The sounds of silence

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Goal

Find a practical experiment for exploring the analogy between quantum fields in curved space-time, and phonons in flowing BECs.

Question

What experiment should we do?

- Construction
- Detection

Wave scattering from black holes

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$$\partial_\mu \left(g^{\mu\nu} \sqrt{-g}\, \partial_\nu \psi \right) = 0$$

“splendorous, joyful, and immensely ornate”

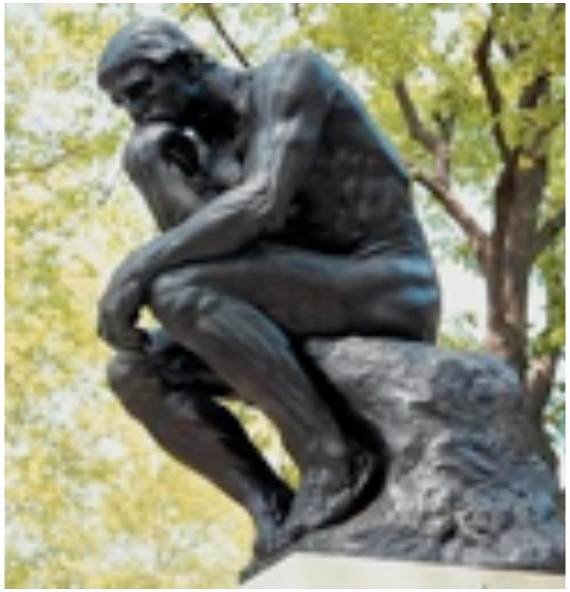
S. Chandrasekhar
Mathematical Theory of Black Holes

Analogous systems

$$\partial_\mu \left(g^{\mu\nu} \sqrt{-g}\, \partial_\nu \psi \right) = 0$$

Classical: same wave equation.
Quantum: same commutation relations.

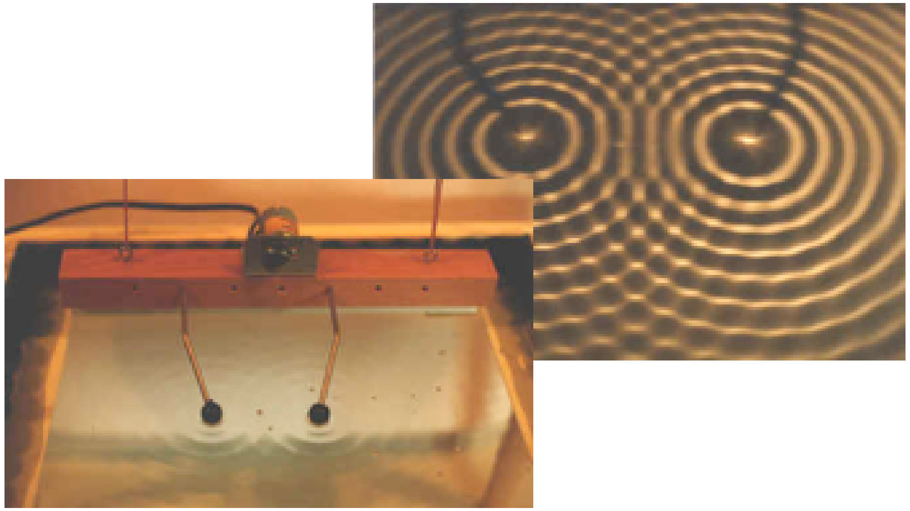
What is the value of physical analogies?



Analogous systems

$$\partial_\mu \left(g^{\mu\nu} \sqrt{-g}\, \partial_\nu \psi \right) = 0$$

- Sound waves in inviscid, irrotational fluids - superfluids.
- Ripples on a ^{3}He-A/B interface.
- Light in flowing media.
- Shallow water waves.



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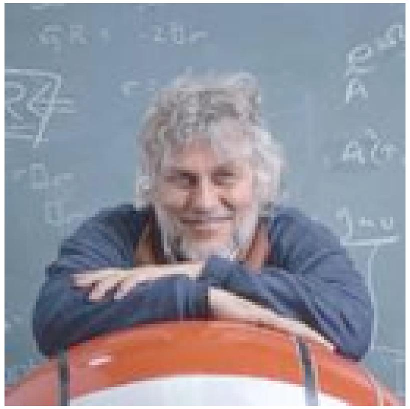
Motivations

- Hawking radiation is not a “slam dunk”: powerful new ideas are used.
- There is no experimental study of these ideas.
- BECs are promising.
- A fresh perspective on BECs.



Bill Unruh
1981

The BEC Analogy

$$\partial_\mu\left(g^{\mu\nu}\sqrt{-g}\,\partial_\nu\psi\right)=0$$

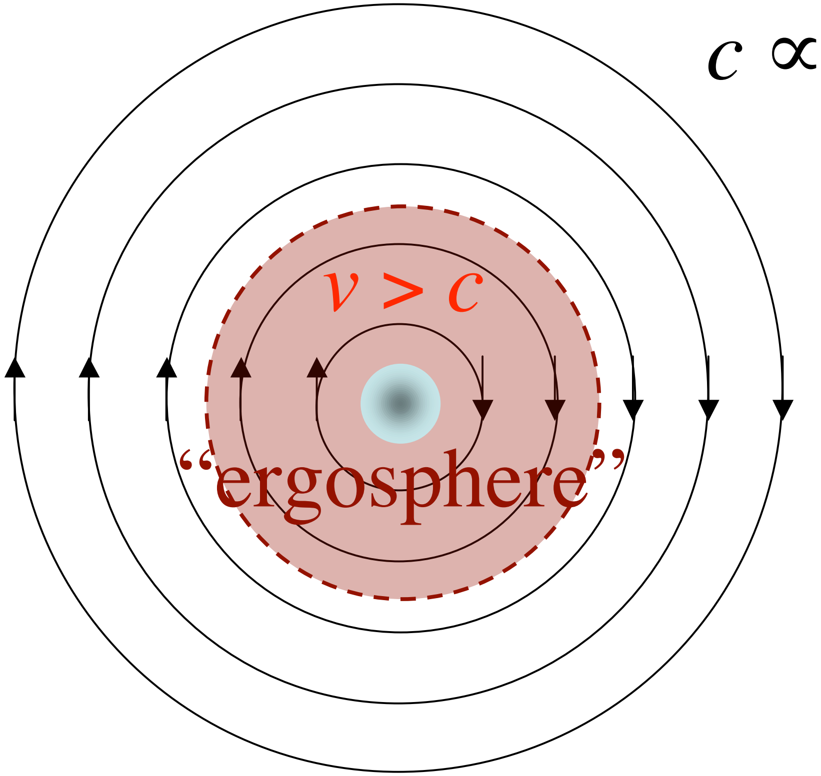
	BEC		Curved space-time QFT
ψ	phonons	←----→	scalars
$g^{\mu\nu}$	flow	←----→	gravity

W. Unruh, Phys. Rev. Lett **46**, 1351 (1981)

Supersonic vortex flow

Slatyer poster

$$v = \frac{l\hbar / m}{r}$$



$$c \propto \sqrt{\rho}$$

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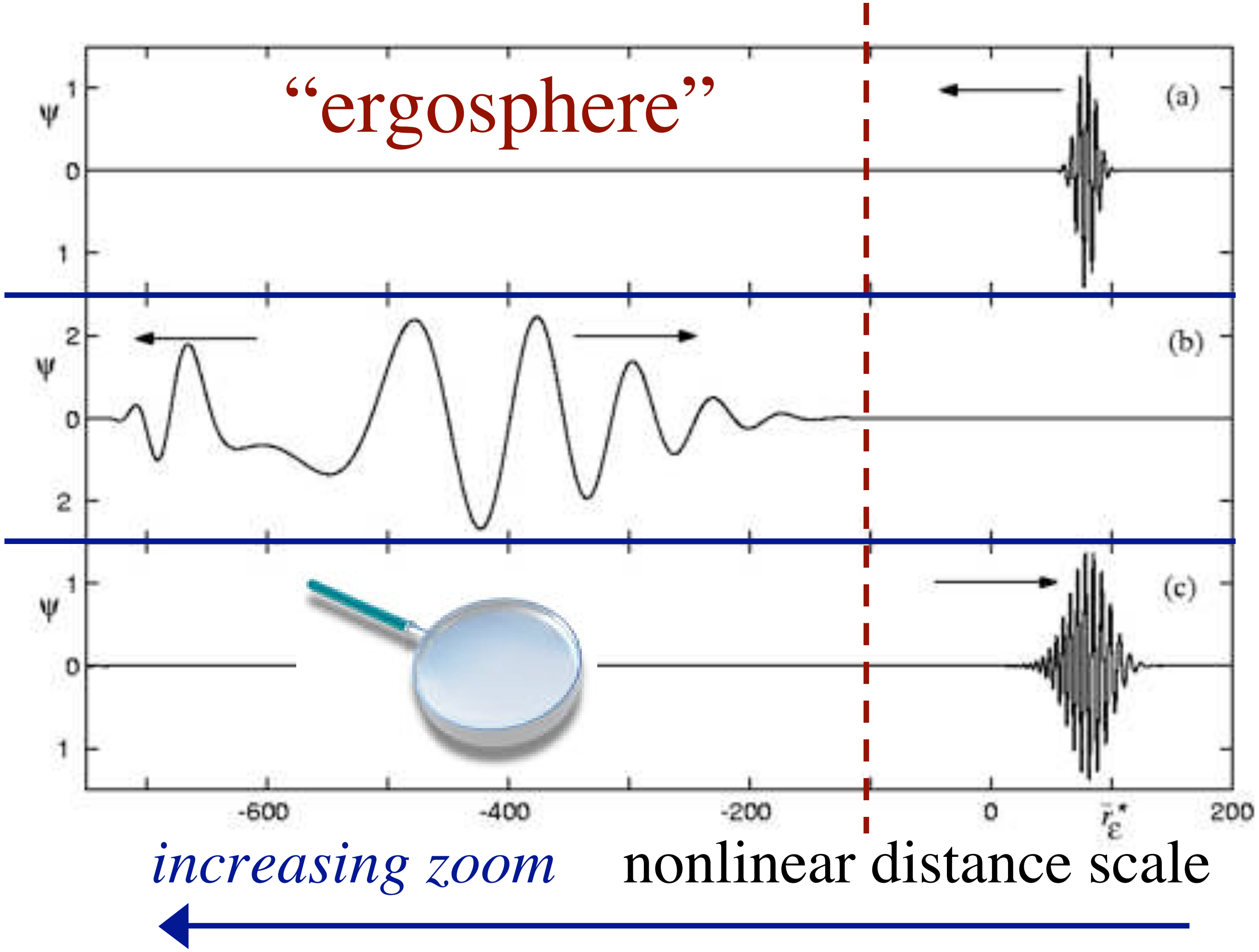
Superradiant scattering from a hydrodynamic vortex

time

incident

interacting

reflected



“ergosphere”

increasing zoom nonlinear distance scale

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Sonic Horizon

horizon

$v > c$ $v = c$ $v < c$

BEC
super-sonic

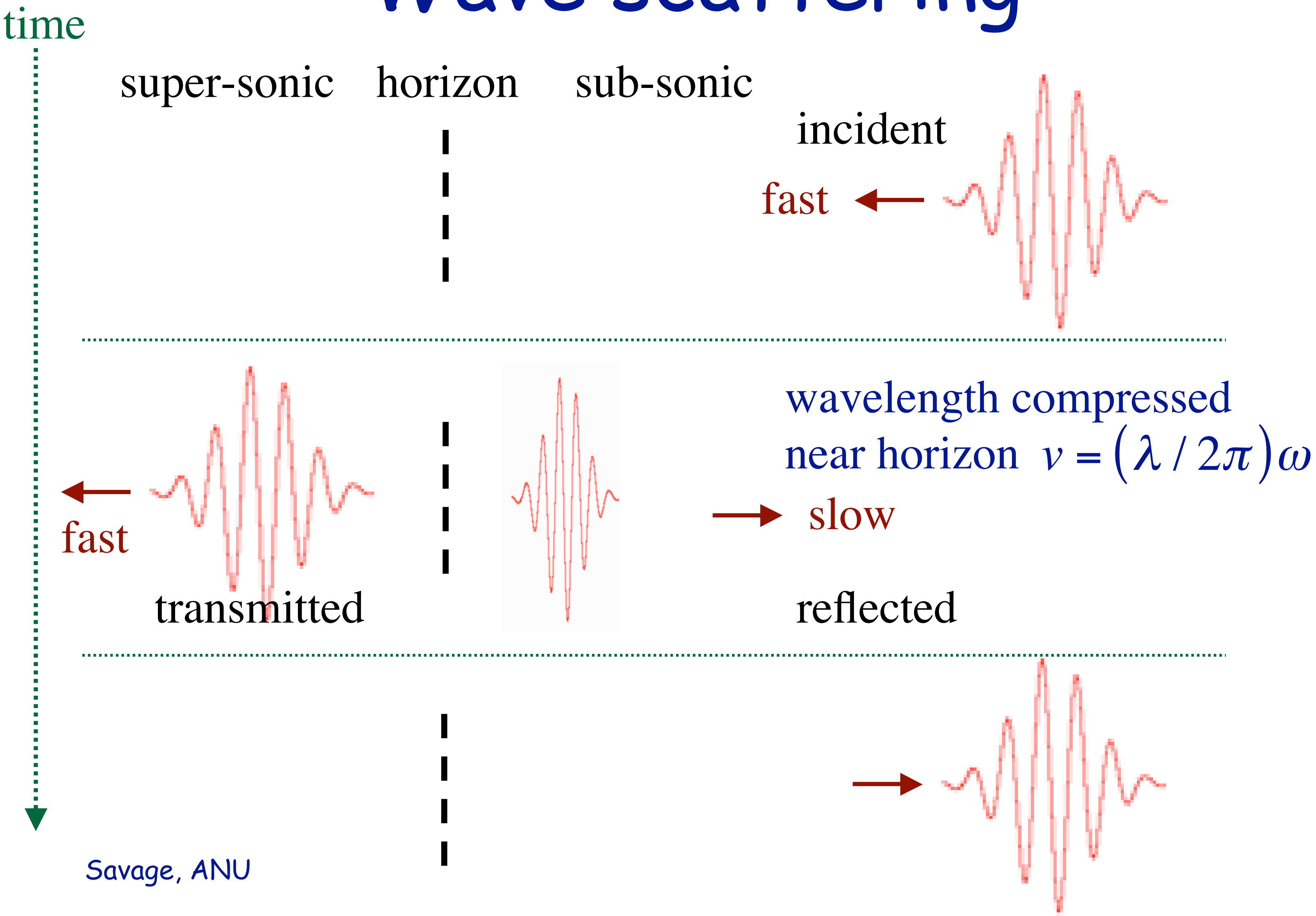
BEC
sub-sonic

only left
moving phonons

left & right
movers

Simple wave physics fails at the horizon.

Wave scattering



time

super-sonic

horizon

sub-sonic

incident

fast

wavelength compressed near horizon $v = (\lambda / 2\pi)\omega$

slow

fast

transmitted

reflected

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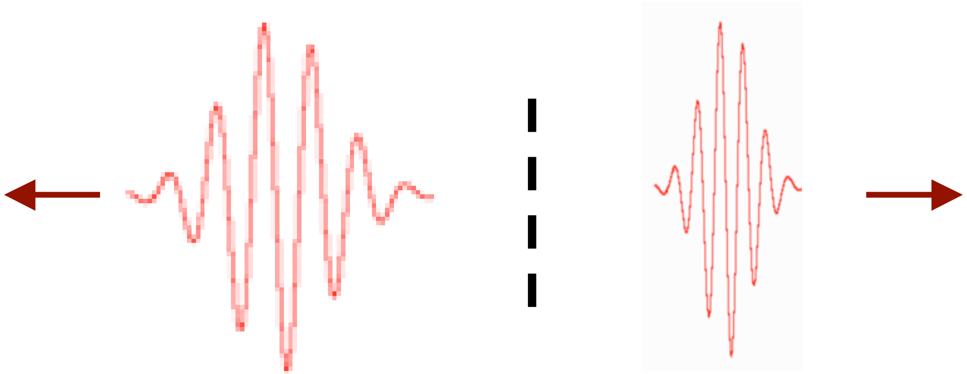
Superradiance



super-sonic horizon sub-sonic

transmitted reflected

Wave-packets have a conserved “norm”:
+ve on the sub-sonic side, -ve on the super-sonic side.

An incident wave-packet (norm 1) splitting into reflected (norm $R > 0$) and transmitted parts (norm $T < 0$), has $R + T = 1$ or $R = 1 - T > 1$: superradiance.

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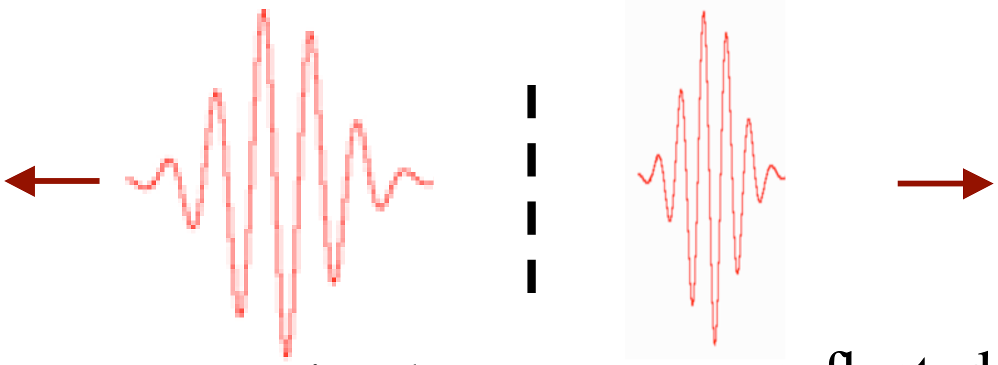
Stimulated & spontaneous emission



super-sonic horizon sub-sonic

transmitted reflected

Quantising: stimulated emission.
The transmitted wave-packet's -ve energy balances the amplification of the incident wave-packet.

The spontaneous counterpart is Hawking radiation.

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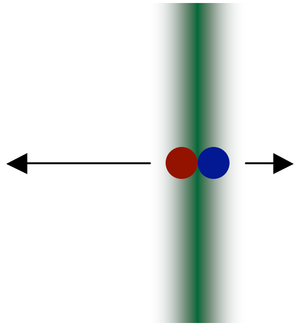
Hawking radiation

Spontaneous pair production of entangled phonons, one on each side of the horizon.



Tracing out one side of the horizon gives a thermal state.

Modes

Matt Visser

Lab frame modes:

$$\phi(r,t) = A(r,t)\exp\left[\mp i\left(\omega t - \int^{r} k(r')\,dr'\right)\right]$$

$$\omega / k = \pm c + v\,, \quad \frac{\text{out}}{\text{in}}\ \text{going}, \quad (v < 0)$$

Ingoing: $\omega / k_{in} \rightarrow -2c_H$

Outgoing: $\omega / k_{out} \rightarrow \left.\frac{d(c+v)}{dr}\right|_H (r - r_H)$

M. Visser, hep-th/0106111

Analogue Hawking radiation

Temperature: $$T_H = \frac{\hbar}{4\pi k_b} \left. \frac{\partial\left(c+v\right)}{\partial r} \right|_H \approx 100 \text{ nK}$$

Power: $$P_H = \frac{\pi^2 k_b^4}{120\hbar^3 c^2} T_H^4 A_H \approx 10^5\, k_b T \text{ s}^{-1}$$

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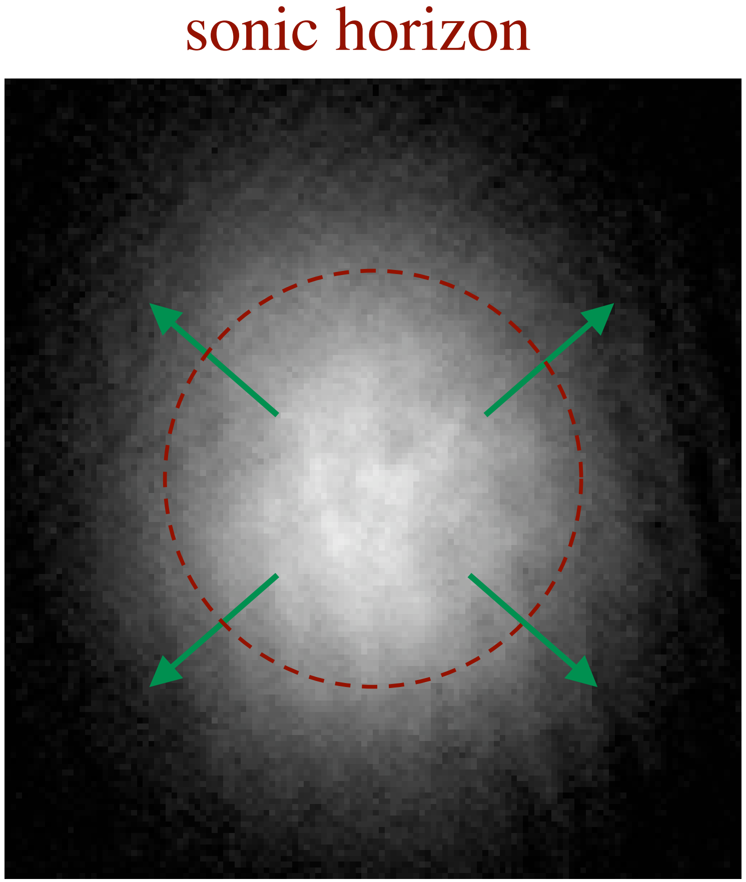
Analogue Hawking radiation in BECs

How can we detect it?

How *should* we make a sonic horizon?

Scheme 1: Expanding BEC



Speed of sound ∝ √density: $c \propto \sqrt{\rho}$

Ideal gas expansion speed, released from trap of frequency ω:

$$v = \frac{\omega^2 t}{1 + \omega^2 t^2} r$$

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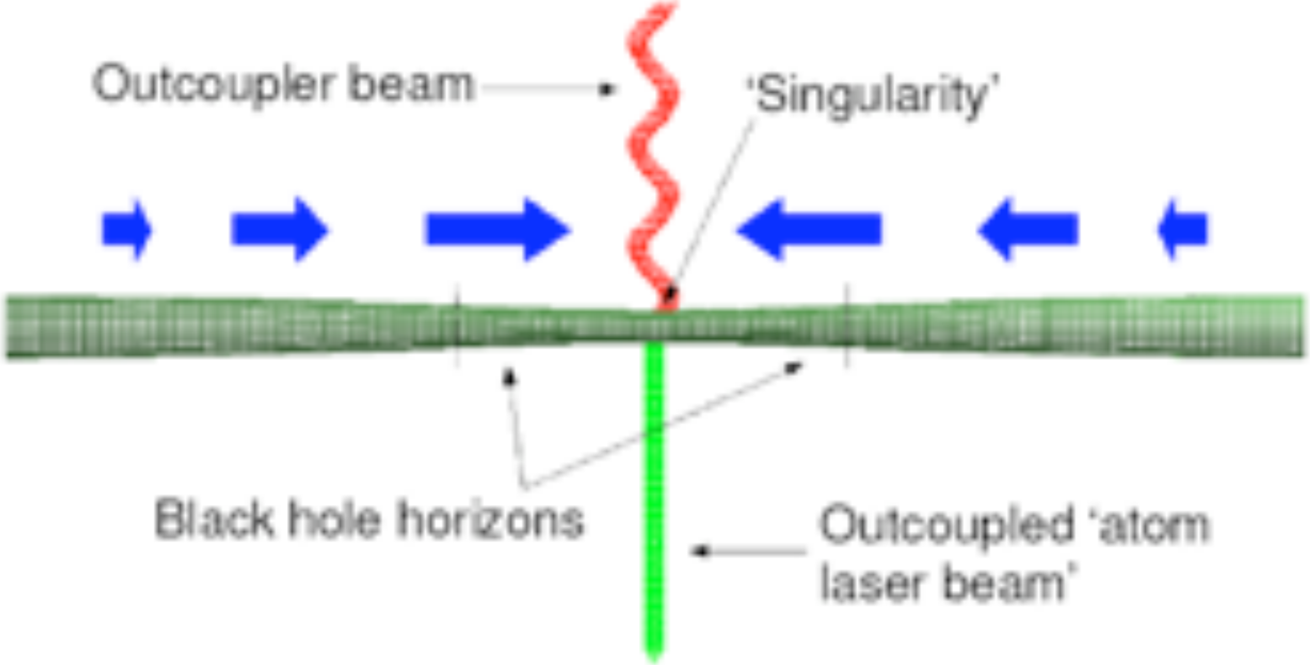
Scheme 2: Atom laser



L.J. Garay, *COSLAB* presentation, Spain July 2003

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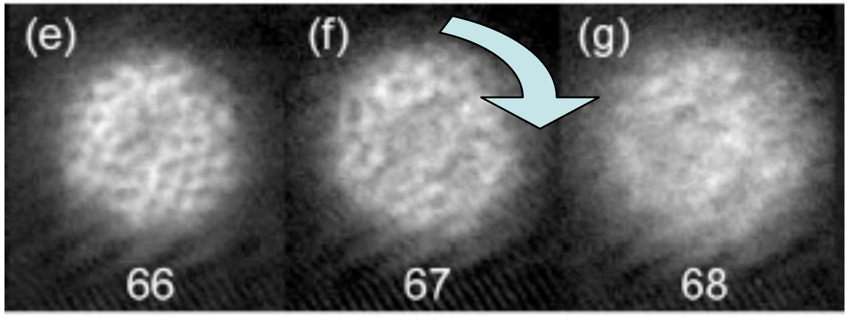
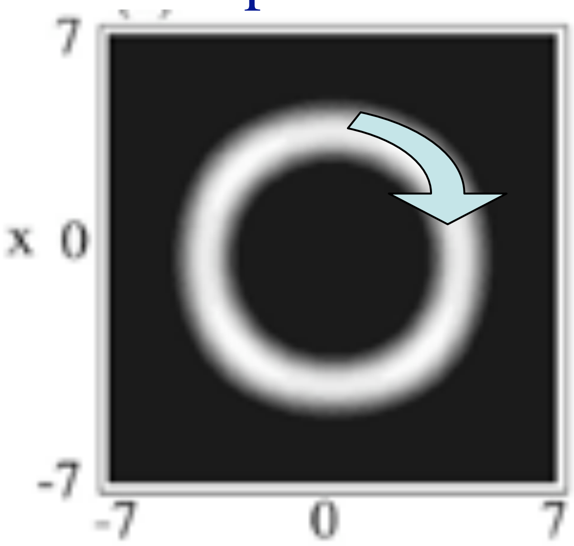
Scheme 3: Giant vortices

Fast Rotation of a Bose-Einstein Condensate

Vincent Bretin, Sabine Stock, Yannick Seurin, and Jean Dalibard



super-sonic

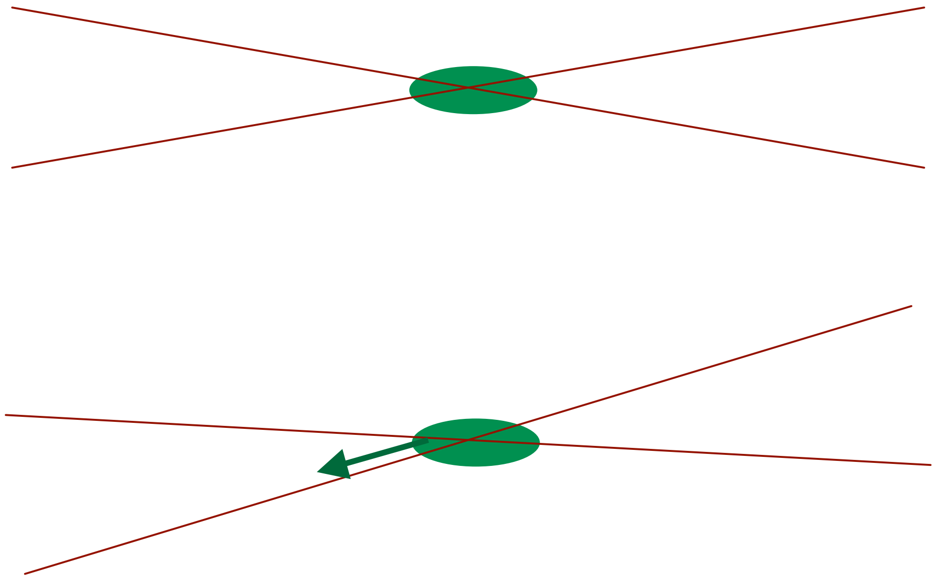


Can we make a super-sonic giant vortex? Can we create a sub-sonic region?

Giant hole and circular superflow in a fast rotating Bose-Einstein condensate

Kenichi Kasamatsu,[1] Makoto Tsubota,[1] and Masahito Ueda[2]

Scheme 4:
Spilling out of a dipole trap



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