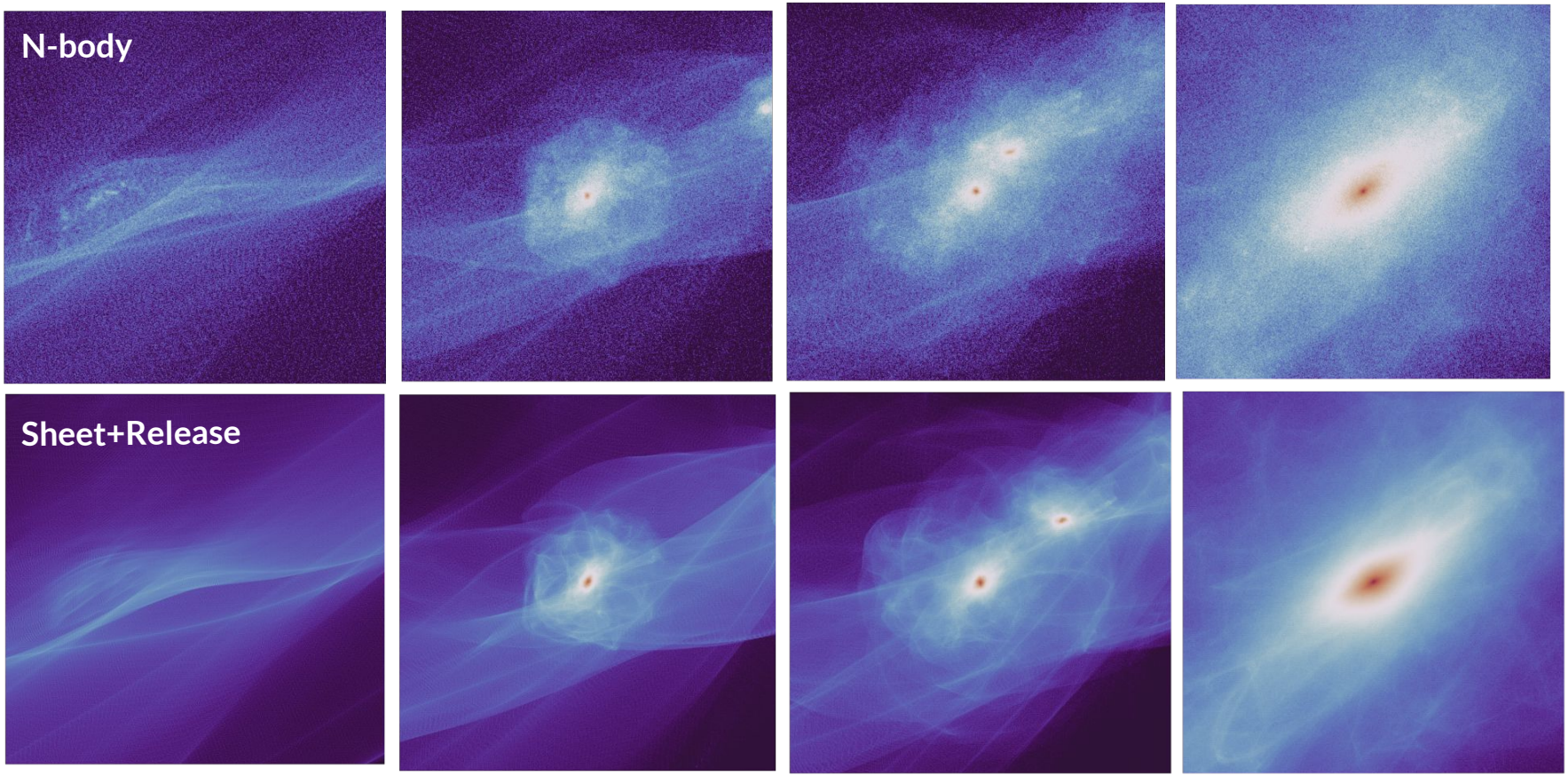




$\propto a^{12}$

Image credit: Jens Stücker

Back-up slides: sheet+release test



Back-up slides: sheet+release test