Observational signatures of early matter domination

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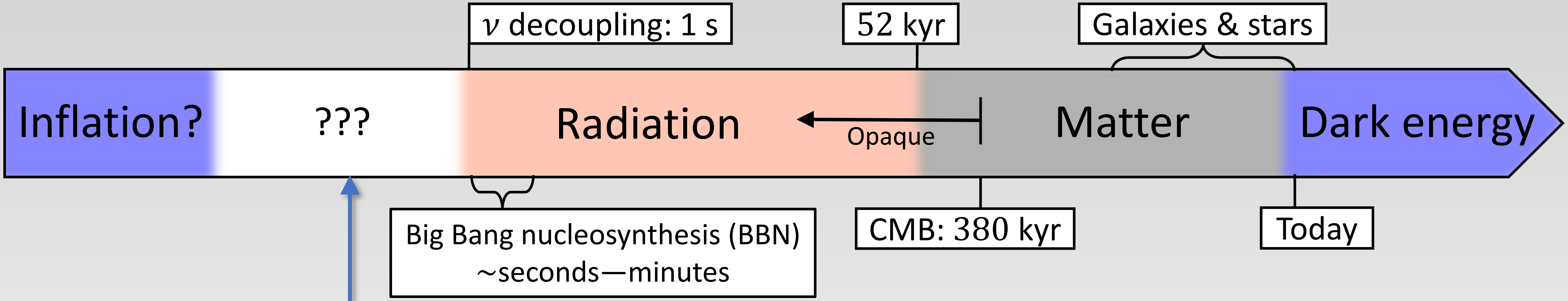
The first second



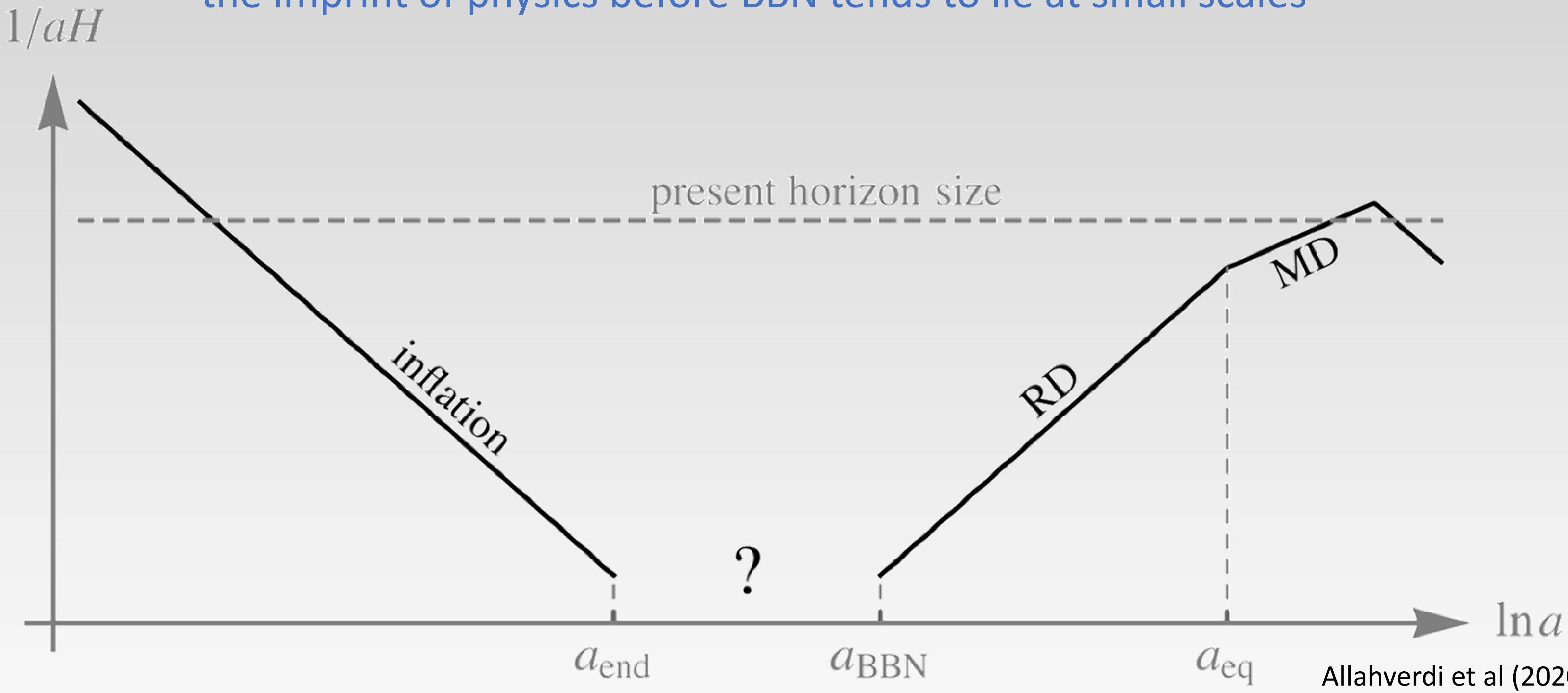
Observations only require radiation domination by ~1s.

What happened earlier?

Evidence at small scales

Evolution of the horizon size means that

the imprint of physics before BBN tends to lie at small scales

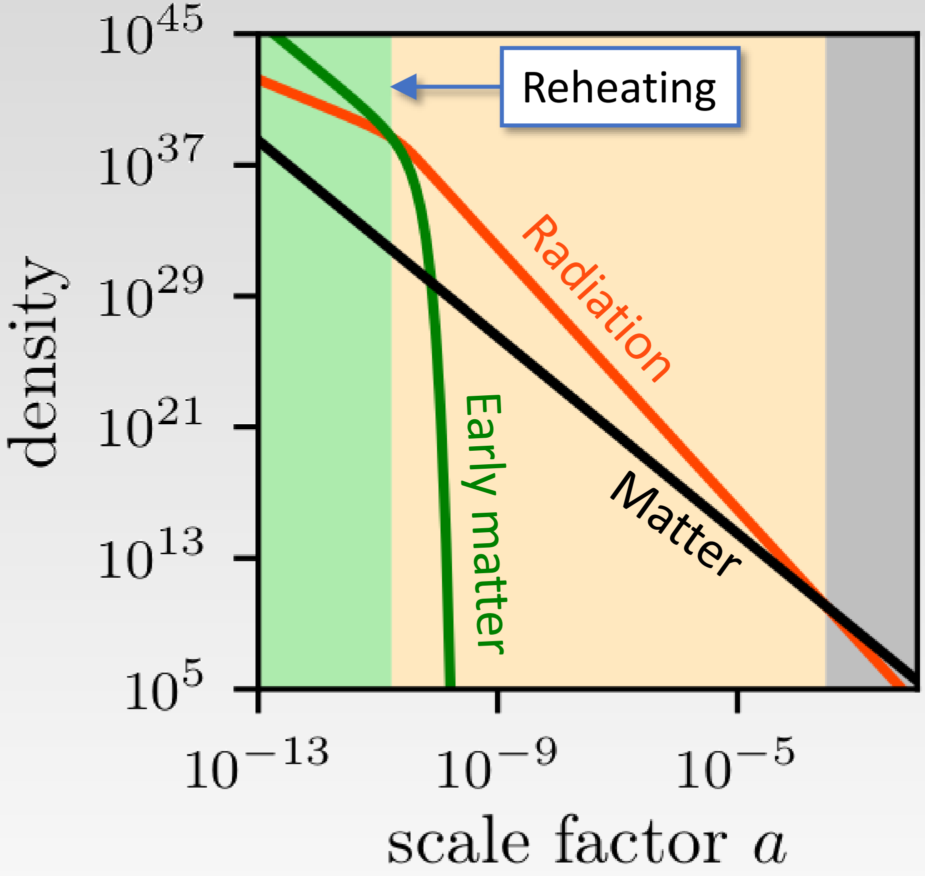


Allahverdi et al (2020)

Early matter domination

Hypothetical domination by an unstable heavy field
that decays into radiation by $t \sim 1$ s

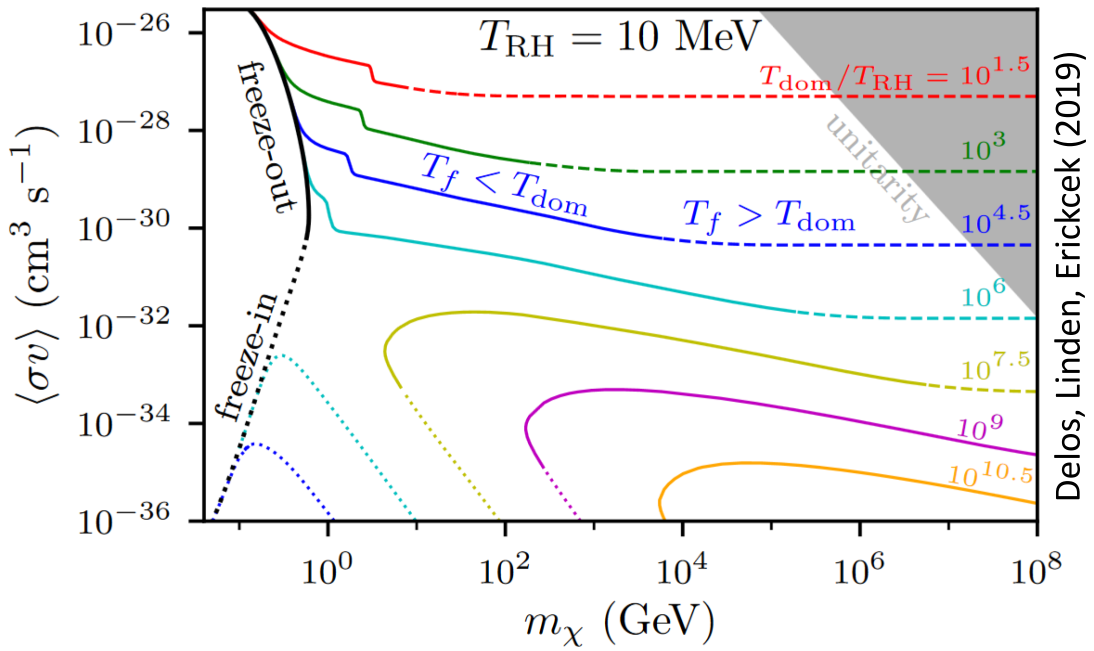
Examples
- String moduli fields
- Hidden sector
  (e.g., dark mediator)
- Inflaton



Impacts of EMD

Altered expansion history and entropy production during EMD change the outcomes of chemical processes.

Example: DM production (freeze-out/in).

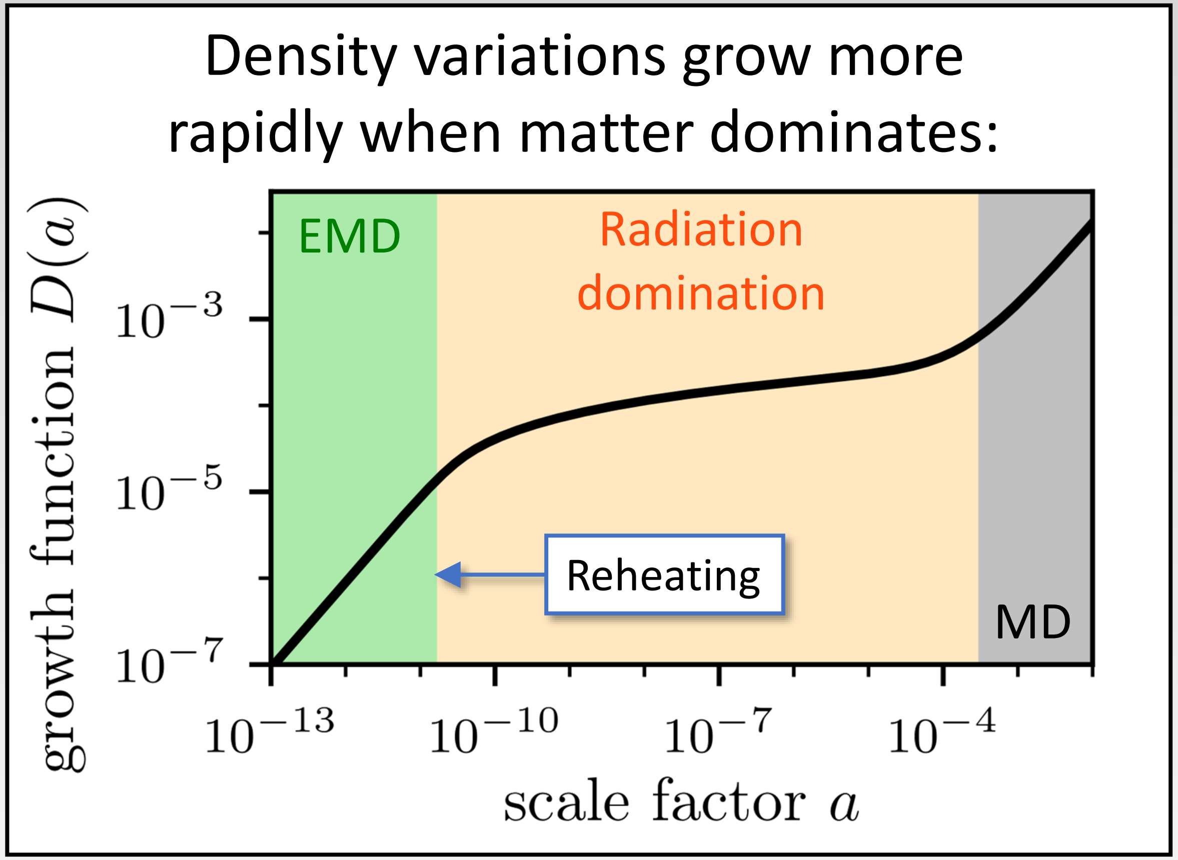


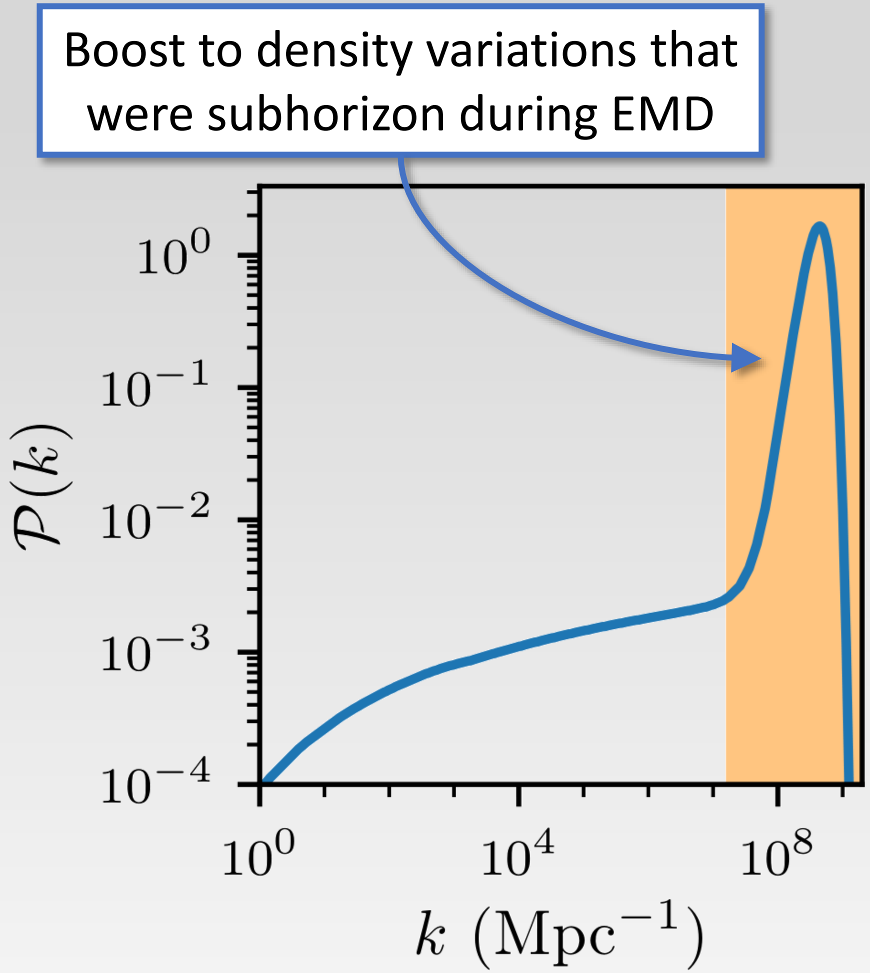
A different cross section is required to achieve the observed abundance.

Other examples include baryogenesis and phase transition dynamics

(see Allahverdi et al 2020 review paper)

EMD boosts density variations

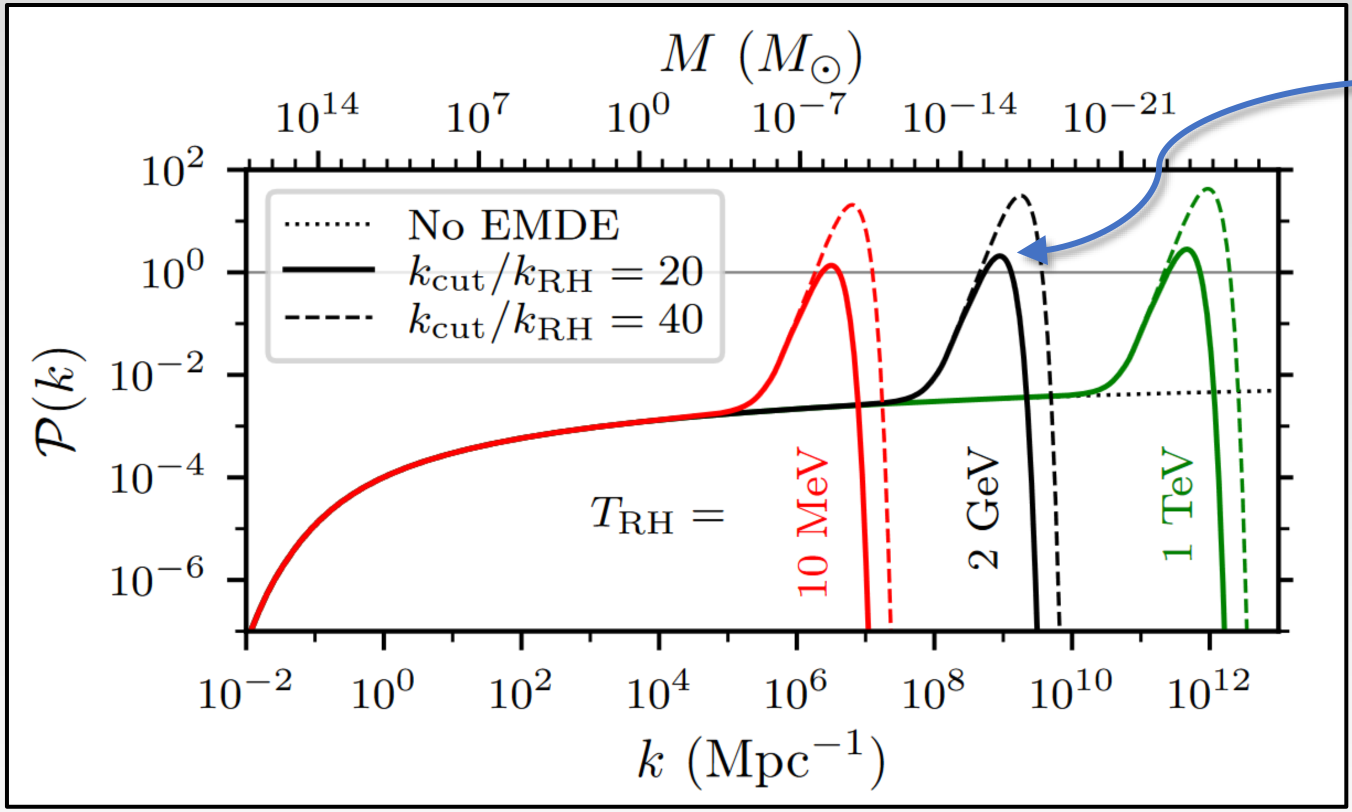


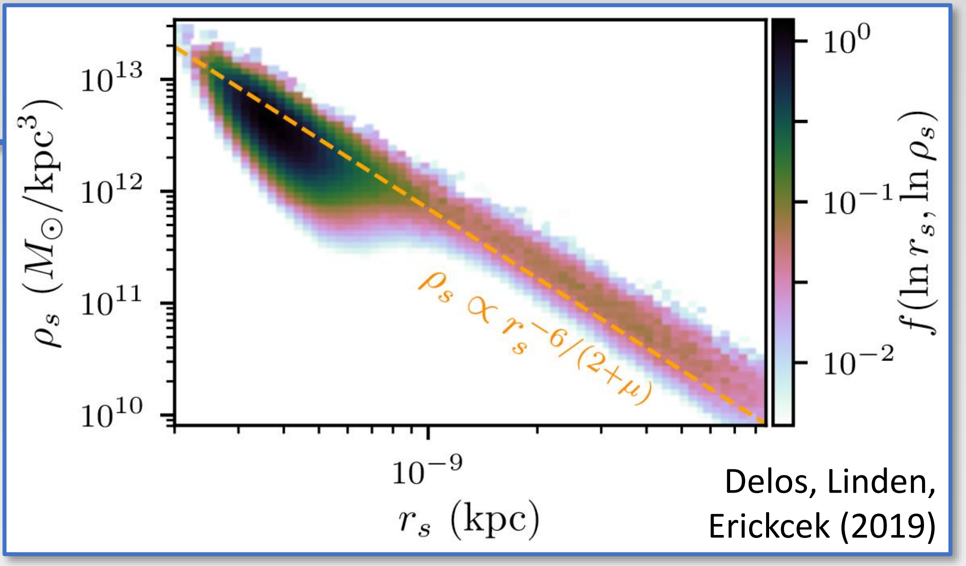


Caveat: the dark matter must be nonrelativistic and decoupled by $T \simeq 2T_{RH}$ to "catch up" to the early matter.

Microhalo formation

Boosted density variations collapse (e.g., during late MD) to produce highly dense sub-Earth-mass DM microhalos.





Delos, Linden, Erickcek (2019)

Higher T_{RH} → smaller mass scale

Cutoff scale [free streaming or kinetic decoupling] sets amplitude of boost ~ density scale

Microhalo detection

How can we hope to detect sub-earth-mass microhalos?

Pulsar timing

Pulsar frequency perturbed by microhalos passing near pulsar or earth (*Doppler*) or between them (*Shapiro*)

Transient distortions of strongly lensed systems

e.g., caustic-crossing stars: Dai and Miralda-Escudé (2020)

Dark matter annihilation

If DM is a thermal relic, microhalos boost the annihilation rate
(yields detectable gamma rays or other annihilation products)

Model dependent, but of special interest because of how EMD changes required $\langle \sigma v \rangle$
e.g., Delos, Linden, and Erickcek (2019)

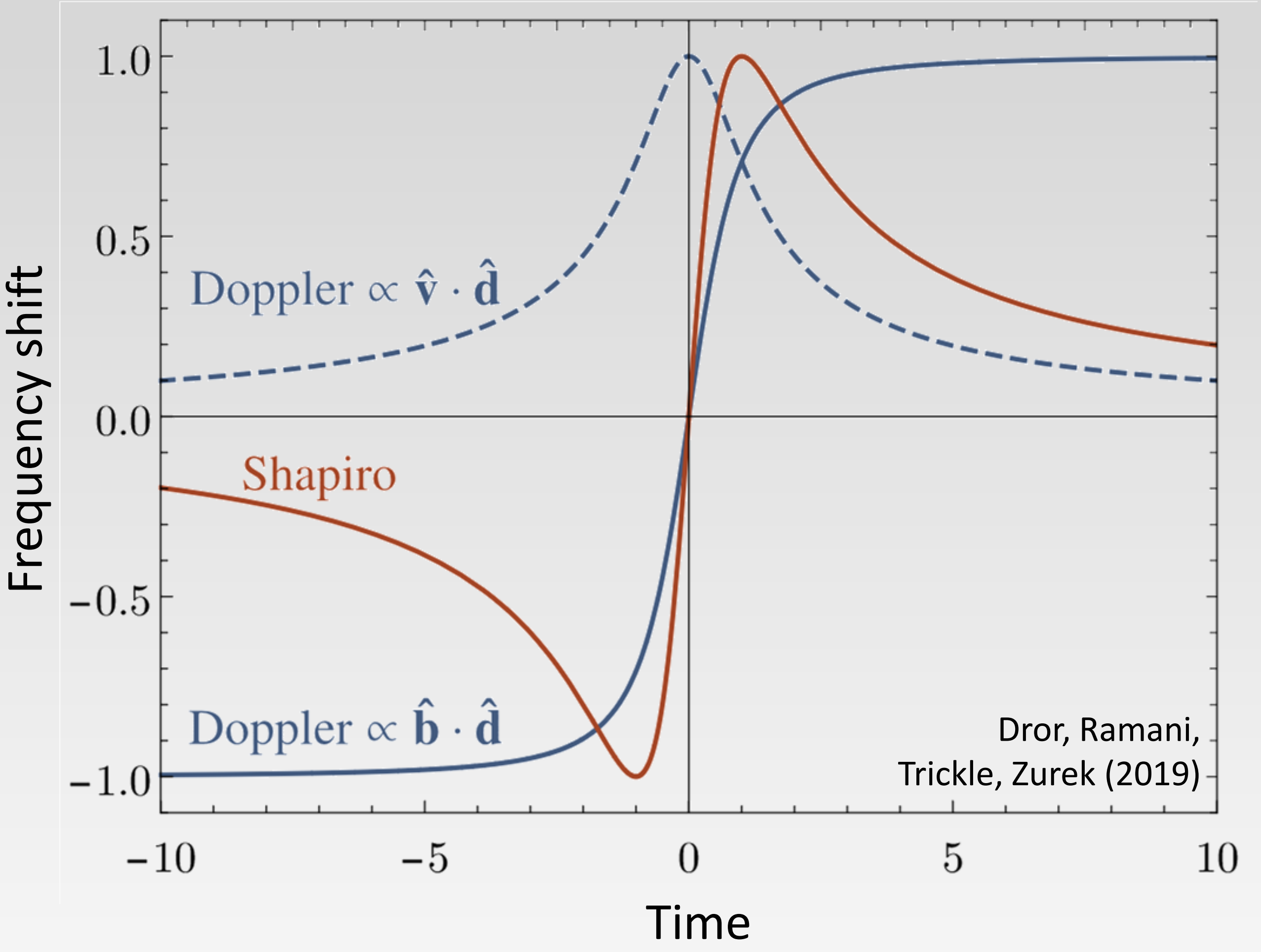
Pulsar timing

Pulsar timing can probe small-scale structure.

Pulsation frequency shifts due to

- Perturbed motion (Doppler effect)
- Perturbations to incoming light (Shapiro effect)

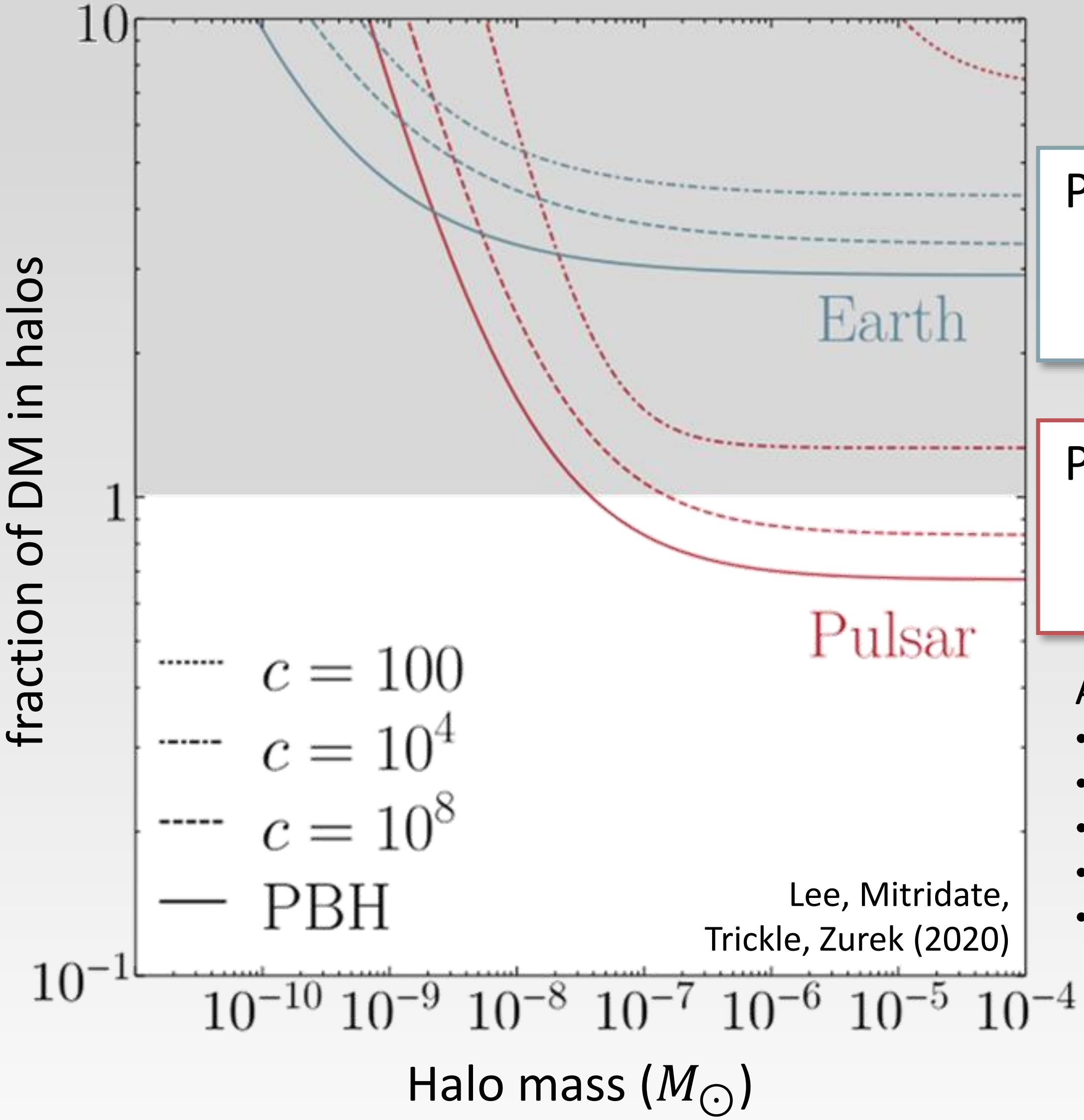
Leads to time-dependent signal:



Pulsar timing

Pulsar timing can probe DM structure down to sub-Earth-mass scales using the Doppler effect.

(Shapiro effect is only sensitive to larger mass scales.)



Perturbation to Earth's motion

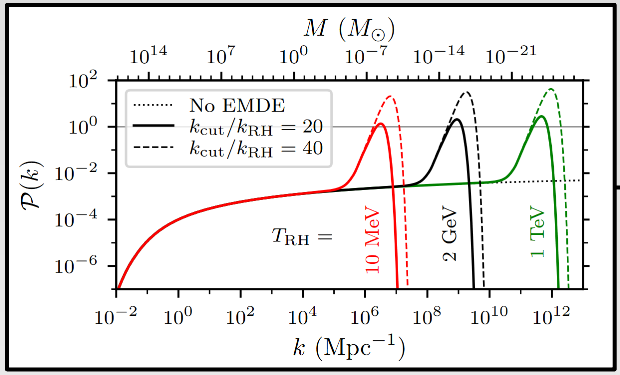
Perturbation to pulsar's motion

Assumes:

- 200 pulsars
- 20 years
- 2-week cadence
- 50-ns residuals
- **All halos have the same mass and density profile**

EMD-induced microhalos

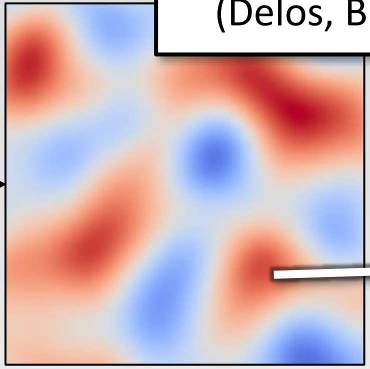
What is the halo distribution that arises from an EMD scenario?



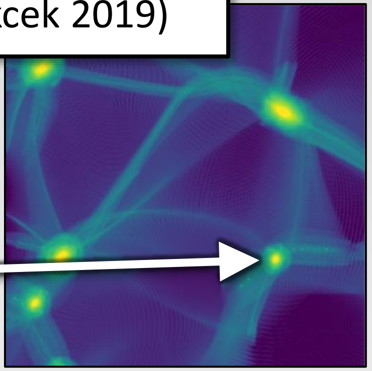
Power spectrum

Gaussian-field statistics

Structure of peak predicts structure of halo (Delos, Bruff, Erickcek 2019)



Peaks in the primordial density field



Collapsed halos

This procedure gives an initial halo distribution

Neglect microhalo-microhalo mergers for now:

- Comparatively rare for sharply peaked $\mathcal{P}(k)$
- Raises halo masses → neglecting is conservative

Microhalos in the solar neighborhood

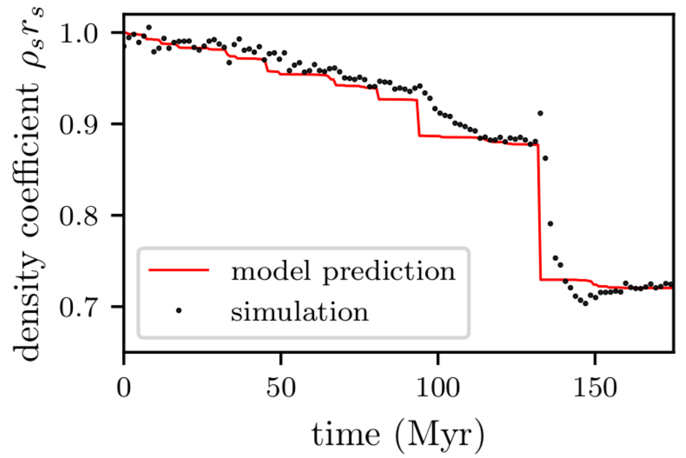
Microhalos relevant to pulsar timing are near the sun
(in a Galactic sense)

Main concerns:

- Tidal stripping by the Galactic potential
- Encounters with stars
  (microhalo-microhalo encounters are subdominant)

Use tidal evolution model
(Delos 2019a)

Use stellar encounter model (Delos 2019b)



(random sequence of encounters)

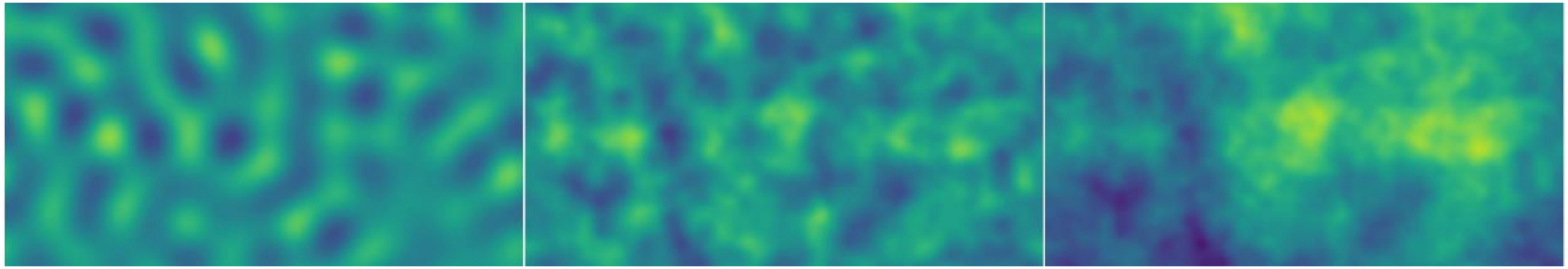
- Randomly sample microhalo orbits in phase space
- Randomly sample stellar encounters for each orbit (using a Galaxy model)

Universal microhalo models

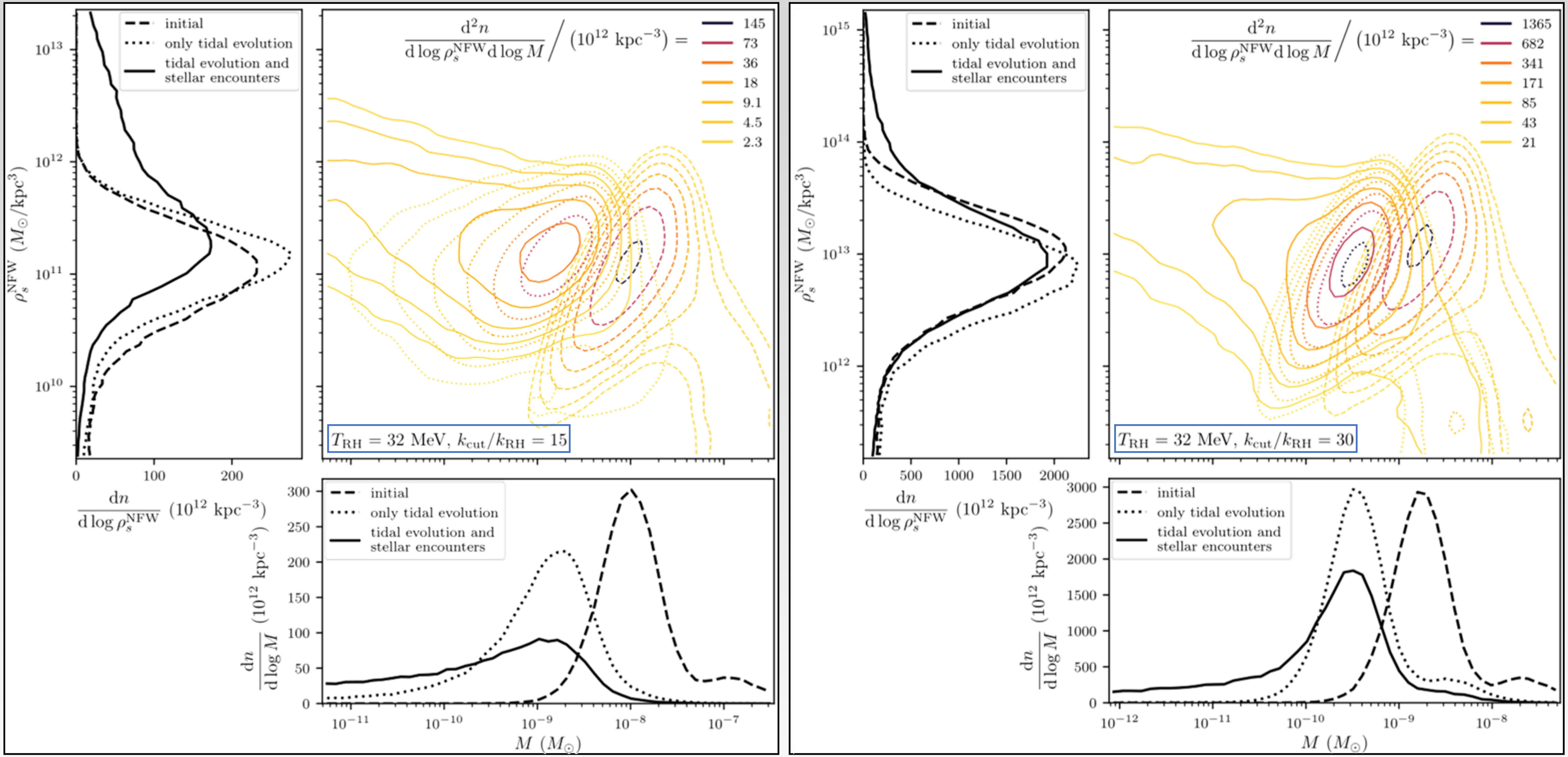
Unlike most models that describe halo internal structures
(e.g., “concentration-mass relations”),
these models of microhalo formation and evolution are universal

(not tied to a specific cosmology)

e.g., peak-to-halo model works for arbitrary peak distribution (set by the power spectrum)



Microhalos in the solar neighborhood



Pulsar timing signals

Consider phase shift $\delta\phi$ due to microhalo encounters.

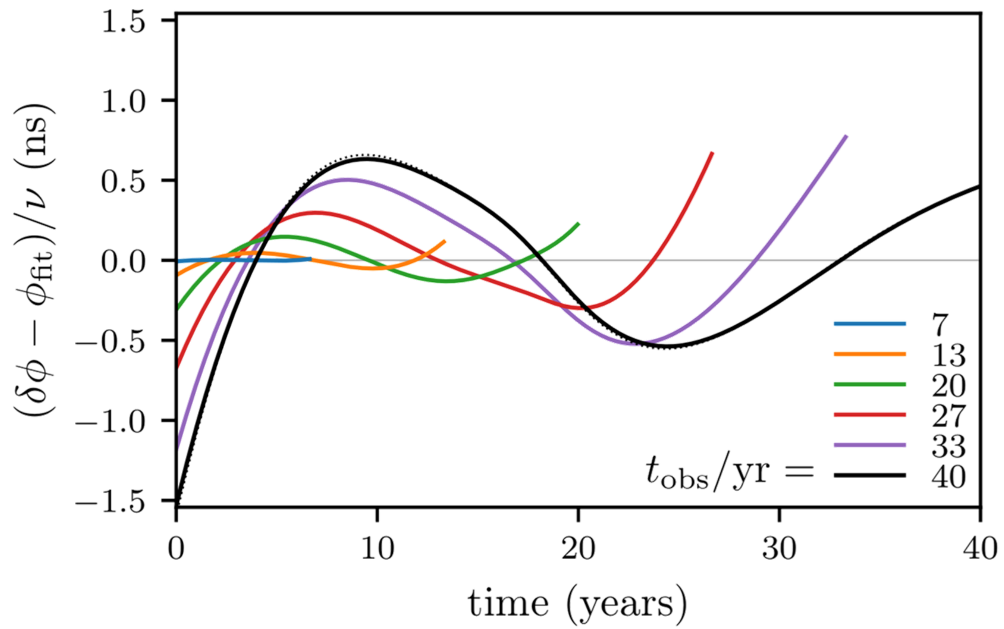
e.g., point mass:

$$\delta\phi_{\rm pt} = \frac{GM\nu}{v^2 c}\hat{\boldsymbol{d}} \cdot \left(\sqrt{1+x^2}\hat{\boldsymbol{b}} - \sinh^{-1}(x)\hat{\boldsymbol{v}}\right)$$

$$x = (b/v)t$$

Subtract quadratic fit – derivatives up to $\dot{\nu}$ are degenerate with natural behavior

[spin-down, acceleration within the Galactic potential]



Integrated signal-to-noise ratio $= \dfrac{1}{\nu^2 t_{\rm rms}^2 \Delta t}\displaystyle\int {\rm d}t\,(\delta\phi - \phi_{\rm fit})^2$

(Lee, Mitridate, Trickle, Zurek 2020)

Results

Plots show conditions for 2σ SNR:

- Smaller T_{RH} → larger mass scale
  → more detectable

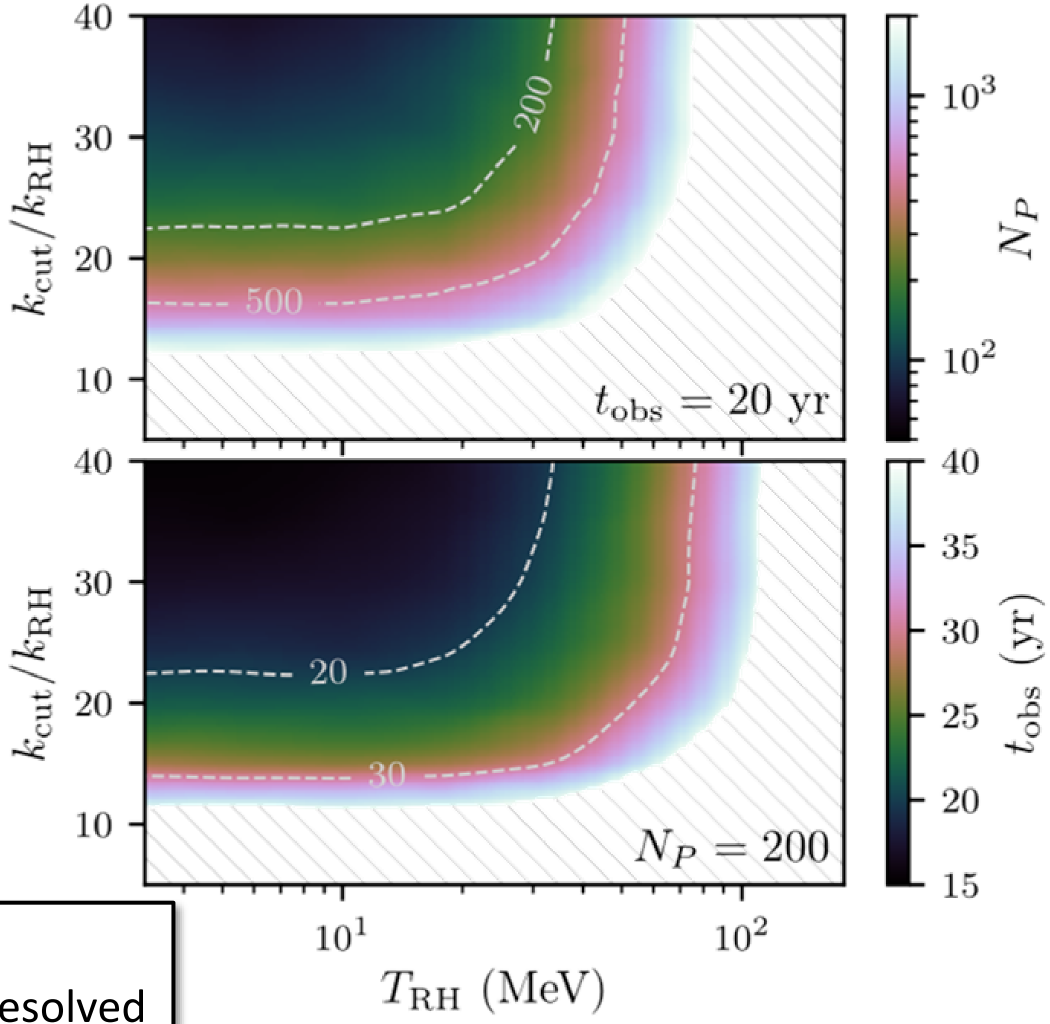
  [Limit as expected encounters drop below 1]

- Larger k_{cut}/k_{RH} → higher density scale
  → more detectable

  [Point-mass limit]

Impact of raising k_{cut}/k_{RH} plateaus around $k_{cut}/k_{RH} > 30$
Impact of lowering T_{RH} plateaus around $T_{RH} < 20$ MeV

t_{obs} = observation duration
N_P = pulsar count



t_{obs} has a much larger impact than N_P.
Encounter timescale ~ years → encounters not fully temporally resolved

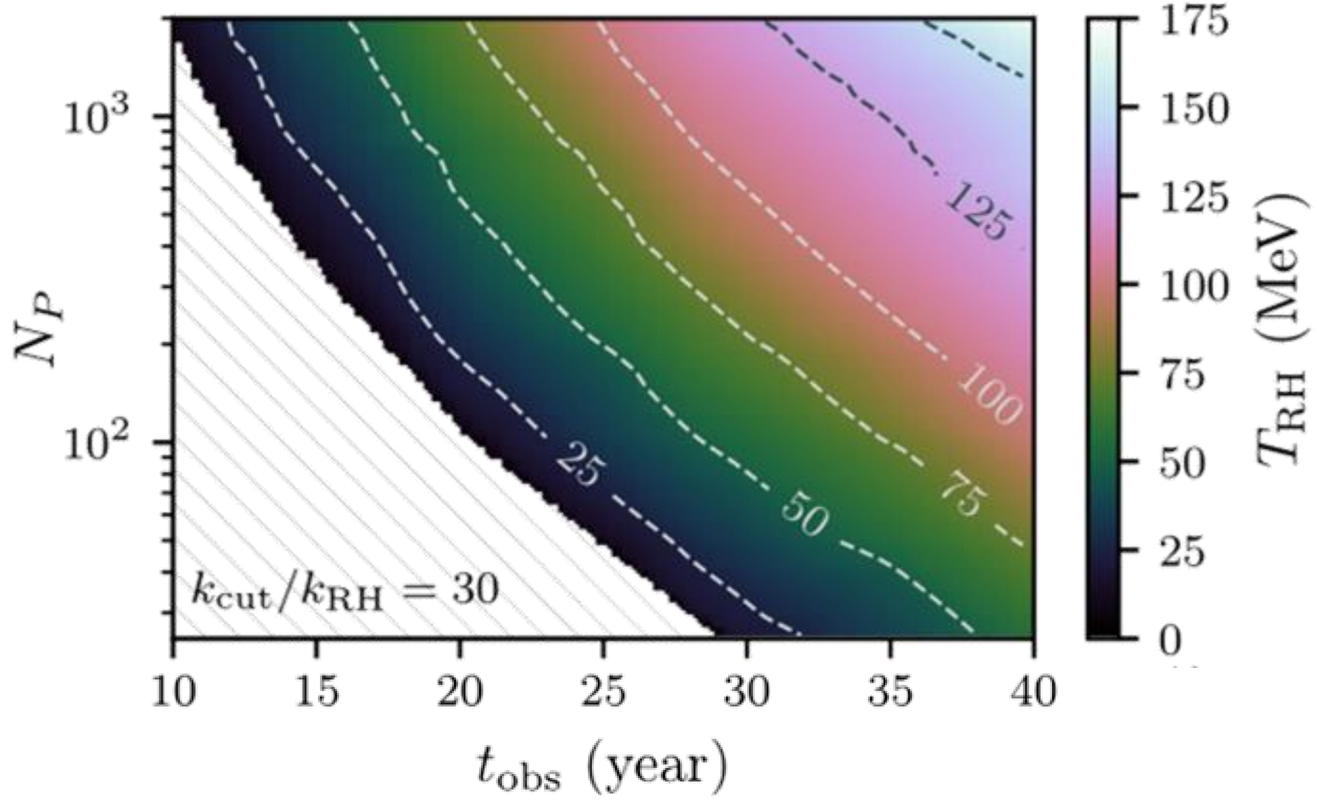
Reheat temperatures

EMDs are accessible with
$\sim$100 pulsars and $\sim$20 years
of observing time

Can probe T_{RH} up to $\sim$150 MeV
with 40 years of observing time

Note: we assume 10 ns
noise residuals

Fix $k_{cut}/k_{RH} = 30$ (high-density plateau)



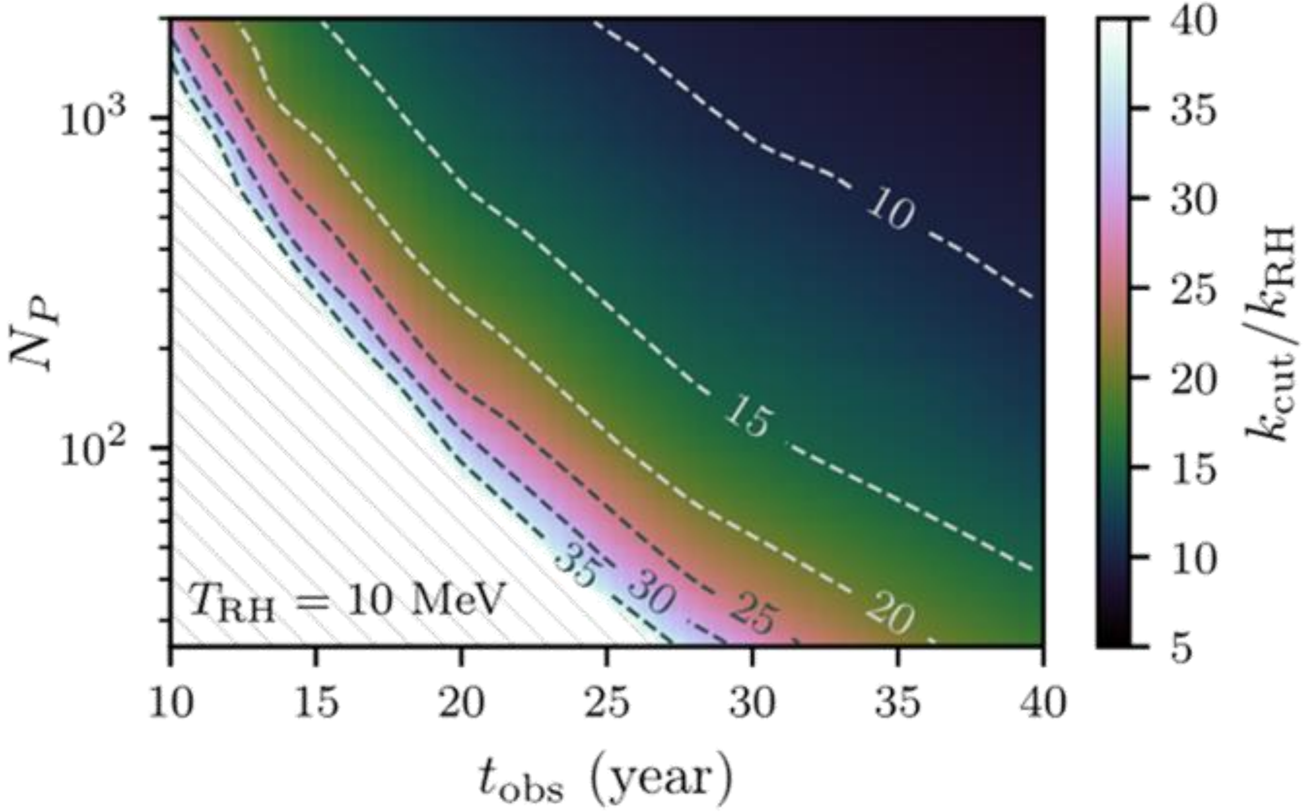
Cutoff ratios

EMDs are accessible with
$\sim$100 pulsars and $\sim$20 years
of observing time

Can probe k_{cut}/k_{RH} down to $\sim$8
with 40 years of observing time

Note: we assume 10 ns
noise residuals

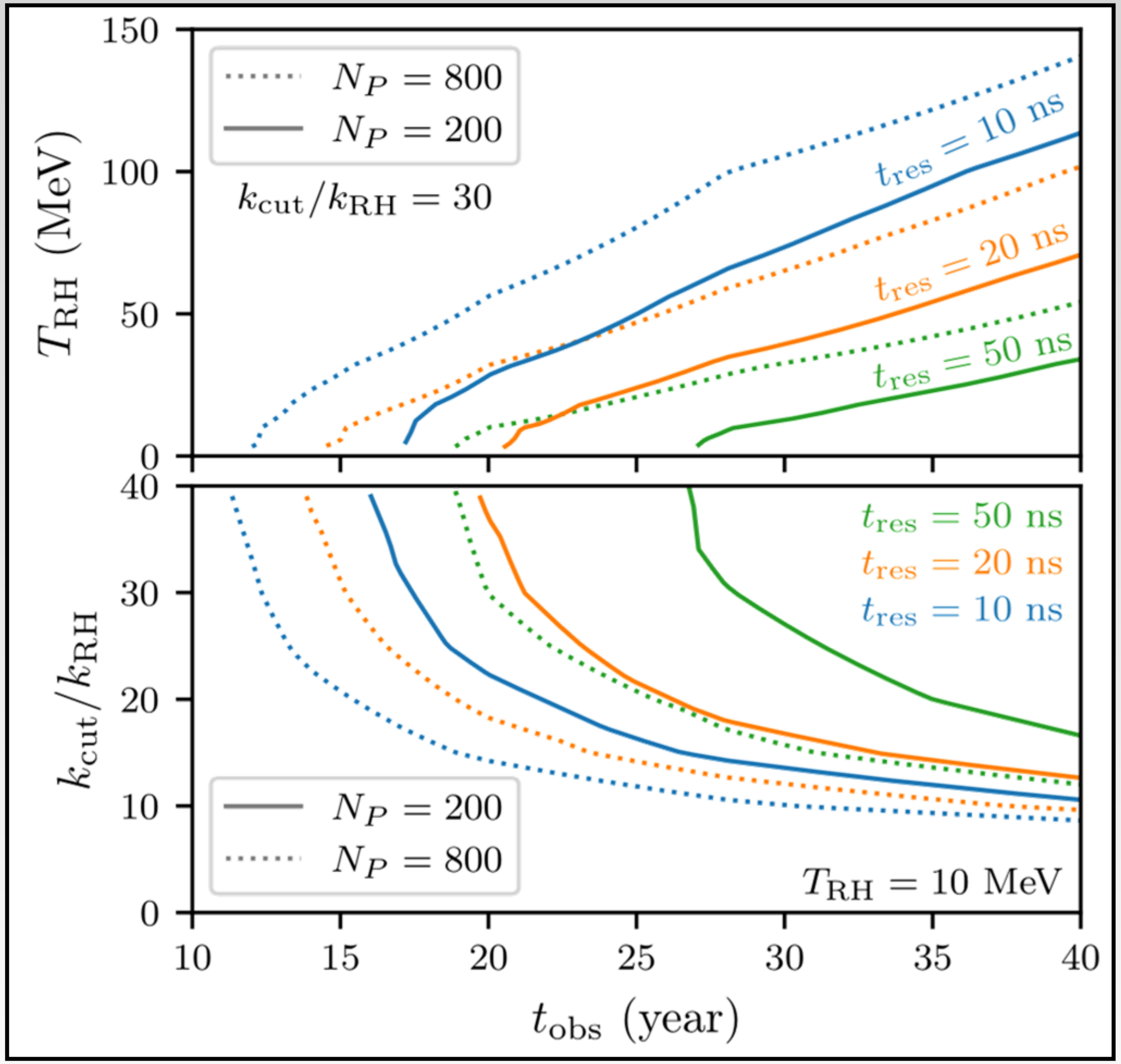
Fix $T_{RH} = 10$ MeV (large-mass plateau)



Timing noise

Results are very sensitive to timing residuals. Need $t_{res} < 100$ ns

Currently, pulsar timing arrays are in the $\sim 1\ \mu s$ range, but SKA is expected/hoped to bring sub-100-ns precision.
[Gravitational wave searches also demand it!]



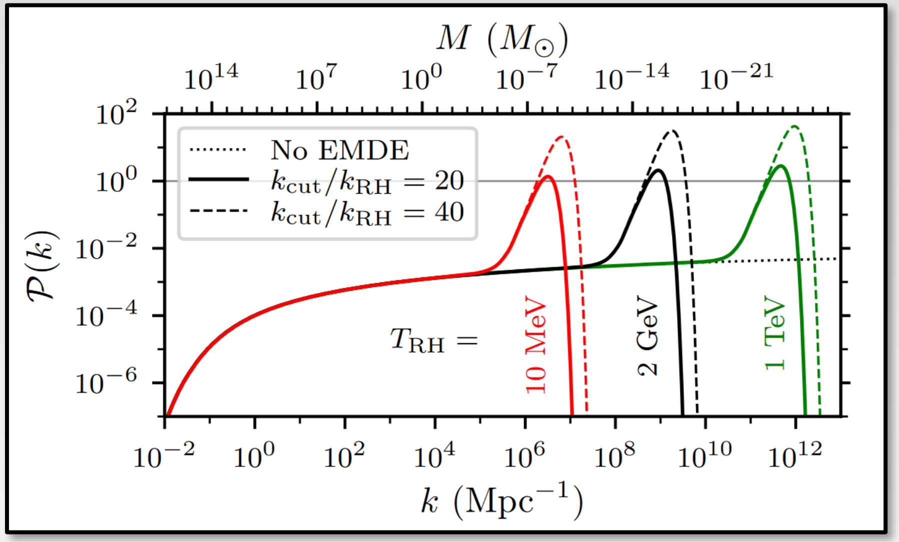
Mitigation options:

- More frequent observations can mitigate uncorrelated (white) noise
- Use better models to mitigate red "spin" noise (largely associated with internal pulsar dynamics)

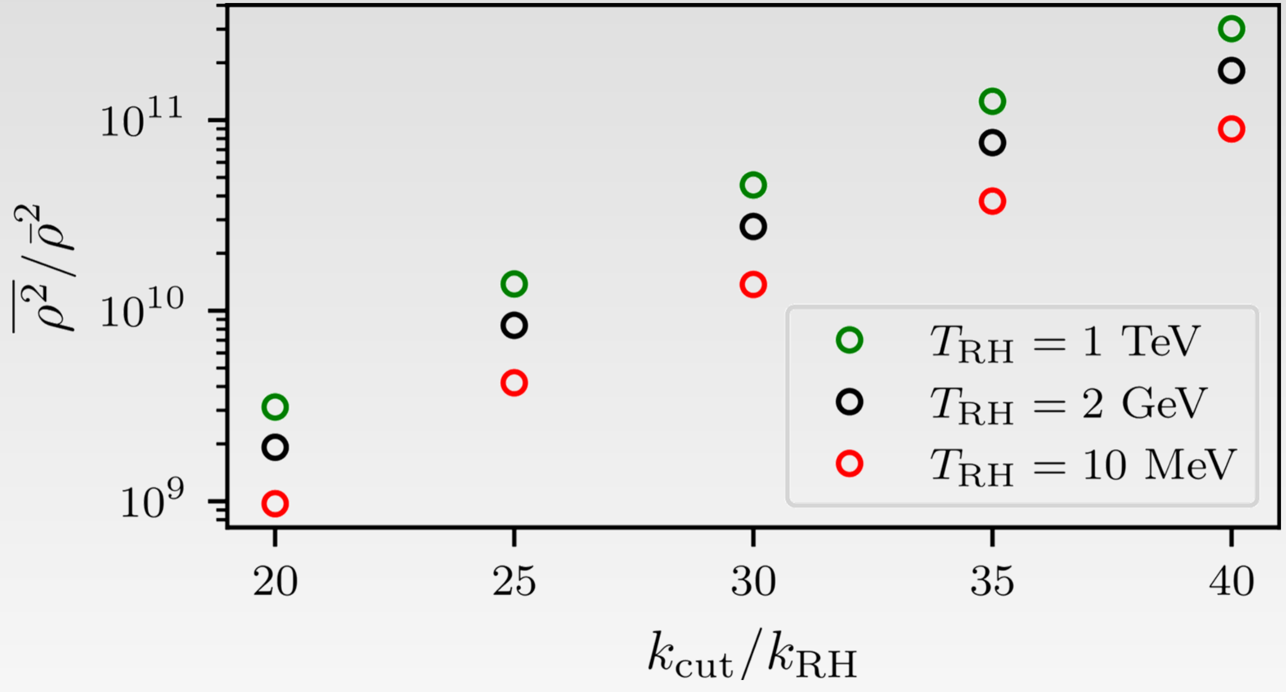
EMD's dark matter annihilation boost

Dark matter annihilation rate $\propto \overline{\rho^2}$ → boosted by highly dense microhalos

EMD-induced power spectrum



Annihilation boost



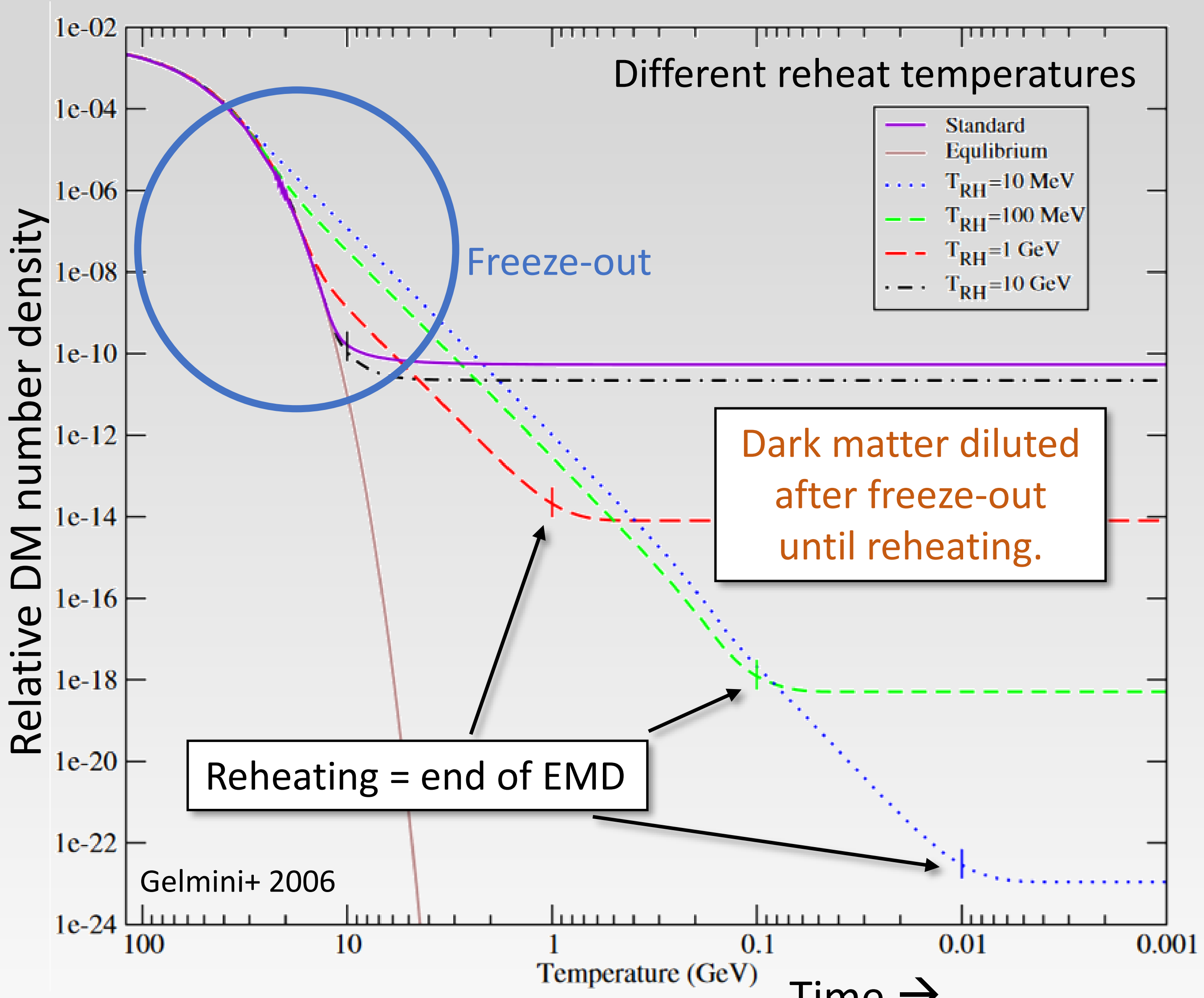
Dark matter production during EMD

During early matter domination, decay of the dominant particle sources radiation.

Dark matter diluted after freeze-out	$\Longrightarrow$	Need smaller cross section for correct relic abundance

We cannot predict DM properties without knowing the reheat temperature!

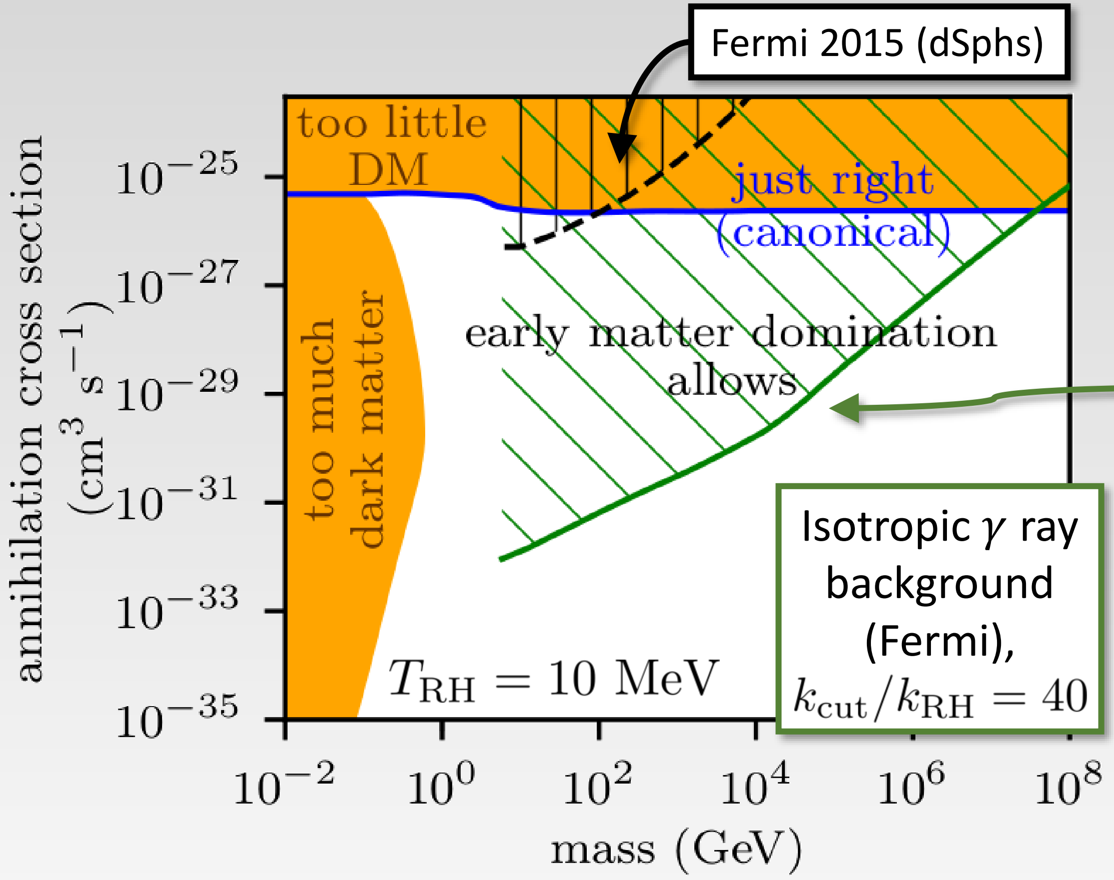
Limits ability to constrain dark matter models.

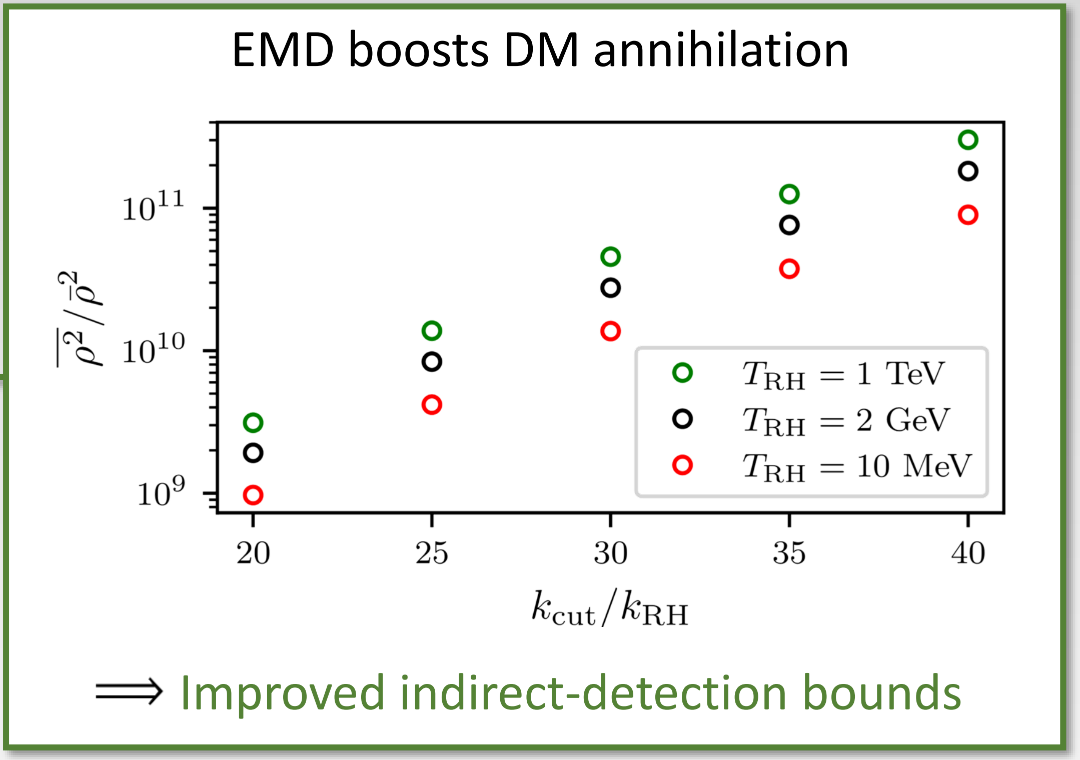


Time →

Breaking a dark degeneracy

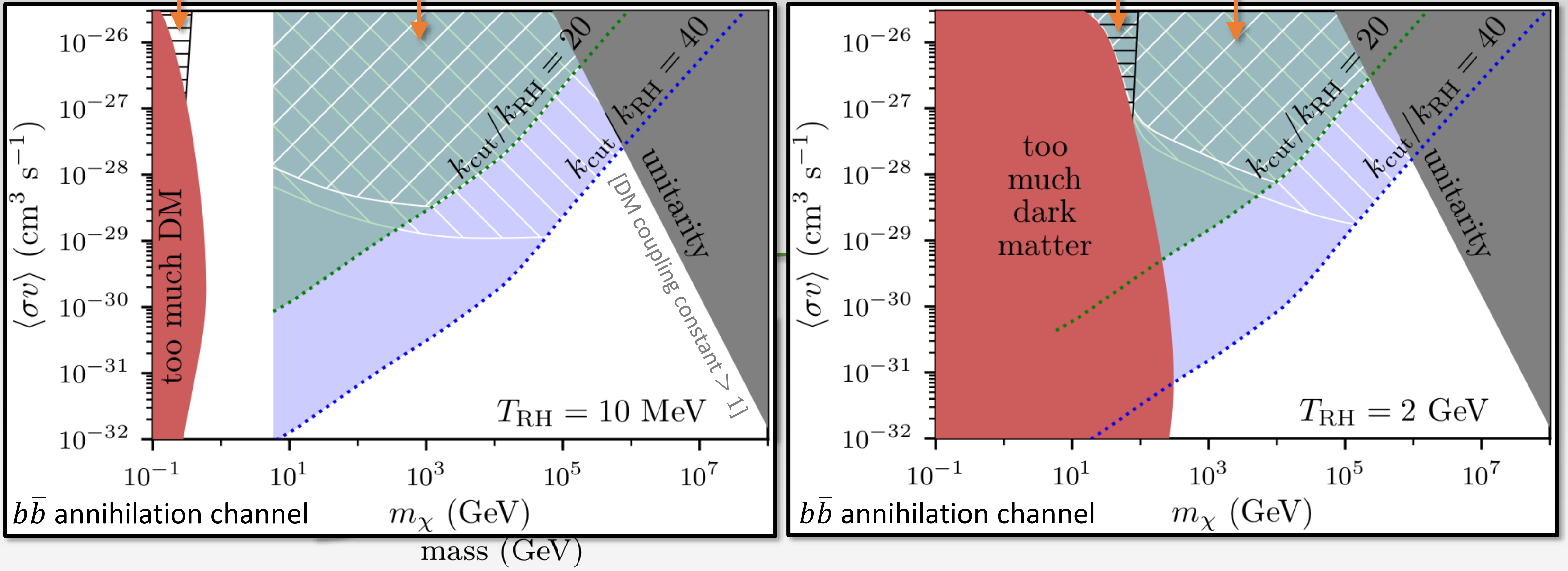
EMD broadens the range of viable dark matter parameters.





Breaking a dark degeneracy

Caveat: assumed $\mathcal{P}(k)$ not valid in hatched regimes [if EMD is tuned to yield observed DM abundance]



EMD's annihilation signature

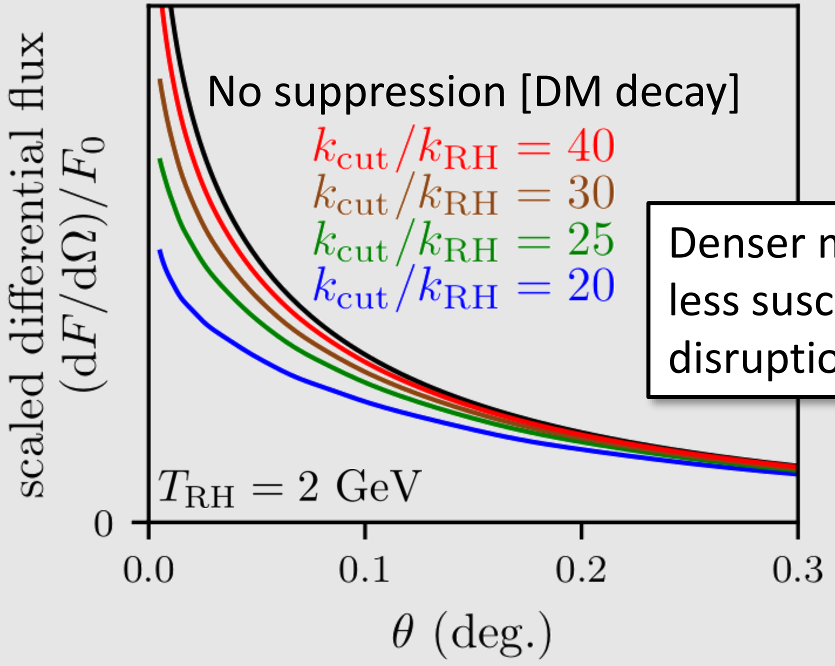
Annihilation signal from microhalos resembles DM decay.

Microhalo distribution ~ DM distribution

Galactic systems can discriminate.

Disruption of microhalos by
tidal forces & stellar encounters
$\Longrightarrow$ Differential microhalo suppression
$\Longrightarrow$ Unique annihilation signal morphology:

- DM decay vs microhalo annihilation
- Different DM & EMDE parameters



Denser microhalos less susceptible to disruption

Summary

Pre-BBN thermal history is largely unprobed; EMD is well motivated
[Important because of its impact on contemporaneous physics, such as DM production]

EMD boosts density variations → tiny, highly dense microhalos

These halos can be detected by pulsar timing, giving an observational avenue for probing EMD:

- $\sim$20 years of observation to begin probing EMD
- Reheat temperatures up to $\sim$150 MeV could be accessible
- Need to get timing noise to sub-0.1-μs levels

Microhalos boost the DM annihilation rate
Thermal relics can be constrained, even if they are produced during EMD [and consequently have a smaller cross section]