Talk prepared for News from the dark

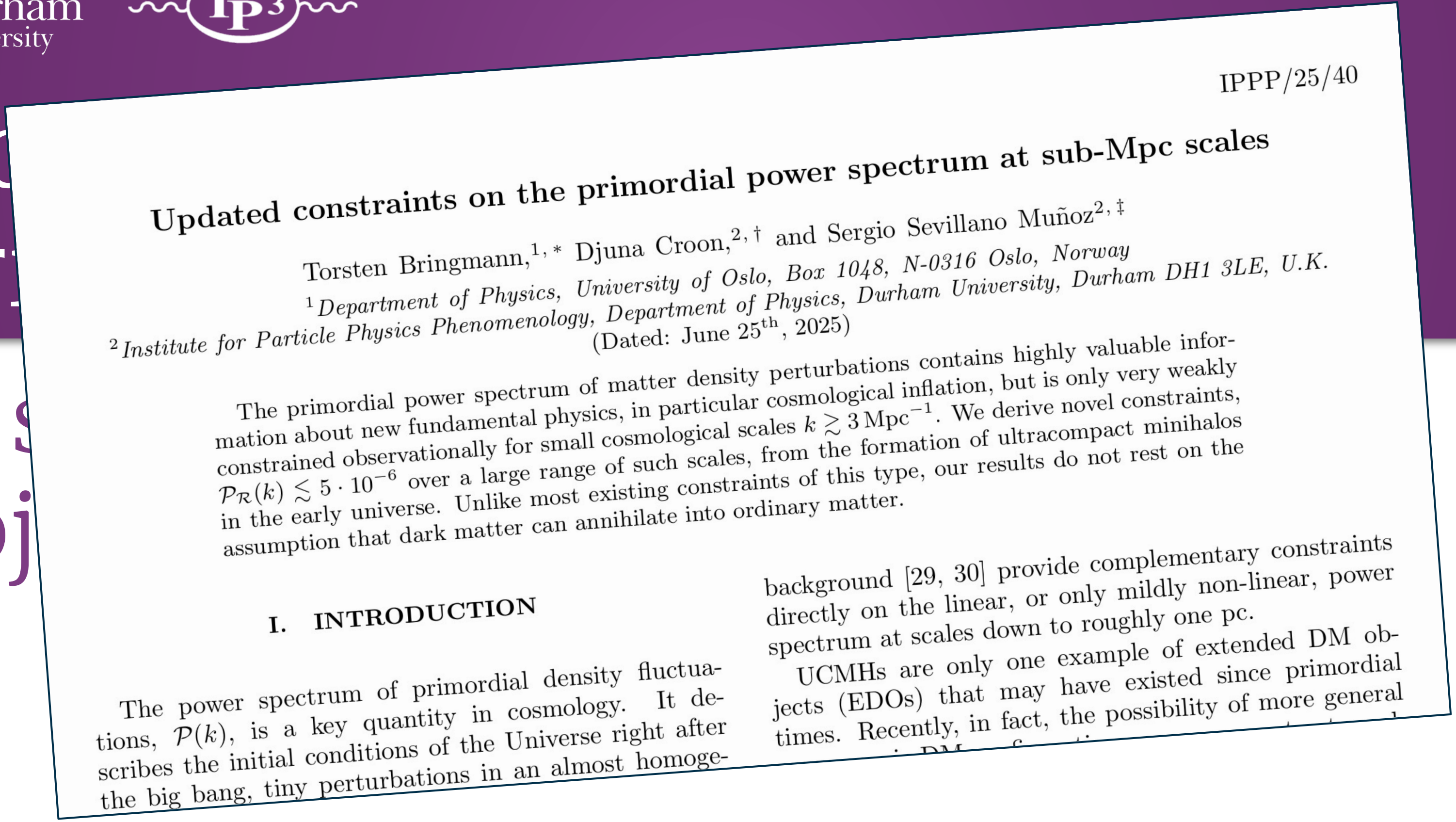
Novel constraints on the primordial power spectrum from extended object formation

Based on arXiv: 2506.20704

Sergio Sevillano Muñoz

Talk prepared for News from the dark

No
pr
at s
obj


IPPP/25/40

Updated constraints on the primordial power spectrum at sub-Mpc scales

Torsten Bringmann,[1,*] Djuna Croon,[2,†] and Sergio Sevillano Muñoz[2,‡]

[1] *Department of Physics, University of Oslo, Box 1048, N-0316 Oslo, Norway*
[2] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, U.K.*

(Dated: June 25$^{\text{th}}$, 2025)

The primordial power spectrum of matter density perturbations contains highly valuable information about new fundamental physics, in particular cosmological inflation, but is only very weakly constrained observationally for small cosmological scales $k \gtrsim 3\,\mathrm{Mpc}^{-1}$. We derive novel constraints, $\mathcal{P}_\mathcal{R}(k) \lesssim 5 \cdot 10^{-6}$ over a large range of such scales, from the formation of ultracompact minihalos in the early universe. Unlike most existing constraints of this type, our results do not rest on the assumption that dark matter can annihilate into ordinary matter.

I. INTRODUCTION

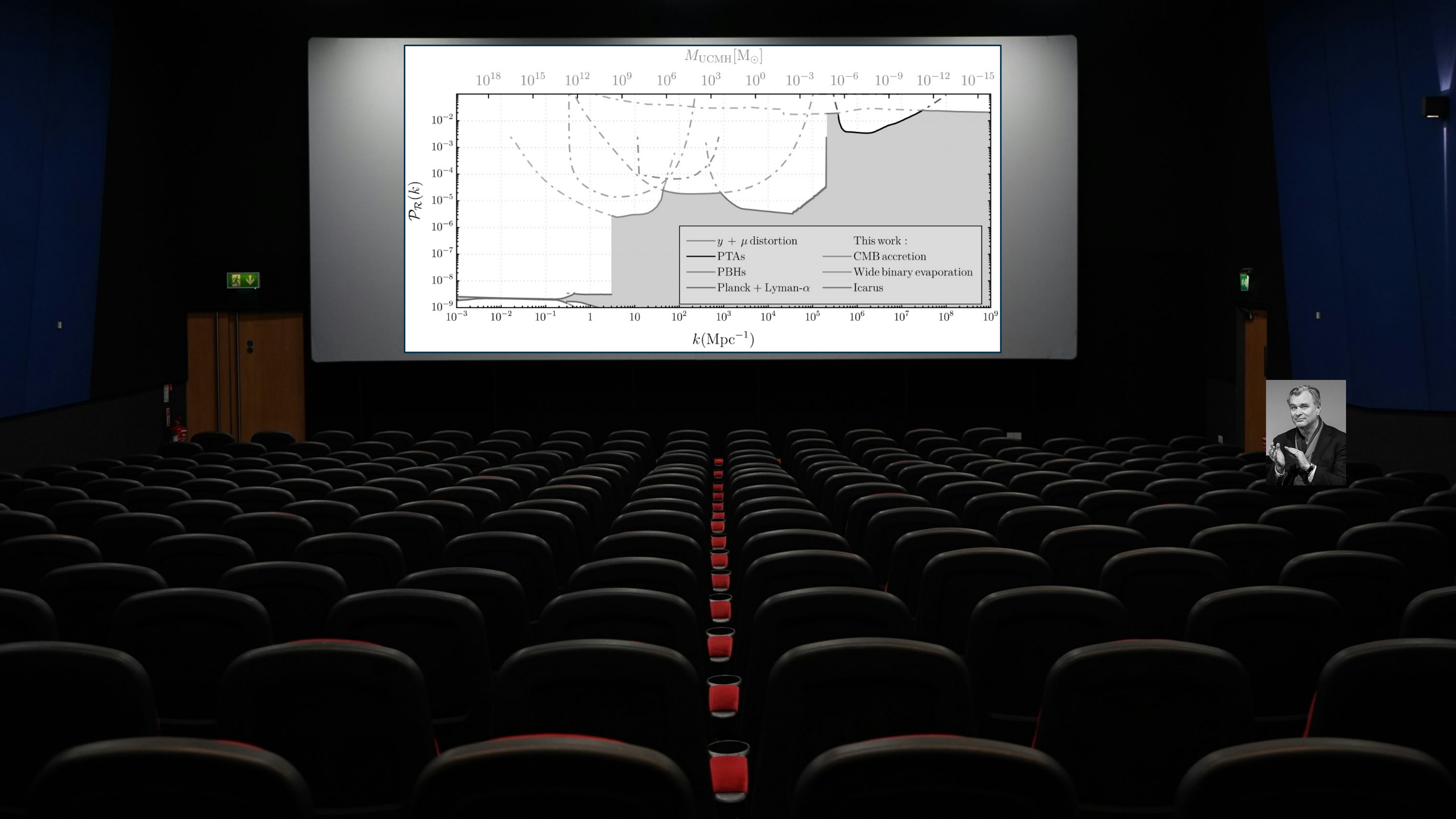
The power spectrum of primordial density fluctuations, $\mathcal{P}(k)$, is a key quantity in cosmology. It describes the initial conditions of the Universe right after the big bang, tiny perturbations in an almost homoge-

background [29, 30] provide complementary constraints directly on the linear, or only mildly non-linear, power spectrum at scales down to roughly one pc.

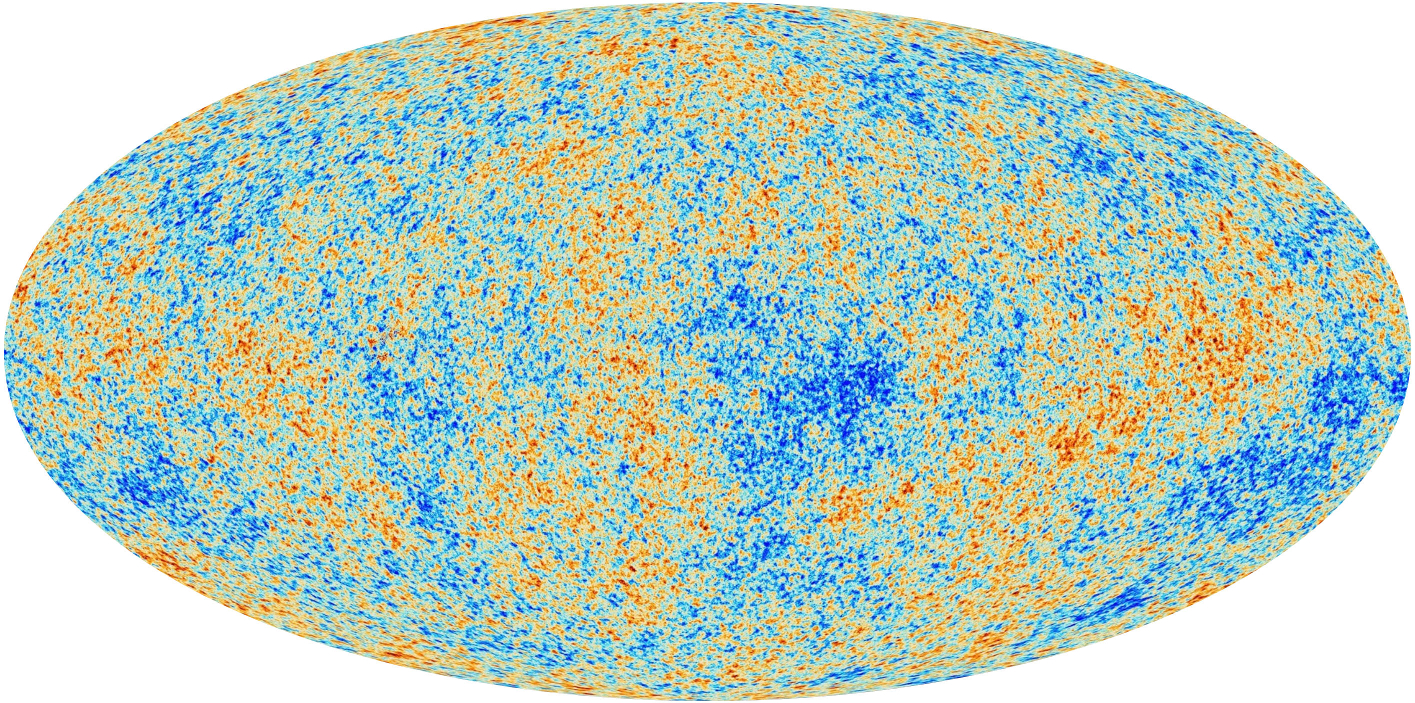
UCMHs are only one example of extended DM objects (EDOs) that may have existed since primordial times. Recently, in fact, the possibility of more general

Based on arXiv: 2506.20704

Sergio Sevillano Muñoz

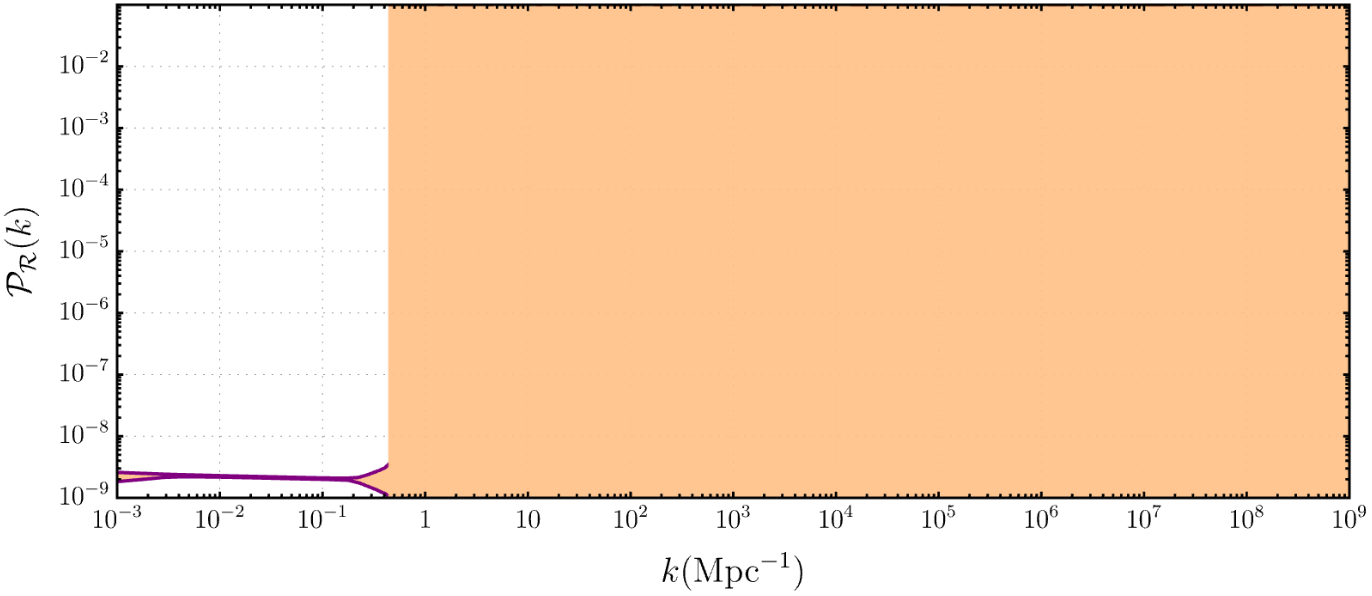

$M_{\rm UCMH}[{\rm M}_\odot]$
10^{18} 10^{15} 10^{12} 10^{9} 10^{6} 10^{3} 10^{0} 10^{-3} 10^{-6} 10^{-9} 10^{-12} 10^{-15}
$\mathcal{P}_{\mathcal{R}}(k)$
10^{-2} 10^{-3} 10^{-4} 10^{-5} 10^{-6} 10^{-7} 10^{-8} 10^{-9}
$y + \mu$ distortion
PTAs
PBHs
Planck + Lyman-α
This work :
CMB accretion
Wide binary evaporation
Icarus
10^{-3} 10^{-2} 10^{-1} 1 10 10^{2} 10^{3} 10^{4} 10^{5} 10^{6} 10^{7} 10^{8} 10^{9}
$k({\rm Mpc}^{-1})$

Cosmic Microwave Background



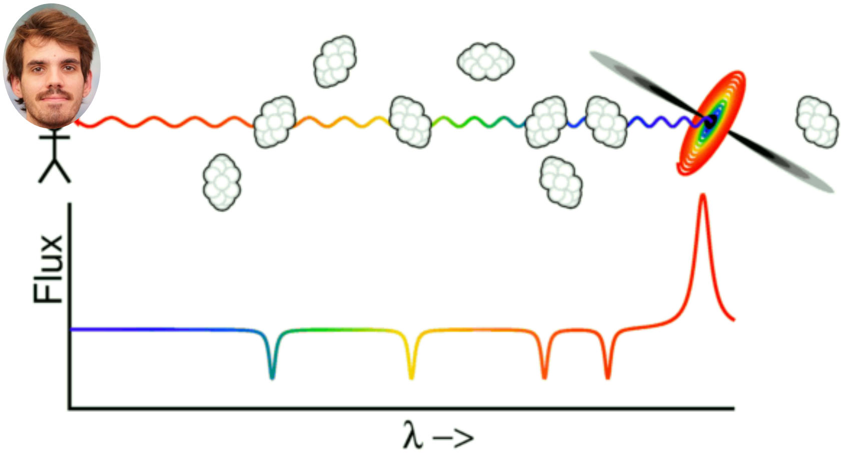
Planck!

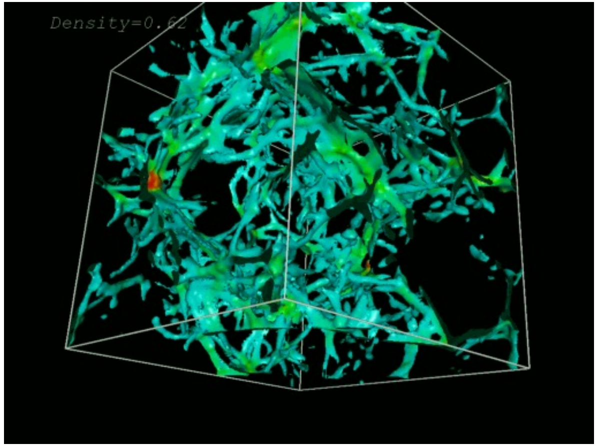
Inferring smaller scales by looking at matter distribution in the late universe



Lyman α Forest

Inferring smaller scales by looking at matter distribution in the late universe

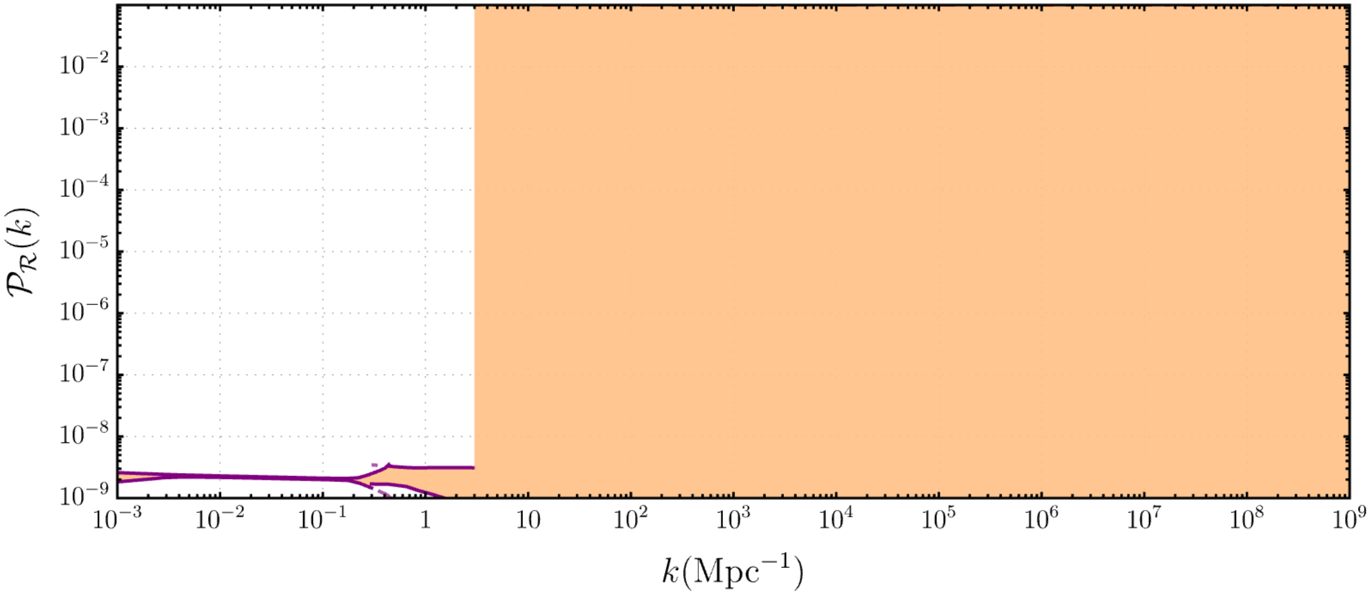




S. Bird, H. V. Peiris, M. Viel, L. Verde (1010.1519v2)

Lyman α and Planck

Inferring smaller scales by looking at matter distribution in the late universe



y and μ distortions

Primordial perturbations create injections of energy into the background that lead to a departure of the perfect black body spectrum:

$$\mu \approx 2.2 \int_{k_{\min}}^{\infty} \mathcal{P}_{\mathcal{R}}(k) \left[\exp\left(-\frac{\hat{k}}{5400} \right) - \exp\left(-\left[\frac{\hat{k}}{31.6} \right]^2 \right) \right] \mathrm{d} \ln k$$

$$y \approx 0.4 \int_{k_{\min}}^{\infty} \mathcal{P}_{\mathcal{R}}(k) \exp\left(-\left[\frac{\hat{k}}{31.6} \right]^2 \right) \mathrm{d} \ln k,$$

$\mu < 9 \times 10^{-5}$

$y < 1.5 \times 10^{-5}$

COBE (9605054)

Where we assume a locally scale-invariant power spectrum

$$\mathcal{P}_{\mathcal{R}}(k) = \begin{cases} \mathcal{P}_{\mathcal{R}}(k_{\mathcal{R}}) & \text{for } 1/3 < k/k_{\mathcal{R}} < 3 \\ 0 & \text{otherwise} \end{cases}$$

J. Chluba, A. L. Erickcek, I. Ben-Dayan (1203.2681)

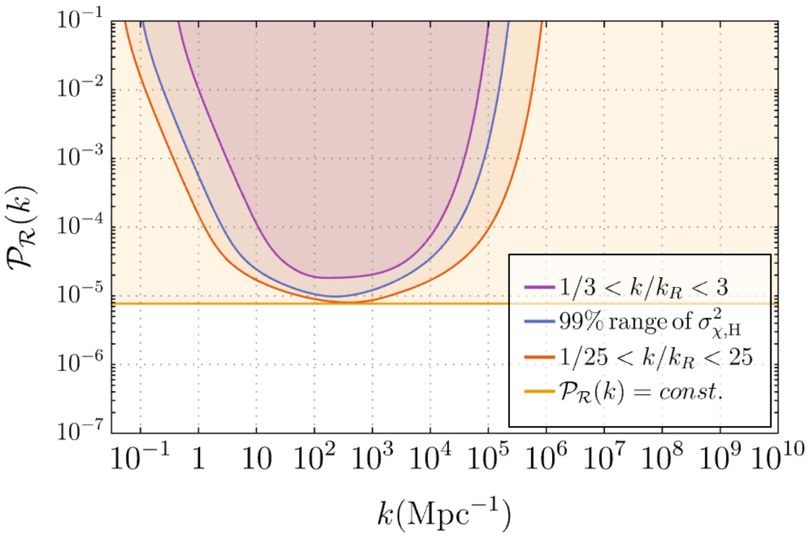
y and μ distortions

Primordial perturbations create injections of energy into the background that lead to a departure of the perfect black body spectrum:

$$\mu \approx 2.2 \int_{k_{\min}}^{\infty} \mathcal{P}_{\mathcal{R}}(k) \left[\exp\left(-\frac{\hat{k}}{5400} \right) - \exp\left(-\left[\frac{\hat{k}}{31.6} \right]^2 \right) \right] \mathrm{d} \ln k$$

$$y \approx 0.4 \int_{k_{\min}}^{\infty} \mathcal{P}_{\mathcal{R}}(k) \exp\left(-\left[\frac{\hat{k}}{31.6} \right]^2 \right) \mathrm{d} \ln k,$$

$$\mathcal{P}_{\mathcal{R}}(k) = \begin{cases} \mathcal{P}_{\mathcal{R}}(k_{\mathcal{R}}) & \text{for } 1/3 < k/k_{\mathcal{R}} < 3 \\ 0 & \text{otherwise} \end{cases}$$

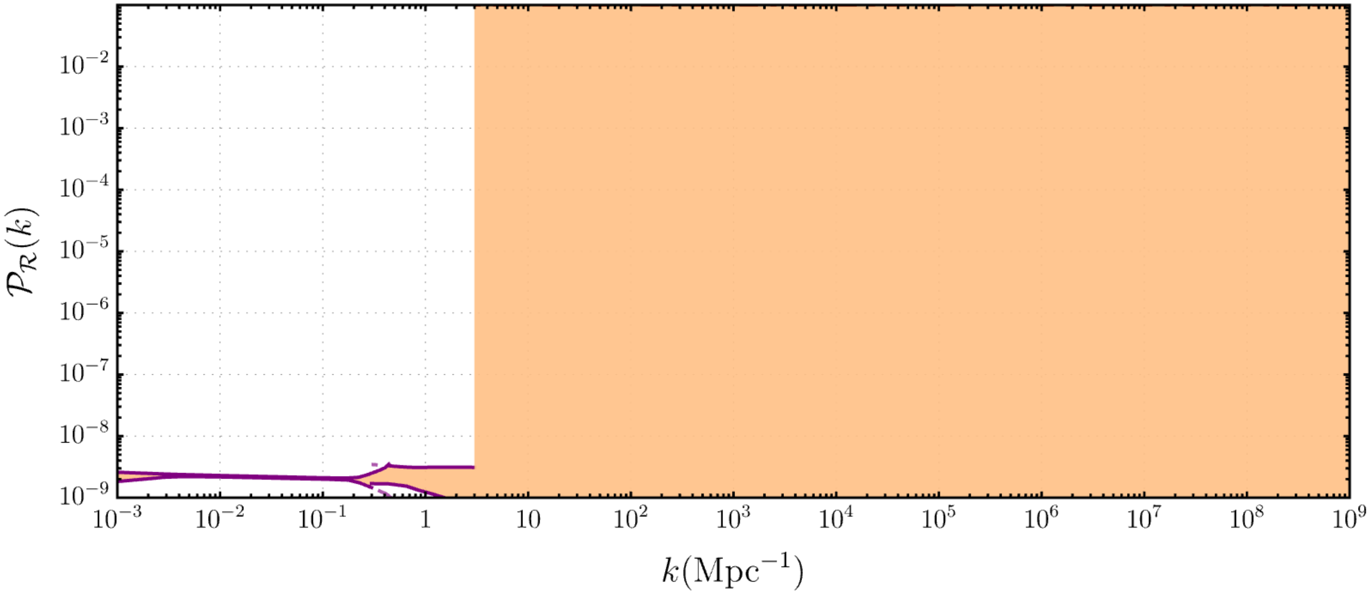


J. Chluba, A. L. Erickcek, I. Ben-Dayan (1203.2681)

y and μ distortions

Primordial perturbations create injections of energy into the background that lead to a departure of the perfect black body spectrum:

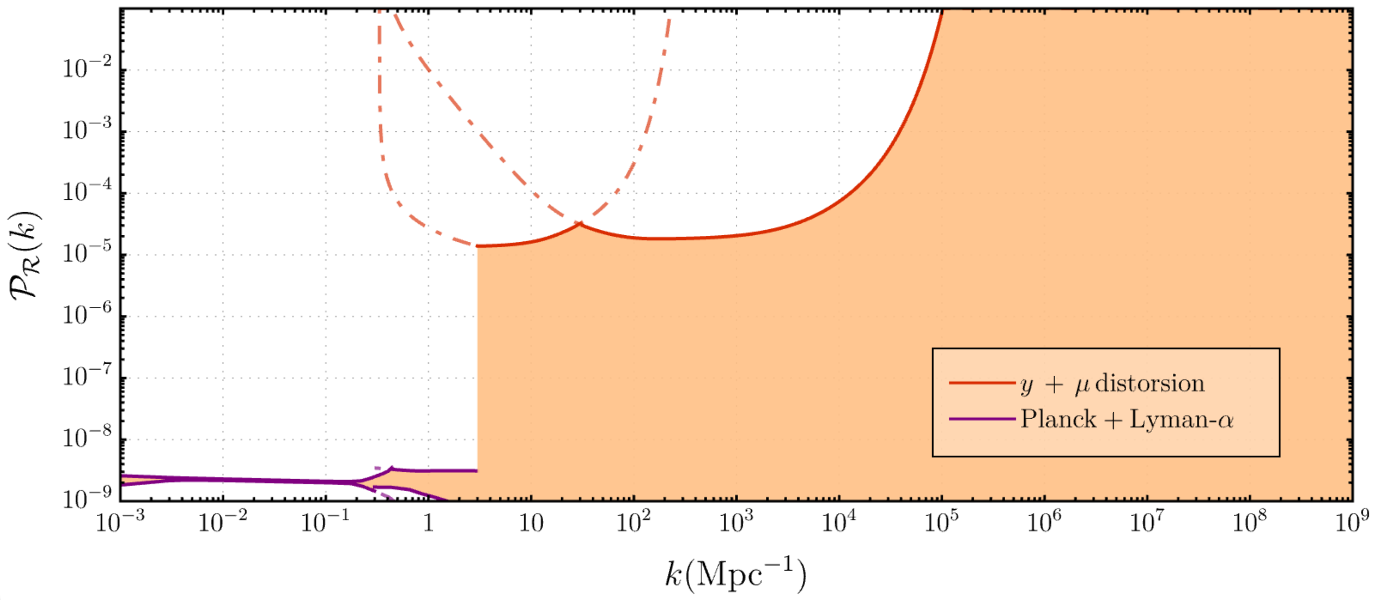
COBE (9605054)   J. Chluba, A. L. Erickcek, I. Ben-Dayan (1203.2681)



y and μ distortions

Primordial perturbations create injections of energy into the background that lead to a departure of the perfect black body spectrum:

COBE (9605054) J. Chluba, A. L. Erickcek, I. Ben-Dayan (1203.2681)



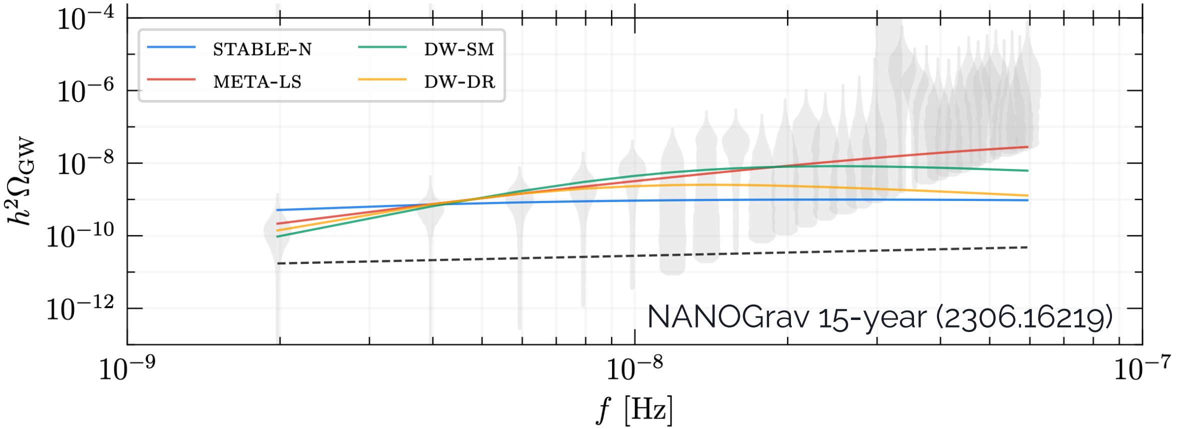
Pulsar Timing Arrays (PTAs)

Any stochastic background of gravitational waves can be constrained via $h^2\Omega_{\rm GW}$

$$\Omega_{\rm GW}(k,\eta) = \frac{1}{24}\left(\frac{k}{aH}\right)^2 \mathcal{P}_h(k,\eta)$$

$$\mathcal{P}_\mathcal{R}(k) = \begin{cases} \mathcal{P}_\mathcal{R}(k_\mathcal{R}) & \text{for } 1/3 < k/k_\mathcal{R} < 3 \\ 0 & \text{otherwise} \end{cases}$$

$$\mathcal{P}_h(k,\eta) = 4\int_0^\infty dv \int_{|1-v|}^{1+v} du \left(\frac{4v^2-(1+v^2-u^2)^2}{4vu}\right)^2 \mathcal{P}_\mathcal{R}(ku)\mathcal{P}_\mathcal{R}(kv) I^2(u,v,k\eta),$$



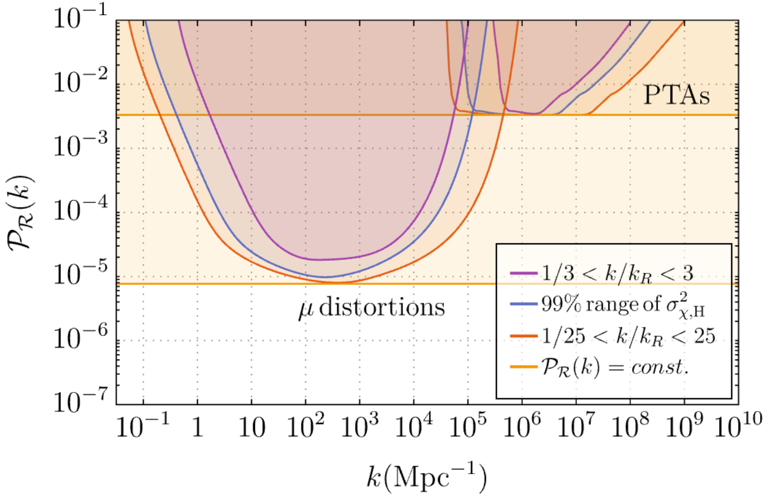
Pulsar Timing Arrays (PTAs)

Any stochastic background of gravitational waves can be constrained via $h^2\Omega_{\rm GW}$

$$\Omega_{\rm GW}(k,\eta) = \frac{1}{24}\left(\frac{k}{aH}\right)^2 \mathcal{P}_h(k,\eta)$$

$$\mathcal{P}_h(k,\eta) = 4\int_0^\infty dv \int_{|1-v|}^{1+v} du \left(\frac{4v^2-(1+v^2-u^2)^2}{4vu}\right)^2 \mathcal{P}_\mathcal{R}(ku)\mathcal{P}_\mathcal{R}(kv) I^2(u,v,k\eta),$$

$$\mathcal{P}_\mathcal{R}(k) = \begin{cases} \mathcal{P}_\mathcal{R}(k_\mathcal{R}) & \text{for } 1/3 < k/k_\mathcal{R} < 3 \\ 0 & \text{otherwise} \end{cases}$$

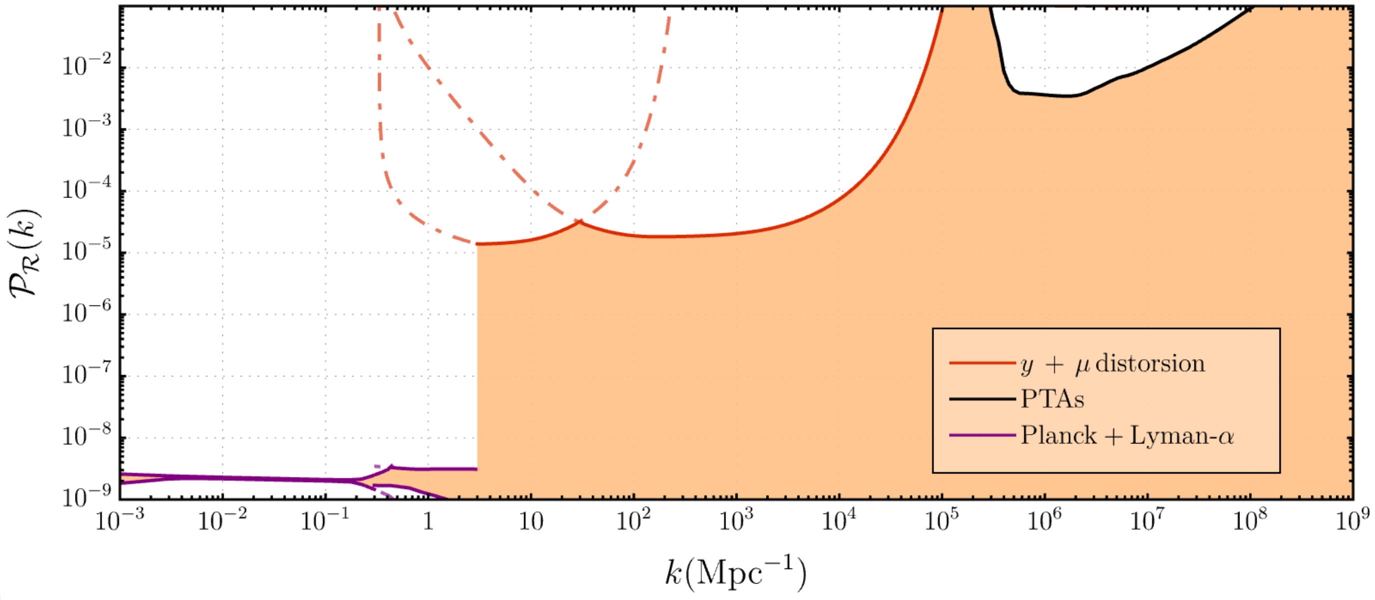


Pulsar Timing Arrays (PTAs)

Any stochastic background of gravitational waves can be constrained via $h^2\Omega_{\rm GW}$

NANOGrav 15-year (2306.16219)

$$\Omega_{\rm GW}(k,\eta) = \frac{1}{24}\left(\frac{k}{aH}\right)^2 \mathcal{P}_h(k,\eta)$$



Primordial Black Holes (PBHs)

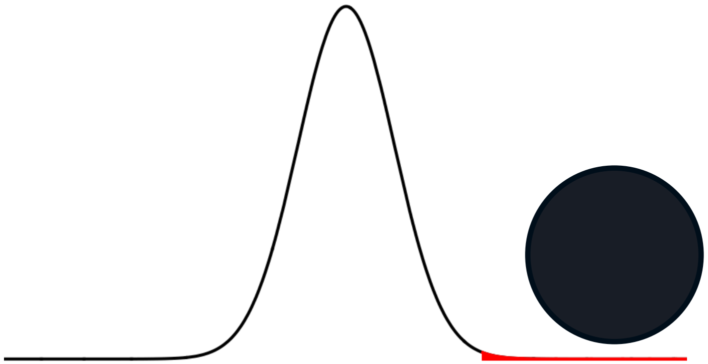
Large enough overdensities can lead to the collapse of a region into a black hole!

$$\beta(M_{\rm H}) = \sqrt{\frac{2}{\pi}} \frac{\alpha}{\sigma(R)} \int_{\delta_{\rm c}}^{\infty} \exp\left(-\frac{\delta^2(R)}{2\sigma^2(R)}\right) {\rm d}\delta(R)$$

Fraction of black holes

$$\delta \equiv (\rho - \bar{\rho})/\bar{\rho}$$

$$\sigma^2(R) = \frac{16}{81} \int_0^{\infty} (kR)^4 W^2(kR) \mathcal{P}_{\mathcal{R}}(k) T^2(kR/\sqrt{3}) \frac{{\rm d}k}{k}$$



We can therefore constrain the power spectrum using limits on PBHs!

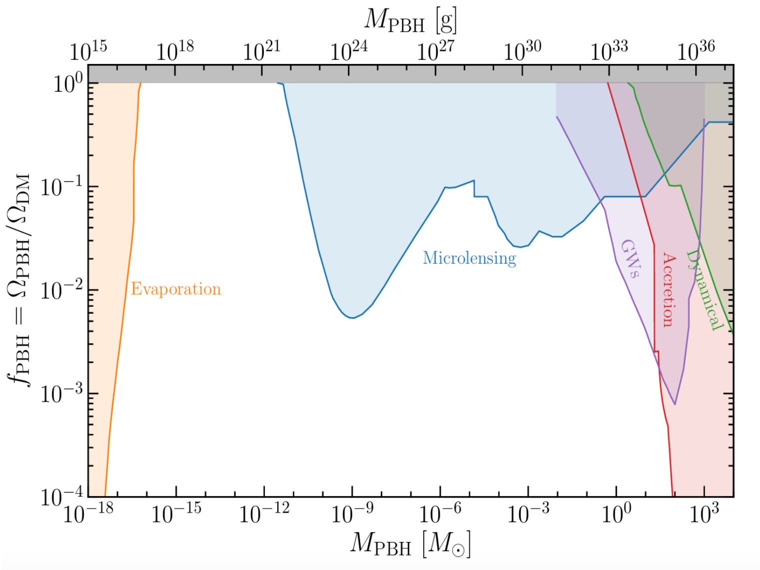
Carr, Kohri, Sndouda and Yokoyama (2002.12778)

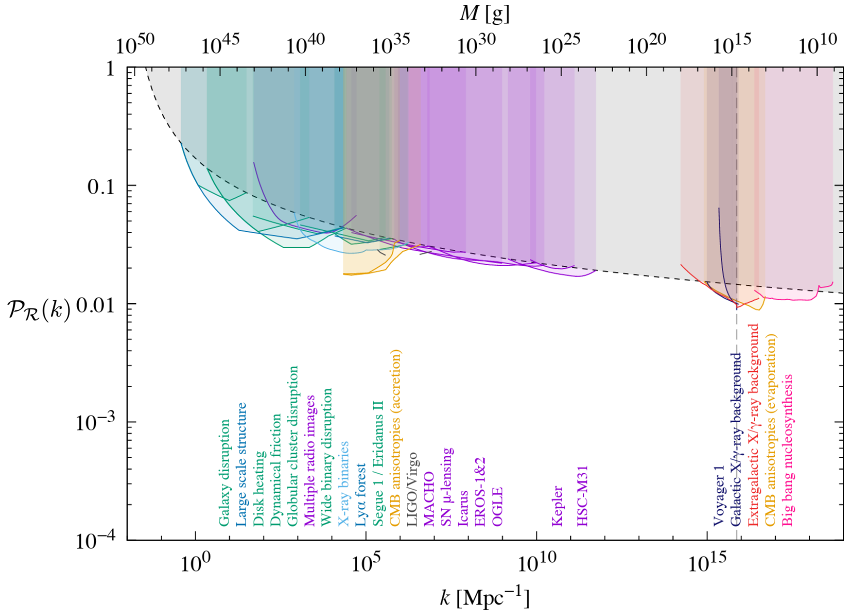
Based on arXiv: 2506.20704

Primordial Black Holes (PBHs)

Large enough overdensities can lead to the collapse of a region into a black hole!

Carr, Kohri, Sndouda and Yokoyama (2002.12778)

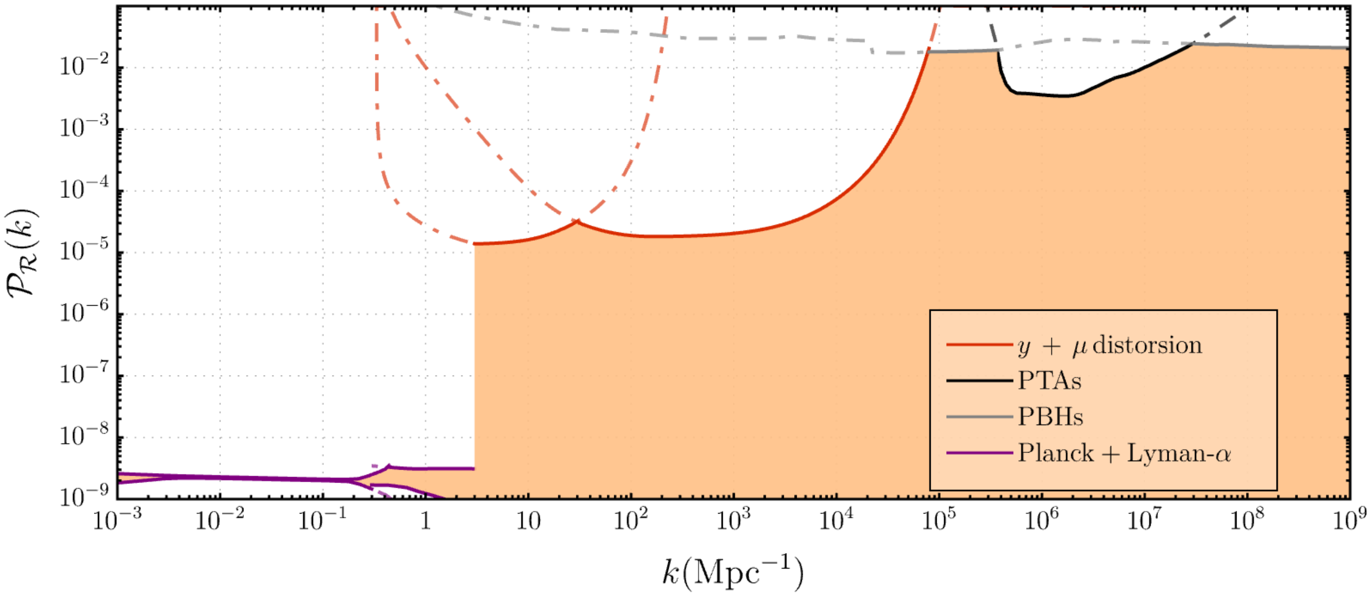




Primordial Black Holes (PBHs)

Large enough overdensities can lead to the collapse of a region into a black hole!

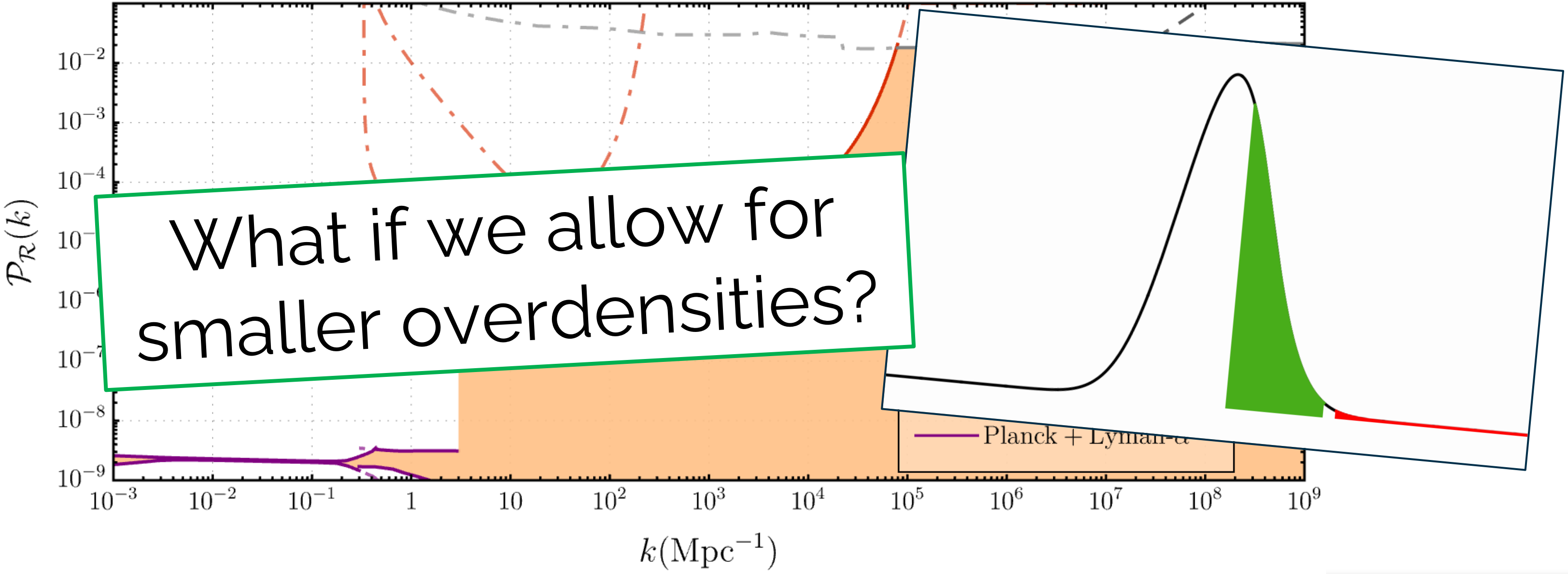
$$\beta(M_{\rm H}) = \sqrt{\frac{2}{\pi}}\frac{\alpha}{\sigma(R)}\int_{\delta_c}^{\infty} \exp\left(-\frac{\delta^2(R)}{2\sigma^2(R)}\right) d\delta(R)$$



Primordial Black Holes (PBHs)

Large enough overdensities can lead to the collapse of a region into a black hole!

$$\beta(M_{\mathrm{H}}) = \sqrt{\frac{2}{\pi}} \frac{\alpha}{\sigma(R)} \int_{\delta_c}^{\infty} \exp\left(-\frac{\delta^2(R)}{2\sigma^2(R)}\right) \mathrm{d}\delta(R)$$



What if we allow for smaller overdensities?

Ultra-compact minihaloes (UCMHs)

That was the idea from this paper, assuming SM-DM interactions

Improved constraints on the primordial power spectrum at small scales from ultracompact minihalos

Torsten Bringmann*
II. Institute for Theoretical Physics, University of Hamburg, Luruper Chausse 149, DE-22761 Hamburg, Germany

Pat Scott†
Department of Physics, McGill University, 3600 rue University, Montréal, QC, H3A 2T8, Canada

Yashar Akrami‡
The Oskar Klein Centre for Cosmoparticle Physics, Department of Physics, Stockholm University, AlbaNova, SE-106 91 Stockholm, Sweden

Can we do this only using gravitational interactions?

Based on arXiv: 2506.20704

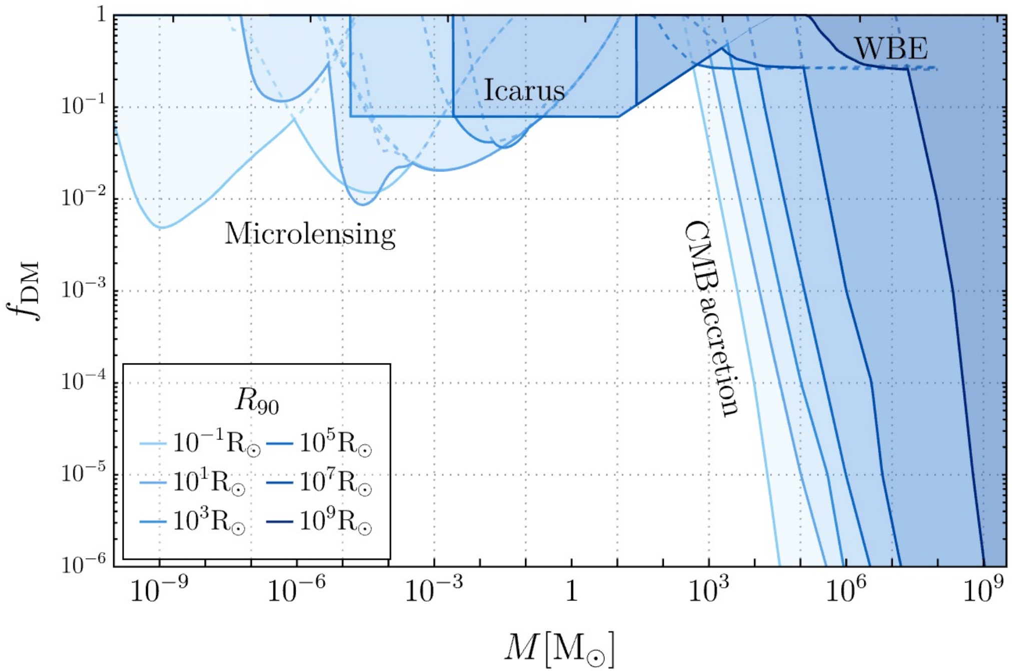
Ultra-compact minihaloes (UCMHs)

EDObounds:

Choose:
-Shape of the object
-Radius
-Bounds to plot
-Mass distributions!!

arXiv:2407.02573

There has been recent interest on constraining these type of objects:

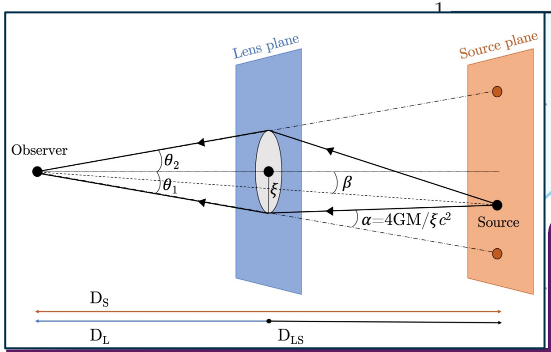


Based on arXiv: 2506.20704

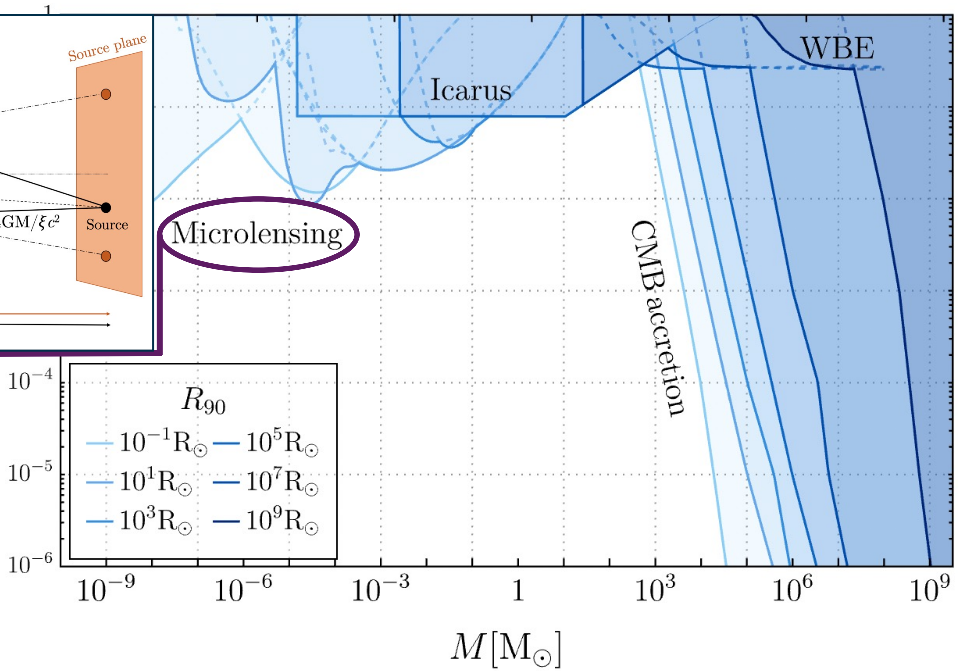
Ultra-compact minihaloes (UCMHs)

EDObounds: arXiv:2407.02573

There has been recent interest on constraining these type of objects:



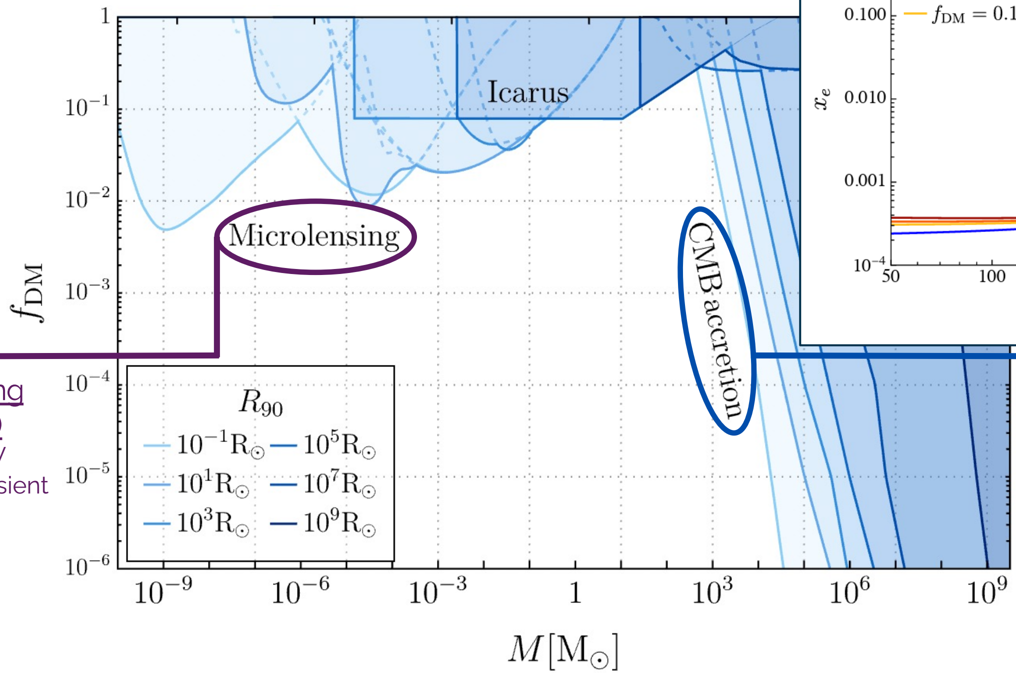
Croon, McKeen, Raj, Wang (2007.12697, 2002.08962)
Subaru, EROS-2 and OGLE-IV Microlensing bounds on transient dark matter objects

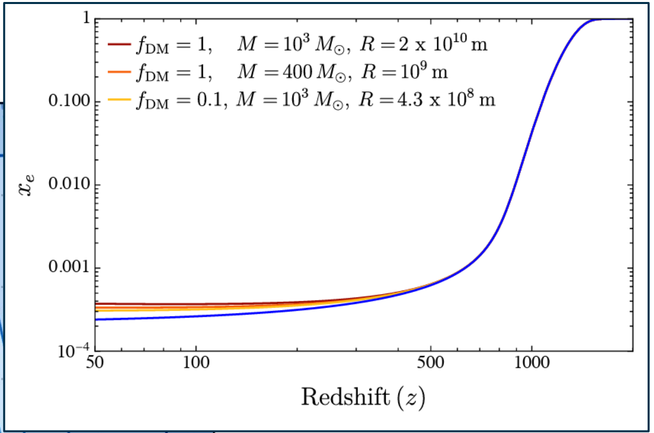


Ultra-compact minihaloes (UCMHs)

EDObounds: arXiv:2407.02573

There has been recent interest on constraining these type of





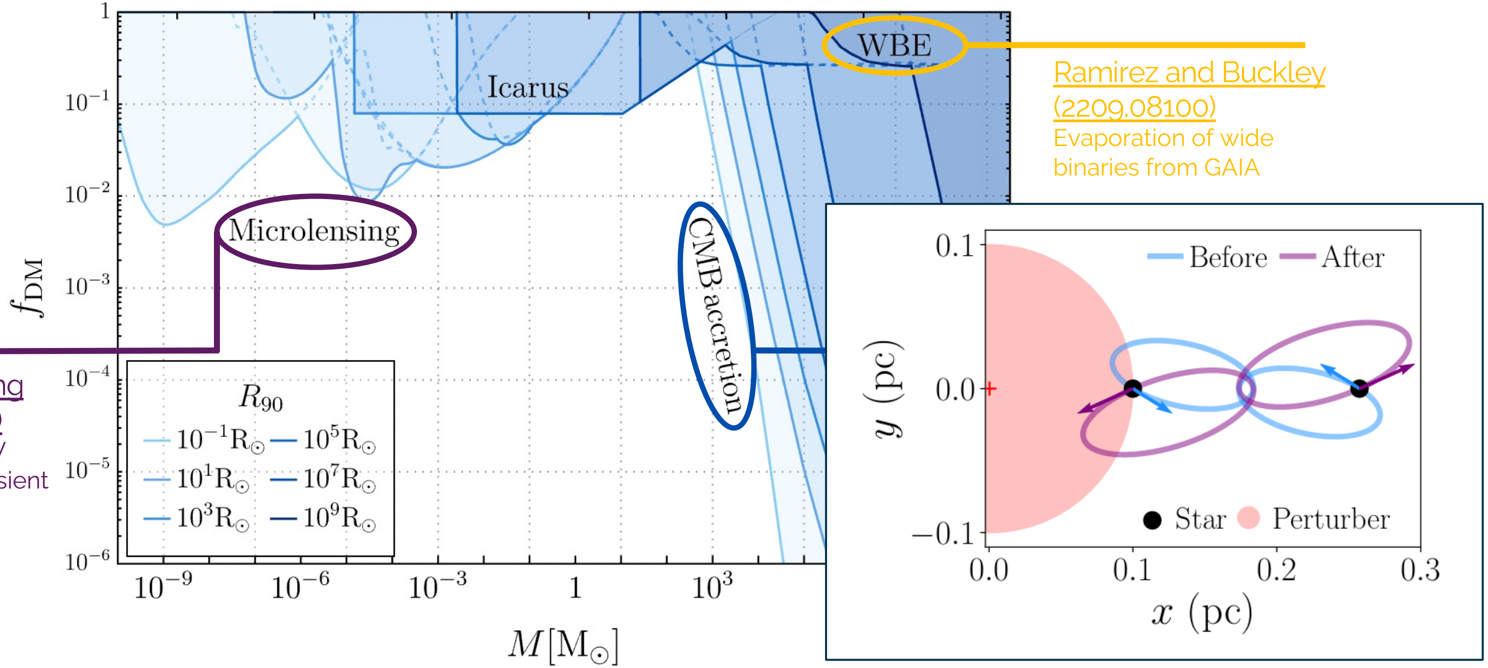
Croon, McKeen, Raj, Wang (2007.12697, 2002.08962)
Subaru, EROS-2 and OGLE-IV Microlensing bounds on transient dark matter objects

Croon and SSM (2403.13072)
Impact that accretion onto these object would have on recombination

Ultra-compact minihaloes (UCMHs)

EDObounds: arXiv:2407.02573

There has been recent interest on constraining these type of objects:



Ramirez and Buckley (2209.08100)
Evaporation of wide binaries from GAIA

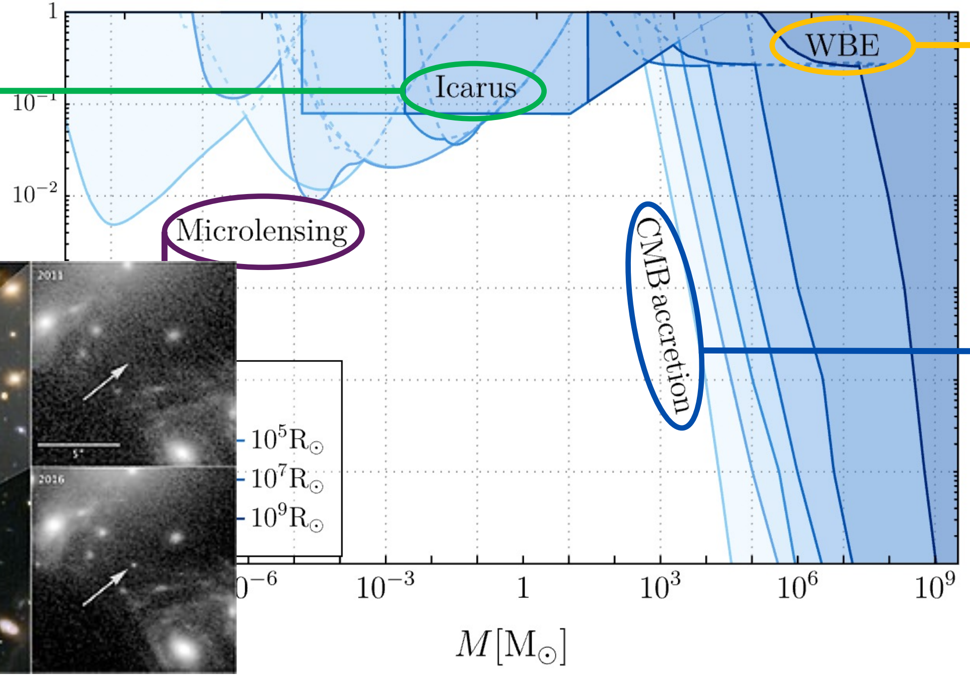
Croon, McKeen, Raj, Wang (2007.12697, 2002.08962)
Subaru, EROS-2 and OGLE-IV Microlensing bounds on transient dark matter objects

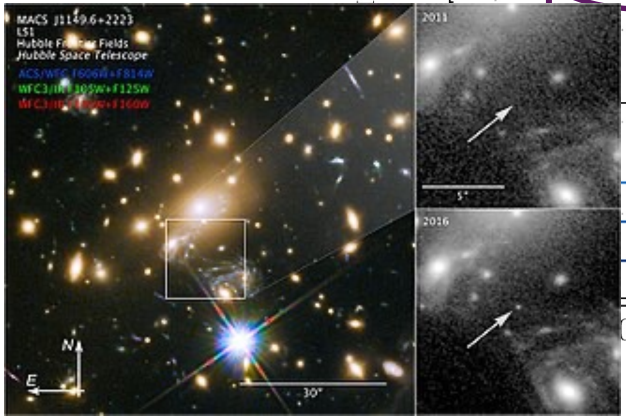
Based on arXiv: 2506.20704

Ultra-compact minihaloes (UCMHs)

EDObounds:
arXiv:2407.02573

There has been recent interest on constraining these type of objects:





(this work)
Perturbation of lensed light curves depending on smoothness of dark matter in clusters

Ramirez and Buckley (2209.08100)
Evaporation of wide binaries from GAIA

Croon and SSM (2403.13072)
Impact that accretion onto these object would have on recombination

Based on arXiv: 2506.20704

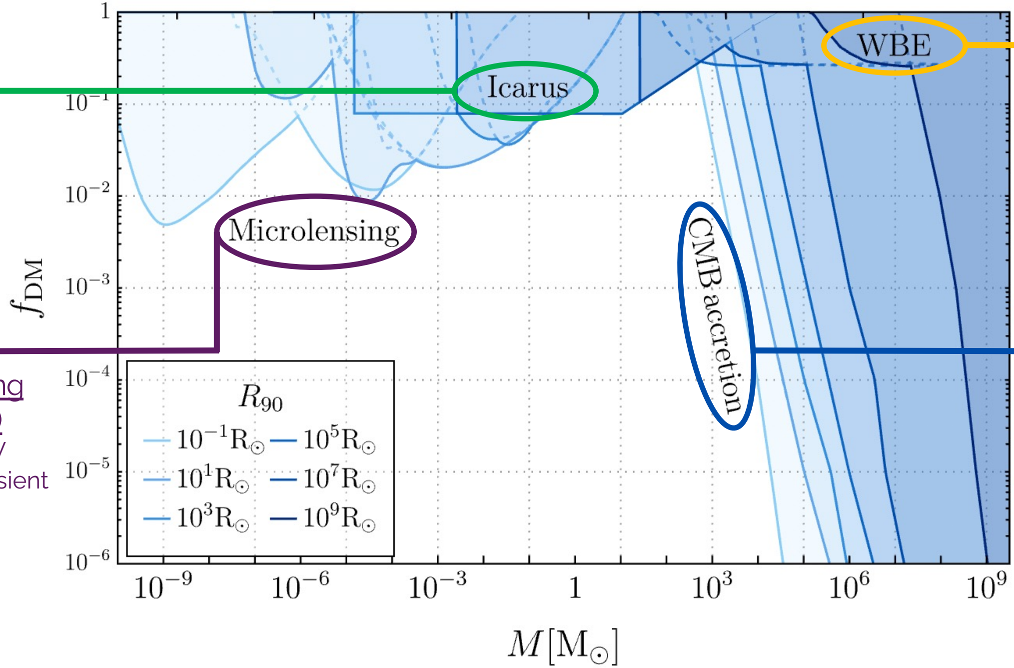
Ultra-compact minihaloes (UCMHs)

EDObounds:
arXiv:2407.02573

There has been recent interest on constraining these type of objects:

(this work)
Perturbation of lensed light curves depending on smoothness of dark matter in clusters

Croon, McKeen, Raj, Wang (2007.12697, 2002.08962)
Subaru, EROS-2 and OGLE-IV Microlensing bounds on transient dark matter objects



Ramirez and Buckley (2209.08100)
Evaporation of wide binaries from GAIA

Croon and SSM (2403.13072)
Impact that accretion onto these object would have on recombination

Ultra-compact minihaloes (UCMHs)

First, we need to know the object mass, radius and density for a given scale k~1/R:

$$M \approx \left[\frac{4\pi}{3}\rho_\chi H^{-3}\right]_{aH=1/R} = \frac{H_0^2}{2G}\Omega_\chi R^3$$

$$\rho_\chi(r, z_c) = \frac{3 f_\chi M(z_c)}{16\pi R(z_c)^{3/2} r^{3/2}}$$

$$\frac{R(z_c)}{\mathrm{pc}} = 0.019\left(\frac{1000}{z_c+1}\right)\left(\frac{M(z_c)}{M_\odot}\right)^{1/3}$$

where z_c is the collapse redshift

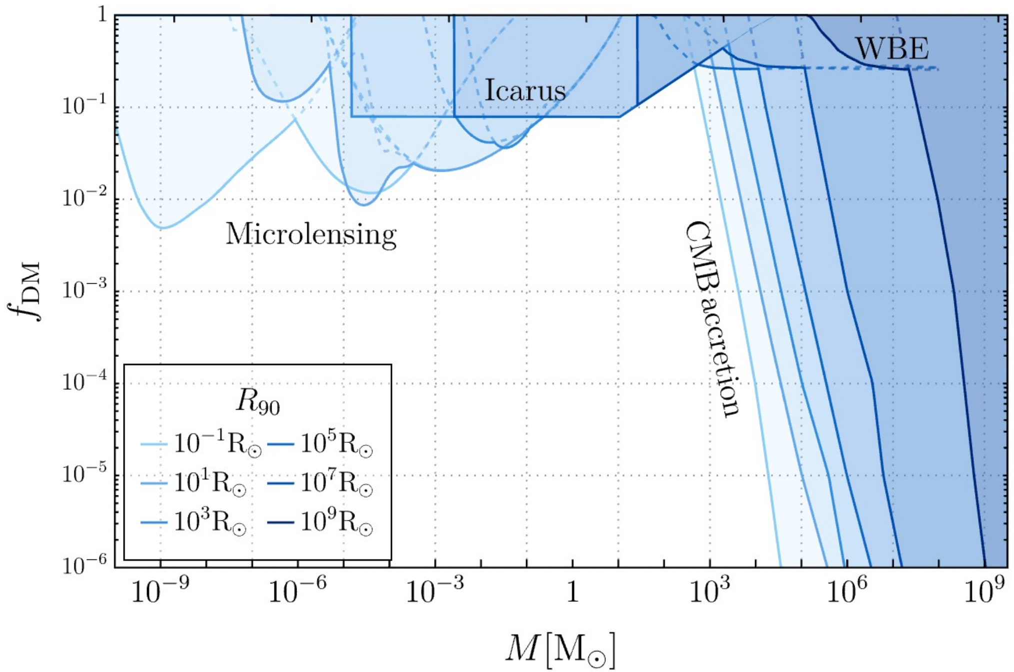
Different density functions have been used, but this is the most conservative

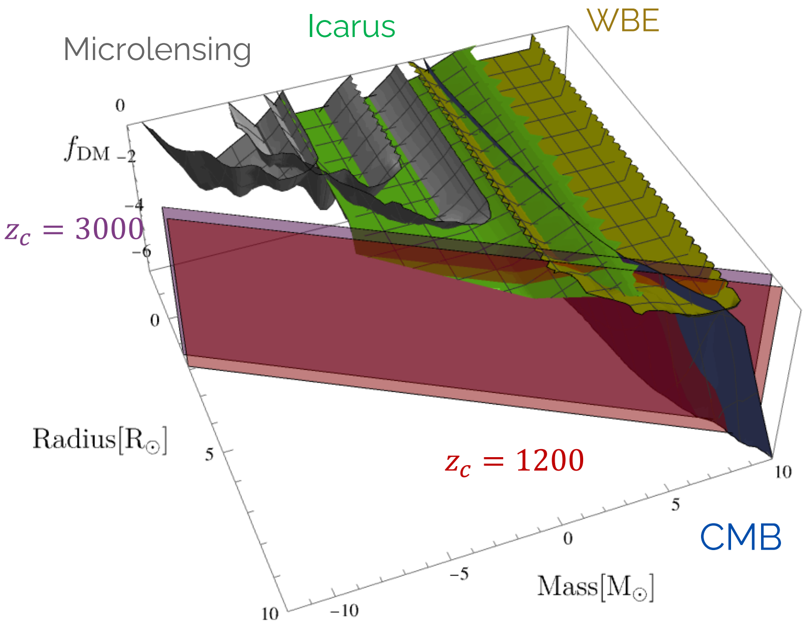
Based on arXiv: 2506.20704

Ultra-compact minihaloes (UCMHs)

$$\frac{R(z_c)}{\mathrm{pc}} = 0.019 \left(\frac{1000}{z_c+1}\right)\left(\frac{M(z_c)}{M_\odot}\right)^{1/3}$$

Only specific objects that have the mass-radius relation can be used to constrain the power spectrum

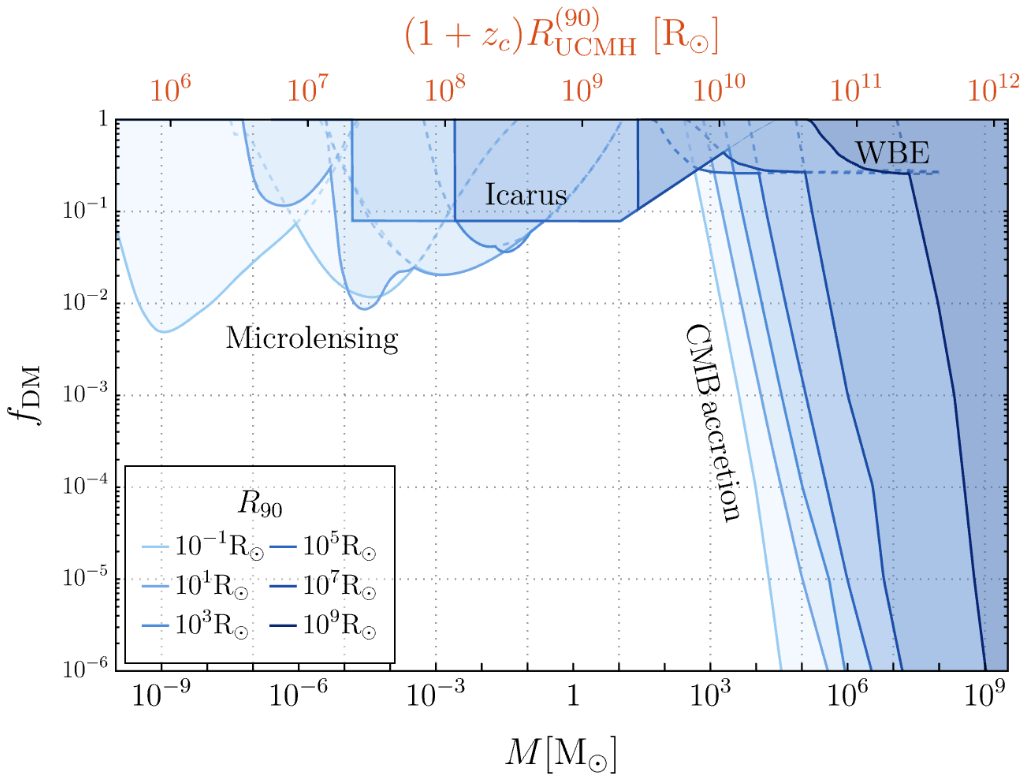


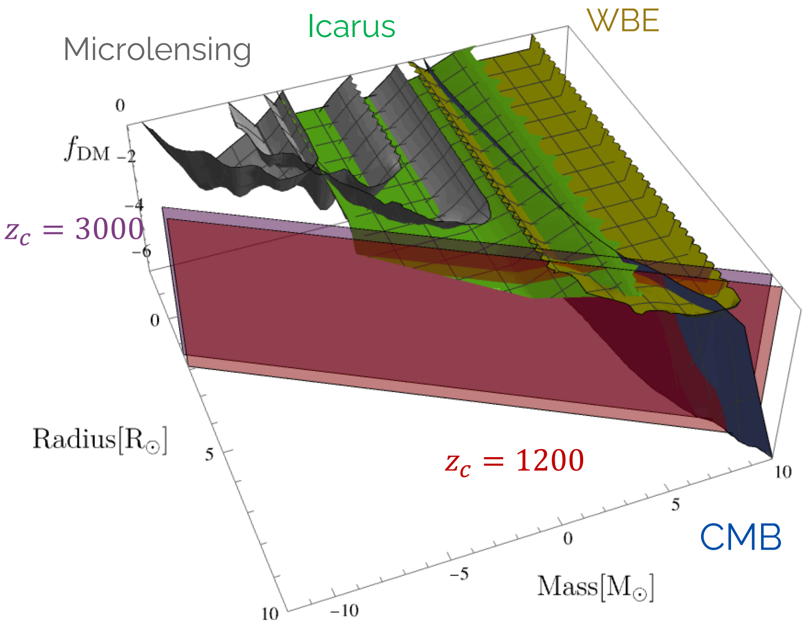


Based on arXiv: 2506.20704

Ultra-compact minihaloes (UCMHs)

$$\frac{R(z_c)}{\mathrm{pc}} = 0.019\left(\frac{1000}{z_c+1}\right)\left(\frac{M(z_c)}{M_\odot}\right)^{1/3}$$

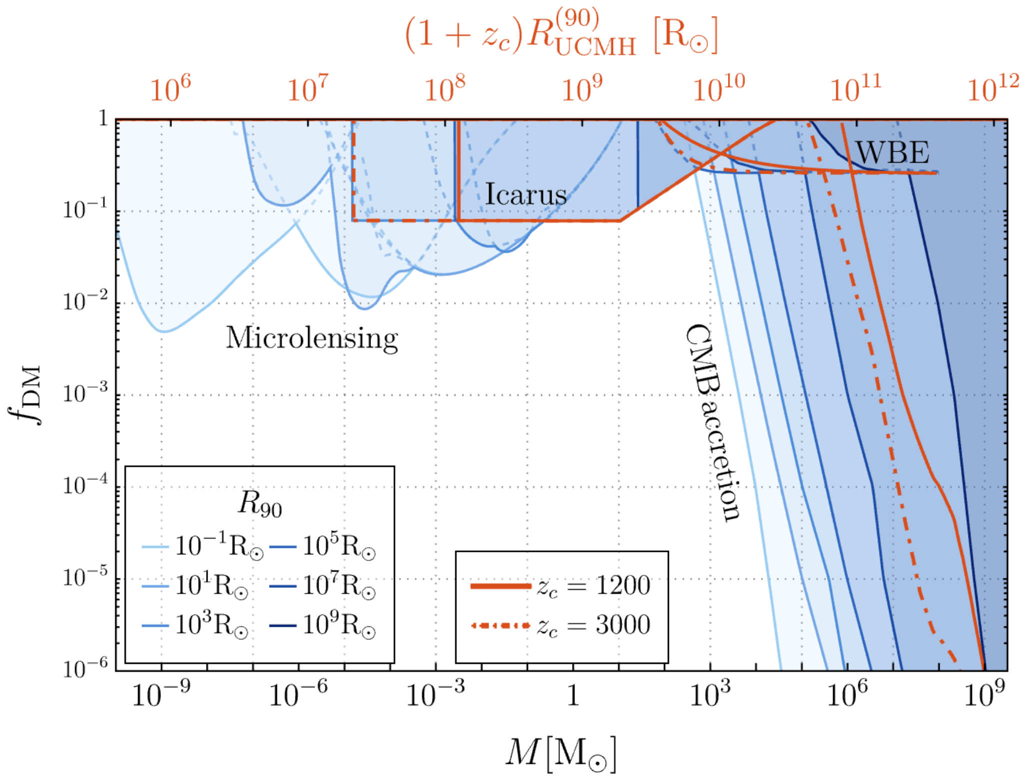


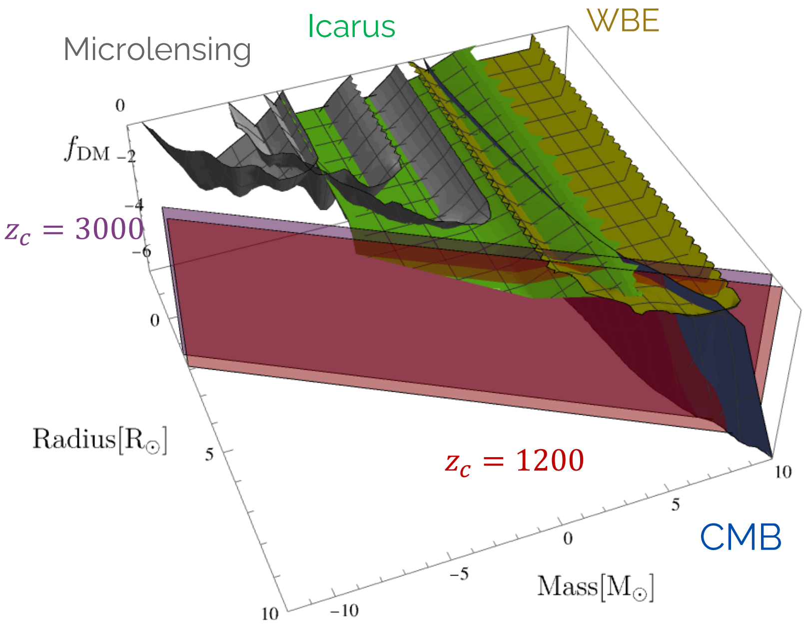


Based on arXiv: 2506.20704

Ultra-compact minihaloes (UCMHs)

$$\frac{R(z_c)}{\mathrm{pc}} = 0.019 \left(\frac{1000}{z_c+1}\right)\left(\frac{M(z_c)}{M_\odot}\right)^{1/3}$$



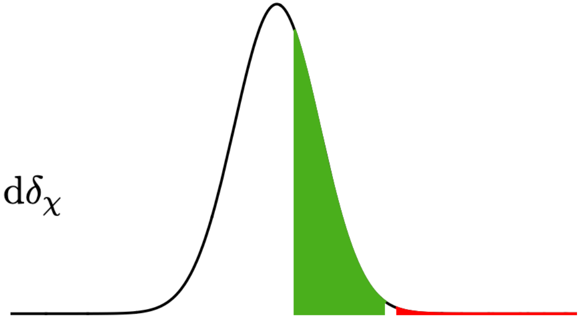


Ultra-compact minihaloes (UCMHs)

We know the properties of the formed objects, but not *how many* are created

Similar to primordial black holes

$$\beta(k) = \frac{1}{\sqrt{2\pi}\sigma_{\chi,H}(k)} \int_{\delta_\chi^{\min}(k)}^{\delta_\chi^{\max}} \exp\left[-\frac{\delta_\chi^2}{2\sigma_{\chi,H}^2(k)}\right] \mathrm{d}\delta_\chi$$



$$\Omega_{\rm UCMH}(k) = \Omega_{\rm DM}\beta(k)$$

$$\sigma_{\chi,H}^2(k) = \frac{1}{9}\int_0^\infty \mathrm{d}x x^3 W_{\rm TH}^2(x) \mathcal{P}_\mathcal{R}(xk) T_\chi^2(\theta = x/\sqrt{3})$$

$$\delta \equiv (\rho - \bar{\rho})/\bar{\rho}$$

Integrating for smaller overdensities

Ultra-compact minihaloes (UCMHs)

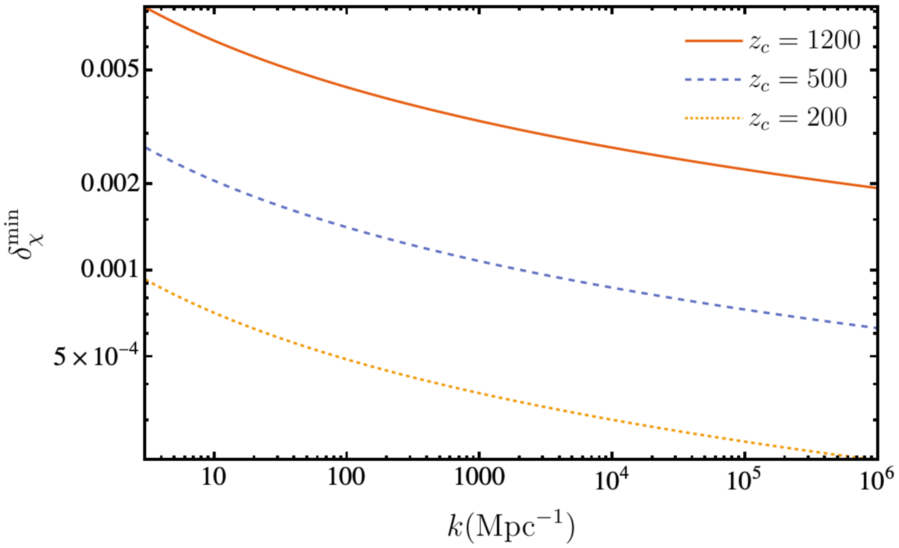
Depending on the scale, different number of objects will be created

$$\Omega_{\rm UCMH}(k) = \Omega_{\rm DM}\beta(k)$$

$$\beta(k) = \frac{1}{\sqrt{2\pi}\sigma_{\chi,H}(k)} \int_{\delta_\chi^{\rm min}(k)}^{\delta_\chi^{\rm max}} \exp\left[-\frac{\delta_\chi^2}{2\sigma_{\chi,H}^2(k)}\right] {\rm d}\delta_\chi$$

$$\delta \equiv (\rho - \bar{\rho})/\bar{\rho}$$

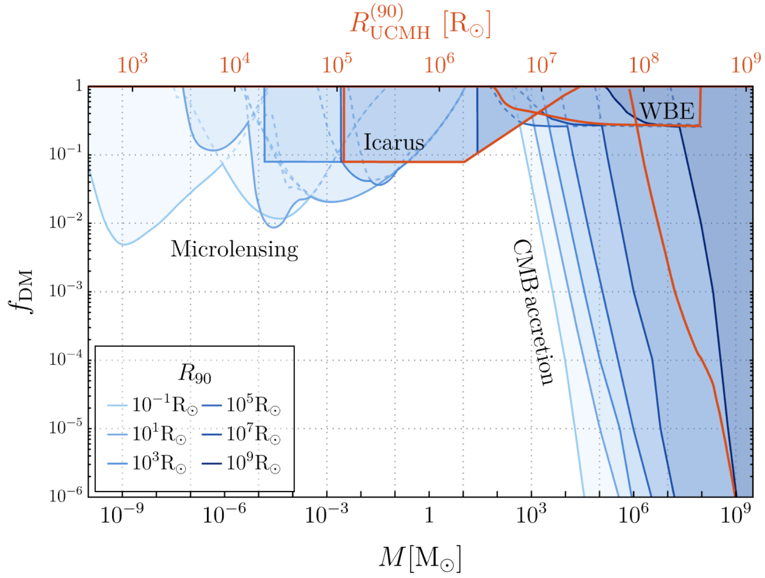
$$\sigma_{\chi,H}^2(k) = \frac{1}{9}\int_0^\infty {\rm d}x x^3 W_{\rm TH}^2(x)\mathcal{P}_{\mathcal{R}}(xk)T_\chi^2(\theta = x/\sqrt{3})$$

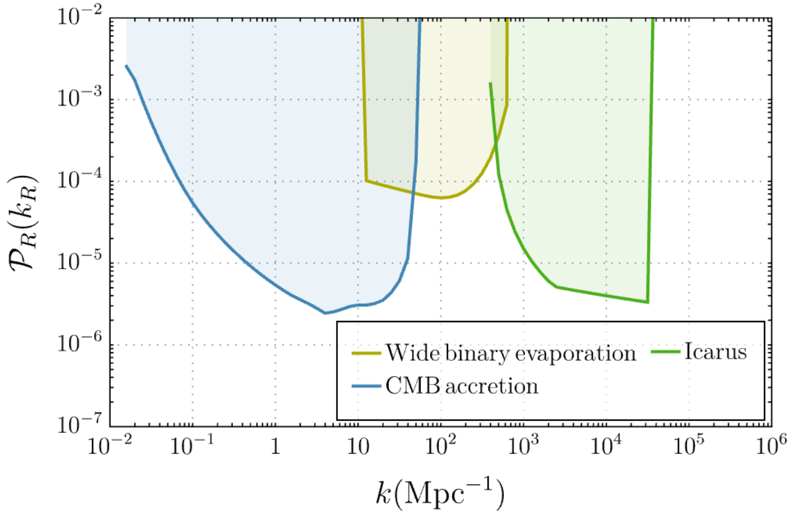


Based on arXiv: 2506.20704

Ultra-compact minihaloes (UCMHs)

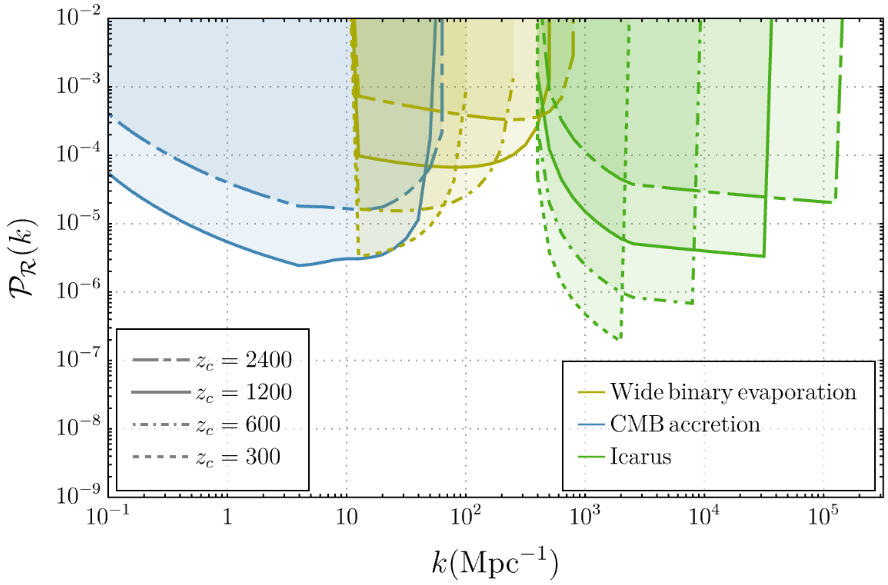
We can now translate these bounds (in red) to power spectrum using $\Omega_{\mathrm{UCMH}}(k) = \Omega_{\mathrm{DM}}\beta(k)$





Ultra-compact minihaloes (UCMHs)

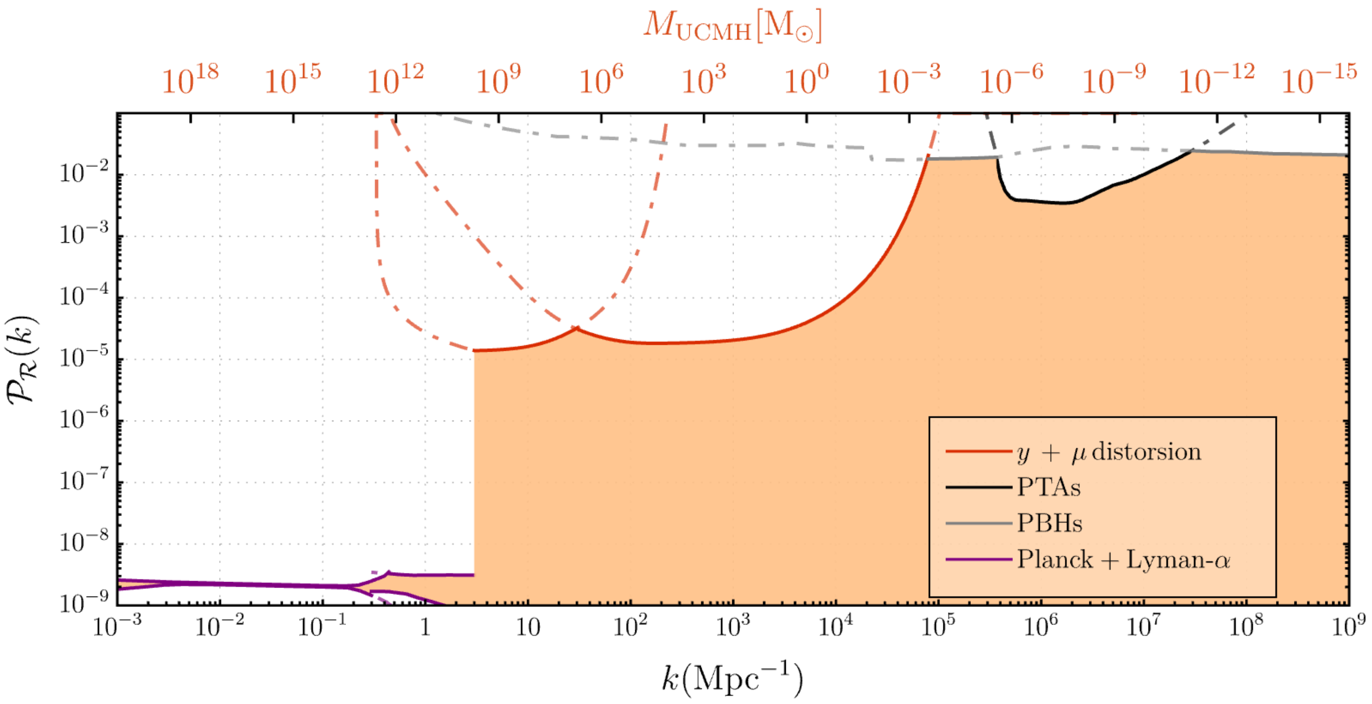
Different collapse times lead to different constraints



We will take the conservative choice $z_c > 1200$

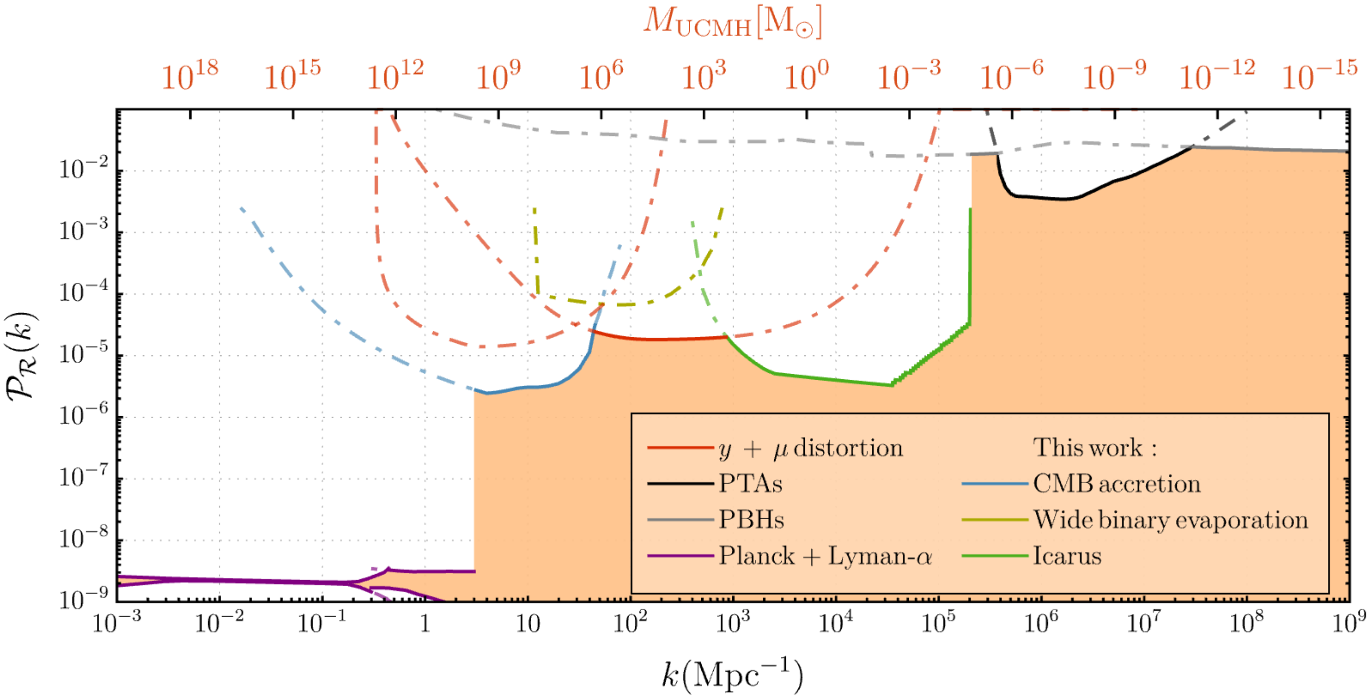
Ultra-compact minihaloes (UCMHs)

We can now translate these bounds to power spectrum using $\Omega_{\rm UCMH}(k) = \Omega_{\rm DM}\beta(k)$

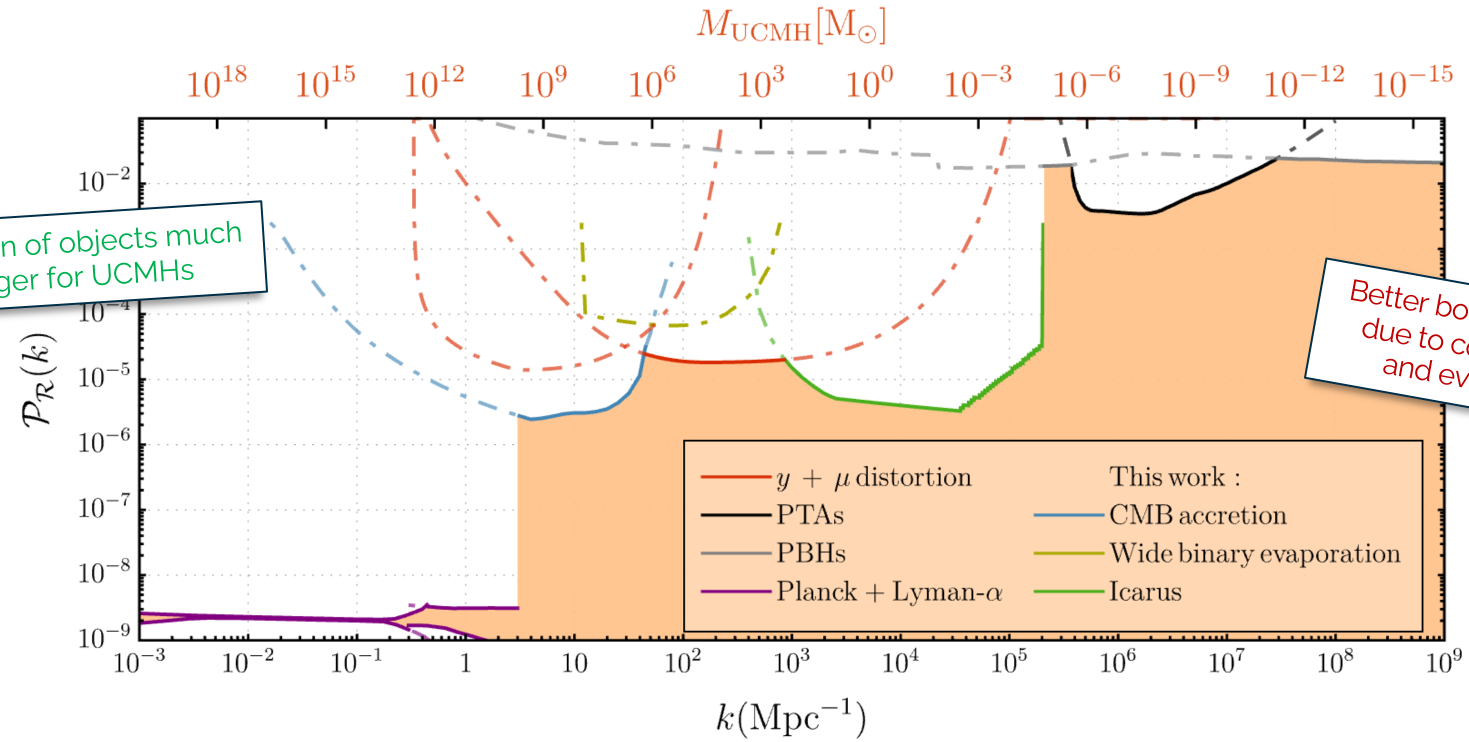


Ultra-compact minihaloes (UCMHs)

We can now translate these bounds to power spectrum using $\Omega_{\rm UCMH}(k) = \Omega_{\rm DM}\beta(k)$



PBHs vs UCMH



Fraction of objects much larger for UCMHs

Better bounds on PBHs due to compactness and evaporation

No PBHs with mass > $100\ M_\odot$

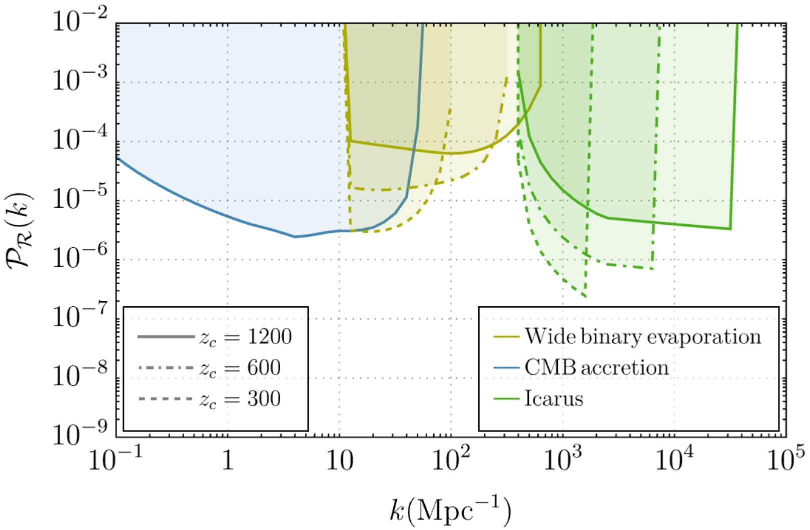
Soon no masses > $10^{-1}\ M_\odot$

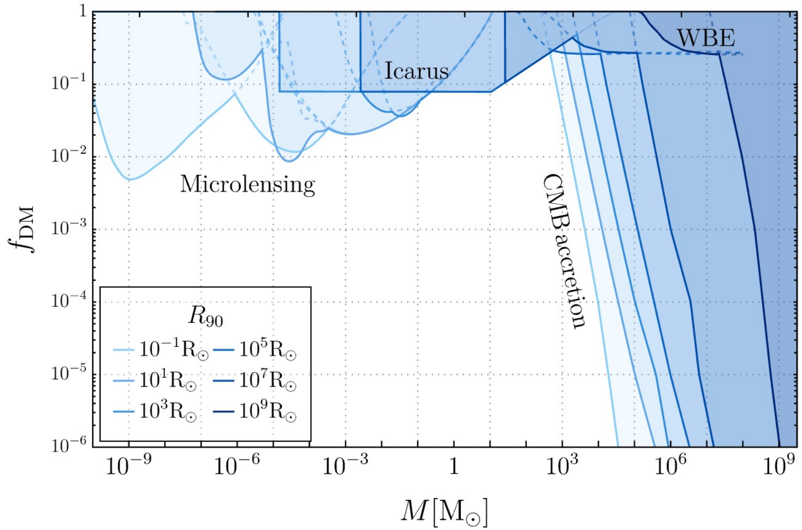
Conclusion

We can obtain improved constraints on the Power Spectrum using UCMHs!

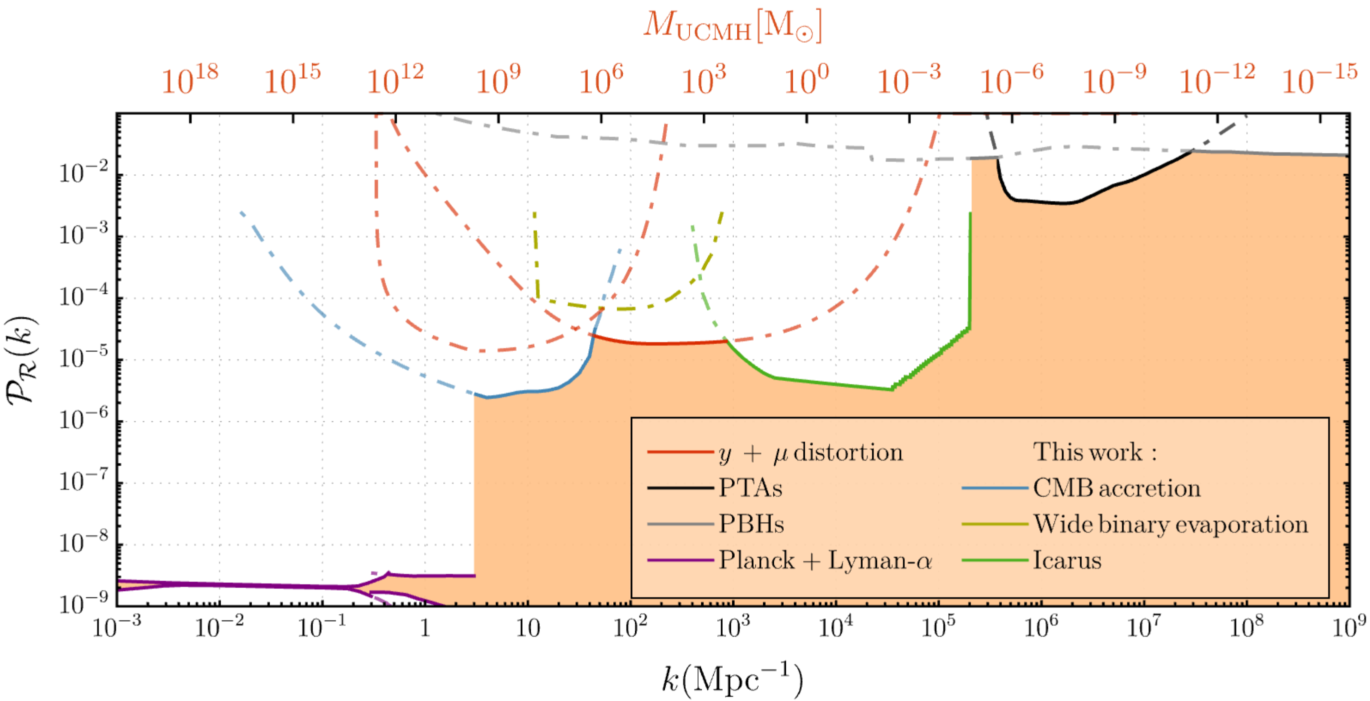
There is room for improvement :)

EDObounds: arXiv:2407.02573





Thank you for you attention!

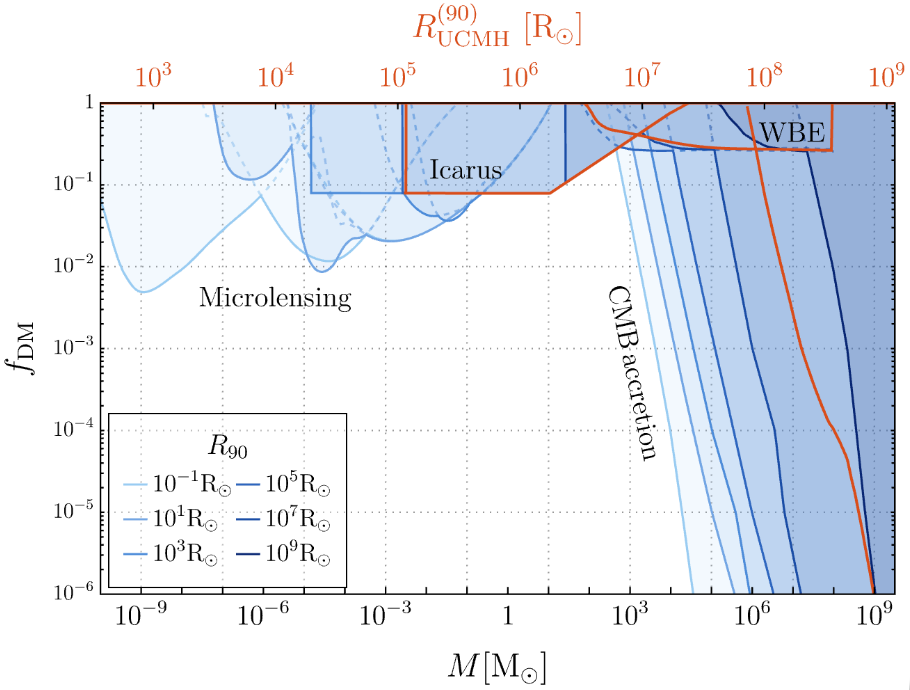


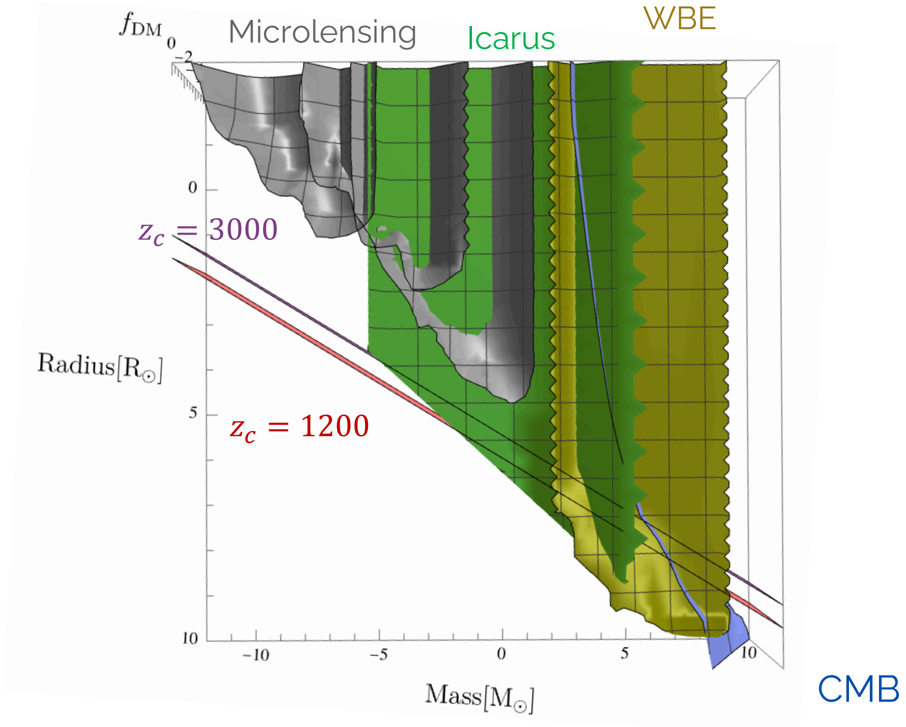
Based on arXiv: 2506.20704

Ultra-compact minihaloes (UCMHs)

$$\frac{R(z_c)}{\mathrm{pc}} = 0.019 \left(\frac{1000}{z_c+1}\right)\left(\frac{M(z_c)}{M_\odot}\right)^{1/3}$$

Only specific objects that have the mass-radius relation can be used to constrain the power spectrum





Ultra-compact minihaloes (UCMHs)

Only specific objects that have the mass-radius relation can be used to constrain the power spectrum