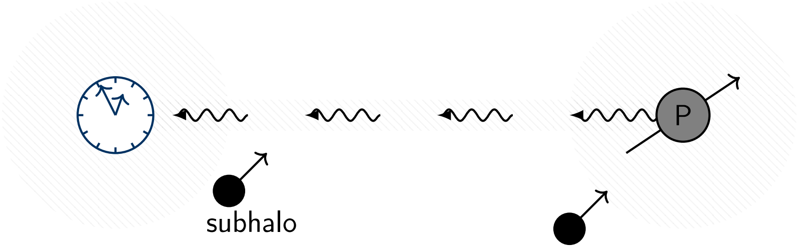
Pulsars as DM detectors

1901.04490

Jeff Dror, Harikrishnan Ramani, Tanner Trickle, Kathryn Zurek



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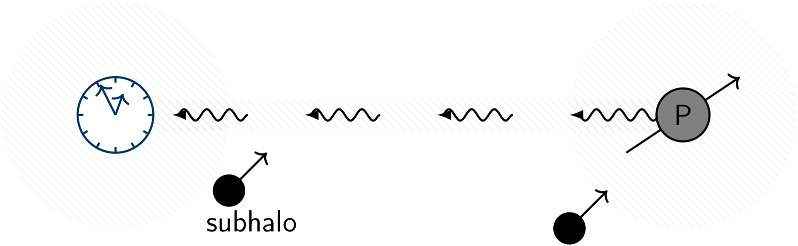
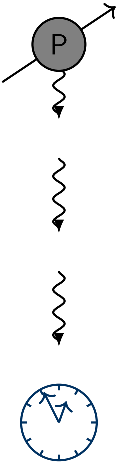


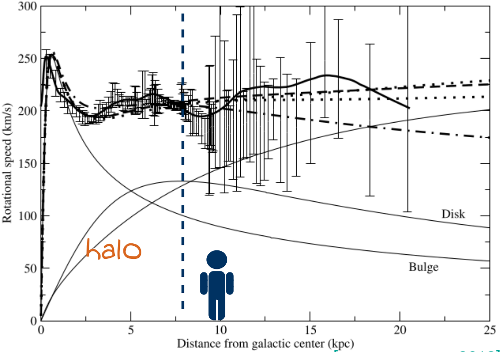
Outline

- Importance of substructure
  - Probe of DM history
- Pulsar basics
  - Properties
  - Past, present, future
- Dark matter on pulsars
  - Shapiro time delay
  - Doppler
- Types of searches
  - Clarify literature
  - Interpolate the different regimes
  - Can probe DM over huge mass range!
- Size



Substructure

- Dark matter (DM) makes up most of the Milky way



[Chan,Ehrlich - 2013]

- Halo fits "NFW" profile:

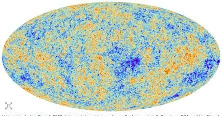
degenerate with M

$$\rho(r) = \frac{\rho_s}{(r/r_s)(1+r/r_s)^2}$$

core radius

But is this halo smooth?

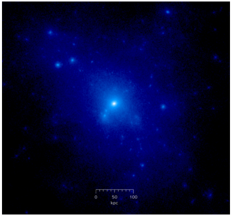
- DM halo our only structure?
- Lore: "DM is floating free particle"
- But DM clumps by gravitational collapse...



[- Planck]

matter domination

$\delta \propto a$



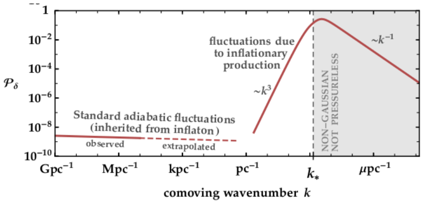
[- Wikipedia]

- Clumps make "subhalos" (survive galaxy formation?)
- Spatial profile depends on model
- Substructure tells you about history of DM

Sources of subhalos

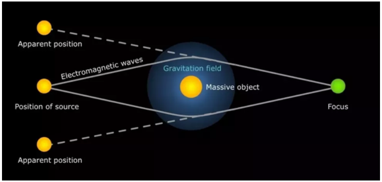
- Inflation + cold dark matter: structure on all scales
- Different histories $\Rightarrow$ different structure
- Examples with different small scale structure ($c \equiv r_{\rm vir}/r_s$):
  - CDM ($c \sim 10^2$)
  - PBH ($c \to \infty$)
  - axion miniclusters ($c \sim 10^4 - 10^7$)
  - early matter domination ($c \sim 10^3$)
  - Inflationary vector production ($c \sim 10^7$?)

$$30\text{pc}\left(\frac{M}{M_\odot}\right)^{1/3}$$

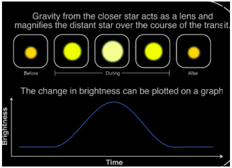


[Graham, Mardon, Rajendran - 1504.02102]

- Seeing dark astrophysical bodies is tough
- Can use types of lensing



- Strong lensing: multiple images
- Weak lensing: angular distortions
- Microlensing: brightness distortions [Paczynski - 1986]
- "low mass" subhalos: need microlensing

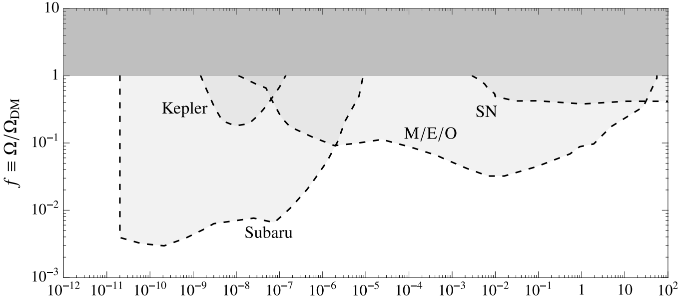


Microlensing

- Relevant distance scale:

$$r_E \sim \sqrt{GMd} \sim 10^{-7}\text{pc}\left(\frac{d}{100\text{kpc}}\right)^{1/2}\left(\frac{M}{10^{-6}M_\odot}\right)^{1/2}$$

- Need: $r_{\text{subhalo}} \lesssim r_E$ and $\Delta t \lesssim r_E/v \lesssim T$



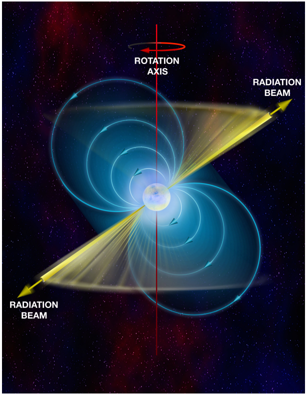
short cadence ⟵ $M/M_\odot$ ⟶ large obs time

Pulsars

Pulsar Basics

- Periodic astronomical light source
- Neutron stars with large magnetic fields
- SN remnants spun up by accretion?
- Near extremal!
- Can be binary (or *trinary*!) star system

property	value
M	$M_\odot$
T	$< 30\text{yr}$
t_{RMS}	$50\text{ns} - 10\mu\text{s}$
Δt	2wk



Pulsars as astrophysical clocks

- Pulsar modeled by oscillator, $\propto \sin\phi(t)$
- Expand phase:

$$\phi(t) = \phi_0 + \nu\, t + \frac{1}{2}\dot{\nu}\, t^2 + \frac{1}{6}\ddot{\nu}\, t^3 + \ldots$$

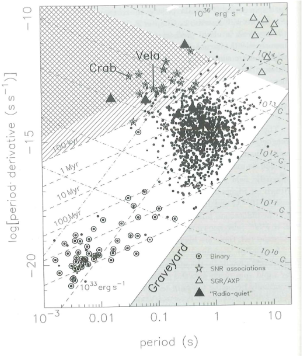
$$\mathcal{O}(\mathrm{ms}^{-1})$$

$$\mathcal{O}(10^{-23}\mathrm{s}^{-1}\cdot\nu)$$

$$\lesssim 10^{-29}\ \mathsf{s}^{-2}\cdot\nu$$

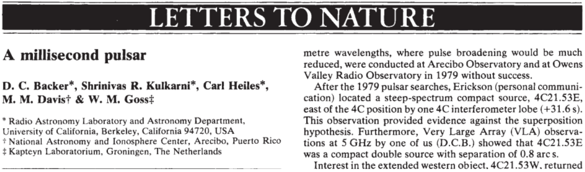
- Contribution from new physics:

$$\delta\phi(t) = \int dt\, \delta\nu_{\mathrm{NP}}$$



[Lorimer, Kramer - Pulsar handbook (2005)]

- First discovered milisecond pulsar (1982):



LETTERS TO NATURE

A millisecond pulsar

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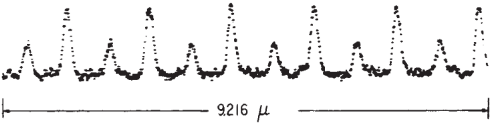
† National Astronomy and Ionosphere Center, Arecibo, Puerto Rico
‡ Kapteyn Laboratorium, Groningen, The Netherlands

metre wavelengths, where pulse broadening would be much reduced, were conducted at Arecibo Observatory and at Owens Valley Radio Observatory in 1979 without success.

After the 1979 pulsar searches, Erickson (personal communication) located a steep-spectrum compact source, 4C21.53E, east of the 4C position by one 4C interferometer lobe (+31.6 s). This observation provided evidence against the superposition hypothesis. Furthermore, Very Large Array (VLA) observations at 5 GHz by one of us (D.C.B.) showed that 4C21.53E was a compact double source with separation of 0.8 arc s.

Interest in the extended western object, 4C21.53W, returned

- Can see its original waveform (over $\sim 9\mathrm{ms}$):



- One of the most rapidly rotating MSP ($\sim 1.5\mathrm{ms}$)

Present

- A few running pulsar timing arrays (PTAs)

- Each tracking ~ 50 (millisecond) pulsars
- ~ 10 "high performance pulsars"
- ~ 200 pulsars in full set (73 useful ones)

- Square Kilometer Array (SKA)

- Will scan entire milky way
- $\sim 30,000$ pulsars in MW
- ~ 6000 milisecond pulsars
- $\sim 10\%$ beaming at us
- ~ 200 milisecond pulsars with 50 ns

[Smits et al - 0811.0211]
[Keane et al - 1501.00056]

What can you measure?

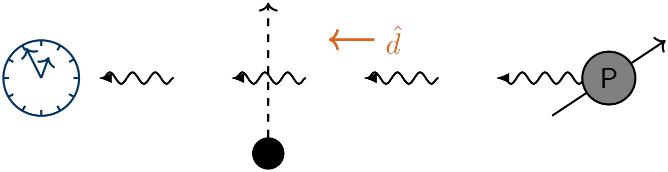
- Need signal shape, "strain", $\delta\nu/\nu$
- Experiments eager for new signals
- Current program: astrophysics focused
  - stochastic GW background
  - supermassive black holes mergers
  - fuzzy dark matter
- Can you use these for substructure?

  [Siegel,Hertzberk,Fry - astro-ph/0702546]
  [Seto,Corray - astro-ph/0702586]
  [Baghram,Afshordi,Zurek - 1101.5487]
  [Kashiyama, Seto - 1208.4101]
  [Clark,Lewis,Scott - 1509.02938]
  [Schutz, Liu - 1610.04234]
  [Kazumi, Oguri, Masamune - 1801.07847]

- This work: additional signals, different regimes, unappreciated features

DM on PTAs

- Two important effects for transitting subhalos
- First effect: Shapiro time delay [Siegel,Hertzberk,Fry - astro-ph/0702546]
- Changes metric around light path



- Induced time delay:

$$\delta t = 2 \int dz \Phi \quad \Longrightarrow \quad \frac{\delta \nu}{\nu} = \dot{\delta t} = 2GM \int dz \frac{\dot{r}}{r^2}$$

- “cylindrical”-coordinates: $\mathbf{r}_\times \equiv \mathbf{r} \times \hat{\mathbf{d}}$ and $\mathbf{v}_\times \equiv \mathbf{v} \times \hat{\mathbf{d}}$

$$t_0 \equiv \frac{\mathbf{r}_{\times,0} \cdot \mathbf{v}_\times}{v_\times^2} \quad ; \quad \tau \equiv \frac{|\mathbf{r}_{\times,0} \times \mathbf{v}_\times|}{v_\times^2}$$

- Carrying out integral...

$$\frac{\delta\nu}{\nu} \simeq 4GM \frac{\dot{r}_\times}{r_\times^2}$$

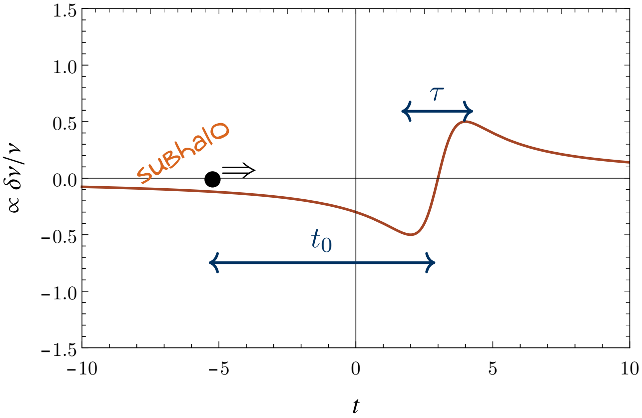
$$t_0^2 + \tau^2 = r_{\times,0}^2 / v_\times^2$$

- This gives, $x \equiv (t - t_0)/\tau$:

$$\frac{\delta\nu}{\nu} = \frac{4GM}{\tau} \frac{x}{1 + x^2}$$

[1901.04490 - **JD**,Ramani,Trickle,Zurek]

- Signal in pulsar timing:



Shapiro - timescales

- Can use "closest-object" approximation
- Minimum distance to line of sight:

$$r_{\rm min} \sim \frac{1}{N_p \cdot n \cdot d \cdot vT} \sim 10^{-3}{\rm pc}\frac{M}{10^{-3}M_\odot}$$

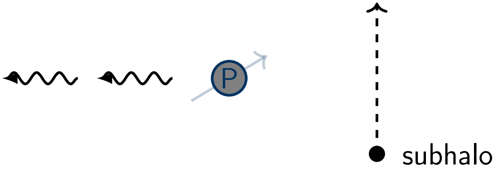
- $\tau, t_0 \sim r_{\rm min}/v$ $[{\rm pc} \sim \pi \ \times \ {\rm year}]$

$$\tau, t_0 \sim {\rm year}\frac{M}{10^{-3}M_\odot}$$

- "Blip" if $\Delta t \ll \tau, t_0 \ll T$
- Analogous to microlensing
- See entire signal for $M \lesssim 10^{-3} M_\odot$

Effect on pulsar timing - Doppler

- Second effect: "Doppler"-Newtonian-like effect
- Gravitional pull on source/detector as it passes by
  [Seto,Corray - astro-ph/0702586]



- Introduces relative velocity between pulsar/Earth
- Strain:

$$\frac{\delta\nu}{\nu} = \dot{\mathbf{r}} \cdot \hat{\mathbf{d}}$$

Effect on pulsar timing - Doppler

- Finding for $\dot{\mathbf{r}}$ $\rightarrow$ solve 2-body problem!
- Simple for fast moving clumps ($\mathbf{r}(t) = \mathbf{r}_0 + \mathbf{v}t$)

$$\dot{\mathbf{r}} = GM \int dt \frac{\mathbf{r}(t)}{|\mathbf{r}(t)|^3}$$

- As before: $|\mathbf{r}| = v\tau \left[1 + x\right]^{1/2}$, $x \equiv (t + t_0)/\tau$

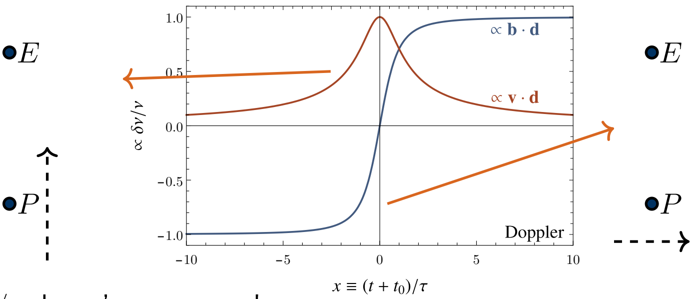
$$\frac{\delta\nu}{\nu} \simeq \frac{GM}{v^2\tau} \int dx \frac{1}{\left[1 + x^2\right]^{3/2}} \Big[\mathbf{r}_0 + \mathbf{v}(\tau x - t_0)\Big] \cdot \hat{\mathbf{d}}$$

$$= \frac{GM}{v^2\tau} \frac{1}{\sqrt{1 + x^2}} \left[x(\mathbf{r}_0 + t_0\mathbf{v}) - \tau\mathbf{v}\right] \cdot \hat{\mathbf{d}}$$

[1901.04490 - JD,Ramani,Trickle,Zurek]

Effect on pulsar timing - Doppler

- Two Doppler signal forms depending on geometry:



- $\delta\nu/\nu$ doesn't go to zero!
- Same signal shape for Earth and pulsar
  - pulsar term more important

Doppler - timescales

- Again can use "closest-object" approximation
- Minimum closest distance to pulsar:

$$r_{\min} \sim \left(\frac{1}{N_p \cdot n \cdot vT}\right)^{1/2} \sim 10^{-3}\text{pc}\left(\frac{M}{10^{-9}M_\odot}\right)^{1/2}$$

- Typical timescales: $\tau, t_0 \sim r_{\min}/v$

$$\tau, t_0 \sim \text{year}\left(\frac{M}{10^{-9}M_\odot}\right)^{1/2}$$

- See entire signal for $M \lesssim 10^{-9}M_\odot$ (Shapiro - $10^{-3}M_\odot$)

Observation

- Optimal search depends on mass
- All in the timescales!

① Dynamic

- $\tau, t_0 \ll T$
- see all of signal
- "blips" in timing
- distinctive

② Static

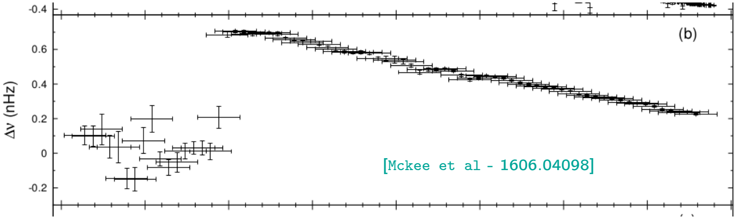
- $\tau, t_0 \gg T$
- subhalo stationary over T
- Look for "static" variations
- bkgs more challenging

- Sometimes can even have both

Dynamic search

Dynamic search strategy

- Look for blips
- Signal has distinct shape
- Possible backgrounds:
  1. Irreducible: space junk (e.g. planets)
     - rare for blip timescales
     - way less junk than DM
  2. Glitches (observed in a few MSP)
     - Different shape...



Dynamic searches

- "Blips" - search strategy is known
- Signal ($\delta\nu/\nu$) over white noise (S_n)
- Solved problem in signal processing [Moore,Cole,Berry - 1408.0740]
- Timing data $\rightarrow$ filter $\rightarrow$ integrate

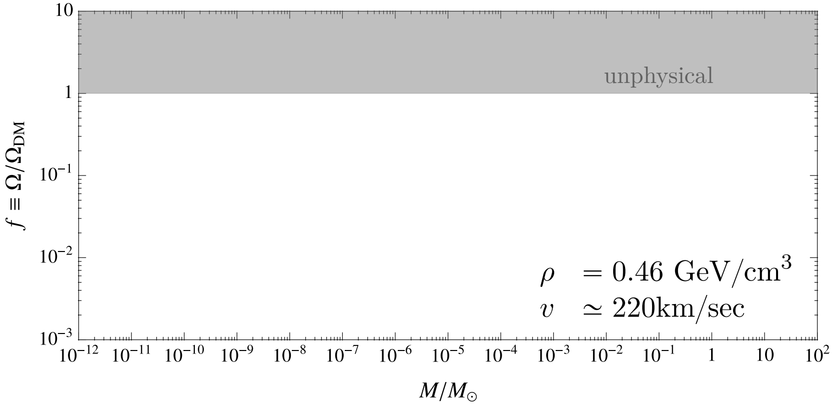
$$\mathrm{SNR}^2 = \frac{1}{S_n^{(0)}} \int \frac{df}{f^2} \left| \frac{\delta\nu}{\nu}(f) \right|^2$$

- Noise:

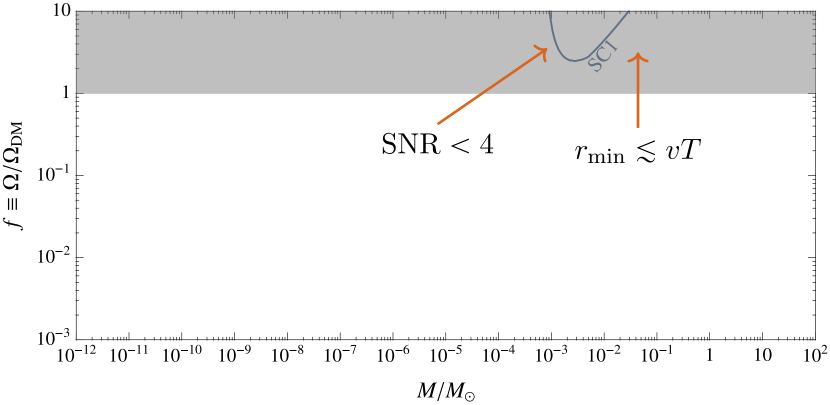
$$S_n^{(0)} \equiv \Delta t \left(\frac{t_{\mathrm{RMS}}}{2\pi T} \right)^2$$

- require no false positives: SNR > 4

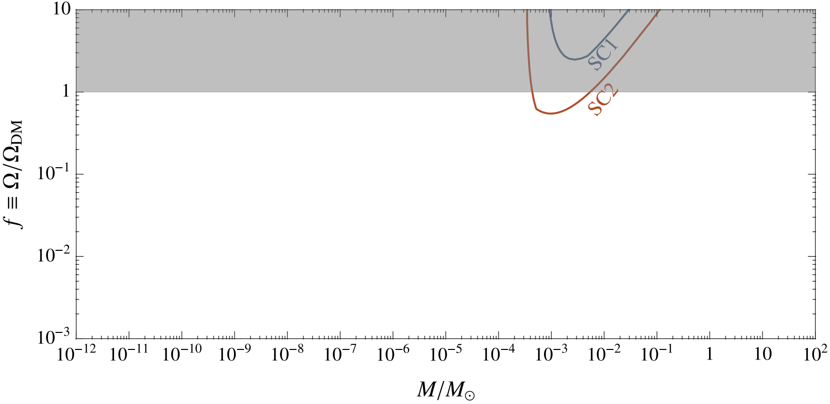
- Putting on constraints:



- "SC1": Current pulsar limits:

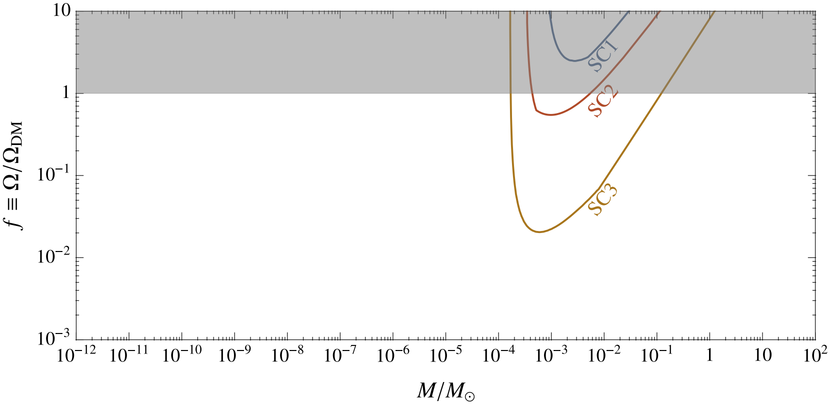


- "SC2": Current pulsars+10 years:



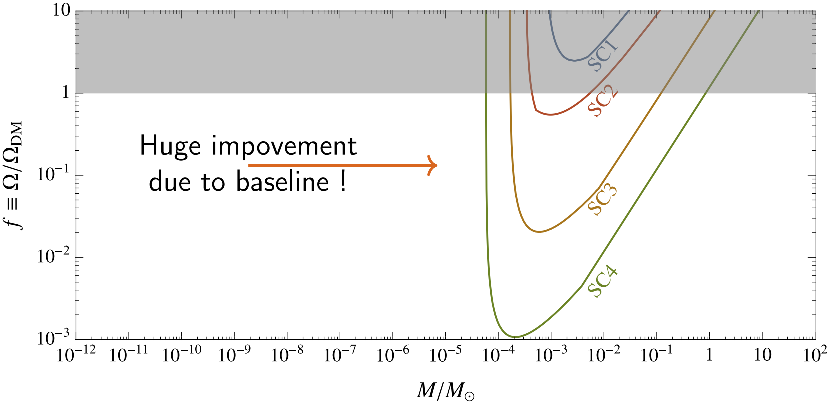
Shapiro dynamic search limits

- "SC3": Current + SKA (conservative)

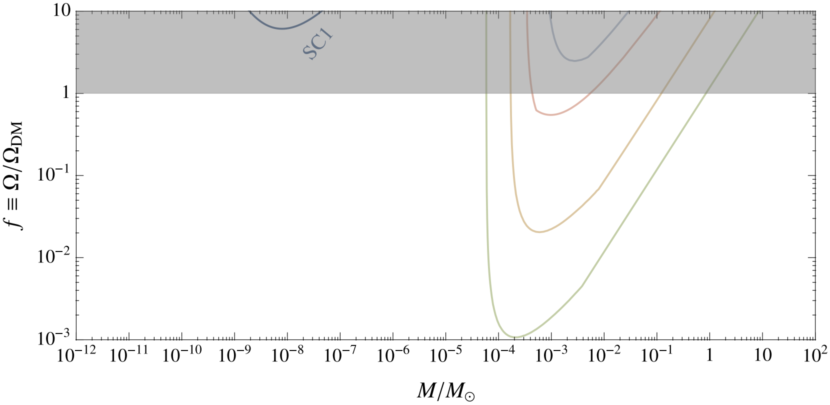


Shapiro dynamic search limits

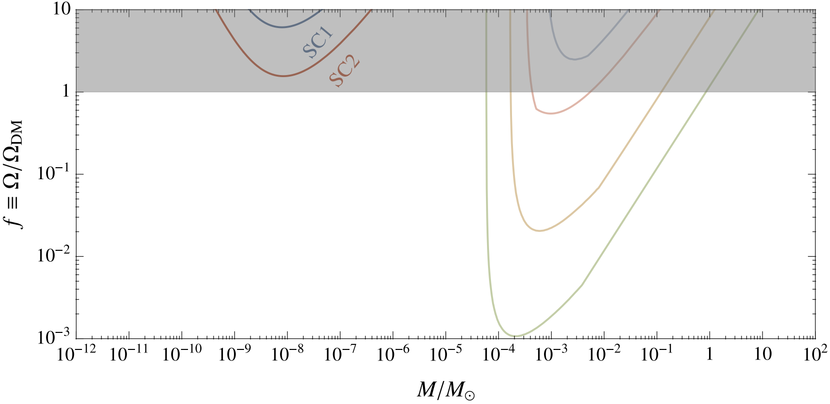
- "SC4": Current + SKA



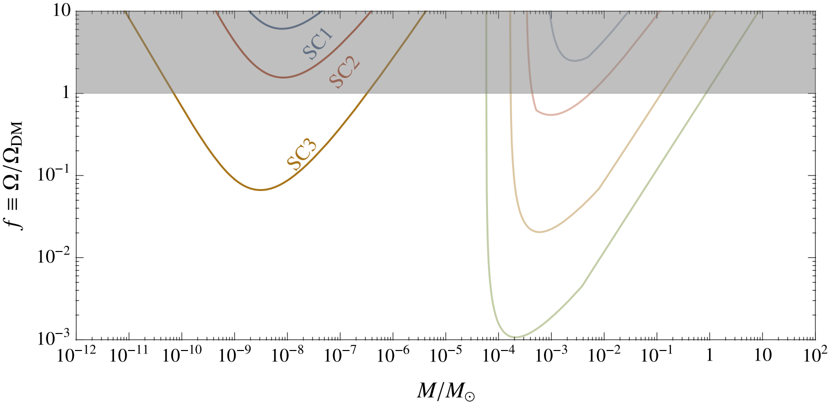
- "SC1": Current pulsar limits:



- "SC2": Current pulsars+10 years:

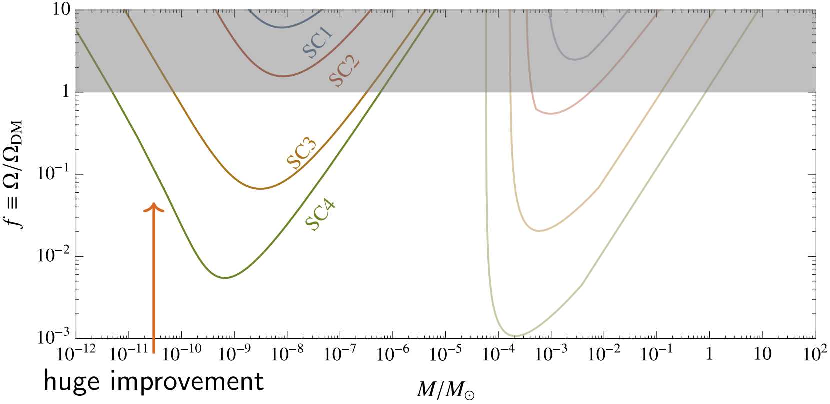


- "SC3": Current + SKA (conservative)



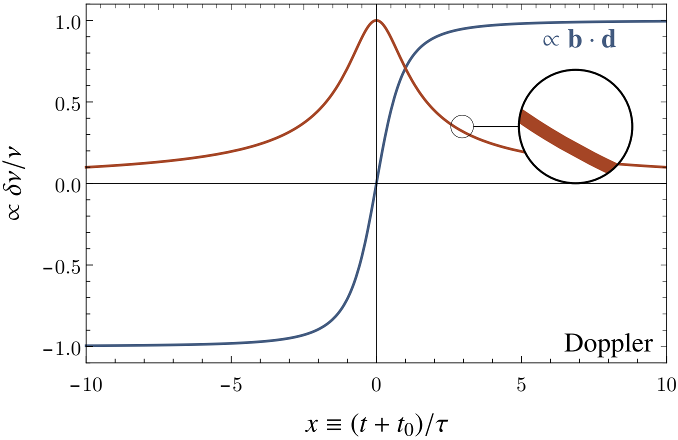
Doppler dynamic search limits

- “SC4”: Current + SKA



huge improvement
due to T

Static search



- What about slow blips?
- Most of signal fitted away

$$\phi(t) = \phi_0 + \nu\, t + \frac{1}{2}\dot{\nu}\, t^2 + \frac{1}{6}\ddot{\nu}\, t^3 + \ldots$$

- Expected: $T \times \dot{\nu}/\nu \ll 1$ $(\sim 10^{-15})$, $\ddot{\nu} = 0$
- To constrain new physics:
  1. "Large" spin down/up $(|\dot{\nu}_{\rm NP}| > |\dot{\nu}_{\rm obs}|)$ [Goldman,Nussinov - 0907.1555]
  2. Higher order corrections $(|\ddot{\nu}_{\rm NP}| > \sigma_{\ddot{\nu}})$ [Clark,Lewis,Scott - 1509.02938] [Schutz, Liu - 1610.04234]
- Studied for Shapiro delay
- Empirically: $\ddot{\nu}/\nu \lesssim 10^{-29}$ s^{-2}

Static searches

- $\ddot{\nu}$ is cubic in $\phi(t)$:
- To get "static" signal, expand blips
- Only observable term is the cubic

$$\left.\frac{\ddot{\nu}}{\nu}\right|_{\text{Shap}} \simeq \frac{GMv_\times^3}{r_\times^3}\left(\frac{t_0 v_\times}{r_\times}\right)^3\left(1-3\frac{\tau^2}{t_0^2}\right)$$

$$\left.\frac{\ddot{\nu}}{\nu}\right|_{\text{Dopp}} \simeq \frac{GMv}{r_0^3}\left(\hat{\mathbf{v}}-3v\frac{t_0}{t_0}\hat{\mathbf{r}}\right)\cdot\hat{\mathbf{d}}$$

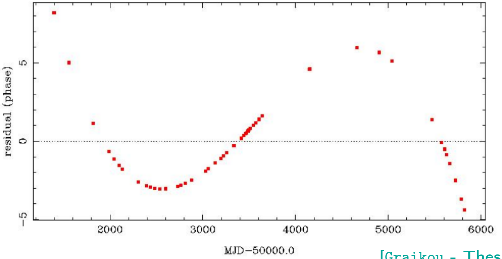
- Limit: signal larger than expected fluctuation: $\frac{\ddot{\nu}}{\nu} > 4\sigma_{\ddot{\nu}/\nu}$

$$\sigma_{\ddot{\nu}/\nu} = 6\sqrt{\frac{2800\Delta t}{T}}\frac{t_{\mathsf{RMS}}}{T^3}$$

[Liu,Bassa,Stappers - 1805.02892]

Backgrounds

- Static searches work in different mass range
- Scary backgrounds (e.g., "dark planets")
- baryons kind of under control (co-rotation)
- Few pulsars already exhibit $\ddot{\nu}$!

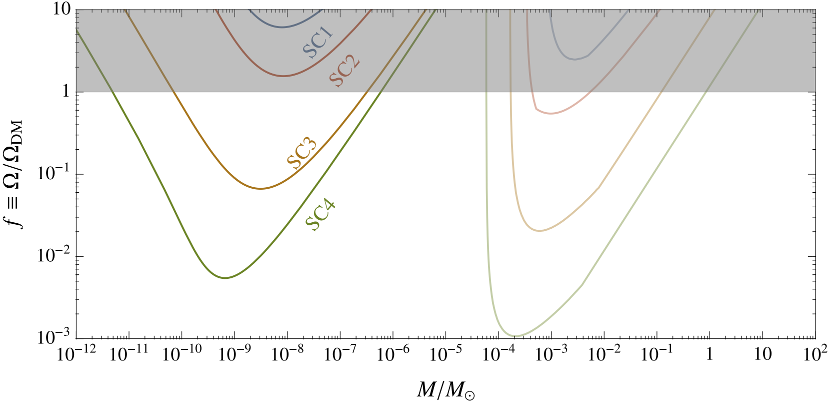


[Graikou - Thesis]

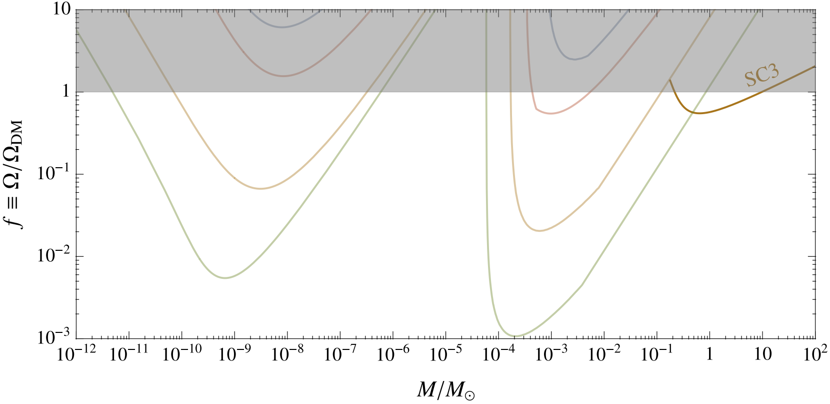
- Can only set limit?

Shapiro static search limits

- Putting on constraints:

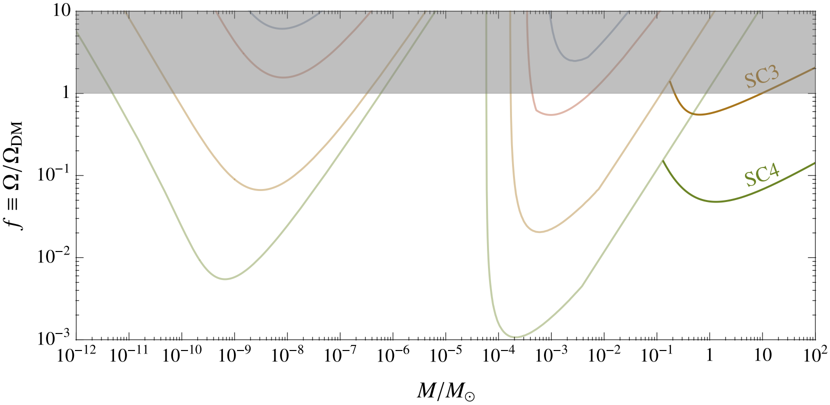


- "SC3": Current + SKA (conservative)

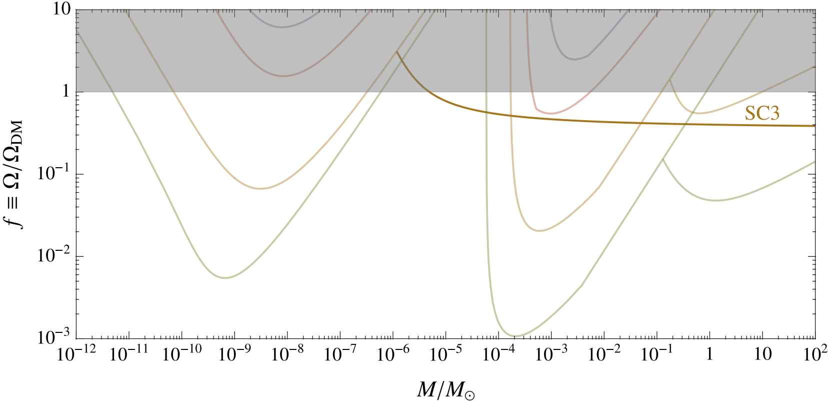


Shapiro static search limits

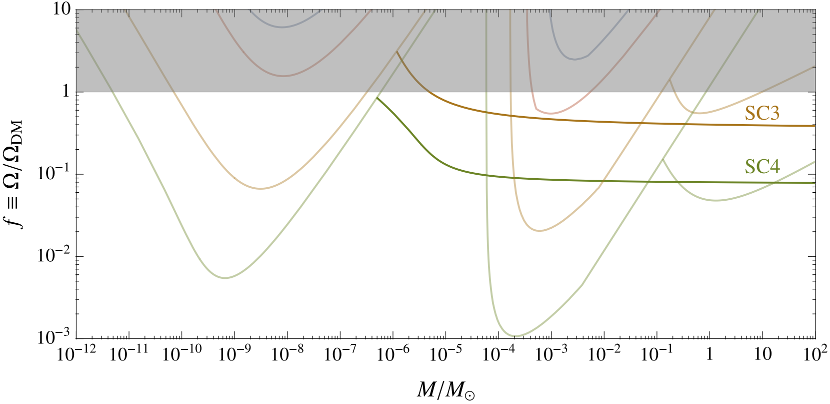
- "SC4": Current + SKA



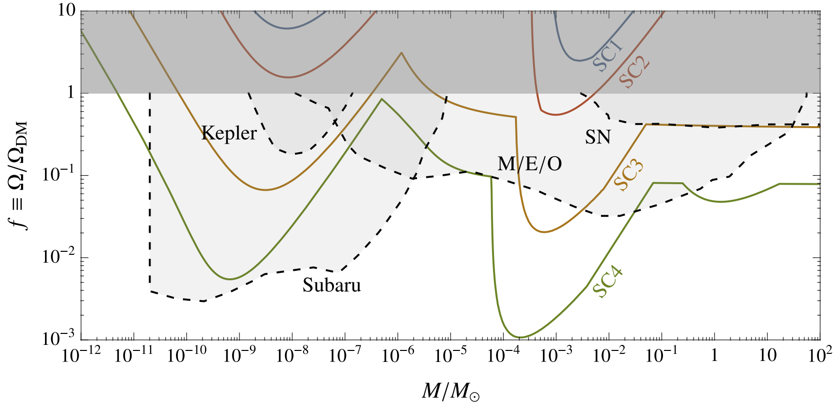
- "SC3": Current + SKA (conservative)



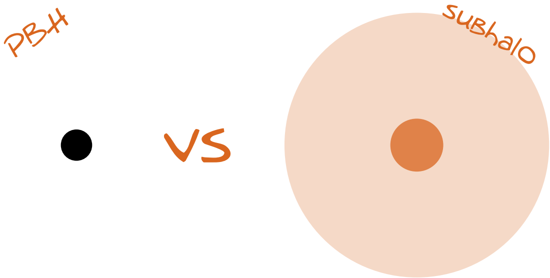
- "SC4": Current + SKA



- Putting it all together...



Size



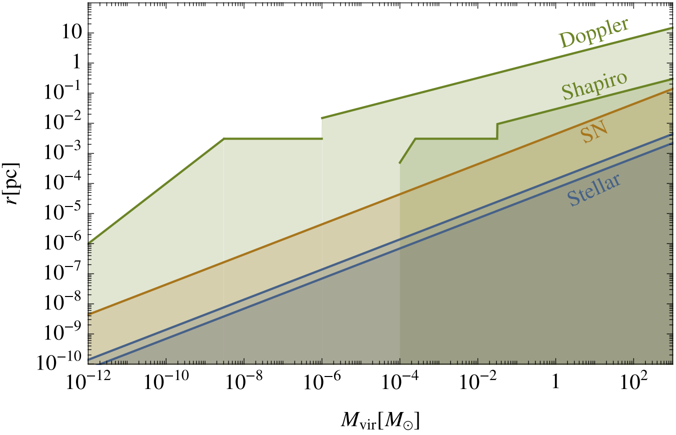
Sensitivity radius

- Large sensitivity radius for PTAs: $r_{\rm PTA} \gg r_{\rm lensing}$
- Can see diffuse subhalos

$$r_{\rm lensing} \sim r_E \sim 10^{-7}\mathrm{pc}\left(\frac{d}{100\mathrm{kpc}}\right)^{1/2}\left(\frac{M}{10^{-6}M_\odot}\right)^{1/2}$$

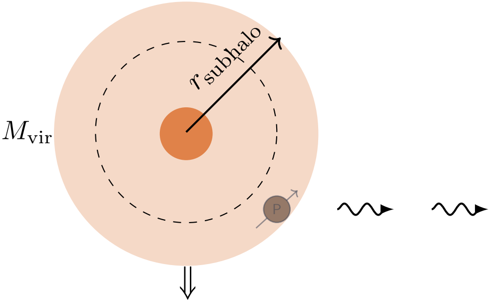
$$r_{\rm PTA} \sim 10^{-3}\ \text{pc} \times \begin{cases} \dfrac{M}{10^{-9}M_\odot} & \text{(Doppler Dynamic)} \\ \left(\dfrac{M}{10^{-3}M_\odot}\right)^2 & \text{(Shapiro Dynamic)} \\ \left(\dfrac{M}{10^{-8}M_\odot}\right)^{\frac{1}{3}} & \text{(Doppler Static)} \\ \left(\dfrac{M}{10^{-3}M_\odot}\right)^{\frac{1}{3}} & \text{(Shapiro Static)} \end{cases}$$

- Typical radius probed by different experiments (point mass):



Sensitivity radius

- Technically constraint only applies if $r_{\mathrm{subhalo}} < r_{\mathrm{PTA}}$
- Still sensitive to "enclosed mass"



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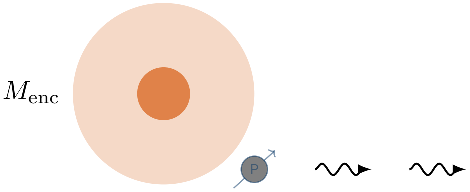
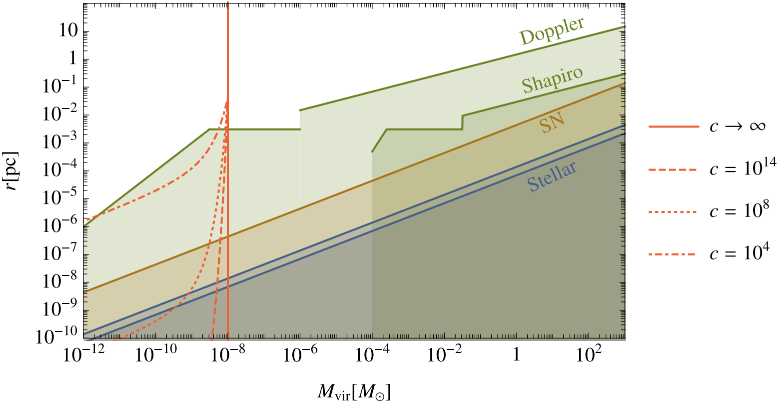


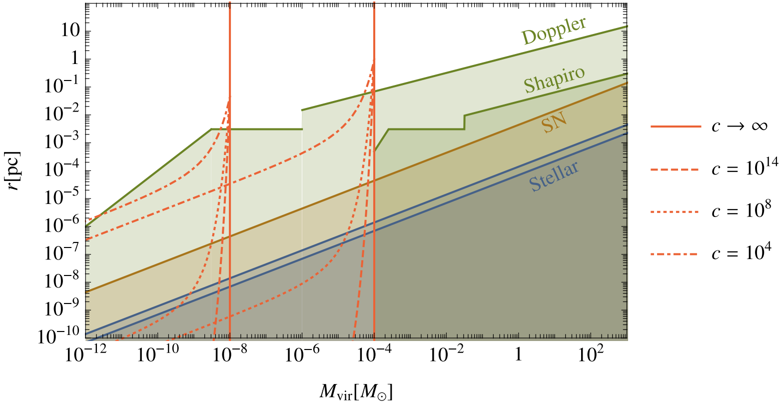
$\Downarrow$

Rescaling limits with enclosed mass

- Mass enclosed often still detectable

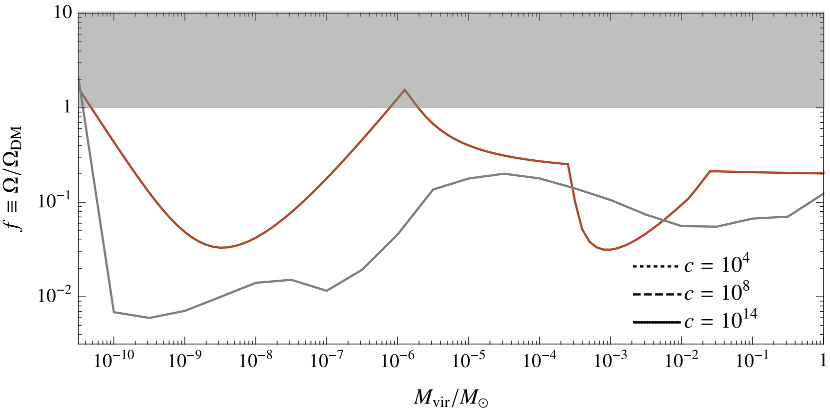


- $\mathrm{Prob}(r < r_{\mathrm{PTA}})+M_{\mathrm{enc}}$ can rescale limits (ignoring ring)

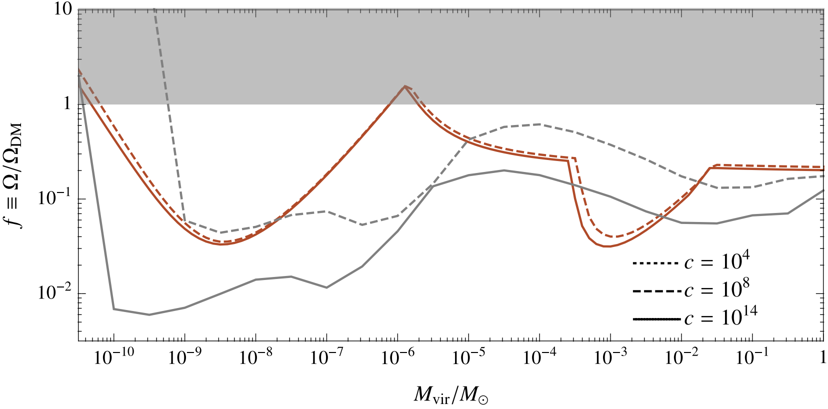


Constraints on diffuse subhalos

- $c \equiv r_{\rm vir}/r_s = 10^{14}$

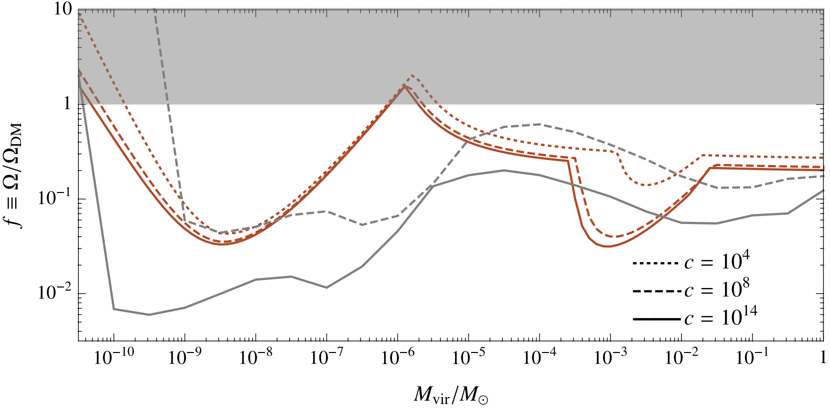


- $c \equiv r_{\rm vir}/r_s = 10^8$



Constraints on diffuse subhalos

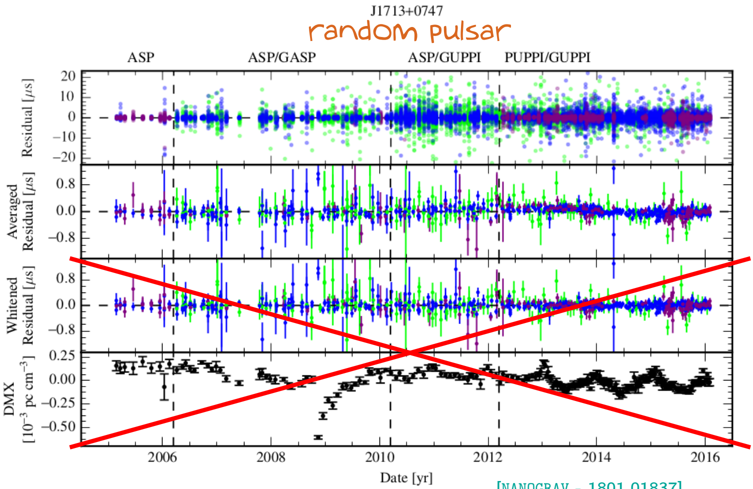
- $c \equiv r_{\mathrm{vir}}/r_s = 10^4$



Conclusion

- PTAs can constrain transitting subhalos
- Constraints over huge range of M
- Two effects can look for (sometimes complementary)
- Different possible strategies $\rightarrow$ all should be used
- Shapiro delay + Doppler kicks
- Static vs dynamic limits
- Can detect diffuse halos!
- High density region?
- Extragalactic pulsars?

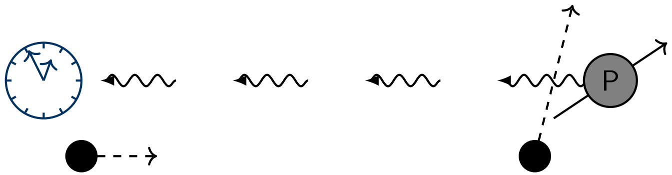
A look at pulsar data *



[NANOGRAV - 1801.01837]

Earth vs Pulsar *

- Signal can pass by Earth or pulsar



- Each induce Doppler delay
- Pulsar term: searching larger volumes → limits scale up as $\sim N_p$
- Earth term: better sensitivity

$$S_n \propto 1/\sqrt{N_P}$$

- Always better to use pulsar term (unlike GW)