ULTRA-LIGHT DARK MATTER AND PULSAR TIMING OBSERVATIONS

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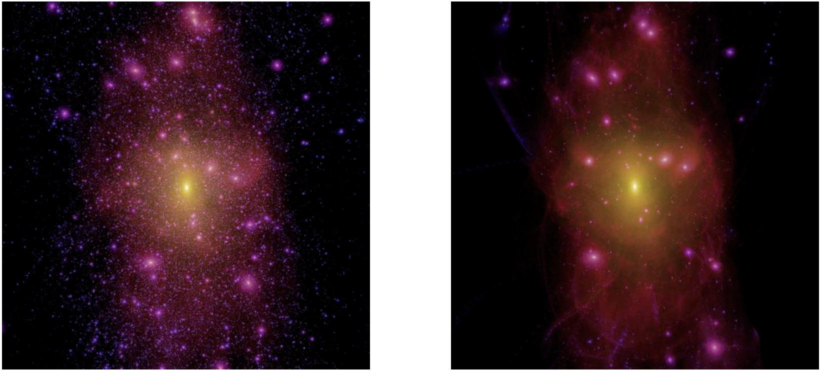
MOTIVATION

Numerical simulations of structure formation in CDM fail to reproduce the observed structure on sub-galactic scales

Primack '12

CDM simulation

WDM simulation



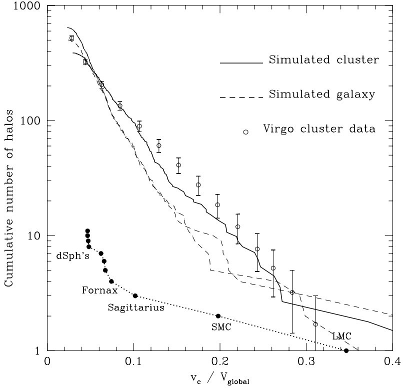
Lovel et al. '13

Hints towards DM models with less structure on small scales (Warm Dark Matter, Self-interacting Dark Matter, . . .)

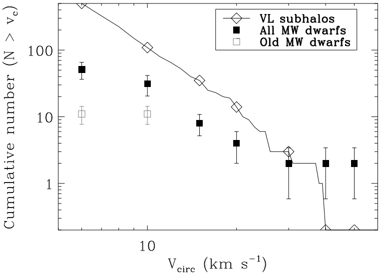
MISSING SATELLITES PROBLEM

Klypin et al., Moore et al., 1999

CDM simulations predict 10^3 satellites in a galaxy like ours
Only 50 are found so far in the Milky Way



Klypin et.al., 1999



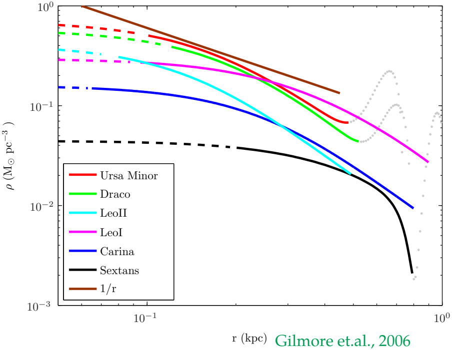
Simon & Geha, 2007

New surveys are expected to discover some more satellites

Star formation may be not efficient in small halos ⇒ they remain dark

CUSPS PROBLEM

Moore, 1994



Gilmore et.al., 2006

CDM density follows the universal NFW profile with $\rho \sim 1/r$ towards galactic center

Stellar kinematics in local satellites suggest shallow central density profiles

Supernova explosions cause gas blowout from central regions and may substantially reduce central density

Governato et al., 2010, 2012

“Too big to fail problem”: out of 10 biggest CDM subhalos, 8 are more massive than any known bright MW satellite

M. Boylan-Kolchin et al., 2011, 2012

ULTRA-LIGHT DM IS 'COLD AND FUZZY'

Hu, Barkana, Gruzinov '00

Just a free massive scalar field

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2$$

Does not behave exactly like the pressureless dust

- Non-zero Jeans length

$$r_J \approx 150\ \mathrm{kpc}\ \left(\frac{10^{-23}\,\mathrm{eV}}{m}\right)^{1/2}$$

Cuts off $P(k)$ at short scales ⇒ No seeds for small haloes

- de Broglie wavelength in galcatic halo

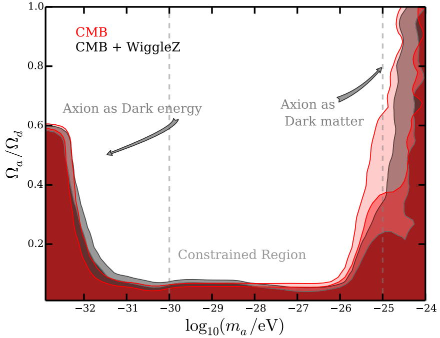
$$\lambda_{dB} = \frac{1}{mv} \approx 600\ \mathrm{pc}\ \left(\frac{10^{-23}\,\mathrm{eV}}{m}\right)\left(\frac{10^{-3}}{v}\right)$$

Minimal localization length for a particle ⇒

No structure on smaller scales

CONSTRAINTS FROM STRUCTURE FORMATION

Even lighter $m \lesssim 10^{-24}$ eV scalar field suppresses the density perturbations too much and contradicts observations



Hlozek et al ’15

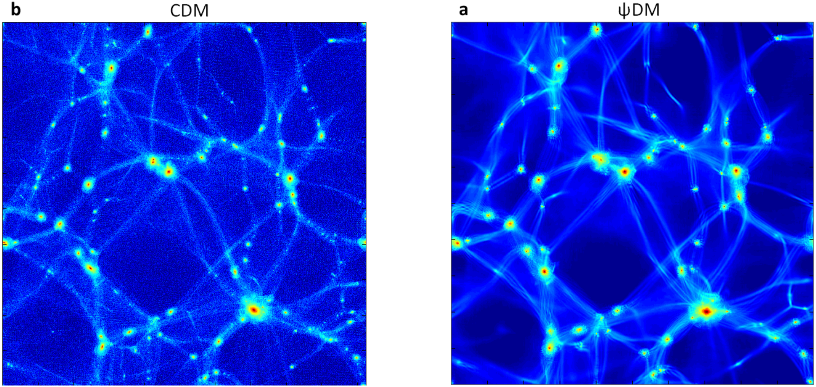
Future measurements of the matter power spectrum and the reionization history will probe $m \sim 10^{-22}$ eV

Bozek et al ’14

STRUCTURES IN ULTRA-LIGHT DM

Schive et al. '14

CDM Ultra-Light DM

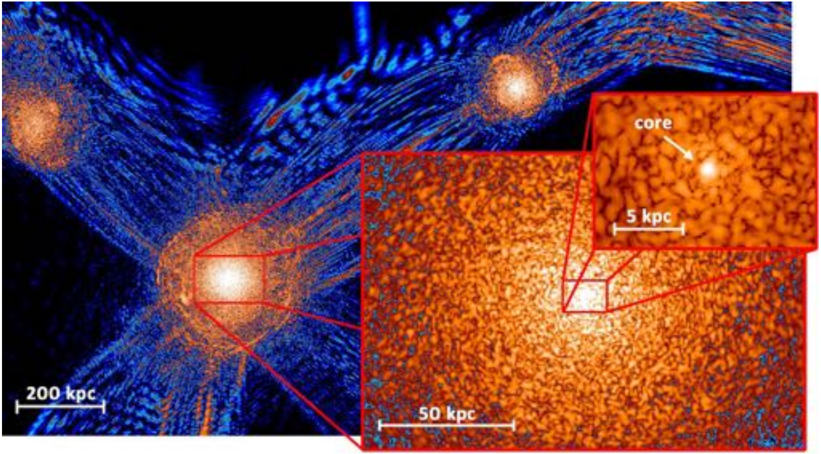


Simulations of structure formation show that Ultra-Light DM helps with CDM small scale issues given $m \lesssim 10^{-22}$ eV

$\Rightarrow$ small allowed mass range, soon might be excluded

Marsh, Pop '15

SCALAR FIELD IN A GALACTIC HALO



Schive et al. '14

SCALAR FIELD IN GALACTIC HALO

- Given the local DM density $\rho_{DM} \approx 0.3\,\mathrm{GeV/cm^3}$ the occupation numbers are enormous

$$\frac{\Delta N}{\Delta x^3 \Delta k^3} \gtrsim \frac{\rho_{DM}}{m} \lambda_{dB}^3 \sim 10^{95}$$

DM is well described by a classical field $\phi(\mathbf{x}, t)$

- Non-relativistic field oscillates in time with frequency

$$E \simeq m \approx 0.5\,\mathrm{yr}^{-1} \left(\frac{10^{-23}\,\mathrm{eV}}{m} \right)$$

- Spatial variation is limited to the scales larger than λ_{dB}:

$$\nabla\phi \lesssim \lambda_{dB}^{-1}\phi \ll \dot{\phi} \sim m\phi$$

- Legitimate to use an ansatz

$$\phi(\mathbf{x}, t) = A(\mathbf{x}) \cos\left(mt + \alpha(\mathbf{x})\right)$$

with $A(\mathbf{x})$ and $\alpha(\mathbf{x})$ are slowly varying

SCALAR FIELD IN GALACTIC HALO

- Energy-momentum tensor of the scalar field

$$T_{\mu\nu} = \partial_\mu\phi\partial_\nu\phi - \tfrac{1}{2}g_{\mu\nu}\left((\partial\phi)^2 - m^2\phi^2\right)$$

- Energy density is time-independent

$$\rho(\mathbf{x}) = \tfrac{1}{2}\left(\dot{\phi}^2 + m^2\phi^2 + (\nabla\phi)^2\right) = \tfrac{1}{2}m^2 A(\mathbf{x})^2 + \mathcal{O}(k^2)$$

- Pressure is non-zero and oscillates with frequency $\omega = 2m$

$$p(\mathbf{x},t) = \tfrac{1}{2}\left(\dot{\phi}^2 - m^2\phi^2 - (\nabla\phi)^2\right)$$

$$= -\tfrac{1}{2}m^2 A(\mathbf{x})^2 \cos\left(2mt + 2\alpha(\mathbf{x})\right) + \mathcal{O}(k^2)$$

- Although, averaged over a period pressure is zero, the oscillations induce time-dependent gravitational potential

EFFECT ON THE METRIC

The halo metric (in Newtonian gauge)

$$ds^2 = (1 + 2\Phi(\mathbf{x}, t))dt^2 - (1 - 2\Psi(\mathbf{x}, t))\delta_{ij}dx^i dx^j$$

Gravitational potentials Φ and Ψ have dominant time-independent parts and small oscillating parts

$$\Psi(\mathbf{x}, t) \simeq \Psi_0(\mathbf{x}) + \Psi_c(\mathbf{x}) \cos(\omega t + 2\alpha(\mathbf{x}))$$

Einstein equations at the leading order read

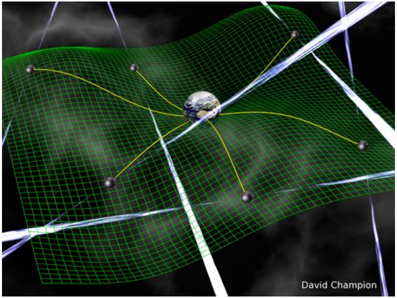
- $\Delta\Psi_0 = \Delta\Phi_0 = 4\pi G\rho$
- $-6\,\ddot{\Psi}(\mathbf{x}, t) = 24\pi G\, p(\mathbf{x}, t)$

The subleading oscillating part $\Psi_c \sim \mathcal{O}(v^2)\,\Psi_0$

$$\boxed{\Psi_c = \frac{1}{2}\pi G A^2 \equiv \pi \frac{G\,\rho_{DM}}{m^2} \approx 10^{-15}\left(\frac{10^{-23}\,\mathrm{eV}}{m}\right)^2}$$

PULSAR TIMING

Oscillations in gravitational field of such scale and frequency happen to be in the range of Pulsar Timing experiments!



- One records pulse arrival times for a number of nearby pulsars
- Time-dependent gravitational potentials cause pulse arrival time shifts (Shapiro delay) $\delta t(t)$
- PT is used to search for Gravitational Waves from astrophysical sources

Janet '05

In distinction from GW signal the Scalar Field DM time delay is isotropic and almost monochromatic: $\delta\omega/\omega \sim v^2 \sim 10^{-6}$

ULTRA LIGHT DM SIGNAL

Pulse arrival time delay is related to the pulse frequency shift

$$\Delta t(t) = -\int_0^t \frac{\Omega_{lab}(t') - \Omega_p}{\Omega_p} dt'$$

Frequency shift is given by an analog of the Sachs–Wolfe effect

$$\frac{\Omega(t_{lab}) - \Omega_p}{\Omega_p} \simeq \Psi(\mathbf{x}_{lab}, t_{lab}) - \Psi(\mathbf{x}_{pulsar}, t_{pulsar})$$

Time-dependent shift of arrival times has rms amplitude

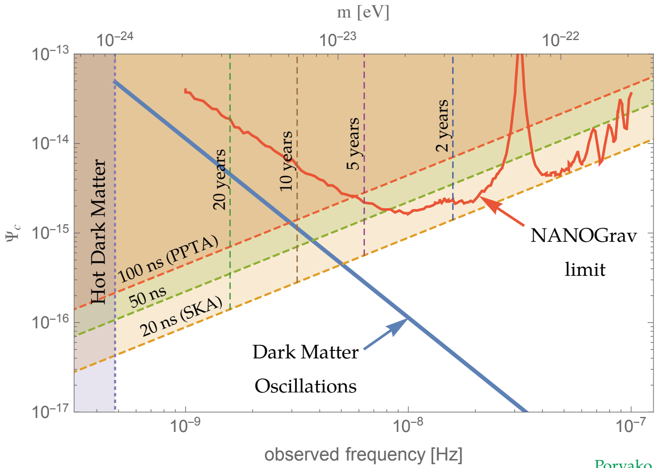
$$\boxed{\delta t_{SF} \sim \frac{\Psi_c}{\omega} = 23\ \mathrm{ns} \left(\frac{10^{-23}\ \mathrm{eV}}{m}\right)^3}$$

NB Single gravitational wave induces a time delay $\delta t_{GW} \sim \frac{h_c}{\omega}$

Sazhin '78, Detweiler '79

δt_{SF} is comparable to the delay from a gravitational wave with amplitude $h_c^{SF} = 2 \cdot 10^{-15} \left(\frac{10^{-23}\ \mathrm{eV}}{m}\right)^2$ and frequency $f = 5\ \mathrm{nHz} \left(\frac{m}{10^{-23}\ \mathrm{eV}}\right)$

PULSAR TIMING ARRAYS SENSITIVITY



Poryako, Postnov '14

The scalar field DM component with $m \sim 10^{-24} \div 10^{-23}$ eV can be probed in forthcoming Pulsar Timing experiments

CONCLUSIONS

- Observations of the DM structure on sub-galactic scales motivate to study alternative DM models
- Only small modifications of CDM structure formation are allowed ⇒ stringent constraints on DM scenarios
- Ultra-Light DM can address CDM issues provided

$$10^{-24}\ \mathrm{eV} \lesssim m \lesssim 10^{-22}\ \mathrm{eV}$$

- Oscillatory nature of Ultra-Light DM has to show up in Pulsar Timing Observations in the similar window

$$10^{-24}\ \mathrm{eV} \lesssim m \lesssim 10^{-23}\ \mathrm{eV}$$