Galactic rotation curves vs. ultra-light dark matter:

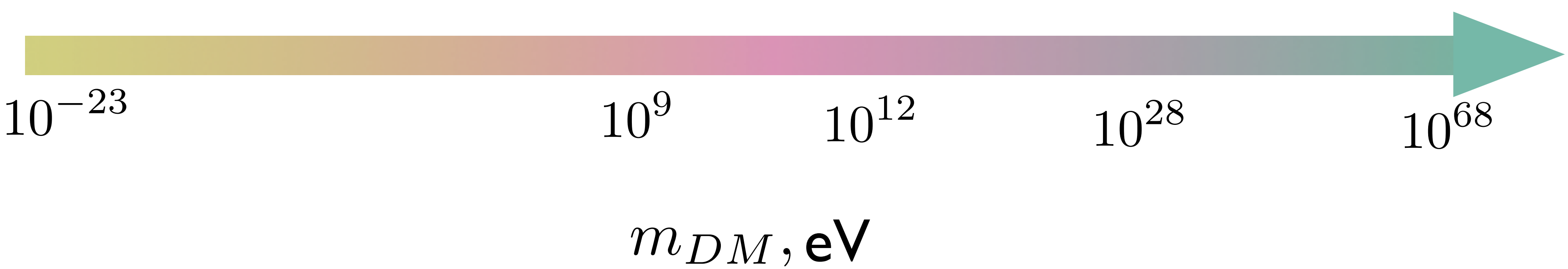
Implications of the soliton — host halo relation

Sergey Sibiryakov

with Nitsan Bar, Diego Blas, Kfir Blum, arXiv:1805.00122

BW2018, Niš, Serbia

What is dark matter ?



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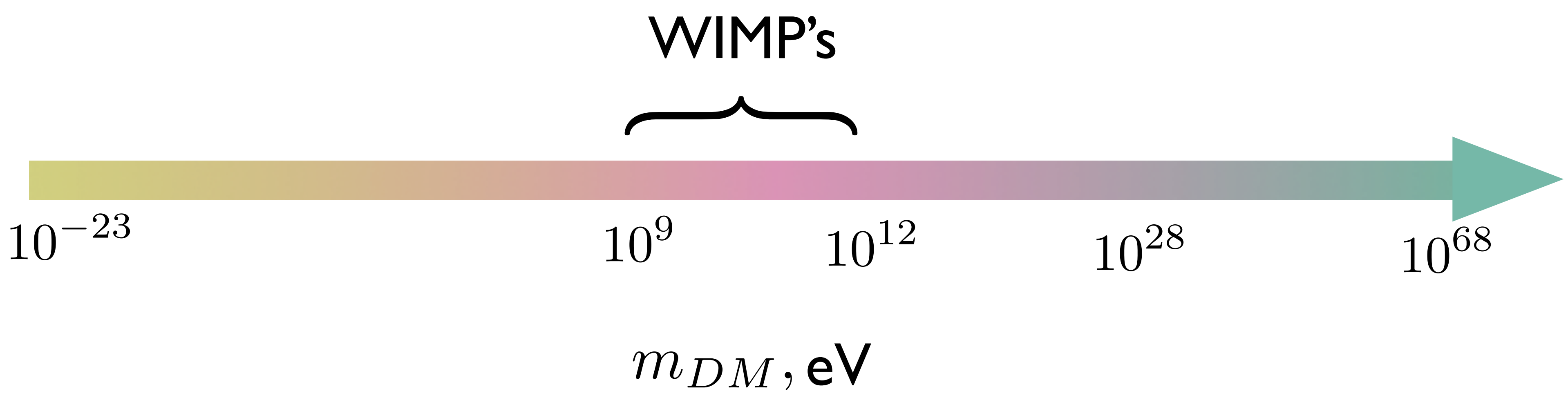

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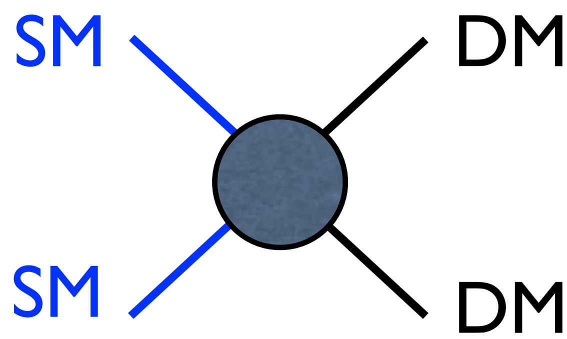

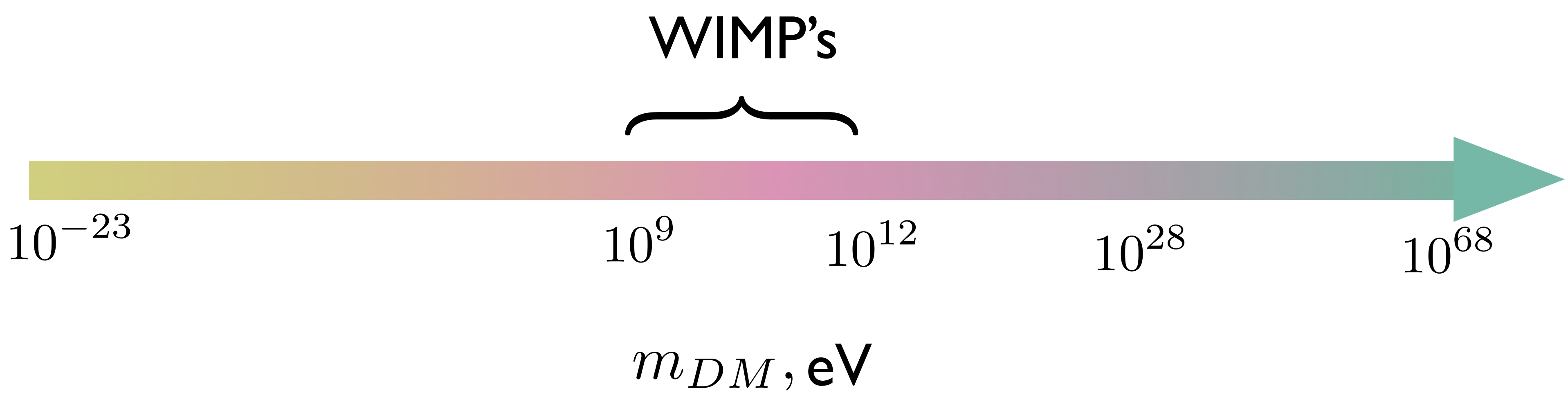

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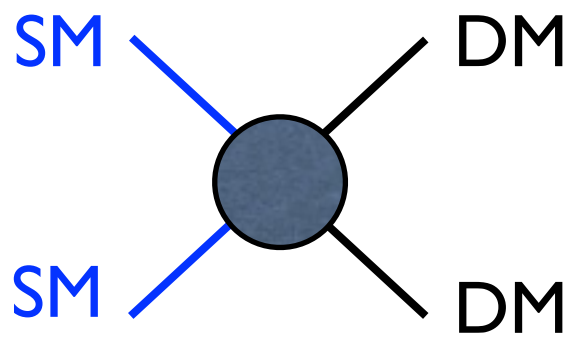

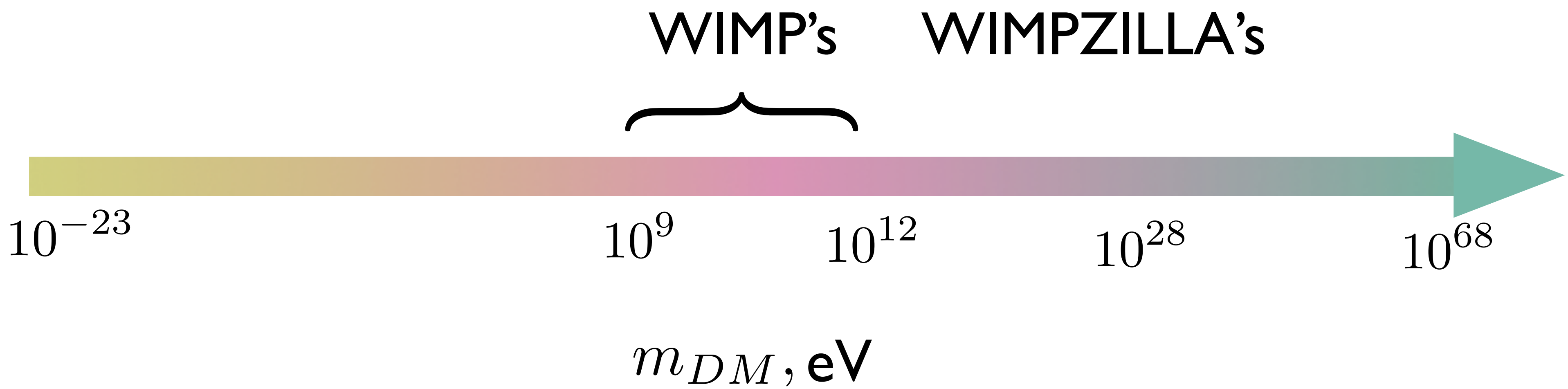

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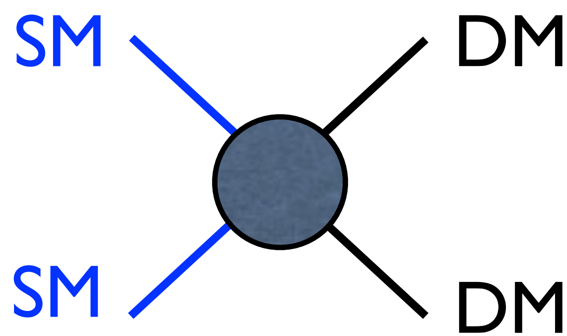

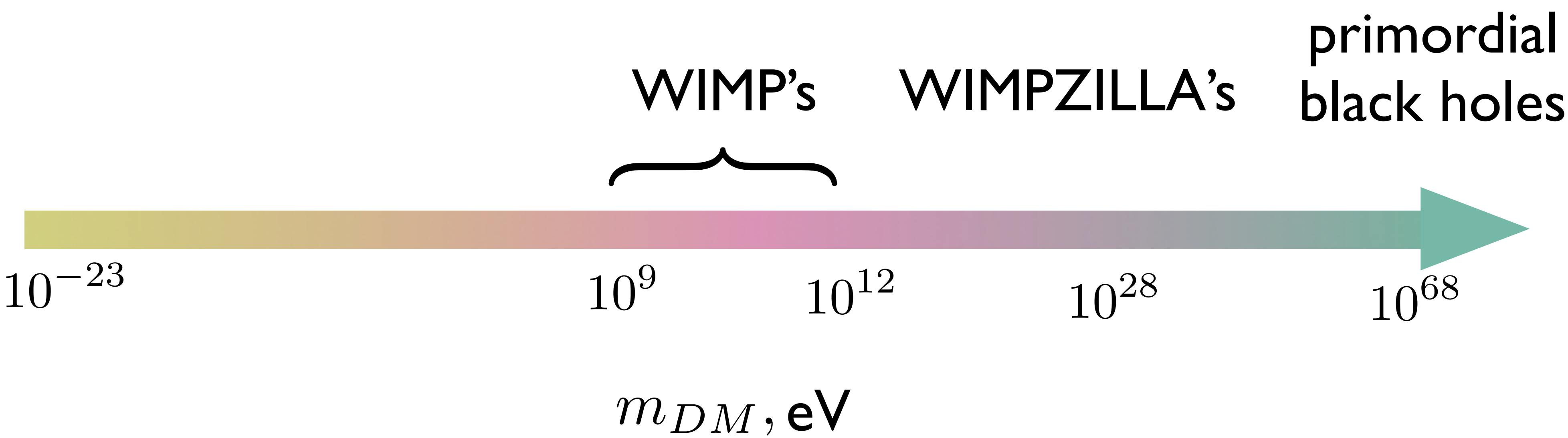

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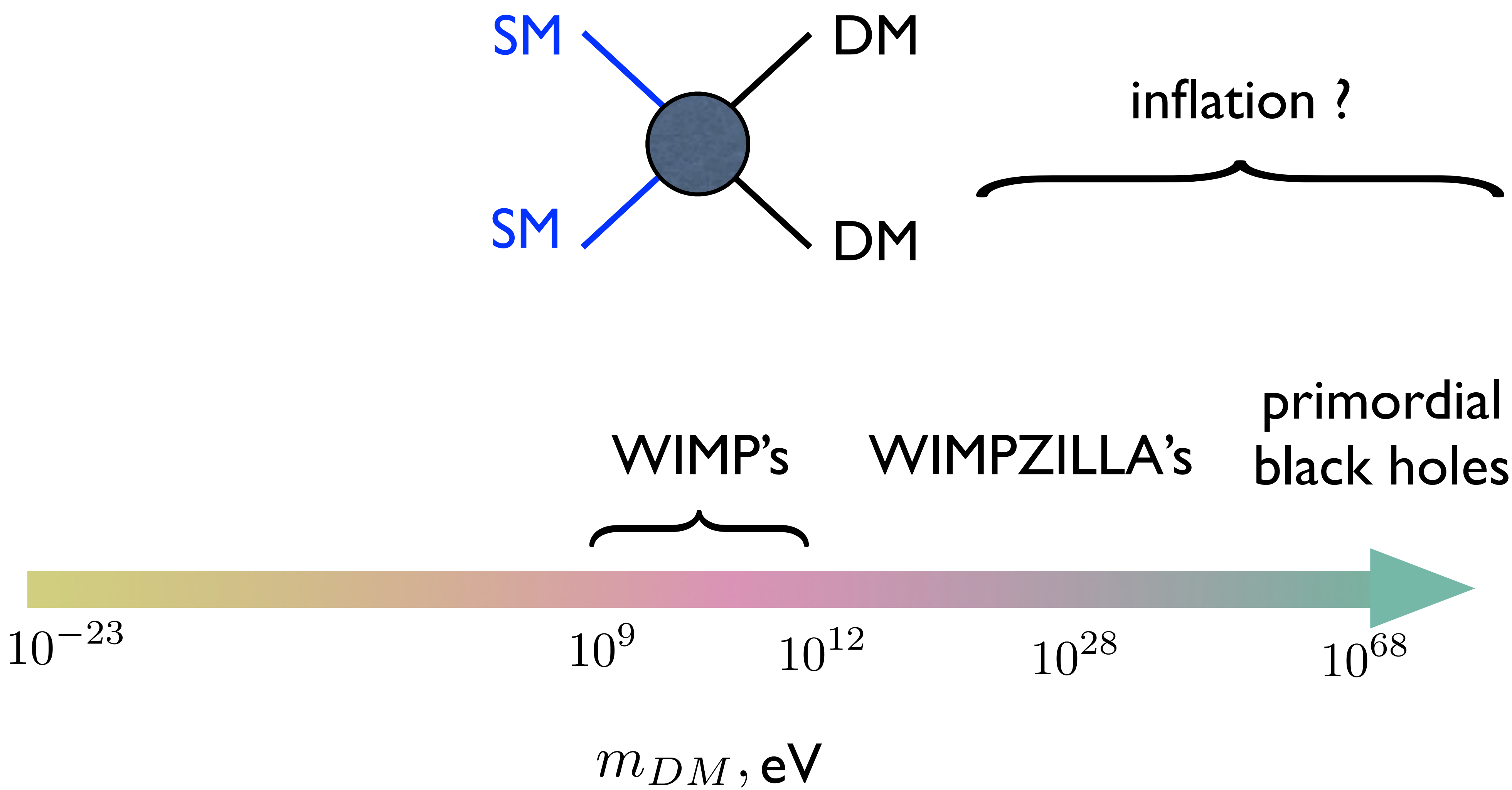

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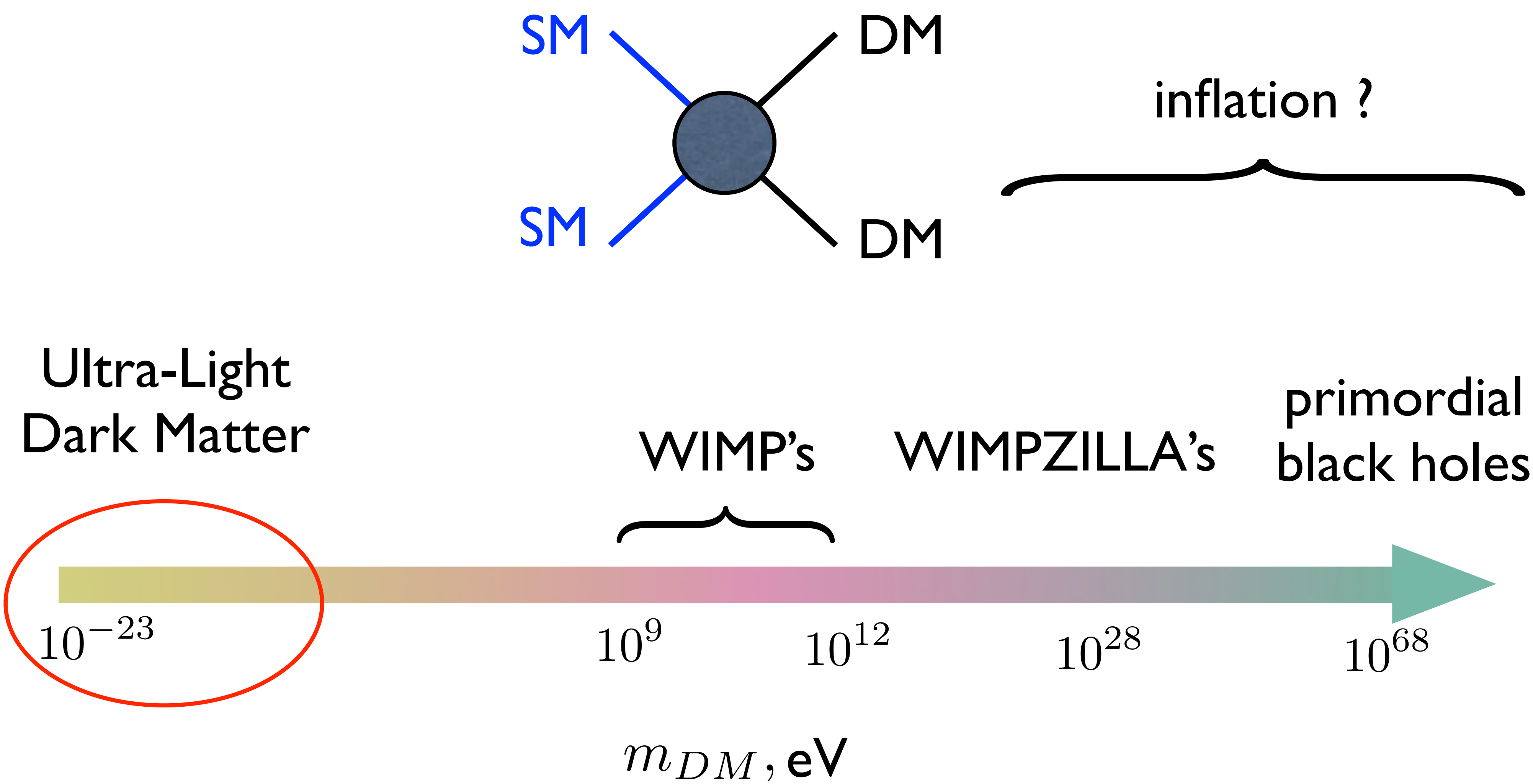

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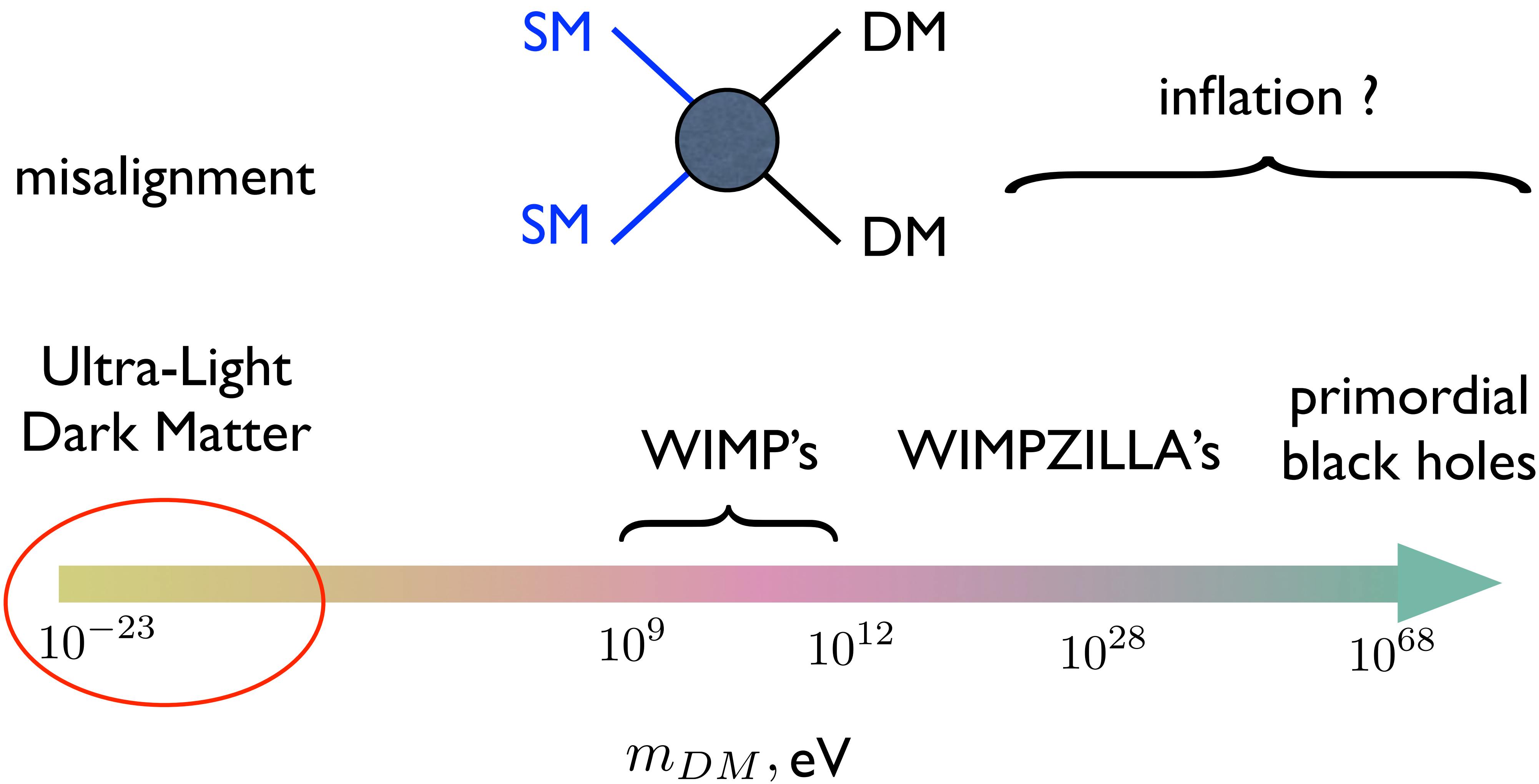
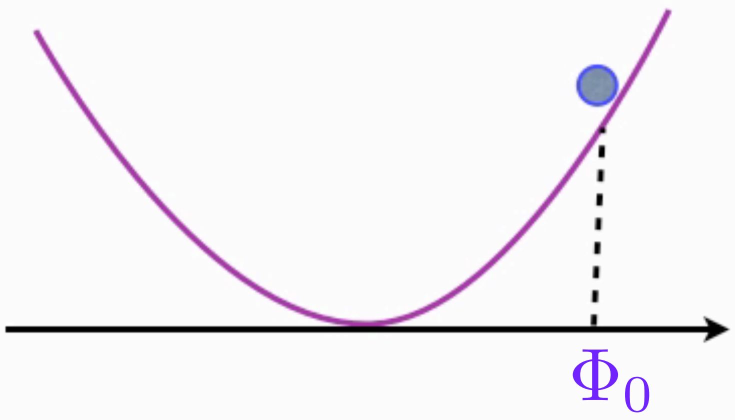


The simplest DM model: free massive scalar

$$\mathcal{L} = \frac{1}{2}\left((\partial_\mu \Phi)^2 - m^2\Phi^2\right)$$



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$$\ddot{\Phi} + 3H\dot{\Phi} + m^2\Phi = 0$$

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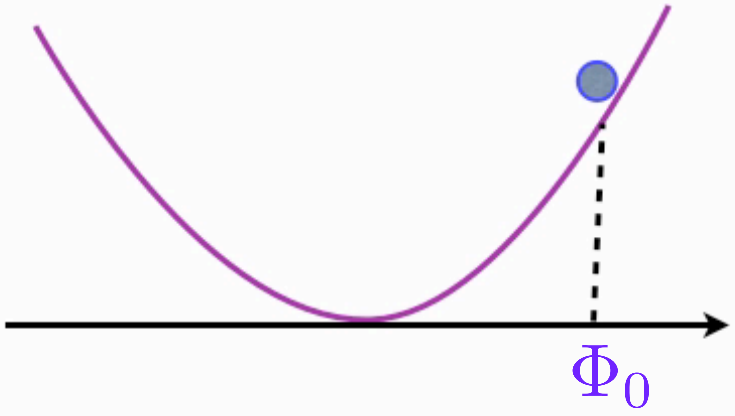

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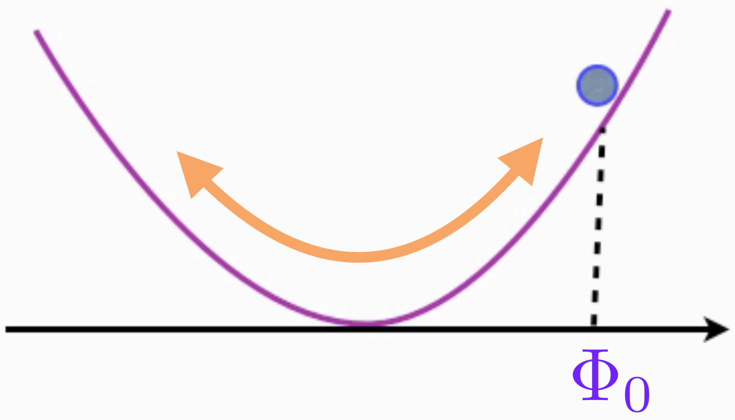

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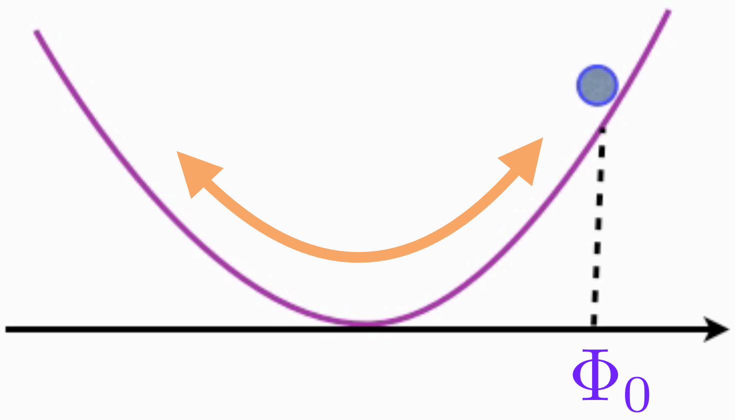

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behaves as DM on times longer than m^{-1}

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$$m \propto \exp(-S_{inst})$$

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- Density fraction:

$\Phi \sim f$ after inflation

$$\Omega_\Phi \simeq 0.05 \times \left(\frac{f}{10^{17}\mathrm{GeV}}\right)^2 \times \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{1/2}$$

Observational probes

- $m \gtrsim 10^{-23}\mathrm{eV}$ from CMB and LSS : otherwise too much suppression of structure

  Ly α forest: $m \gtrsim 10^{-21}\mathrm{eV}$ based on complicated modelling

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focus of this talk: $m \sim 10^{-22} \div 10^{-18}\mathrm{eV}$

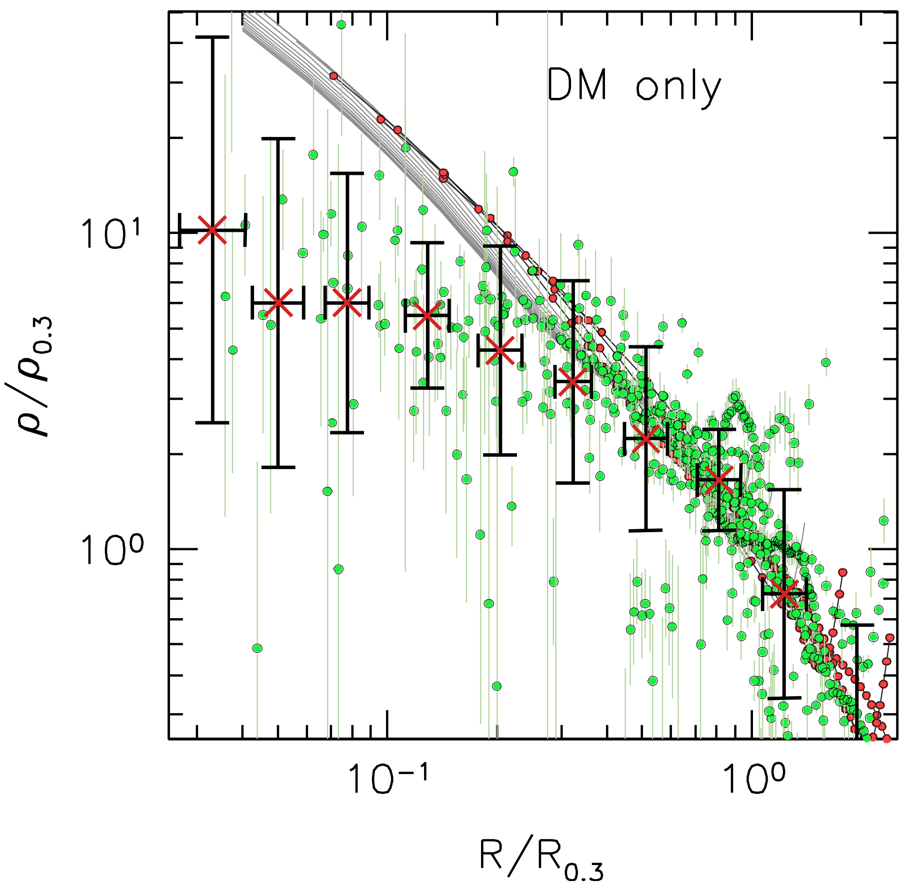
NB. Can be axion-like particle, but *not* QCD axion

Challenges to particle CDM at sub-kpc scales ?

- cores vs. cusps

- missing satellites

- too big to fail



from Oh et al., arXiv:1502.01281

perhaps are explained by baryonic physics

Dynamics of ULDM in the Newtonian limit

$$\Phi = \Psi(\mathbf{x}, t)\mathrm{e}^{-imt} + h.c.$$

slowly varying amplitude

$$\left.\begin{aligned} &-i\dot{\Psi} - \frac{\nabla^2}{2m}\Psi + m\varphi(\mathbf{x}, t)\Psi = 0 \\ &\nabla^2\varphi = 2Gm^2|\Psi|^2 \end{aligned}\right\}$$

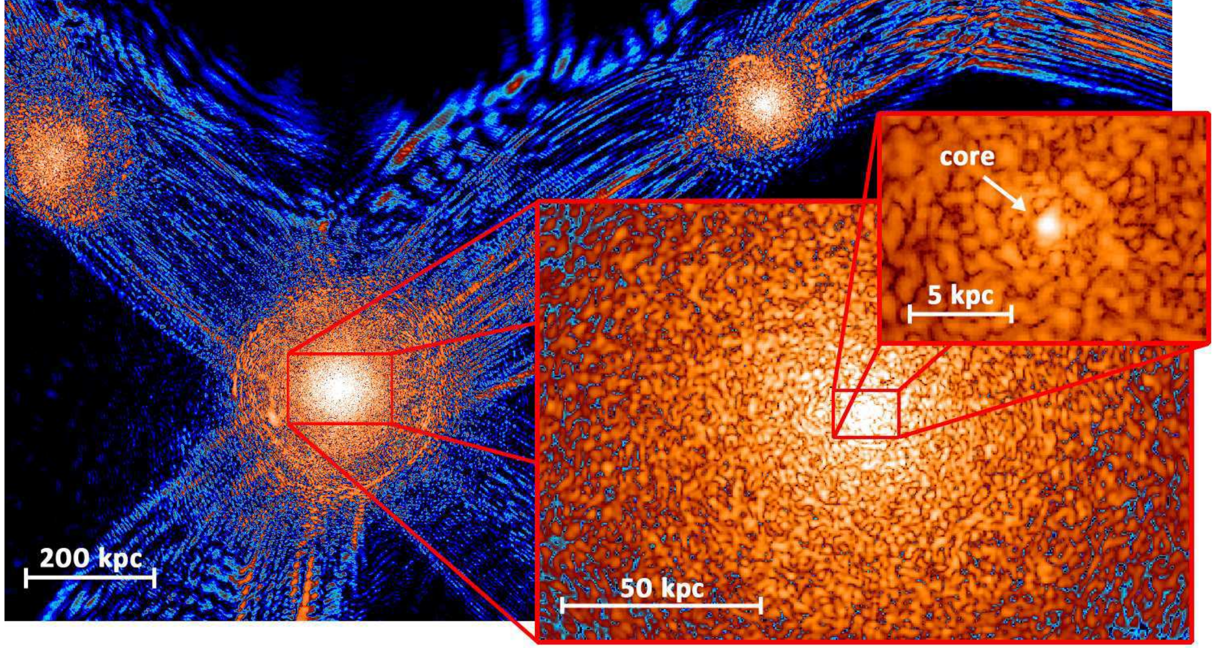
Schroedinger --
Poisson
system

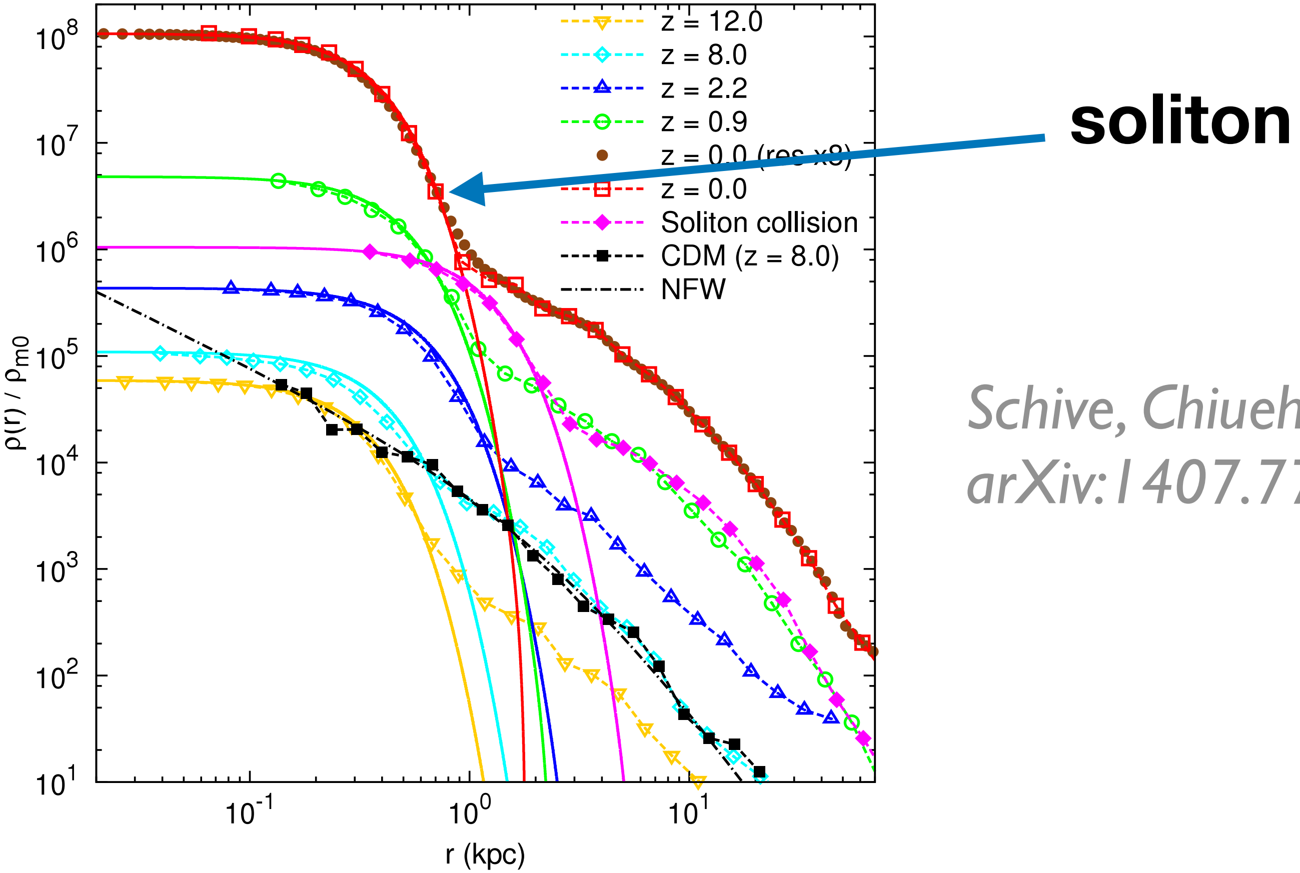
leads to suppression of fluctuations at short scale --- "quantum pressure"

Probing ULDM with galactic rotation curves

ULDM in the halo

Schive, Chiueh, Broadhurst, arXiv: 1406.6586

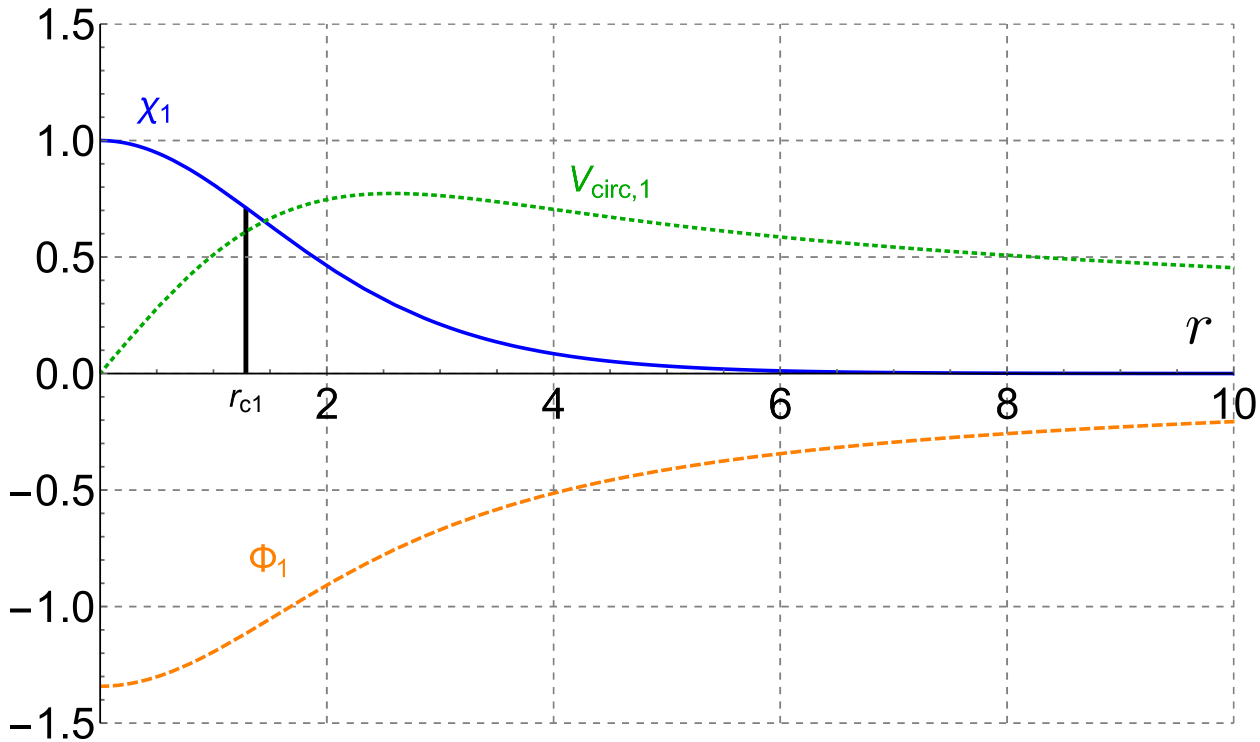




Schive, Chiueh, Boardhurst, arXiv:1407.7762

Properties of the soliton

$$\psi(x,t) = \left(\frac{mM_{pl}}{\sqrt{4\pi}}\right) e^{-i\gamma m t}\chi(x)$$



$$\chi_\lambda(r) = \lambda^2 \chi_1(\lambda r)$$

$$x_{c\lambda} = \lambda^{-1} x_{c1}$$

$$M_\lambda = \lambda M_1$$

$$\gamma_\lambda = \lambda^2 \gamma$$

$$\rho_{c\lambda} = \lambda^4 \rho_{c1}$$

Soliton - host halo relation

Schive, Chiueh, Boardhurst, arXiv:1407.7762

$$M \approx 1.4 \times 10^{9} \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{-1} \left(\frac{M_h}{10^{12}\ \mathrm{M}_\odot}\right)^{\frac{1}{3}} \mathrm{M}_\odot$$

$$\Longleftrightarrow \qquad M_c \approx \alpha \left(\frac{|E_h|}{M_h}\right)^{\frac{1}{2}} \frac{M_{pl}^2}{m}$$

$$\Longleftrightarrow \qquad \boxed{\left.\frac{E}{M}\right|_{\mathrm{soliton}} \approx \left.\frac{E}{M}\right|_{\mathrm{halo}}}$$

Exercise for NFW halo

$$\rho_{NFW}(x) = \frac{\rho_c \delta_c}{\frac{x}{R_s}\left(1 + \frac{x}{R_s}\right)^2}$$

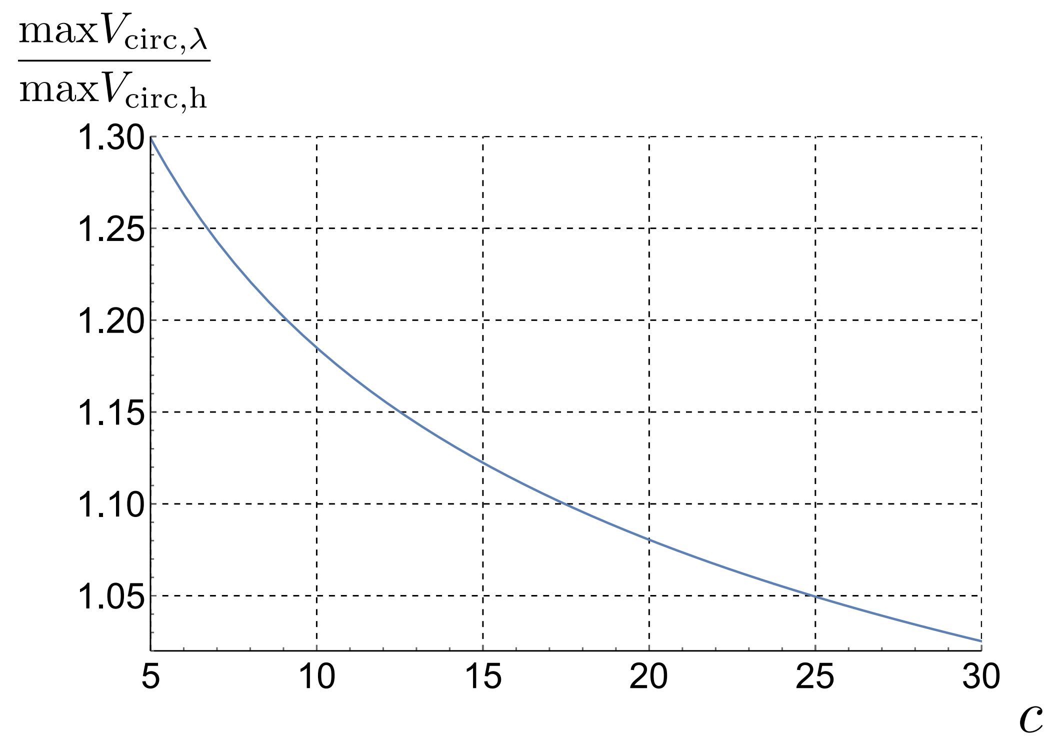
scale radius

$$\rho_c(z) = \frac{3H^2(z)}{8\pi G}, \quad \delta_c = \frac{200}{3}\frac{c^3}{\ln(1+c) - \frac{c}{1+c}}.$$

concentration

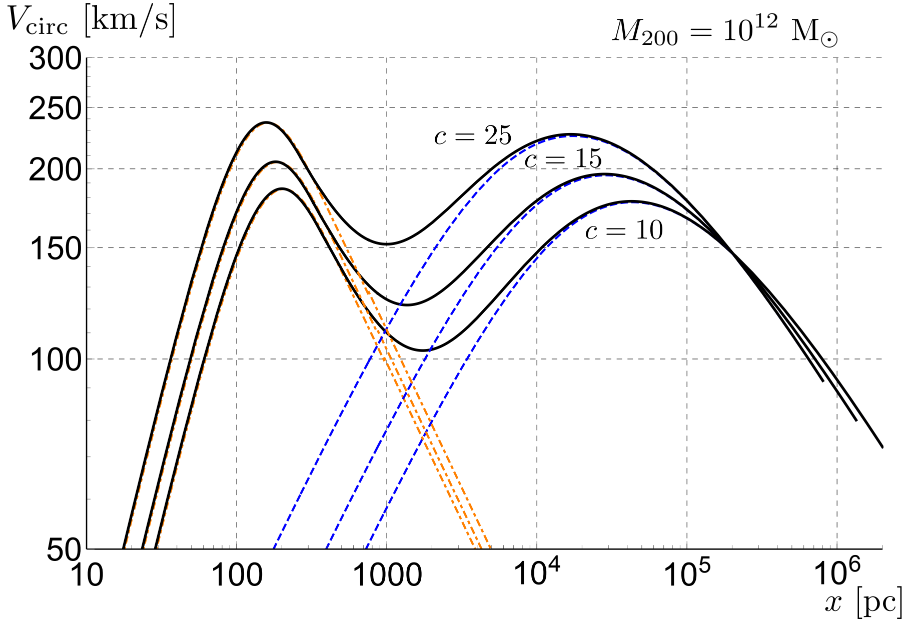
$$c \sim 5 \div 30$$

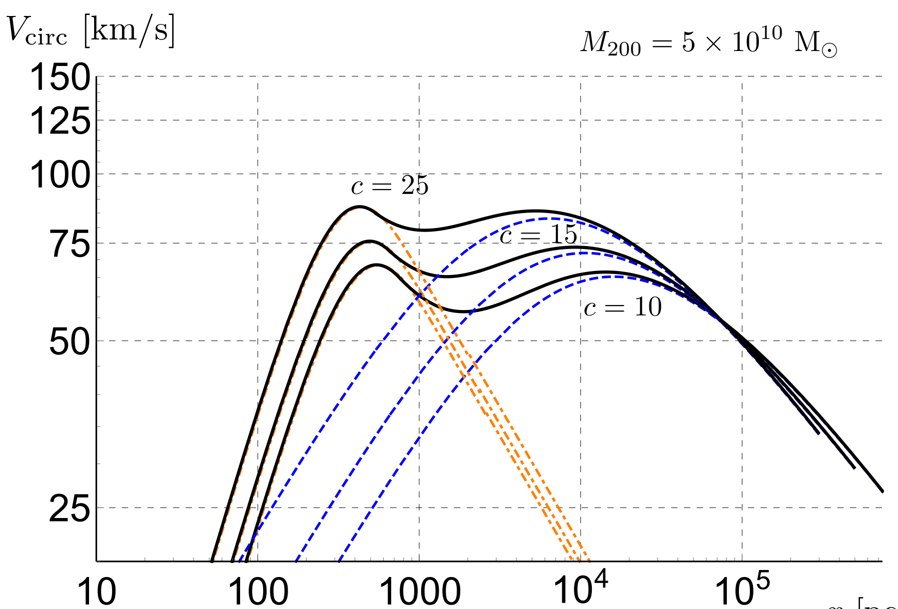
$$\boxed{\frac{\max V_{\mathrm{circ},\lambda}}{\max V_{\mathrm{circ,h}}} \approx 1.1\left(\frac{\tilde{c}}{0.4}\right)^{\frac{1}{2}}}$$



predictions vs data

$$m = 10^{-22}\mathrm{eV}$$





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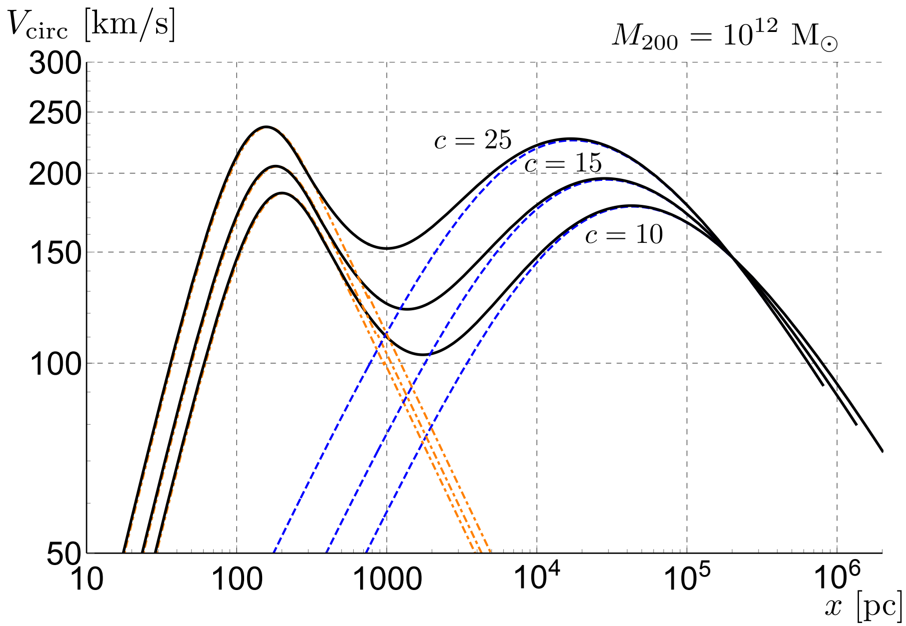

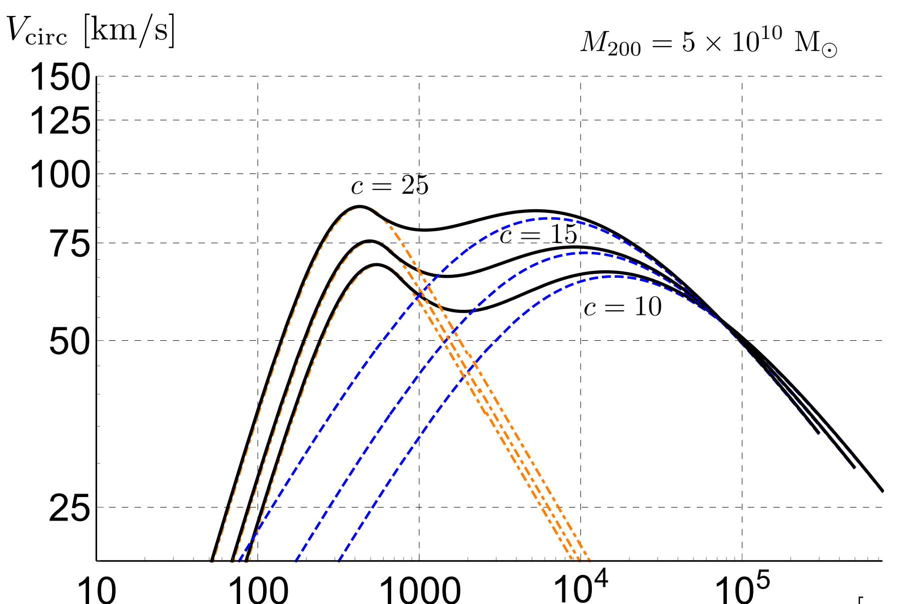

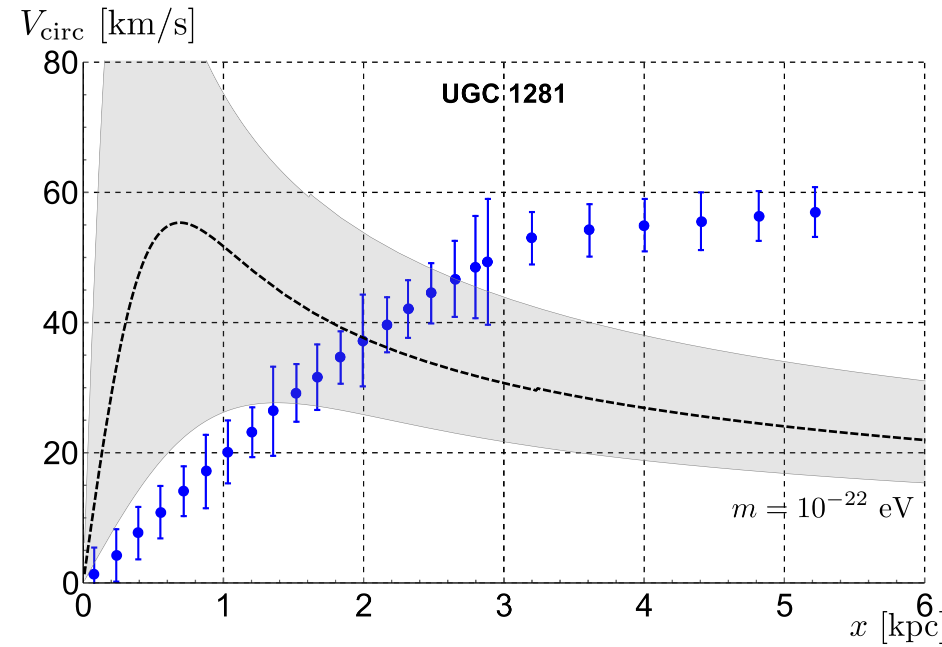

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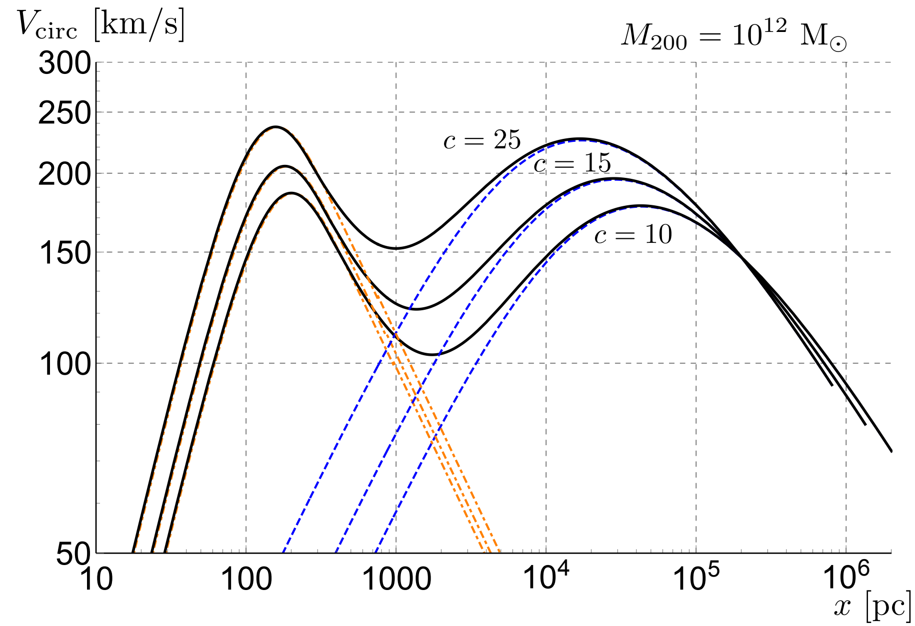
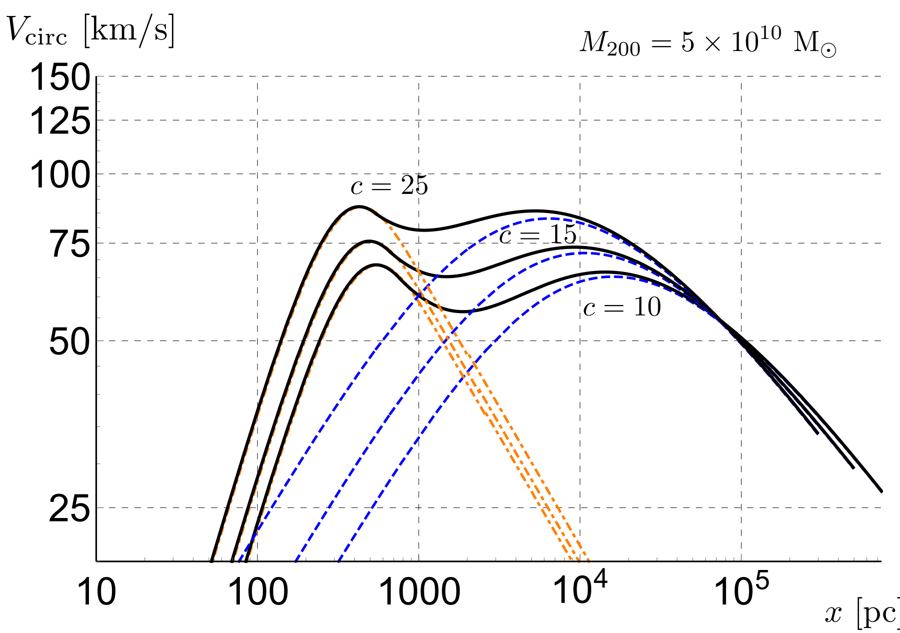
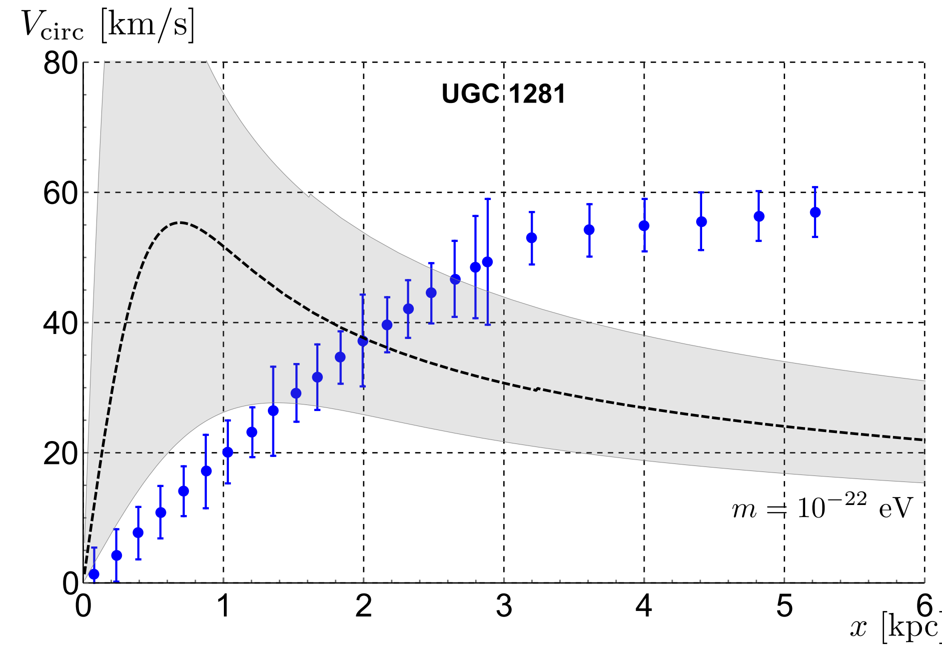
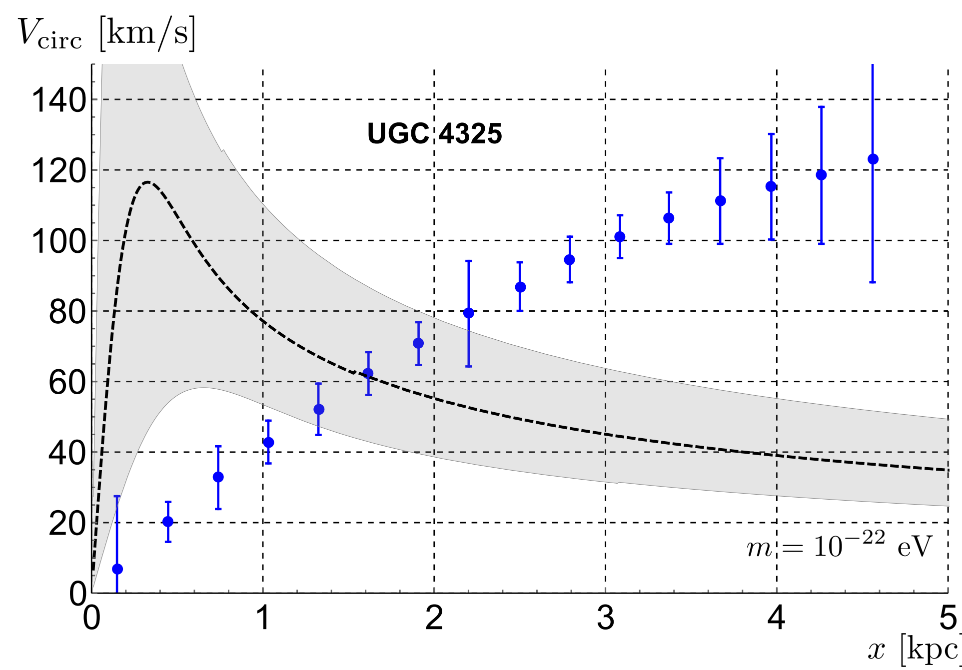






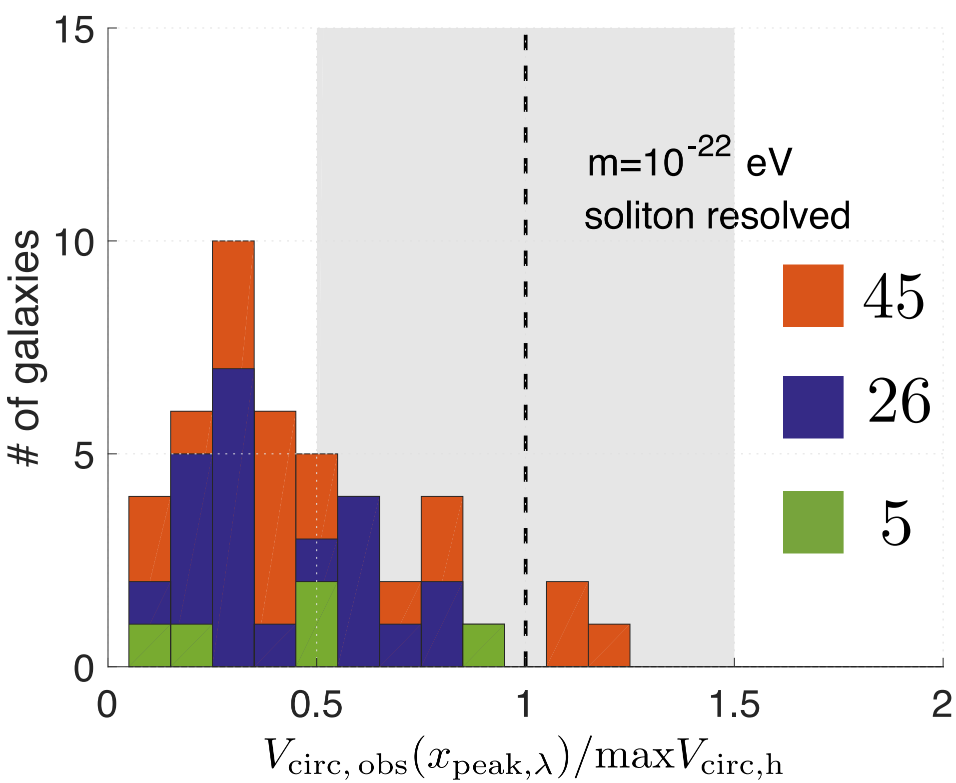


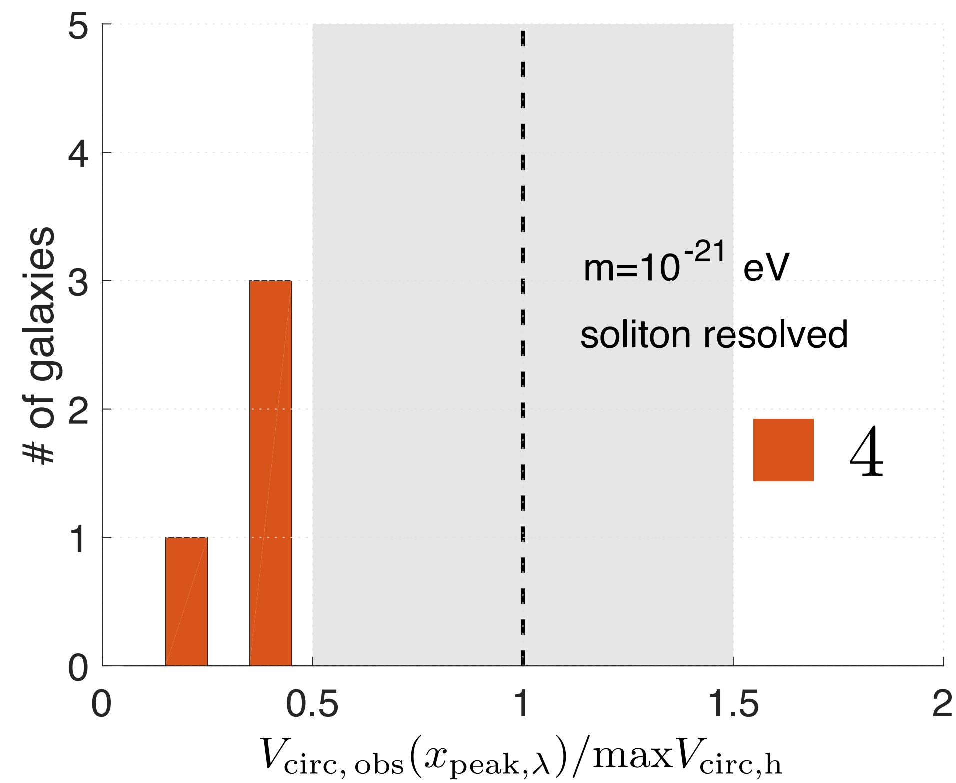
Analyzing SPARC data

175 high resolution rotation curves

cuts:

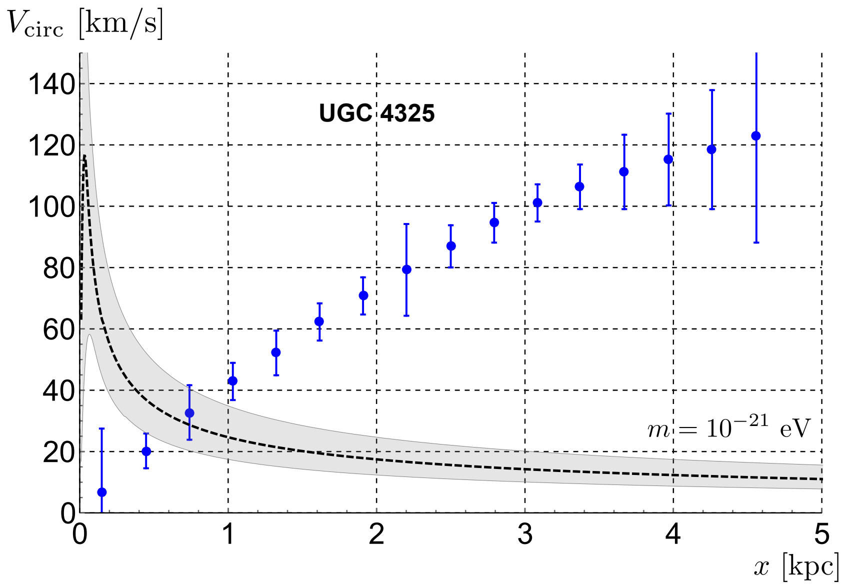
- $5 \times 10^8 \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{-\frac{3}{2}} M_\odot < M_{\mathrm{halo}} < 5 \times 10^{11} M_\odot$
- $f_{\mathrm{bar2DM}} = \frac{V_{\mathrm{circ,h}}^{(\mathrm{bar})}}{V_{\mathrm{circ,h}}^{(\mathrm{DM})}}$ < 1 < 0.55 < 0.33



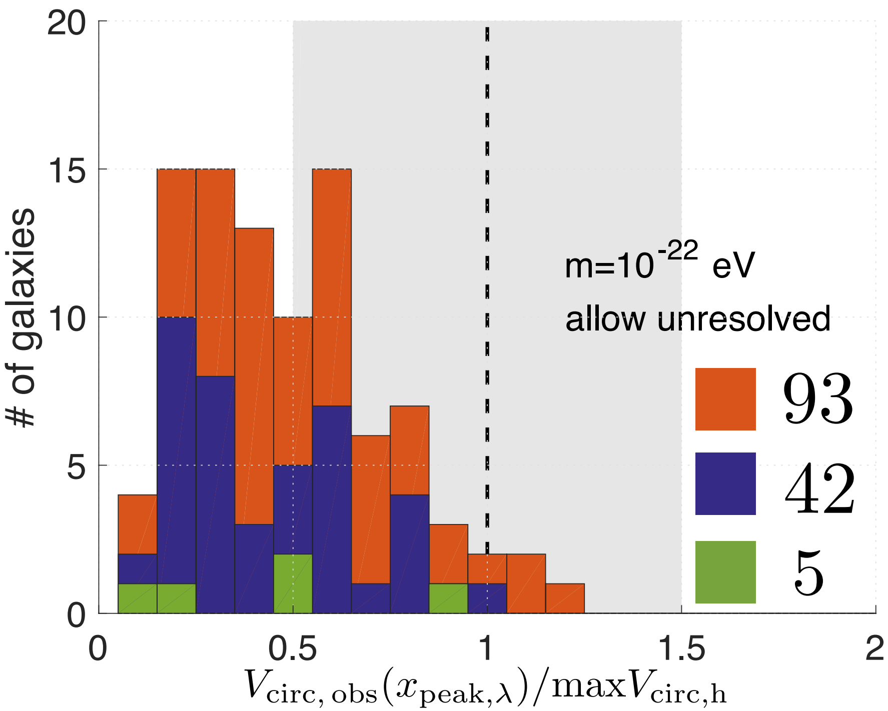


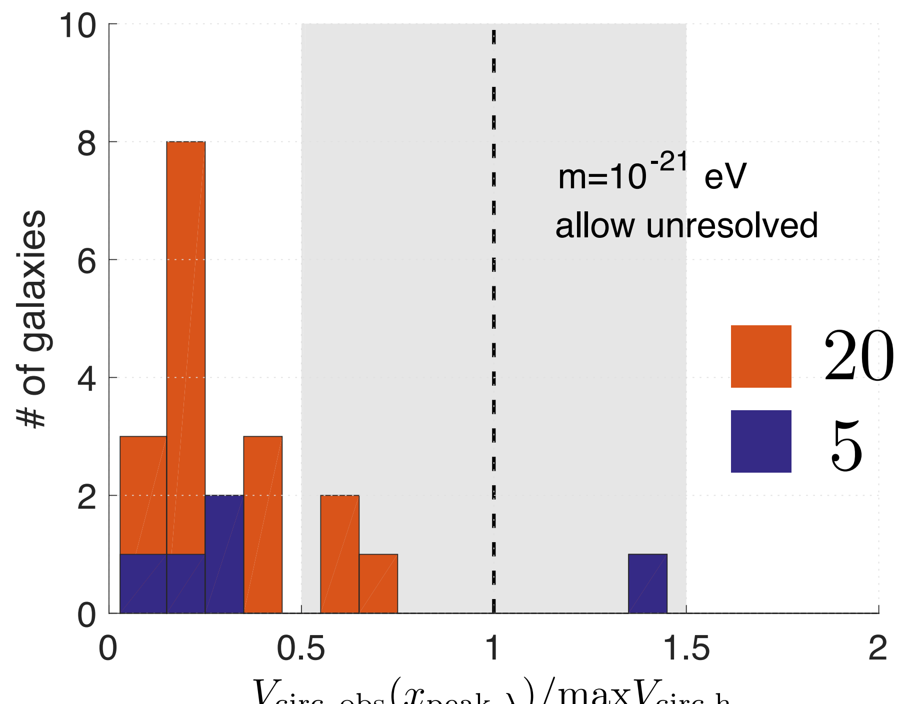
Analyzing SPARC data cntd.

if soliton peaks inside the innermost point



$$\frac{V_{\rm circ,\,obs}(x_{{\rm peak},\lambda})}{\max V^{\rm (DM)}_{\rm circ,h}} \to \frac{V_{\rm circ,\,obs}(x_{\rm min,data})}{\max V^{\rm (DM)}_{\rm circ,h}} \times \sqrt{\frac{x_{\rm min,data}}{x_{{\rm peak},\lambda}}}$$





Conclusion:

$\boxed{\text{ULDM with } m \simeq (10^{-22} \div 10^{-21})\mathrm{eV} \text{ is disfavoured by rotation curves of disk galaxies}}$

→ cannot play a role in solving small-scale problems of LambdaCDM

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  - stars tend to increase the soliton mass (*J.H.H.Chan et al. (2017)*); their potential can be taken into account self-consistently
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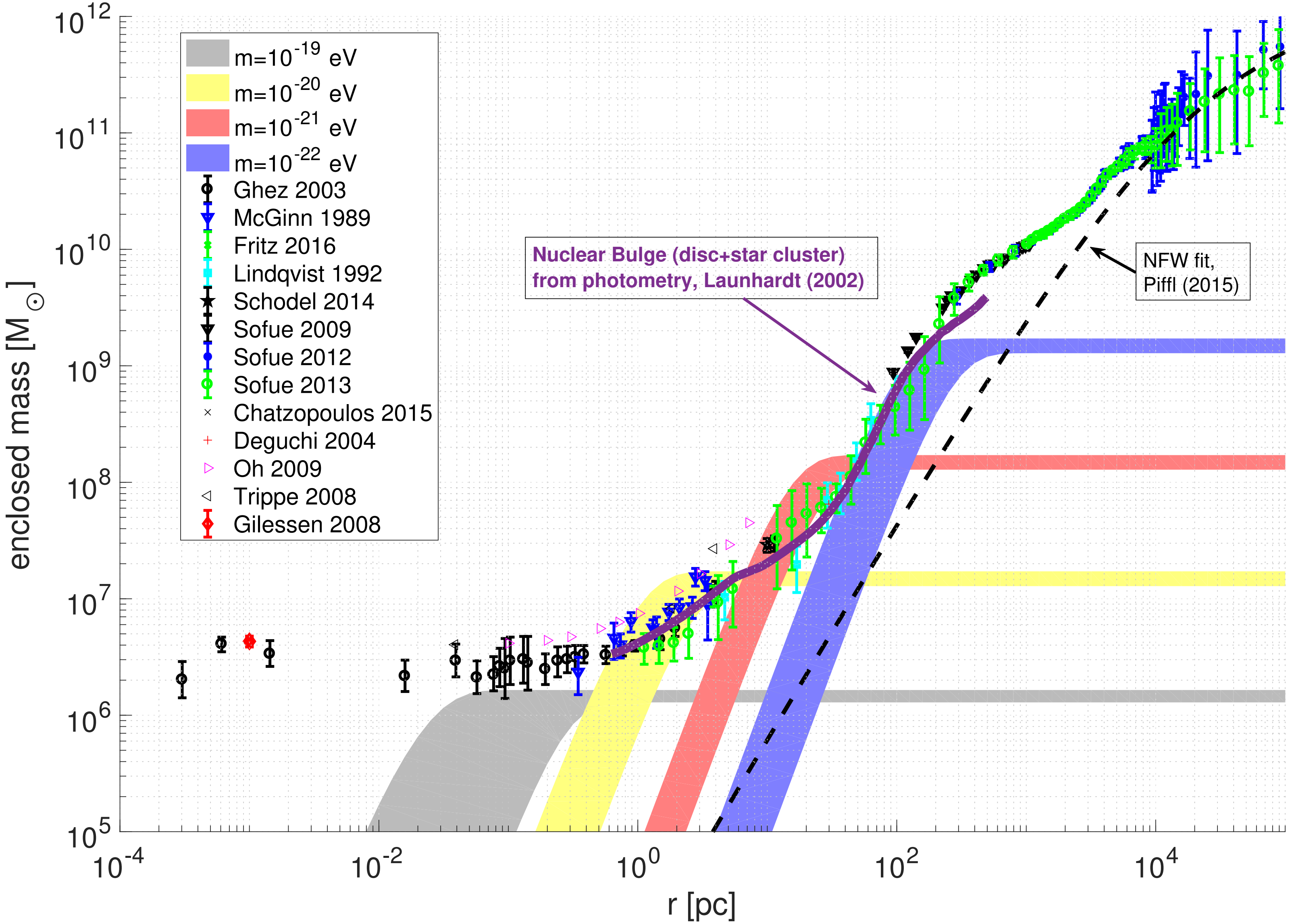
- Accretion on supermassive black hole
  - negligible for $m \lesssim 10^{-21}\mathrm{eV}$ and $M_{\rm SMBH} < 10^{10} M_{\odot}$,

    but quickly increases with the mass of the field

Future: probing higher masses

- Inner dynamics of the Milky Way



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Outlook

- Further understanding of structure formation with ULDM (baryonic effects, supermassive black hole)

- More probes: Inner Milky Way, 21 cm, pulsar timing (*see talk by Diego Blas*)