GRAVITATIONAL WAVES AT PARTICLE STORAGE RINGS

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ω_g

10^{-10}nHz — 10kHz — ...

Size of the Universe

Largest from Astrophysics


ω_g
10 Hz
kHz
LIGO-VIRGO


ω_g
nHz
μHz
10 Hz
kHz
PULSAR TIMING
LIGO-VIRGO

Any new idea for detection is interesting, even the most "ambitious" ones

ARIES WP6 Workshop: Storage Rings and Gravitational Waves — SRGW2021

https://indico.cern.ch/event/982987/

https://arxiv.org/pdf/2105.00992.pdf

Sensitivity to Deformations

LIGO	10^{-15} mm
LHC	mm

	Sensitivity to Deformations	Effective Size
LIGO	10^{-15} mm	10^3 km $(4 \text{ km}) \times 300$
LHC	mm	$10^5 \text{ km} \left(\frac{\tau}{\text{s}}\right)$

Everything interacts with the gravitational wave: magnets, tunnel, protons, EM fields, us observers, …

CAVEAT: large gauge symmetry of GR (i.e. rigid objects in flat space can move a lot in certain coordinate systems)

$$x^{\mu} \rightarrow x^{\mu\prime}(x^{\mu})$$

Any change of coordinates still describes the same physics

We can use this symmetry to our advantage: choose a frame where our Newtonian intuition applies (**proper detector frame**) at least for small distances compared to the wavelength

$$\frac{L}{\lambda_g} \ll 1$$

This is the frame of an observer standing still next to the LHC and watching the protons fly by, i.e. exactly what we want

Everything interacts with the gravitational wave: magnets, tunnel, protons, EM fields, us observers, …

However if we focus on a **small frequency range**, the **majority of** potential **detectors are rigid**

Any system in equilibrium if displaced by a small amount δ responds as a harmonic oscillator

$$\ddot{\delta}(t) + \frac{\dot{\delta}(t)}{\tau_s} + \omega_s^2 \delta(t)$$

Everything interacts with the gravitational wave: magnets, tunnel, protons, EM fields, us observers, …

$$\ddot{\delta}(t) + \frac{\dot{\delta}(t)}{\tau_s} + \omega_s^2 \delta(t) = \omega_g^2 f(\omega_g, t)$$

Everything interacts with the gravitational wave: magnets, tunnel, protons, EM fields, us observers, …

$$\tilde{\delta}(\omega) = \tilde{f}(\omega_g, \omega) \frac{\omega_g^2}{(\omega_s^2 - \omega^2) + i\tau_s\omega}$$

Everything with $\omega_s \gg \omega_g$

Has a very suppressed response

$$\tilde{\delta}(\omega_g) \simeq \frac{\omega_g^2 \tilde{f}(\omega_g, \omega_g)}{\omega_s^2} \ll \tilde{f}(\omega_g, \omega_g)$$

This is useful also if the wave is not at all monochromatic, i.e. we can always ignore objects with characteristic frequencies much larger than our readout frequency

$$\omega_s \gg \omega_r$$

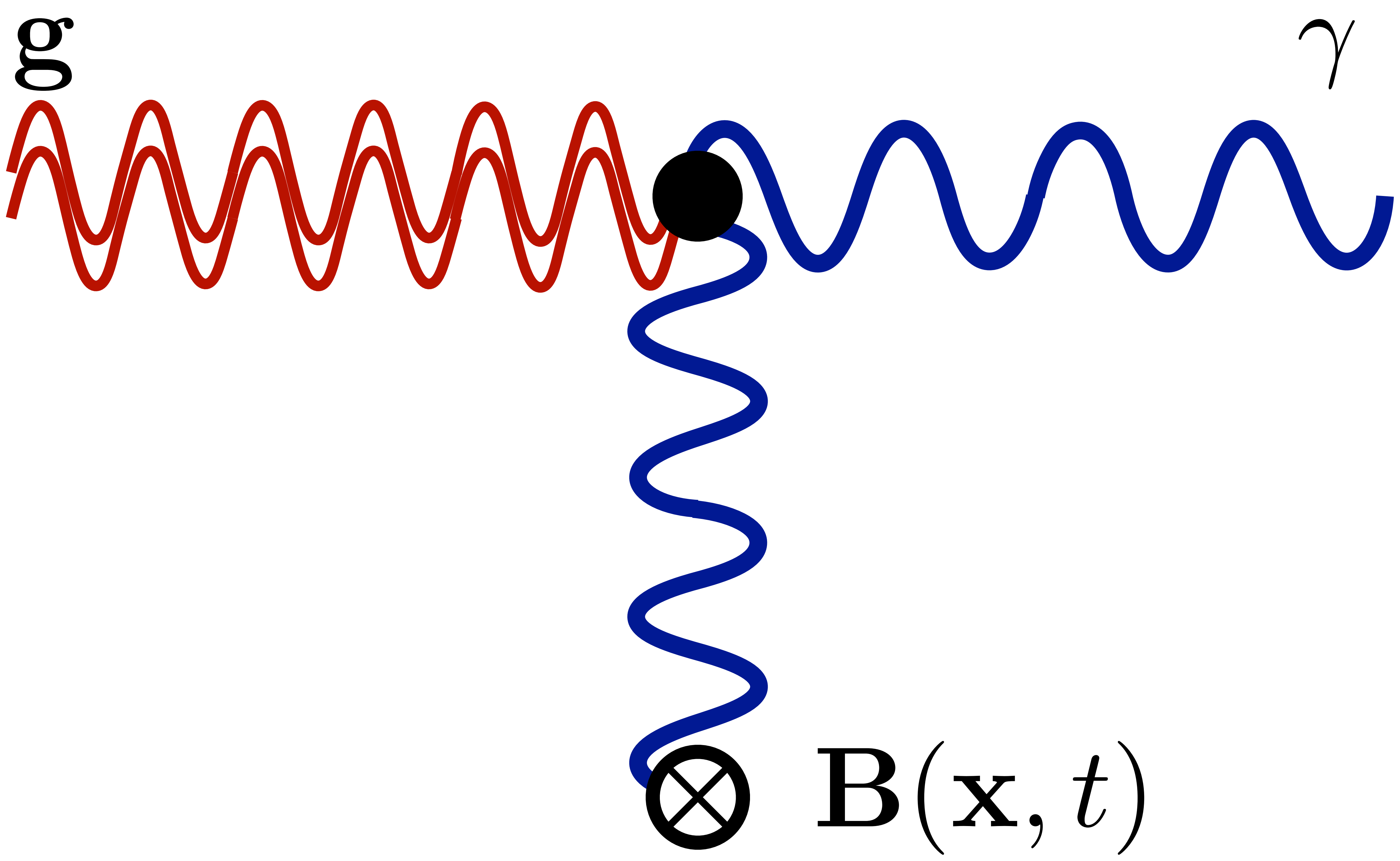
$$\tilde{\delta}(\omega_r) \simeq \frac{\omega_r^2 \tilde{f}(\omega_g, \omega_r)}{\omega_s^2}$$

CAVEAT: large gauge symmetry of GR (i.e. rigid objects in flat space can move a lot in certain coordinate systems)

In the **proper detector frame** rigid objects don’t move (magnets, tunnel, measuring devices, …) so focus on **protons** and **EM fields**

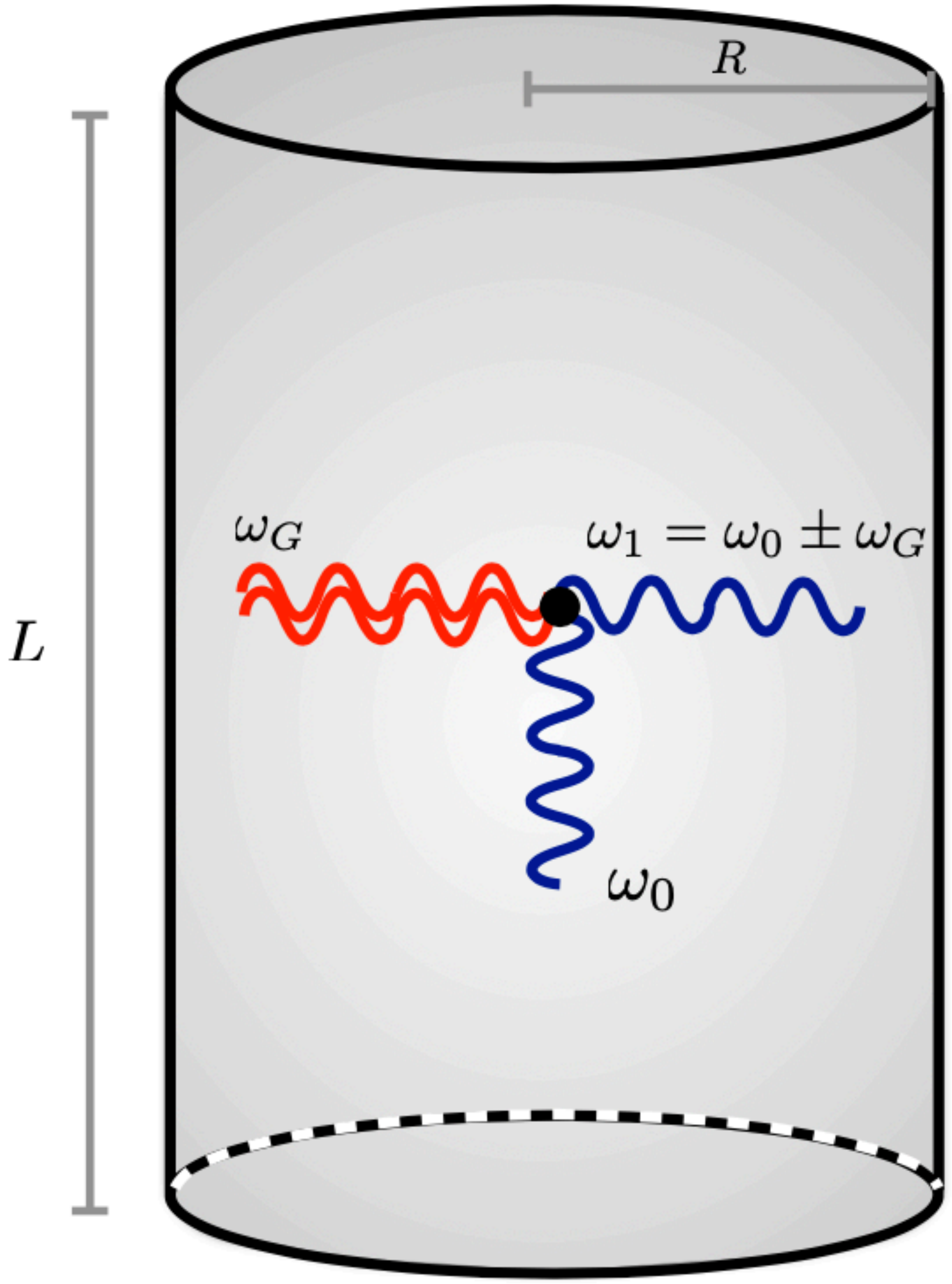
- **EM fields**
- **Radial**
- **Vertical**
- **Longitudinal**

EM fields



Braginskii & Menskii, 1971

A. Berlin, D. Blas, **RTD**, S. Ellis, R. Harzig, Y. Kahn, J. Schuette-Engel



Superconducting RF Cavity

~ Proton Acceleration

$$\omega_0 \simeq \mathrm{GHz}$$

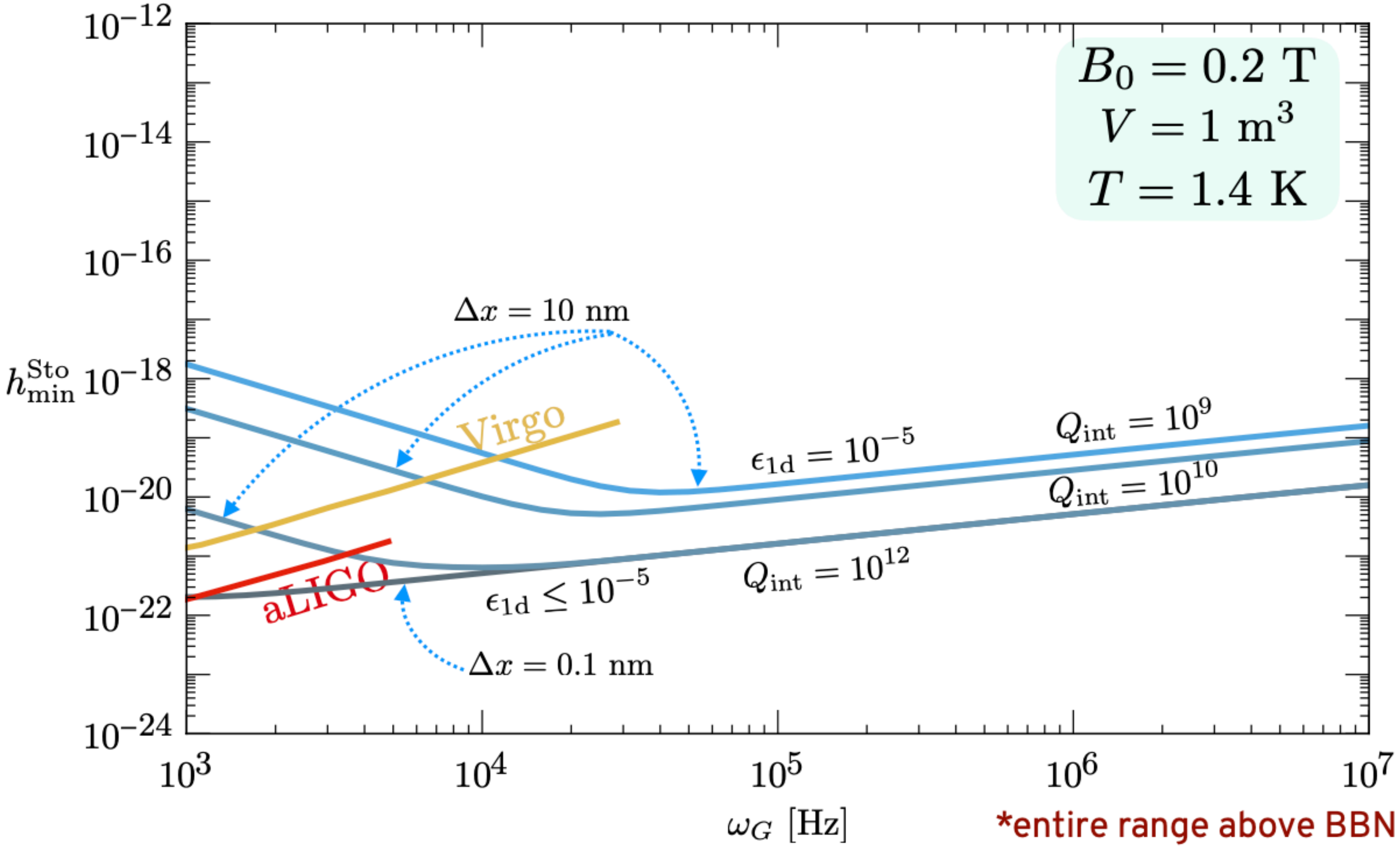
$$\omega_G \simeq \mathrm{kHz} \div \mathrm{GHz}$$

Pegoraro, Picasso & Radicati, 1978

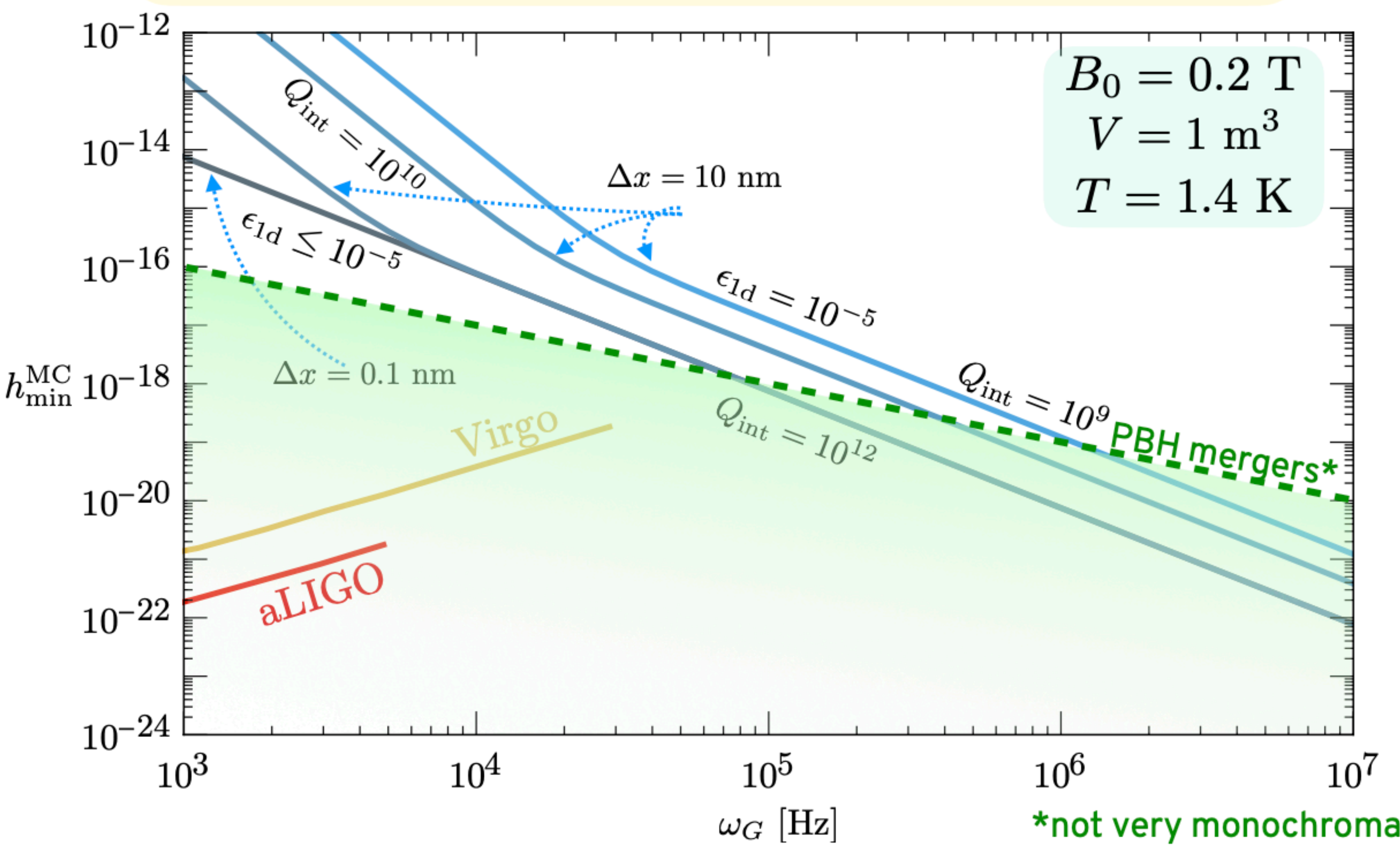
Pegoraro, Radicati, Bernard & Picasso, 1978 and MAGO collaboration

A. Berlin, D. Blas, **RTD**, S. Ellis, R. Harzig, Y. Kahn, J. Schuette-Engel

Ultra-preliminary



*entire range above BBN bou



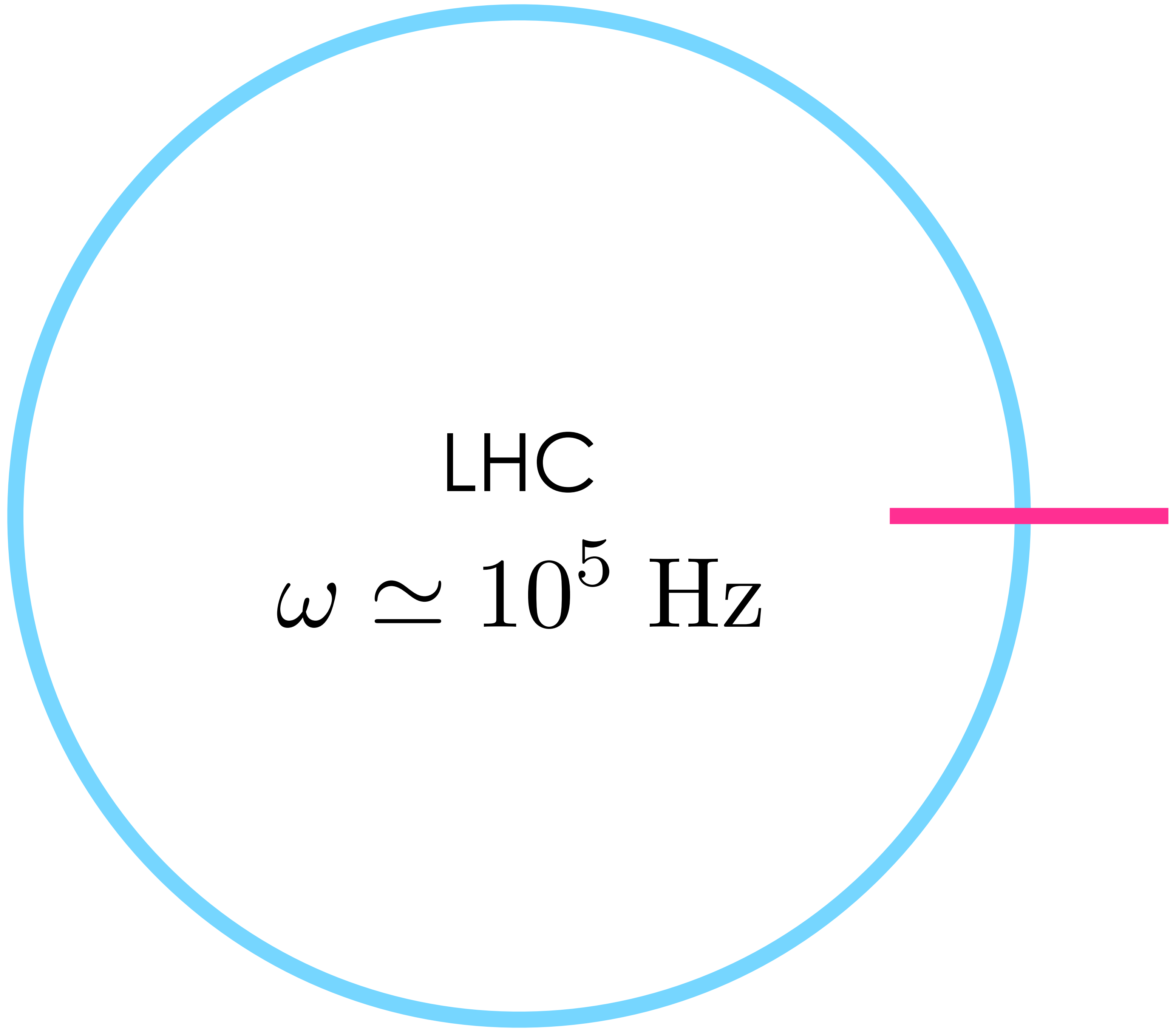
*not very monochroma

Many other ideas in this range: See F. Muia's talk
and 2011.12414

In the **proper detector frame** rigid objects don't move (magnets, tunnel, measuring devices, …) so focus on **protons** and **EM fields**

- **EM fields** ✓
- **Radial**

First record of the idea
that I could find: D. Zer Zion
(n.b. very optimistic damping time)
https://inspirehep.net/literature/533999
https://inspirehep.net/literature/529085
https://inspirehep.net/literature/470998



See talk by K.Oide,
https://indico.cern.ch/event/982987/

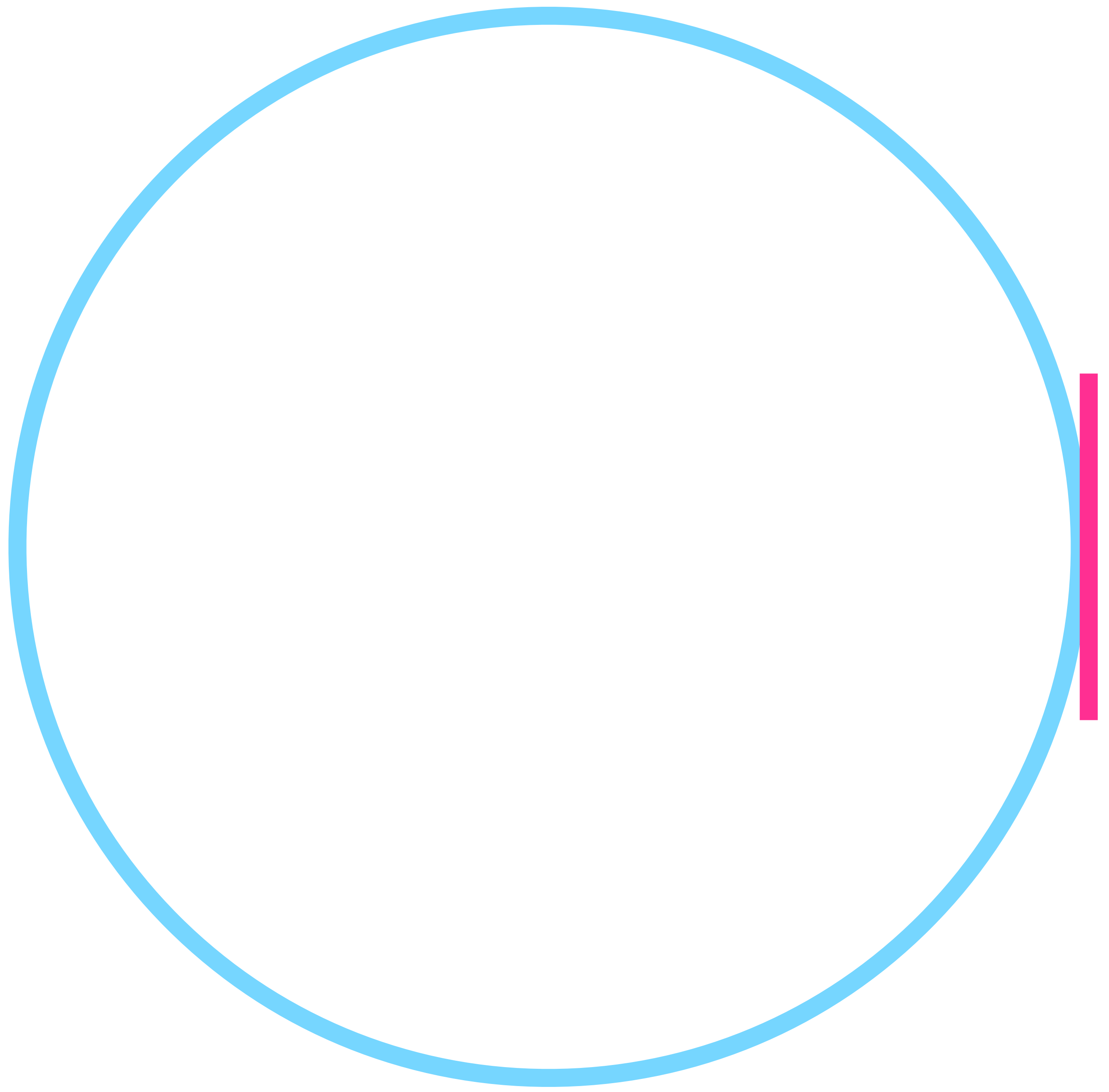
In the **proper detector frame** rigid objects don't move (magnets, tunnel, measuring devices, ...) so focus on **protons** and **EM fields**

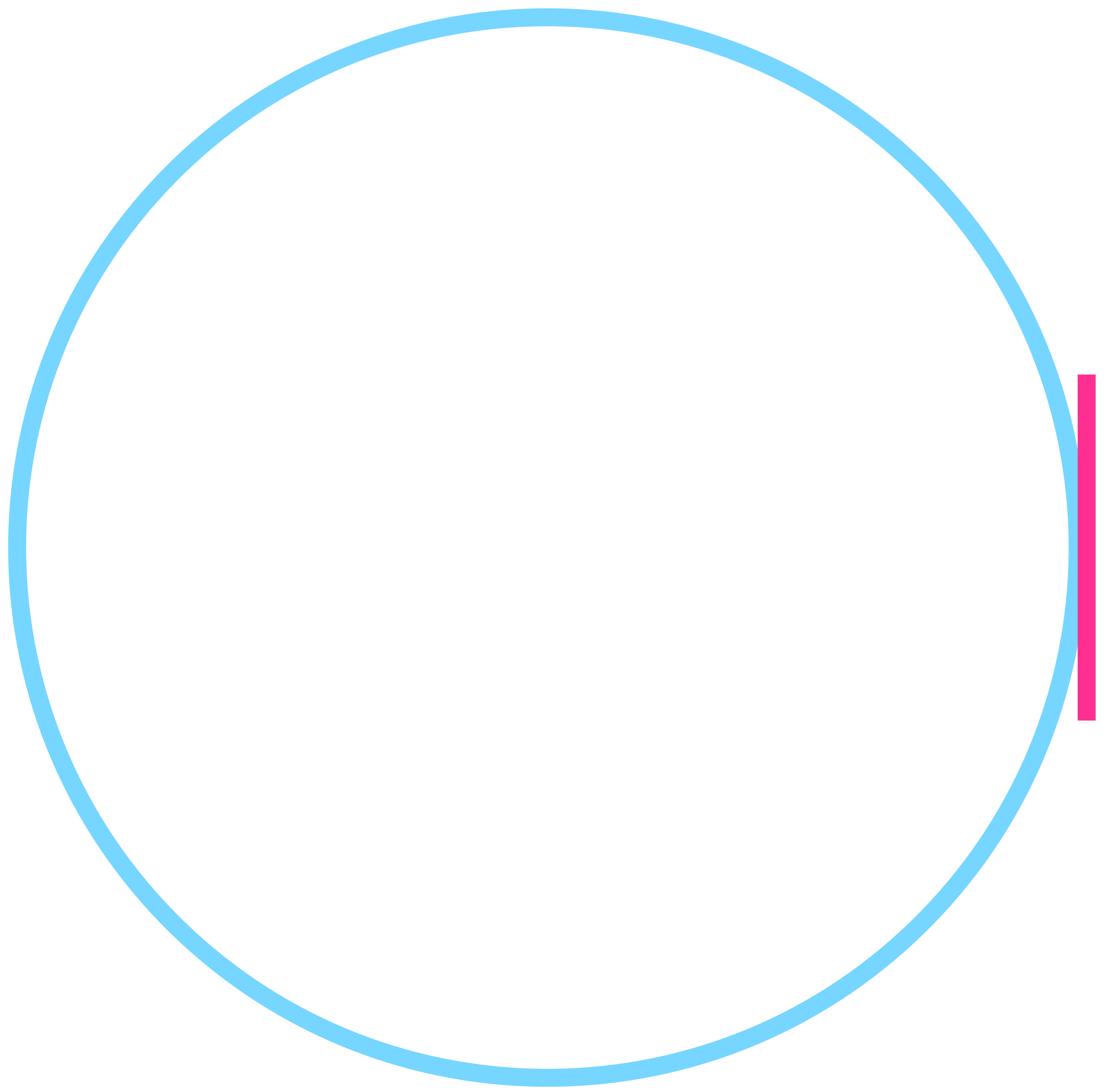
- **EM fields** ✓
- **Radial** ✓
- **Vertical**

$$\Delta z \simeq hz \simeq h \times \mathrm{cm} \ll h \times \mathrm{km}$$

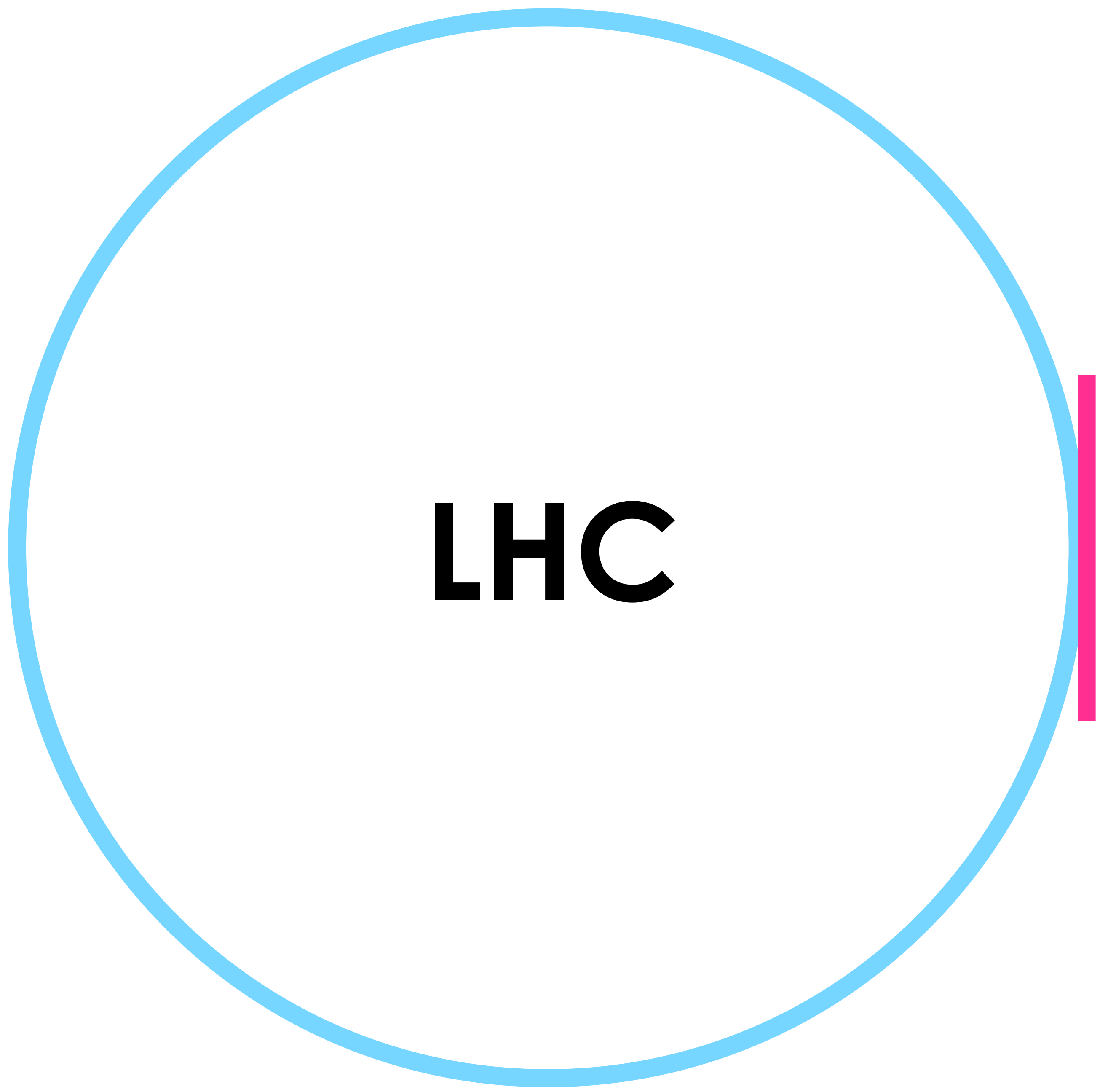
In the **proper detector frame** rigid objects don't move (magnets, tunnel, measuring devices, …) so focus on **protons** and **EM fields**

- **EM fields** ✓
- **Radial** ✓
- **Vertical** ✓
- **Longitudinal**



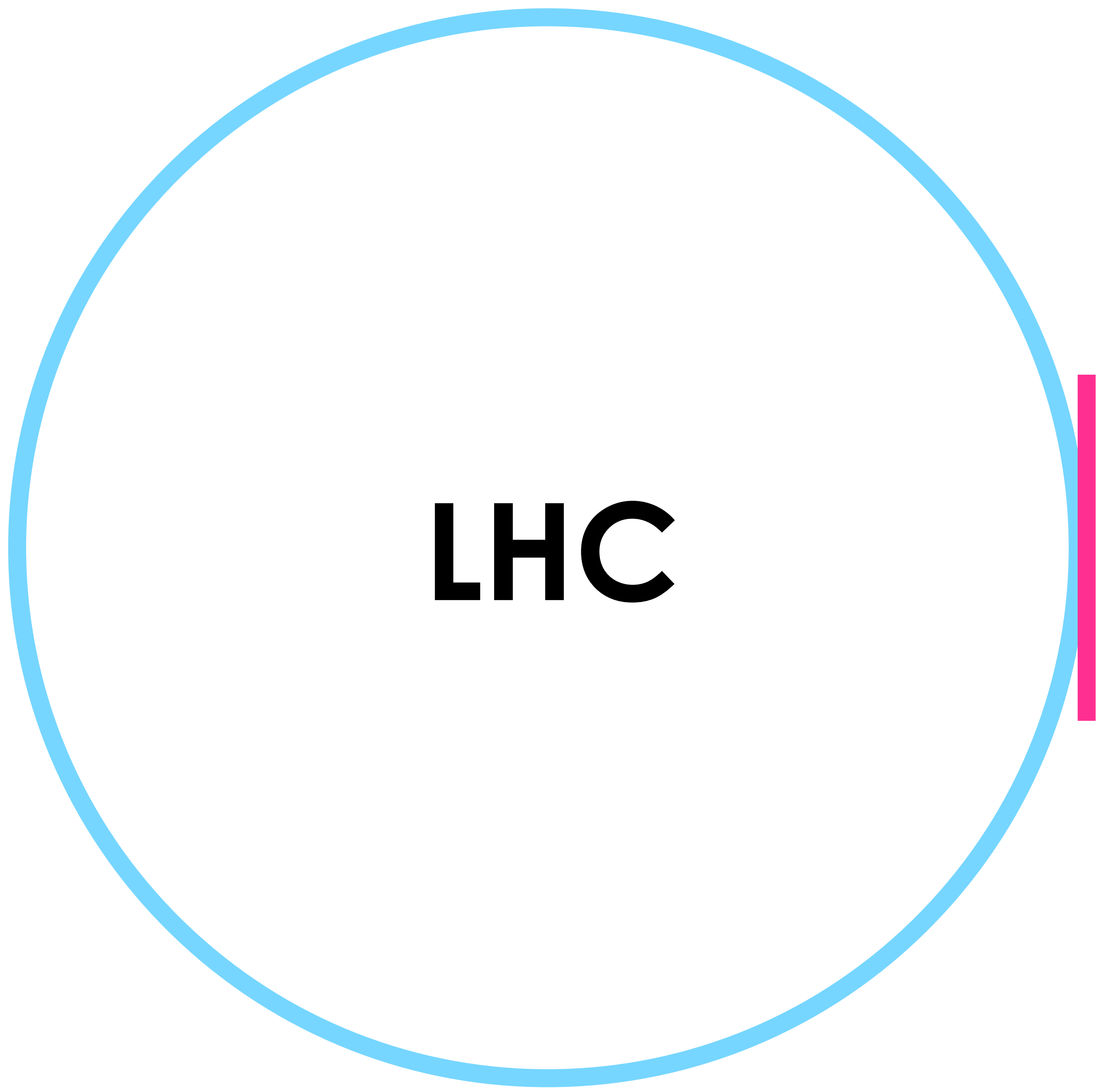


$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \omega_g^2 f(\omega_g, t)$$



$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \omega_g^2 f(\omega_g, t)$$

$$\omega_l \approx \omega_0 \sqrt{\frac{\tilde{h} \alpha_C q V_{\mathrm{RF}}}{R}} \approx 2\pi \times 10\ \mathrm{Hz}$$



$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \underline{\omega_g^2 f(\omega_g, t)}$$

Compute

$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \omega_g^2 f(\omega_g, t)$$

DIMENSIONAL ANALYSIS

$$f(\omega_g, t) \simeq h \times L \times \cos(\omega_g t + \phi)$$

$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \omega_g^2 f(\omega_g, t)$$

DIMENSIONAL ANALYSIS

$$f(\omega_g, t) \simeq \underline{h} \times L \times \cos(\omega_g t + \phi)$$

Dimensionless strength of the wave

$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \omega_g^2 f(\omega_g, t)$$

DIMENSIONAL ANALYSIS

$$f(\omega_g, t) \simeq h \times \underline{L} \times \cos(\omega_g t + \phi)$$

Length of the ring

$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \omega_g^2 f(\omega_g, t)$$

DIMENSIONAL ANALYSIS

$$f(\omega_g, t) \simeq h \times L \times \underline{\cos(\omega_g t + \phi)}$$

For simplicity: perfectly monochromatic

$$\ddot{\delta}_l + \frac{\dot{\delta}_l}{\tau_l} + \omega_l^2 \delta_l = \omega_g^2 f(\omega_g, t)$$

ON RESONANCE

$$f(\omega_g, t) \simeq h \times L \times \cos(\omega_g t + \phi)$$

$$\delta_t = \frac{\delta_l}{c} \simeq (hT)(\omega_l \tau_l)$$

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$$\left(\frac{\Delta T}{T}\right)_{\text{exp}} \simeq 10^{-7}$$

PHASE MEASUREMENT IN THE RF CAVITY

$$\delta_t = \frac{\delta_l}{c} \simeq (hT)(\omega_l \tau_l)$$

$$\left(\frac{\Delta T}{T}\right)_{\mathrm{exp}} \simeq 10^{-7}$$

$$\omega_l \simeq 2\pi \times 10 \text{ Hz}$$

$$\delta_t = \frac{\delta_l}{c} \simeq (hT)(\omega_l \tau_l)$$

$$\left(\frac{\Delta T}{T}\right)_{\text{exp}} \simeq 10^{-7}$$

$$\omega_l \simeq 2\pi \times 10 \text{ Hz}$$

$$\tau_l \simeq 10 \text{ hours}$$

$$\delta_t = \frac{\delta_l}{c} \simeq (hT)(\omega_l \tau_l)$$

$$\boxed{h \gtrsim 10^{-13}}$$

$$\left(\frac{\Delta T}{T}\right)_{\rm exp} \simeq 10^{-7}$$

0.2 deg @ 400 MHz

$$h \gtrsim 10^{-13}$$

$$\delta_t = \frac{\delta_l}{c} \simeq (hT)(\omega_l \tau_l)$$

- AT LEAST 7 ORDERS OF MAGNITUDE ABOVE KNOWN SOURCES
- BUT THERE IS A WAY FORWARD

$$h \gtrsim 10^{-13}$$

$$\boxed{\delta_t = \frac{\delta_l}{c} \simeq (hT)(\omega_l \tau_l)}$$

- WAY FORWARD
  - (MUCH) SLOWER PROTONS. Saturation:

$$T \simeq \frac{1}{\omega_g} = \frac{1}{\omega_l}$$

$$h \gtrsim 10^{-13}$$

$$\delta_t = \frac{\delta_l}{c} \simeq (hT)(\omega_l \tau_l)$$

- WAY FORWARD
  - (MUCH) SLOWER PROTONS **[3 orders of magnitude better ?]**
  - IMPROVE TIME RESOLUTION (Electro-Optical Sampling)

$$\left(\frac{\Delta T}{T}\right)_{\rm exp} \simeq 10^{-8}$$

$$h \gtrsim 10^{-13}$$

$$\delta_t = \frac{\delta_l}{c} \simeq (hT)(\omega_l \tau_l)$$

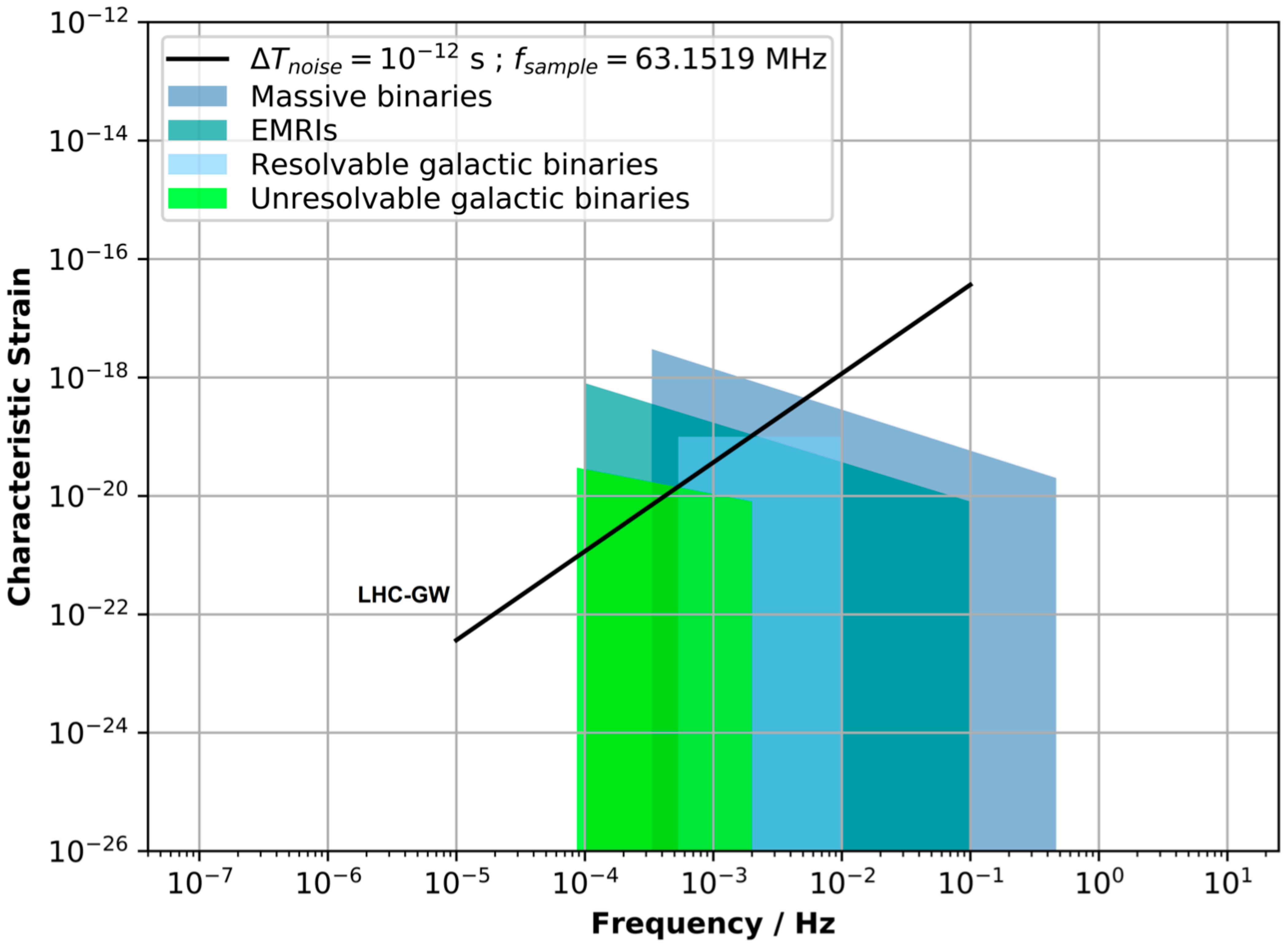
- WAY FORWARD
  - (MUCH) SLOWER PROTONS **[3 OM]**
  - IMPROVE TIME RESOLUTION **[1 OM]**
  - IMPROVE BEAM STABILITY
    - THE BEAM INTENSITY CAN BE CONSIDERABLY REDUCED
    - THE LOWER THE ENERGY THE BETTER
    - A SMALLER RING WITH SLOWER PROTONS CAN HAVE THE SAME SENSITIVITY

- MORE RADICAL WAY FORWARD:

  TURN OFF THE RF (coasting beam)

$$\omega_l \to 0$$

Rao, Bruggen, Liske
Phys.Rev.D 102 (2020) 12, 122006 2012.00529



Potential Problem: TIDES

- MORE RADICAL WAY FORWARD:

  TURN OFF THE RF (coasting beam)

$$\omega_l \to 0$$

Rao, Bruggen, Liske
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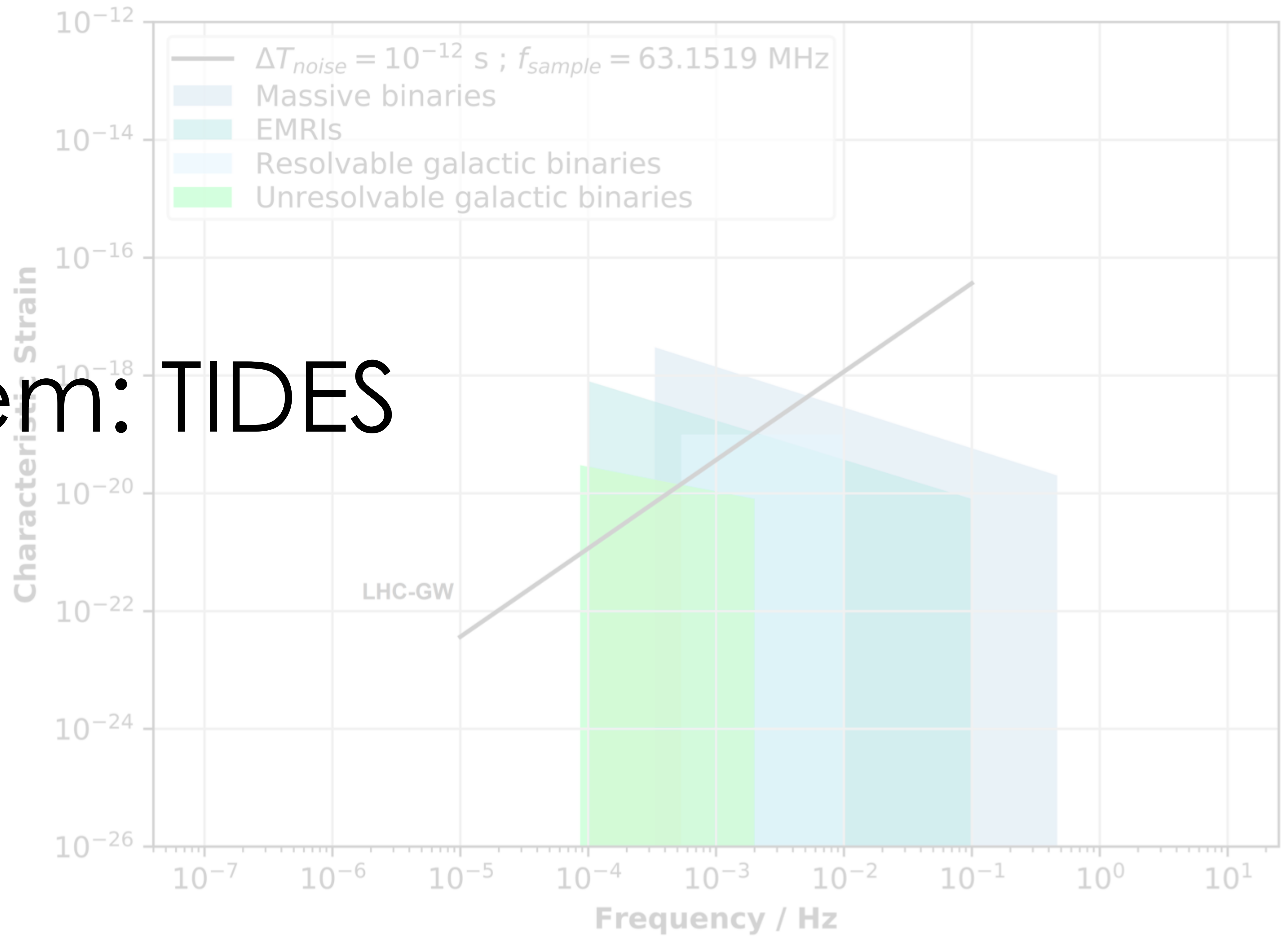

- MEASURING GRAVITATIONAL WAVES USING STORAGE RINGS MIGHT BE HOPELESS
- HOWEVER MEASURING GRAVITATIONAL WAVES WAS CONSIDERED ALTOGETHER HOPELESS FOR DECADES AND WE WERE WRONG
- THE PRESENCE OF A POTENTIAL PATH TOWARDS GW-LEVEL SENSITIVITY FOR LONGITUDINAL DEFORMATIONS IS INTERESTING AND MIGHT DESERVE FURTHER STUDY