Ultra-light axion dark matter

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Light axion dark matter

mass $m \sim 10^{-22\pm1}$ eV

Fuzzy dark matter
Hu, Barkana, Gruzinov

- A natural candidate for such a light particle is a pseudo Nambu-Goldstone boson.

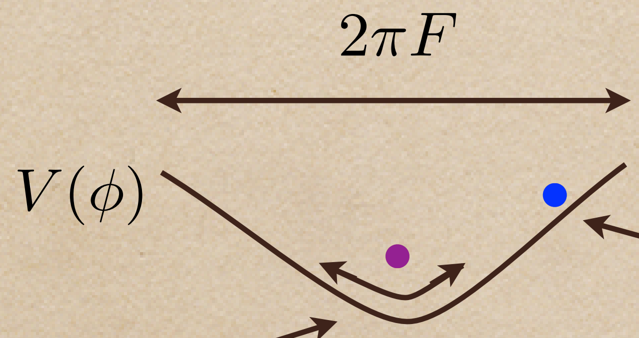
- Concrete realization (ALP): an angular field of periodicity $2\pi F$ i.e. an axion-like field with a potential from non-perturbative effects (not QCD axion).

$$\mathcal{L} \sim -\frac{1}{2}(\partial\phi)^2 - \Lambda^4(1 - \cos[\phi/F])$$

$$m \sim \Lambda^2/F$$

- Relic abundance:

(standard story - see Kolb & Turner; review by Marsh)



$\phi \sim F$ at early times until $H \sim m$

$\rho_\phi \sim m^2 F^2 \quad , \quad \rho_{\rm rad.} \sim H^2 M_{\rm pl}^2 \sim m^2 M_{\rm pl}^2 \sim T^4$

subsq. oscill. : $\rho_\phi \propto a^{-3}$

self − interaction can be ignored

$$\Omega_{\rm axion} \sim 0.1 \left(\frac{F}{10^{17}\,\mathrm{GeV}}\right)^2 \left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)^{1/2}$$

(low scale inflation)

Dynamics of a free massive scalar

- Ignoring self-interaction:

$$m^{-1} \sim 0.06\,\mathrm{pc}$$
$$(mv)^{-1} \sim 2 \text{ kpc } (10\,\mathrm{km\,s^{-1}}/v)$$

$$-\Box\phi + m^2\phi = 0$$

- Non-relativistic limit:

$$\phi = \frac{1}{\sqrt{2m}}\left[\psi e^{-imt} + \psi^* e^{imt}\right]$$

$$|\ddot{\psi}| \ll m|\dot{\psi}| \quad \longrightarrow \quad i\dot{\psi} = \left[-\frac{\nabla^2}{2m} + m\Phi_{\mathrm{grav.}}\right]\psi$$

- High occupancy implies ψ should be thought of as a classical scalar. See simulations by Hsi-Yu Schive, Tzihong Chiueh & Tom Broadhurst, Mocz et al., Veltmaat & Niemeyer.

- An alternative viewpoint: ψ as a (classical) fluid.

$$\rho = m\,|\psi|^2 \quad \text{i.e.} \quad \psi = \sqrt{\rho/m}\,e^{i\theta}$$

Recall conservation of probability: current $\propto i(\psi\nabla\psi^* - \psi^*\nabla\psi)$

Reinterpreted as conservation of mass:

$$\dot{\rho} + \nabla\cdot\rho v = 0 \quad \text{where} \quad v = \frac{1}{m}\nabla\theta \qquad \text{i.e. a superfluid.}$$

Fluid formulation (Madelung)

- Euler equation:

$$\dot{v} + v \cdot \nabla v = -\nabla \Phi_{\rm grav.} + \frac{1}{2m^2} \nabla \left(\frac{\nabla^2 \sqrt{\rho}}{\sqrt{\rho}} \right)$$

"quantum pressure"

- More precisely, an unusual form of stress:

$$T_{ij} = \rho v_i v_j + \frac{1}{2m^2} \left[\partial_i \sqrt{\rho}\, \partial_j \sqrt{\rho} - \sqrt{\rho}\, \partial_i \partial_j \sqrt{\rho} \right]$$

- Can be implemented in standard hydrodynamics codes (Mocz & Succi).

- For linear perturbations (on cosmological bgd.):

  Jeans scale $\sim 0.1\,\mathrm{Mpc}$

  Perturbations suppressed on small scales - could help avoid small scale problems of standard CDM (Hu, Barkana, Gruzinov: Fuzzy DM ; Amendola, Barbieri).

  Typical focus: density profile (cusp versus core), number of satellite galaxies.

  Issue: baryonic effects complicate the interpretation of the data.

Possible diagnostics of FDM vs conventional CDM:

- dynamical friction

- evaporation of sub-halos by tunneling

- interference

- tidal streams and gravitational lensing

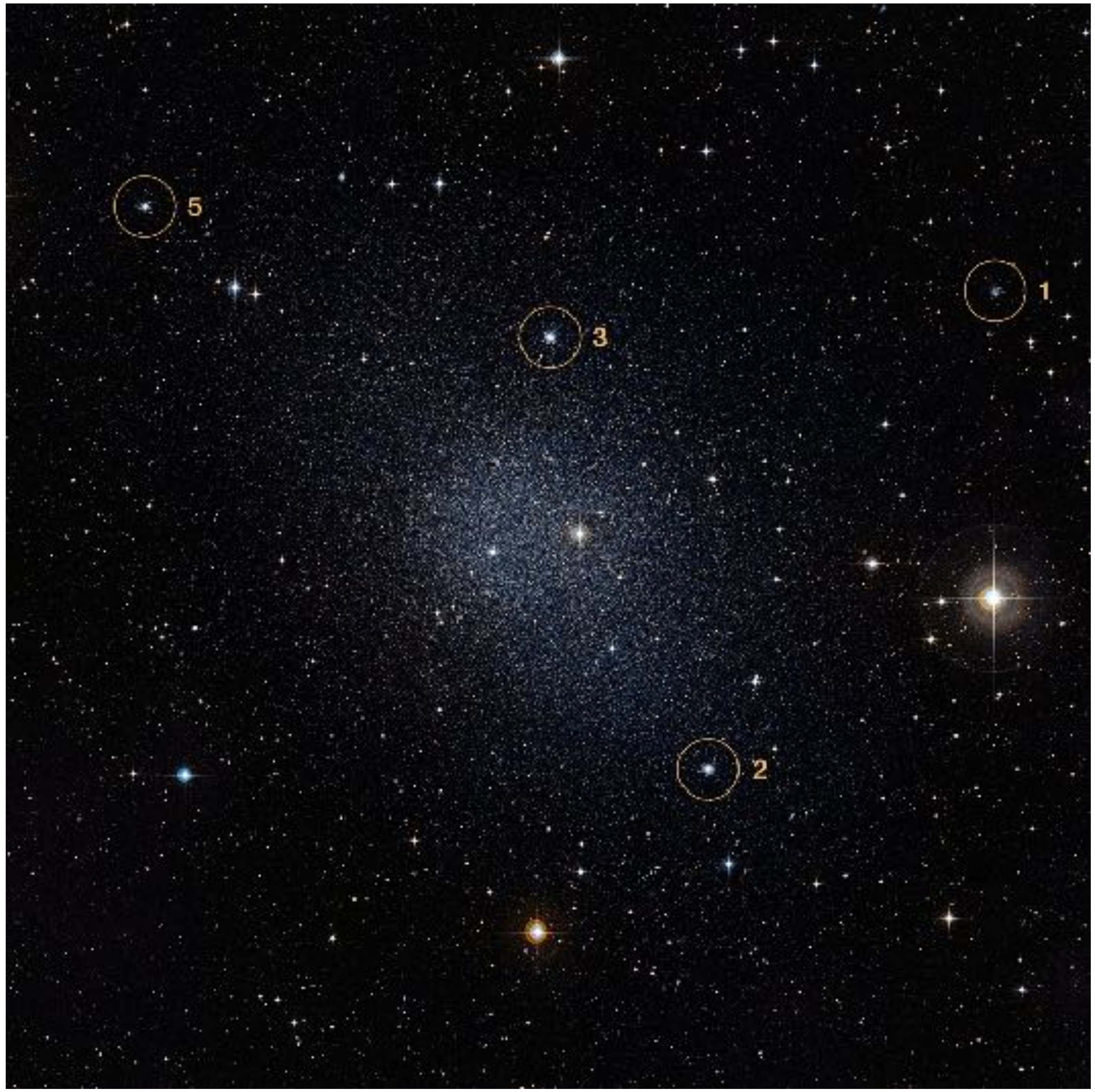
- Lyman-alpha forest

- direct detection

- detection by pulsar timing array

Fornax galaxy and its globular clusters

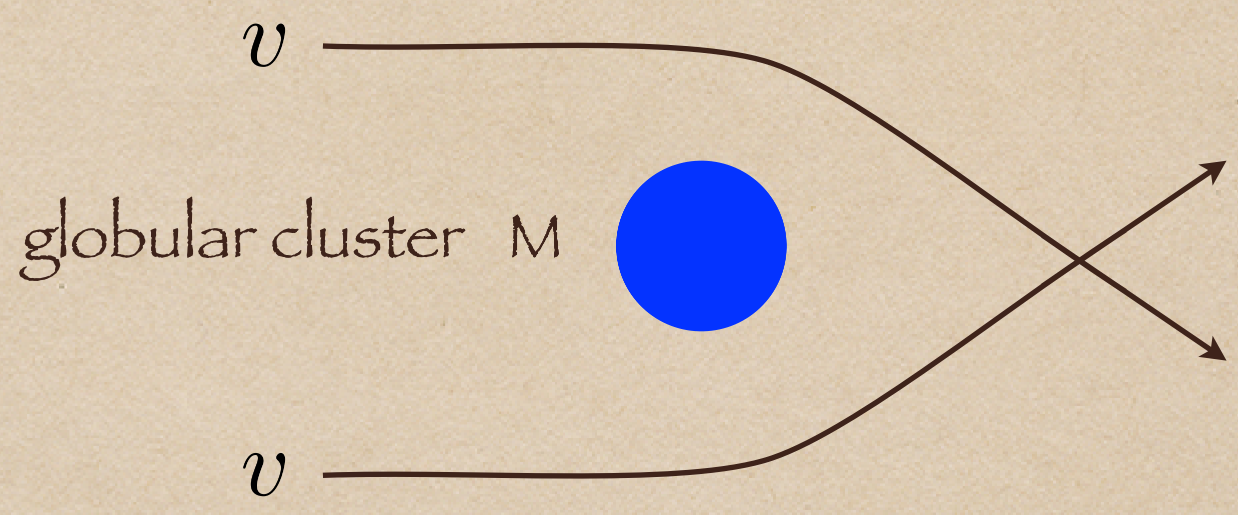
ESO/Digitized Sky Survey 2



Dynamical friction issue: Tremaine 1976

Dynamical friction

- Chandrasekhar's classic calculation:



- Quantum stress smooths out density wake, lowering friction.
  (see also Lora et al.)

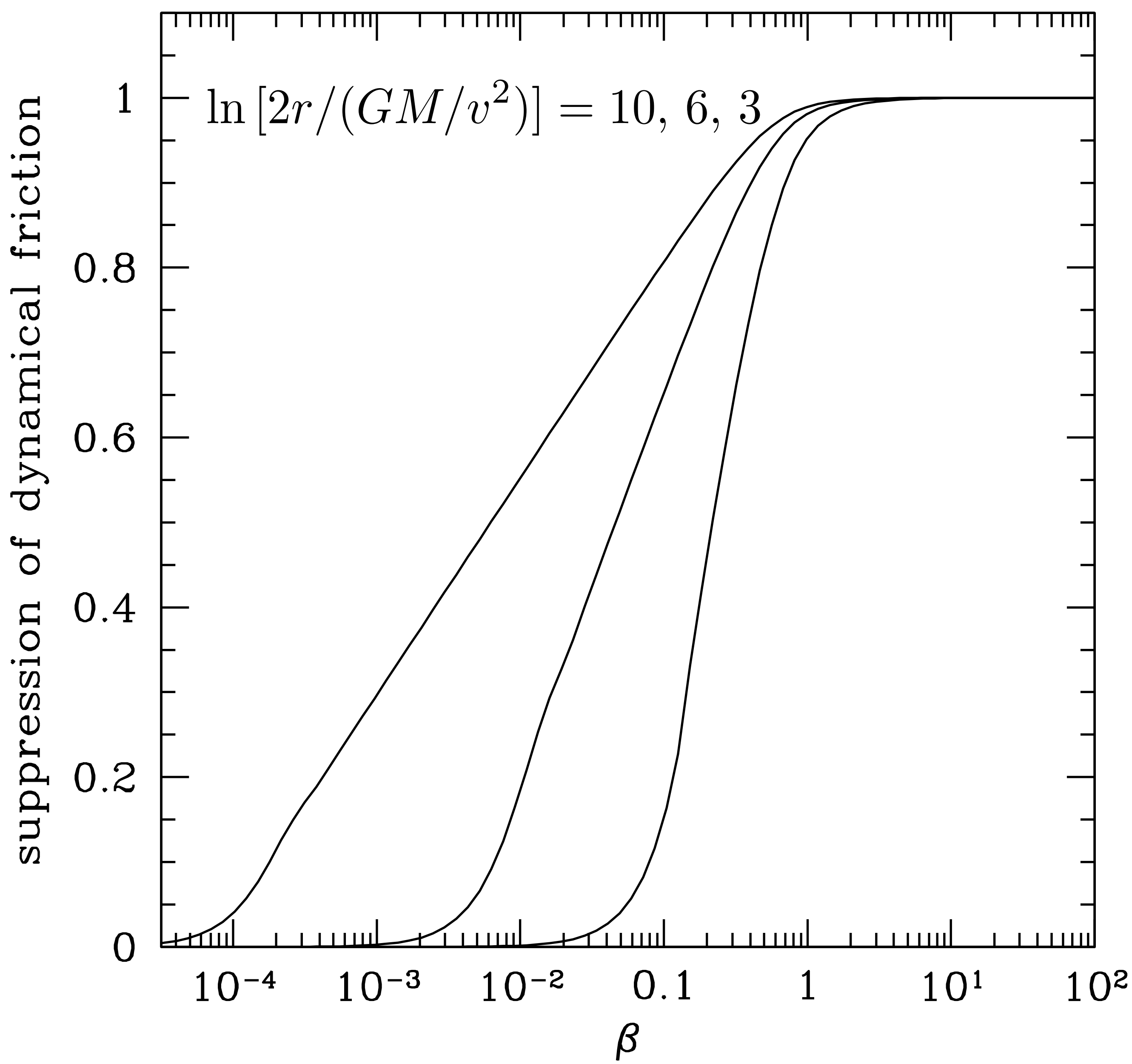
- Use known solution for the Coulomb scattering problem:

  $\psi \propto F\,[\,i\beta, 1, ikr(1 - \cos\theta)\,]$ where F is the confluent hypergeometric func.

  $\beta \equiv (GM/v^2)/k^{-1}$ with $k^{-1} = (mv)^{-1} =$ de Broglie wavelength

  Small β means quantum stress is important.

- Key - integrate momentum flux to compute friction: $\oint dS_j\, T_{ij}$



$$\beta \equiv (GM/v^2)/k^{-1}$$
$$= 0.0023 \left(\frac{M}{10^5 M_\odot}\right)\left(\frac{10\,\mathrm{km/s}}{v}\right)\left(\frac{m}{10^{-22}\,\mathrm{eV}}\right)$$

Conclusion:

Given the density profile of a galaxy (which can be experimentally determined), standard CDM has a definite prediction for the dynamical friction, which can be checked against observations.

Fuzzy DM of m $\sim 10^{-22} - 10^{-21}\,\mathrm{eV}$ can lower dynamical friction by an order of magnitude.

Would be useful to study other systems: Lotz et al. 2001

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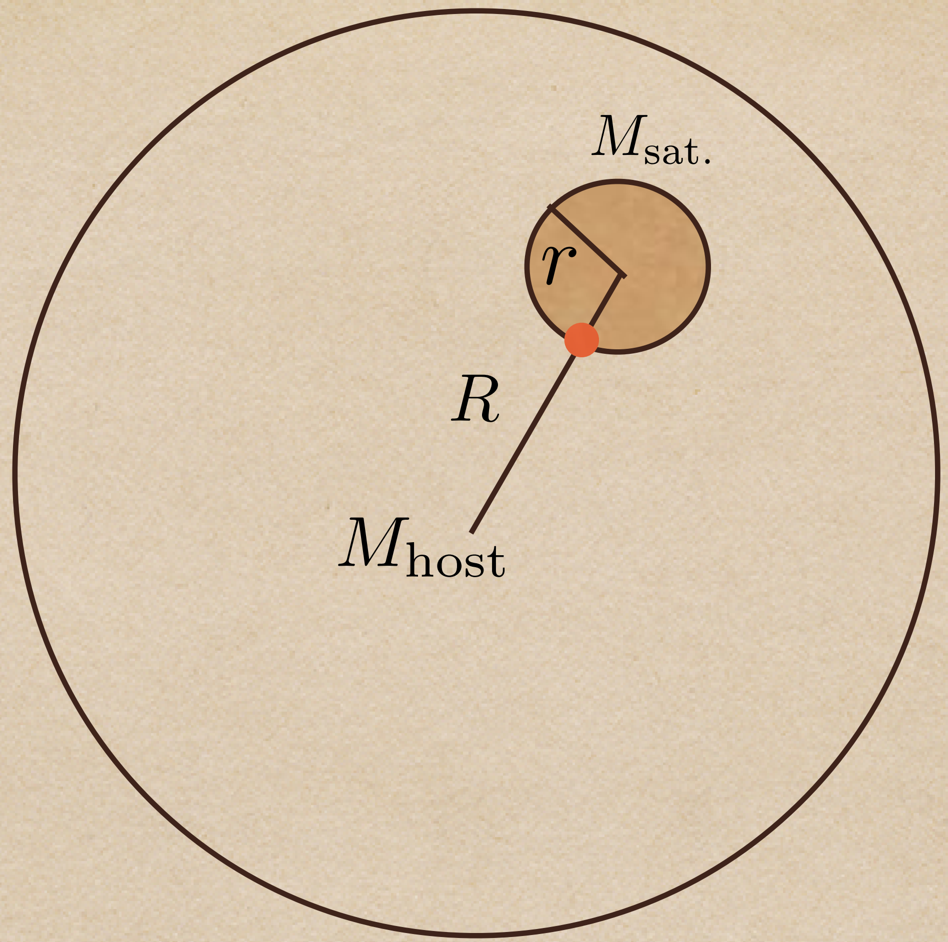
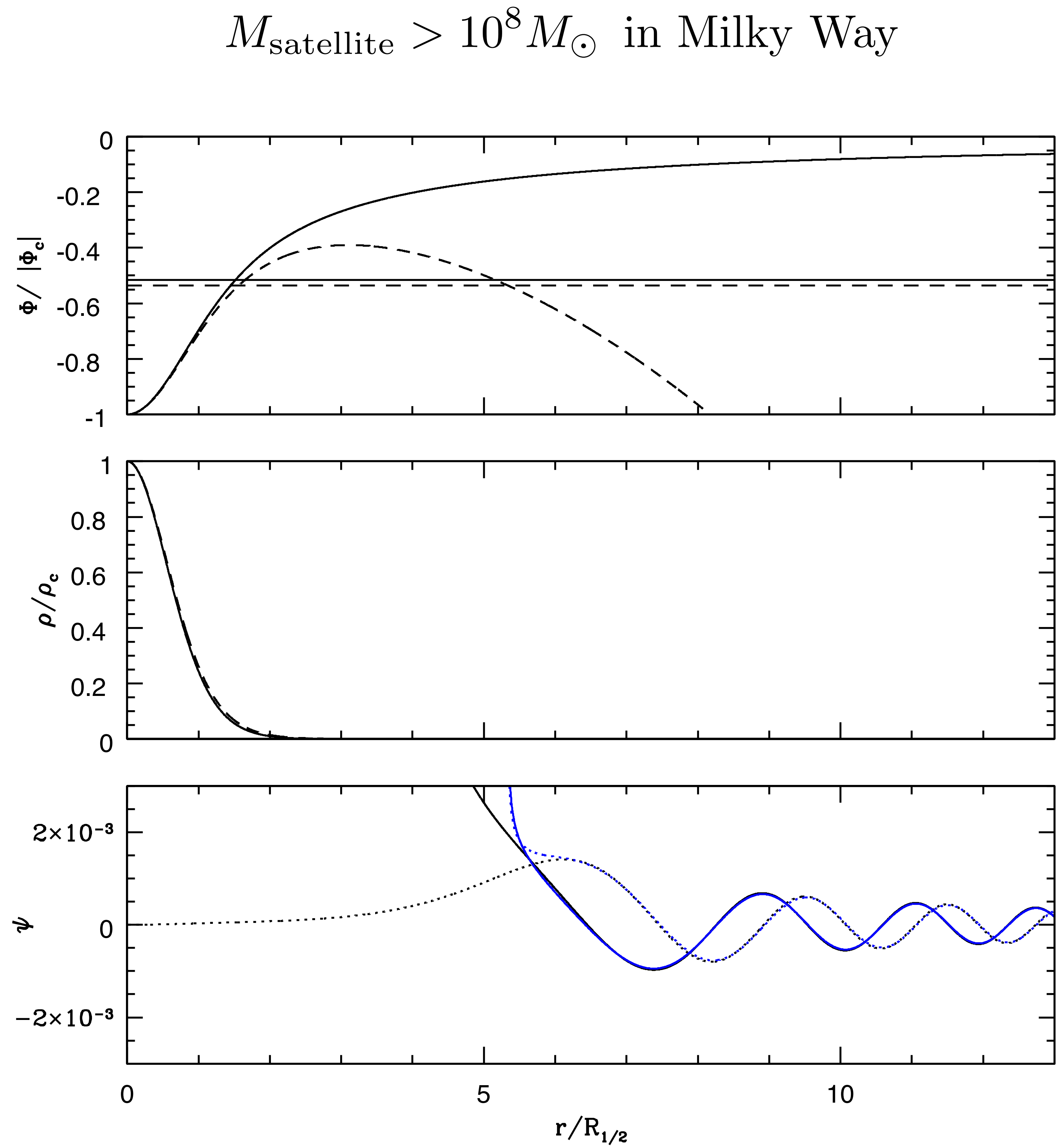


Recall tidal disruption:

$$\frac{GM_{\mathrm{host}}}{R^2}\frac{r}{R} \sim \frac{GM_{\mathrm{sat.}}}{r^2}$$

$$r = \text{disruption radius}$$

Quantum pressure is expected to alter this.



$M_{\rm satellite} > 10^8 M_\odot$ in Milky Way
0
-0.2
-0.4
-0.6
-0.8
-1
$\Phi/|\Phi_c|$
1
0.8
0.6
0.4
0.2
0
ρ/ρ_c
2×10^{-3}
0
-2×10^{-3}
ψ
0
5
10
$r/R_{1/2}$

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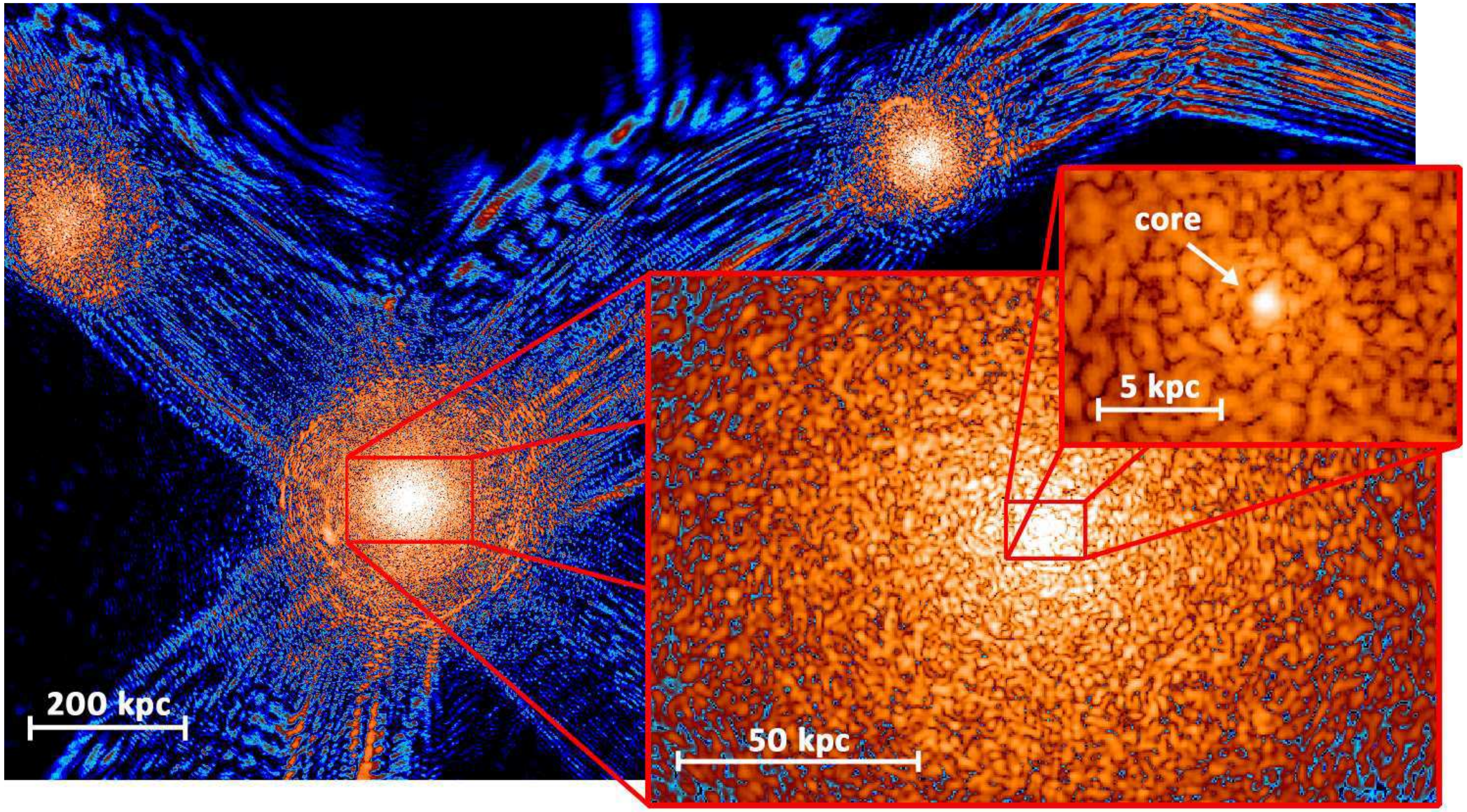

Figure 2: A slice of density field of ψDM simulation on various scales at $z = 0.1$. This scaled sequence (each of thickness 60 pc) shows how quantum interference patterns can be clearly seen everywhere from the large-scale filaments, tangential fringes near the virial boundaries, to the granular structure inside the haloes. Distinct solitonic cores with radius $\sim 0.3 - 1.6$ kpc are found within each collapsed halo. The density shown here spans over nine orders of magnitude, from 10^{-1} to 10^{8} (normalized to the cosmic mean density). The color map scales logarithmically, with cyan corresponding to density $\lesssim 10$.

Schive, Chiueh, Broadhurst

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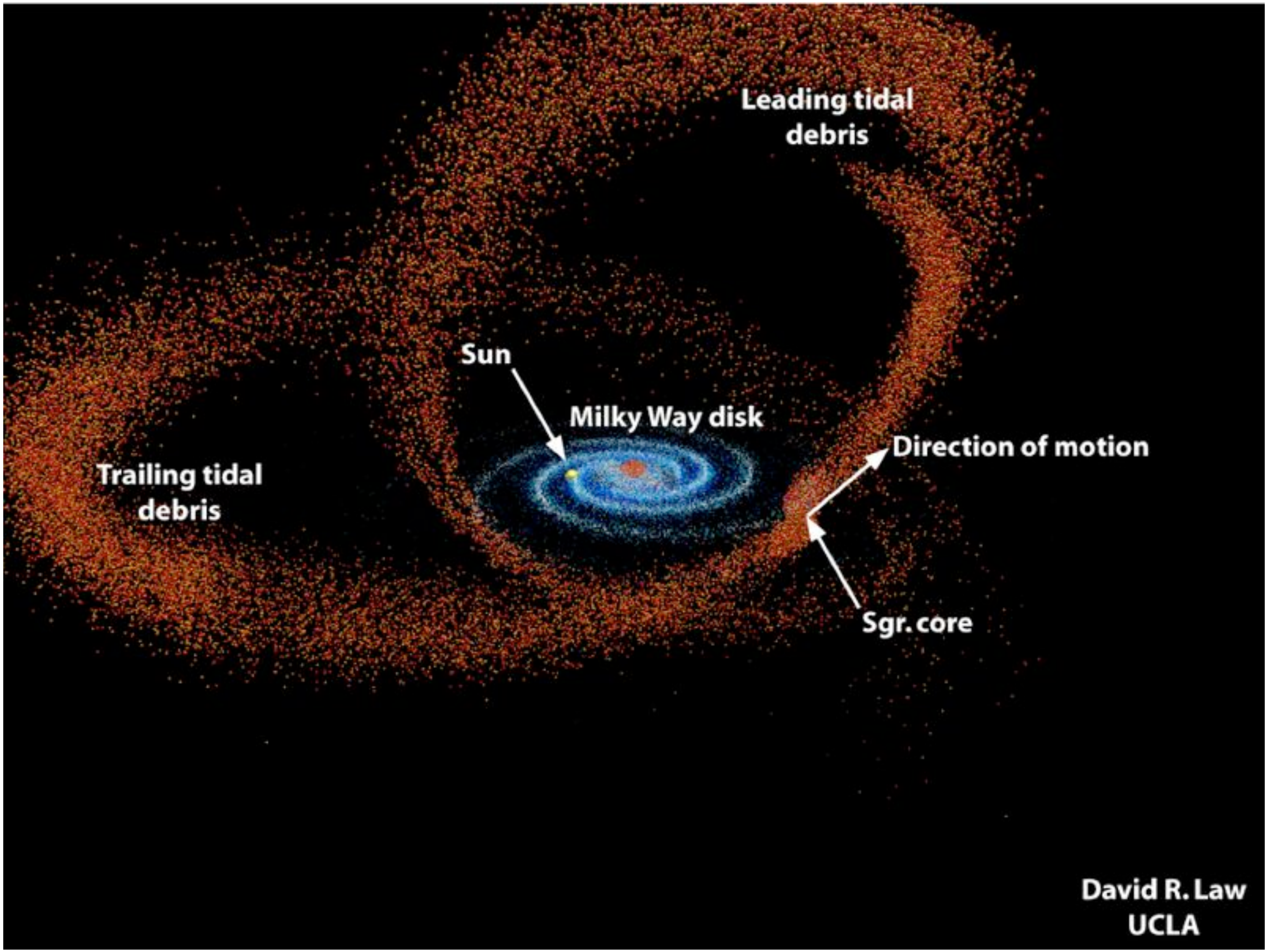
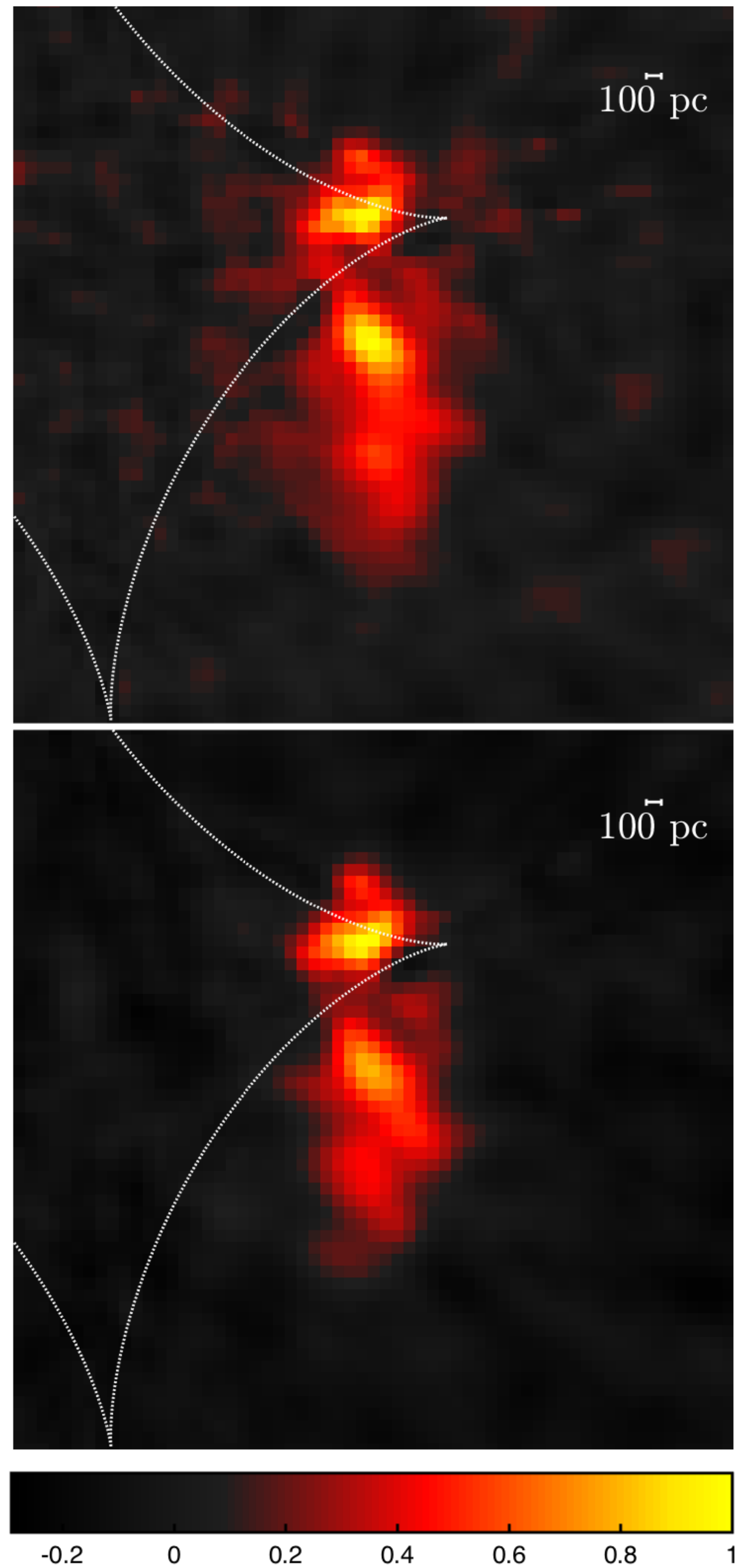


Law, Majewski, Johnston model of Sagittarius stream



Hezaveh, Dalal et al. ALMA

Figure 8. Reconstructed source continuum emission from Band 6 (top panel) and Band 7 (bottom panel) data on a 10 milli-arcsec pixel grid. The white dashed curve shows the tangential caustic predicted by our best-fit smooth model.

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Irsic, Viel, Haehnelt, Bolton, Becker 2017

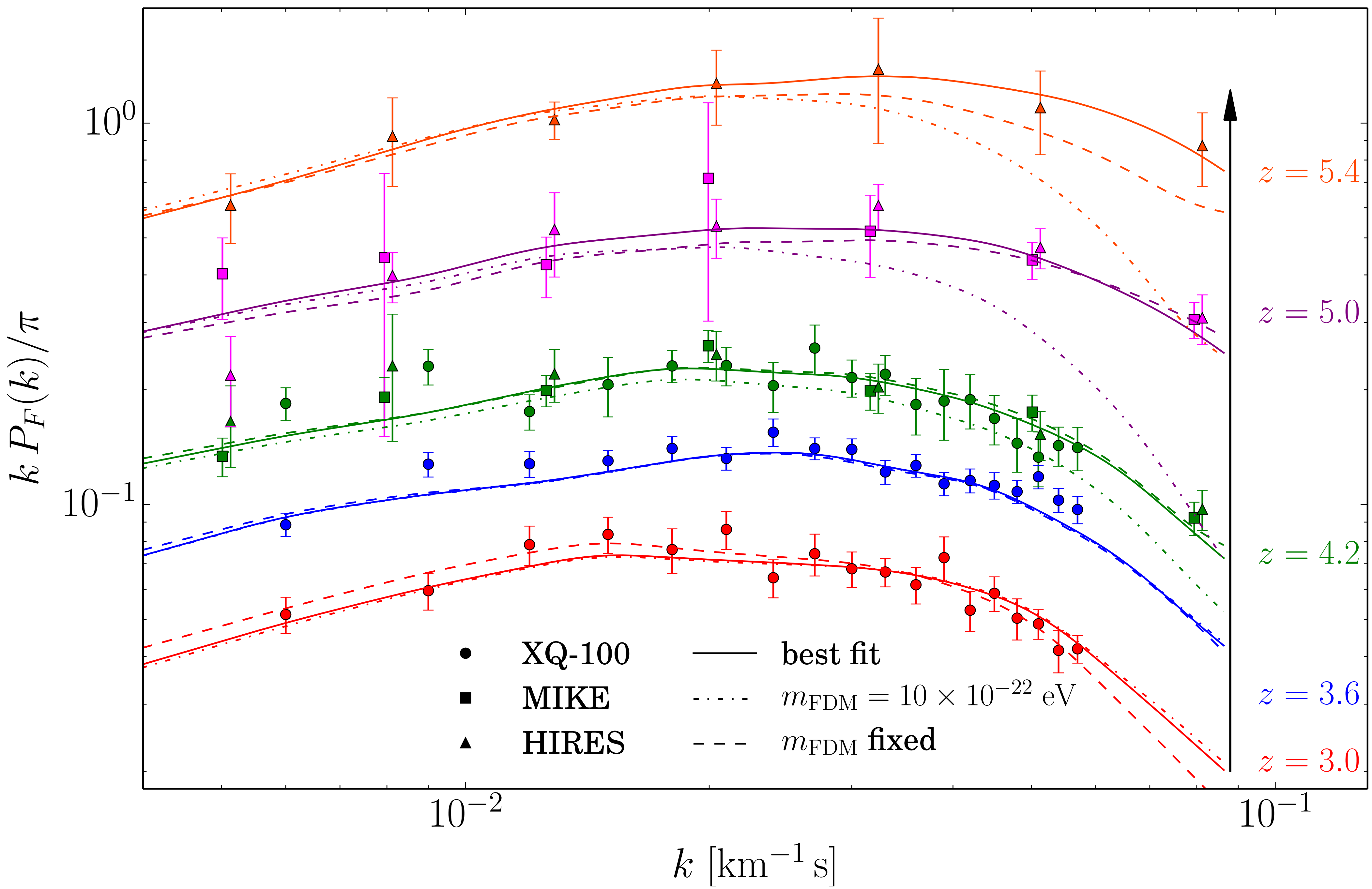

Figure thanks to Vid Irsic and Matteo Viel

Importance of ionizing background and reionization history fluctuations?

Possible diagnostics of FDM vs conventional CDM:

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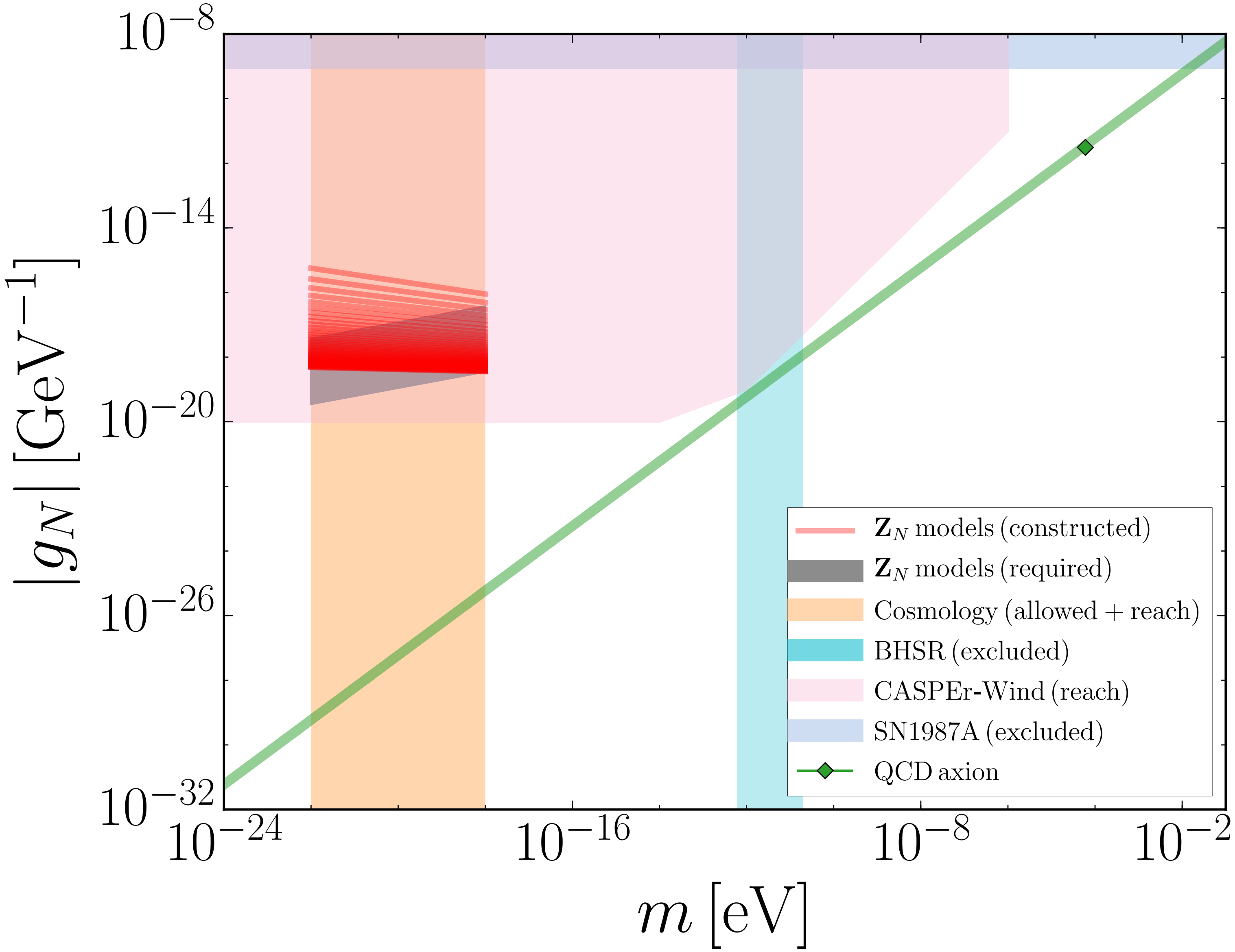
from Kim, Marsh 2015 (see also Graham, Rajendran 2013, Budker et al. 2013) 10



$$\partial_\mu \phi \, \bar{\Psi} \gamma^\mu \gamma_5 \Psi$$

FIG. 3: Axion parameter space, (m, g_N). The QCD axion paired with the ULA is shown for reference, along with the specific point $f_{\rm QCD} = 10^{11}$ GeV, which is our reference value. BHSR excludes a range of masses at 2σ independent of DM abundance and coupling strength [76]. SN1987A excludes the shaded region with $g_N \gtrsim 8.2 \times 10^{-10}$, independent of DM abundance and axion mass [79]. The region both allowed and detectable using cosmology, and relevant to the small-scale crises of CDM is 10^{-22} eV $\lesssim m \lesssim 10^{-18}$ eV [24–26, 28–30]. We show the $\mathbf{Z}_N$ models in this regime only, and also show the target region where $f_{\rm ULA}$ allows for the ULAs to be the dominant form of DM without fine tuning. The region accessible to direct detection using the spin precession technique of CASPEr-Wind [34, 35] is also shown. The cosmologically relevant regime of the $\mathbf{Z}_N$ models lies well within the projected sensitivity of CASPEr-Wind, and is not excluded by any other probes.

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Pulsar timing signal from ultralight scalar dark matter

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Abstract: An ultralight free scalar field with mass around $10^{-23} - 10^{-22}$ eV is a viable dark mater candidate, which can help to resolve some of the issues of the cold dark matter on sub-galactic scales. We consider the gravitational field of the galactic halo composed out of such dark matter. The scalar field has oscillating in time pressure, which induces oscillations of gravitational potential with amplitude of the order of 10^{-15} and frequency in the nanohertz range. This frequency is in the range of pulsar timing array observations. We estimate the magnitude of the pulse arrival time residuals induced by the oscillating gravitational potential. We find that for a range of dark matter masses, the scalar field dark matter signal is comparable to the stochastic gravitational wave signal and can be detected by the planned SKA pulsar timing array experiment.

See also Martino, Broadhurst, Tye, Chiueh, Schive, Lazkoz
Blas, Nacir, Sibiryakov

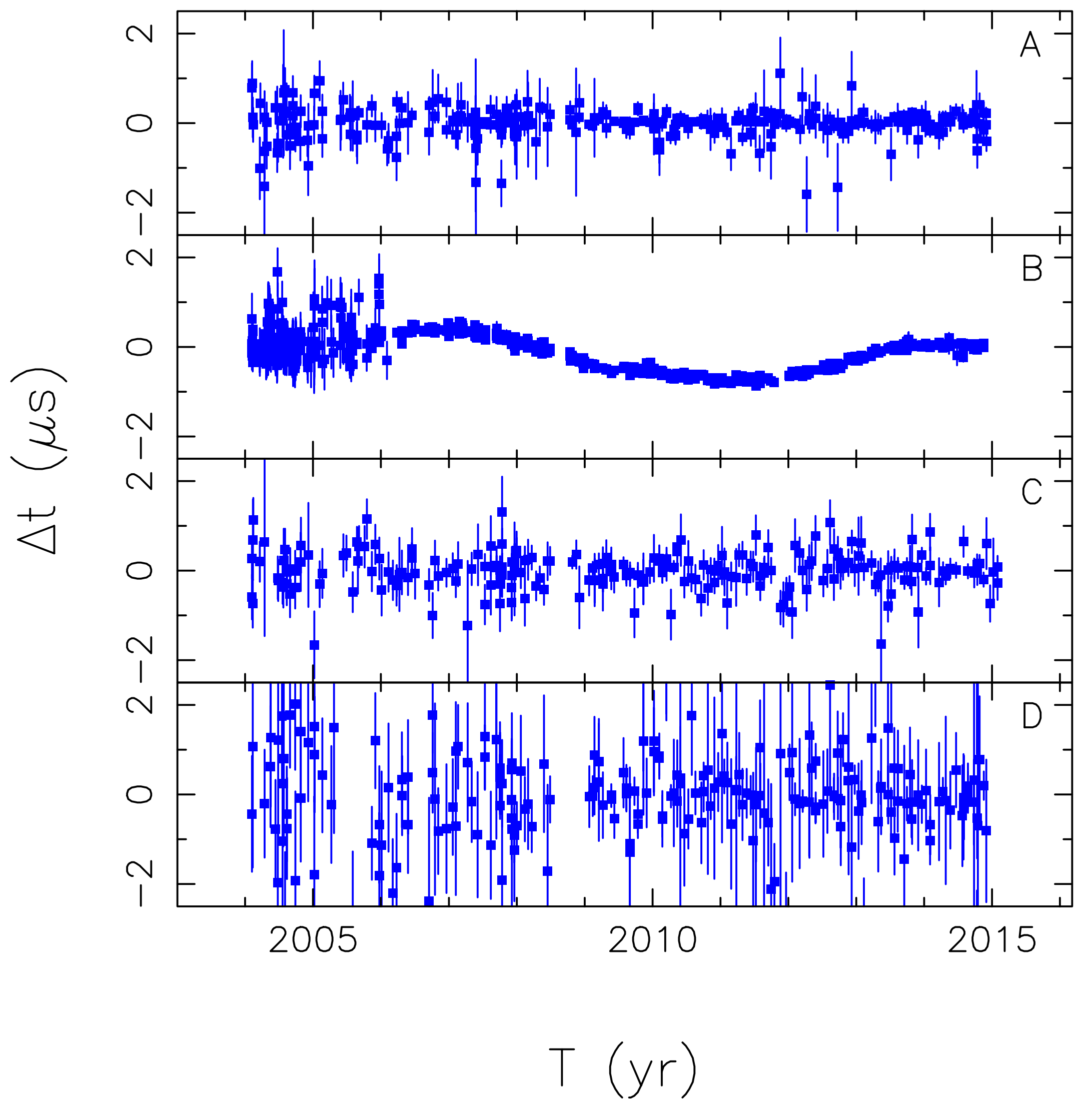

Fig. 1. **Residual pulse times of arrival, Δ*t*, for the four pulsars used in our analysis**. These are PSR J1909-3744 (panel *A*), PSR J0437-4715 (panel B), PSR J1713+0747 (panel *C*), and PSR J1744-1134 (panel *D*).

Shannon et al.

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- Lyman-alpha forest ✓

- direct detection ✓

- detection by pulsar timing array ✓

Additional slides follow.

Question: shouldn't the quantum and classical answers be identical?

Recall that for Coulomb differential cross section,

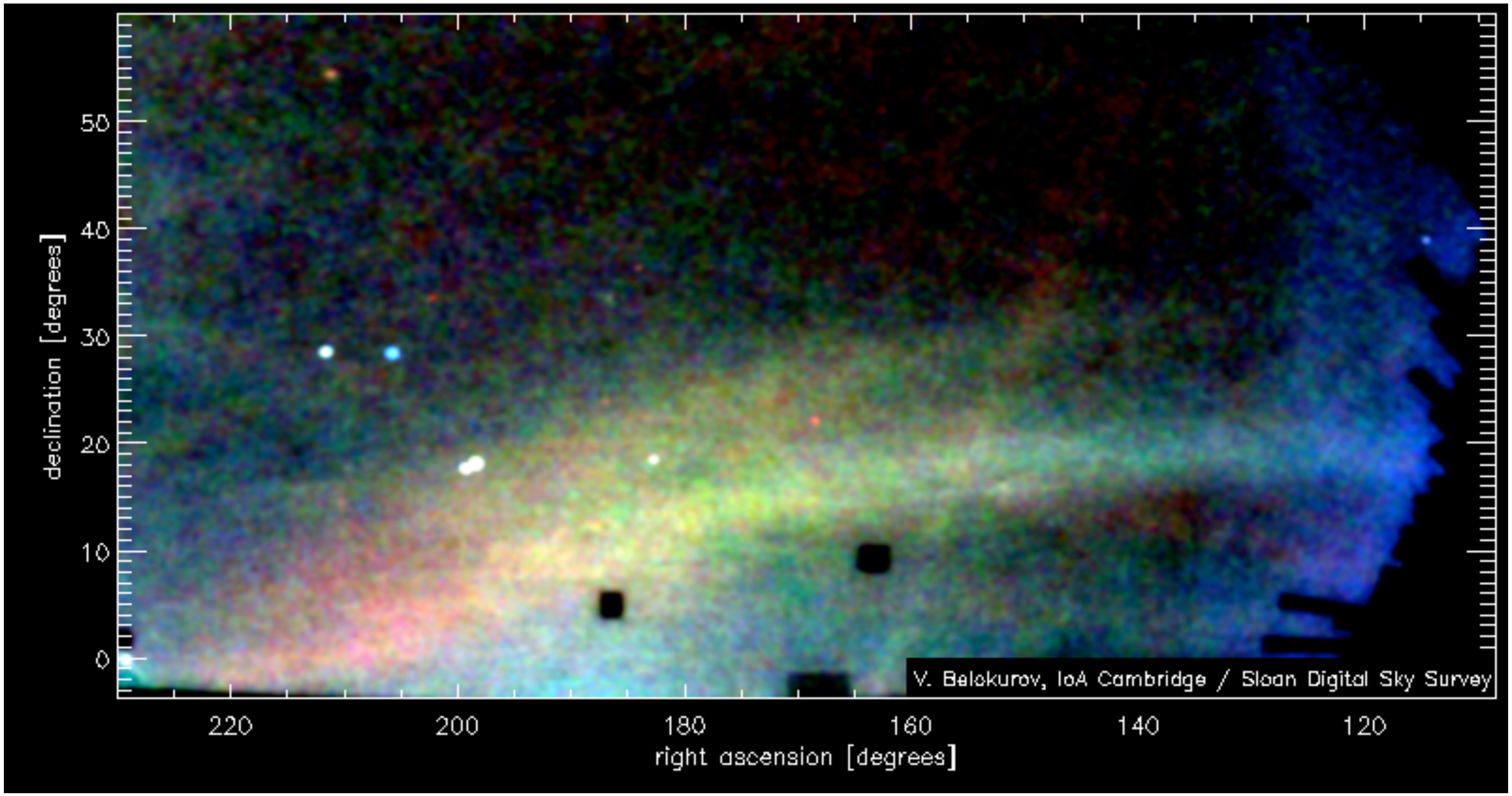
quantum = classical.

- But recall also the integrated cross section has a logarithmic divergence.

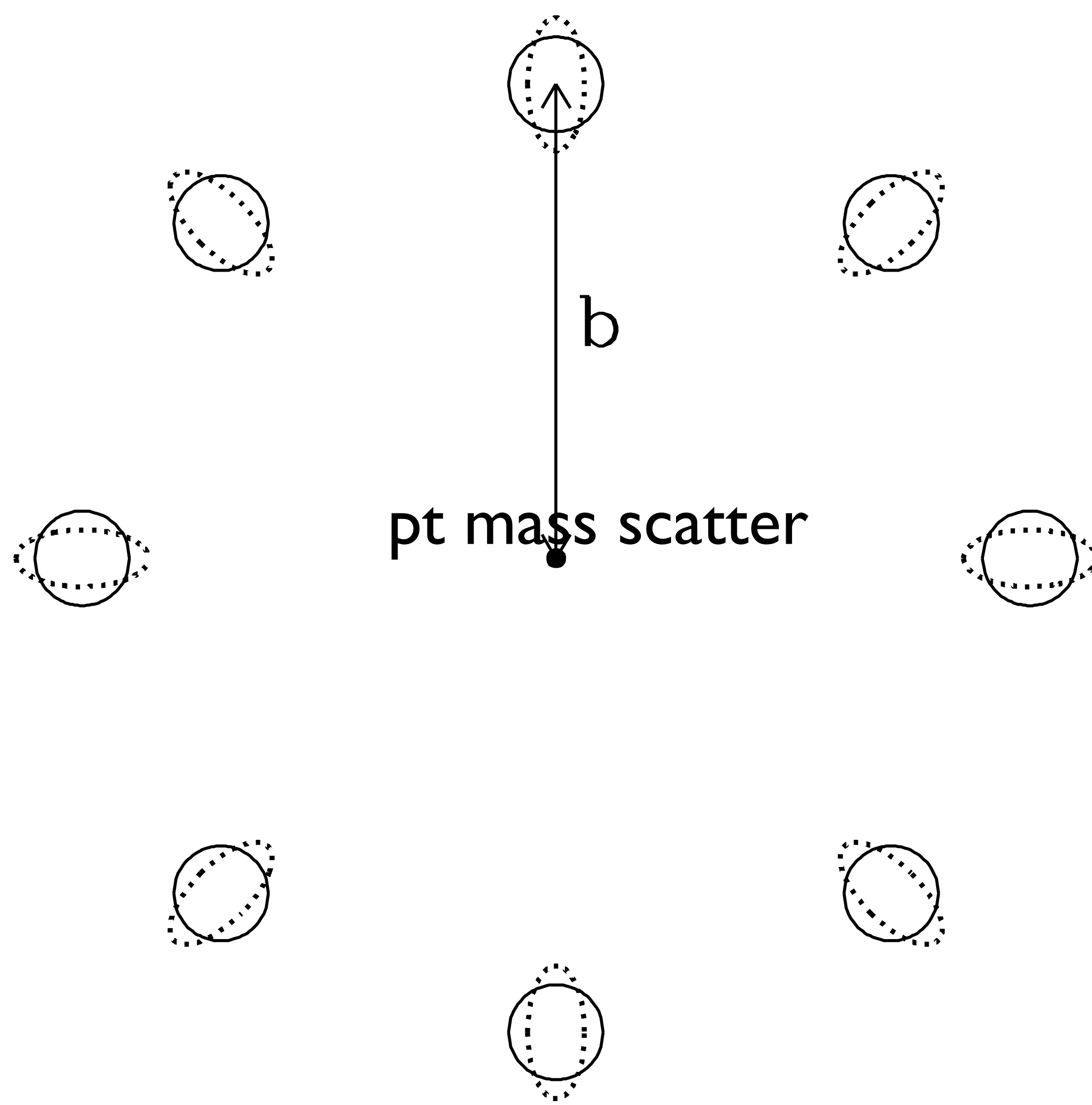
- Thus, we expect dynamical friction $\propto \ln[r/r_{\rm c}]$ where $r \sim$ size of galaxy,

  $r_c \sim GM/v^2$ or k^{-1}

- This is borne out by analytic calculation, made possible by obscure identities involving hypergeometric functions.



Belokurov, Zucker et al. SDSS II data


b
pt mass scatter

New Observables for Direct Detection of Axion Dark Matter

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We propose new signals for the direct detection of ultralight dark matter such as the axion. Axion or axion like particle (ALP) dark matter may be thought of as a background, classical field. We consider couplings for this field which give rise to observable effects including a nuclear electric dipole moment, and axial nucleon and electron moments. These moments oscillate rapidly with frequencies accessible in the laboratory, $\sim$ kHz to GHz, given by the dark matter mass. Thus, in contrast to WIMP detection, instead of searching for the hard scattering of a single dark matter particle, we are searching for the coherent effects of the entire classical dark matter field. We calculate current bounds on such time varying moments and consider a technique utilizing NMR methods to search for the induced spin precession. The parameter space probed by these techniques is well beyond current astrophysical limits and significantly extends laboratory probes. Spin precession is one way to search for these ultralight particles, but there may well be many new types of experiments that can search for dark matter using such time-varying moments.

Search for axion-like dark matter through nuclear spin precession in electric and magnetic fields

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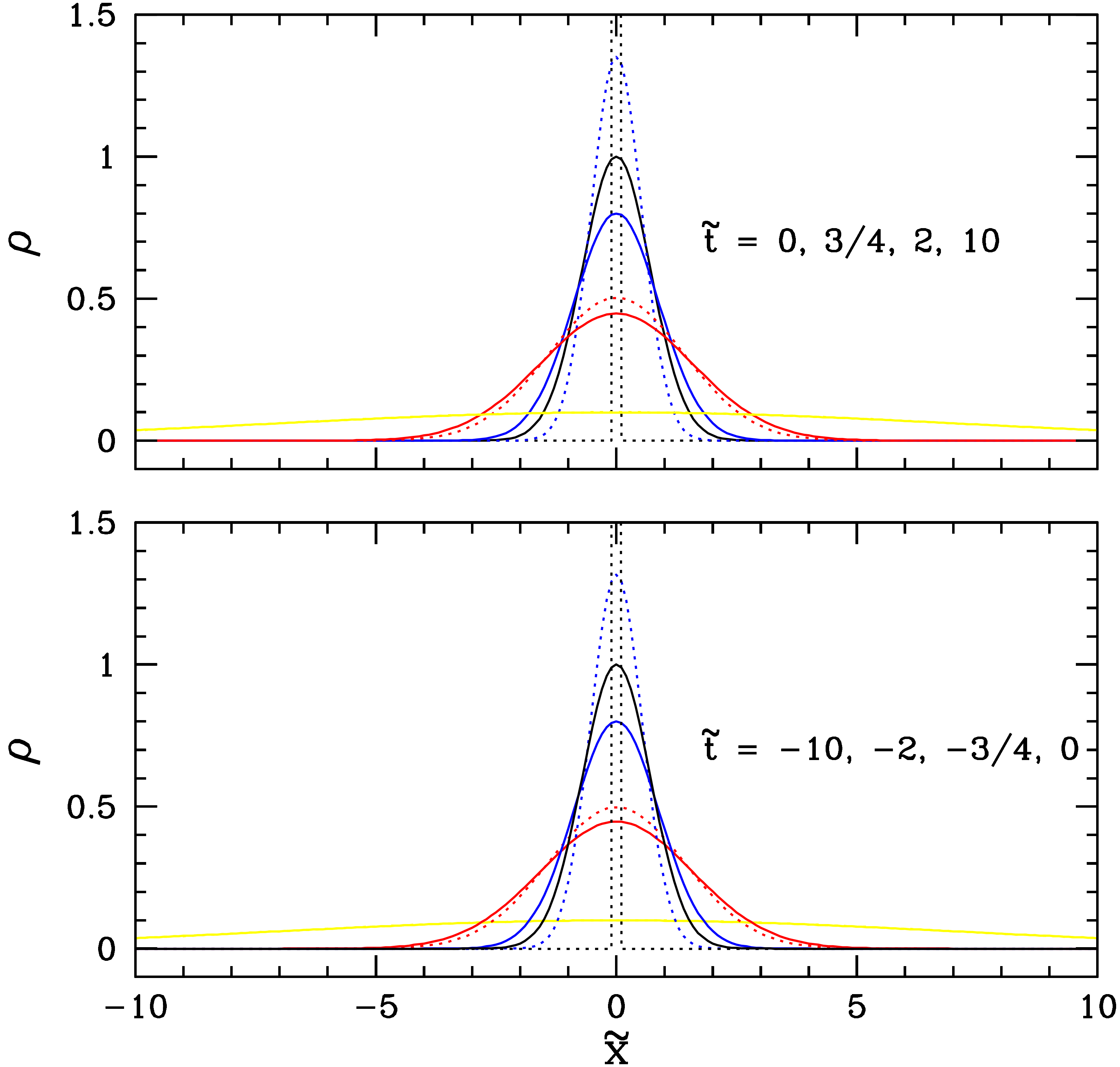
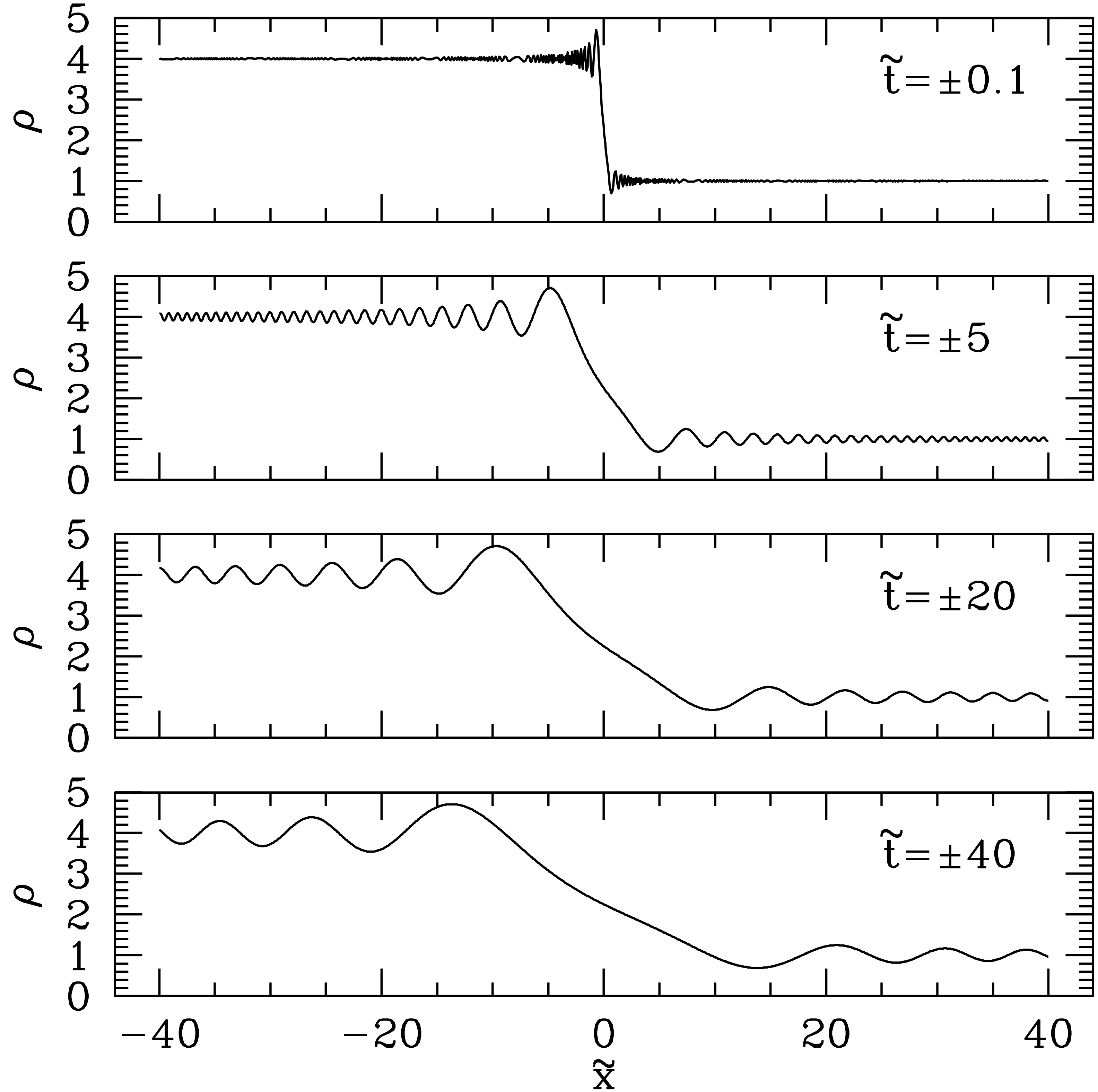
(Dated: August 23, 2017)

We report on a search for ultra-low-mass axion-like dark matter by analysing the ratio of the spin-precession frequencies of stored ultracold neutrons and ^{199}Hg atoms for an axion-induced oscillating electric dipole moment of the neutron and an axion-wind spin-precession effect. No signal consistent with dark matter is observed for the axion mass range 10^{-24} eV $\leq m_a \leq 10^{-17}$ eV. Our null result sets the first laboratory constraints on the coupling of axion dark matter to gluons, which improve on astrophysical limits by up to 3 orders of magnitude, and also improves on previous laboratory constraints on the axion coupling to nucleons by up to a factor of 40.



1.5
1
0.5
0
ρ
t̃ = 0, 3/4, 2, 10
t̃ = −10, −2, −3/4, 0
−10
−5
0
5
10
x̃



$\tilde{t} = \pm 0.1$
$\tilde{t} = \pm 5$
$\tilde{t} = \pm 20$
$\tilde{t} = \pm 40$
ρ
$\tilde{x}$
0
1
2
3
4
5
−40
−20
0
20
40