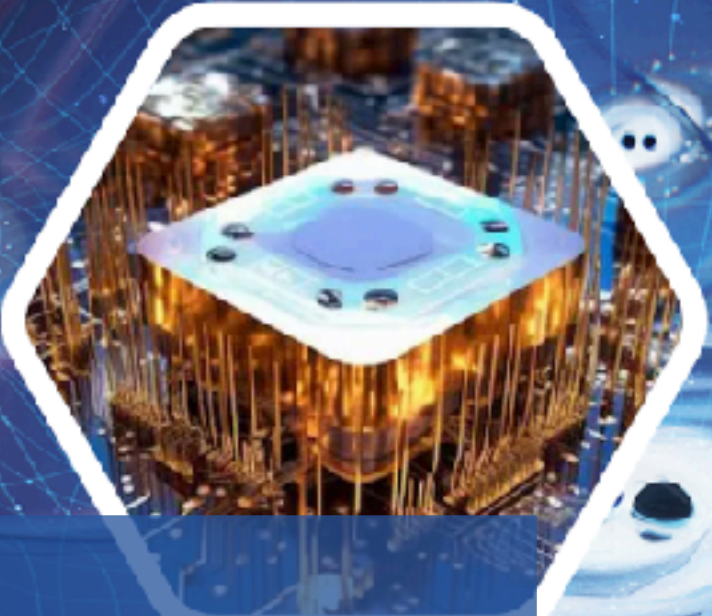
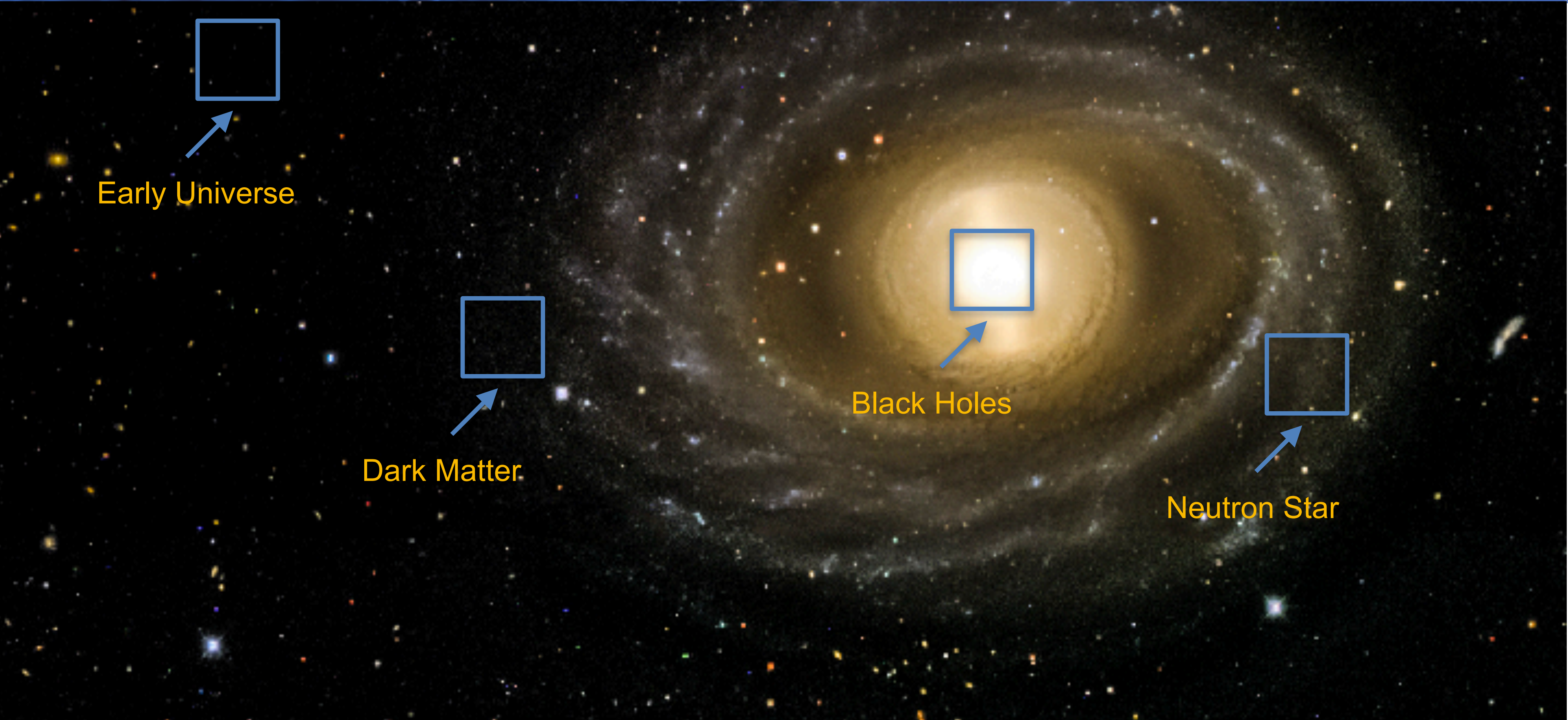


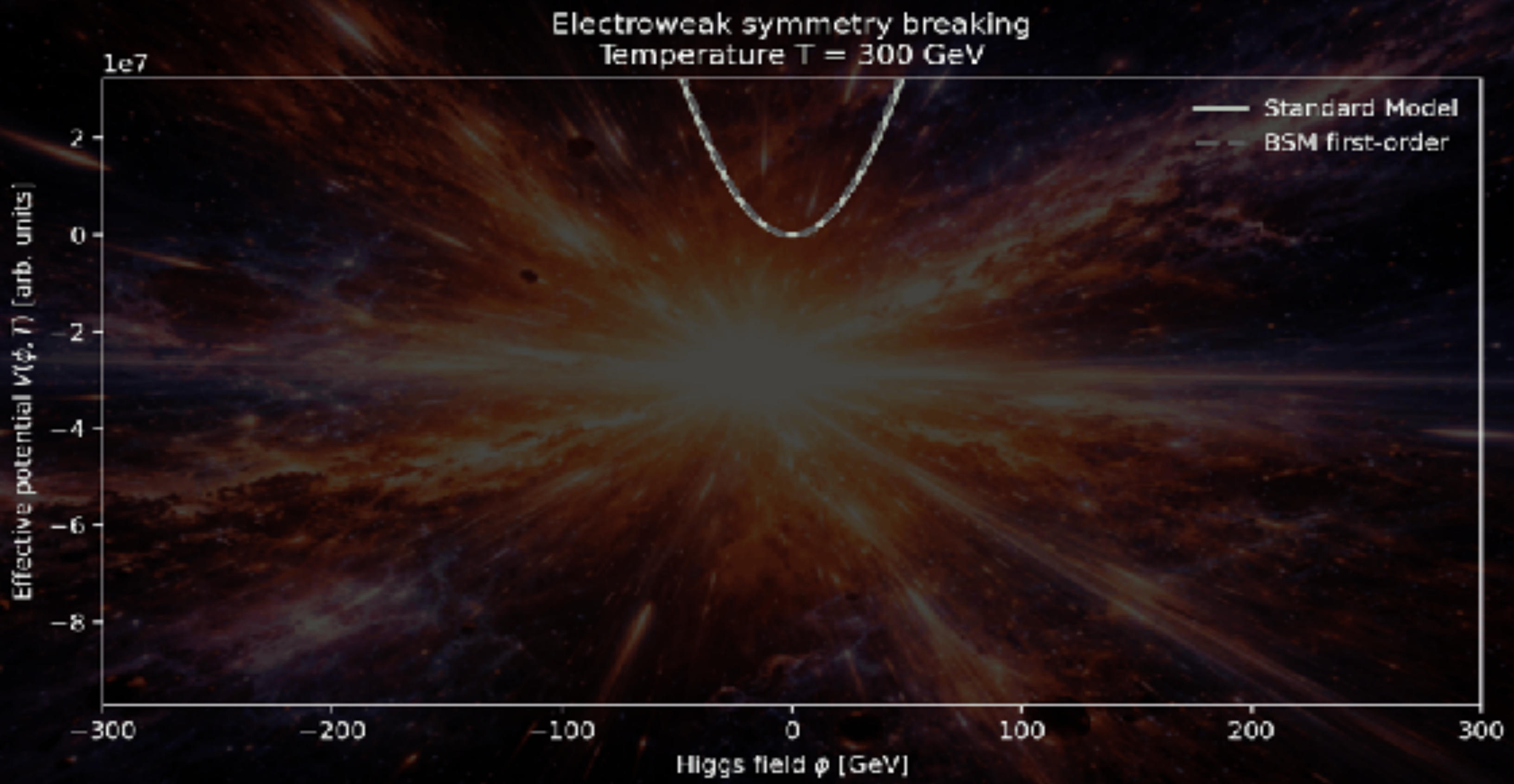
GravNet

Searching for High Frequency Gravitational Waves and Axions with Table Top Experiments

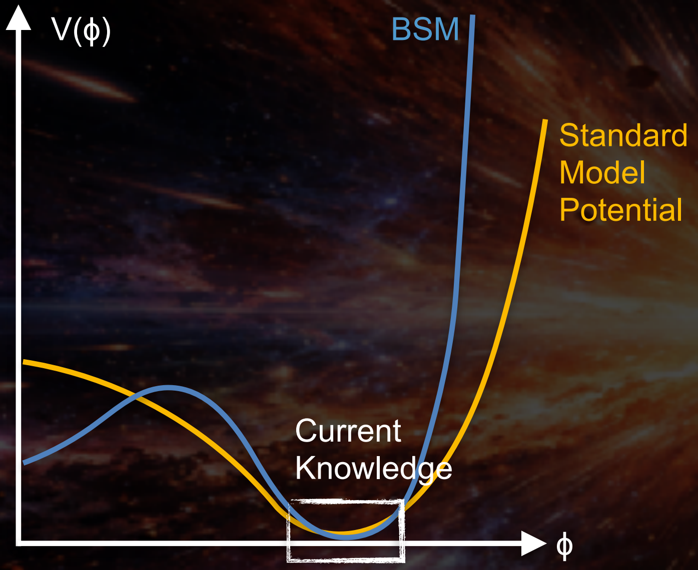
Let’s have a look at our universe



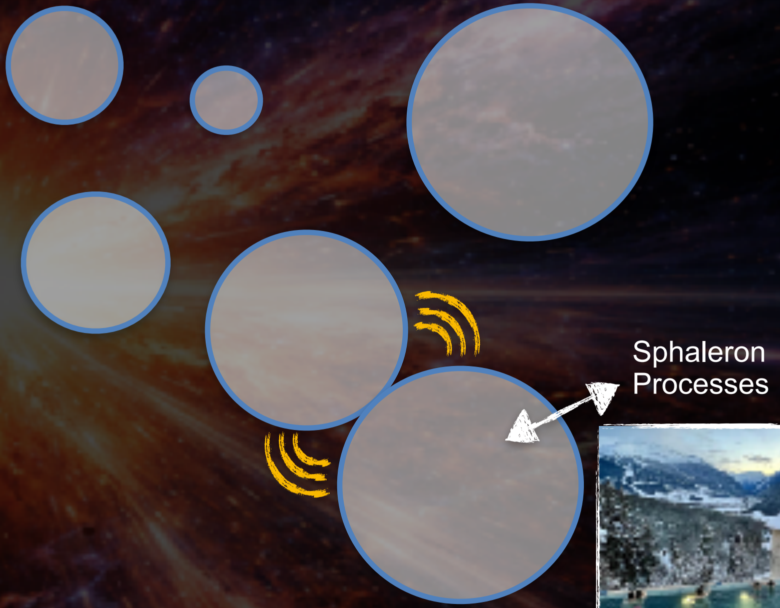
Electroweak Symmetry Breaking



Electroweak Symmetry Breaking



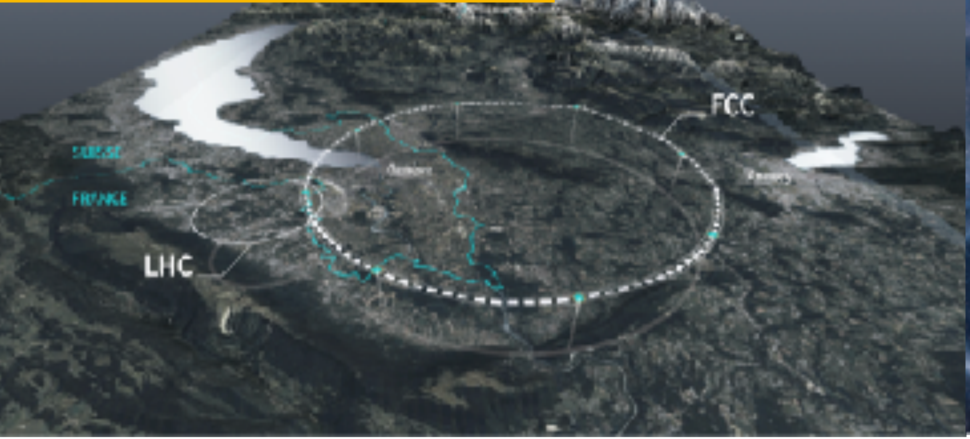
Higgs field value
in our Universe



I need to come again
to talk about Sphalerons

Probing the Higgs Potential

Particle Physics



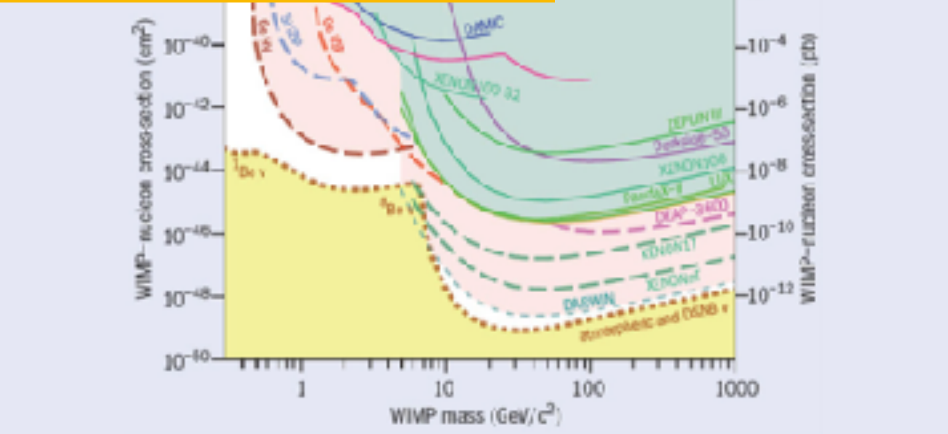
Gravitational Waves

- Build a new collider and measure the Higgs Boson self coupling

- The Higgs field changes rapidly at the wall of bubbles
  - Vacuum energy is converted into kinetic energy. This makes the wall an efficient HFGW radiator

Dark Matter

Particle Physics

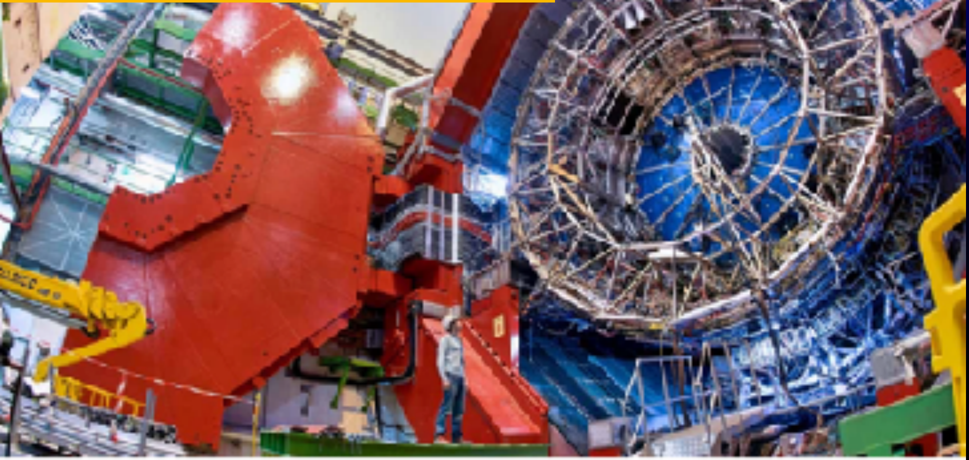


Gravitational Waves

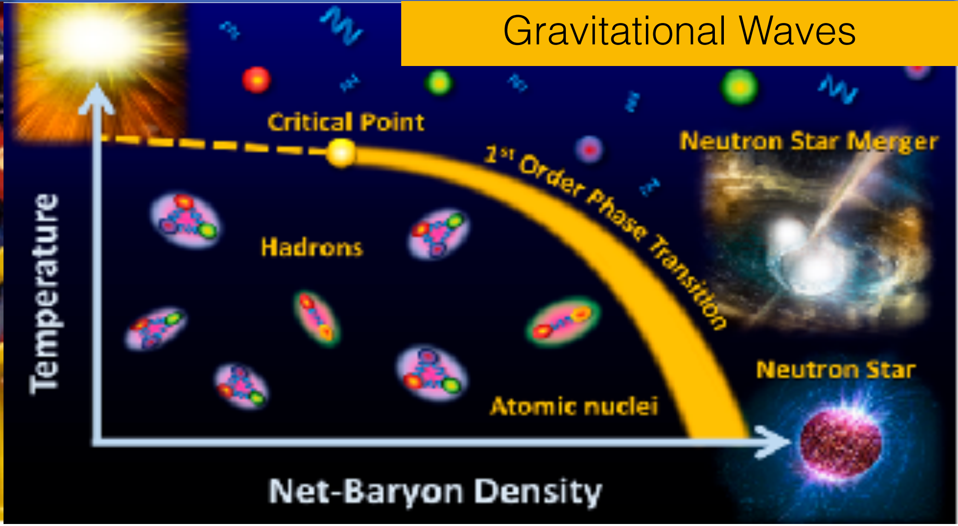
- Dark Matter might be WIMPs
  - No indication of any WIMPs at the LHC nor at any other Experiment
- New Idea: Primordial black holes!
  - should be formed in the early universe
  - Small masses 10^{-20} $M_\odot$ to $\geq 10^4$ $M_\odot$!
  - Merges of primordial black holes emit High Frequency Gravitational Waves

Neutron Stars

Particle Physics



Gravitational Waves



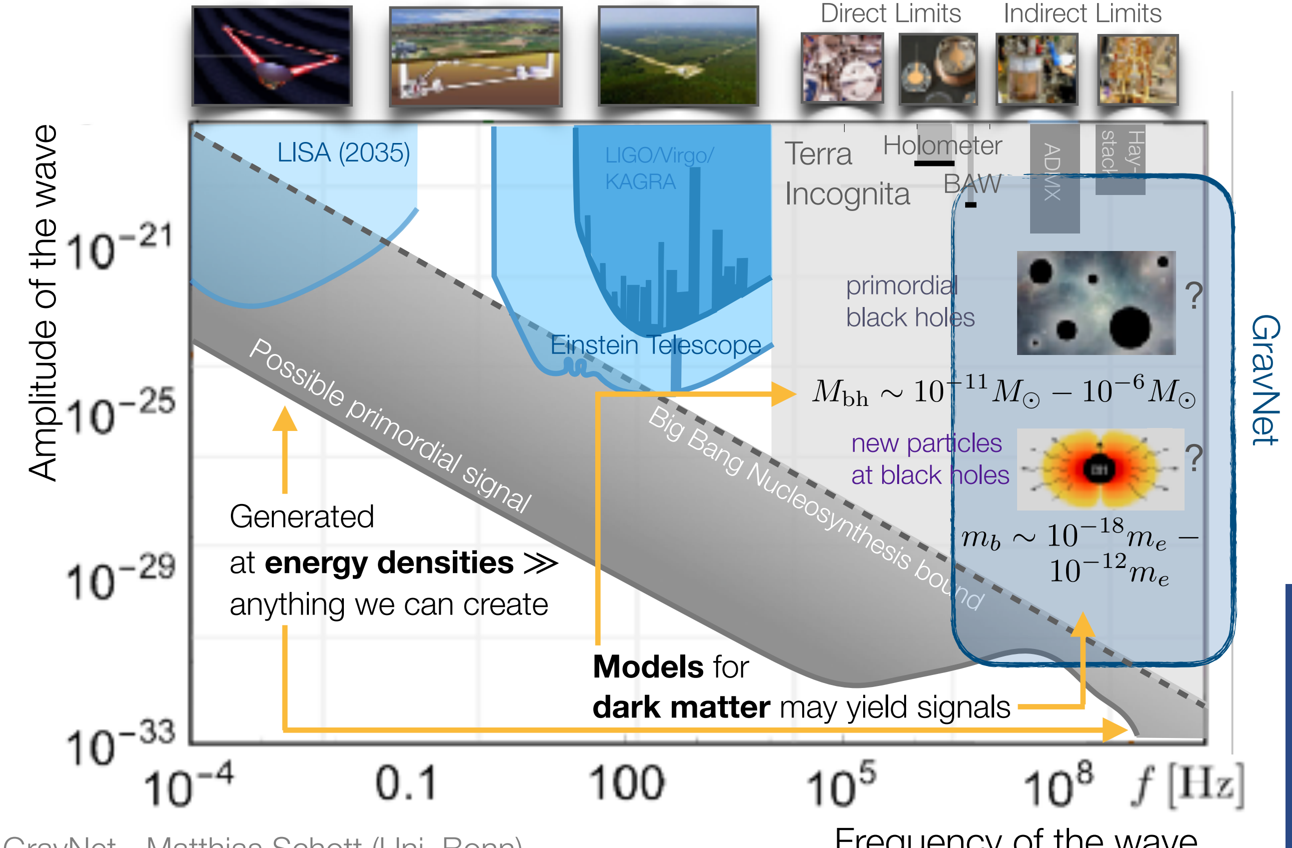
- Understand Neutron Stars by measuring Heavy Ion Collisions and the Equation of State
- Phase transitions (hadron → quark matter) within Neutron stars should emit High Frequency Gravitational Waves

What you should learn until here

- Collider experiments will never be able to answer core questions of particle physic
- High Frequency Gravitational waves are a unique new tool since gravity couples to all components of the universe

The next big breakthrough will come **from listening not from smashing**

Gravitational Wave Soundscape



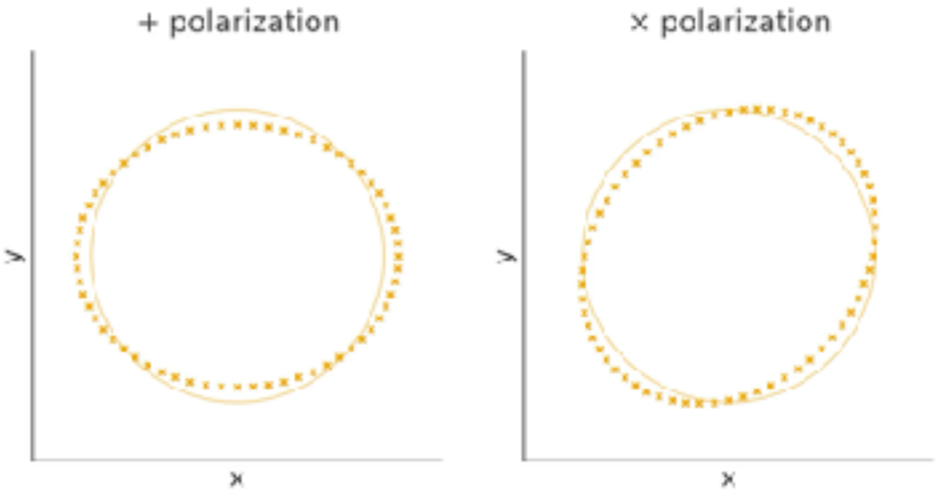
- Interesting observations below 1kHz
- Very mild limits for
  - f =1 MHz - 10 GHz

GravNet:
dedicated effort probing high-frequency gravitational waves with cavities

Basics on Gravitational Waves

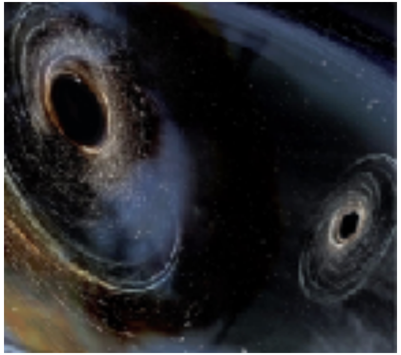
- Two polarization states
  - Don't observe polarization states of GWs directly, but the tidal forces
  - stretching and shrinking of distances quantified by the time-dependent strain h(t):

$$h(t) = \frac{\delta L(t)}{L}$$

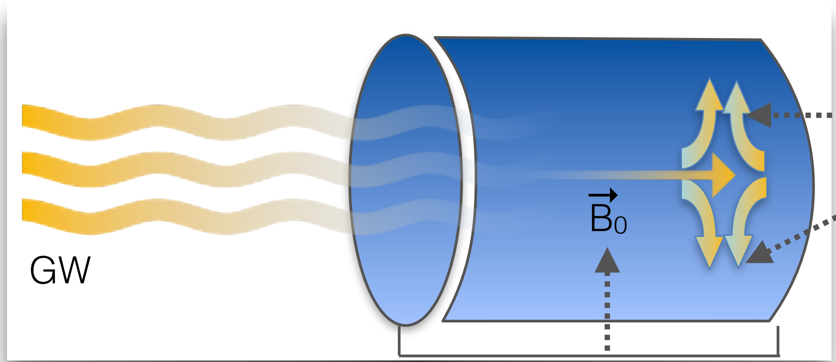


How to Detect High Frequency Gravitational Waves

- Gravitational waves convert to photons in presence of magnetic fields

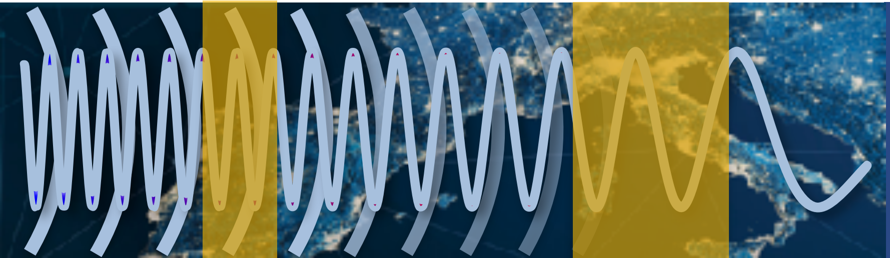


Source



Strong static magnetic field

- If photon matches **resonance** frequency of cavity, signal is enhanced and **detectable**

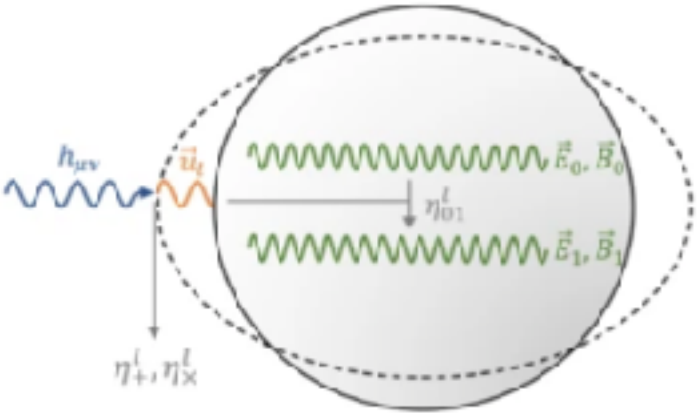


GravNet approach

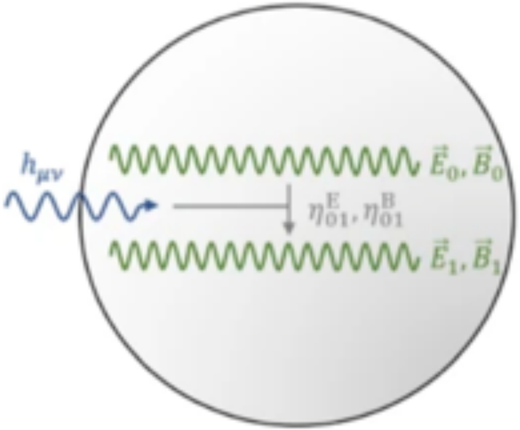
- HFGWs may sweep through frequency space
  - Focus on frequencies with best sensitivity!
- HFGWs yield coherent signals across Earth

GW Signals in electromagnetic cavities

- Mechanical coupling: GW leads to deformation of cavity boundaries
  - induces overlap between the initial eigenmodes.



- Direct coupling via the inverse Gertsenshtein effect: Conversion of GWs to EM waves in an external magnetic field

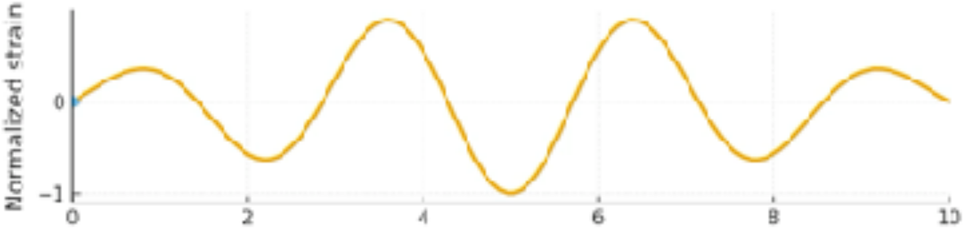


Eur.Phys.J.C 83 (2023) 12

- EM coupling much weaker than mechanical coupling at low frequencies but dominant >1 GHz

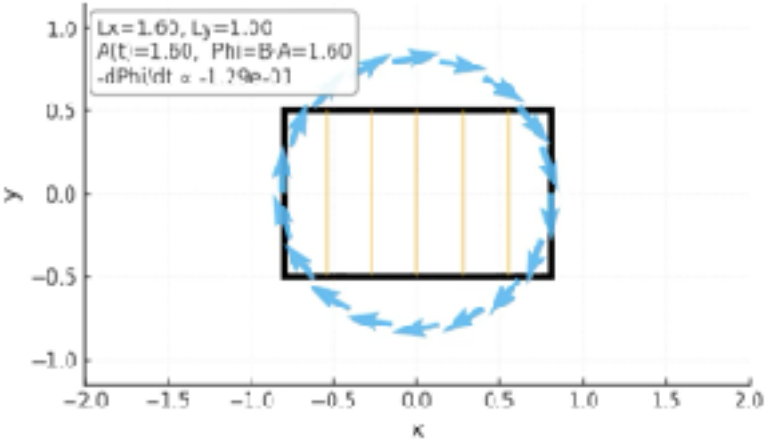
How to Detect High Frequency Gravitational Waves

- Measurement via antennas inside the cavity and read out into two part time series data



- Induced Signal Power

$$P_{sig} = \frac{1}{2} Q \, \omega_g^3 \, V_{Cav.}^{5/3} \, (\eta \cdot h_0 \cdot B_0)^2$$



- Note: Large cavity volume imply lower resonance frequencies and hence longer integration times

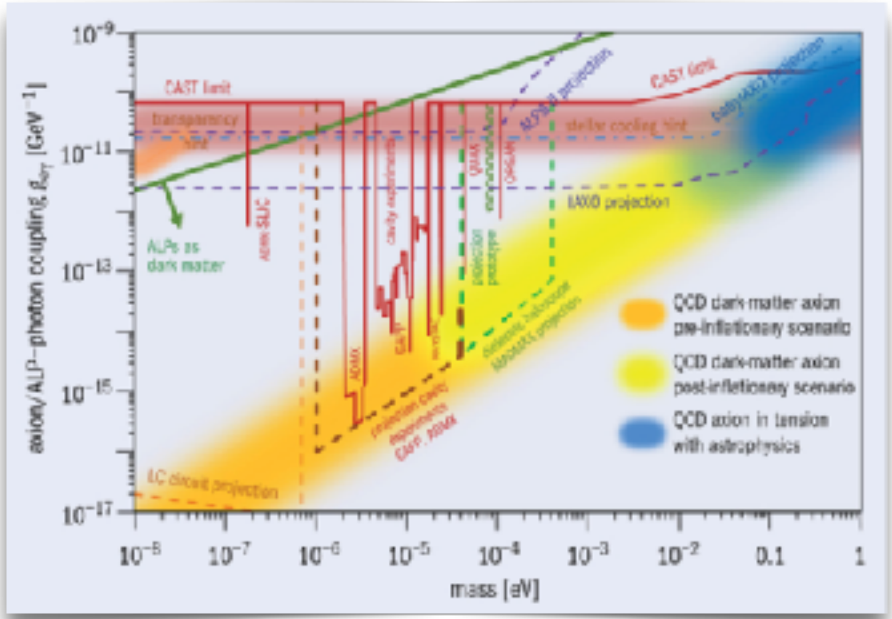
Interplay: Axion Searches

Searches for Axionic Dark Matter

- Axions could not only solve the strong CP Problem, but also good candidate for DM

- Several detection ideas
  - Light-through-Wall
  - Helioscopes
  - Colliders
  - …

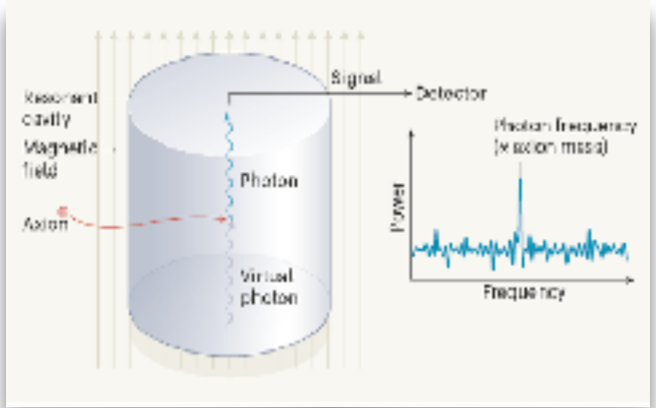
- Haloscope Experiments
  - Well-known approach: Cavity-based searches (among others: lumped circuits, spin-based haloscopes, antennas, …)
  - But also new broadband search concepts



Cavity Based Searches

- Axion can convert into photon in a magnetic field within an EM-cavity
  - If axion mass corresponds to resonance frequency of the cavity
- Cavities transverse axion-field in galaxy
- Challenges
  - only sensitive at one frequency, i.e. need to make cavity tunable
  - Very small signal power ($<10^{-24}$ W)

… well-established experimental method



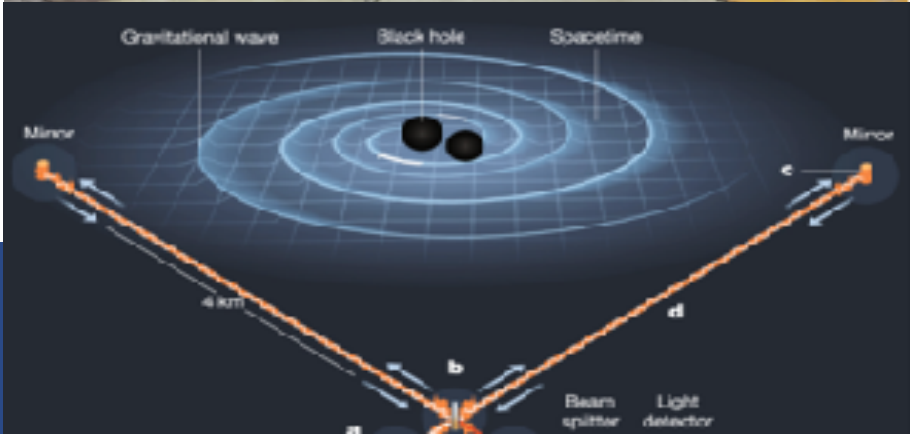
Back to Gravitational Waves

Going from Axions to Gravitational Waves

- Axion signal is different from HFGW signal
  - Duration
  - Coupling to the cavity and the magnetic field: orientation of the GW w.r.t. to B and cavity shape

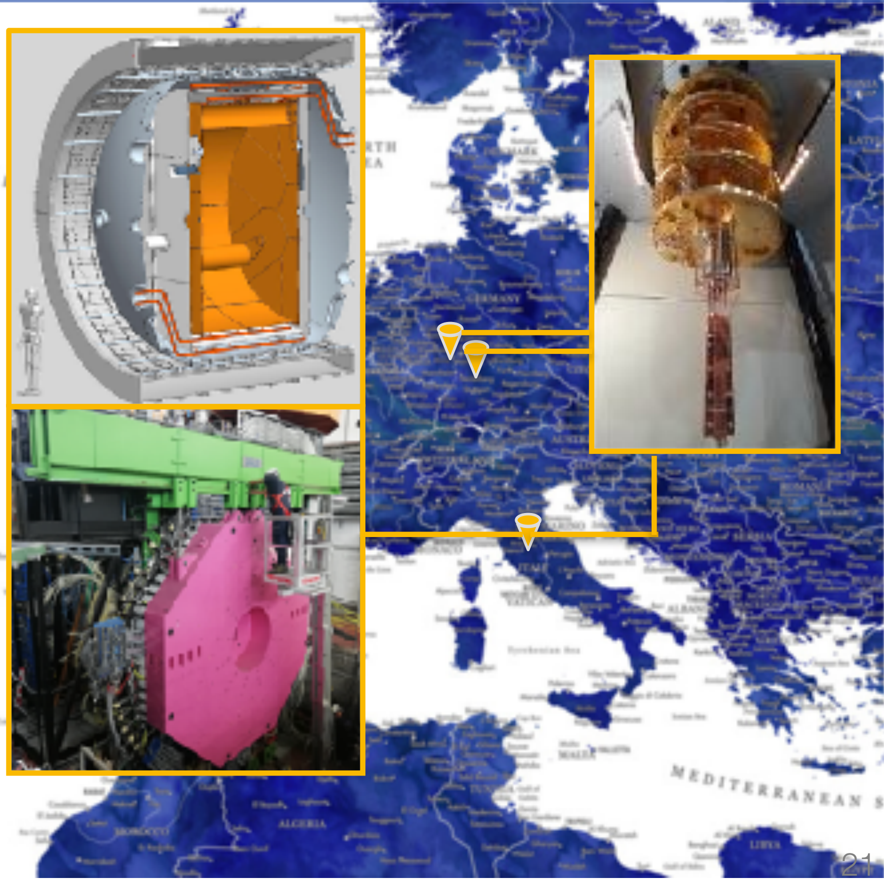
- However, same technological challenges
  - High field magnets
  - Ultra low noise amplifier
  - Highly sensitive readout systems

Everybody who searches for axions, typically can also search for HFGW



A Global Network of HFGW Detectors

- Starting point of GravNet
  - Initial sites: Bonn, Mainz, Rome
  - Technical synergies: magnets and local infrastructure already available
- GPS based data-acquisition scheme
  - Experience from GNOME Network
- Nine small resonant cavities (5-9 GHz)
  - operation of three cavities in one magnet
- One large resonant cavities (100 MHz)



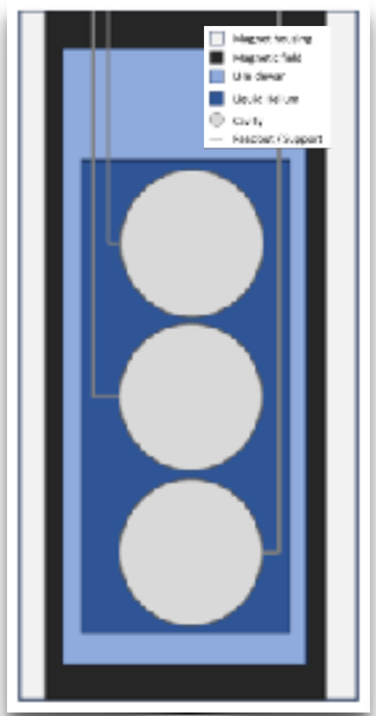
5-8 GHz Cavities

- High frequencies typically correspond to small volumes
  - Example: 8 GHz corresponds to a sphere of r≈5cm

- Challenge: Signal power depends nearly quadratically on V

$$P_{sig} = \frac{1}{2} Q \omega_g^3 V^{5/3} (\eta_n h_0 B_0)^2 \frac{1}{\mu_0 c^2}$$

- Advantages
  - Higher Magnetic Fields
  - Single Photon Readout
  - Operation of several cavities in parallel

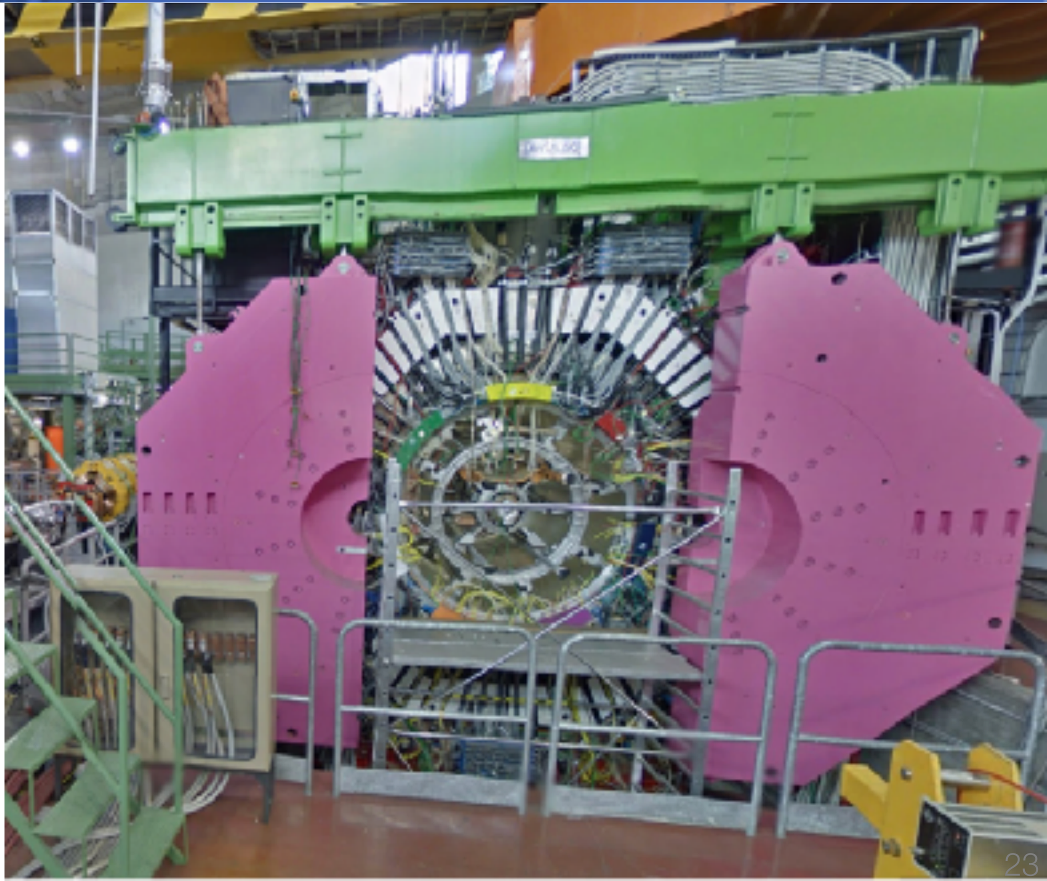


The FLASH Cavity

- Reuse of the FIDUNA magnet system at INFN Frascati within the FLASH Experiment
  - Axion Search (0.49-1.49 μeV)
  - Res. Frequency: 100-300 MHz

- Magnet Properties
  - $V = 4.15\ m^3$, $B=1.1T$
  - $Q_L = 1.4x10^5$, $T_{sys} = 4.9K$

- Readout
  - SQUID Readout
  - Limited by thermal noise



R&D Efforts

Drastically reduce noise in readout

- Use of quantum sensing revolution
- Quantum non-demolition measurements
- Entanglement in two-qubit devices

Optimize Cavity

- Shape to improve coupling
- Enhance quality factor with superconductors

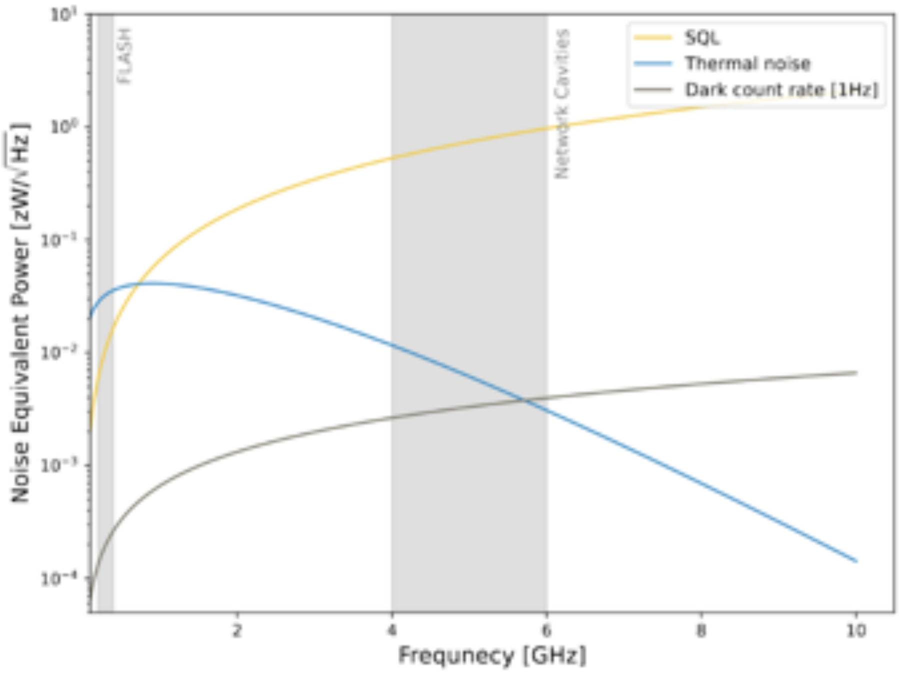
Optimize Data Analysis

- Precise signal modelling
- Advanced neural networks for combined data analyses

GravNet Goal: gain in sensitivity to amplitude by O(100) - O(1000)

Noise at the Readout

- Quantum amplifiers (SQUIDs or JPAs)
  - Optimal for f < 1 GHz
  - Quantum noise (SQL) < 50 mK
- Quantum sensors based on superconducting qubits
  - Optimal for f > 1 GHz
  - Quantum noise (SQL) > 50 mK
- QS get dark counts to thermal limit
  - Quantum non-demolition measurements
  - Entanglement in two-qubit device

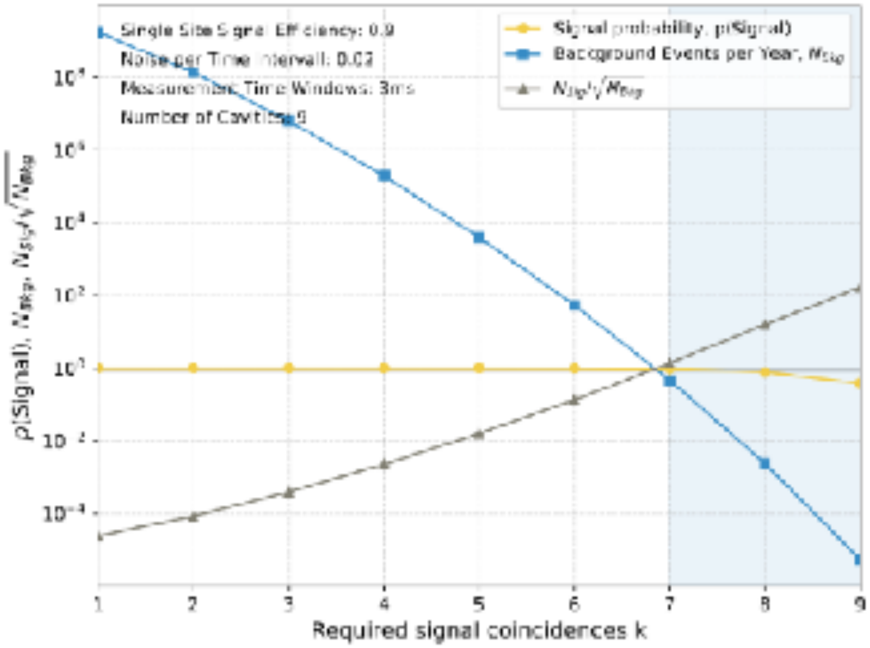


Expectations

- We expect about 1 transient signal per year with a duration of 3 ms

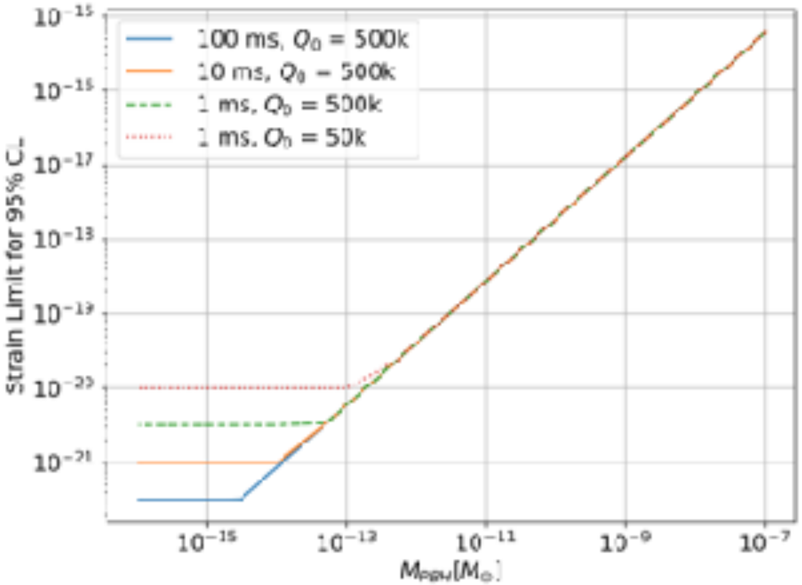
- Interpret situation as counting experiment
  - Thermal/quantum noise yields a certain number of photons per time-interval

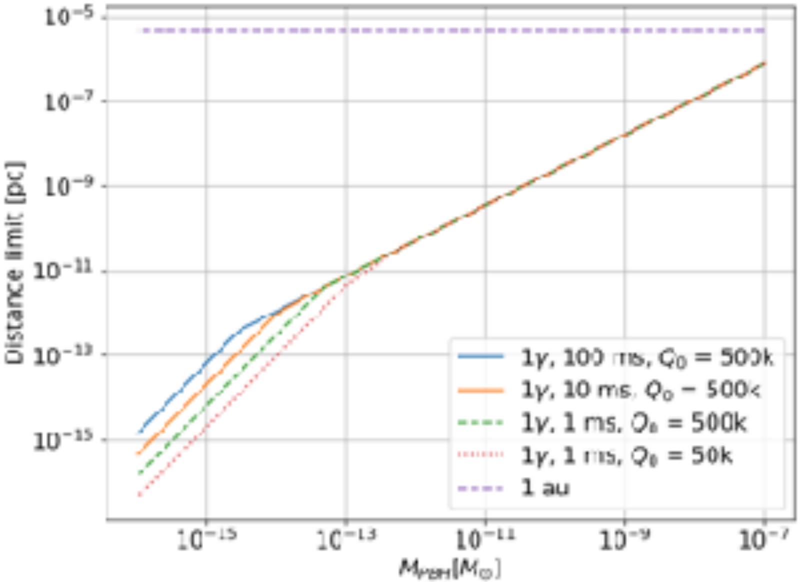
- Gain combinatorially in background rejection when combining sites
  - No background problem as long as $p_{signal} > p_{background}$



- Relevant quantity: Induced power should be in the order of O(1) photon

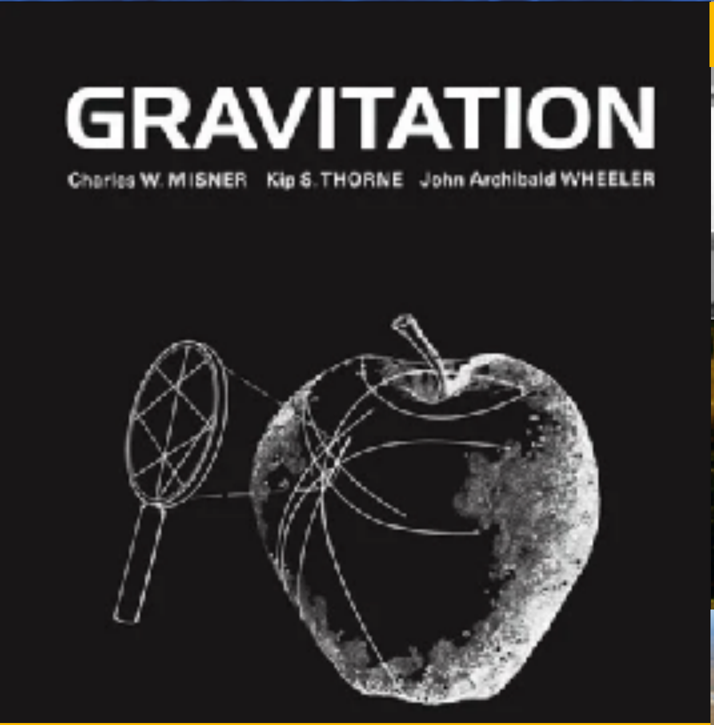
GravNet: Expected Sensitivities





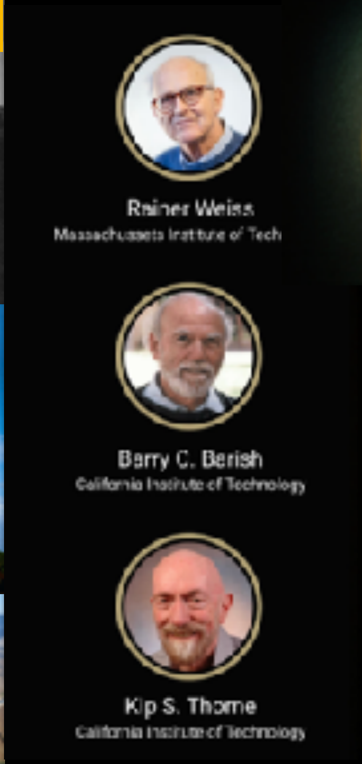
- Limit for Primodial Black Hole Mergers
  - Only a few orders of magnitude missing

Isn't this depressive?



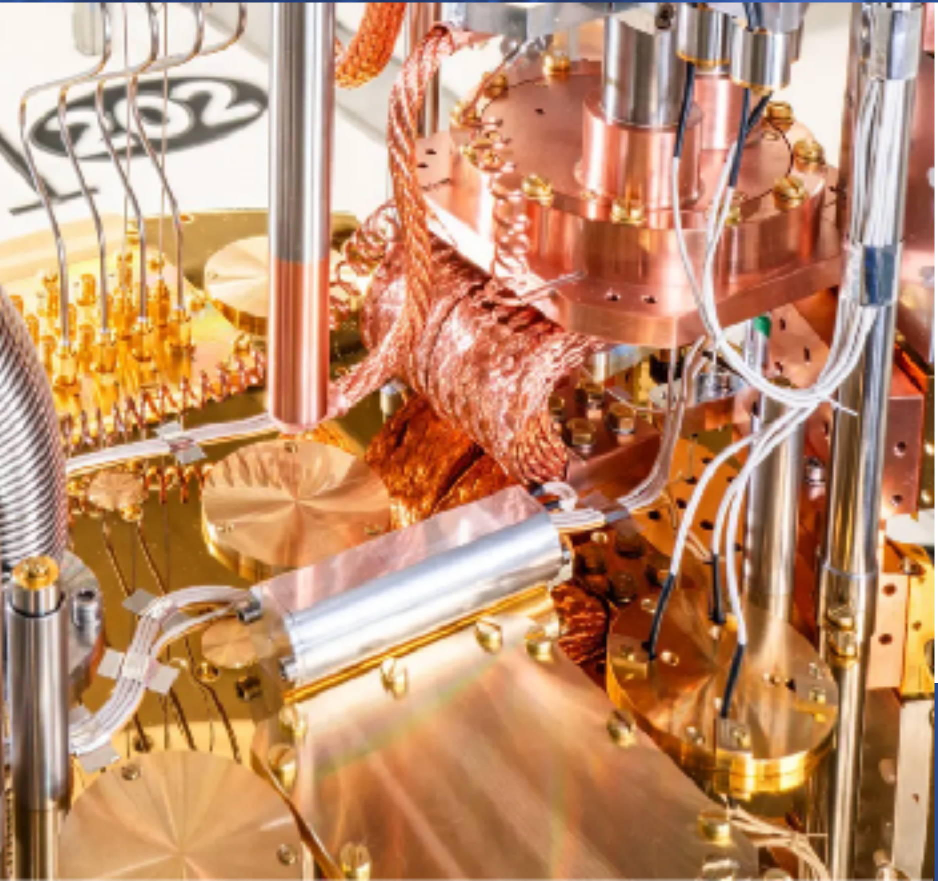
"[interferometers] have so low sensitivity that they are of little experimental interest"

50 years of work



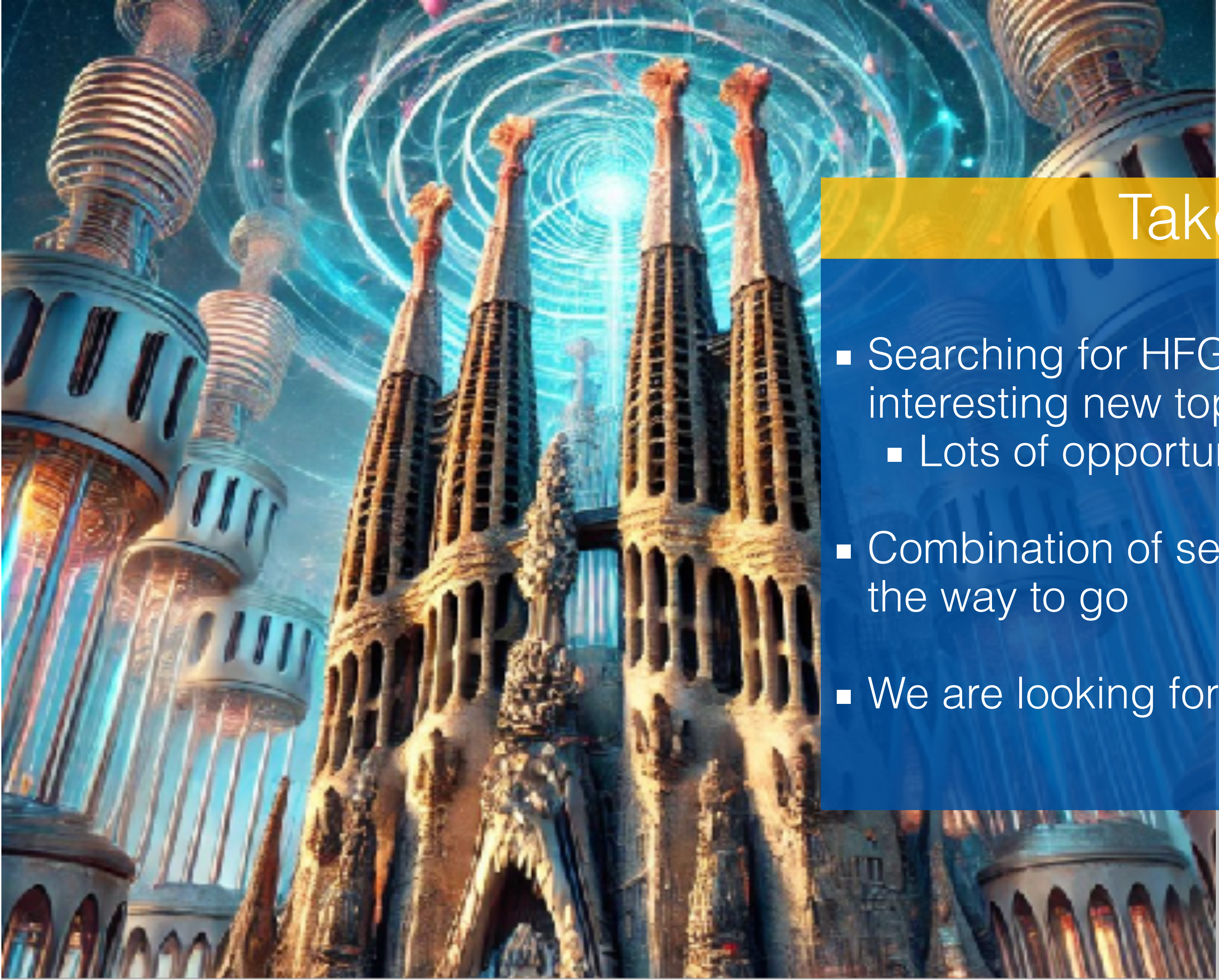
Nobel Prize 2017

Which Technologies to Choose?



- GravNet will start with cavities since their technology is mature
- Most interesting HFGW sources are transient
  - Any HFGW search will profit from combining signals
  - Most developments (Quantum sensing, Superconducting cavities, analysis) is from generic use
  - Magnetic fields and ultra cold volumes are used in most approaches

We will switch to the most promising experimental approach in the next years



Take Away Messages

- Searching for HFGW is one of the most interesting new topics in town
  - Lots of opportunities, lots of challenges
- Combination of several detector concepts is the way to go
- We are looking for new collaborators