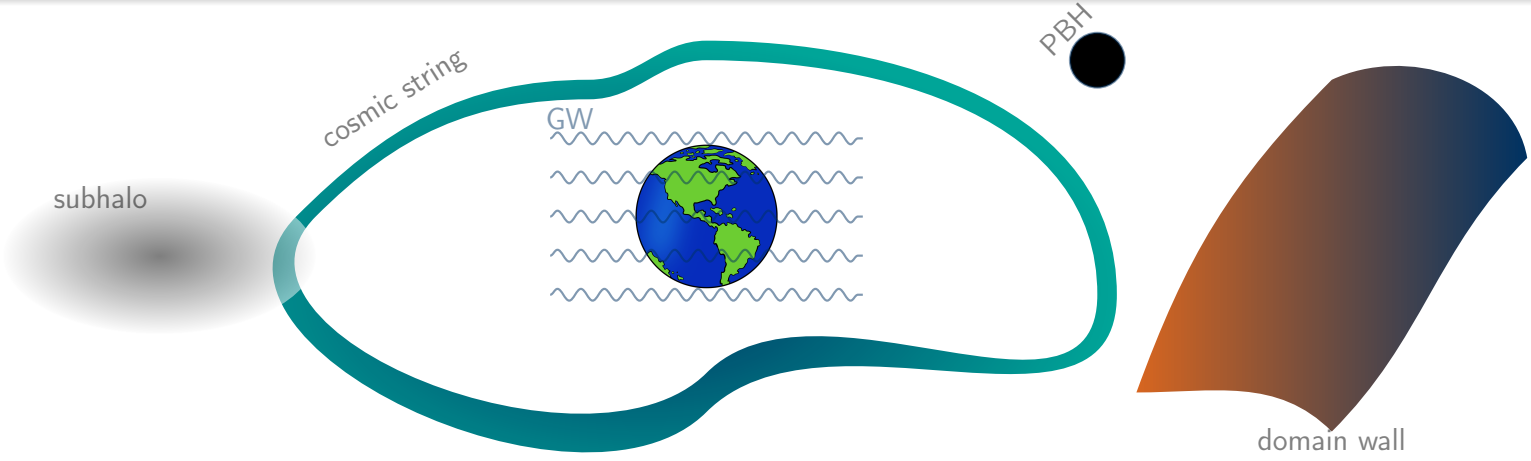
Remnants of the early universe

production and detection

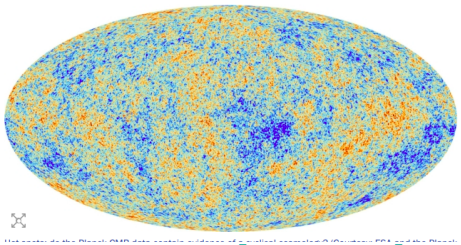
Jeff Dror

In collaboration with...
Eric Kuflik, Brandon Melcher, Scott Watson, ...
Avital Dery, Laurel Stevenson-Haskins, Yonit Hochberg,...
Harikrishnan Ramani, Tanner Trickle, Kathryn Zurek, ...



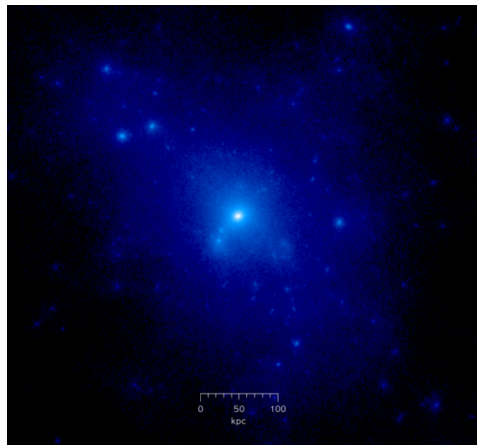
How smooth is our DM halo?

- DM halo our only structure?
- Lore: "DM is floating free paste"
- Gravitational collapse already produces subhalos...



[- Planck]

$$+ \qquad \rho_{\rm DM} + \rho_b > \rho_\gamma$$



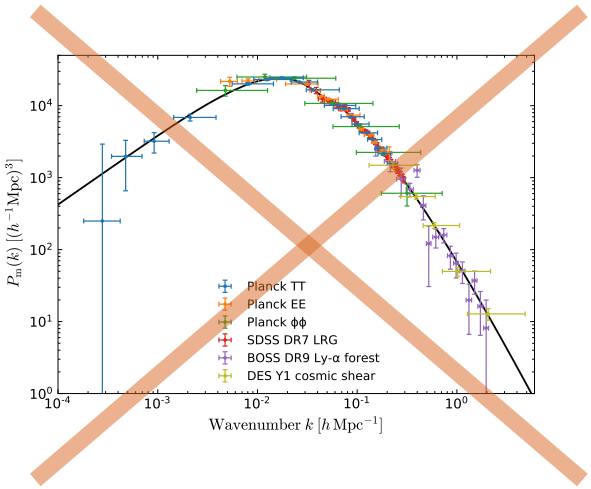
[- Wikipedia]

- Inflation + cold dark matter: diffuse structure on all scales

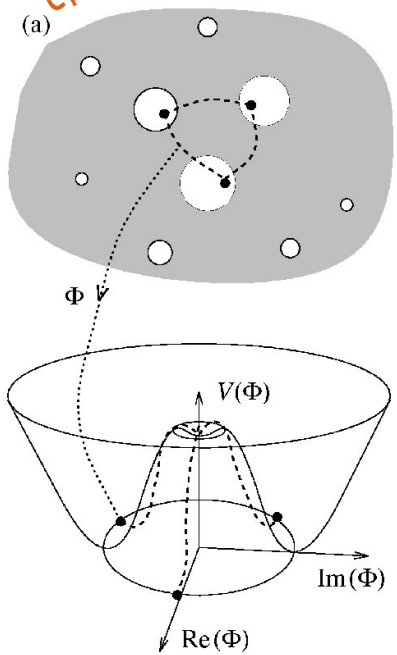
Sources of subhalos

- Different history ⇒ different substructure
- Sources of additional structure:

Broken primordial scale invariance

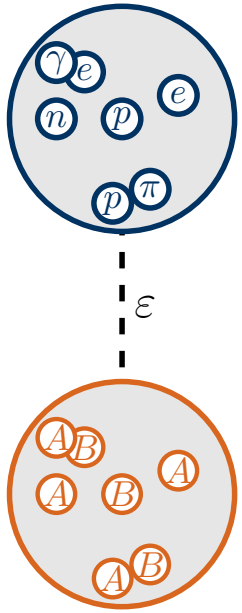


Phase transition



See talk by Graham

early matter domination



Why early matter domination?

- Motivation:
  - Dark matter freeze-out
    - e.g., *codecaying DM*
  - Dilute unwanted relics
  - Leptogenesis

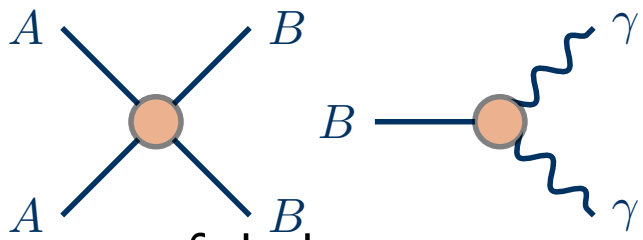
[0912.4415 - Bezrukov, H. Hettmansperger, M. Lindner]
[1507.01977 - Patwardhan, Fuller, Kishimoto, Kusenko]
[1607.03110 - Dror, Kuflik, Ng]
[1711.04773 - JD, Kuflik, Melcher, Watson]
[1901.02018 - Dery, Dror, Haskins, Hochberg, Kuflik]
[1910.06319 - Evans, Ghalsasi, Gori, Tammaro, Zupan]

[1204.5477 - Bezrukov, A. Kartavtsev, M. Lindner]

- Implications depend on rest of universe...
  - WIMPs [hep-ph/0005123 - Giudice, Kolb, Riotto]
    [1106.0536 - Erickcek, Sigurdson]
    [1311.4034 - Barenboim, Rasero]
    [1405.7373 - Fan, Ozsoy, Watson]
    [1510.04291 - Erickcek, Sinha, Watson]
    [1910.08553 - Delos, Linden, Erickcek]
    [1906.00010 - Blanco, Delos, Erickcek, Hooper]
  - Axions [1807.07176 - Nelson, Xiao]
    [1808.01879 - Visinelli, Redondo]
    [1911.07853 - Blinov, Dolan, Draper]
  - Cosmic strings
    [1808.08968 - Cui, Lewicki, Morrissey, Wells]
  - PBH production
    [1902.04082 - Georg, Melcher, Watson]

Ex: Codecaying dark matter

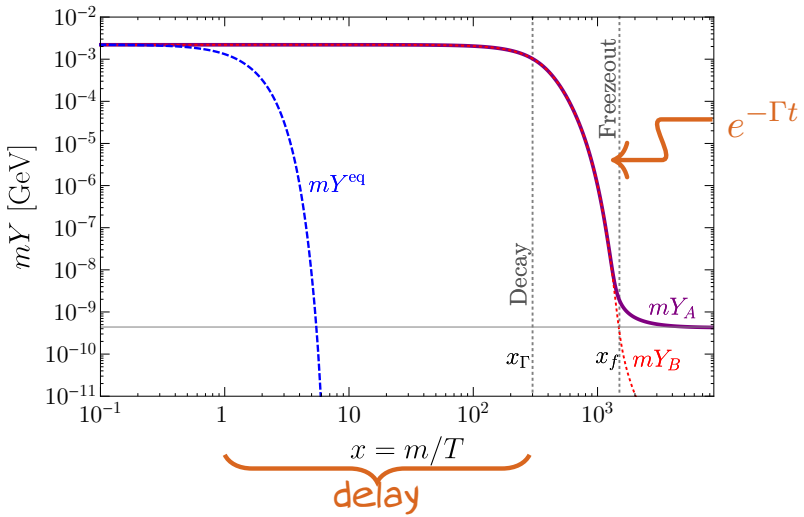
- Early matter domination needed for dark matter?
- Weak connection to SM

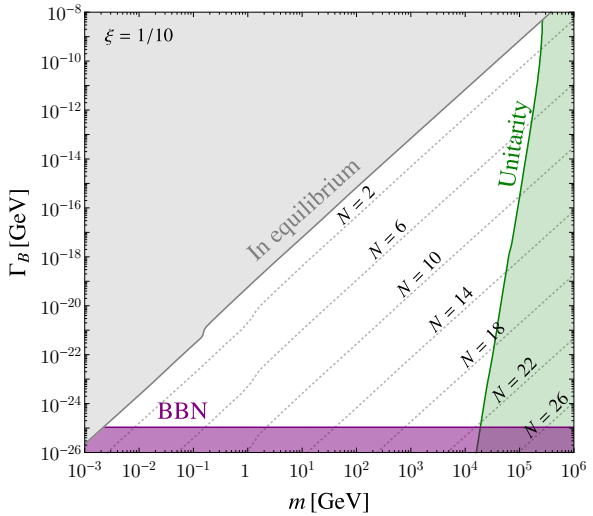


$$m_A \simeq m_B$$

- Decays drive thermal freezeout of dark matter
- Degeneracy $\Rightarrow$ relic abundace

[1607.03110 - JD, Kuflik, Ng]
[1607.03108 - Farina, Pappadopulo, Ruderman, Trevisan]
[1901.02018 - Dery, Dror, Haskins, Hochberg, Kuflik]

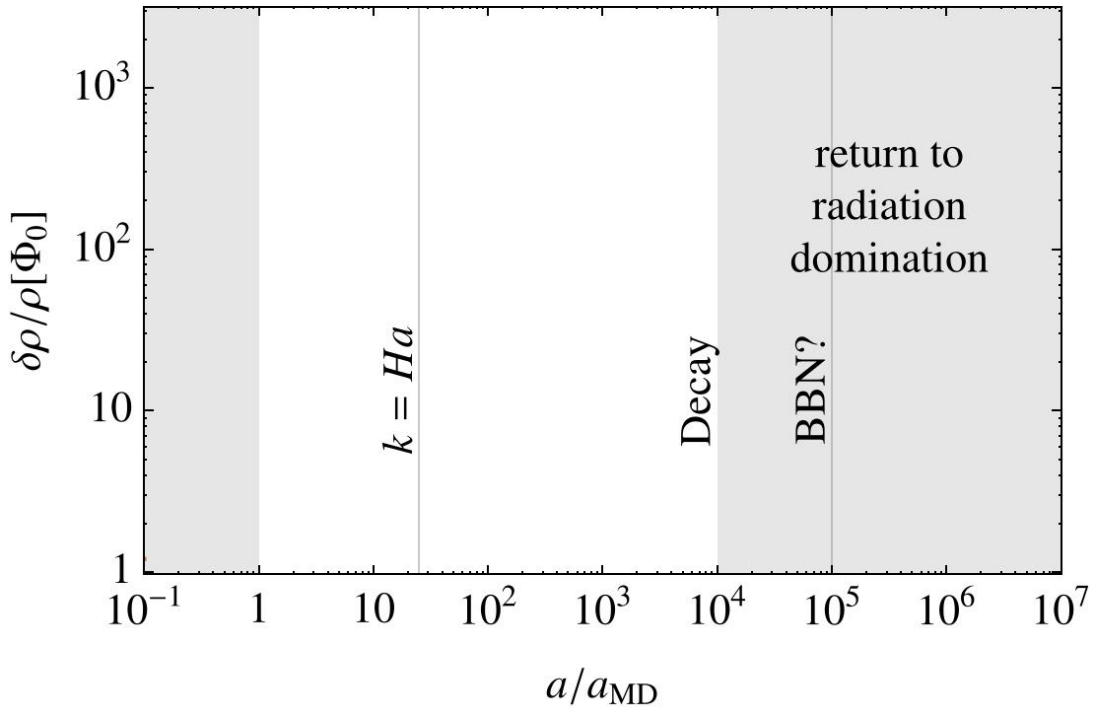




Growing perturbations

- Modes grow rapidly with scale factor

[1106.0536 - Erickcek, Sigurdson]
[1911.07853 - JD, Kuflik, Melcher, Watson]



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Growing perturbations

- Modes grow rapidly with scale factor

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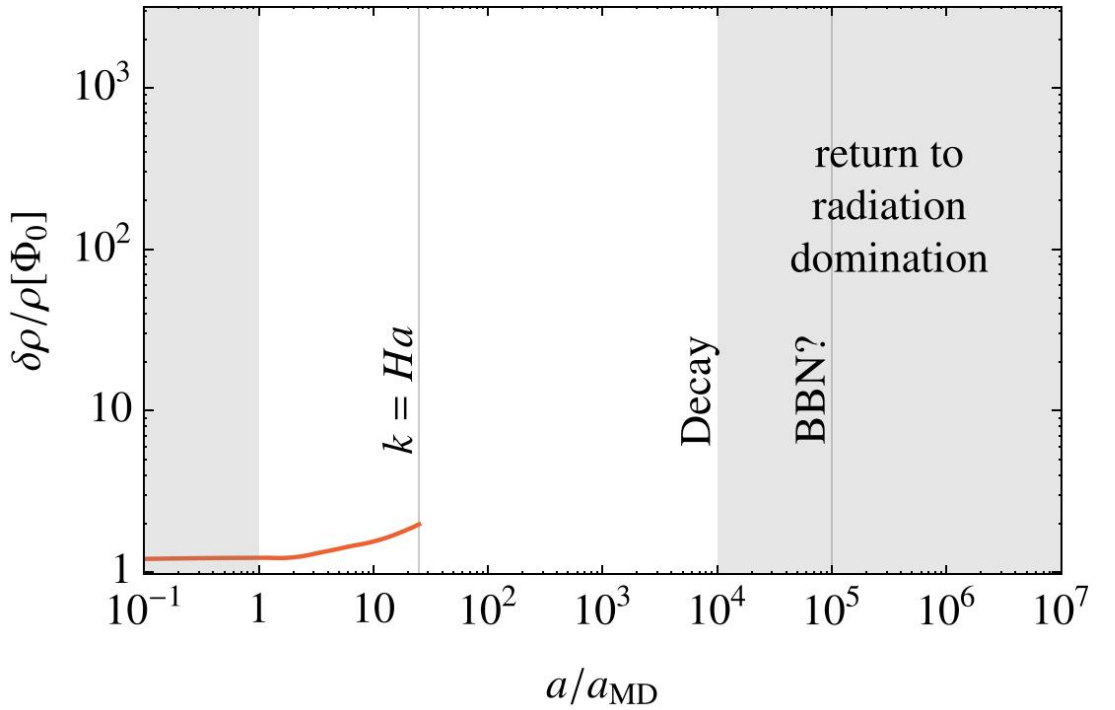
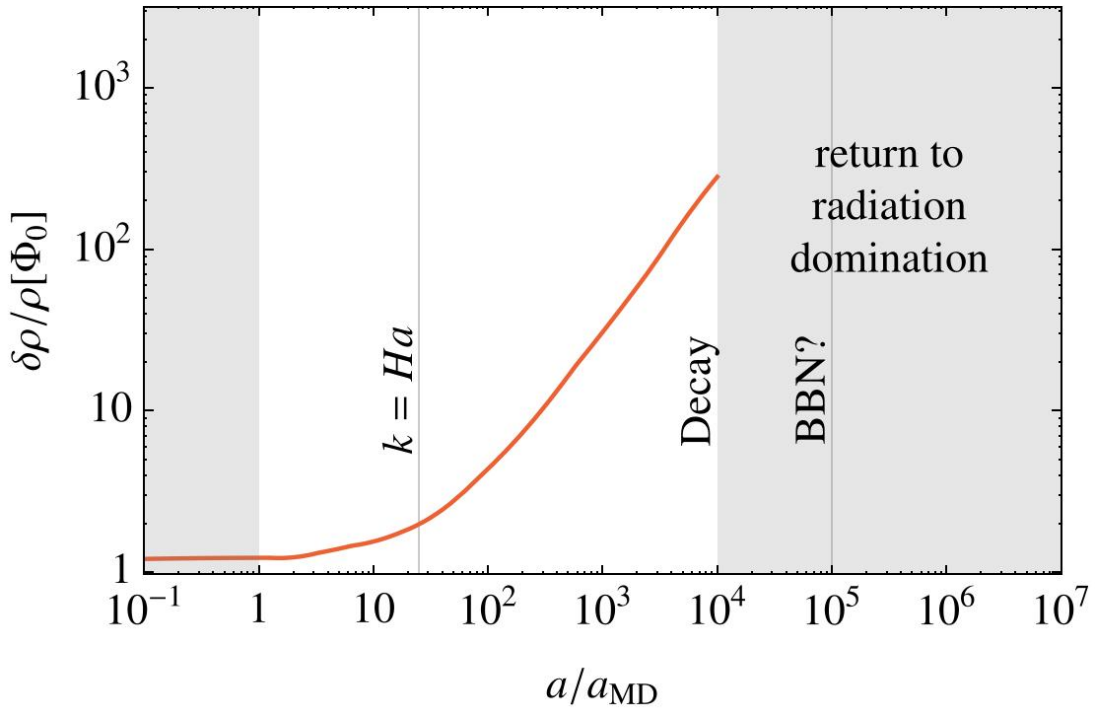


- Limited growth during radiation domination

Growing perturbations

- Modes grow rapidly with scale factor

[1106.0536 - Erickcek, Sigurdson]
[1911.07853 - JD, Kuflik, Melcher, Watson]

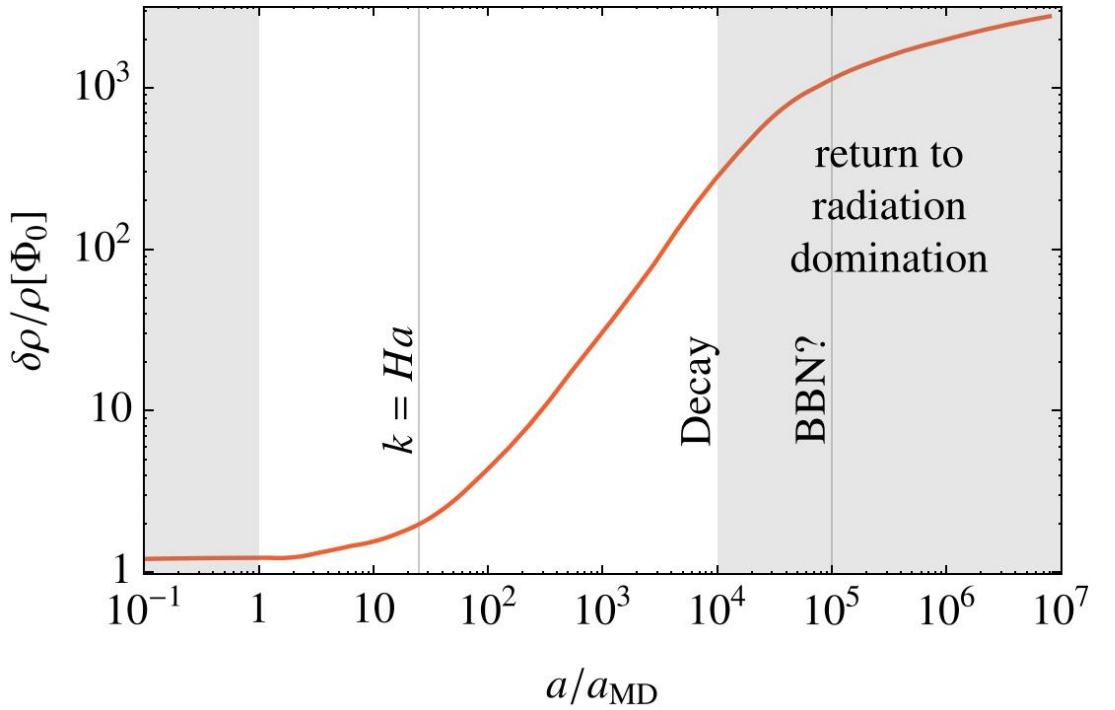


- Modes with $k > a_{\rm dec} H_{\rm dec}$ grow as they enter horizon

Growing perturbations

- Modes grow rapidly with scale factor

[1106.0536 - Erickcek, Sigurdson]
[1911.07853 - JD, Kuflik, Melcher, Watson]

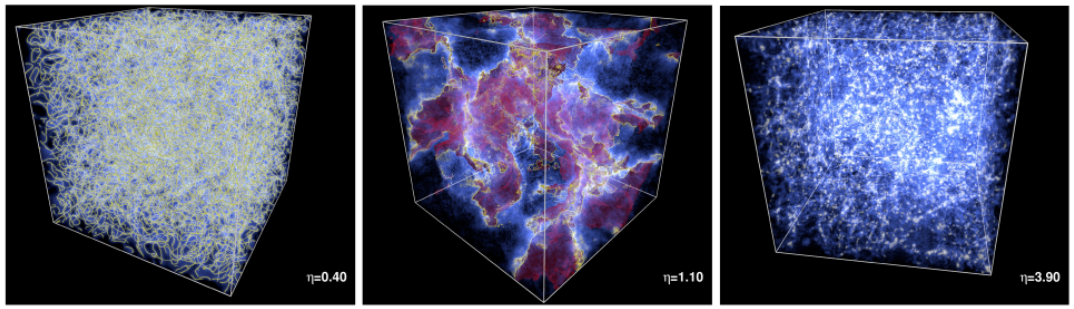


- Growth ceases upon dark matter freeze-out

Maneuvering non-linearities

- Modes with $\delta\rho/\rho \gtrsim 1$ collapse
- How to predict spectrum?
- Some attempts to use simulations for ultra light subhalos

[hep-ph/9303313 - Kolb, Tkachev]
[1906.00967 - Buschmann, Foster, Safdi]



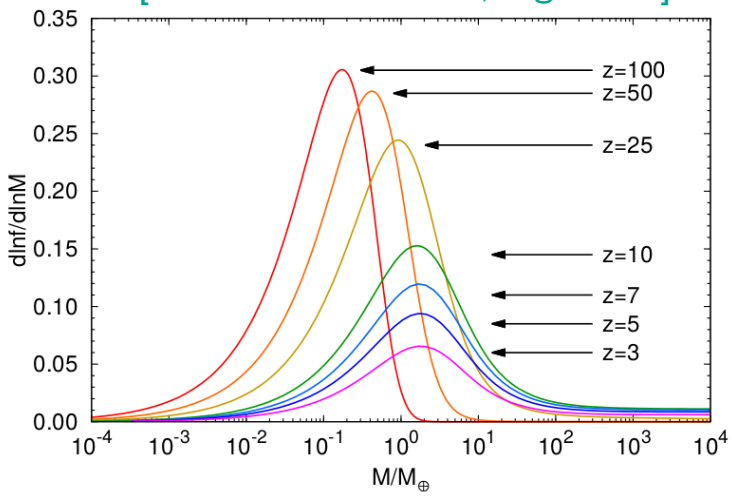
- Quick and dirty: Press-Schector formalism
  - uses linear theory as input for non-linear collapse
- Rough rough rough...

$$M \sim \rho_{\rm DM}(z_{\rm dec}) H(z_{\rm dec})^{-3} \sim 30 M_\oplus \left(\frac{z_{\rm dec}}{10 z_{\rm BBN}}\right)^3$$

What do we see today?

- Primordial spectrum:

[1106.0536 - Erickcek, Sigurdson]



Big questions:

① Collision damp (kin. decoupling?)

② Free stream (DM temperature?)

③ Tidal strip (halo-halo?)

- Showed substructure forms for codecay
- Generic feature of early matter domination
- Subhalos detection?

  (early matter domination or otherwise)

Detection

Detection

Pulsars as astrophysical clocks

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

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

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

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

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

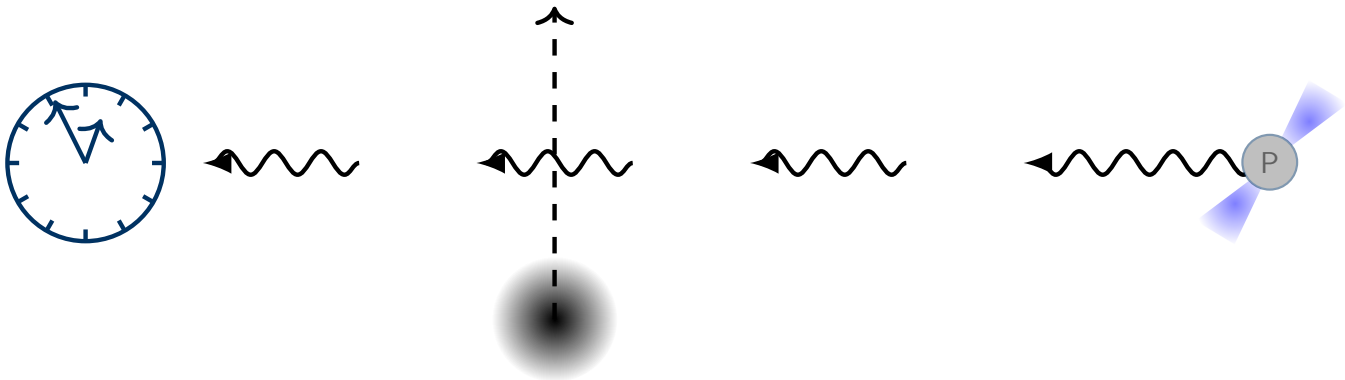
- DM induces "strain": $\delta\nu/\nu$?
- This work: additional signals, different regimes, unappreciated features

[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]

Effect on pulsar timing-Shapiro delay

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

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



- Induced time delay:

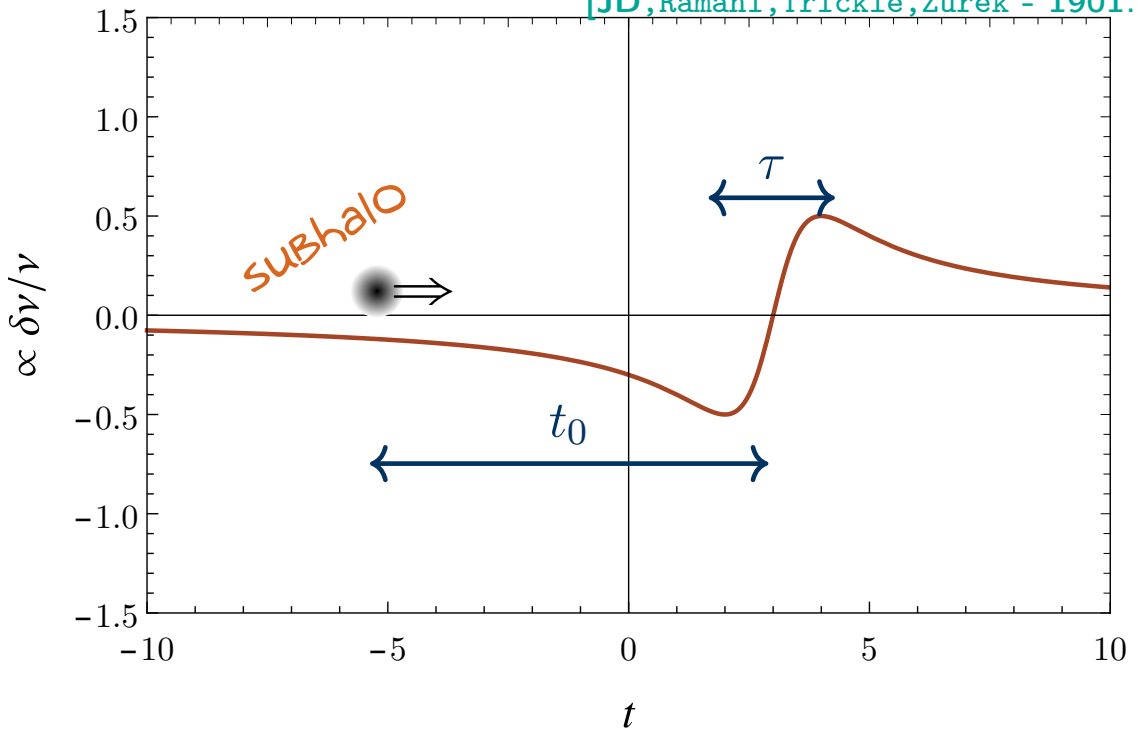
$$\delta t = 2\int dz \frac{GM}{r} \qquad \Longrightarrow \qquad \frac{\delta\nu}{\nu} = \dot{\delta t} = 2GM\int dz \frac{\dot{r}(t)}{r^2(t)}$$

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 ($x \equiv (t + t_0)/\tau$):

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

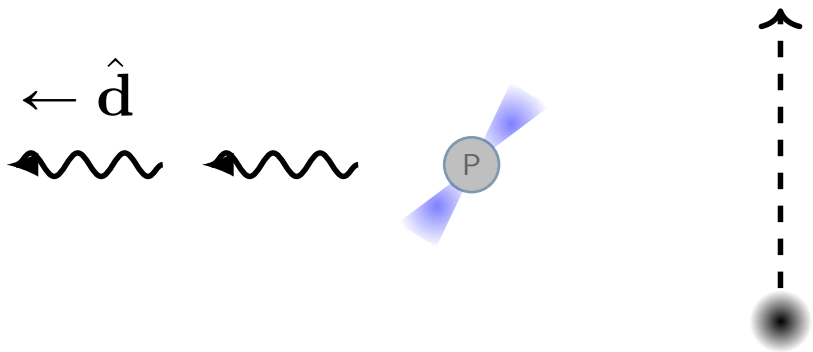
[JD, Ramani, Trickle, Zurek - 1901.04490]



Effect on pulsar timing - Doppler

- **Doppler effect**: gravitional pull on source/detector

  [Seto,Corray - astro-ph/0702586]



- Relative velocity between pulsar/Earth
- Strain:

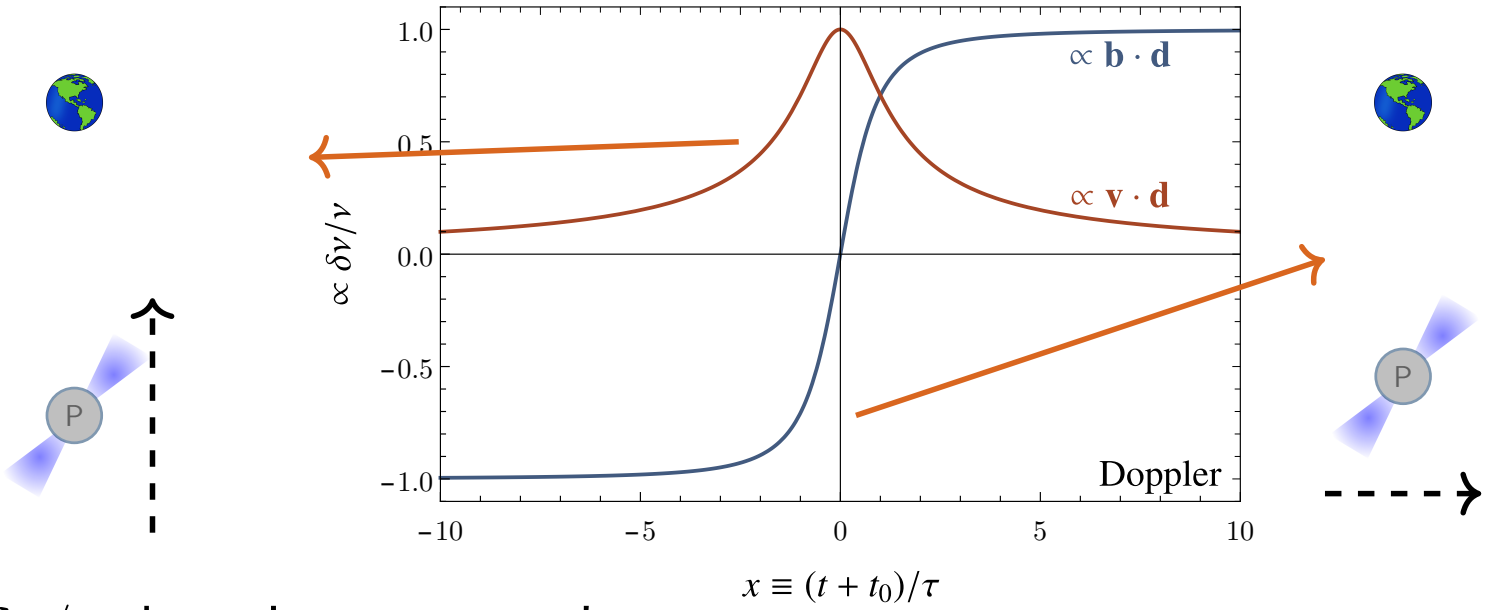
$$\frac{\delta\nu}{\nu} = \dot{\mathbf{r}}(t) \cdot \hat{\mathbf{d}}$$

- Two-body problem

Effect on pulsar timing - Doppler

- **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:

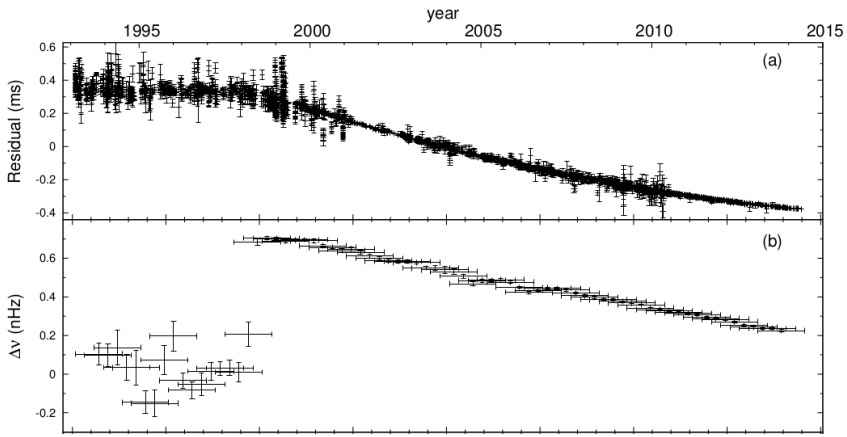
Space junk

TABLE 1
THE COSMIC ENERGY INVENTORY

Parameter		Components[a]
Dark sector:		
Dark energy		0.72 ± 0.03
Dark matter		0.23 ± 0.03
Primeval gravitational waves		$\lesssim 10^{-10}$
Primeval thermal remnants:		
Electromagnetic radiation		$10^{-4.3 \pm 0.0}$
Neutrinos		$10^{-2.9 \pm 0.1}$
Prestellar nuclear binding energy		$-10^{-4.1 \pm 0.0}$
Baryon rest mass:		
Warm intergalactic plasma		0.040 ± 0.003
Virialized regions of galaxies	0.024 ± 0.005	
Intergalactic	0.016 ± 0.005	
Intracluster plasma		0.0018 ± 0.0007
Main-sequence stars: spheroids and bulges	→	0.0015 ± 0.0004
Main-sequence stars: disks and irregulars	→	0.00055 ± 0.00014
White dwarfs	→	0.00036 ± 0.00008
Neutron stars	→	0.00005 ± 0.00002
Black holes	→	0.00007 ± 0.00002
Substellar objects	→	0.00014 ± 0.00007
H I + He I	→	0.00062 ± 0.00010
Molecular gas	→	0.00016 ± 0.00006
Planets	→	10^{-6}
Condensed matter	→	$10^{-5.6 \pm 0.3}$
Sequestered in massive black holes	→	$10^{-5.4}(1 + \epsilon_n)$

[Fukugita,Peebles - astro-ph/0406095]

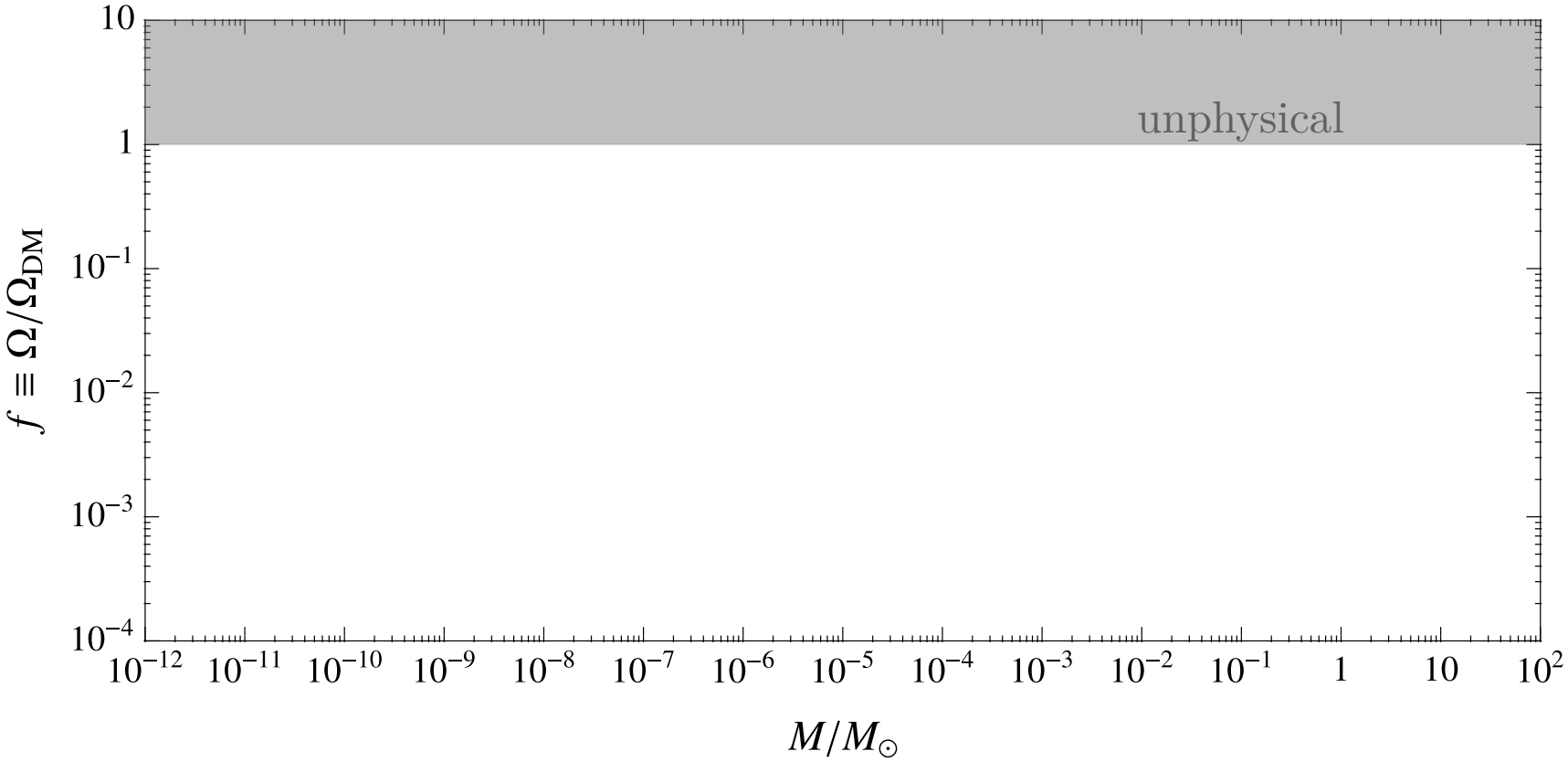
Glitches



[Mckee et al - 1606.04098]

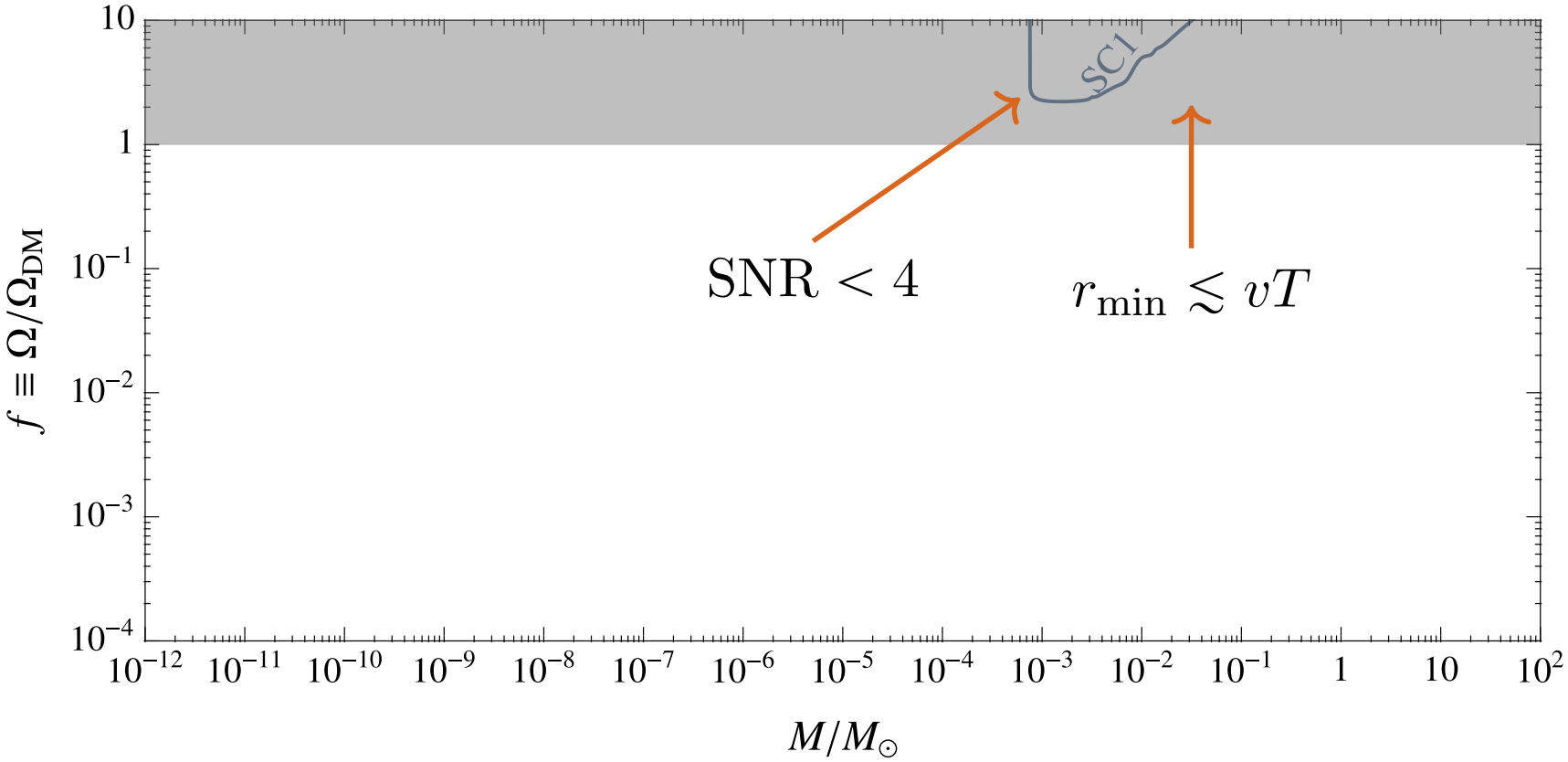
Shapiro dynamic search limits

- Putting on constraints:



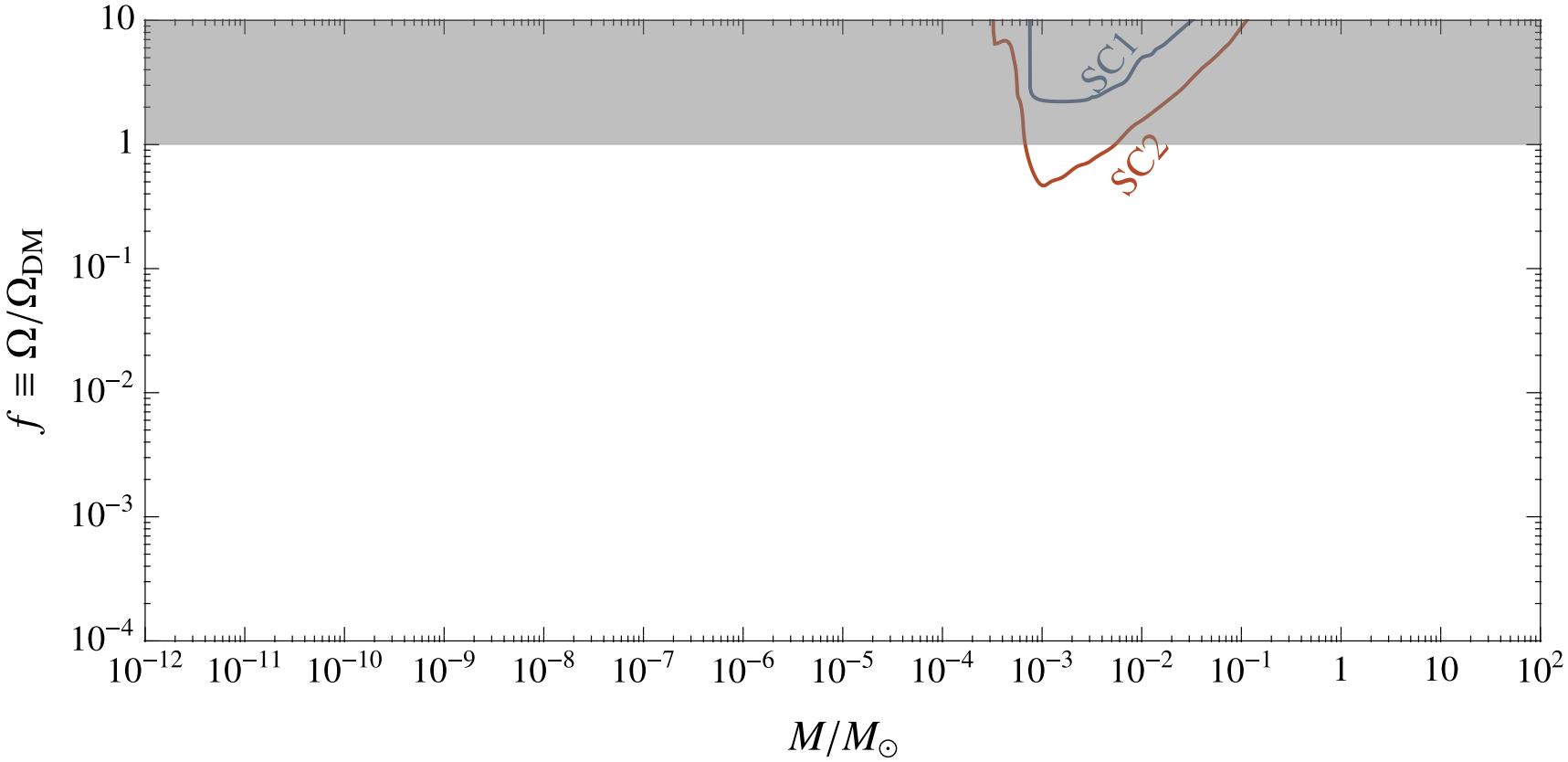
Shapiro dynamic search limits

- "SC1": Current pulsar limits:



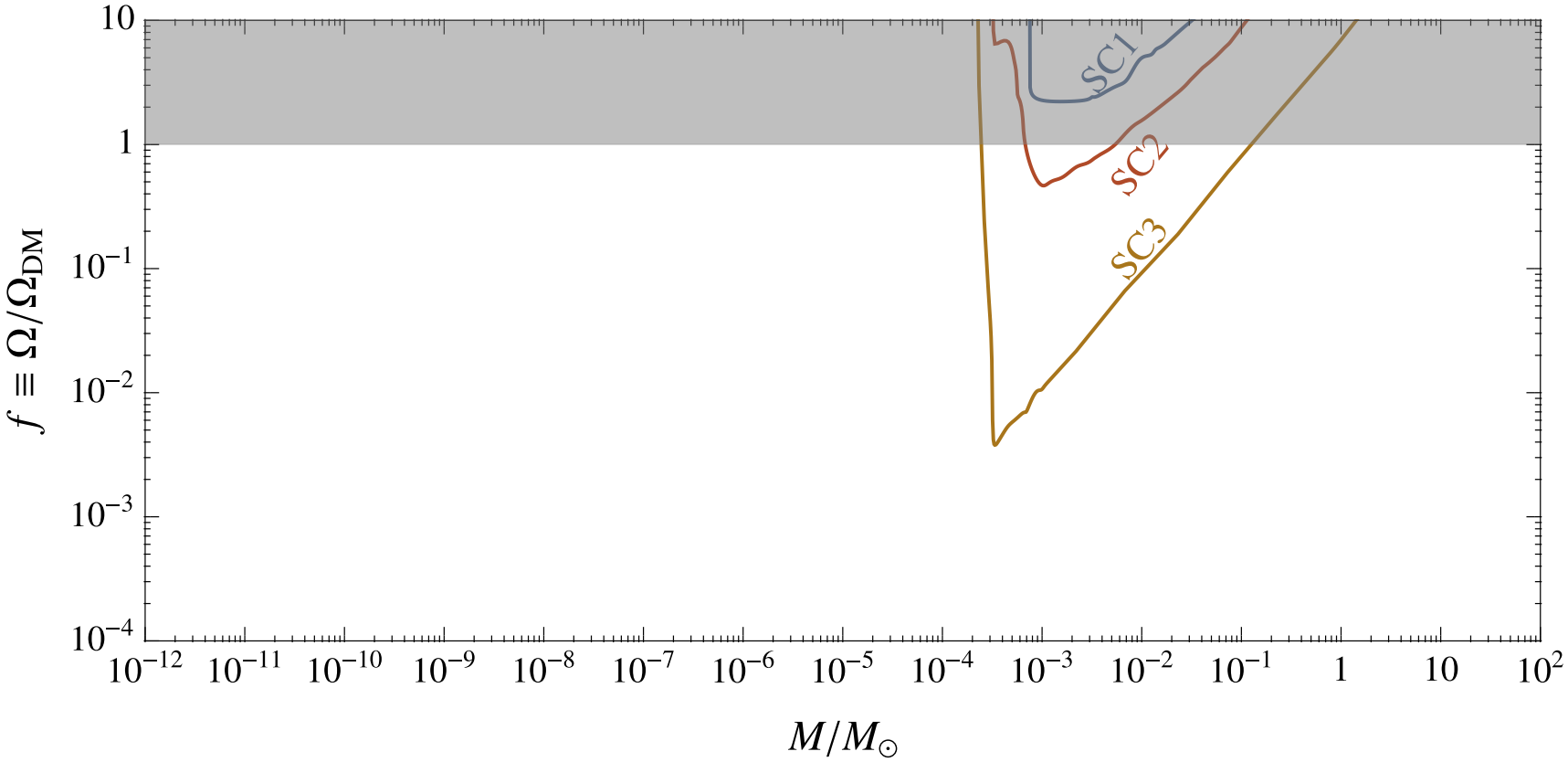
Shapiro dynamic search limits

- "SC2": Current pulsars + 10 years:



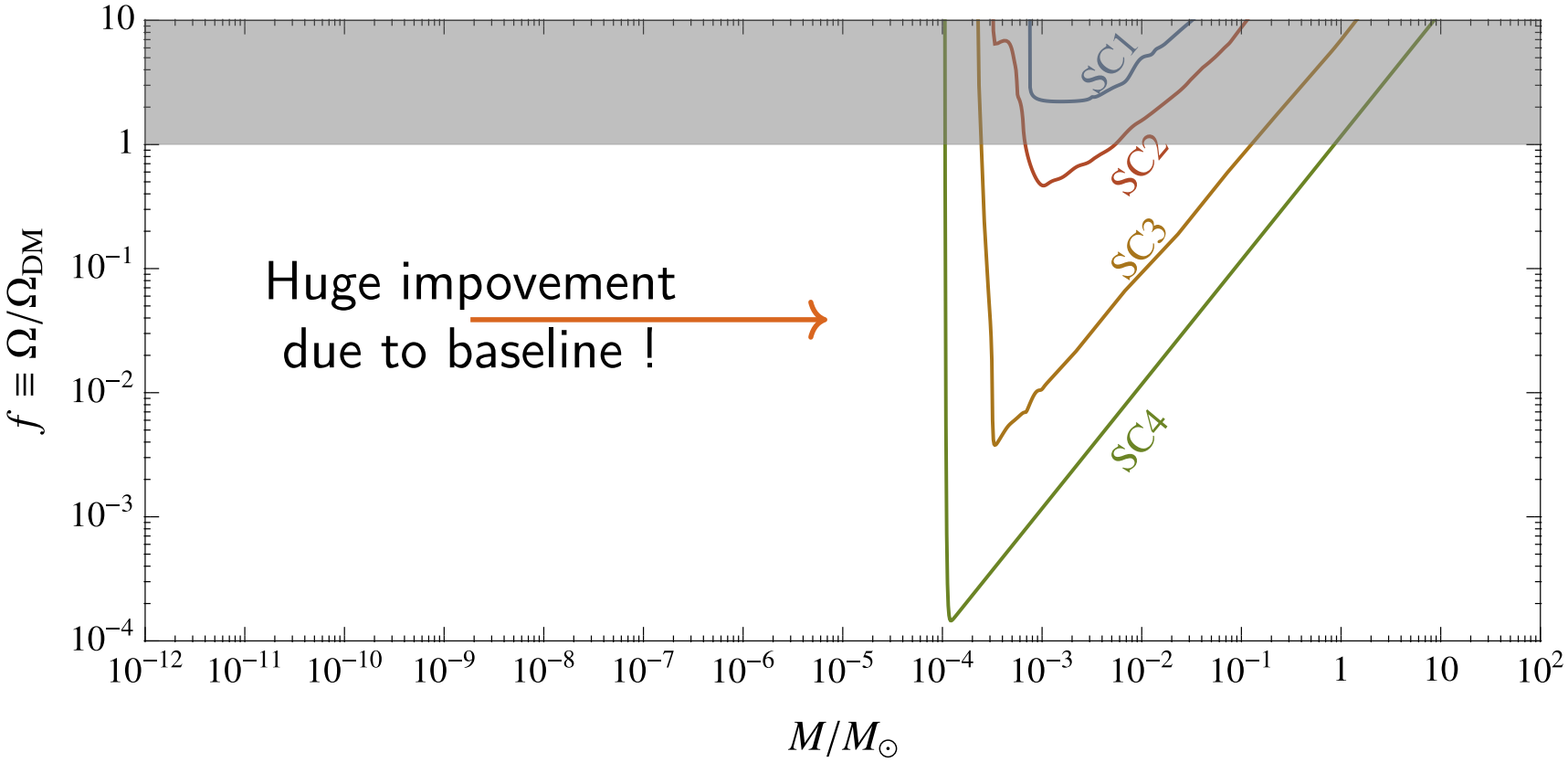
Shapiro dynamic search limits

- "SC3": Current + SKA (conservative)



Shapiro dynamic search limits

- "SC4": Current + SKA



Doppler dynamic search limits

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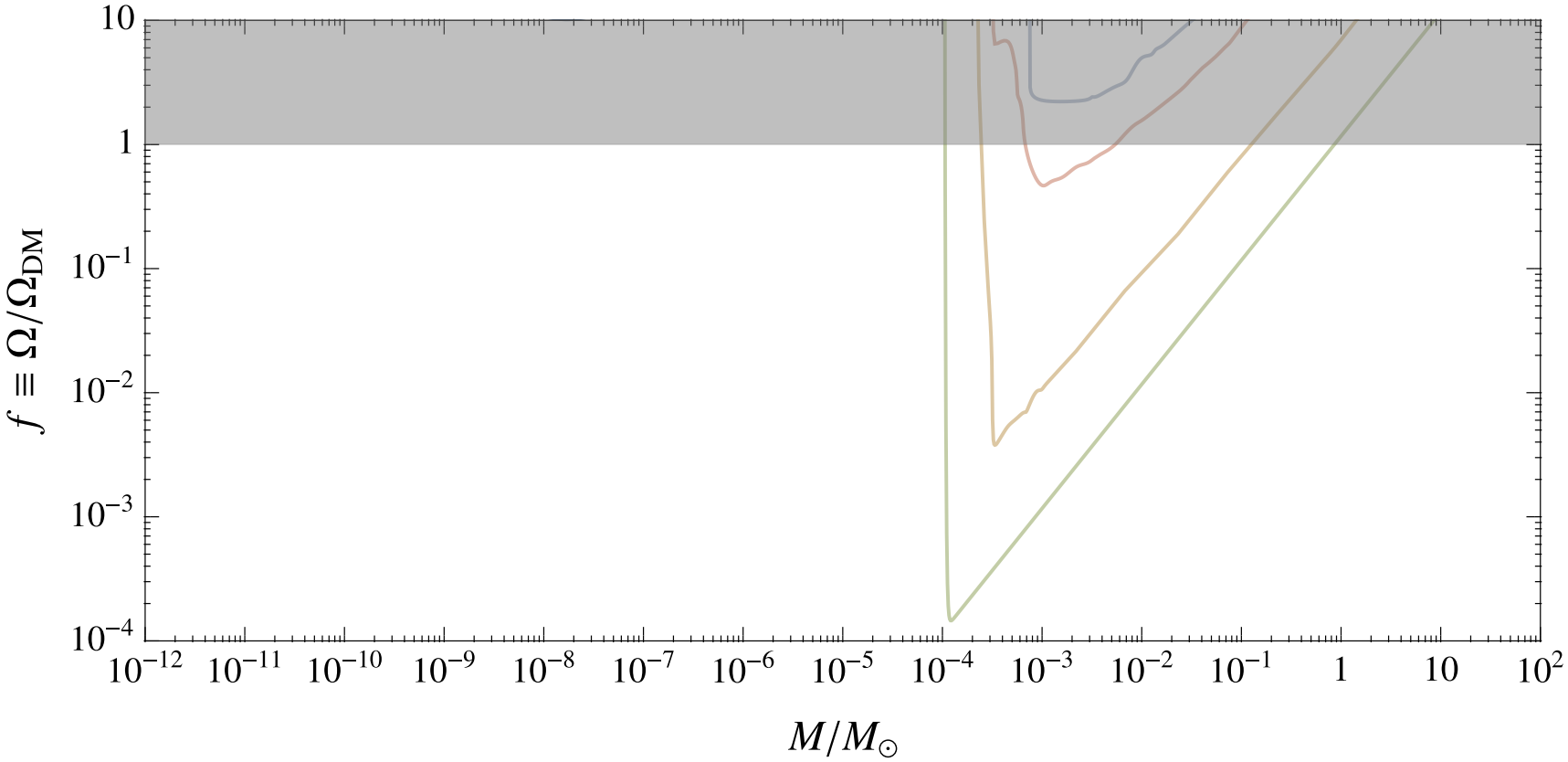

Doppler dynamic search limits

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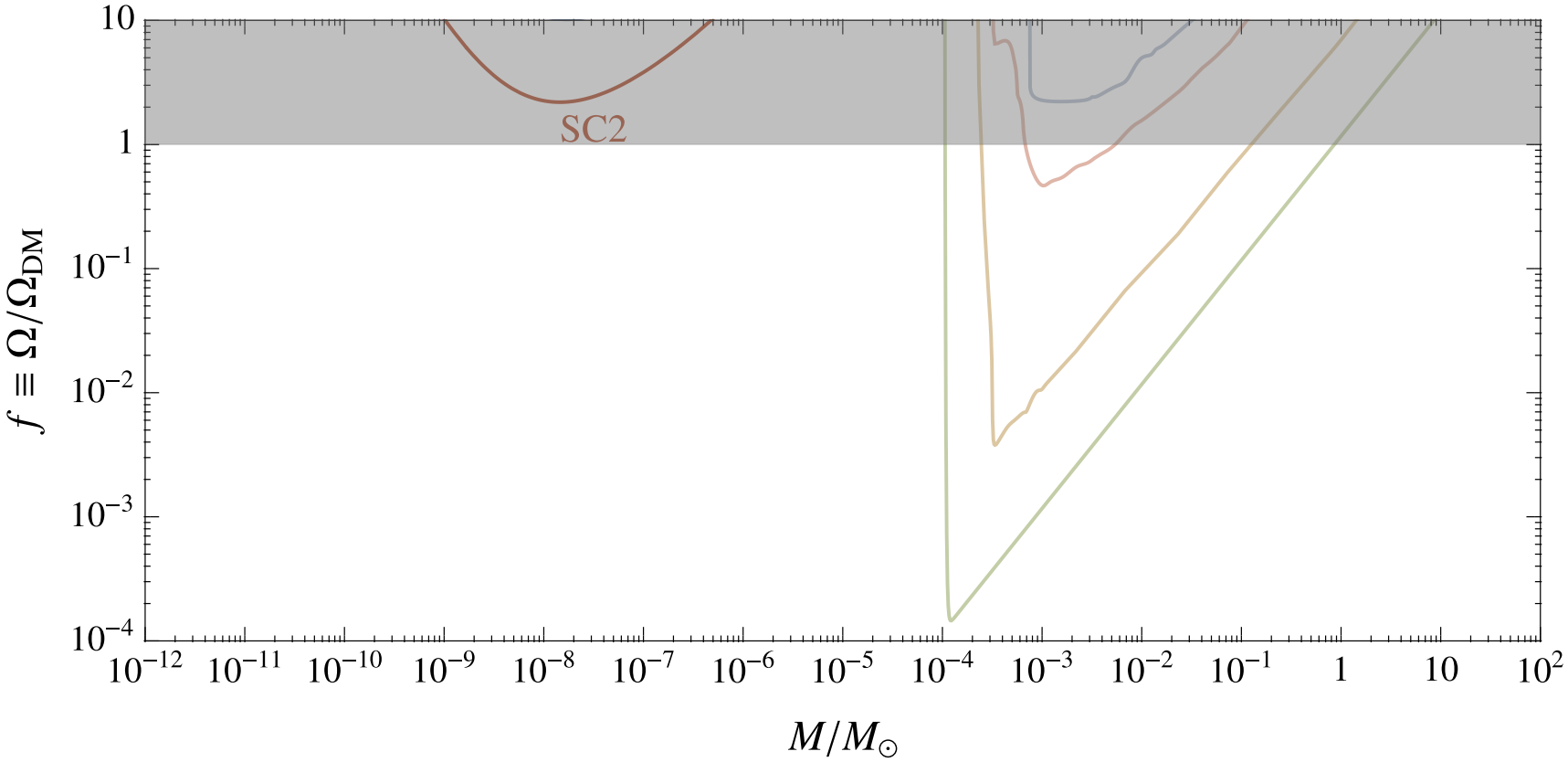

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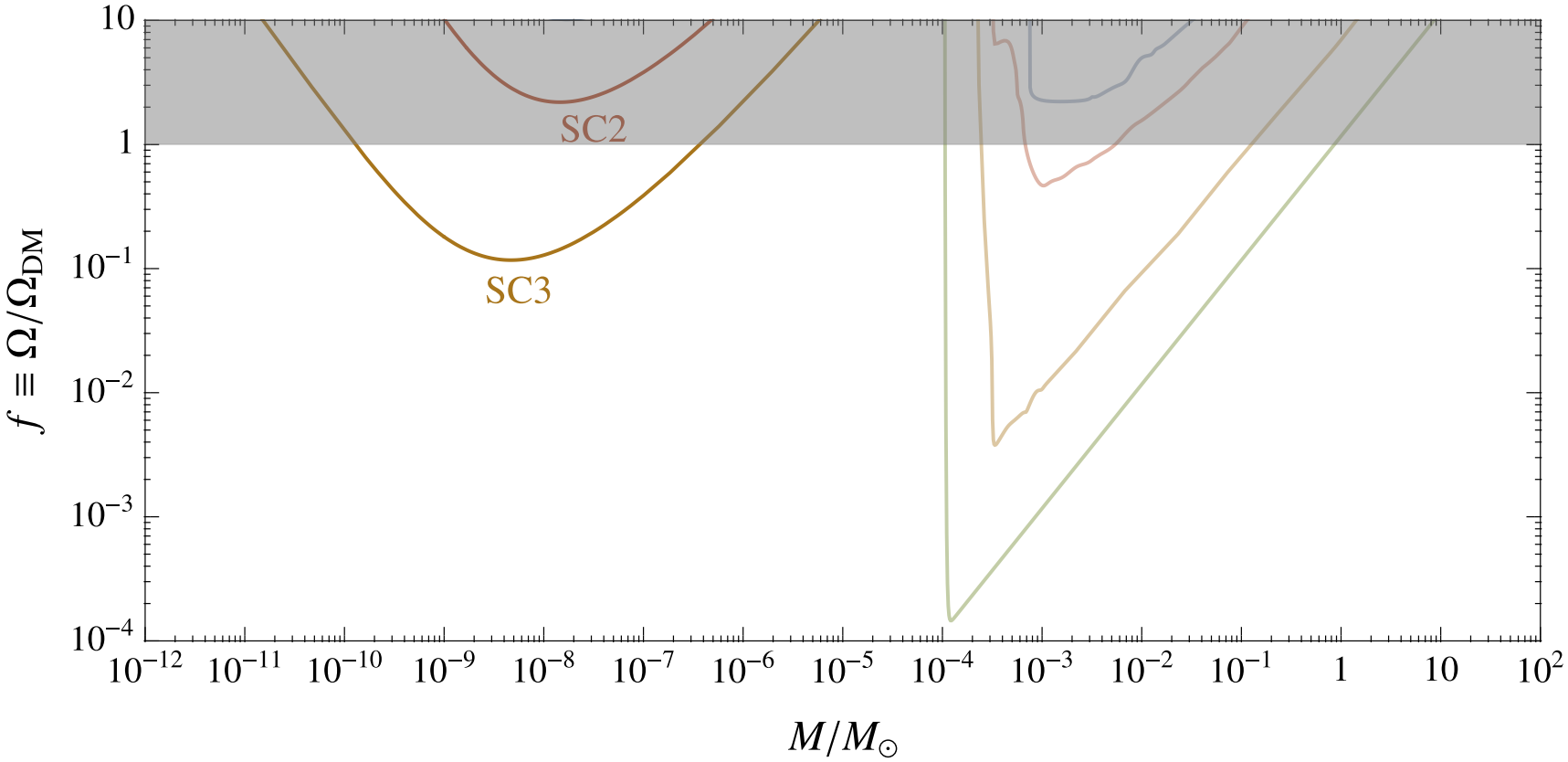
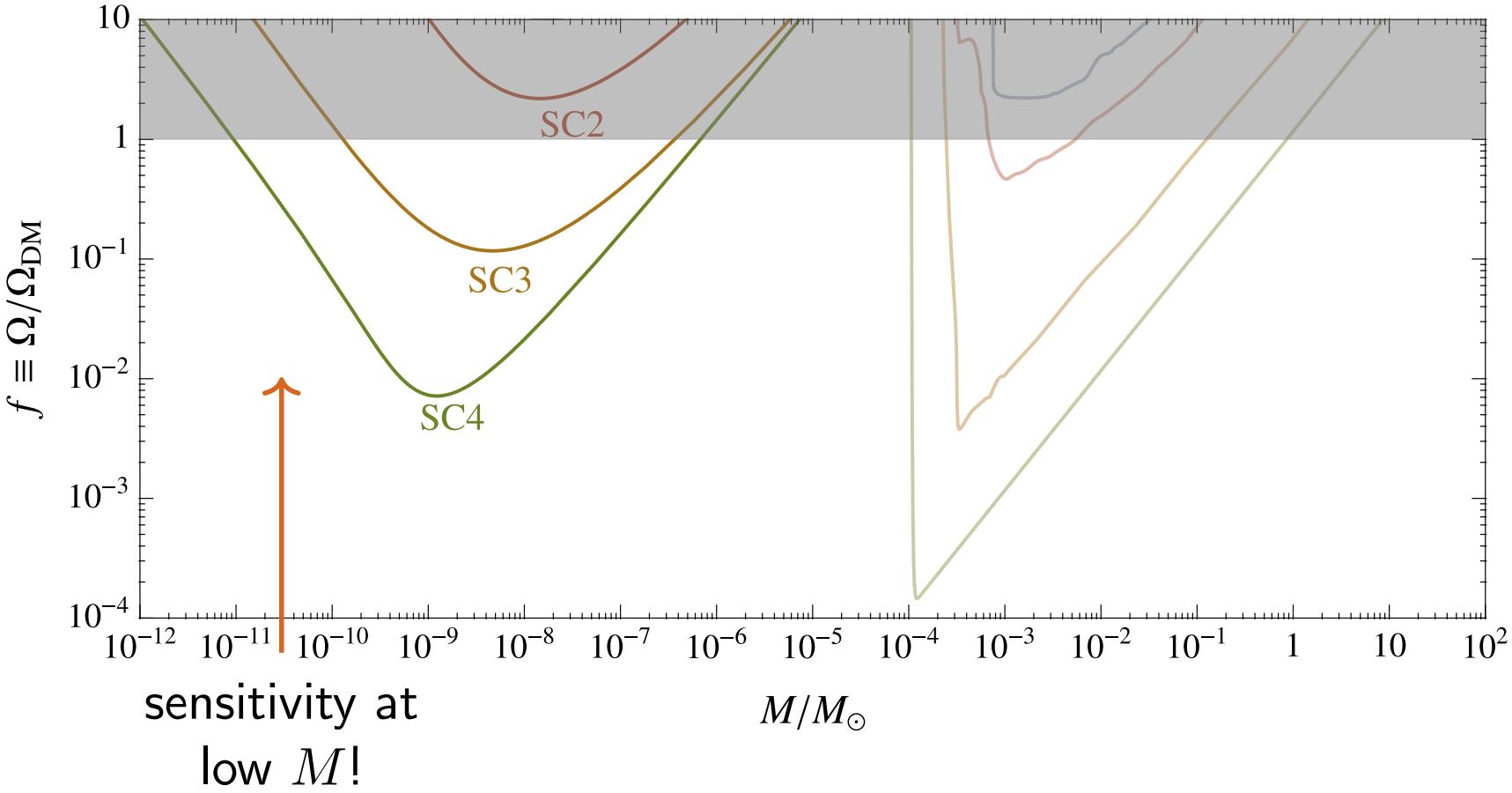


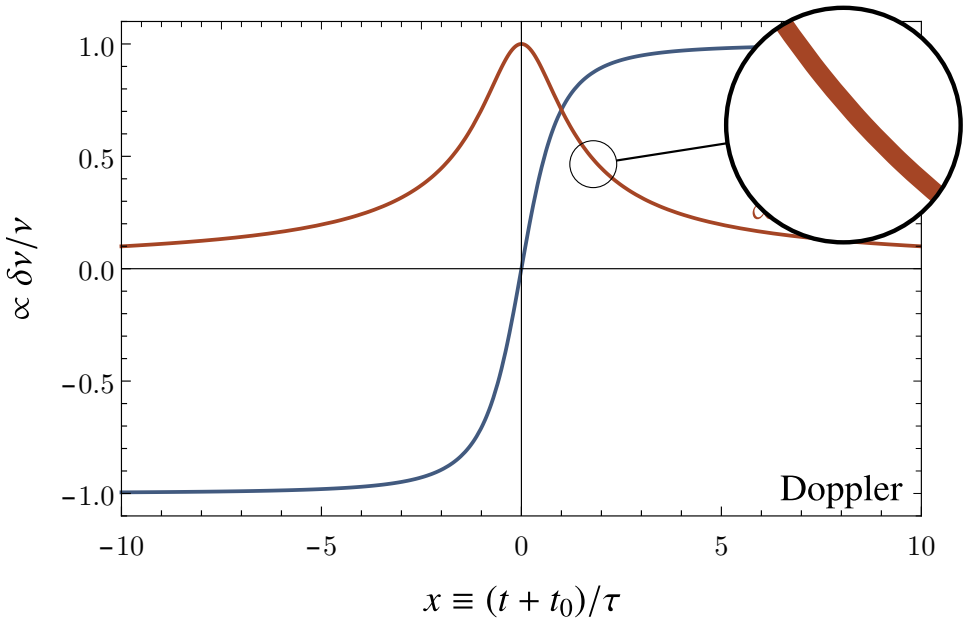
Doppler dynamic search limits

- "SC4": Current + SKA



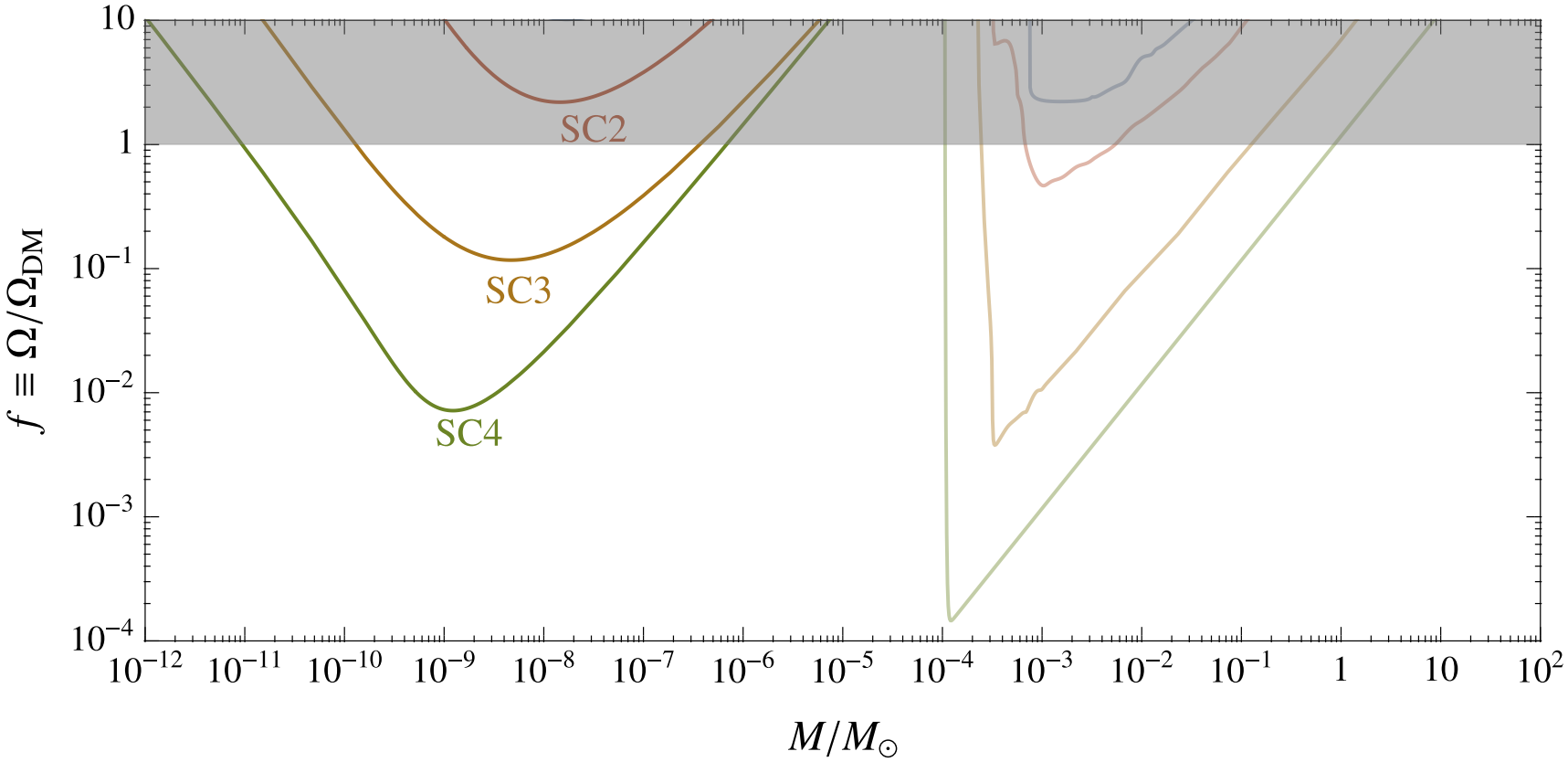
Static searches

- 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



Shapiro static search limits

- Putting on constraints:



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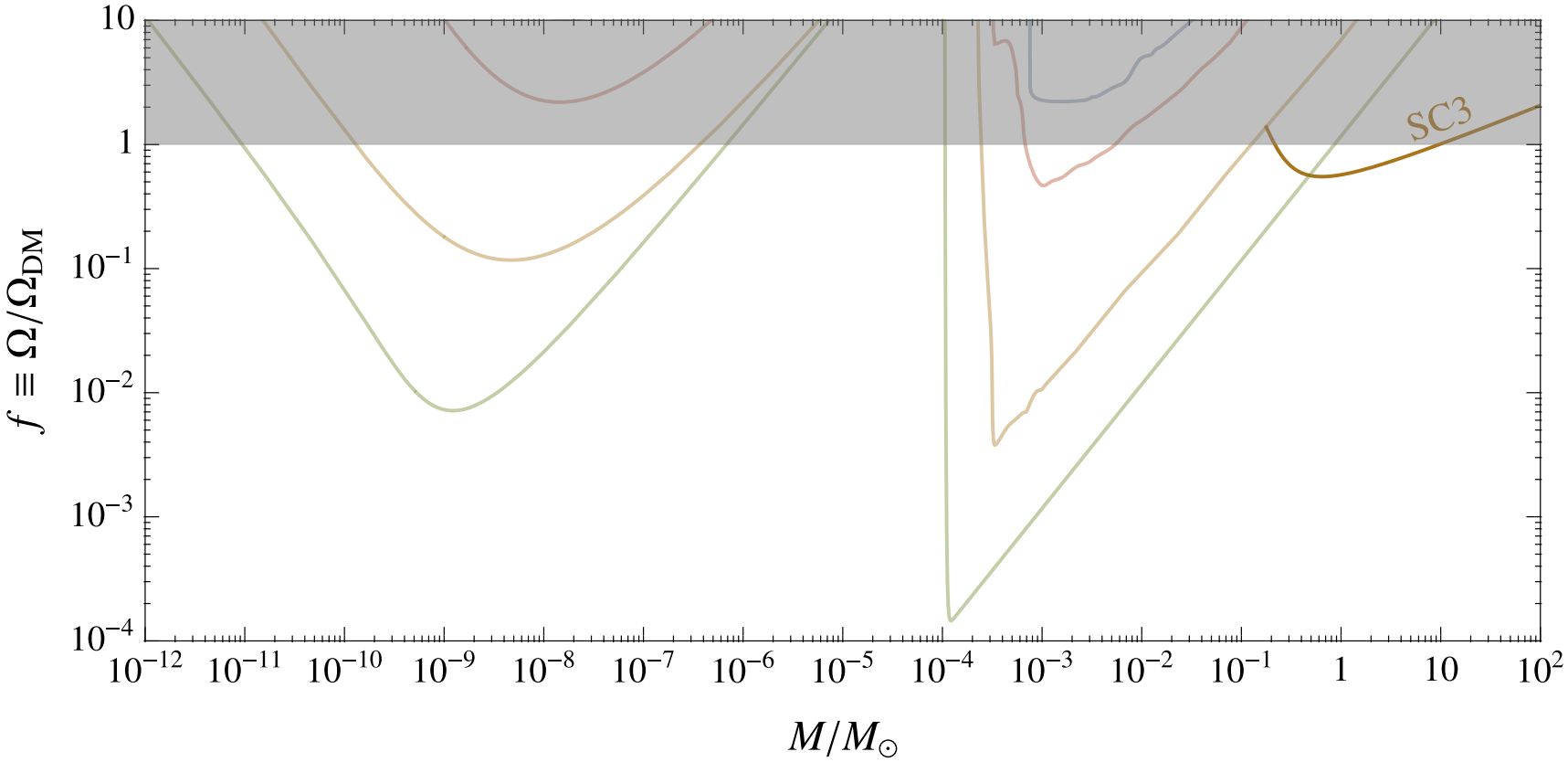
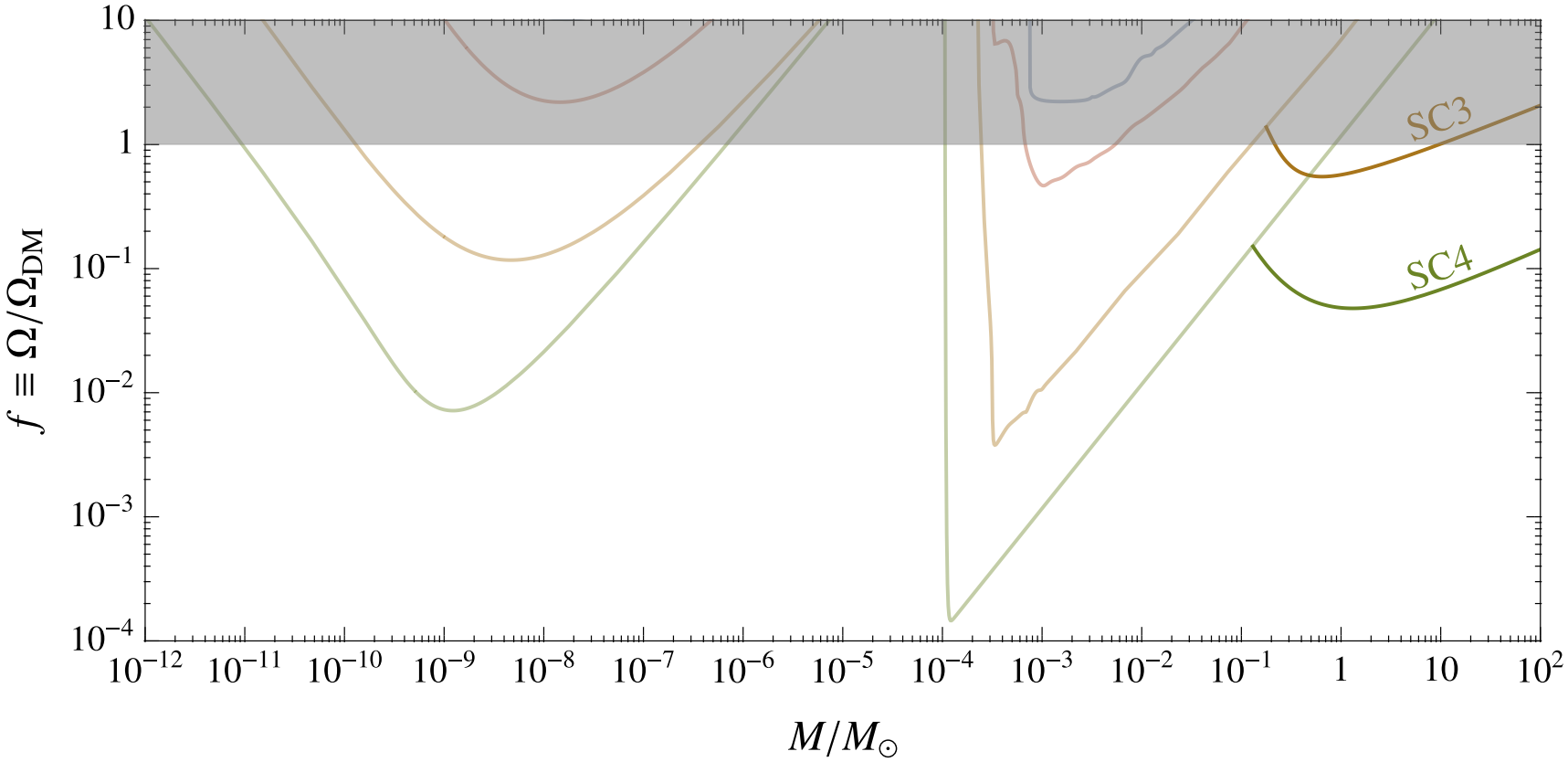


Shapiro static search limits

- "SC4": Current + SKA



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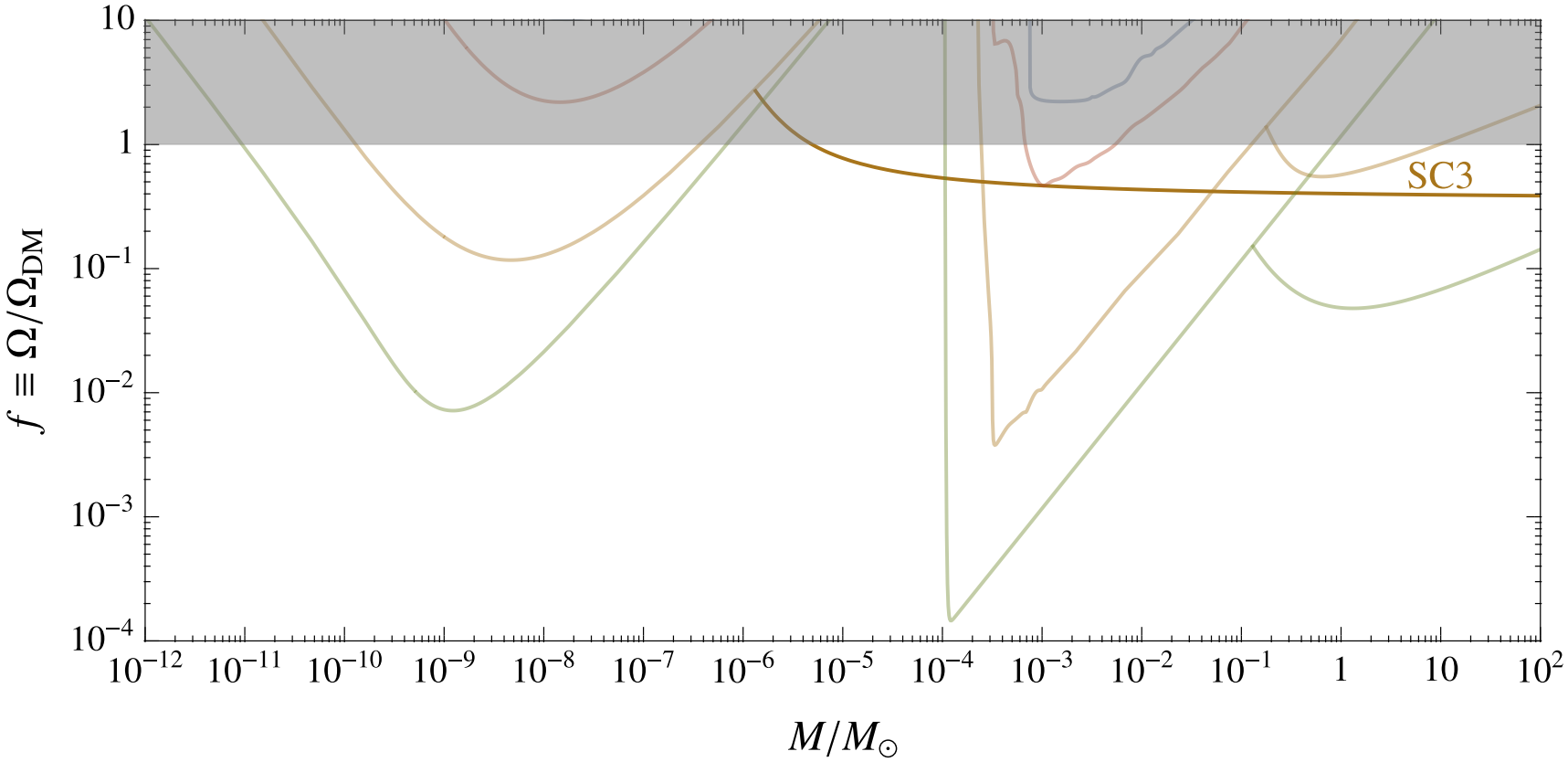

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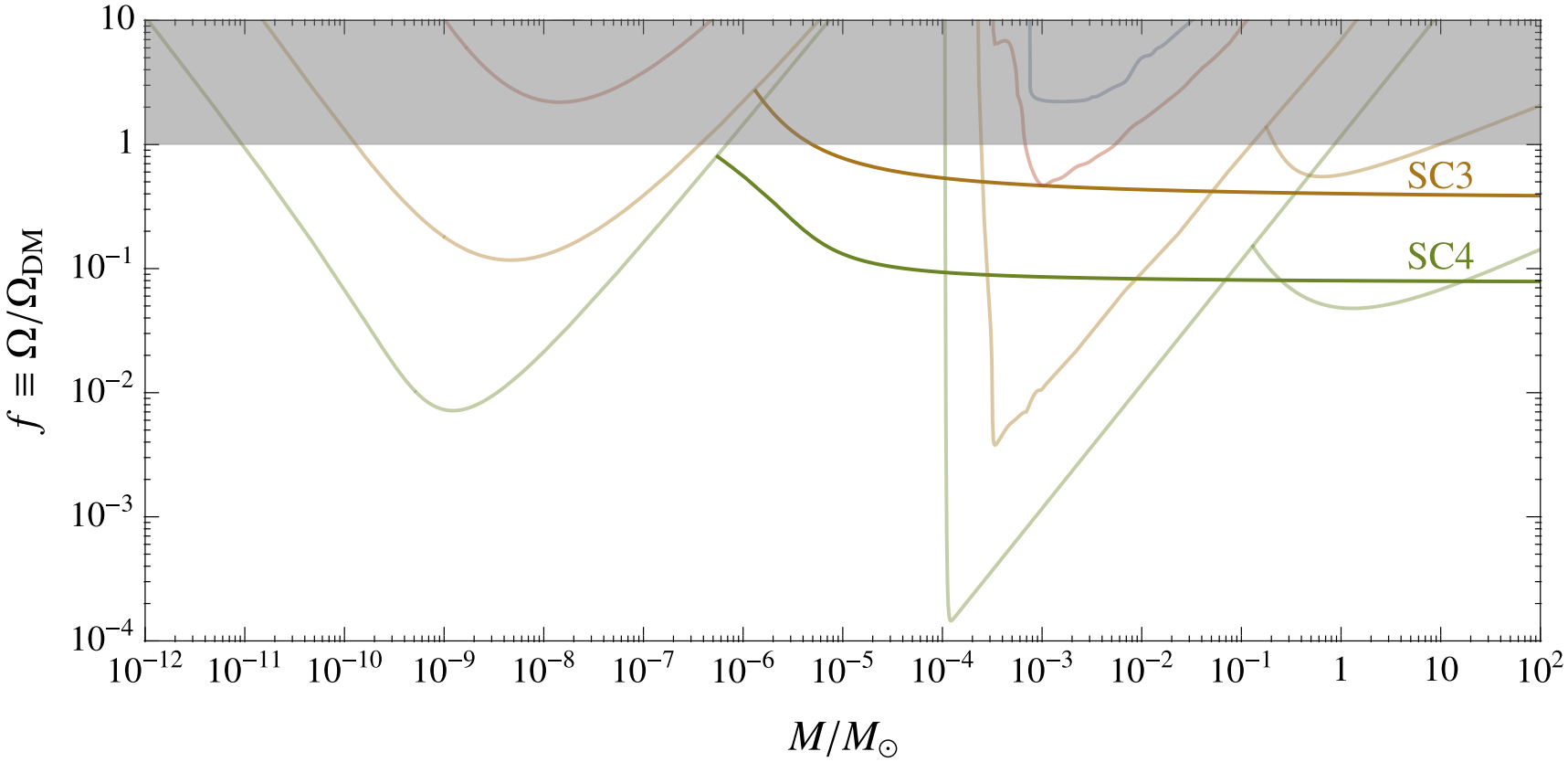
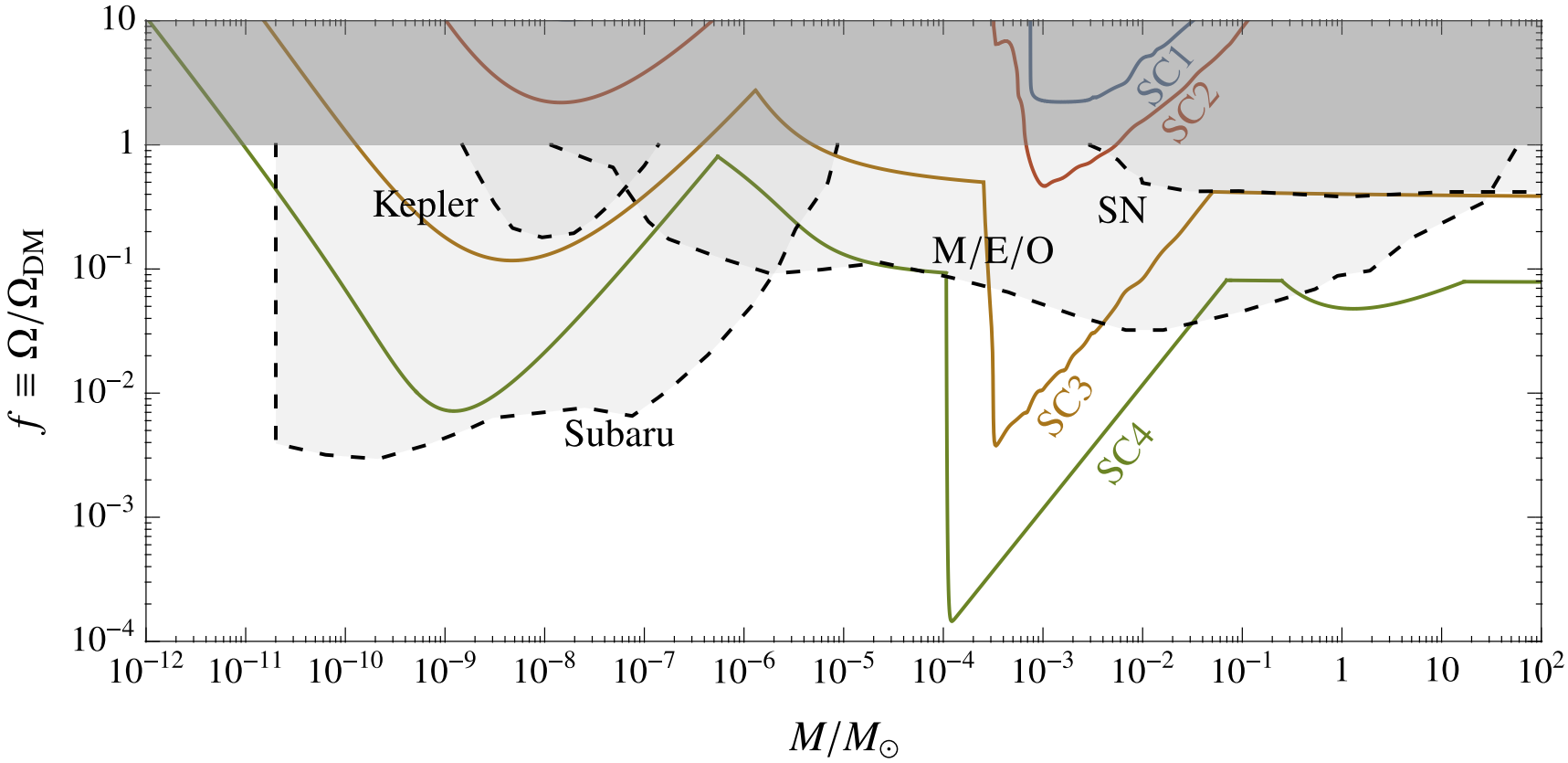


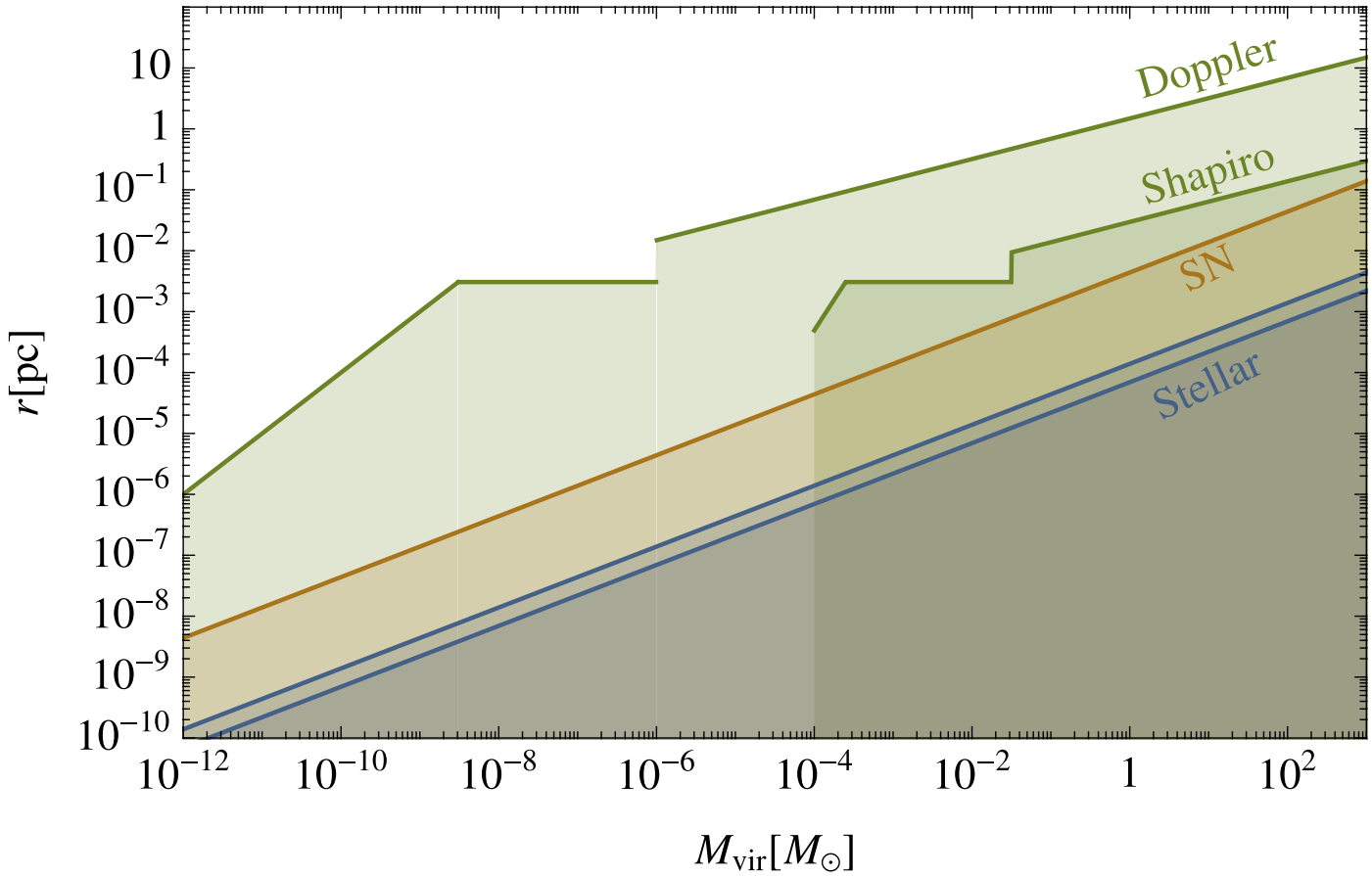
Summary of constraints

- Putting it all together...



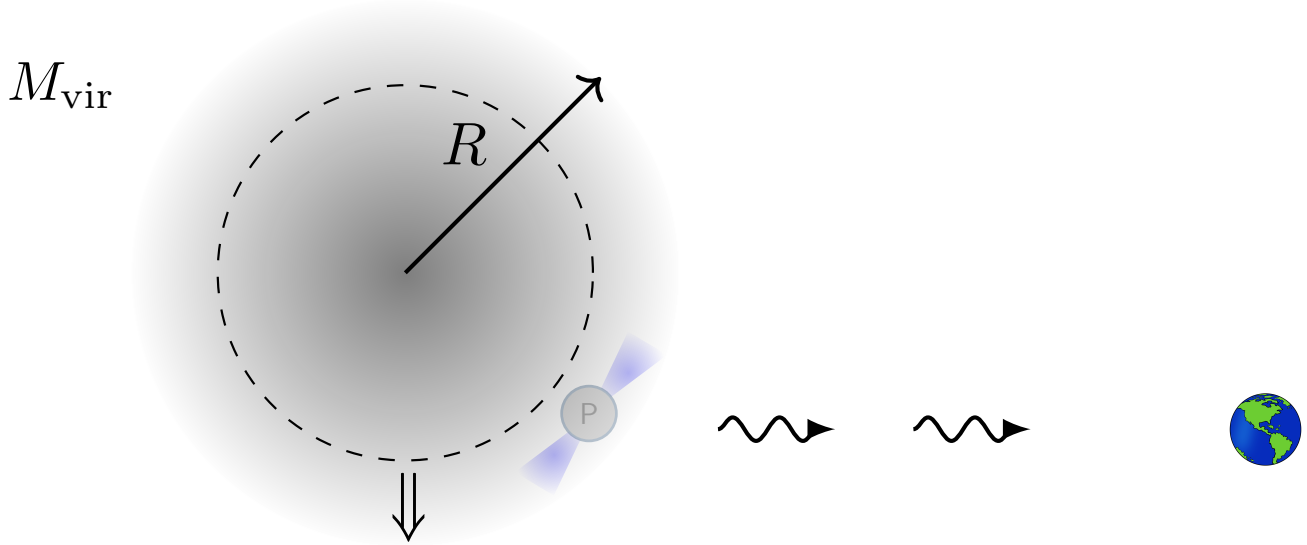
Sensitivity radius

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



Sensitivity radius

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



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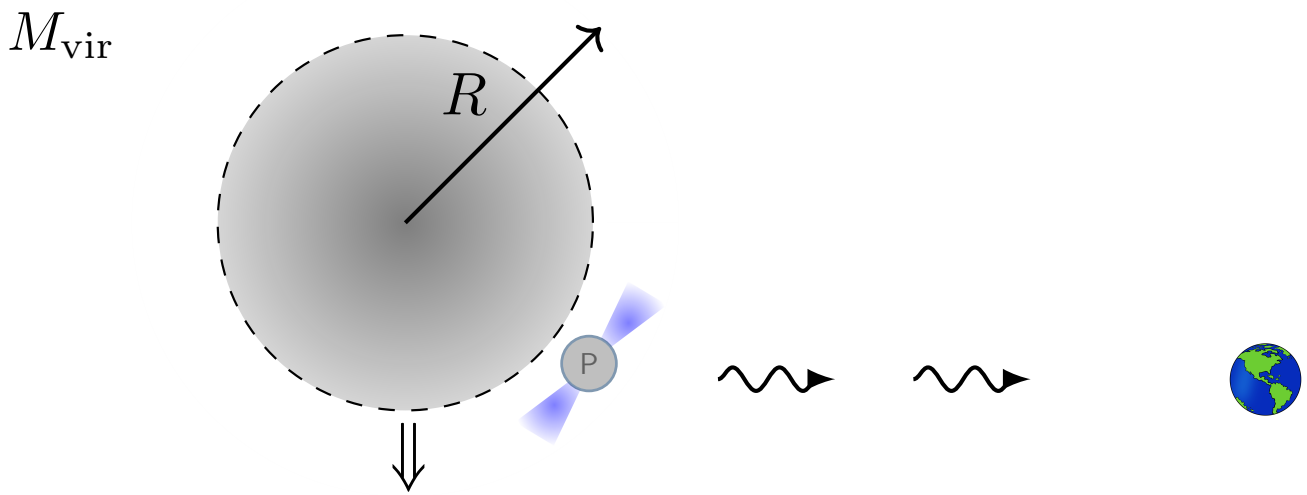
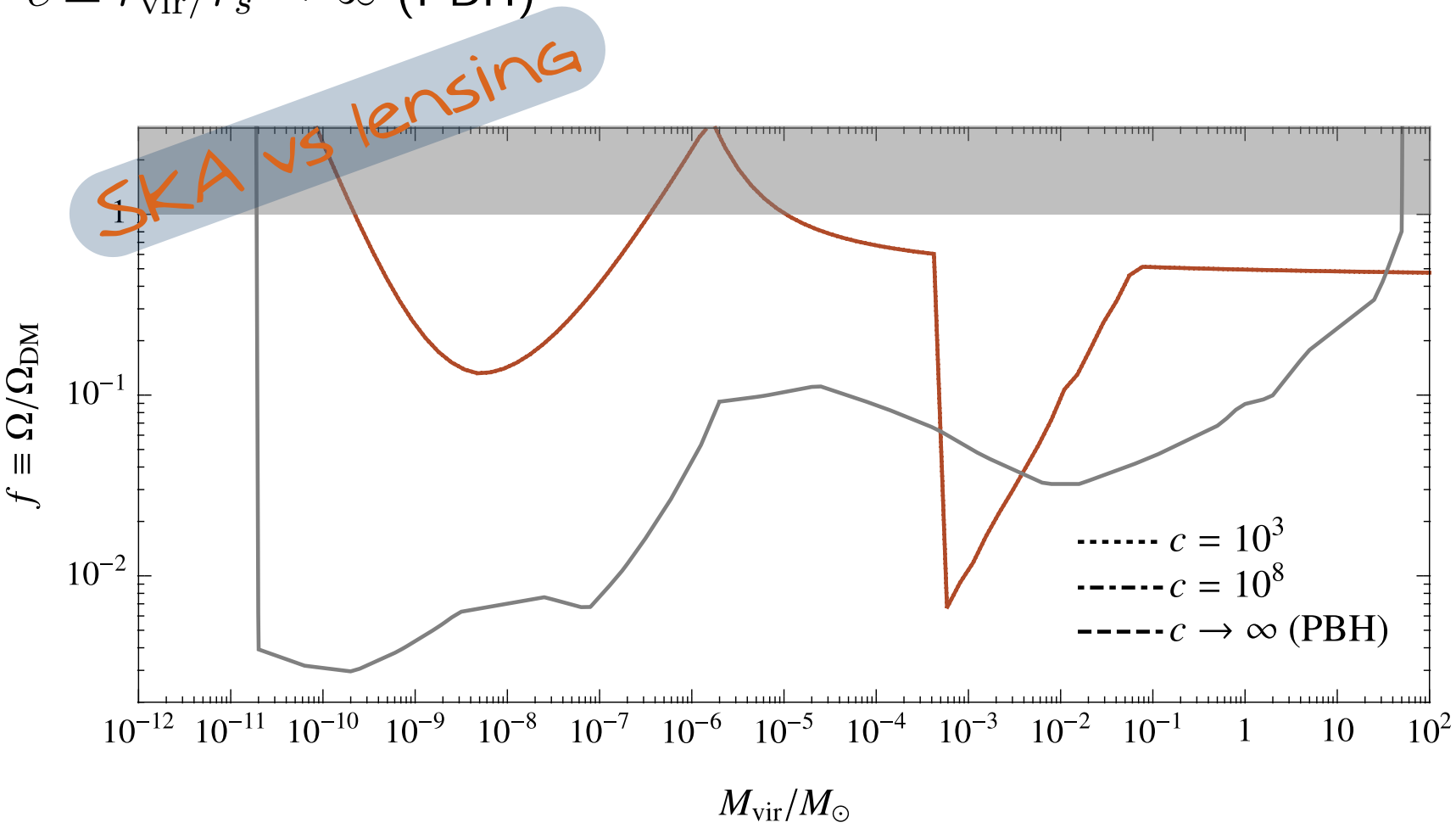


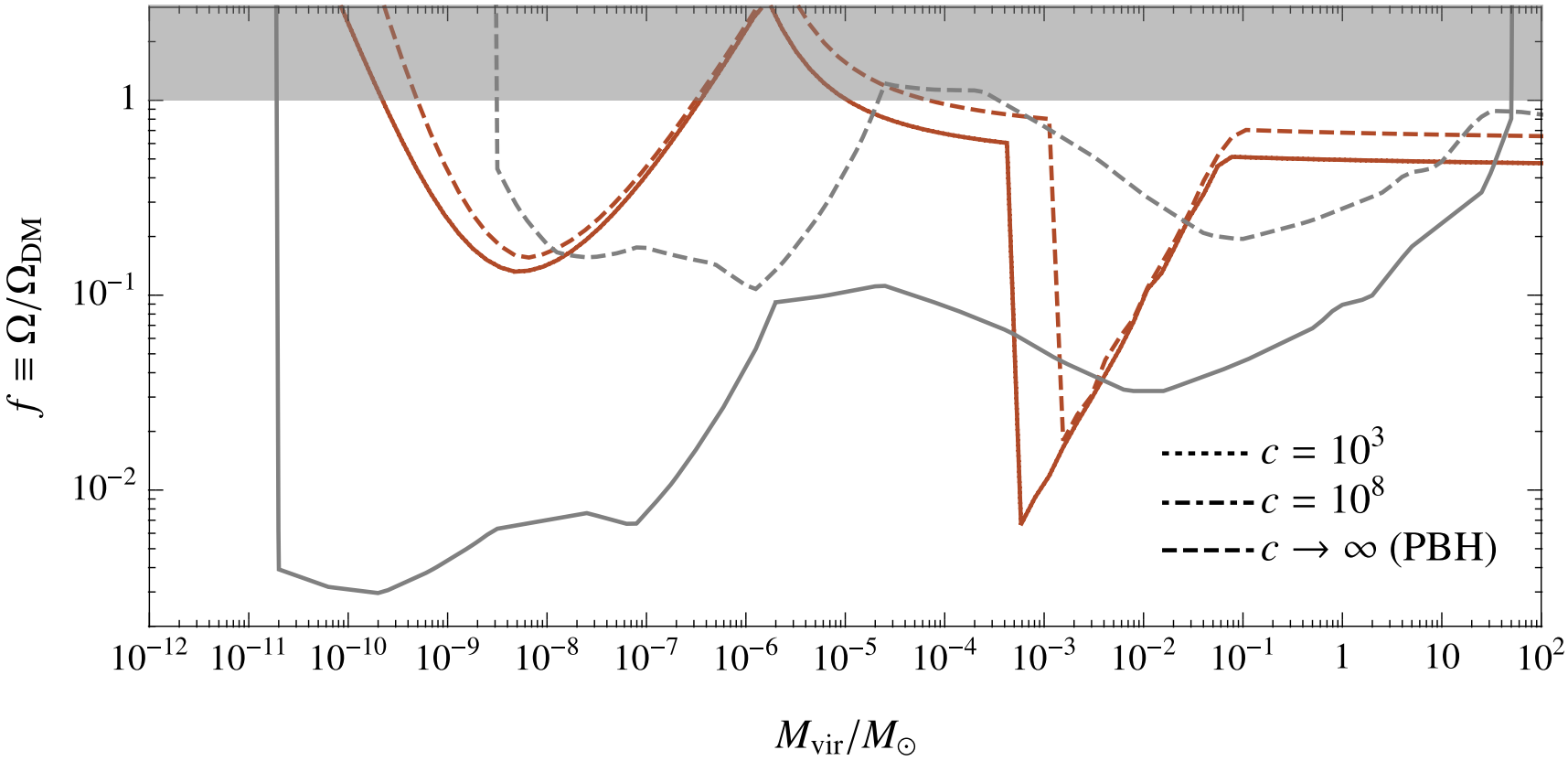
Constraints on diffuse subhalos

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



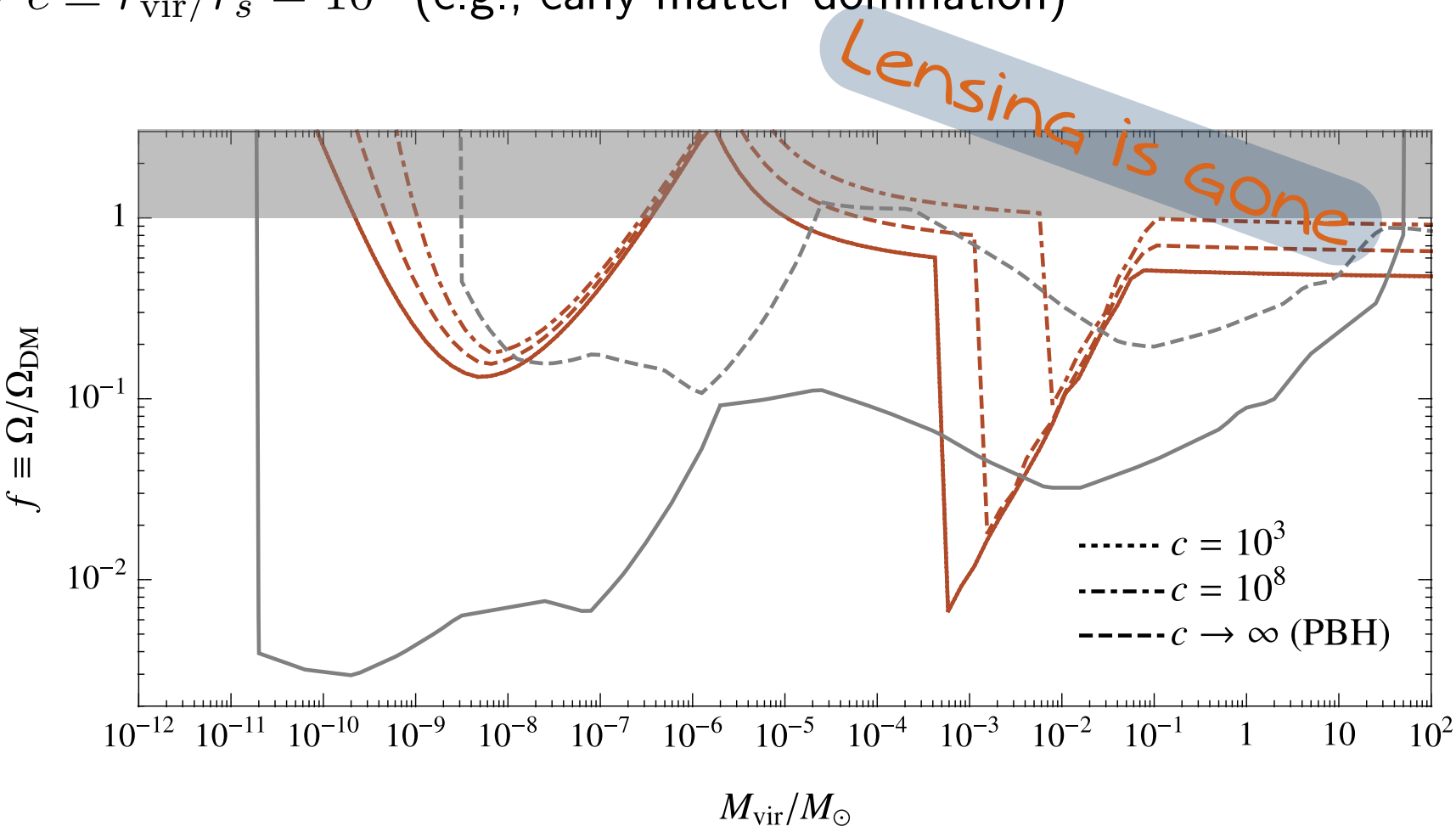
Constraints on diffuse subhalos

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



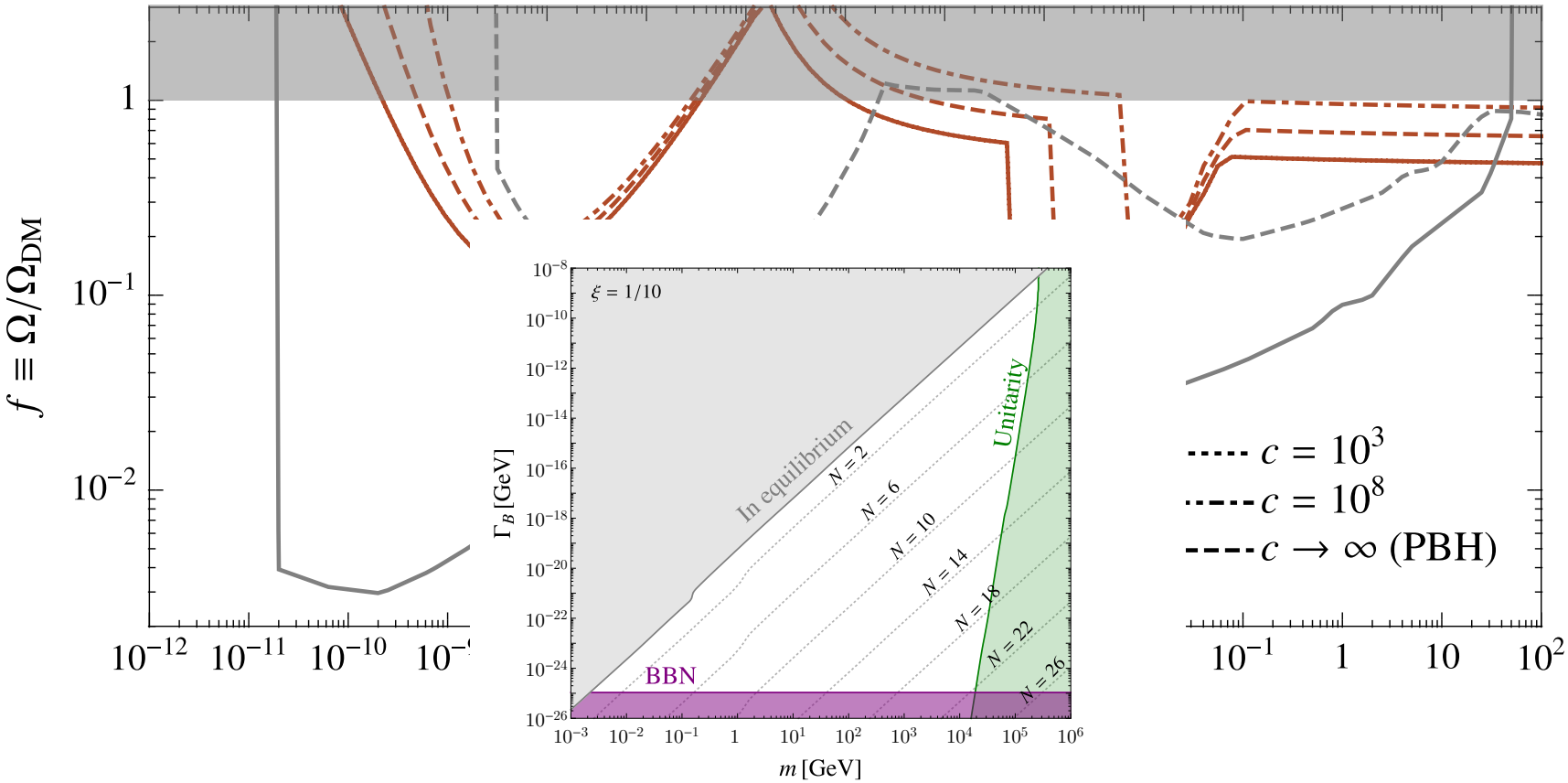
Constraints on diffuse subhalos

- $c \equiv r_{\rm vir}/r_s = 10^3$ (e.g., early matter domination)



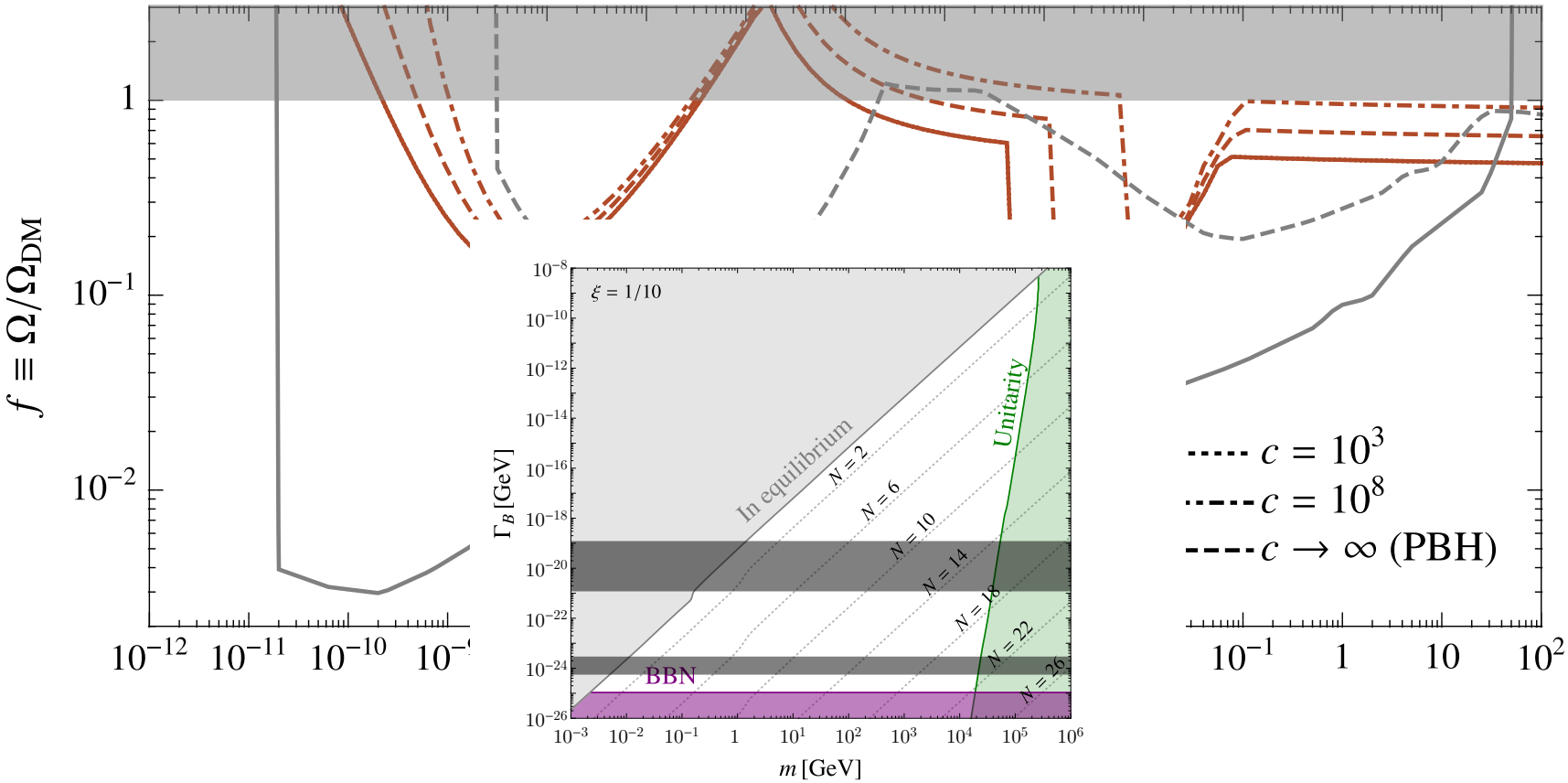
Constraints on diffuse subhalos

- $c \equiv r_{\rm vir}/r_s = 10^3$ (e.g., early matter domination)



Constraints on diffuse subhalos

- $c \equiv r_{\rm vir}/r_s = 10^3$ (e.g., early matter domination)



Conclusion

- DM has substructure within the Milky way
- Prediction of early matter dominated era
- Can look for gravitational couplings
- Pulsar timing can look for transitting subhalos
- Can search huge range of M
- Different possible strategies → all should be used
- Shapiro delay + Doppler kicks
- Static vs dynamic limits
- Can detect diffuse halos!
- High density region?
- Extragalactic pulsars?