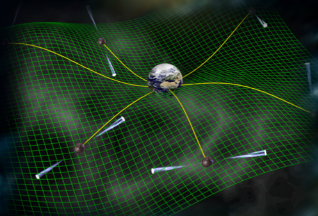
Detectability of Small-Scale Dark-Matter Clumps using Pulsar Timing Arrays

1801.07847

Kazumi Kashiyama

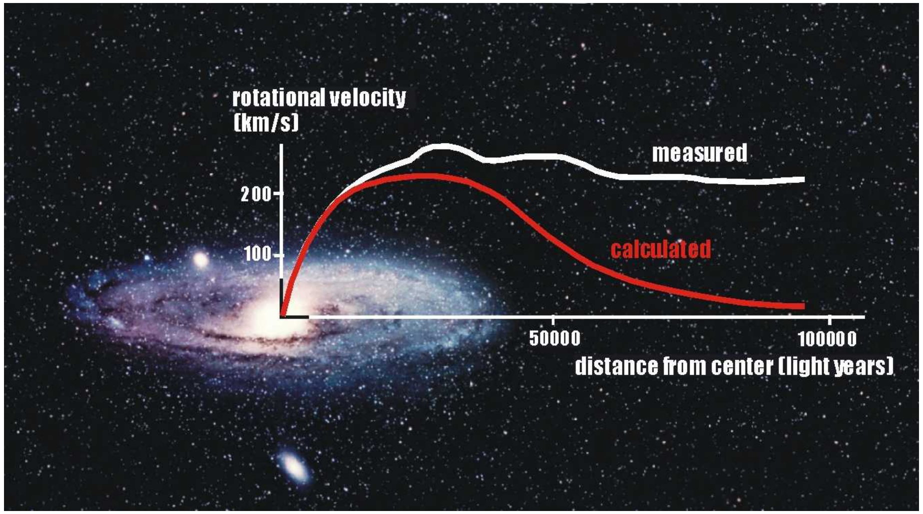
U. of Tokyo, RESCEU

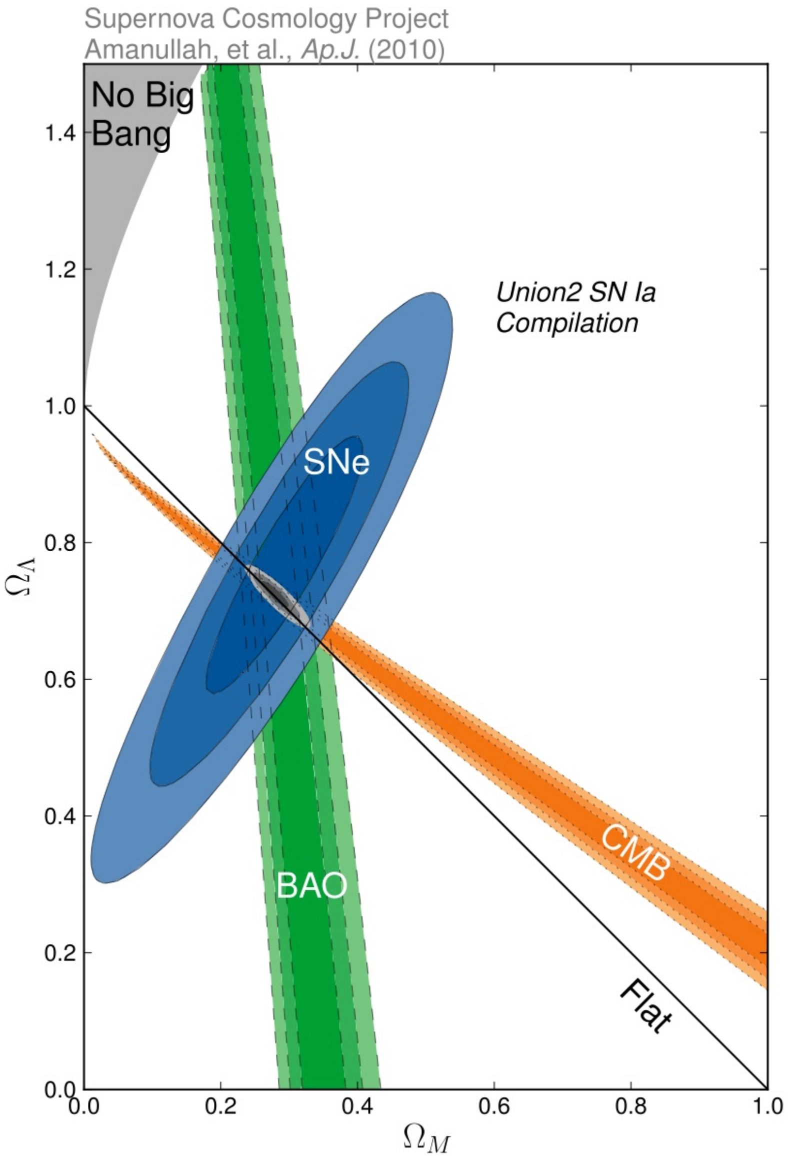


Contents

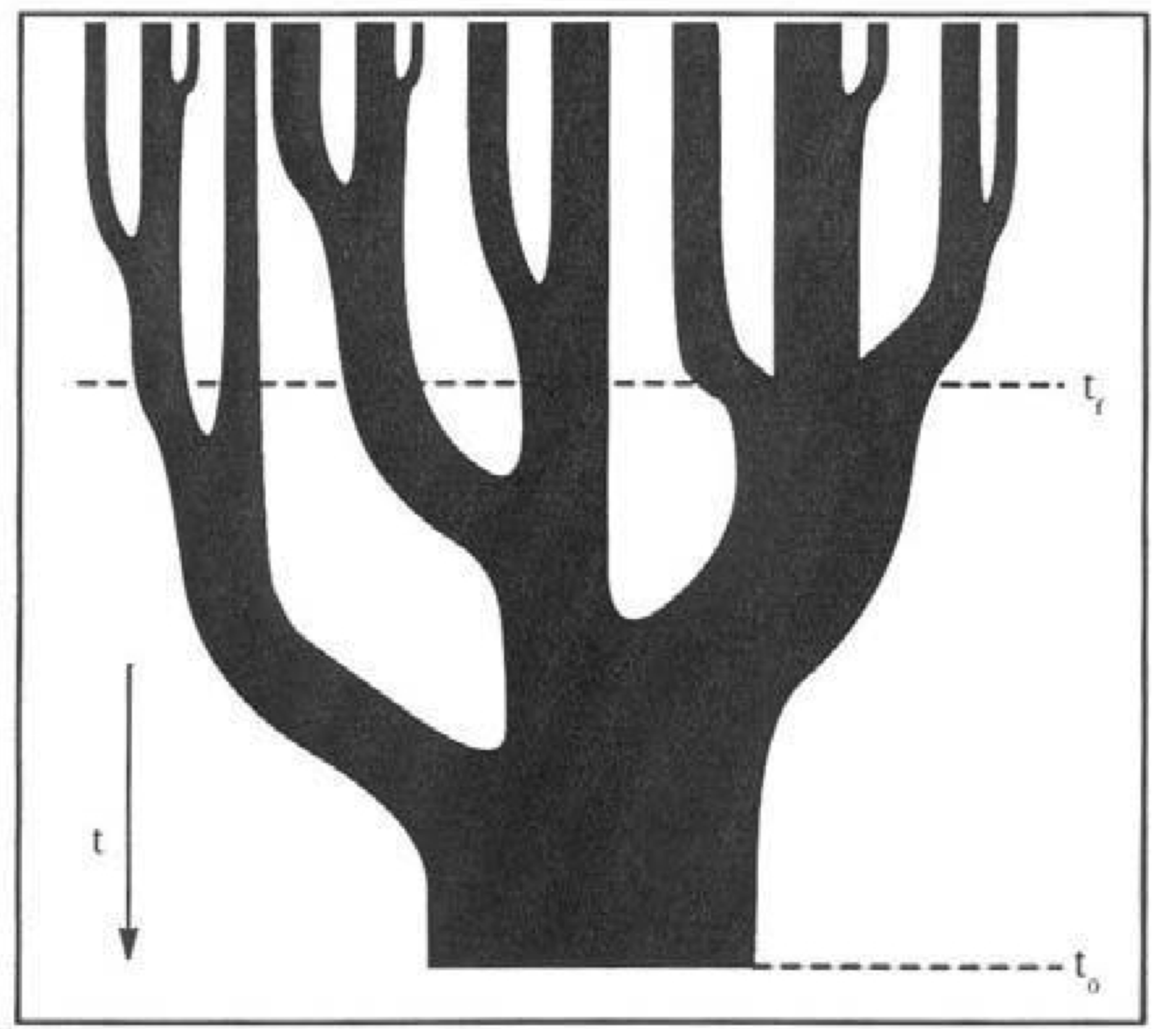
1. Intro

Don’t know what, but they do exist

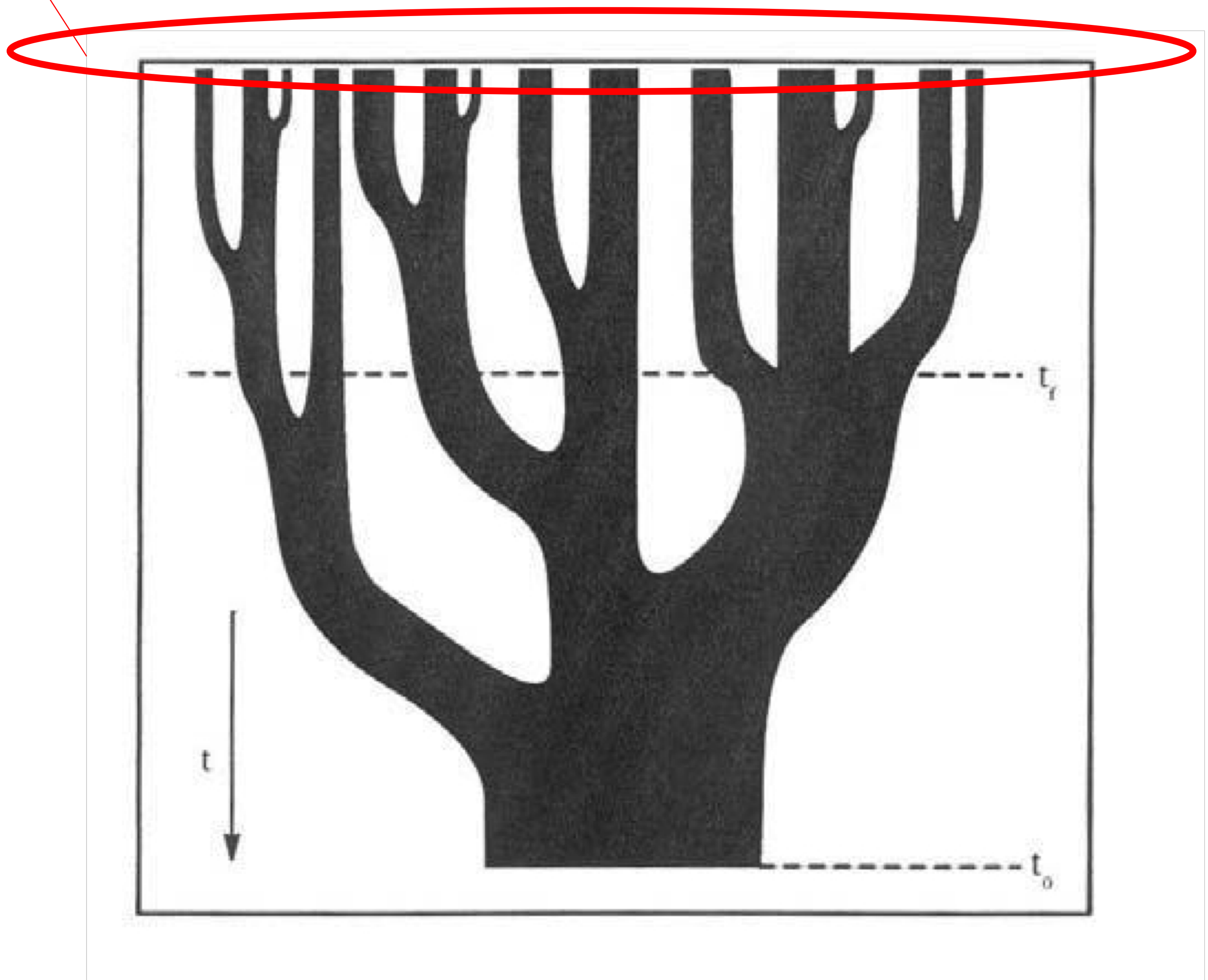


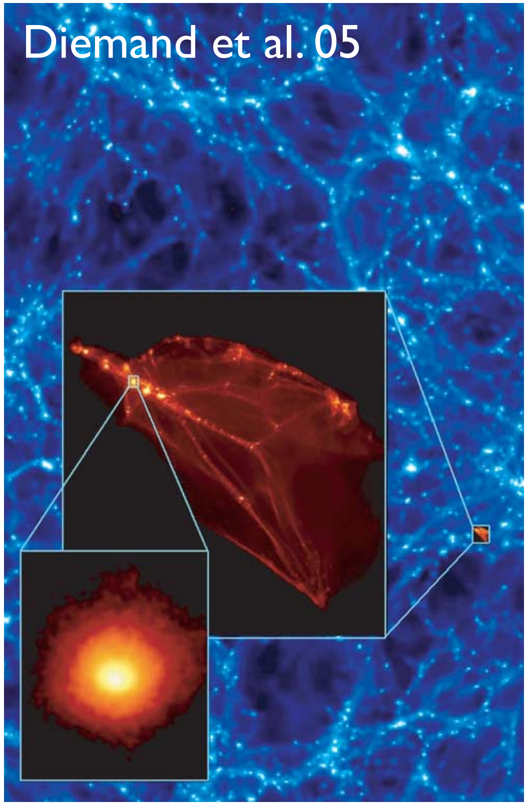


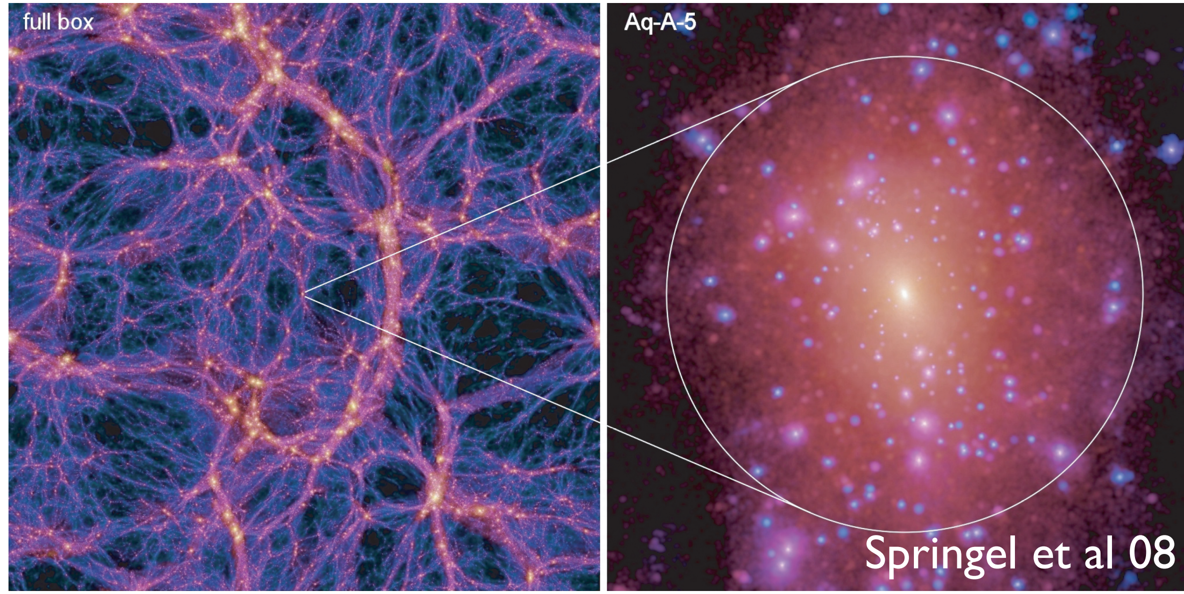
Hierarchical structure formation

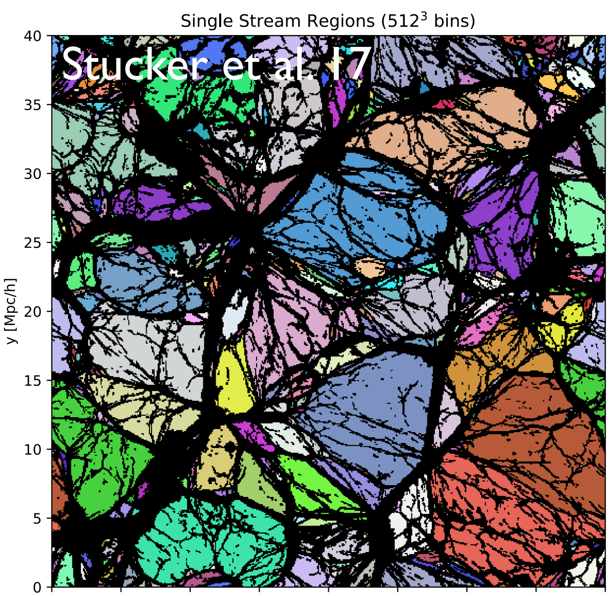


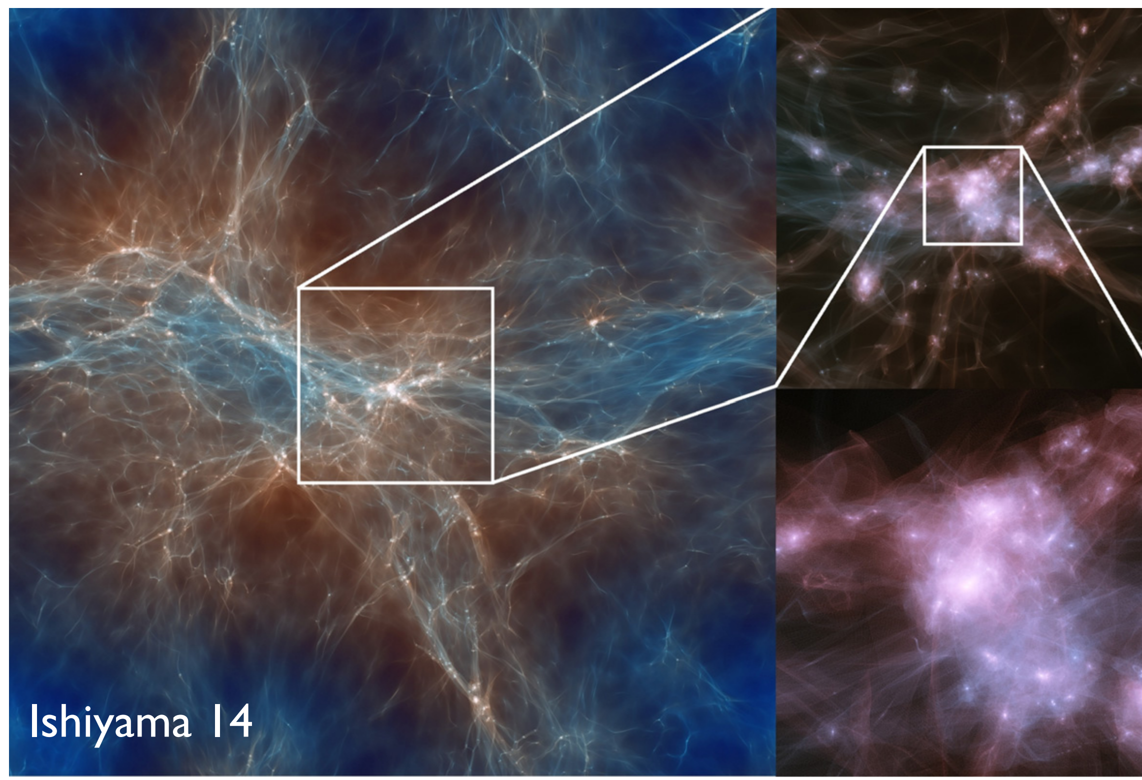
Imprint of inflation, the nature of DM, evolution history of the Galaxy, …




Diemand et al. 05


full box
Aq-A-5
Springel et al 08


Single Stream Regions (512^3 bins)
Stucker et al. 17
y [Mpc/h]
40
35
30
25
20
15
10
5
0


Ishiyama 14

2. DM clumps in the Galaxy

Dark matter clump formation

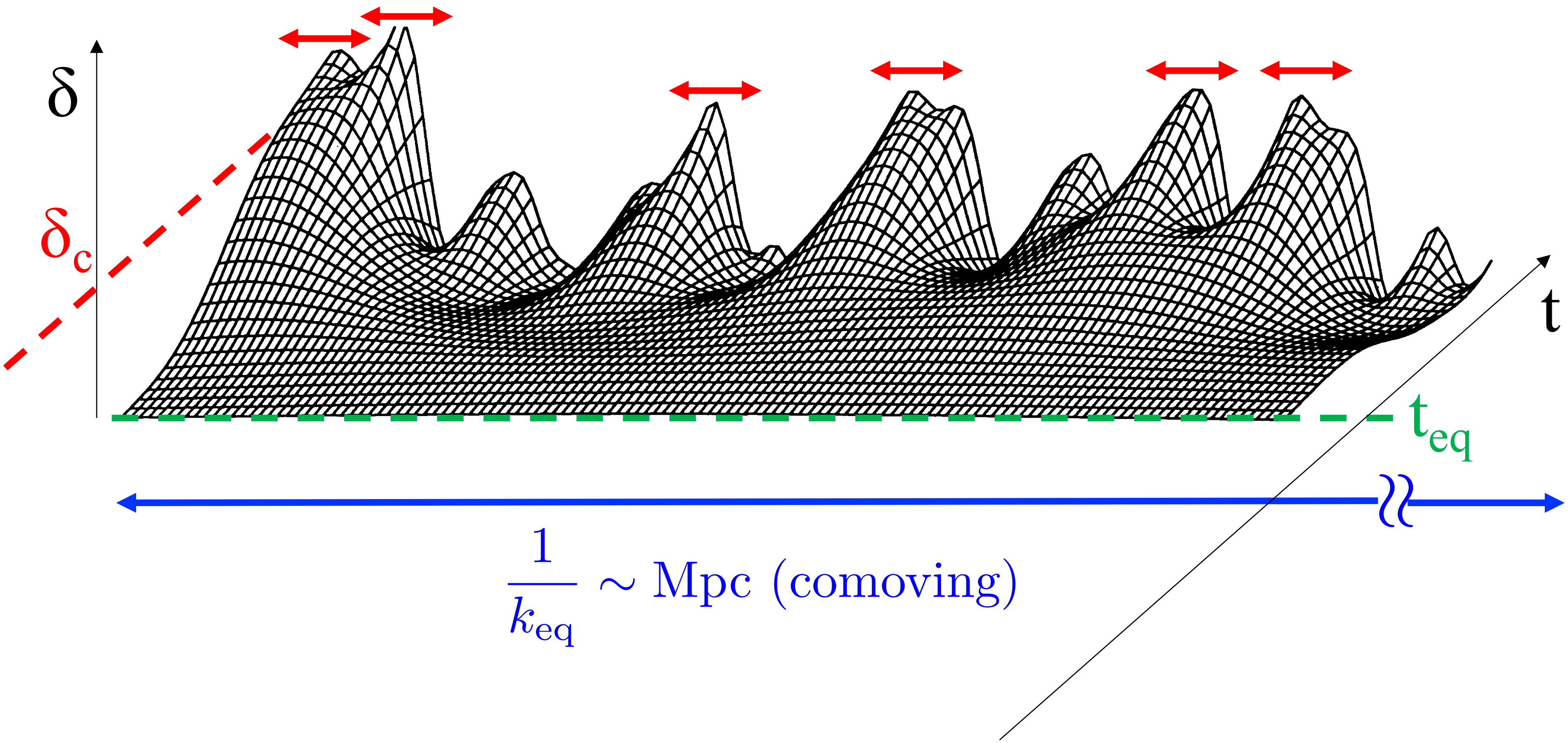
1) by the growth of adiabatic or iso-thermal fluctuations (originating at inflation) during matter dominated epoch
2) from the density fluctuations in models with e.g., topological defects (cosmic strings, domain walls)
3) during radiation dominated epoch from non-linear iso-thermal fluctuations (originating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

the most conservative case

DM clumps with the smallest scale ~ the free-streaming scale

e.g., 100 GeV WIMP → $\frac{1}{k} \sim 1000\ \mathrm{AU},\ \mathrm{M} \sim 10^{-6}\ \mathrm{M}_\odot$

10 μeV axion → $\frac{1}{k} \sim 10\ \mathrm{AU},\ \mathrm{M} \sim 10^{-12}\ \mathrm{M}_\odot$



Dark matter clump formation

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

$$\bar{\rho}_i = \kappa \rho_{\rm eq} \left[\frac{\nu \sigma_{\rm eq}(M)}{\delta_{\rm c}} \right]^3 \sim 1.4 \times 10^{-23} \ {\rm g\ cm^{-3}} \ \left(\frac{\nu}{2} \right)^3 \left(\frac{M}{M_\oplus} \right)^{-3\alpha}$$

$$\bar{R} = \left(\frac{3M}{4\pi \bar{\rho}_i} \right)^{1/3} \sim 2900 \ {\rm AU} \ \left(\frac{\nu}{2} \right)^{-1} \left(\frac{M}{M_\oplus} \right)^{\alpha + 1/3}$$

where $\alpha = 0.0204.$

simply extrapolating the Planck 15 power spectrum

Dark matter clump destruction by the tidal interaction

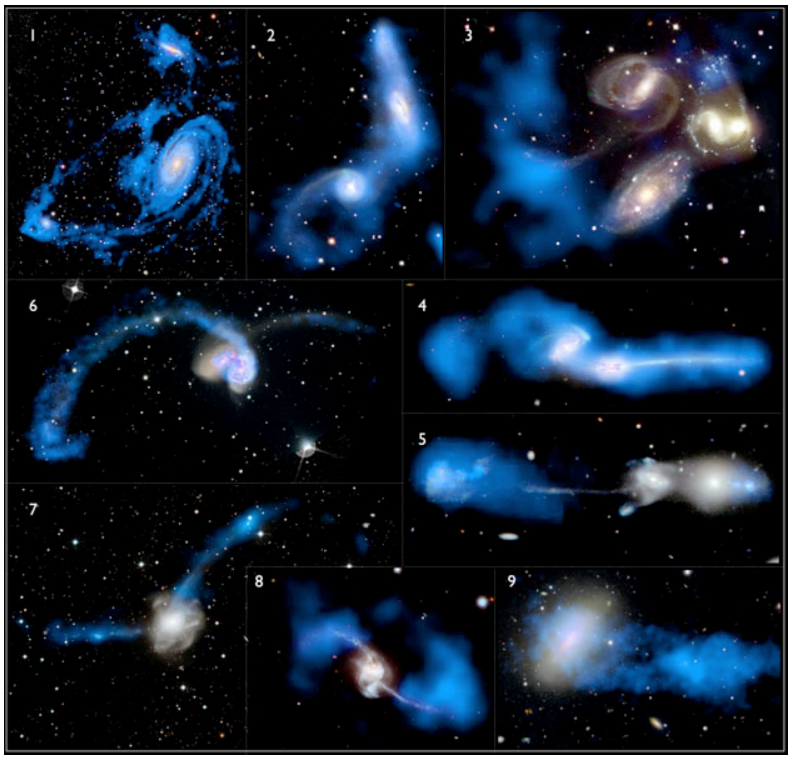
e.g., an iso-thermal earth-mass scale clump passing nearby the solar system

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

$$E_{\rm b} \sim \Delta E \quad \Leftrightarrow$$

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

Dark matter clump destruction by the tidal interaction



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

Image Credit: Jon Lomberg

Dark matter clump destruction by the tidal interaction

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

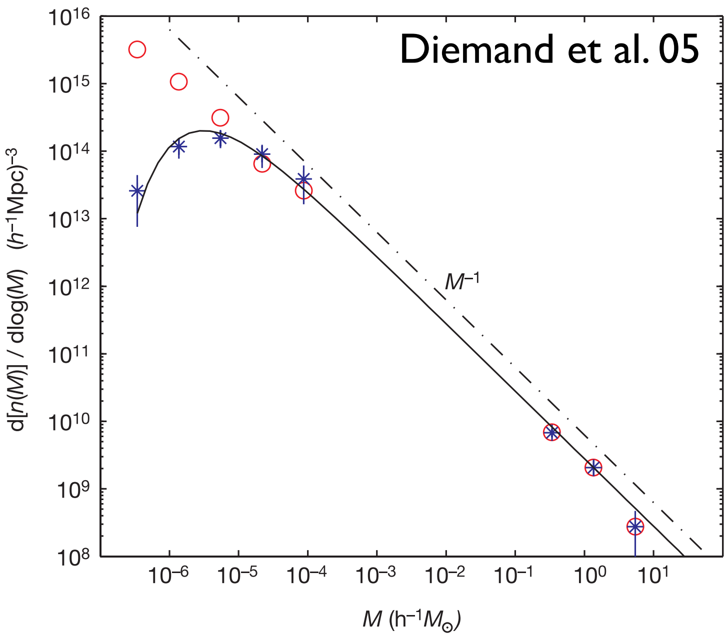
✓ The survival probability of clumps with M (integrated over ν)

$$\xi_\mathrm{i}\frac{dM}{M} \simeq 0.02(n+3)\frac{dM}{M}$$

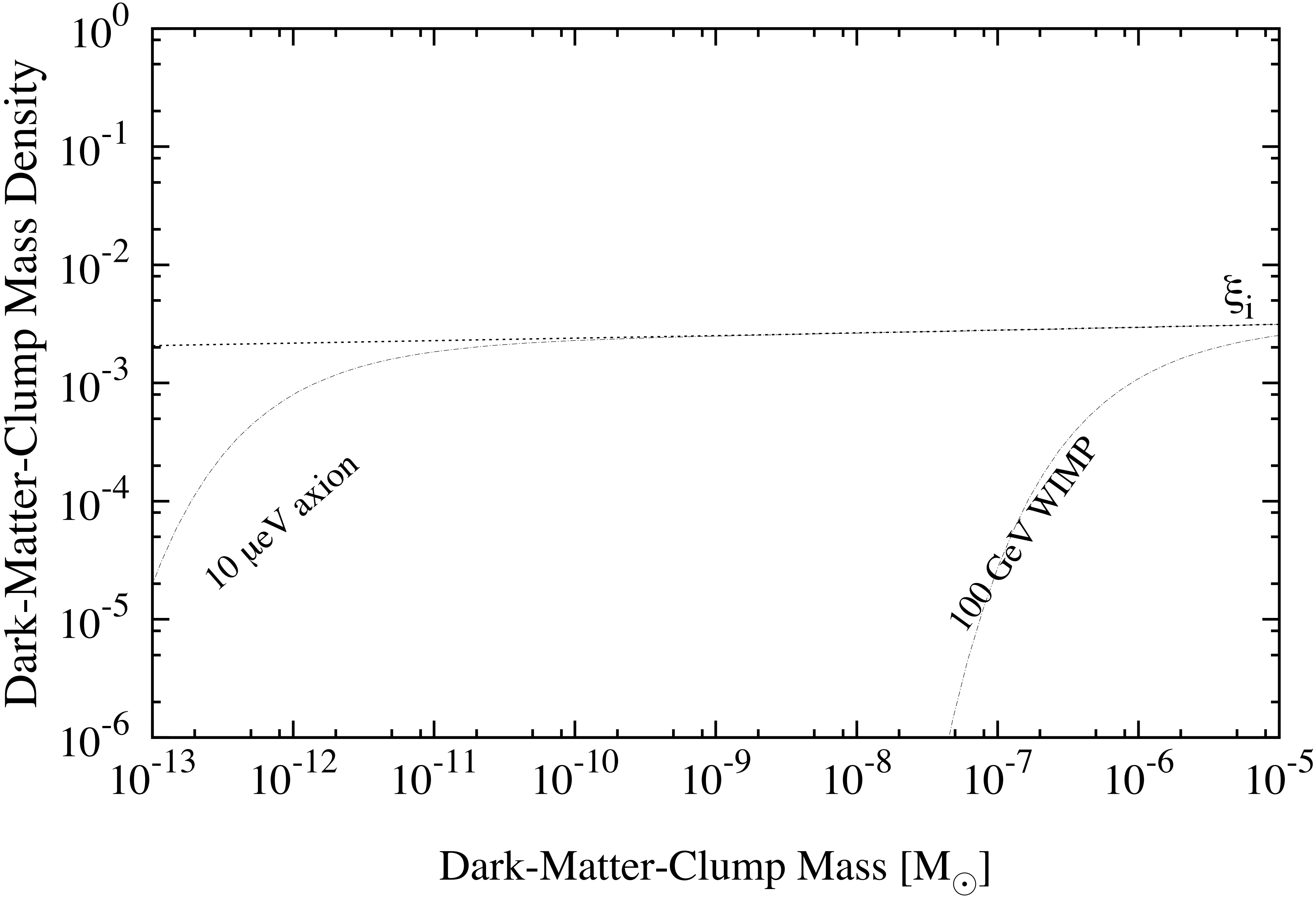
where

$$n = -3\left[1 + 2\frac{\partial \log \sigma_\mathrm{eq}(M)}{\partial \log M}\right].$$

The survived clumps are typically from $\nu \sim 2$.



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



Dark-Matter-Clump Mass Density
10^0
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-13
10^-12
10^-11
10^-10
10^-9
10^-8
10^-7
10^-6
10^-5
ξi
10 μeV axion
100 GeV WIMP
Dark-Matter-Clump Mass [M⊙]

Dark matter clump destruction by the tidal interaction

(2) with the Galactic disk and halo stars

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

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

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

Dark matter clump destruction by the tidal interaction

(2) with the Galactic disk and halo stars

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

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

VS

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

→ 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!

Dark matter clump destruction by the tidal interaction

(2) with the Galactic disk and halo stars

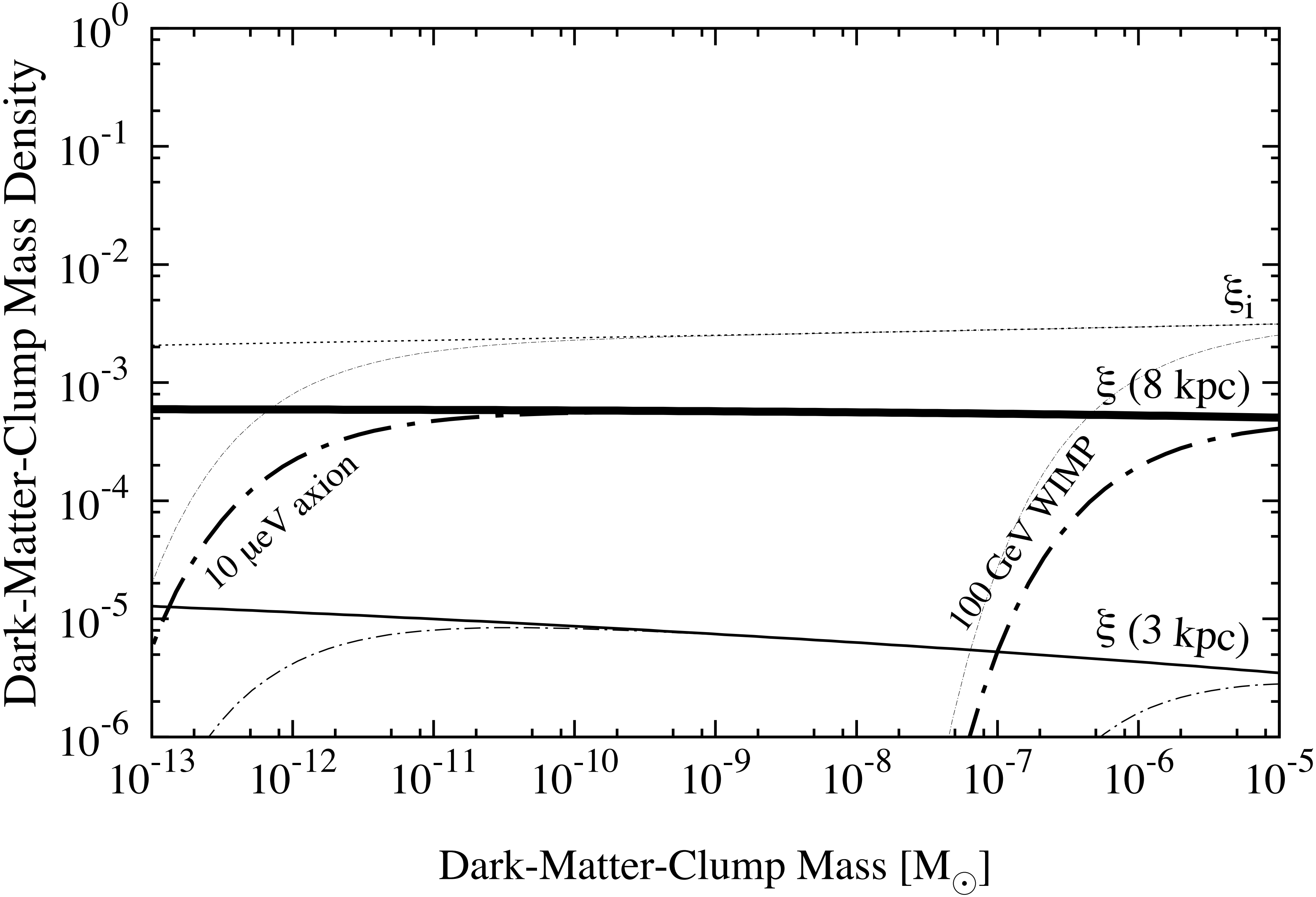
How many times a clump crosses the Galactic disk depends on

i) energy E

ii) angular momentum L

of the clump.

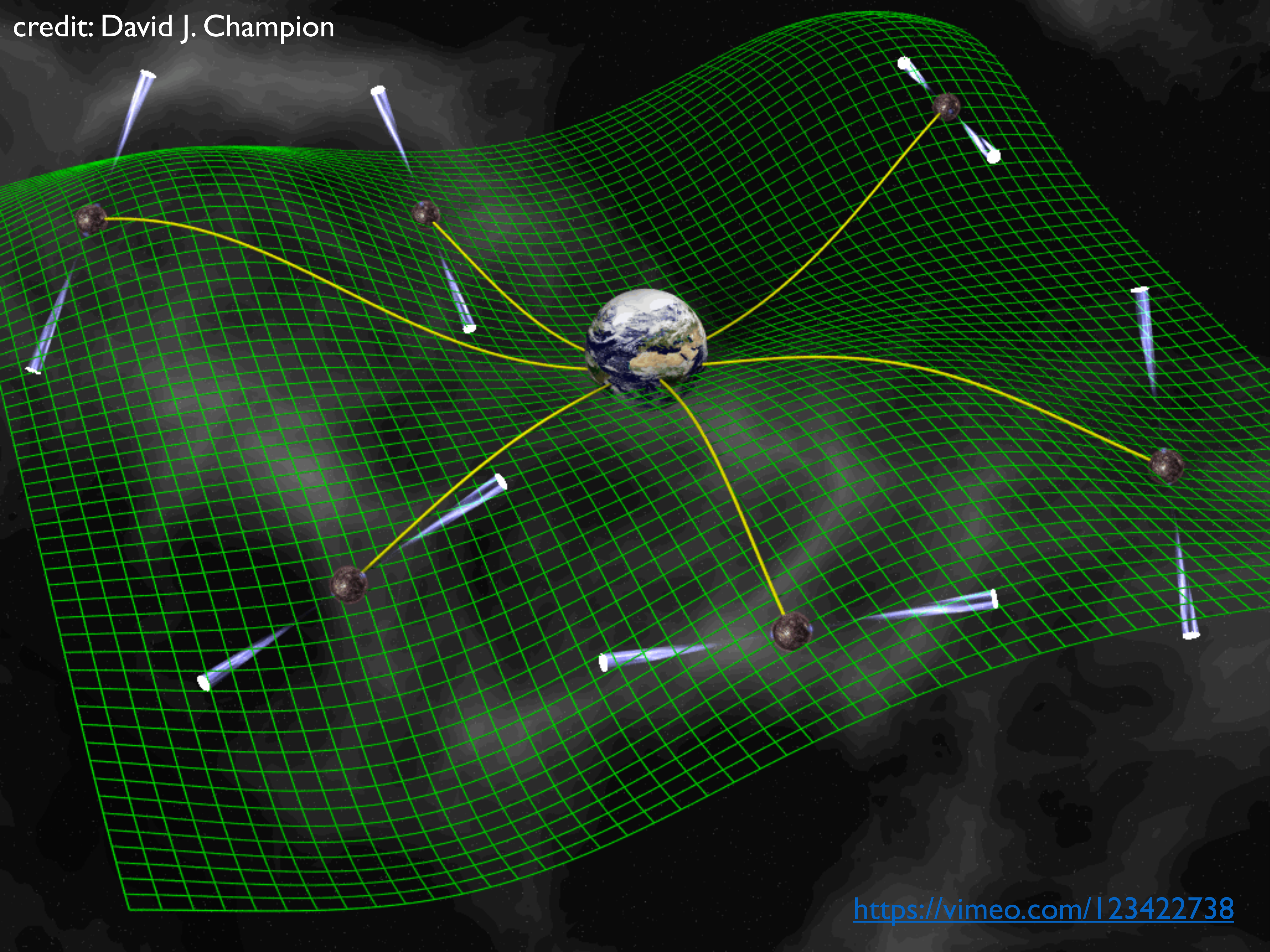
The distribution of (E, L) and thus of orbits and survival probabilities at the Galactic age can be calculated for a given MW DM halo profile (e.g., NFW profile).



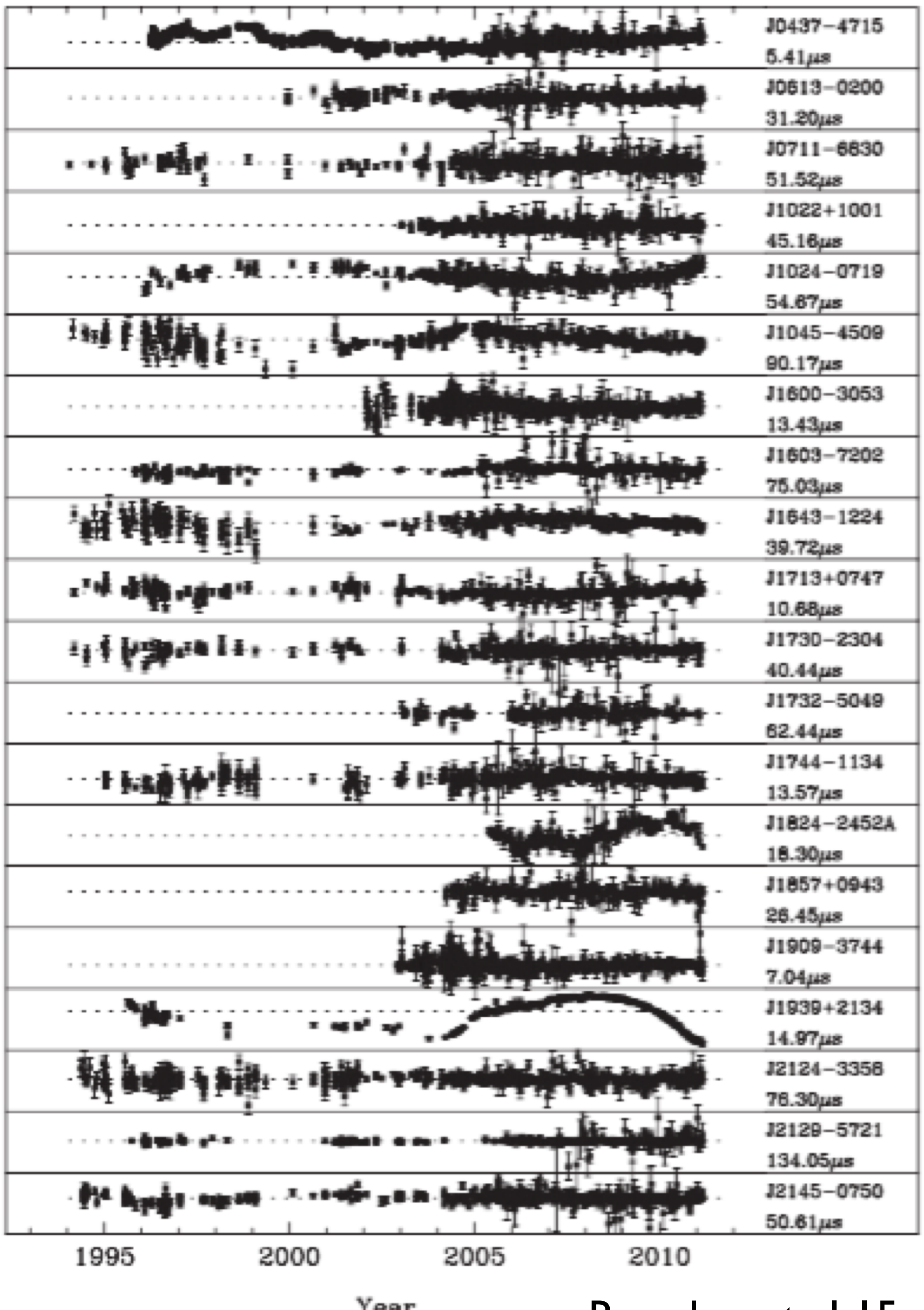
Dark-Matter-Clump Mass Density
Dark-Matter-Clump Mass [M$_\odot$]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
ξ_i
ξ (8 kpc)
ξ (3 kpc)
10 μeV axion
100 GeV WIMP

3. Sensitivity of a PTA

credit: David J. Champion



https://vimeo.com/123422738



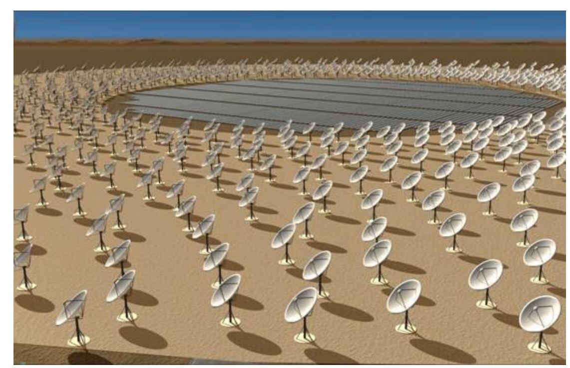
Reardon et al 15

Parkes

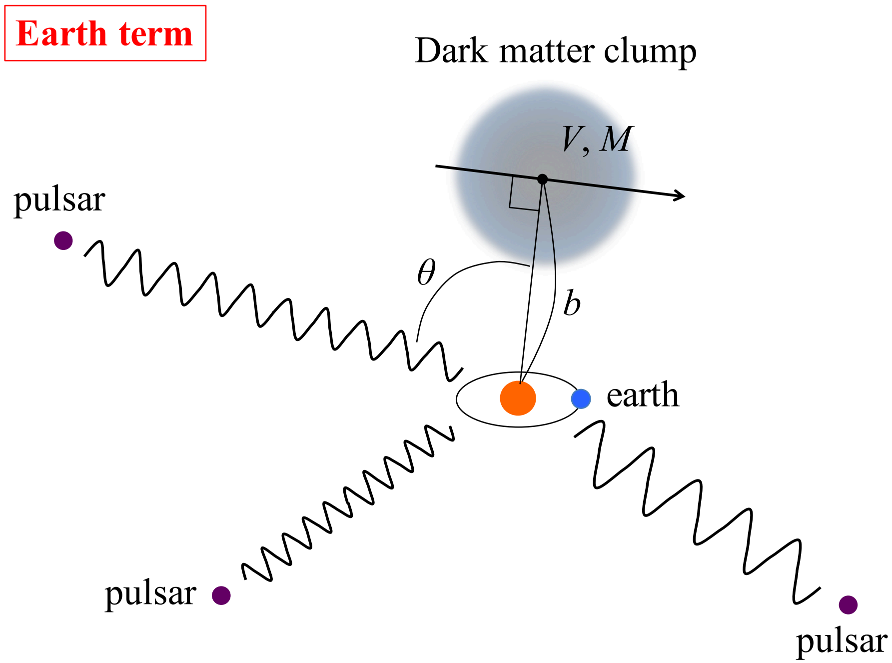
20 PSRs with timing precision ~100 ns

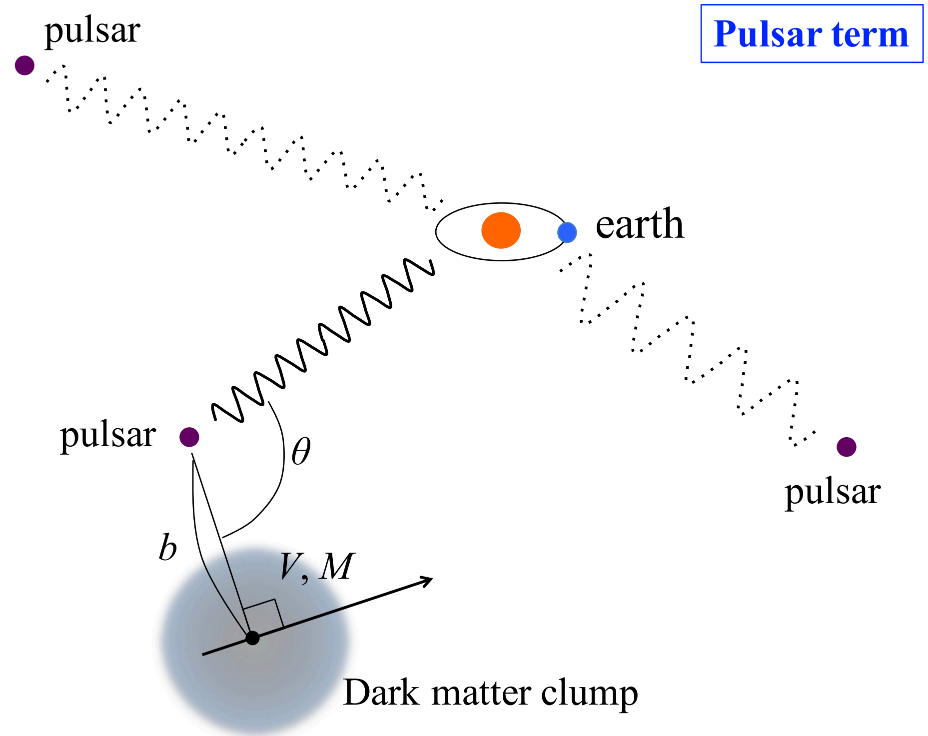
SKA

>100 PSRs with timing precision ~10 ns?



Our proposal





Kashiyama & Oguri 18

Signal

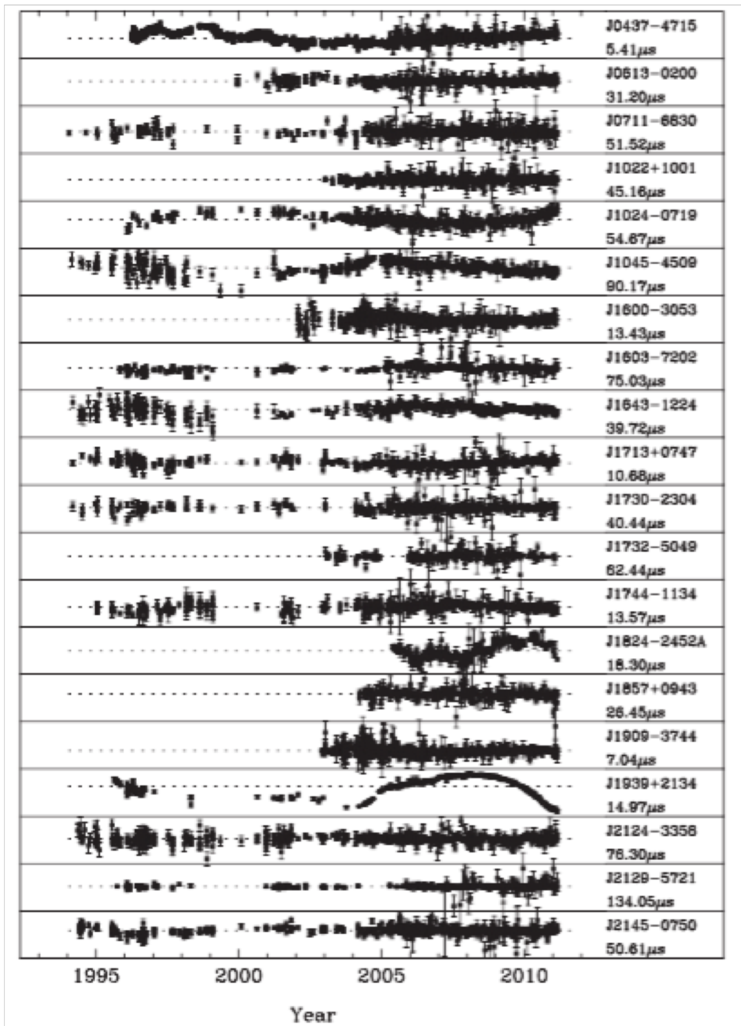
In the Fourier space, the main contribution of the impulse acceleration is the mode with the frequency $f = 1/T$, where

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

and the signal amplitude is

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

Noise



Reardon et al 15

✓ Pulsar term

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

$$n_f \approx \frac{\sigma}{\sqrt{T\nu}}$$

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

✓ Earth term

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

Event rate

✓ Earth term

For a given DM density, $\rho_{\rm h}(r) = \dfrac{\bar{\rho}_{\rm h}}{(r/L)(1+r/L)^2}$ and a survival probability, $\xi(M,r)$

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

$$\mathcal{R} \approx \pi b^2 V \left. \frac{\xi(M,r)\rho_{\rm h}(r)}{M} \right|_{r_\odot}$$

$$\sim 0.032\ {\rm yr}^{-1} \left(\frac{\xi}{1}\right) \left(\frac{\rho_{\rm h}}{0.011\ M_\odot\ {\rm pc}^{-3}}\right) \left(\frac{M}{10^{25}\ {\rm g}}\right)^{-1} \left(\frac{b}{740\ {\rm AU}}\right)^2 \left(\frac{V}{350\ {\rm km/s}}\right)$$

✓ Pulsar term

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

Conditions for detections

1. 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

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

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

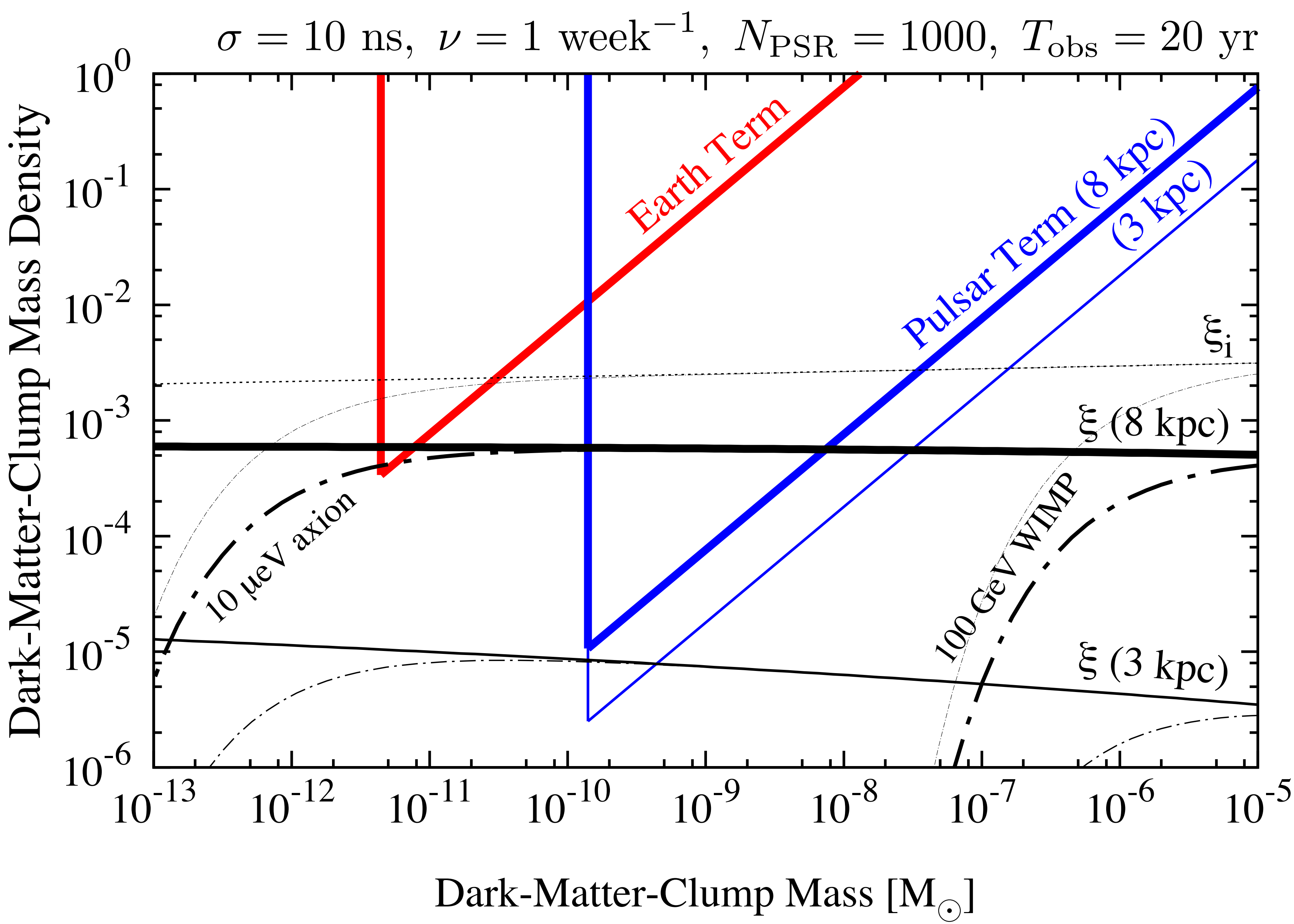
2. At least one event occurs during the observation time;

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

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

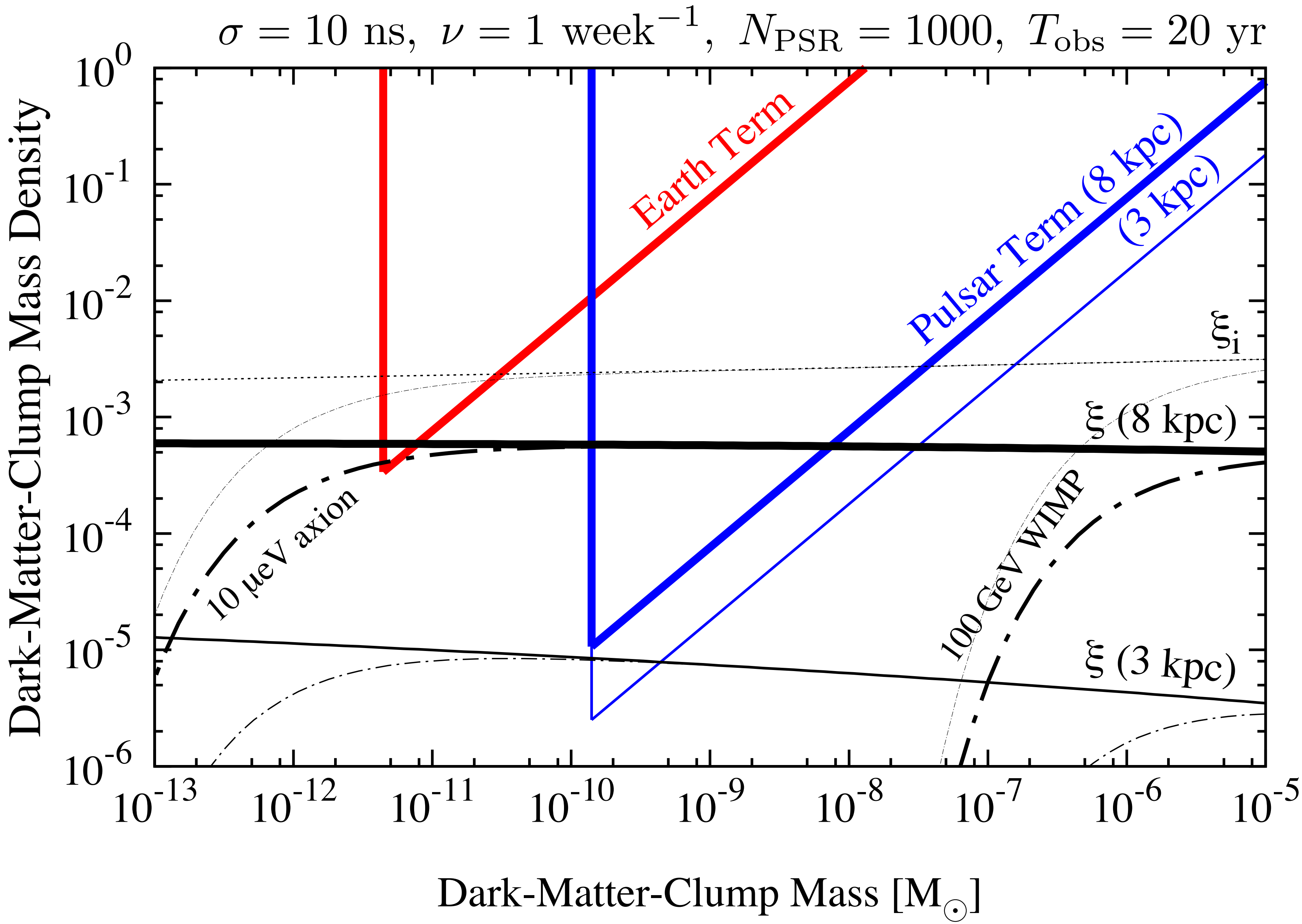
$$b \lesssim b_{\mathrm{max}} = 740\ \mathrm{AU}\left(\frac{T_{\mathrm{obs}}}{10\ \mathrm{yr}}\right)\left(\frac{V}{350\ \mathrm{km/s}}\right)$$

$E = 0$ for Earth term and 1 for pulsar term



$\sigma = 10$ ns, $\nu = 1$ week^{-1}, $N_{\rm PSR} = 1000$, $T_{\rm obs} = 20$ yr
Dark-Matter-Clump Mass Density
Dark-Matter-Clump Mass [M$_\odot$]
Earth Term
Pulsar Term (8 kpc)
(3 kpc)
ξ_i
ξ (8 kpc)
ξ (3 kpc)
10 μeV axion
100 GeV WIMP
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}

3. Discussion



$\sigma = 10$ ns, $\nu = 1$ week^{-1}, $N_{\rm PSR} = 1000$, $T_{\rm obs} = 20$ yr
Dark-Matter-Clump Mass Density
Dark-Matter-Clump Mass [$M_\odot$]
Earth Term
Pulsar Term (8 kpc)
(3 kpc)
ξ_i
ξ (8 kpc)
ξ (3 kpc)
10 μeV axion
100 GeV WIMP
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}