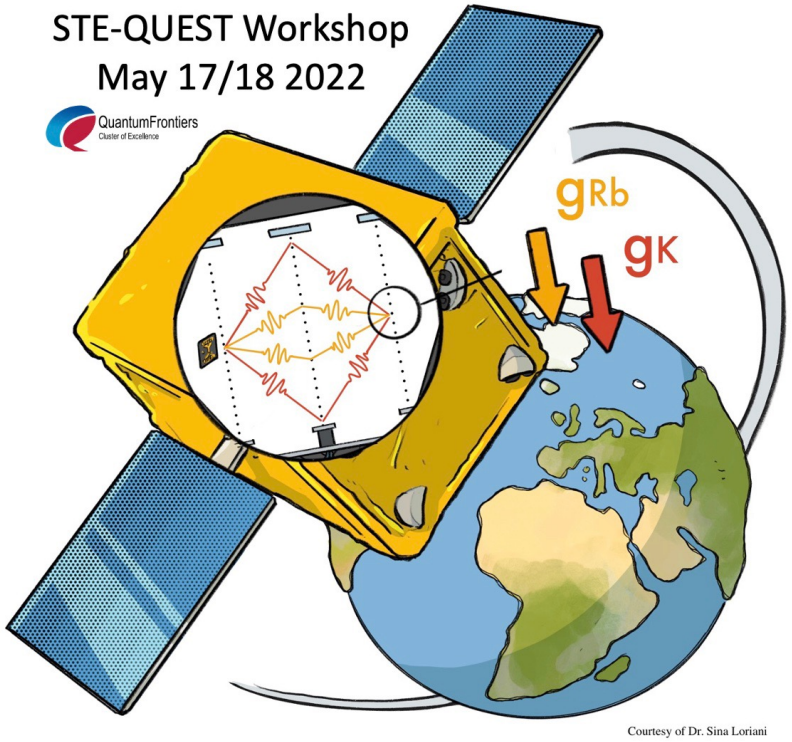
QUEEN'S UNIVERSITY BELFAST

STE-QUEST and the Foundations of Quantum Mechanics

Matteo Carlesso
(Queen's University Belfast, previously University of Trieste)

STE-QUEST's Scientific Objectives



Foundations of Quantum Mechanics

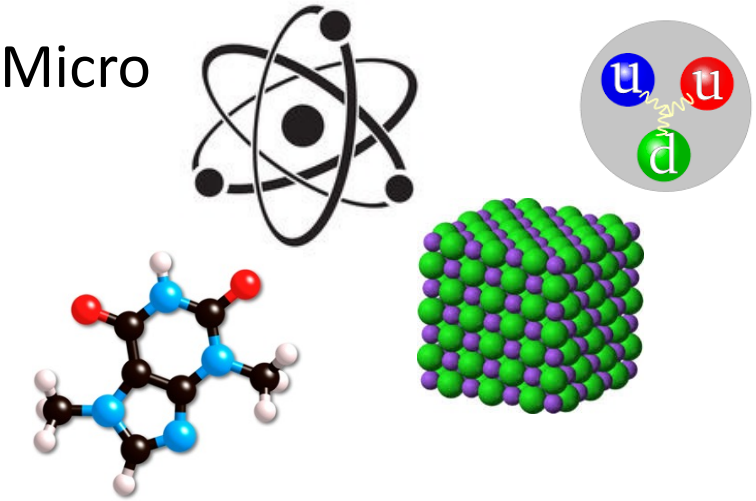
Einstein Equivalence Principle

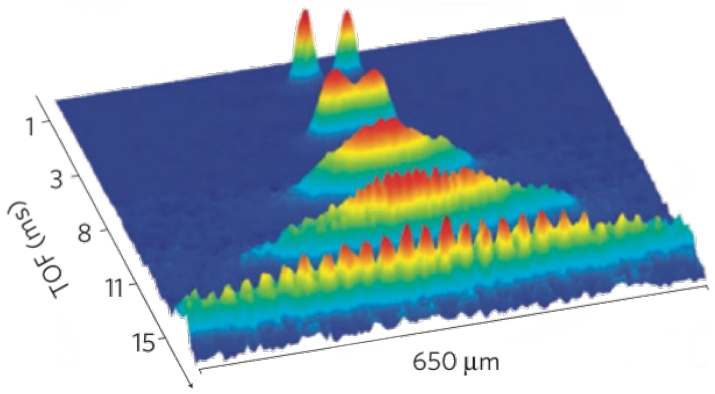
Dark Matter

Limits of the Quantum Superposition Principle

Quantum World

Micro





Classical World

Macro

Collapse models

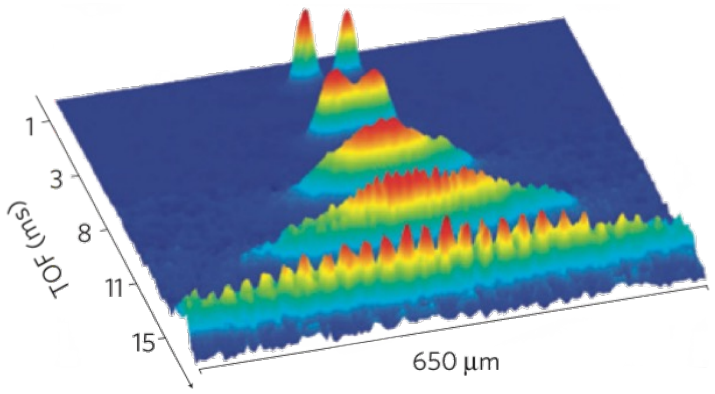
Stochastic noise

Non-linear wavefunction dynamics

Negligible microscopic action
No effective collapse
Quantum systems

Strong macroscopic action
Rapid collapse
Systems behave classically

Amplification mechanism



General structure of the dynamical equation

$$\mathrm{d}|\psi_t\rangle = \left[-\frac{\mathrm{i}}{\hbar}\hat{H}\mathrm{d}t + \int \mathrm{d}^3\mathbf{x}\, \left(\hat{M}(\mathbf{x}) - \langle \hat{M}(\mathbf{x})\rangle_t\right) \mathrm{d}W_t(\mathbf{x}) - \frac{1}{2}\int \mathrm{d}^3\mathbf{x}\mathrm{d}^3\mathbf{y}\, \mathcal{D}(\mathbf{x}-\mathbf{y}) \prod_{\mathbf{q}=\mathbf{x},\mathbf{y}} \left(\hat{M}(\mathbf{q}) - \langle \hat{M}(\mathbf{q})\rangle_t\right) \mathrm{d}t \right] |\psi_t\rangle$$

Q. Hamiltonian

Mass density operator

Non-linear term

White noise

Noise's spatial correlation

Two main models

Continuous Spontaneous Localization (CSL) model

Fully phenomenological model

$$\mathcal{D}_{\mathrm{CSL}}(\mathbf{x}-\mathbf{y}) = \frac{\lambda}{m_0^2}\exp\left(-|\mathbf{x}-\mathbf{y}|^2/4r_{\mathrm{C}}^2\right)$$

λ collapse rate

r_{C} correlation length

Diósi-Penrose model

Gravity-related model

$$\mathcal{D}_{\mathrm{DP}}(\mathbf{x}-\mathbf{y}) = \frac{G}{\hbar}\frac{1}{|\mathbf{x}-\mathbf{y}|}$$

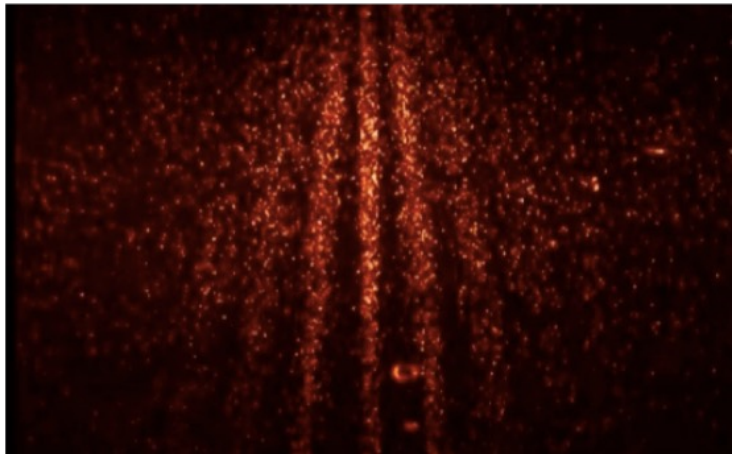
R_0 spatial cutoff
gravity regularization at small distances

Experiments

Destruction of quantum superposition

Interferometric Experiments

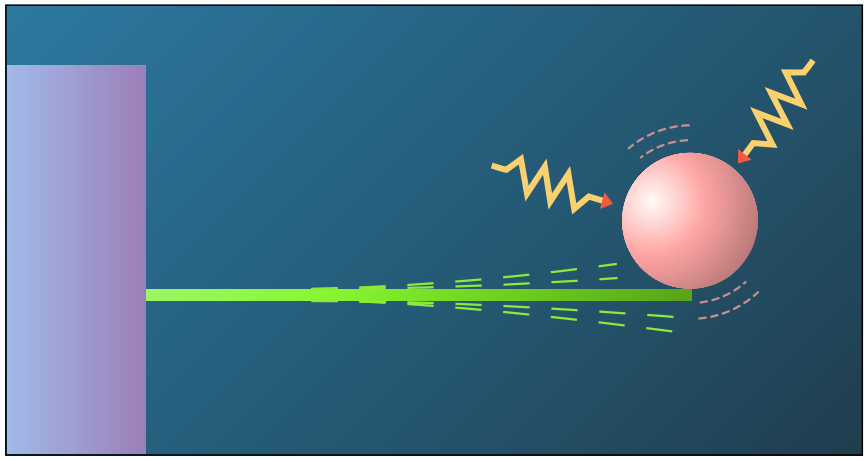
$$\Delta V = \frac{V_{\max} - V_{\min}}{V_{\max} + V_{\min}}$$



Extra jiggling due to collapse noise

Non-Interferometric Experiments

$$S_{xx}(\omega) = \frac{1}{4\pi} \int d\Omega \, \langle \{\tilde{x}(\omega), \tilde{x}(\Omega)\} \rangle$$



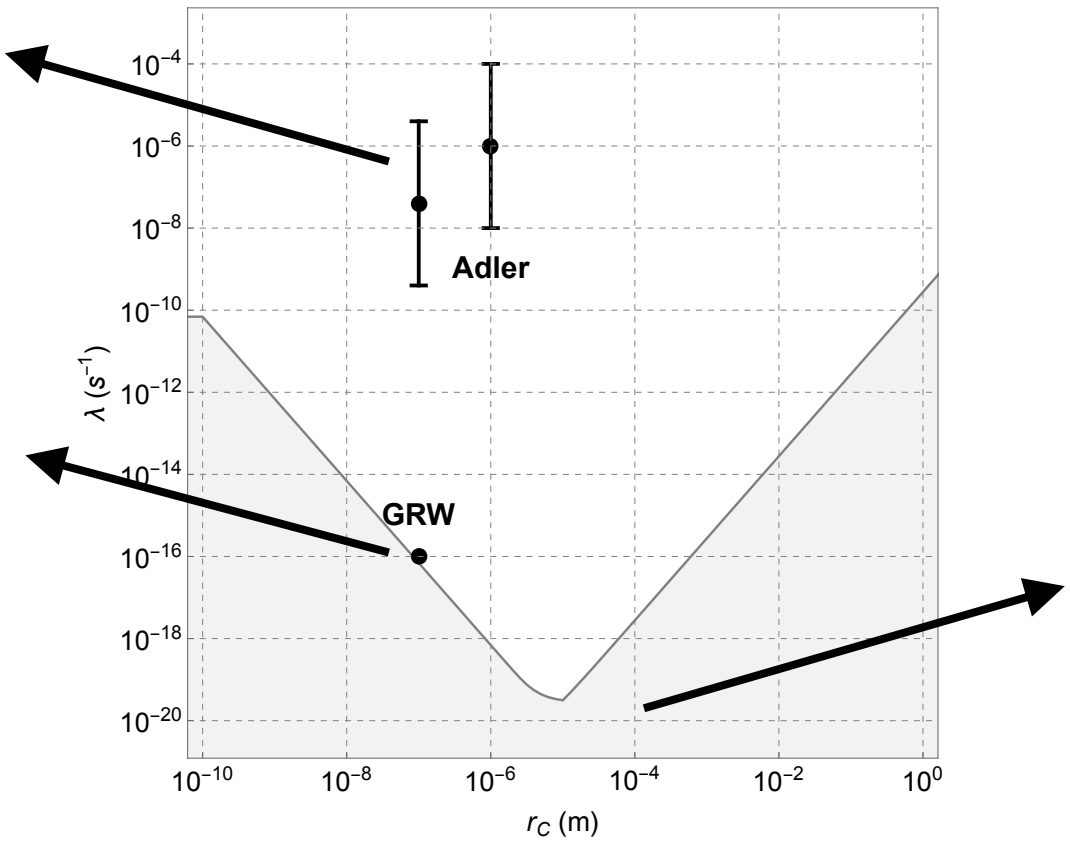
CSL parameter space

Adler's proposed values

Adler, J. Phys. A **40**, 2935 (2007)

GRW's proposed values

Ghirardi *et al.,* Phys. Rev. D **34**, 470 (1986)



Theoretical lower bound

Toros *et al.,* Phys. Lett. A **381**, 3921 (2017)

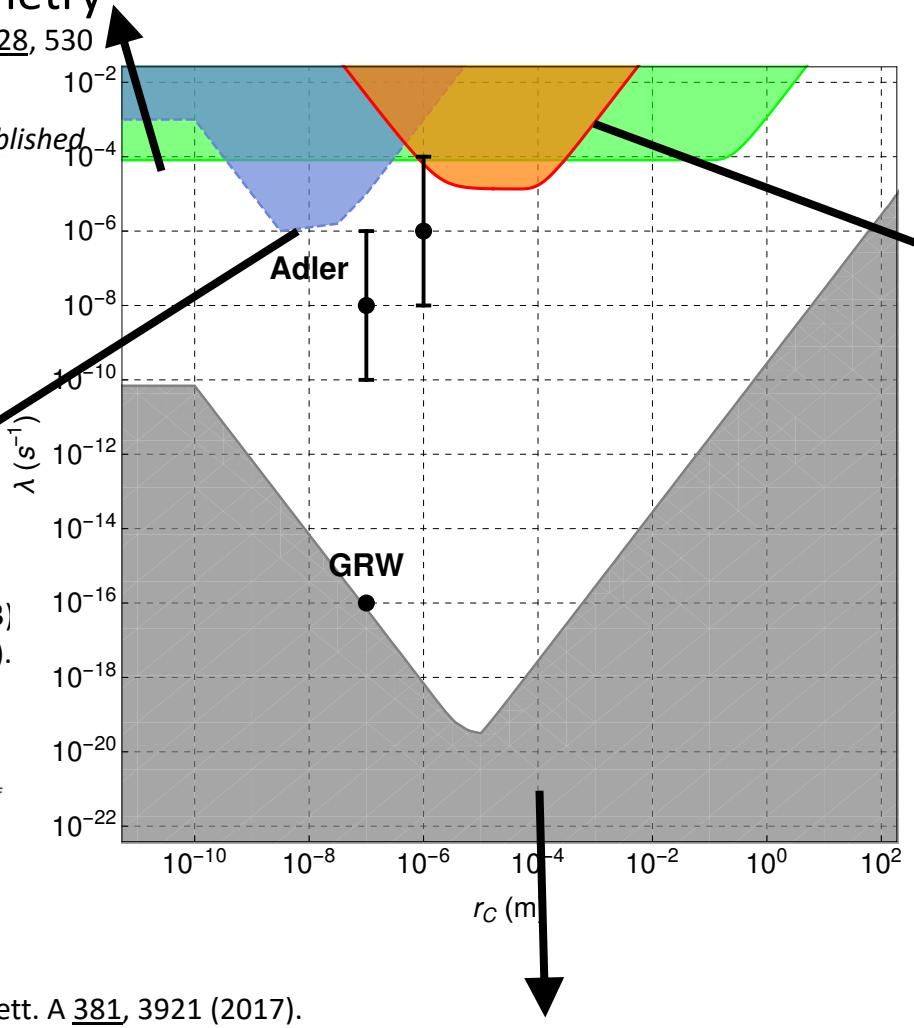
Interferometric Tests

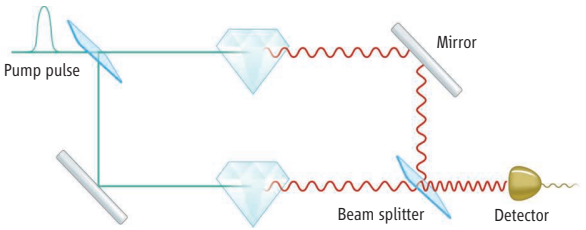
Atom Interferometry

T. Kovachy *et al.,* Nature 528, 530 (2015)

M. Carlesso *et al., to be published*

M = 87 amu
d = 0.54 m
T = 1 s

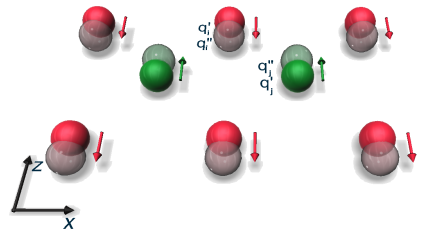




Entangling Diamonds

K. C. Lee *et al.*, Science. 334, 1253 (2011).
S. Belli *et al,* Phys. Rev. A 94, 012108 (2016).

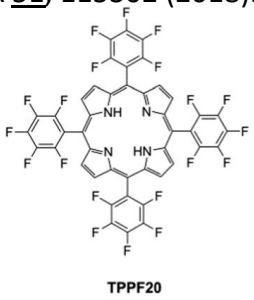
M = 10^{16} amu
d = 10^{-11} m
T = 10^{-12} s



Molecular Interferometry

S. Eibenberger *et al.* PCCP 15, 14696 (2013)
M. Toros *et al.*, J. Phys. A 51, 115302 (2018).

M = 10^{4} amu
d = 10^{-7} m
T = 10^{-3} s



M. Toros *et al.*, Phys. Lett. A 381, 3921 (2017).

Lower bound: Collapse effective at the macroscopic level
Graphene disk: N = 10^{11} amu, d = 10^{-5} m, T = 10^{-2} s

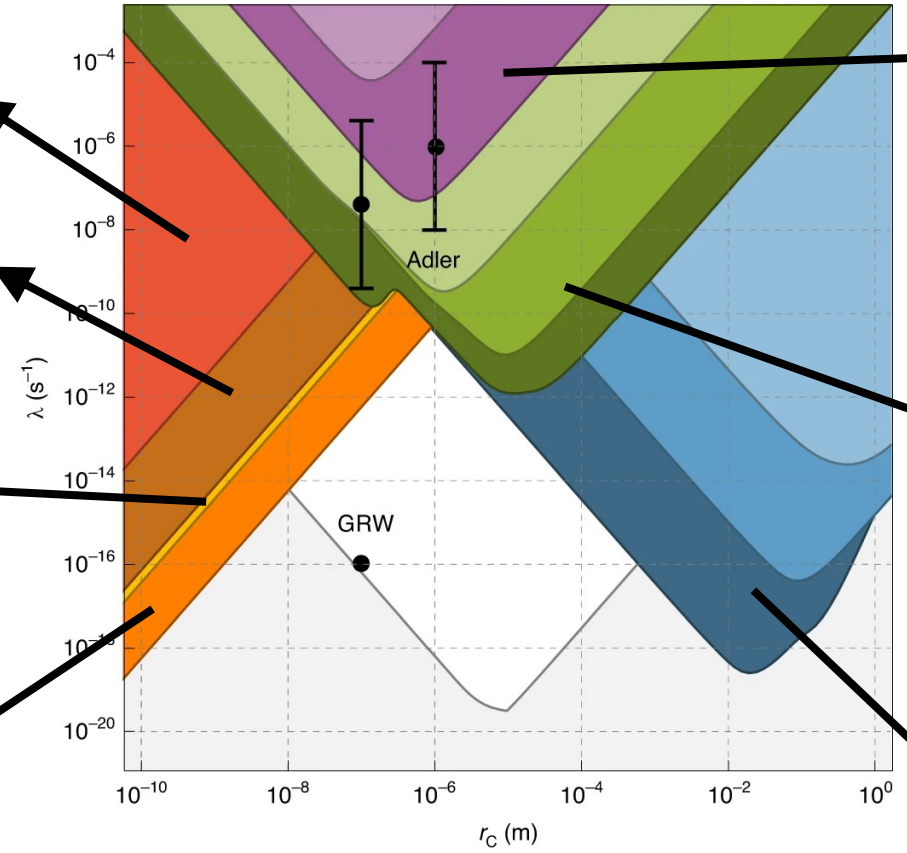
Non-interferometric Tests

Cold Atoms
Kovachy *et al.,* Phys. Rev. Lett. **114**, 143004 (2015)
Bilardello *et al.,* Physica A, **462**:764-782 (2016)

Neptune
S.L. Adler *et al., Phys. Rev. D* ***99***, 103001 (2019)

Phonon Spectrum
Adler *et al.,* Phys. Rev. A **97**, 052119 (2018).
Bahrami, Phys. Rev. A **97**, 052118 (2018).

X-rays emission
Donadi *et al,* Eur. Phys. J. C ***81***, 1 (2021)



Levitated nano-oscillators
Pontin *et al.*, Phys. Rev. Res. **2**, 023349 (2020)
Zheng *et al.*, Phys. Rev. Res. **2**, 013057 (2020)

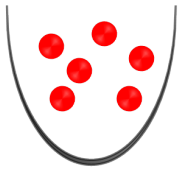
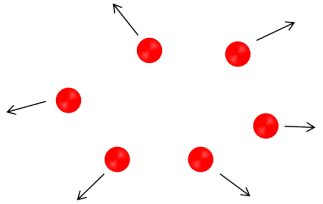
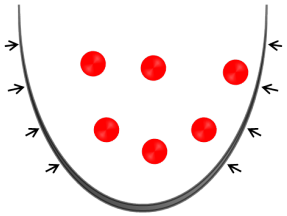
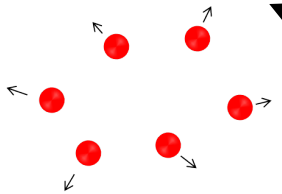
Nanomechanical cantilevers
Vinante *et al.*, Phys. Rev. Lett. **116**, 090402 (2016)
Vinante *et al.*, Phys. Rev. Lett. **119**, 110401 (2017)
Vinante *et al.*, Phys. Rev. Lett. **125**, 100404 (2020)

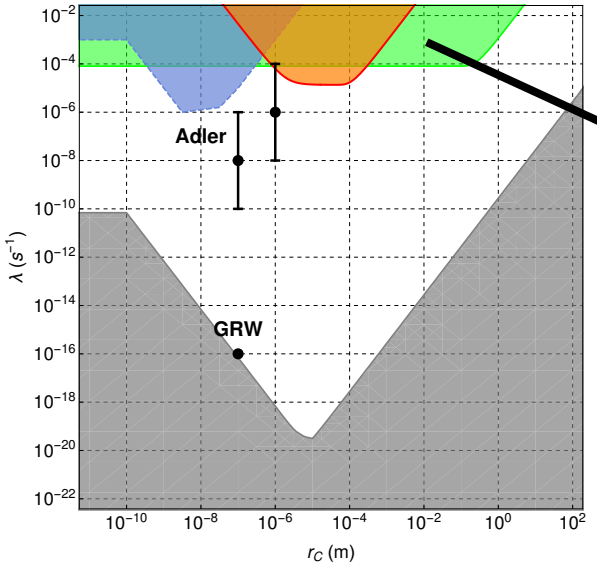
Gravitational wave detectors
Auriga, LIGO, LISA Pathfinder
Carlesso *et al,* Phys. Rev. D ***94***, 124036 (2016)

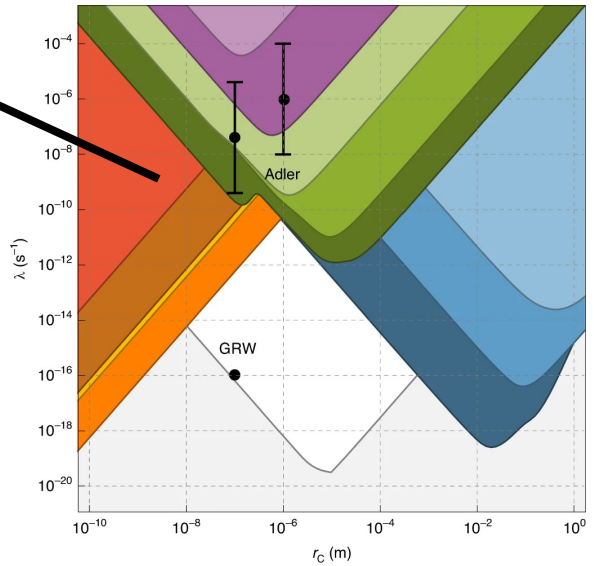
Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

Non-interferometric Test

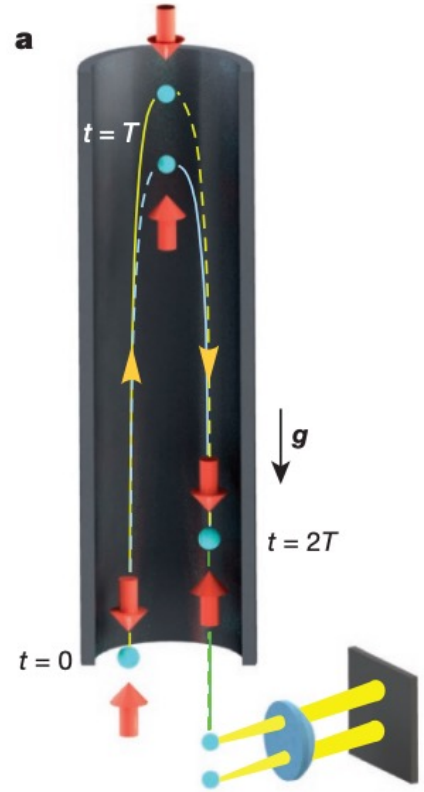
Kovachy *et al.,* Phys. Rev. Lett. **114**, 143004 (2015)

Initial state: t = 0  gas confined: T=1600 pK Δx=56 μm,	Step 1: t ∈ [0,t_1], $\Delta t_1 = t_1$ = 1100 ms  gas evolves freely
Step 2: t ∈ [t_1, t_2], $\delta t_2 = t_2 - t_1$ = 35 ms  delta-kick ω=6.7 Hz	Step 3: t ∈ [t_1, t_3], $\Delta t_3 = t_3 - t_2$ =1800 ms  gas evolves freely: T=50^{+50}_{-30} pK, $\Delta x = 120^{+40}_{-40}$ μm





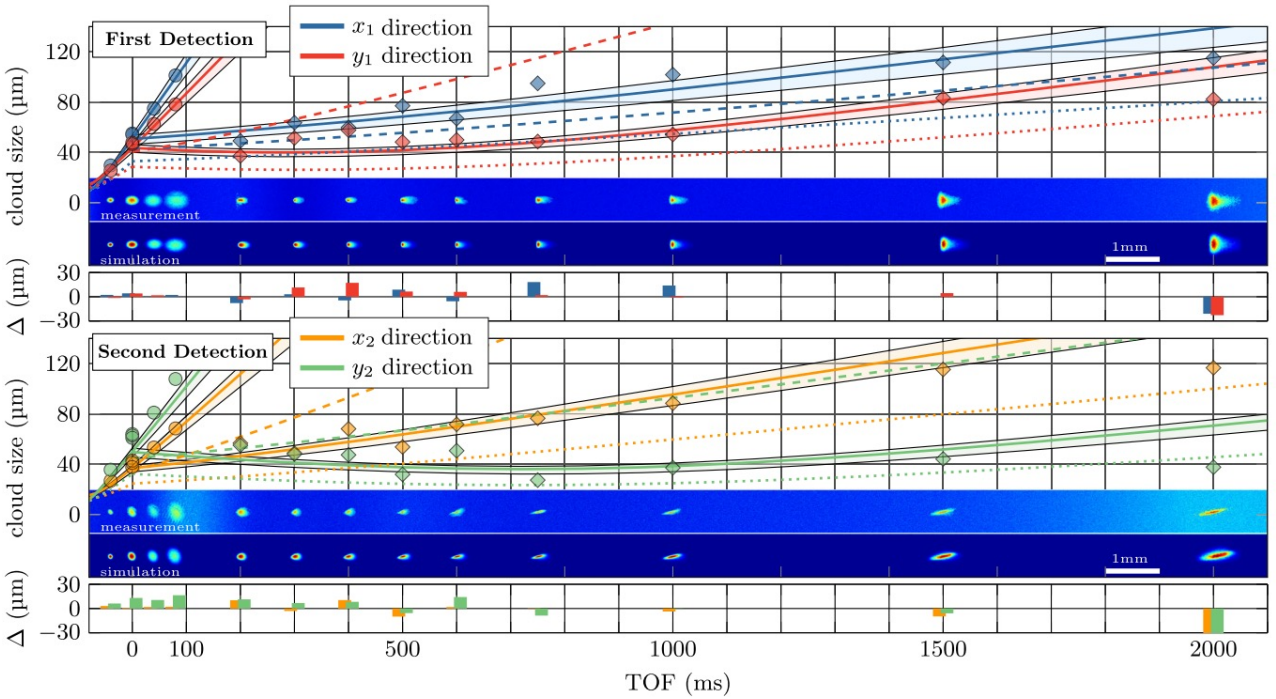
Interferometric Test



Kovachy *et al.,* Nature **528**, 530 (2015)

STE-QUEST capabilities

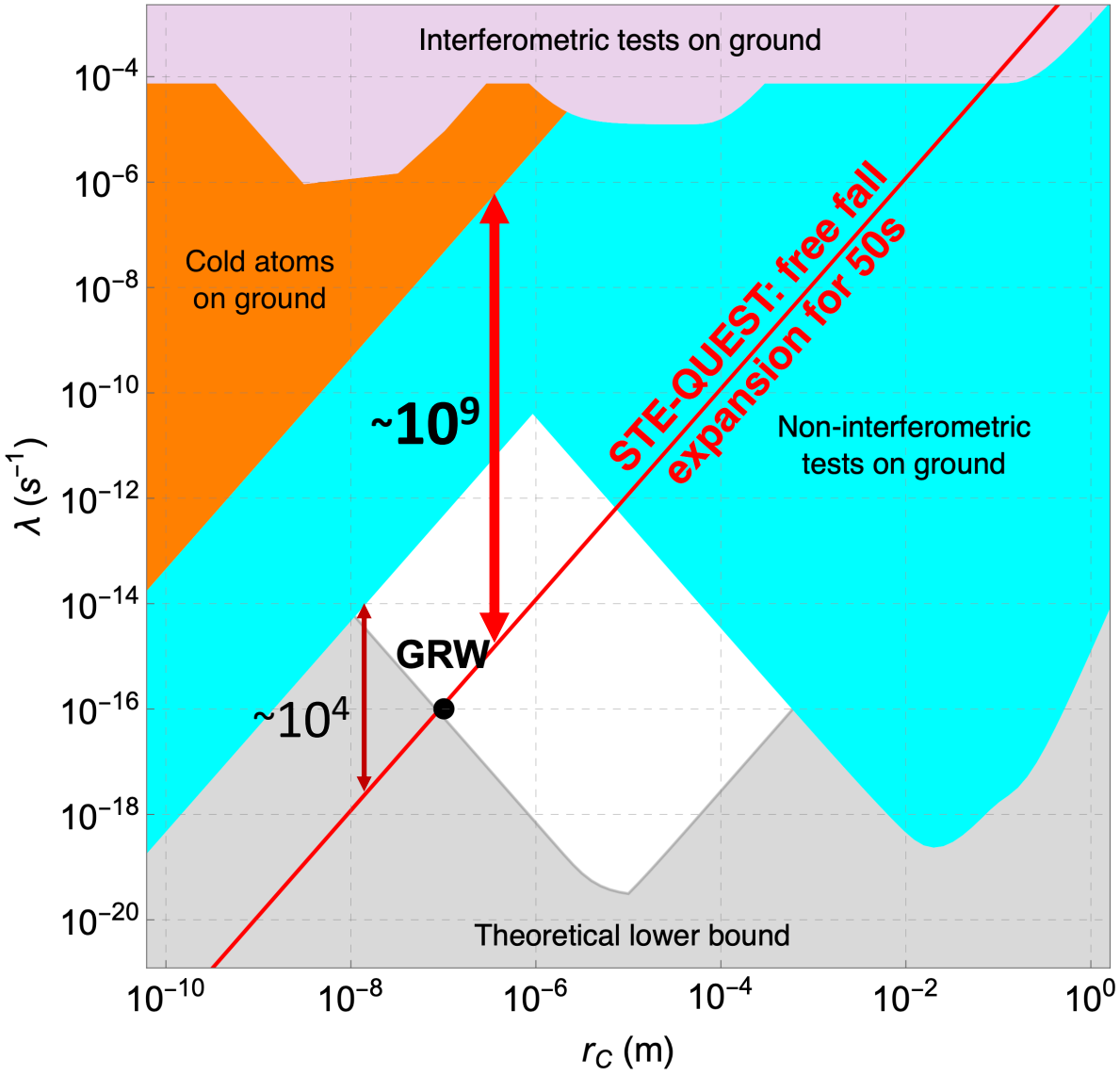
Deppner *et al.*, Phys. Rev. Lett. **127**, 100401 (2021)



Time Of Flight = 50 s

Position resolution = 10^{-6} m

In progress work with Hannover and Trieste

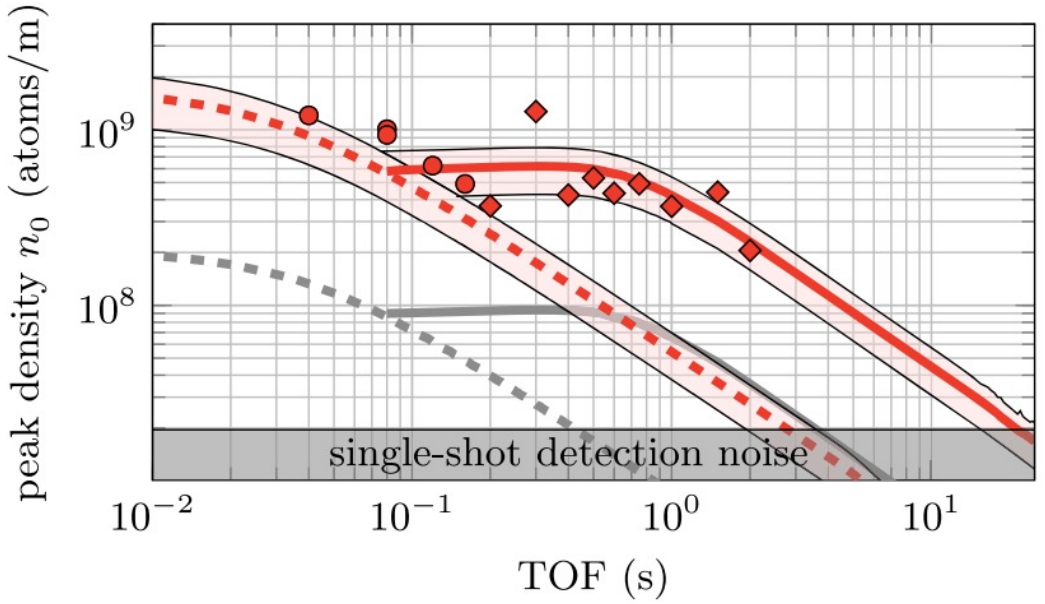


STE-QUEST challenges

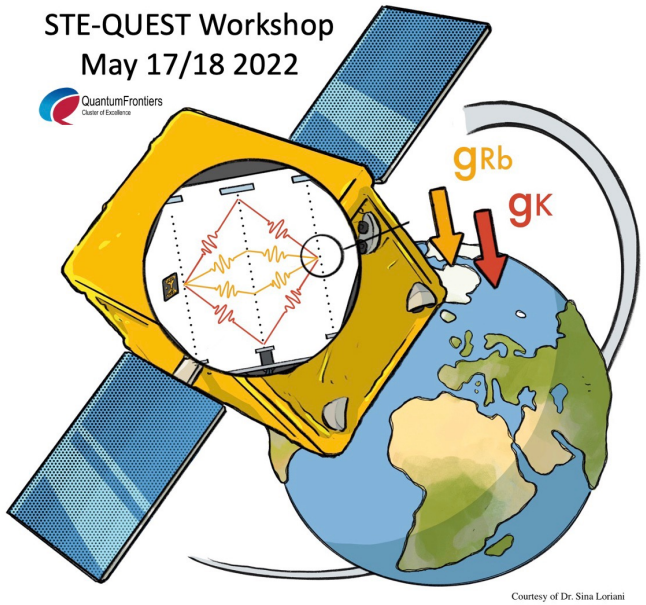
1) Long evolution time – TOF
   - Longer TOF stronger bounds
   - Drifts due the atmospheric drag

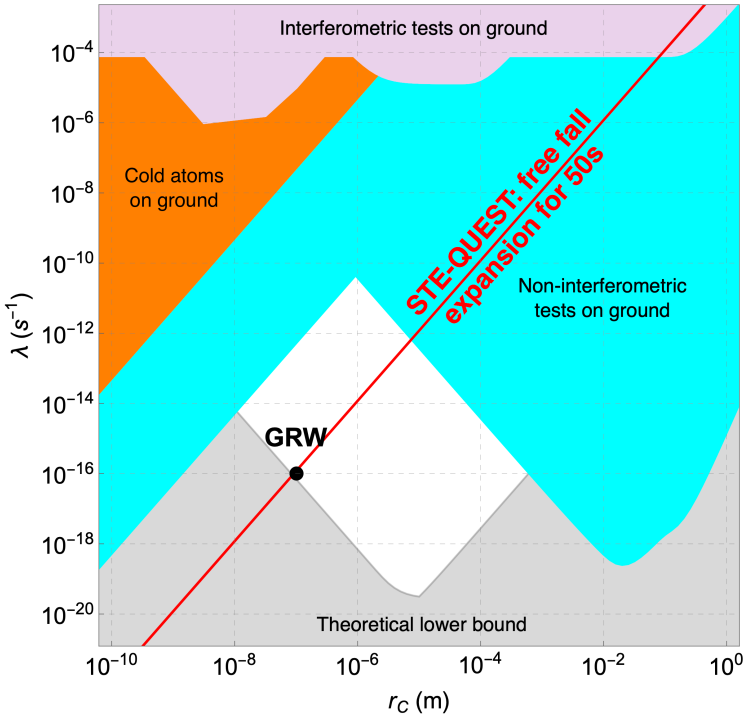
2) Low noise levels
   - Similar action as collapse noises

3) Resolution of the position spread – Density peak
   - Long free evolution will strongly dimmish the density
   - Becomes harder to detect the limits of the cloud
   - The resolution in position degrades



Summary





- STE-QUEST can pose strong bounds on collapse models
- Some technical challenges to overcome
- Details will be presented soon

Review Paper: Carlesso *et al.* Nature Physics **18**, 243-250 (2022)

UKRI Engineering and Physical Sciences Research Council