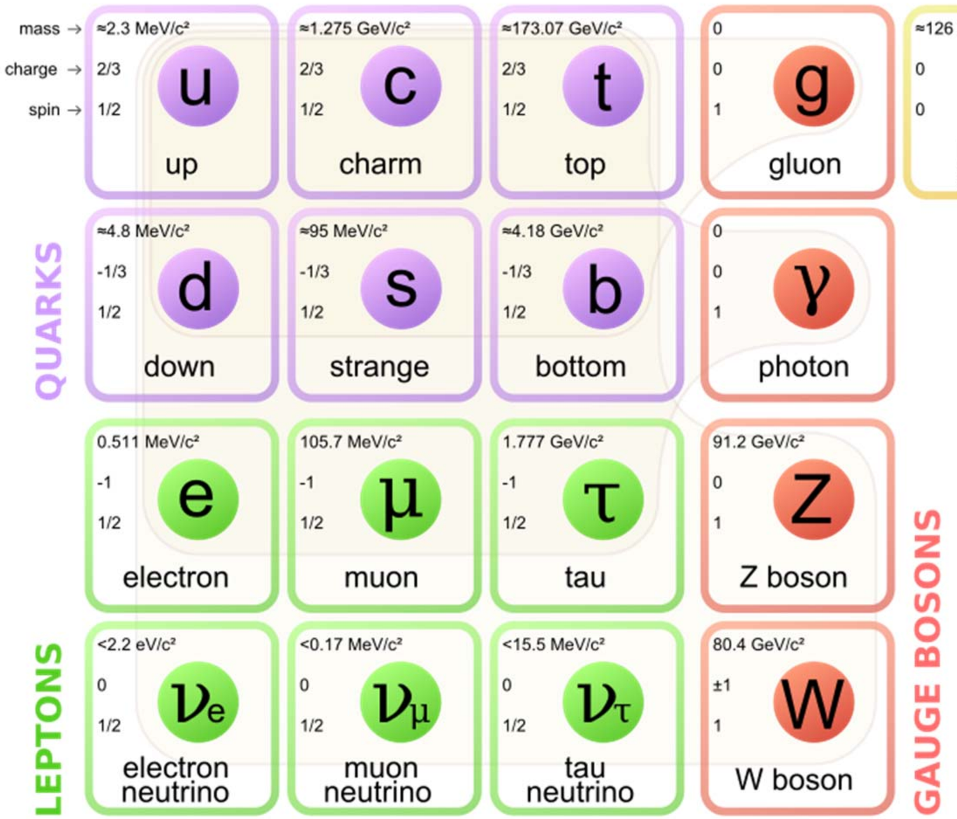
GW experiments for dark matter direct detections

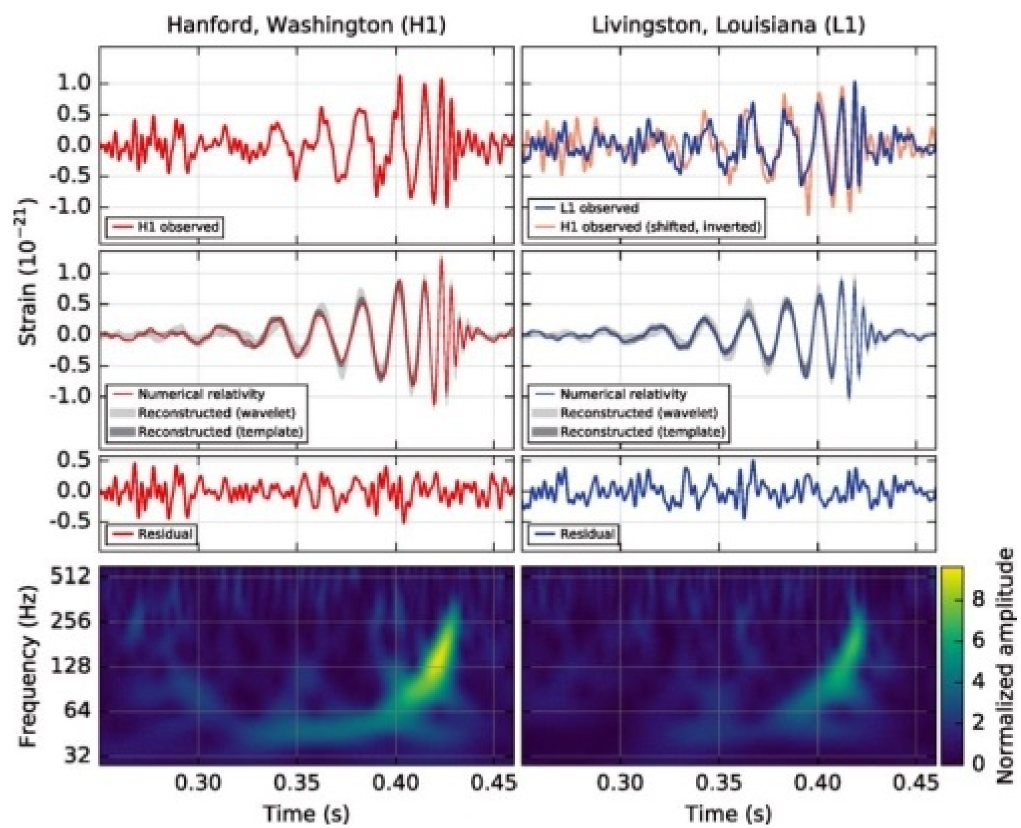
Yue Zhao

University of Utah

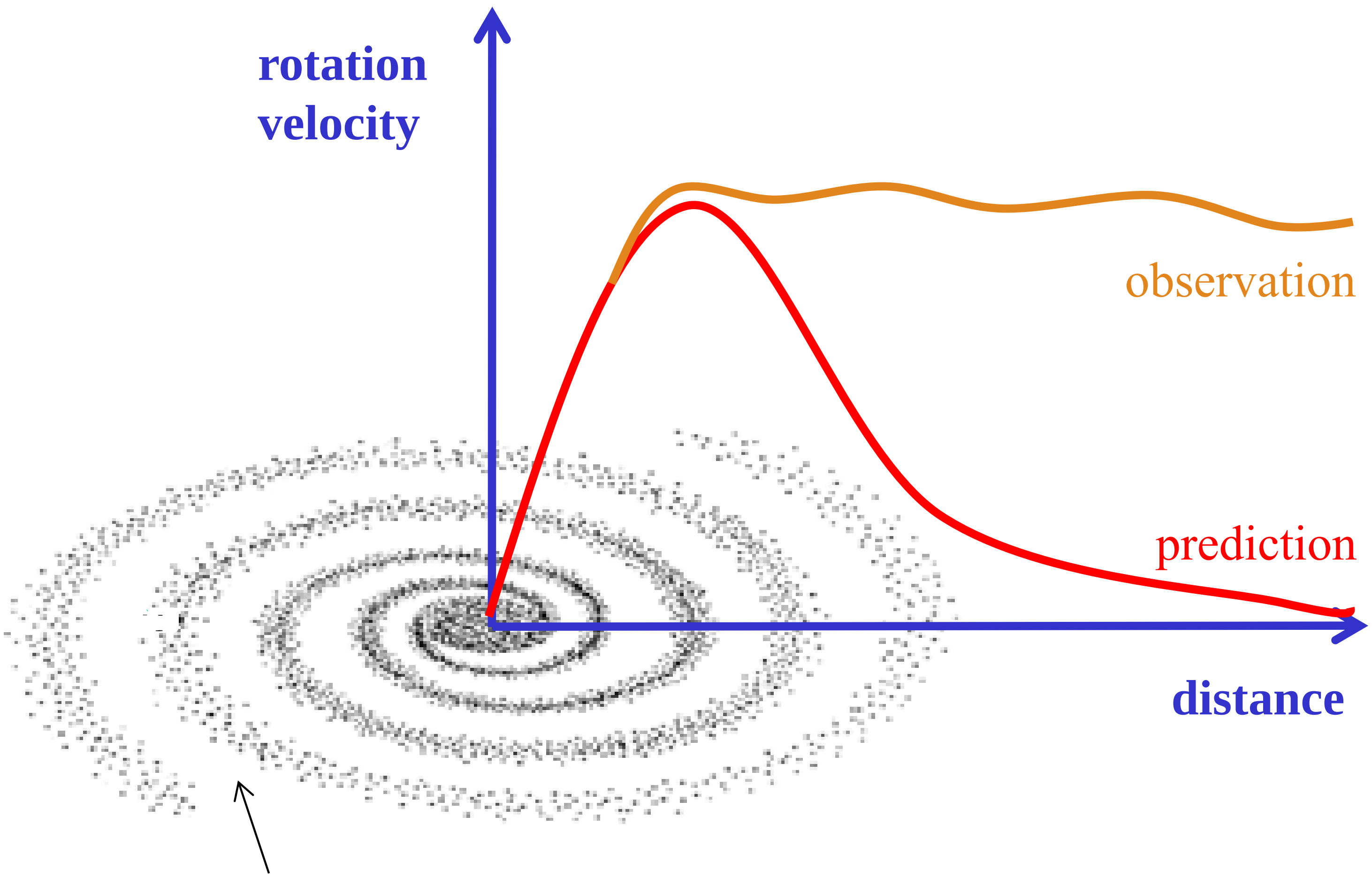
Current Status of Particle Physics:



+ Dark Sector?

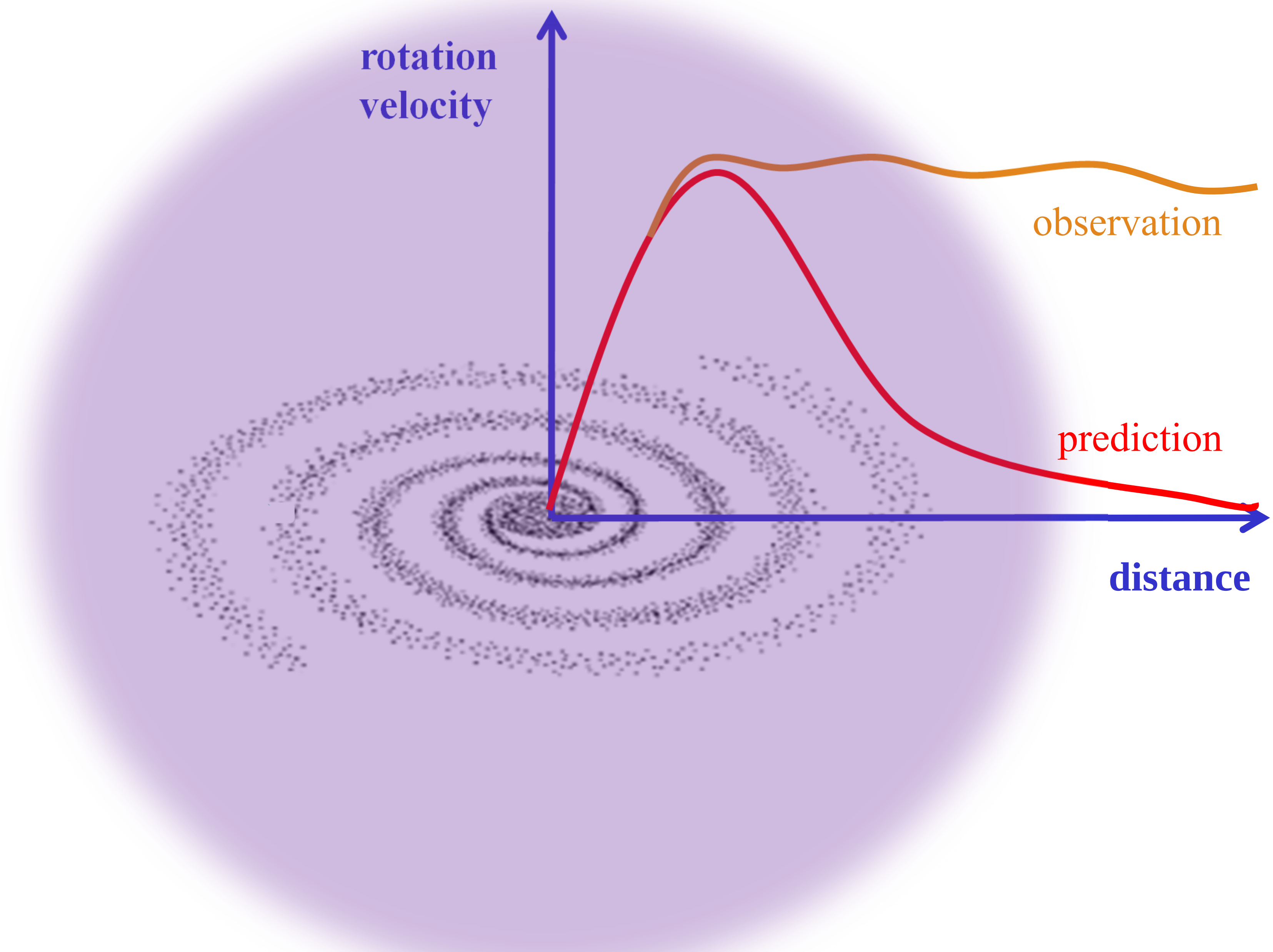


Dark Matter Exists – Galaxy Rotation Curve

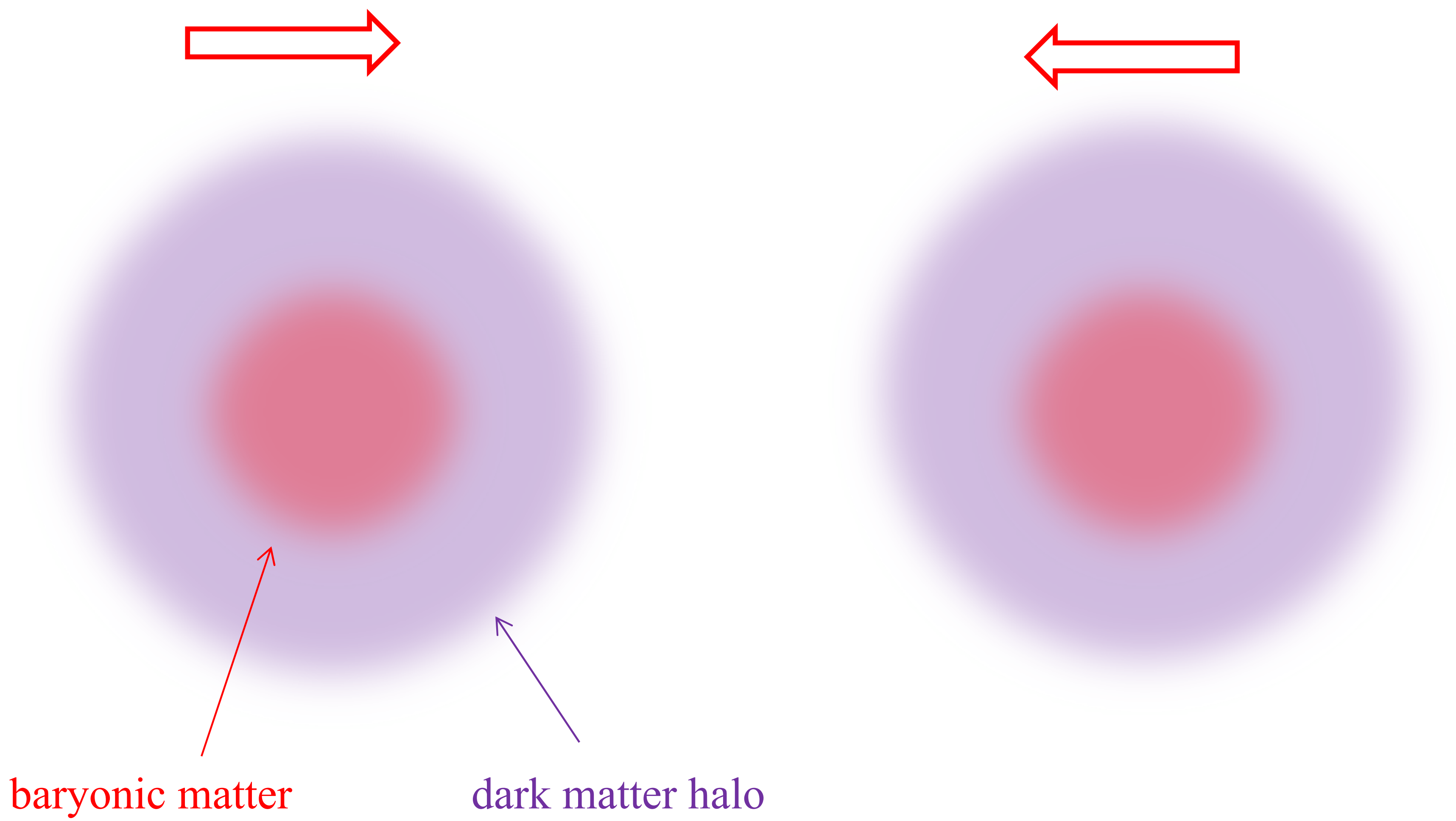


(observed luminous material, baryonic matter)

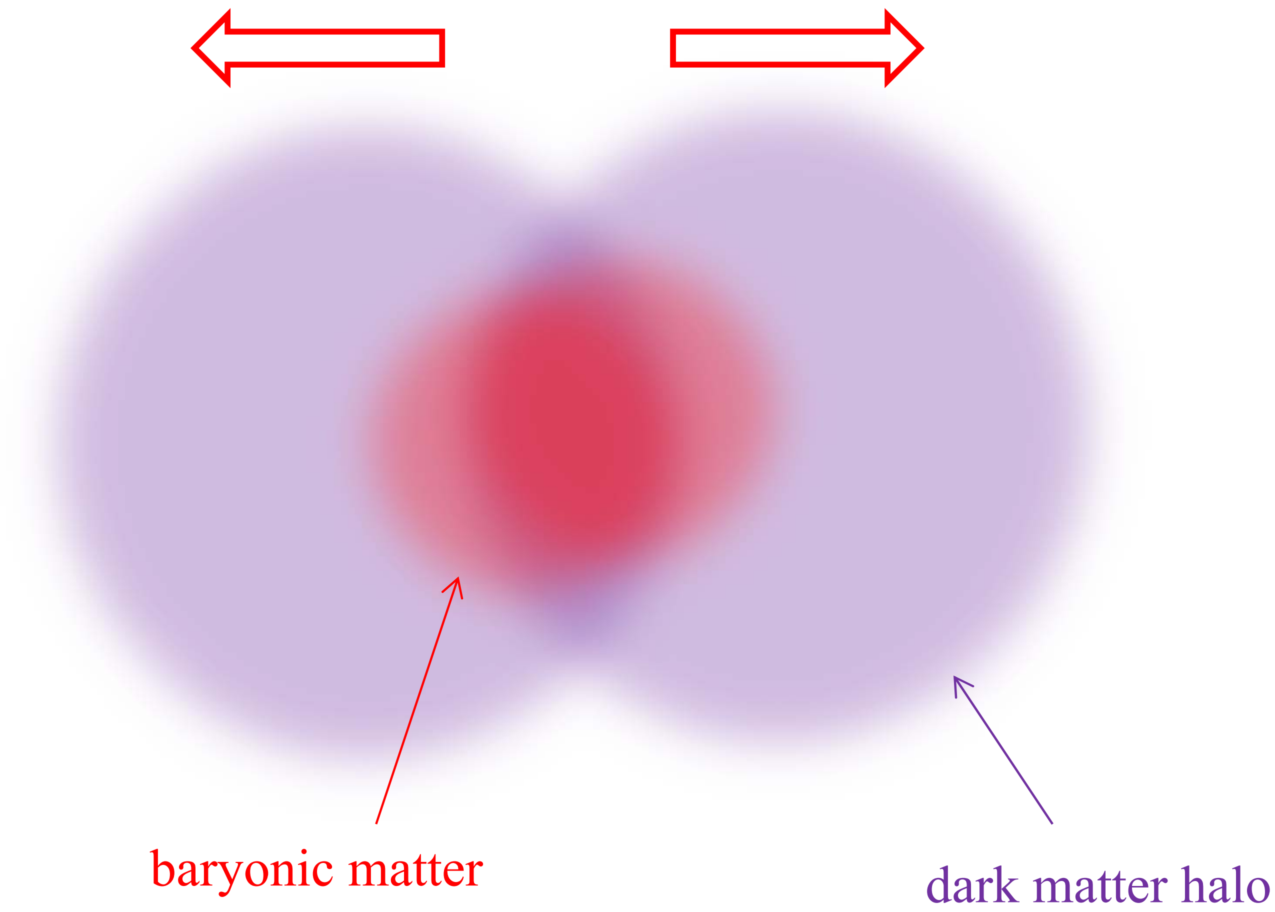
Dark Matter Exists – Galaxy Rotation Curve



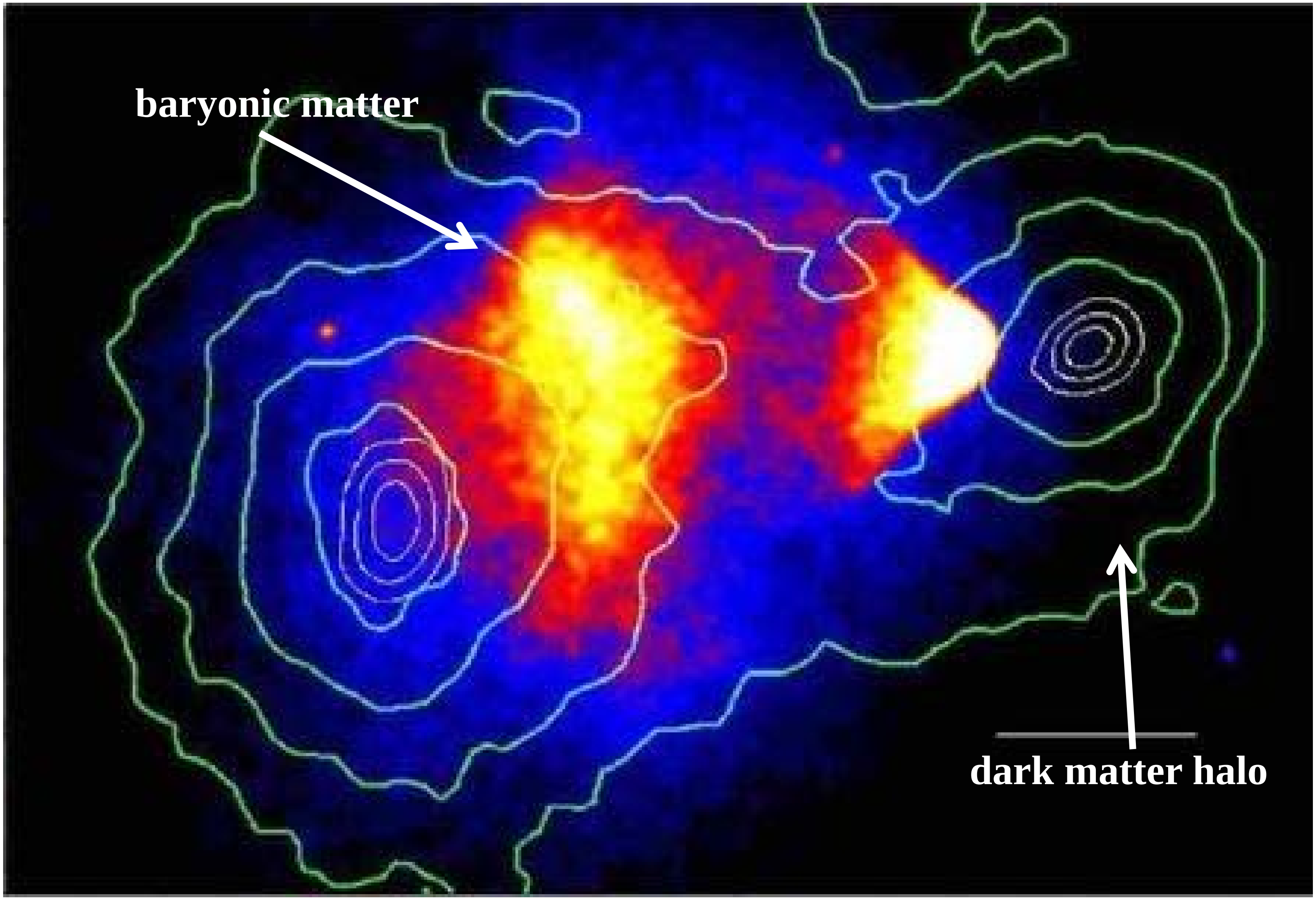
Dark Matter Exists – Bullet Cluster



Dark Matter Exists – Bullet Cluster



Dark Matter Exists – Bullet Cluster

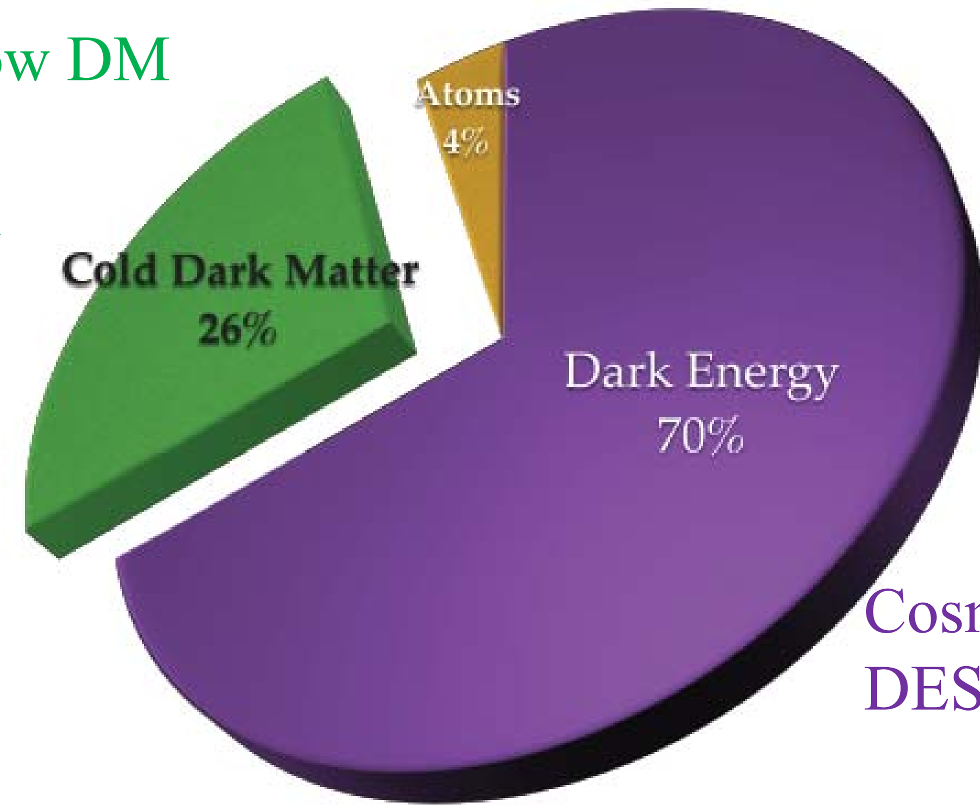


(NASA)

Dark Matter Overview:

We only understand
~4% of the Universe!

We only know DM
through its
gravitational
interaction!



Cosmological constant?
DES, DESI, eBOSS…

Local DM
energy density:

$$\rho_{DM} = 0.4\mathrm{GeV}/\mathrm{cm}^3$$

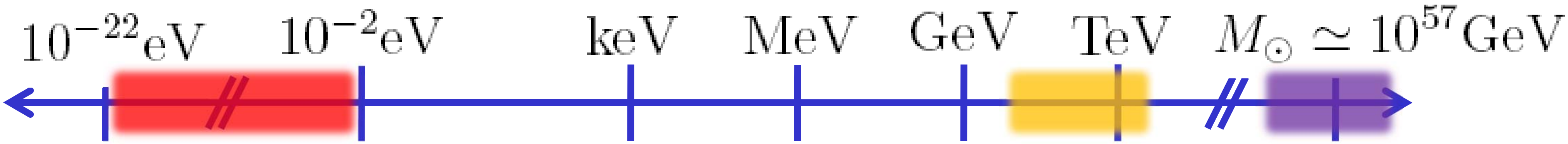
Local DM velocity:

$$v_{\mathrm{vir}} \sim 10^{-3}c$$

DM cannot be hot!

~~neutrinos~~

Popular Choices:



- WIMPs:

  100 GeV ~ TeV

- Very light DM particles

  Axion and Dark "Photon"

  10^{-22} eV ~ 10^{-2} eV

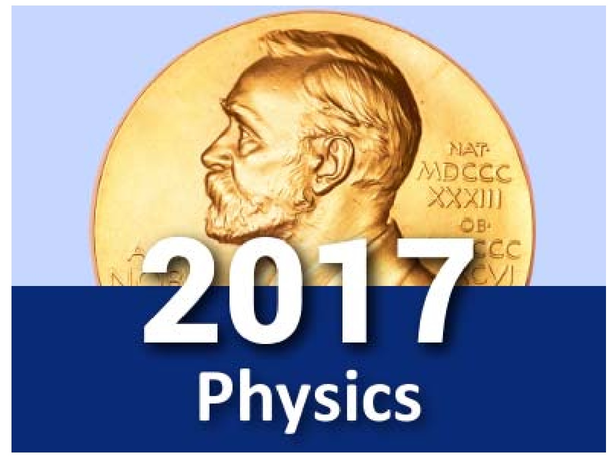
- Primordial Black Holes:

  10^{-7} ~ 100 solar mass

Both ultra-light and ultra-heavy scenarios
can be proved by GW detectors!

Laser Interferometer Gravitational-Wave Observatory

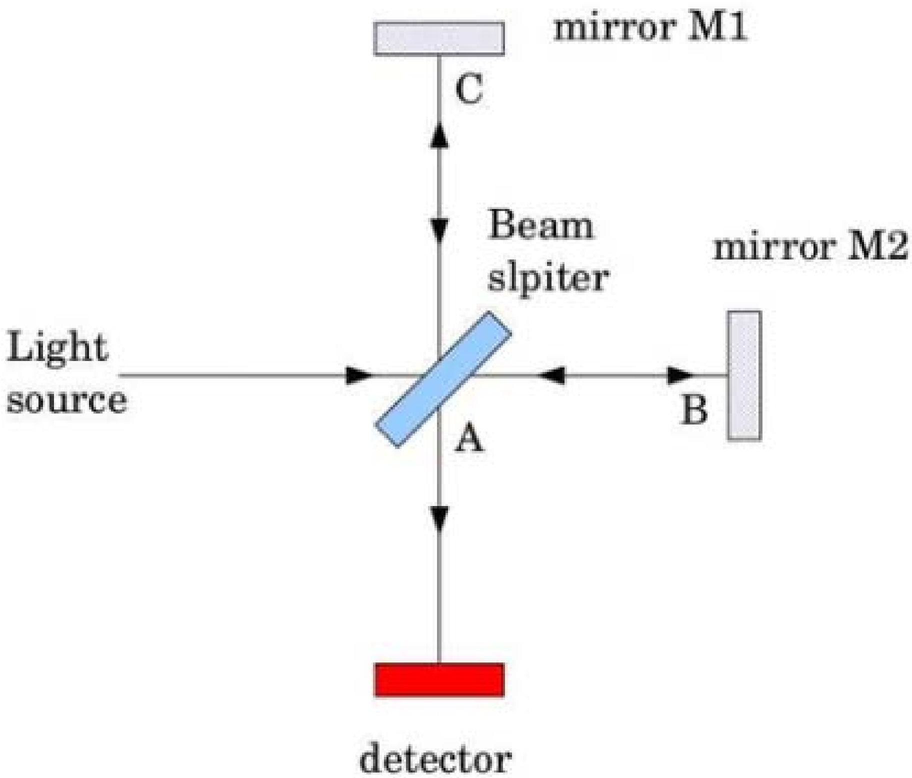
LIGO (ground-based)

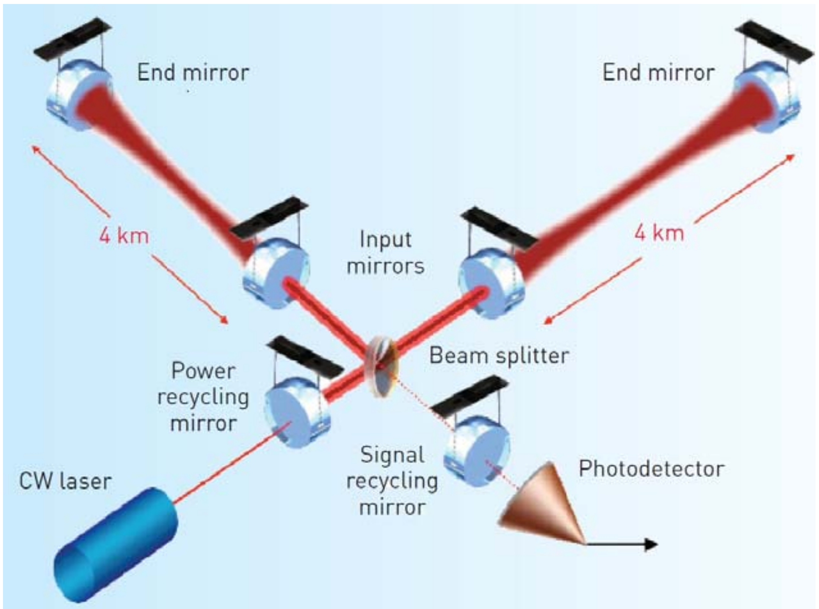


Opened a field:
Gravitational Wave Astronomy

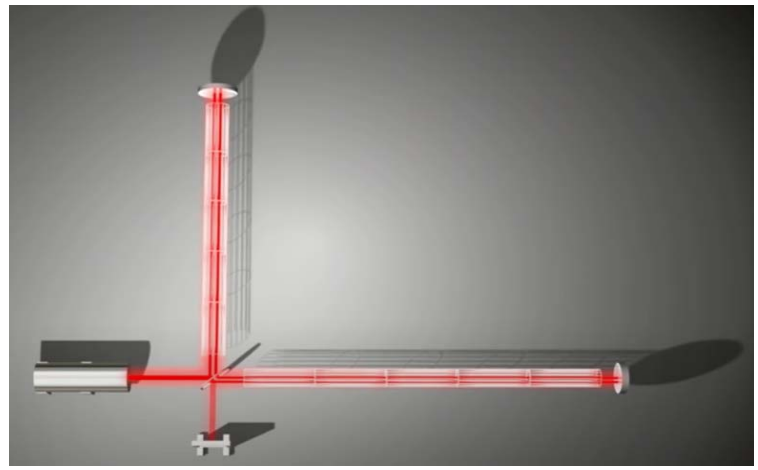
Enrich our understanding on fundamental physics and early cosmology.

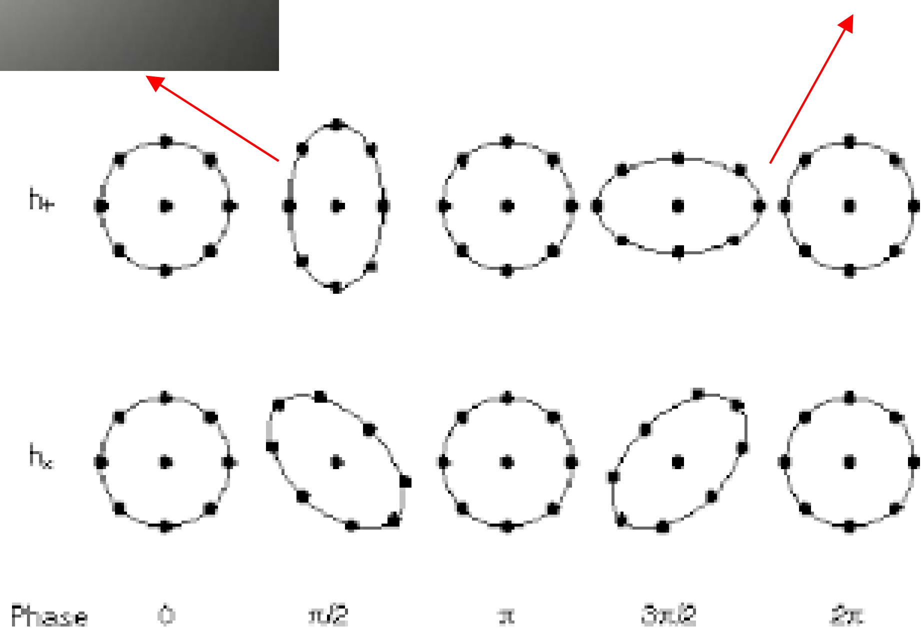
Michelson Morley experiment





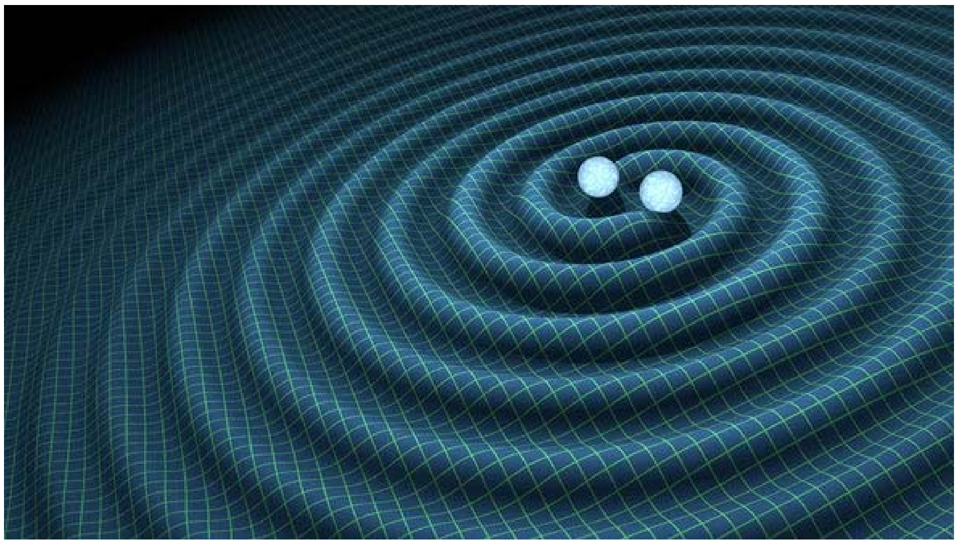
LIGO for GW detection

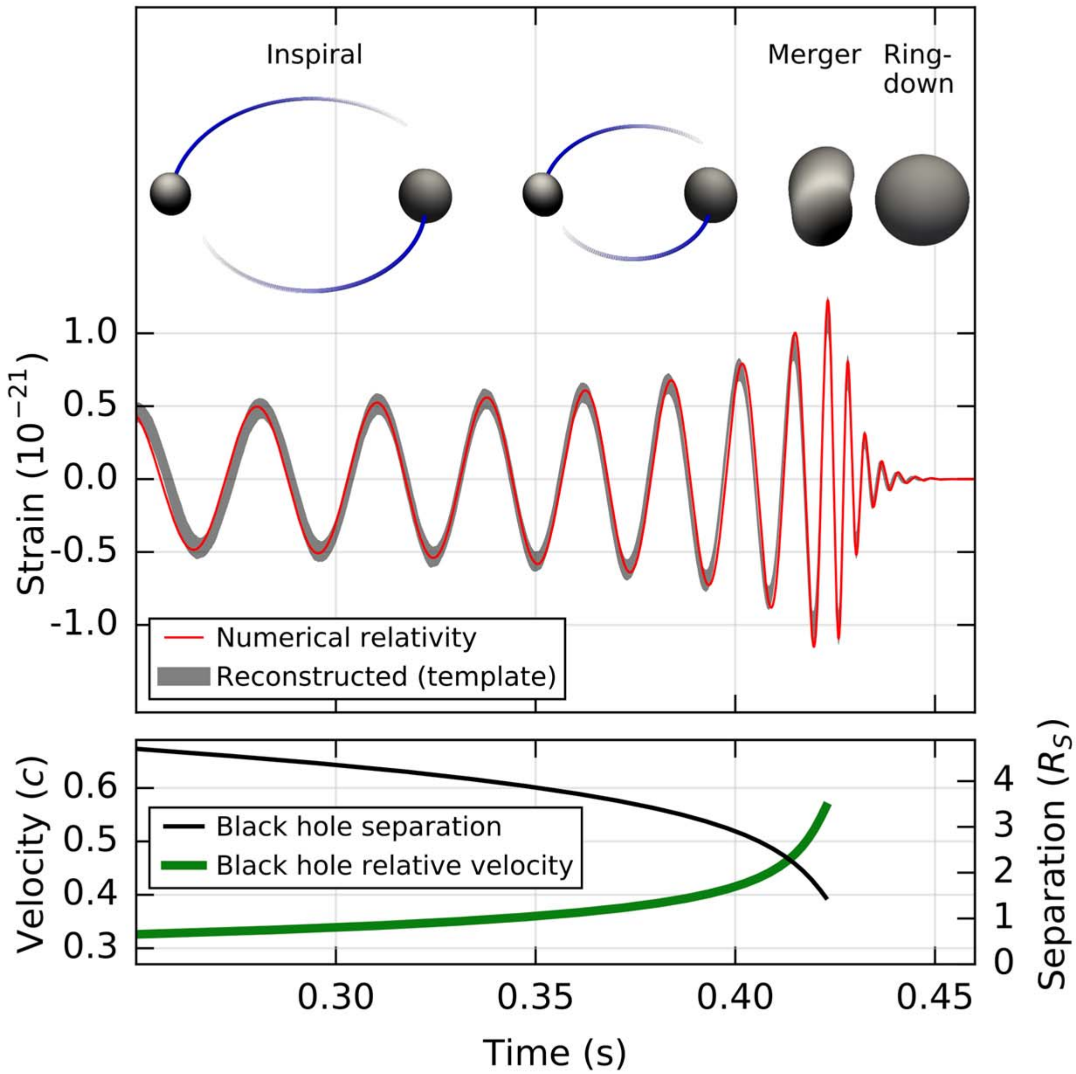




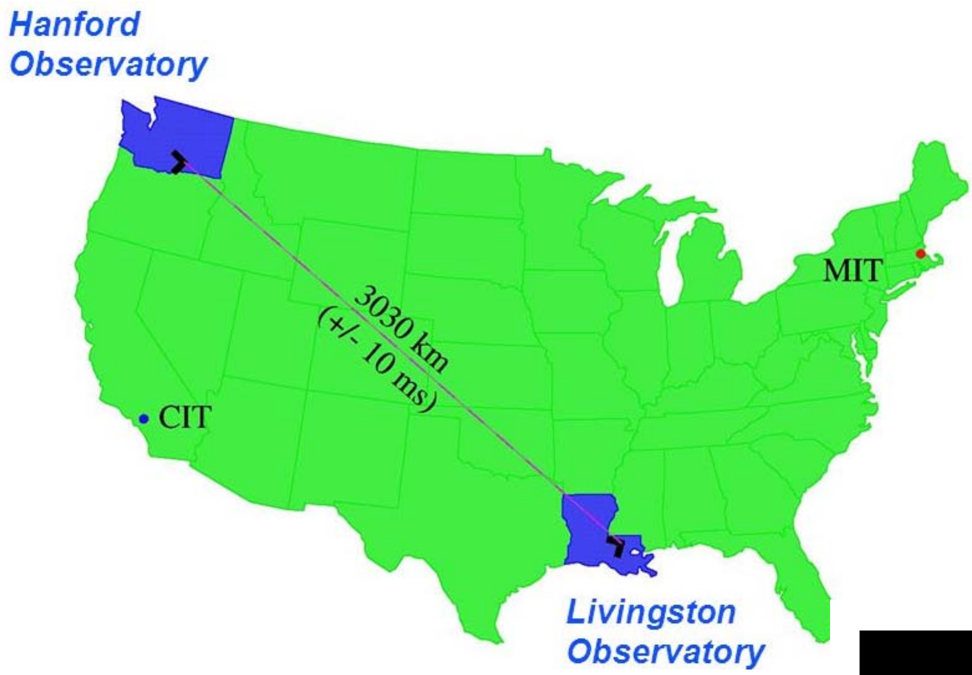
Amazing precision at LIGO: O(1/1000) the radius of a single proton!

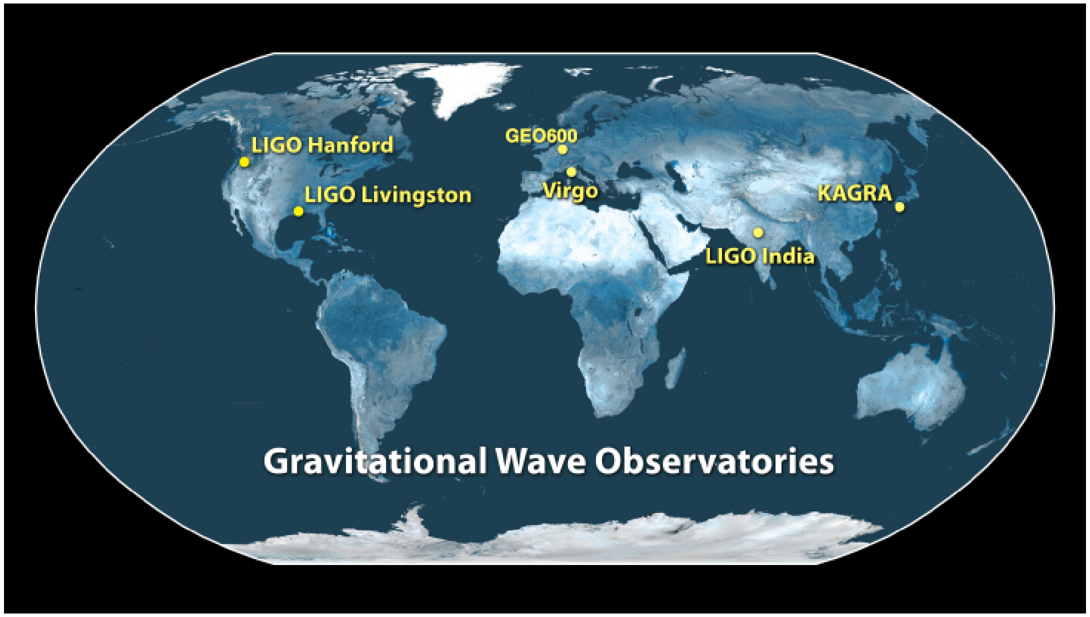
LIGO for GW detection





LIGO for GW detection





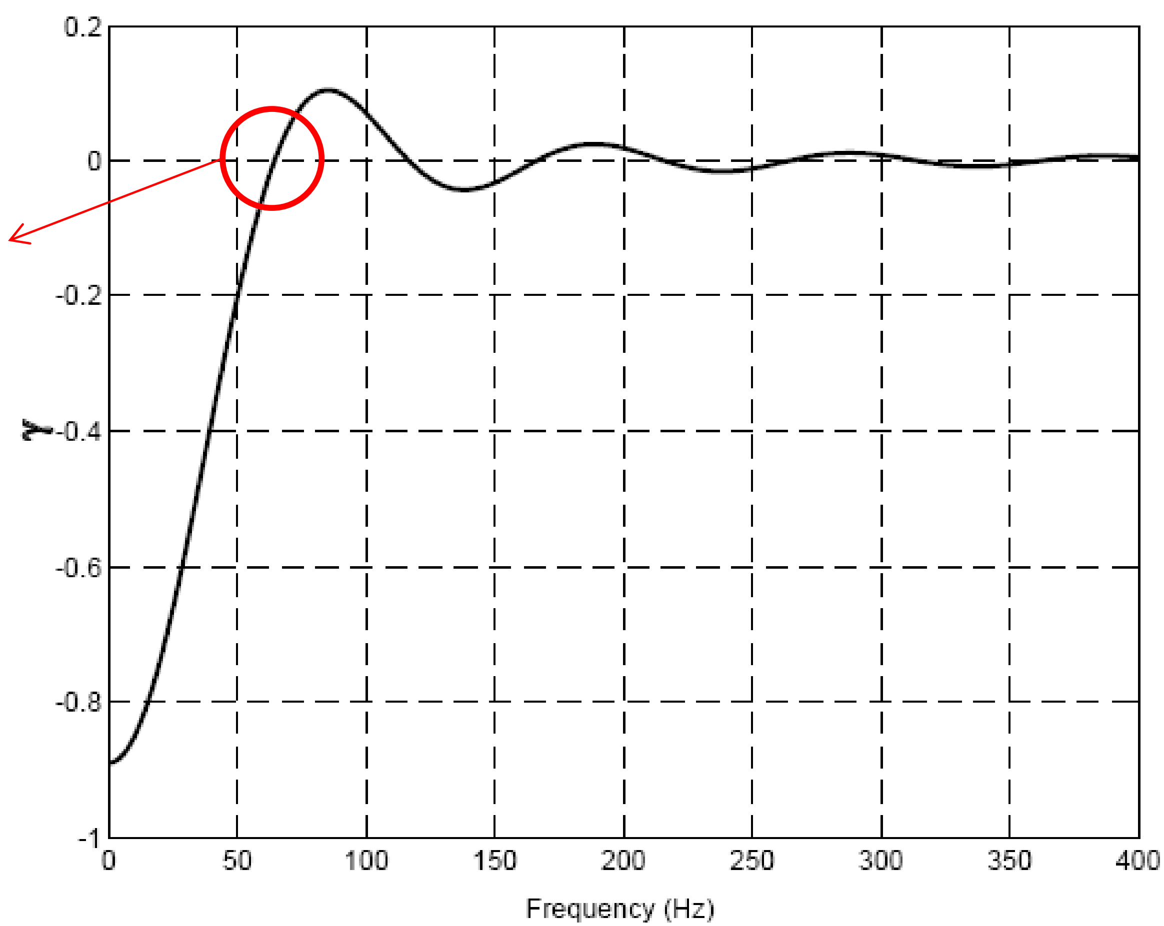
Sensitivity to DPDM signal of GW detectors:

Stochastic GW:

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

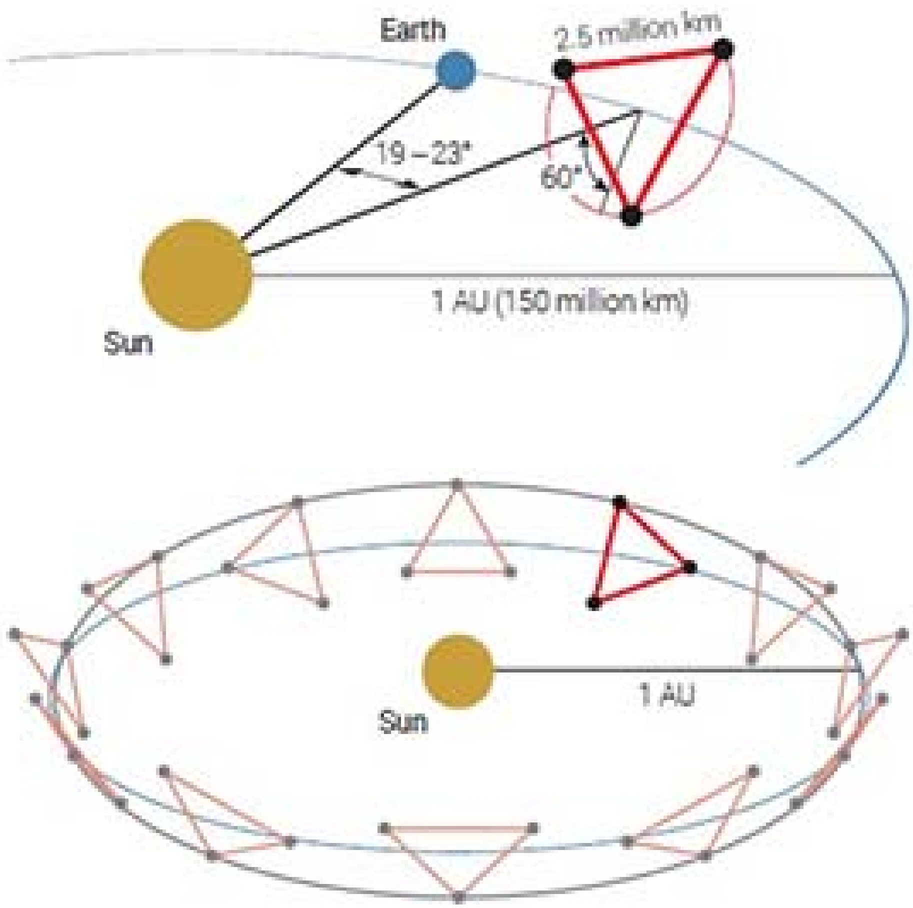
Signal correlation between two sites is lost when the separation is comparable to one wavelength.

LIGO



Laser Interferometer Space Antenna

LISA (space-based)



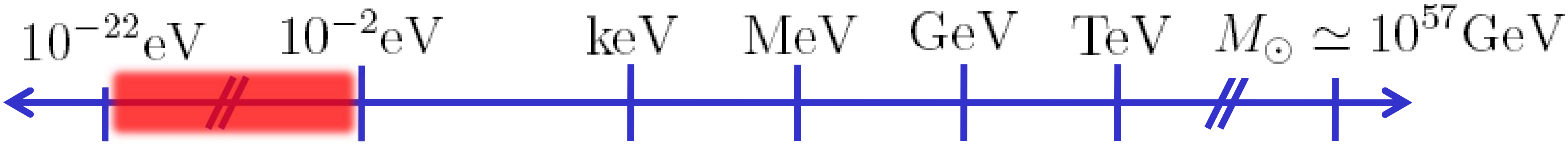
(LISA Mission Consortium)

Recently approved by the European Space Agency.

U.S. (NASA) just rejoined the program.

LISA PathFinder is a great success!

Popular Choices:



gauge boson of the

$U(1)_B$ or $U(1)_{B\text{-}L}$

(p+n) (n)

- Very light DM particles

  Axion and Dark "Photon"

  10^{-22} eV ~ 10^{-2} eV

DM is an oscillating background field.

$$\mathcal{S} = \int \mathrm{d}^{D-1}x\mathrm{d}t\mathcal{L}$$

$$= \int \mathrm{d}^{D-1}x\mathrm{d}t\left[\frac{1}{2}\eta^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - \frac{1}{2}m^2\phi^2\right]$$

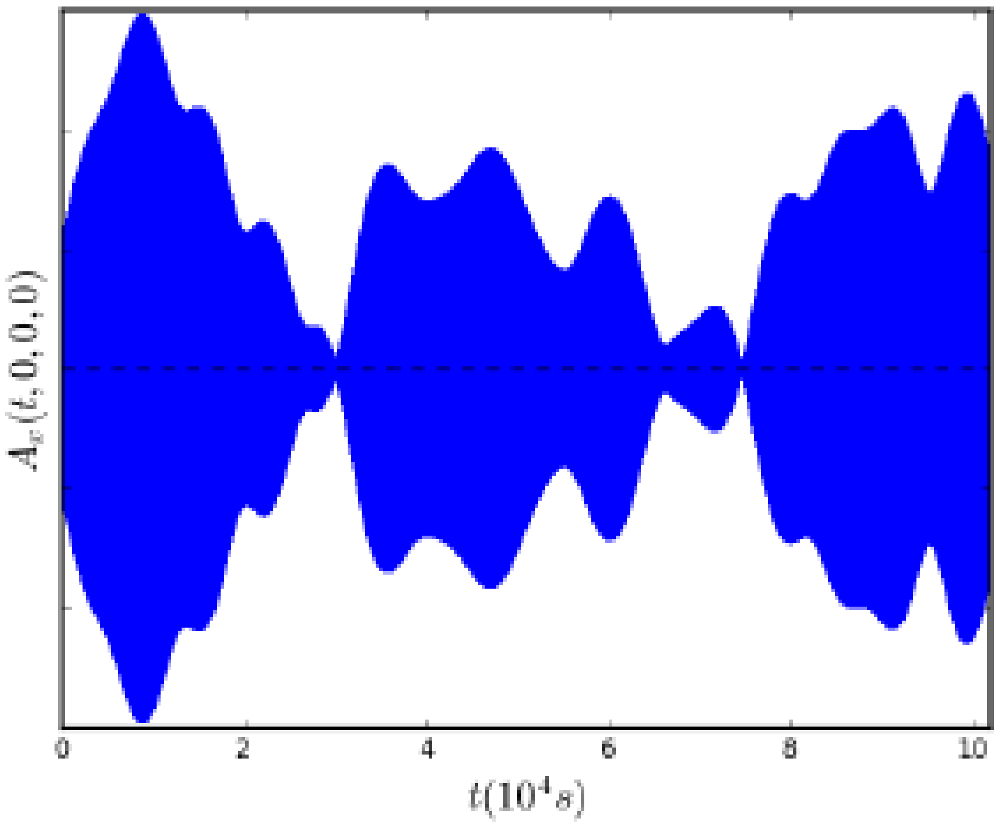
$$\partial_t^2\phi - \nabla^2\phi + m^2\phi = 0$$

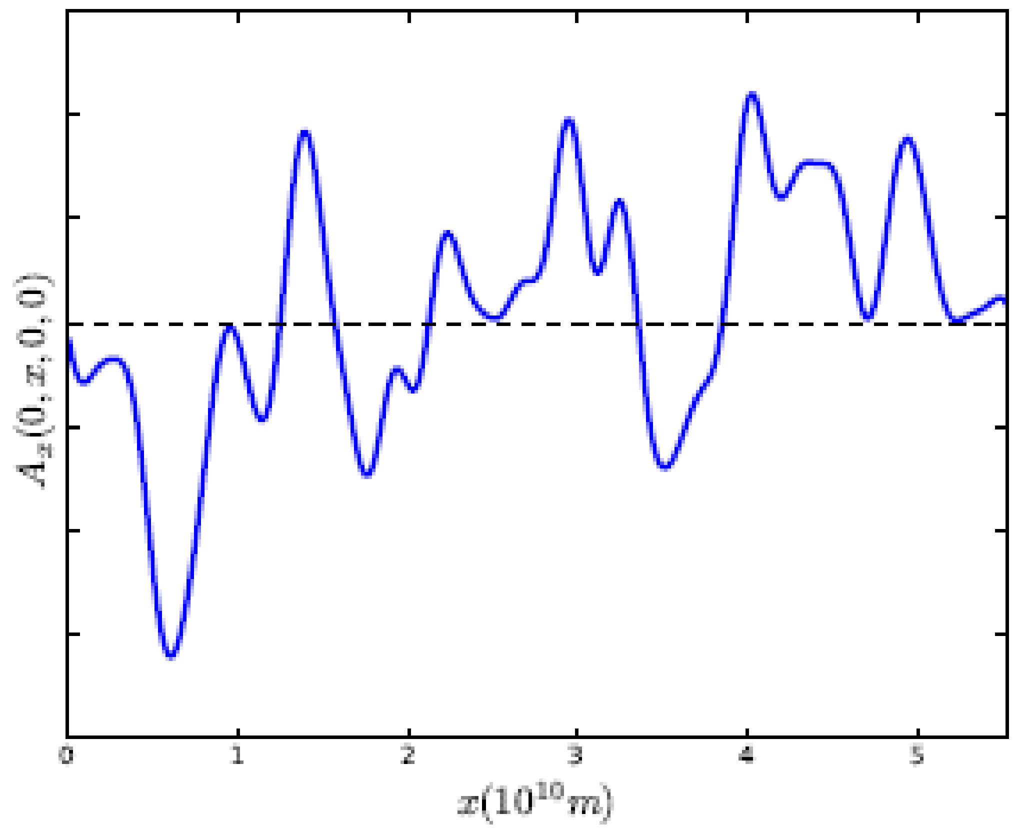
harmonic oscillator

Solution is a planewave.

Modeling DPDM background:

$$\vec{A}_{total}(t, \mathbf{x}) = \sum_{i=1}^{N} \vec{A}_{i,0} \sin(\omega_i t - \vec{k}_i \cdot \vec{x} + \phi_i)$$





Maximal Displacement:

Local DM energy density:

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

→ local field strength of DP →

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

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

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

Dark Photon is dominantly oscillating background dark electric field.

→

Driving displacements for particles charged under dark gauge group.

Maximal Displacement:

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

dark photon coupling

dark electric field

charge mass ratio of the test object

Silicon mirror:

$U(1)_B$: 1/GeV

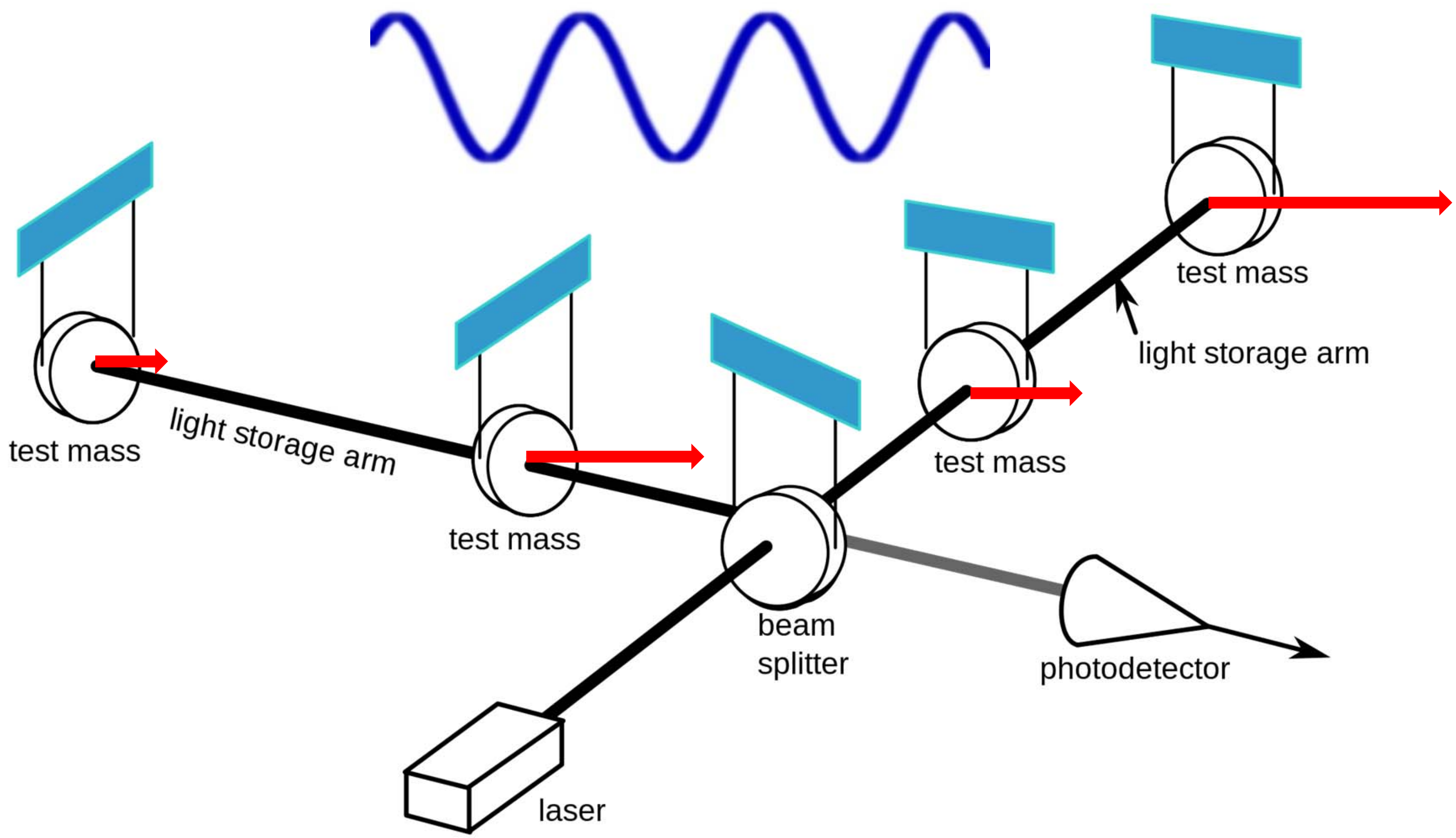
$U(1)_{B-L}$: 1/(2GeV)

projected along the arm direction

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

General Picture:

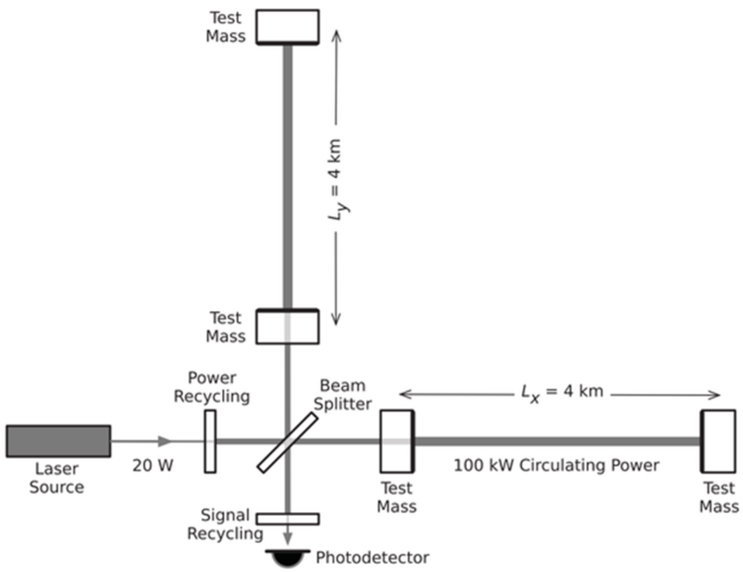
Ultra-light DM: coherent state ⇨ background classical radio wave

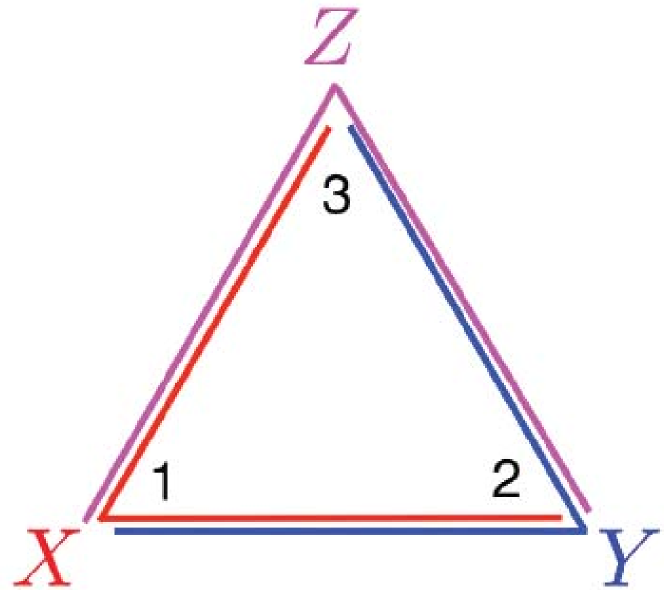


Dark photon dark matter moves mirrors. ⇨ Change photon propagation time between mirrors. ⇨ interferometer pattern

Maximal GW-like Displacement:

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





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

Compare this with the sensitivity on strain h.

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

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.

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.

Properties of DPDM Signals:

Signal:

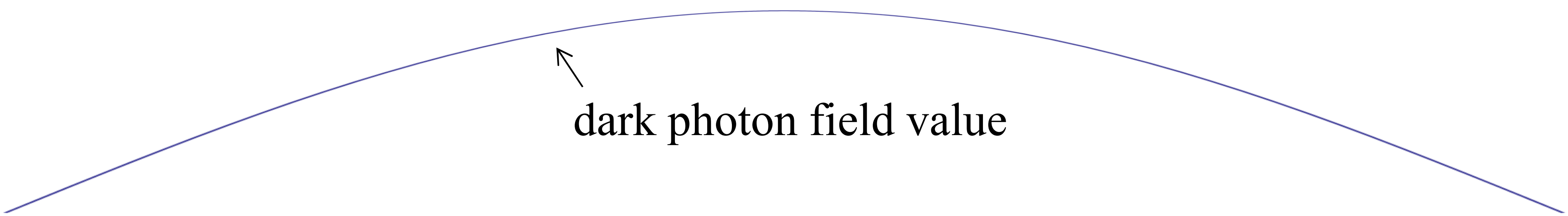
- very long coherent distance

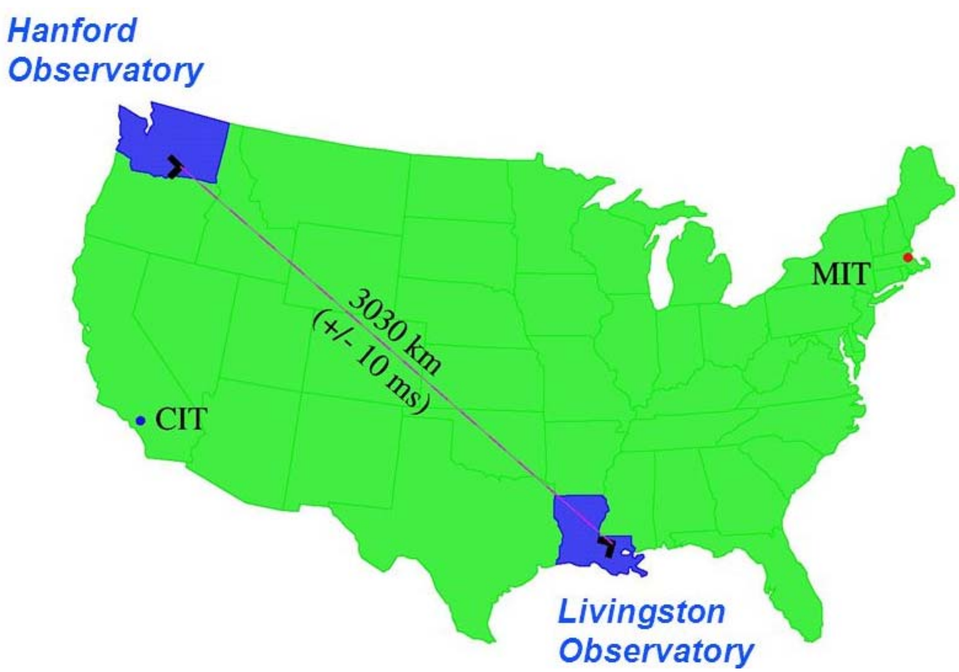
$$l_{coh} \simeq \frac{1}{m_A v_{vir}} \simeq 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f} \right)$$

Propagation and polarization directions remain constant approximately.

Properties of DPDM Signals:

Correlation between two sites is important to reduce background!





Due to long coherence length, signal is almost the same for both sites.

Sensitivity to DPDM signal of GW detectors:

First we estimate the sensitivity in terms of GW strain.

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

later map to ΔL/L

One-sided power spectrum function:

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

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

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

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

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)

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

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

optimal filter function
maximize SNR

one-sided strain noise power spectra

Sensitivity to DPDM signal of GW detectors:

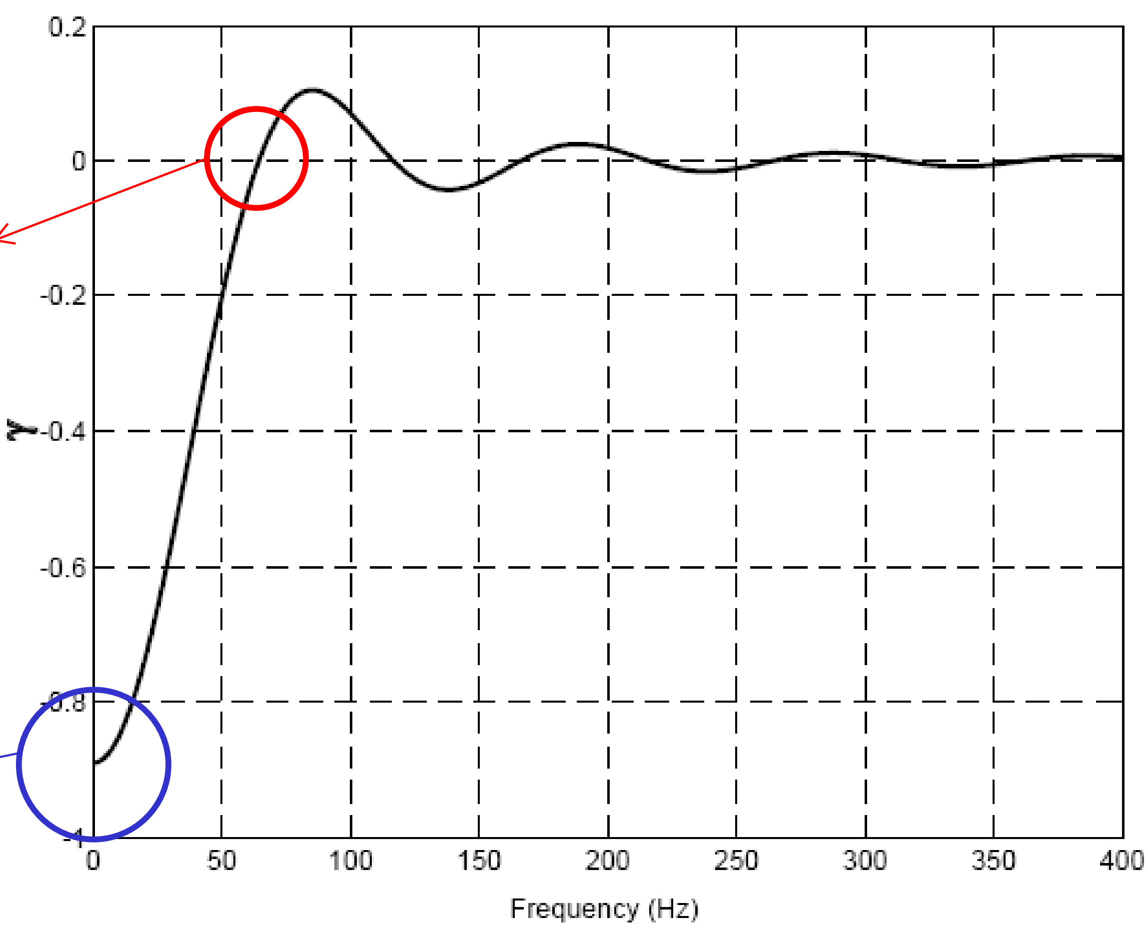
Stochastic GW:

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

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

DPDM correlation

LIGO

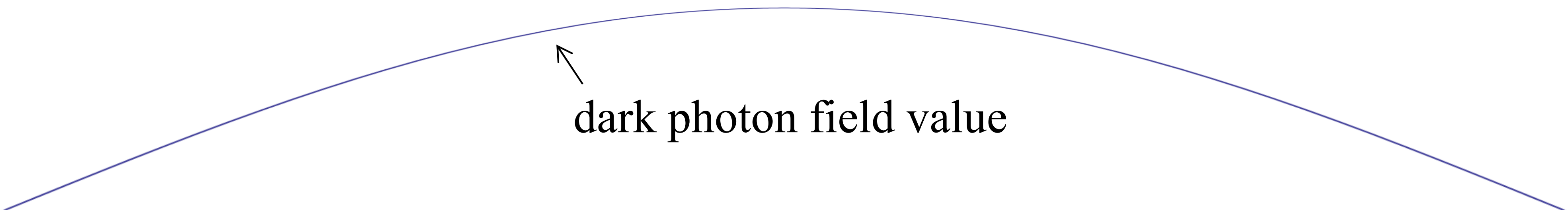


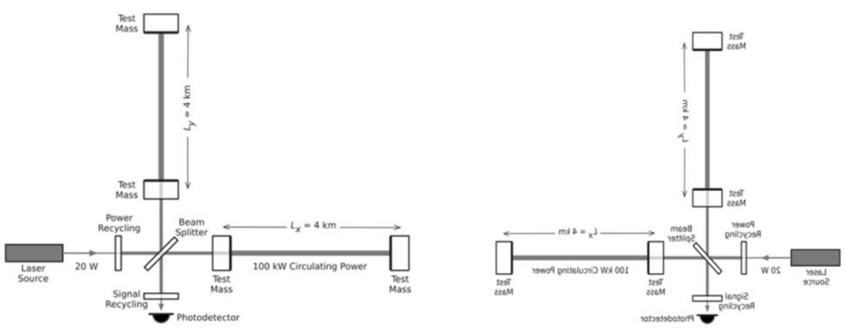
Sensitivity to DPDM signal of GW detectors:

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.

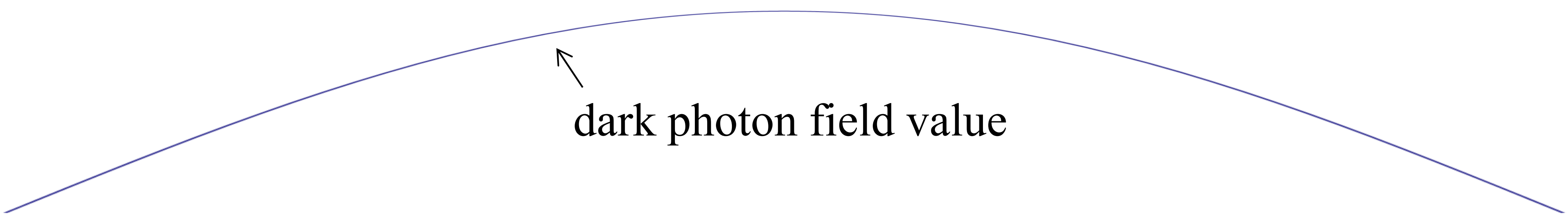
Sensitivity to DPDM signal of GW detectors:

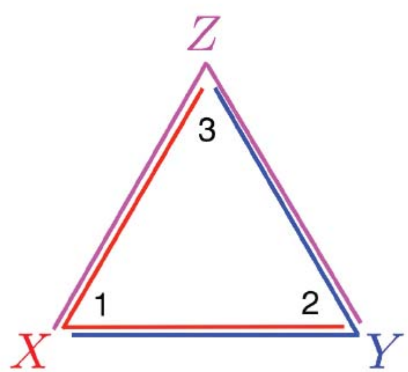
DPDM:

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:

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

effectively the max differential displacement of two arms

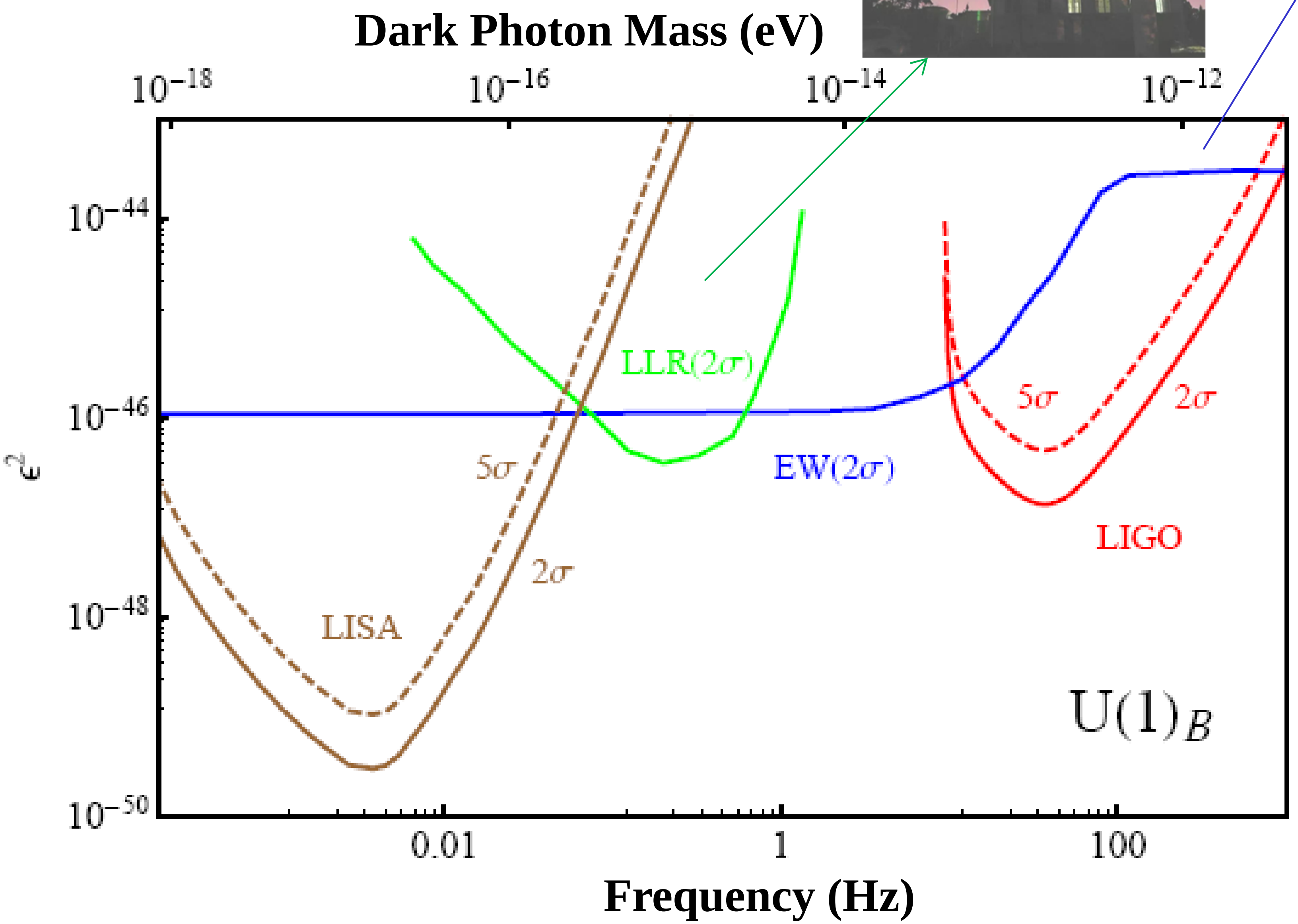
a GW with strain h ⇨ change of relative displacement as h

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

⇨ sensitivity of DPDM parameters (mass, coupling)

Sensitivity Plot:

(Eöt-Wash web)



Loránd Eötvös

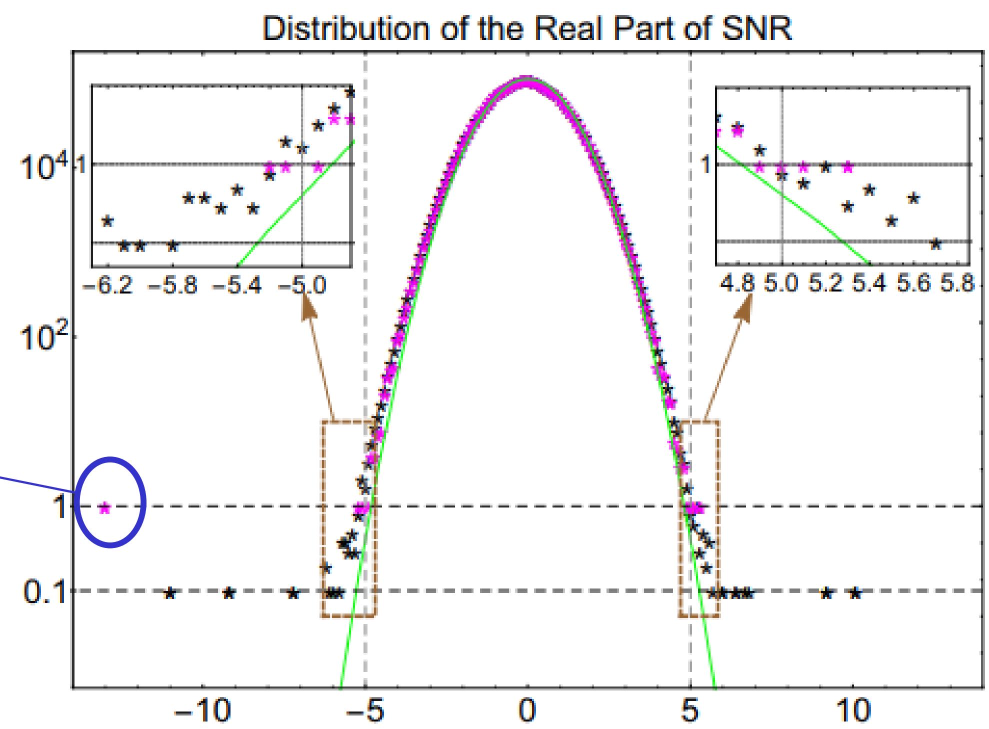
→ Eöt-Wash

design sensitivities, 2 yrs

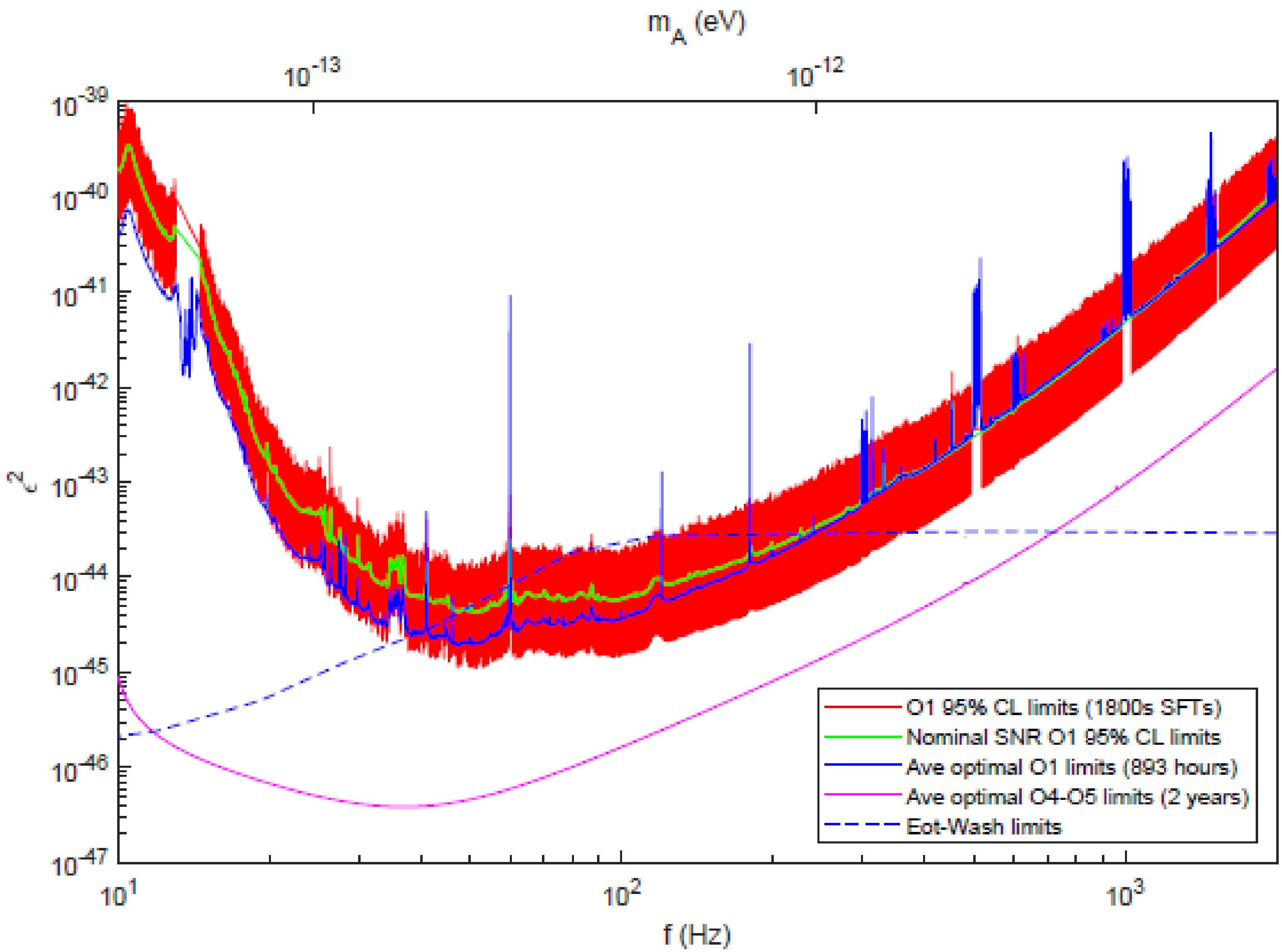
O1 Result:

- 1800s FT: optimized for a signal at f~500 Hz
- Remove known noise bins and their neighbor bins
- Within 10-2000 Hz frequency band, require Re[SNR] < −5.8
  ~ 1% false alarm probability after including trial factors.
- Frequency lags: to deal with non-Gaussian noise
  offset bins (−50, −40, ..., −10, +10, ..., +50)
  Remove single interferometer artifacts and broadband correlated artifacts

known continuous wave "hardware injections" with random phase

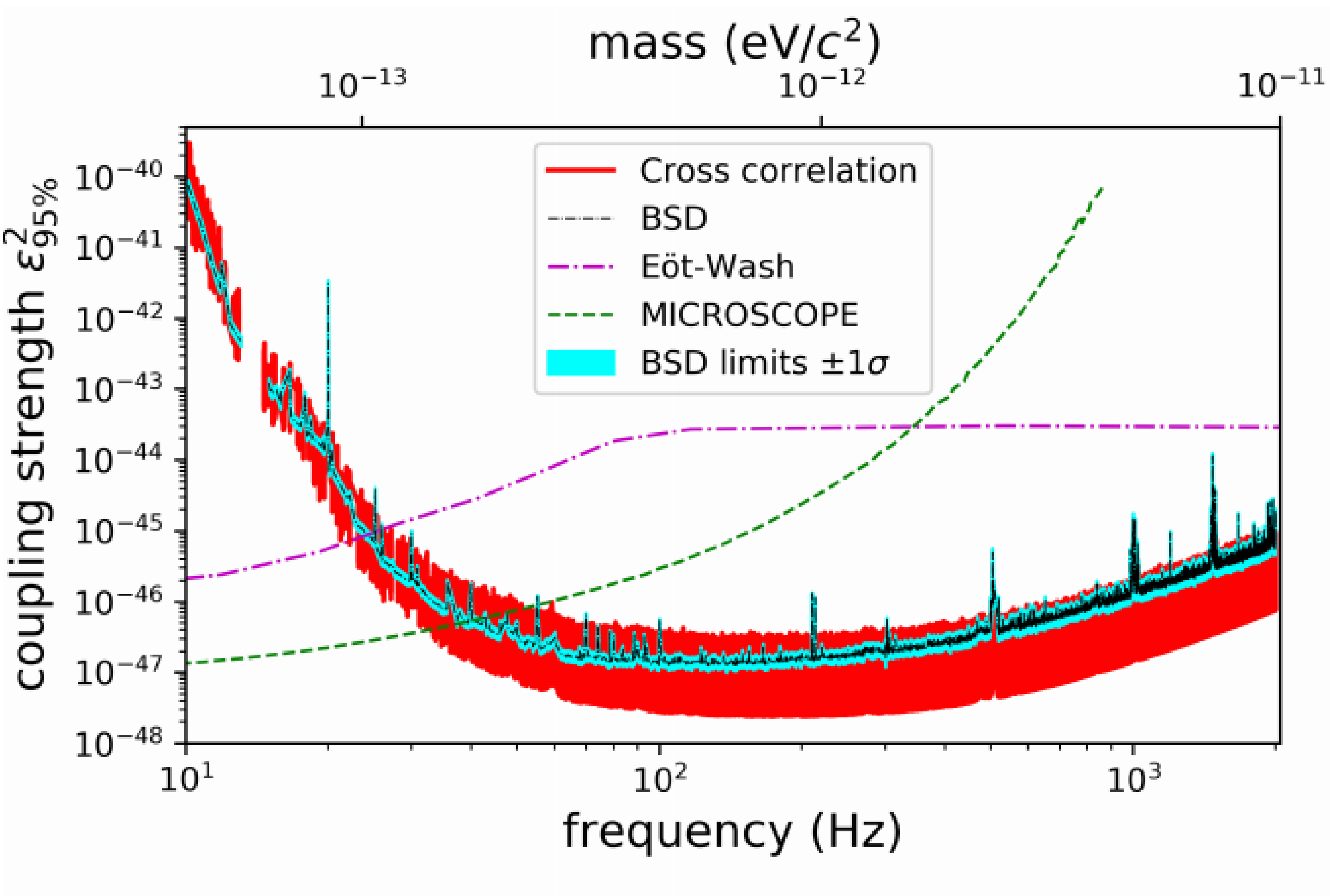


O1 Result:



m_A (eV)
10^{-13}
10^{-12}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
ϵ^2
10^1
10^2
10^3
f (Hz)
O1 95% CL limits (1800s SFTs)
Nominal SNR O1 95% CL limits
Ave optimal O1 limits (893 hours)
Ave optimal O4-O5 limits (2 years)
Eot-Wash limits

O3 Improvements:



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 achieve 5-sigma discovery at unexplored parameter regimes.

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