Quantum Fields as sensors for fundamental physics

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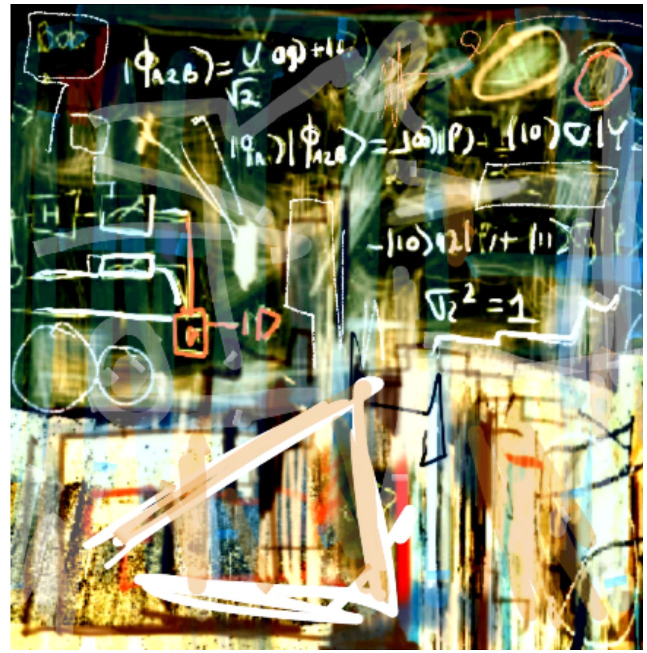
Thanks to people in my group that contributed



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Thanks to collaborators:

Theory
David Bruschi (Saarlandes)
Jorma Louko (Nottingham)
Gerardo Adesso (Nottingham)
Christian Käding (Nottingham)

Experiment
Philippe Bouyer (CNRS)
Chris Westbrook (l'Institut d'Optique, Palaiseau)
Ernst Rasel (Hannover)
Devang Naik (CNRS)
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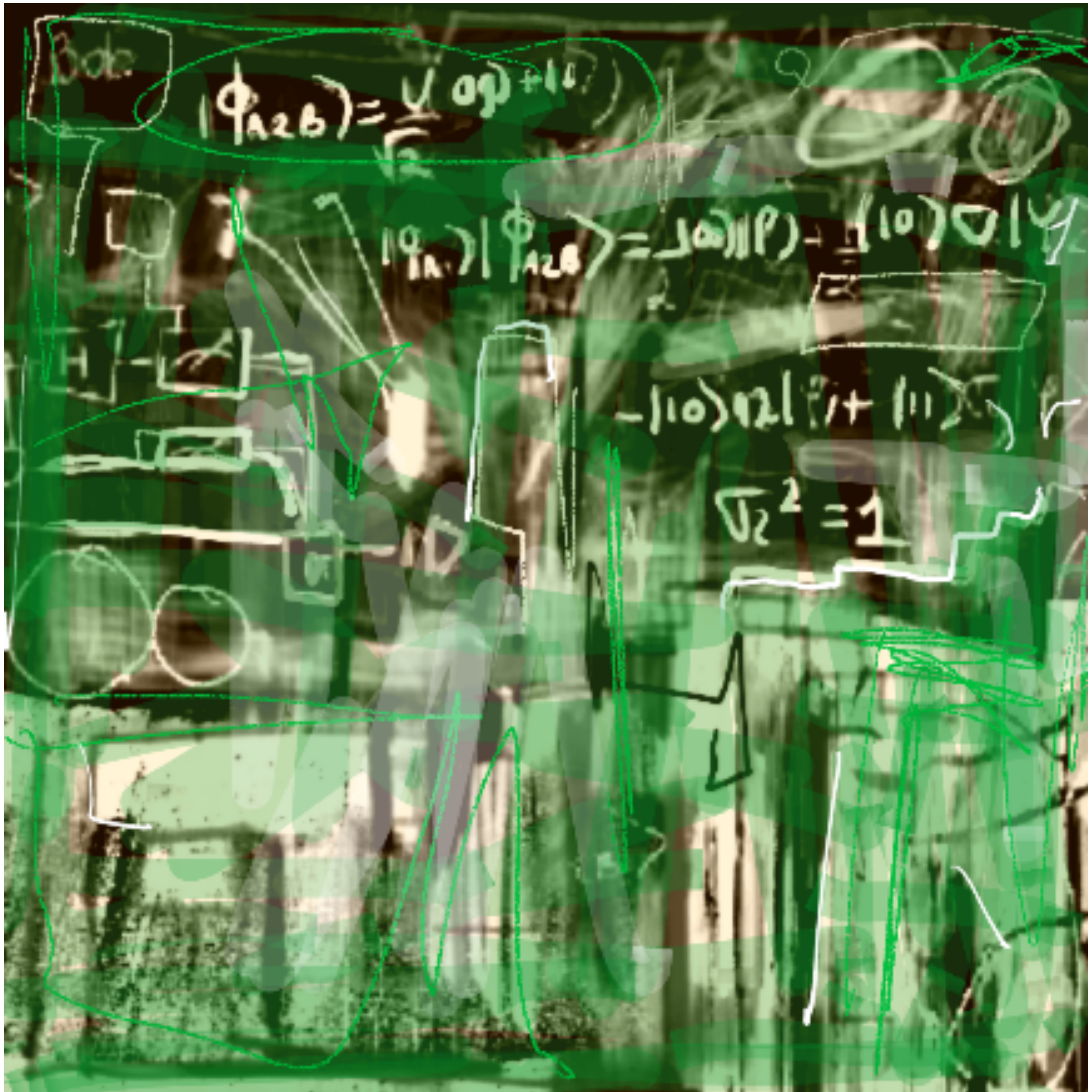
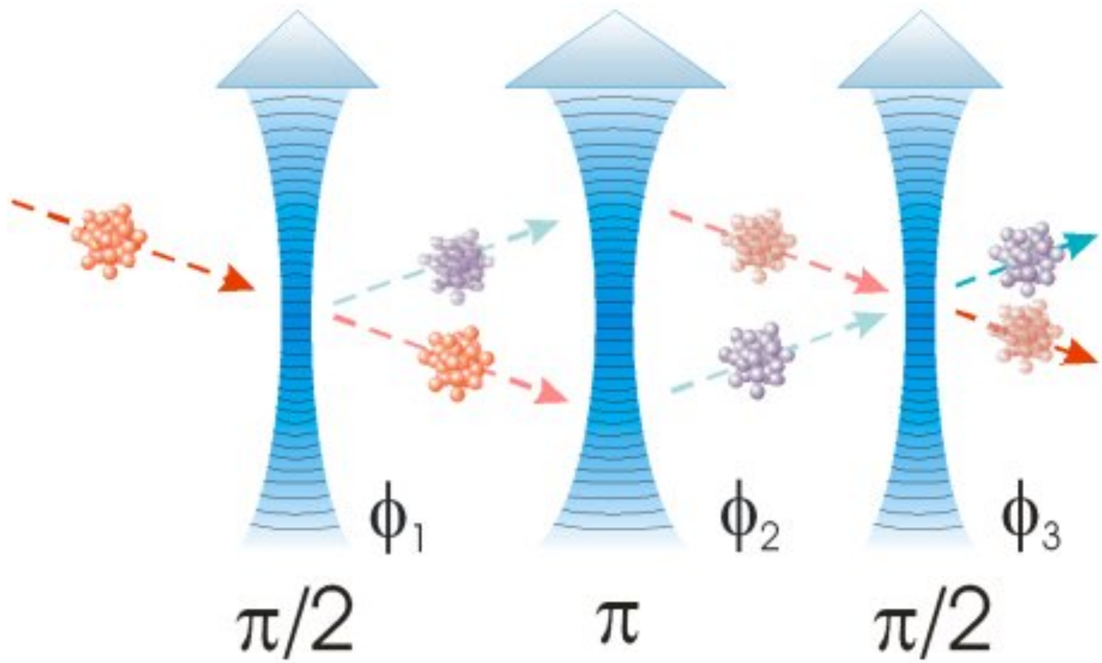
http://rqinottingham.weebly.com/

Motivation



Atom interferometer

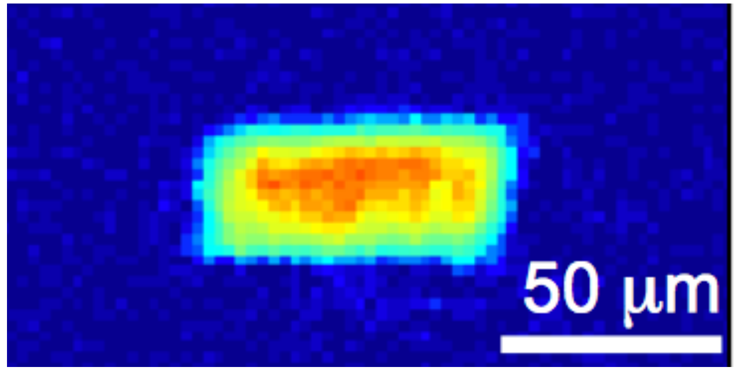


Single particle detector, local

Interferometry in the spatial domain: limited by time of flight

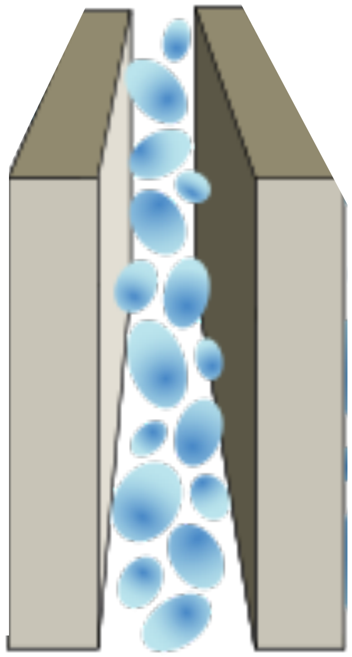
Compatible with Newtonian physics

Phononic detector



- Uses interactions: collective excitations, entanglement between atoms
- Interferometry in the frequency (time) domain, non-local
- We use parametric amplification produced by the non-linearity introduced by atomic collisions
- Compatible with General Relativity

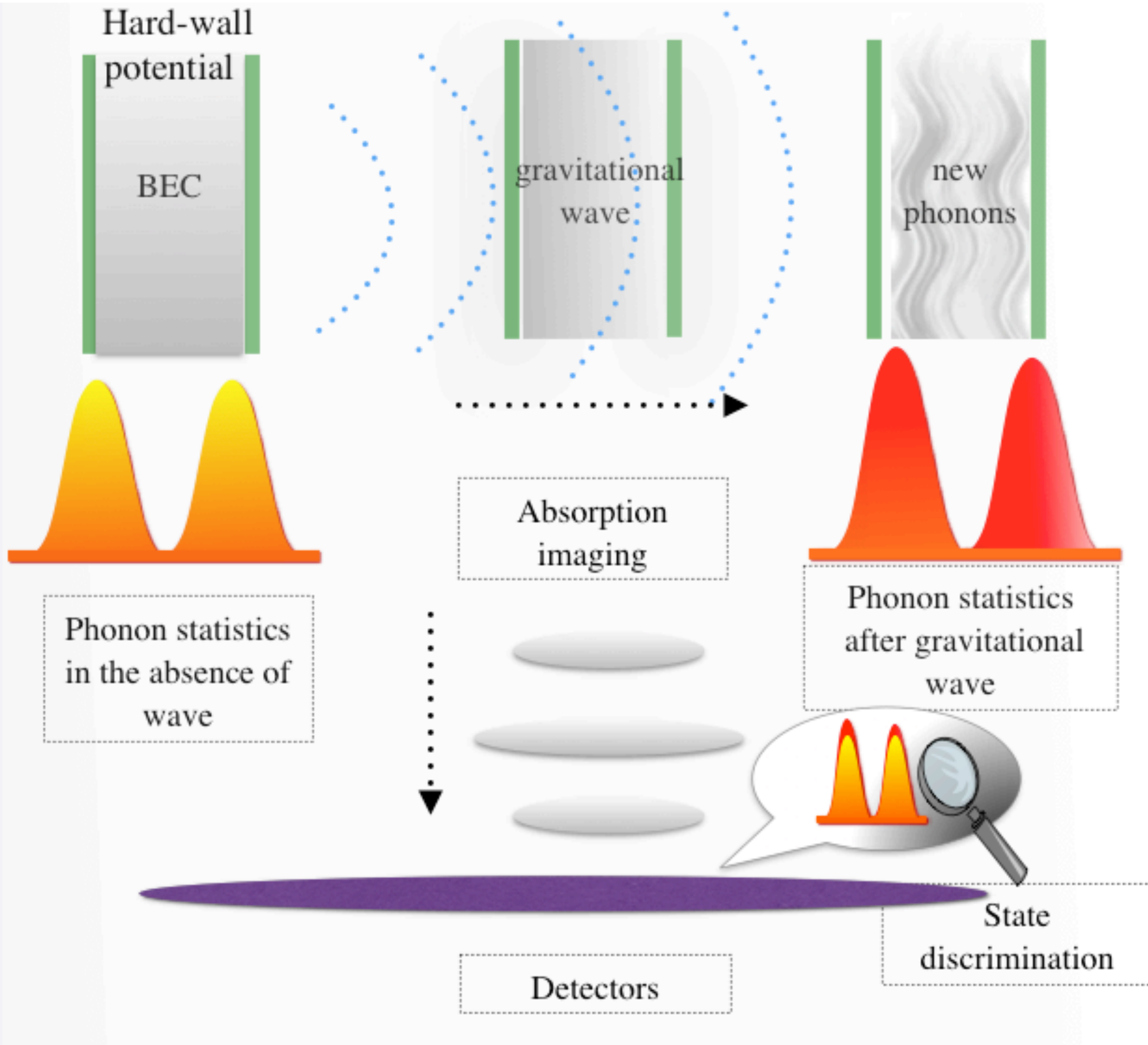
Advantages of using phonons



- Can be miniaturized
- High sensitivity
- High resilience to noise

Applications in GR

- Gravitational waves
- Dark energy
- Proper acceleration
- Local gravitational fields (gravimetry)
- Gravitational gradients (gradiometry)
- Curvature
- Spacetime parameters
- Dark Matter!



Hard-wall potential
BEC
gravitational wave
new phonons
Phonon statistics in the absence of wave
Absorption imaging
Phonon statistics after gravitational wave
State discrimination
Detectors

Different principle

Interferometer arm length L

$$\frac{\Delta L}{L}$$

Resonance

$$\Omega = \omega_n + \omega_m$$

wave

quantum excitations

Weber bar

T~ 4 K

Quantum Weber Bar

Temperature

Weber bar	BEC
$T \sim 4$ K	$T \sim 5 \times 10^{-10}$ K

Initial quantum states
Squeezing
Parametric amplification

How can it work if its so small?

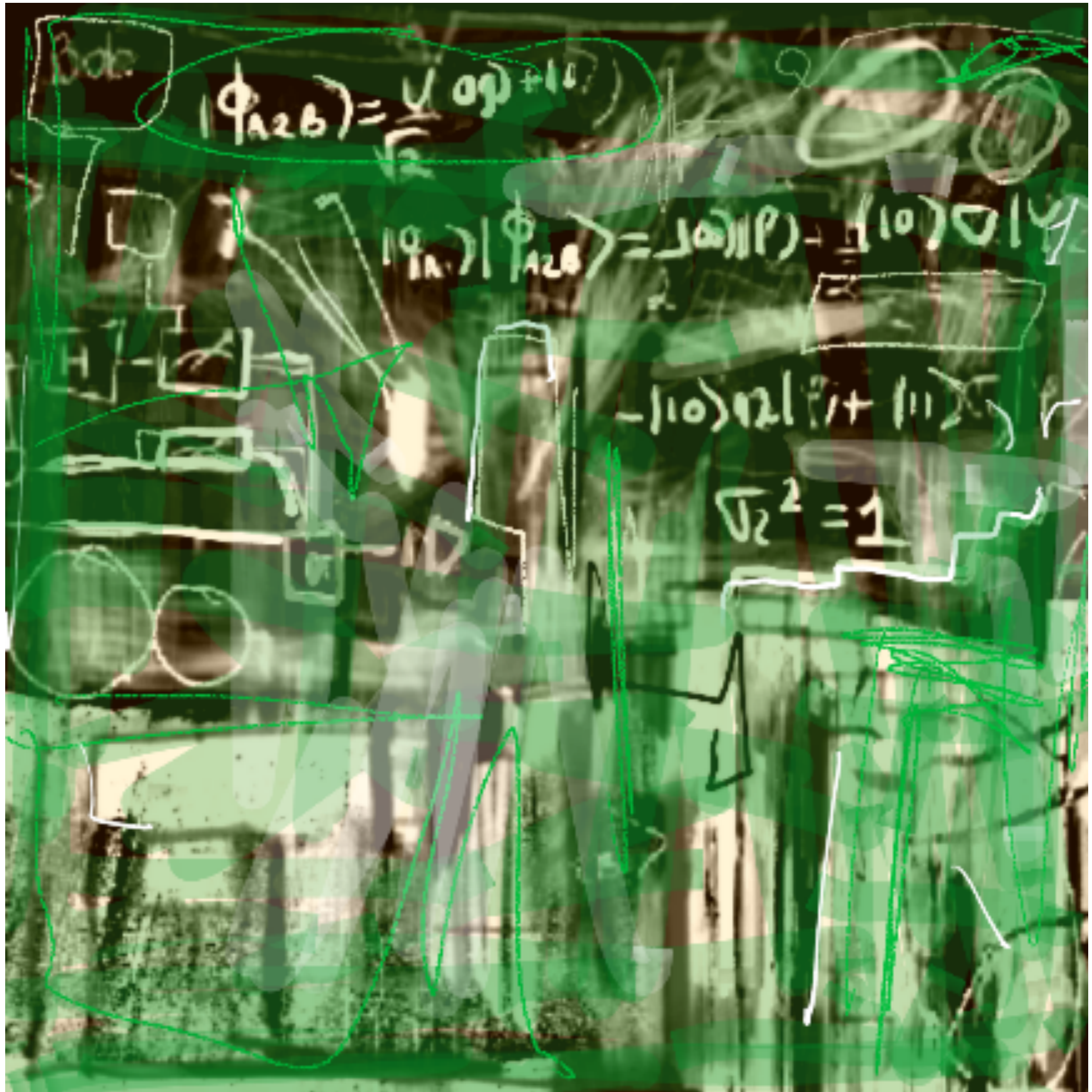
$$\omega \sim \frac{C_s}{L}$$

$$\omega \sim \frac{C}{L}$$

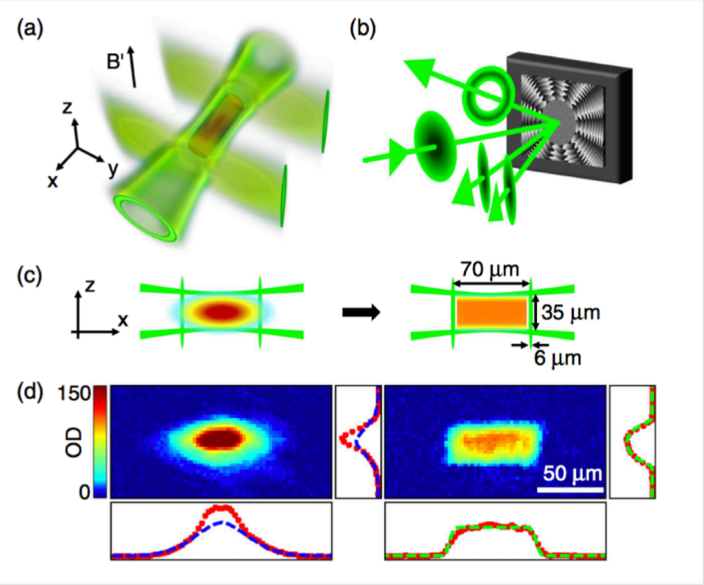
Speed of sound: $C_s = 10\text{mm/s}$
$L = 10^{-1}\text{-}10^{-3}\text{mm}$

Speed of light: C= $2.99\text{x}10^{11}$mm/s
L =2.99Km-2990Km

QFT description of a BEC



Bose Einstein Condensate in a box



mean field (ground state)

$$\hat{\Phi} = \phi(1 + \widehat{\psi})$$

phonons

density fluctuations due to interactions

quasi-uniform density

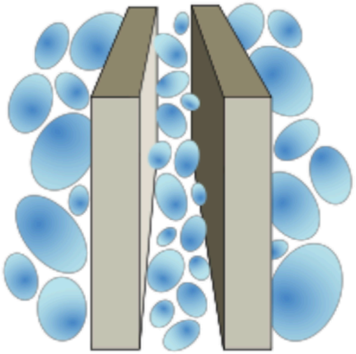
$$\rho = \phi^{\dagger}\phi$$

Gaunt *et. al.* PRL 110 200406 (2013)

BEC in spacetime

A covariant formalism is available

Phonons are a relativistic quantum field



$$\mathcal{L} = -\sqrt{-g}\left\{g^{\mu\nu}\partial_\mu\hat{\Phi}^\dagger\partial_\nu\hat{\Phi} + \left(\frac{m^2c^2}{\hbar^2} + V\right)\hat{\Phi}^\dagger\hat{\Phi} + U\left(\hat{\Phi}^\dagger\hat{\Phi}, \lambda_i\right)\right\}$$

$$U\left(\hat{\Phi}^\dagger\hat{\Phi}, \lambda_i\right) \approx \frac{\lambda}{2}\hat{\Phi}^\dagger\hat{\Phi}^\dagger\hat{\Phi}\hat{\Phi}$$

$$\widehat{\Phi} = \phi(1 + \widehat{\psi})$$

For uniform density

$$\Box\,\psi = \frac{1}{\sqrt{-\mathfrak{g}}}\partial_\mu(\sqrt{-\mathfrak{g}}\mathfrak{g}^{\mu\nu}\partial_\mu)\psi$$

effective metric

$$\mathfrak{g}_{ab} = \rho\frac{c}{c_s}\left[g_{ab} + \left(1 - \frac{c_s^2}{c^2}v_a v_b\right)\right]$$

spacetime metric

analogue metric

Demonstrate QFT in CS

Fagnocchi et. al NJP 2010 (quantum field flat spacetime)
Visser & Molina-Paris NJP 2010 (classical field in curved spacetime)
D. E. Bruschi et. al., NJP 16 5:053041, 2014 (quantum field in curved spatime)
D. Hartley. et. al., PRD 89 025011, 2018

Quantum field theory basics

field equation: Klein Gordon $\Box \Phi = 0$

$$\Box = (\sqrt{-g})^{-1} \partial_\mu \sqrt{-g} g^{\mu\nu} \partial_\nu$$

determinant of the metric

metric

solutions

$$\Phi = \sum_n [\phi_n a_n + \text{h.c.}]$$

creation and annihilation operators

Cavity at rest

Minkowski coordinates (t, x)

$$\Box\phi(t,x) = 0$$ field equation

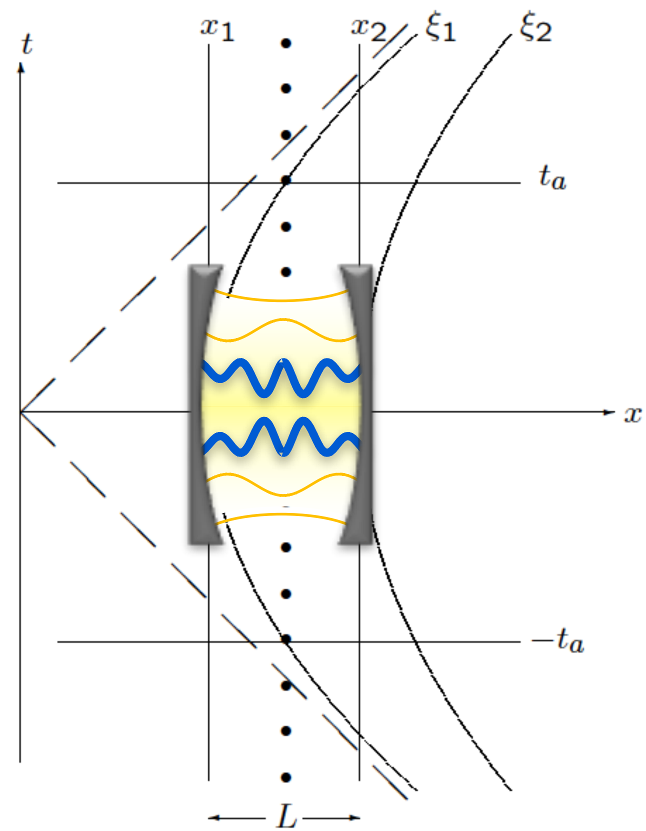
solutions: plane waves+ boundary

$$u_k(x,t) = \frac{1}{\sqrt{k\pi}} \sin\left[\frac{k\pi}{L}(x - x_A)\right] e^{-i\omega_k t},$$

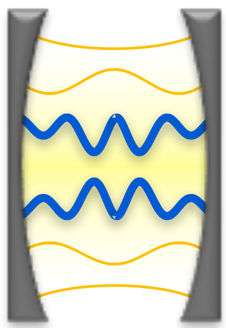
$$\omega_k = \frac{1}{L}\sqrt{(k\pi)^2 + m^2},$$

creation and annihilation operators

$$\hat{\phi}(x,t) = \sum_n (u_n(t,x)\hat{a}_n + u_n^*(t,x)\hat{a}_n^\dagger)$$



BEC in flat spacetime



$$\mathfrak{g}_{ab} = \left(\frac{n_0^2\, c_s^{-1}}{\rho_0 + p_0}\right) \begin{pmatrix} -c_s^2 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Minkowski space but with speed of sound

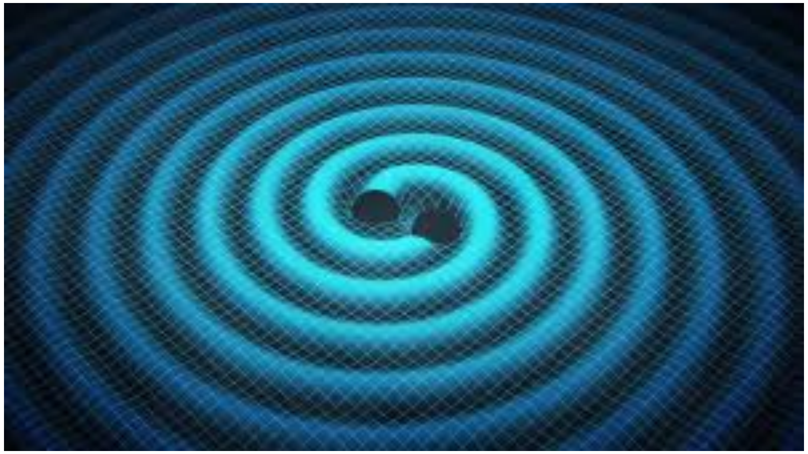
$$\tau = (c/c_s)t \;\Rightarrow\; ds^2 = -cdt^2 + dx^2$$

phonons in a cavity-type 1-dimensional trap

$$\omega_n = \frac{n\,\pi\,c_s}{L}$$ spectrum

$$\phi_n = \frac{1}{\sqrt{n\,\pi}} \sin\frac{n\pi(x - x_L)}{L}\, e^{-i\,\omega_n\,t}$$ Solutions to the K-G equation

Gravitational wave spacetime



$$\mathfrak{g}_{ab} = \left(\frac{n_0^2\, c_s^{-1}}{\rho_0 + p_0}\right) \begin{pmatrix} -c_s^2 & 0 & 0 & 0 \\ 0 & 1 + h_+(t) & h_\times(t) & 0 \\ 0 & h_\times(t) & 1 - h_+(t) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

In a one-dimensional trap

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

$$ds^2 = -c_s^2\, dt^2 + (1 + h_+(t))\, dx^2.$$

$$h_{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+(t) & h_\times(t) & 0 \\ 0 & h_\times(t) & -h_+(t) & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

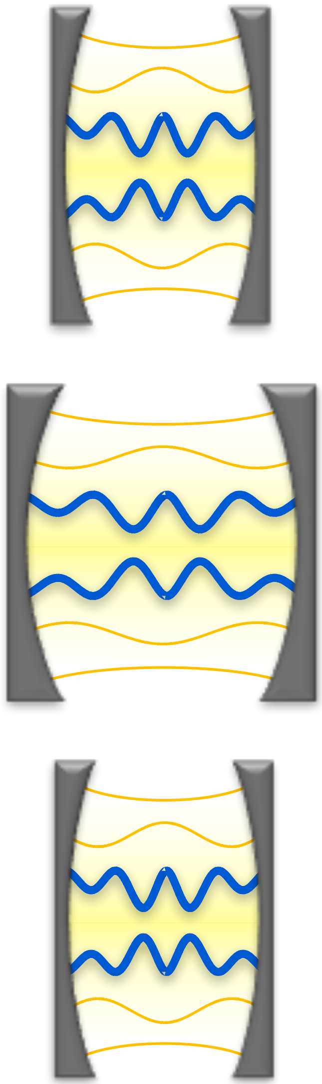
$$h_+(t) = \epsilon \sin \Omega\, t$$

$$\omega_n = \frac{n\, \pi\, c_s}{L}$$

Resonance!

Field transformations

Bruschi, Fuentes & Louko PRD (R) 2011



Bogoliubov transformations

$$\tilde{a}_m = \sum_n \left(\alpha^*_{mn}\, a_n - \beta^*_{mn}\, a^\dagger_n \right)$$

$$\alpha_{mn} = (\tilde{\phi}_m, \phi_n) \text{ and } \beta_{mn} = -(\tilde{\phi}_n, \phi^*_m)$$

$$h = aL$$

acceleration

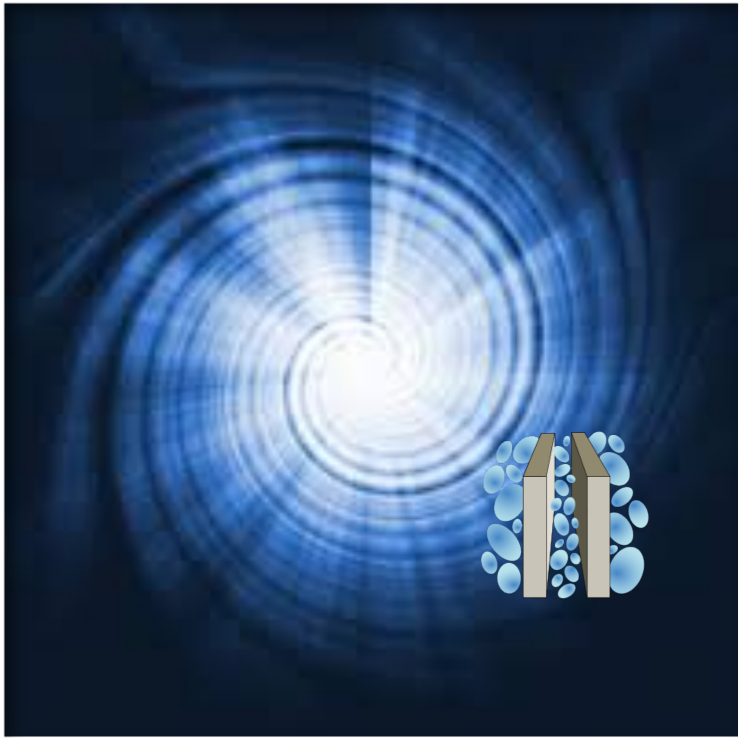
length

$$\alpha = \alpha^{(0)} + \alpha^{(1)} + \alpha^{(2)} + O(h^3)\,,$$

$$\beta = \beta^{(1)} + \beta^{(2)} + O(h^3)\,,$$

computable transformations

Phonon creation by gravitational waves



Sabin, Bruschi, Ahmadi, and Fuentes, NJP 2014

Probe state: Two-mode squeezed state

$$\boldsymbol{\sigma} = \begin{pmatrix} \cosh 2r\,\mathbf{1} & \sinh 2r\,\boldsymbol{R}_\theta \\ \sinh 2r\,\boldsymbol{R}_\theta & \cosh 2r\,\mathbf{1} \end{pmatrix},$$

$$\mathbf{1} := \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix},$$

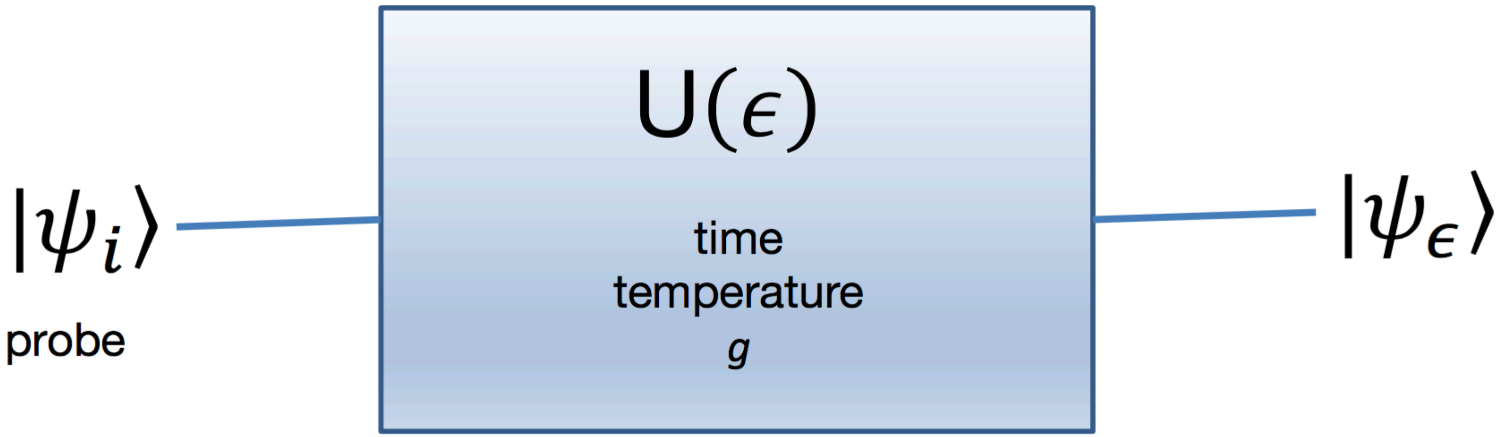
$$\boldsymbol{R}_\theta := \begin{pmatrix} \cos\theta & \sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix}.$$

Bogoliubov coeficients

$$\beta_{jk}(t) = -\frac{\epsilon}{2}\sqrt{\frac{n}{m}}\,\omega_m\, t\,[-x_L + (-1)^{m+n}(L + x_L)]\delta_{jm}\,\delta_{kn} + \mathcal{O}(\epsilon^2)$$

$$\alpha_{jk}(t) = 0 + \mathcal{O}(\epsilon^2),$$

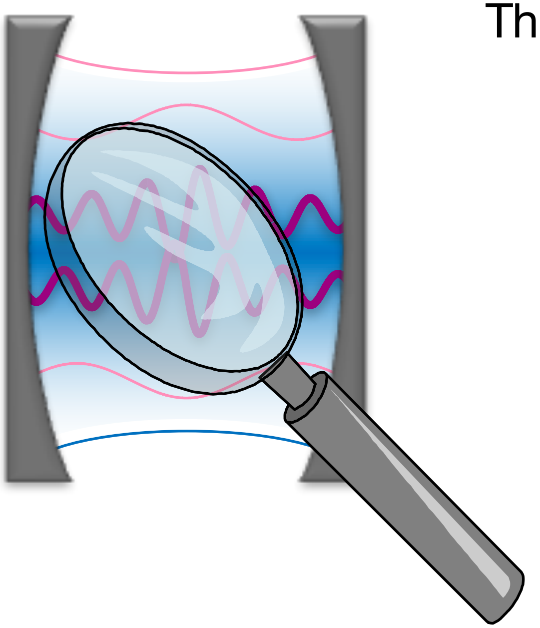
Quantum Metrology



$$\langle \psi_\epsilon | \psi_{\epsilon + d\epsilon} \rangle \ll 1$$

Exploit quantum properties of the probe state to estimate with high precision parameters in the theory (Hamiltonian)

Quantum Metrology



There is an optimal measurement such that

parameter

$$\langle (\Delta \hat{\epsilon})^2 \rangle \geq \frac{1}{M\, H_\epsilon}$$

Error

Quantum Fisher information

M number of measurements

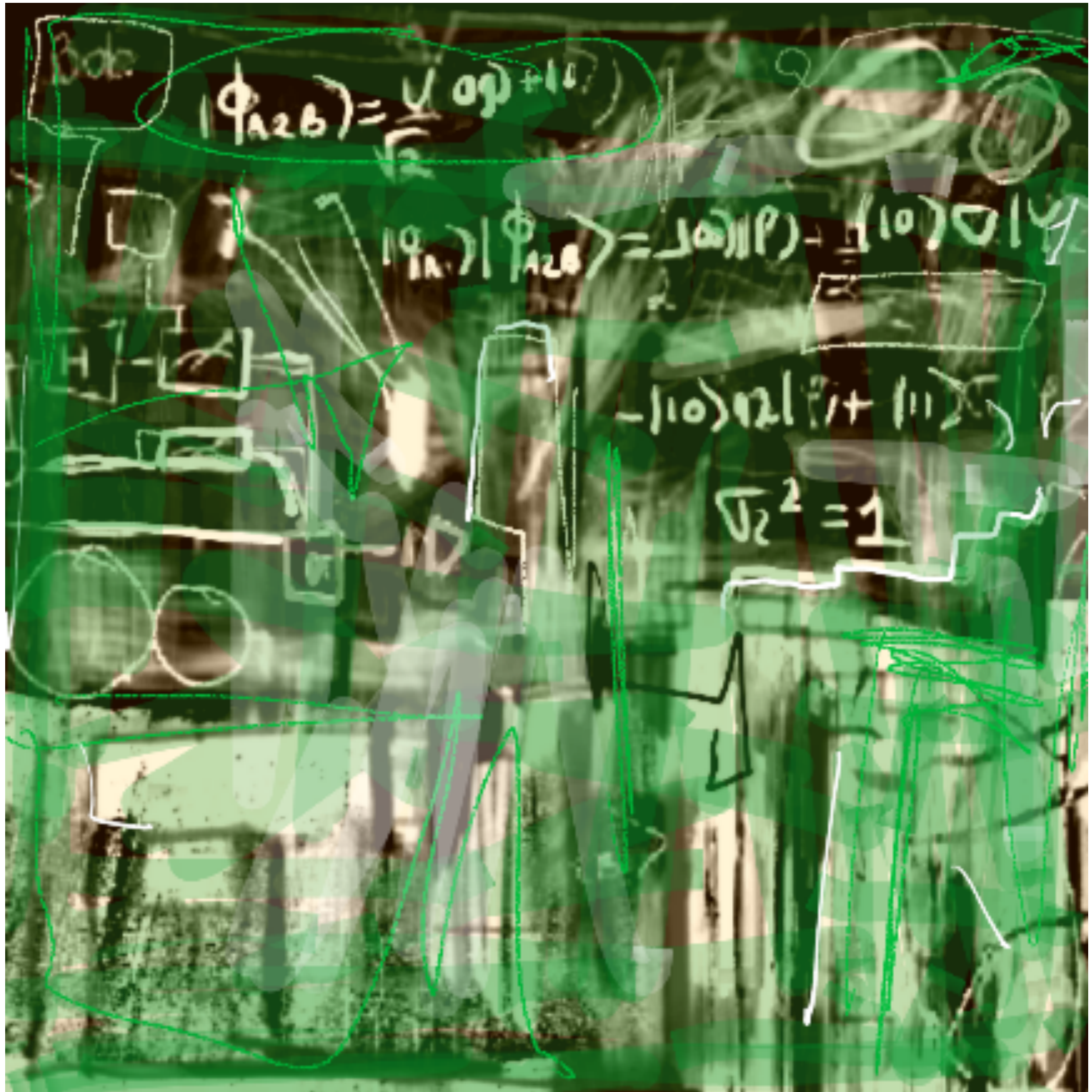
$$H_\epsilon = \frac{8\left(1 - \sqrt{\mathcal{F}(\sigma_\epsilon, \sigma_{\epsilon+d\epsilon})}\right)}{d\epsilon^2}$$

Fidelity

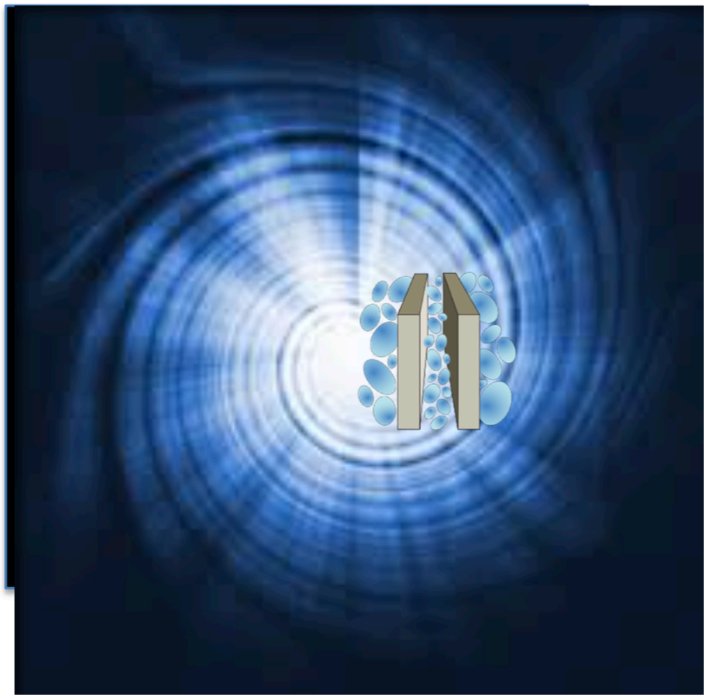
state σ_ϵ

$\langle \psi_\epsilon | \psi_{\epsilon+d\epsilon} \rangle \ll 1$

Application: GW detector



gravitational wave detector



Quantum Fisher information

$$H = \frac{1}{4}\omega_m\omega_n t^2[1+\sin^2(\theta-\phi_\beta)\sinh^2 2r]$$
$$= \frac{1}{4}\omega_m\omega_n t^2[1+\sinh^2 2r] \;\; when \;\; \theta = \phi_\beta + \frac{\pi}{2}$$
$$\to_{r\gg 1} \frac{1}{4}\omega_m\omega_n t^2 N_P^2,$$

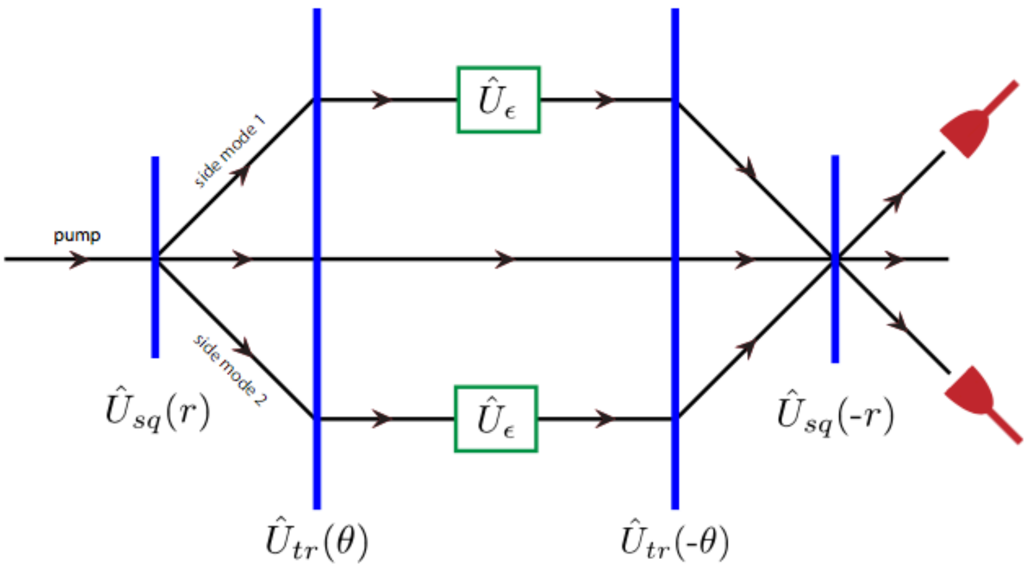
$$\Delta\epsilon \geq \frac{2}{\sqrt{M\omega_m\omega_n t^2 N_p^2}}$$

$$Mt^2 = N_d N_r t^2 = N_d \tau\, t$$

N_p Number of phonons
N_d Number of detectors
M Number of measurements
t phonon lifetime
τ integration time
$\omega_m = (\pi m c_s/L)$

Measurement: Active interferometry with active channels

Details now in: Howl and Fuentes, arXiv:1902.09883



$$\Delta\epsilon \sim \frac{\sqrt{Var(N_p)}}{\left|\frac{\partial\langle N_p\rangle}{\partial\epsilon}\right|} = \frac{C}{\sqrt{N_o N_p}}$$

Heisenberg limit $\sim \frac{1}{\sqrt{N_o^2}}$

Based on Pumped-up SU(1,1) interferometer by Szigeti et al. PRL 2017

For persistent sources (pulsars)

Sensitivities

We get sensitivities between 10^{-19}–10^{-23}

For frequencies $\Omega \sim \mathrm{KHz}$

Considering with $\mathrm{N_o} \sim 10^8 - 10^{10}$

and number of phonons $\mathrm{N_p} \sim 10^3 - 10^8$

Phonon lifetime ~ 0.1-15sec

Many more details on specific species coming soon!

REVIEW OF SCIENTIFIC INSTRUMENTS **78**, 013102 (2007)

Large atom number Bose-Einstein condensate of sodium

K. M. R. van der Stam, E. D. van Ooijen,[a)] R. Meppelink,
J. M. Vogels, and P. van der Straten
Atom Optics and Ultrafast Dynamics, Utrecht University, P.O. Box 80,000, 3508 TA Utrecht, The Netherlands

(Received 4 September 2006; accepted 24 November 2006; published online 4 January 2007)

We describe the setup to create a large Bose-Einstein condensate containing more than 120×10^6 atoms. In the experiment a thermal beam is slowed by a Zeeman slower and captured in a dark-spot magneto-optical trap (MOT). A typical dark-spot MOT in our experiments contains 2.0×10^{10} atoms with a temperature of 320 μK and a density of about 1.0×10^{11} atoms/cm^3. The sample is spin polarized in a high magnetic field before the atoms are loaded in the magnetic trap. Spin polarizing in a high magnetic field results in an increase in the transfer efficiency by a factor of 2 compared to experiments without spin polarizing. In the magnetic trap the cloud is cooled to degeneracy in 50 s by evaporative cooling. To suppress the three-body losses at the end of the evaporation, the magnetic trap is decompressed in the axial direction.
[DOI: 10.1063/1.2424439]

New Journal of Physics
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Deutsche Physikalische Gesellschaft

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Squeezing in Bose–Einstein condensates with large numbers of atoms

To cite this article: Mattias T Johnsson *et al* 2013 *New J. Phys.* **15** 123024

$$\frac{N^{1\mathrm{D}}_{\mathbf{k}\neq 0}(t_3)}{N} \approx \sqrt{L}\,\frac{1}{N}\sqrt{\frac{MU^{1\mathrm{D}}_{aa}n_a}{2\hbar^2\pi^2}}\Lambda_a^{3/2}\cos^2\theta f^{1\mathrm{D}}(\Lambda_a) \quad \propto \sqrt{L},$$

New Journal of Physics **15** (2013) 123024 (http://www.njp.org/)

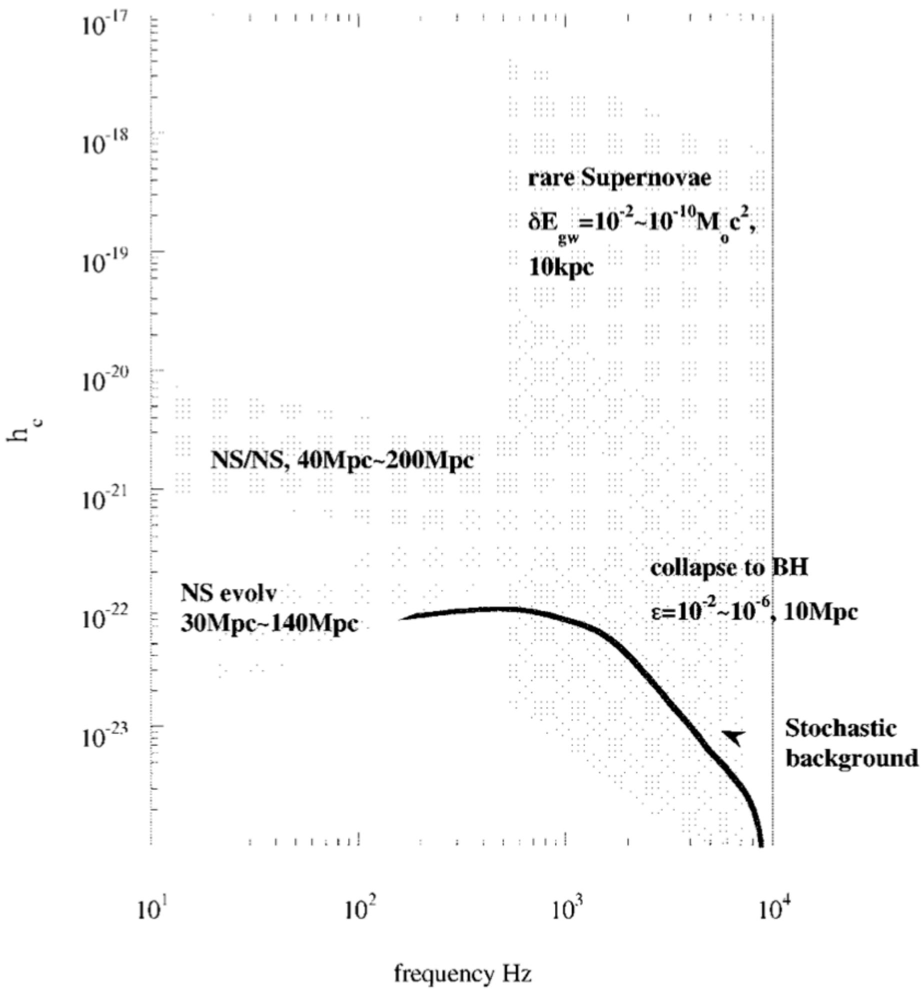
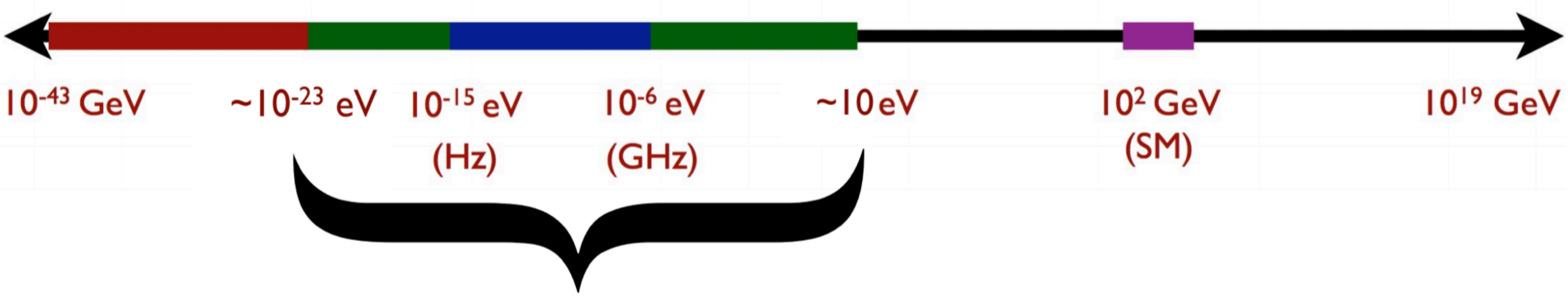


Figure 8. Spectrum of gravitational wave sources [18, 22]. In this figure, the abbreviations are: BH, collapse to black hole; NS/NS, neutron star coalescence; NS evol, secular evolution of a nonaxisymmetric neutron star.

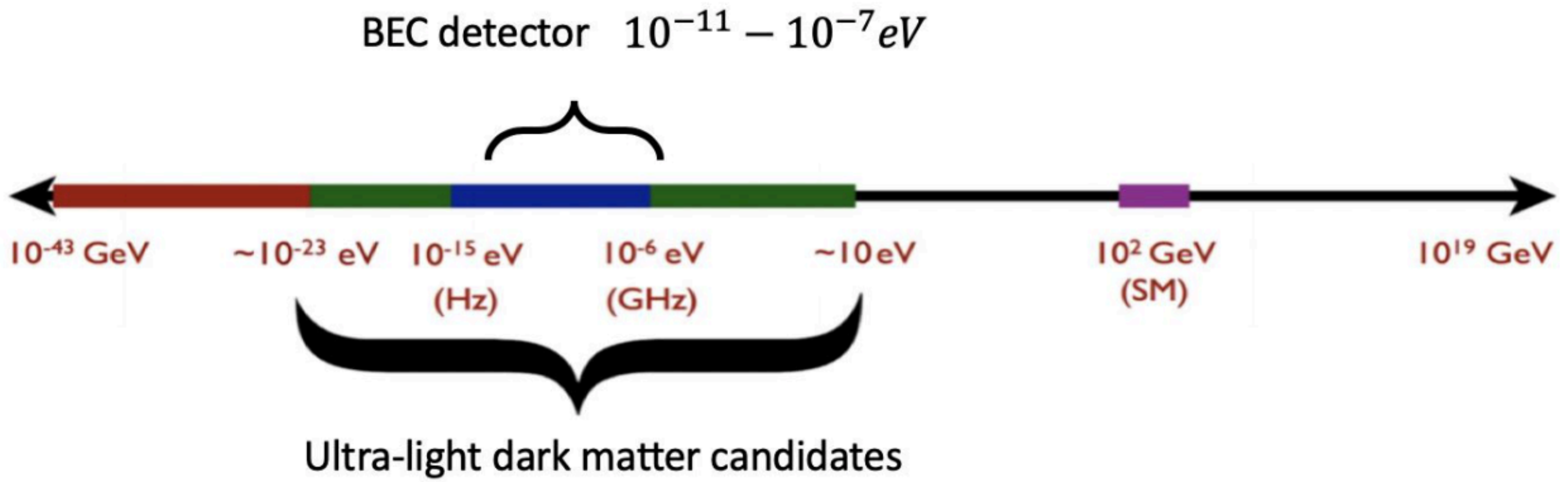
Ultra-Light Dark Matter
(bosonic)



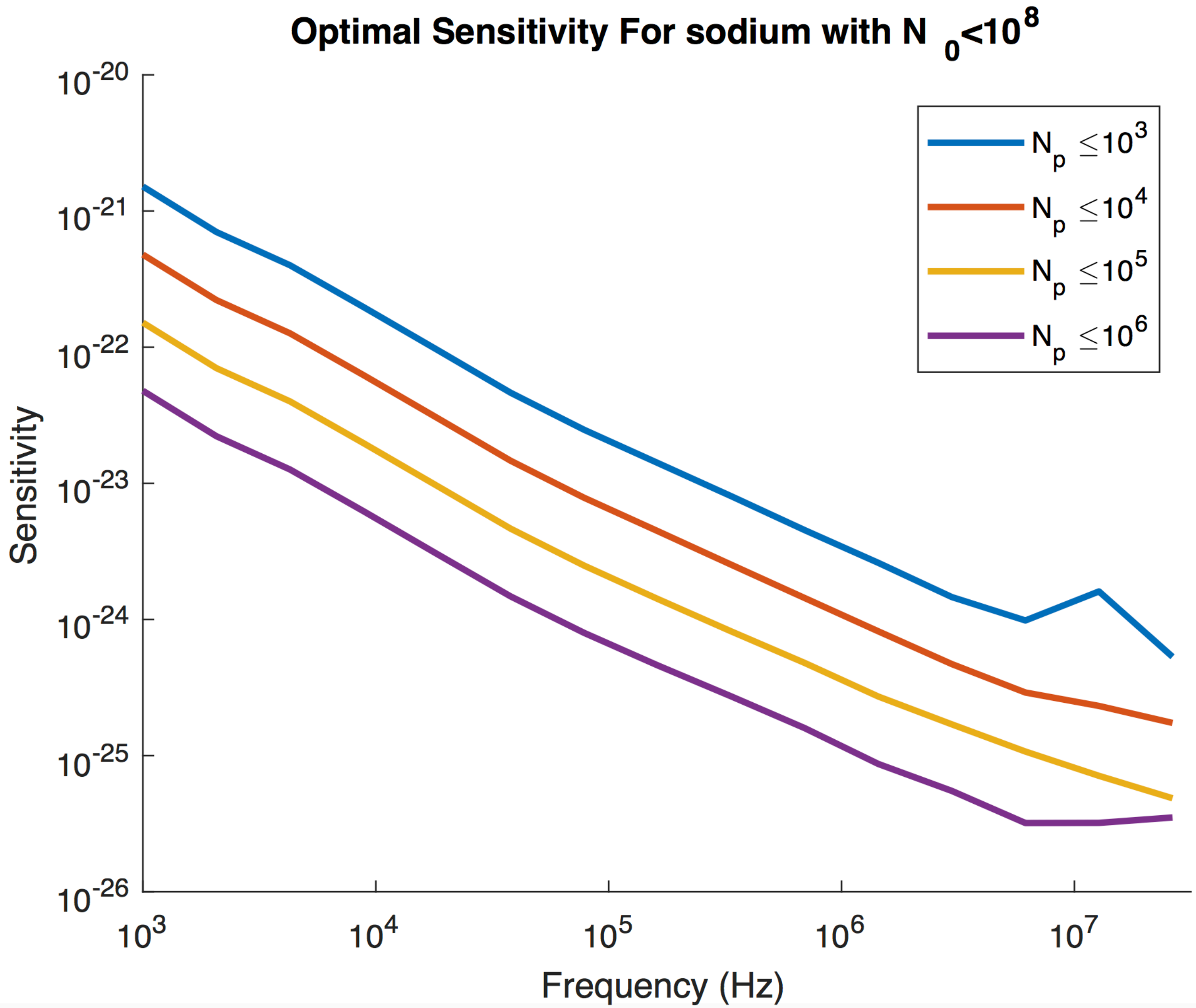
→ search for *coherent effects of the entire field*, not single hard particle scatterings

Generic Candidates: Light pseudo-Nambu-Goldstones (axions and "axion like particles" — ALPs); Massive hidden vector bosons (aka "dark photons"); Light scalars (moduli/dilatons…)

Slide by John March-Russel



BEC detector $10^{-11} - 10^{-7} eV$
10^{-43} GeV
$\sim 10^{-23}$ eV
10^{-15} eV (Hz)
10^{-6} eV (GHz)
~10 eV
10^{2} GeV (SM)
10^{19} GeV
Ultra-light dark matter candidates



Optimal Sensitivity For sodium with $N_0 < 10^8$
$N_p \leq 10^3$
$N_p \leq 10^4$
$N_p \leq 10^5$
$N_p \leq 10^6$
Sensitivity
Frequency (Hz)
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
10^{-26}
10^3
10^4
10^5
10^6
10^7

As an example of the quantities involved we show the following tables for a single sodium condensate ($N_d = 1$) with $N_0 = 10^8$ atoms and integration time $\tau = 1\ year$. **Table 1** is for the detection of gravitational waves of 3kHz, and **Table 2** for 100kHz. Sensitivities can be calculated using equations (3) and (4).

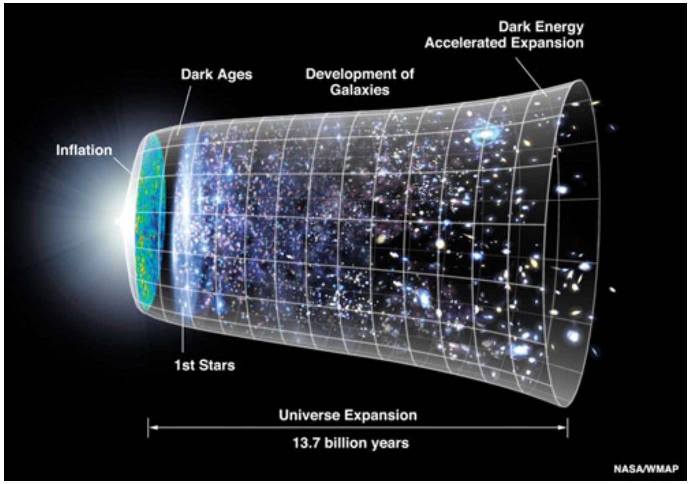
Table 1

N_p	j	k	L	a	t	$\omega_1 = c_s/L$	c_s (m/s)	θ	C_{nm}	sens
10^3	5	1	6.03×10^{-4}	6.82×10^{-12}	9.9	1.61×10^2	9.73×10^{-2}	3.06×10^{-1}	7.16×10^{-7}	4.89×10^{-20}
10^4	3	1	4.82×10^{-4}	4.87×10^{-12}	10	2.39×10^2	1.51×10^{-1}	2.83×10^{-1}	3.65×10^{-7}	6.41×10^{-21}
10^5	33	31	2.221×10^{-3}	5.27×10^{-11}	10	1.51×10^{-1}	3.5×10^{-2}	3.04×10^{-1}	2.84×10^{-7}	1.25×10^{-21}
3.87×10^5	3	1	4.81×10^{-4}	5.16×10^{-12}	10	2.32×10^2	1.21×10^{-1}	2.96×10^{-1}	3.59×10^{-7}	1.13×10^{-21}

Table 2

N_p	j	k	L	a	t	$\omega_1 = c_s/L$	c_s (m/s)	θ	C_{nm}	sens
10^3	3	1	6.51×10^{-5}	2.42×10^{-13}	9.9	7.93×10^3	5.17×10^{-1}	7.65×10^{-2}	1.36×10^{-5}	6.09×10^{-21}
10^4	3	1	6.63×10^{-5}	2.67×10^{-13}	7.5	7.95×10^3	5.28×10^{-1}	3.1×10^{-1}	7.87×10^{-7}	5.11×10^{-22}
5.62×10^4	3	1	6.45×10^{-5}	2.38×10^{-13}	10	8.06×10^3	5.2×10^{-1}	2.93×10^{-1}	9.28×10^{-7}	2.08×10^{-22}
10^6	3	1	6.5×10^{-5}	2.41×10^{-13}	10	7.96^{-3}	5.17×10^{-1}	2.91×10^{-1}	9.46×10^{-7}	4.91×10^{-23}

Screened scalar fields



$$A(\varphi) =: \exp\left[a^2(\varphi)\right]$$

$$a^2 \ll 1$$

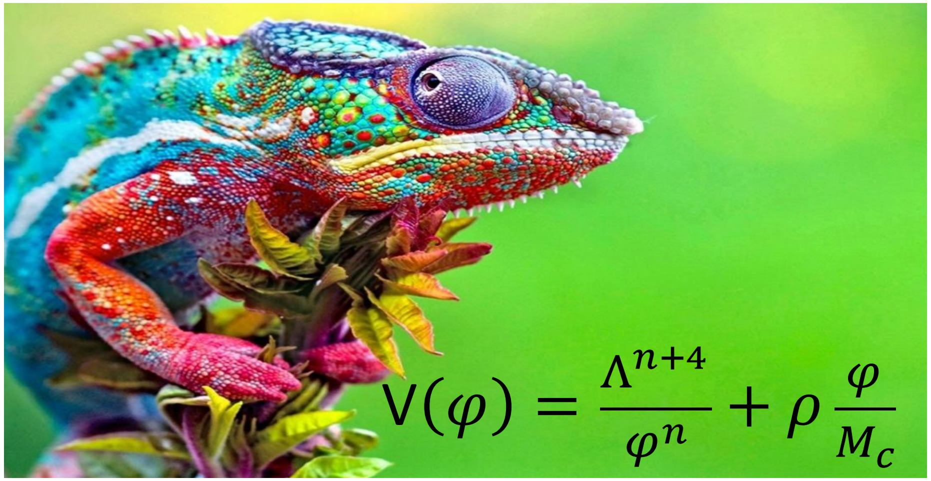
$$\tilde{g}_{\mu\nu} = \left(1 + a^2 + \mathcal{O}\left(a^4\right)\right) g_{\mu\nu}.$$

$$a^2 = \frac{\varphi}{M_c}$$

Chameleon fields
Fifth force fields

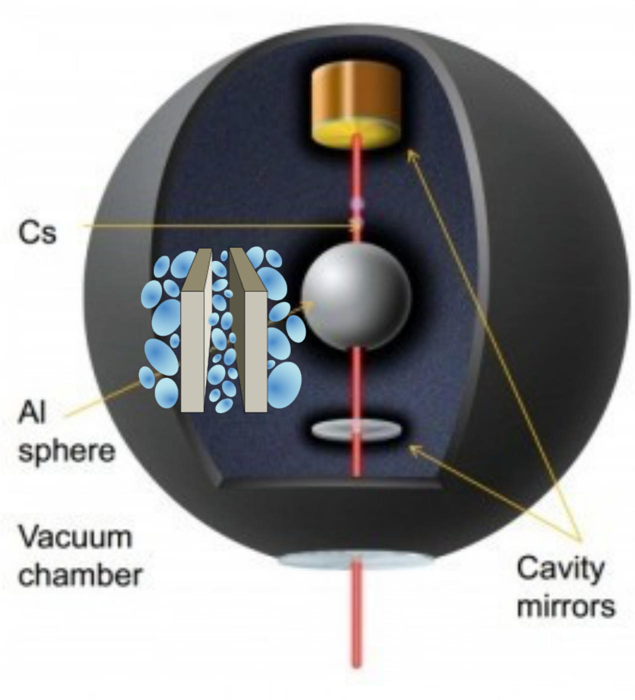
$$\tilde{g}_{\mu\nu} = A(\varphi)\, g_{\mu\nu}$$

They produces the effects of dark energy in deep space, but also gets inhibited by the presence of mass. In this way you get cosmic expansion between galaxies, but you don’t see its effect in galaxies (or in our solar system).



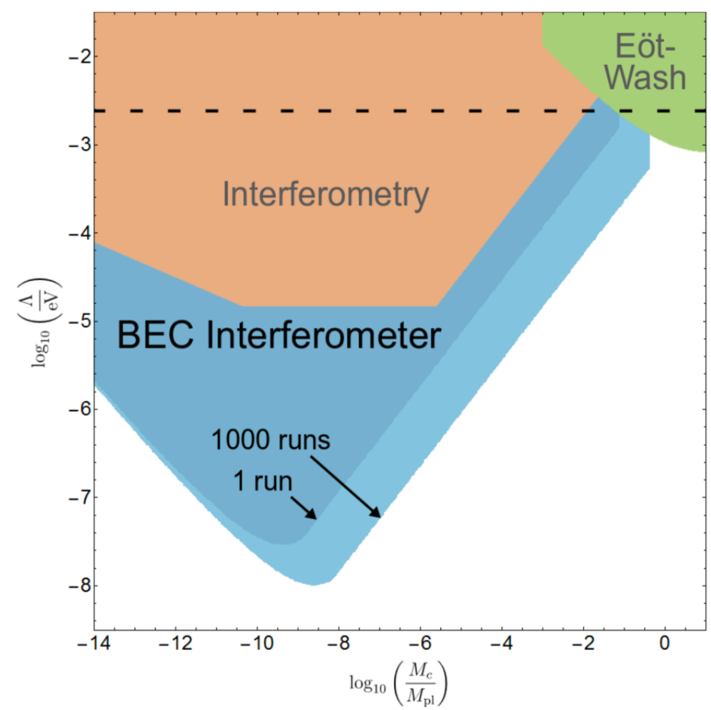
$$\mathrm{V}(\varphi) = \frac{\Lambda^{n+4}}{\varphi^n} + \rho\,\frac{\varphi}{M_c}$$

Constraining dark energy



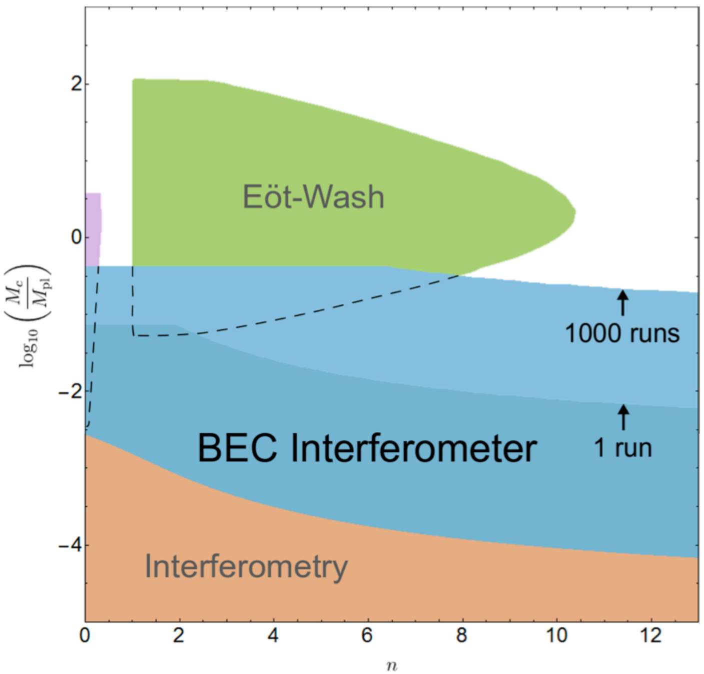
CREDIT: P. HAMILTON

Hartley, Käding, Howl, and Fuentes, arXiv:1909.02272

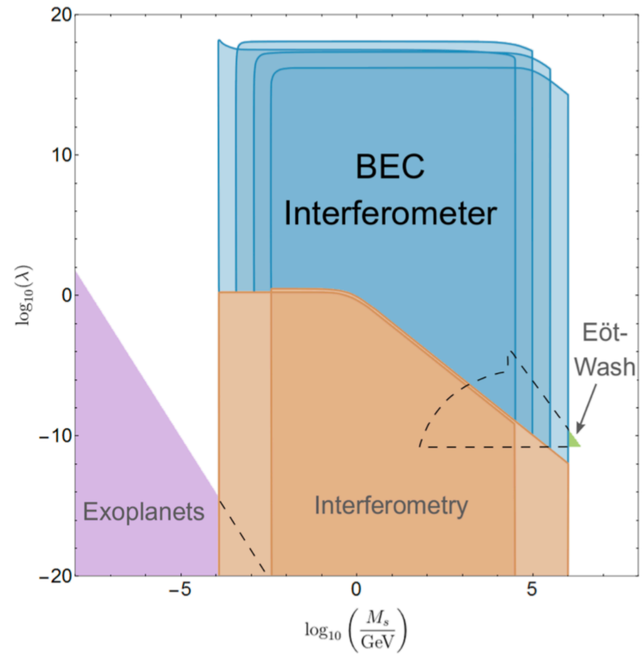


Constraints for the parameter space of the chameleon model n = 1. The brown area corresponds to constraints from atom interferometry and the green area to those from E¨öt-Wash experiments. The dotted line indicates the DE scale $\Lambda = 2.4$ meV. New constraints predicted in this work are coloured in blue, where dark blue corresponds to 1 run of the experiment

Constraining dark energy models



Constraints for the value of Mc for positive n chameleon models at $\Lambda = 2.4$ meV.



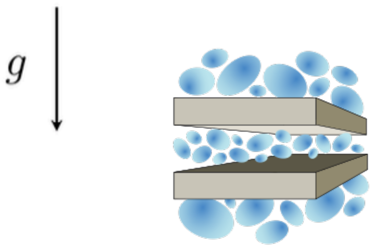
Constraints for the parameter space of the symmetron model. Different shades of blue correspond to $\mu = 10^{-4}, 10^{-4.5}, 10^{-5}$ and $10^{-5.5}$eV in natural units respectively.

Schwarzchild spacetime (Earth)

$$\boldsymbol{g} = \mathrm{diag}\left(-f(r), \frac{1}{f(r)}, r^2, r^2 \sin^2 \vartheta\right)$$

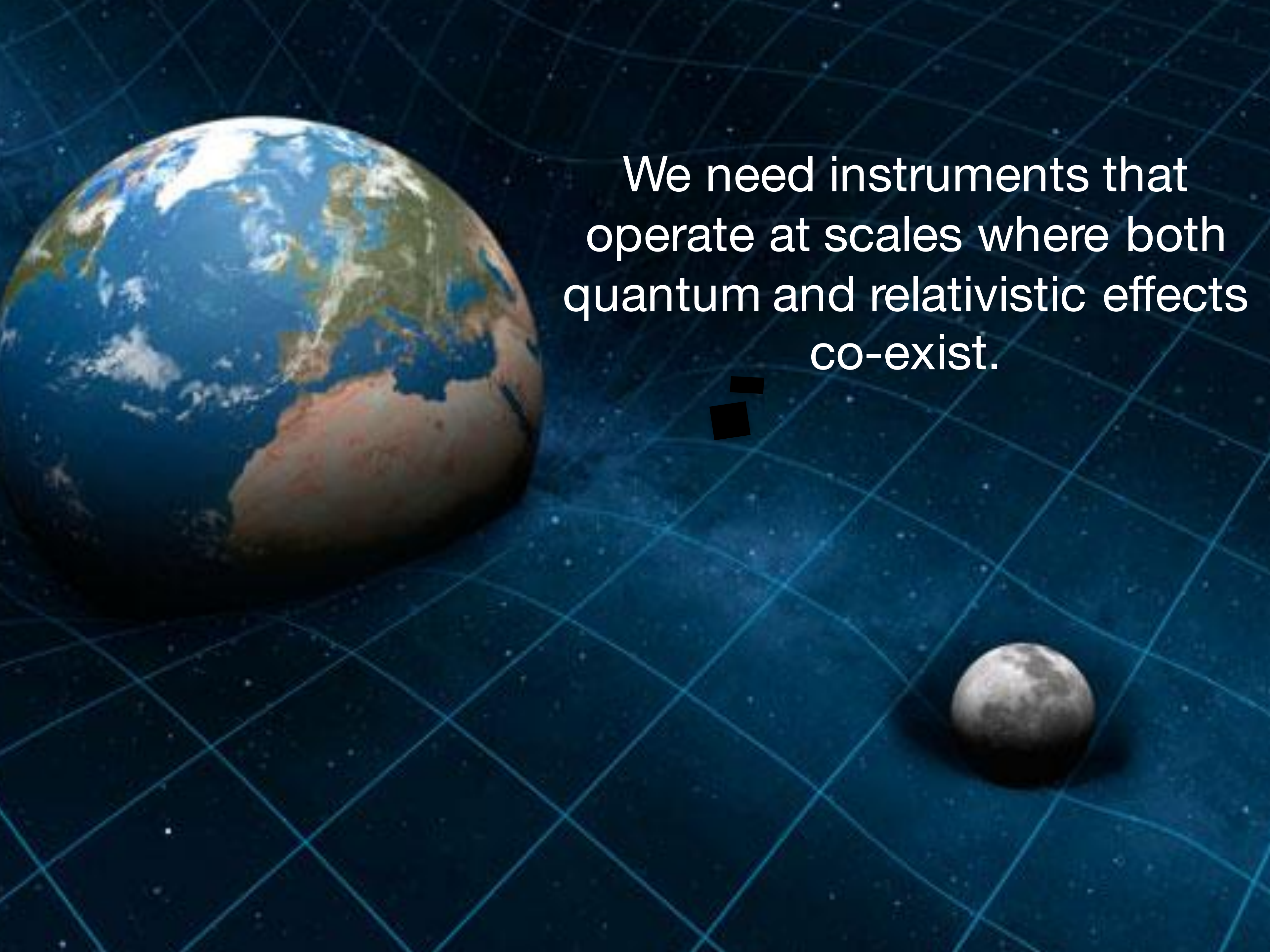
$$f(r) = 1 - r_S/r$$

Setup	Running time	Length	$\Delta r_S/r_S$
[14, 15, 17] Atom. Int.	100 s – 8 h	0.2 – 2.5 m	10^{-9}
[16] BEC-chip	100 s	10^{-2} m	10^{-10}
Phononic MZI	6 s	10^{-4} m	10^{-8}



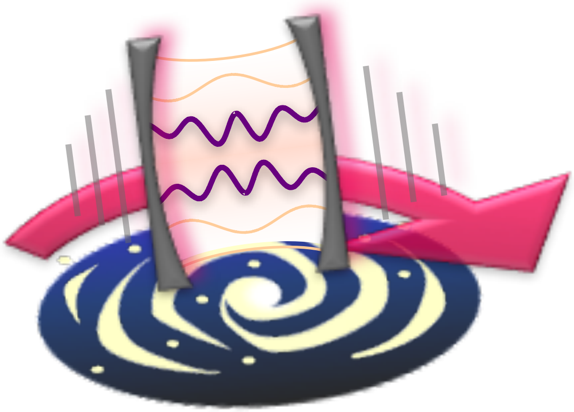
Phononic gravimeter:
Relative error bound of 10^{-11} in 1 yr. Commercial gravimeters reach 10^{-9} in 15 days with a device that measure $100 \times 50 \times 70 cm^3$.

Phononic gradiometer:
Improves the state of the art by two orders of magnitude


We need instruments that operate at scales where both quantum and relativistic effects co-exist.

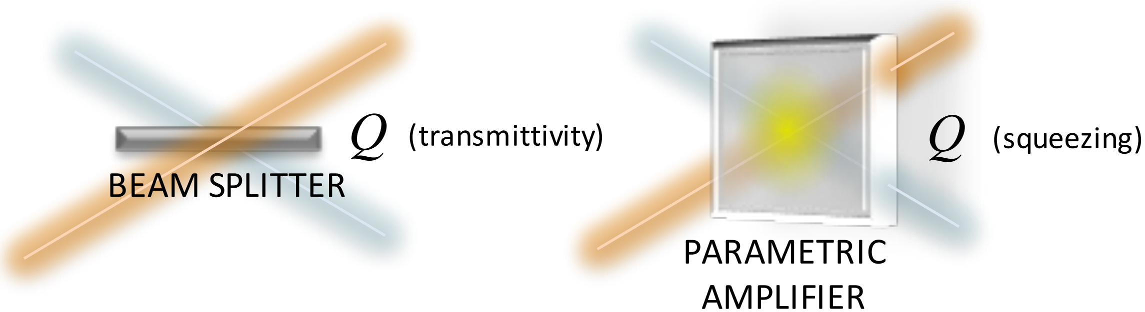
THANK YOU

Bogoliubov transformations



Bogoliubov transformation

- Realizes a linear transformation of the modes: $\tilde{a}_m = \sum_n \left(\alpha_{mn} a_n + \beta^*_{mn} a^\dagger_n\right)$
- *Alphas*: passive terms (beam-splitter like)
- *Betas*: active terms (two-mode squeezers)



covariance matrix formalism

covariance matrix: information about the state

$$\sigma_{ij} = \langle \mathrm{X}_i \mathrm{X}_j + \mathrm{X}_j \mathrm{X}_i \rangle - 2 \langle \mathrm{X}_i \rangle \langle \mathrm{X}_j \rangle \qquad [X_i, X_j] = 2i\Omega_{ij}$$

$$\mathrm{X}_{(2n-1)} = \frac{1}{\sqrt{2}}(a_n + a_n^\dagger) \;\; \text{and} \;\; \mathrm{X}_{(2n)} = \frac{-i}{\sqrt{2}}(a_n - a_n^\dagger)$$

symplectic matrix: evolution

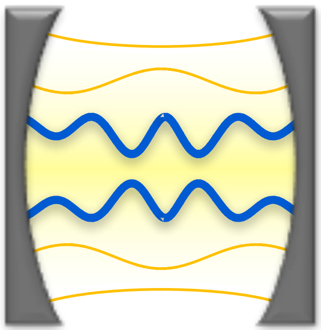
$$\tilde{\sigma} = S\,\sigma\,S^T$$

$$S\,\Omega\,S^T = \Omega$$

Computations are much simpler

QFT in the symplectic formalism

Friis and Fuentes JMO (invited) 2012



general symplectic matrix

$$S = \begin{pmatrix} \mathcal{M}_{11} & \mathcal{M}_{12} & \mathcal{M}_{13} & \dots \\ \mathcal{M}_{21} & \mathcal{M}_{22} & \mathcal{M}_{23} & \dots \\ \mathcal{M}_{31} & \mathcal{M}_{32} & \mathcal{M}_{33} & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

$$\mathcal{M}_{mn} = \begin{pmatrix} \Re(\alpha_{mn} - \beta_{mn}) & \Im(\alpha_{mn} + \beta_{mn}) \\ -\Im(\alpha_{mn} - \beta_{mn}) & \Re(\alpha_{mn} + \beta_{mn}) \end{pmatrix}$$

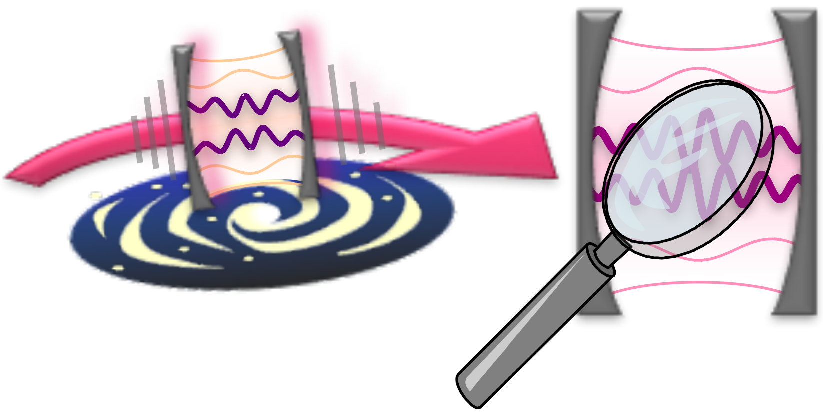
General framework for RQM

Ahmadi, Bruschi, Sabin, Adesso, Fuentes, Nature Sci. Rep. 2014
Ahmadi, Bruschi, Fuentes PRD 2014

Fisher information in QFT:
Analytical formulas in terms of general Bogoliubov coefficients

for small parameters

$$
\begin{aligned}
H &= \epsilon^{-2}\Re\Big[4\cosh r(f_\alpha^n + f_\beta^n + f_\alpha^m + f_\beta^m) \\
&+ 4\cosh^2 r(2|\beta_{nm}(t)|^2 - f_\alpha^n + f_\beta^n - f_\alpha^m + f_\beta^m) \\
&- 4\sinh^2 r(-f_\alpha^n + f_\beta^n - f_\alpha^m + f_\beta^m + 2\beta_{nm}(t)^2 - 2\alpha_{nm}(t)^2 \\
&+ 4\sinh r\,\Re[\mathcal{G}_{nm}^{\alpha\beta} + \mathcal{G}_{nm}^{\alpha\beta}] - 4\cosh^4 r|\beta_{nm}(t)|^2 \\
&- \frac{1}{2}\sinh^2 2r(2|\alpha_{nm}(t)|^2 - 3|\beta_{nm}(t)|^2 - \beta_{nm}(t)^2\Big].
\end{aligned}
$$



$$
\begin{aligned}
f_\alpha^i &= \frac{1}{2}\sum_{n\neq k,k'} |\alpha_{ni}|^2 \\
f_\beta^i &= \frac{1}{2}\sum_{n\neq k,k'} |\beta_{ni}|^2 \\
\mathcal{G}_{ij}^{\alpha\beta} &= \sum_{n\neq k,k'} \alpha_{ni}\beta_{nj}^*
\end{aligned}
$$

Probe states:
- Single-mode
- Two-mode channels

Resilience to noise

Sabin, Kohlrus, Bruschi and Fuentes, EPJ Quantum Technology 2016

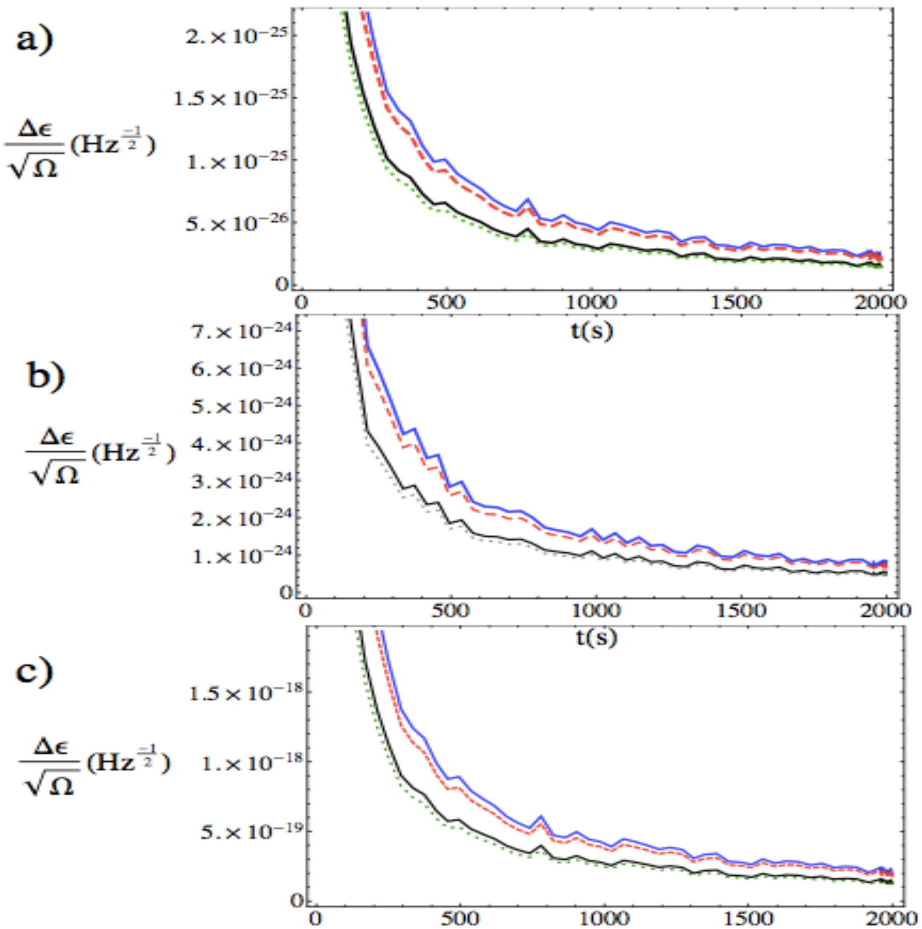
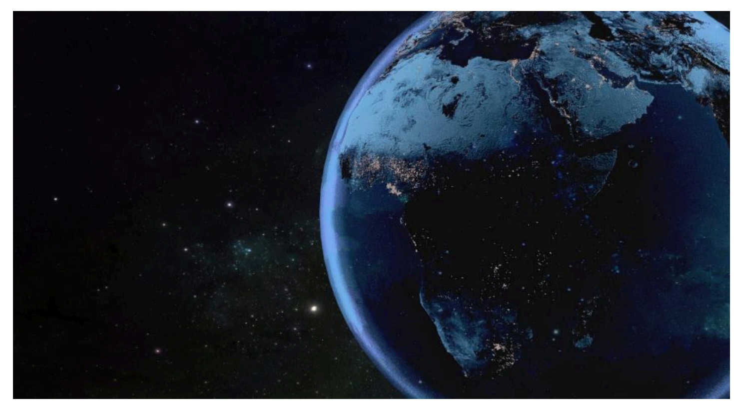


FIG. 2: Optimal bound for the strain sensitivity as provided by the QFI for $n = 1$, $m = 2$, $T = 0$ (blue, solid), $T = 150$ nK (red,dashed) and a) $r = 10$, $\omega_1 = 5\,10^3$ Hz, b) $r = 10$, $\omega_1 = 5\,10^2$ Hz, c) $r = 2$, $\omega_1 = 5\,10^3$ Hz .

$$\omega_n = \frac{n\,\pi\,c_s}{L}$$

Resonance

Many detectors



- We find that decoherence is of the order of a few seconds for KHz phonons

- In one dimension these processes are supressed

Howl, Sabin, Hackermüler and Fuentes, Journal of Phys B (2018)

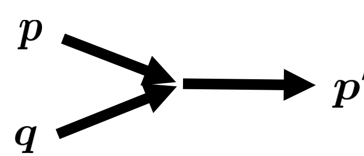
Phonon interaction: decoherence

- Non-interacting gas of quasi-particles $\Rightarrow$ infinite lifetime, no decoherence

$$\hat{H} \approx \hat{H}_0 + \frac{g}{2}\Big(N_0 f(two\ \hat{a}^{\dagger}_{\boldsymbol{p}}, \hat{a}_{\boldsymbol{p}}) + \sqrt{N_0} f(three\ a^{\dagger}_{\boldsymbol{p}}, \hat{a}_{\boldsymbol{p}}) + f(four\ \hat{a}^{\dagger}_{\boldsymbol{p}}, a_{\boldsymbol{p}})\Big)$$

- Interactions, decoherence

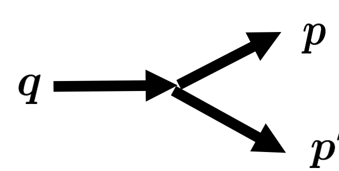
- 1. Landau: $\hat{b}_{\boldsymbol{q}}\hat{b}_{\boldsymbol{p}}\hat{b}^{\dagger}_{\boldsymbol{p'}}$



$k_B T \gg \hbar\omega_q$

  - Requires thermal quasi-particles

- 2. Beliaev: $\hat{b}_{\boldsymbol{q}}\hat{b}^{\dagger}_{\boldsymbol{p}}\hat{b}^{\dagger}_{\boldsymbol{p'}}$

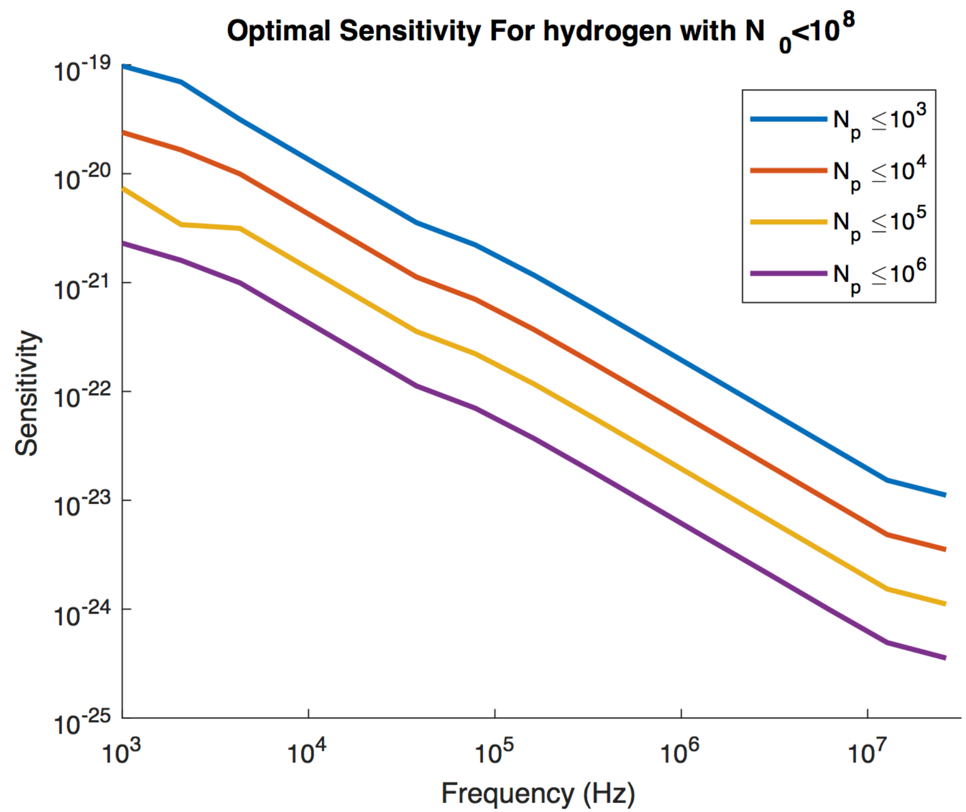


$k_B T \ll \hbar\omega_q$

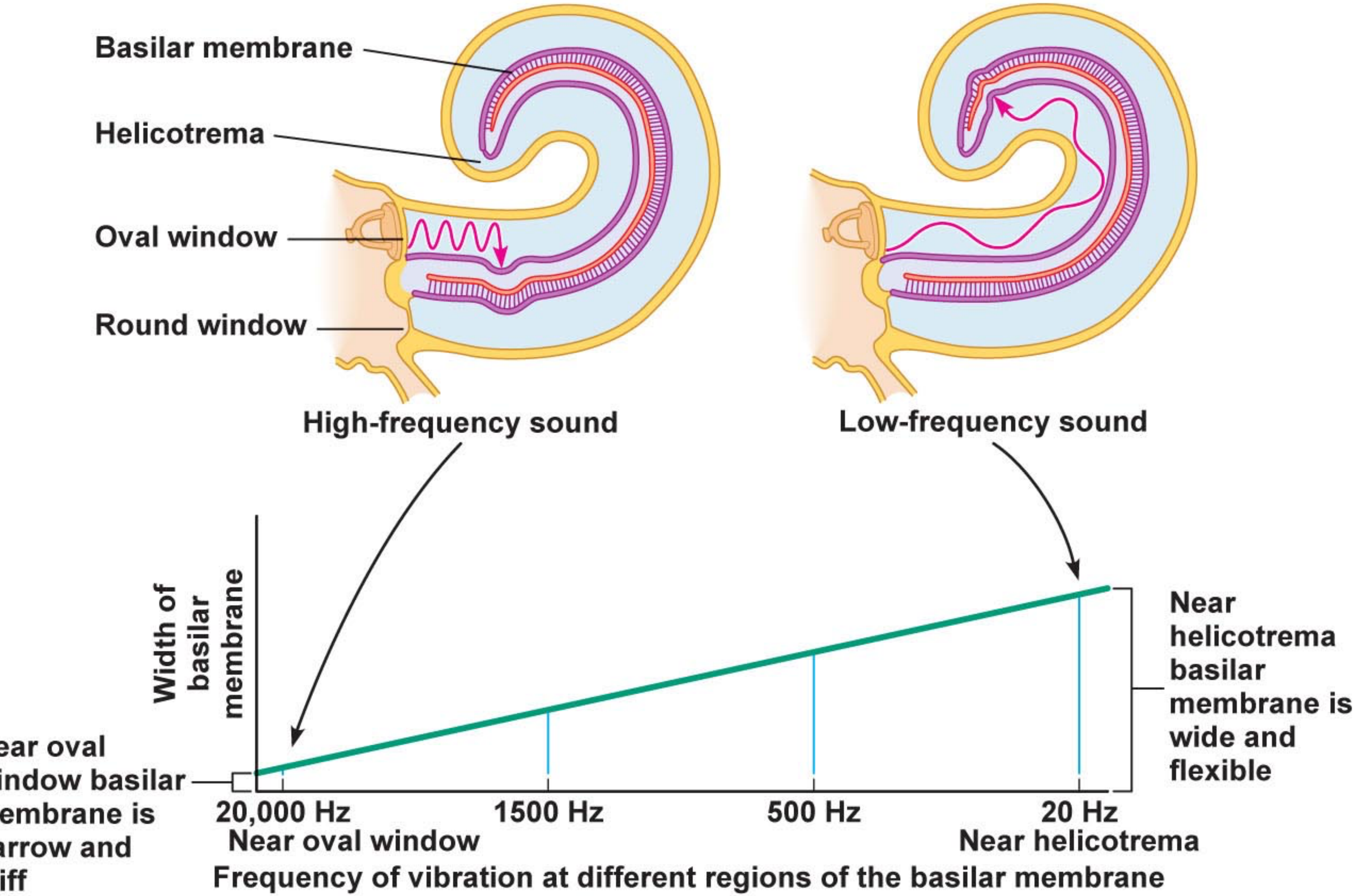
  - Also present at T=0.

Sensitivities

BEC	N_0	N_P	L (nm)	R (mm)	t (s)	k	j	N_d	Ω (kHz)	$\Delta\epsilon$
^{1}H	10^{10}	10^3	1	0.01	15	3	1	10	3.9	2.68×10^{-21}
^{1}H	10^{10}	10^8	1	0.01	15	3	1	10^3	3.9	8.48×10^{-25}
^{87}Rb	10^{10}	10^3	1	0.1	0.22	100	98	10	2.1	6.81×10^{-20}
^{87}Rb	10^{10}	10^8	1	0.1	0.22	100	98	10^3	2.1	2.15×10^{-23}

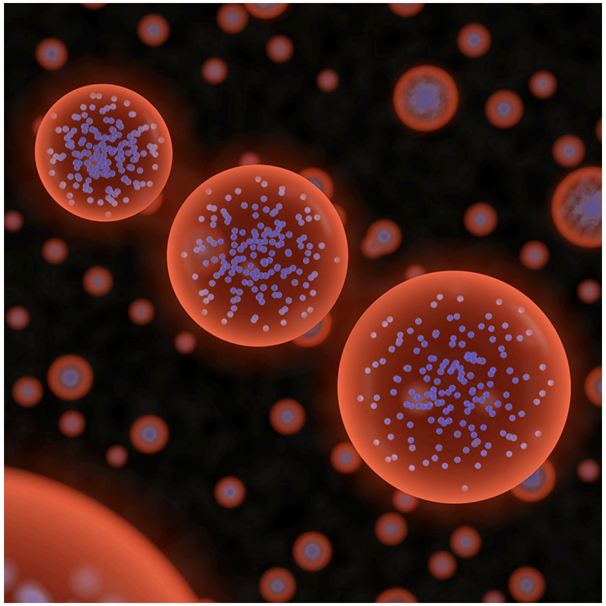


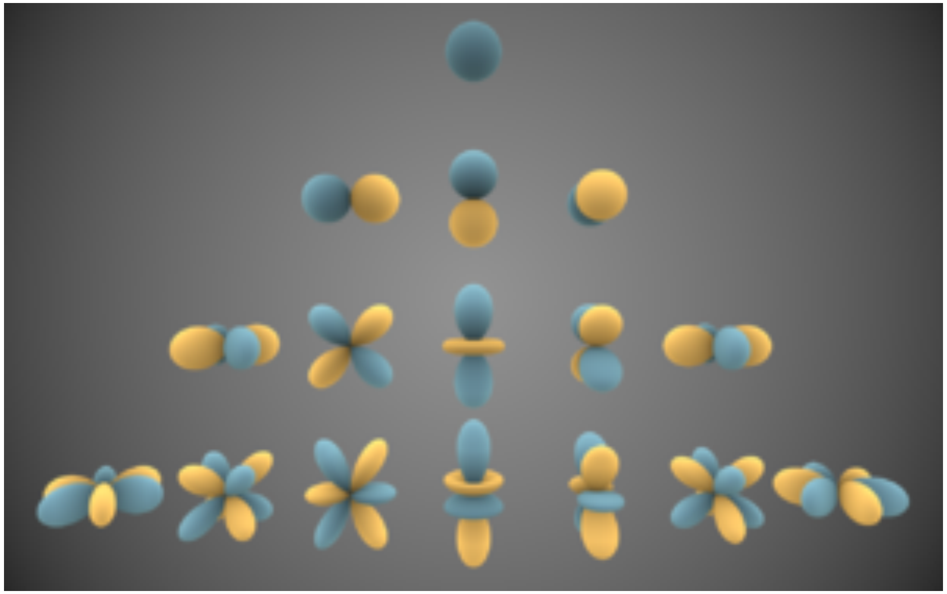
Optimal Sensitivity For hydrogen with $N_0 < 10^8$
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Sensitivity
10^3
10^4
10^5
10^6
10^7
Frequency (Hz)
$N_p \leq 10^3$
$N_p \leq 10^4$
$N_p \leq 10^5$
$N_p \leq 10^6$


Basilar membrane
Helicotrema
Oval window
Round window
High-frequency sound
Low-frequency sound
Width of basilar membrane
ear oval
indow basilar
embrane is
arrow and
iff
Near helicotrema basilar membrane is wide and flexible
20,000 Hz
1500 Hz
500 Hz
20 Hz
Near oval window
Near helicotrema
Frequency of vibration at different regions of the basilar membrane

Broadband: 3D

Spherical BEC





We are studying different geometries

Energy transference

Efficient thermal machine

Bruschi & Fuentes arXiv: 1607.01291

Work in progress

Noise studies:

Seismic noise

Trap inestabilities

Decoherence in 1-d

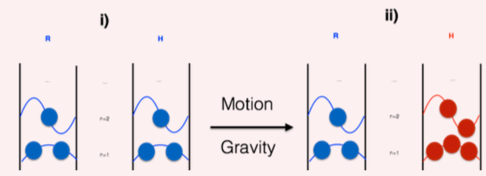
A protocol to extract energy

Here we briefly illustrate the protocol that we employ to extract energy from a cavity that is affected by motion or gravity. This protocol has been extensively studied in literature [31].

---

i) Cavities R and H are identical and at the same temperature. Cavity modes are excited.

ii) Motion or gravity affect cavity H, Its field, at the end, is left in a slightly excited state.



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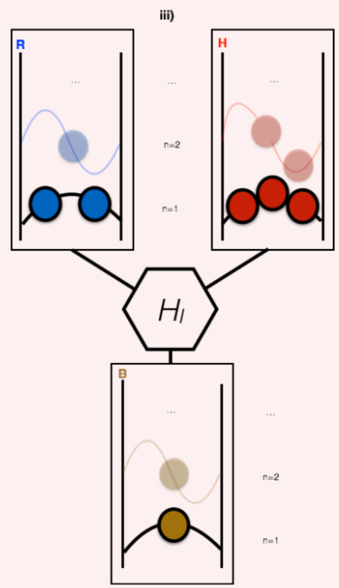
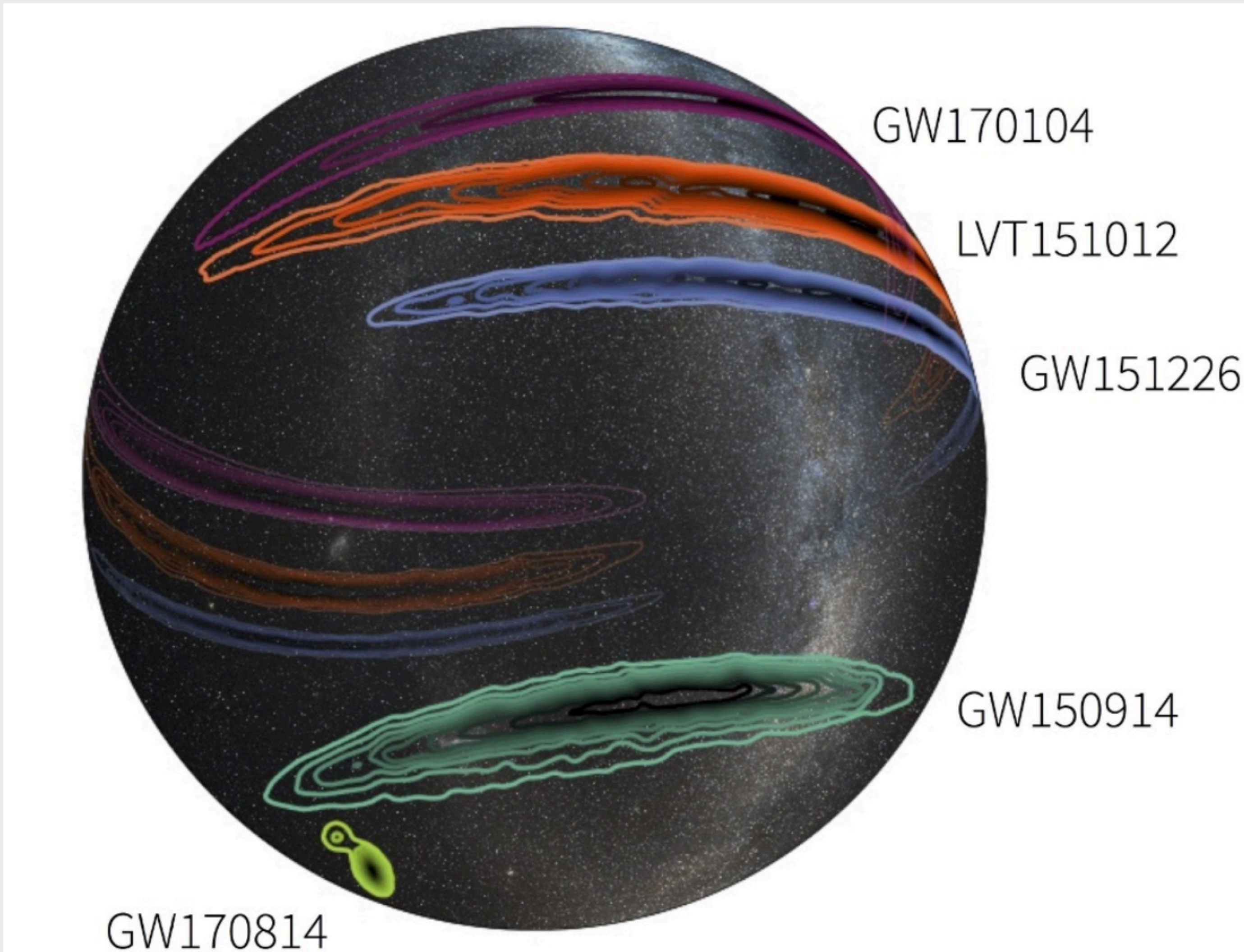
iii) The highlighted mode of choice of cavities R, H and battery B (as an example, mode $n = 1$) interacts through the interaction Hamiltonian H_I.



Ideally, we can extract excitations from cavity H and store them in the battery B.

---

iv) We can compute the total bound of the efficiency and obtain the final result (27).



This three-dimensional projection of the Milky Way galaxy onto a transparent globe shows the probable locations of the three confirmed black-hole merger events observed by the two LIGO detectors—GW150914 (dark green), GW151226 (blue), GW170104 (magenta)—and a fourth confirmed detection (GW170814, light green, lower-left) that was observed by Virgo and the LIGO detectors. Also shown (in orange) is the lower significance event, LVT151012. Image credit: LIGO/Virgo/Caltech/MIT/Leo Singer (Milky Way image: Axel Mellinger).

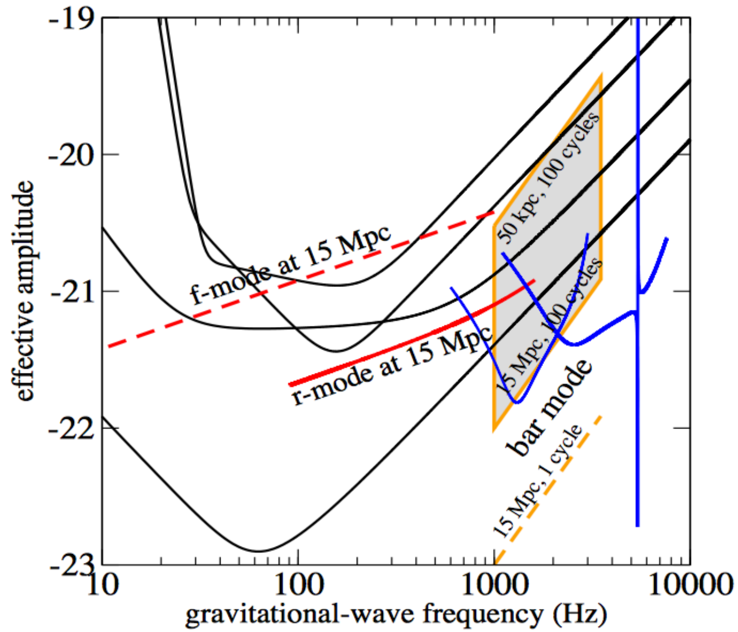


Fig. 5. The estimated strength of gravitational waves from the dynamical bar-mode instability and the CFS instability of the f- and r-modes. The estimates are compared to the predicted noise of the various interferometers and also the possible noise curve for a dual cylinder detector.