Title: Theory Modelling for the Analogue Unruh Effect

Speakers:

Collection: Quantum Simulators of Fundamental Physics

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Theory Modelling for the Analogue Unruh Effect

Bridging from theory to experiment

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Circular motion analogue Unruh effect in a $2+1$ thermal bath: Robbing from the rich and giving to the poor

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arXiv[2303.12690]

Third sound detectors in accelerated motion

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arXiv[2302.12023]

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APPROVED

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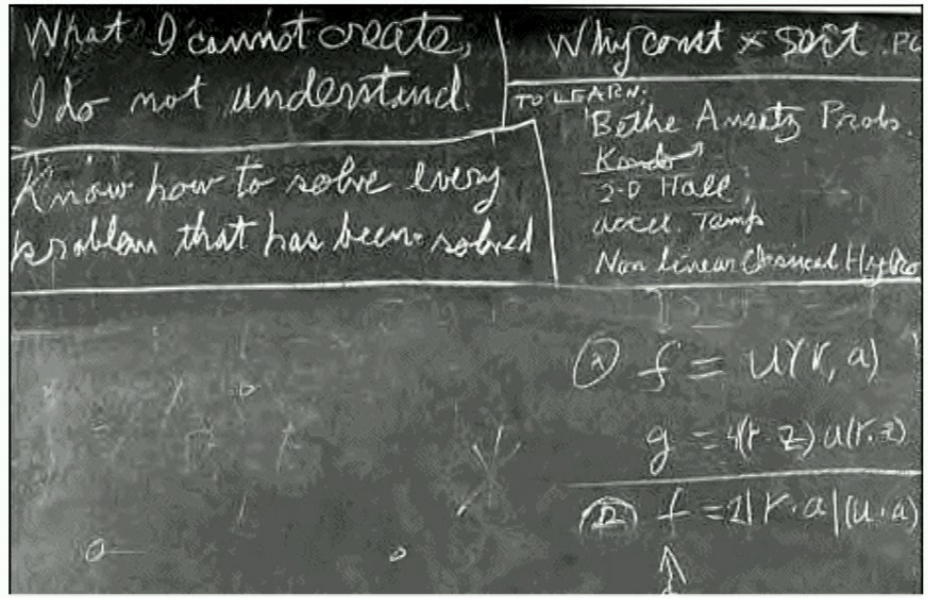
A primer on the Unruh effect



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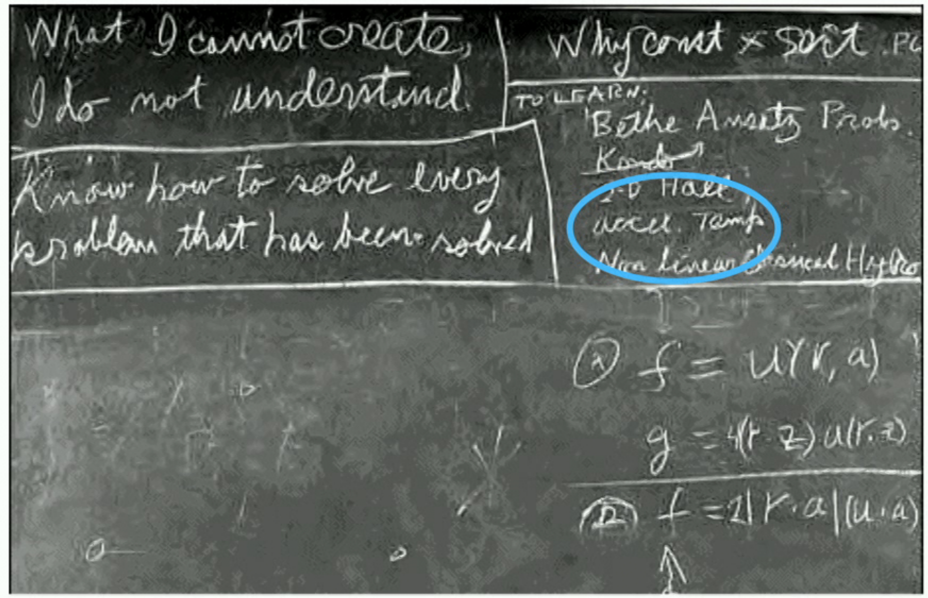

Feynman's blackboard

- Quantum scalar field $\hat{\phi}(\mathsf{x})$ in Minkowski spacetime $\eta_{\mu\nu} = \mathrm{diag}(-1,1,1,1)$
- Couple to a detector $\mathrm{H}_{int} = \lambda\chi(\tau)\hat{\phi}(\mathsf{x})\hat{\mu}(\tau)$, the *Unruh-DeWitt detector*

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- λ (small) coupling constant
- $\chi(\tau)$ *switching function*
- $\hat{\mu}(\tau)$ *monopole moment operator* for two level detector with energy gap E

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- Couple to a detector $\mathrm{H}_{int} = \lambda\chi(\tau)\hat{\phi}(\mathsf{x})\hat{\mu}(\tau)$, the *Unruh-DeWitt detector*
- Detector excitation probability $\mathscr{P}(E) = \lambda^2 |\langle E|\hat{\mu}(0)|0\rangle|^2 \int_{\mathbb{R}} \mathrm{d}\tau' \int_{\mathbb{R}} \mathrm{d}\tau'' \, \mathrm{e}^{-\mathrm{i}E(\tau'-\tau'')} \langle \hat{\phi}(\tau')\hat{\phi}(\tau'')\rangle$

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- Excitation and de-excitation probabilities obey *Einstein's detailed balance condition*:

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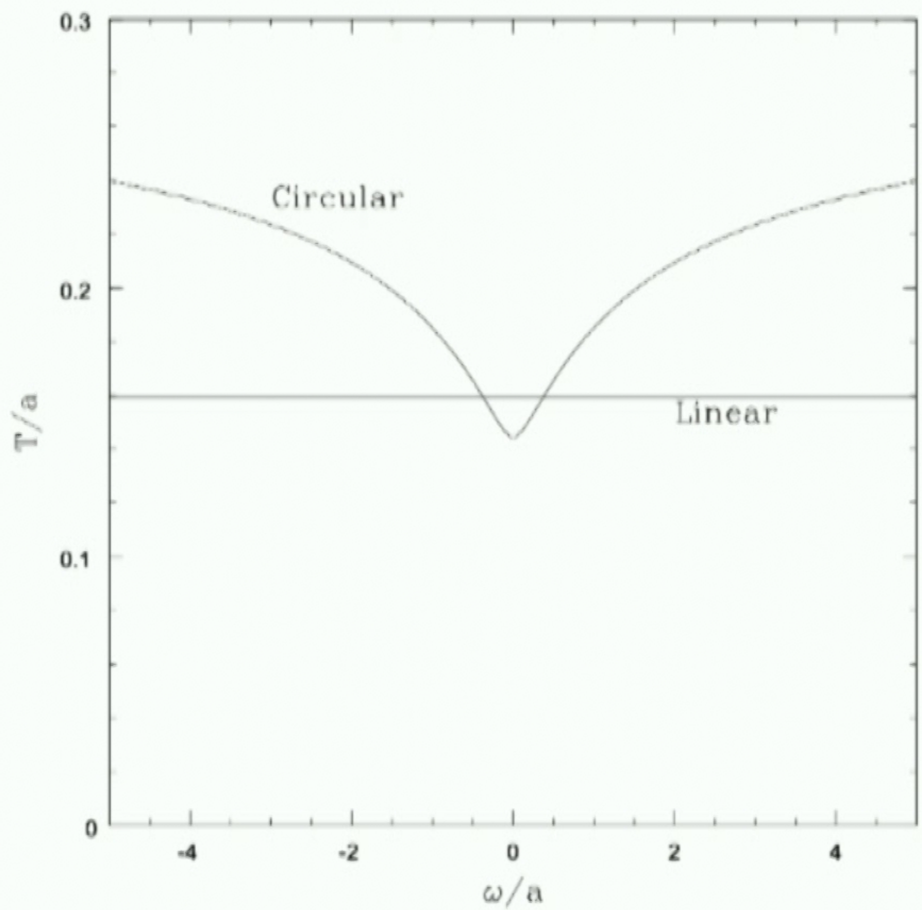
$$\mathscr{P}(E)\mathrm{e}^{E/T} = \mathscr{P}(-E)$$

The Unruh Effect: $T = \dfrac{a}{2\pi}$

A primer on the circular motion Unruh effect



W. G. Unruh, *Acceleration Radiation for Orbiting Electrons, 1998*

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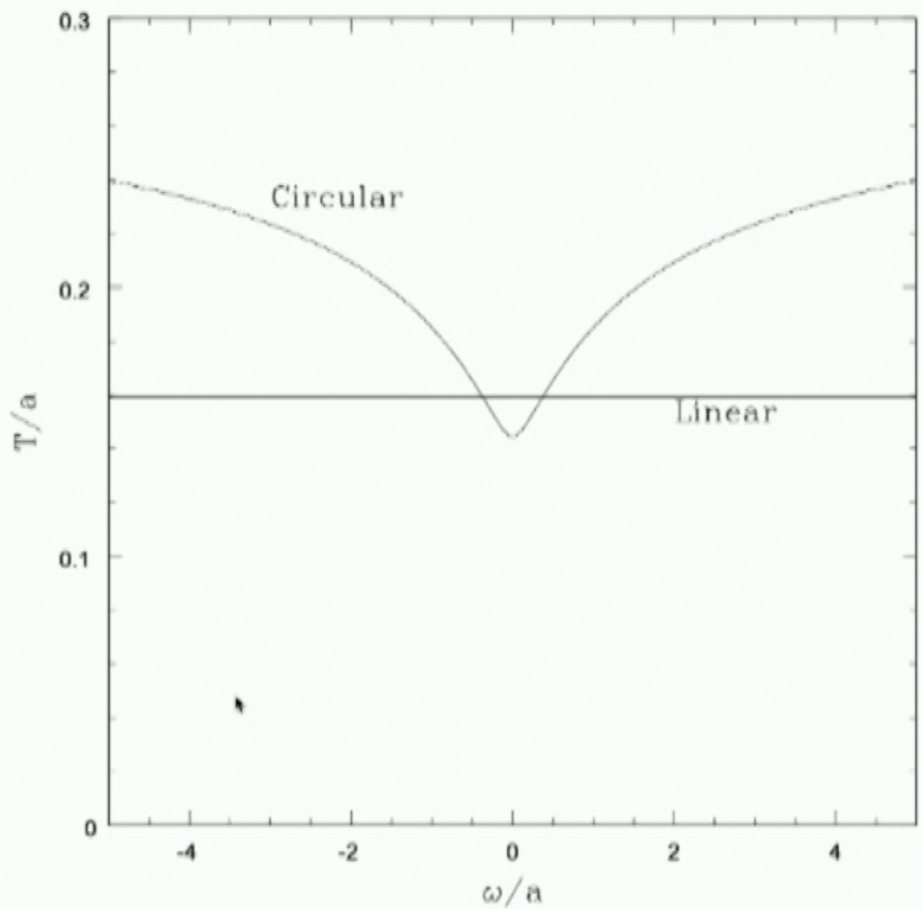
Effective temperature

$$T(\omega) = \frac{\omega}{\ln\left(\frac{\mathscr{P}(-\omega)}{\mathscr{P}(\omega)}\right)}$$



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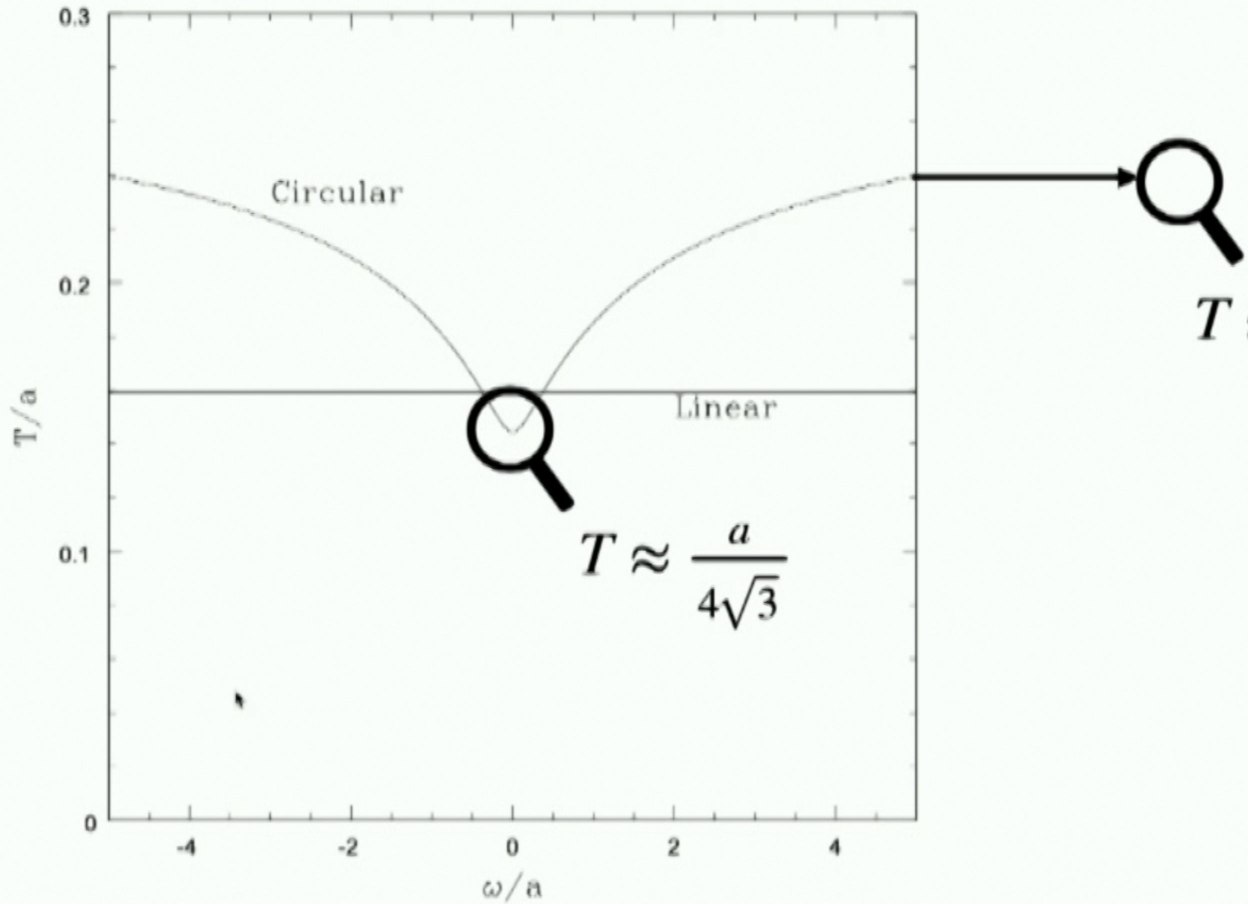
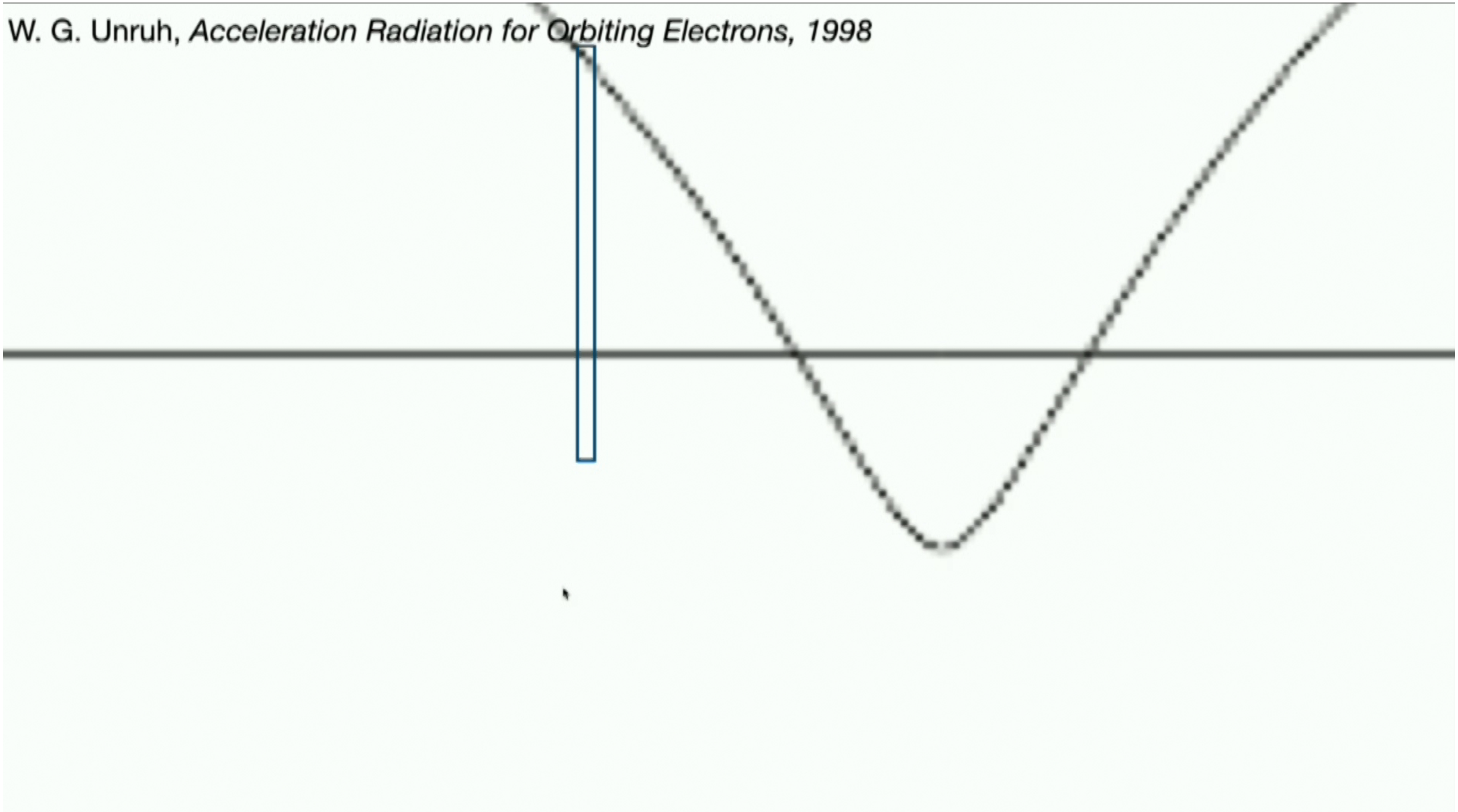


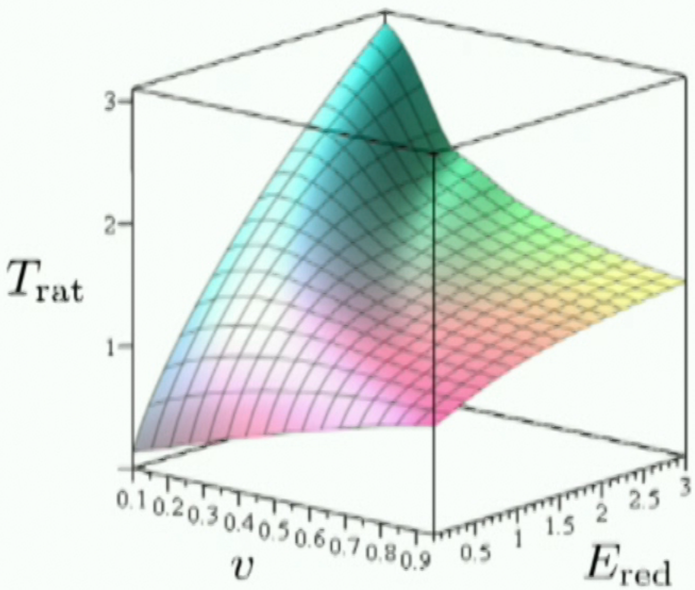
$$T \approx \frac{a}{4\sqrt{3}}$$

$$T \approx \frac{a}{2\sqrt{3}}$$

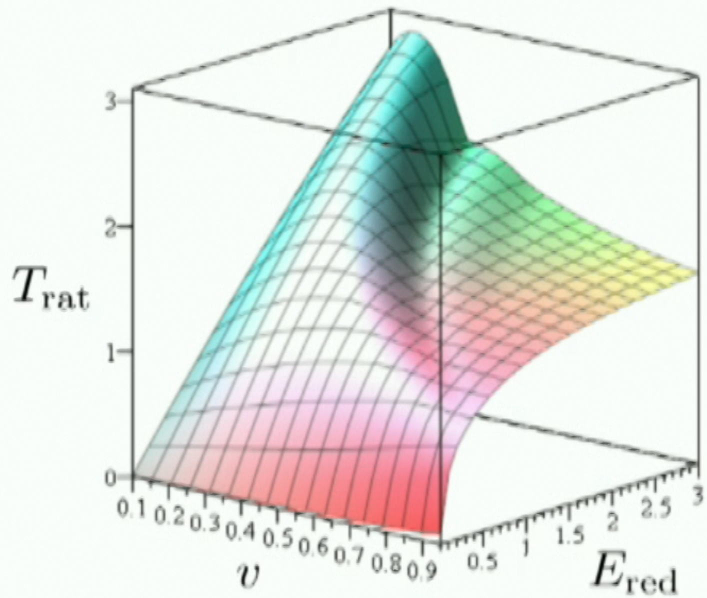
W. G. Unruh, *Acceleration Radiation for Orbiting Electrons*, 1998



Biermann et al., *Phys.Rev.D 102 (2020)*



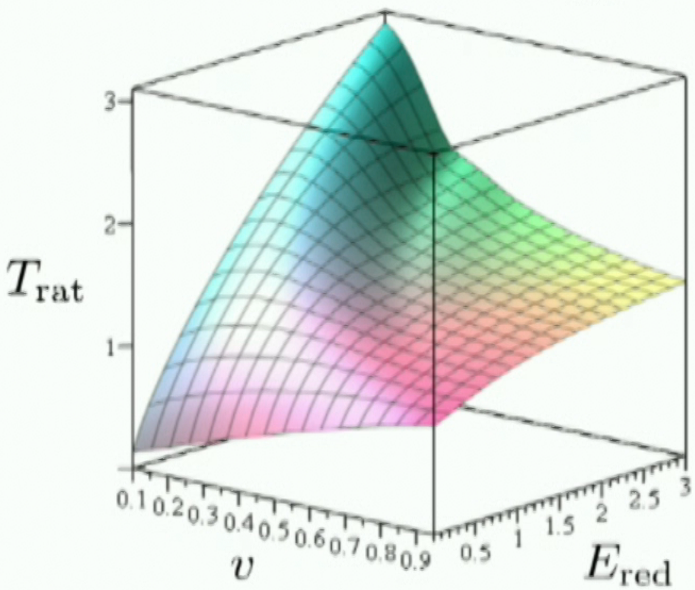
$3 + 1$ dimensions



$2 + 1$ dimensions

Biermann et al., *Phys.Rev.D 102 (2020)*

$$T_{\text{rat}} := \frac{T_{\text{circ}}}{T_{\text{lin}}} \quad E_{\text{red}} := \frac{E}{a}$$



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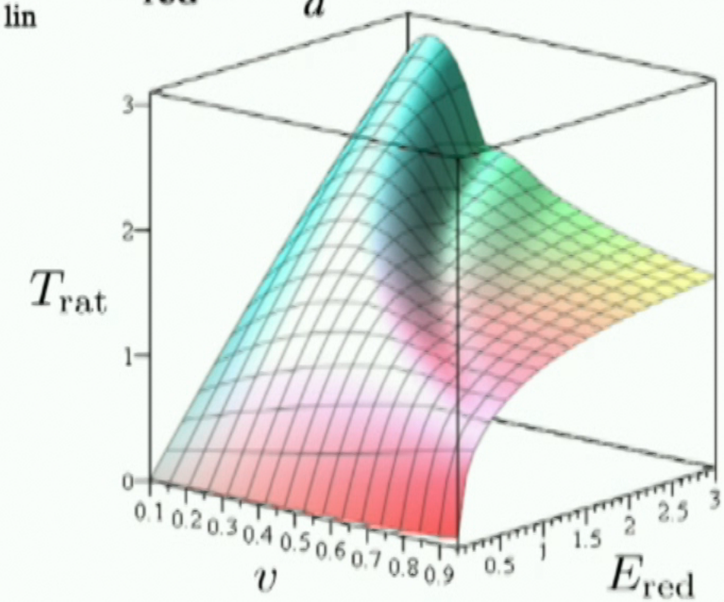

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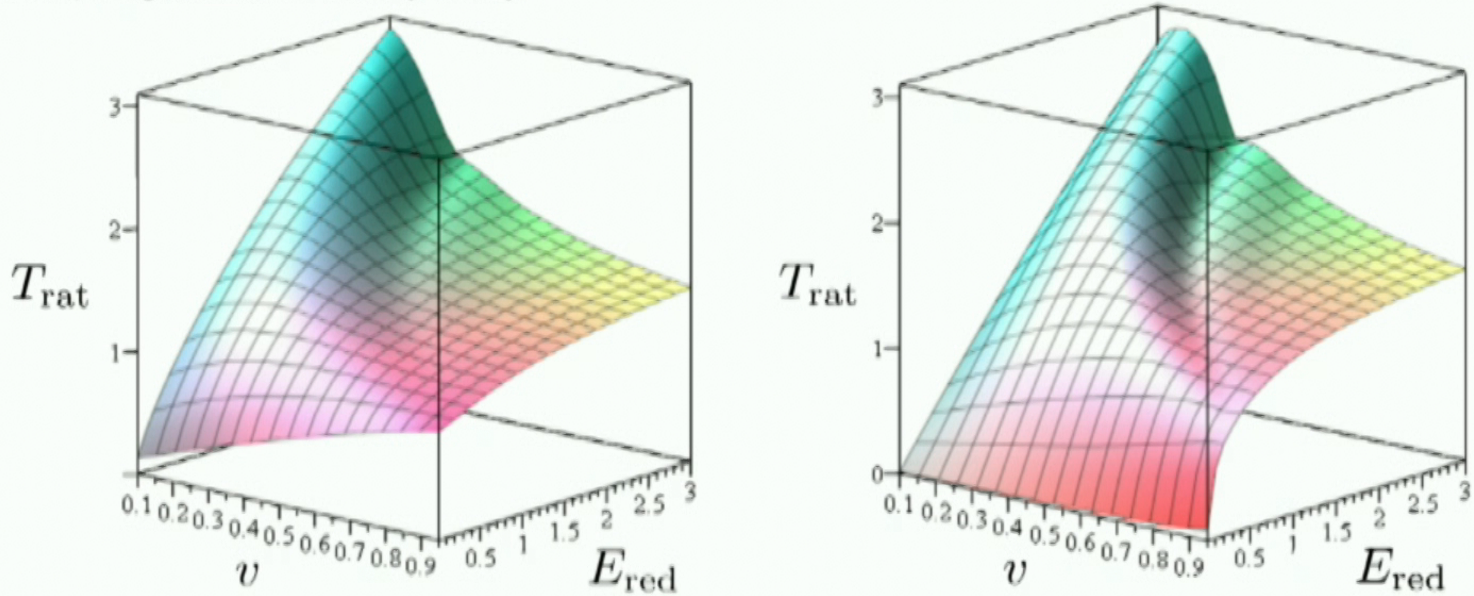


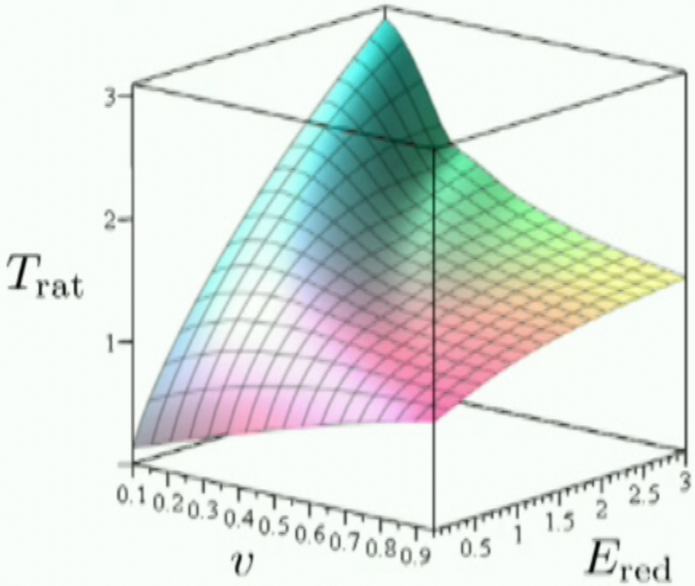
$3+1$ dimensions $\qquad$ $2+1$ dimensions

$$T_{\text{rat}} := \frac{T_{\text{circ}}}{T_{\text{lin}}}$$

$T_{\text{circ}} \rightarrow \dfrac{E}{\ln\left(\frac{\mathscr{P}(-E)}{\mathscr{P}(E)}\right)}$

$T_{\text{lin}} \rightarrow \dfrac{a}{2\pi}$

Biermann et al., *Phys.Rev.D 102 (2020)*



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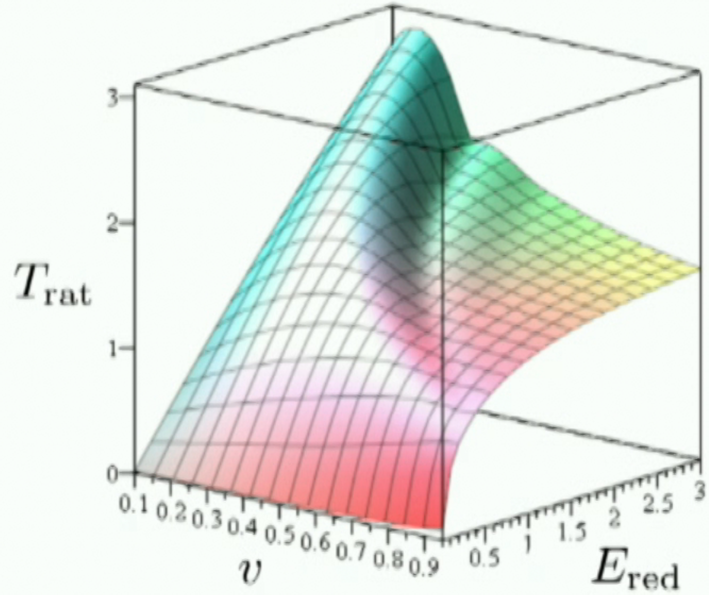

$2+1$ dimensions

$$T_{\rm rat} := \frac{T_{\rm circ}}{T_{\rm lin}} \longrightarrow \frac{E}{\ln\left(\frac{\mathscr{P}(-E)}{\mathscr{P}(E)}\right)}, \qquad \longrightarrow \frac{a}{2\pi}$$

Let's build an experiment

Defining the theory (From a theorist's point of view)

1) W r i t e d o w n

Examples

Gravity waves

$$\omega^2 = \left(gk + \frac{\sigma}{\rho}k^3\right)\tanh(hk)$$

BEC (Боголюбов) dispersion

$$\omega^2 = \frac{k^2}{2m}\left(\frac{k^2}{2m} + \mu\right)$$

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$$\omega^2 \approx ghk^2 =: c_{eff}^2 k^2 \text{ for } hk \ll 1$$

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$$\omega^2 \approx \frac{\mu}{2m} k^2 =: c_{eff}^2 k^2 \text{ for } k \ll 1$$

$\omega^2 \approx c_{eff}^2 k^2$ a linear regime, matching with QFT

Examples

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BEC (Боголюбов) dispersion

$$\omega^2 = \frac{k^2}{2m} \left(\frac{k^2}{2m} + \mu \right)$$

Defining the theory

Vacuum?

2) Initial state

$$\mathscr{P}(E) = \lambda^2 |\langle E|\hat{\mu}(0)|0\rangle|^2 \int_{\mathbb{R}} \mathrm{d}\tau' \int_{\mathbb{R}} \mathrm{d}\tau''\, \mathrm{e}^{-\mathrm{i}E(\tau'-\tau'')} \langle \hat{\phi}(\tau')\hat{\phi}(\tau'')\rangle$$

$$\mathscr{P}(E;\beta) = \lambda^2 |\langle E|\hat{\mu}(0)|0\rangle|^2 \int_{\mathbb{R}} \mathrm{d}\tau' \int_{\mathbb{R}} \mathrm{d}\tau''\, \mathrm{e}^{-\mathrm{i}E(\tau'-\tau'')} \langle \hat{\phi}(\tau')\hat{\phi}(\tau'')\rangle_\beta$$

← Thermal?

Defining the theory

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Labs have $T > 0$

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Thermal?

$$\langle \hat{O}\rangle_\beta = \frac{\mathrm{Tr}(\mathrm{e}^{-\hat{H}\beta}\hat{O})}{\mathrm{Tr}(\mathrm{e}^{-\hat{H}\beta})}$$

Labs have $T > 0$

Defining the theory

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Thermal?

$$\langle \hat{O} \rangle_{\beta} = \frac{\mathrm{Tr}(\mathrm{e}^{-H\beta}\hat{O})}{\mathrm{Tr}(\mathrm{e}^{-H\beta})}$$

~~Lorentz invariance~~

Labs have $T > 0$

Defining the theory

3) Boundary conditions?

No lab is infinite*:

➡ Constrain the field to a finite size

Experimentally-informed choice

*except for Poincaré disc-mapped ones

Dirichlet?

Neumann?

Mixed/Robin?

Defining the theory

4) Finite time

Have to turn the experiment on and off

Infinite interaction time easier analytically

Can we salvage something?

For a *stationary* system, infinite time can give us finite time

$$W(\tau', \tau'') \stackrel{!}{=} \langle \hat{\phi}(\tau')\hat{\phi}(\tau'')\rangle = W(\tau' - \tau'', 0)$$

Define a probability rate

$$\mathscr{F}(E) = \int_{\mathbb{R}} \mathrm{d}\tau \, \mathrm{e}^{-\mathrm{i}E\tau} W(\tau, 0)$$

Finite time $\mathscr{F}(E) = \frac{1}{2\pi}\int_{\mathbb{R}} \mathrm{d}\omega \, |\, \hat{\chi}(\omega)\,|^2 \int_{\mathbb{R}} \mathrm{d}\tau \, \mathrm{e}^{-\mathrm{i}(E+\omega)\tau} W(\tau, 0)$

"Waiting for Unruh", Fewster et al. *Class.Quant.Grav.* 33 (2016)

Analogue Setting

- Lab frame time t and energy gap $\overline{E}$ instead of proper time τ and energy E
- Analogue (condensed matter) spacetime such as BEC or superfluid helium
- Reduced spacetime dimension $(2+1)$
- Analogue scalar fields: BEC density perturbations/helium surface waves

Gooding et al. *Phys.Rev.Lett.* 125 (2020)
Bunney et al. *arXiv[2302.12023]*

- Circular motion trajectory
  $x^\mu(t) \;=\; (t, R\cos(\Omega t), R\sin(\Omega t))$
- Spectrum no longer exactly thermal - but still has acceleration-dependent response
- Only stationary situations; deal with response function $\mathscr{F}(\overline{E})$

Putting it all together

Unruh-DeWitt detector in circular motion in a $(2+1)$ analogue spacetime of finite size (Dirichlet boundary conditions at $r = a$), interacting with scalar field with modified* dispersion relation prepared in a thermal state for a finite time

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$$\mathscr{F}[\omega_{mn},\chi](\overline{E};a,\beta) = \frac{1}{2\pi}\int_{\mathbb{R}} d\varpi\,|\,\hat{\chi}(\varpi)\,|^2 \frac{(\overline{E}+\varpi)^2}{a^2}\sum_{n\in\mathbb{N}}\sum_{m\in\mathbb{Z}}\Bigg[\left(1+\frac{1}{e^{\omega_{mn}\beta}-1}\right)\frac{J^2_{|m|}(\omega_{mn}R)}{\omega_{mn}J^2_{|m|+1}(\omega_{mn}a)}\delta(\overline{E}+\varpi+\omega_{mn}-m\Omega) + \frac{1}{e^{\omega_{mn}\beta}-1}\frac{J^2_{|m|}(\omega_{mn}R)}{\omega_{mn}J^2_{|m|+1}(\omega_{mn}a)}\delta(\overline{E}+\varpi-\omega_{mn}+m\Omega)\Bigg]$$

*Bunney et al. *arXiv[2303.12690]*

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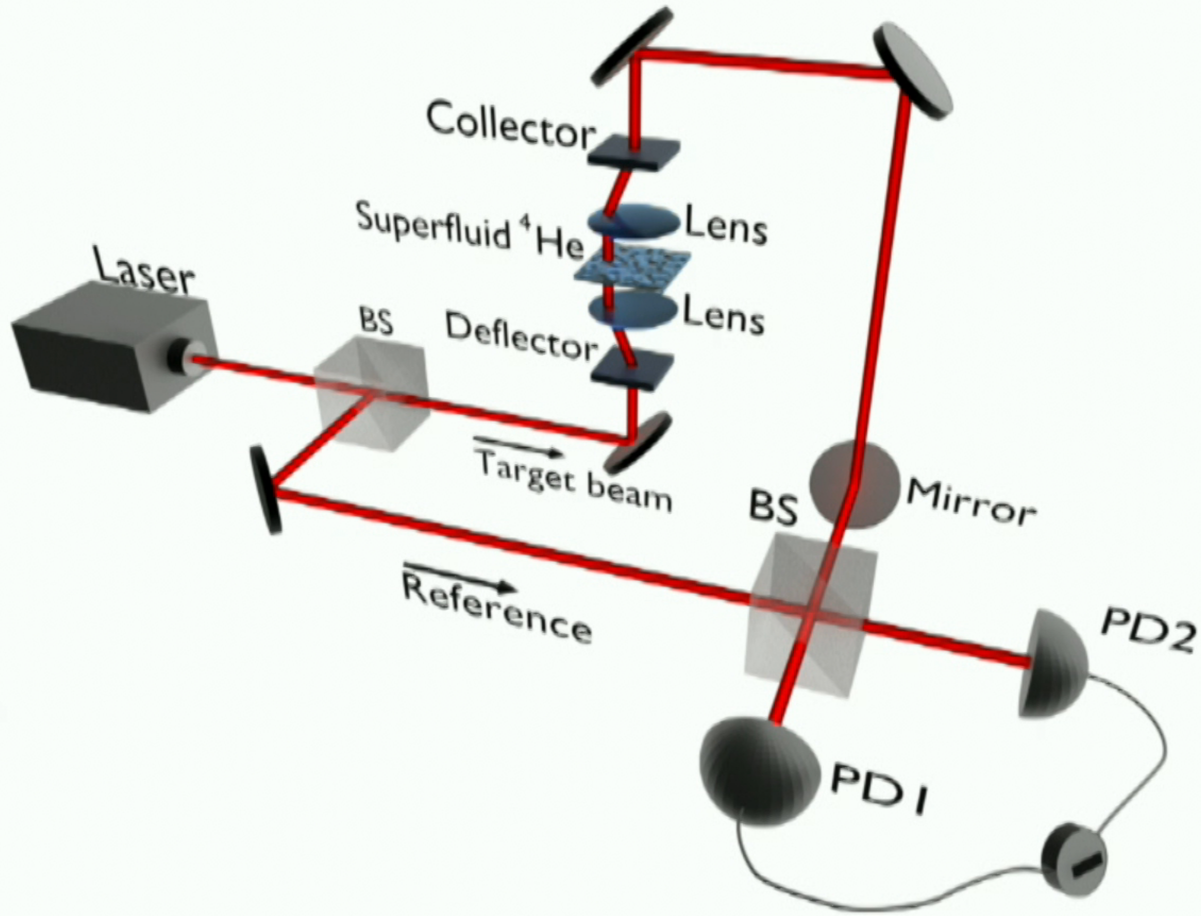
*Bunney et al. *arXiv[2303.12690]*

Initial Thermal State

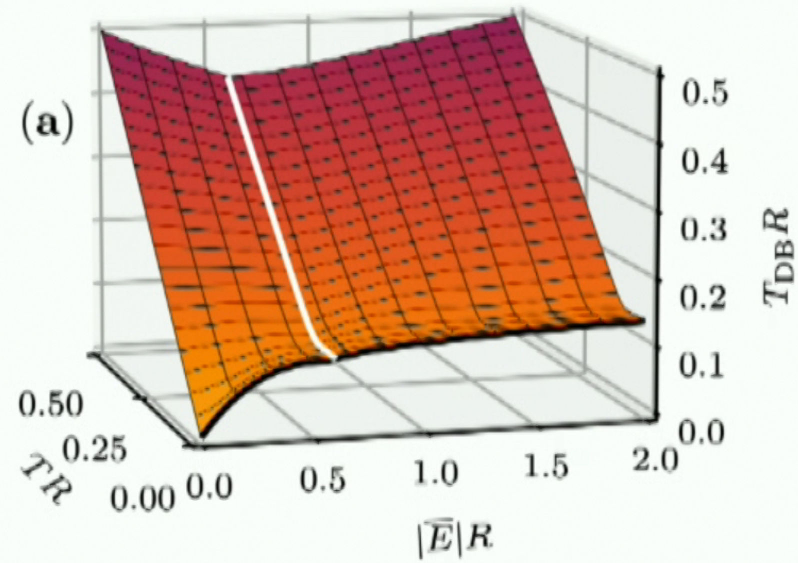


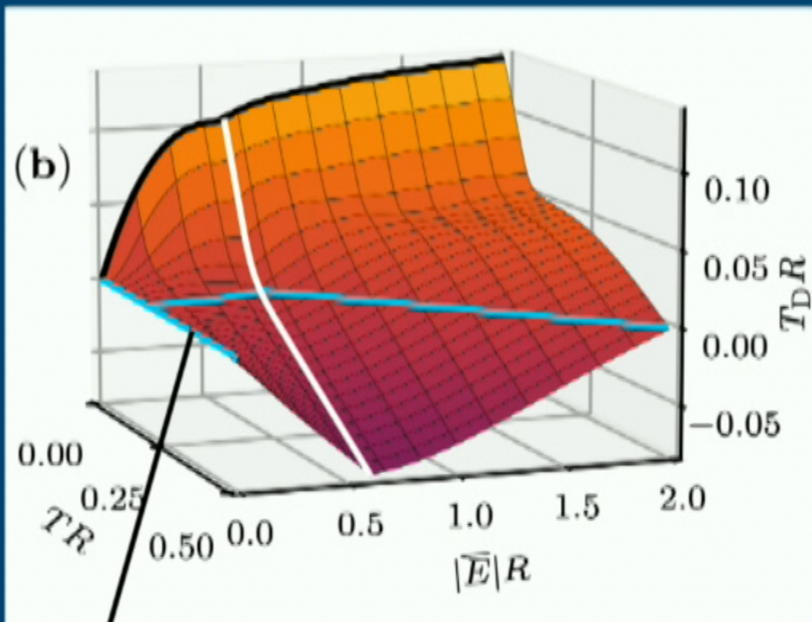
Bunney et al. *arXiv[2302.12023]*, image produced by Radivoje Prizia

Acceleration-dependent signal?

Quantifier of detector response

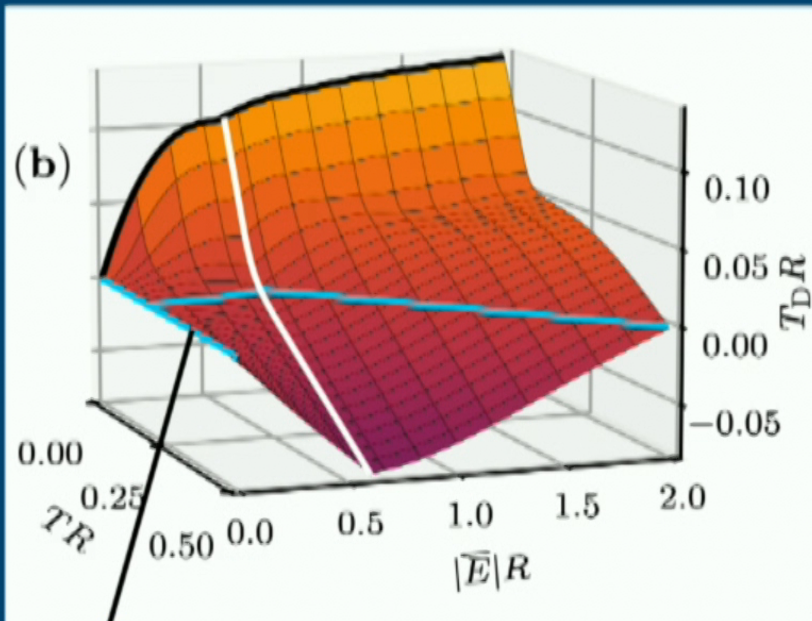
$$T_{\mathrm{DB}} = \frac{\overline{E}}{\ln\left(\frac{\mathcal{F}(-\overline{E};\beta)}{\mathcal{F}(\overline{E};\beta)}\right)}$$





$$T_D = T_{DB} - T_{\text{thermal state}}$$

Line: $T_{DB} = T_{\text{initial state}}$



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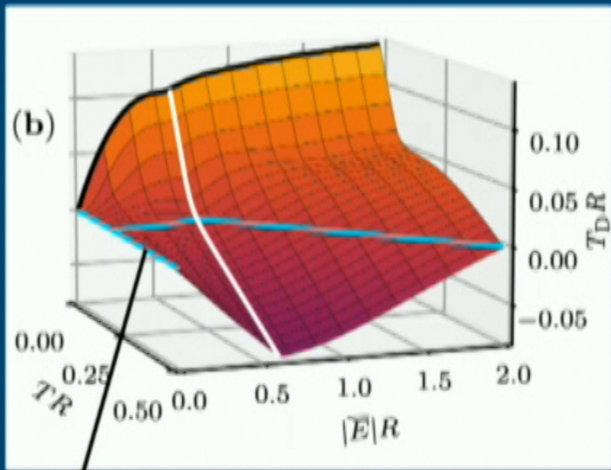

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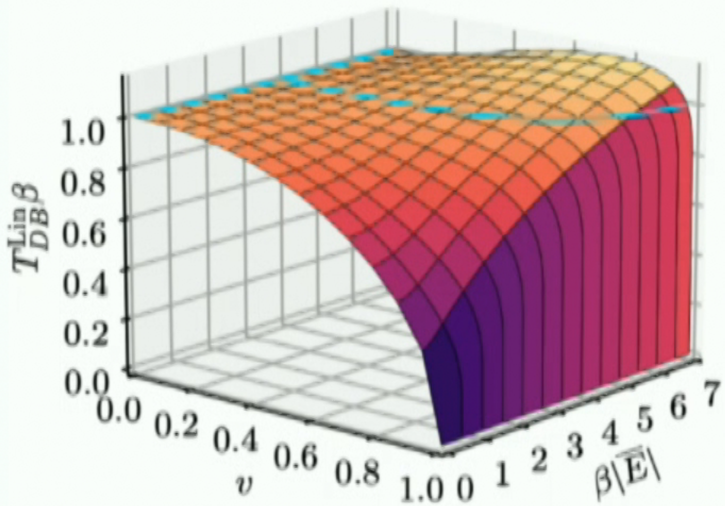
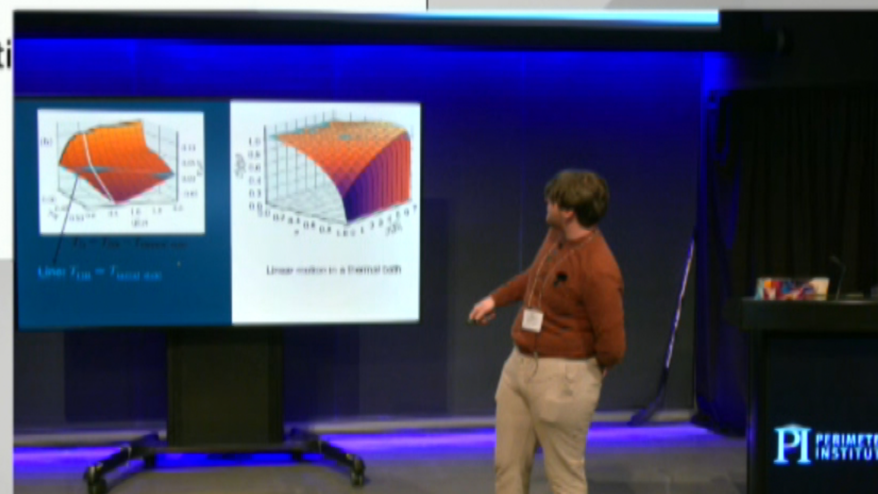
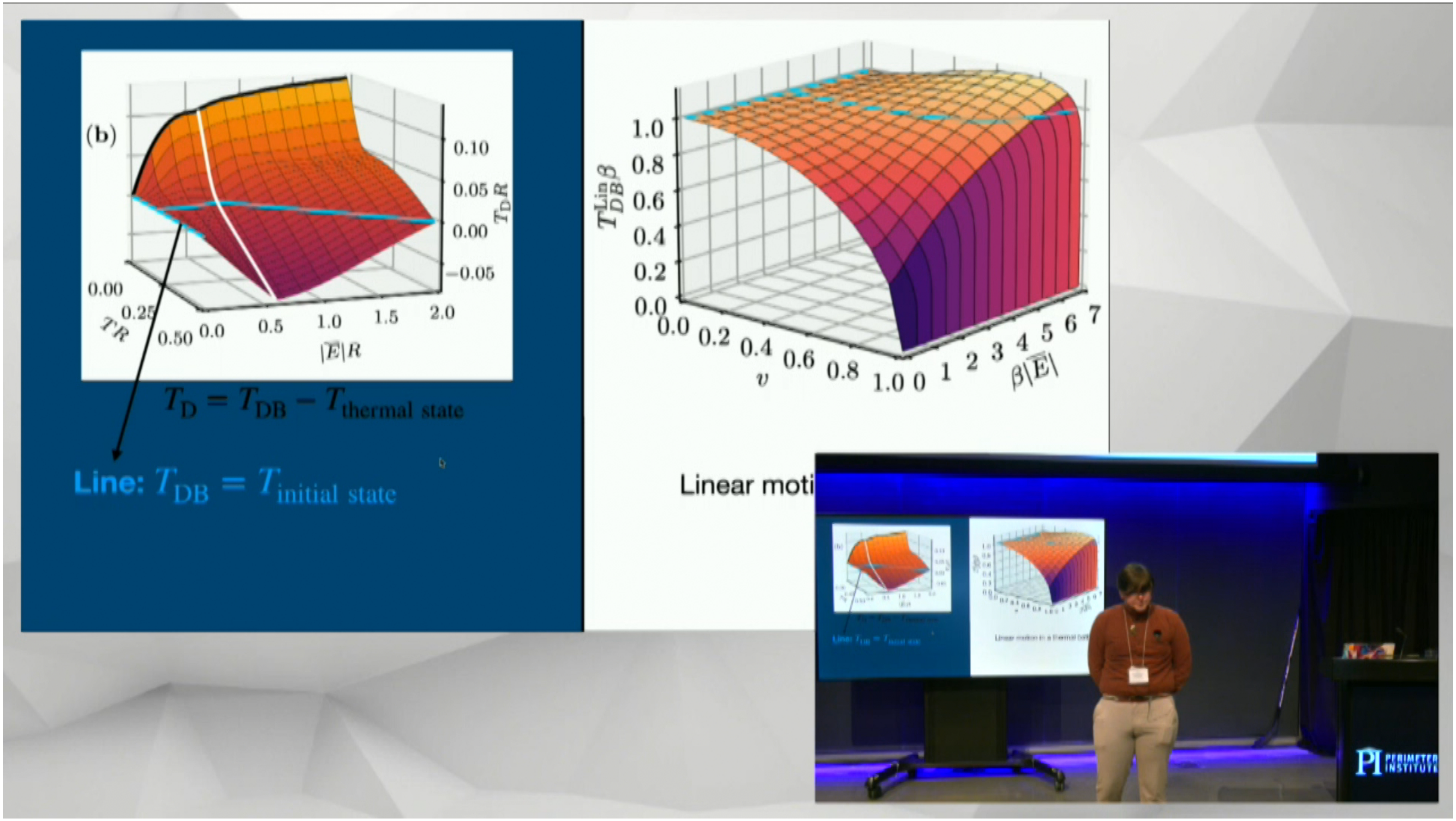


Linear moti




(b)
$T_D R$
TR
$|\overline{E}|R$
$T_D = T_{DB} - T_{\text{thermal state}}$
Line: $T_{DB} = T_{\text{initial state}}$
$T_{DB}^{\text{Lin}}\beta$
v
$\beta|\overline{E}|$
Linear moti

Velocity vs. Acceleration

- Circular motion: 2 free parameters
  - Choose acceleration and velocity
- Special case $a = 0,\ v = \text{const}$
  - Straight line motion
- $\mathscr{F}(\overline{E};\beta) - \mathscr{F}_{\text{Lin}}(\overline{E};\beta)$ removes velocity contribution

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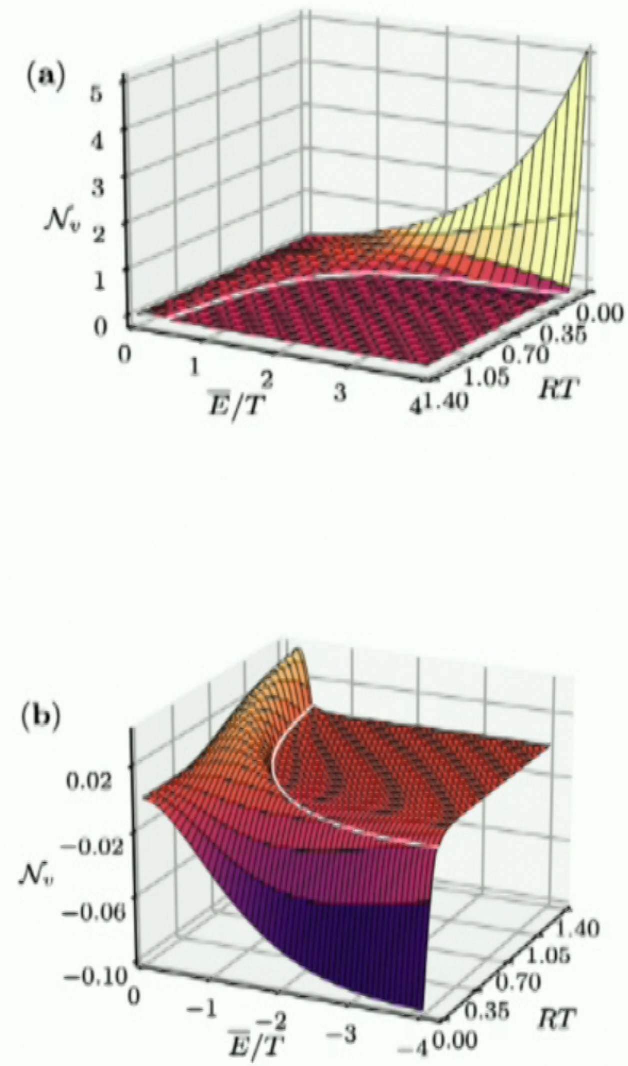
$$\mathcal{N}_v(\overline{E}\beta, R/\beta) = \frac{\mathscr{F}(\overline{E};\beta) - \mathscr{F}_{\text{Lin}}(\overline{E};\beta)}{\mathscr{F}_{\text{Lin}}(\overline{E};\beta)}$$



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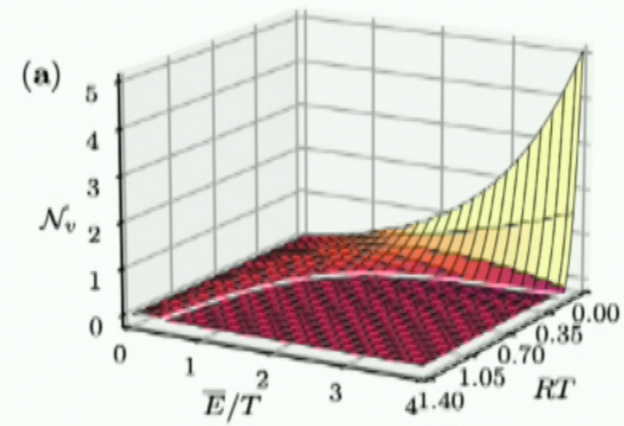
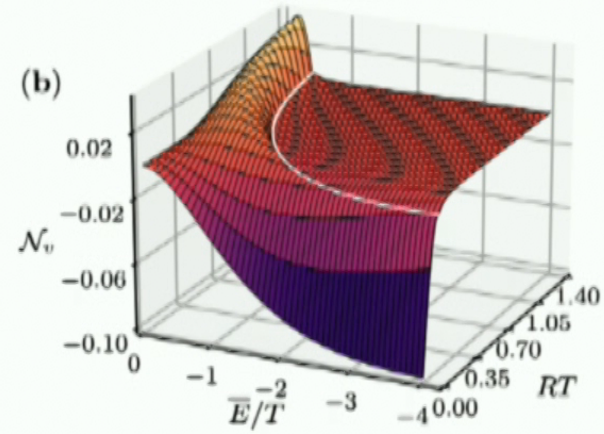
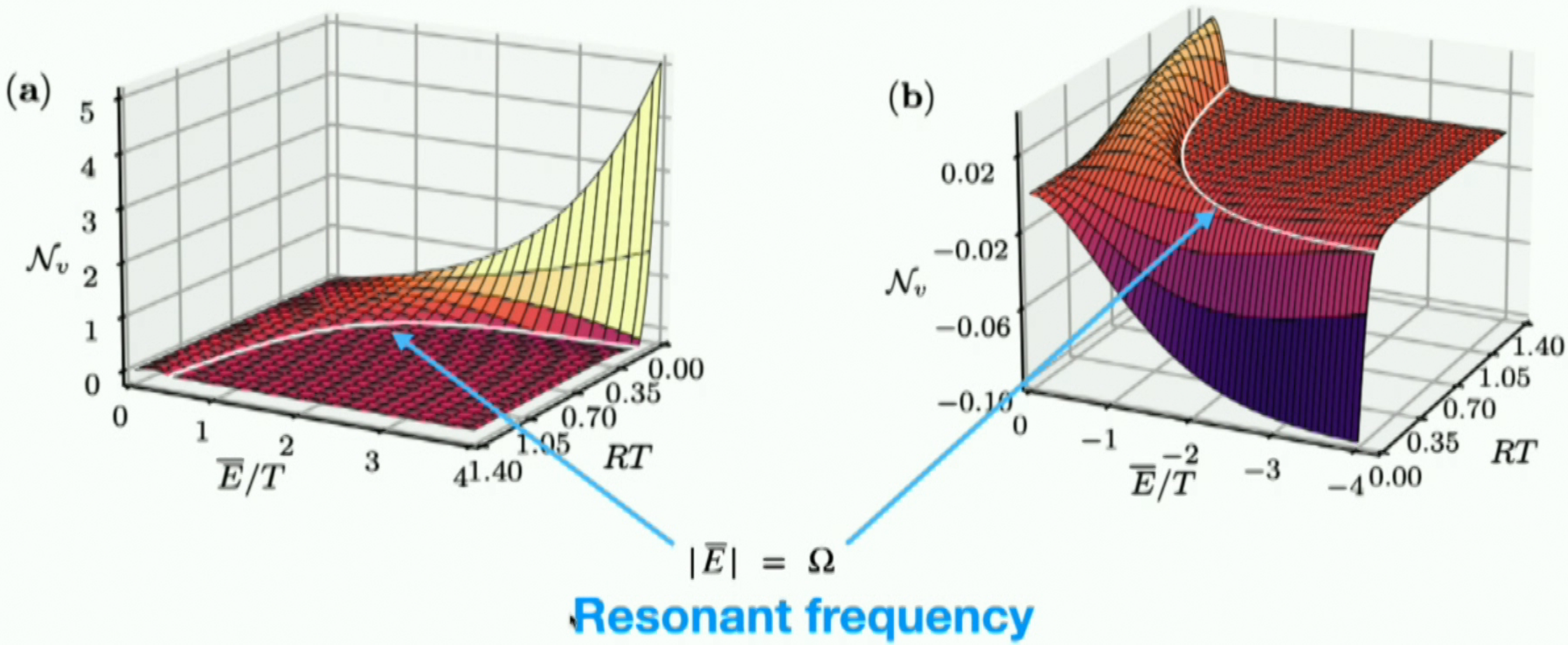


Structure independent of temperature!





Take-home:

Probing below resonance, non-negligible acceleration contribution

Helium setup

Focus on an initial thermal state

- Thin film superfluid helium-4
  - Equilibrium height $h_0 = 100\text{nm}$

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signal extraction (in progress)

Post signal extraction

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Index of refraction

Laser wave number

Van der Waals-dominated effective gravity

Mass density

Read-off and acceleration isolation

$$S_\psi(\omega) = \kappa \mathscr{F}(\omega; T) + \sigma_{\text{sn}}^2$$

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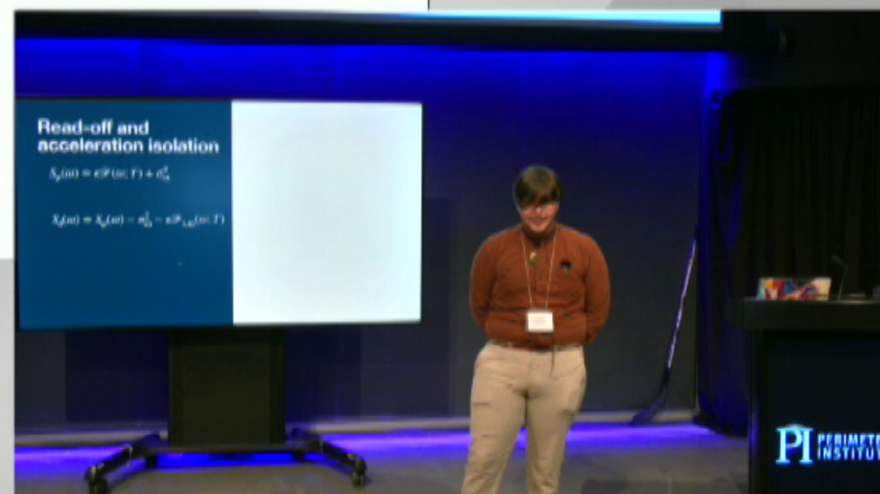

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Recall $\mathcal{N}_\nu(\overline{E}\beta, R/\beta) = \dfrac{\mathcal{F}(\overline{E};\beta) - \mathcal{F}_{\rm Lin}(\overline{E};\beta)}{\mathcal{F}_{\rm Lin}(\overline{E};\beta)}$

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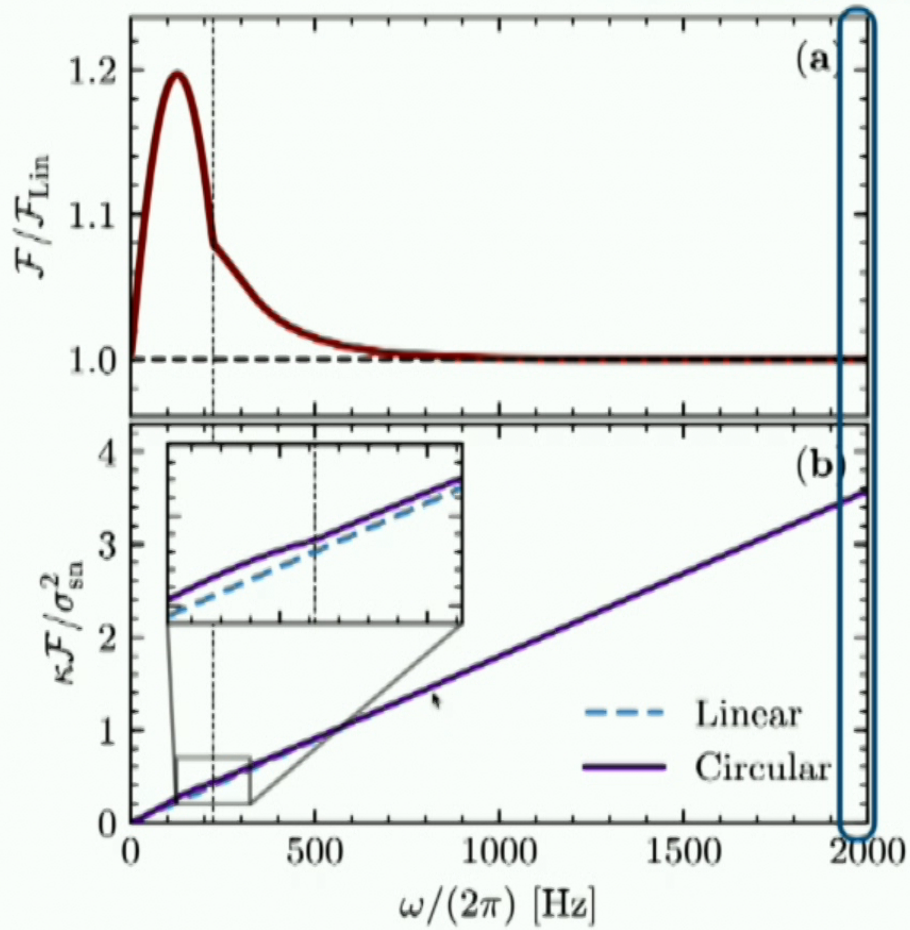
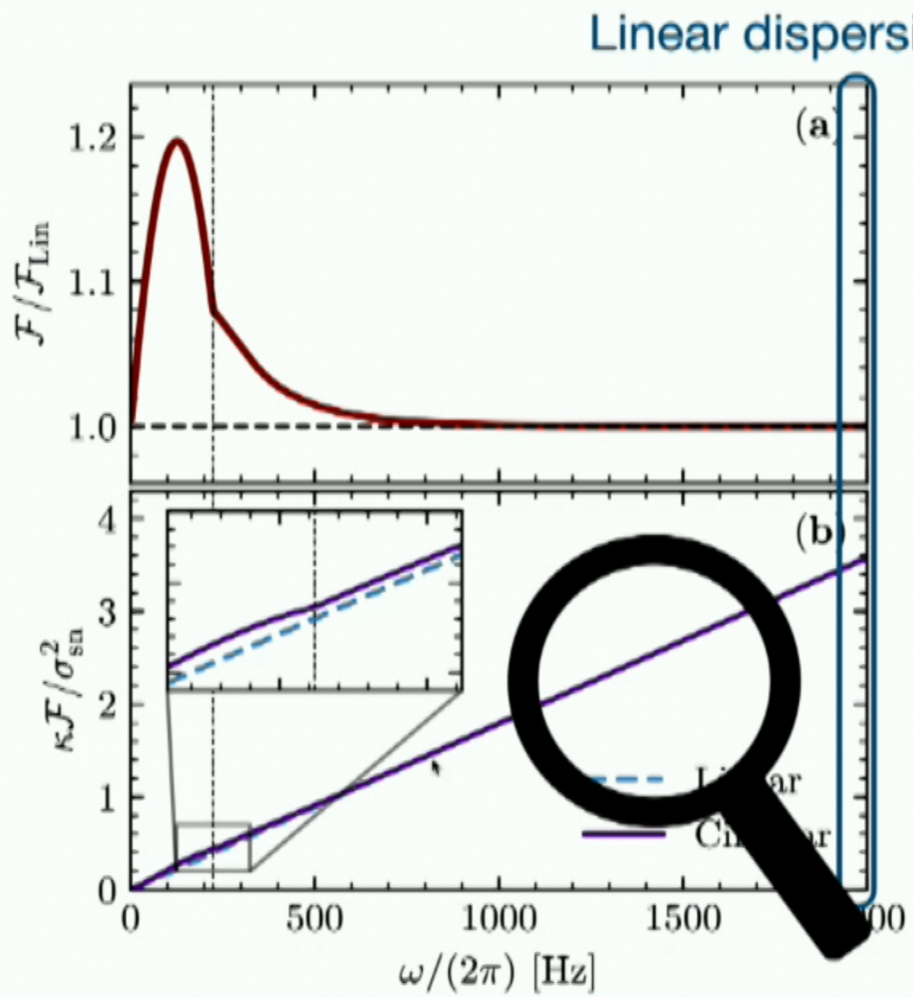
$$\text{SNR} \propto \frac{S_\delta(\omega)}{\sigma_{\text{sn}}^2 \sqrt{1 + 2\frac{S_\delta(\omega)}{\sigma_{\text{sn}}^2} + 2\frac{S_\delta^2(\omega)}{\sigma_{\text{sn}}^2}}}$$

Gooding et al. *Phys.Rev.Lett.* 125 (2020)

Linear dispersion cutoff



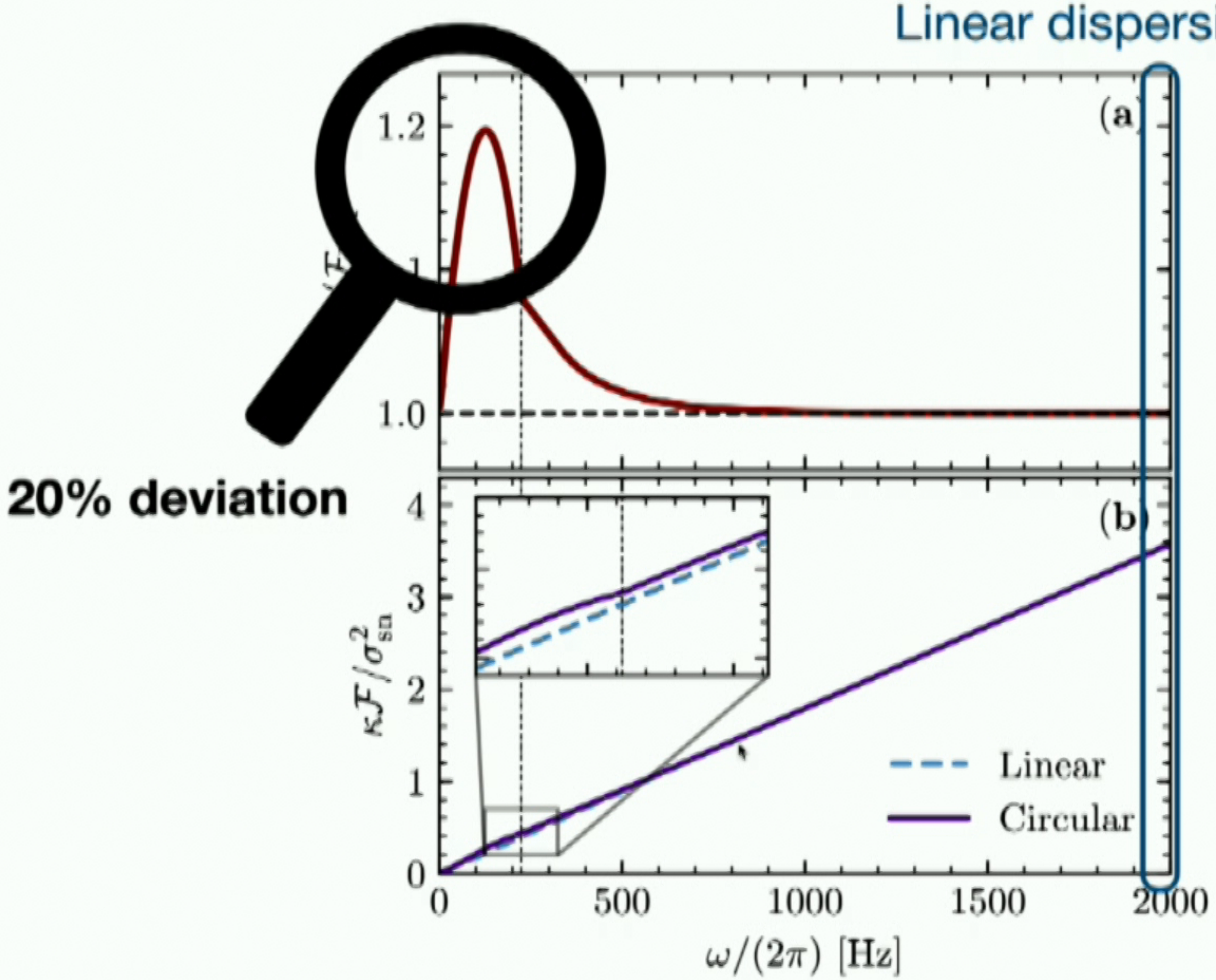


"Linear" has linear regime

$\mathscr{F}_{\rm Lin}(\omega) \propto \omega,\ (\omega > 0)$

Can approximate linear response

Linear dispersion cutoff



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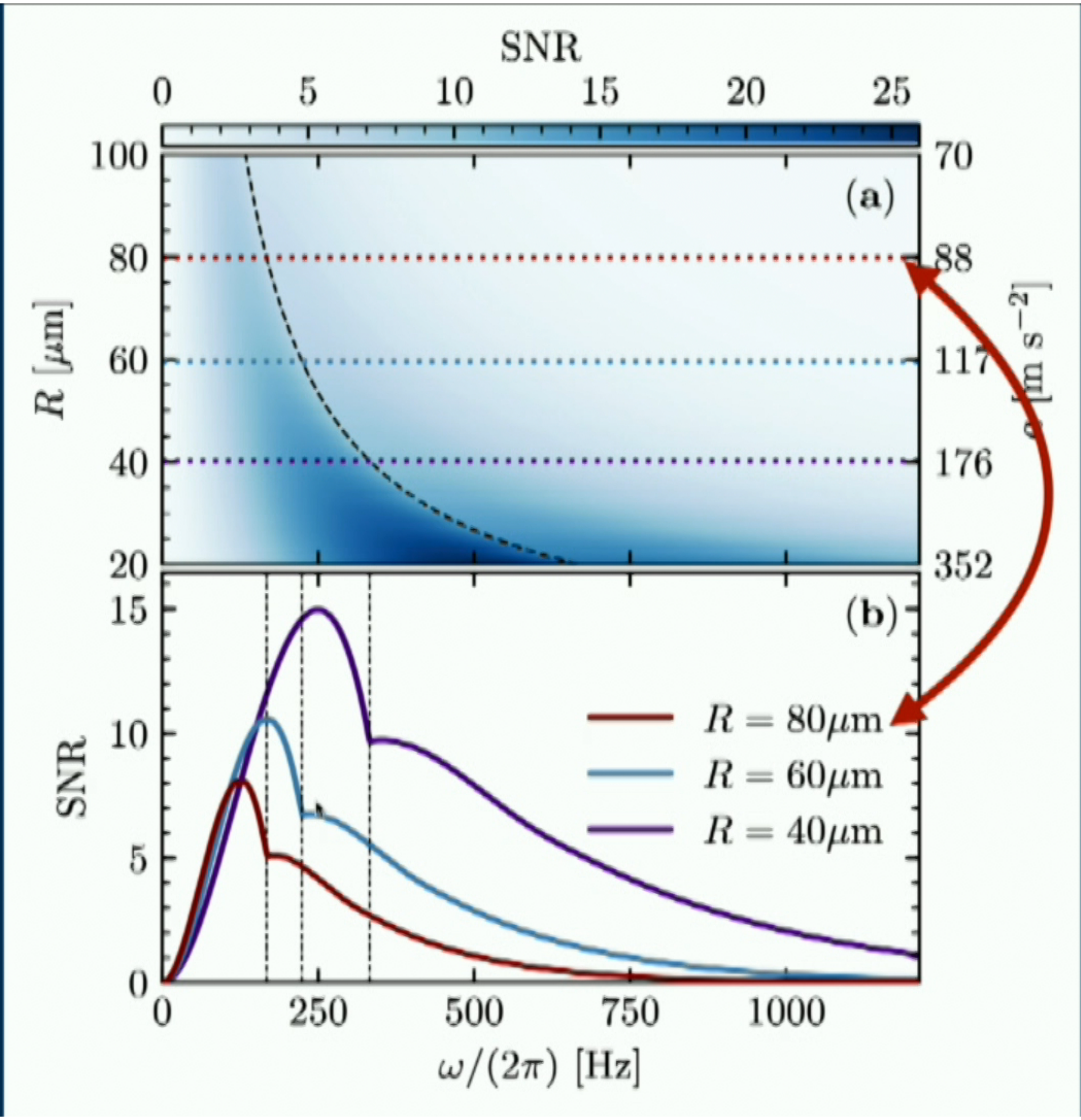
(Parameter) Space Exploration

$T = 10$ mK
$v = 0.95 c_3$ fixed



Bunney et al. *arXiv[2302.12023]*

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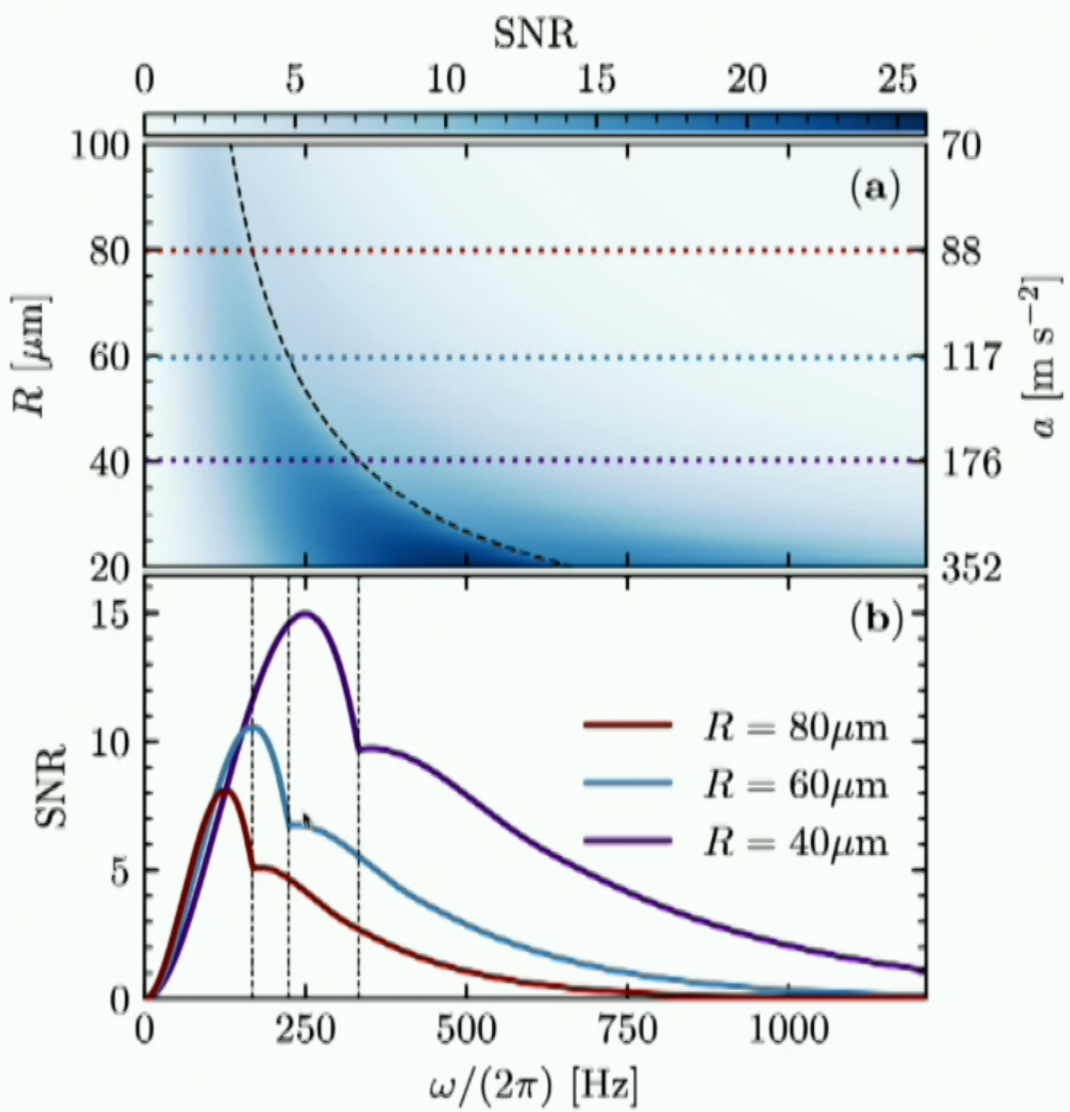

Resonant probing

$\omega = \Omega$

Bunney et al. *arXiv[2302.12023]*

$R = 60\ \mu m$
$v = 0.95 c_3$ fixed

Resonant probing
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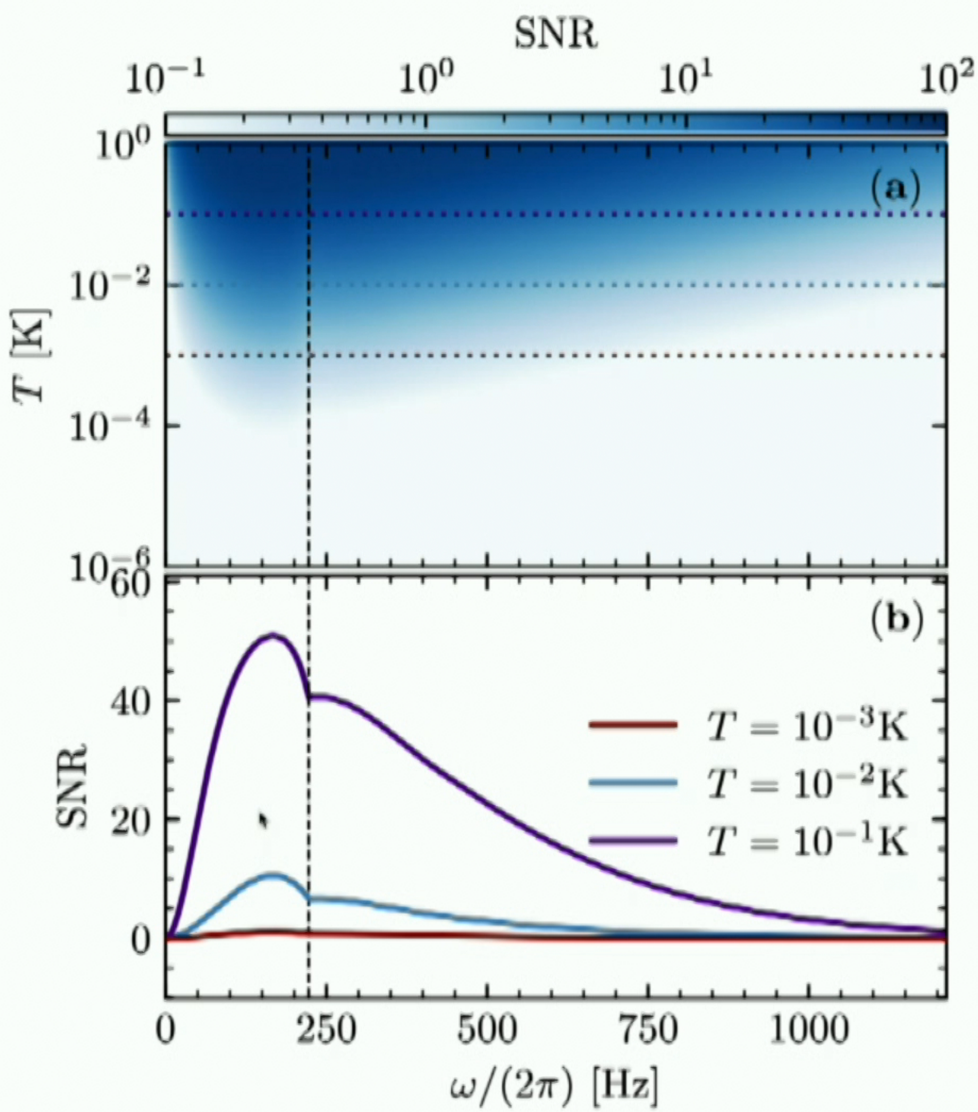

Operational measuring of $\mathscr{F}_{\mathrm{Lin}}(\omega)$ over wide parameter space

Bunney et al. *arXiv[2302.12023]*

- Even when $\hbar\omega < k_B T$ (or $\hbar\omega \ll k_B T$), can still find non-negligible acceleration-dependent signal

- Higher initial thermal state temperatures emphasise the acceleration-dependent structure

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Thank you for listening!

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