Title: Microscopic structure of quantum black holes

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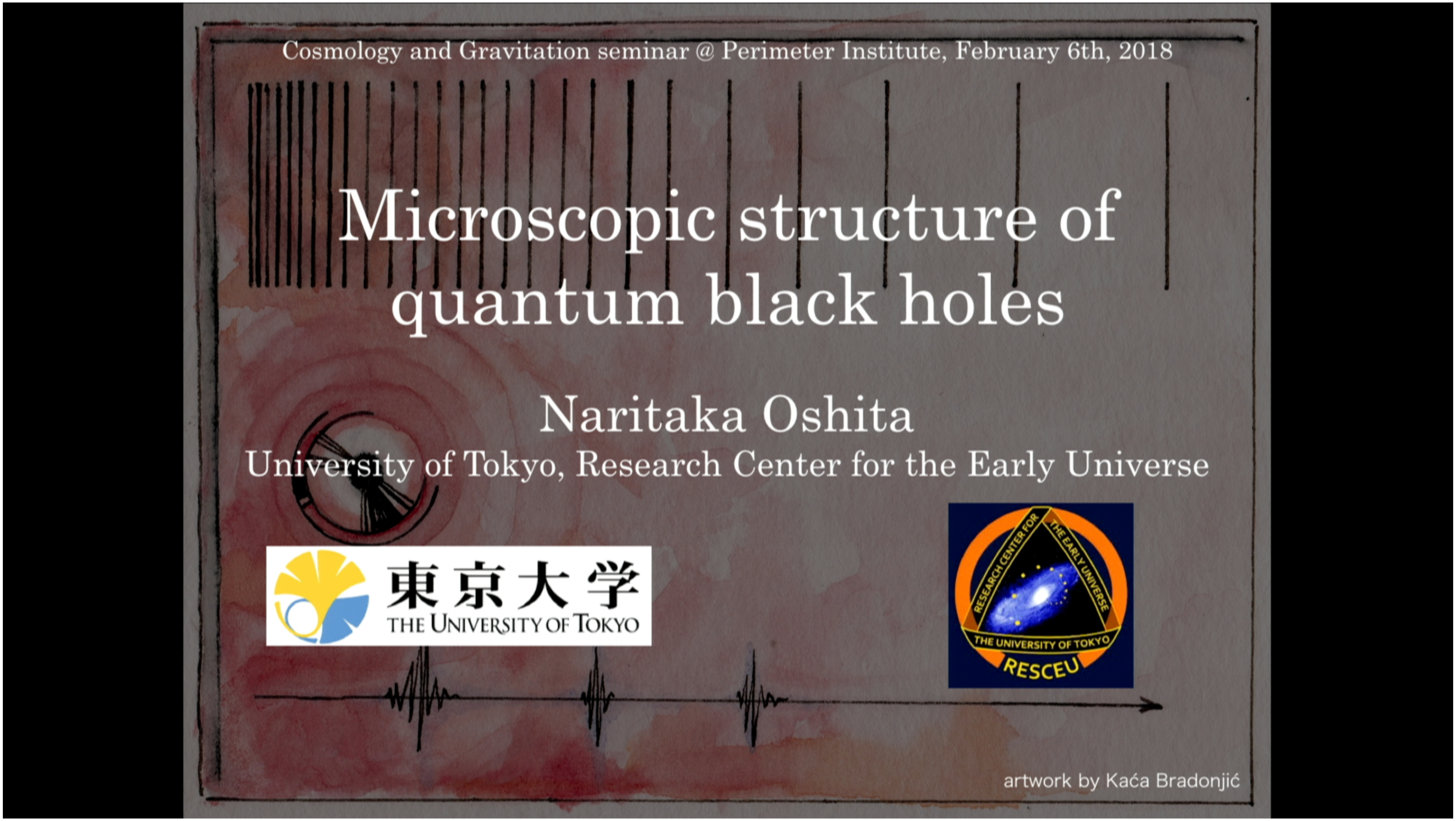
Abstract: <p>If a black hole horizon has its microscopic structure as is conjectured by the candidates of quantum gravity, the dispersion relation of gravitational waves (GWs) near the horizon may be drastically modified since its wavelength can be comparable to the size of the microscopic structure because of its infinite gravitational blue-shift near the horizon. We investigate ringdown-GWs from a perturbed black hole with such a modified dispersion relation and found that the change of modified dispersion relation near the horizon would lead to the partial reflection of infalling GWs at the horizon and echo-signals may appear in the late-time of ringdown-GWs. This implies that the echoes can be a supporting evidence of the existence of microscopic degrees of freedom on black hole horizons.</p>


Cosmology and Gravitation seminar @ Perimeter Institute, February 6th, 2018
Microscopic structure of quantum black holes
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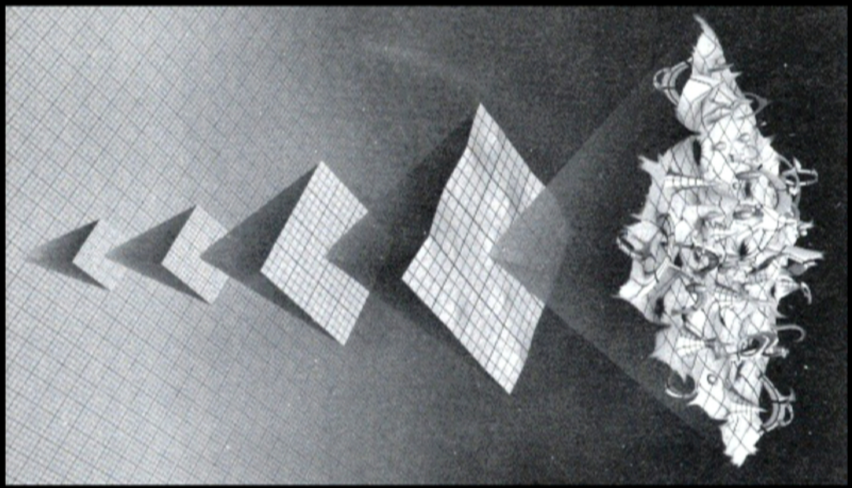
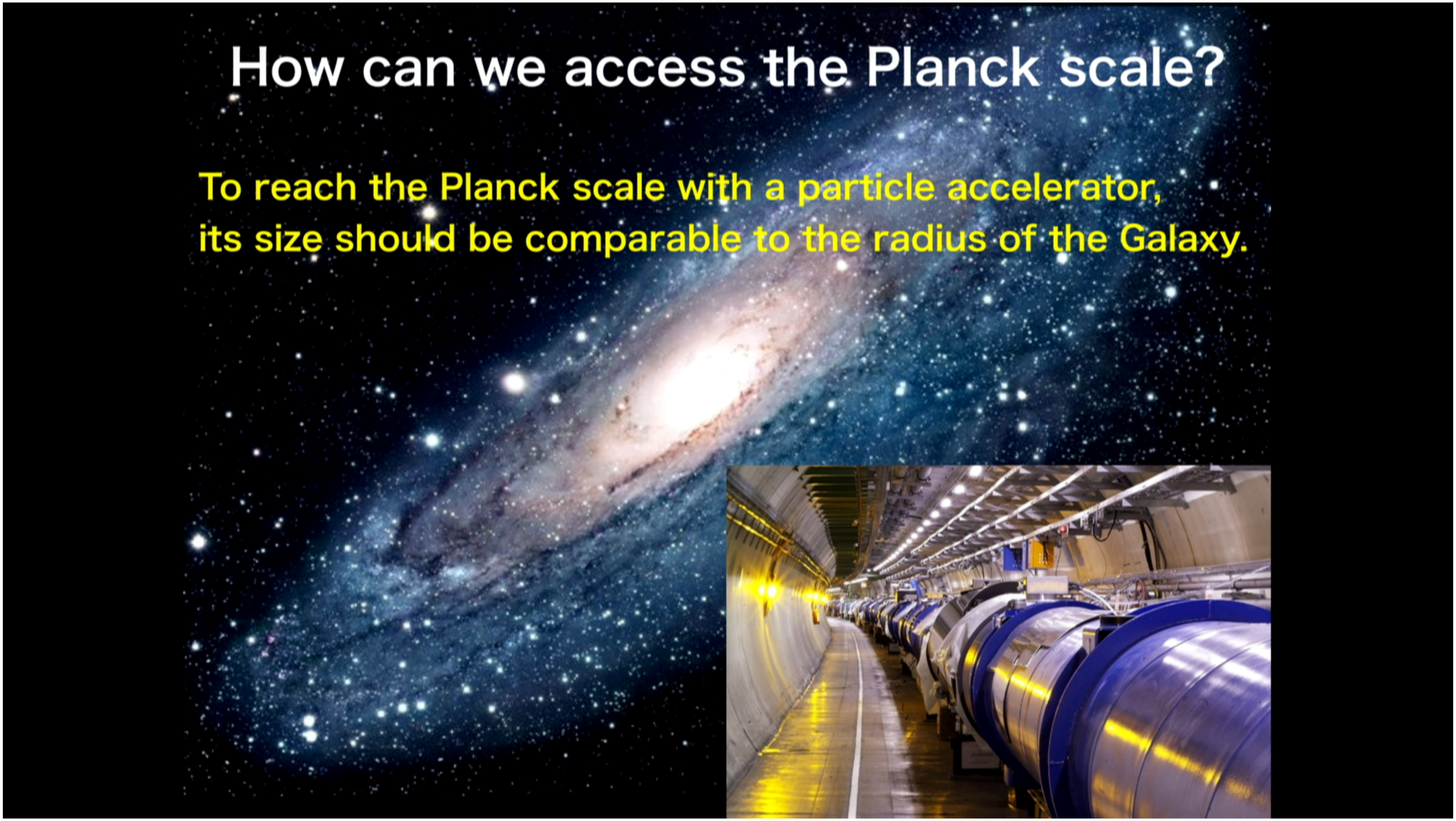
artwork by Kaća Bradonjić

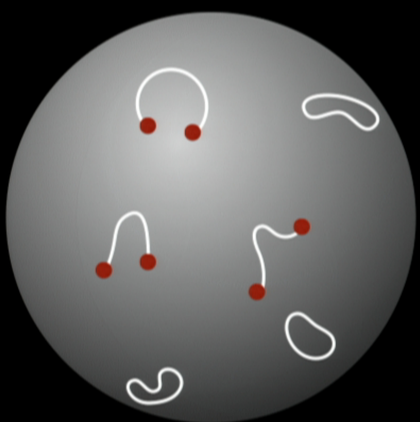
- There seems to be an operational limitation in measuring lengths smaller than the Planck length ℓ_{Pl} .

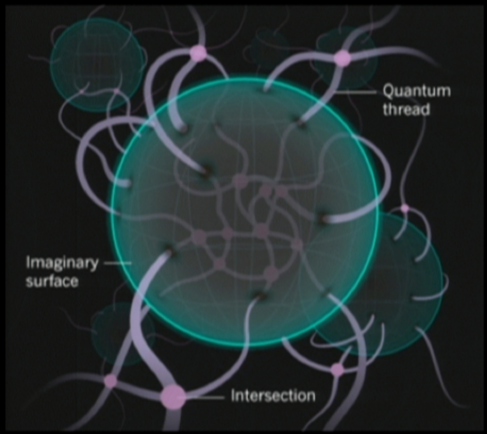
- superstring theories and the spin network formalism might have ingredients to describe the microscopic structure of spacetime.

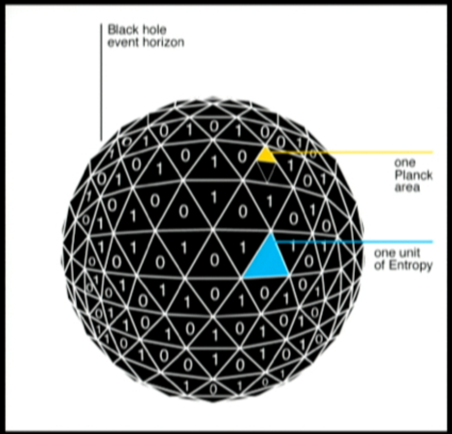



How can we access the Planck scale?
To reach the Planck scale with a particle accelerator,
its size should be comparable to the radius of the Galaxy.

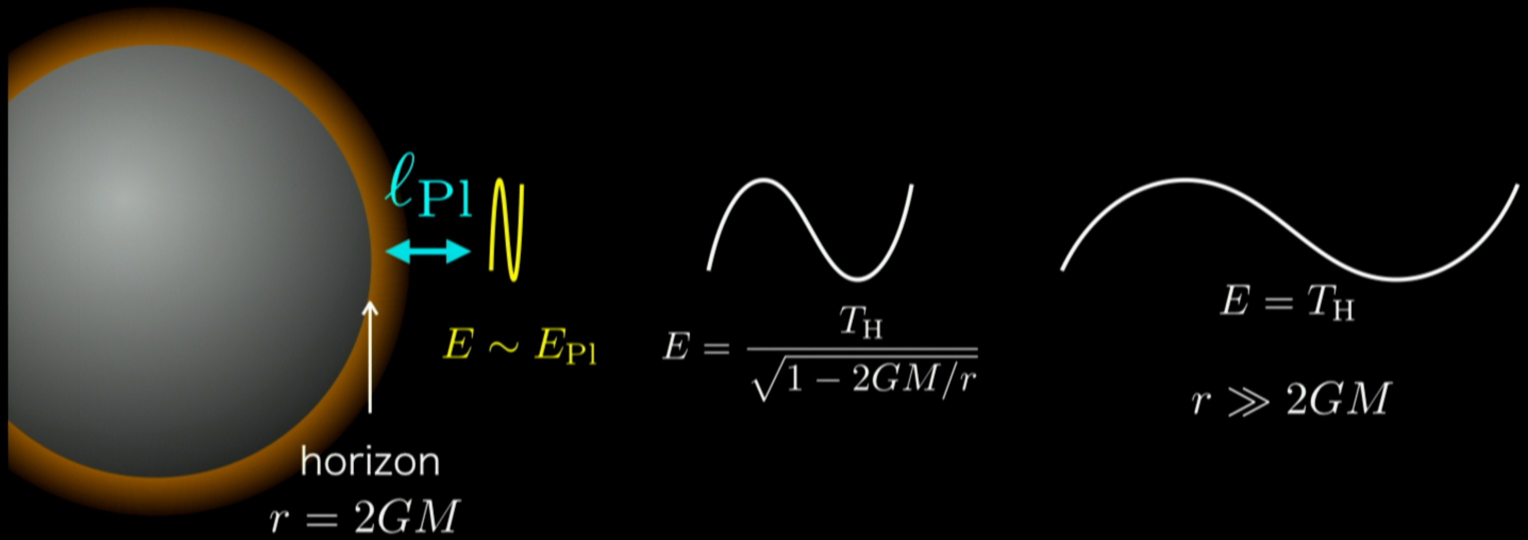
- Bekenstein entropy (generalized second law of thermodynamics)
  → black hole may be complicated
- Hawking radiation (black holes may possess their temperatures)
  → black hole may be thermodynamical
- superstring theory gives the Bekenstein entropy and Hawking temperature



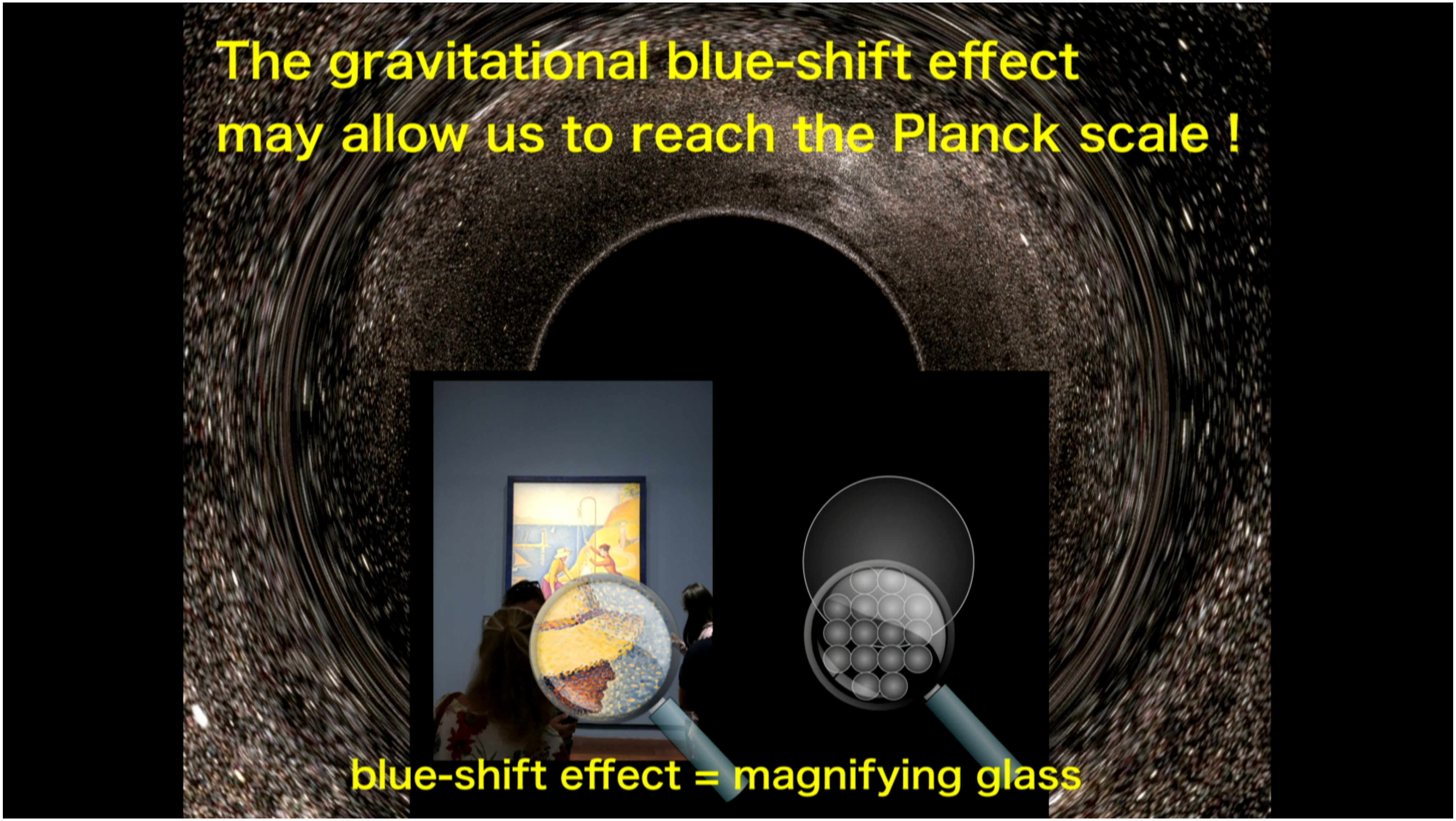




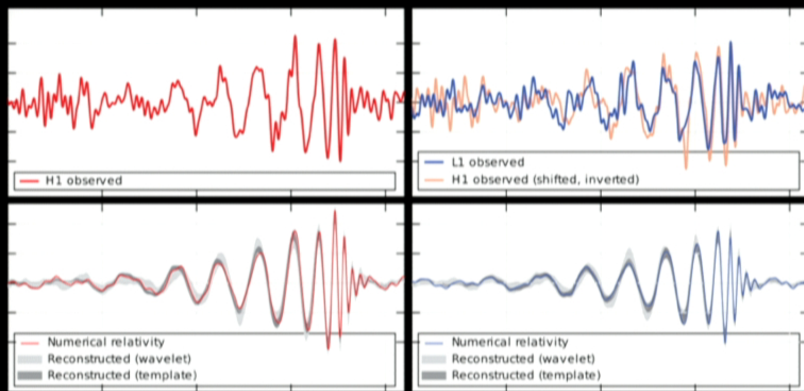
Trans-Palnckian problem on blackholes



physics beyond Planck scale!

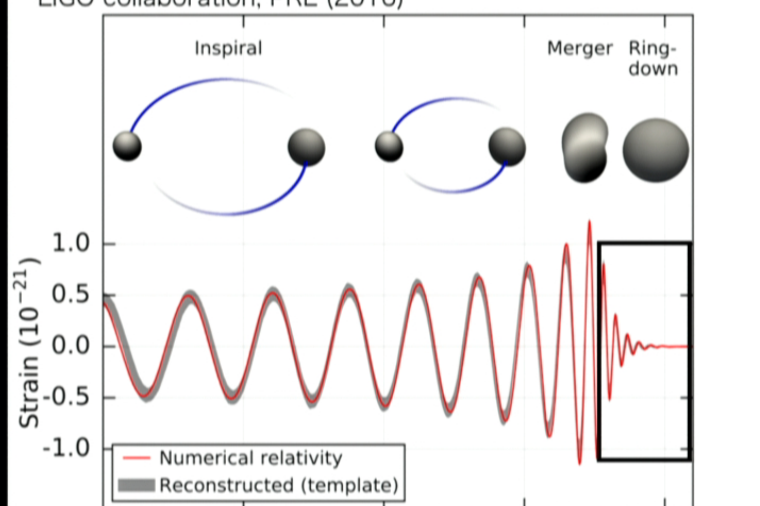

The gravitational blue-shift effect
may allow us to reach the Planck scale !
blue-shift effect = magnifying glass

Gravitational waves from a binary black hole



GW150914
(the first detection of GWs by LIGO)

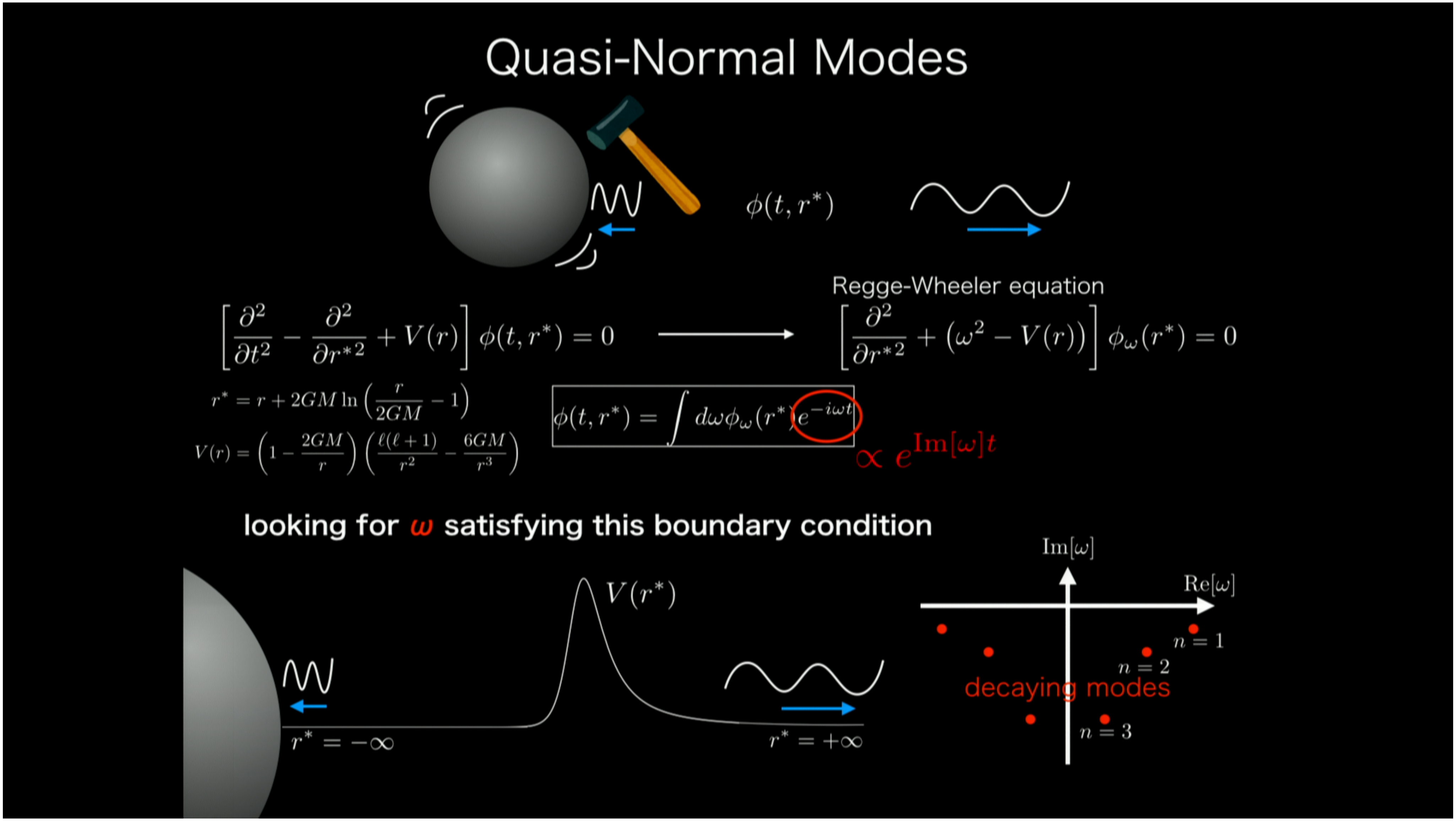
LIGO collaboration, PRL (2016)



- consist of specific modes
  (Quaisi-Normal Modes)
- QNMs determined only by
  its mass and angular momentum

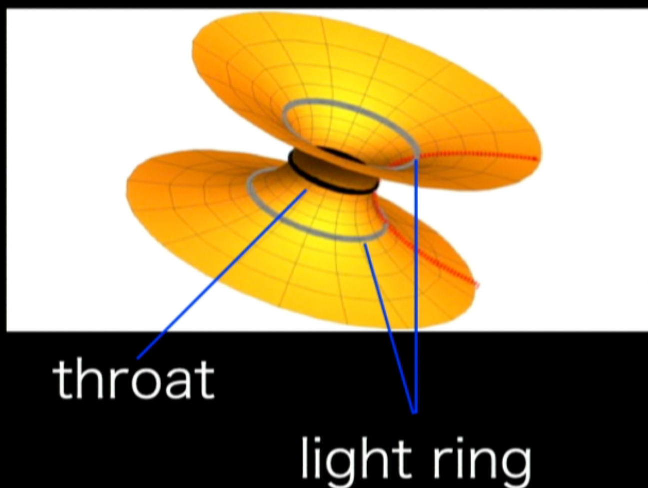
↓

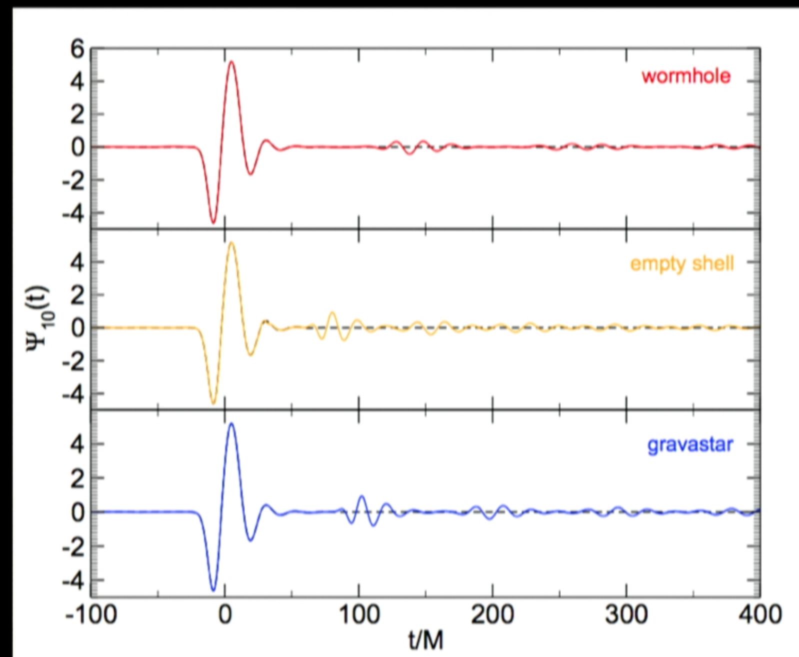
ringdown is useful to test a BH

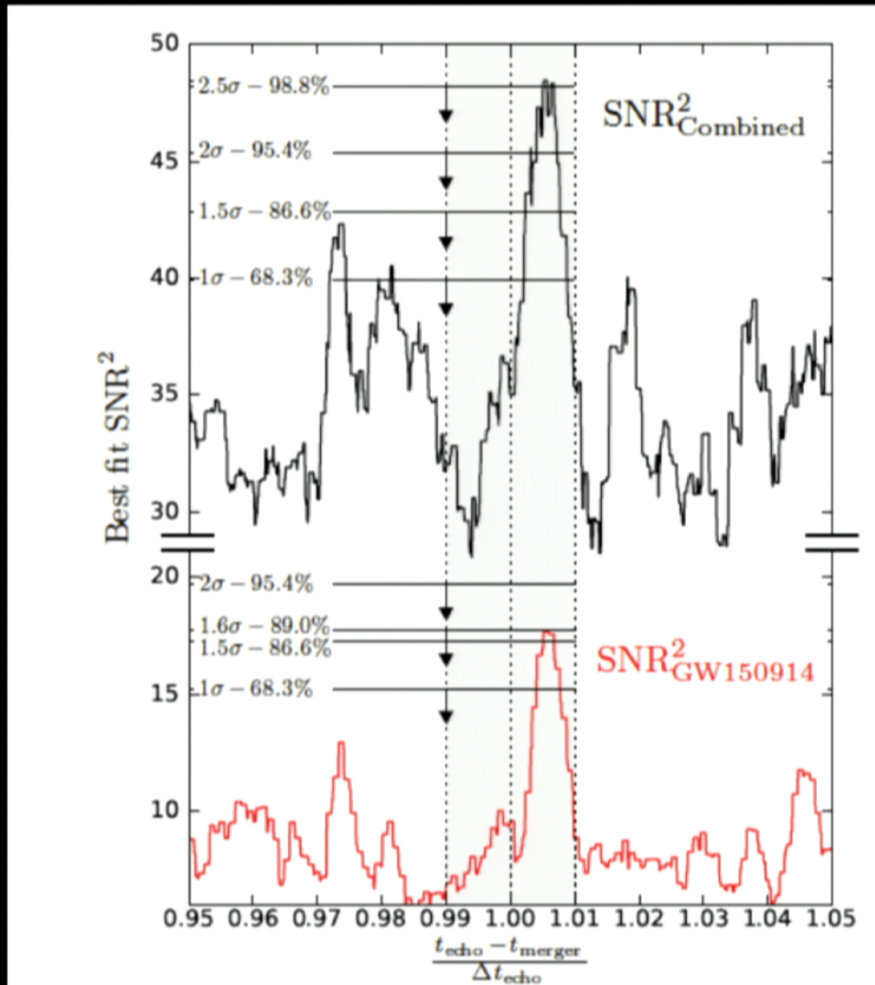

Quasi-Normal Modes
$\phi(t, r^*)$
Regge-Wheeler equation
$\left[\frac{\partial^2}{\partial t^2} - \frac{\partial^2}{\partial r^{*2}} + V(r)\right]\phi(t, r^*) = 0$
$\left[\frac{\partial^2}{\partial r^{*2}} + \left(\omega^2 - V(r)\right)\right]\phi_\omega(r^*) = 0$
$r^* = r + 2GM \ln\left(\frac{r}{2GM} - 1\right)$
$V(r) = \left(1 - \frac{2GM}{r}\right)\left(\frac{\ell(\ell+1)}{r^2} - \frac{6GM}{r^3}\right)$
$\phi(t, r^*) = \int d\omega \phi_\omega(r^*) e^{-i\omega t}$
$\propto e^{\mathrm{Im}[\omega]t}$
looking for ω satisfying this boundary condition
$V(r^*)$
$r^* = -\infty$
$r^* = +\infty$
$\mathrm{Im}[\omega]$
$\mathrm{Re}[\omega]$
$n = 1$
$n = 2$
decaying modes
$n = 3$

Blackholes? Exotic Compact Objects?

Cardoso et al. (2016)



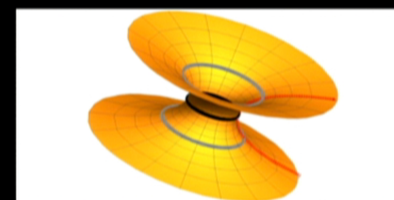




Abedi, Dykaar, Afshordi (2017)

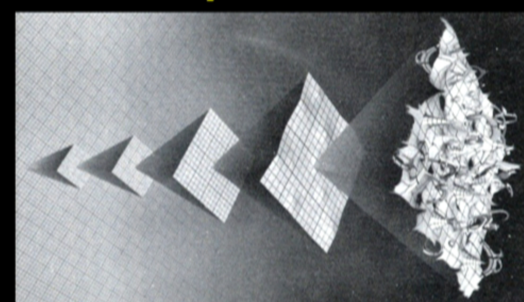
echo!

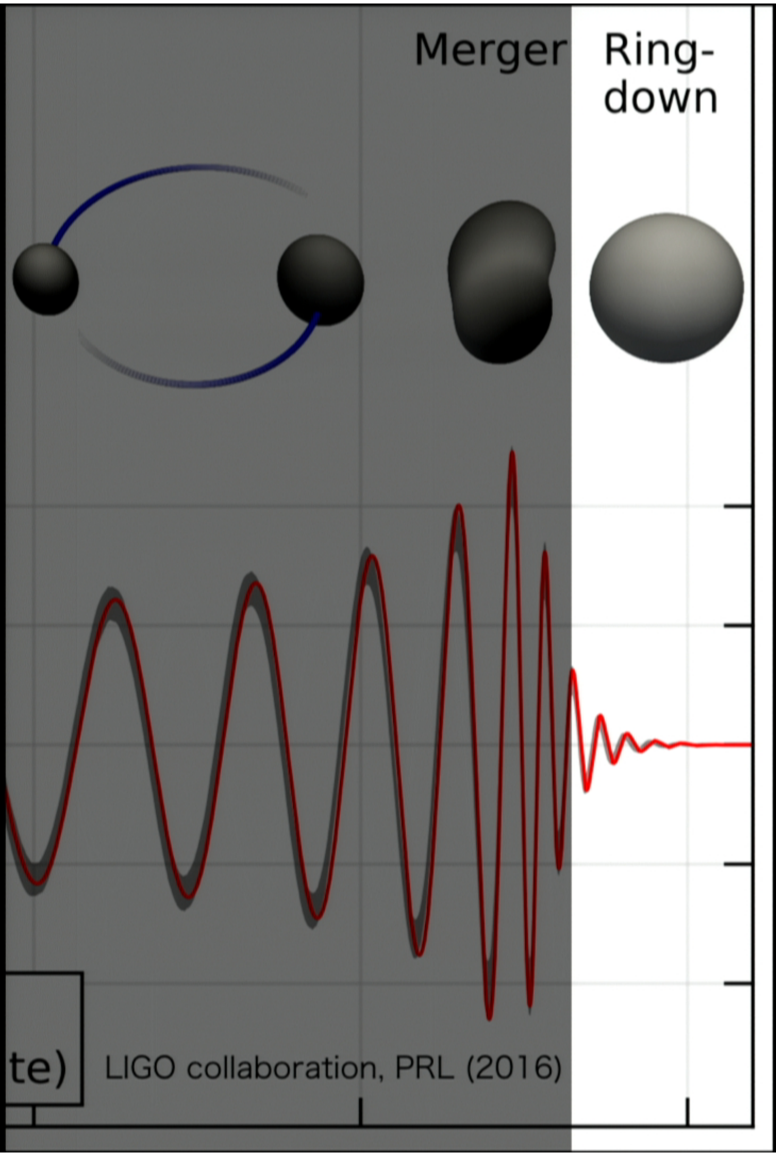
ECOs?



or

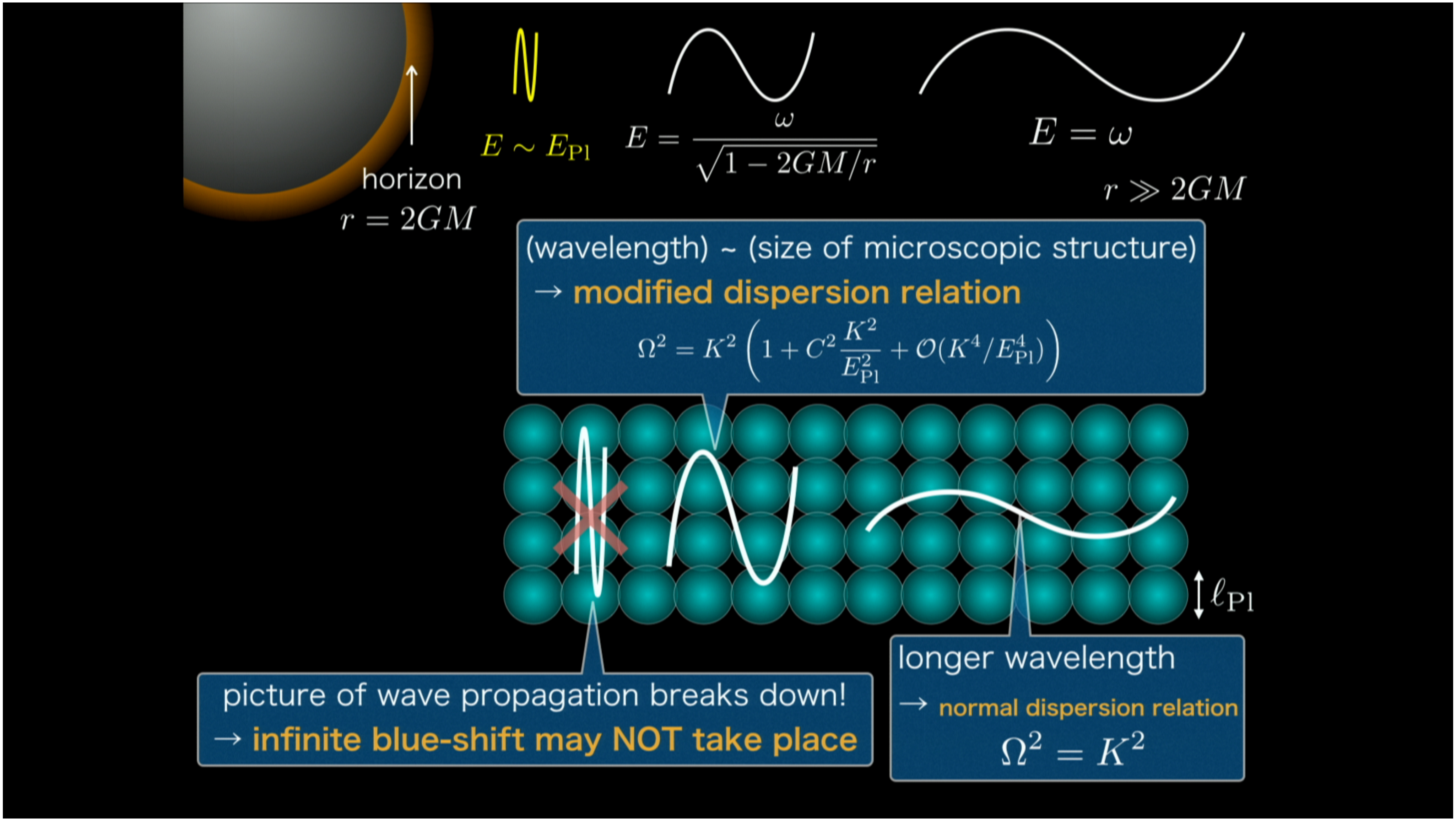
microscopic structure of spacetime ?

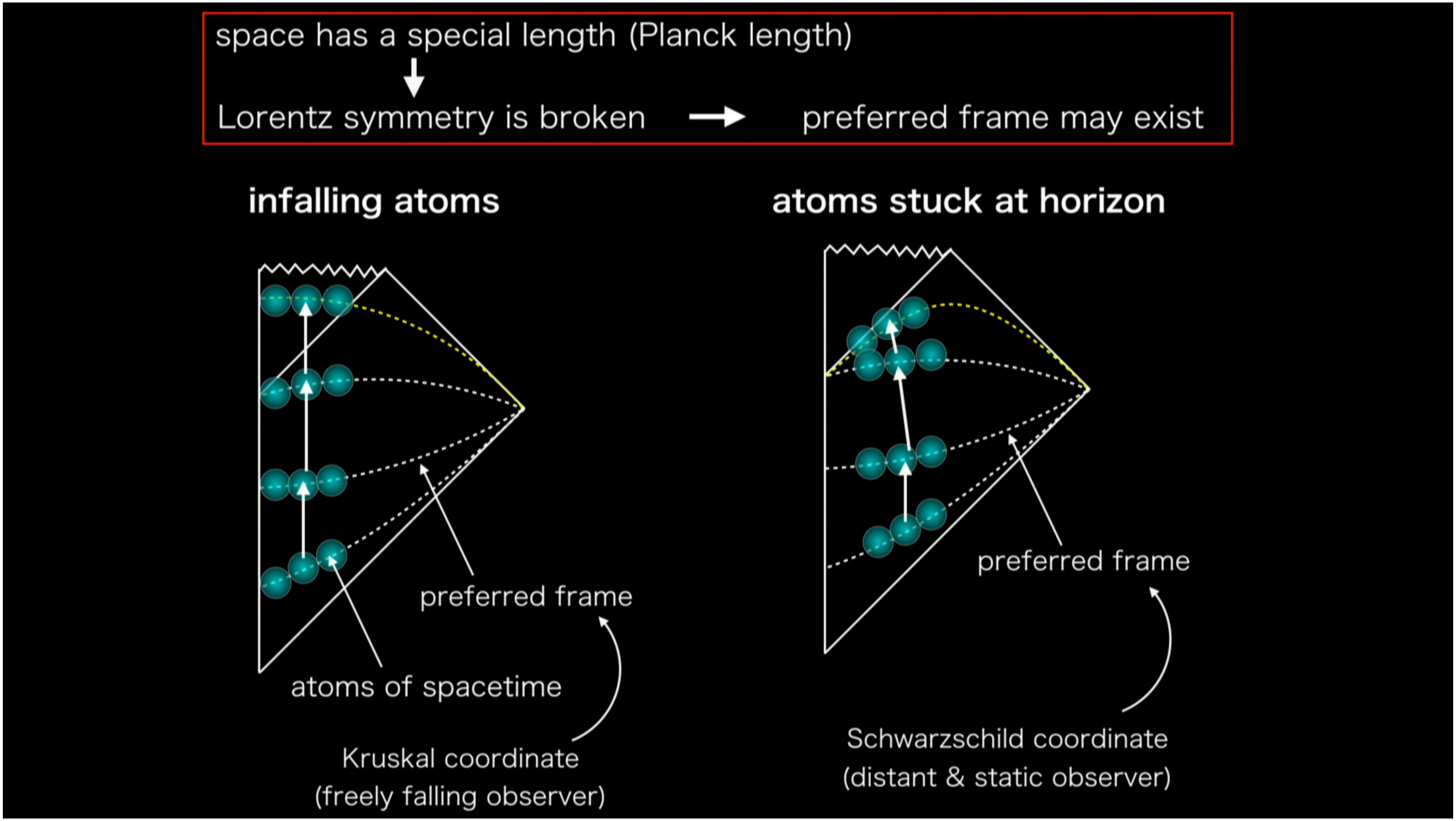


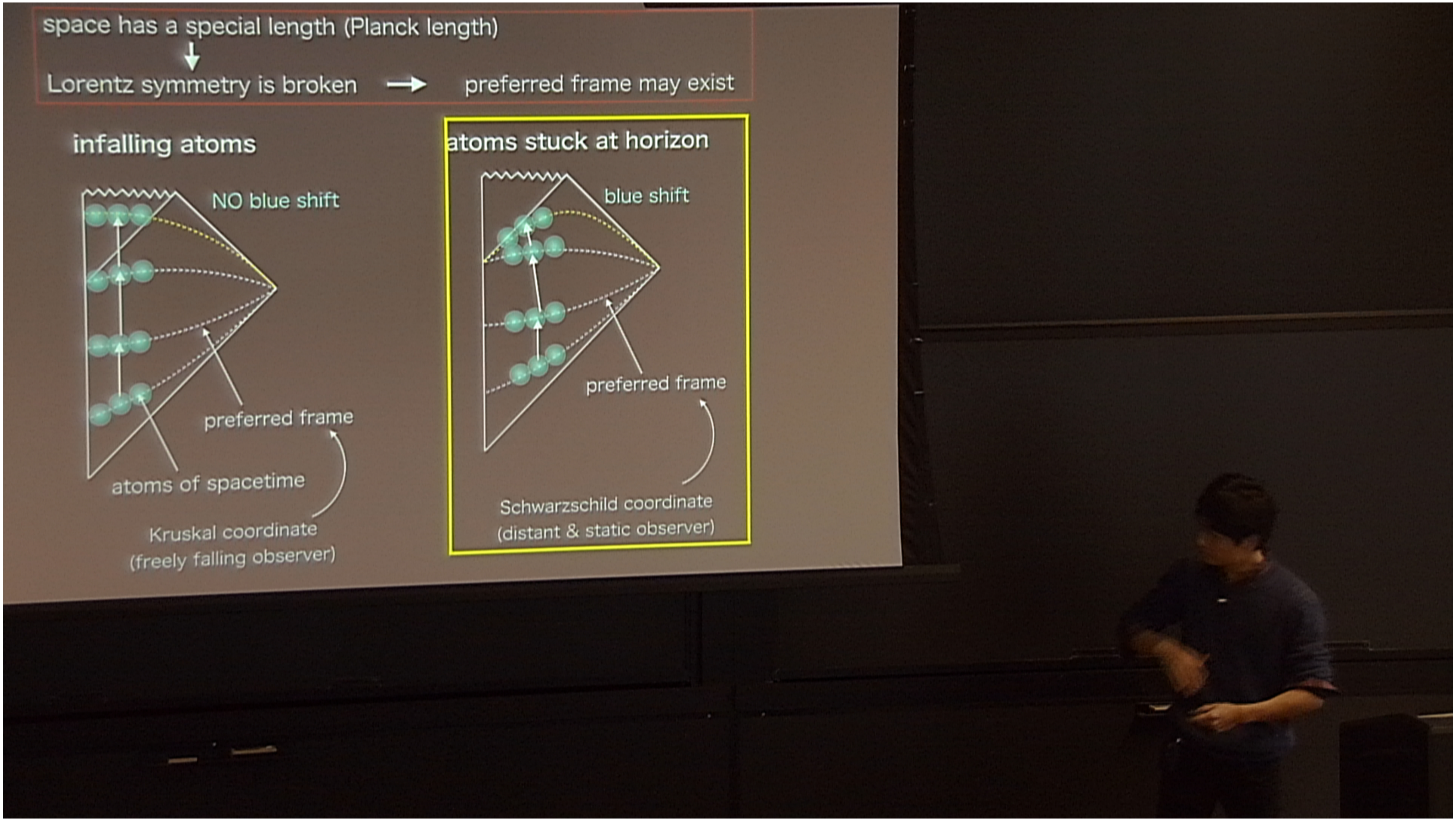


Is it possible to test the candidates of **quantum gravity** with **ringdown** ??

(e.g., **loop quantum gravity**
Horava-Lifshitz gravity,
causal dynamical triangulation)


horizon
$r = 2GM$
$E \sim E_{\rm Pl}$
$E = \dfrac{\omega}{\sqrt{1-2GM/r}}$
$E = \omega$
$r \gg 2GM$
(wavelength) ~ (size of microscopic structure)
→ modified dispersion relation
$\Omega^2 = K^2 \left(1 + C^2 \dfrac{K^2}{E_{\rm Pl}^2} + \mathcal{O}(K^4/E_{\rm Pl}^4)\right)$
$\ell_{\rm Pl}$
picture of wave propagation breaks down!
→ infinite blue-shift may NOT take place
longer wavelength
→ normal dispersion relation
$\Omega^2 = K^2$


space has a special length (Planck length)
Lorentz symmetry is broken
preferred frame may exist
infalling atoms
atoms stuck at horizon
preferred frame
atoms of spacetime
Kruskal coordinate
(freely falling observer)
preferred frame
Schwarzschild coordinate
(distant & static observer)


space has a special length (Planck length)
Lorentz symmetry is broken
preferred frame may exist
infalling atoms
NO blue shift
preferred frame
atoms of spacetime
Kruskal coordinate
(freely falling observer)
atoms stuck at horizon
blue shift
preferred frame
Schwarzschild coordinate
(distant & static observer)

model

dispersion relation

$$\Omega^2 = K^2\left(1 + C^2\frac{K^2}{E_{\rm Pl}^2}\right)$$

e.g.

$C^2 > 0$ Horava-Lifshitz gravity

$C^2 = -\frac{4\pi}{3}$ Padmanabhan (1998)

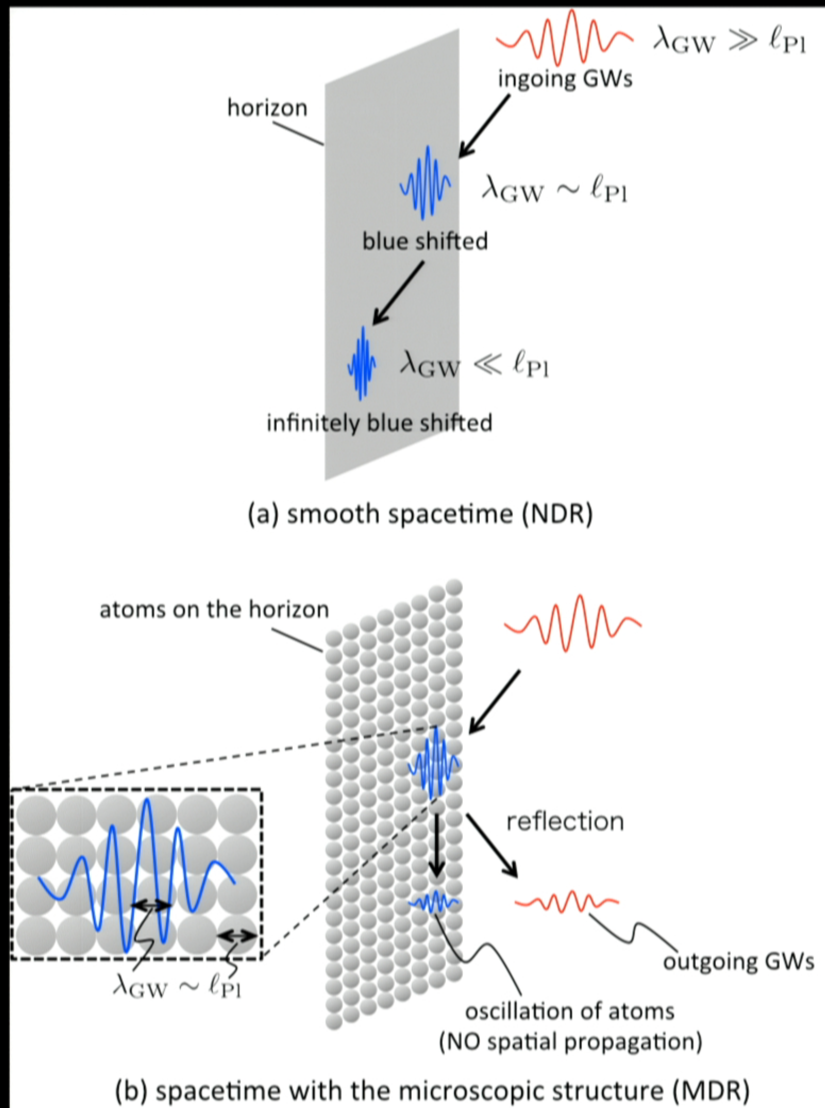
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\Omega^2 \qquad f(r) \equiv 1 - \frac{2GM}{r}$$

e.g. Horava-Lifshitz gravity

$$f(r) = 1 - \alpha r^{(2\lambda \pm \sqrt{6\lambda - 2})/(\lambda - 1)} \qquad 1/3 < \lambda < 1$$

reduce to the Schwarzschild spacetime with $\lambda \to 1/3$

α : arbitrary constant



$\lambda_{GW} \gg \ell_{Pl}$
ingoing GWs
horizon
$\lambda_{GW} \sim \ell_{Pl}$
blue shifted
$\lambda_{GW} \ll \ell_{Pl}$
infinitely blue shifted
(a) smooth spacetime (NDR)
atoms on the horizon
reflection
outgoing GWs
$\lambda_{GW} \sim \ell_{Pl}$
oscillation of atoms
(NO spatial propagation)
(b) spacetime with the microscopic structure (MDR)

$$\Omega^2 = K^2\left(1 + C^2\frac{K^2}{M_{\rm Pl}^2}\right)$$

size of microstructure
$|C|/M_{\rm Pl} = |C|\ell_{\rm Pl}$

$$-K^2 \to \nabla = g^{ij}\partial_i\partial_j$$

$$1 - \frac{C^2 M_{\rm Pl}^{-2}}{1 - r_g/r}\partial_{r^*}^2 - C^2\left(\frac{\ell_{\rm Pl}}{r}\right)^2\left(\partial_\theta^2 + \frac{1}{\sin^2\theta}\partial_\varphi^2\right)$$

$\ll 1$

$\ell_{\rm Pl} \ll 2GM < r$

$$\Omega^2 = g^{00}\omega^2 = \frac{\omega^2}{1 - 2GM/r}$$

modified-Regge-Wheeler Eq.

$$\left[-\frac{C^2 M_{\rm Pl}^{-2}}{1 - r_g/r}\partial_{r^*}^4 + \partial_{r^*}^2 + (\omega^2 - V(r))\right]\tilde{\psi}(\omega, r^*) = 0$$

$$\left[-\frac{C^2 M_{\rm Pl}^{-2}}{1-r_g/r}\partial_{r^*}^4 + \partial_{r^*}^2 + (\omega^2 - V(r))\right]\tilde{\psi}(\omega, r^*) = 0$$

impossible to impose ingoing modes at horizon

What is the new guiding principle ?

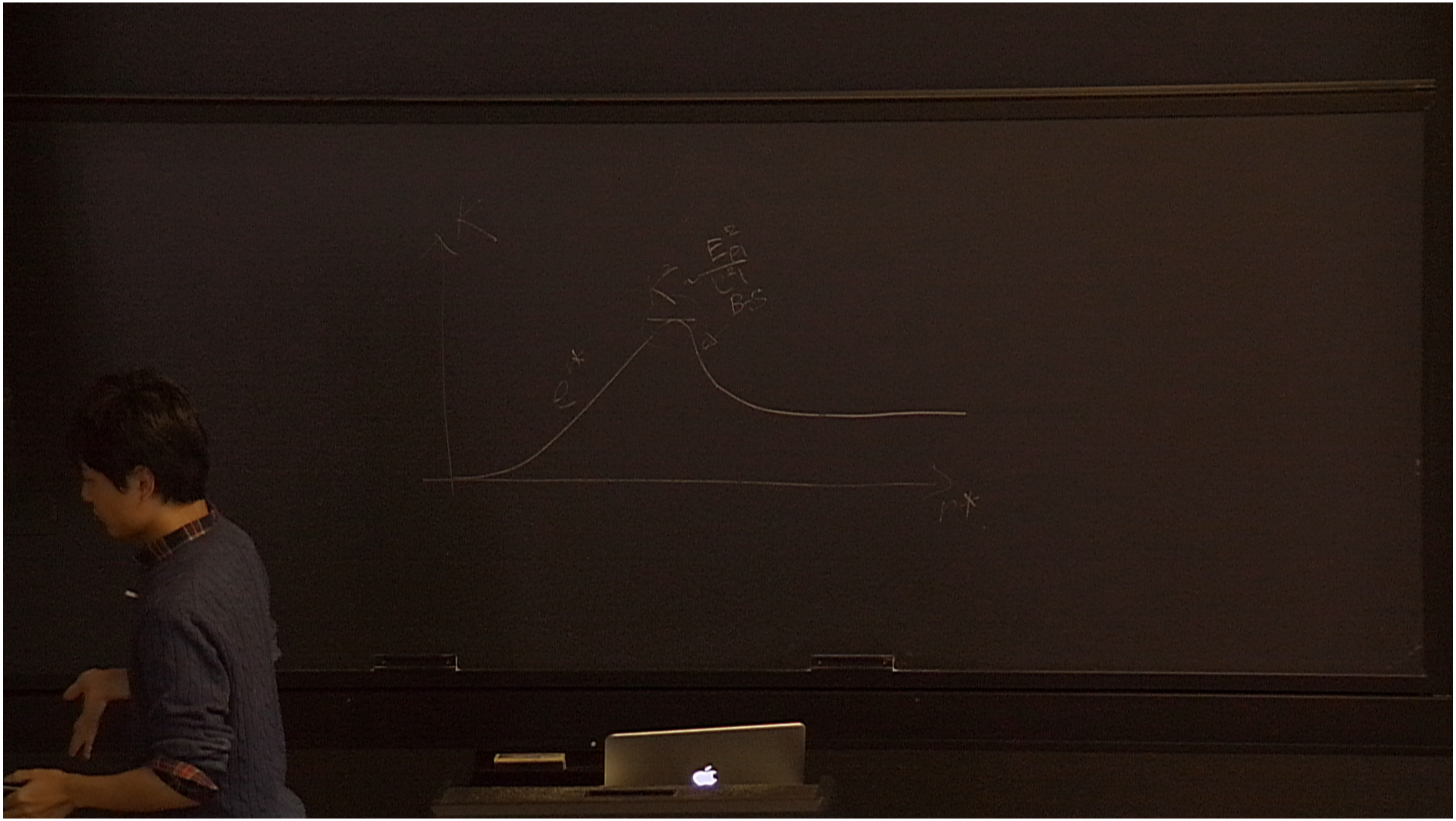
(boundary condition)

minimum size of space

$$\delta L \gtrsim |C|\ell_{\rm Pl}$$

upper bound for wavenumber

$$K \lesssim E_{\rm Pl}/|C|$$



Solving the modified RW equation

$$\left[-\frac{C^2}{M_{\rm Pl}^2}\frac{1}{1-r_g/r}\partial_{r*}^4+\partial_{r*}^2+\omega^2-V(r)\right]\tilde{\psi}(\omega,r^*)=0 \qquad \tilde{\psi}(\omega,r^*)=\sum_{n=0}^{3}C_n\phi_n$$

$$\Big\downarrow \; r^*\to-\infty$$

$$\left[-\frac{C^2 e}{M_{\rm Pl}^2}e^{-r^*/r_g}\partial_{r*}^4+\partial_{r*}^2+\omega^2-V(r)\right]\tilde{\psi}(\omega,r^*)=0$$

solution

$$\phi_n(\omega,r^*)=\left(\frac{r^*}{r_g}\right)^n+\epsilon(r^*)f_n(r^*,r_g\omega)+\mathcal{O}(\epsilon^2) \qquad n=0,1,2,3$$

power law

$$\epsilon(r^*)=e^{r^*/r_g}\frac{r_g^2}{eC^2\ell_{\rm Pl}^2} \qquad |\epsilon(r^*)|<1$$

f_n : quartic function of r^*

substitute boundary condition $K \lesssim E_{\rm Pl}/|C|$

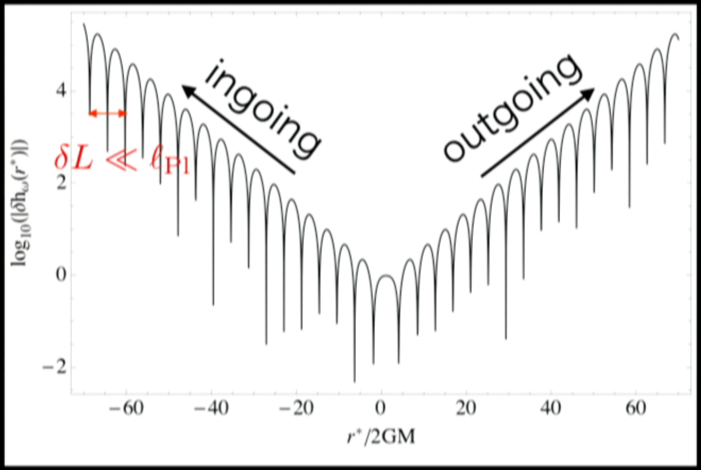
$$K \sim \phi_n^{-1}\partial_L \phi_n \simeq e^{-r^*/2r_g}\phi_n^{-1}\partial_{r^*}\phi_n \simeq \begin{cases} e^{-r^*/2r_g}/r^* & n=1,2,3 \\ e^{+r^*/2r_g}/r_g & n=0 \end{cases}$$

divergence ($n=1,2,3$)

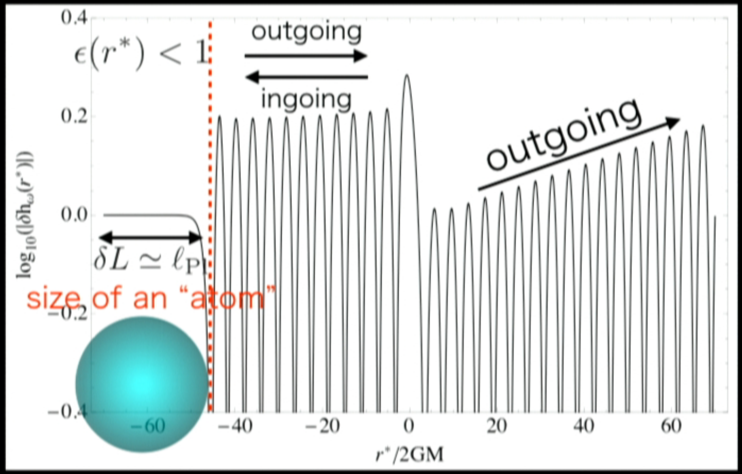
suppressed ($n=0$)

$$\phi_n(\omega, r^*) = \left(\frac{r^*}{r_g}\right)^n + \epsilon(r^*) f_n(r^*, r_g\omega) + \mathcal{O}(\epsilon^2)$$

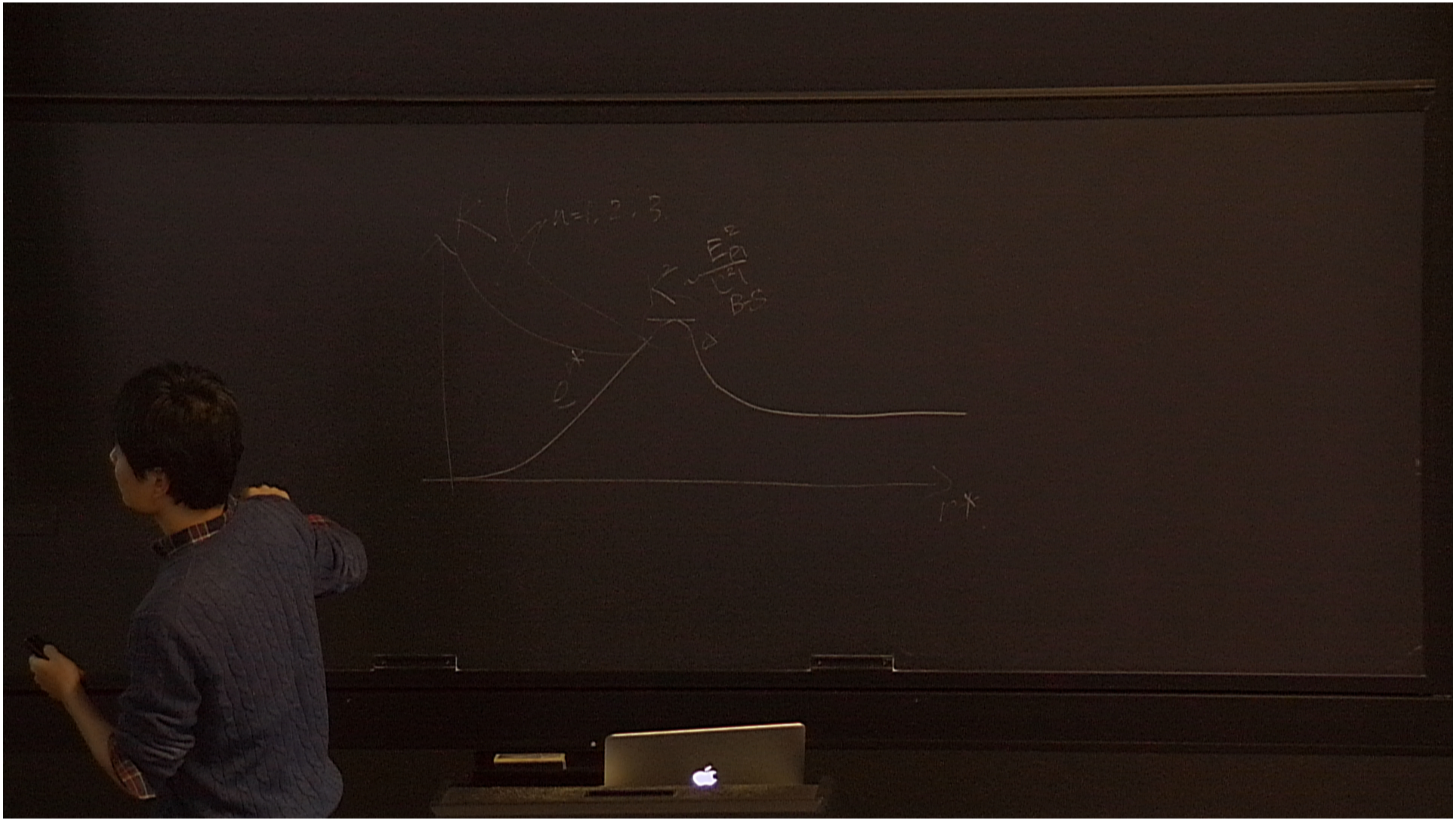
$$\epsilon(r^*) = e^{r^*/r_g}\frac{r_g^2}{eC^2\ell_{\rm Pl}^2} \qquad |\epsilon(r^*)| < 1$$



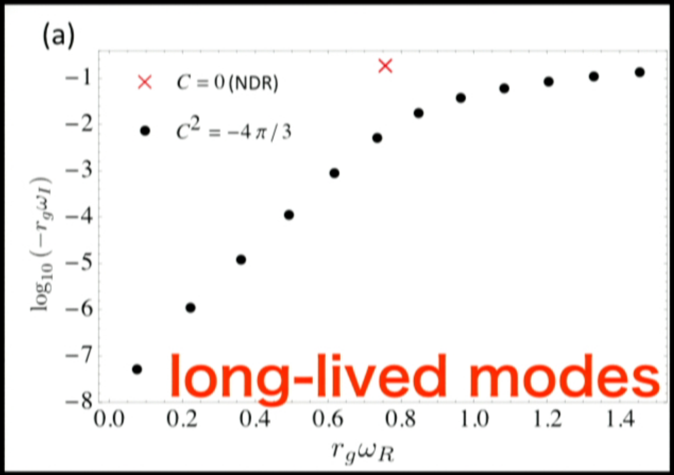
$$\lim_{r^*\to-\infty}\tilde{\psi} = e^{-i\omega r^*}, \quad \lim_{r^*\to\infty}\tilde{\psi} = e^{+i\omega r^*}$$



$$\lim_{r^*\to-\infty}\tilde{\psi} = \text{const.}, \quad \lim_{r^*\to\infty}\tilde{\psi} = e^{+i\omega r^*}$$



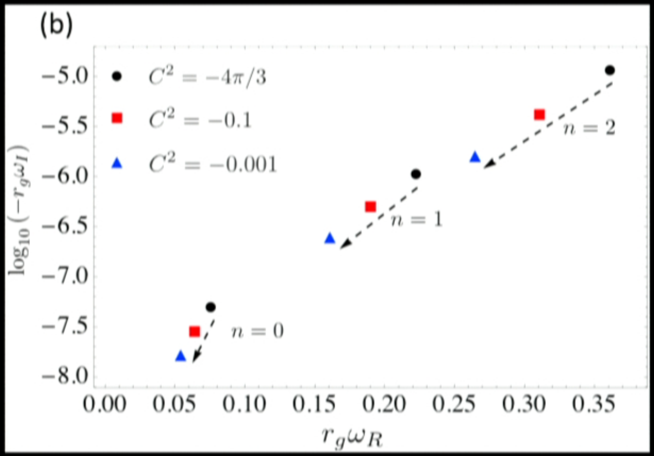
QNMs with modified DRs

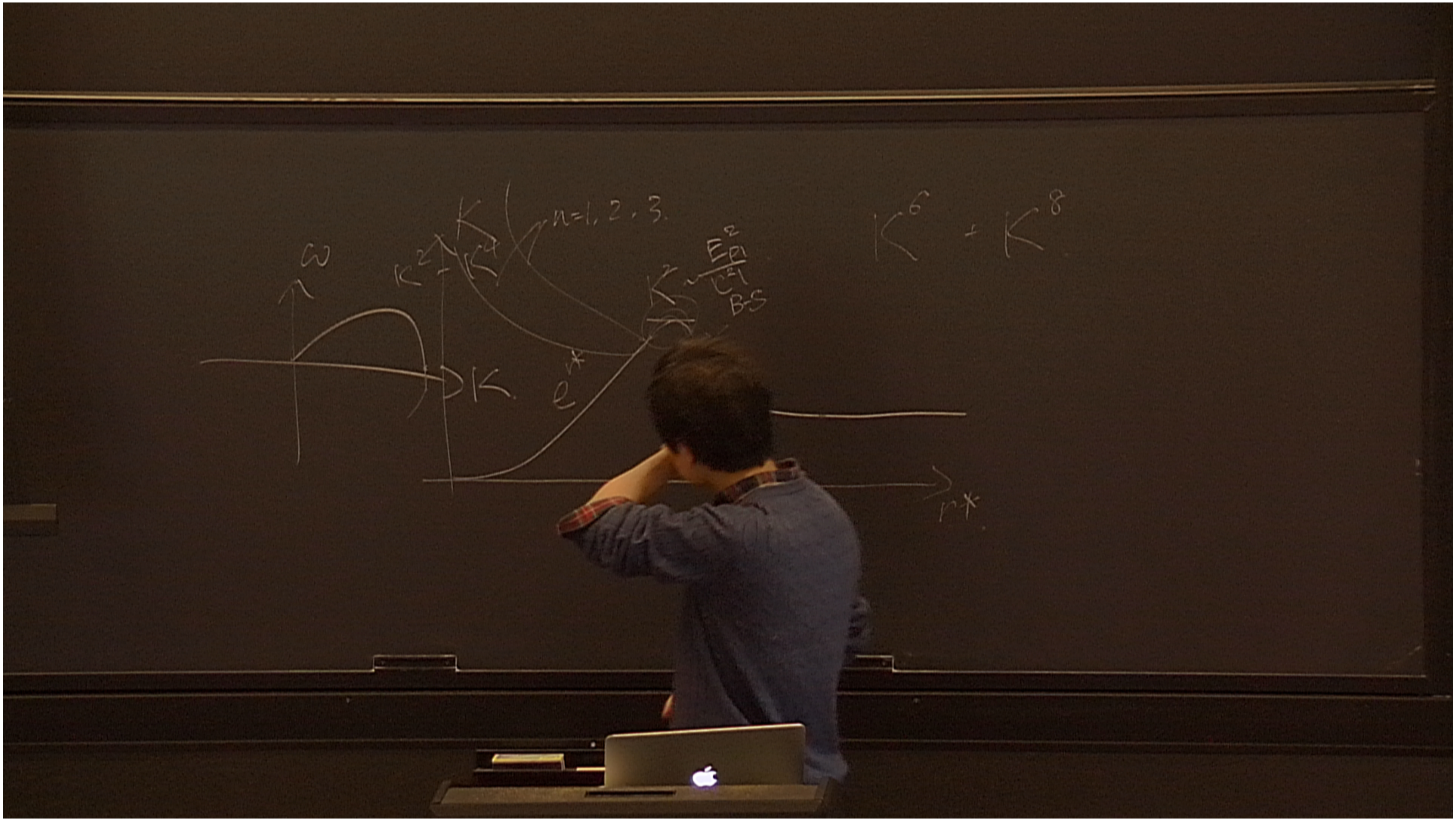


smaller microstructure

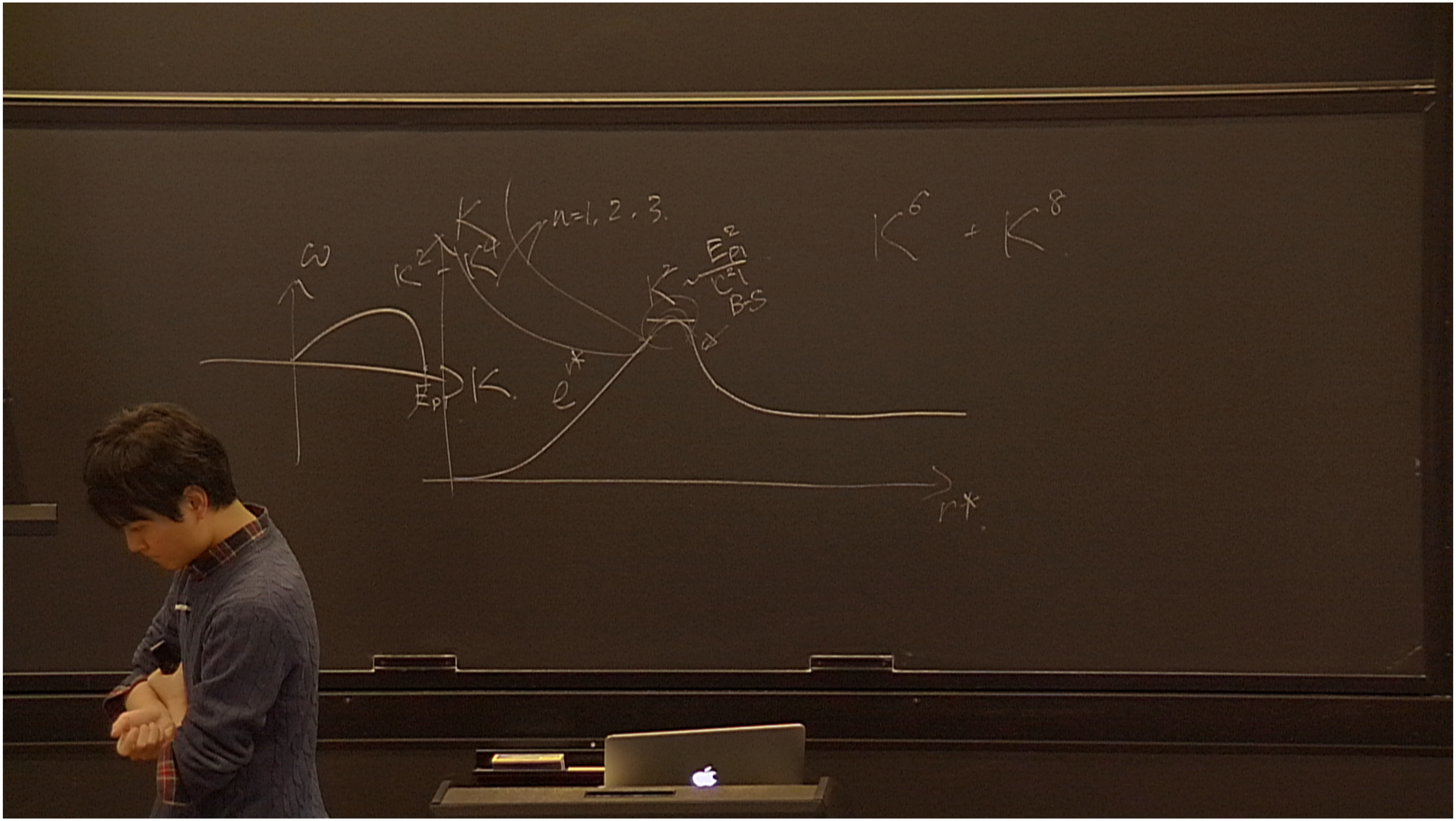
⇕

more long-lived QNMs

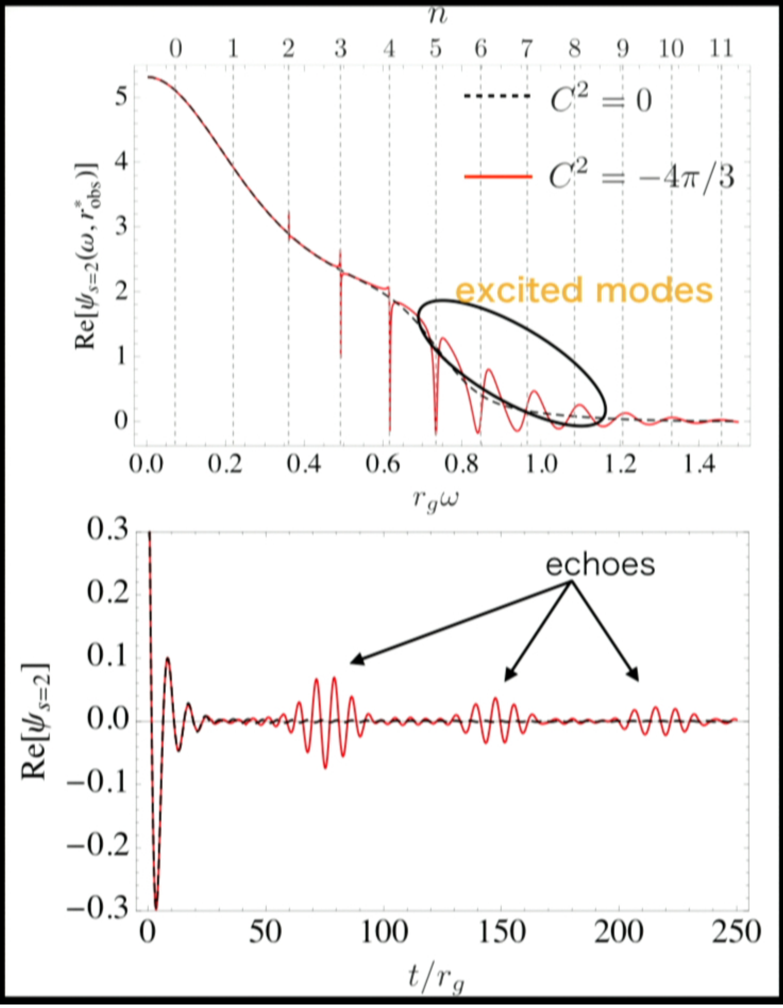




ω
K
$n=1,2,3.$
$K^2 \sim K^4$
$K^2 \sim \frac{E_{pl}^2}{c^2 l}$
B-S
$K^6 + K^8$
e^{r^*}
$K.$
r^*


ω
K
n=1, 2, 3.
K^2 + K^4
E_Pl
C^2 l
B-S
E_Pl > K.
e^{r*}
K^6 + K^8
r*

Supporting evidence of atoms of spacetime
- echoes from a black hole -



Supporting evidence of atoms of spacetime
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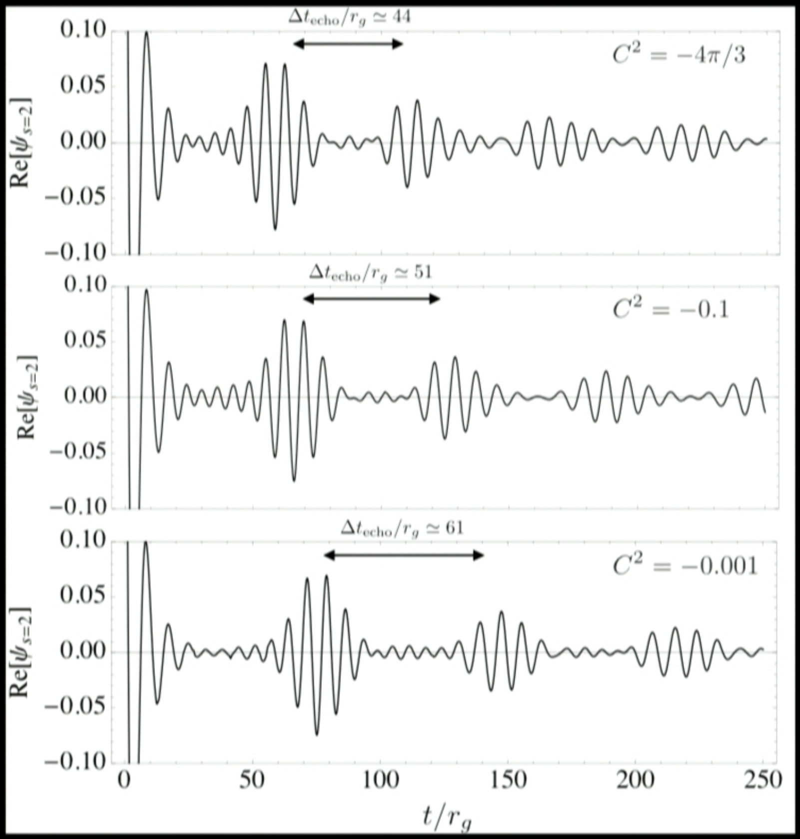
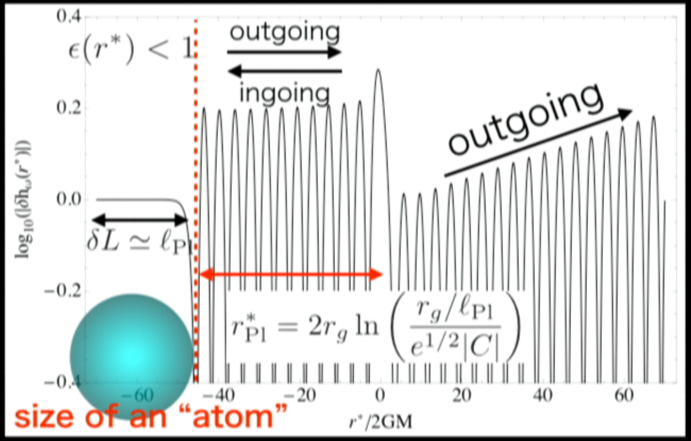


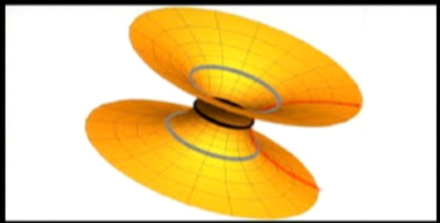
$$\Delta t_{\rm echo} \equiv 4 r_g \ln\left(\frac{r_g/\ell_{\rm Pl}}{e^{1/2}|C|}\right)$$



Probing atoms of spacetime with BH ringdowns

Previous works show that a ECHO-signal can be a probe of the Exotic Compact Objects (ECOs) which imitate black holes.

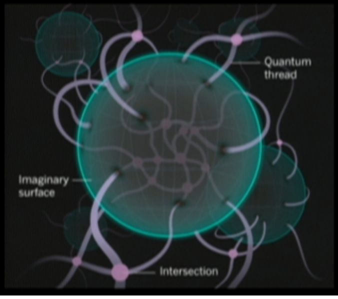
e.g. wormhole, gravaster, mirror, firewall etc



Cardoso et al. PRL (2016)

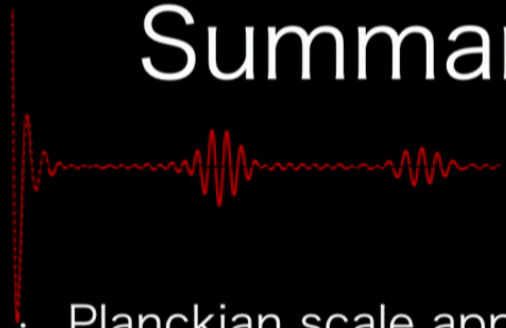
Our work implies that the non-trivial dispersion relation of quantum gravity can be testable with ringdown GWs.

e.g. **loop quantum gravity, Horava-Lifshitz Gravity** etc



non-trivial dispersion relation

Summary & Conclusions



- Planckian scale appears near a horizon.
- We can model the microscopic structure of spacetime by modifying its dispersion relation
- NO ingoing modes (NO oscillatory solution) near the horizon → boundary condition changed there
- Then, quantum gravity can be testable with ringdown-GWs from a black hole.