EARLY MATTER DOMINATION

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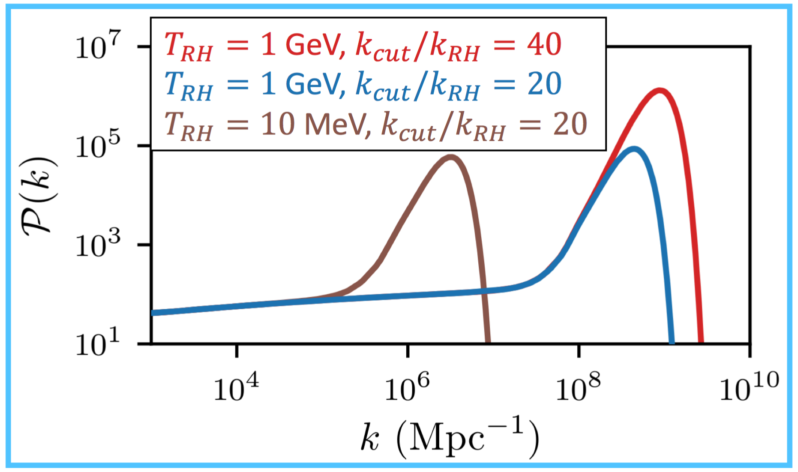
EARLY MATTER DOMINATION

- Arguably, most generic departure from early radiation domination
- Naturally realized in many well-motivated theories:
    - coherent scalar fields
        - post-inflationary reheating
        - moduli
        - saxions, axions
    - relic thermal states
        - hidden sector dark matter models
        - RH neutrinos in neutral naturalness models

OBSERVABLE CONSEQUENCES

- Impact on terrestial signatures of dark matter
  - thermal production: entropy injection, direct DM production
  - ALPs: altered cosmic history
- Impact on the matter power spectrum
  - Subhorizon dark matter density perturbations grow faster during an EMDE
  - Leads to an enhanced inhomogenity on scales that enter the horizon during the EMDE
- Impact on stochastic gravitational wave background
  - best discovery prospects require nonlinear dynamics and/or enhanced primordial power spectra



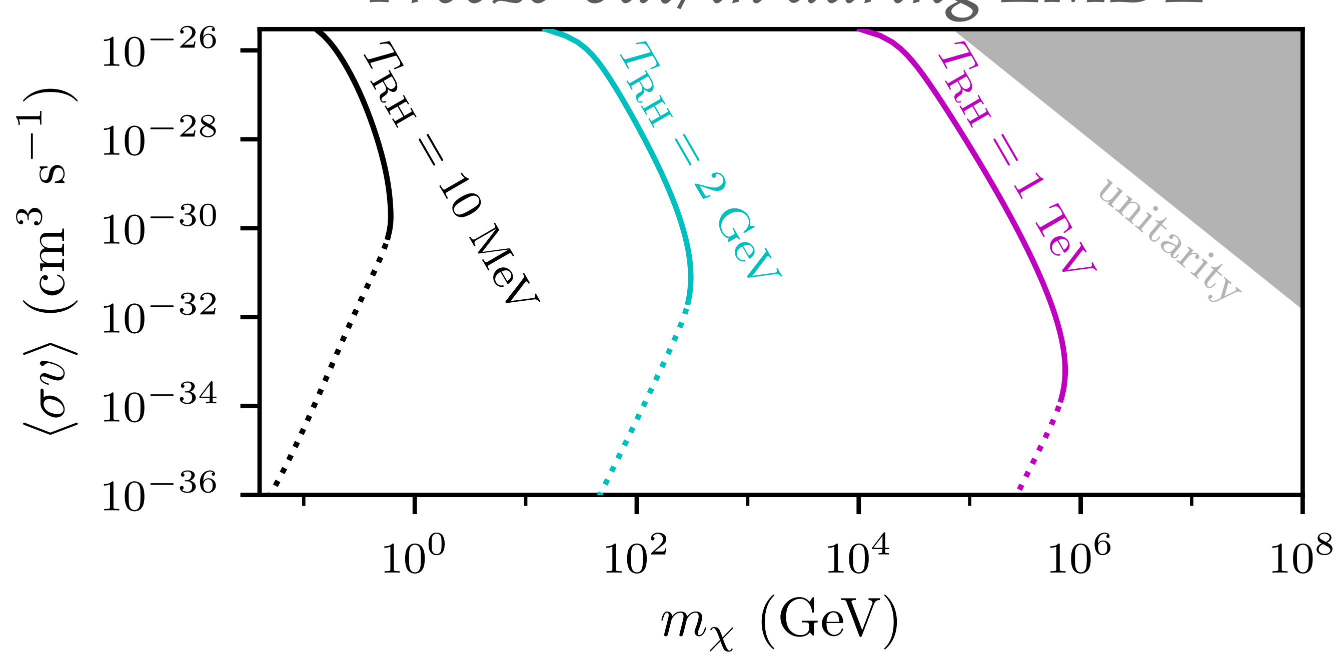
PARAMETRICS

- Phenomenologically, onset and duration of EMDE can be taken as free parameters
- EMDE generically ends when metastable particle decays
  - results in sizeable entropy dump
  - "gradual" decay: $\Gamma \sim H_{\rm end}$
- Coherent scalar fields may offer more exotic possibilities
  - formation and decay of solitonic objects (oscillons, Q-balls, …): abrupt decay
  - time-dependent eos (e.g., axion kination): no entropy generation

THERMAL DM PRODUCTION AND EMDES

- If DM abundance set by couplings to SM: entropy injection can have major impact on detection prospects
- Freeze-out: more DM ⇒ weaker couplings ⇒ can be consistent with stringent DD (ID, collider) bounds
- Freeze-in: more DM ⇒ stronger couplings ⇒ testability at colliders (long-lived particle searches)

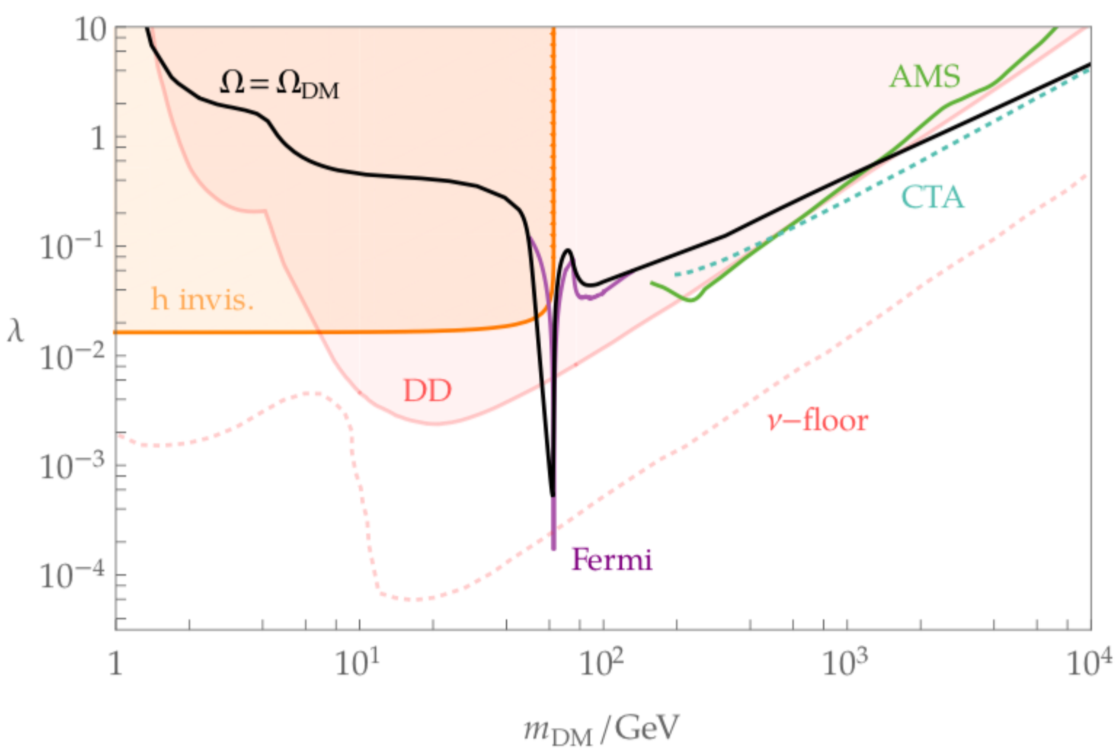
Freeze-out/in during EMDE



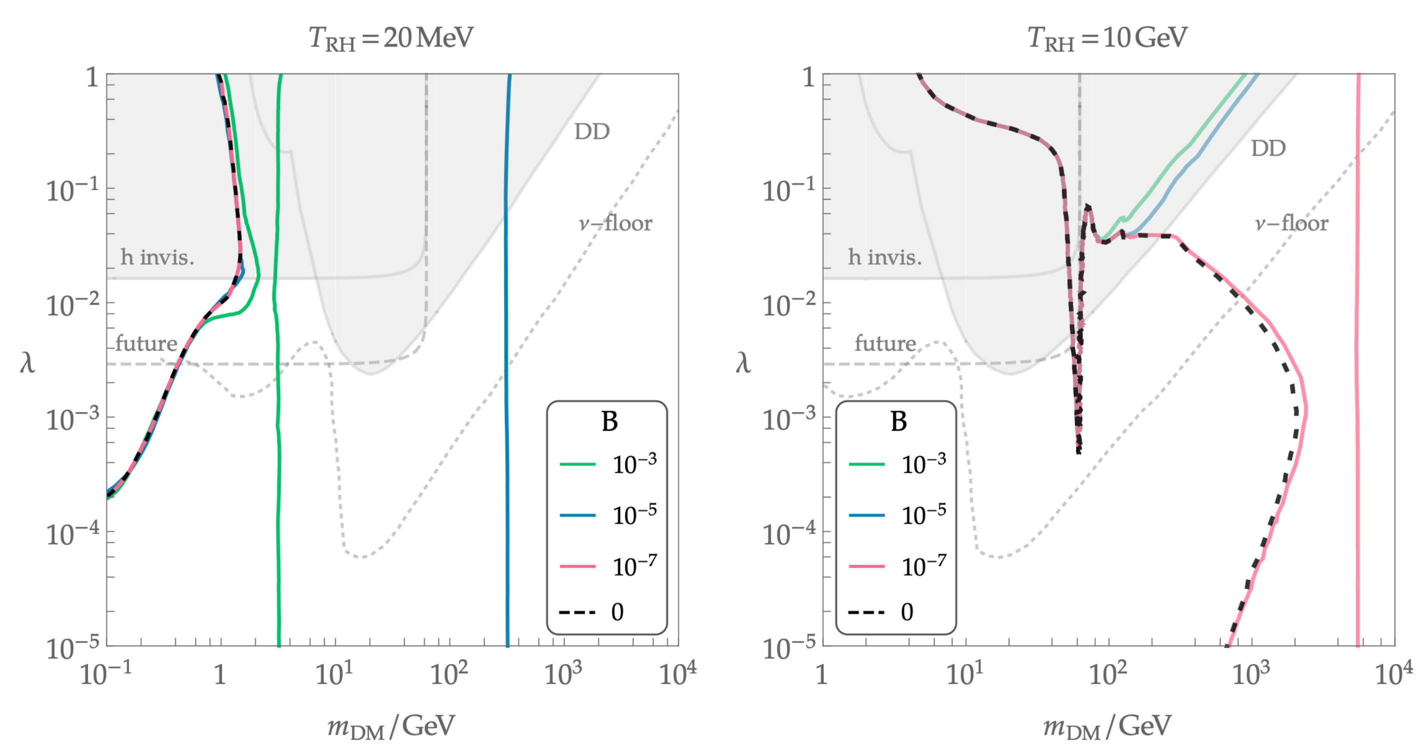
[Delos, Linden, Erickcek]

DM PRODUCTION AND EMDES: FREEZE-OUT

- simple example: minimal Higgs portal DM $\Delta\mathscr{L} = -\frac{\lambda}{2}S^2|H|^2$



- model is nearly fully excluded by combination of DD, Higgs decays (also indirect detection)

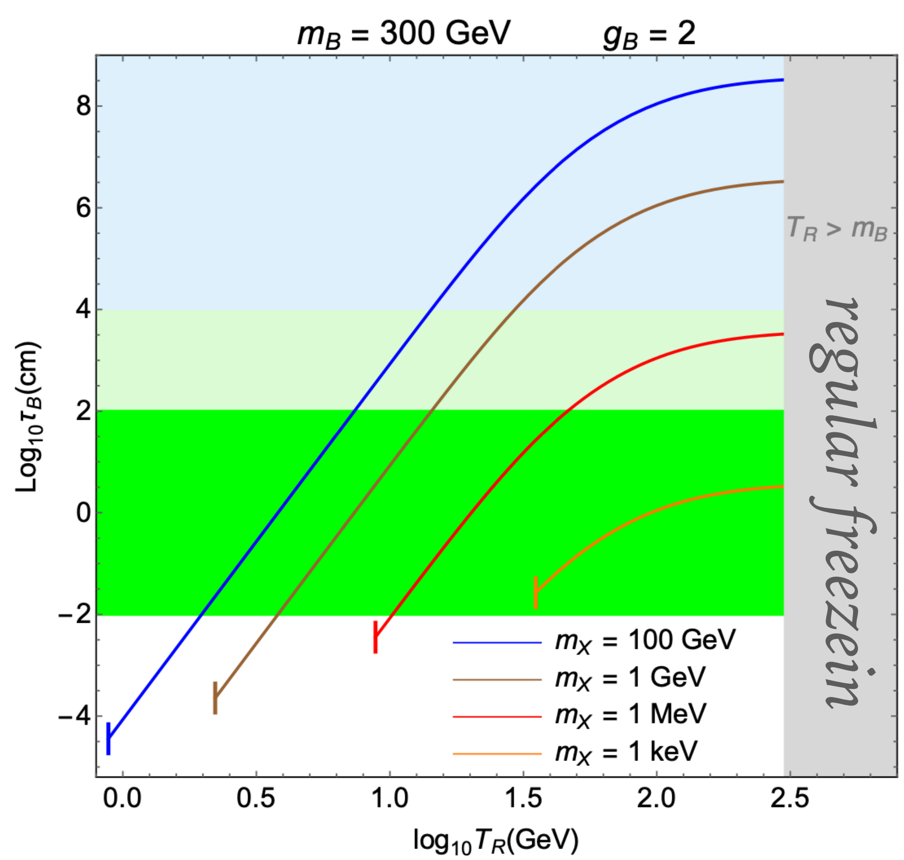


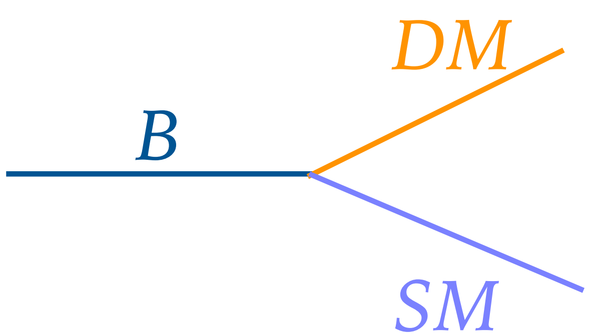
- entropy dump, direct DM production from decays reopen viable parameter space

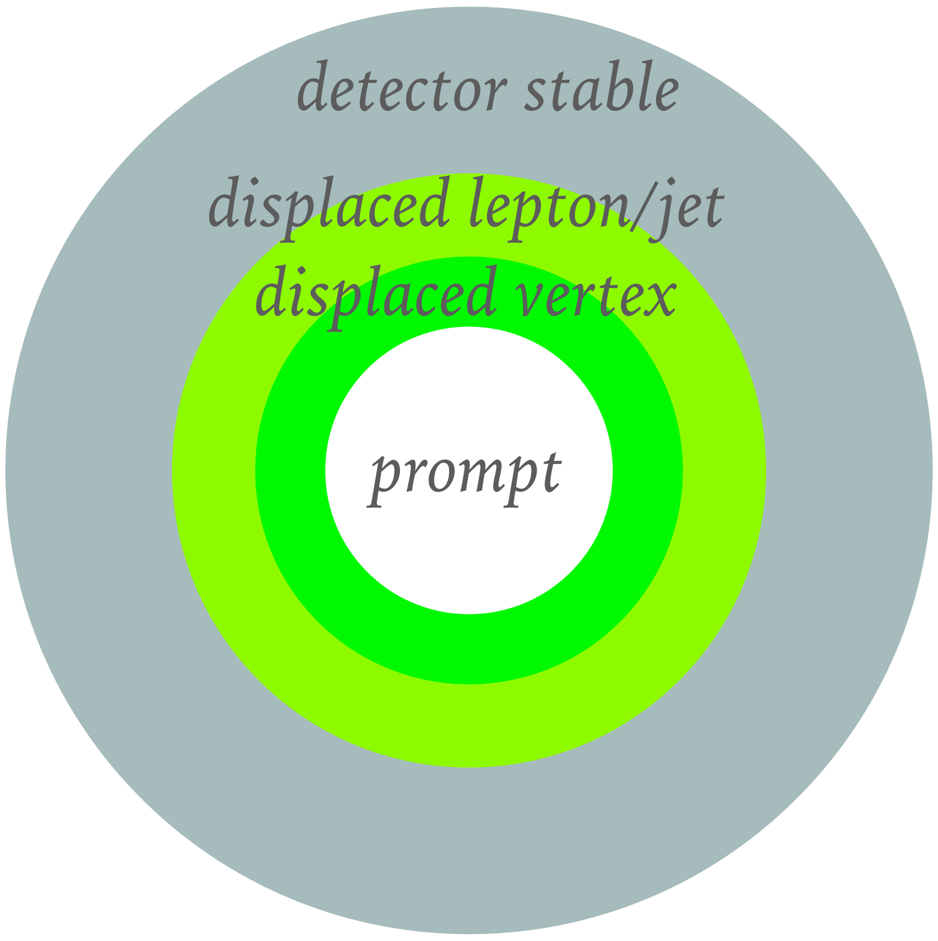
[Hardy, 2018]

DM PRODUCTION AND EMDES: FREEZE-IN

➤ Larger cross-sections for freeze-in can make DM-producing processes visible as displaced decays at colliders



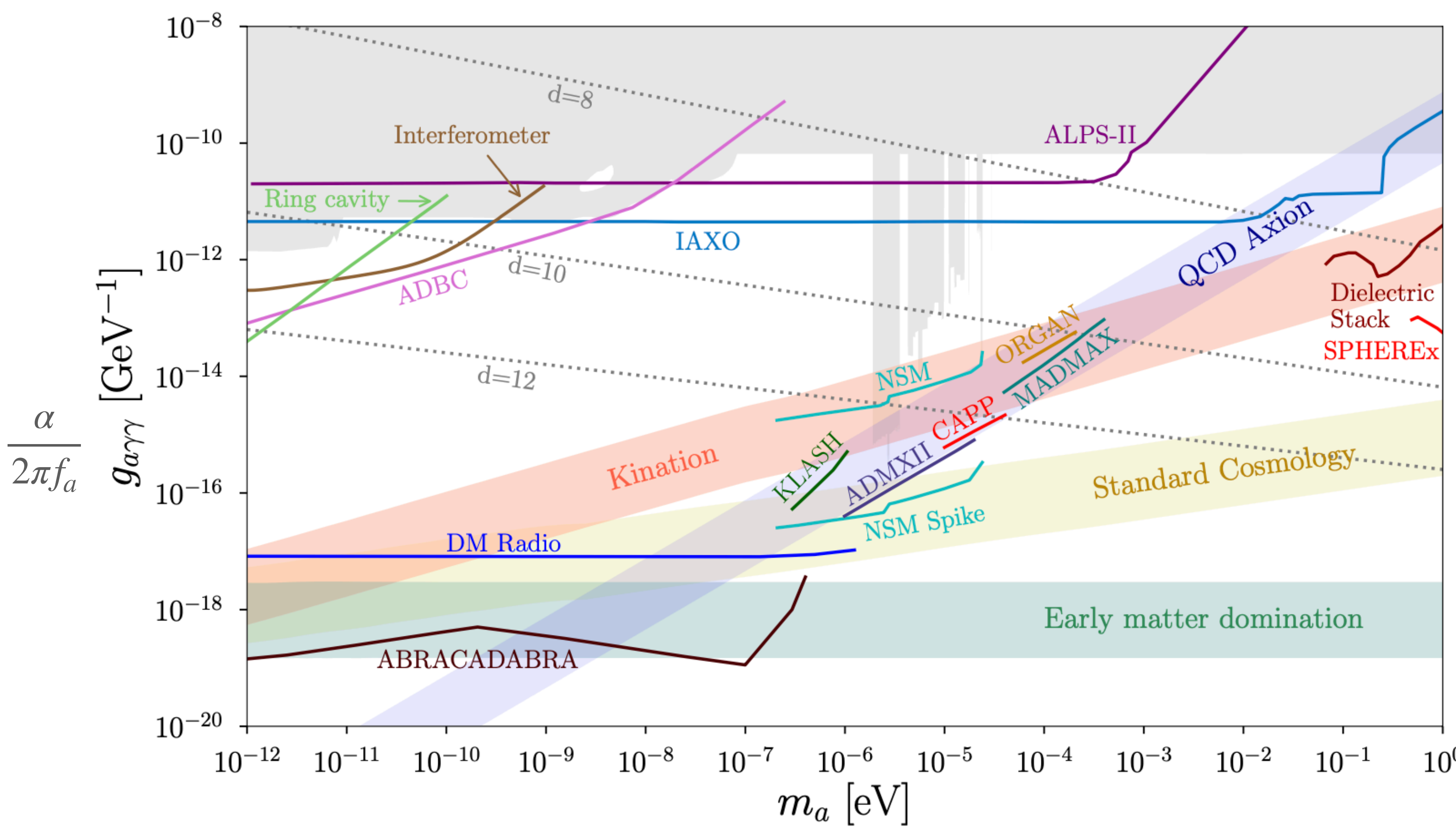




[Co, D'Eramo, Hall, Pappadopulo]

ABUNDANCE OF AXION DARK MATTER

- predictions for axion DM also depends on cosmic history
- E.g., misalignment, temperature-independent ALP mass:



$$\Omega_a = \frac{1}{2}\frac{m_a^2 f_a^2 \theta_0^2}{\rho_c}\left(\frac{R_{\rm osc}}{R_{\rm ad}}\right)^3\left(\frac{T_0}{T_{\rm ad}}\right)^3\frac{g_{*S}(T_0)}{g_{*S}(T_{\rm ad})}.$$

[Banks and Dine; Blinov, Dolan, Draper, Kozaczuk; Visinelli et al; …]

A DARK MATTER NIGHTMARE SCENARIO

- early universe: self-interacting HS, SM

[HS]

[SM]

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A DARK MATTER NIGHTMARE SCENARIO

cosmic abundance of this state can give rise to detectable consequences

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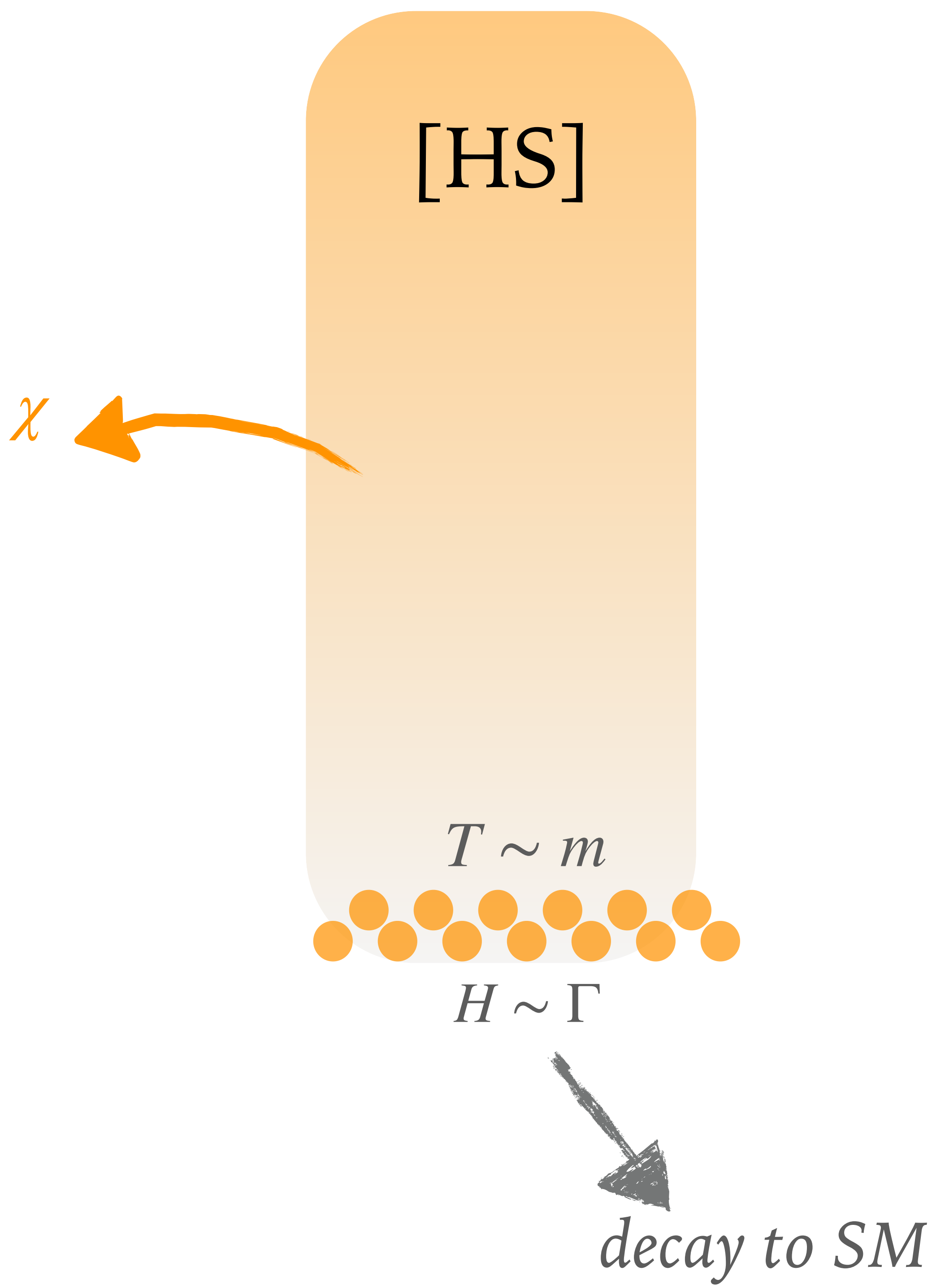
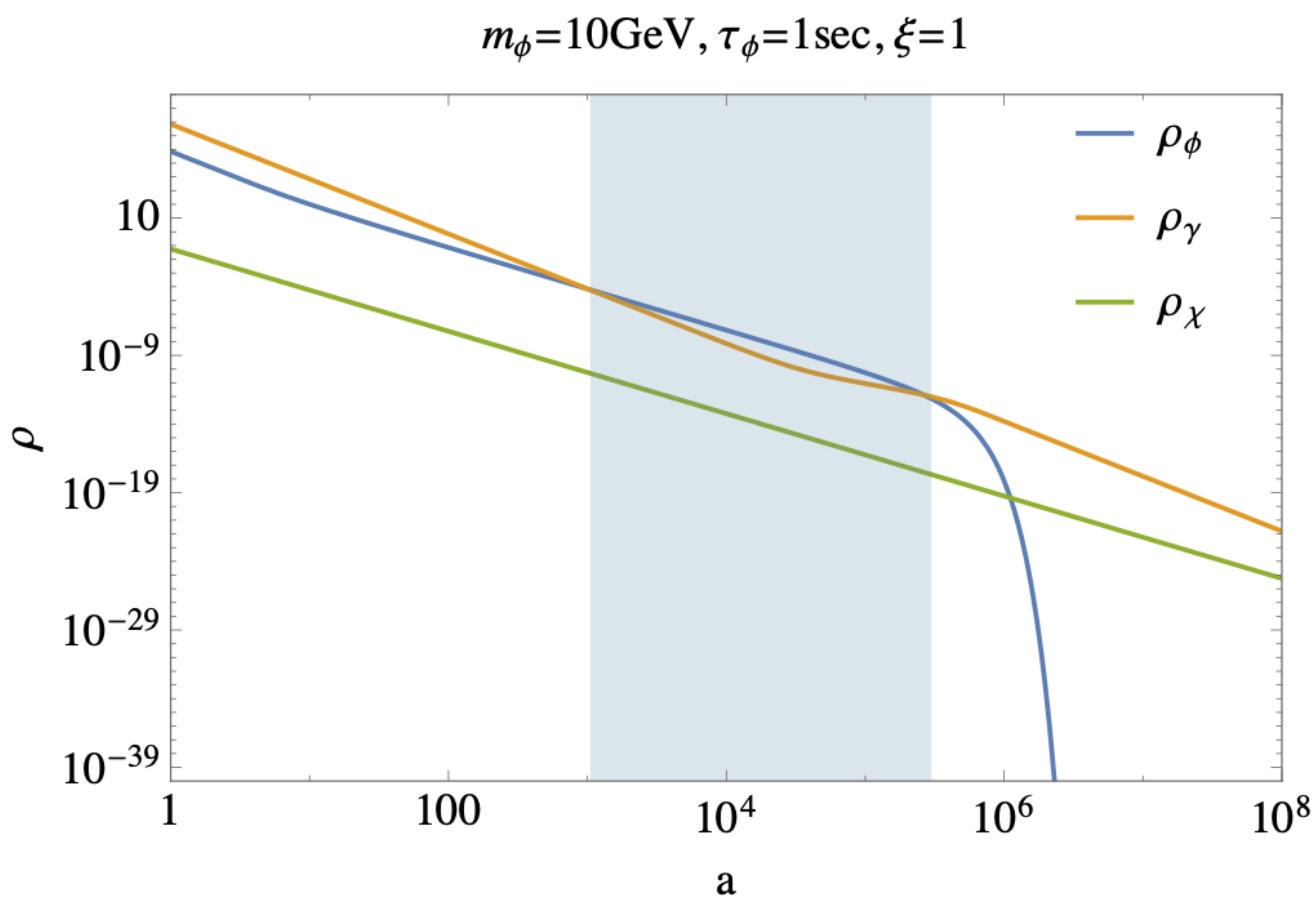


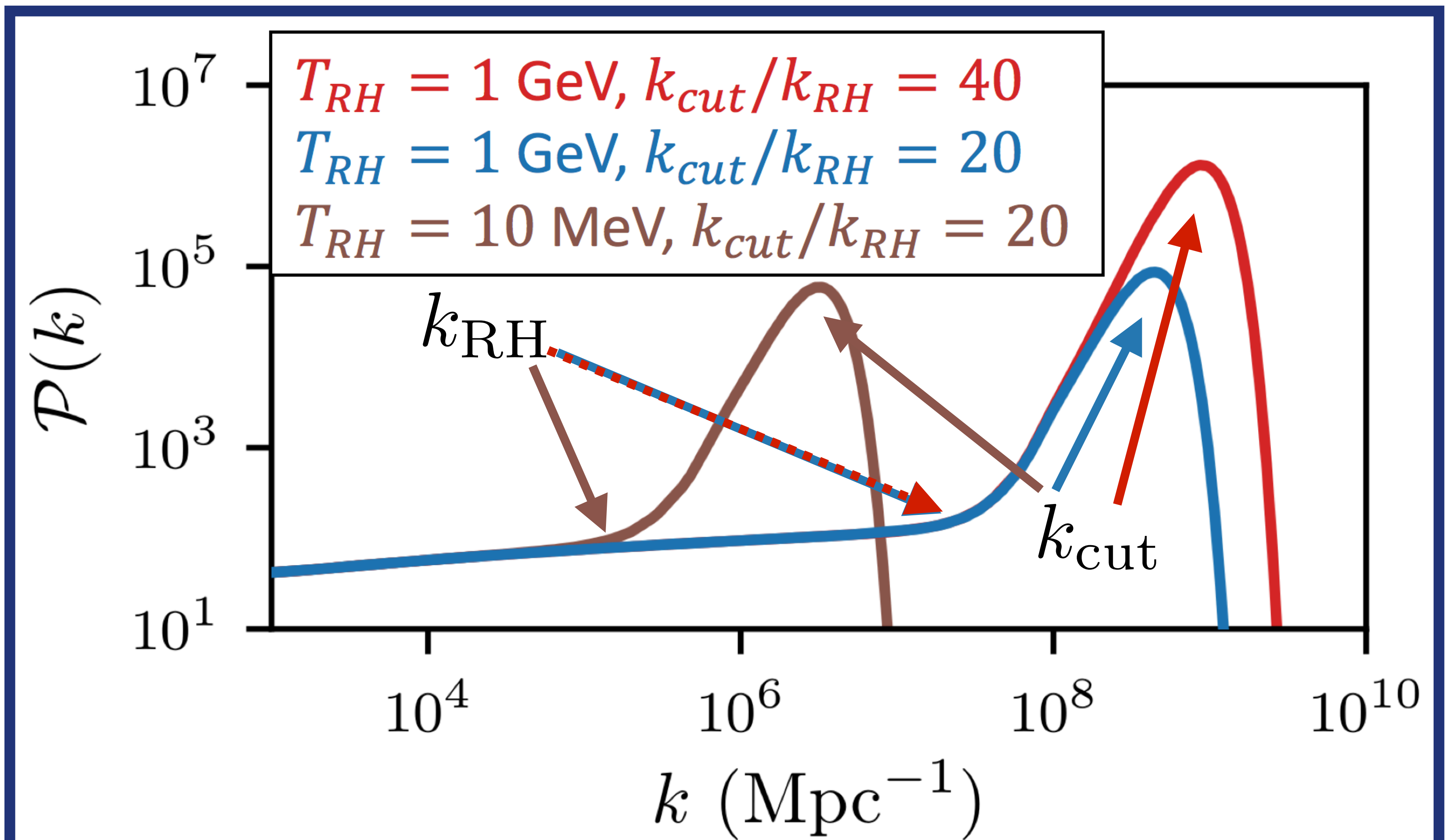


[Zhang]

- for composite metastable states, need significantly sub-Planckian operators for pre-BBN decays
- fundamentals: dark photon, heavy neutral lepton…

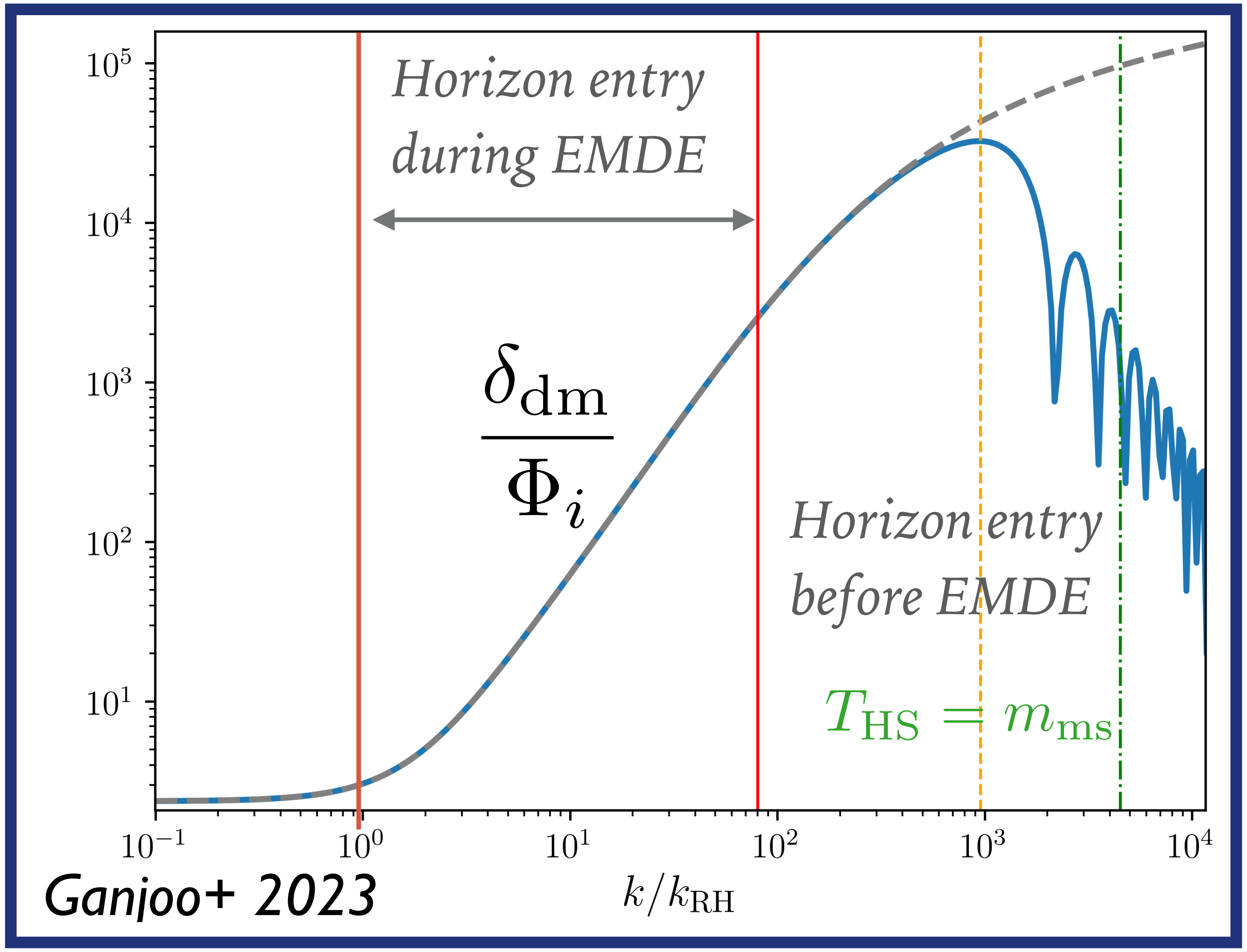
IMPRINT ON THE MATTER POWER SPECTRUM

- Linear growth of DM perturbations during EMDE: $\delta_{\rm dm} \propto \frac{a_{\rm RH}}{a_{\rm hor}} \propto \frac{k^2}{k_{\rm RH}}$
- $k_{\rm RH} = a_{\rm RH} H(a_{\rm RH})$ sets beginning of enhancement
- Amplitude of enhancement set by the duration of the EMDE and/or the cutoff scale in the matter power spectrum



THE SMALL-SCALE CUTOFF

- small-scale cutoff: microphysics
- often, from DM free streaming: esp. if DM is kinetically coupled to the radiation bath [Gelmini & Gondolo 2008; ALE, Sinha, Watson 2016; Waldstein, ALE, Illie 2017] or generated from the decay of the metastable species [Fan, Ozsoy, Watson 2014; Miller, ALE, Murgia 2019]
- If DM is sufficiently cold (e.g. from hidden sector), the microphysics of the metastable species that drives the EMDE sets the cutoff
  - Mass of metastable species: suppression on scales that enter horizon while $T_{\rm HS} > m$ [Ganjoo, ALE, Lin, Mack 2023]
  - Cannabilistic self-interactions of metastable species [ALE, Ralegankar, JS 2022, 2023]

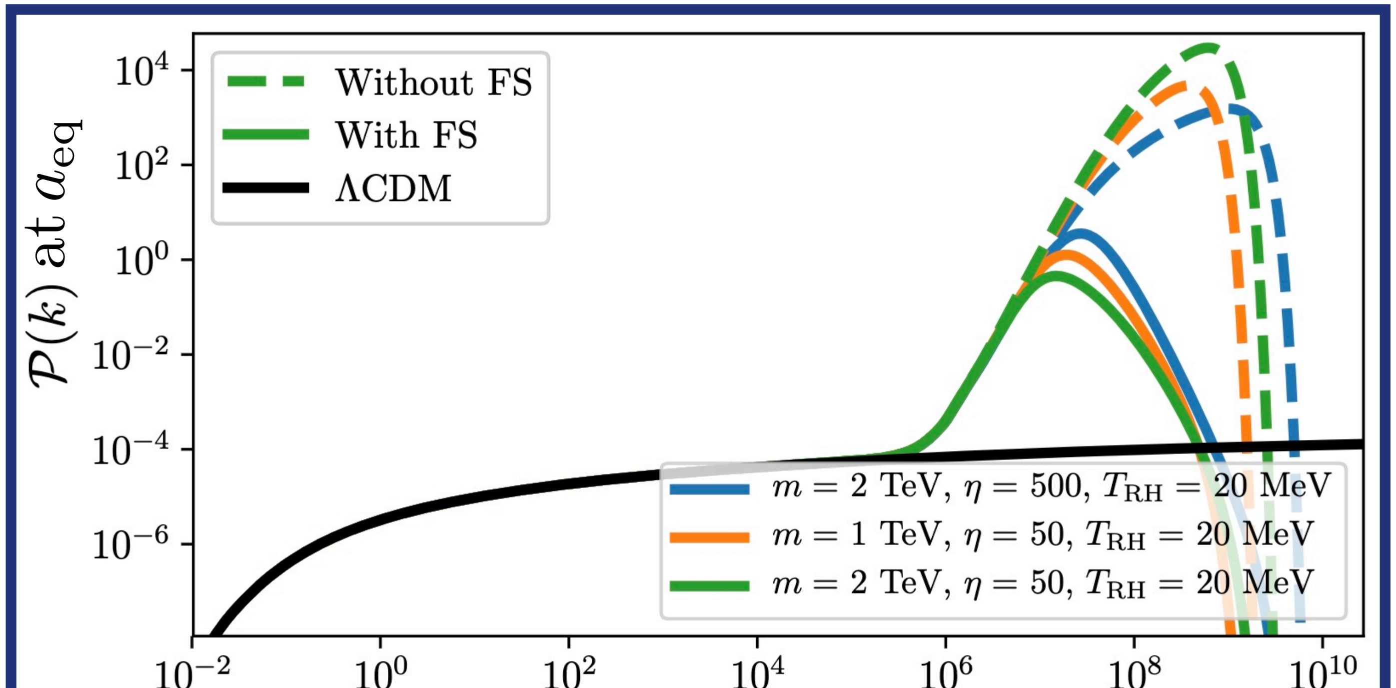


STRUCTURE DURING THE EMDE?

- If the EMDE is sufficiently long, the metastable particles can clump and form bound structures.
- Dark matter particles fall into these halos and then are released when the metastable particles decay.
- The subsequent free streaming of the DM sets a new cutoff.
  [Blanco, Delos, ALE, Hooper 2019; Barenboim, Blinov, Stebbins 2021; Ganjoo and Delos 2024]

- Gravitational waves from early halo collapse

  [Jedamzik, Lemoine, Martin 2010; Fernandez, Foster, Lillard, JS 2023]

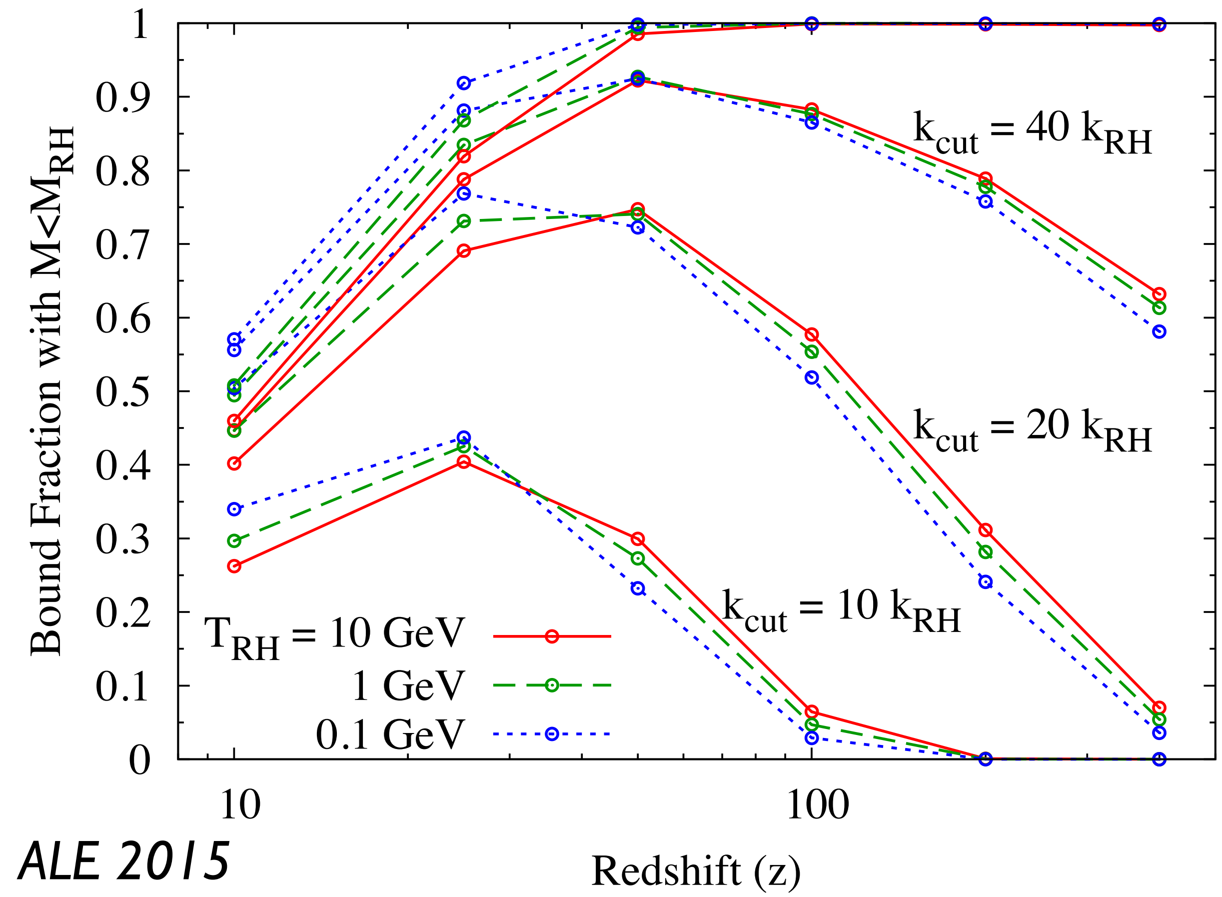


Ganjoo & Delos 2024

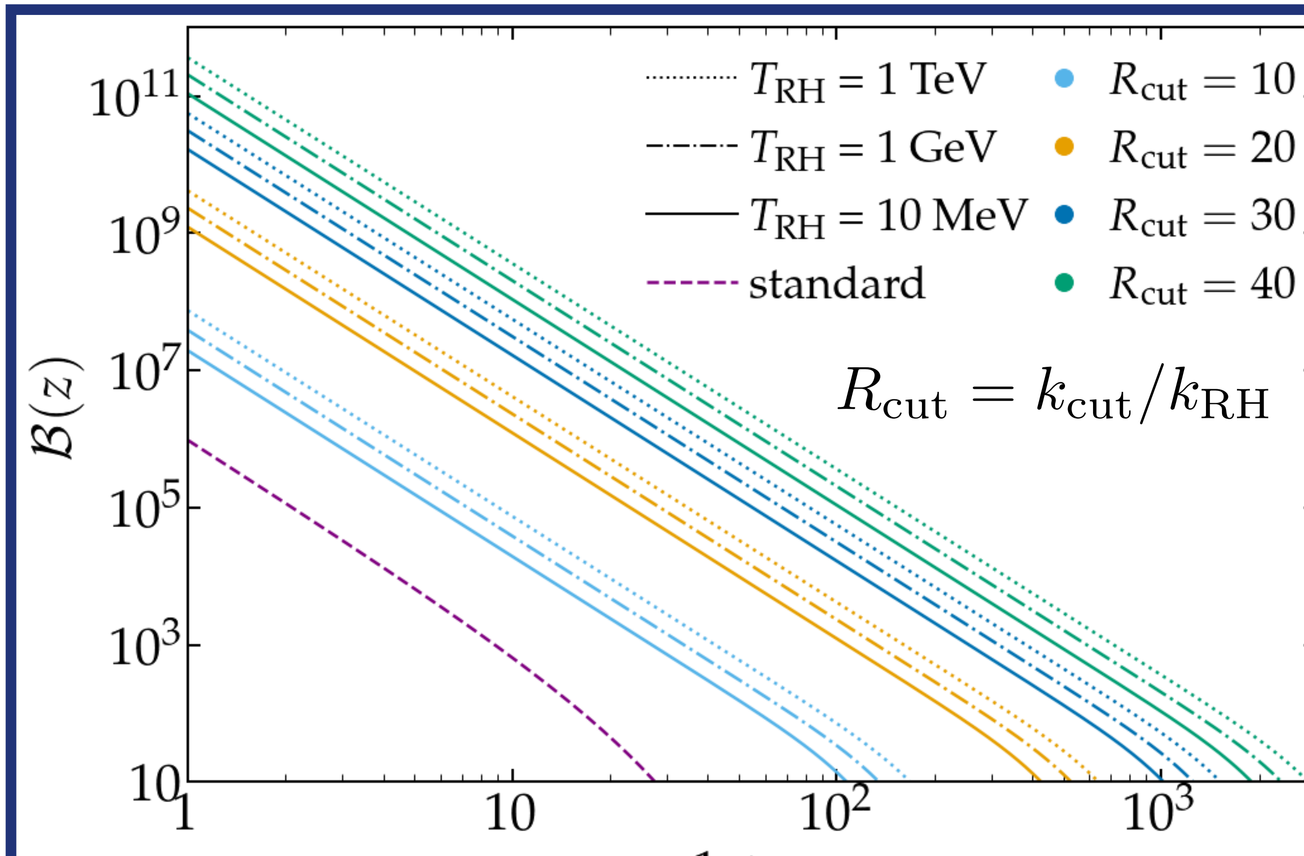
MICROHALOS

- The ratio k_{cut}/k_{RH} sets the amplitude of the peak in the power spectrum and the formation time of the first microhalos.
- Microhalos can form during radiation domination. [Blanco, Delos, ALE, Hooper 2019]
- Earlier-forming microhalos are denser and are more likely to survive within larger halos.[Delos 2019a, 2019b; Blinov, Dolan, Draper, JS 2021; Shen, Xiao, Hopkins, Zurek 2024]
- Microhalos increase the dark matter annihilation rate [ALE 2015; Blanco, Delos, ALE, Hooper 2019; Delos, Linden, ALE 2019; Ganjoo & Delos 2024…]

$$B(z) \equiv \frac{\langle \rho_\chi^2 \rangle}{\bar{\rho}_\chi^2}$$



ALE 2015

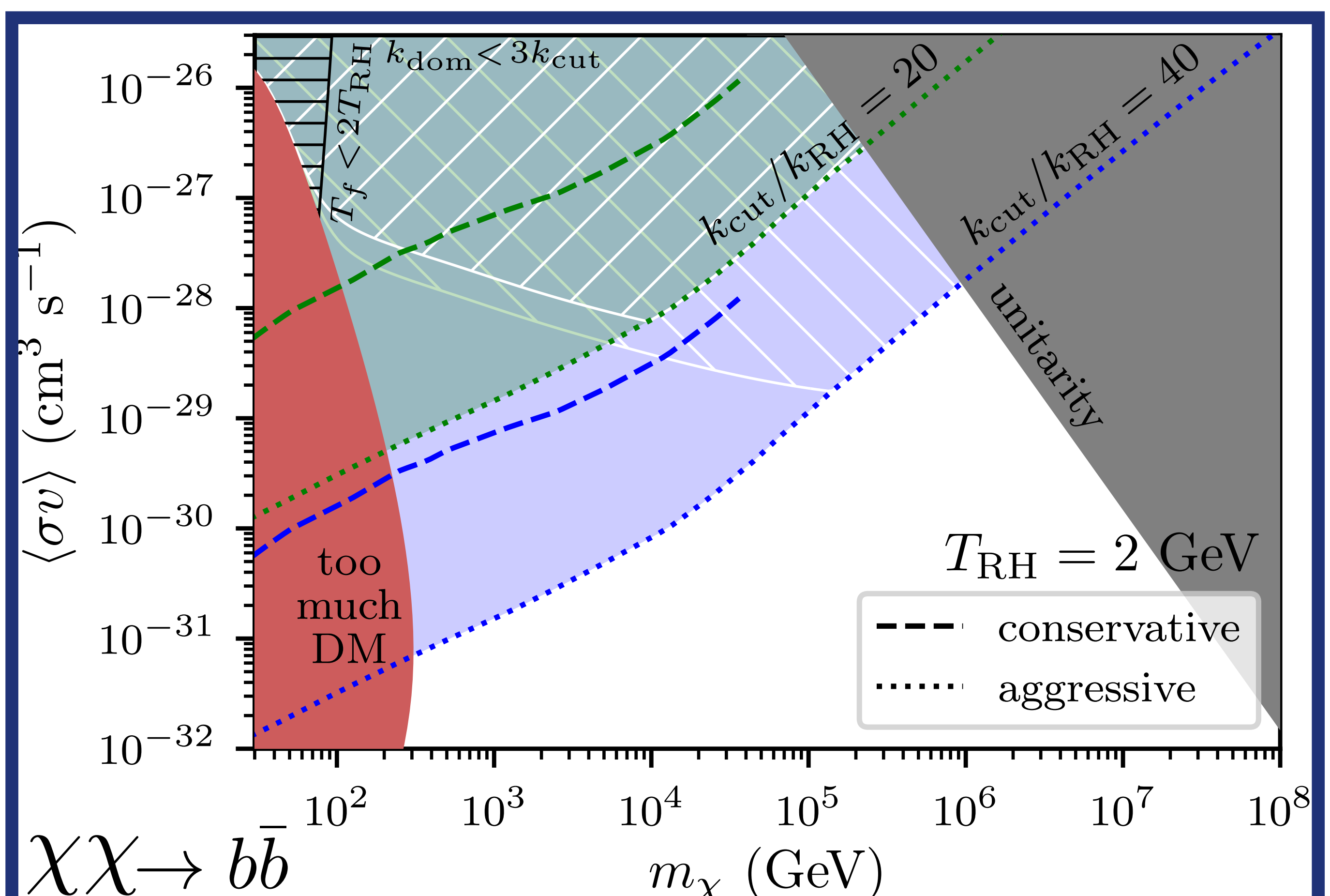


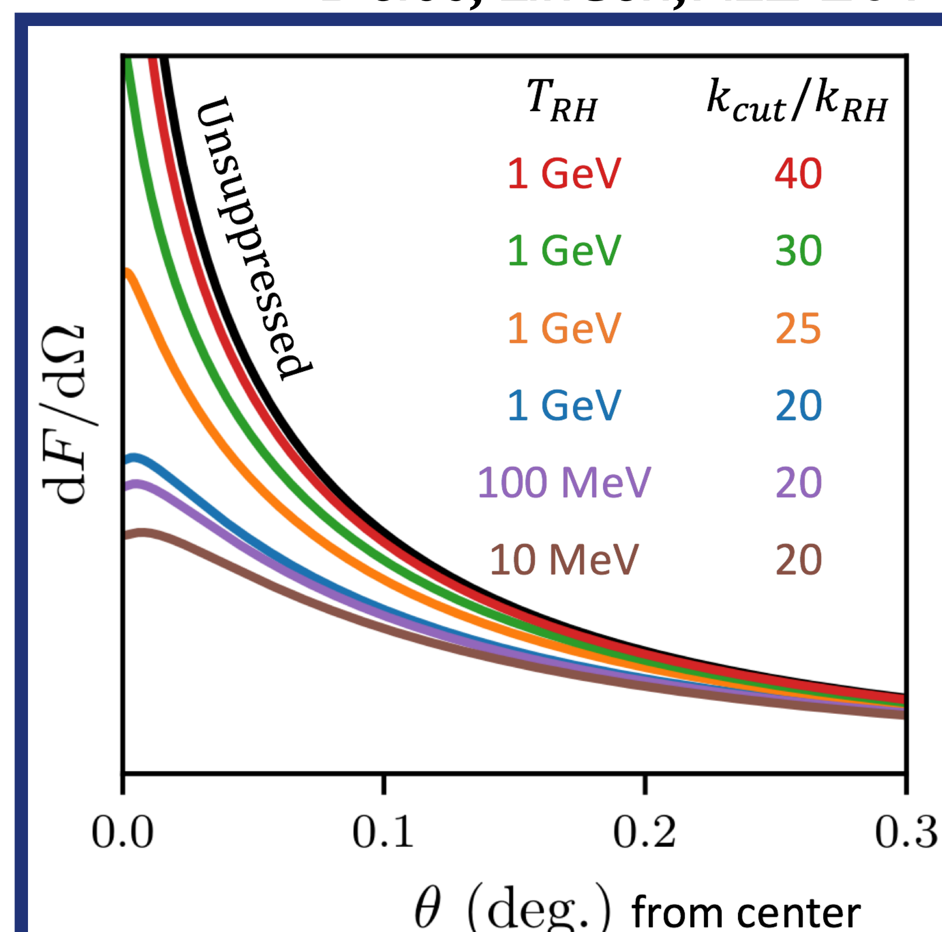
Bae, ALE, Delos, Munoz, coming soon

CONSTRAINTS ON DM ANNIHILATION WITH EMDES

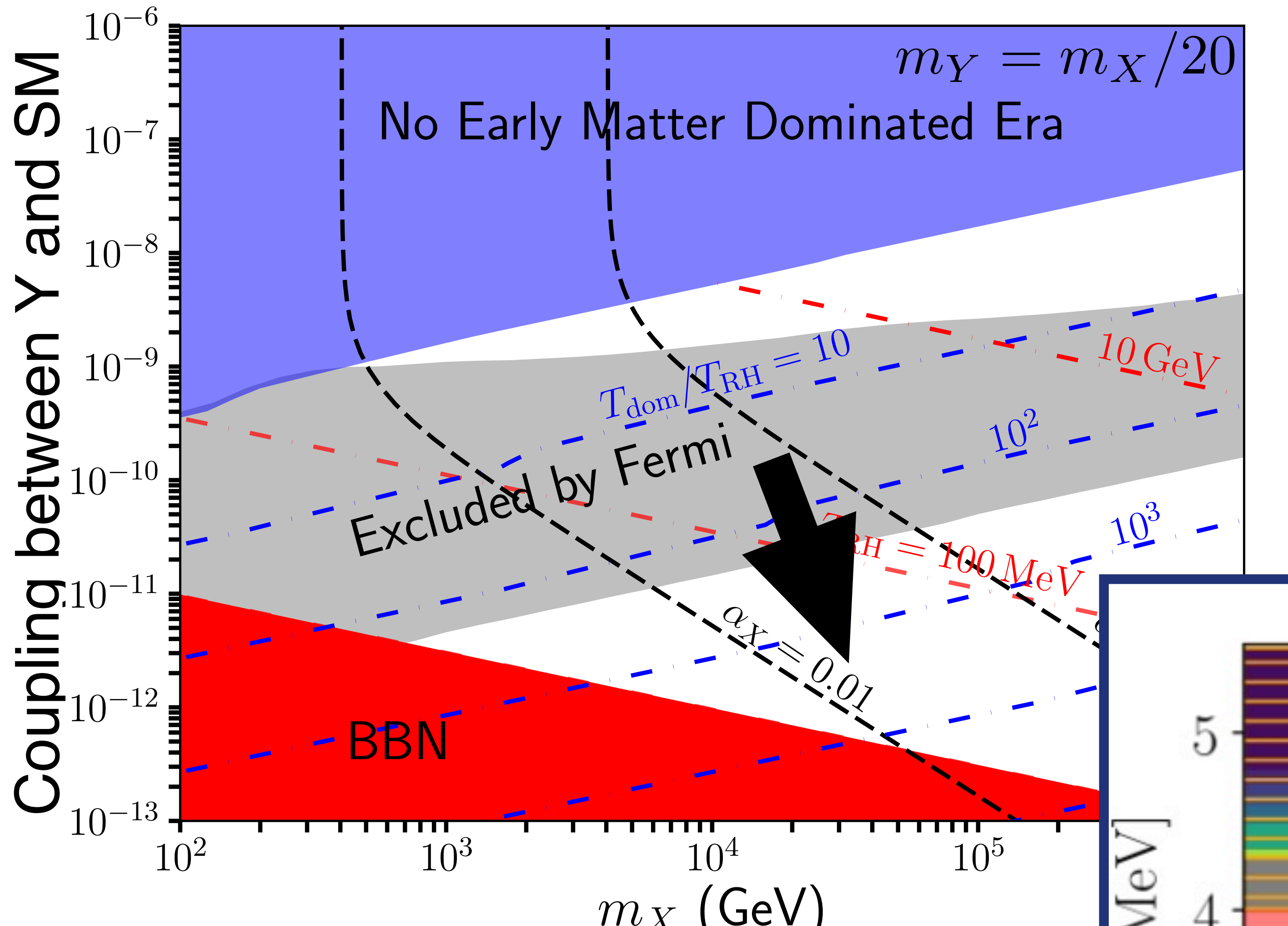
- Dark matter annihilation within microhalos mimics dark matter decay because energy output tracks DM density.
- Strongest current limits from isotropic gamma-ray background constraints on decaying DM [Delos+ 2019, Blanco+ 2019, Ganjoo & Delos 2024].
- Dwarf galaxies could distinguish annihilation within microhalos from decaying DM [Delos, Linden, ALE + 2019].

Delos, Linden, ALE 2019

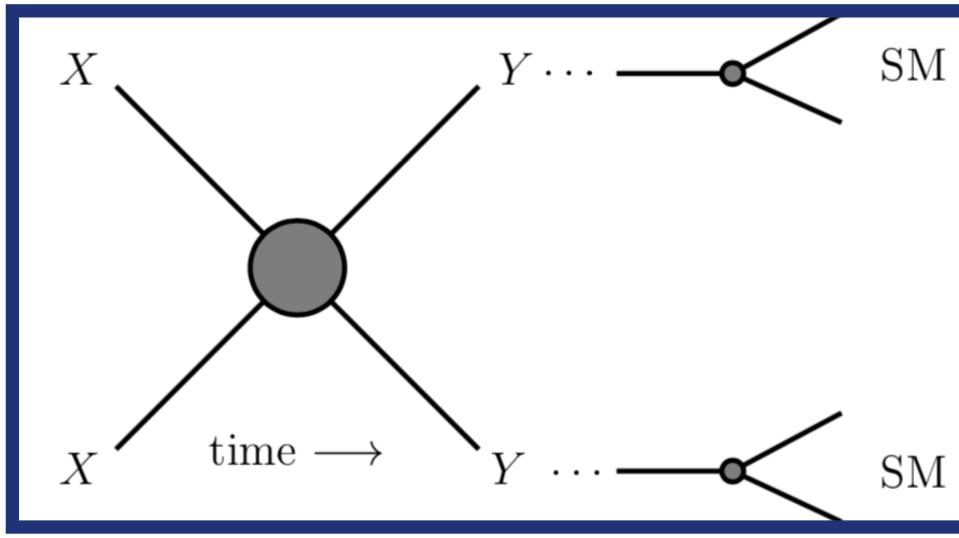


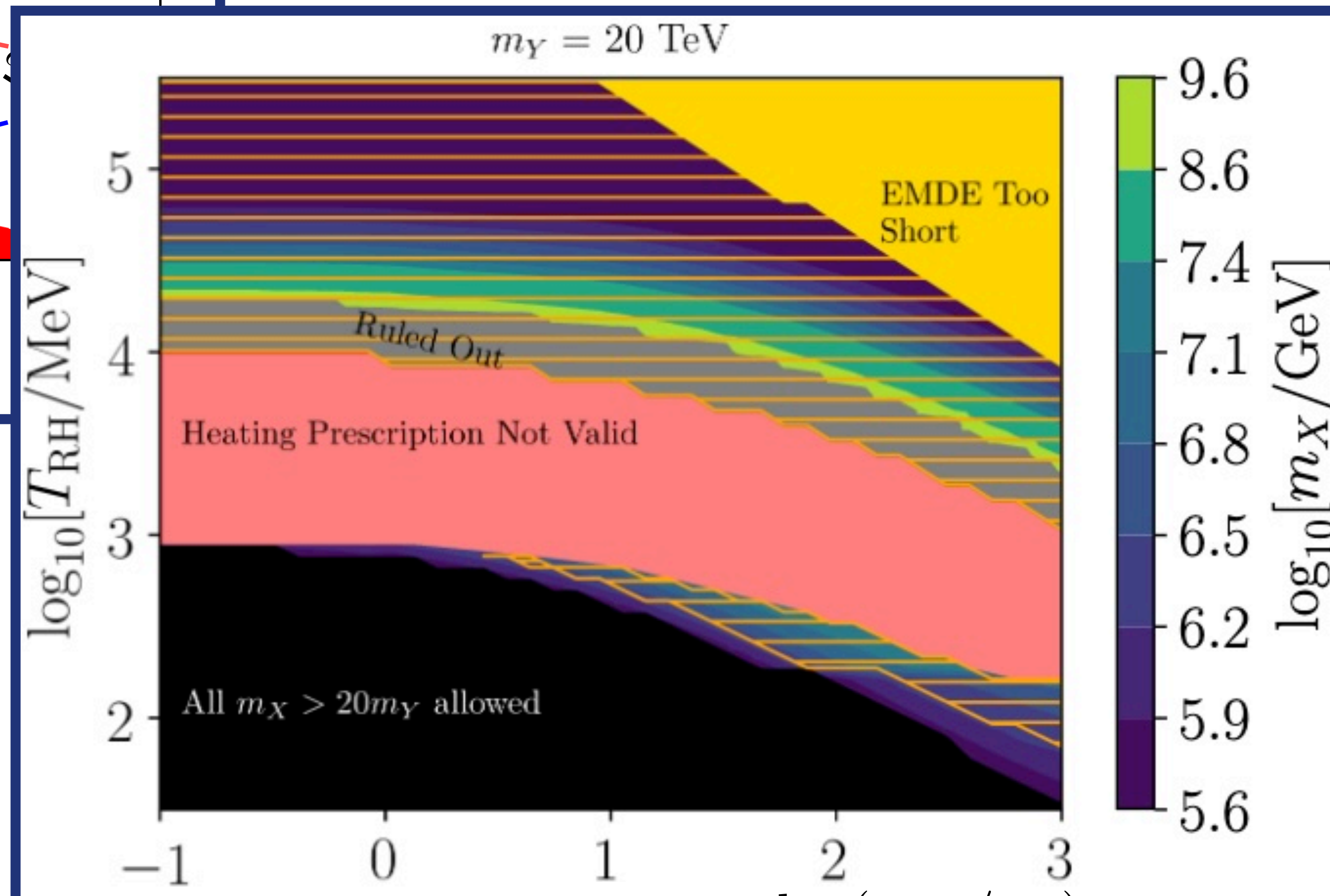


CONSTRAINING DM PRODUCTION IN EMDE COSMOLOGIES



Blanco, Delos, ALE, Hooper 2019

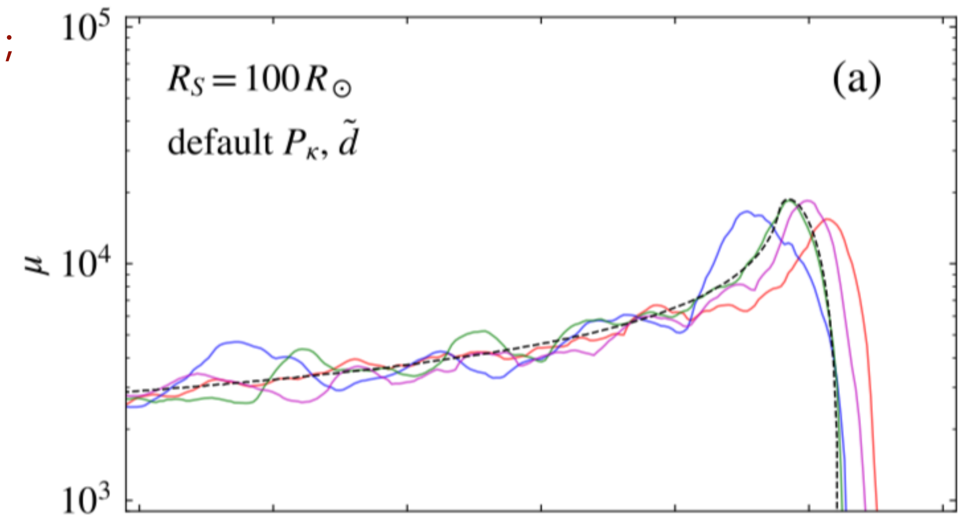


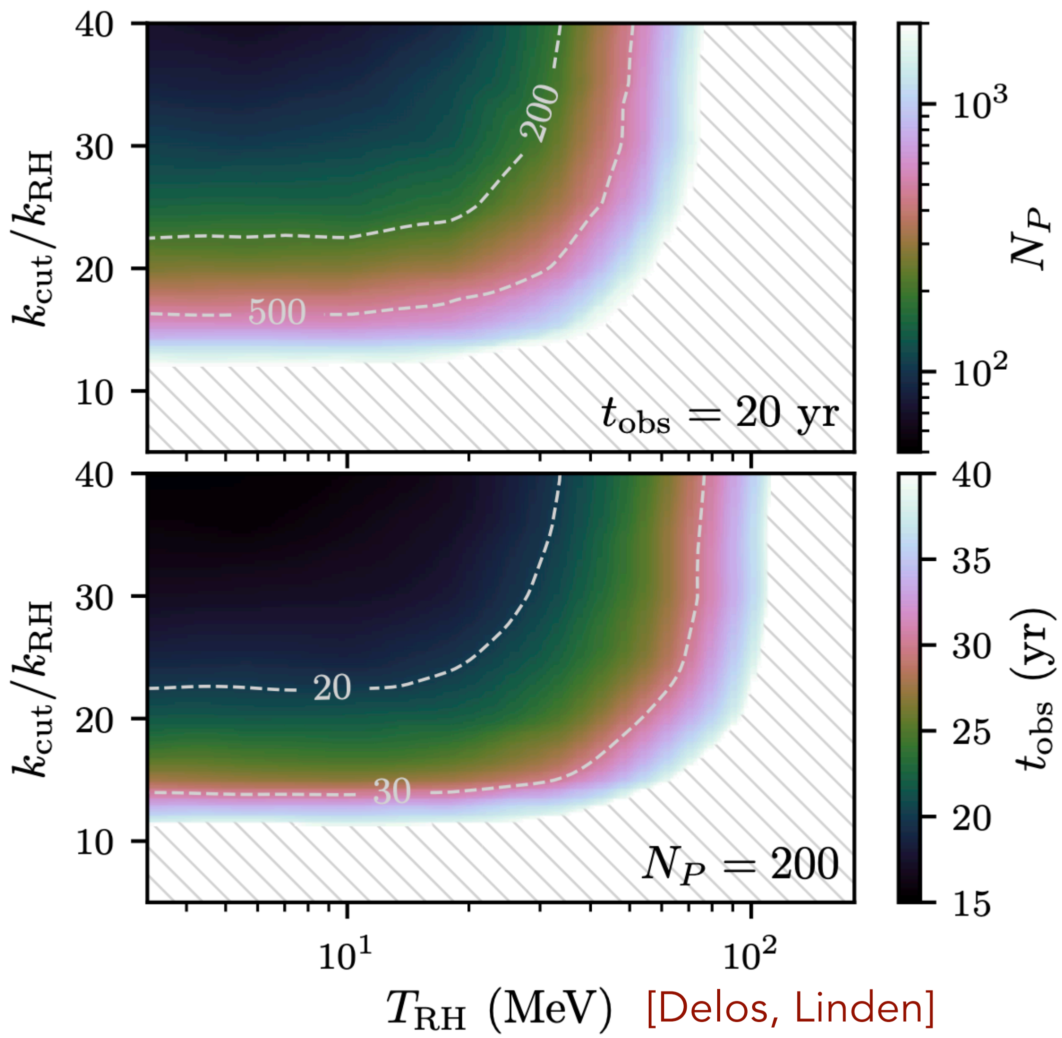


Ganjoo & Delos 2024

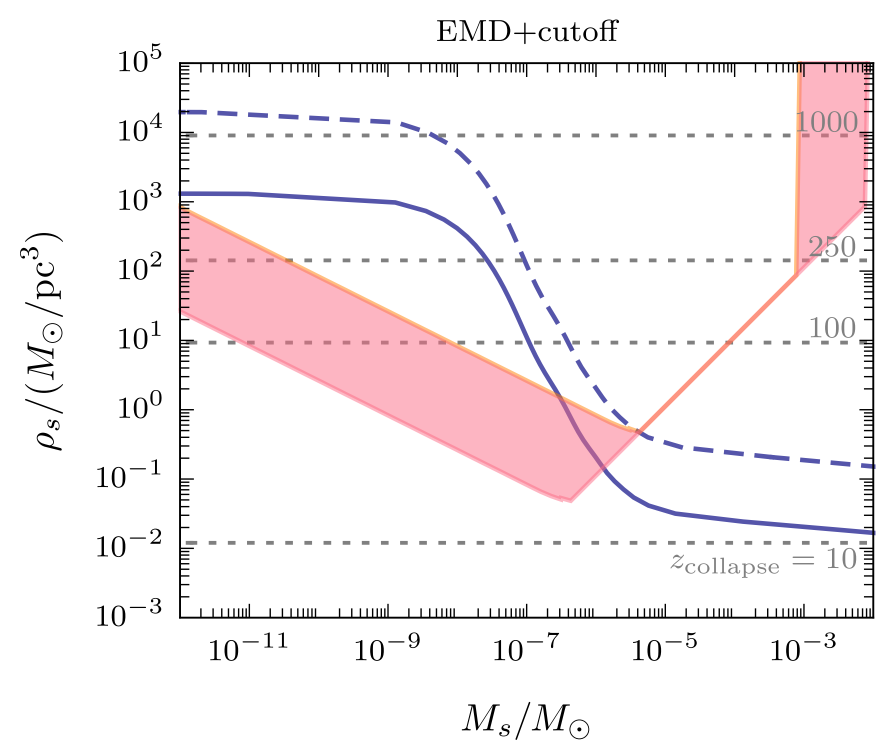
GRAVITATIONAL SEARCHES FOR MICROHALOS

- gravitational observational prospects are still futuristic
  - pulsar timing arrays [Ramani, Trickle, Zurek; Delos, Linden; Lee, Mitridate, Trickle, Zurek; …]
  - cluster caustic microlensing [Diego et al; Oguri et al; Dai, Miralda-Escude]
  - 20 AU-baseline radio interferometry of FRBs [Xiao, Dai, McQuinn]





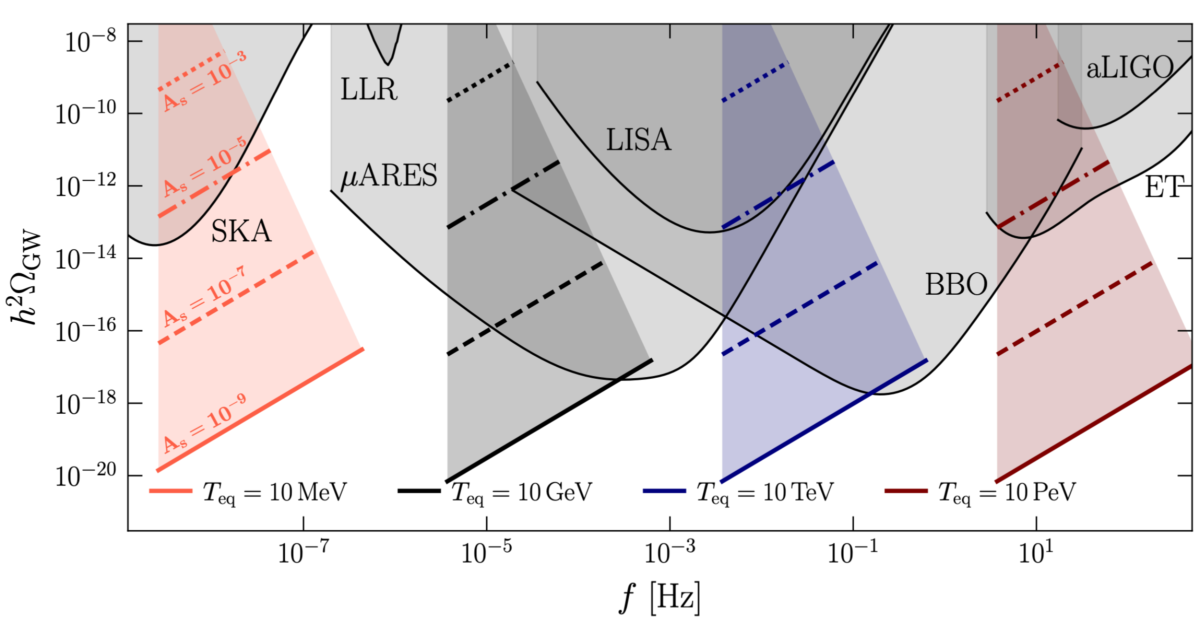
[Delos, Linden]



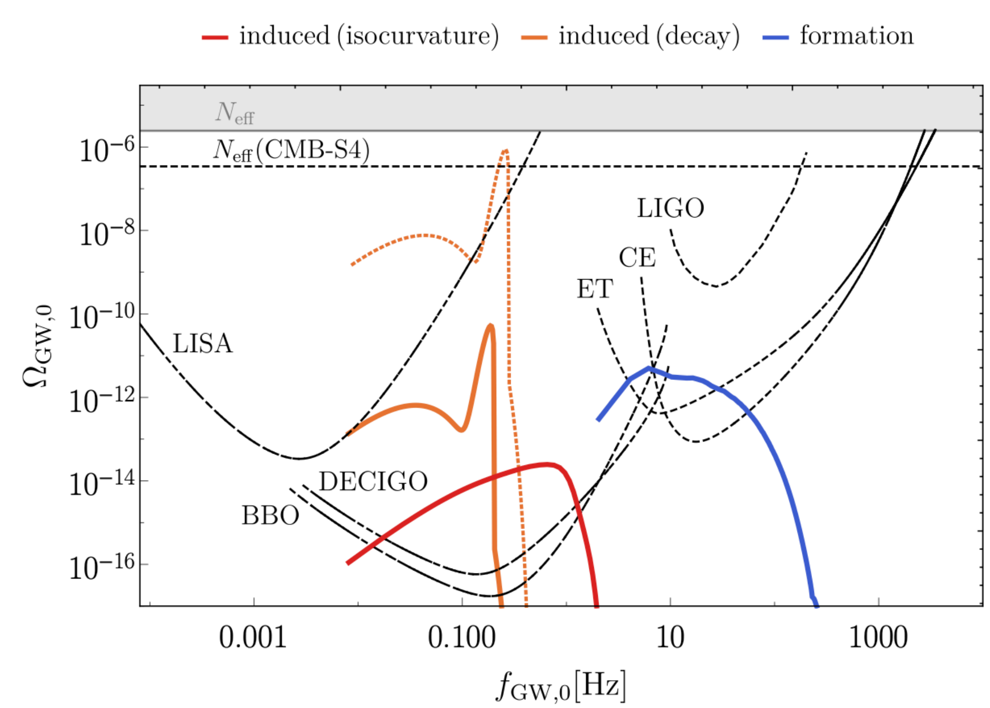
[Blinov, Dolan, Draper, JS]

GRAVITATIONAL WAVES FROM NONLINEAR STRUCTURE

- induced gravitational wave signature in linear theory, generically undetectably small unless:
  - faster-than-Hubble decays (oscillons, PBHs)
  - enhanced primordial power spectrum
- nonlinear regime: halo collapse during EMDE; soliton formation



[Fernandez, Foster, Lillard, JS]



[Lozanov, Sasaki, Takhistov]

OPEN QUESTIONS FOR DISCUSSION

- Many avenues for refinement, especially in nonlinear regimes
  - microhalo formation (esp during RD) and disruption
  - soliton formation and decay
  - early nonlinear structure formation and maximum possible enhancement to matter power spectrum
- Prospects for detecting enhanced microstructure gravitationally remain somewhat futuristic
  - more ideas for detection important!
- Room to further characterize gravitational wave signatures
- Interplay with baryogenesis important but generically less directly testable

DISCUSSION: THE GAP IN THE EMDE MATTER POWER SPECTRUM

- From Ganjoo & Delos 2024 [JCAP04(2024)015]

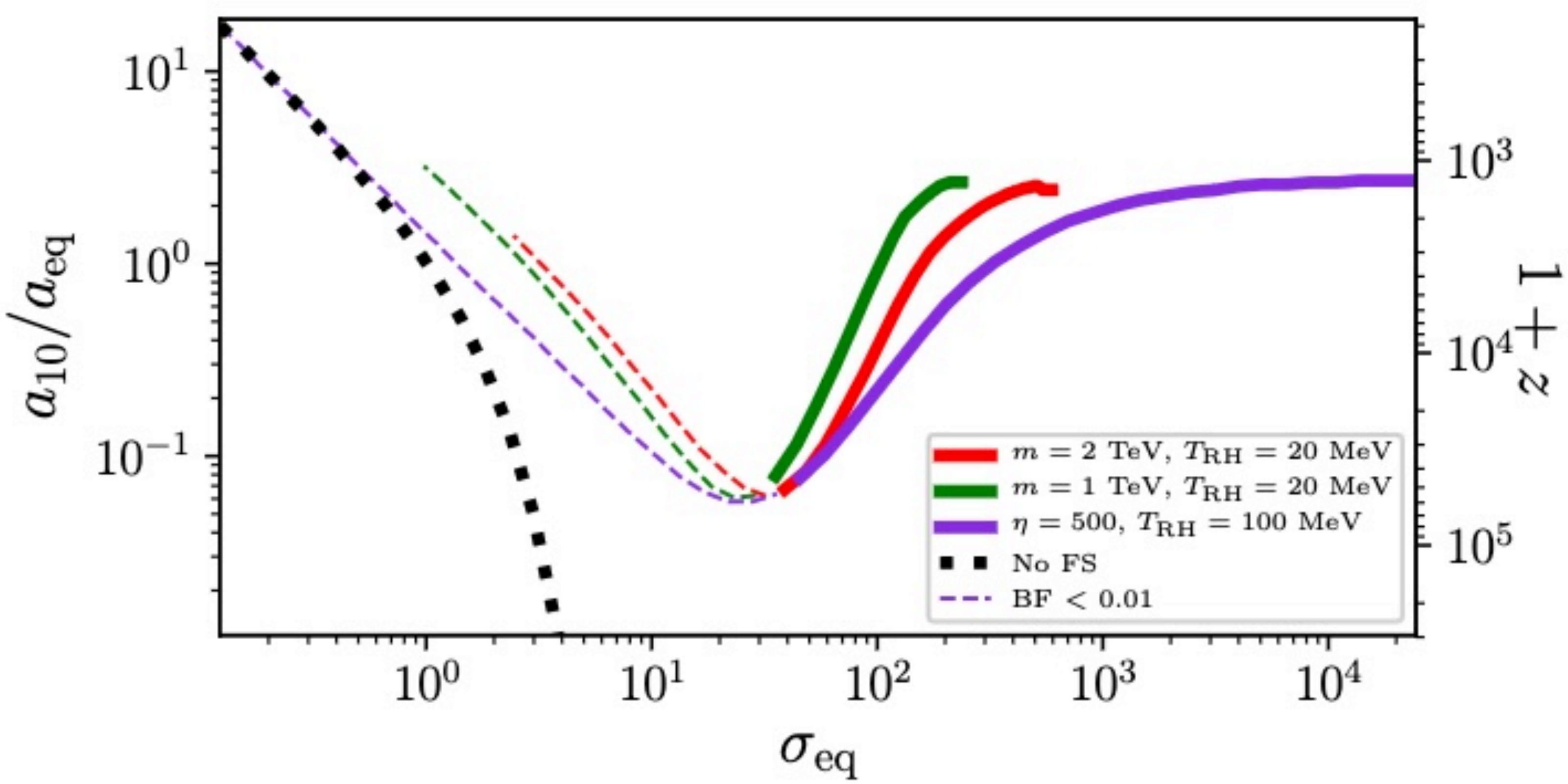
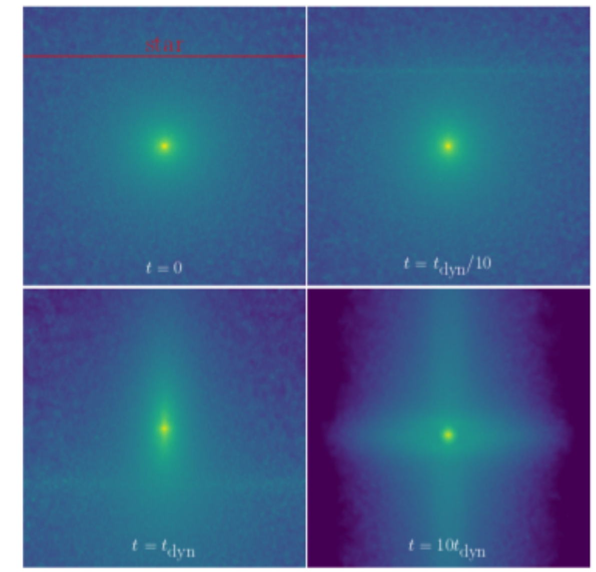


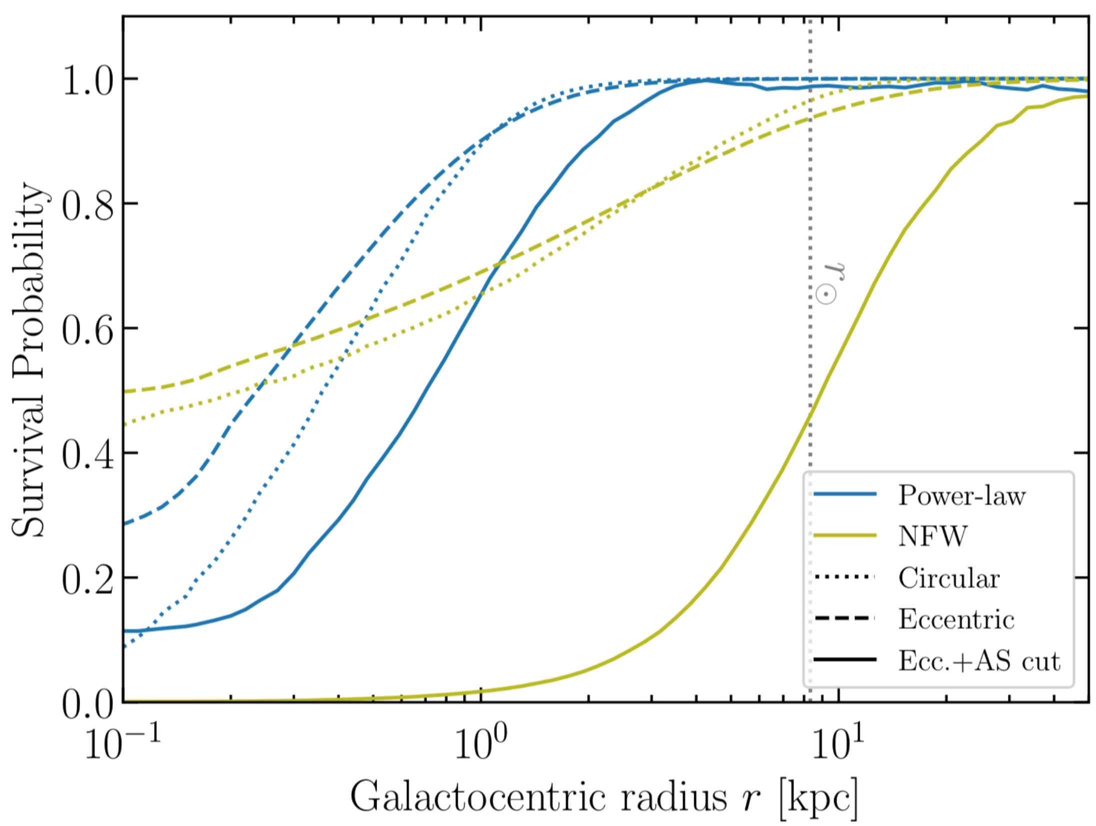
Figure 14: The scale factor at which 10% of the dark matter is predicted to be bound in halos according to Press-Schechter theory, plotted against σ_{eq} (Eq. 6.3), which quantifies the extent to which the small-scale power spectrum is enhanced during an EMDE. The curves are obtained by varying η (red and green) and m (purple) to vary σ_{eq} by varying the shape and peak of the EMDE-enhanced power spectrum. The dashed curves show cases in which the bound fraction at $a_{RH} < 0.01$, the regime in which our free-streaming cut-off prescription is untested. The dotted line shows a_{10} for the same EMDE cases without the free-streaming cut-off, which only depends on σ_{eq} regardless of the power spectrum shape.

GRAVITATIONAL SEARCHES FOR MICROHALOS

- Do these microhaloes survive in galaxies?
  - Probably
  - an *O(1)* fraction are likely to survive, albeit:
    - tidally stripped
    - not in dense galactic bulge environments



[Delos]



[Kavanagh, Edwards, Visinelli, Weniger]

- early formation redshift critical:

$$z_c \gtrsim 250$$

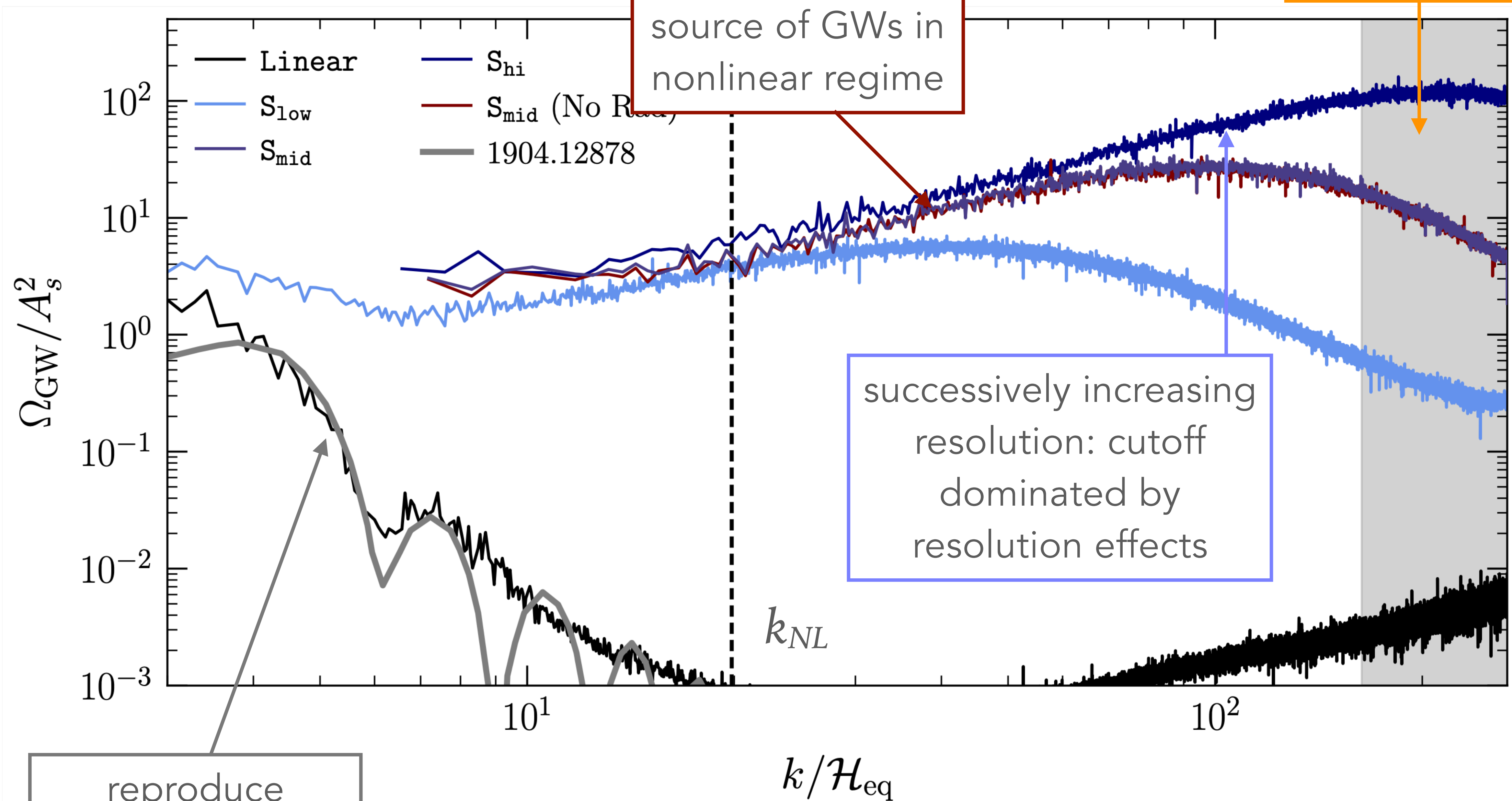
(Milky Way)

[Blinov, Dolan, Draper, JS]

GRAVITATIONAL WAVES FROM HALO FORMATION

frequencies are larger than light-crossing times of largest halos

decay radiation is not an important source of GWs in nonlinear regime



successively increasing resolution: cutoff dominated by resolution effects

reproduce analytic result in linear regime

[Fernandez, Foster, Lillard, JS]