Searching for Dark Photon Dark Matter with Gravitational Wave Detectors

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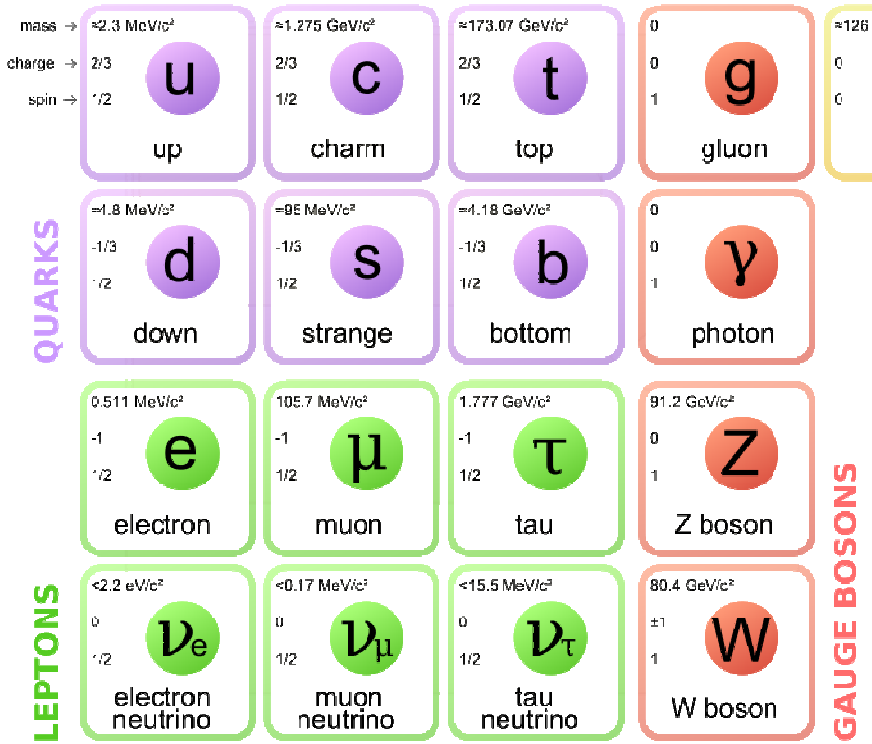
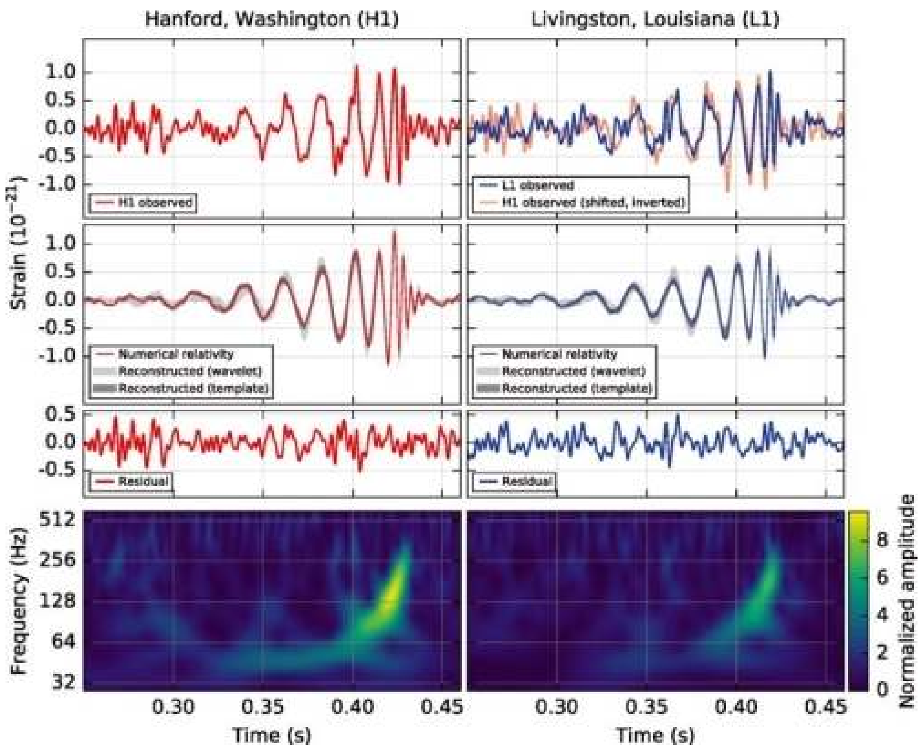
Current Status of Particle Physics:

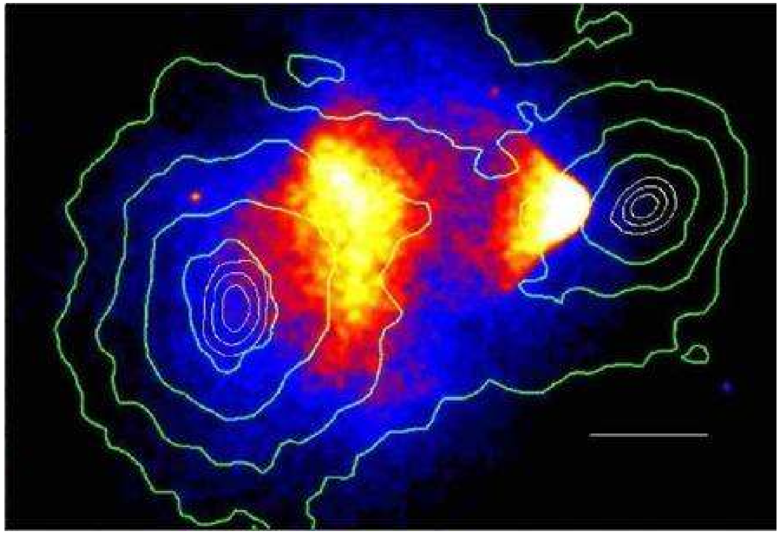


+ Dark Sector?



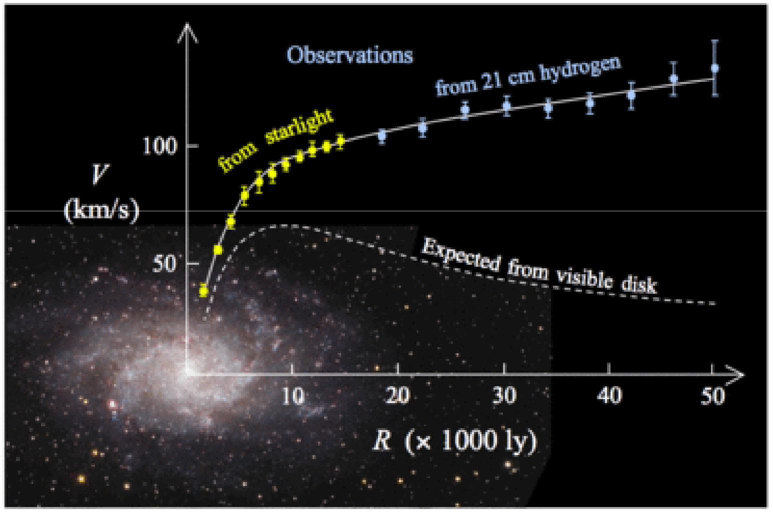
Dark Matter Overview:

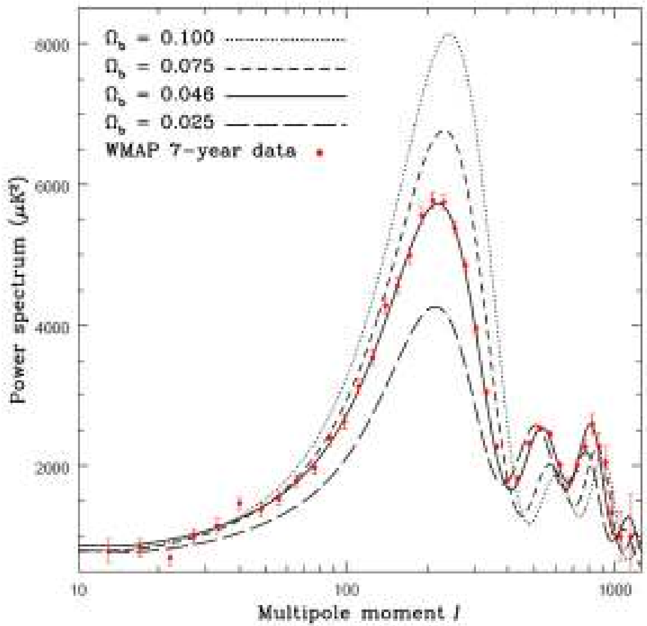
• Bullet Cluster (Deep Chandra)



Why do we need DM?

• Galaxy rotation curve (Wikipedia)



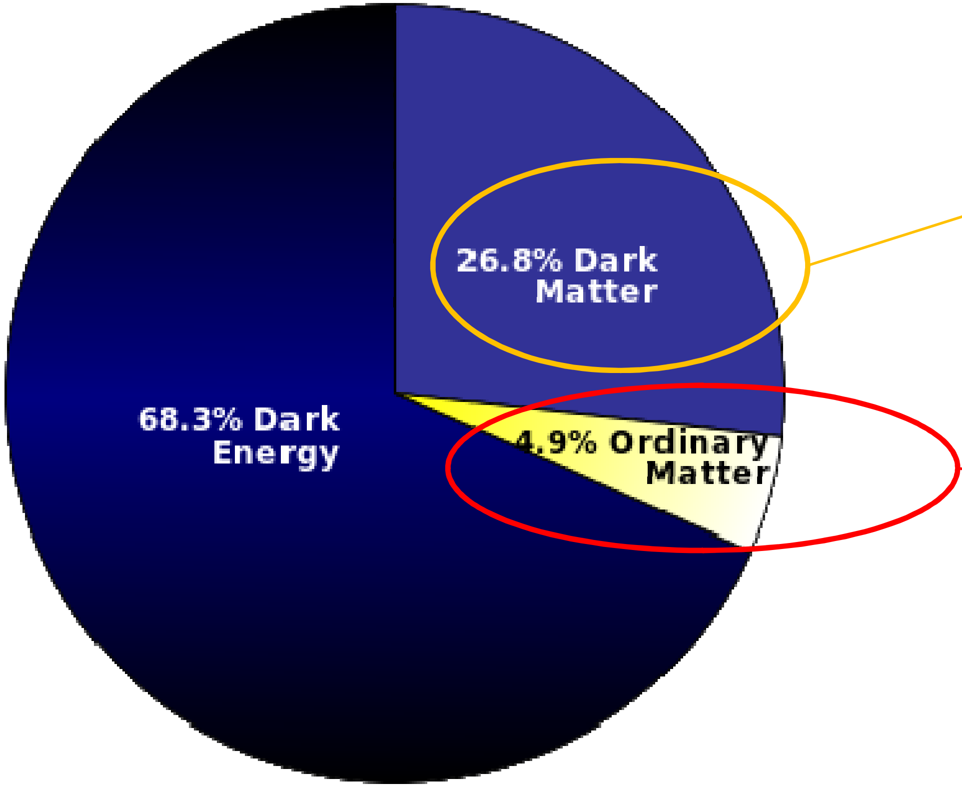


• The CMB Anisotropy Power Spectrum

(WMAP year 5 data)

Dark Matter Overview:

How much do we have?



(Wikipedia)

We only know DM through its gravitational interaction!

We only understand 5% of the Universe!

Popular Choices:

- WIMP:

  100 GeV ~ TeV

- Very light DM particles

  Axion and $\boxed{\text{Dark "Photon"}}$

  10^{-22} eV ~ 10 eV

- Primordial Black Holes:

  10^{-7} ~ 100 solar mass

gauge boson of the $\boxed{U(1)_B}$ or $\boxed{U(1)_{B-L}}$

(p+n) (n)

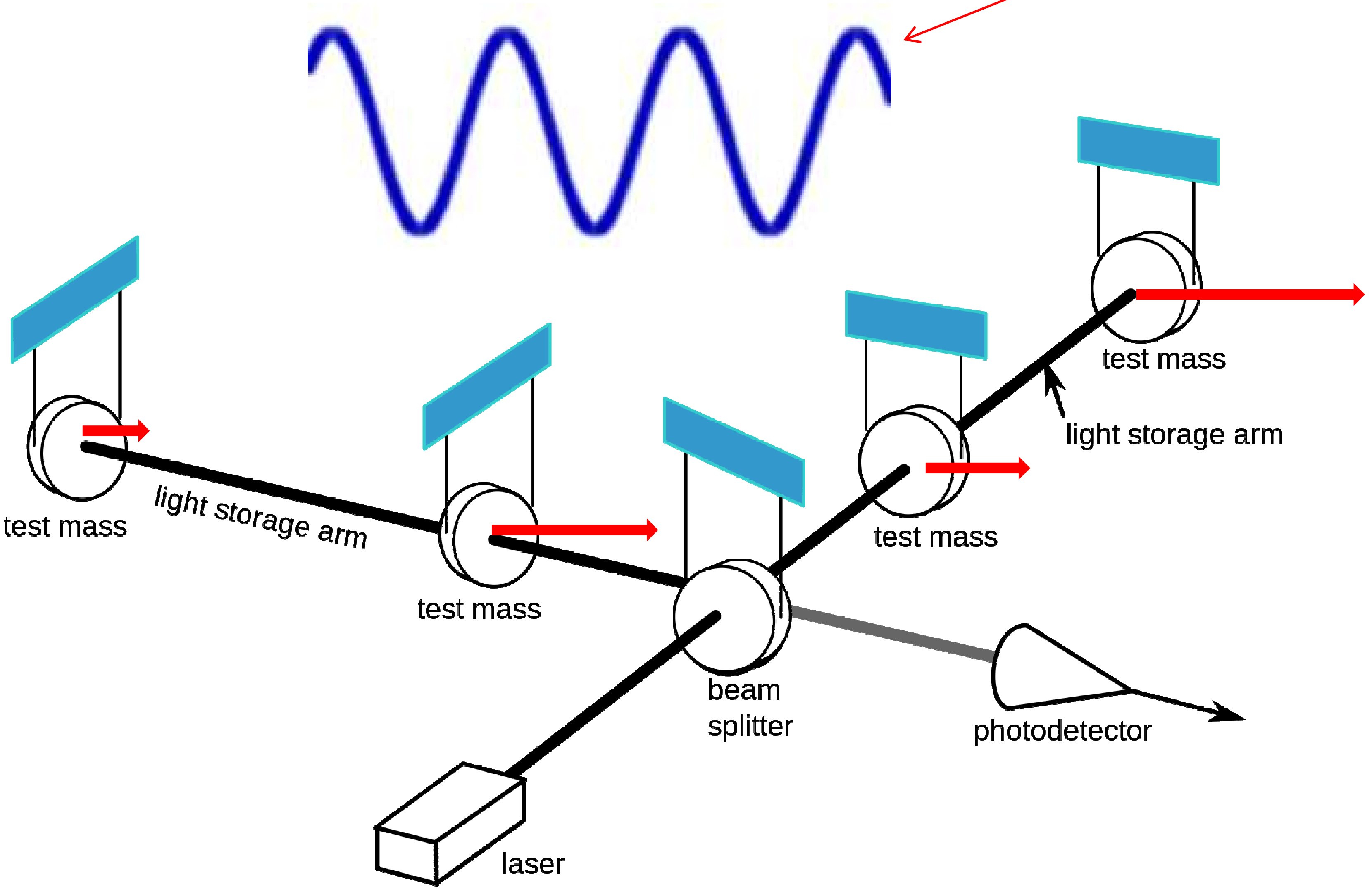
DM is an oscillating background field.

Dark Photon is dominantly oscillating background dark electric field.

Driving displacements for particles charged under dark gauge group.

Intuitive Picture:

(not the precise pic)



GW detector: precise measurement on $\Delta L \equiv |\Delta L_x - \Delta L_y|$

Serendipity?

LIGO → LIDMO

Maximal Displacement:

Local DM energy density:

$$\boxed{\frac{1}{2}m_A^2 A_{\mu,0}A_0^{\mu} \simeq 0.4\ \mathrm{GeV/cm^3}}$$

local field strength of DP

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\partial^\mu A_\mu = 0$$

$$E_i \sim m_A A_i \qquad >> \qquad B^i \sim m_A v_j A_k \epsilon^{ijk}$$

Maximal Displacement:

$$\vec{a}_i(t) = \frac{\vec{F}_i(t)}{M_i} \simeq \boxed{\epsilon e}\boxed{\frac{q_{D,i}}{M_i}}\boxed{\partial_t \vec{A}(t, \vec{x}_i)}$$

dark photon coupling

dark electric field

charge mass ratio of the test object

Silicon mirror:

$U(1)_B$: 1/GeV

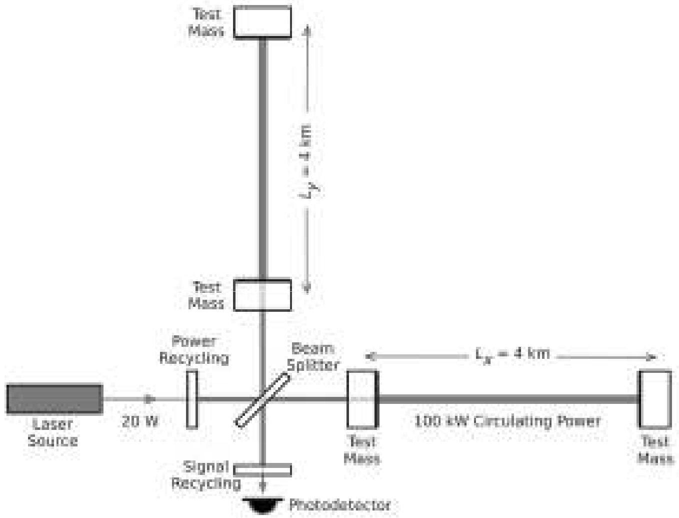
$U(1)_{B-L}$: 1/(2GeV)

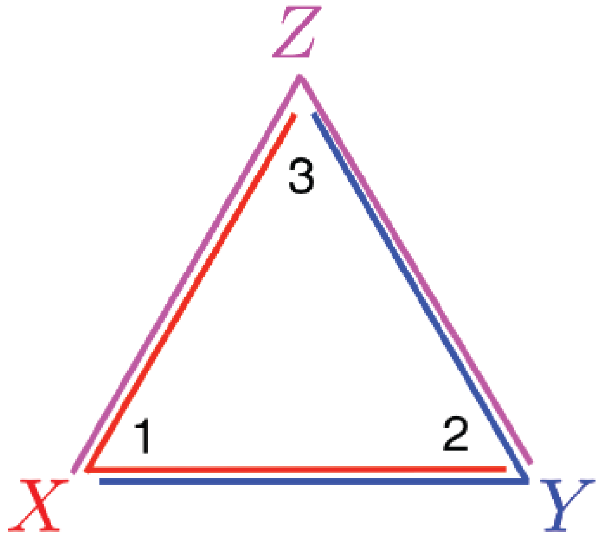
projected along the arm direction

$$\Delta s_{\parallel,i} = \int dt \int dt\ a_{\parallel,i}(t)$$

Maximal GW-like Displacement:

$$\Delta L[t] = (x_1[t] - x_2[t]) - (y_1[t] - y_2[t])$$





$$\boxed{\sqrt{\langle \Delta L^2 \rangle}_{LIGO}\Big|_{max} =} \frac{\sqrt{2}}{3} \frac{|a||k|L}{m_A^2}$$

Compare this with the sensitivity on strain h.

$$\sqrt{\langle \Delta L^2 \rangle}_{LISA}\Big|_{max} = \frac{1}{\sqrt{6}} \frac{|a|\boxed{|k|}L}{m_A^2}$$

v_{vir}=0 gives same force to all test objects, not observable.
Net effect is proportional to velocity.

Maximal GW-like Displacement:

$$\sqrt{\langle \Delta L^2 \rangle}_{LIGO}\Big|_{max} = \frac{\sqrt{2}}{3}\frac{|a||k|L}{m_A^2}$$

$$\sqrt{\langle \Delta L^2 \rangle}_{LISA}\Big|_{max} = \frac{1}{\sqrt{6}}\frac{|a||k|L}{m_A^2}$$

Averaging on directions of
acceleration and momentum vectors.

For non-relativistic particles,
polarization vector and momentum vector are independent.

Compared with other DPDM/axion experiments (ADMX),

no resonance is required at measurement, thus no need to scan frequency!

Search for a large frequency band simultaneously!

Properties of DPDM Signals:

Signal:

- almost monochromatic

$$f \simeq \frac{m_A}{2\pi}$$

- very long coherence time

$$\Delta f / f = v_{vir}^2 \simeq 10^{-6}$$

DM velocity dispersion.
Determined by gravitational potential of our galaxy.

⇨ A bump hunting search in frequency space.

Can be further refined as a detailed template search, assuming Boltzmann distribution for DM velocity.

Once measured, we know great details of the local DM properties!

Properties of DPDM Signals:

Signal:

- very long coherent distance

$$l_{coh} \simeq \frac{1}{m_A v_{vir}} \simeq 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f} \right)$$

Propagation and polarization directions remain constant approximately.

⇨ Signals are almost the same for different sites of the detectors!

One can reduce noise by correlating the measurements at different sites!

↓

Similar to stochastic GW search

Overlap functions are O(1) for all frequency (Hanford/Livingston).

More details when we talk about SNR calculation.

Relation to stochastic GW searches:

Stochastic GW: (Abbott et. al. Phys.Rev. D69 (2004) 122004)

Correlation is lost every oscillation period.

DPDM signal:

Dominated by single plane wave for a long period of time.

Correlation is maintained for millions of oscillation periods.

Directions of polarization and propagation are fixed over each coherence time and length, but randomly vary over longer time scales.

⇨ Signal well suited to stochastic search techniques exploiting correlations between interferometers (despite signal's being more monochromatic than continuous waves)

Sensitivity to DPDM signal of GW detectors:

First we estimate the sensitivity on in terms of GW strain.

(Allen & Romano, Phys.Rev.D59:102001,1999)

One-sided power spectrum function:

$$S_{GW}(f) = \frac{3H_0^2}{10\pi^2} f^{-3} \Omega_{GW}(f)$$

energy density carried by
a GW planewave $\rho_{GW}(f) = \frac{\langle \dot{h}^2 \rangle}{16\pi G}$

$$\Omega_{GW}(f) \equiv \frac{f}{\rho_c} \frac{d\rho_{GW}}{df} = \frac{f}{\rho_c} \frac{\boxed{\rho_{GW}(f)}}{\Delta f}$$

$$\Delta f / f = v_{vir}^2 \simeq 10^{-6}$$

Concretely predicted by
Maxwell–Boltzmann distribution!

A template search is possible,
and a better reach is expected!

We make simple estimation based
on delta function as a guideline.

Sensitivity to DPDM signal of GW detectors:

Signal-to-Noise-Ratio can be calculated as:

$$S = < s_1, s_2 > \equiv \int_{-T/2}^{T/2} s_1(t) s_2(t) dt.$$

overlap function
describe the correlation among sites

observation time of an experiment, O(yr)

$$S = \frac{\boxed{T}}{2} \int df \, \boxed{\gamma(|f|)} \, S_{GW}(|f|) \, \boxed{\tilde{Q}(f)},$$

$$N^2 = \frac{T}{4} \int df \, \boxed{P_1(|f|)} \, |\tilde{Q}(f)|^2 \, P_2(|f|).$$

optimal filter function
maximize SNR

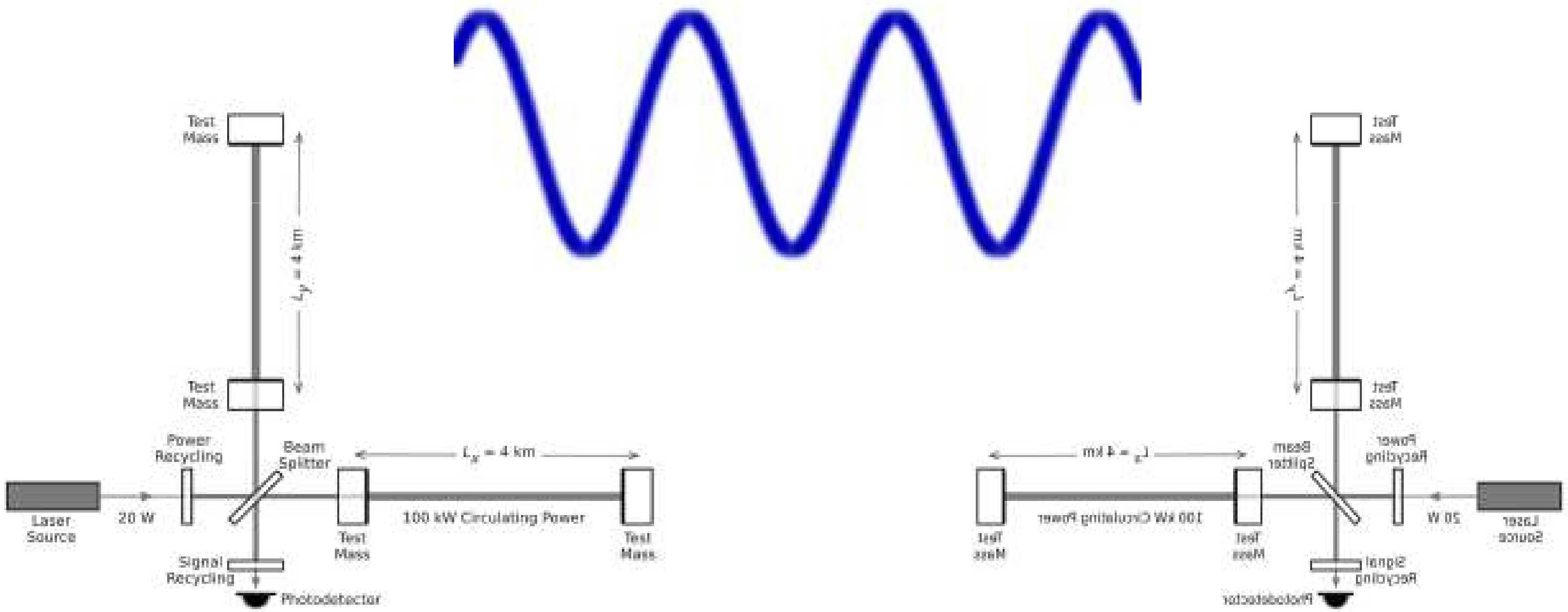
one-sided strain noise power spectra

Sensitivity to DPDM signal of GW detectors:

Stochastic GW:

LIGO

$$\gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle}$$



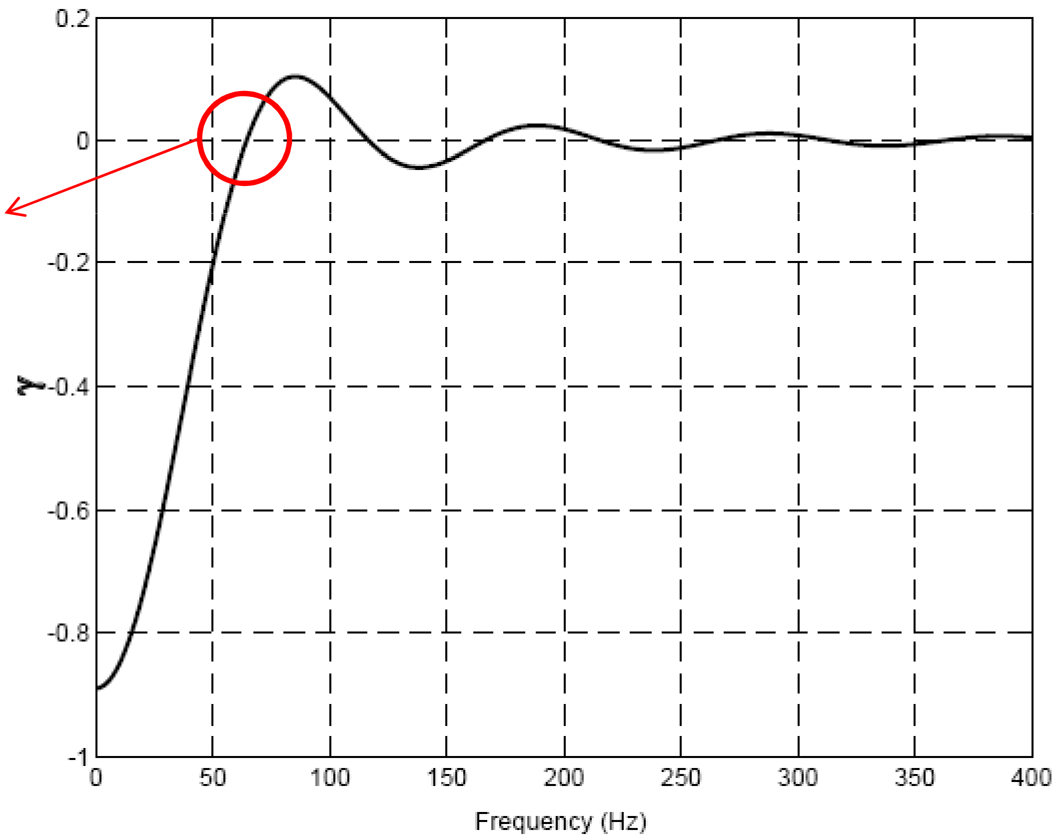
Sensitivity to DPDM signal of GW detectors:

Stochastic GW:

$$\gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle}$$

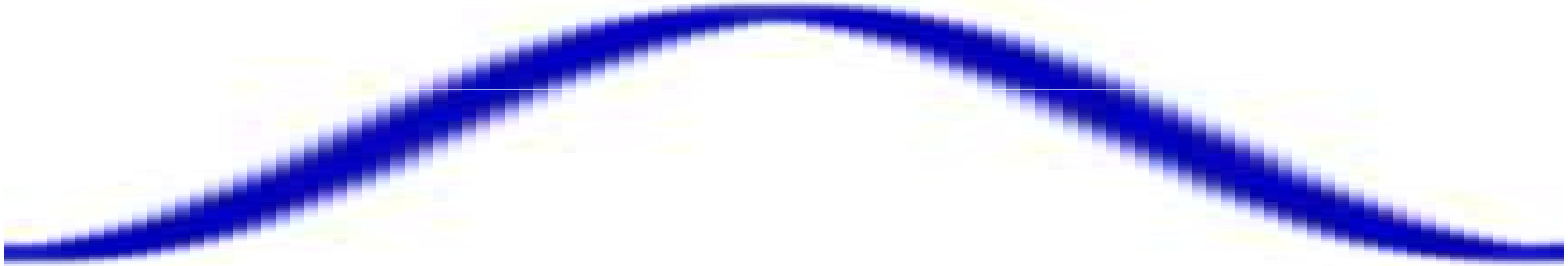
Signal correlation between two sites is lost when the separation is comparable to one wavelength.

LIGO



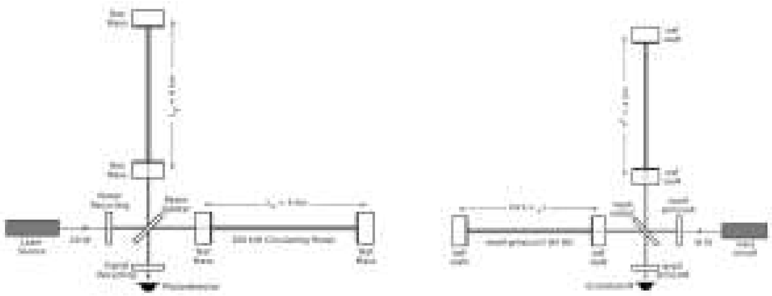
Sensitivity to DPDM signal of GW detectors:

DPDM:



LIGO

$$\gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle}$$



Livingston/Hanford:
Approximately a constant (-0.9) for all frequencies we are interested.

Virgo (-0.25) may be useful for cross checks.

Sensitivity to DPDM signal of GW detectors:

DPDM:

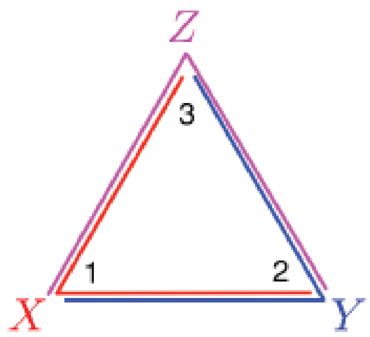
LISA

$$\gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle}$$

$$A \equiv \frac{1}{3}(2X - Y - Z)\,,$$

$$E \equiv \frac{1}{\sqrt{3}}(Z - Y)\,,$$

$$\langle AE \rangle$$



Approximately a constant (-0.3) for all frequencies we are interested.

Sensitivity to DPDM signal of GW detectors:

Translate strain sensitivity to parameters of DPDM:

$$\mathrm{SNR} = \frac{\gamma(|f|) h_0^2 \sqrt{T}}{10\sqrt{P_1(f)P_2(f)\Delta f}}$$

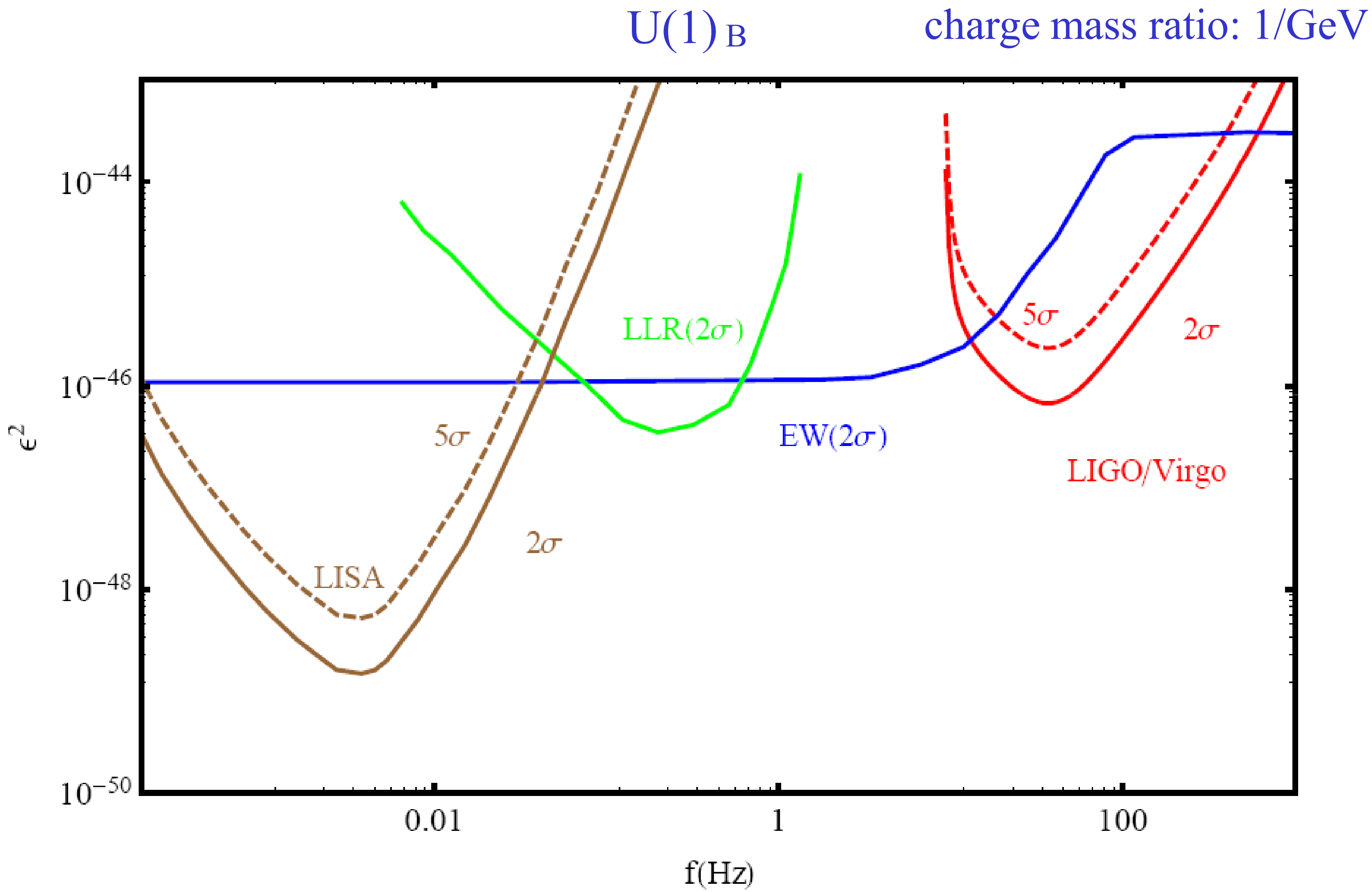
effectively the max differential displacement of two arms

a GW with strain h ⇨ change of relative displacement as h/2

⇨ $\sqrt{\langle \Delta L^2 \rangle}_{LIGO}\big|_{max}$

⇨ sensitivity of DPDM parameters (mass, coupling)

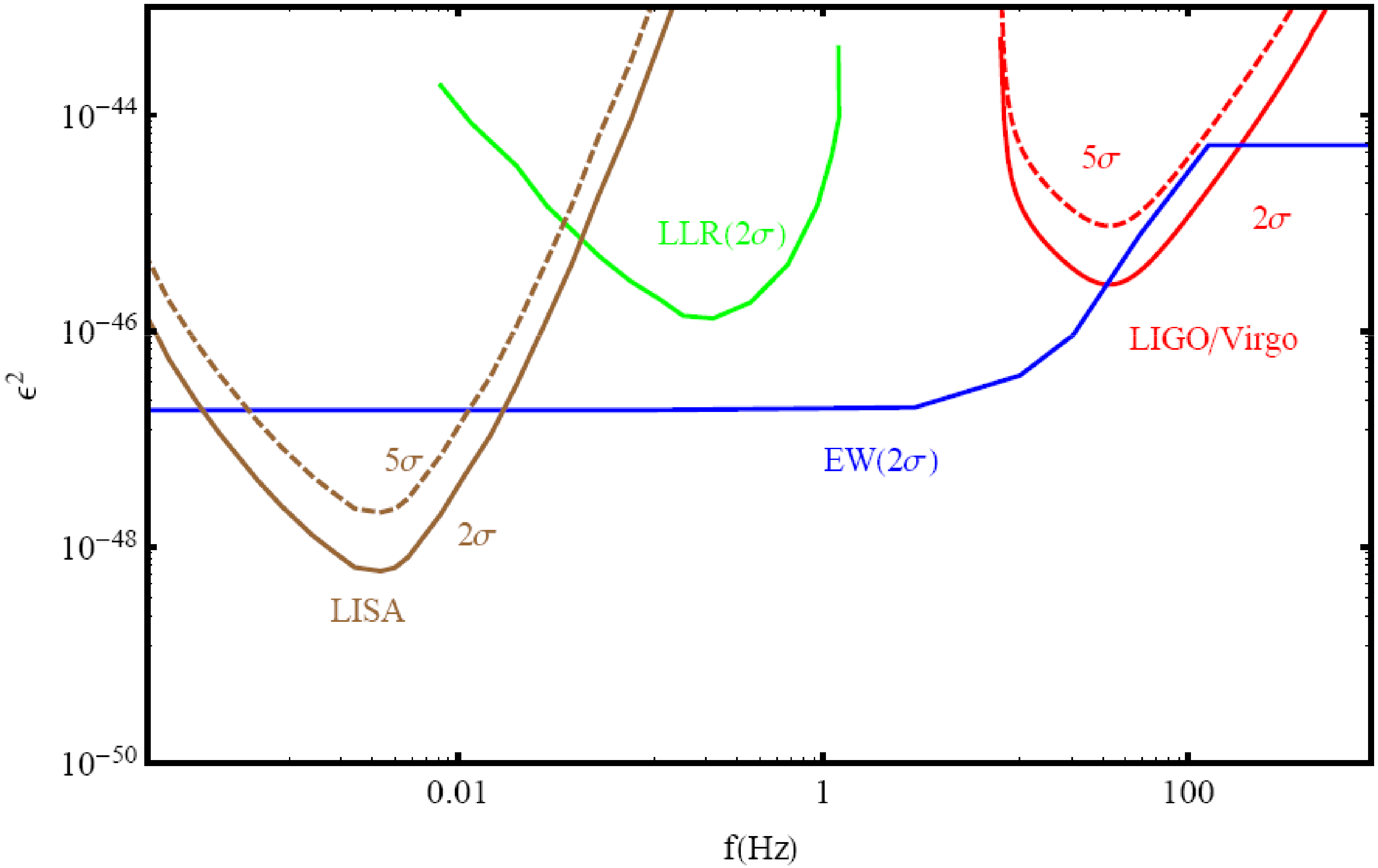
Sensitivity Plot:



design sensitivities operating for 2 years

Sensitivity Plot:

$U(1)_{B-L}$ charge mass ratio: 1/2GeV



design sensitivities operating for 2 years

Conclusion

The applications of GW experiments can be extended!

⇨ Particularly sensitive to relative displacements.

Coherently oscillating DPDM generates such displacements.

It can be used as a DM direct detection experiment.

The analysis is straightforward!

⇨ Very similar to stochastic GW searches.

Better coherence between separated interferometers
than Stochastic GW BG.

The sensitivity can be extraordinary!

⇨ Can beat existing experimental constraints.

Can achieve 5-sigma discovery at unexplored parameter regimes.

Once measured, great amount of DM information can be extracted!

1801.02807:

Direct Detection of Ultralight Dark Matter via Astronomical Ephemeris

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1801.02807:

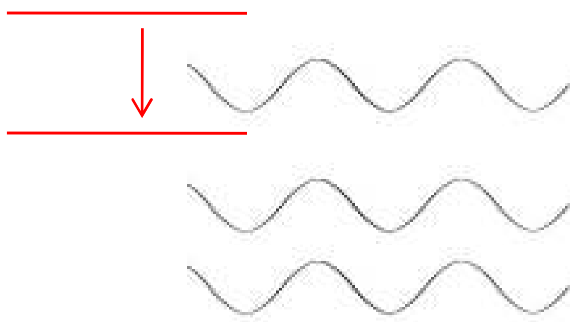
$$\mathscr{L}_{\rm int} = \frac{c_N}{2}\phi^2 \bar{N} N$$

matter cannot be an ultralight dark matter due to the Tremaine-Gunn bound [12]. We impose a Z_2 symmetry not to have a less-dimensional interaction, $\phi \bar{N} N$, because it induces a long-range force between a pair of nucleons and already severely constrained [13]. The

stimulate emission effect

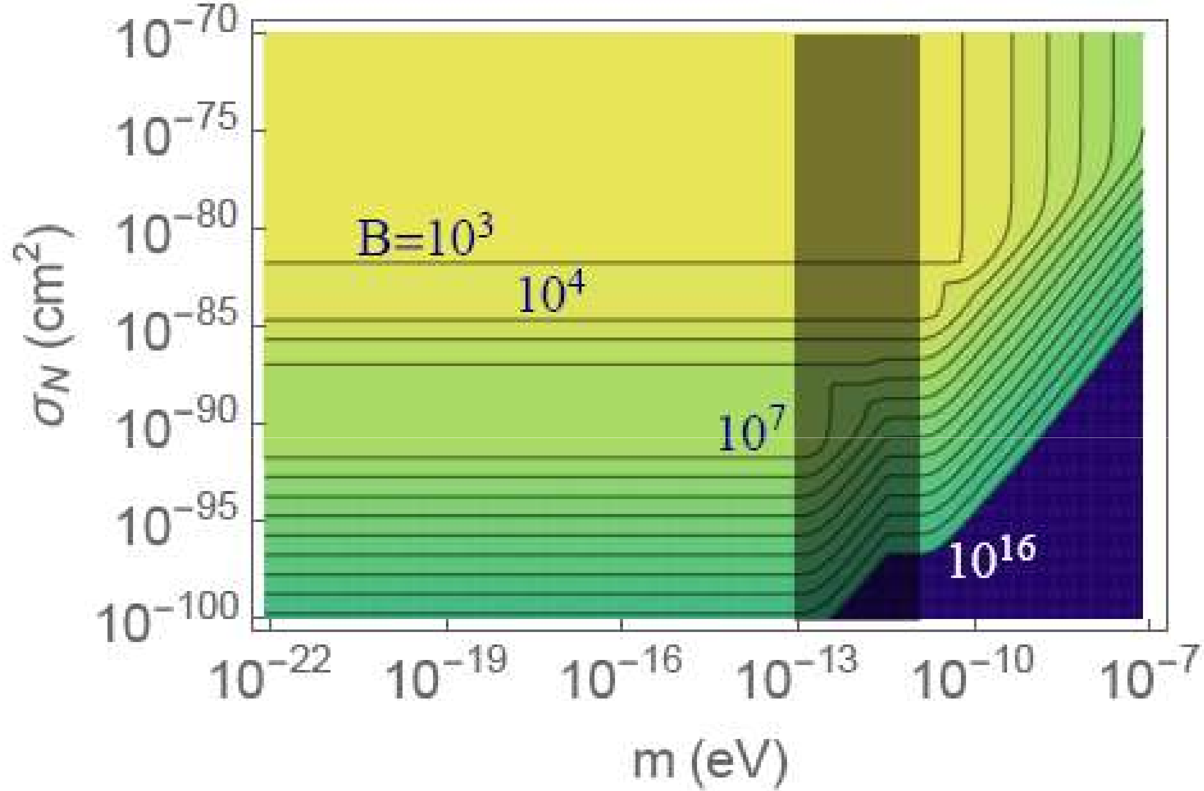
$$\boxed{(\rho_{\rm DM}/m)(2\pi)^3/(m v_0)^3} \sim 10^{37}(10^{-10}\,{\rm eV}/m)^4$$

initial state



Stimulate emission requires
multiple synced FINAL states!

1801.02807:



Compton scattering cross section:

$$\sigma_N \sim 10^{-122}\left(\frac{\epsilon^2}{10^{-46}}\right)^2 \mathrm{cm}^2$$