CONSTRAINTS ON SUBSTRUCTURE FROM ULTRA-FAINT DWARF DYNAMICS

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2404.01378, 2311.07654

With Peter Graham

NIGHTMARE SCENARIO

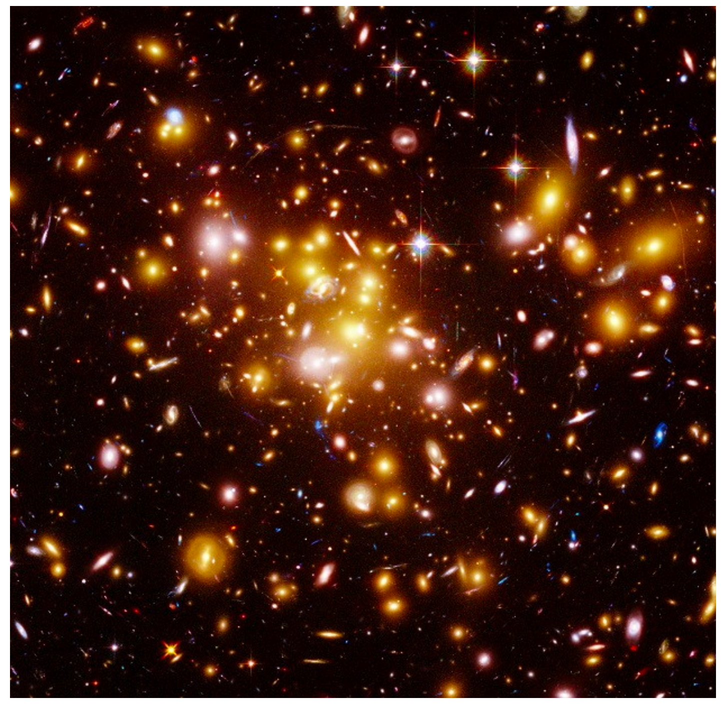
- Our only evidence for dark matter is through its gravitational interactions
- Strong limits on non-gravitational interactions: direct, indirect and colliders
- Nightmare scenario: Gravity is our only hope

STUDYING DM HALOS

- Study dark matter halos of different sizes:
  - Clusters : Limits on self-interactions
  - Galaxy-scale anomalies : hints on self-interactions
  - Dwarf galaxies : limits on ultralight mass
  - Can we go smaller?

DARK MATTER HALOS

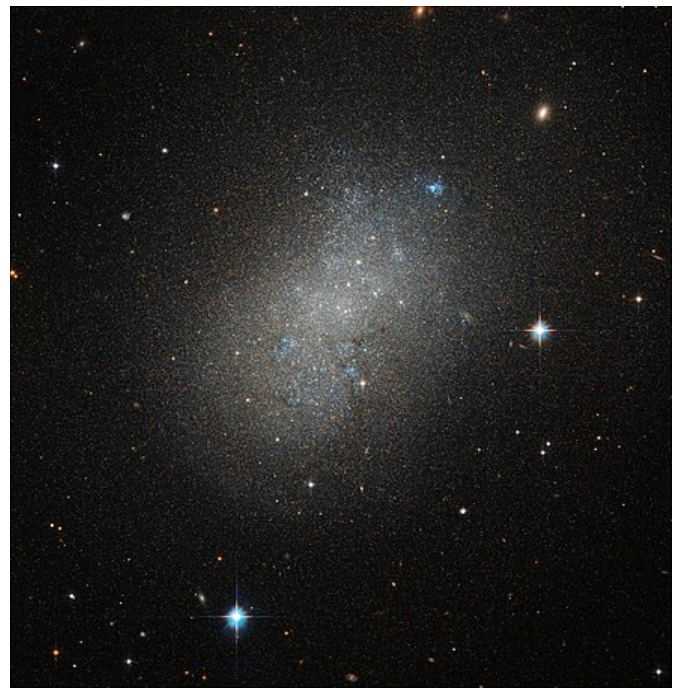
Galaxy Clusters



Galaxies

$\approx 10^{11}$ stars

Dwarf Galaxies



$\approx 10^{7}$ to 10^{9} stars

Ultrafaint Dwarf Galaxies

$\approx 10^{3}$ stars

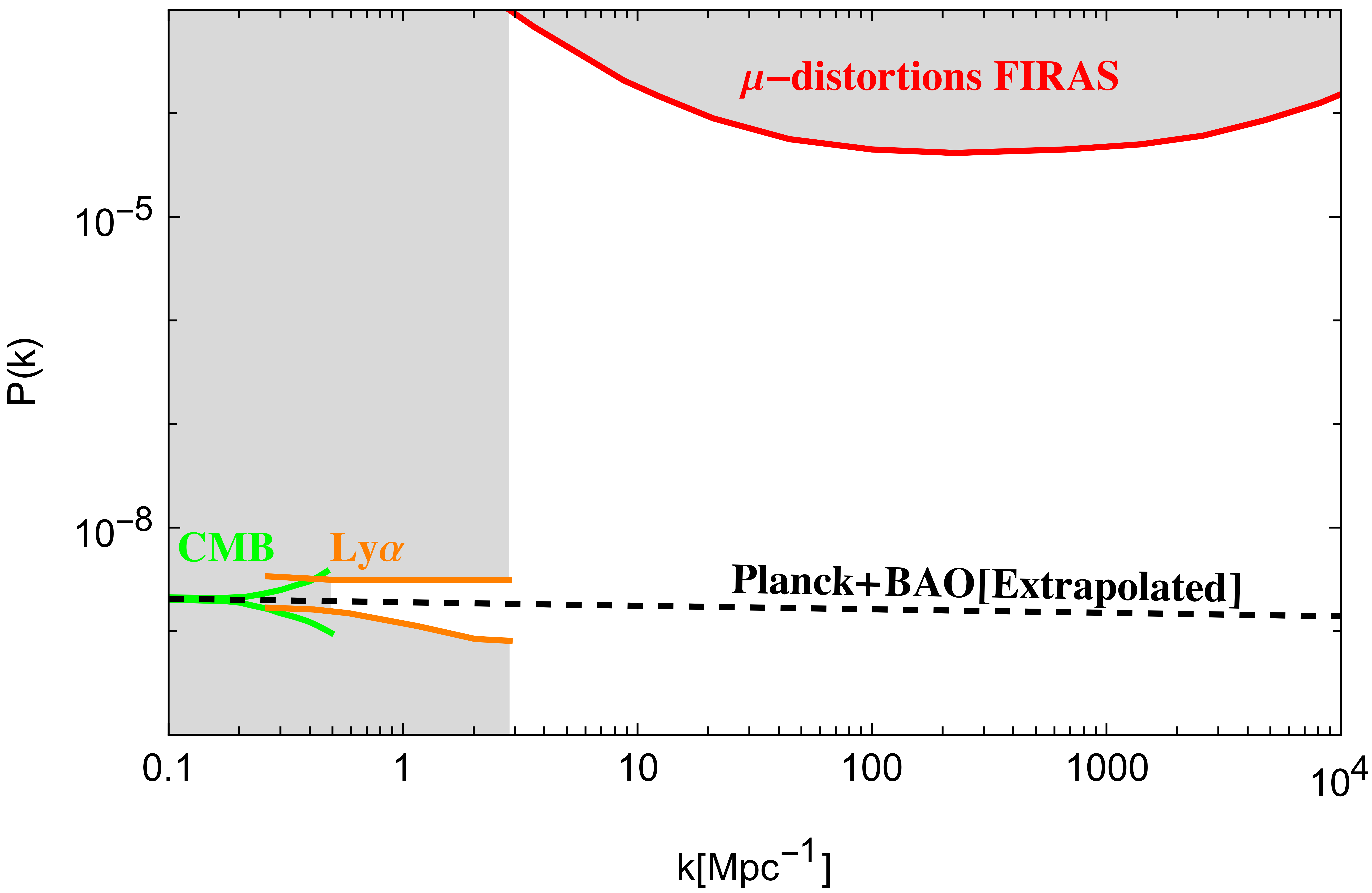
Too Few Stars

How to Study?

WHY CARE?

Primordial Power Spectrum - Models of Inflation	Enhanced Dense Substructure
Ultralight Dark Matter - Free-streaming scale & enhanced power at high k	Presence/absence of substructure
Warm dark matter	Washes out small scale structure
SIDM - Gravothermal collapse	Dense Substructure
Early Matter Domination	Enhanced substructure
Long Range Forces	Enhanced substructure

MATTER POWER SPECTRUM



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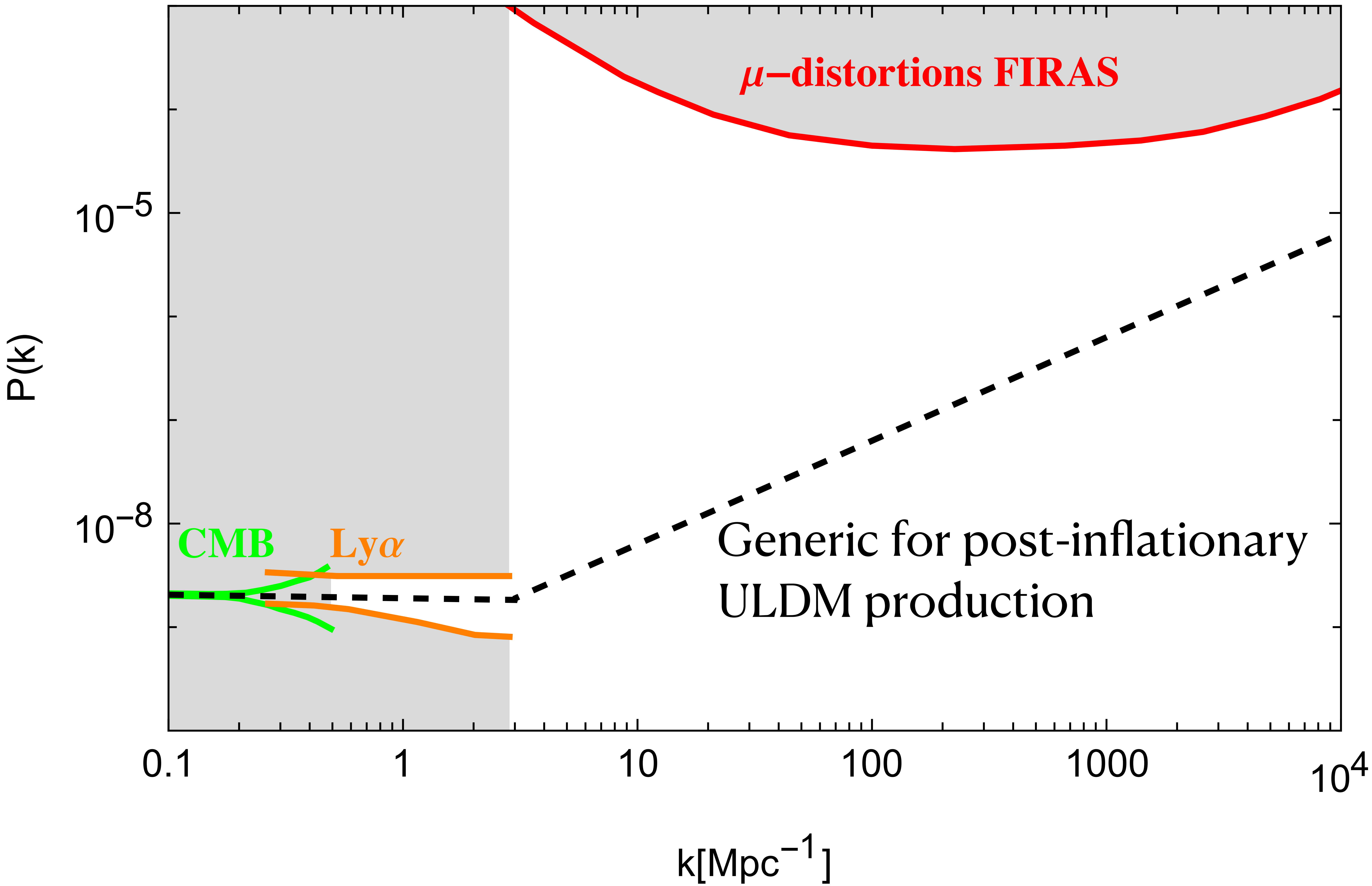

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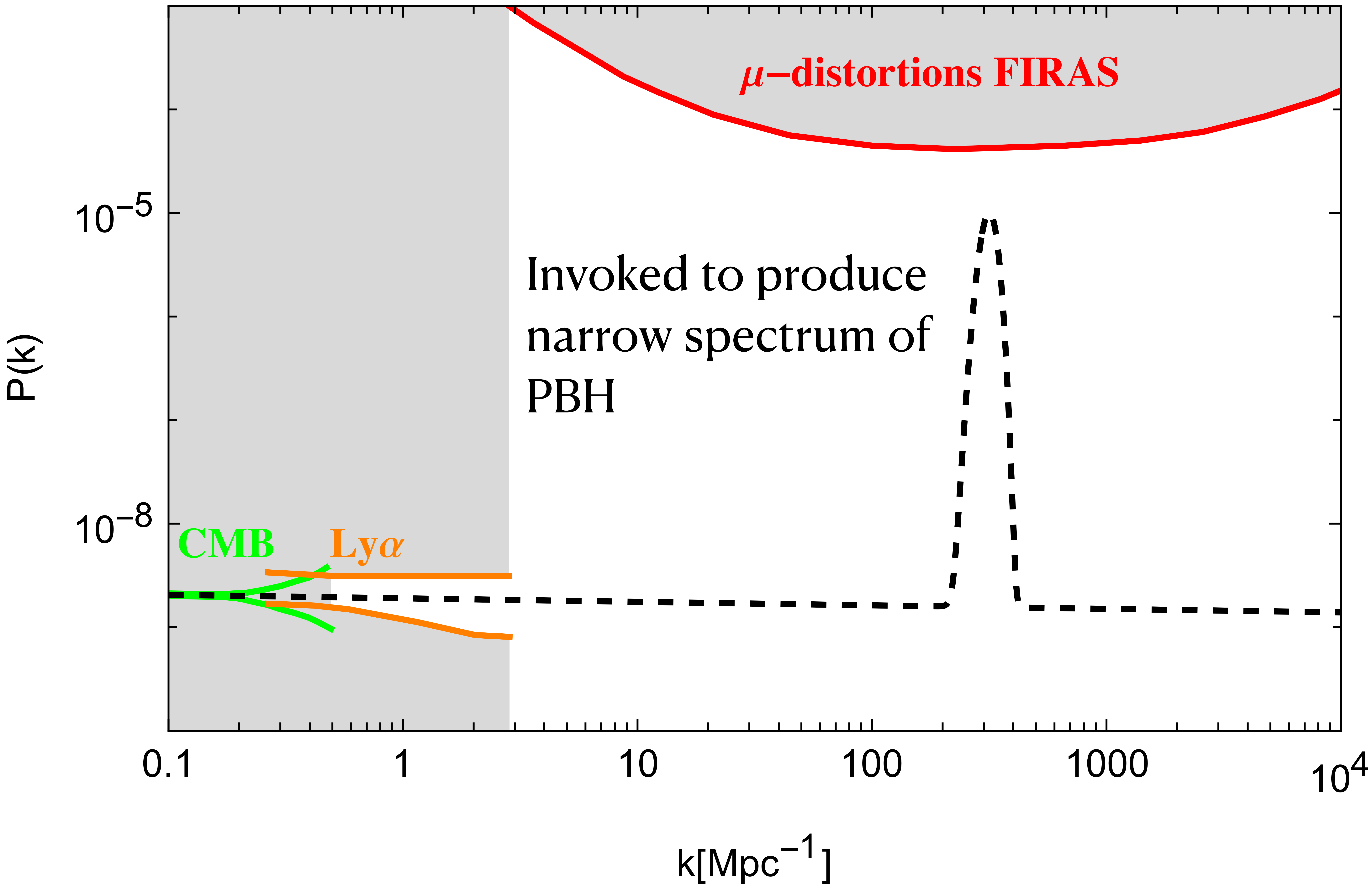
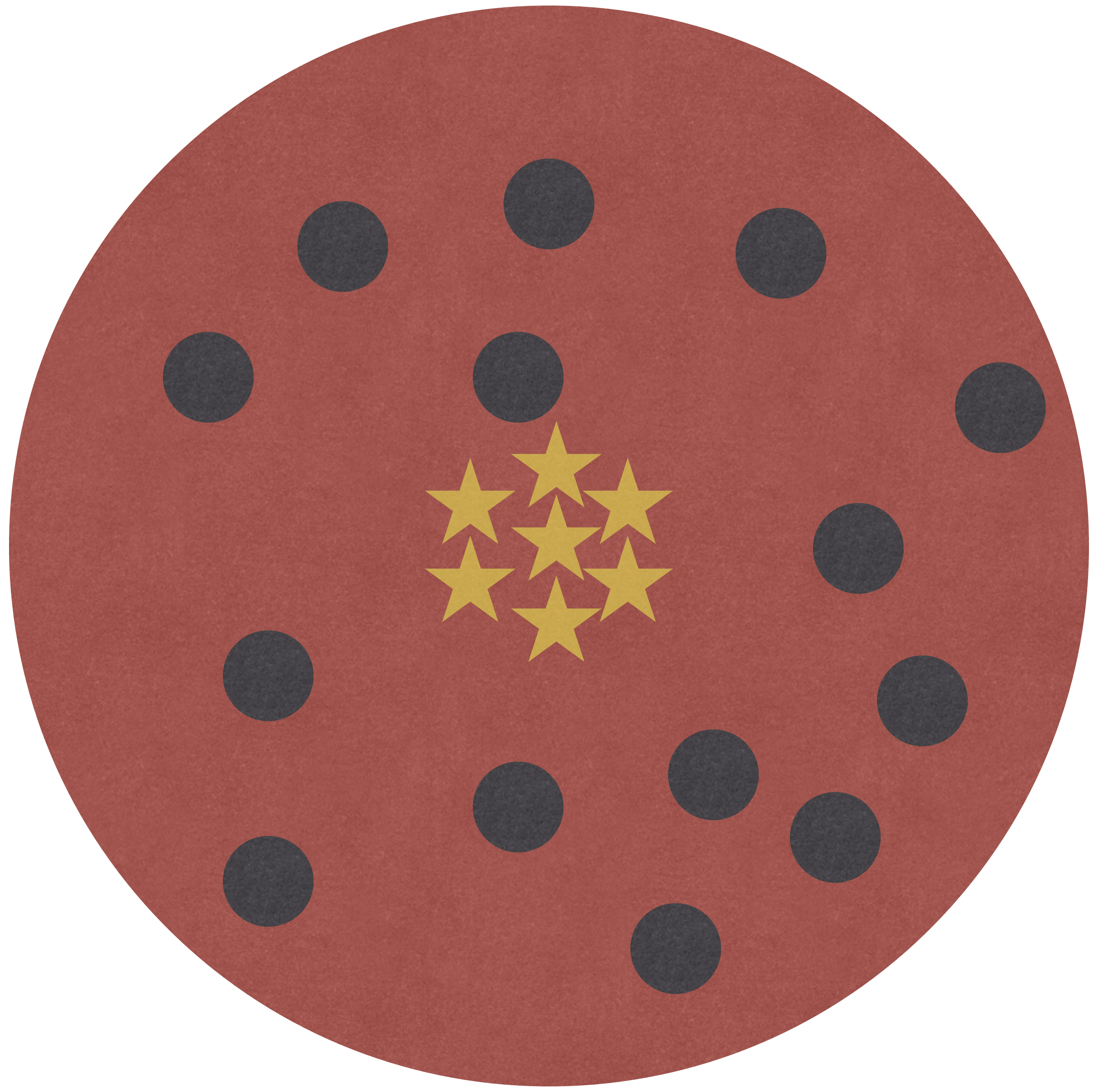
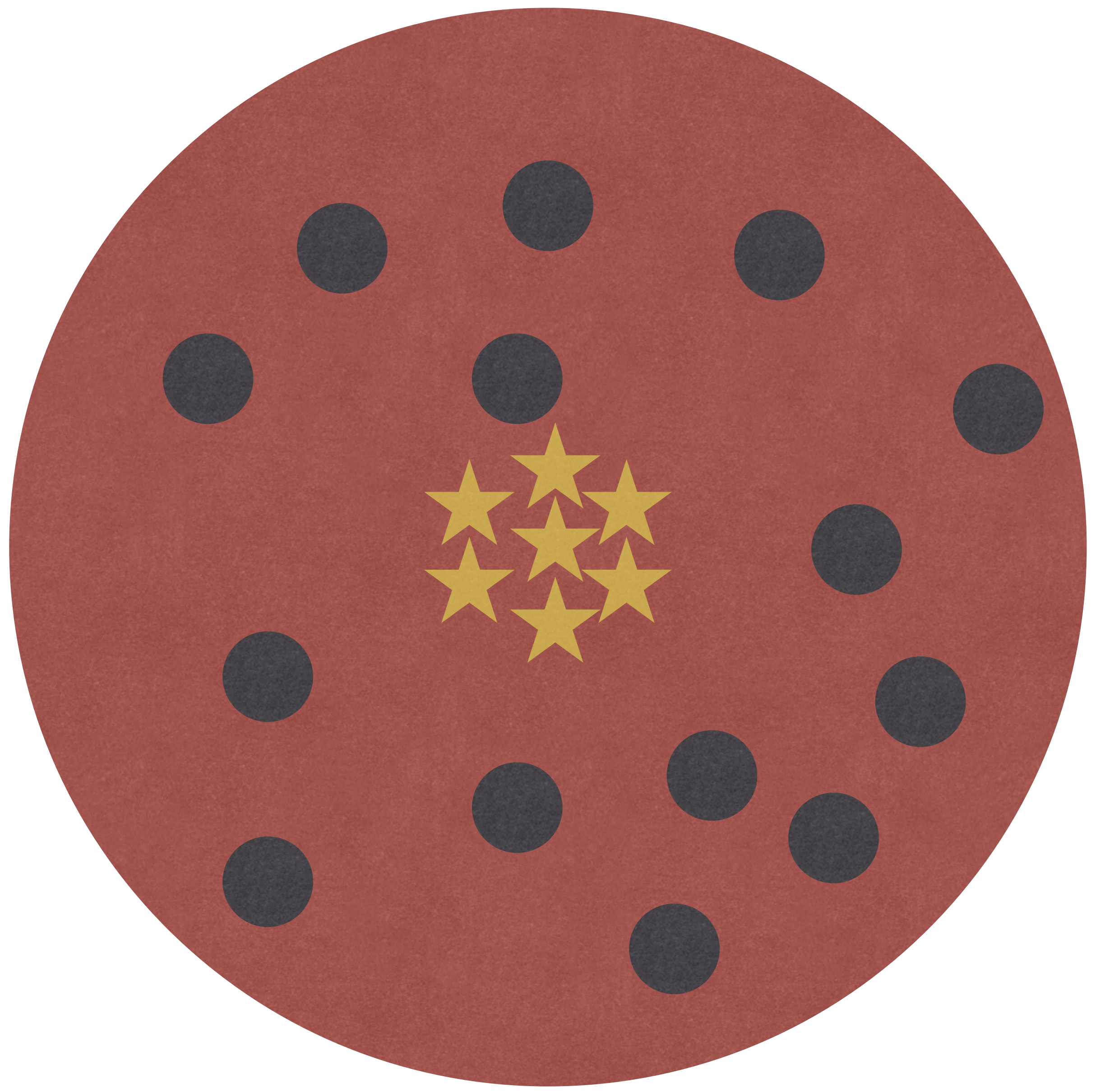


SUBSTRUCTURE

- Large power at small scales produces **Small** yet **Dense** clumps
- Hierarchical structure formation $\Longrightarrow$ small clumps are seeds for larger halos



DYNAMICAL HEATING



Ultra Faint Dwarf Galaxy

- When $M_{\rm clump} \gg M_\star$
- KE of clumps = $M_{\rm clump}\sigma^2 \gg$
  KE of stars = $M_\star\sigma^2$
- Thermodynamics $\Longrightarrow$
- Heat Transfer from clumps to stars
- Causes the star cluster to expand

$$H_A = 4\sqrt{2\pi}\frac{G^2\rho_B\left(m_B\sigma_B^2 - m_A\sigma_A^2\right)}{\left(\sigma_A^2+\sigma_B^2\right)^{\frac{3}{2}}}\log\Lambda$$

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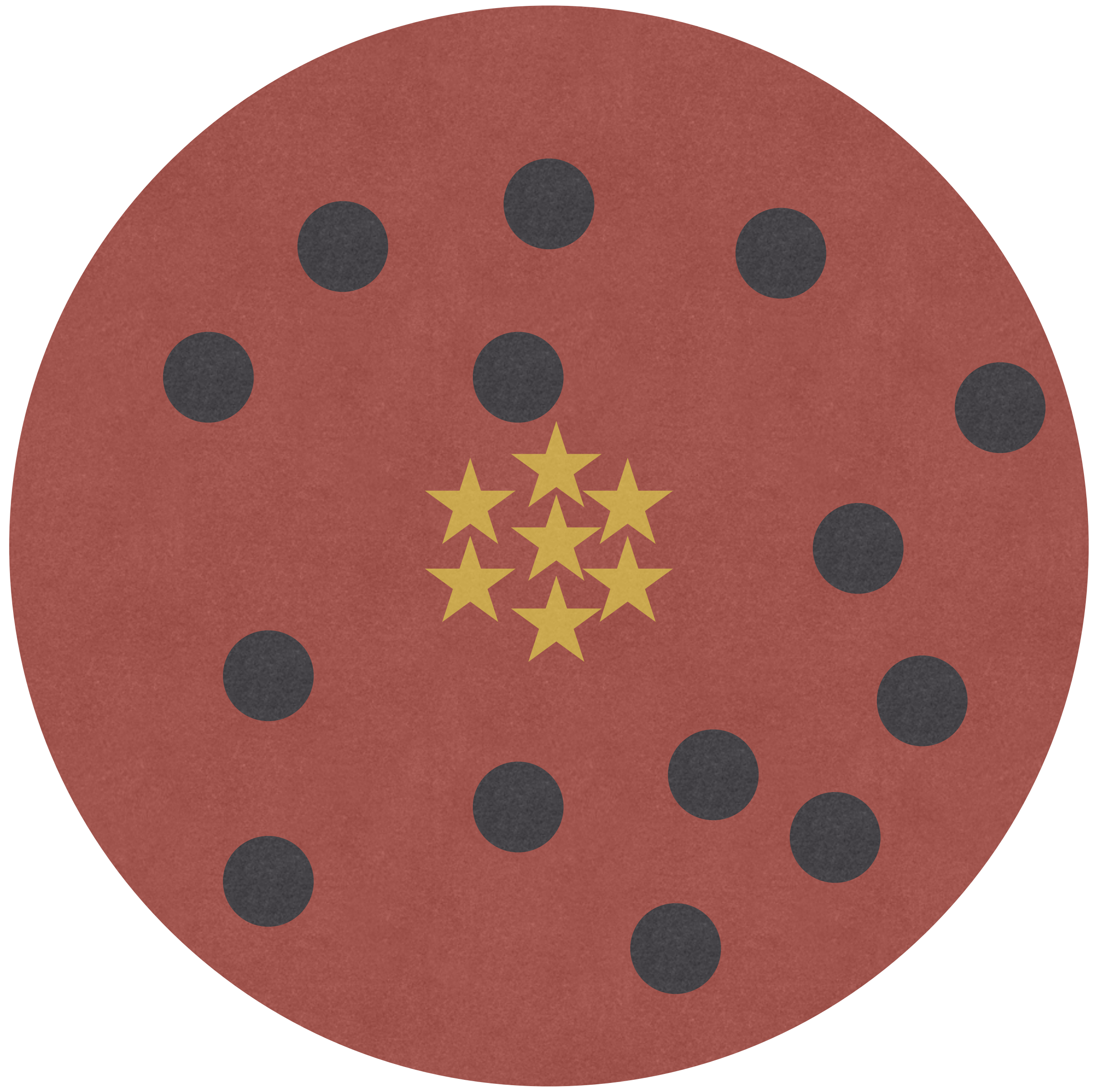

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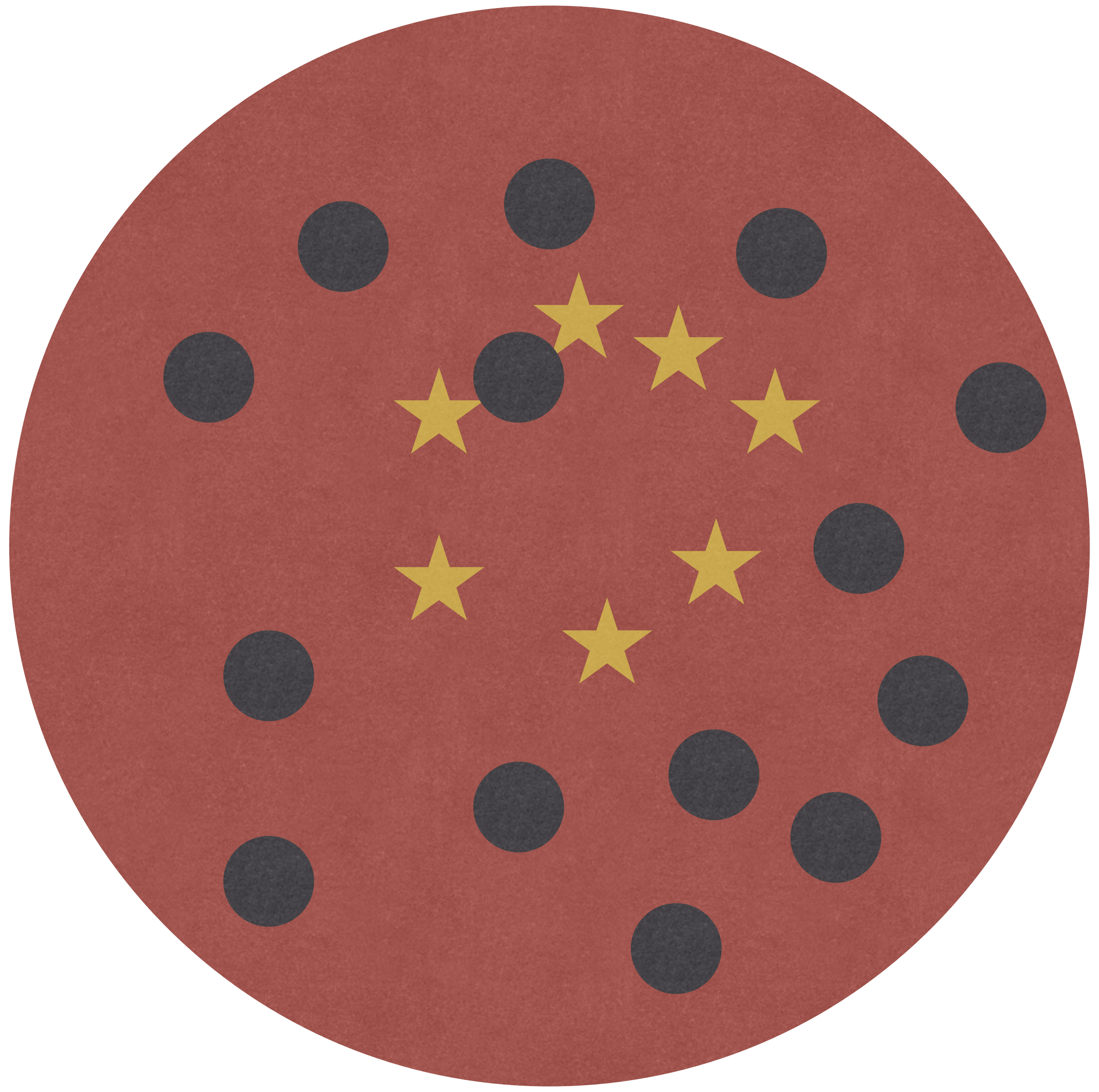
DYNAMICAL HEATING

$$R_{0,\star}[t_{\rm UFD}]^2 \approx \left(76\text{pc}\right)^2 \frac{t_{\rm UFD}}{10^{10}\text{year}} \frac{f_{\rm clump}}{1} \frac{M_{\rm clump}}{100 M_\odot} \frac{\log\Lambda}{10} \frac{18\text{km/s}}{\sigma_{\rm clump}} + (R^i_{0,\star})^2$$



$$f_{\rm equiv} \equiv \frac{\rho_{\rm clump}}{\rho_{\rm DM}}$$

Galaxy name	Projected r_h (pc)	σ_* (km s^{-1})	L_V ($L_\odot$)
Wil I	25 ± 6	$4.3^{+2.3}_{-1.3}$	1000
Seg I	29^{+8}_{-5}	$3.9^{+0.8}_{-0.8}$	300
Seg II	35 ± 3	$3.4^{+2.5}_{-1.2}$	900
Ret II	32^{+2}_{-1}	$3.2^{+1.6}_{-0.5}$	1500
Hor I	25^{+9}_{-4}	$4.9^{+2.8}_{-0.9}$	2000

Not Observed!

Stringent Constraints on clumps

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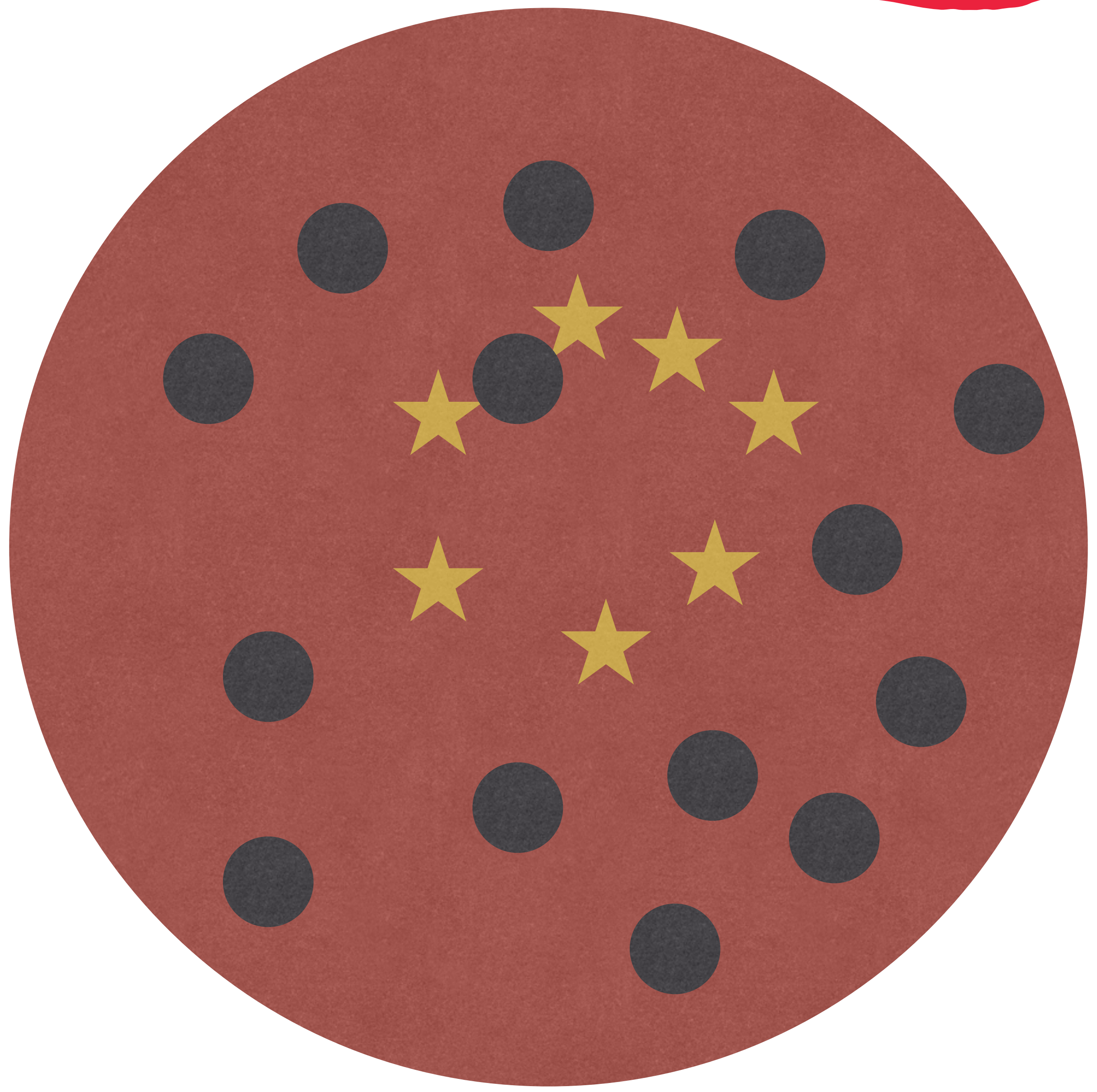

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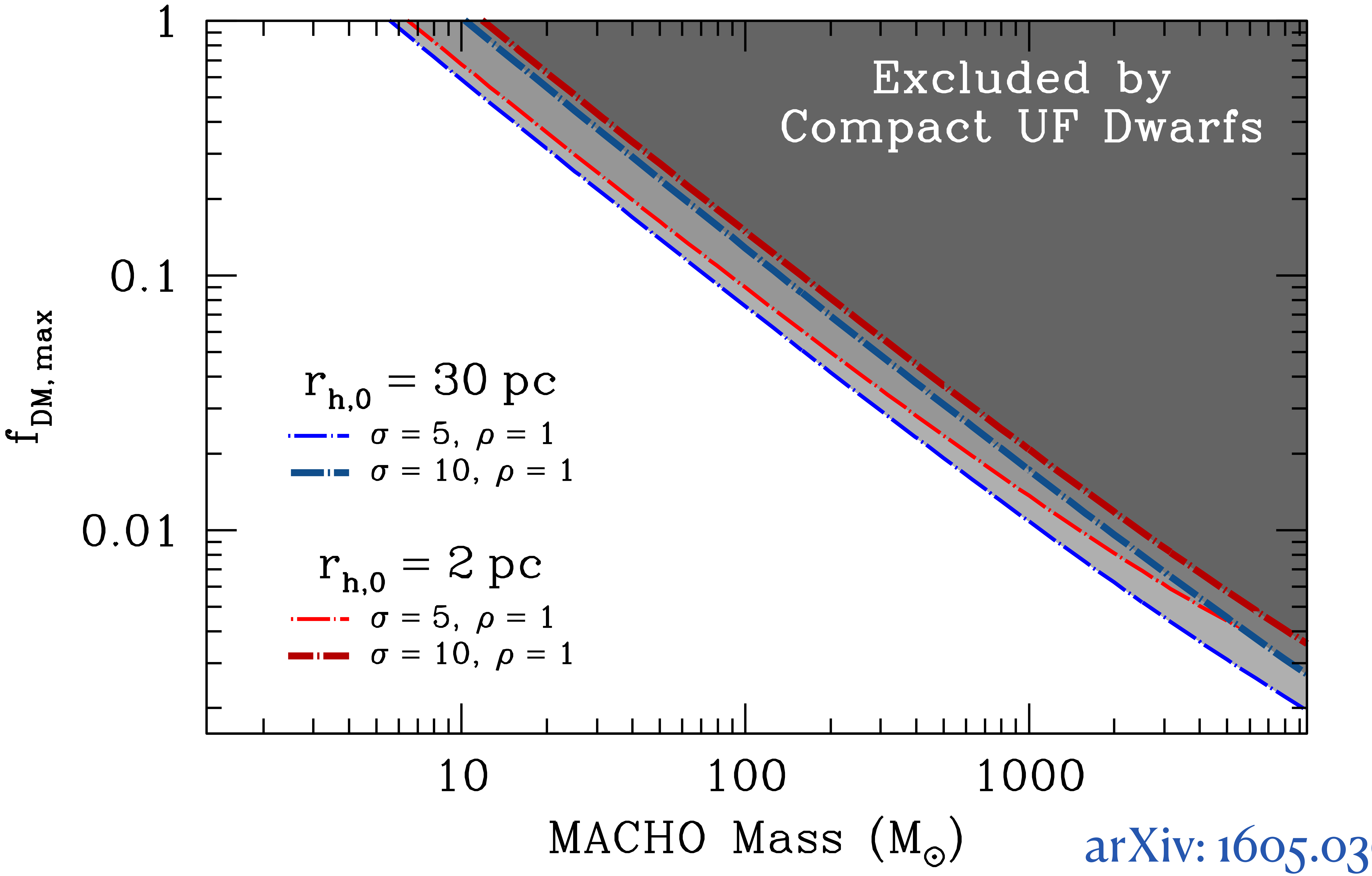
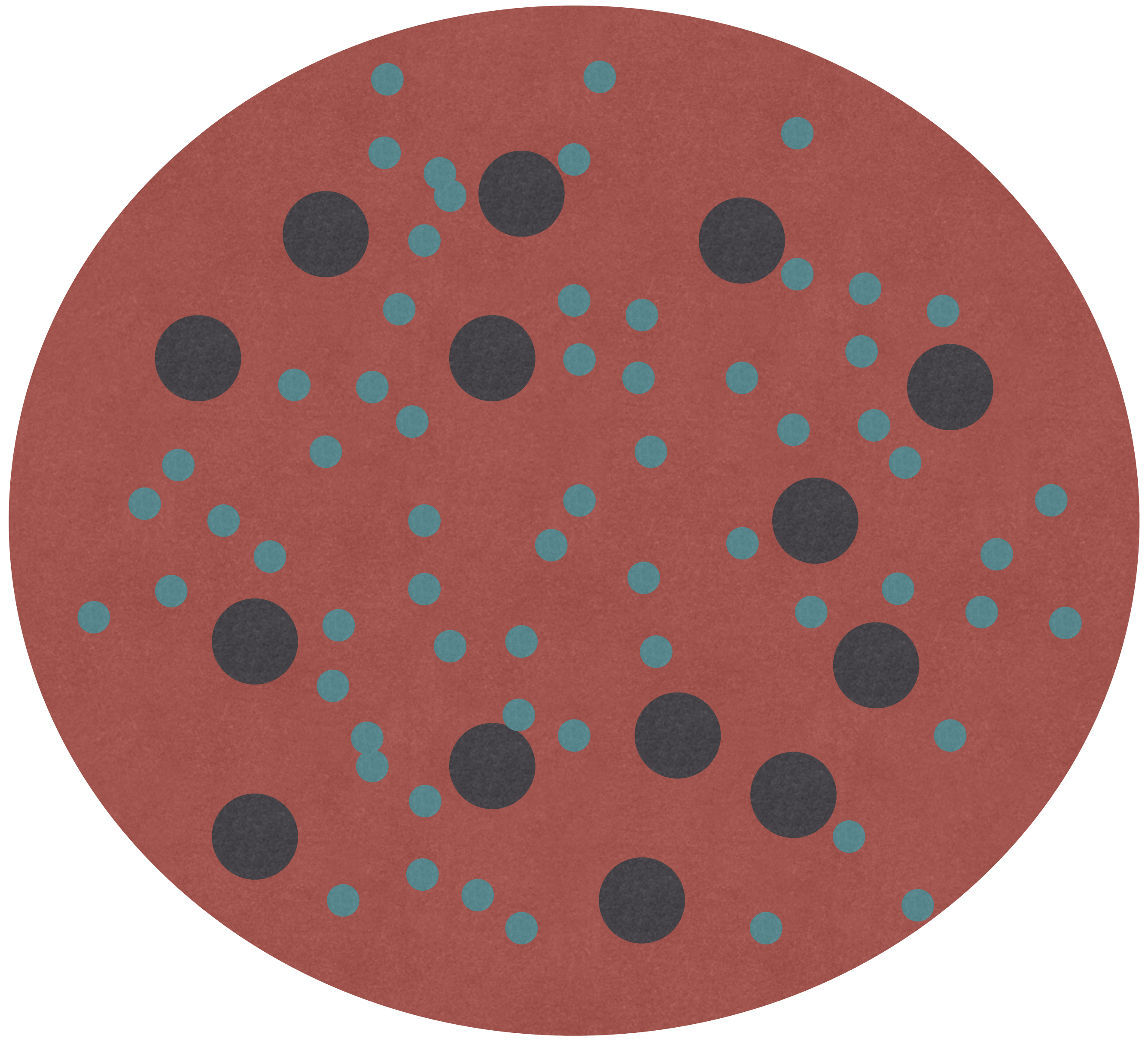
LIMITS ON PBH



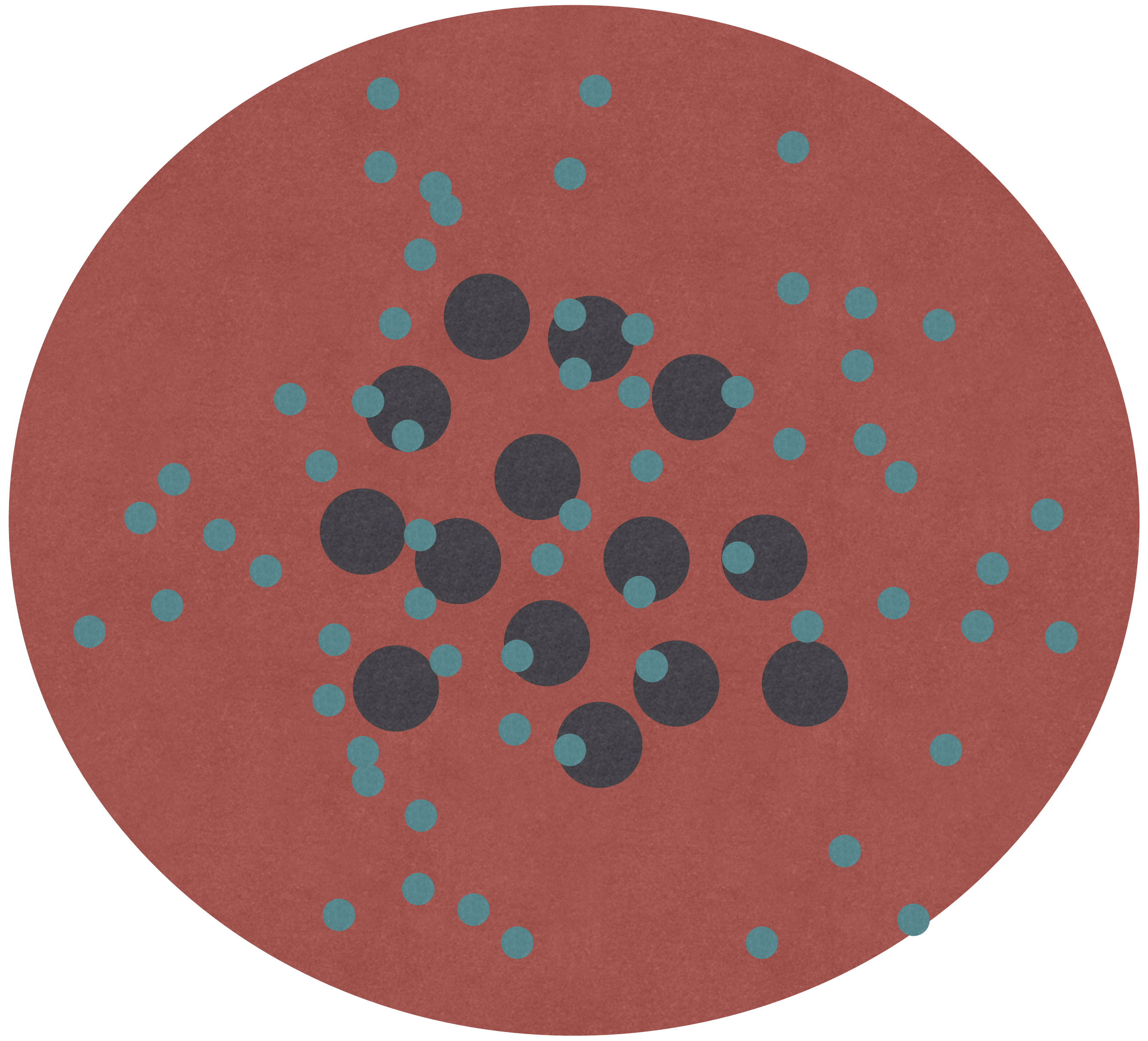
arXiv: 1605.03665 Brandt

MIGRATION



- Three Distinct Thermal Populations
- Temperatures
- $m_{\text{smooth}}\sigma^2_{\text{smooth}}$ & $m_{\text{MACHO}}\sigma^2_{\text{MACHO}}$
- Thermodynamics → Equilibration
- If $m_{\text{MACHO}} \gg m_{\text{smooth}}$
- MACHOs migrate inward

MIGRATION



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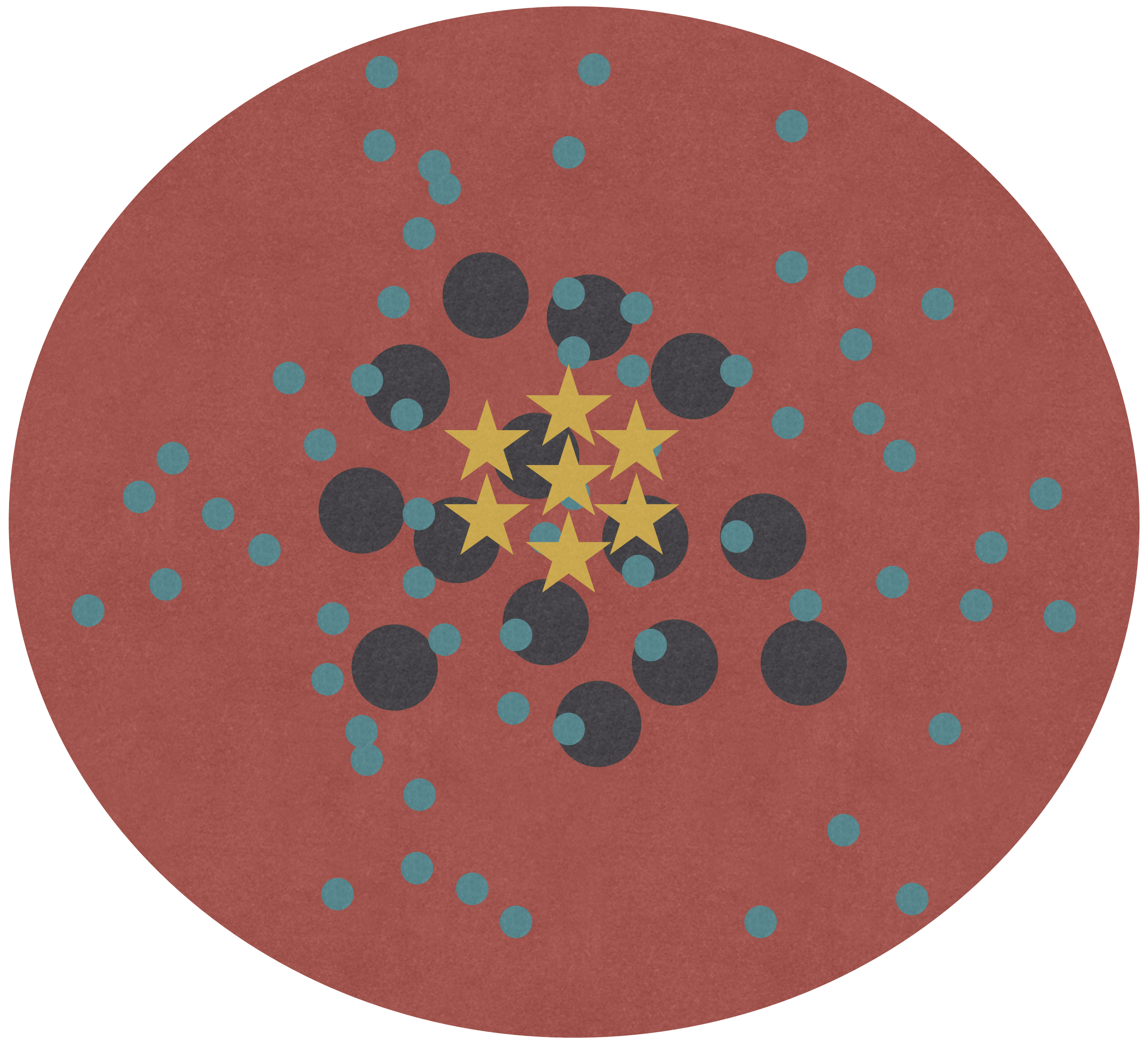
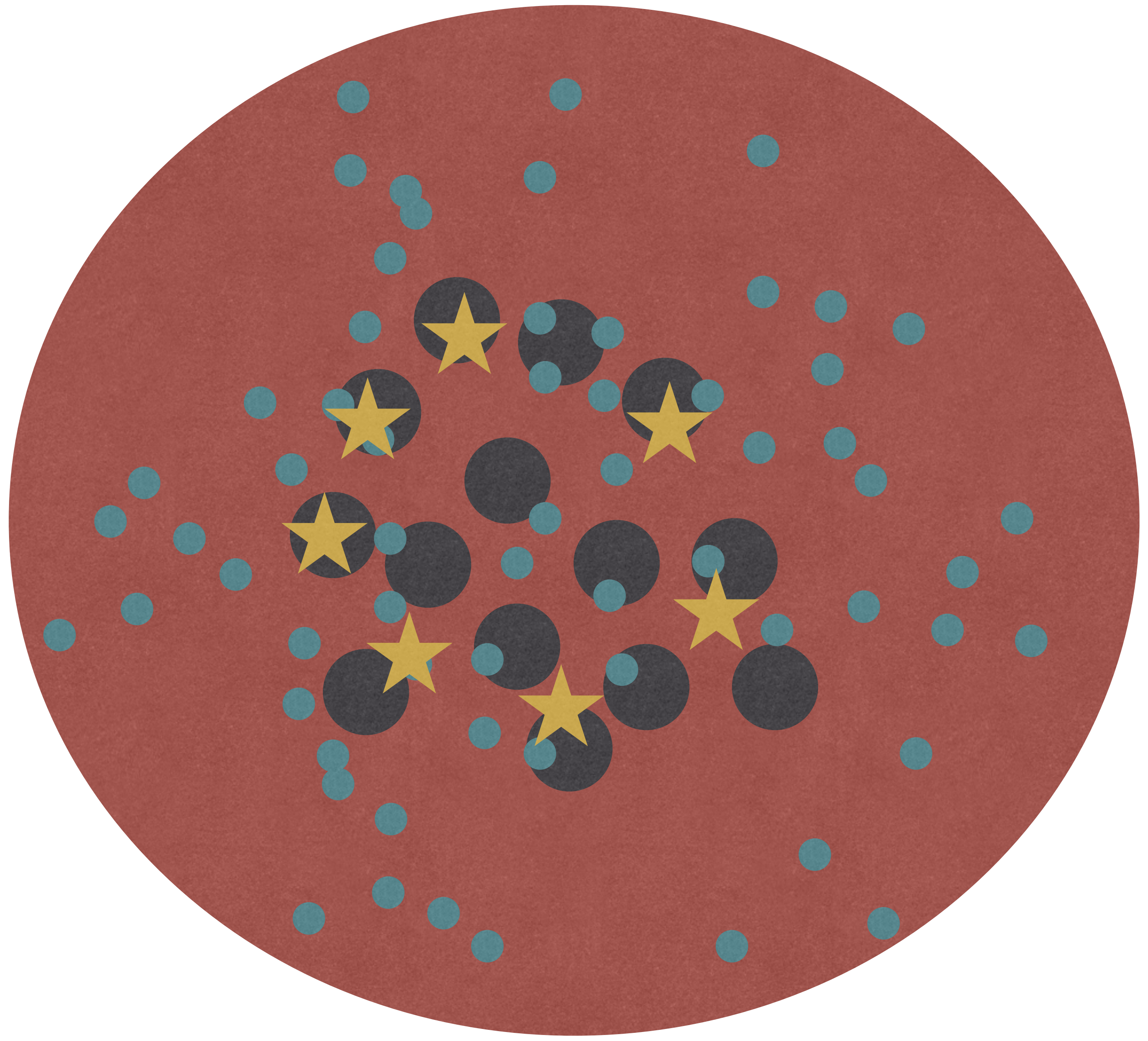


- Migration increases MACHO density @ stellar core
- More heating

MIGRATION



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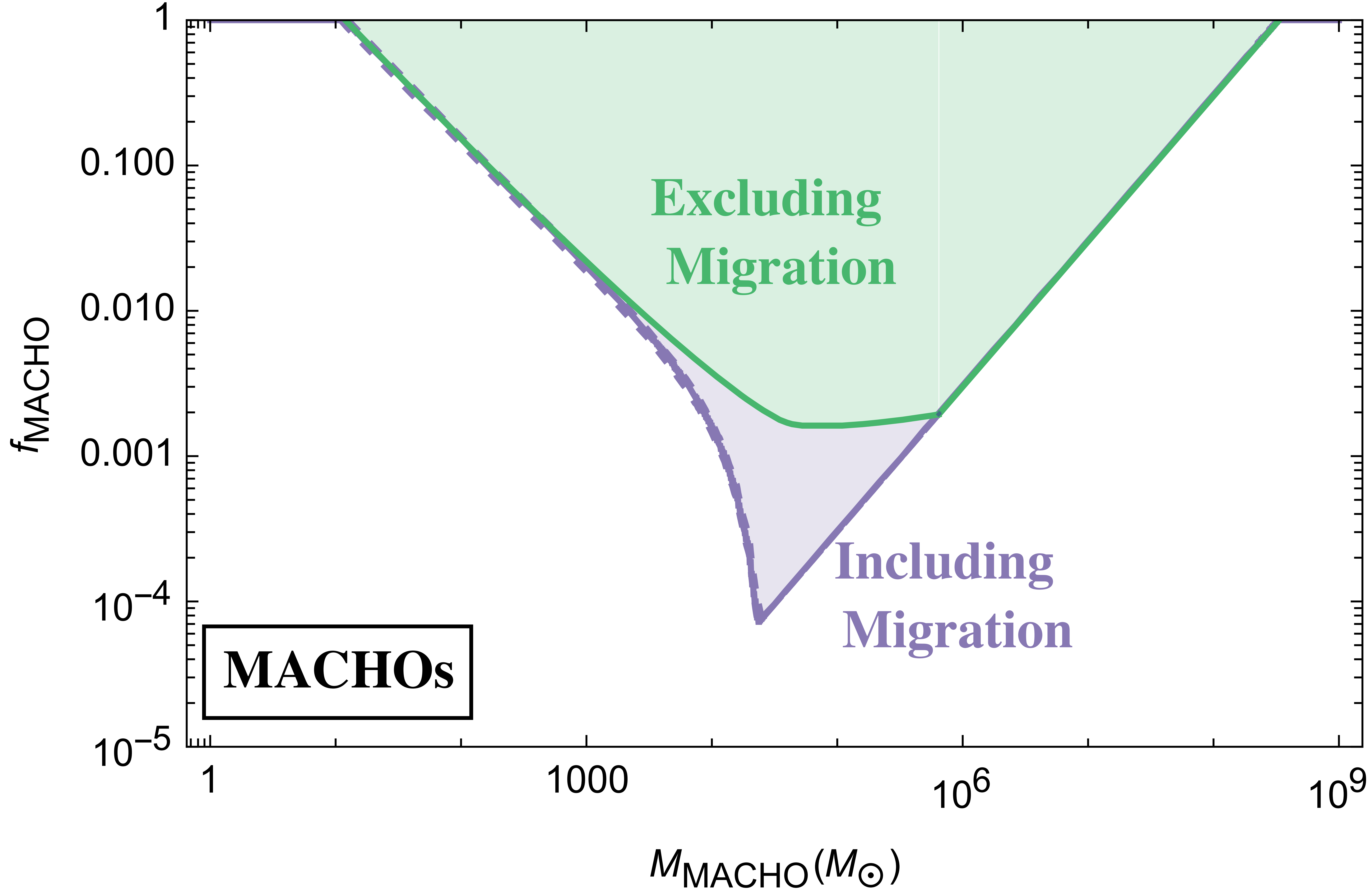
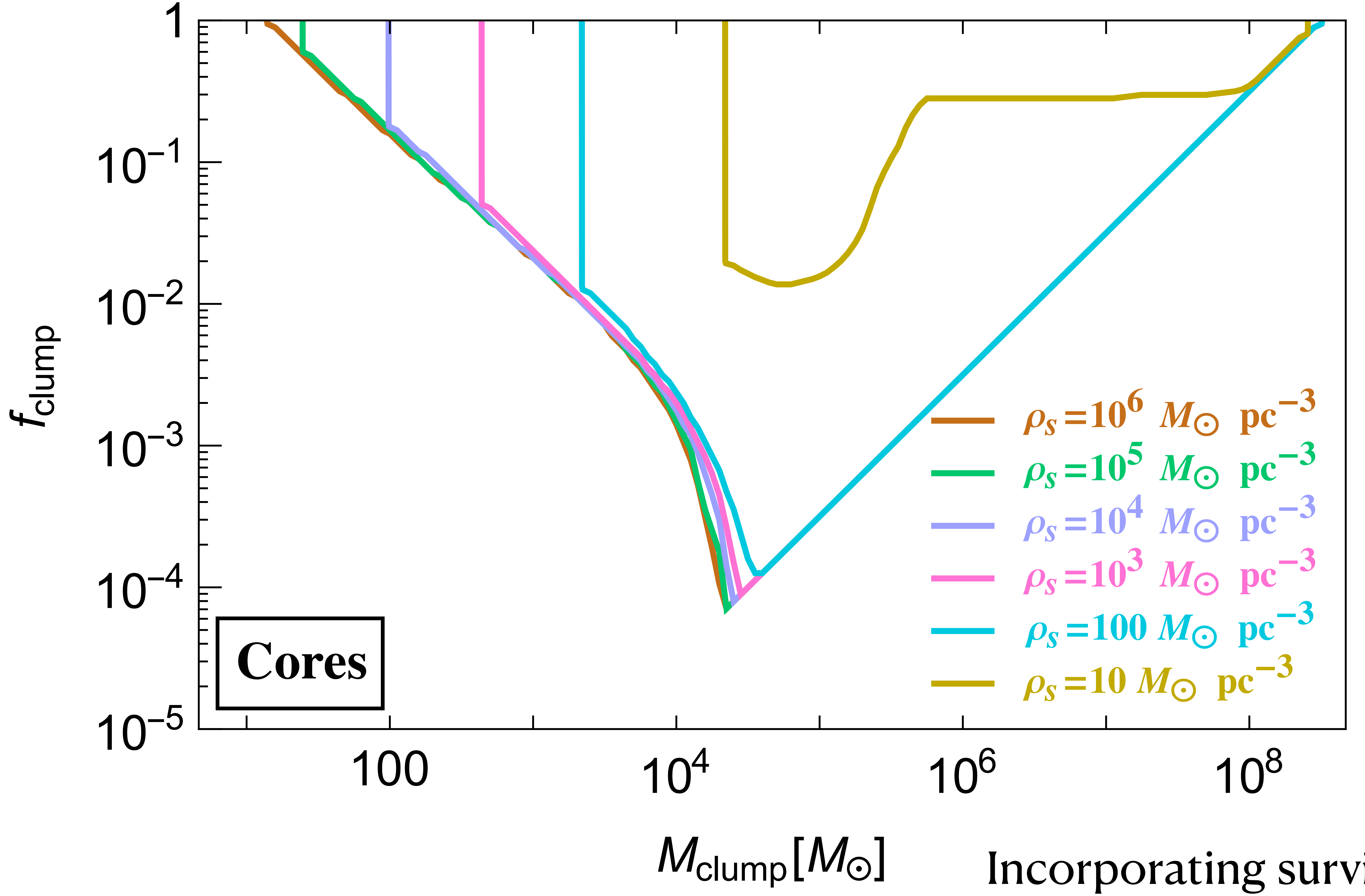
PBH LIMITS



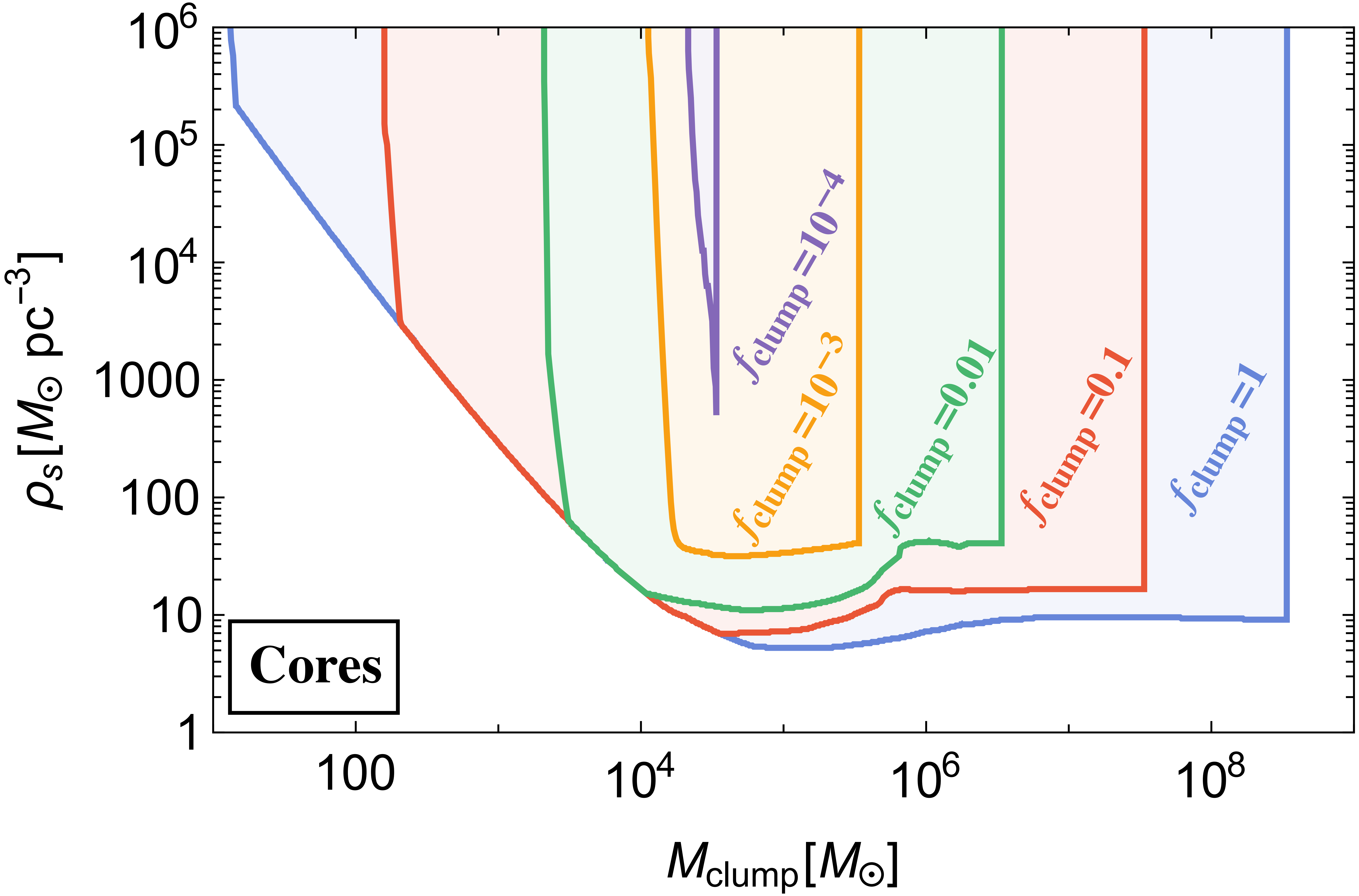
1
0.100
0.010
0.001
10^{-4}
10^{-5}
f_{MACHO}
1
1000
10^6
10^9
$M_{MACHO} (M_\odot)$
Excluding Migration
Including Migration
MACHOs

CLUMPS



Incorporating survival from tidal effects

NEW LIMITS

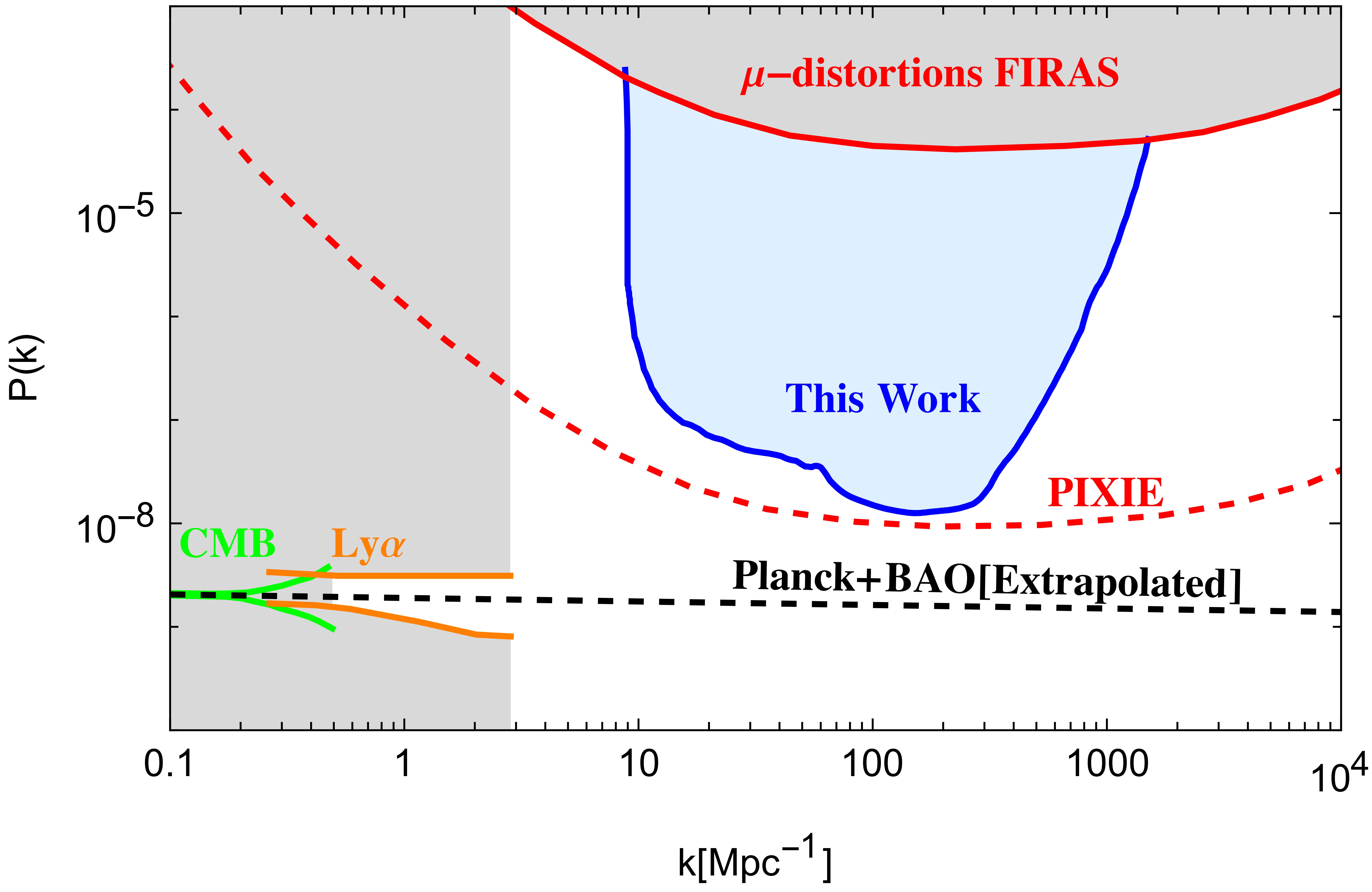


M_{clump}: Mass of the clump

ρ_s : Scale density of the clump

f_{clump} : Mass fraction of DM present in clumps

LIMITS ON THE POWER SPECTRUM



Ursa Major III/UNIONS 1: The Darkest Galaxy Ever Discovered?

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Abstract

The recently discovered stellar system Ursa Major III/UNIONS 1 (UMa3/U1) is the faintest known Milky Way satellite to date. With a stellar mass of $16^{+6}_{-5}\,\mathrm{M}_{\odot}$ and a half-light radius of $3 \pm 1\,\mathrm{pc}$, it is either the darkest galaxy ever discovered or the faintest self-gravitating star cluster known to orbit the Galaxy. Its line-of-sight velocity dispersion suggests the presence of dark matter, although current measurements are inconclusive because of the unknown contribution to the dispersion of potential binary stars. We use N-body simulations to show that, if self-gravitating, the system could not survive in the Milky Way tidal field for much longer than a single orbit (roughly 0.4 Gyr), which strongly suggests that the system is stabilized by the presence of large amounts of dark matter. If UMa3/U1 formed at the center of a $\sim 10^9\,\mathrm{M}_{\odot}$ cuspy LCDM halo, its velocity dispersion would

OUTLOOK

- Primordial Power Spectrum - Models of Inflation?
- Strongly Interacting Dark Matter
- Atomic dark matter
- Long Range Self-Interactions

LONG RANGE INTERACTIONS