Gravitational Wave Measurement and wavelike axion searches with a Novel Mössbauer Spectrometer

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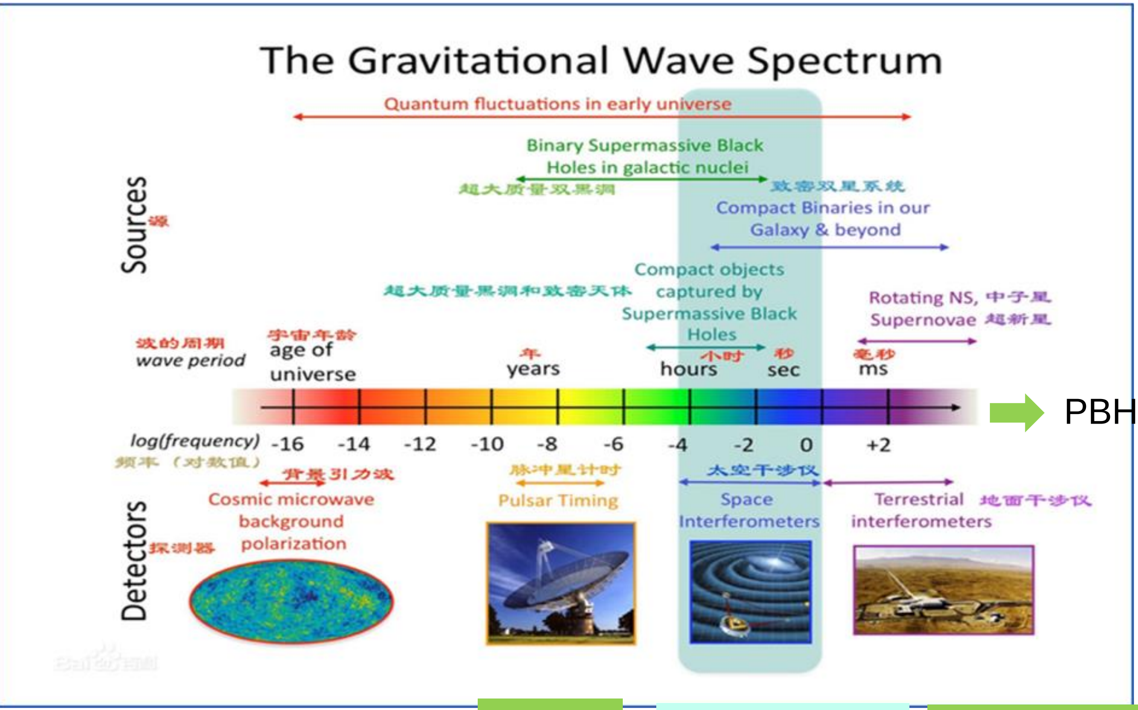
Outline

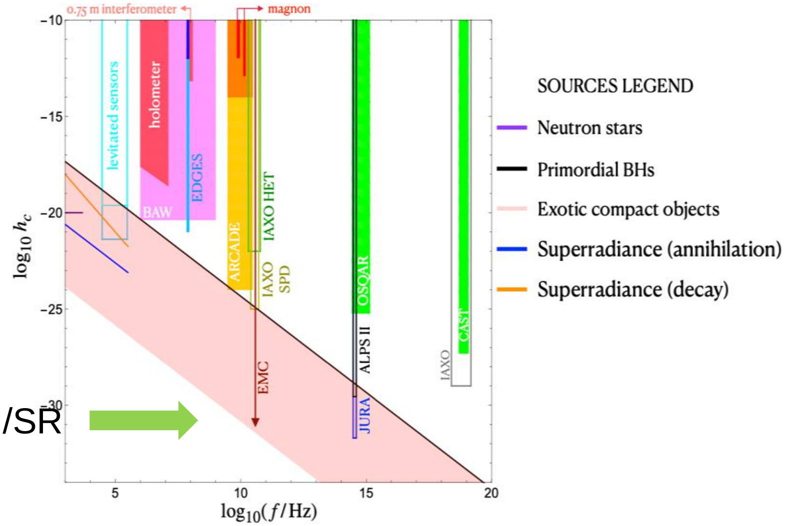
- Introduction
- How to achieve precision and speed needed for gravitational wave use novel Mossbauer Spectrometer
- Setup for Multi-band gravitational wave detection use this novel Mossbauer Spectrometer
- Sensitivity on wave like axion dark matter
- Summary and proposals

Gravitational Wave

GW：a new way to explore our universe



PBH/SR



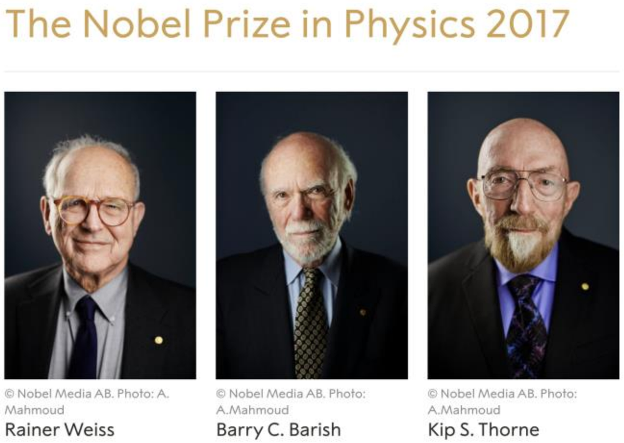
ALi

PTA
(Fast)

Taiji, Tianqin
Lisa

Ligo,Virgo
Kargra,ET…

Accuracy needed at the order of thickness
of a paper over the diameter of solar system



The Nobel Prize in Physics 2017

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Mössbauer effect

- Recoil-less emission and resonant absorption of nuclear transition photons
  - Mössbauer active nucleus bound to solid state lattice
  - Thermal vibration(~10^{13} Hz) much faster than nuclear transitions (lifetime ~>10^{-7} s)
    - Effect averages to zero, no 1st Doppler broadening
    - Recoil to the whole crystallite(>10^{14} atom)
    - Without phonon excitations➔ recoil free

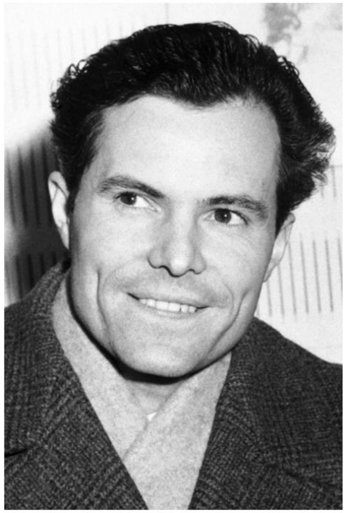
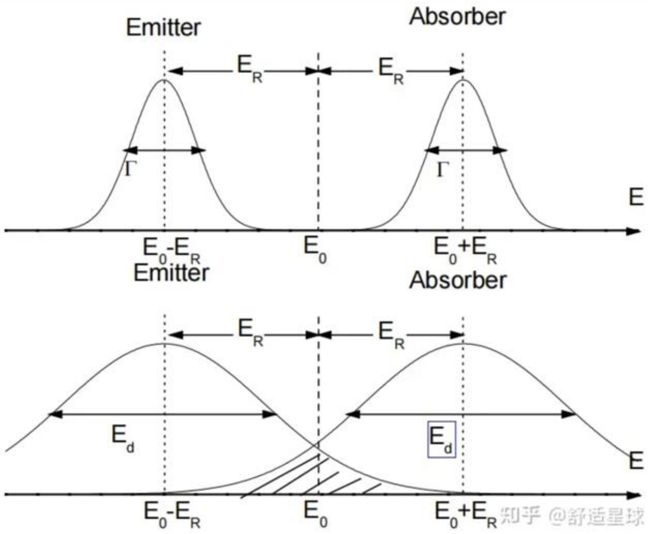
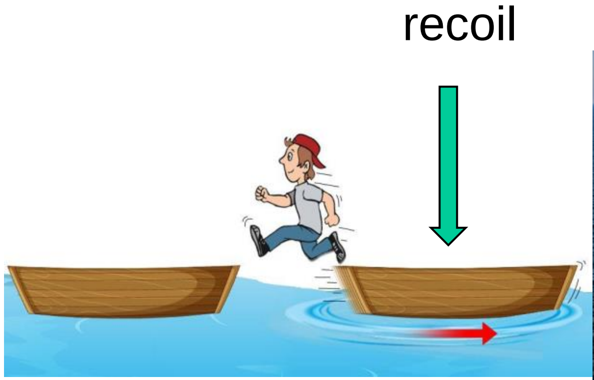


Photo from the Nobel Foundation archive.

Rudolf Ludwig Mössbauer

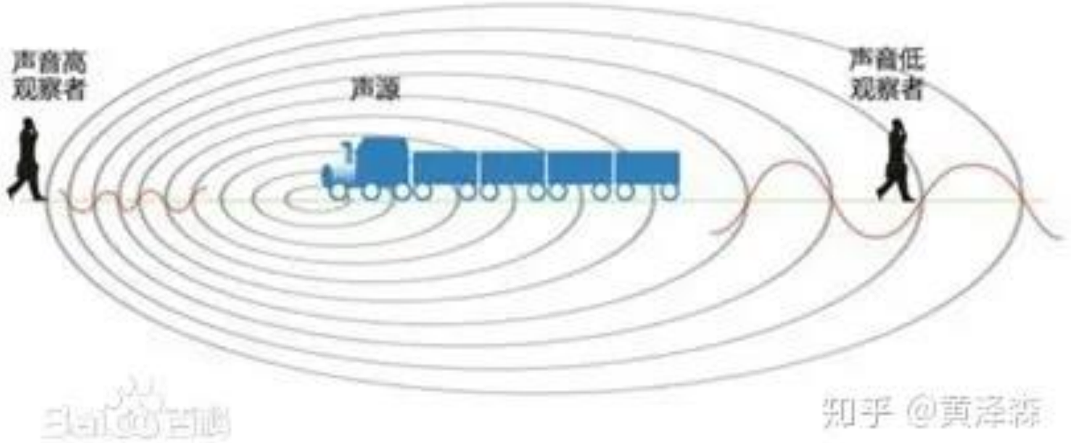
Prize share: 1/2



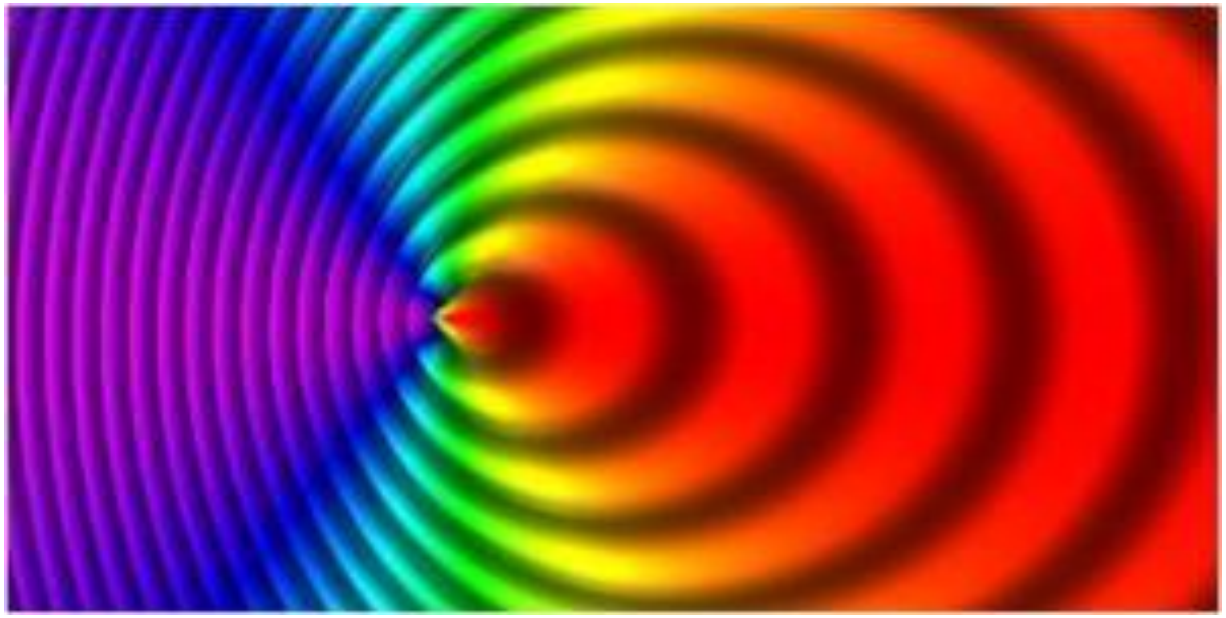


Doppler shift

- Sound

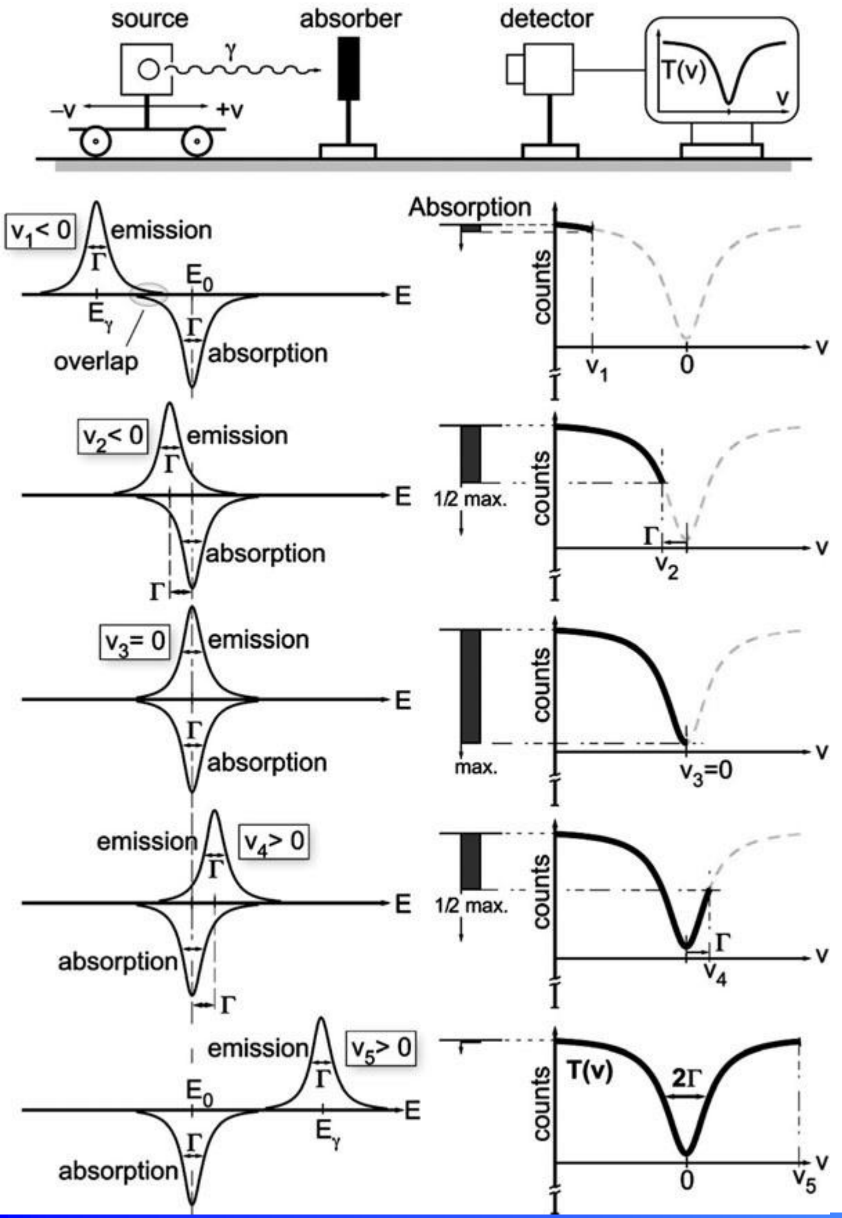


- Photon：E=hv



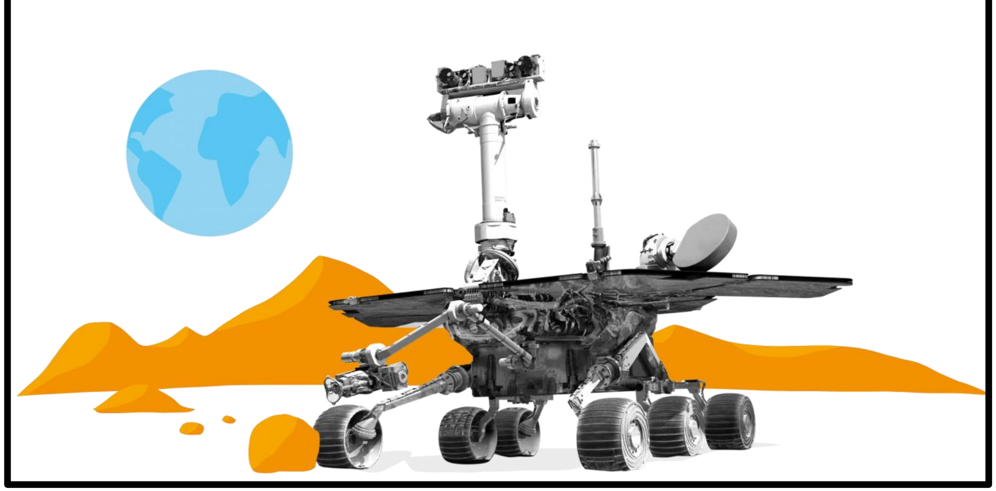
Red shift

“Traditional” Mössbauer Spectrometer



- Change the recoil-less emission and absorption overlap with doppler effects
- Strength of recoilless nuclear resonant absorption as determined by the “overlap” of emission and absorption lines when the emission line is shifted by Doppler modulation
- High accuracy of the resonant absorption width w.r.t. photon energy

Widely used in material science, chemistry, and even on mars rovers

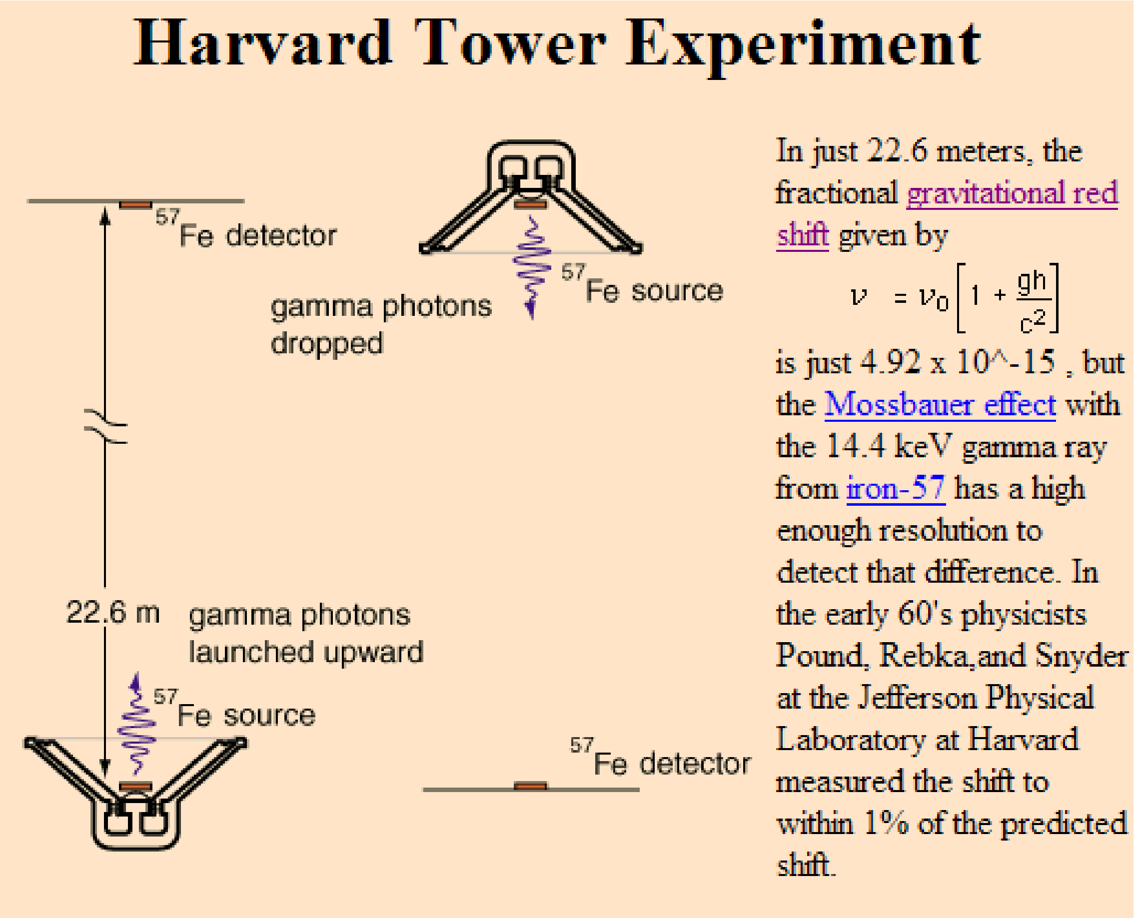


Relativity test with Mössbauer effect

- Gravitational redshift test with Mössbauer effect

Jefferson laboratory at Harvard University. The experiment occurred in the left "tower". The attic was later extended in 2004.

Pound, Rebka & Snyder (1960-1965)



Harvard Tower Experiment

In just 22.6 meters, the fractional gravitational red shift given by

$$\nu = \nu_0 \left[1 + \frac{gh}{c^2} \right]$$

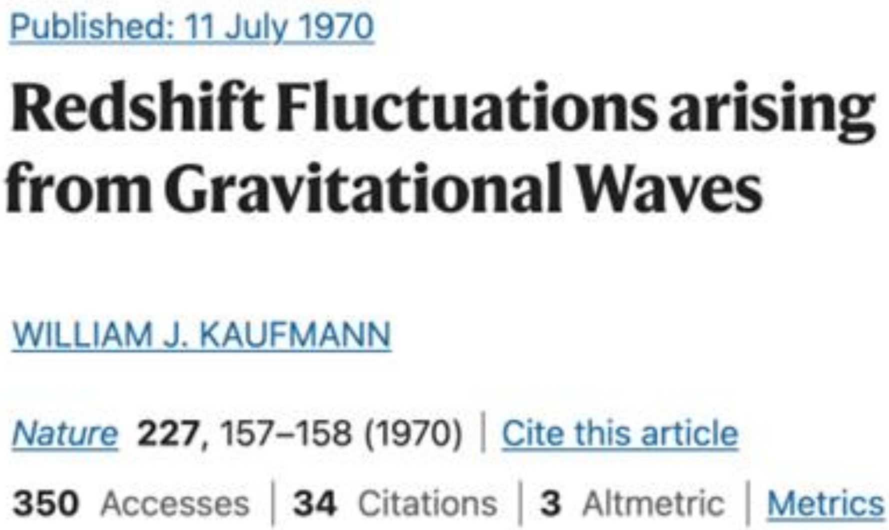
is just 4.92 x 10^-15 , but the Mossbauer effect with the 14.4 keV gamma ray from iron-57 has a high enough resolution to detect that difference. In the early 60's physicists Pound, Rebka,and Snyder at the Jefferson Physical Laboratory at Harvard measured the shift to within 1% of the predicted shift.

Observation of a height-induced frequency shift

$$ghc^{-2} \sim 4.92 \times 10^{-15}$$

Mössbauer for Gravitational Wave

- Idea since 1970
  - Photon frequency varies when it propagates in an uneven space-time background.
  - No experimental proposal till our work
- Gave way to clock-based experiments in later tests of "static" gravity.
  - See K. Hentschel, *Annals of Science* 53, 269–295 (1996)



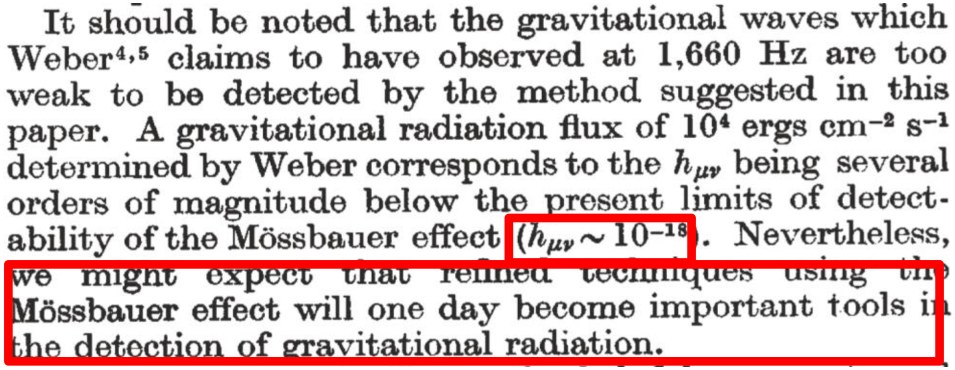
Published: 11 July 1970

Redshift Fluctuations arising from Gravitational Waves

WILLIAM J. KAUFMANN

Nature **227**, 157–158 (1970) | Cite this article

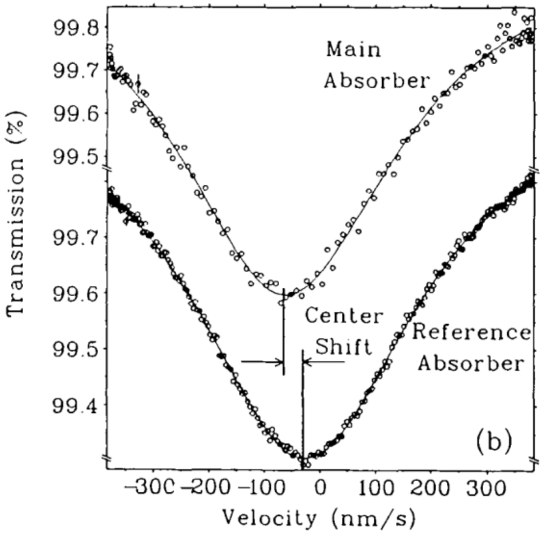
350 Accesses | **34** Citations | **3** Altmetric | Metrics

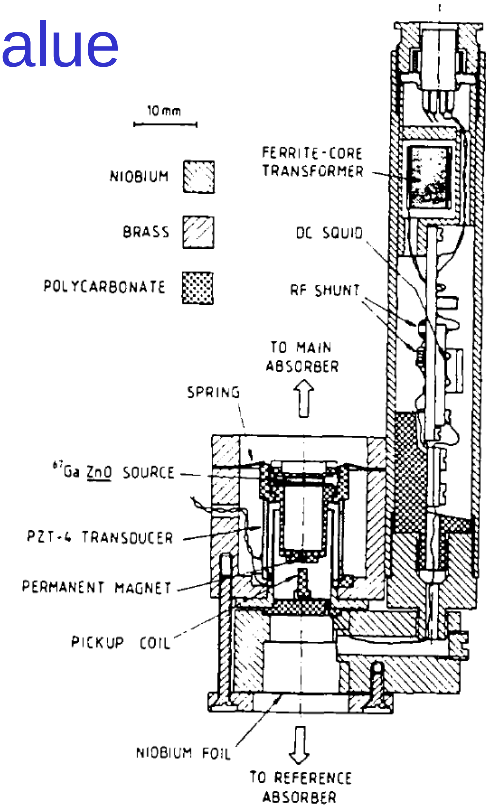


It should be noted that the gravitational waves which Weber[4,5] claims to have observed at 1,660 Hz are too weak to be detected by the method suggested in this paper. A gravitational radiation flux of 10^4 ergs cm^{-2} s^{-1} determined by Weber corresponds to the $h_{\mu\nu}$ being several orders of magnitude below the present limits of detectability of the Mössbauer effect ($h_{\mu\nu} \sim 10^{-18}$). Nevertheless, we might expect that refined techniques using the Mössbauer effect will one day become important tools in the detection of gravitational radiation.

Issues in traditional Mössbauer Gravity tests

- A cryogenic ^{65}Zn measurement of the local *g*-value
  (Potzel et.al. 1992)
- Differential measurement of the resonance with a sinusoidal oscillator
  - Resonance is achieved
  - g-value is off, possibly due to various line-shifts
  - Take hours-days to achieve high acc.





Can be improved with
a stationary scheme:
Quoted from the paper

"such solid-state effects might be difficult …… there might exist two exceptions. The first are <u>null redshift experiments</u>, in particular measurements with stationary source and absorber".

Idea of the stationary measurement

- Doppler shift ==> Gravitational shift

$$\boxed{1+z=\frac{1+v\cos(\theta)/c}{\sqrt{1-v^2/c^2}}}$$

V=1mm/s ➔ ~10^{-12}

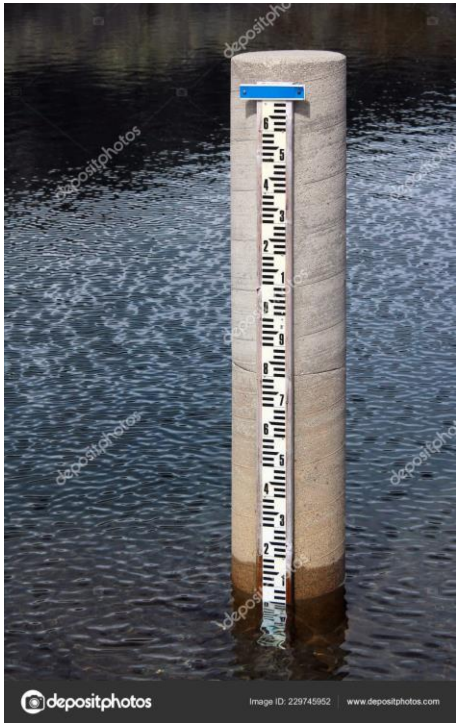
$$\boxed{1+z=\frac{1}{\sqrt{1-\frac{2GM}{rc^2}}},}$$

△ h<<r

$$\boxed{\frac{\delta E}{\mathrm{E}}=z=\frac{g}{c^2}*\triangle h}$$

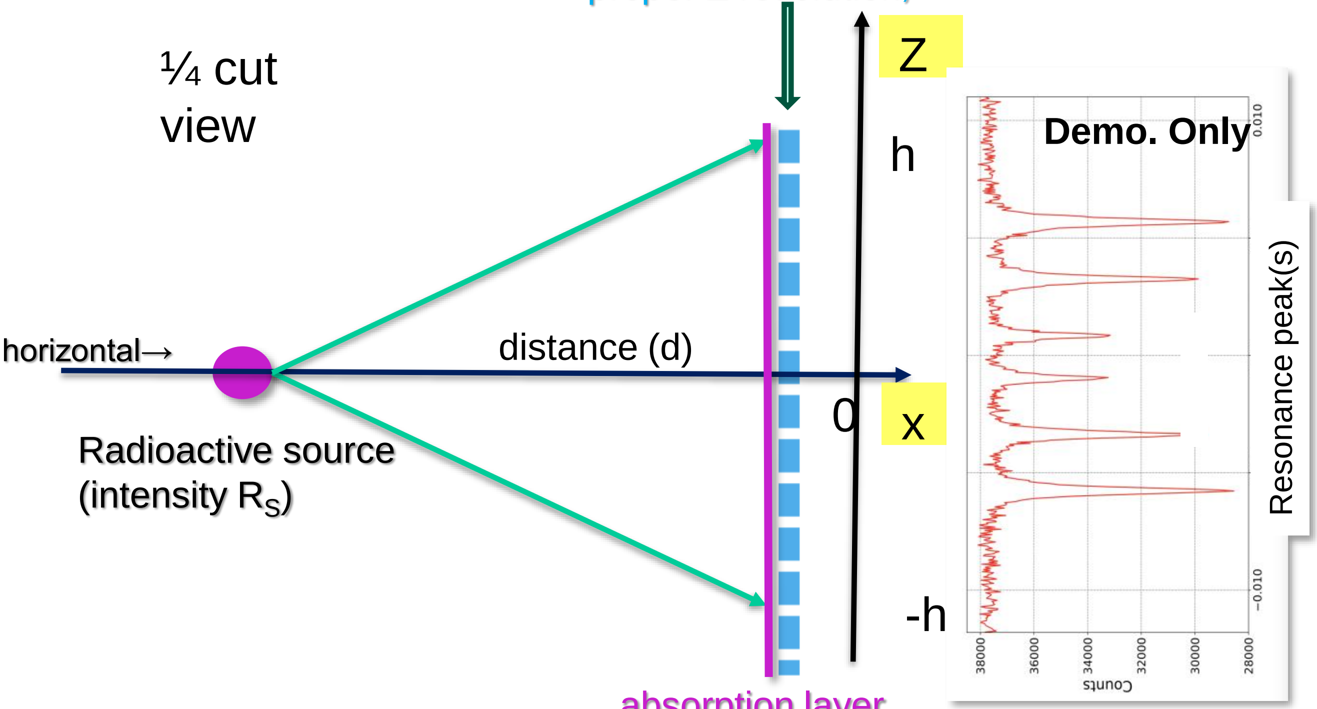
△ h = 1mm ➔ ~10^{-19}

Improve on sensitivity to energy shift



Design of a gravitational shift Mössbauer Spectrometer

- Replace Doppler shift with gravitational shift
- Parallel readout the resonant absorption shape
- Time dependent resonance's *height-shift*（not absolute height）
  - Frequency of resonance peak hight shift ➔ GW frequency: multi-band

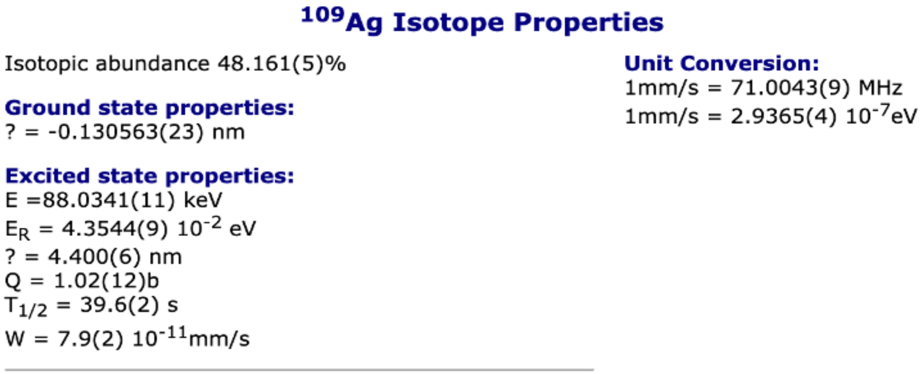


Energy loss E_R is compensated by a slight height difference between absorber and source: *can be calibrated in advance.*

--- the absolute height of resonance (Z_0) is affected by large systematics: 2nd Doppler, chemical composition, etc.

--- but its time-dependent shift under GW is *not* affected.

The choice of isotope source: ^{109}Ag



^{109}Ag Isotope Properties

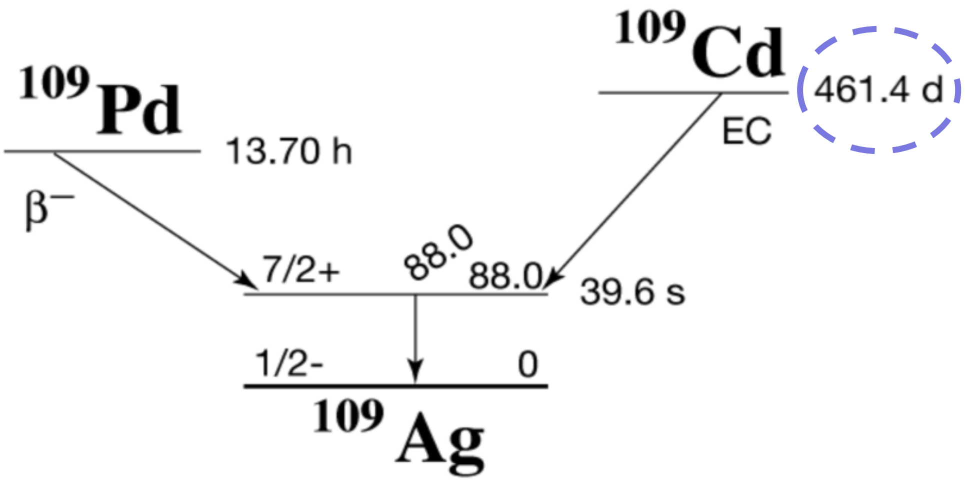
Isotopic abundance 48.161(5)%

Ground state properties:
? = -0.130563(23) nm

Excited state properties:
E =88.0341(11) keV
E_R = 4.3544(9) 10^{-2} eV
? = 4.400(6) nm
Q = 1.02(12)b
$T_{1/2}$ = 39.6(2) s
W = 7.9(2) 10^{-11}mm/s

Unit Conversion:
1mm/s = 71.0043(9) MHz
1mm/s = 2.9365(4) 10^{-7}eV

Decay Diagram



Mössbauer database (DICP, CAS)

- Narrow 88 keV linewidth: O(10^{-22}) sensitivity
- Workable ΔZ ~ 10μm under terrestrial (1 g) gravity field for $\Gamma_{exp} = 4.1\Gamma$
- Long parent nuclei lifetime: 461 days allow for sufficient operation time

- IC ~ 26, small fraction of gamma emitted

The quest of the ^{109}Ag resonance:

$\Gamma_{exp} \sim 30\Gamma$, (W. Wildner and U. Gonser, 1979)

Improved resonance resolution, w broadening factors down to 16 (US)
R. D. Taylor and G. R. Hoy, SPIE **875**, 126 (1988).
S.RezaieSerej, G. R. Hoy, and R. D. Taylor, Laser Phys. **5**, 240 (1995).

Russian group: improvements with Grav. Effects
V. G. Alpatov, et.al. Laser Physics 17, 1067–1072 (2007).
Yu. D. Bayukov, et.al. JETP Letters 90, 499–503 (2009).

The transmission integral

- Photon emission at source
  - Fractional recoil-less : f_s,
  - Fractional recoiled:1-f_s

$$f(T) = \exp\left[\frac{-3E_\lambda^2}{k_B \Theta_D M c^2}\left\{\frac{1}{4} + \left(\frac{T}{\Theta_D}\right)^2 \int_0^{\Theta/T} \frac{x}{e^x - 1}\mathrm{d}x\right\}\right]$$

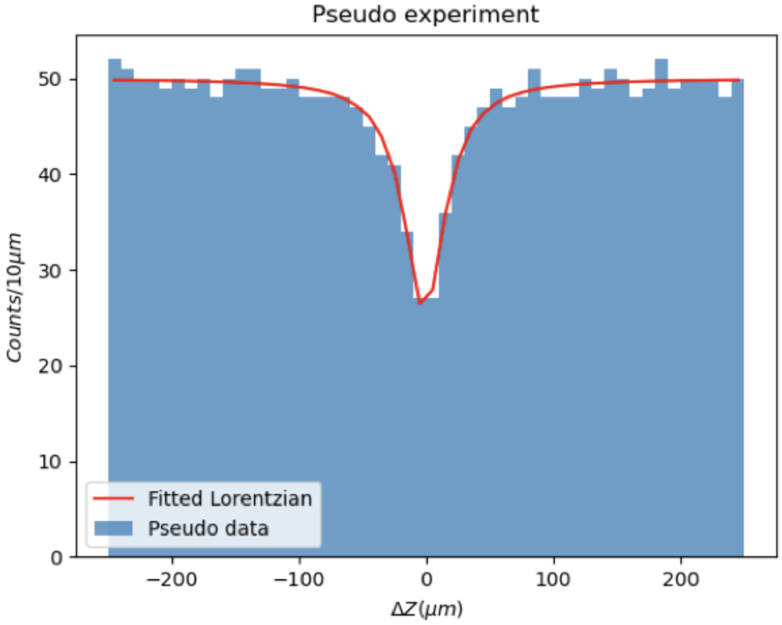
- Photon absorption at absorber
  - Mass attenuation effect: all photons
  - Resonant absorption: only resonant emitted photons
- The transmission integral (textbook)
  - Replaced the doppler shift with gravitational shift

$$C(Z) \ = \ \dot{N}_0 \ e^{-\mu_e t'} \cdot \left[(1 - f_S) + \int_{-\infty}^{\infty} f_S \xi(Z_S, E_0) \cdot \mathrm{e}^{-t\xi(Z, E_0 + \Delta E_0)\Gamma/2\pi} \mathrm{d}E\right]$$

$$\xi(Z, E_0) \ \equiv \ \frac{\Gamma/2\pi}{[E - g(Z - Z_S)E - E_0]^2 + (\Gamma/2)^2},$$

Accuracy from Pseudo experiments

- Pseudo experiment simulation with reasonable parameter
  - Ex: vertical z-position resolution 10 μm, detection efficiency ~100%
  - Readout frequency ~10 f_{GW}, Energy resolution exclude non-88 keV BG
- Sensitivity extracted by fitting the resonance absorption peak



Recoil free fraction	C_∞			
f_S	50	500	5000	50000
0.05*	-	-	-	1.2e-22
0.10	-	-	1.3e-22	3.8e-23
0.20	-	1.3e-22	4.5e-23	1.4e-23
0.30	-	7.9e-23	1.9e-23	7.0e-24
0.40	-	4.8e-23	1.5e-23	4.5e-24
0.50	-	3.3e-23	9.4e-24	2.9e-24
0.60	7.3e-23	2.2e-23	7.2e-24	2.1e-24
0.70	5.0e-23	1.5e-23	5.0e-24	1.5e-24
0.80	4.1e-23	1.2e-23	4.0e-24	
0.90	3.7e-23	9.5e-24	3.1e-24	

* for metallic silver

Silver alloy/compound with higher T_{deBye} helps improve f_S
e.g. AgB_2 has a higher T_{deBye} and f_S =0.2 (@ 4K)

Accuracy compatible to the accuracy needed for GW strain

Parallel measure of resonance absorption shape: fast enough for GW

The GW signal: photon energy shifts

Energy shift due to different space-time matrix for photon emission and absorption

Estabrook and Wahlquist, Gen. Relat. Gravit. 6, 439–447 (1975);
Hellings, Phys. Rev. D 23, 832–843 (1981).

Consider a plain-wave strain perturbation

$$h(\boldsymbol{x},t) = h_0\, e^{i(\omega t-\boldsymbol{k}\cdot\boldsymbol{x})}$$

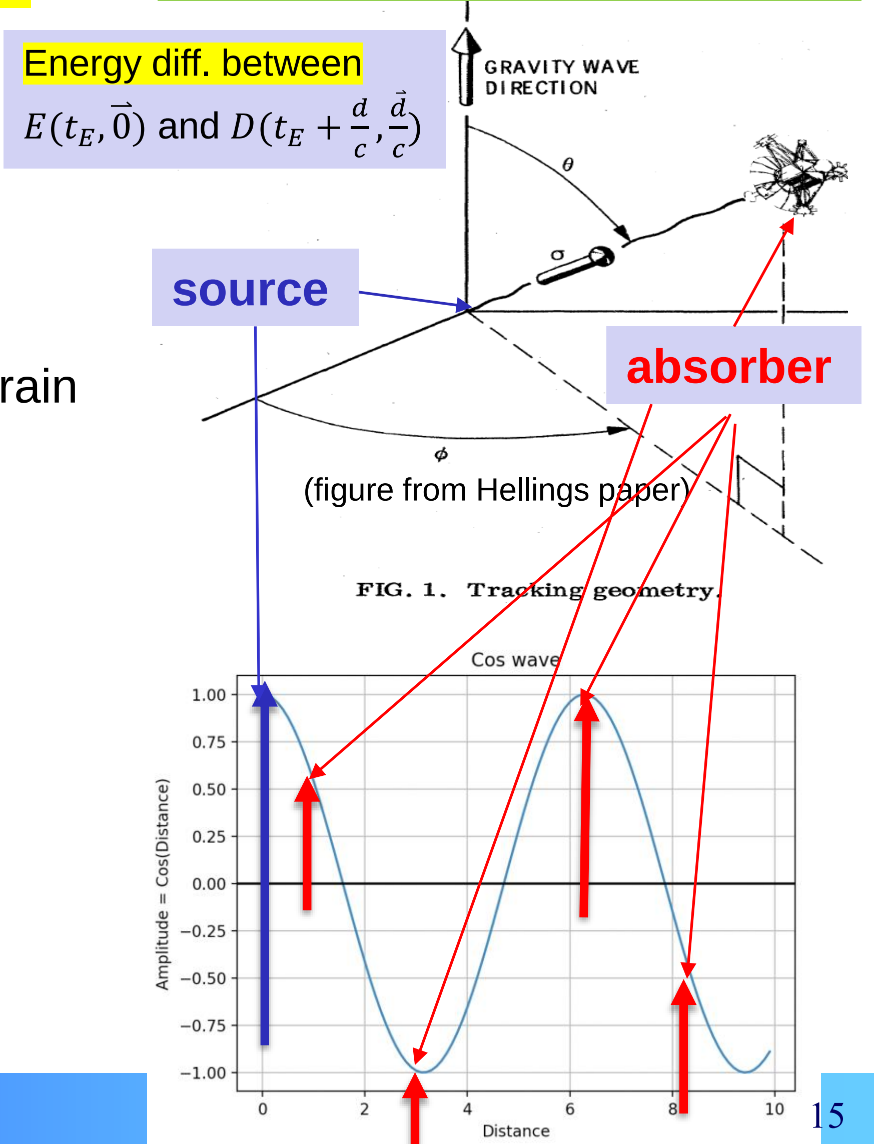
$$\mathrm{ds}^2 = \mathrm{c}^2\mathrm{dt}^2 - [1+\mathrm{h}]\mathrm{dx}^2 - [1-\mathrm{h}]\mathrm{dy}^2 - \mathrm{dz}^2$$

A particle’s 4-momentum response to GW strain after one-way propagation:

$$\frac{\Delta f}{f_\gamma} = \frac{\ell^\mu \ell^\nu}{1-\cos\theta}[h^{\mathrm{D}}_{\mu\nu} - h^{\mathrm{E}}_{\mu\nu}]$$

$$\ell^\mu = f_\gamma(1, \sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$\boxed{\begin{aligned}\frac{\Delta f}{f_\gamma} &= 2h_0\cos^2\frac{\theta}{2}\cos 2\phi\sin\left(\omega d\sin^2\frac{\theta}{2}\right)\\ &\cdot\ \sin\left(\omega t-\omega d\cos^2\frac{\theta}{2}\right),\end{aligned}}$$



Energy diff. between $E(t_E,\vec{0})$ and $D(t_E+\frac{d}{c},\frac{\vec{d}}{c})$

source

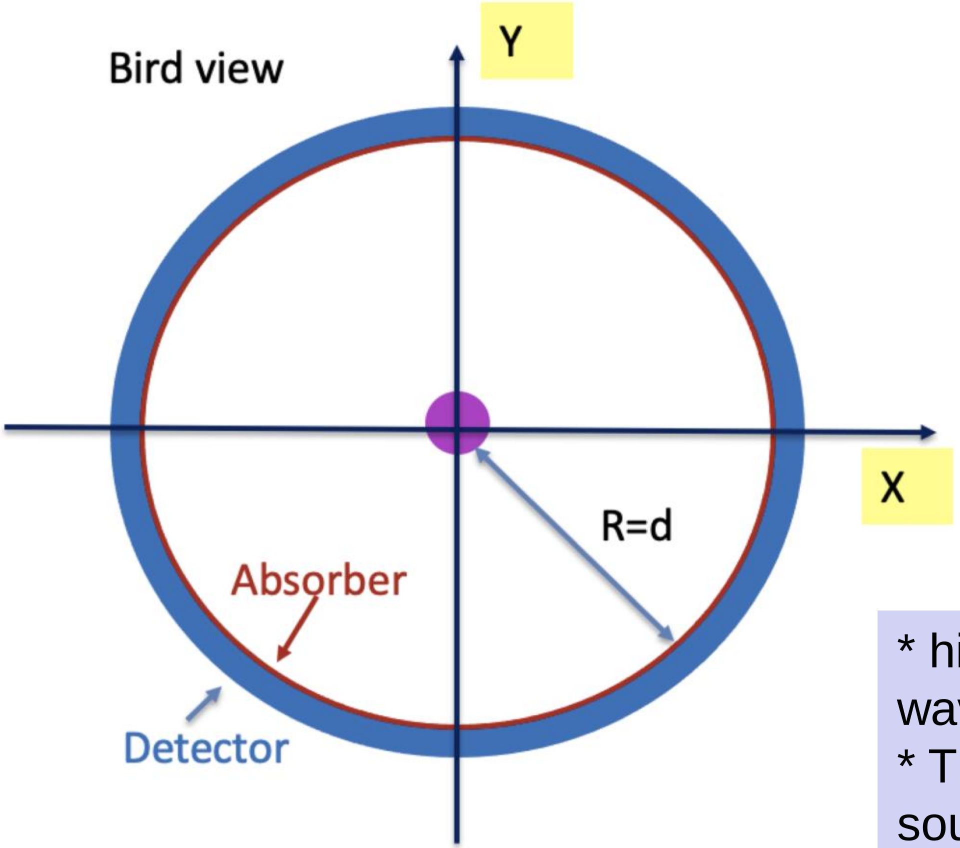
absorber

(figure from Hellings paper)

FIG. 1. Tracking geometry.

Stationary Mössbauer GW setup

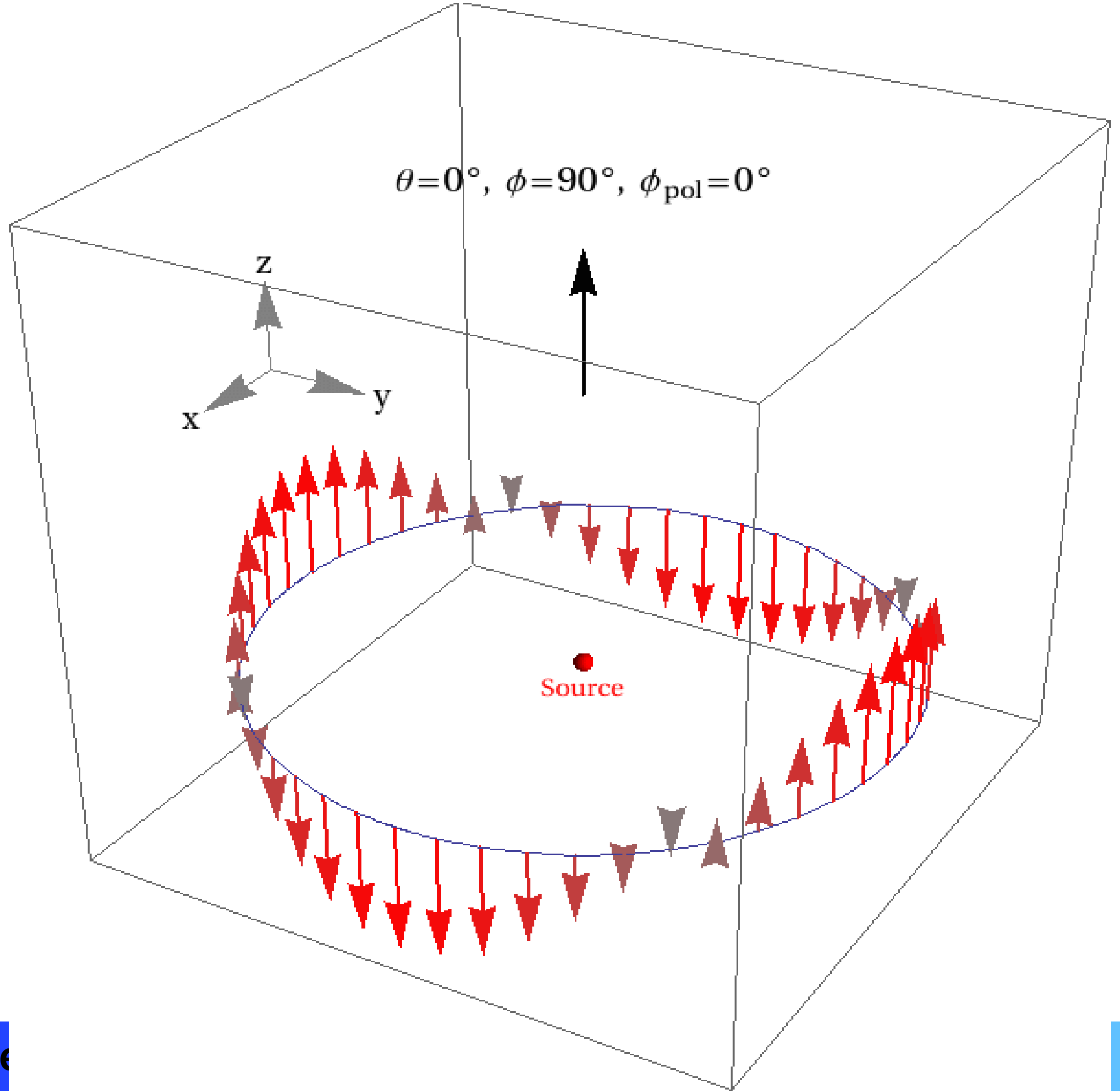
- Absorber+detectors are in the resonance plane around source
  - At least two perpendicular directions relative to any GW incident θ angle.
  - Enhance acceptance of resonances photons



* highest sensitive to GW wavelength ~d/2
* The distance d between source and absorber can be tabletop size

Hypothetical GW signal “seen” by our experiment

- Modulation of resonance peak shifts in the ring
  - Allow GW direction and polarization reconstruction



Expected sensitive on GWs

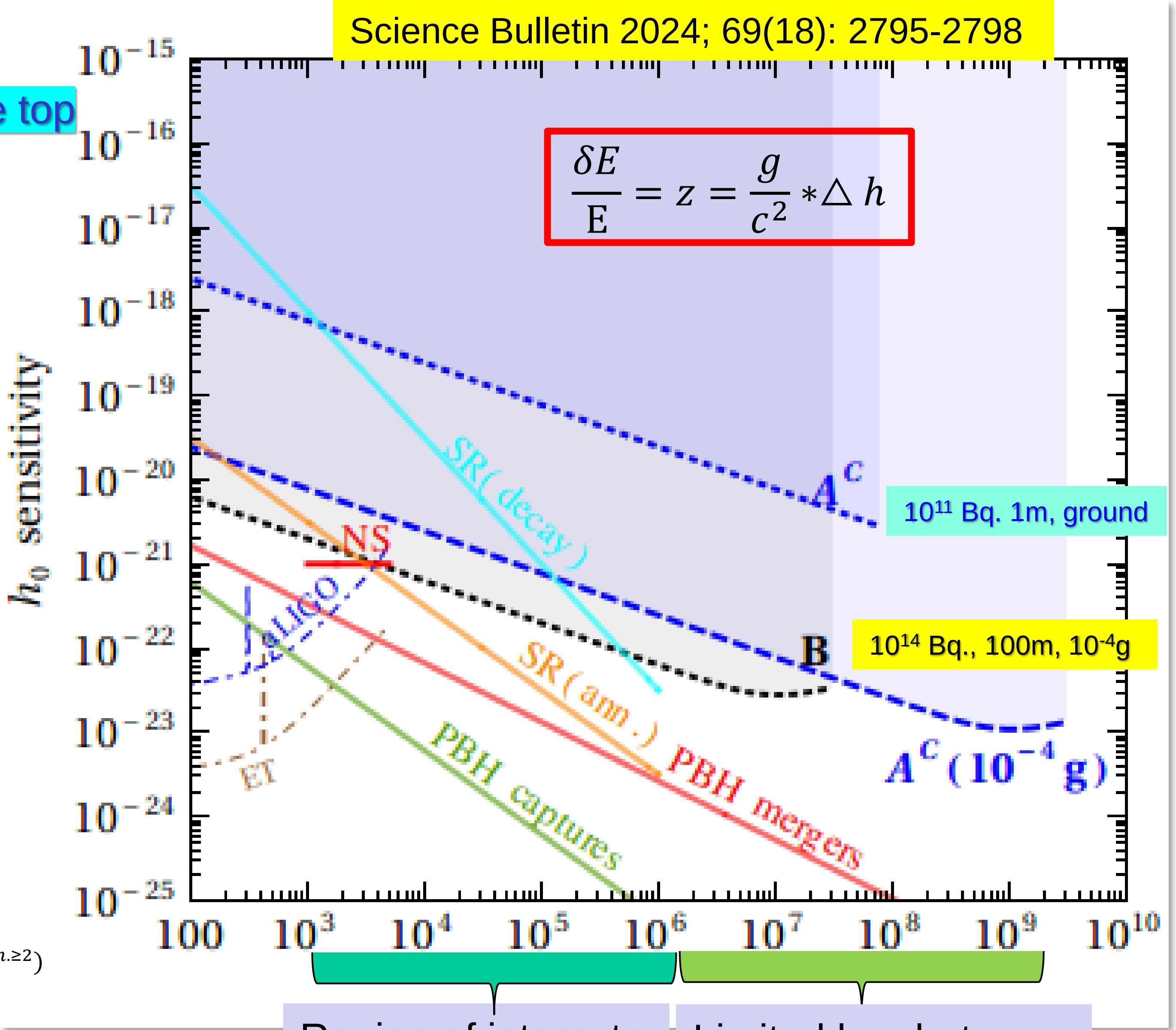
A^C: 10^6 periods: table top

B: single period

Max Freq. Reach:
cutoffs at:
*3σ peak with C_∞,
$C_\infty > (\sigma)^2/(f_S \epsilon)^2$
* $2\pi f d < O(10)$

Coherent GWs from NS, SR, PBHs, see [N.Aggarwal et al., Living Rev. Rel. 24, 4 (2021)]

Inverse Gentsenshtein:
$\Delta F = F_0\, h * (form\ factor{\sim}\omega d^{n\geq 2})$
also see: [2305.00877]



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$$\frac{\delta E}{E} = z = \frac{g}{c^2} * \triangle h$$

10^{11} Bq. 1m, ground

10^{14} Bq., 100m, 10^{-4}g

Region of interests

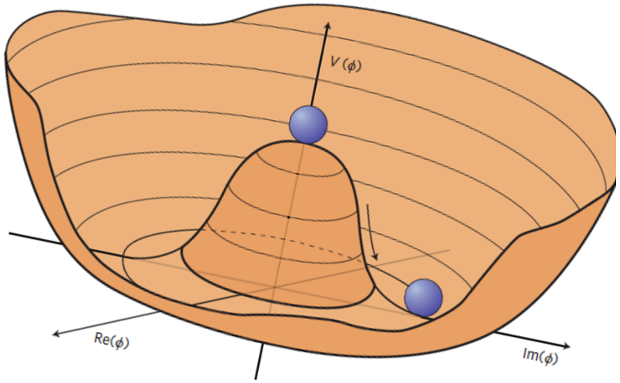
Limited by photon counter and readout

The dark matter signal: nucleon energy level shifts

Strong CP-problem:

$$\underbrace{(\theta - \arg\det \mathrm{M_q})}_{\bar{\theta} < 10^{-10}} \frac{\alpha_s}{8\pi} \mathrm{G}\tilde{\mathrm{G}}$$

Introduce axion field:



Couplings:

axion-gluon-gluon
axion-photon-photon
axion-fermion-fermion

Axion DM leads to a time dependent θ

$$a(t,\vec{x}) \approx \frac{\sqrt{2\rho_{\mathrm{DM,local}}}}{m_a} \sin\left(\omega_a t - \vec{p}\cdot\vec{x}\right)$$

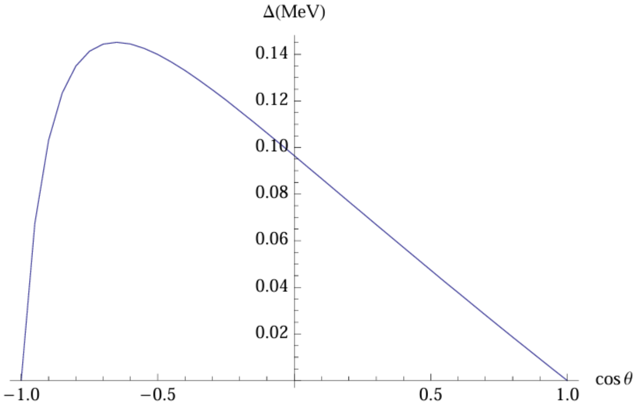
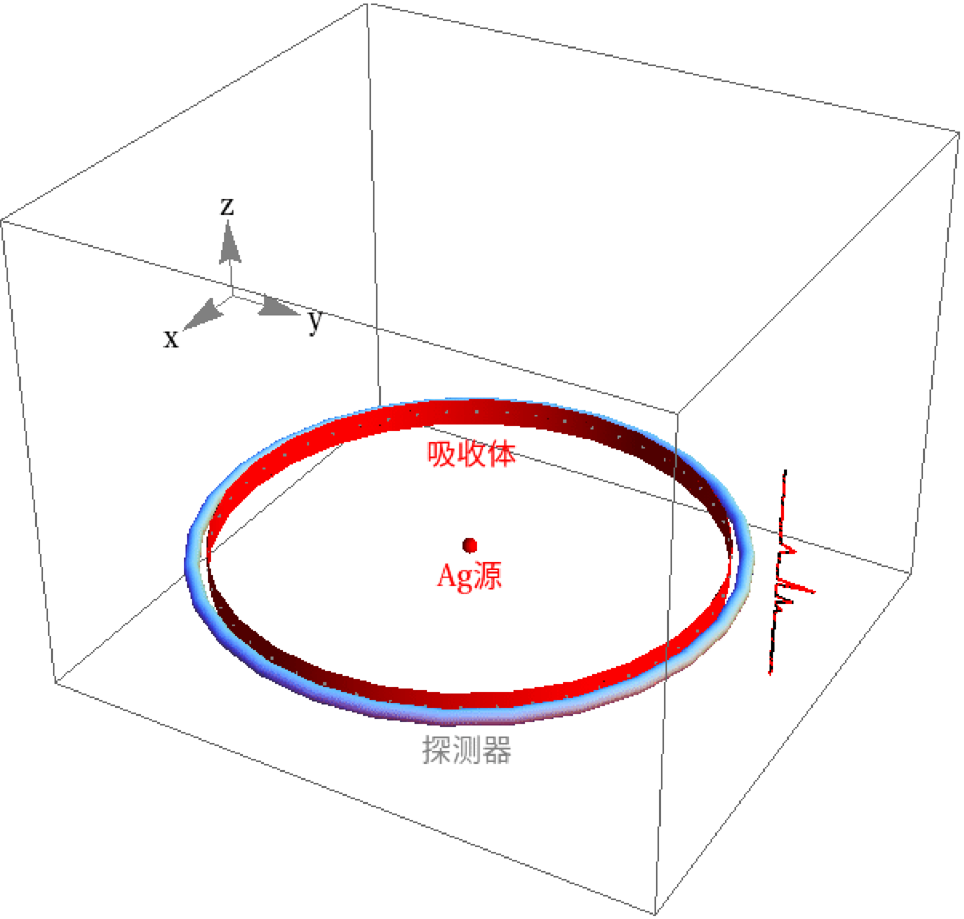
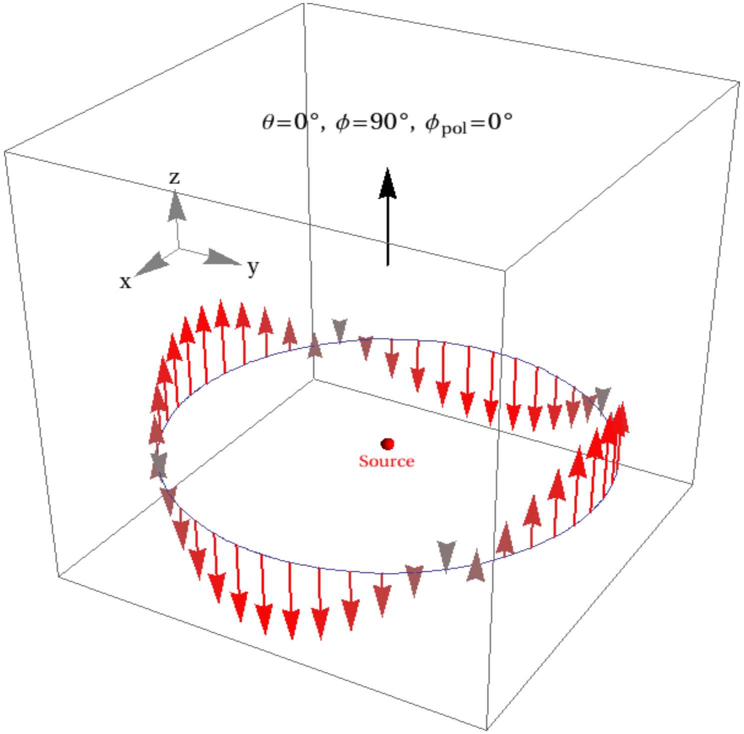


Figure 2: *Shift in the deuteron binding energy as a function of* $\cos\theta$

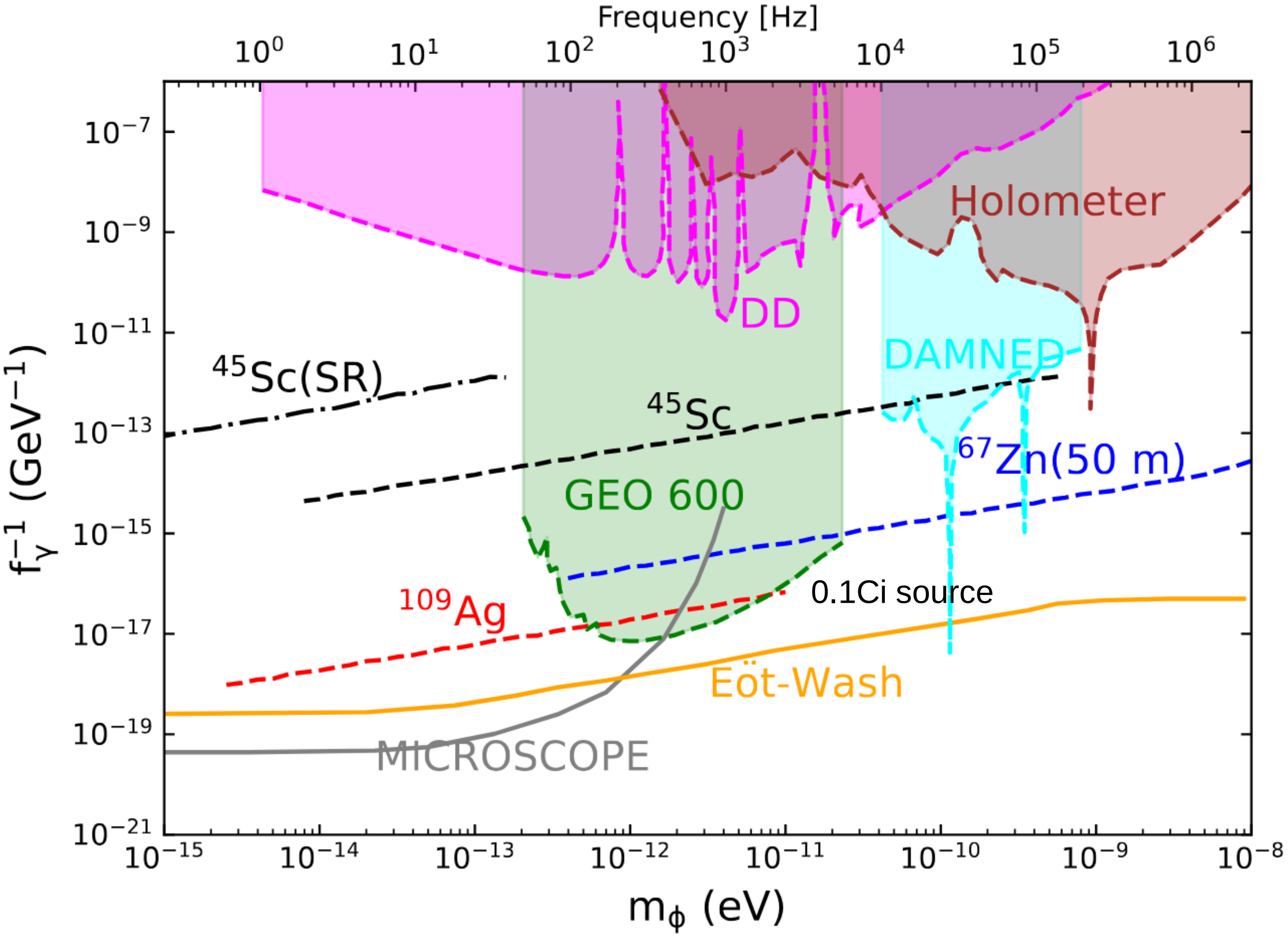
Time dependent binding energy (very small deviation)

Hypothetical dark matter signal “seen” by our experiment





Sensitivity on wake like axion dark mater



Phase 0: Tabletop exotic/axtion physics searches
Phase 1: Tabletop Ground based GW+DM experiment
Phase 2: low-g GW+DM experiment (higher sensitivity)
  Space based experiment
  Moon/Asteroid based experiment
  saddle/Lagrangian point based experiment？