Ultra-light scalar dark matter:

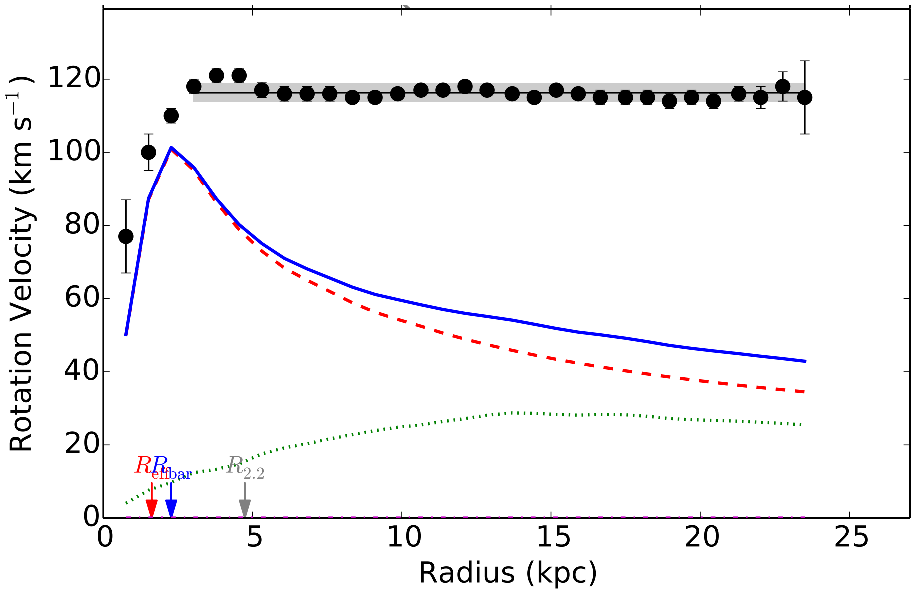
Motivation, Dynamics, Probes

Sergey Sibiryakov

Quarks, Valday, May 27, 2018

Dark matter is out there

- Galactic rotation curves



credit: SPARC database http://astroweb.cwru.edu/SPARC/

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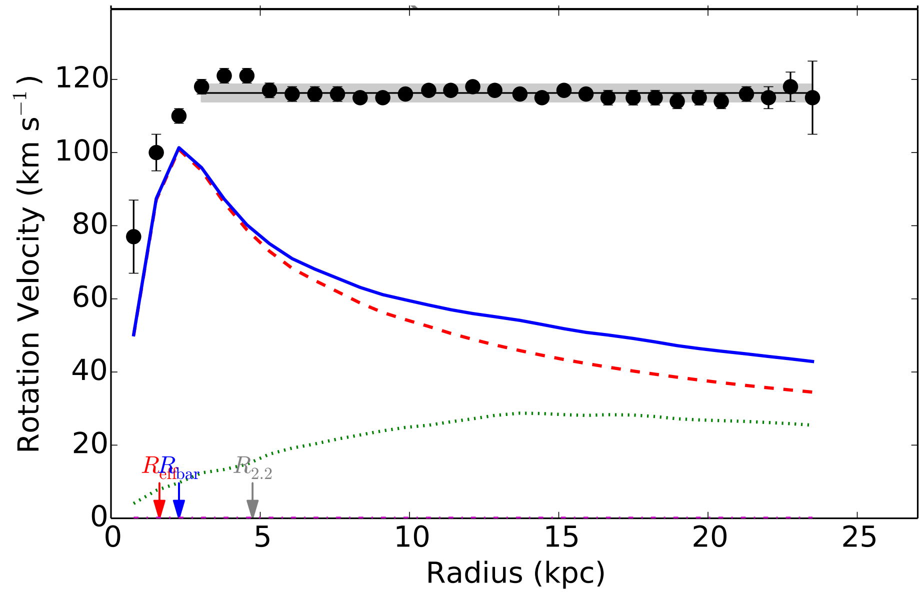

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- Dynamics of clusters

- hot gas (X-ray observations)

- total mass (reconstructed from gravitational lensing)

Dark matter is out there

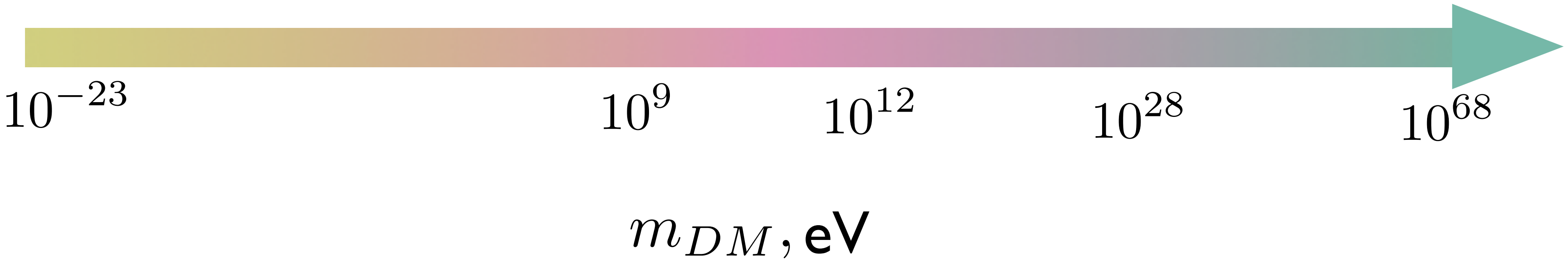
- Cosmic microwave background and large-scale structure

→ Standard cosmological model ΛCDM

PLANK Collaboration, arXiv:1502.01589

Parameter	[1] *Planck* TT+lowP	[2] *Planck* TE+lowP	[3] *Planck* EE+lowP	[4] *Planck* TT,TE,EE+lowP
$\Omega_b h^2$	0.02222 ± 0.00023	0.02228 ± 0.00025	0.0240 ± 0.0013	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1187 ± 0.0021	$0.1150^{+0.0048}_{-0.0055}$	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04094 ± 0.00051	1.03988 ± 0.00094	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.053 ± 0.019	$0.059^{+0.022}_{-0.019}$	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.031 ± 0.041	$3.066^{+0.046}_{-0.041}$	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.965 ± 0.012	0.973 ± 0.016	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.73 ± 0.92	70.2 ± 3.0	67.27 ± 0.66
Ω_m	0.315 ± 0.013	0.300 ± 0.012	$0.286^{+0.027}_{-0.038}$	0.3156 ± 0.0091
σ_8	0.829 ± 0.014	0.802 ± 0.018	0.796 ± 0.024	0.831 ± 0.013
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.865 ± 0.019	1.907 ± 0.027	1.882 ± 0.012

What is it made of ?



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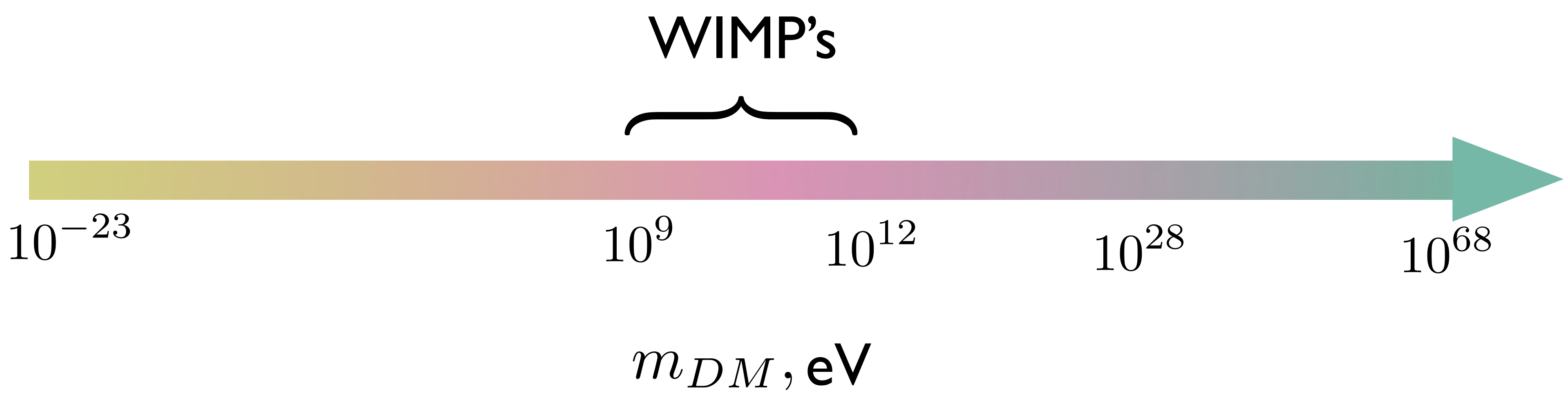

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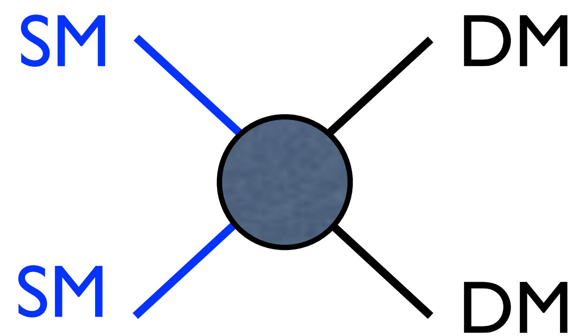

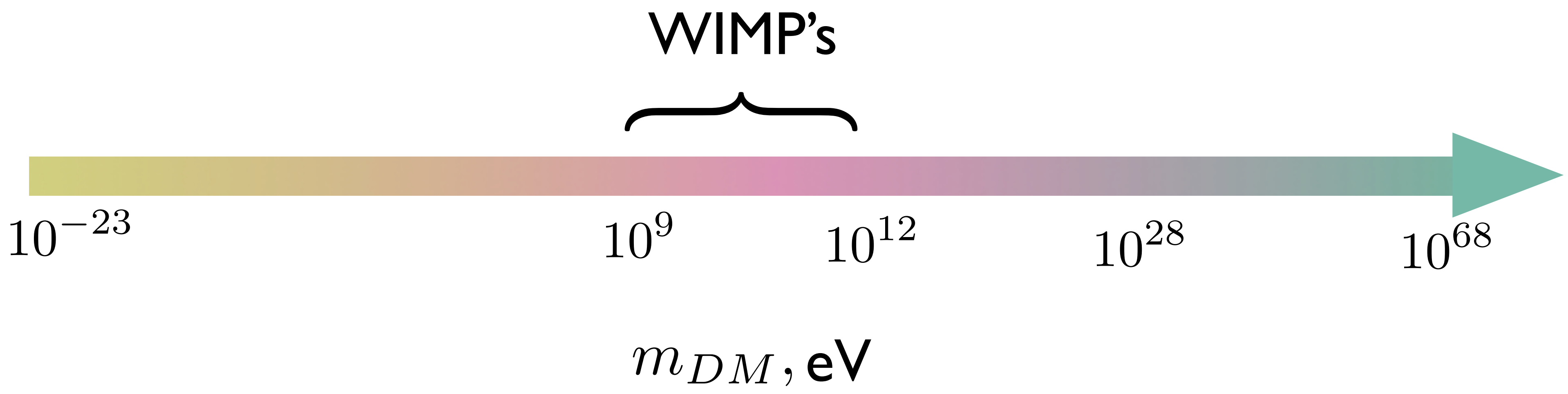

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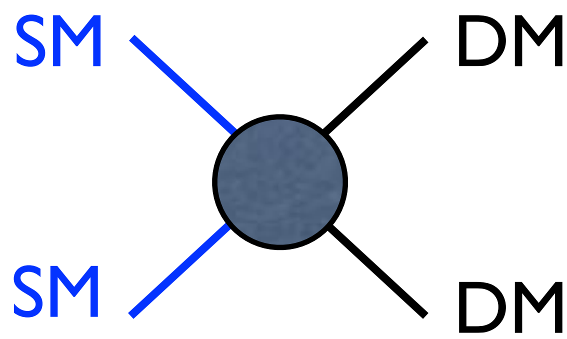

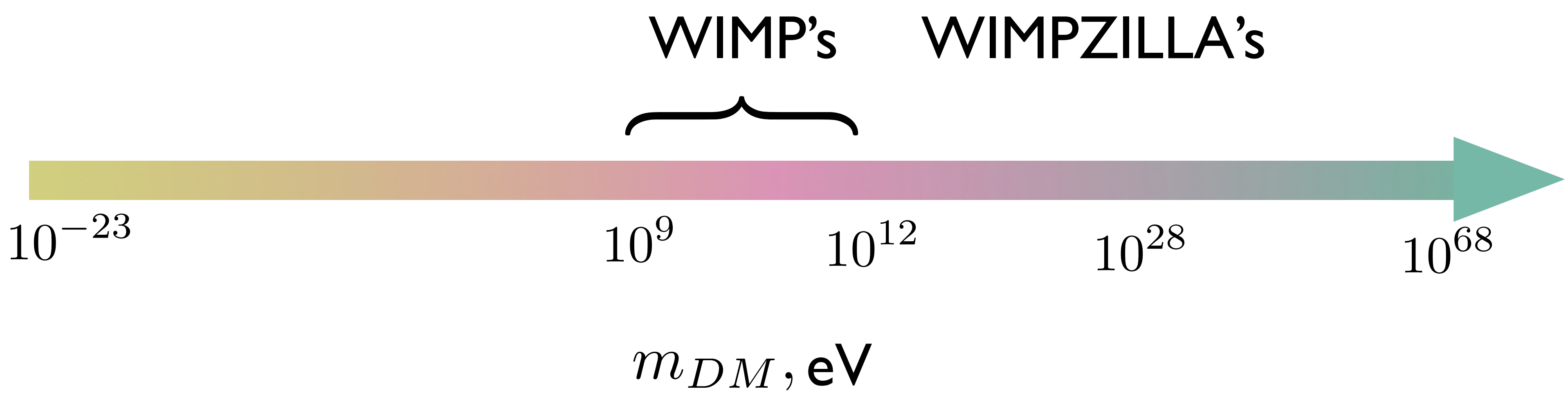

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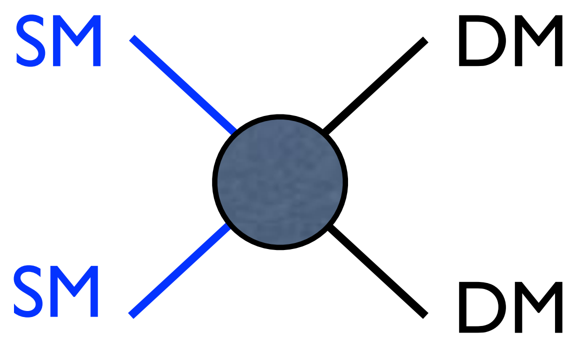

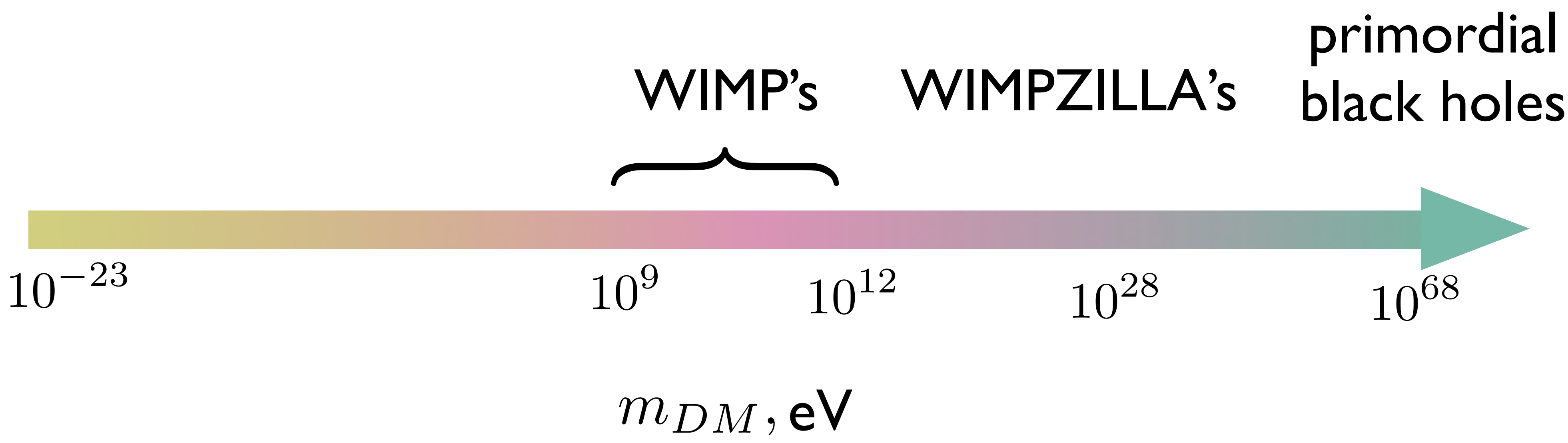

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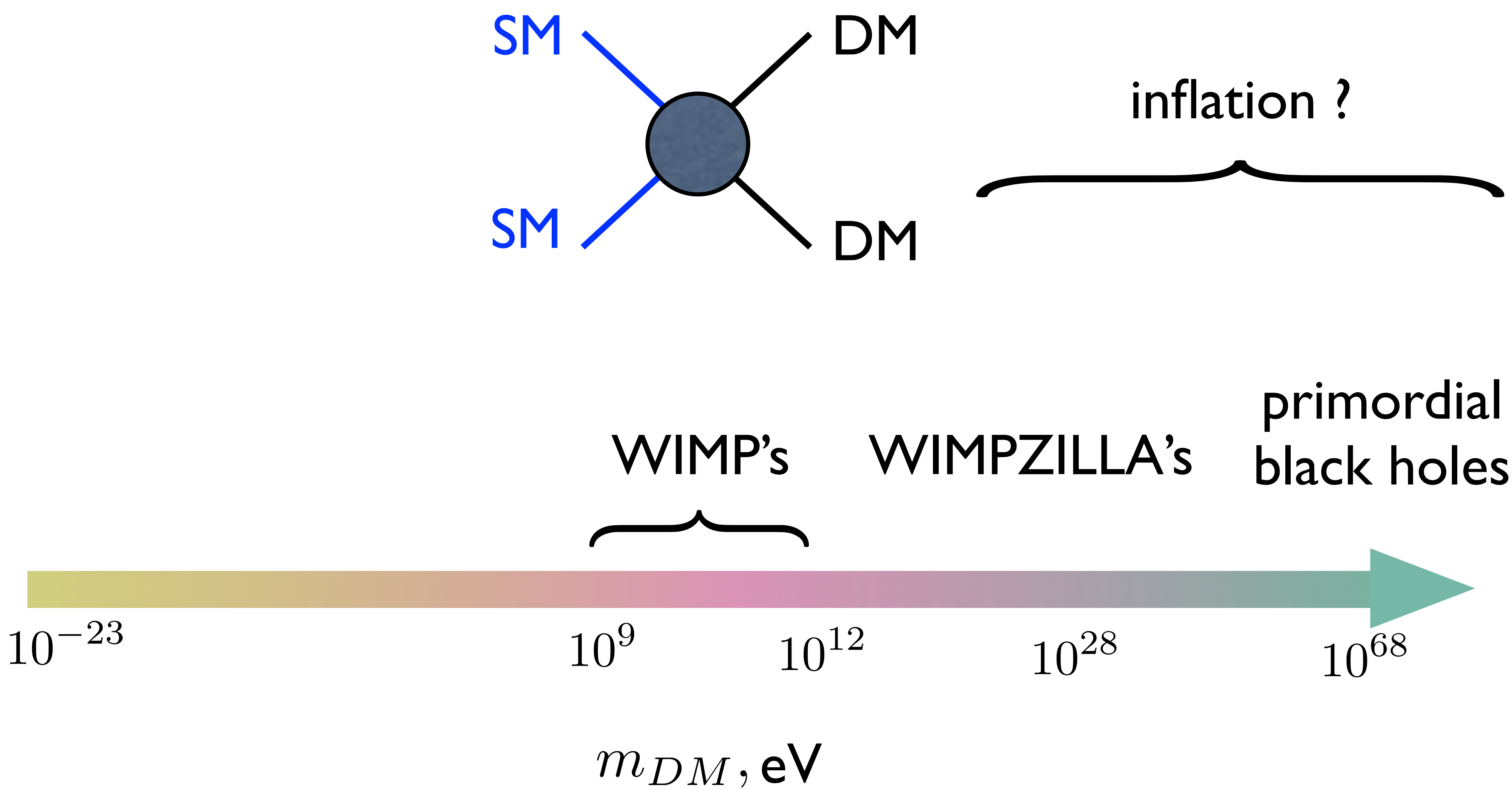

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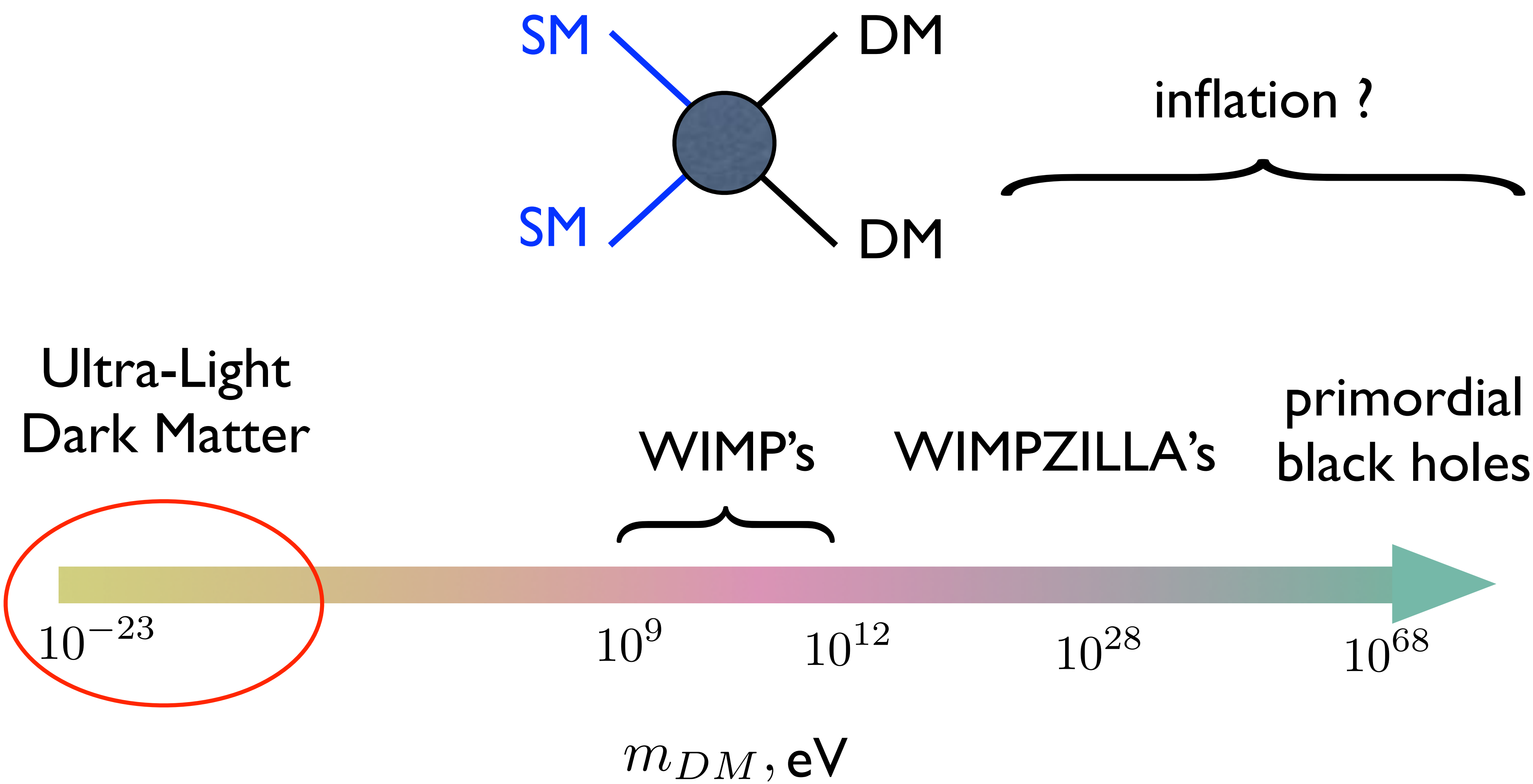

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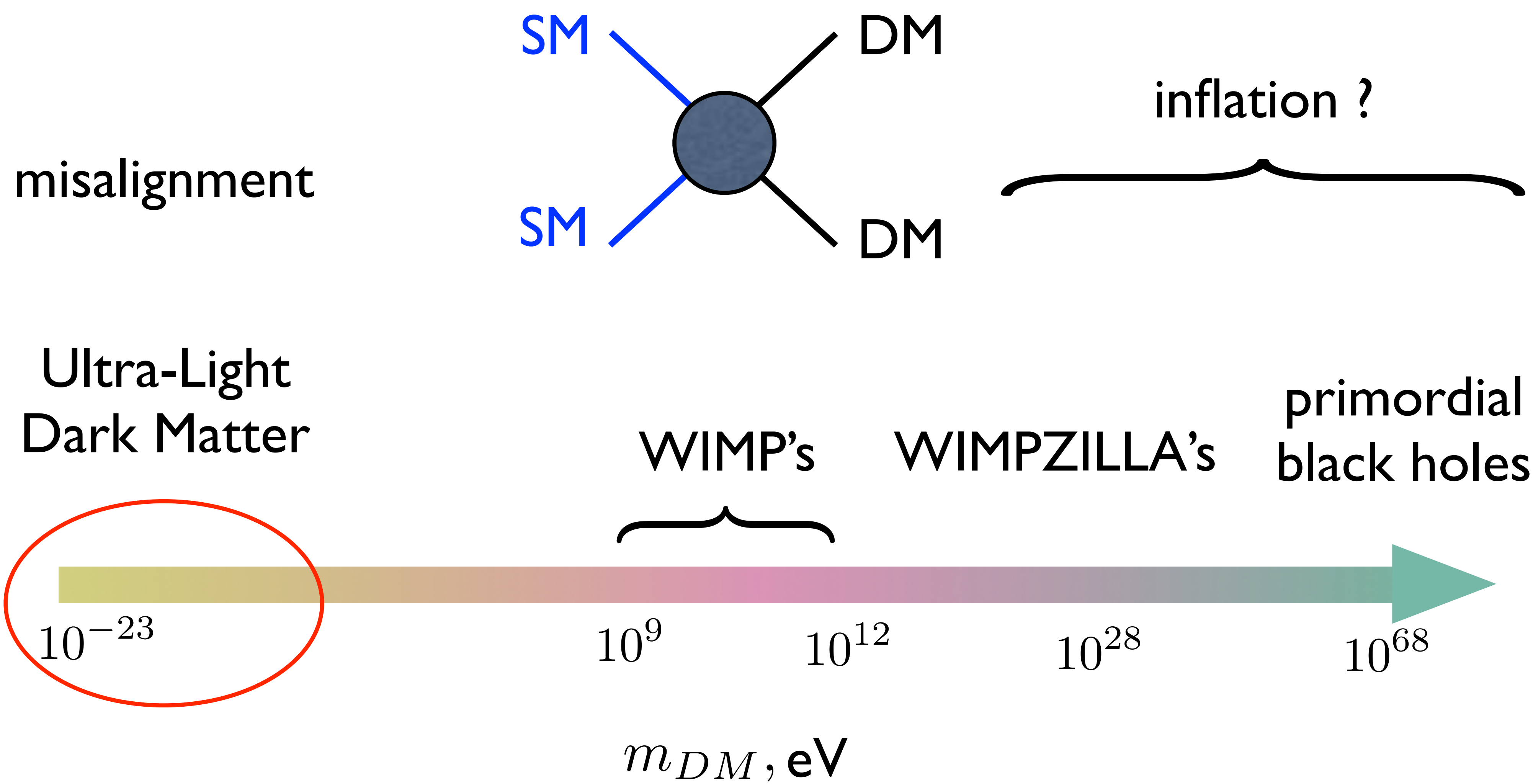

The simplest DM model: free massive scalar

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

e.o.m. in expanding Universe:

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

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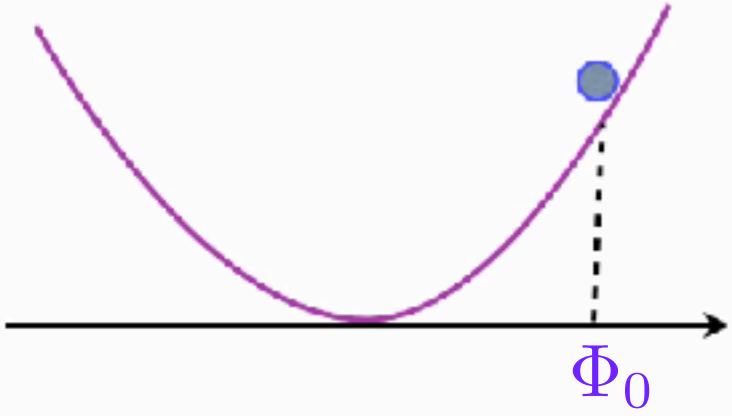

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density: $\rho = \dfrac{m^2\Phi_0^2}{2}$

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

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non-zero mass can be generated by non-perturbative effects ➡

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

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- Density fraction:

  $\Phi \sim f$ after inflation

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

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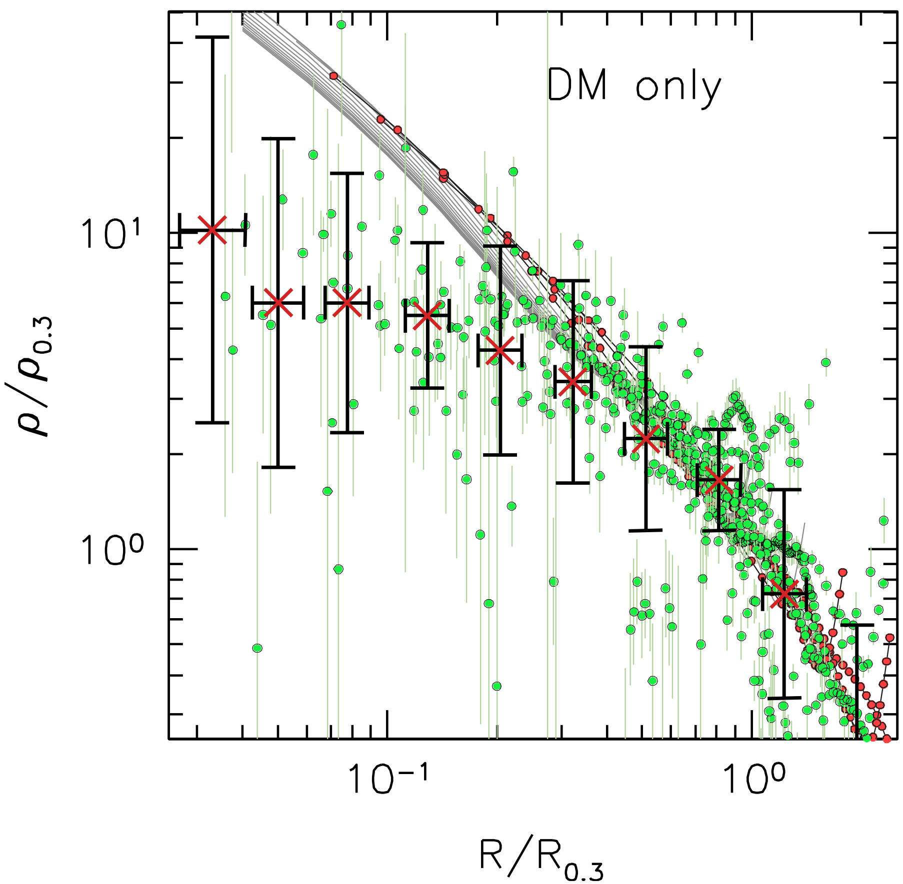
focus of this talk: $m \sim 10^{-22} \div 10^{-18}\text{eV}$

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

$$-i\dot{\Psi} - \frac{\nabla^2}{2m}\Psi + m\varphi(\mathbf{x}, t)\Psi = 0$$

$$\nabla^2\varphi = 2Gm^2|\Psi|^2$$

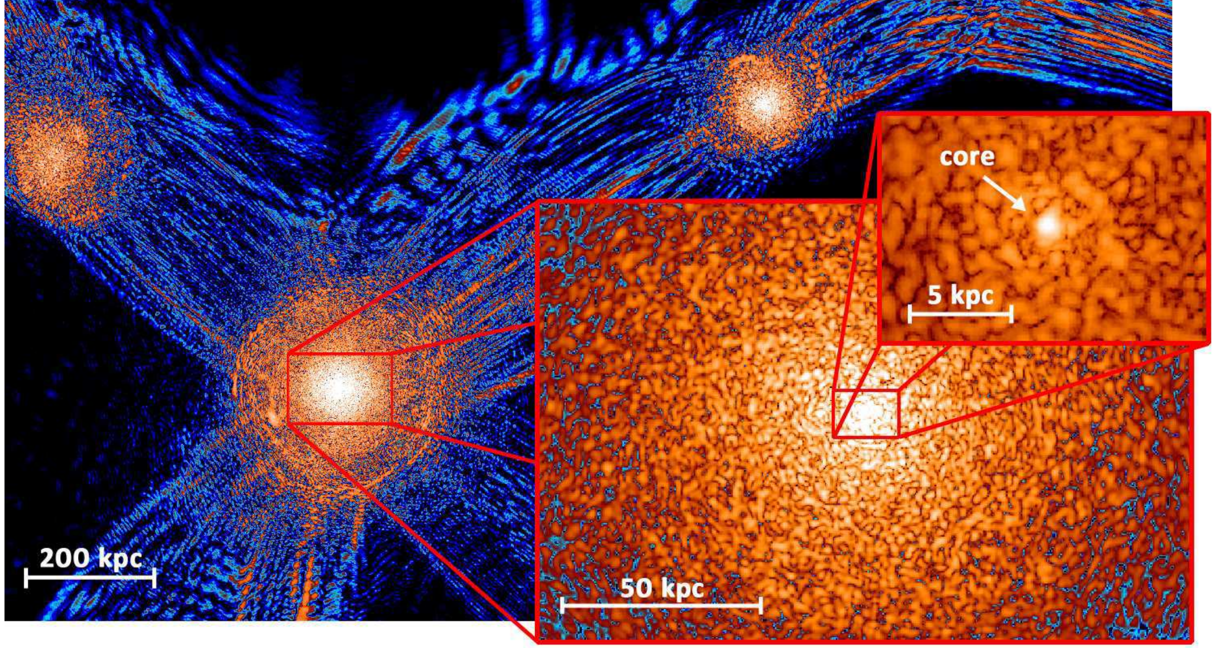
Schroedinger -- Poisson system

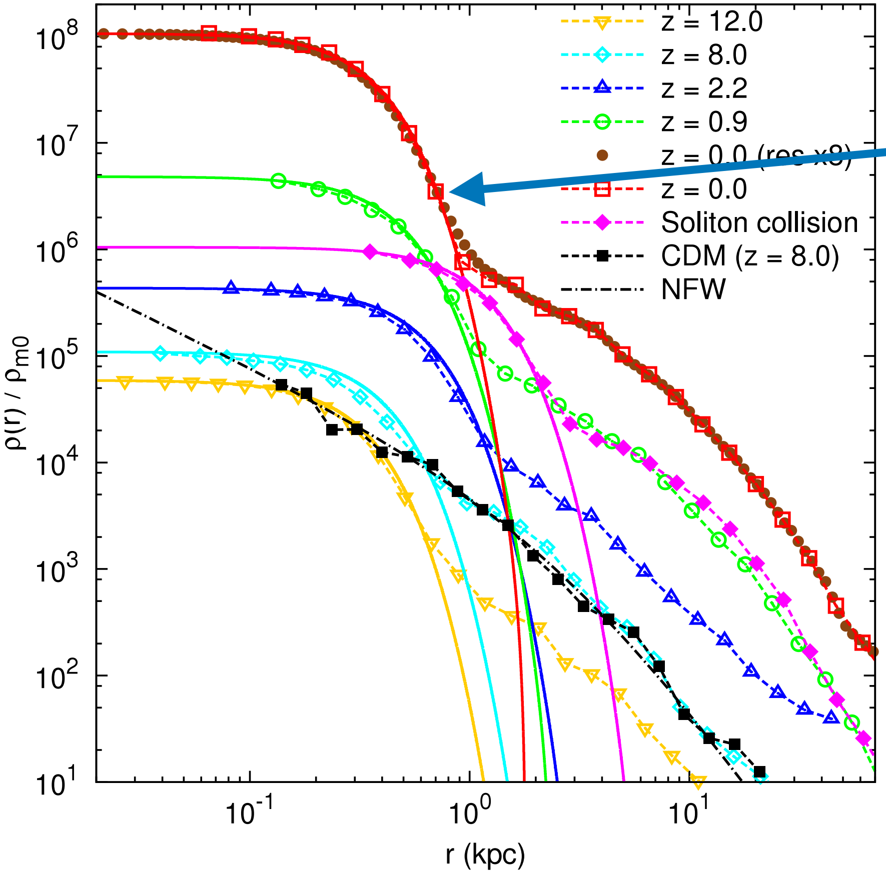
leads to suppression of fluctuations at short scale --- “quantum pressure”

Probing ULDM with galactic rotation curves

ULDM in the halo

Schive, Chiueh, Broadhurst, arXiv: 1406.6586

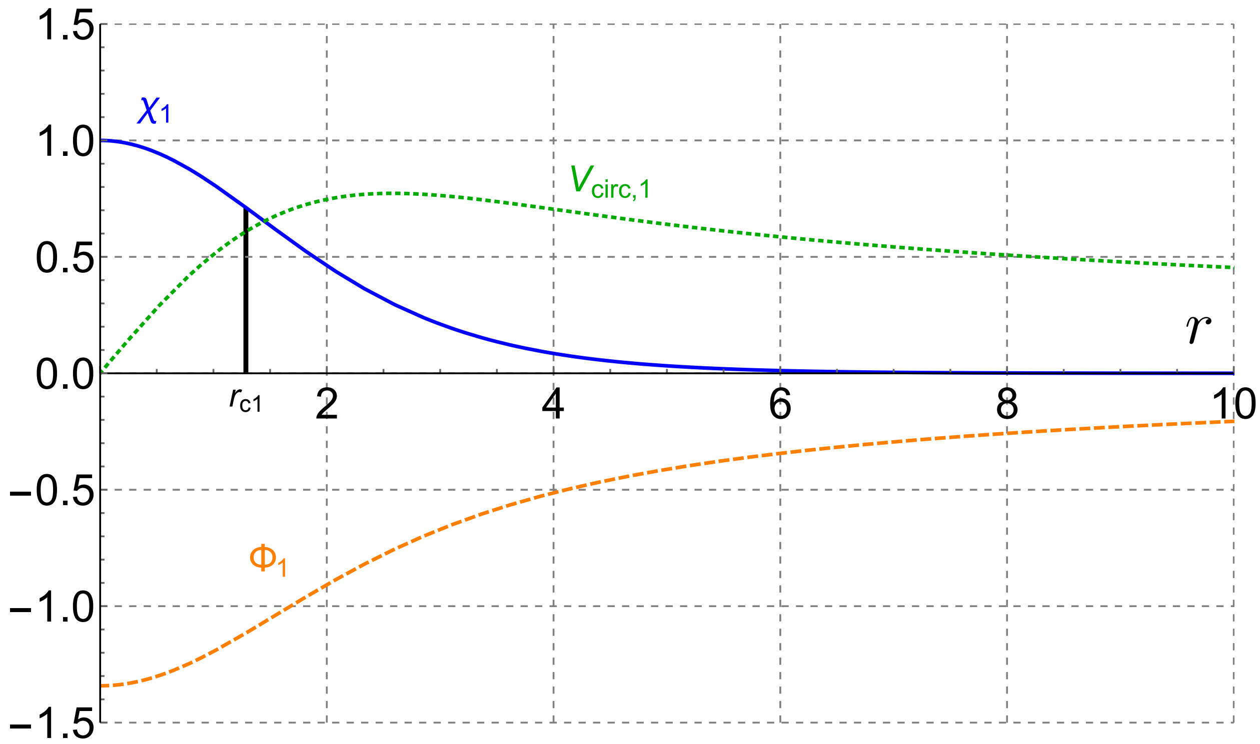




Schive, Chiueh, Boardhurst, arXiv:1407.7762

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

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

⟺

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

⟺

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

Exercise for NFW halo

Nitsan Bar, Diego Blas, Kfir Blum, SS., arXiv:1805.00122

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

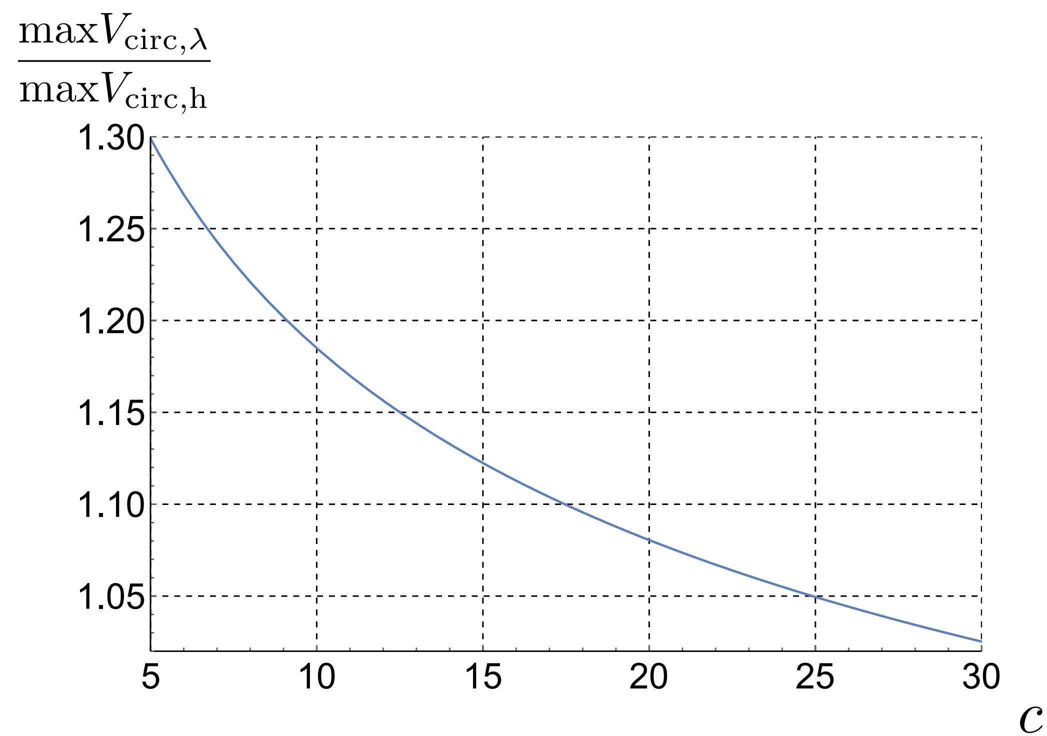
scale radius

concentration

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

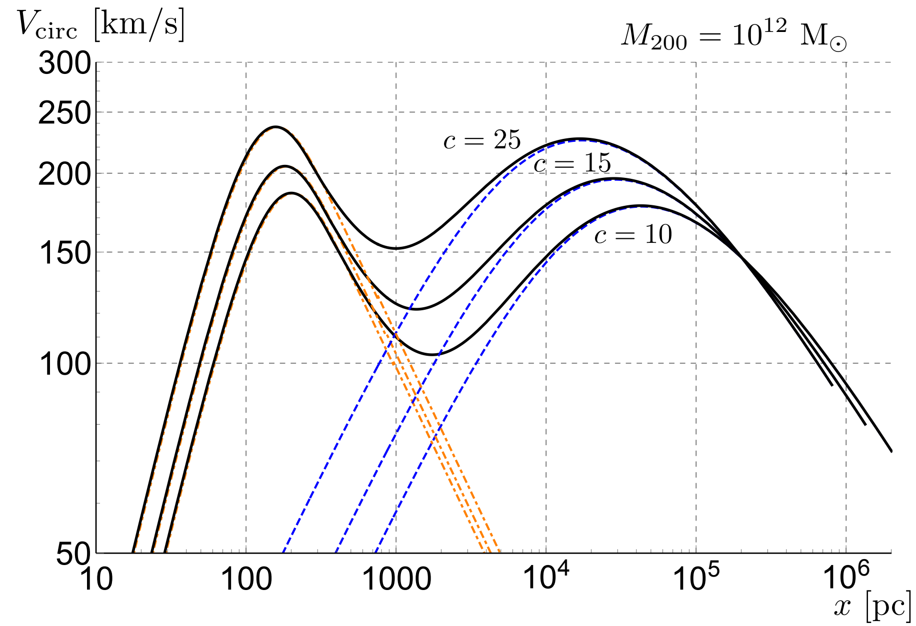
$$c \sim 5 \div 30$$

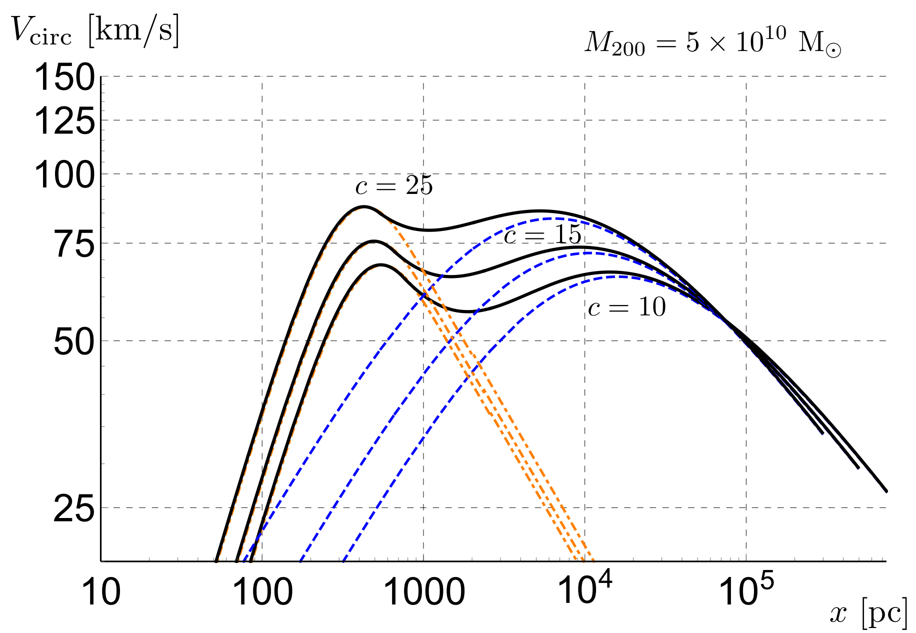
$$\frac{\max V_{\mathrm{circ},\lambda}}{\max V_{\mathrm{circ,h}}} \approx 1.1\left(\frac{\tilde{c}}{0.4}\right)^{\frac{1}{2}}$$



predictions vs data

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





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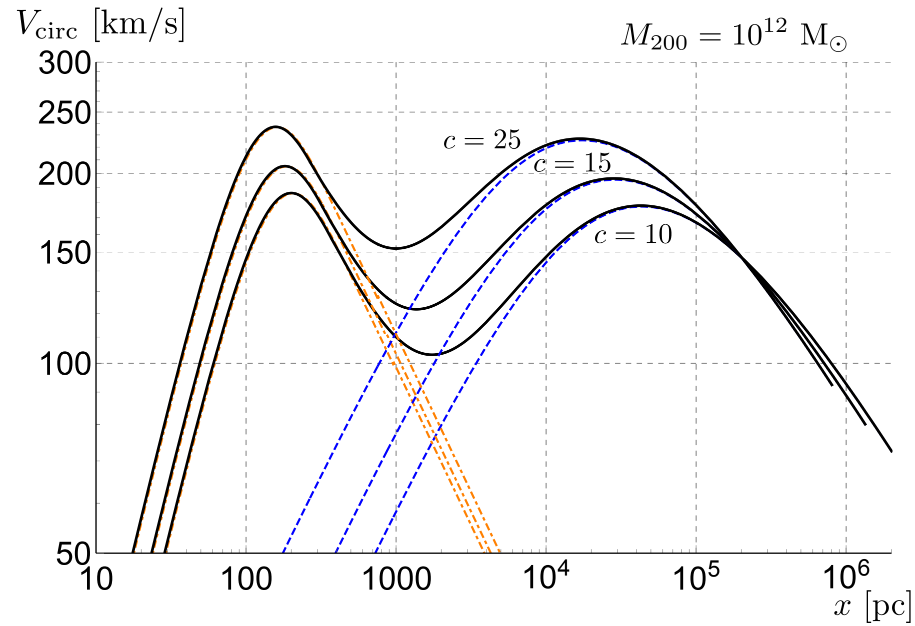

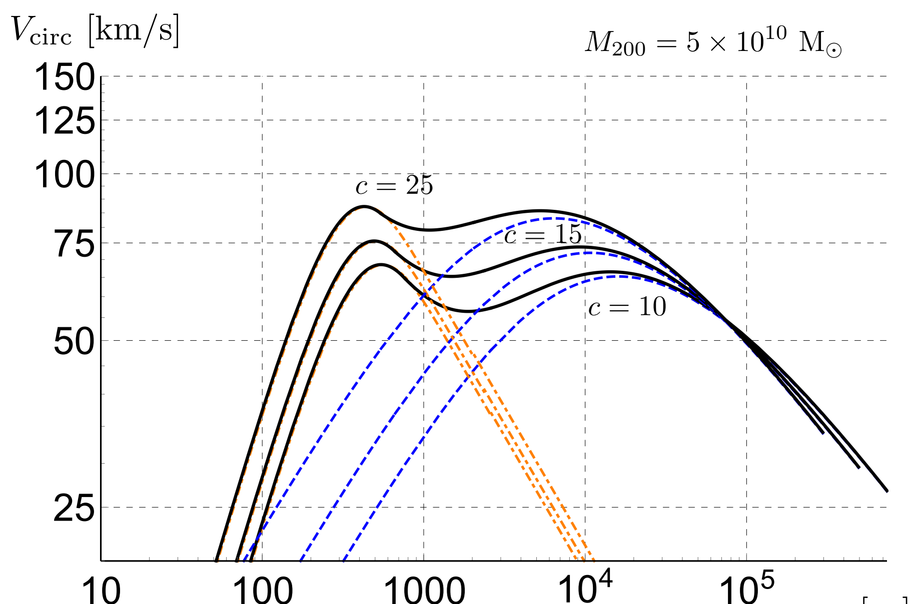

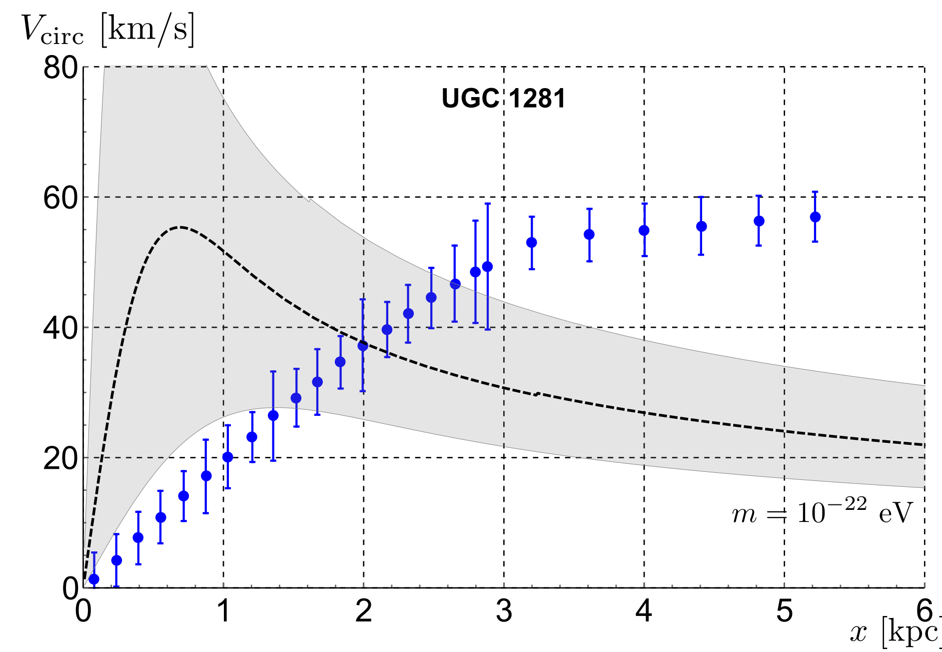

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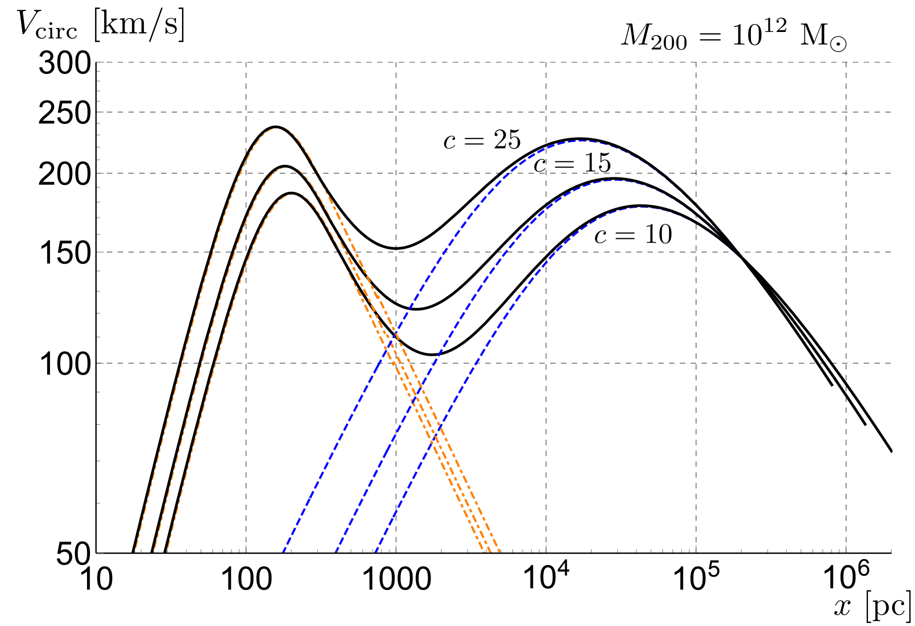
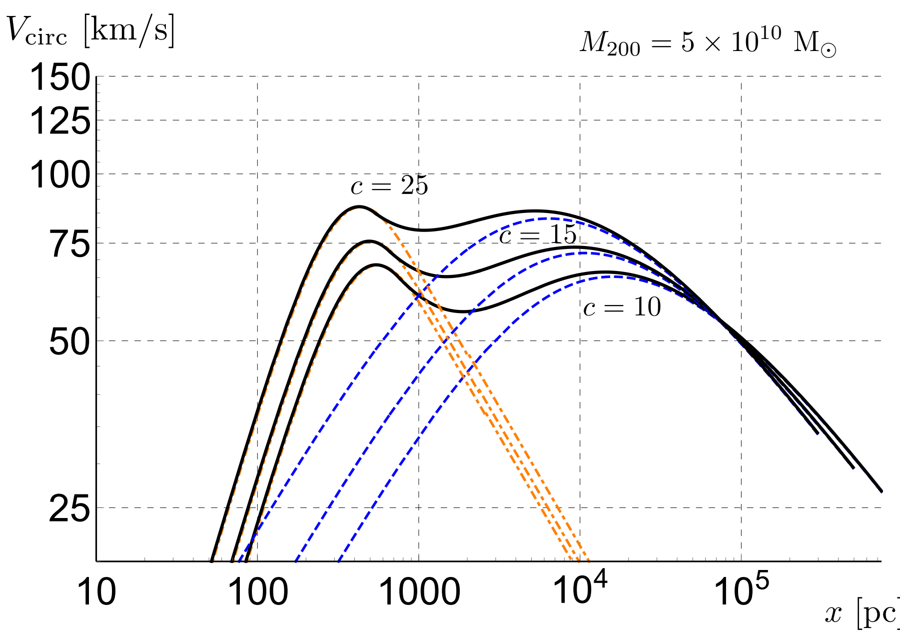
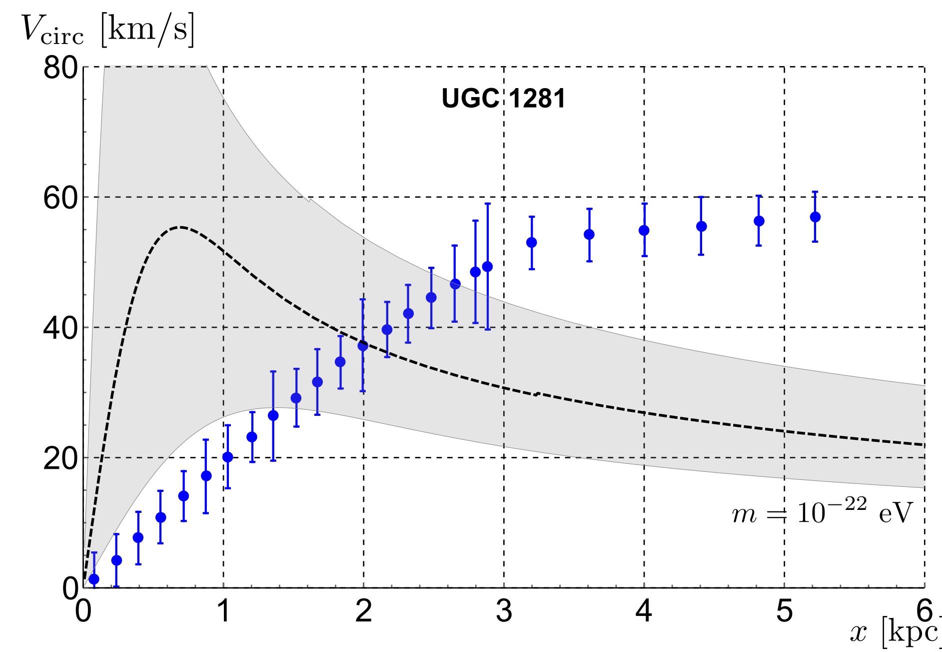
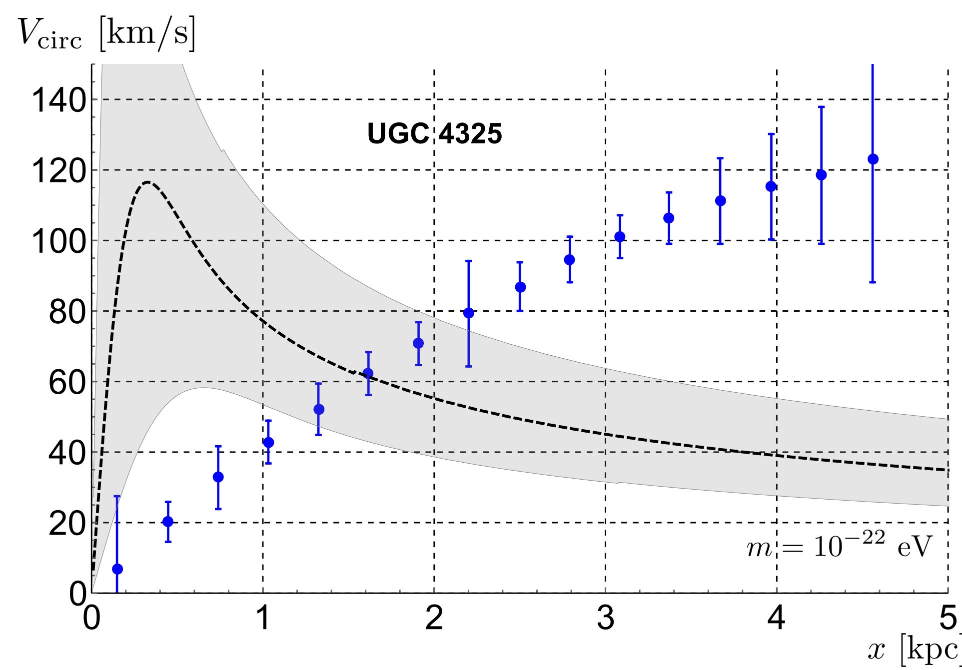






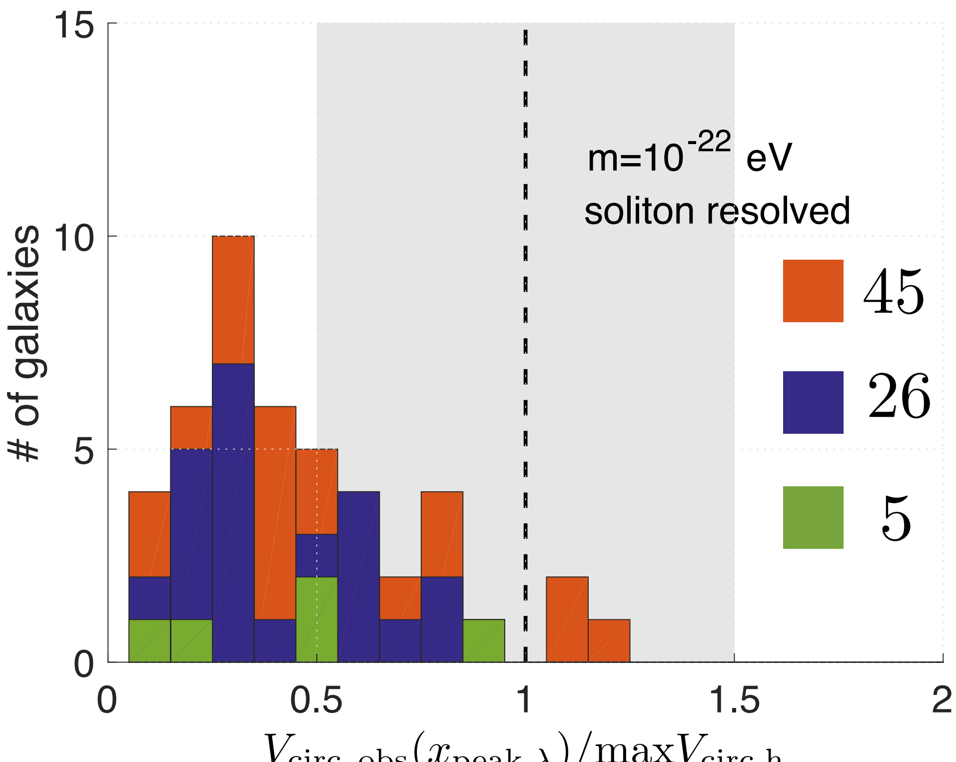


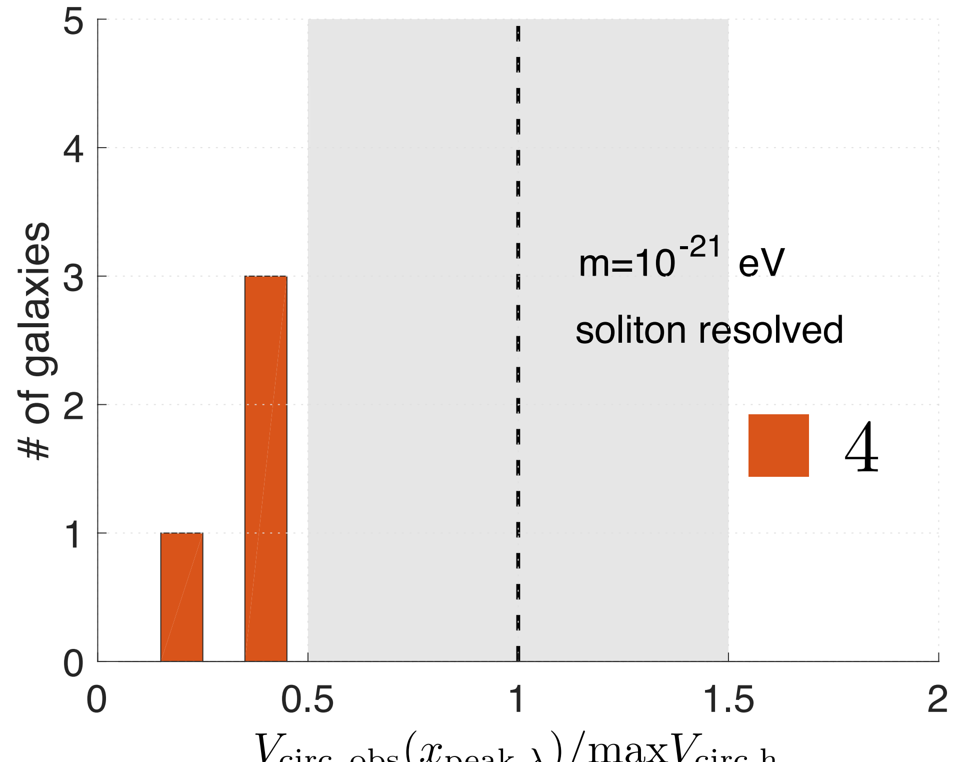
Analyzing SPARC data

175 high resolution rotation curves

cuts:

- $5\times10^{8}\left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{-\frac{3}{2}} M_\odot < M_{\rm halo} < 5\times10^{11} M_\odot$
- $f_{\rm bar2DM} = \frac{V^{\rm (bar)}_{\rm circ,h}}{V^{\rm (DM)}_{\rm circ,h}}$ < 1 (orange) < 0.55 (blue) < 0.33 (green)





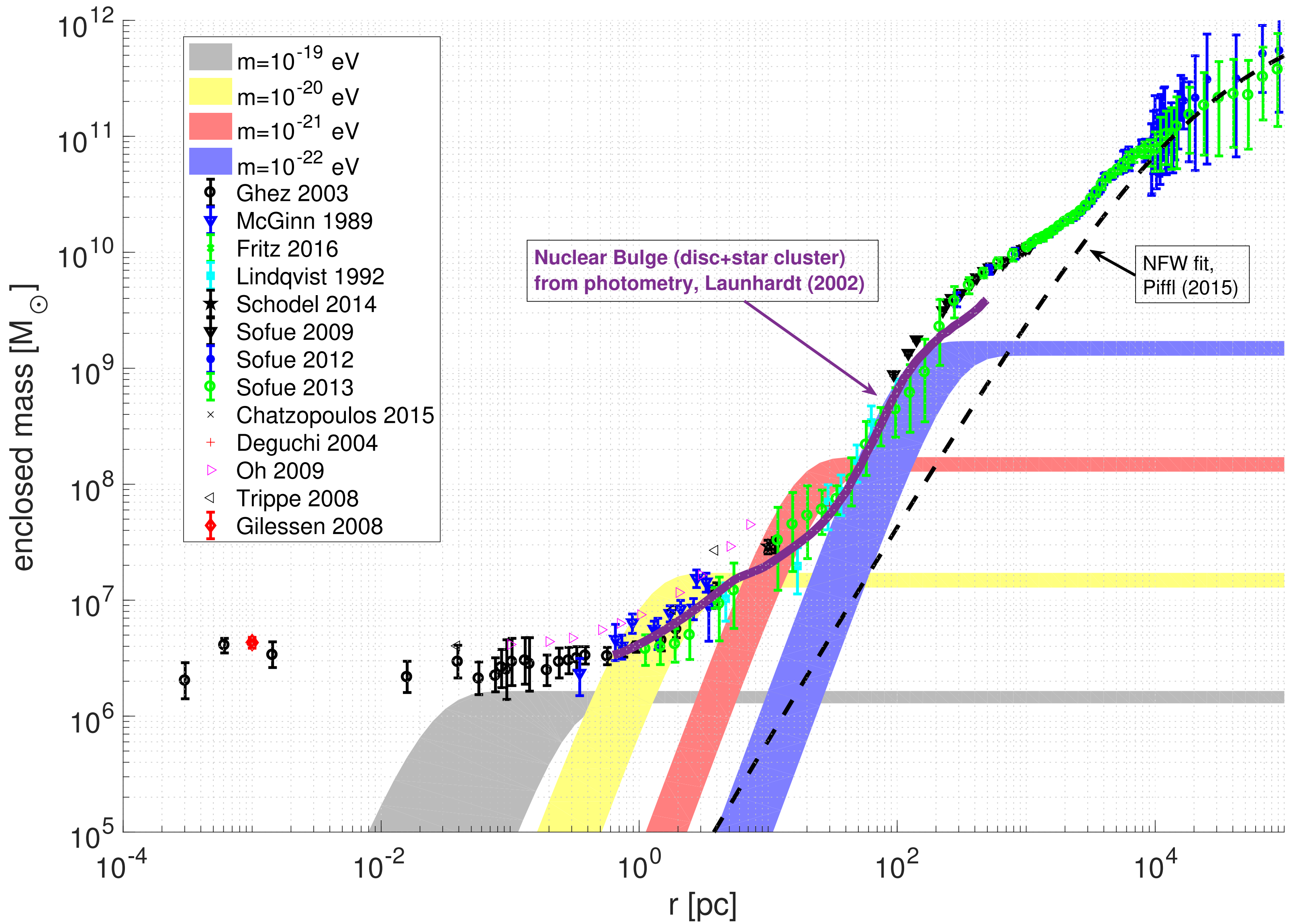
Conclusion:

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

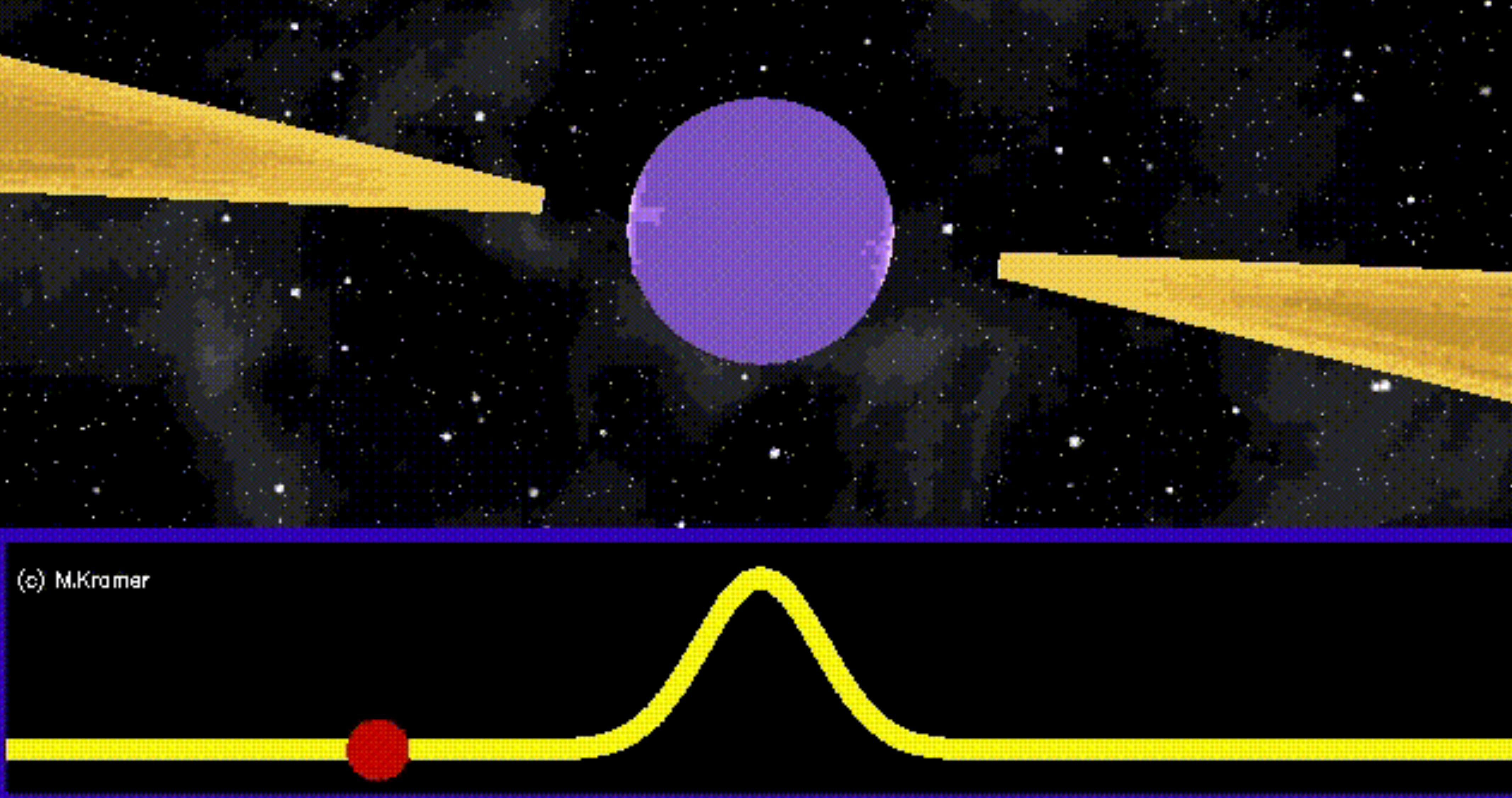
→ cannot play a role in solving small-scale problems of LambdaCDM

Future: probing higher masses

- Inner dynamics of the Milky Way



Probing ULDM with pulsar timing



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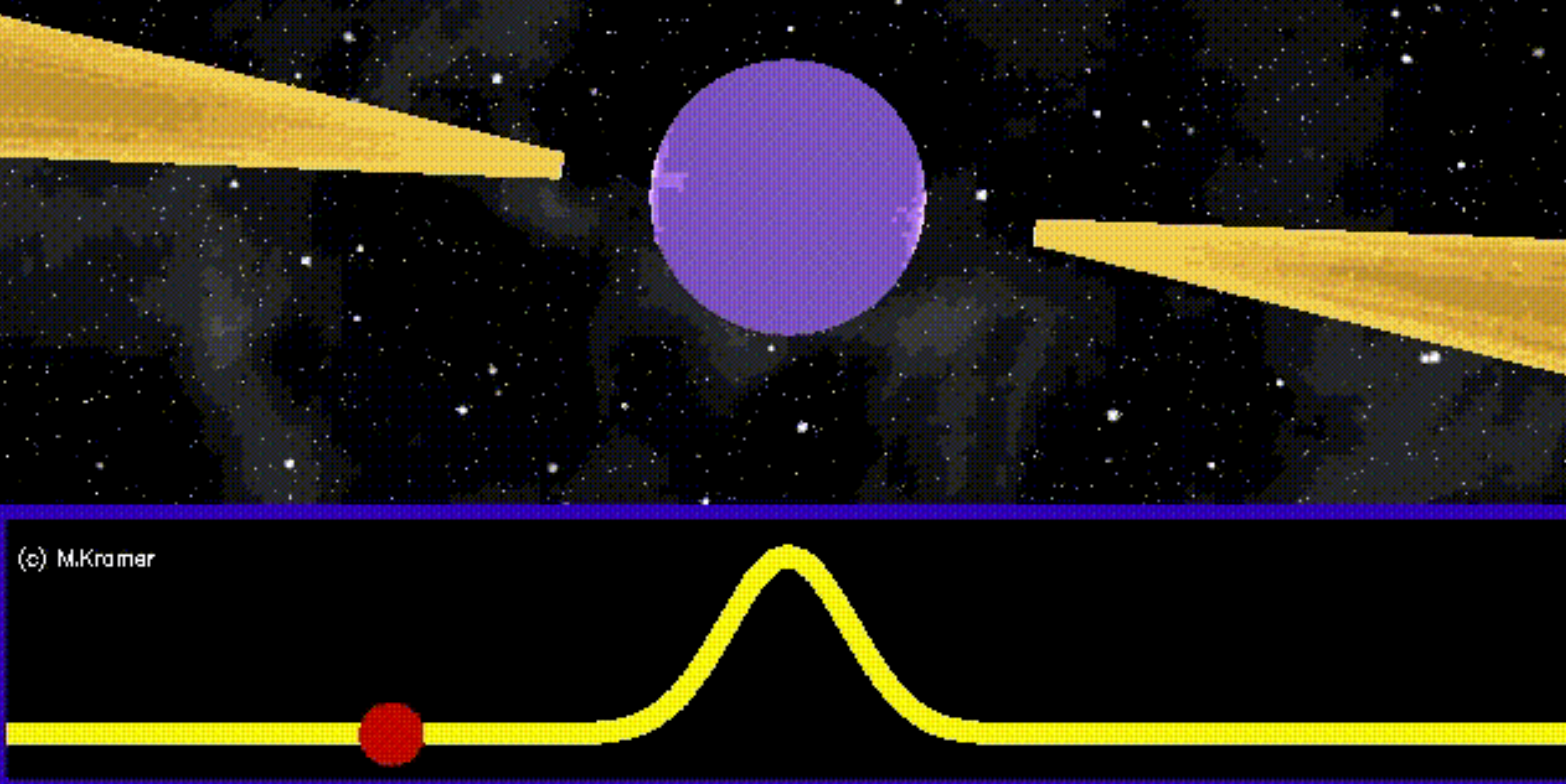

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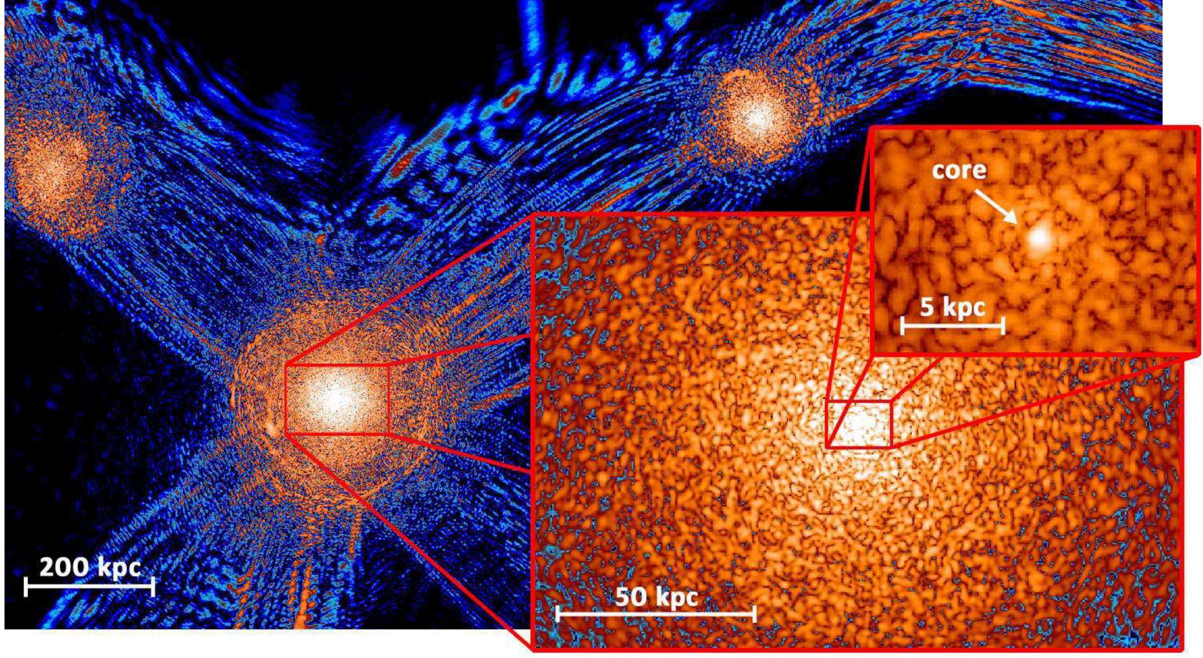

oscillation period: $\sim 480\,\mathrm{days} \times \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{-1}$

coherence length: $(m v_{\mathrm{vir}})^{-1} \sim 60\,\mathrm{pc} \times \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{-1} \left(\frac{v_{\mathrm{vir}}}{10^{-3}}\right)^{-1}$

coherence time: $(m v_{\mathrm{vir}}^2/2)^{-1} \sim 4 \times 10^5\,\mathrm{years} \times \left(\frac{m}{10^{-22}\mathrm{eV}}\right)^{-1} \left(\frac{v_{\mathrm{vir}}}{10^{-3}}\right)^{-2}$

$$\Phi(\mathbf{x}, t) = \Phi_0(\mathbf{x}) \cos\left(mt + \Upsilon(\mathbf{x})\right)$$

slowly varying in space

Oscillating pressure

$$ds^2 = -(1+2\phi)dt^2 + (1-2\psi)\delta_{ij}dx^i dx^j$$

from *(ij)*-equation neglecting spatial gradients:

$$\ddot{\psi} = 4\pi G p_\Phi = -4\pi G \rho_\phi \cos(2mt + 2\Upsilon)$$

~ scalar gravitational wave

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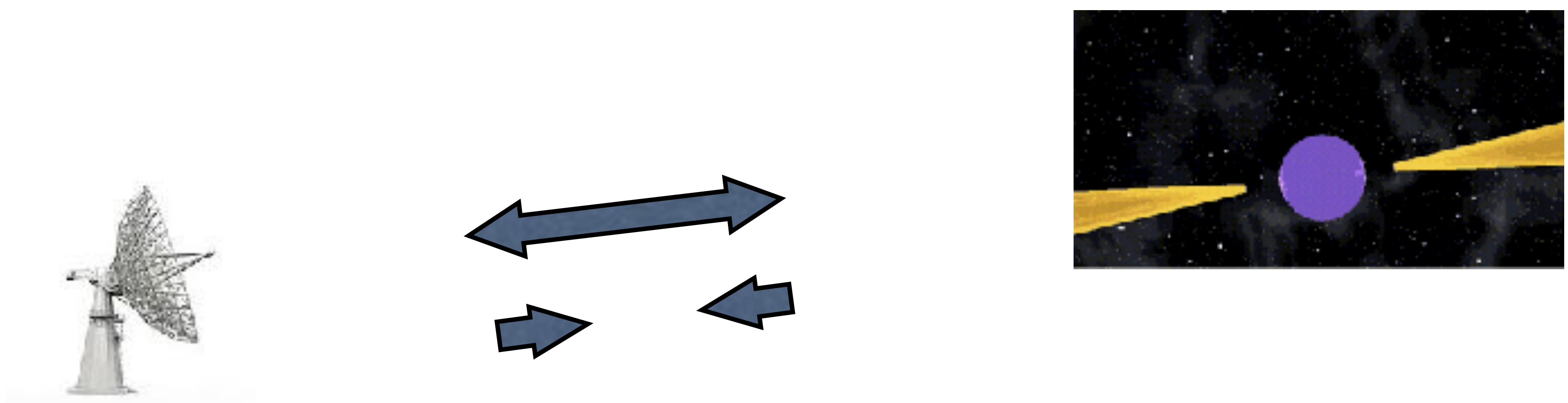
Khmelnitsky, Rubakov (2013)

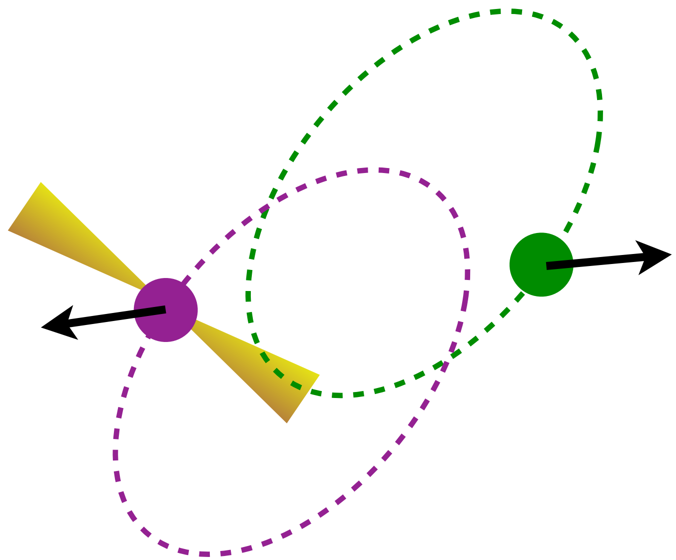


modulation of pulse arrival times

$$\frac{\Omega(t) - \Omega_0}{\Omega_0} = \psi(\mathbf{x}, t) - \psi(\mathbf{x}_p, t_p)$$

probes up to $m = (\text{a few}) \times 10^{-23}\text{eV}$

Dynamical effect in binary pulsars



D.Lopez Nacir, D.Blas, S.S. (2016)

$$\ddot{\mathbf{r}} = -\ddot{\psi}\mathbf{r}$$

$$\delta E_b = \mu \int_0^{P_b} \dot{\mathbf{r}}\ddot{\mathbf{r}}\, dt$$

resonance if

$$\delta\omega \equiv 2m - \frac{2\pi N}{P_b} \ll 2m$$

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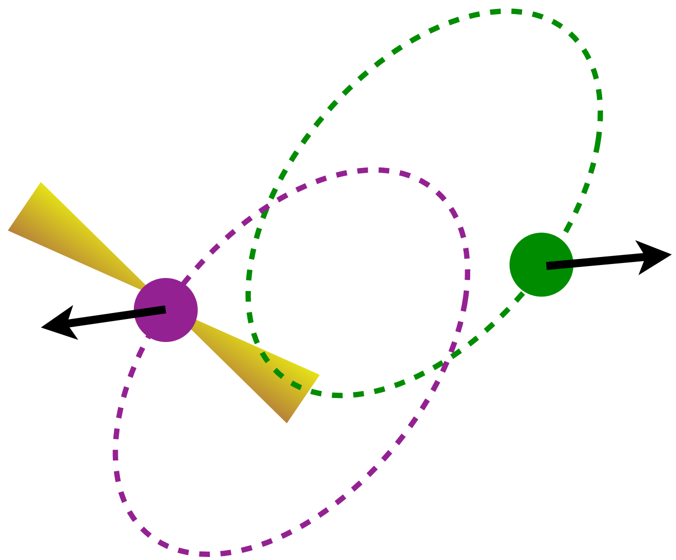

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$$P_b \propto |E_b|^{-3/2}$$

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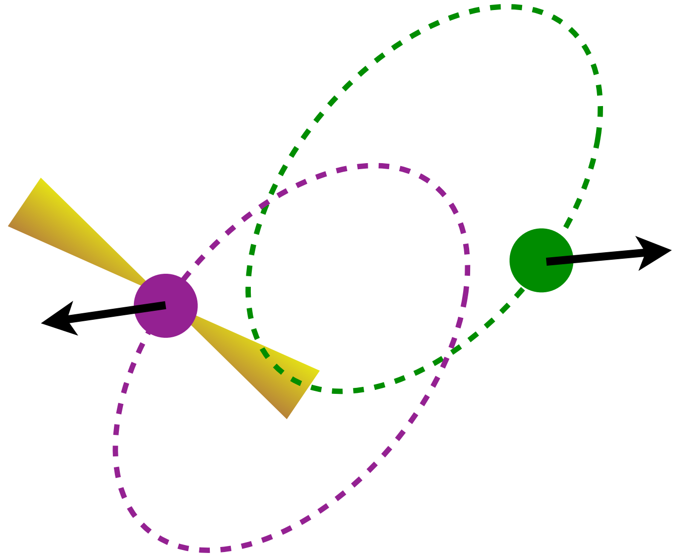

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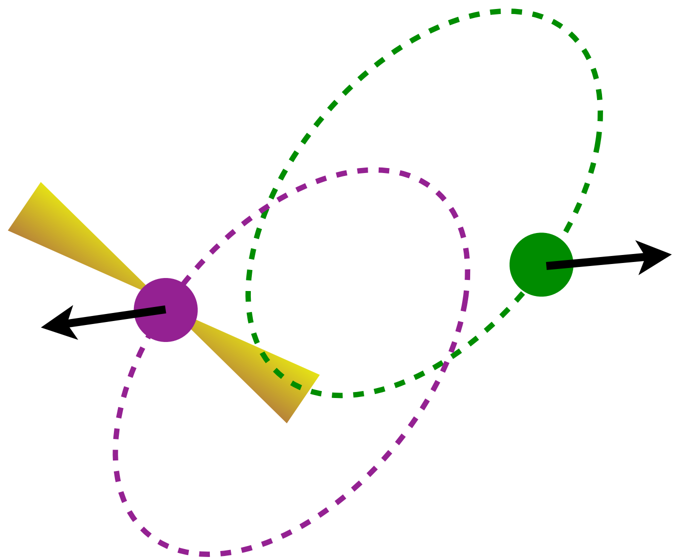
$$P_b \propto |E_b|^{-3/2}$$

orbital eccentricity

$$\langle \dot{P}_b \rangle \simeq -1.6 \times 10^{-17} \left(\frac{\rho_\Phi}{0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}} \right) \left(\frac{P_b}{100\,\mathrm{d}} \right)^2 \frac{J_N(Ne)}{N} \sin\left(\delta\omega\, t + 2\, m\, t_0 + 2\Upsilon\right)$$

Dynamical effect in binary pulsars

D.Lopez Nacir, D.Blas, S.S. (2016)



$$\ddot{\mathbf{r}} = -\ddot{\psi}\,\mathbf{r}$$

$$\delta E_b = \mu \int_0^{P_b} \dot{\mathbf{r}}\ddot{\mathbf{r}}\, dt$$

resonance if

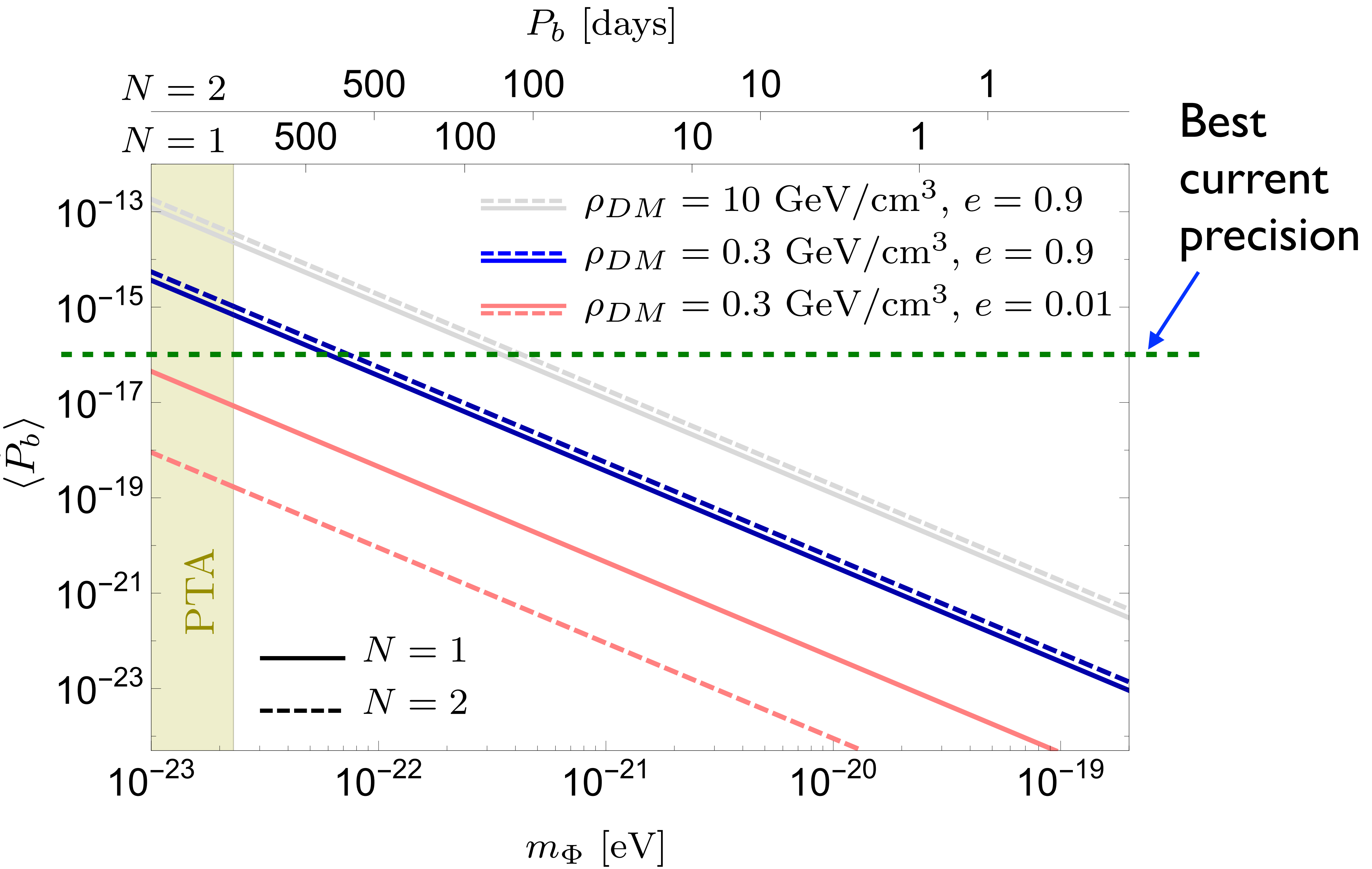
$$\delta\omega \equiv 2m - \frac{2\pi N}{P_b} \ll 2m$$

$$P_b \propto |E_b|^{-3/2}$$

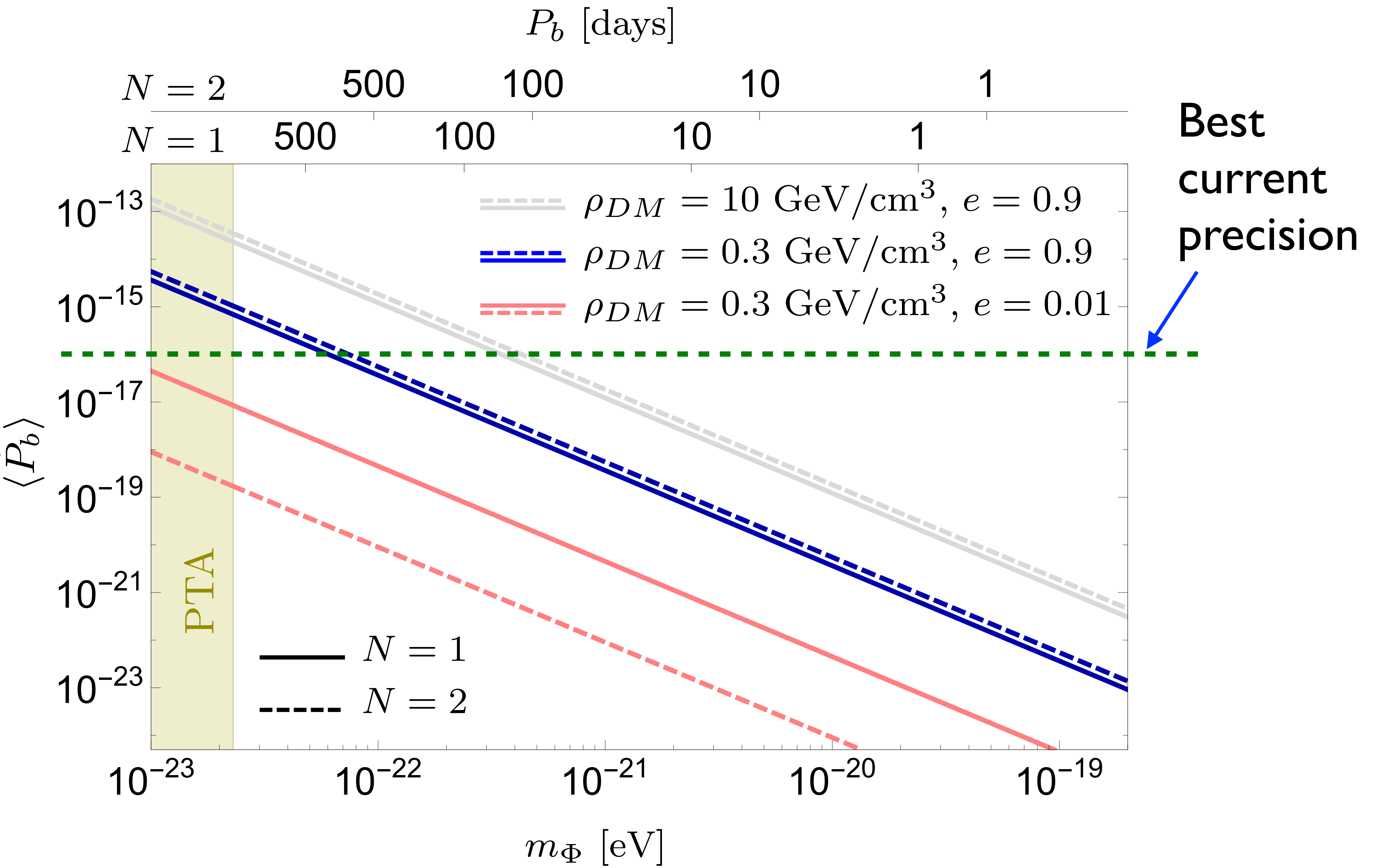
orbital eccentricity

$$\Rightarrow \langle \dot{P}_b \rangle \simeq -1.6 \times 10^{-17} \left(\frac{\rho_\Phi}{0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3}} \right) \left(\frac{P_b}{100\,\mathrm{d}} \right)^2 \frac{J_N(Ne)}{N} \underbrace{\sin\left(\delta\omega\, t + 2\, m\, t_0 + 2\Upsilon\right)}$$

periodic modulation with low frequency



P_b [days]
$N=2$
500
100
10
1
$N=1$
500
100
10
1
Best current precision
$\rho_{DM} = 10$ GeV/cm^3, $e = 0.9$
$\rho_{DM} = 0.3$ GeV/cm^3, $e = 0.9$
$\rho_{DM} = 0.3$ GeV/cm^3, $e = 0.01$
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
$\langle \dot{P}_b \rangle$
PTA
$N=1$
$N=2$
10^{-23}
10^{-22}
10^{-21}
10^{-20}
10^{-19}
m_Φ [eV]



☹ for slow systems ($P_b >$ day) the precision is worse

For now: Constraints on a direct coupling

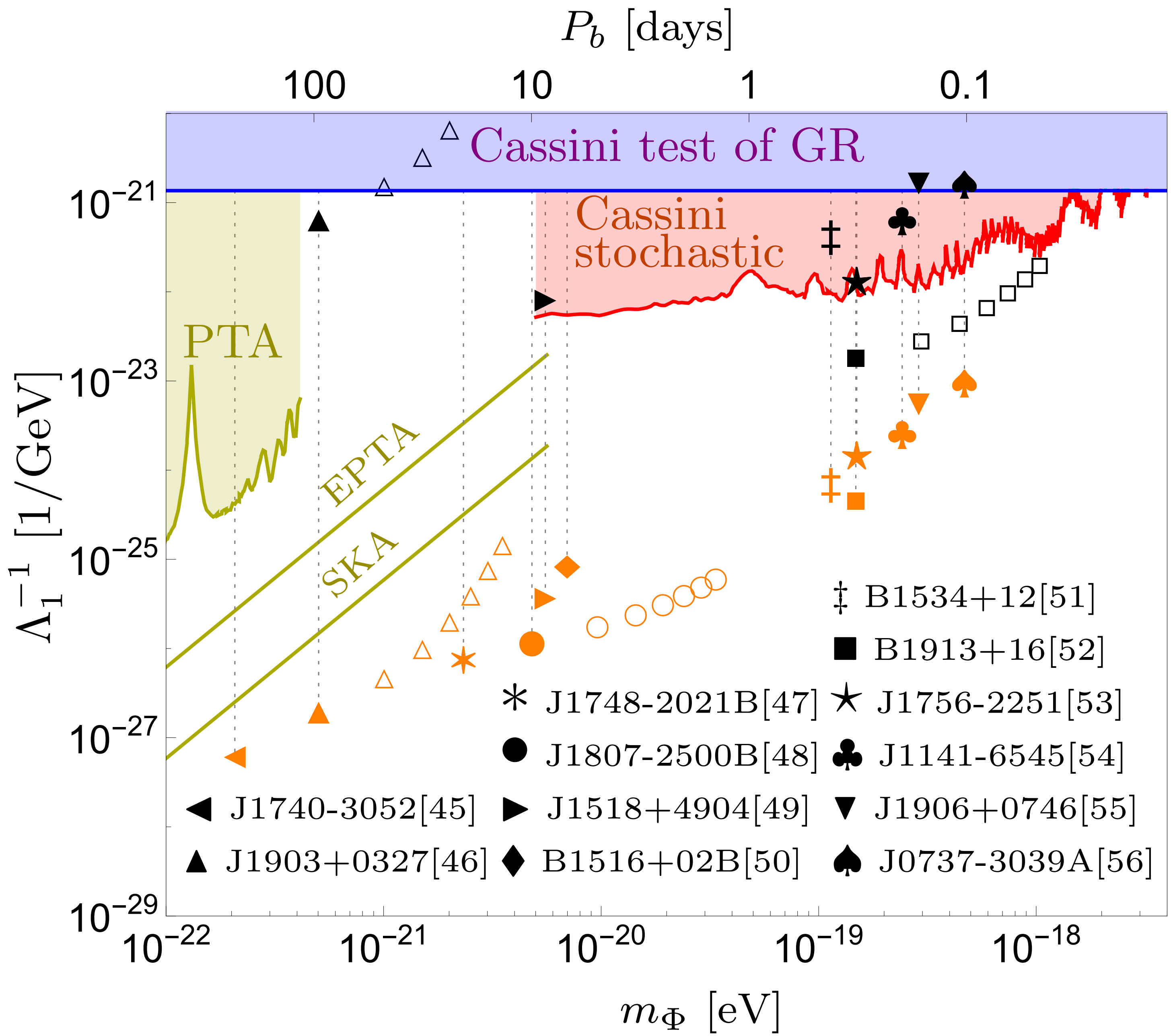
$$M_{1,2}(\Phi) = M_{1,2} \cdot (1 + \alpha_{1,2}(\Phi))$$

$$\mathcal{L} = M_1(\Phi)\left(1 + \frac{v_1^2}{2}\right) + M_2(\Phi)\left(1 + \frac{v_2^2}{2}\right) + \frac{G M_1(\Phi) M_2(\Phi)}{r}$$

Linear coupling $\alpha(\Phi) = \frac{\Phi}{\Lambda_1}$

$$\langle \dot{P}_b \rangle \simeq 2.5 \times 10^{-12} \left(\frac{\rho_\Phi}{0.3 \frac{\mathrm{GeV}}{\mathrm{cm}^3}} \right)^{\frac{1}{2}} \left(\frac{P_b}{100\,\mathrm{d}} \right)$$

$$\times \left(\frac{10^{23}\mathrm{GeV}}{\Lambda_1} \right) J_N(Ne) \sin\left(\delta\omega\, t + \ m\ t_0 + \Upsilon\right)$$



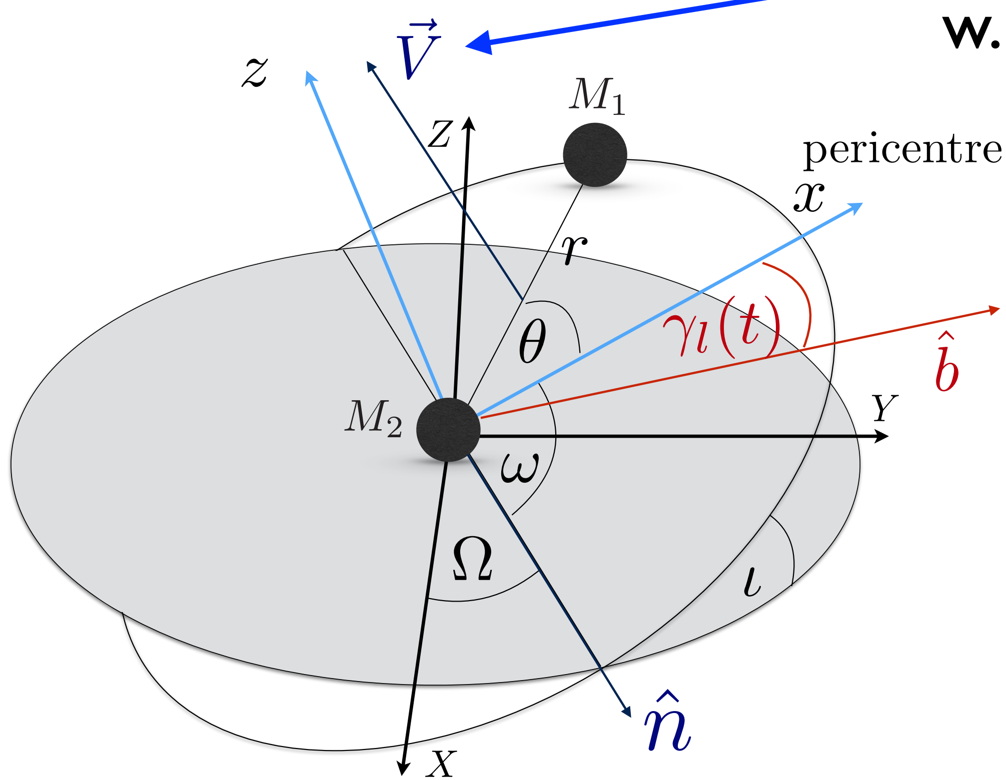
Warning:

- Assumed $\sin(\dots) = 1$; need multiple systems
- Bounds in narrow bands $\delta m \sim 5 \times 10^{-23}/(\text{years of observations})$

Future: non-universal coupling

$$\ddot{\mathbf{r}} = -\frac{d\alpha_\mu}{d\Phi}\dot{\Phi}\,\dot{\mathbf{r}} + \frac{GM\alpha_M(\Phi)}{r^3}\mathbf{r} + \frac{d\Delta\alpha}{d\Phi}\dot{\Phi}\,\mathbf{v}_{\rm cm}$$

velocity of the binary w.r.t. dark matter



- isotropy broken ➡ precession of the orbit
- affects period, eccentricity etc. even for circular orbits

Summary

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  direct coupling to the mass already within reach, pure gravitational interaction may be probed with future surveys

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Outlook

- Further understanding of structure formation with ULDM (baryonic effects, supermassive black hole)
- More probes: Inner Milky Way, 21 cm, more …