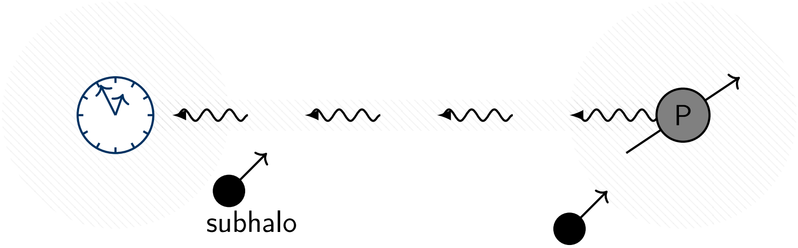
Pulsars as DM detectors

1901.04490

Jeff Dror, Harikrishnan Ramani, Tanner Trickle, Kathryn Zurek



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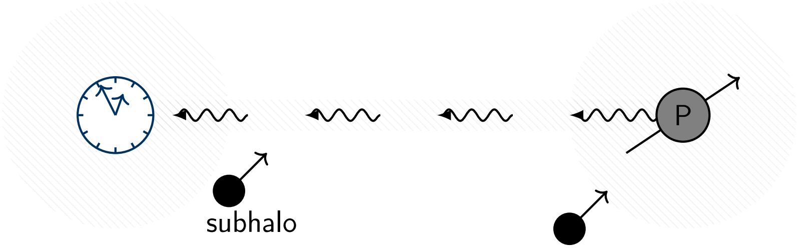
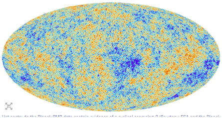
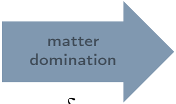


But is this halo smooth?

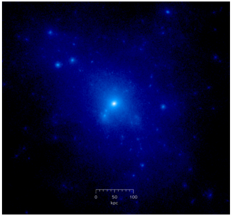
- DM halo our only structure?
- Lore: "DM is floating free particle"
- But DM clumps by gravitational collapse...



[- Planck]



$\delta \propto a$



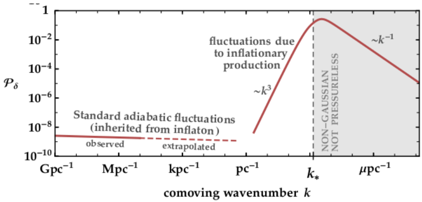
[- Wikipedia]

- Inhomogeneities make "subhalos"
- Details (profile, abundance) depends on model

Sources of subhalos

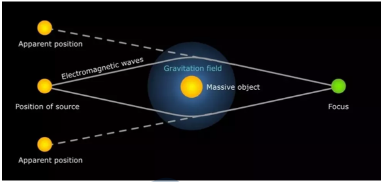
- Inflation + cold dark matter: structure on all scales
- Different histories ⇒ different structure
- Examples with different small scale structure ($c \equiv r_{\rm vir}/r_s$):
  - CDM $(c \sim 10^2)$
  - PBH $(c \to \infty)$
  - axion miniclusters $(c \sim 10^4 - 10^7)$
  - early matter domination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

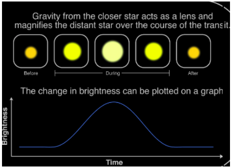
$$30\text{pc}\left(\frac{M}{M_\odot}\right)^{1/3}$$

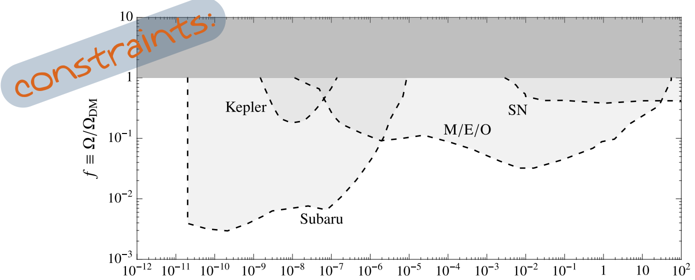


[Graham, Mardon, Rajendran - 1504.02102]

- Microlensing: brightness distortions [Paczynski - 1986]







short cadence ← $M/M_\odot$ → large obs time

Pulsars as astrophysical clocks

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

$$\phi(t) = \phi_0 + \nu\, t + \frac{1}{2}\dot{\nu}\, t^2 + \frac{1}{6}\ddot{\nu}\, t^3 + \ldots + \int dt\, \delta\nu_{\rm NP}$$

ν: $\mathcal{O}(\mathrm{ms}^{-1})$

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

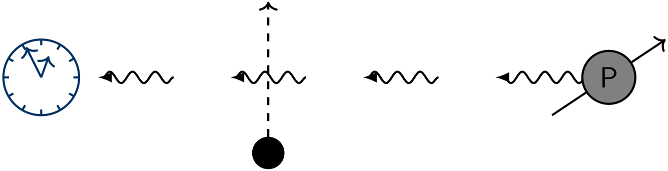
$\ddot{\nu}$: $\lesssim 10^{-29}\ \mathrm{s}^{-2} \cdot \nu$

- DM produces "strain": $\delta\nu/\nu$?
- This work: additional signals, different regimes, unappreciated features

[Siegel,Hertzberg,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]

- Two main effects for transitting subhalos
- Shaprio time delay: DM changes metric around light path

[Siegel,Hertzberk,Fry - astro-ph/0702546]



- Induced time delay:

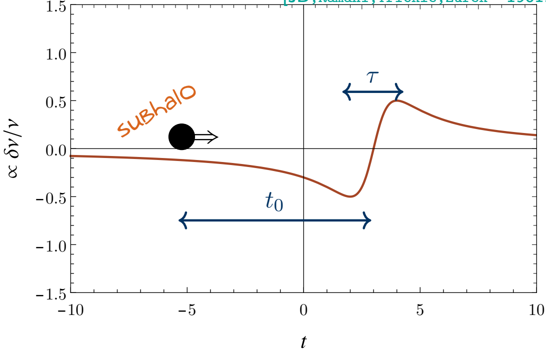
$$\delta t = 2\int dz \frac{GM}{r} \quad \Longrightarrow \quad \frac{\delta\nu}{\nu} = \dot{\delta t} = 2GM\int dz \frac{\dot{r}(t)}{r^2(t)}$$

Effect on pulsar timing - Shapiro

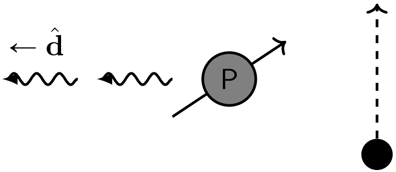
- Timescales: $t_0 \sim \mathbf{r}_0 \cdot \mathbf{v}/v^2$, $\tau \sim |\mathbf{r}_0 \times \mathbf{v}|/v^2$
- Carrying out integral ($x \equiv (t+t_0)/\tau$):

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

[JD, Ramani, Trickle, Zurek - 1901.04490]



- **Doppler effect**: gravitional pull on source/detector
  [Seto,Corray - astro-ph/0702586]



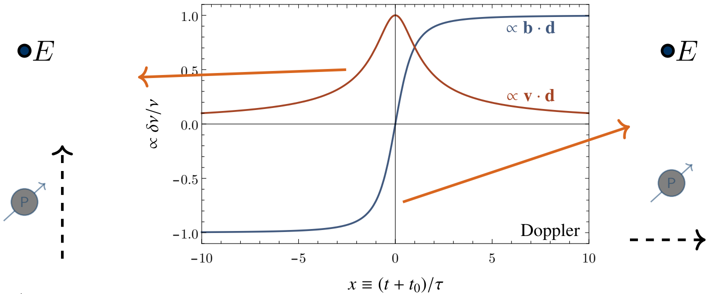
- Relative velocity between pulsar/Earth
- Strain:

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

- Two-body problem

- Two signals depending on geometry:

[JD, Ramani, Trickle, Zurek - 1901.04490]

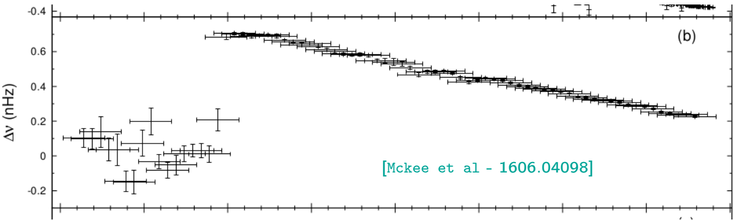


- $\delta\nu/\nu$ doesn't go to zero!
- Non-transient signal dominates
- Same signal shape for Earth and pulsar

Search strategy

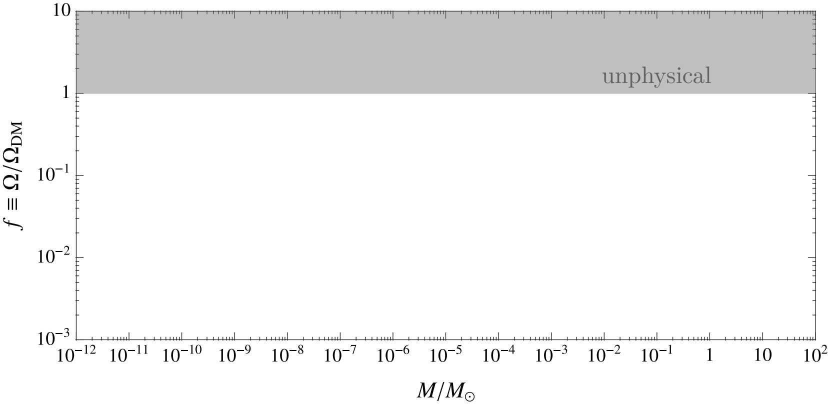
- Look for blips ($\Delta t \ll \tau, t_0 \ll T$)
- Possible backgrounds:

  1. Irreducible: space junk (e.g. planets)
     - way less junk than DM (rare!)
  2. Glitches (observed in a few MSP)
     - Different shape...

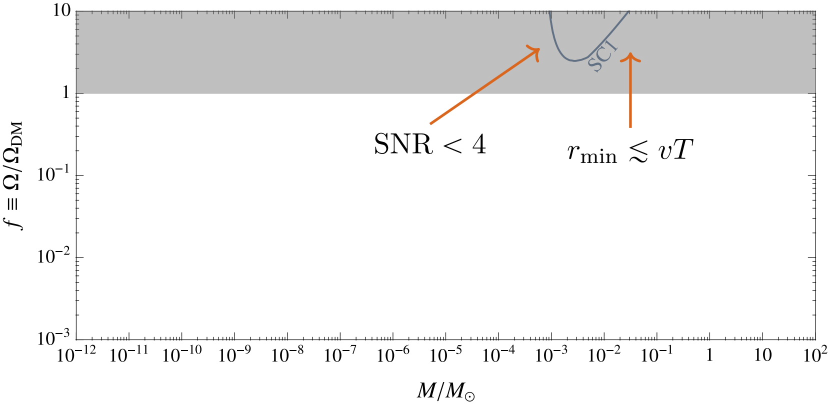


[Mckee et al - 1606.04098]

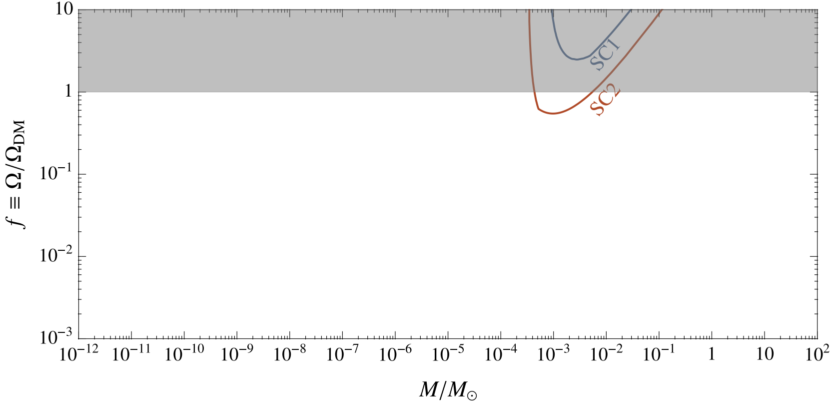
- Putting on constraints:



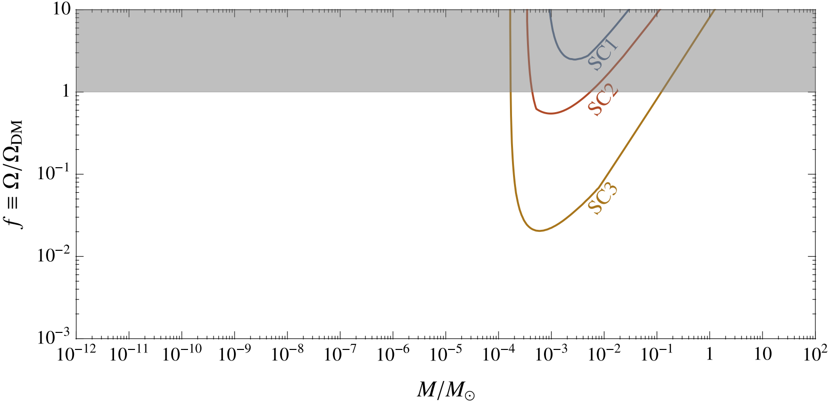
- “SC1”: Current pulsar limits:



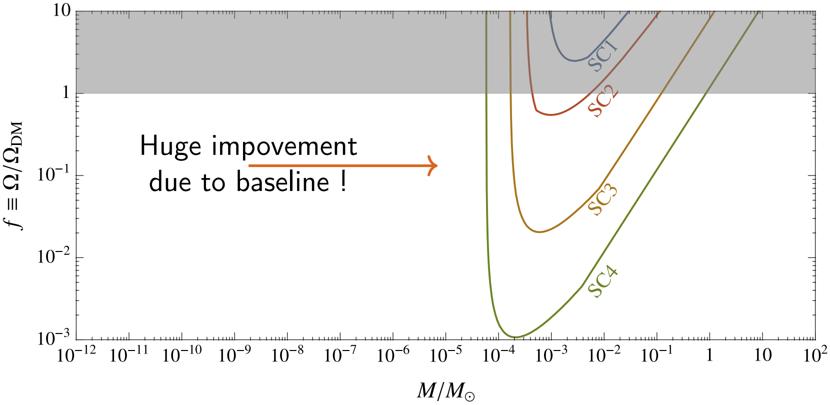
- "SC2": Current pulsars + 10 years:



- “SC3”: Current + SKA (conservative)



○ "SC4": Current + SKA



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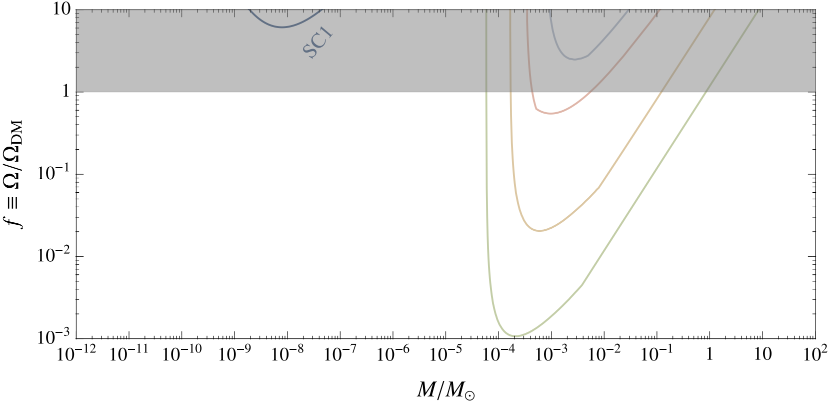
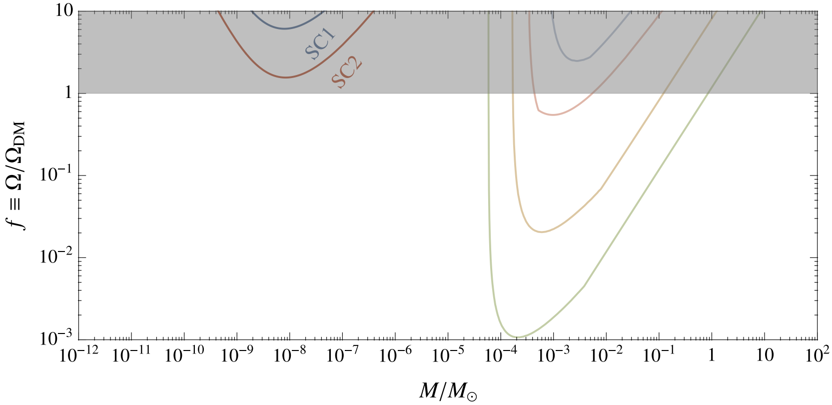


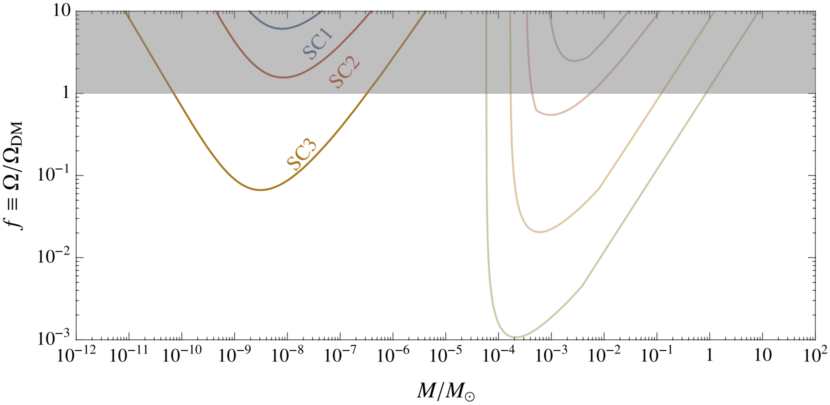
Doppler dynamic search limits

- "SC2": Current pulsars + 10 years:

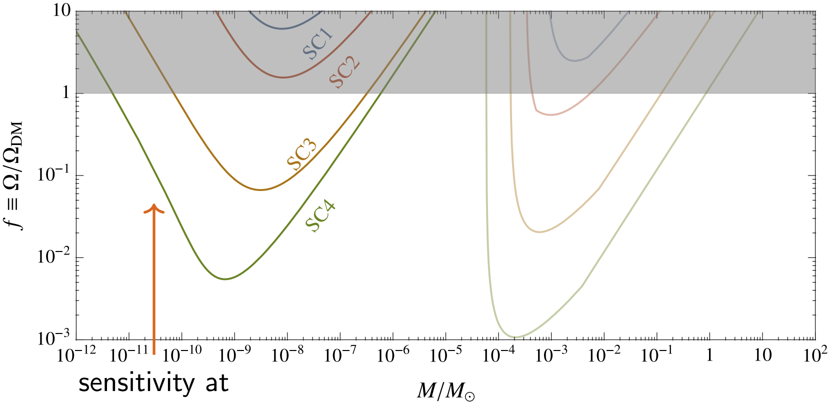


Doppler dynamic search limits

- "SC3": Current + SKA (conservative)



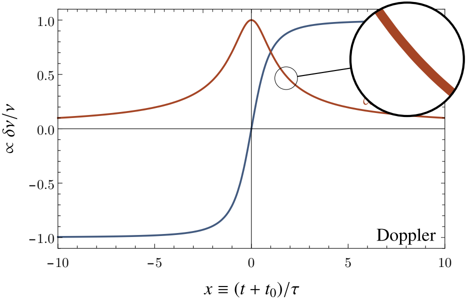
- “SC4”: Current + SKA



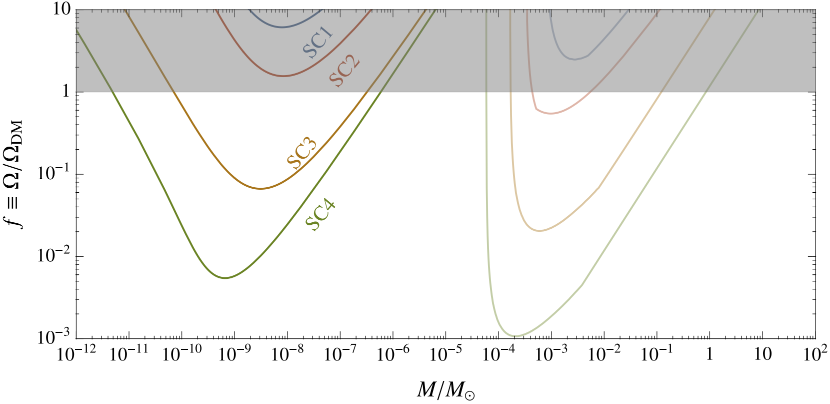
sensitivity at low M!

Static searches

- When blip timescales are long situation is not hopeless!
- Studied for Shapiro delay [Clark,Lewis,Scott - 1509.02938] [Schutz, Liu - 1610.04234]
- Doppler is typically stronger [JD,Ramani,Trickle,Zurek - 1901.04490]
- Challenging to pick out of background



- Putting on constraints:



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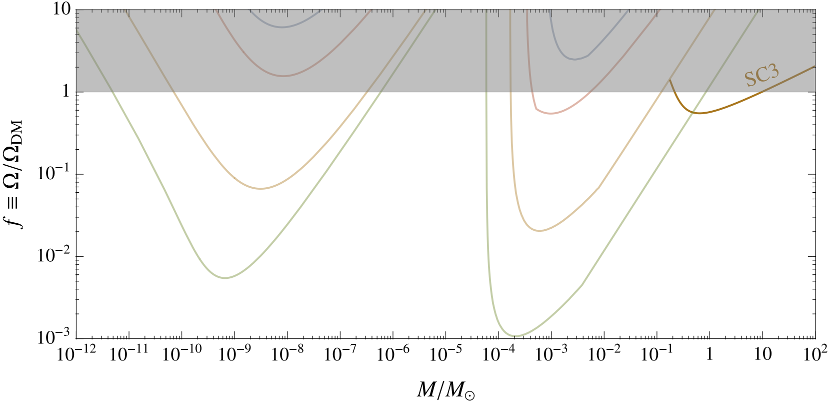
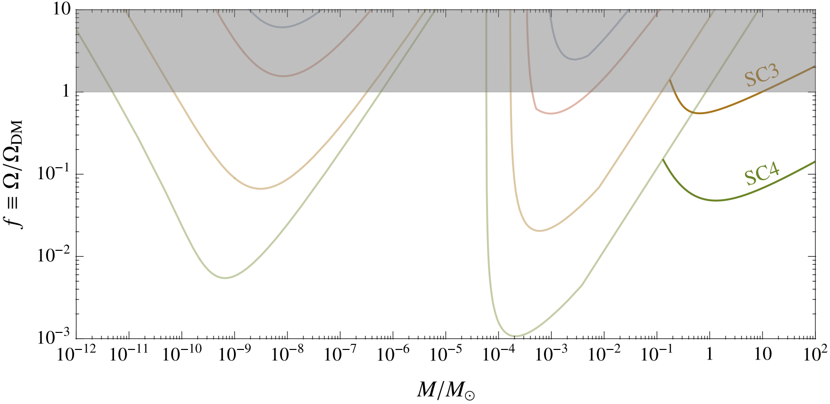
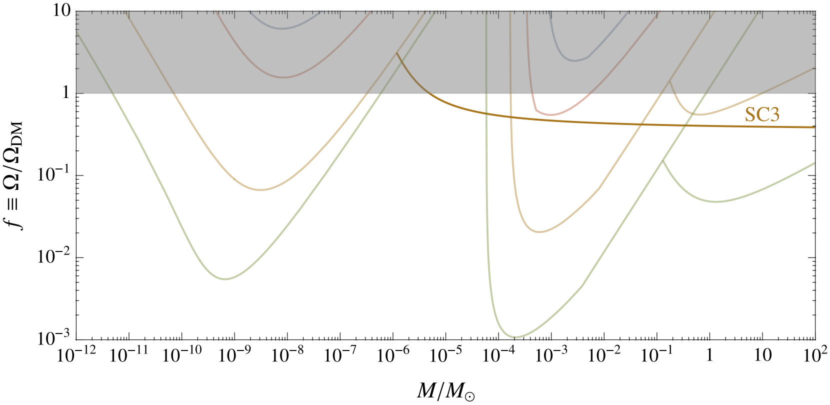


Shapiro static search limits

- “SC4”: Current + SKA

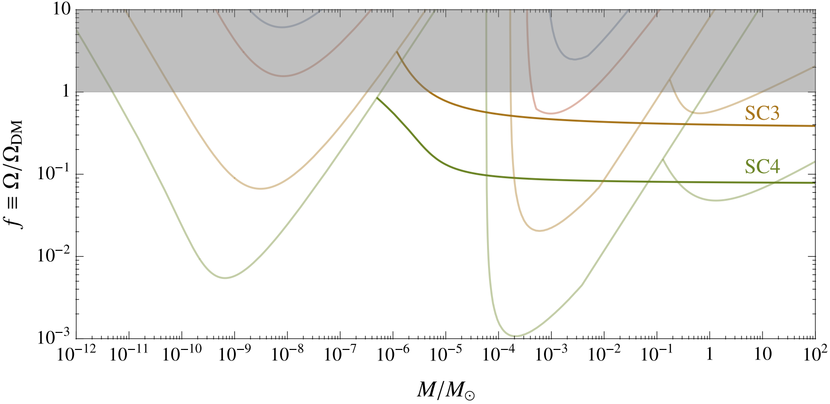


- "SC3": Current + SKA (conservative)

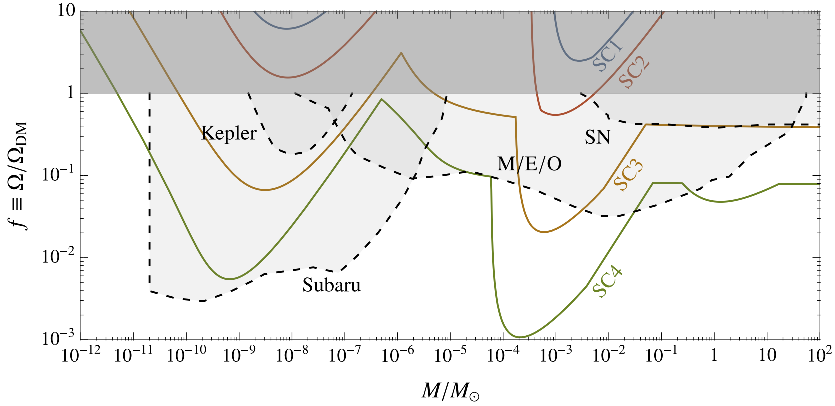


Doppler static search limits

- "SC4": Current + SKA

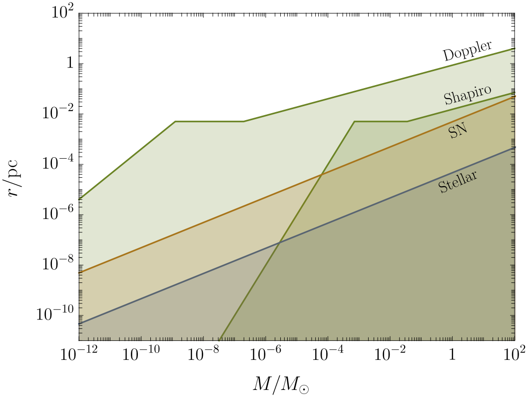


- Putting it all together...



Sensitivity radius

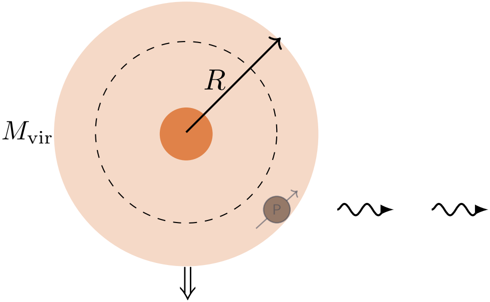
- Sensitivity radius for different searches: $r_{\mathrm{PTA}} \gg r_{\mathrm{lensing}}$



- Can see diffuse subhalos with pulsar timing

Sensitivity radius

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



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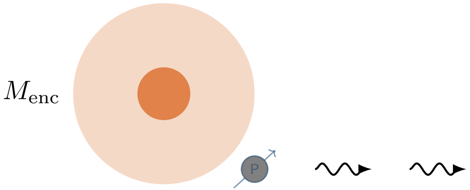
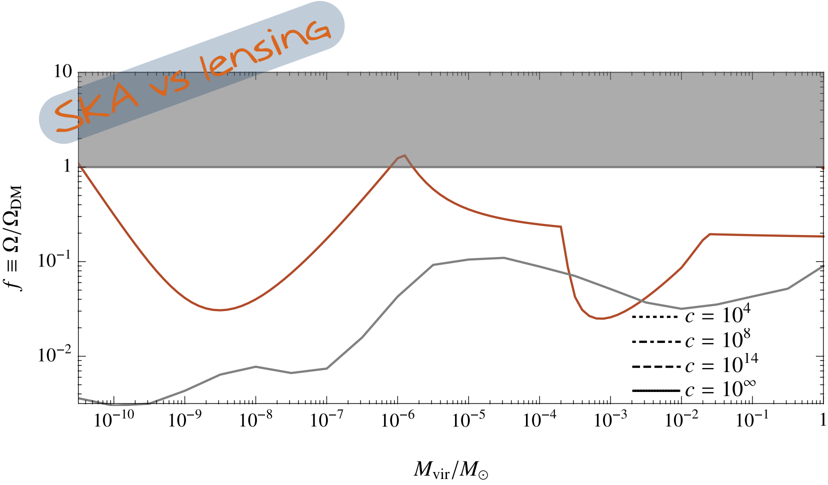
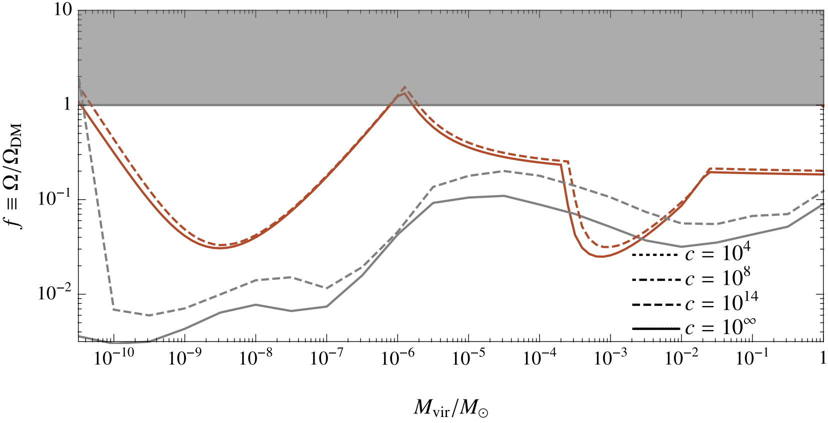


$\Downarrow$

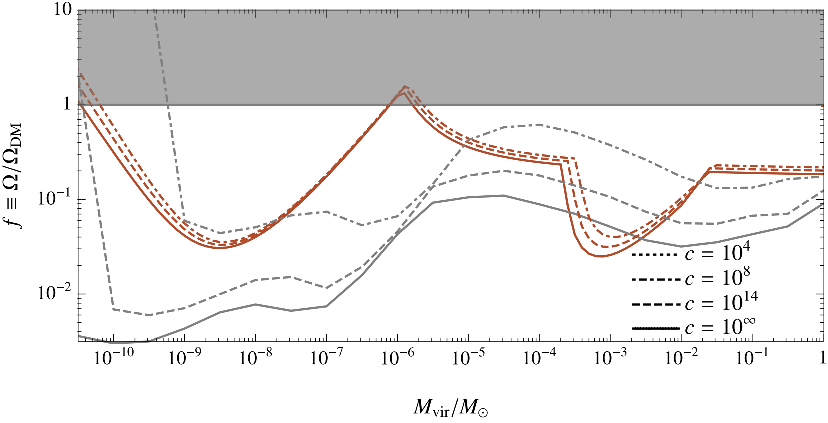
- $c \equiv r_{\rm vir}/r_s \to \infty$ (PBH)



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

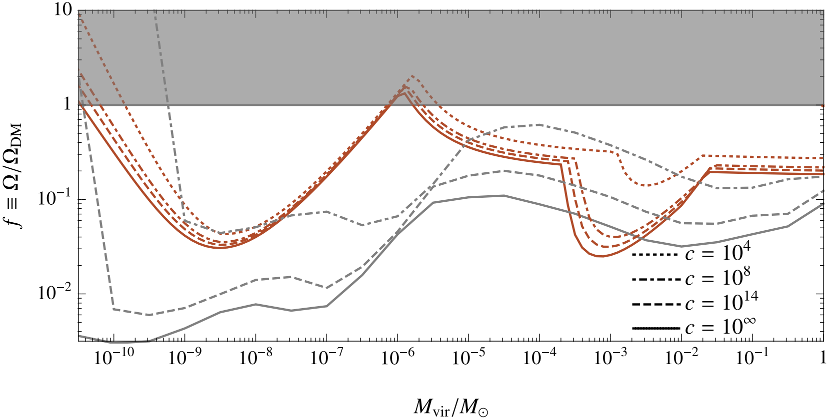


- $c \equiv r_{\rm vir}/r_s = 10^8$ (e.g., minicluster)



Constraints on diffuse subhalos

- $c \equiv r_{\rm vir}/r_s = 10^4$ (e.g., early matter dom)



Conclusion

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