Detectability of Small-Scale Dark-Matter Clumps using Pulsar Timing Arrays 1801.07847

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## I. Intro

## Don't know what, but they do exist





## Hierarchical structure formation



#### Imprint of inflation, the nature of DM, evolution history of the Galaxy, ...





Single Stream Regions (512<sup>3</sup> bins)







## 2. DM clumps in the Galaxy

## Dark matter clump formation

- → I) by the growth of adiabatic or iso-thermal fluctuations (originating at inflation) during matter dominated epoch
  - 2) from the density fluctuations in models with e.g., topological defects (cosmic strings, domain walls)
  - during radiation dominated epoch from non-linear iso-thermal fluctuations (originating in phase transitions in the early universe)

the most conservative case



## Dark matter clump formation

by the growth of adiabatic or iso-thermal fluctuations (originating at inflation) during matter dominated epoch

$$\bar{\rho}_{i} = \kappa \rho_{eq} \left[ \frac{\nu \sigma_{eq}(M)}{\delta_{c}} \right]^{3} \sim 1.4 \times 10^{-23} \text{ g cm}^{-3} \left( \frac{\nu}{2} \right)^{3} \left( \frac{M}{M_{\oplus}} \right)^{-3\alpha}$$
$$\bar{R} = \left( \frac{3M}{4\pi \bar{\rho}_{i}} \right)^{1/3} \sim 2900 \text{ AU } \left( \frac{\nu}{2} \right)^{-1} \left( \frac{M}{M_{\oplus}} \right)^{\alpha+1/3}$$
where  $\alpha = 0.0204$ .

simply extrapolating the Planck 15 power spectrum

e.g., an iso-thermal earth-mass scale clump passing nearby the solar system

$$E_{\rm b} \sim \frac{1}{2} \frac{GM^2}{R}, \quad \Delta E \sim \frac{1}{6} M \frac{4b^2}{V^2} \left(\frac{GM_*}{b^2} \frac{R}{b}\right)^2$$

 $E_{\rm b} \sim \Delta E \iff$ 

$$b_{\rm crit} \sim 4000 \ {\rm AU} \left(\frac{\nu}{2}\right)^{-3/4} \left(\frac{M}{M_{\oplus}}\right)^{3\alpha/4} \left(\frac{V}{300 \ {\rm km/s}}\right)^{-1/2} \left(\frac{M_*}{M_{\odot}}\right)^{1/2}$$



From "Tides in colliding galaxies" by Pierre-Alain Duc and Florent Renaud

Image Credit: Jon Lomberg

(1) at the formation of hierarchical structures (Berezinsky et al. 03)

 $\checkmark$  The survival probability of clumps with M (integrated over v)



compatible with numerical studies (see also, e.g., Springel et al 08, Ishiyama 14, Stucker et al. 17)



(2) with the Galactic disk and halo stars

e.g., an iso-thermal earth-mass scale clump passing the Galactic disk

$$E_{\rm b} \sim \frac{1}{2} \frac{GM^2}{R}, \quad \Delta E \sim \frac{1}{6} M \frac{4R^2}{V^2} [2\pi G\sigma_{\rm d}(r)]^2$$

where  $\sigma_{\rm d}(r) = \frac{m_{\rm d}}{2\pi r_{\rm d}^2} e^{-r/r_{\rm d}}$  with  $m_{\rm d} = 6 \times 10^{10} M_{\odot}$  and  $r_{\rm d} = 2.6$  kpc

(2) with the Galactic disk and halo stars

e.g., an iso-thermal earth-mass scale clump passing the Galactic disk

$$\frac{E_{\rm b}}{\Delta E}\Big|_{r_{\odot}} \sim 90 \left(\frac{\nu}{2}\right)^3 \left(\frac{M}{M_{\oplus}}\right)^{-3\alpha} \left(\frac{V}{250 \text{ km/s}}\right)^2 \left(\frac{\sigma_{\rm d}}{53 M_{\odot} \text{ pc}^{-2}}\right)^{-2}$$

$$\frac{\text{VS}}{\frac{2T_{\rm Gal}}{T_{\rm circ}}}\Big|_{r_{\odot}} \sim 100 \left(\frac{T_{\rm Gal}}{10 \text{ Gyr}}\right) \left(\frac{V}{250 \text{ km/s}}\right)$$

 $\rightarrow$  Clumps with a circular motion at the solar system radii are destructed within the Galaxy age. But a non-negligible fraction of clumps have eccentric orbits and cross the disk less than ~100 times!

### (2) with the Galactic disk and halo stars

How many times a clump crosses the Galactic disk depends on

i) energy E

ii) angular momentum L

of the clump.

The distribution of (E, L) and thus of orbits and survival probabilities at the Galactic age can be calculated for a given MW DM halo profile (e.g., NFW profile).



Dark-Matter-Clump Mass  $[M_{\odot}]$ 

## 3. Sensitivity of a PTA

#### credit: David J. Champion

https://vimeo.com/123422738

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### Parkes

20 PSRs with timing precision ~100 ns



### SKA >100 PSRs with timing precision ~10 ns?



## Our proposal



Kashiyama & Oguri 18

## Signal

In the Fourier space, the main contribution of the impulse acceleration is the mode with the frequency f = 1/T, where

$$T \approx \frac{b}{V} \sim 10 \text{ yr} \left(\frac{b}{740 \text{ AU}}\right) \left(\frac{V}{350 \text{ km/s}}\right)^{-1},$$

and the signal amplitude is

$$s_f \approx \frac{GM}{b^2} \times T^2 \times \frac{1}{c} \times |\cos\theta|$$
  
~ 10 ns  $\left(\frac{M}{10^{25} \text{ g}}\right) \left(\frac{V}{350 \text{ km/s}}\right)^{-2} \left(\frac{|\cos\theta|}{0.58}\right).$ 

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#### ✓ Pulsar term

Using the sampling rate v of timing of arrivals (TOAs) and the rms noise  $\sigma$  each TOA, the Fourier mode of the timing noise at the frequency f = 1/T is

$$n_f \approx \frac{\sigma}{\sqrt{T\nu}}$$
  
~ 6.2 ns  $\left(\frac{\sigma}{100 \text{ ns}}\right) \left(\frac{T}{10 \text{ yr}}\right)^{-1/2} \left(\frac{\nu}{0.5 \text{ wk}^{-1}}\right)^{-1/2}$ 

#### ✓ Earth term

The noise can be reduced by a factor of  $(N_{PSR})^{1/2}$ .

## Event rate

### ✓ Earth term

For a given DM density,  $ho_{
m h}(r)=rac{ar
ho_{
m h}}{(r/L)(1+r/L)^2}$  and a survival probability,  $\xi(M,r)$ 

the event rate of close encounter of a DM clump with the earth is

$$\mathcal{R} \approx \pi b^2 V \left. \frac{\xi(M, r) \rho_{\rm h}(r)}{M} \right|_{r_{\odot}}$$
  
~ 0.032 yr<sup>-1</sup>  $\left( \frac{\xi}{1} \right) \left( \frac{\rho_{\rm h}}{0.011 \ M_{\odot} \ {\rm pc}^{-3}} \right) \left( \frac{M}{10^{25} \ {\rm g}} \right)^{-1} \left( \frac{b}{740 \ {\rm AU}} \right)^2 \left( \frac{V}{350 \ {\rm km/s}} \right)$ 

### ✓ Pulsar term

The event rate is much larger by a factor of  $N_{PSR}$ (but also depends on  $\xi(r)$ ,  $\rho_h(r)$ , V at each pulsar's position).

## Conditions for detections

I. S/N is larger than a threshold value, e.g.,

$$s_f/n_f > 3$$

- 2. At least one event occurs during the observation time;  $\mathcal{R}T_{\rm obs}>1$
- 3. The duration of signal is shorter than the observation time;

$$T < T_{\rm obs}$$

## Conditions for detections

I. S/N is larger than a threshold value, e.g.,

$$\left(\frac{M}{10^{25} \text{ g}}\right) \left(\frac{b}{740 \text{ AU}}\right)^{-2} \lesssim 0.32 \left(\frac{\xi}{1}\right) \left(\frac{\rho_{\text{h}}}{0.011 \ M_{\odot} \text{ pc}^{-3}}\right) \left(\frac{V}{350 \text{ km/s}}\right) \left(\frac{T_{\text{obs}}}{10 \text{ yr}}\right) N_{\text{PSR}}^{1-E}$$

2. At least one event occurs during the observation time;

$$\left(\frac{M}{10^{25} \text{ g}}\right) \left(\frac{b}{740 \text{ AU}}\right)^{1/2} \gtrsim 0.56 \left(\frac{\sigma}{100 \text{ ns}}\right) \left(\frac{\nu}{0.5 \text{ week}^{-1}}\right)^{-1/2} \left(\frac{V}{350 \text{ km/s}}\right)^{5/2} \left(\frac{\text{S/N}}{3}\right) N_{\text{PSR}}^{-E/2}$$

3. The duration of signal is shorter than the observation time;

$$b \lesssim b_{\text{max}} = 740 \text{ AU} \left(\frac{T_{\text{obs}}}{10 \text{ yr}}\right) \left(\frac{V}{350 \text{ km/s}}\right)$$

E = 0 for Earth term and 1 for pulsar term



Dark-Matter-Clump Mass  $[M_{\odot}]$ 

## 3. Discussion



Dark-Matter-Clump Mass  $[M_{\odot}]$ 

