Der Wissenschaftsfonds.

Dark matter as a complex scalar field: new cosmological constraints and detectability by LIGO

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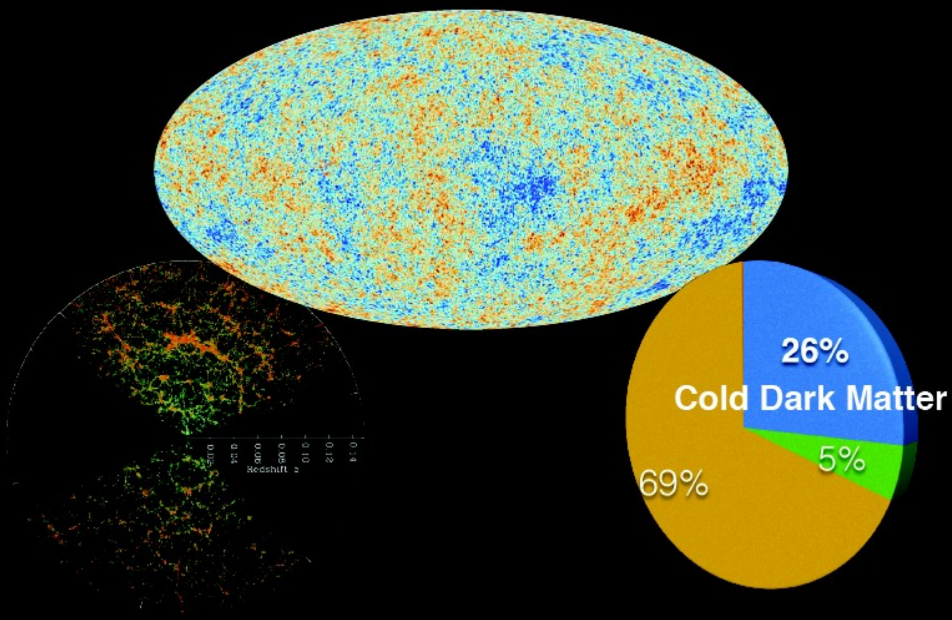
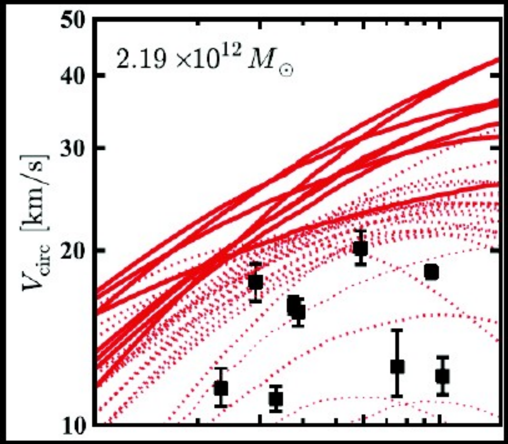
2017/3/15

Scalar Field Dark Matter: Cold Dark Matter Variant



Small-Scale Problems:
Discrepancies between dark matter simulations and observations on sub-halo scales

- **Missing satellites**
- **Cuspy Core**
- **Too big to fail**



Boylan-Kolchin et. al. 2012

Cold Dark Matter (CDM) candidates

- *Standard* CDM: WIMP, QCD Axion, etc.
- **Scalar Field Dark Matter**

Motivation for Scalar Field Dark Matter (SFDM):

alternative DM candidate to explain discrepancies

SFDM: **Ultra-light ($m \ll 10^{-5}$ eV), "cold" bosons ($T \approx 0$) in an (effective) classical field description**

Astrophysics motiv':

Suppression of DM clustering below a scale compatible with observations

Suppression of central DM densities in galaxies to explain cored density profiles in DM-dominated (dwarf) galaxies

Accomplish all this, even if we never detect DM

Particle physics motiv':

Ultra-light bosons in extensions of the SM, e.g.

(a multitude of) axion-like particles ("string axiverse")),

other extra-dimensional cosmologies (akin to KK modes),

pseudo-Nambu-Goldstone bosons (upon symmetry breaking in early Universe)

Scalar Field Dark Matter (SFDM), aka Bose-Einstein Condensed Cold Dark Matter (BEC-CDM)

- **Particles created with low entropy per particle → BEC**
  → classical field Lagrangian for the DM condensate („order parameter“)

- **complex scalar field** $\psi = |\psi| e^{i\theta}$ **→ U(1) symmetry: charge conservation**

$$\mathscr{L} = \frac{\hbar^2}{2m} g^{\mu\nu} \partial_\mu \psi^* \partial_\nu \psi - V(\psi)$$

units: $[\mathcal{L}] = [\mathrm{eV/cm^3}]$, $[\psi] = \mathrm{cm}^{-3/2}$, (+,-,-,-)

- **assume no coupling to the SM within this EFT description**

- **choice of V(ψ) and initial conditions determine**
  i) the evolution of SFDM, hence the evolution of the background Universe
  ii) suppression of small-scale structure for $L < L_{SFDM}$ **with** $L_{SFDM} = \max\{\lambda_{deB}, l_{SI}\}$

Scalar Field Dark Matter (SFDM), aka Bose-Einstein Condensed Cold Dark Matter (BEC-CDM)

- **choice of potential V:**

  (rest-mass) quadratic term, $(mc^2/2)\,|\psi|^2$

  (→ CDM-like in late Universe),

  plus a possible repulsive self-interaction, $(\lambda/2)\,|\psi|^4$

  (→ radiation-like in early Universe)

  → ***fundamental SFDM parameters:*** **m and λ** $\lambda = \hat{\lambda}\frac{\hbar^3}{m^2 c}$

- **Initial condition:**

  conserved charge Q of SFDM determines energy density of DM today

  large-Q limit „spintessence“: $\rho_{SFDM,0} = Qmc^2$

  (a version of “asymmetric DM”)

$$\rho_{SFDM,0} = n_{SFDM,0}mc^2 = \Omega_{DM}\rho_{crit,0}$$

Equations of motion

Klein-Gordon equation for the SFDM field ψ .....

$$g^{\mu\nu}\partial_\mu\partial_\nu\psi - g^{\mu\nu}\Gamma^\sigma{}_{\mu\nu}\partial_\sigma\psi + \frac{m^2c^2}{\hbar^2}\psi + \frac{2\lambda m}{\hbar^2}|\psi|^2\psi = 0$$

...which evolves in a classical GR background

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = \frac{8\pi G}{c^4}T_{\mu\nu}$$

Well into the matter-dominated era, they simplify to ...

nonlinear Schrödinger-Poisson system

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2m}\Delta\psi + \lambda|\psi|^2\psi + m\Phi\psi$$

$$\Delta\Phi = 4\pi G m|\psi|^2$$

Numbers for SFDM parameters

„Typical“ numbers of models:

QCD axion: $m \simeq 6 \times 10^{-6}\ \mathrm{eV}\,\dfrac{10^{12}\ \mathrm{GeV}}{f}$ $\quad 10^{9} \lesssim f \lesssim 10^{12}$ GeV

(attractive) SI usually neglected: $\lambda \sim 10^{-57}$

$$\lambda = \hat{\lambda}\frac{\hbar^3}{m^2 c}$$

ultra-light axion-like particles: m ~ (10^{-33} – 1) eV ,
f unknown, but reasons for f ~ 10^{16} GeV

SI usually neglected

(other) bosons for DM: m ~ (10^{-27} – 1) eV,

SI usually neglected, but we don't: (positive) $\lambda \sim 10^{-93} - 10^{-83}$

For the latter two: Jeans/virial scale can extend to galactic scales ~ kpc !

	Halo mass [$M_\odot$]	Size [kpc]	Boson mass [eV]
Milky Way (MW)	10^{12}	100	$1.066 \cdot 10^{-25}$
Dwarf galaxy (DG)	10^{10}	10	$3.371 \cdot 10^{-24}$
Dwarf spheroidal (dSph)	10^{8}	1	$1.066 \cdot 10^{-22}$
Minihalo (MH)	10^{6}	0.1	$3.371 \cdot 10^{-21}$

TRD, Shapiro (1209.1835)

Jeans / virial scales bounded from below by

- no self-interaction: $\mathbf{L_{deB} \lesssim R}$ → $\mathbf{m \gtrsim m_H}$ (Heisenberg uncertainty "pressure")

$$m_H := \frac{\hbar}{R^2(\pi G \bar{\rho})^{1/2}} = 1.066 \cdot 10^{-22} \left(\frac{R}{1\ \mathrm{kpc}}\right)^{-1/2} \left(\frac{M}{10^8\ M_\odot}\right)^{-1/2} \mathrm{eV}$$

- or else gravity is balanced by a *positive* self-interaction coupling:

$\mathbf{L_{deB} \ll R}$ → $\mathbf{m \gg m_H}$ ***and*** $\boldsymbol{\lambda \gg \lambda_H}$ (self-interaction „pressure")

$$\lambda_H := \frac{\hbar^2}{2\bar{\rho}R^2} = 2.252 \cdot 10^{-62} \left(\frac{R}{1\ \mathrm{kpc}}\right) \left(\frac{M}{10^8\ M_\odot}\right)^{-1} \mathrm{eV\ cm}^3$$

ΛSFDM Model (2014) + GW (2016)

2014: take the same cosmic inventory as the basic ΛCDM model, except that

CDM is replaced by SFDM → ΛSFDM (1310.6061, PRD 89, 083536 (2014))

2016: add stochastic GW background (SGWB) from inflation self-consistently to it

(1611.07961)

$\Omega_m = \Omega_b + \Omega_c$

Cosmological parameters from **Planck 2013/2015**

(assume SM neutrinos massless)

$\Omega_\Lambda = 1 - \Omega_m - \Omega_r$ (2014)

$\Omega_\Lambda = 1 - \Omega_m - \Omega_r - \Omega_{GW}$ (2016)

- SFDM particle parameters: m, $\lambda/(mc^2)^2$

$\lambda/(mc^2)^2 = 1\times10^{-18}\,\mathrm{eV}^{-1}\mathrm{cm}^3 \implies l_{SI} \approx 0.8kpc$

$$\mathcal{L} = \frac{\hbar^2}{2m} g^{\mu\nu}\partial_\mu\psi^*\partial_\nu\psi - \frac{1}{2}mc^2|\psi|^2 - \frac{\lambda}{2}|\psi|^4,$$

- Global U(1) symmetry $\Rightarrow$ Charge (particle number density) conservation

$Q \equiv n - \bar{n} = \rho_{SFDM,0}/(mc^2)$

- Tensor-to-scalar ratio: r
- Reheating temperature: T_{reheat}

Holistic Evolution of the ΛSFDM Universe

- Friedmann equation

$$H^2(t) \equiv \left(\frac{\mathrm{d}a/\mathrm{d}t}{a}\right)^2 = \begin{cases} H_{\mathrm{inf}}^2, & a < a_{\mathrm{inf}}, \\ H_{\mathrm{inf}}^2 \left(\frac{a_{\mathrm{inf}}}{a(t)}\right)^3, & a_{\mathrm{inf}} < a < a_{\mathrm{reheat}}, \\ \frac{8\pi G}{3c^2}\left[\rho_r(t) + \rho_b(t) + \rho_\Lambda(t) + \rho_{\mathrm{SFDM}}(t) + \rho_{\mathrm{GW}}(t)\right], & a > a_{\mathrm{reheat}}, \end{cases}$$

SGWB contribution to the expansion history *self-consistently* included

$$\Omega_{\mathrm{GW}}(k,a) \equiv \frac{\mathrm{d}\Omega_{\mathrm{GW}}(a)}{\mathrm{d}\ln k} = \frac{1}{\rho_{\mathrm{crit}}(a)} \frac{\mathrm{d}\rho_{\mathrm{GW}}(a)}{\mathrm{d}\ln k} = \frac{\Delta_h^2(k,a)c^2}{24a^2H^2(a)}\left(\left|\frac{h_k'(a(\tau))}{h_k(a(\tau))}\right|^2 + k^2\right)$$

- Klein-Gordon Equation

$$\frac{\hbar^2}{2mc^2}\ddot{\psi} + 3\frac{\hbar^2}{2mc^2}\frac{\dot{a}}{a}\dot{\psi} + \frac{1}{2}mc^2\psi + \lambda|\psi|^2\psi = 0,$$

Cosmological evolution of SFDM in an FLRW Universe

Compare size of SF oscillation freq **ω** to Hubble expansion rate **H**

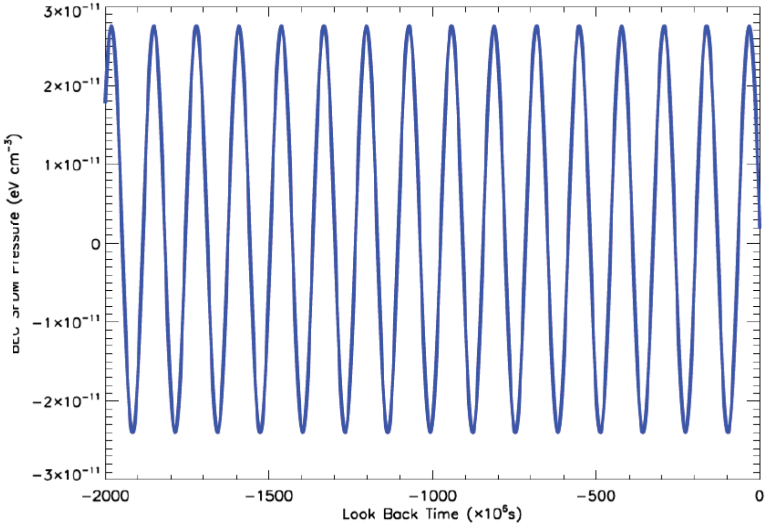
- Fast oscillation regime („oscillation“):

  ω / H >> 1

  disp.relation: ω = ω (V),

  e.g.

$$\omega = \frac{mc^2}{\hbar}\sqrt{1 + \frac{2\lambda}{mc^2}|\psi|^2}$$



“easier”

- Slow oscillation regime:

  ω / H << 1

“harder”

kinetic energy ≡ 0:   w = - 1 CC EOS

kinetic energy ≠ 0:   w = 1 stiff EOS (“kination”)

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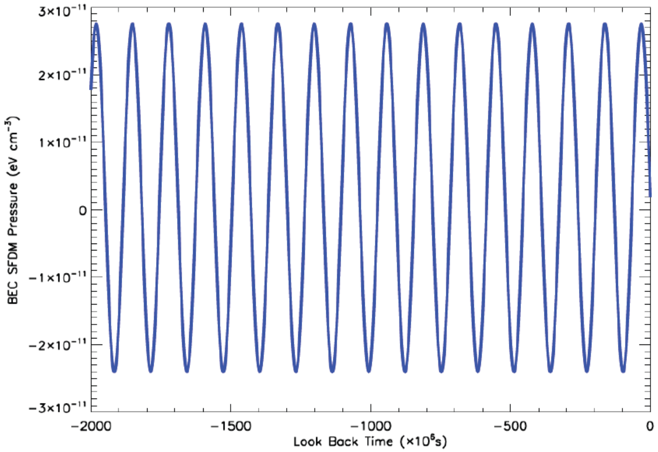


- Slow oscillation regime:

  ω / H << 1

  “harder”

kinetic energy ≡ 0: w = - 1 CC EOS
kinetic energy ≠ 0: w = 1 stiff EOS (“kination”)

affects the early Universe differently !

Behavior is determined by choice of initial conditions !

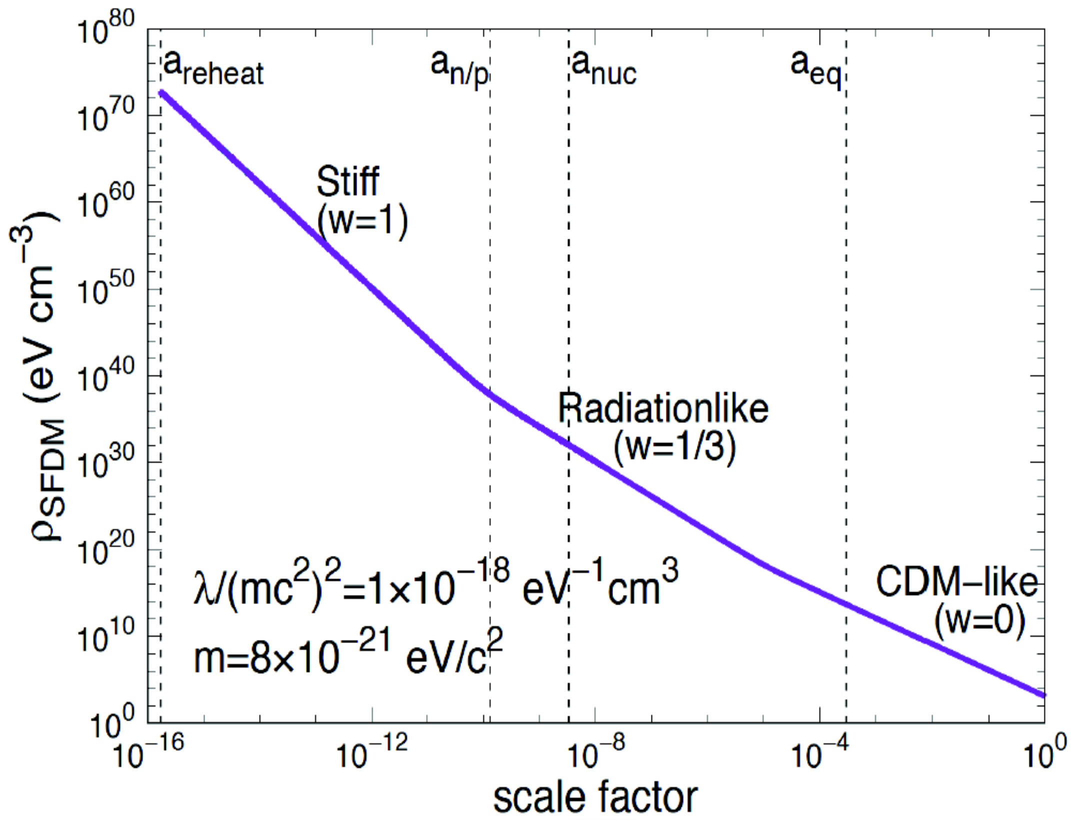
„spintessence“ SFDM with repulsive SI has 3 phases

EOS: $(p/\rho)_{SFDM} = w(t)$

(1) Early: w = 1
(stiff)
(2) Intermediate: w = 1/3
(radiationlike)
(3) Late: w = 0
(non-relativistic matter)

→ ***change of expansion history !***

Ω_{SFDM} → 1 at early times

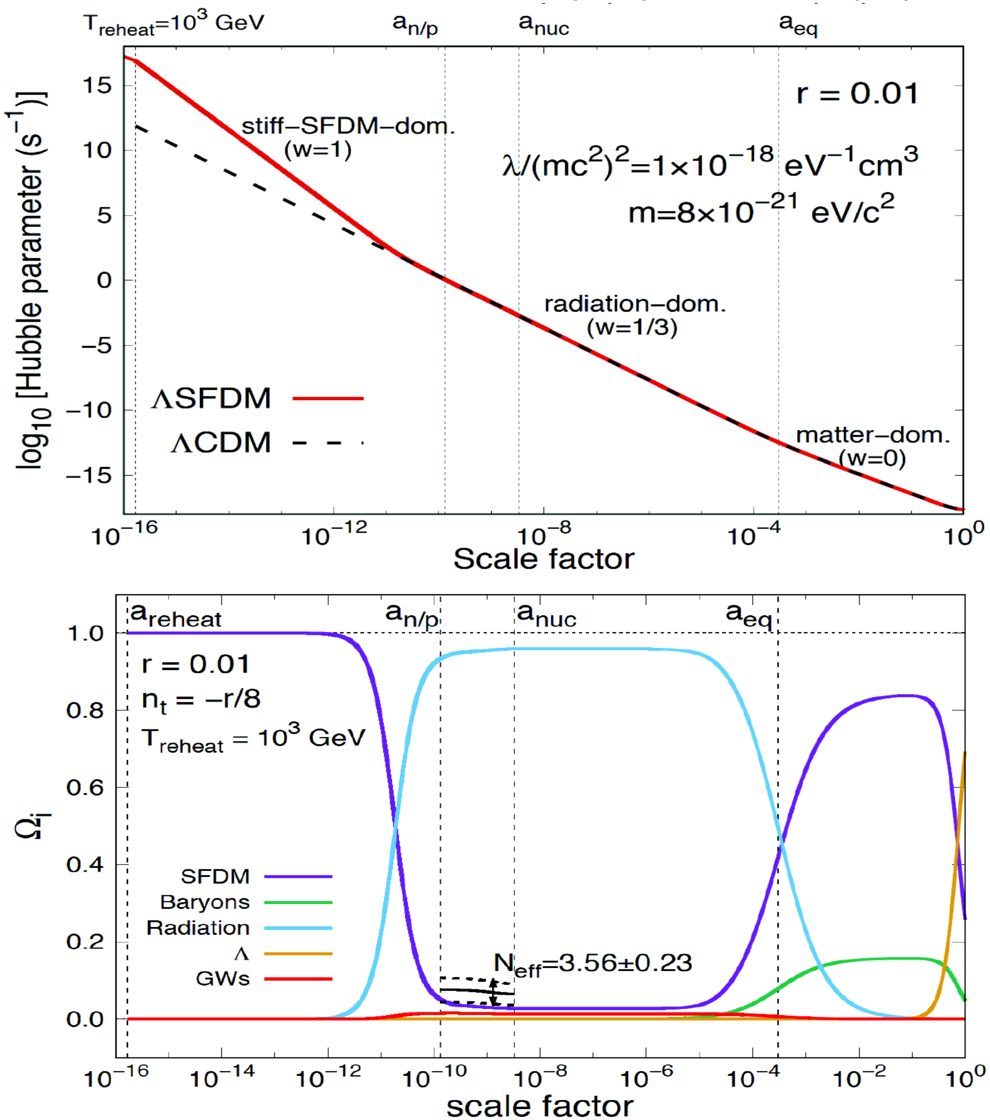


Stiff-SFDM-dominated early Universe
→ ***additional N_{eff} during (1) and (2)***
→ ***amplifies primordial GWs from inflation during (1)***

ΛSFDM+SGWB: the Universe has 6 eras

Inflation —> Reheating —> Stiff-SFDM-dom. —> Radiation-dom. —> Matter-dom. —> Λ-dom.

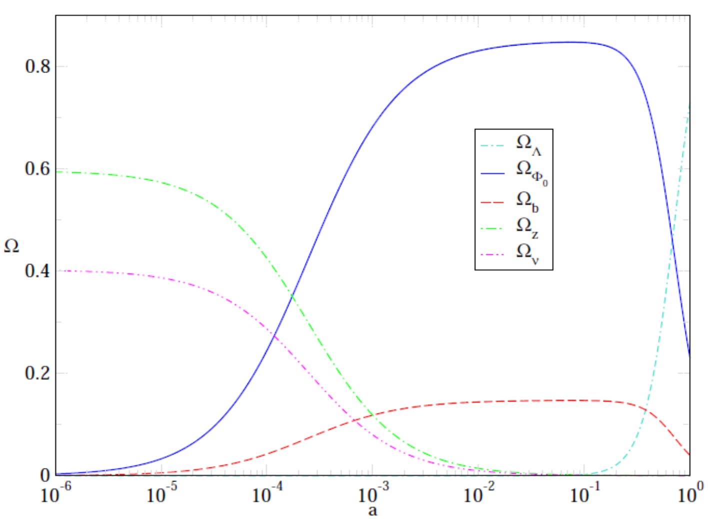
(w=-1) (w=0) (w=1) (w=1/3) (w=0) (w=-1)

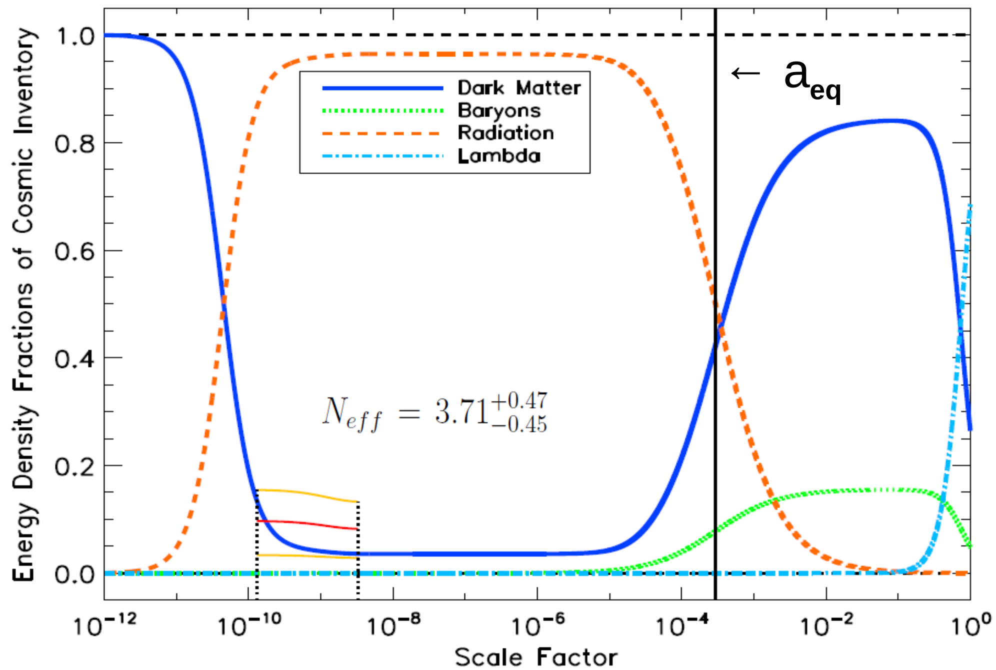


Cosmological evolution in an FLRW Universe of real vs. complex SFDM

Li,TRD,Shapiro (1310.6061)

Magaña, Matos (2012)





m = 10^{-22} eV

$$(m, \lambda)_{\text{fiducial}} = (3 \times 10^{-21}\ \text{eV}/\text{c}^2, 1.8 \times 10^{-59}\ \text{eV cm}^3)$$

ΛSFDM + SGWB

Limiting the duration of the stiff phase after reheating and before BBN constrains SFDM parameters via their contribution to $N_{\mathbf{eff}}$

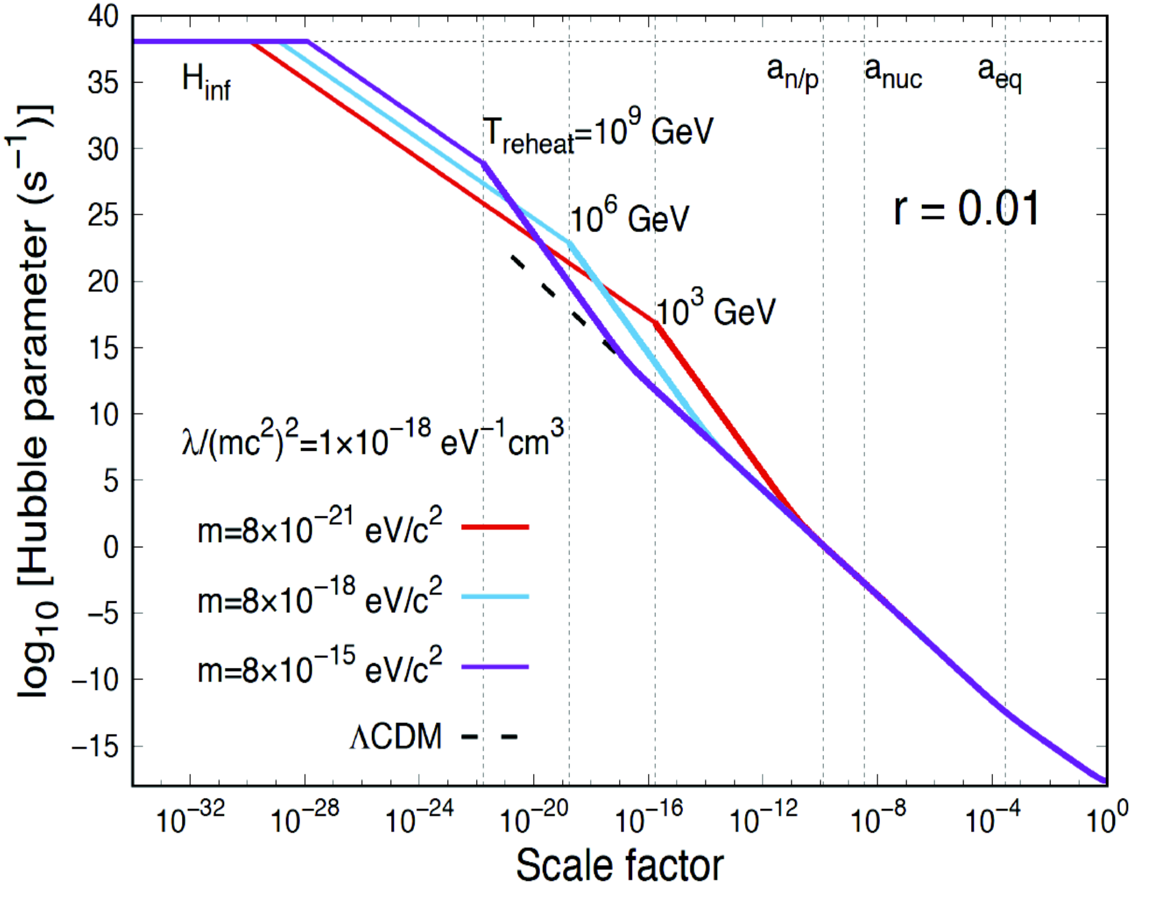
- for given r: the smaller the DM mass, the later must reheating occur

- Matter-radiation equality:

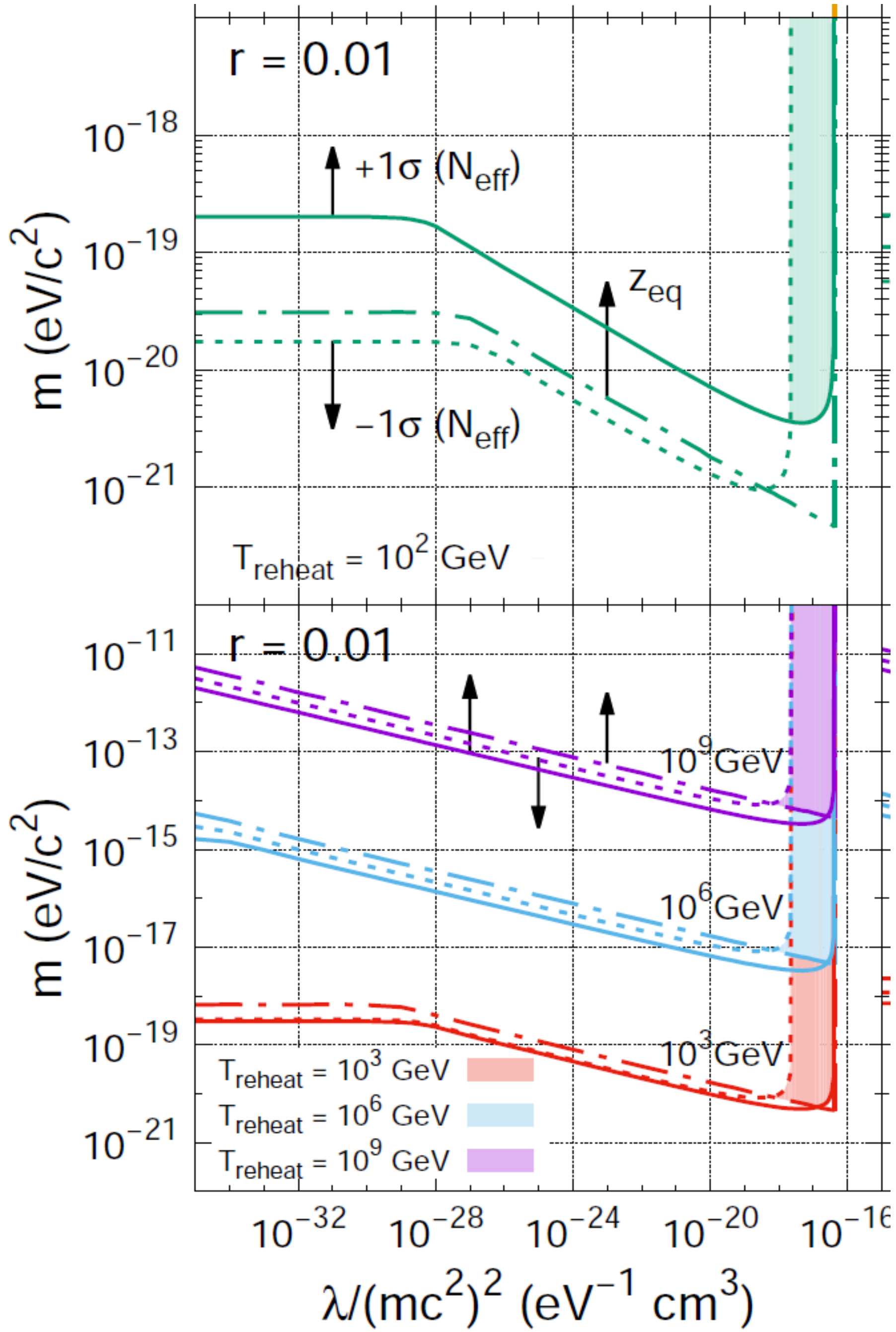
$$1 + z_{\rm eq} \equiv \frac{1}{a_{\rm eq}} = \frac{\Omega_b h^2 + \Omega_c h^2}{\Omega_r h^2 + \Omega_{\rm GW} h^2}$$

- $N_{\mathbf{eff}}$ during BBN:

$$\frac{\Delta N_{\rm eff,BBN}(a)}{N_{\rm eff,standard}} = \frac{\Omega_{\rm SFDM}(a) + \Omega_{\rm GW}(a)}{\Omega_\nu(a)}$$



Cosmological Constraints on the SFDM parameters



ΛSFDM + SGWB:
enhanced signal of inflationary SGWB due to DM !

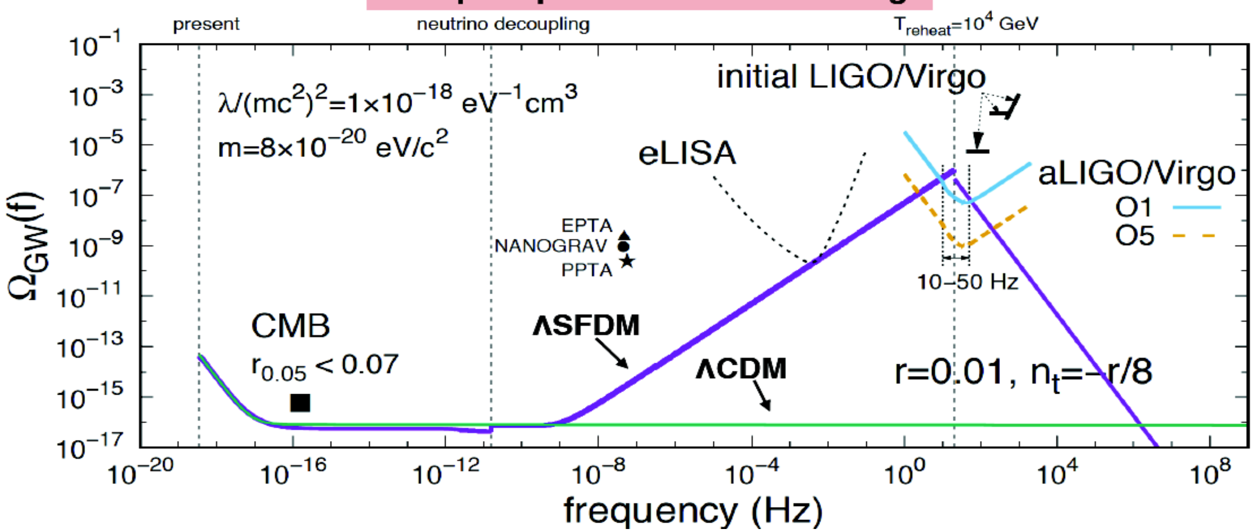
Any grav.waves which enter horizon while the background EOS obeys w > 1/3 amplifies Ω_{GW} ! (Grishtshuk, Giovannini, Boyle, …..)

<u>Stiff-SFDM-dominated era</u> amplifies SGWB from (standard) inflation: can be measured/constrained by GW laser interferometers !

ΛSFDM predicts 2-parameter broken power-law spectrum at high frequencies:

$$\Omega_{GW}(f) = \Omega_{GW,peak} \times \begin{cases} f / f_{peak}, & f \leq f_{peak} \\ \frac{9\pi}{64}(f / f_{peak})^{-2}, & f > f_{peak} \end{cases}$$

Example 1 prediction for aLIGO/Virgo



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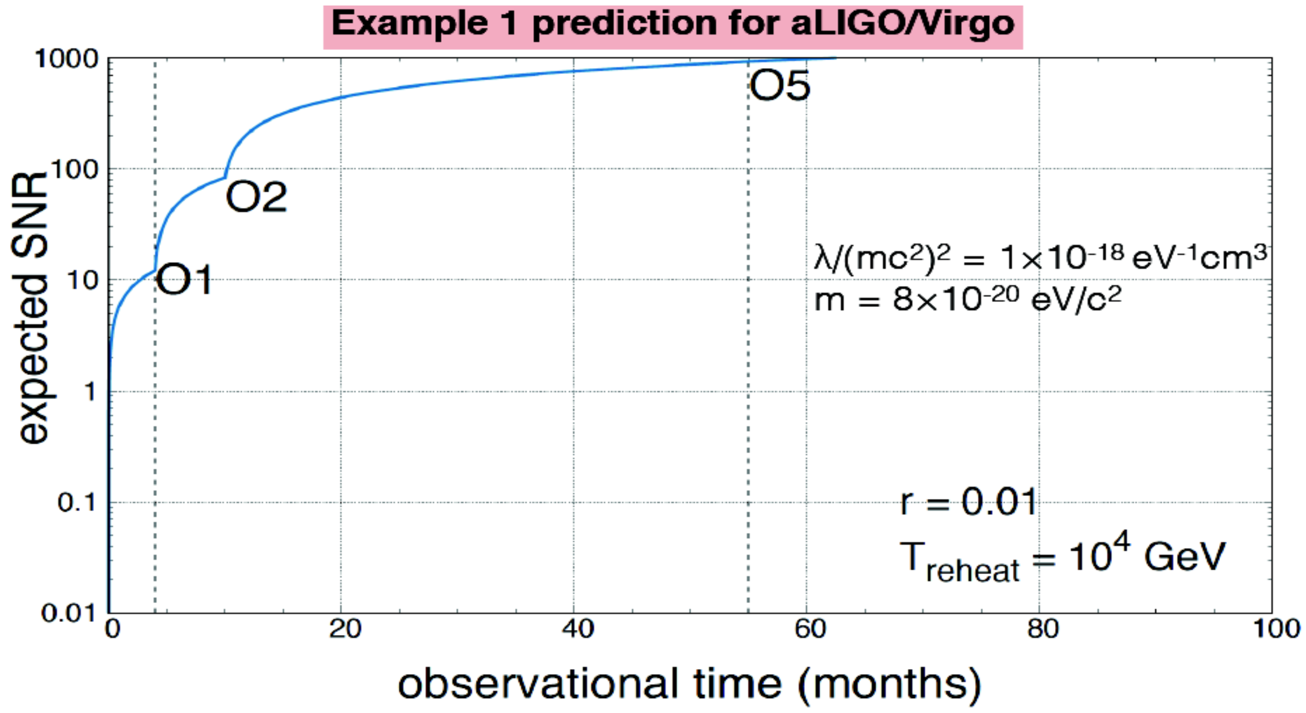

NEW upper limit from O1 excludes this example case at 95% CL
→ The Age of DM Search/Constraints by GW Detection has begun !

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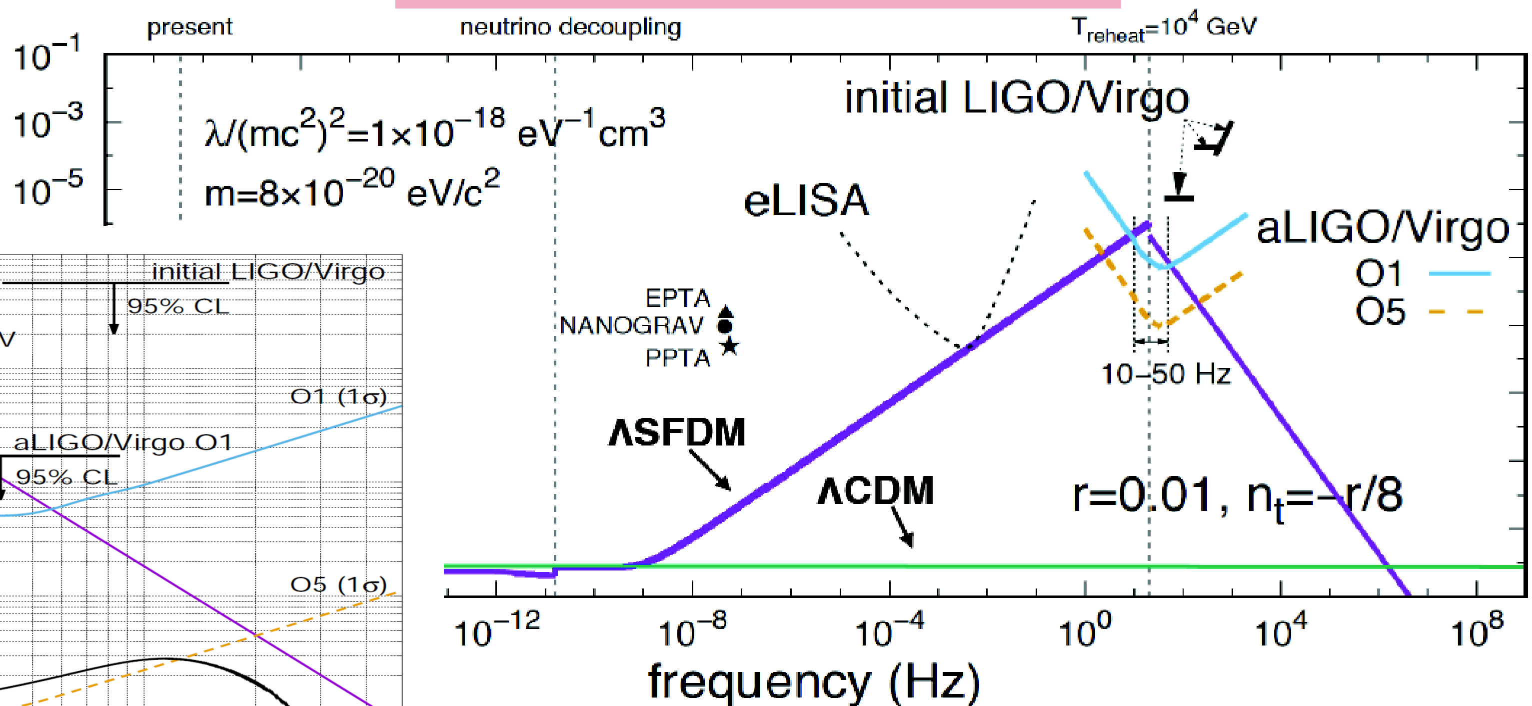

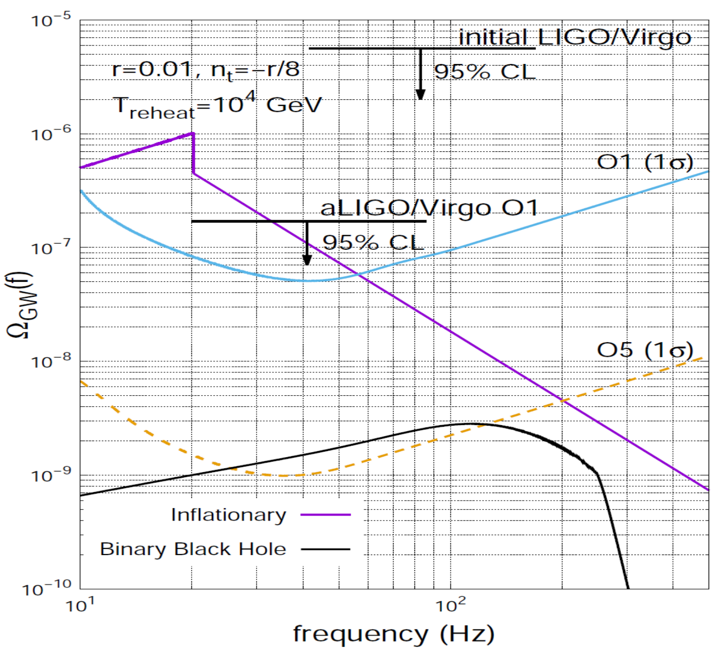

ΛSFDM + SGWB:

enhanced signal of inflationary SGWB due to DM !

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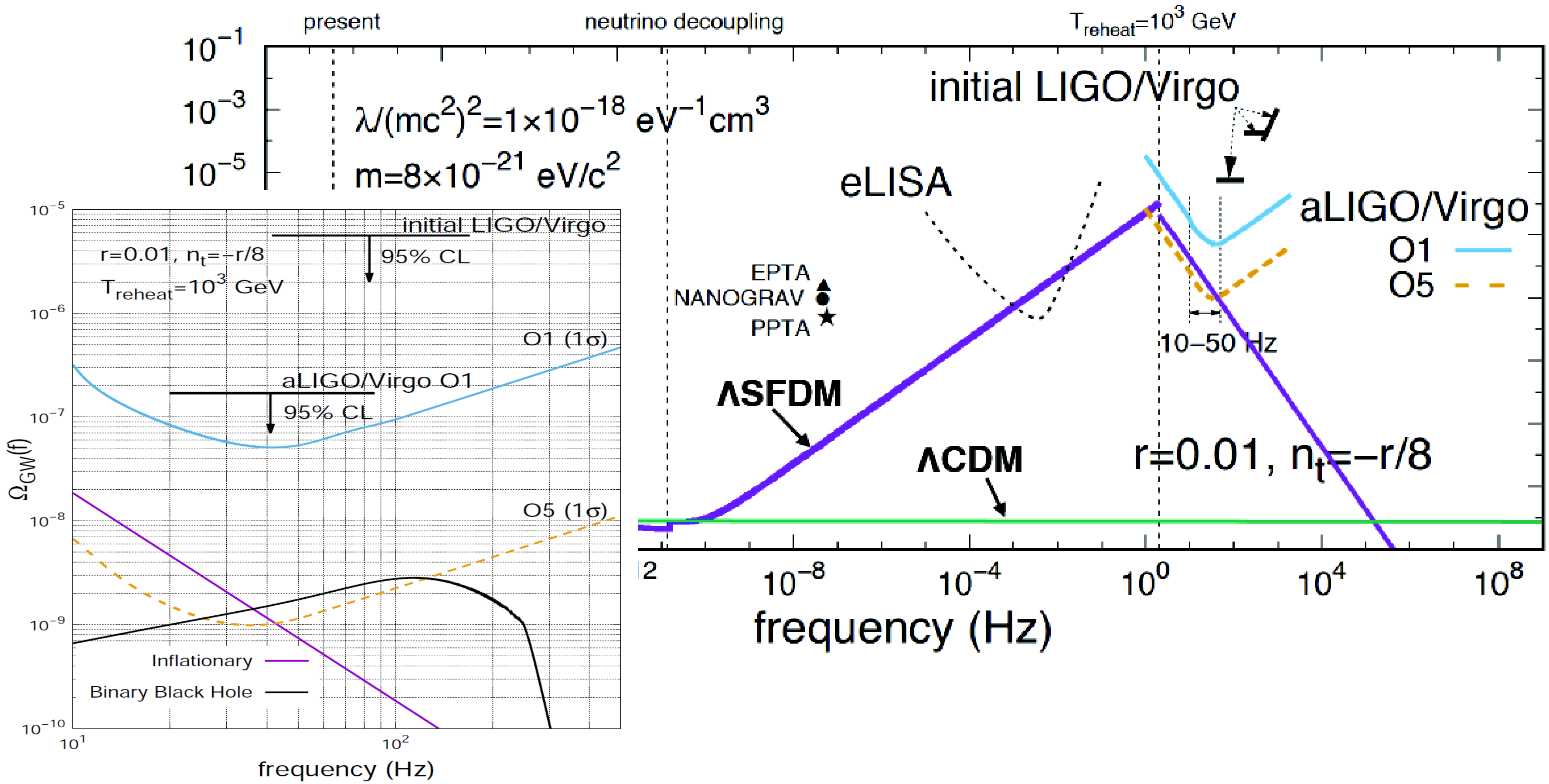
can be measured/constrained by GW laser interferometers !

Example 2 prediction for aLIGO/Virgo

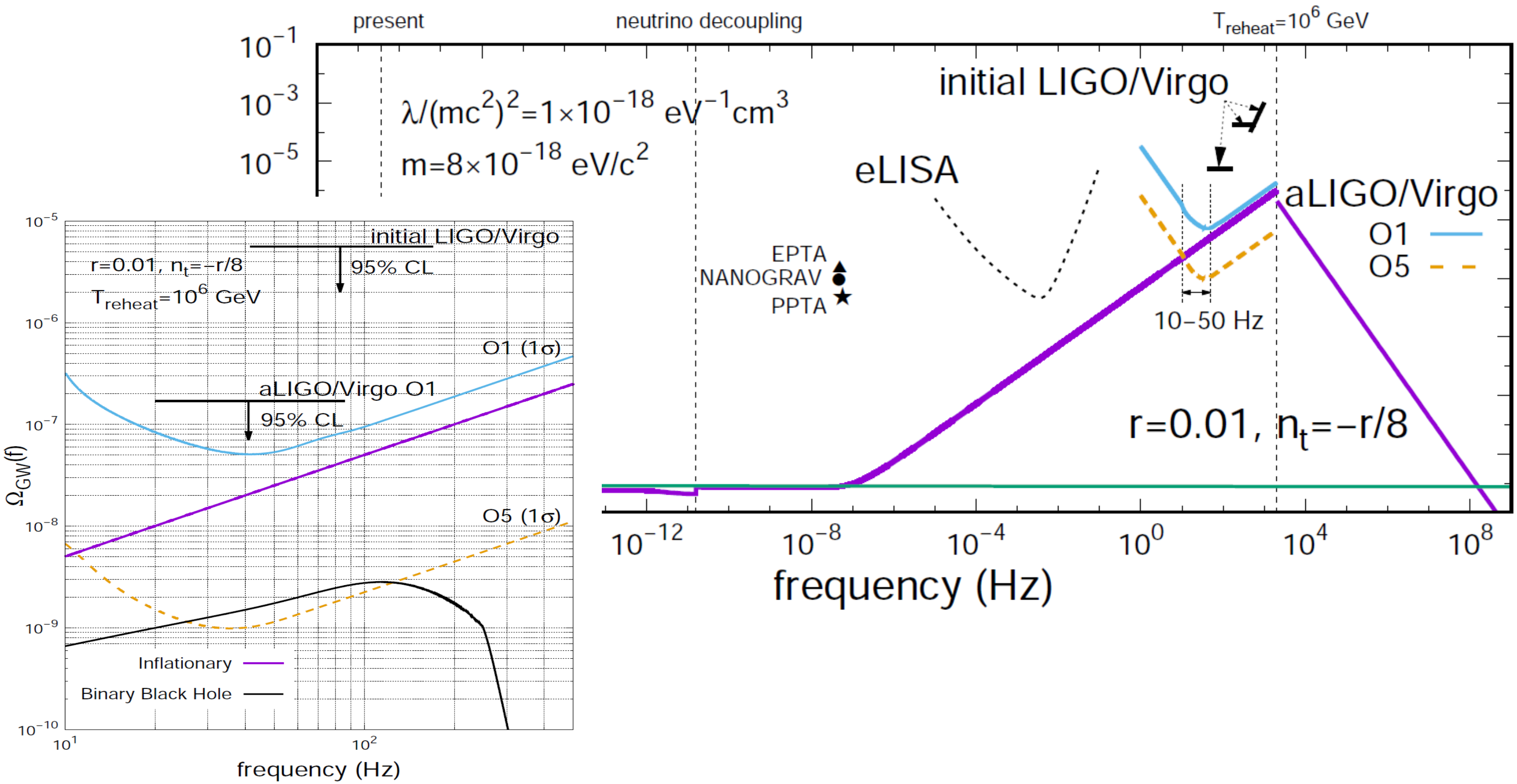


ΛSFDM + SGWB:
enhanced signal of inflationary SGWB due to DM !

<u>Stiff-SFDM-dominated era</u> amplifies SGWB from (standard) inflation:

can be measured/constrained by GW laser interferometers !

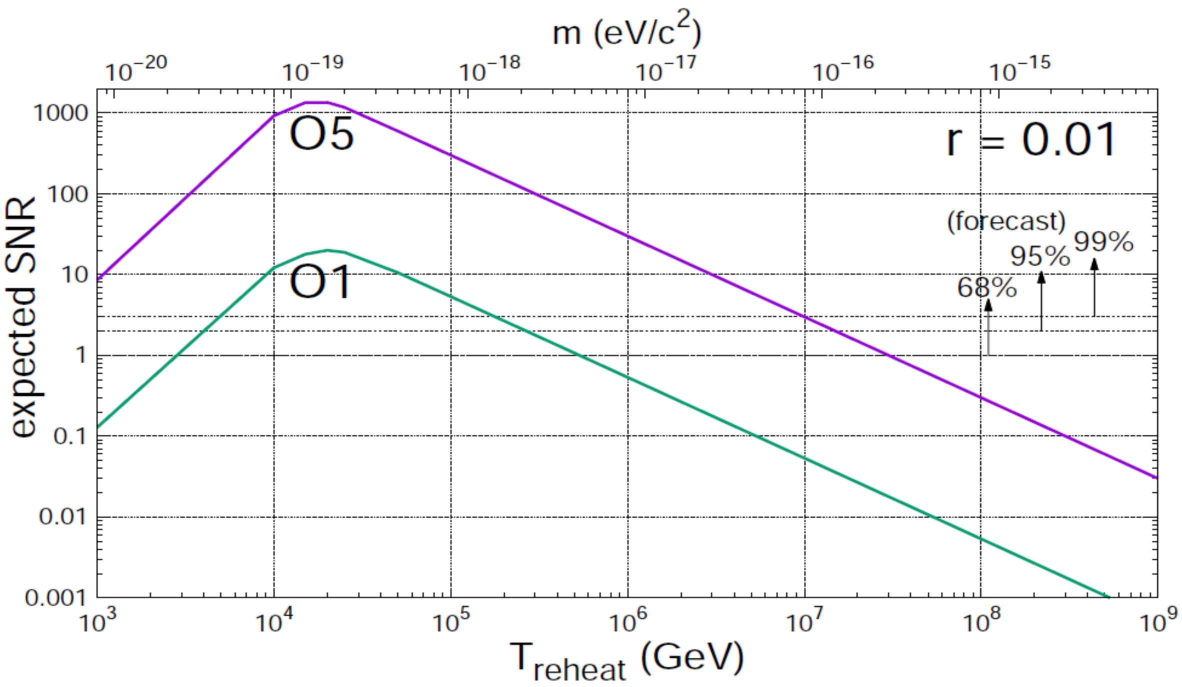
Example 3 prediction for aLIGO/Virgo



ΛSFDM + SGWB:
enhanced signal of inflationary SGWB due to DM !

<u>Stiff-SFDM-dominated era</u> amplifies SGWB from (standard) inflation:

can be measured/constrained by GW laser interferometers ! → FORECASTS



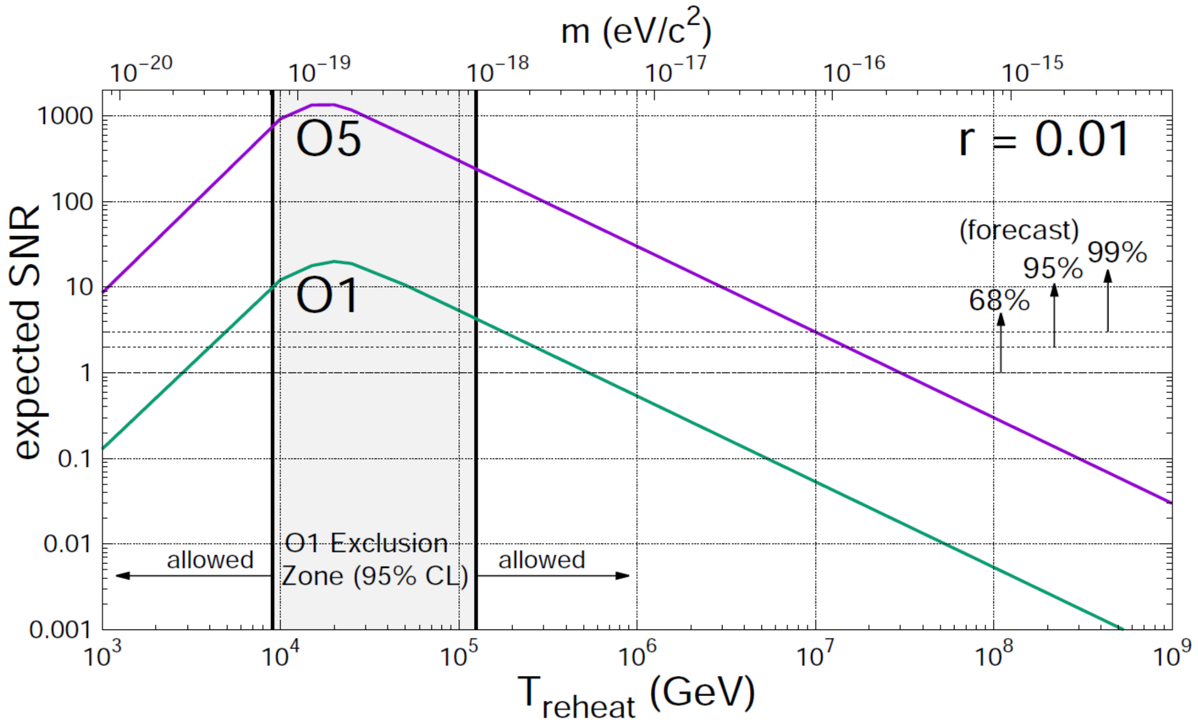
Marginally allowed ΛSFDM models for $\lambda/(mc^2)^2 = 1\times10^{-18}$ eV^{-1}cm^3

ΛSFDM + SGWB:
enhanced signal of inflationary SGWB due to DM !

<u>Stiff-SFDM-dominated era</u> amplifies SGWB from (standard) inflation:

can be measured/constrained by GW laser interferometers !

Current limits: O1 from LIGO (1612.02029)



Marginally allowed ΛSFDM models for $\lambda/(mc^2)^2 = 1\times10^{-18}\ \mathrm{eV}^{-1}\mathrm{cm}^3$

Conclusions: SFDM is a good DM candidate

- may resolve small-scale problems of CDM *structure formation*

- rich variety of models allows non-standard *expansion histories* in the early Universe:
  particle parameters are constrained by the CMB, BBN, other PTs, primordial GWs from inflation (SGWB)

- puts into reach the *possible detection of the inflationary SGWB:*
  a wide range of DM particle parameters and reheat temperatures can be already tested by aLIGO/VIRGO O1 run, and more with O5 !
  (some examples are already ruled out from O1)

→ **ongoing/upcoming GW laser interferometer experiments can detect/constrain DM !**