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Scalar portal verifiable light DM and correlated GW signatures

Ongoing work..

Collaboration with Ki-Young Choi (SKKU) & Satyabrata Mahapatra (IIT Goa)

2026 CAU-IBS Beyond the Standard Model Workshop

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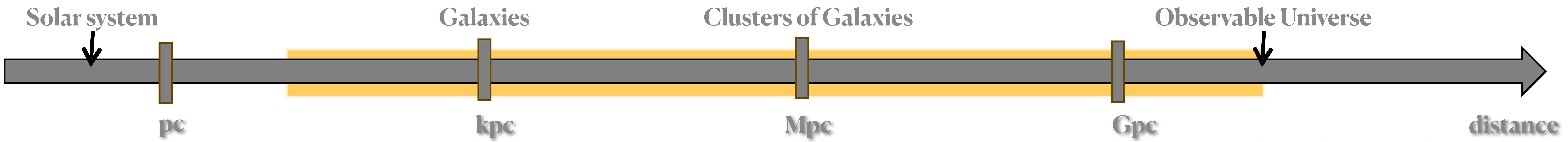
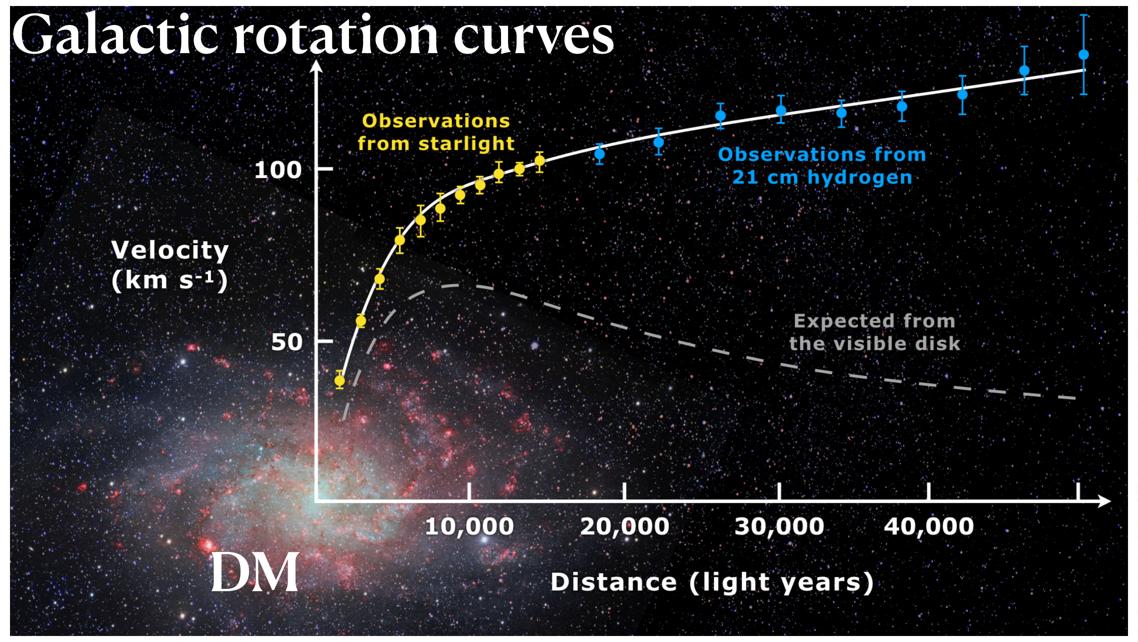
2026.06.07

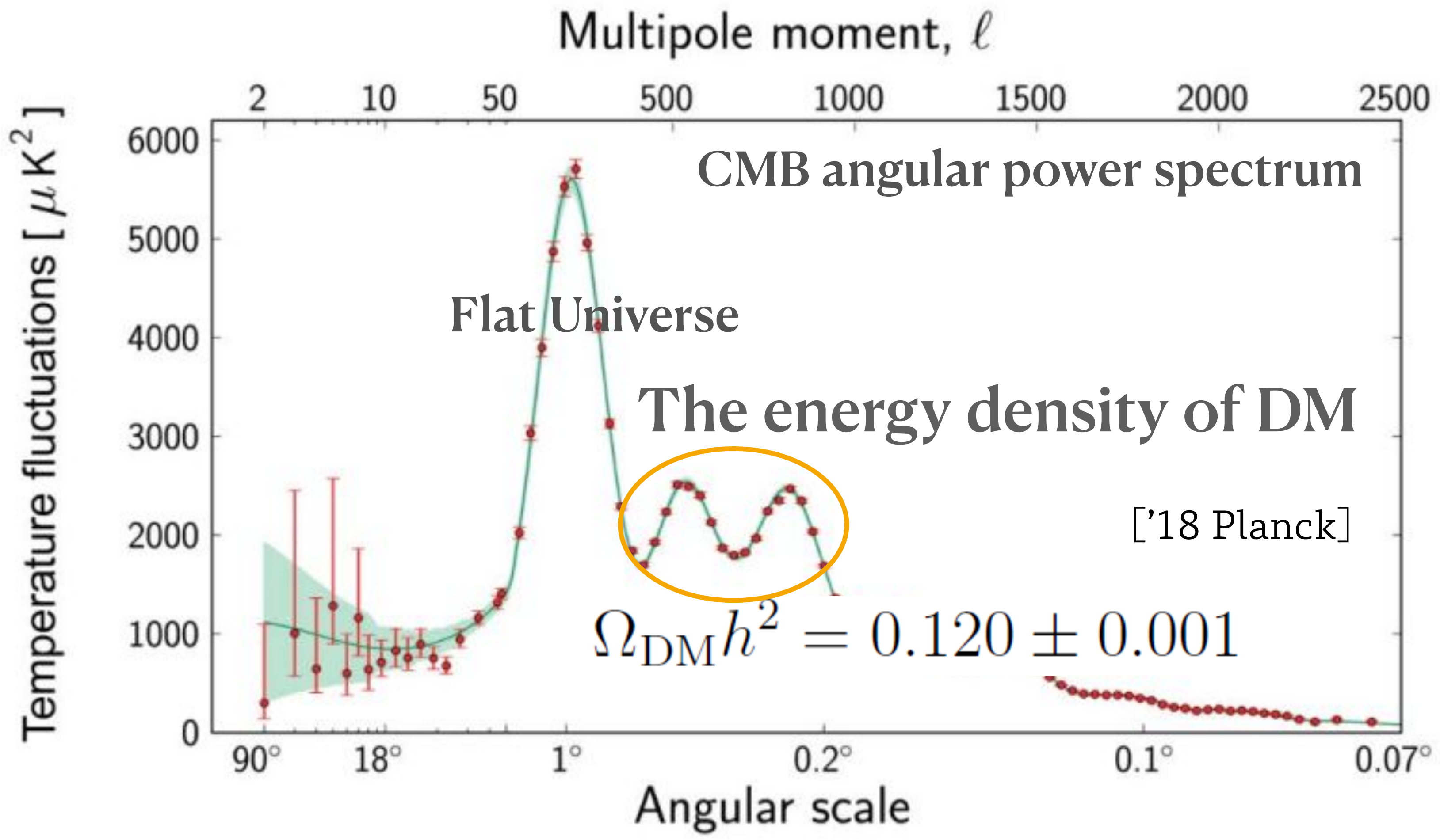
Introduction: Evidence for Dark Matter

Several observations indicate the existence of dark matters at very different scales:

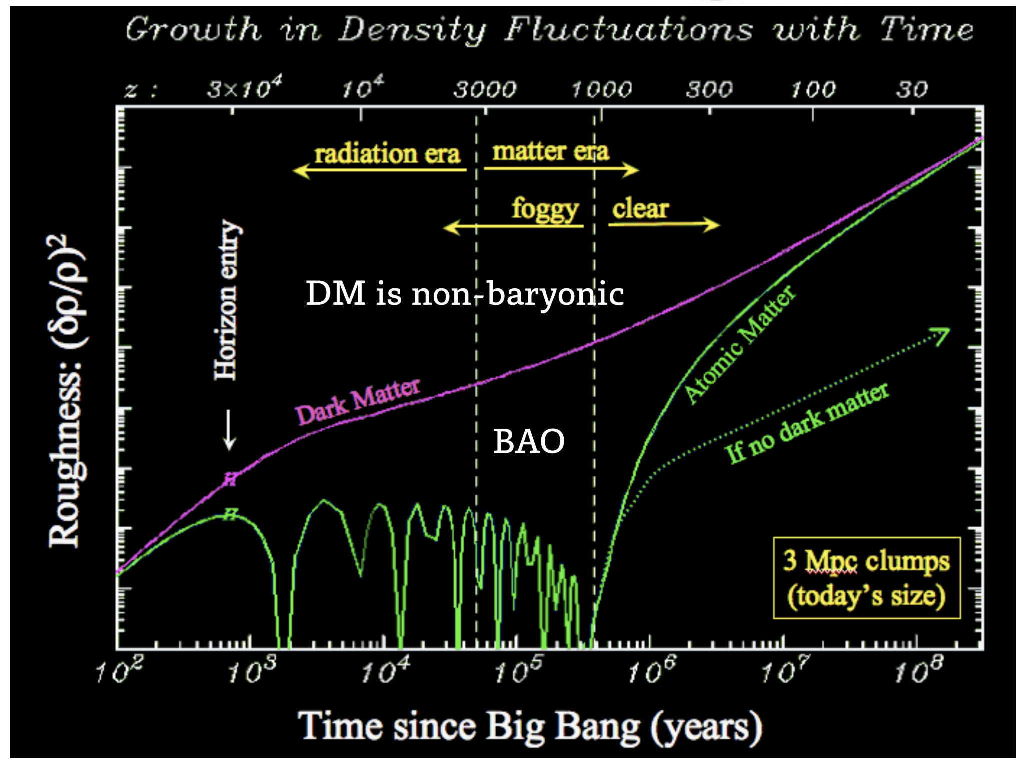




$$\frac{v^2}{r} = \frac{GM(r)}{r^2} \rightarrow v \propto 1/\sqrt{r}$$

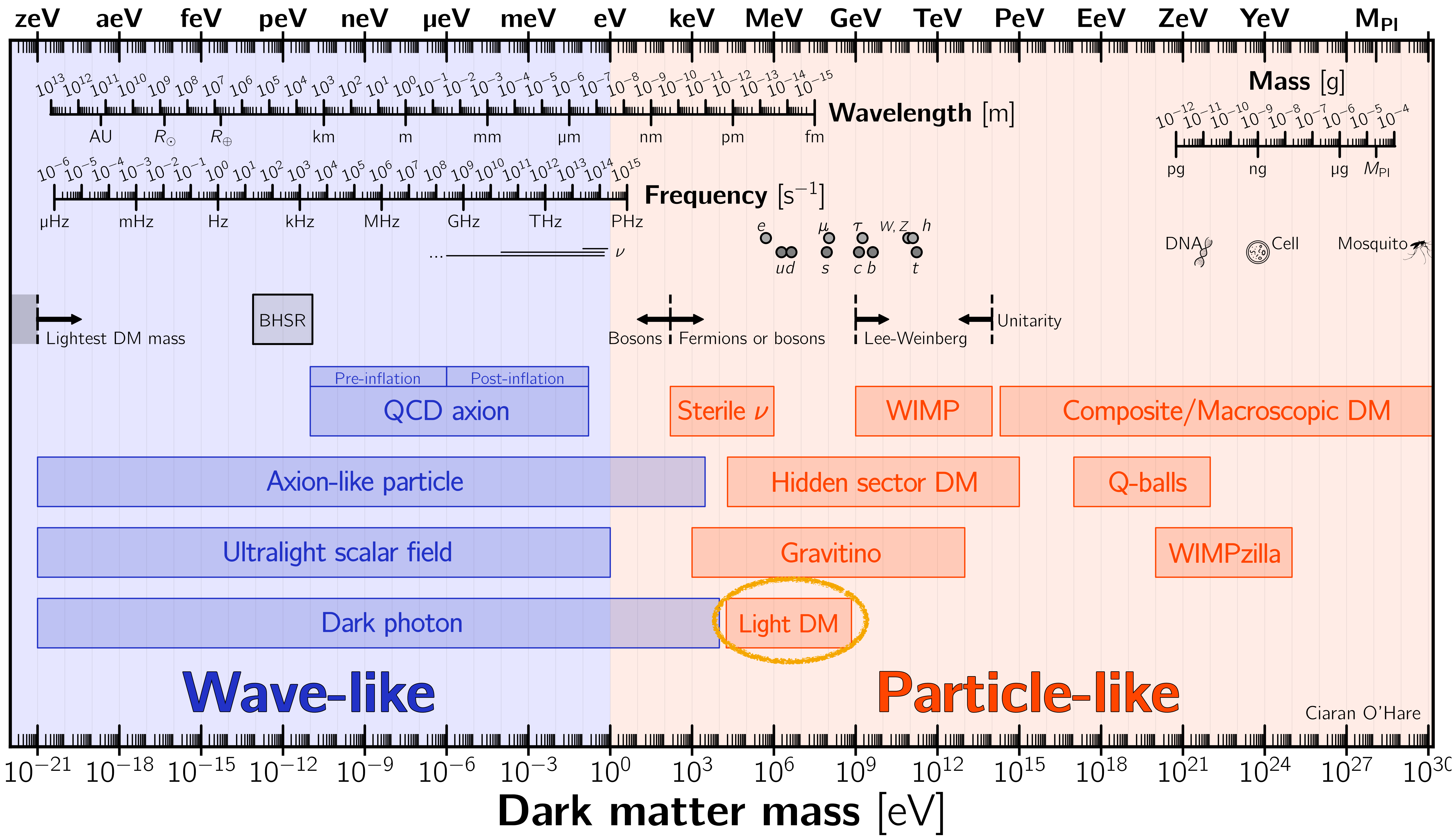


$$\Omega_{\rm DM} h^2 = 0.120 \pm 0.001$$



Credit: Mark Whittle: Big Bang Acoustics

Introduction: Dark Matter Candidates



Interaction with the SM:

1. Portal operators

$$\epsilon F^{\mu\nu} F_{\mu\nu}$$

$$(\mu\phi + \lambda\phi^2)\,|H|^2$$

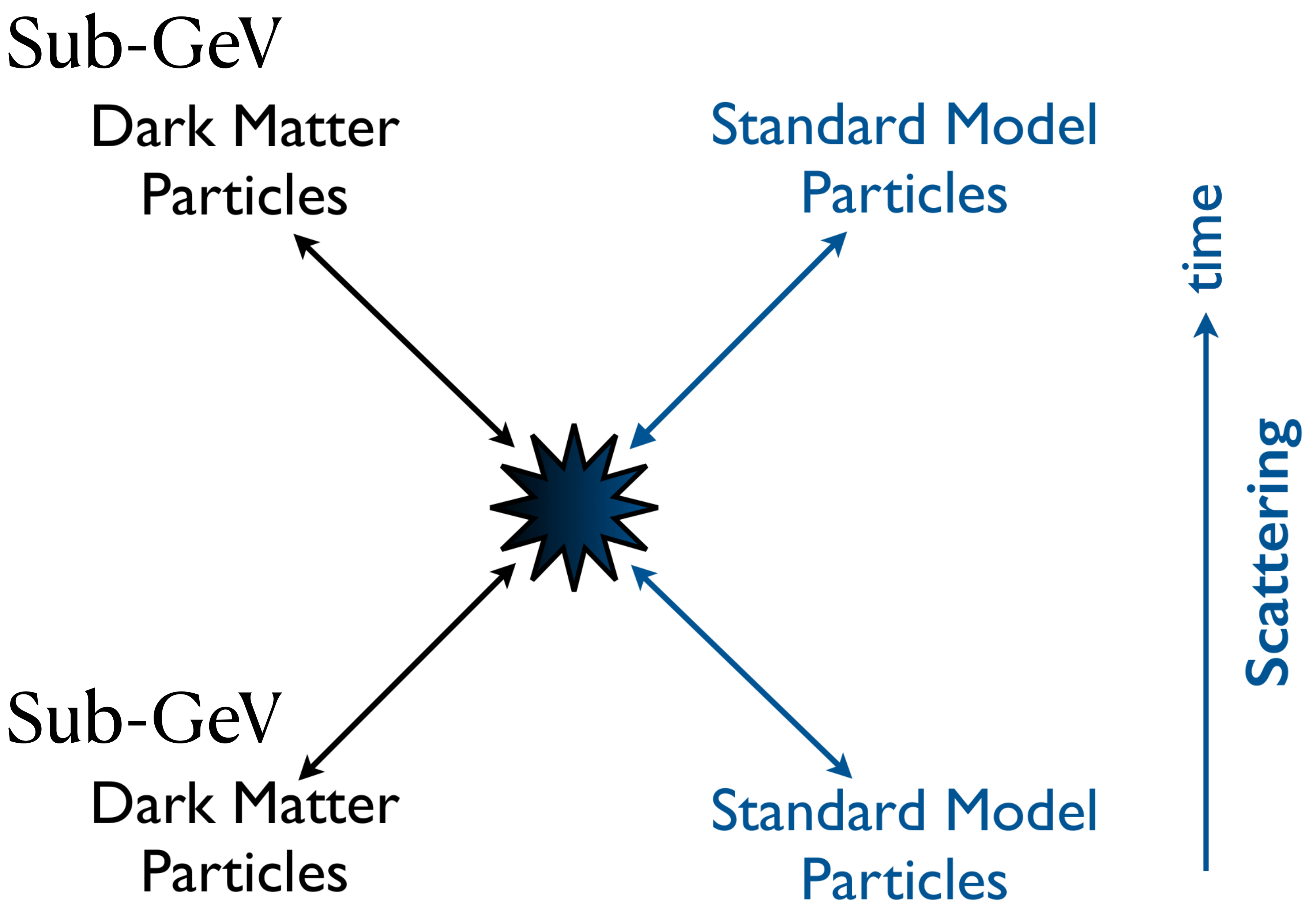
$$yLHN$$

2. WIMPs

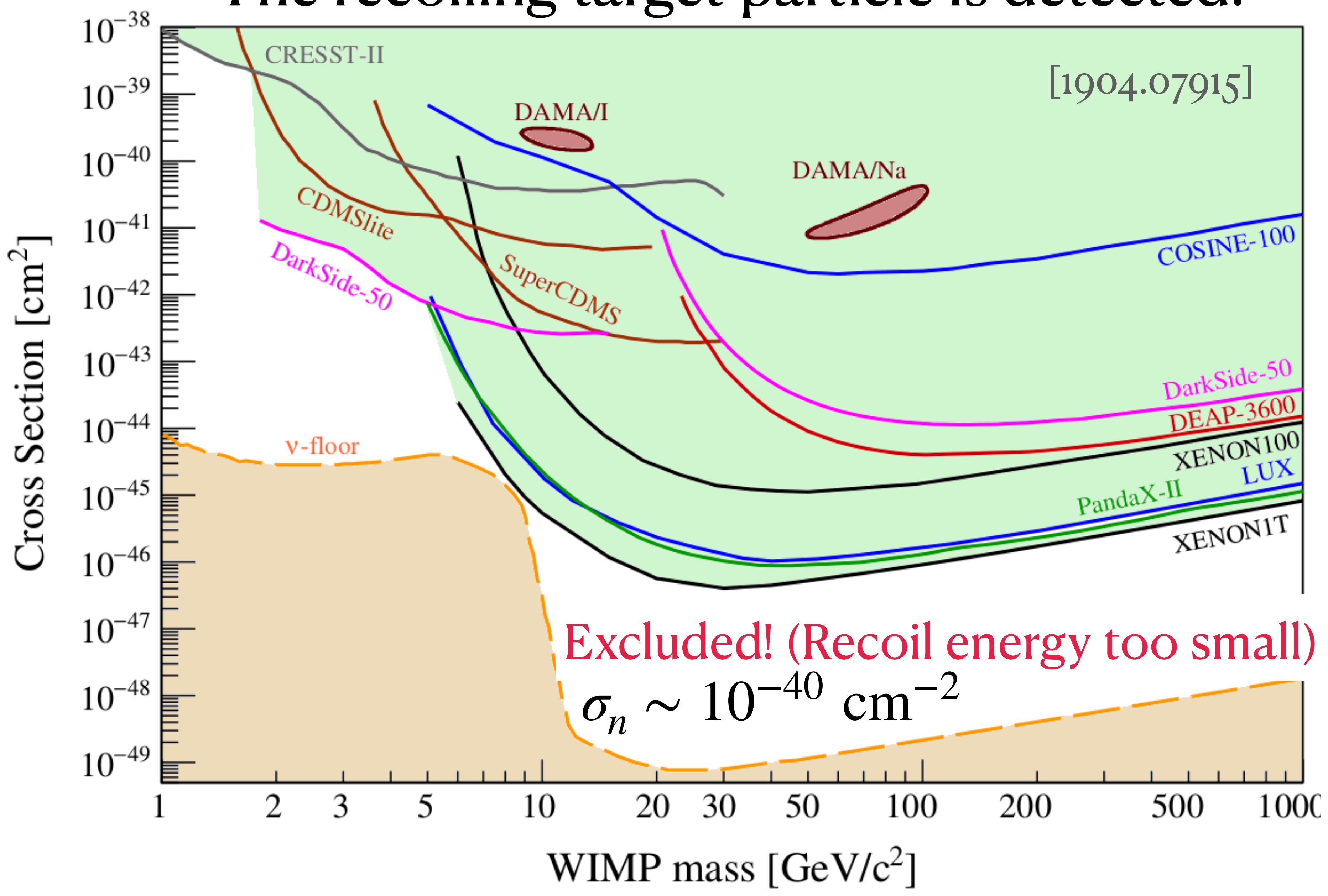
3. Heavy mediators via EFTs

Motivation

Direct DM detection:



The recoiling target particle is detected:



- **For $m_{\rm DM} \ll m_n$, the maximum recoil energy scales as $E_R \propto \frac{(m_{\rm DM} v)^2}{2m_n} \sim 20\ \mathrm{eV} \left(\frac{\mathrm{m_{DM}}}{\mathrm{GeV}}\right)^2 \left(\frac{100\ \mathrm{GeV}}{\mathrm{m_n}}\right)$, causing sub-GeV DM to fall below detector threshold.**
- **Need large scattering cross section: sub-GeV DM models require the presence of relatively light mediator particle that facilitates interaction with the SM particles.**

Challenges for Model Building

LDM+ light mediator = Need large scattering cross section

$$\sigma_{\psi N} = \frac{\mu_{\psi N}^2}{\pi} \frac{\left(y_\psi \, y_{\phi N}^{\text{eff}}\right)^2}{\left[m_{h_2}^2 + m_\psi^2 v_\psi^2\right]^2},$$

1. Light mediators coupled to nucleon is tightly constrained (coupling constant $\ll 1$)

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2. Sizeable LDM-mediator coupling + light mediator mass → Efficient DM annihilation in the early Universe

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1. **Light mediators coupled to nucleon is tightly constrained (coupling constant $\ll 1$)**
2. **Sizeable LDM-mediator coupling + light mediator mass** → **Efficient DM annihilation in the early Universe**

↓

DM in thermal equilibrium for longer period → **The resulting DM relic abundance is underabundant due to the Boltzmann suppression**

Challenges for Model Building

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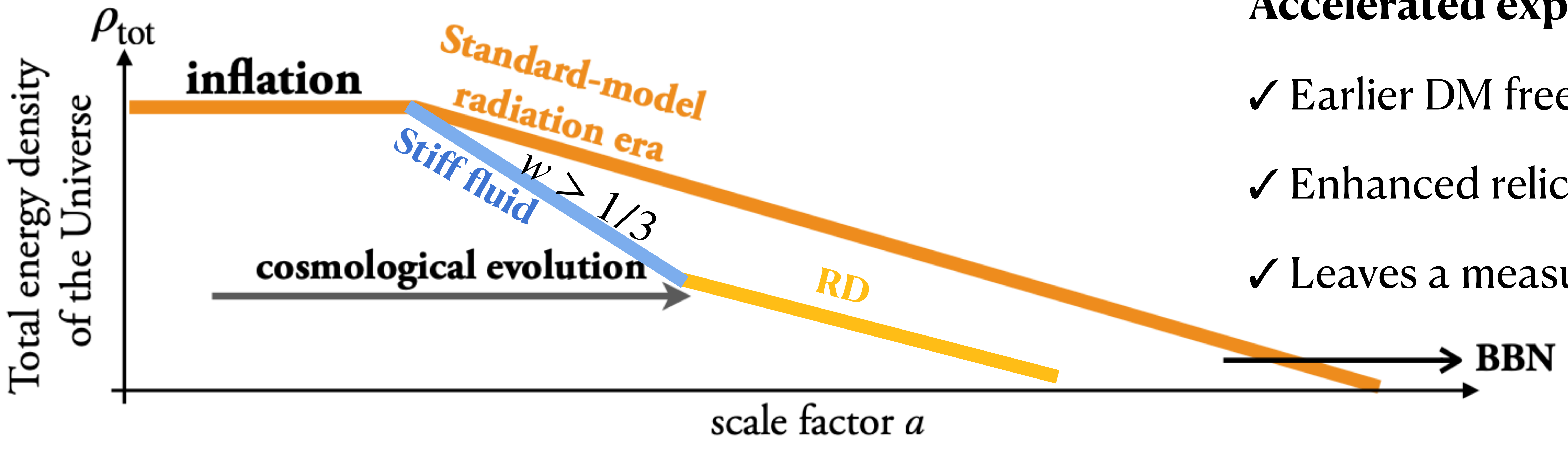
Non-standard cosmology solution:



Accelerated expansion w:

✓ Earlier DM freeze out at higher temperature

✓ Enhanced relic abundance to match the observed value

✓ Leaves a measurable, tightly correlated signature in the SGWB

DM Phenomenology in Non-standard Cosmology

The Lagrangian characterizing the dark sector and its portal to the SM sector:

$$\mathscr{L} \supset i\bar{\psi}\gamma^\mu\partial_\mu\psi - m_\psi\bar{\psi}\psi - y_\psi\bar{\psi}\Phi\psi - V(\Phi, H)$$

where $H = \begin{pmatrix} 0 & \frac{v_H + h}{\sqrt{2}} \end{pmatrix}$, $\Phi = v_\Phi + \phi$

Vector-like singlet fermion (DM candidate)

Real singlet scalar

Scalar potential

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ \phi \end{pmatrix}$$

The new light scalar mediator

Mixing angle: $$\tan(2\theta) = \frac{2\lambda_{H\Phi}v_H v_\Phi - \mu_{H\Phi}v_H}{\lambda_H v_H^2 - 4\lambda_\Phi v_\Phi} = \frac{4\lambda_{H\Phi}v_H v_\Phi - 2\mu_{H\Phi}v_H}{m_h^2 - 8m_\phi^2}$$

- The presence of the non-zero mixing angle θ guarantees that the light scalar mediator h_2 couples to the quarks and gluons within nucleons.
- Therefore, this provides a channel for the elastic scattering of the DM candidate ψ off target nuclei in terrestrial direct detection experiment.

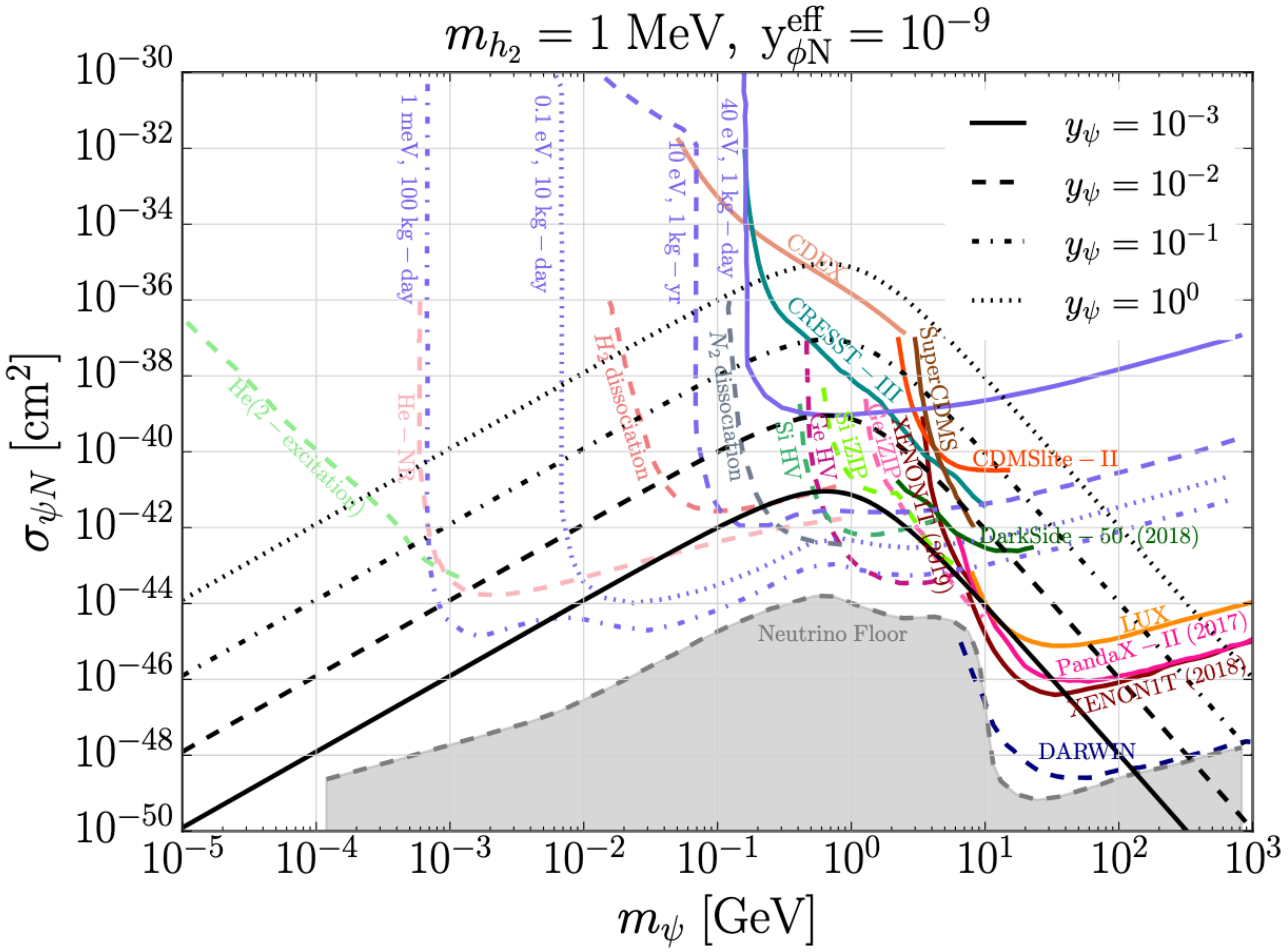
$$\sigma_{\psi N} = \frac{\mu_{\psi N}^2}{\pi}\frac{\left(y_\psi\ y_{\phi N}^{\rm eff}\right)^2}{\left[m_{h_2}^2 + m_\psi^2 v_\psi^2\right]^2}, \qquad \mu_{\psi N} = m_\psi m_N/(m_\psi + m_N)$$

$$y_{\phi N}^{\rm eff} \sim \sin\theta \frac{m_N}{v_H}$$

Parameter Space for the Direct DM Detection

Constraints & projections for the spin-independent DM-nucleon scattering cross section

Preliminary



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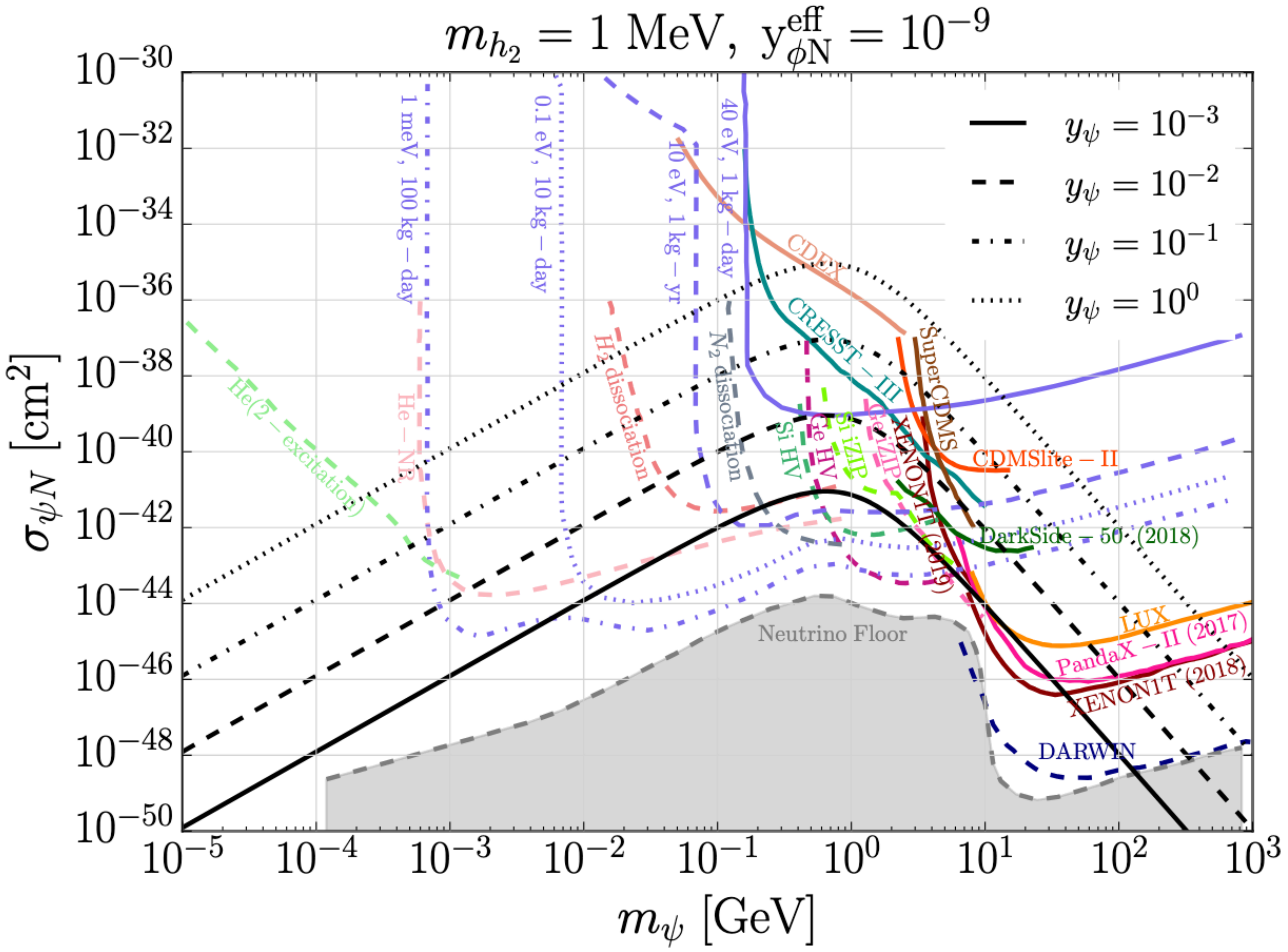
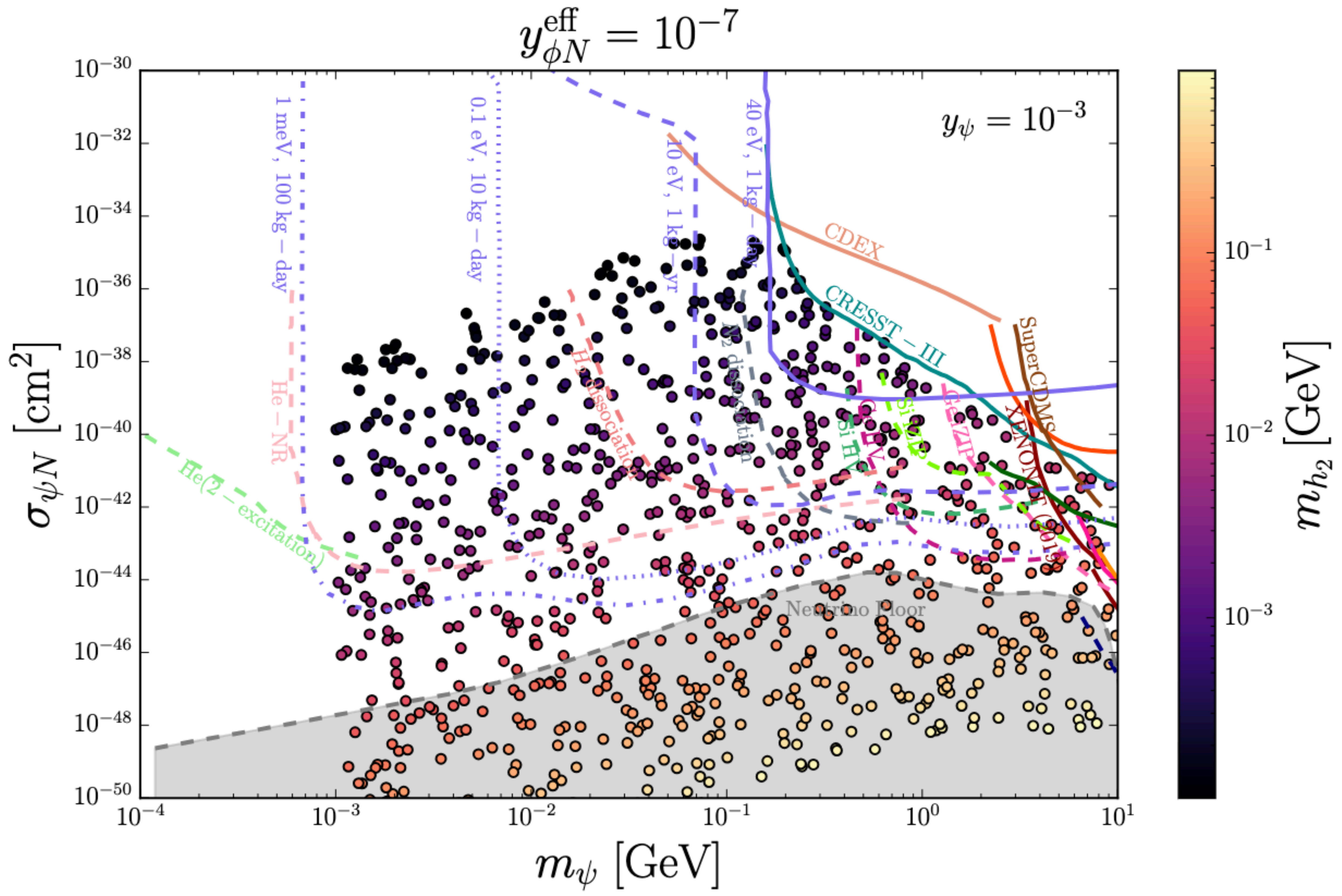
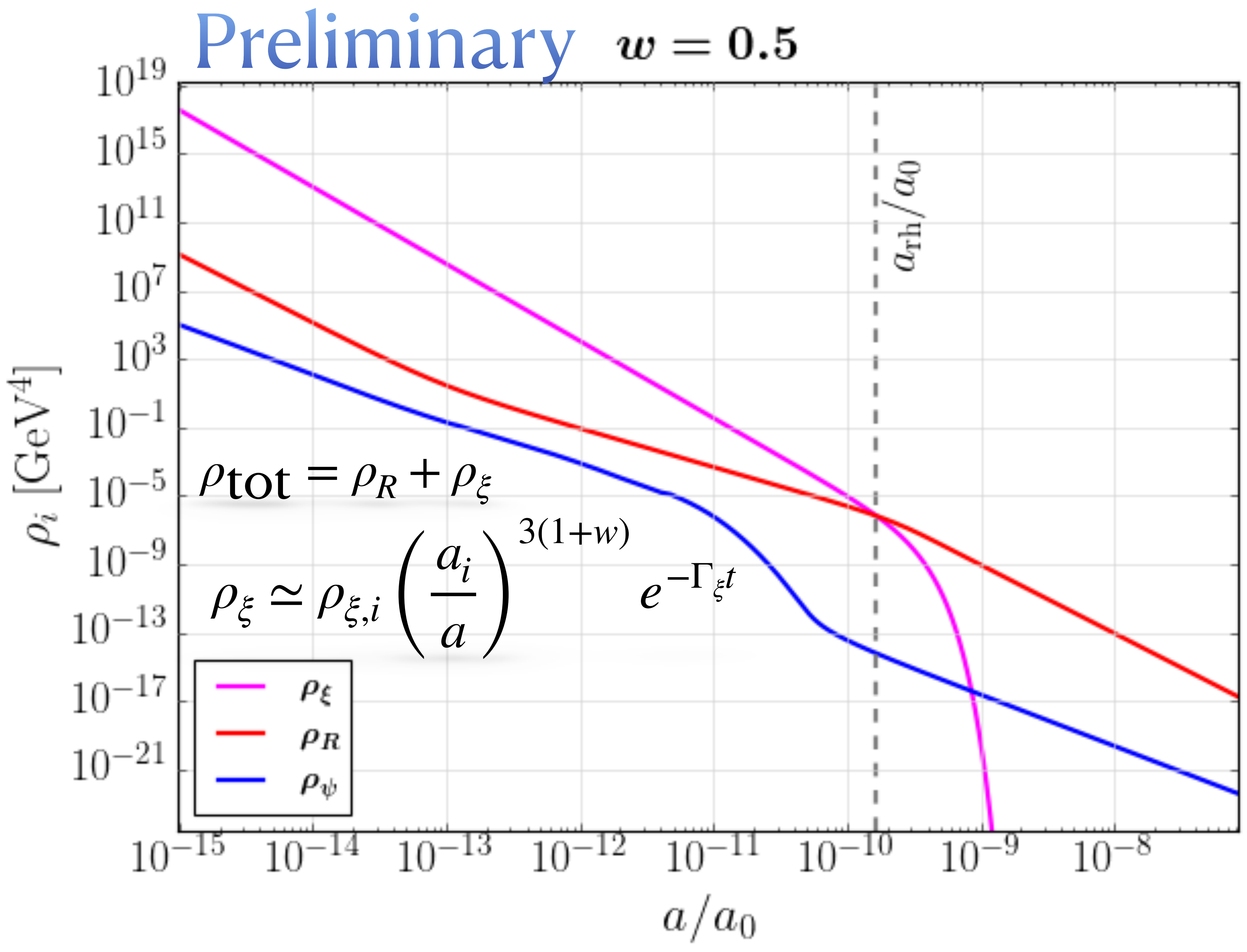


Compatible with the current constraint from CRESST-III



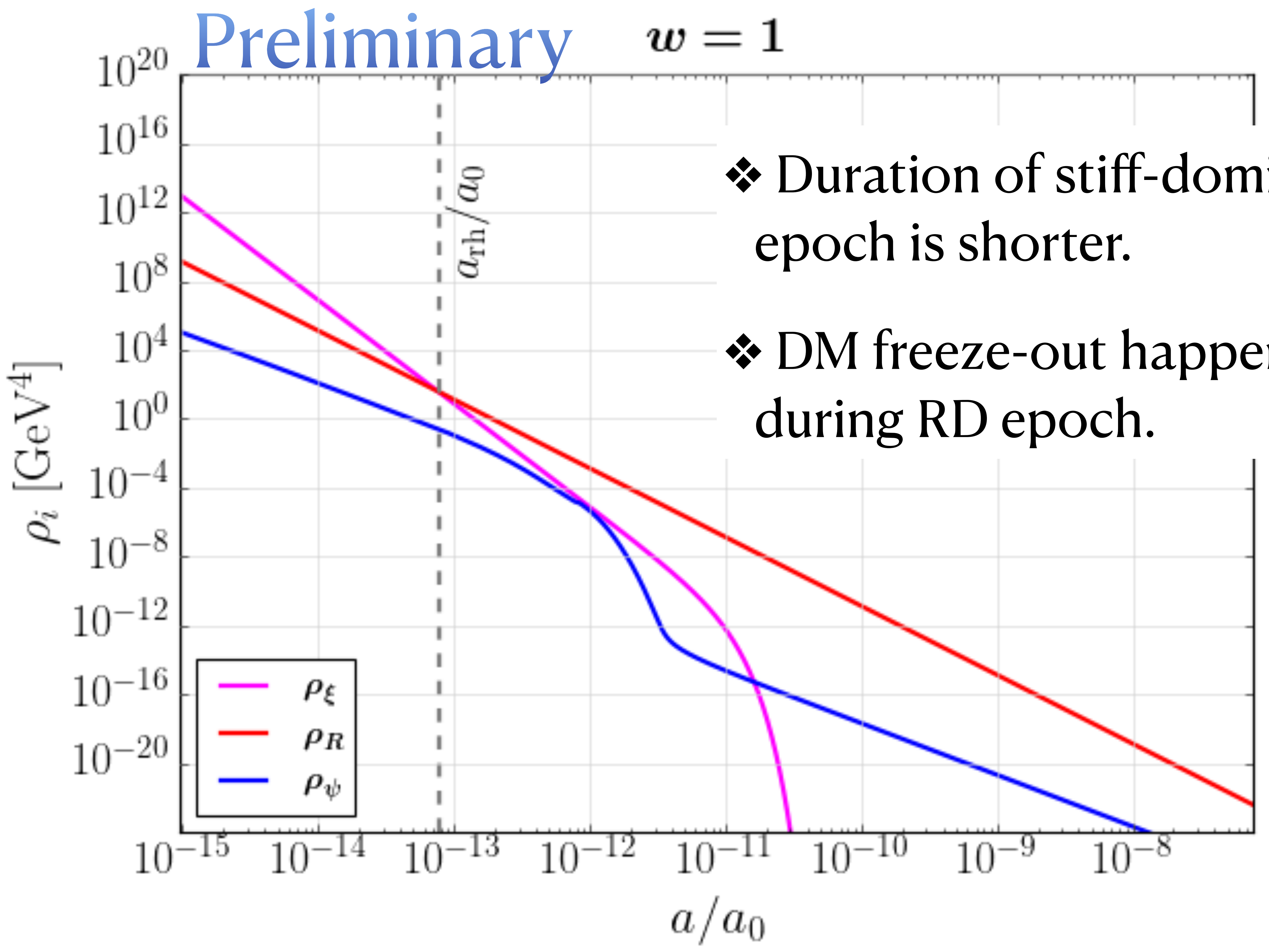
Energy density evolution

$m_\psi = 1$ GeV, $y_\psi = 5 \times 10^{-2}$, $m_{h_2} = 1$ MeV, $T_{RH} =$ 10 MeV



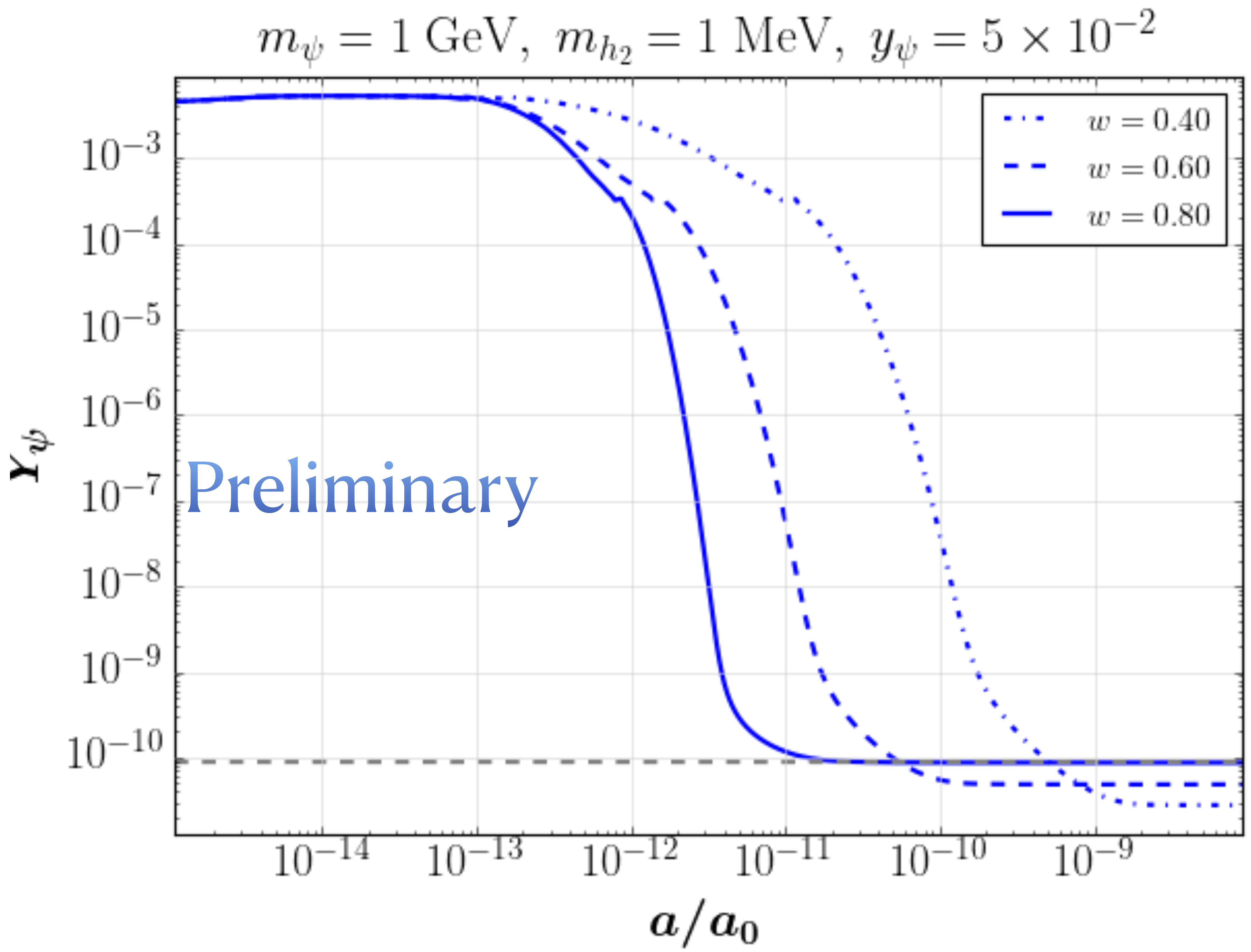
$$\rho_{tot} = \rho_R + \rho_\xi$$

$$\rho_\xi \simeq \rho_{\xi,i} \left(\frac{a_i}{a}\right)^{3(1+w)} e^{-\Gamma_\xi t}$$



- ❖ Duration of stiff-dominated epoch is shorter.
- ❖ DM freeze-out happens during RD epoch.

Dark Matter evolution



During the stiff-dominated epoch:

❖The Hubble rate is larger at a given temperature than the RD epoch

❖The freeze-out occurs at an earlier time or higher temperature (when ω increases).

❖The resulting DM yield is enhanced as giving the correct relic abundance.

$$\frac{dY_\psi}{dx} = -\sqrt{\frac{\pi g_*(T)}{45}}\frac{M_p m_\psi \sigma_1}{x^2}\left(\frac{T_{\rm RH}}{m_\psi/x}\right)^{\frac{3w-1}{2}}\left(Y_\psi^2 - Y_{\psi,\rm eq}^2\right),$$

$$T_{\rm RH} \simeq \left(\frac{45}{4\pi^3}\right)^{1/4} g_*^{-1/4}(T_{\rm RH})(M_p\Gamma_\xi)^{1/2}$$

Gravitational Wave production

Assuming a nearly scale invariant primordial GW spectrum, the late-time GW spectrum acquires a characteristic shape with any deviations serving as potential signatures of non-standard thermal history.

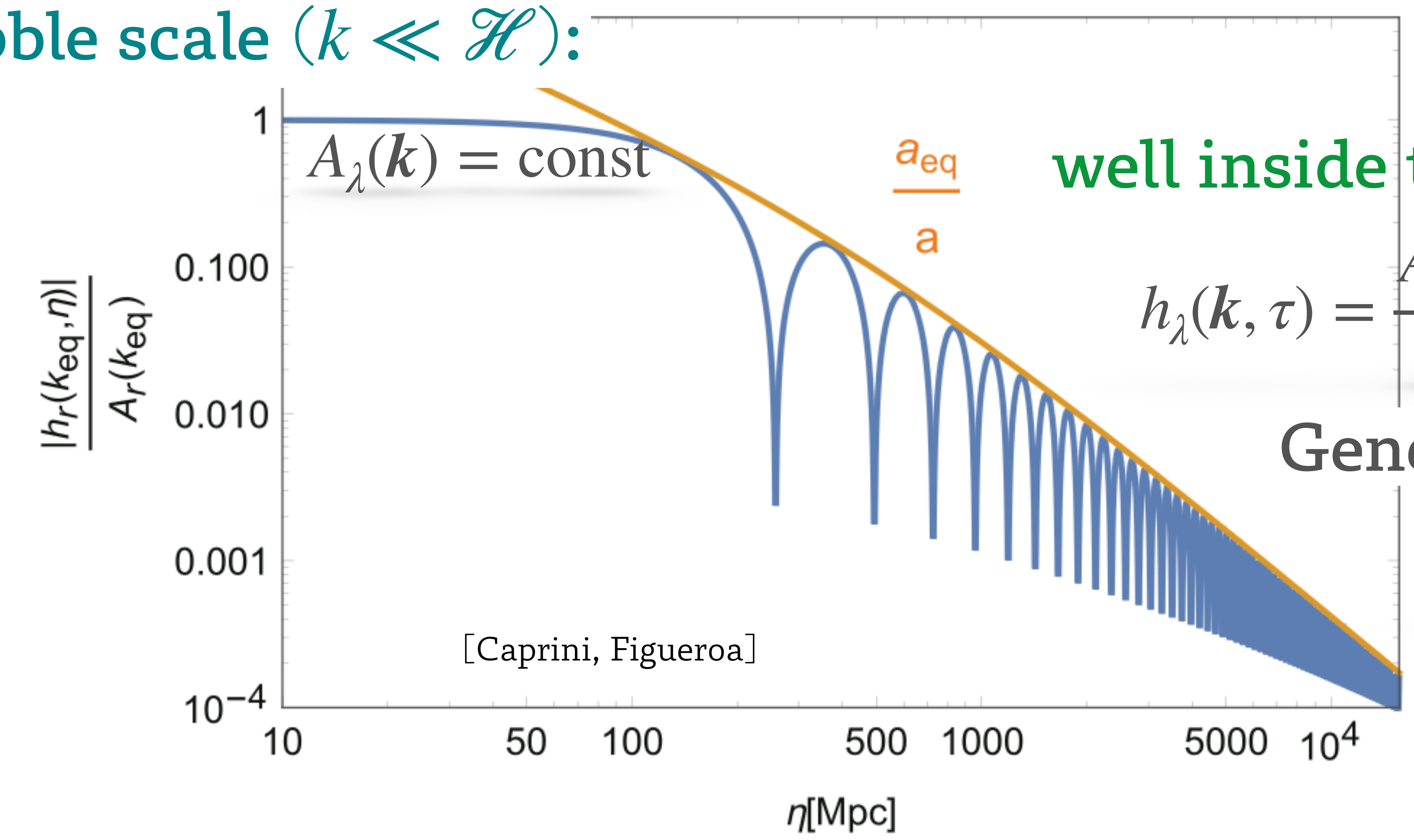
The EOM for GW:

$$h''_{ij}(\tau,\boldsymbol{k}) + \frac{2a'}{a}h'_{ij}(\tau,\boldsymbol{k}) + k^2 h_{ij}(\tau,\boldsymbol{k}) = 0.$$

$$h_{ij}(\boldsymbol{x},\tau) = \sum_{\lambda=+,\times}\int \frac{d^3\boldsymbol{k}}{(2\pi)^3} h_\lambda(\boldsymbol{k},\tau) e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \epsilon^\lambda_{ij}(\hat{\boldsymbol{k}})$$

super-Hubble scale $(k \ll \mathscr{H})$:

$A_\lambda(\boldsymbol{k}) = \text{const}$



well inside the horizon $(k \gg \mathscr{H})$:

$$h_\lambda(\boldsymbol{k},\tau) = \frac{A_\lambda(\boldsymbol{k})}{a(\tau)}e^{ik\tau} + \frac{B_\lambda(\boldsymbol{k})}{a(\tau)}e^{-ik\tau}$$

General Solution:

$$h_\lambda(\boldsymbol{k},\tau) \simeq h_{\lambda,\mathrm{prim}}(k)\frac{a_k}{a(\tau)}\cos[k(\tau-\tau_k)+\phi_k]$$

Constant inflationary solution

The scale factor at horizon crossing

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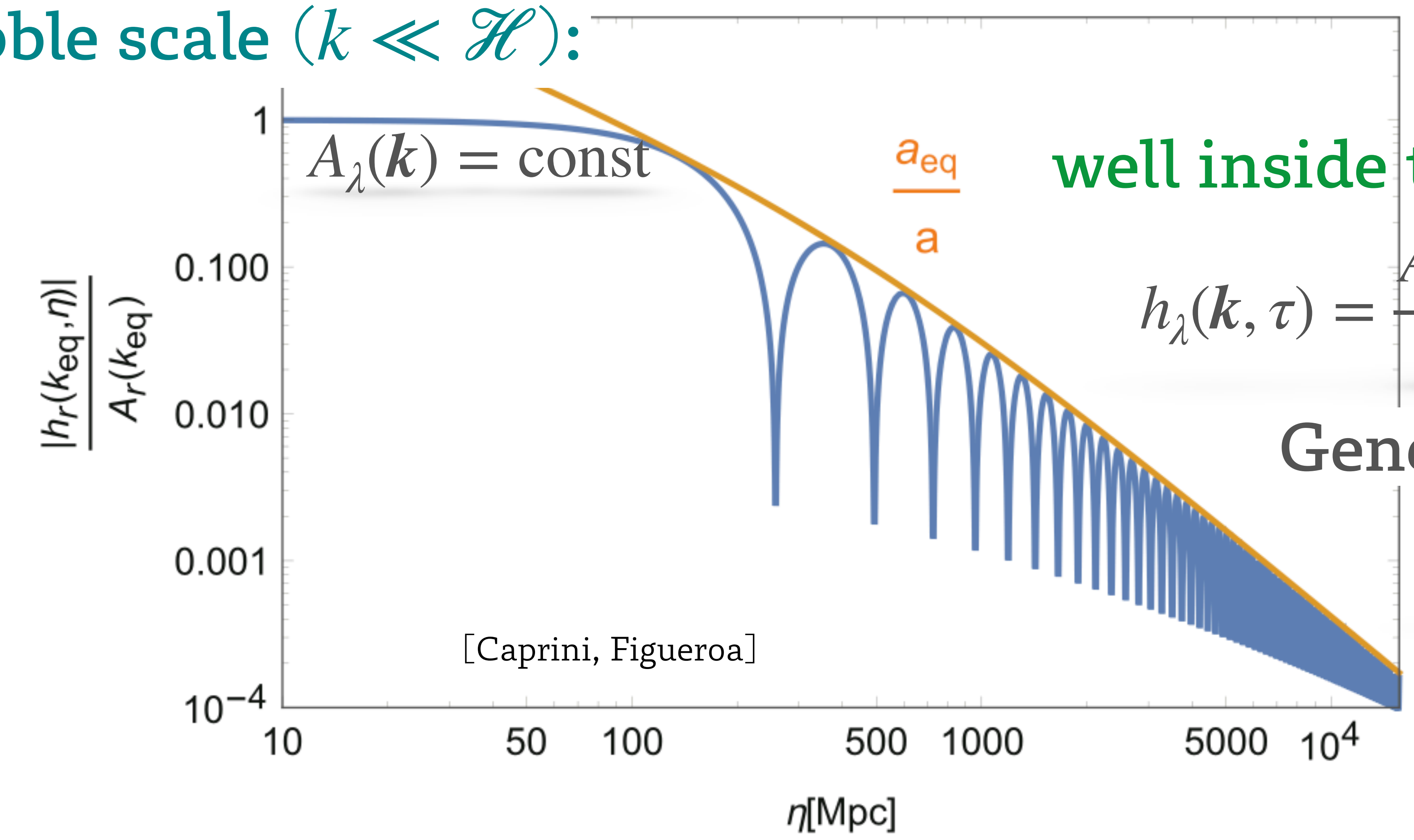

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Constant inflationary solution

The scale factor at horizon crossing

The present GW spectrum becomes:

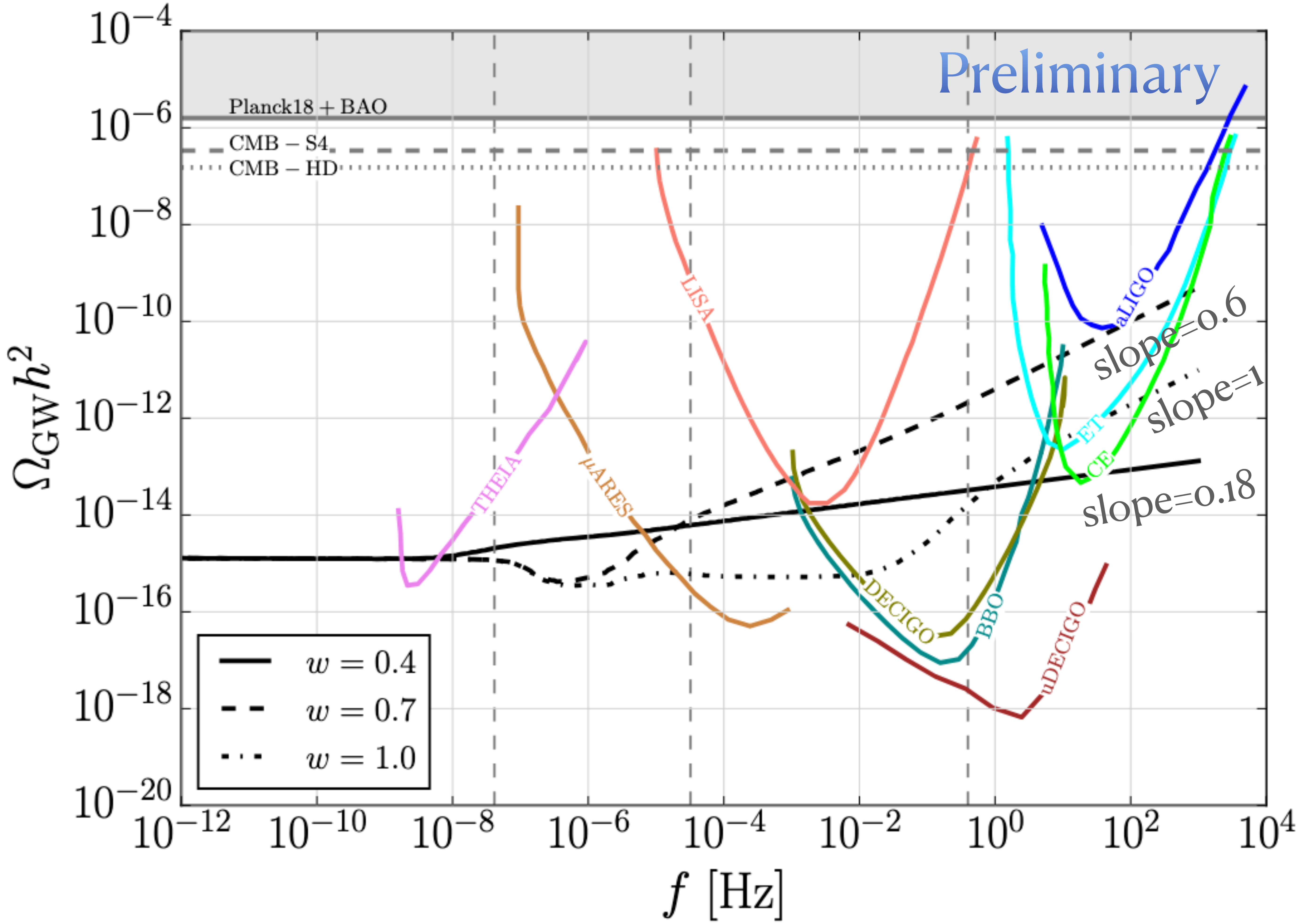
$$\Omega_{\rm GW,0}(f) \propto \Omega^{R,0}_{\rm GW} \times \begin{cases} f^{\frac{2n-4}{2n-1}} & \text{for} \quad a_{\rm end} < a \leq a_{\rm rh} \quad \text{(SD)} \\ 1 & \text{for} \quad a_{\rm rh} < a \leq a_{\rm eq} \quad \text{(RD)} \end{cases}$$

$$f \simeq \frac{1}{2}\sqrt{\frac{g_*(T_{\rm rh})}{90}}\frac{T_{\rm rh}T_0}{M_p}\left(\frac{g_{*,s}(T_0)}{g_{*,s}(T_{\rm rh})}\right)^{1/3} \times \begin{cases} \left(\frac{a}{a_{\rm rh}}\right)^{\frac{1-2n}{n+1}} & \text{for} \quad a_{\rm end} < a \leq a_{\rm rh} \quad \text{(SD)} \\ \left(\frac{a_{\rm rh}}{a}\right) & \text{for} \quad a_{\rm rh} < a \leq a_{\rm eq} \quad \text{(RD)} \end{cases}$$

where $\Omega^{R,0}_{\rm GW} \simeq \frac{\mathscr{P}^{\rm prim}_T(k)}{24}\left(\frac{k_r}{a_0H_0}\right)^2\left(\frac{a_r}{a_0}\right)^2 \simeq 10^{-16}$

where $w = \frac{n+1}{n-1}$

Stochastic Gravitational Wave spectrum



Here, vertical dashed lines represent the corresponding wavenumber that re-enter the Hubble horizon during the stiff-dominated fluid.

The resulting GW spectrum is high-frequency blue tilted (index $n > 0$).

Conclusion & Outlook

- Model-building effort is required to investigate the light DM signatures.
- In the stiff-dominated non-standard cosmology,
  - The correct relic abundance can be obtained within the framework of the LDM + light mediator particle with sizable coupling constant.
  - The enhanced GW spectrum can be tested by upcoming terrestrial and space-based interferometers.
- Therefore, the precise measurements of the expansion history (the equation of state w and the reheating temperature $T_{\rm rh}$) to yield the correct DM relic density dictate the spectral shape, tilt and peak frequency of the SGWB.

○ In next step, we will perform a parameter scan for w vs $T_{\rm rh}$ with respect to LISA SNR.

Thank you!